International Committee for Future Accelerators

Sponsored by the Particles and Fields Division of IUPAP

# Beam Dynamics Newsletter

No. 77

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# 1. FOREWORD

## 1.1 From the Chair

Ingo Hofmann, GSI/TUD

This Newsletter is dedicated to our esteemed colleague Prof. Yong Ho Chin, who passed away in January 2019. Yong Ho Chin was a distinguished accelerator physicist, who had served as chair of the ICFA Beam Dynamics Panel since 2016. The Panel is especially grateful to its member Dr. Yoshihiro Shobuda from J-PARC for having taken responsibility to edit this special edition.

Some news about ICFA itself: The ICFA Board had its second meeting in 2019 in Toronto on August 7, which was embedded in the *29th International Symposium on Lepton Photon Interactions 2019 at High Energies* (`https://indico.cern.ch/event/688643/overview`) from August 5-11. Panel chair persons are asked to attend this meeting (not necessarily every time) and report about past and ongoing activities of their panel - so I took the chance this time to attend. The current ICFA chair, Geoffrey Taylor, gave a *summary about the ICFA-meeting* (`https://indico.cern.ch/event/688643/timetable/#20190810.detailed`) on the final day of the *Lepton Photon Symposium*. As a small feedback: when summarizing some of the panels, Taylor particularly emphasized the remarkable number of workshops under the umbrella of the Beam Dynamics Panel as well as the impressive amount of work that has entered into the Beam Dynamics Newsletters over a long period of time.

As already in its previous meeting at the University of Tokyo in March 2019, the central topic of this ICFA-meeting has been again about the "political" prospects of how to realize the International Linear Collider. Note that the currently discussed ILC250 is the new version, which has a total collision energy of 250 GeV - reduced from the original 500 GeV for cost and time saving reasons. Its scientific mission is now clearly understood as "Higgs factory" to enable precision experiments around the Higgs particle (self-coupling etc.). Hope has not yet been given up that Japan, as host country of this international endeavor, would take a positive decision soon. The yet pending situation sets coordination of Japanese plans with the European plans regarding CLIC and FCC increasingly under pressure. On this matter Japanese Officials have undertaken consultations with the European partners, besides the already established consultations with the US. Decisions on the *European Strategy for Particle Physics* are coming closer and are expected to start - step by step - with the beginning of 2020 until final decisions mid-2020.

As far as upcoming ICFA meetings, we are glad to announce the following events for 2019:

- The 63rd ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs (ERL2019), September 15-20, 2019 in Berlin, Germany. It is the eighth of the series of international workshops covering accelerator physics and technology of energy recovery linacs. See `https://www.helmholtz-berlin.de/events/erl19/index_en.html`

- ICFA Mini-Workshop on Mitigation of Coherent Beam Instabilities in Particle Accelerators (MCBI), September 23-27, 2019, in Zermatt, Switzerland. See `https://indico.cern.ch/`

`event/775147/`

- ICFA Mini-Workshop on Design of Synchrotron Light Sources, October 28-30, 2019 in Mexico City, Mexico. This is the first workshop of this kind to support the development of Synchrotron Light Sources in this region.
- ICFA Mini-Workshop on Space Charge, November 4-6, 2019 at CERN, Switzerland. This workshop is the fourth of this series since 2013.

For 2020 the ICFA Board has already endorsed:

- The 64th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders (eeFACT2020), Sept. 14-16, 2020 on Elba, Italy (organized by INFN-LNF) as follow-up to eeFACT18.
- The 65th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (HB2020), September 28-October 2, 2020 at FNAL, Batavia, USA. It is the 10th event of this series since 2002 as primary beam dynamics conference for this community.

For the present Newsletter #77 our thanks go to Yoshihiro Shobuda as editor. Thematically it is dedicated to Yong Ho Chin, his personal achievements, in particular the MOSES code and the wider range of topics related to his work, which includes klystrons and feedback methods with application to J-PARC.

## 1.2 From the Editor

. Yoshihiro Shobuda, J-PARC/JAEA, Tokai, Japan

Prof. Yong Ho Chin at KEK, serving as an ICFA Beam Dynamics Panel Chair since 2016, unexpectedly passed away on January 8th, 2019. He was an outstanding scientist and had dedicated to serving the international accelerator physics community. In the last Newsletter # 76 (April 2019), several colleagues wrote their tributes for Yong Ho Chin (`http://www.icfa-bd.org/Newsletter76.pdf`). This Newsletter is a memorial issue in the honor of Prof. Yong Ho Chin containing a variety of articles on topics that he covered in his career.

His career in accelerator physicist started at KEK around 1981. In 1984, he received a PhD thesis from the University of Tokyo for his study at KEK on bunched beam instabilities. After graduation, he moved to CERN, where he met Dr. Bruno Zötter, one of the most renowned pioneers of theoretical accelerator physics. According to Yong Ho Chin, Bruno Zötter said that Yong Ho Chin could have been more successful if he had been born earlier (`https://www.gac-epa.org/History/Tributes/2016/Zotter-Bruno/Zotter-Bruno-en.html`). Nevertheless, he played an important role in discovering Transverse Mode Coupling Instabilities.

Yong Ho Chin developed two significant computer codes : MOSES (MOde-coupling Single bunch instabilities in an Electron Storage ring `http://abci.kek.jp/moses.htm`) in 1986 and ABCI (Azimuthal Beam Cavity Interaction `http://abci.kek.jp/`) in 1988, which are going to be served and maintained by KEK Computer Center almost permanently. These codes have been used worldwide in the past decades. MOSES code is a program that computes complex coherent betatron tune shifts as a function of the bunch current for a Gaussian beam. ABCI code is a computer program for impedance and wakefield calculations that solves the Maxwell equations directly in the time domain when a bunched beam goes through an axisymmetric structure on or off axis. In 2007, MOSES was successfully compared with the particle tracking simulation code HEADTAIL (`https://oraweb.cern.ch/pls/hhh/code_website.disp_code?code_name=HEADTAIL`), which is delineated in section 2.1 written by Drs. Elias Métral and Benoit Salvant from CERN.

In 1988, Yong Ho Chin became a staff scientist at LBNL, where he did some essential works on understanding 3D effects in FEL (Free Electron Laser). Together with Dr. Ming Xie (`https://physicstoday.scitation.org/doi/pdf/10.1063/1.1996493`) and Prof. Kwang-Je Kim, he developed a theory for calculating FEL gain based on Maxwell-Vlasov equations including the effects of the energy spread, the emittance, and the betatron oscillations of the electron beam.

After spending several years abroad, Yong Ho Chin moved back to KEK in 1994 and handled the development of X-Band PPM Klystron for JLC (Japan Linear Collider), which is the predecessor of today's ILC (International Linear Collider), as the X-Band RF Power Source group leader. This hardware work was performed in collaboration with a Japanese electronics company Toshiba and is specifically delineated in section 2.2 written by Mr. Osamu Yushiro *et al.* Mr. Yushiro, then a Toshiba staff member, is now the CEO of ScandiNova Systems K.K.(`https://scandinovasystems.com/`).

Feedback systems have recently become inevitable for both hadron and electron machines to cope with beam instabilities. For the hadron machine, Dr. John Fox from SLAC delineates the wide-band intra-bunch feedback for handling the beam instabilities at CERN in section 2.3, while in section 2.4 Dr. Takeshi Nakamura from SPring-8 explains the characteristics of the bunch-by-bunch feedback system for the electron machine.

In 2003, Yong Ho Chin became a member of the J-PARC Center, and in the same year, he served as the leader of the Impedance and Instability Group in J-PARC. Concerning this topic, the history of the development of the feedback system at the Main Ring of J-PARC is delineated in section 2.5 written by Prof. Takeshi Toyama from KEK, the leader of the Monitor Group at the Main Ring of J-PARC.

Besides his scientific contribution, Yong Ho Chin was dedicated to numerous service-related activities in the accelerator community. He was a member of the Scientific Program Committee for conferences and workshops including the LINAC conference and the HB workshop series. Since 1996, which was the pioneering time in electronic publication of conference proceedings, he was a JACoW (Joint Accelerator Conferences Website `https://www.jacow.org/`) team member and webmaster who maintained its Asian mirror site. Nowadays, the JACoW server plays an important role as an archive of previous conferences and workshops. Mrs. Christine Petit-Jean-Genaz at CERN, who was then a JACoW coordinator, pays her tribute in a section 2.6, in which she writes about the roles performed by Yong Ho Chin in the JACoW team.

Yong Ho Chin was a cheerful person, an excellent educator, and a mentor too, which made his lectures popular both in Japan and abroad. Outside Japan, he served as a lecturer at the Joint US-CERN-Japan-Russia Accelerator School in 1986 and 1988. In Japan, he taught accelerator physics at KEK as a professor of SOKENDAI (the Graduate University for Advanced Studies), and he also taught electromagnetism at the University of Tsukuba from 2001 to 2010.

We are honored to have had a chance to work with such a wonderful person.

Finally, this is my first opportunity to serve as the editor of ICFA Newsletter since I became a member of the ICFA Beam Dynamics Panel. I would like to express my gratitude to Prof. Dr. Ingo Hofmann from GSI/TUD, Drs. Chris Prior from STFC, Elias Métral from CERN, John Fox from SLAC, and all contributors for their help and efforts to publish this issue.

# 2. YONG HO CHIN'S ACHIEVEMENTS AND RELATED TOPICS

## 2.1 Yong Ho Chin's MOSES code and its impact on beam dynamics studies for the CERN LHC complex

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### 2.1.1 Introduction

Leading accelerator physicist Yong Ho Chin passed away on January 8th 2019. His career left a long list of major contributions to the field of beam coupling impedance and related beam stability.

As an example, he left the famous MOSES code as legacy [1]. MOSES is a rather far-fetched acronym for MOde-coupling Single bunch instability in an Electron Storage ring. It computes complex coherent betatron tune shifts as a function of bunch current for a beam coupling impedance modelled as a resonator. Yong Ho Chin wrote the first version of this computer program in 1986 [2], and made a major update in 1988 [3].

An example of successful application of MOSES to high energy protons 2 decades after the code was written is given here as a recognition of the importance of Yong Ho Chin's contribution for the field of accelerators.

### 2.1.2 The birth of MOSES in the 1980s

MOSES implements a mode coupling formalism, which was developed to explain fast transverse instabilities that were observed in electron storage rings in the beginning of the 1980s and were limiting their beam current [4]. The formalisms available at the time for the transverse plane were two-particle models and implementations of Sacherer methods at low intensity that assume that betatron oscillation modes - so-called head-tail modes - are independent [5]. Mode coupling was first described by R. Kohaupt for the transverse instability at PETRA accounting for positive azimuthal modes of oscillations [6], while the MOSES formalism also includes negative azimuthal modes and higher order radial modes [4]:

- The Vlasov equation with transverse deflecting force and chromaticity is linearized with respect to the perturbation.

- The resulting relation for small dipole oscillations with mode coupling is expanded into Fourier series of azimuthal mode numbers.

- The resulting Sacherer integral equation for a longitudinal Gaussian distribution can be further expanded into series of radial modes to obtain a matrix eigenvalue equation, which can be solved numerically [7].

Yong Ho Chin applied that formalism to PETRA, PEP and TRISTAN [4], and he visited CERN in the mid-1980s after he obtained his PhD. It is at this occasion that he implemented the formalism into the MOSES code [2] and applied it to the CERN Super Proton Synchrotron (SPS) as proton-antiproton collider and as lepton injector into the Large Electron-Positron Collider (LEP) [7]. He found out that the coupling of the modes is much weaker with long proton bunches, which explained the absence of observation of fast instability in the SPS at the time, while the transverse mode-coupling instability (TMCI) would be limiting the SPS performance when operating as an electron injector for LEP.

It has to be noted that the second version of MOSES accounts for betatron tune spread (with the formalism described in [8]) but neither versions account for the impact of space charge forces, which are not negligible for the case of the SPS with protons (see for instance recent studies in [9, 10]).

Incidentally, reading through the MOSES user guides [2, 3] highlights the computational challenges that scientists were facing at the time, which are quite difficult to imagine nowadays.

### 2.1.3 MOSES as benchmark in the new millennium

Following these studies in the mid-1980s, computational power and programming techniques improved drastically, so that it became possible in the beginning of the new millennium to routinely simulate the interaction of millions of macroparticles with an impedance source over many machine revolutions thanks to - for instance - the HEADTAIL code [11].

Furthermore the SPS was to be used as a proton injector for the CERN Large Hadron Collider (LHC), and its performance reach was probed before the LHC started, in view of the upcoming installation of new extraction kickers. Once the microwave instability could be mitigated by a significant impedance reduction campaign in 2001, a fast vertical instability was observed far from transition with a high intensity proton bunch right after its injection when the longitudinal emittance and vertical chromaticity was low enough [12]. At the time, the transverse damper system was not designed to damp single bunch instabilities and was therefore not used.

MOSES was used as benchmark for the HEADTAIL macroparticle simulations and the measurements with the SPS beam and a very good agreement was found for the instability thresholds [13]. The installation of new extraction kickers was found to be a threat to SPS operation and a mitigation was initiated as a consequence of these studies.

In addition, complex tune shifts for each azimuthal and radial mode were computed from MOSES as a function of beam current for an SPS bunch interacting with the impedance of a round beam chamber modelled as a resonator impedance (see Fig. 1 and 2), and were compared to a precise frequency analysis of the coherent motion simulated with HEADTAIL of a Gaussian SPS bunch with the same parameters interacting with the same impedance (see Fig. 3 and 4 as well as detailed MOSES and HEADTAIL parameters in [14]). The remarkable agreement between theory and macroparticle simulations of the shifts of many azimuthal and radial modes as well as the observation of the coupling-decoupling pattern of azimuthal modes 0 and -1 observed when increasing intensity attests the predictive power of the MOSES code, of its underlying formalism and its ability to solve complex problems.

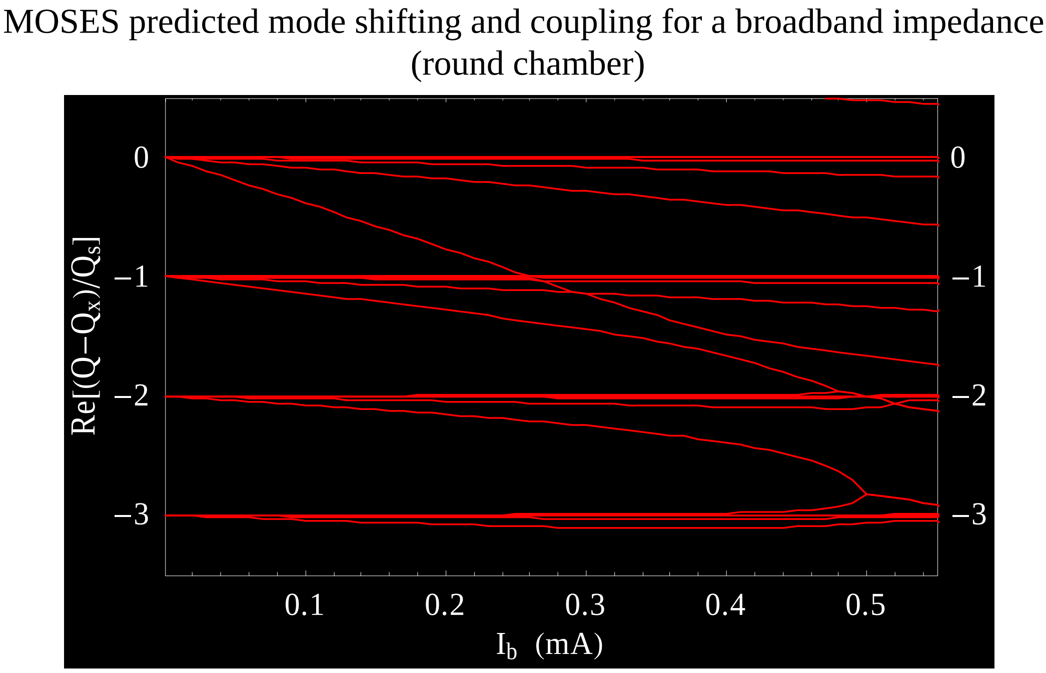


Figure 1: Real part of the transverse mode spectrum of the bunch (from azimuthal mode 0 to azimuthal mode -3) as a function of the bunch intensity $I_b$ computed with MOSES for the LHC bunch in the SPS at injection (see [14] for detailed MOSES parameters). The transverse mode spectrum is shown as a shift $Q - Q_x$ from the unperturbed betatron tune $Q_x$ and normalized to the synchrotron tune $Q_s$.

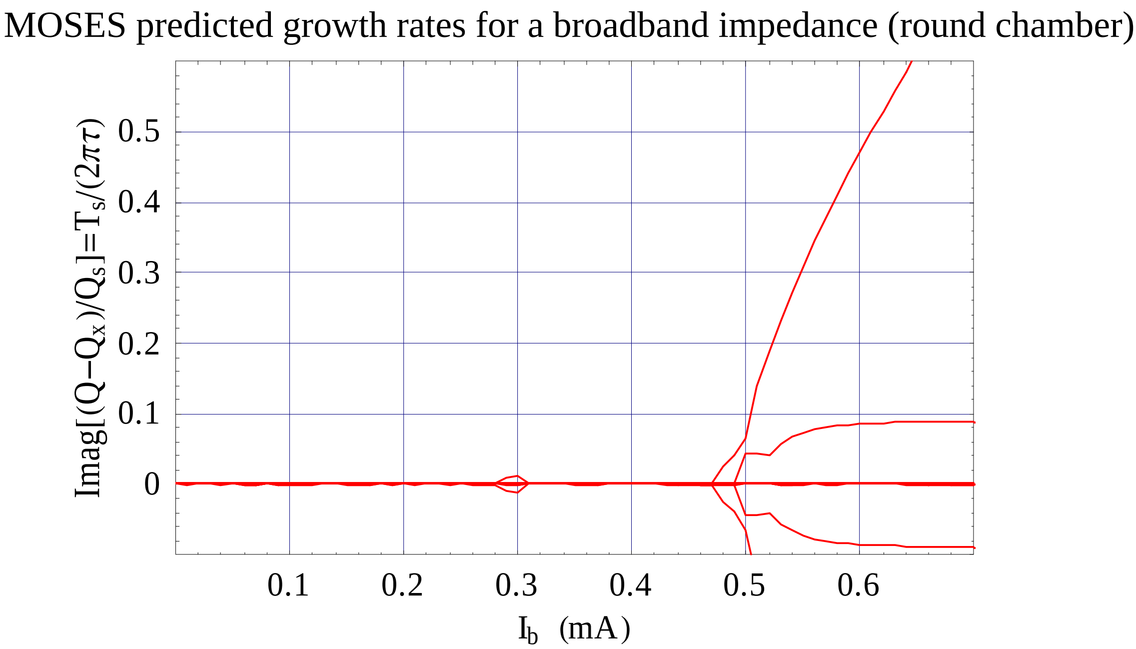


Figure 2: Imaginary part of the transverse mode spectrum of the bunch as a function of the bunch intensity $I_b$ computed with MOSES for the LHC bunch in the SPS at injection (see [14] for detailed MOSES parameters). The transverse mode spectrum is shown as a shift $Q - Q_x$ from the unperturbed betatron tune $Q_x$ and normalized to the synchrotron tune $Q_s$.

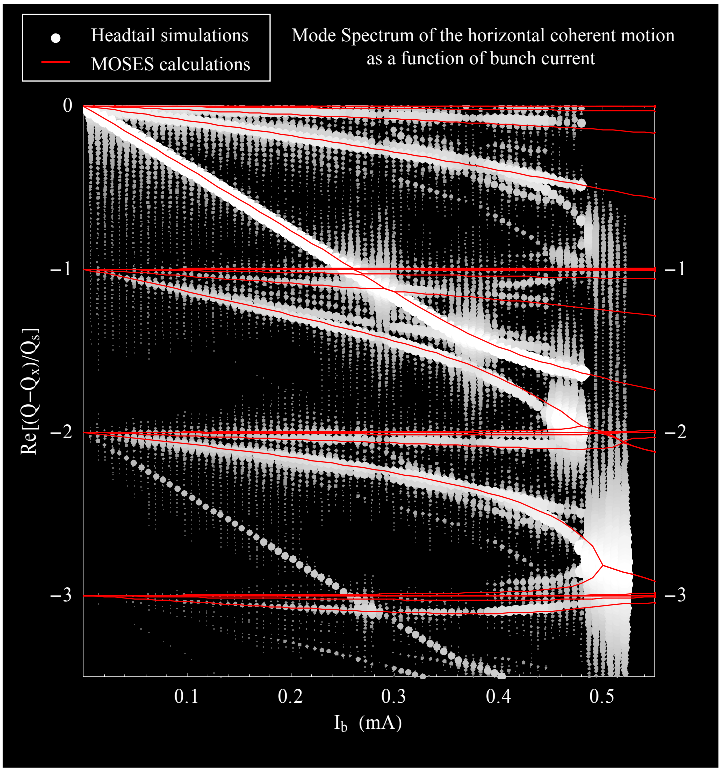


Figure 3: Comparison of the real part of mode spectra as a function of intensity computed with HEADTAIL simulations (white dots) and MOSES theoretical calculations (red lines). The size and brightness of the white dots are growing non-linear functions of their spectral amplitude. See [14] for detailed MOSES and HEADTAIL parameters.

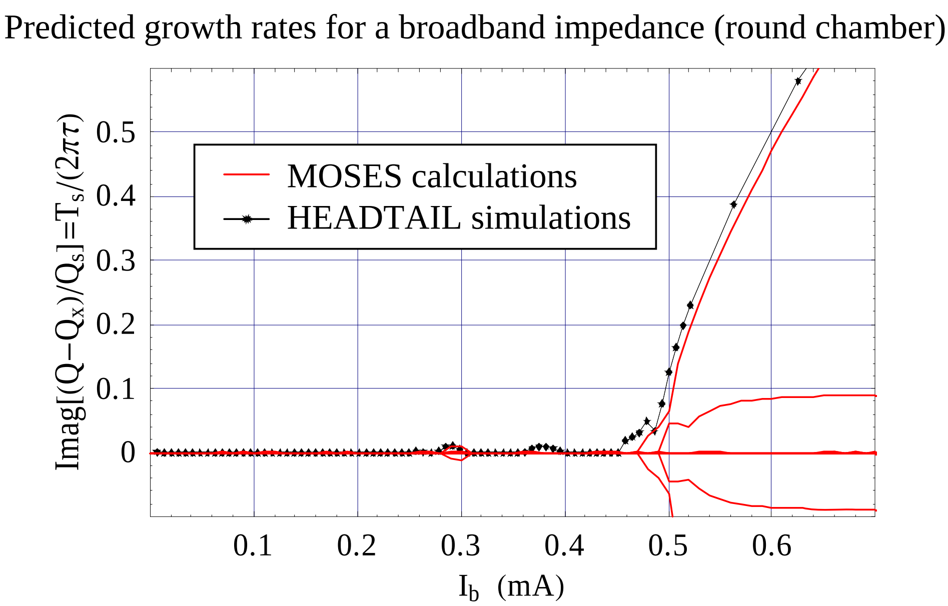


Figure 4: Comparison of the imaginary part of mode spectra as a function of intensity computed with HEADTAIL simulations (black line) and MOSES theoretical calculations for each mode (red lines). See [14] for detailed MOSES and HEADTAIL parameters.

Several beam measurements campaigns were performed and confirmed the mechanisms predicted by the MOSES code and HEADTAIL simulations for both simple and more realistic impedance models [14, 15]. Efficient mitigations could be found thanks to these studies: shielding of the ferrite of the extraction kickers to reduce impedance as well as a change of the optics to reduce transition energy and push the instability threshold [15].

Despite all the improvements in computational power and tools, macroparticle simulations of multibunch instabilities still require a significant amount of resources and the predictive power of analytical solutions of Vlasov/Vlasov Fokker Planck equations is of crucial importance to the accelerator physics community. Recent advances have taken place and are taking place in the wake of the MOSES code and other related formalisms to include e.g. any type of frequency dependent impedance contributions [16], the impact of transverse damper [17] and synchrotron radiation damping and diffusion [18]. Fundamental phenomena at the source of observed instabilities were recently unveiled by such theoretical approaches, in particular the destabilizing effect of linear coupling and transverse damper [19, 20].

### 2.1.4 Outlook

Yong Ho Chin is greatly missed by all his accelerator physics friends at CERN, from the distinguished colleagues he interacted with in the mid-1980s to the younger colleagues he was collaborating with in the last months. He was always kind, respectful, ready to share knowledge and discuss ideas with us. As for the example of MOSES reported here, his important contributions to the field will continue to have a large impact on our community for many years.

### Acknowledgments

The authors thank G. Arduini and N. Mounet for reviewing the manuscript, as well as K. Hübner and M. Schenk for sharing their experience of collaborating with Yong Ho Chin.

### References

[1] Y. H. Chin, “MOSES Home Page”, `http://abci.kek.jp/moses.htm`

[2] Y. H. Chin, “MOSES Users’ Guide (MOde-coupling Single bunch instability in an Electron Storage ring)”, CERN Report CERN/SPS/86-2 DI-MST (1986).

[3] Y. H. Chin, “User’s Guide for New MOSES Version 2.0 (MOde-coupling Single bunch instability in an Electron Storage ring)”, CERN Report CERN/LEP-TH/88-05 (1988).

[4] K. Satoh and Y. H. Chin, “Transverse Mode Coupling in a bunched Beam”, Nuclear Instruments and Methods 207 (1983) 309-320.

[5] E. Métral, “Overview of Single-Beam Coherent Instabilities in Circular Accelerators”, proceedings of the 1st CARE-HHH-APD Workshop on Beam Dynamics in Future Hadron Colliders and Rapidly Cycling High-Intensity Synchrotrons, Geneva, Switzerland (2004).

[6] R. D. Kohaupt, “Head Tail Turbulence and the Transverse PETRA Instability”, DESY 80/22, 1980.

[7] Y. H. Chin, “Transverse Mode Coupling Instabilities in the SPS” CERN Report CERN/SPS/85-2 DI-MST (1985).

[8] Y. H. Chin, K. Satoh and K. Yokoya, “Instability of a bunched beam with synchrotron-frequency spread”, Particle Accelerators, Vol. 13, 45-66 (1983).

[9] A. Oeftiger, “SPS Impedance-driven Instability with Space Charge”, presented at the 163rd CERN BE-ABP/HSC section meeting, (2018). `https://indico.cern.ch/event/778893/contributions/3241191/attachments/1768019/2871838/oeftiger_TMCI_SPS_SC.pdf`

[10] Y. H. Chin, A. W. Chao and M. Blaskiewicz, “Two particle model for studying the effects of space-charge force on strong head-tail instabilities”, Phys. Rev. Accel. Beams 19, 014201 (2016).

[11] G. Rumolo and F. Zimmermann, “Practical user guide for HEADTAIL”, CERN SL-note 2002-036-AP (2002).

[12] G. Arduini, E. Benedetto, H. Burkhardt, E. Métral, G. Rumolo, “Observation of a Fast Single-Bunch Transverse Instability on Protons in the SPS”, Proceedings of EPAC 2004, Lucerne, Switzerland (2004).

[13] E. Métral, G. Arduini, E. Benedetto, H. Burkhardt, G. Rumolo, E. Shaposhnikova. “Transverse mode-coupling instability in the CERN-SPS”, Proceedings of the ICFA Workshop on High Brightness and High Intensity Beams, 18-22 October, Bensheim, Germany (2004).

[14] B. Salvant, “Impedance model of the CERN SPS and aspects of LHC single-bunch stability”, EPFL PhD thesis number 4584, Switzerland (2010).

[15] H. Bartosik, “Beam dynamics and optics studies for the LHC injectors upgrade”, CERN-THESIS-2013-257 (2013).

[16] N. Mounet, “Vlasov Solvers and Macroparticle Simulations”, Proceedings of ICFA Mini-Workshop on Impedances and Beam Instabilities in particle accelerators, Benevento, Italy, 18 - 22 Sep 2017, pp.77-85 (2018).

[17] A. Burov, “Nested Head-Tail Vlasov Solver”, Phys. Rev. ST AB 17, 021007 (2014).

[18] R. R. Lindberg, “Fokker-Planck analysis of transverse collective instabilities in electron storage rings”, Phys. Rev. Accel. Beams 19, 124402 (2016).

[19] L. R. Carver *et al.*, “Transverse beam instabilities in the presence of linear coupling in the Large Hadron Collider”, Phys. Rev. Accel. Beams 21, 044401 (2018).

[20] E. Métral *et al.*, “Destabilising Effect of the LHC Transverse Damper”, in Proc. IPAC’18, Vancouver, Canada, Apr.-May 2018, pp. 3076-3079 (2018).

## 2.2 Memorial Paper for Prof. Yong Ho Chin of Klystron development work

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### 2.2.1 Introduction

First of all, we would like to express our heartfelt condolences over the passing of Y. H. Chin. We are honored to have the opportunity to express our deep admiration for Chin's work in the field of klystron development. We would like to report on the development history of Chin's X-band klystron and L-band multi-beam klystron at KEK.

One of the authors S. Miyake was co-developer with Chin from the very early stage of the project at Toshiba. K. Takata was involved in klystron development at KEK since 1980's. V. Vogel was in charge of L-Band MKB from the actual performance point of view. O. Yushiro is currently working at ScandiNova Systems K.K., but he used to work at Toshiba since 1986, where he worked with Chin 1999 onward.

### 2.2.2 The development project of the X-band Klystron : JLC

In 1986, the R&D program of the JLC (Japan e + e-Linear Collider) project [1] was officially launched as a plan for KEK. The accelerator parameter of the central mass energy was 0.5 TeV, and an extension to 1 TeV was also planned for the future (Figure 1) [2]. One of the RF source candidates was an X-band klystron with 75 MW output power and 1.5 ms pulse width, and it was designed to use more than 3000 units of X-band klystrons. In response to this strategy, the development of the X-band klystron started at KEK in collaboration with Toshiba. On the other hand, KEK made an agreement between SLAC and BINP for the development of the X-band klystron, and they were exploring the best design solutions together.

[1] current company name is changing to "Canon Electron Tubes & Devices"

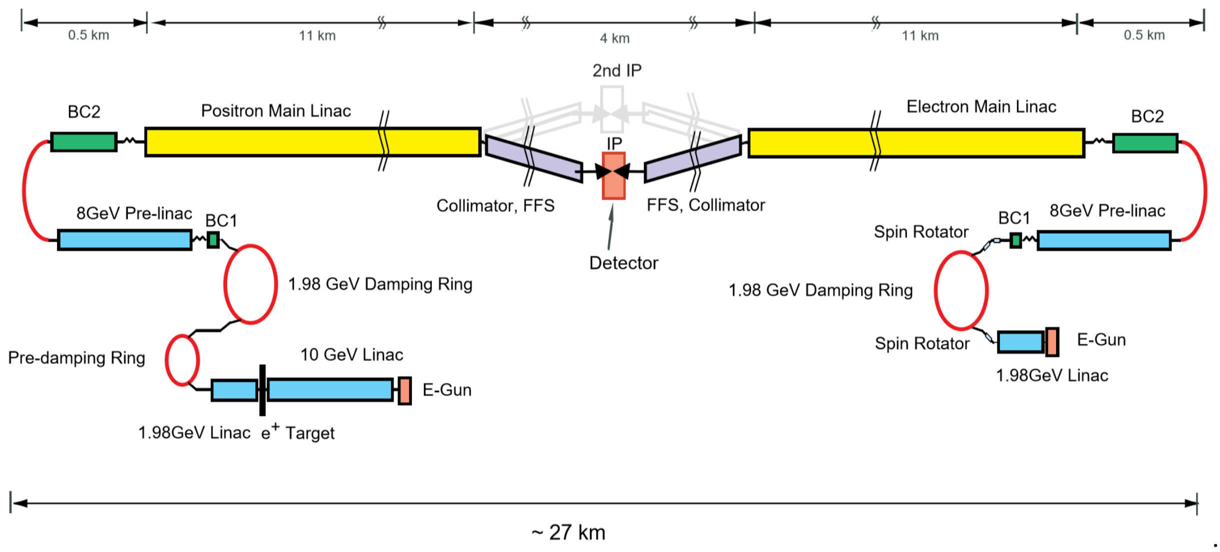


Figure 1: Schematic layout of JLC [2]

### 2.2.2.1 Y. H. Chin's development results

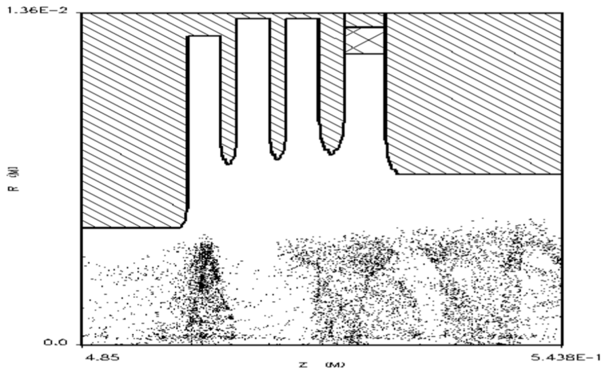


Figure 2: An example of MAGIC of output structure

The development of the X-band klystron, which began in 1986, started from the 50-MW specification and was promoted as E3715 (Toshiba model number)/XB-50 (KEK name). In the subsequent model E3716/XB-72K (late 1990s), several improvements were made, and an output power of 60 MW was confirmed [3]. This resulted in the optimum design of the TW mode output cavity with the adopted PIC (Particle-In-Cell) code and MAGIC. Chin was deeply involved in the development of a simple-minded theory for a constant group/phase velocity TW structure [3].

On the other hand, the power consumption of the focusing coil was 24 kW against the klystron average power of 3.75 kW (50 MW, 1.5 $\mu$s, 50 pps); the mean net efficiency including the focusing coil was quite low. Therefore, in order to make the JLC project realistic, it was essential to reduce the power consumption and operating costs. Under the initiative of KEK, the development of PPM (Period Permanent Magnet) X-band Klystron started in collaboration with BINP around 1997, and Chin was appointed as the head of KEK for this work. The first BINP PPM X-band Klystron was delivered to KEK in 1998, and it confirmed an output power of up to 54 MW. However, when the pulse width was more than 30 ns, unstable phenomena were observed [3]. In those days, PPM was used in travelling wave tube (TWT) devices for commercial usage with kW-output power. This meant that the PPM focusing klystron in MW-level power was quite a challenge to develop. Chin first started with a trial production of PPM. Along with the selection of magnet manufacture, a manufacturing problem was solved by making a 1/4 size model and a prototype of a real size model compatible with the magnetic field. Simultaneously, the Toshiba and KEK/BINP team started a detailed design of the first PPM X-band Klystron. Since KEK had the PIC/MAGIC know-how, KEK/BINP took charge of the detailed design of the cavity, and Toshiba took charge of the manufacturing design. The initial test results of the first PPM X-band klystron (PPM-1) reached 56 MW, 1.5 $\mu$s, 5 pps and 68 MW, 300 ns, 5 pps, 47% (efficiency), but the test was interrupted because of window cracking. After this head start in the first PPM klystron development, PPM-2 klystron development started in 2000 with some modifications. The main modifications were klystron body cooling, dimension change at the gun section, and the mixed mode window, which can sustain transmitted RF power of more than 100 MW. This mixed mode window was tested at KEK in advance for 80 MW with 1.5 $\mu$s duration at a 30-Hz repetition at the resonant ring. The PPM-2 klystron produced 73.2 MW at 1.4 $\mu$sec pulse with 56% efficiency (Figures 3 and 4) [2, 4].

After the development of PPM-1 and PPM-2, KEK prepared a budget for a two-year plan. With the cooperation of BINP, Chin decided to adopt the second harmonic cavities in order to improve the efficiency of the PPM-3 klystron. Development performance was set to 75 MW, 1.5 $\mu$s, and 100 pps. In the subsequent PPM-4, it was expected that the pulse width would be extended up to 3 $\mu$s. Although PPM-3 had an unexpected cavity oscillation and window breakage, the following data were verified: 65 MW, 1.5 $\mu$s, 50 pps, and 53%. On the other hand, PPM-4 changed the design based on these results, removed the second harmonic cavity, added window improvement (TE01) and so on, so it finally achieved 77 MW, 1.6 $\mu$s, and 50 pps [4]. Chin thus laid the foundation for the future of JLC.

Figure 3: PPM-1 (right)/PPM-2(left)

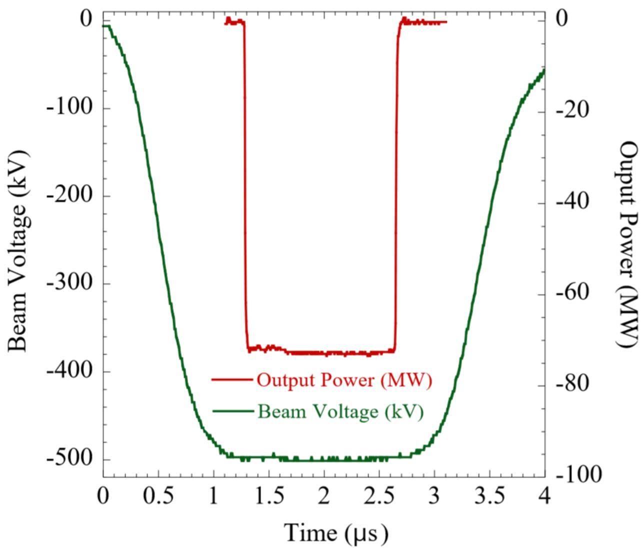


Figure 4: PPM-2 pulse shape for 73 MW

#### 2.2.2.2 Technology Choice

KEK proposed a linear collider with normal conduction technology (X band/C band). However, from the second half of 1990 to 2000, the US, Russia, and Europe began to advocate the linear collider project independently. JLC was renamed as GLC (Global Linear Collider) and ILC, and the verification of detailed design was promoted again with normal conduction technology. On the other hand, in Europe, the same proposal was promoted in superconducting technology. Then the ILCSC (International Linear Collider Steering Committee) was established [5] in 2000, and in August 2004, when it was decided by ICFA that the chosen technology would be a superconducting technology, the development project of the X-band klystron at KEK terminated.

Meanwhile, KEK participated in TTC (Tesla Technology Collaboration) since around 2000. KEK began exploring the possibility of developing an RF source for superconducting accelerators, and Chin was appointed as the MBK's responsible person in KEK.

### 2.2.3 MBK development project

Since the beginning of 1990, the TESLA superconducting linear collider project was studied by DESY (see Figure 5) [6].

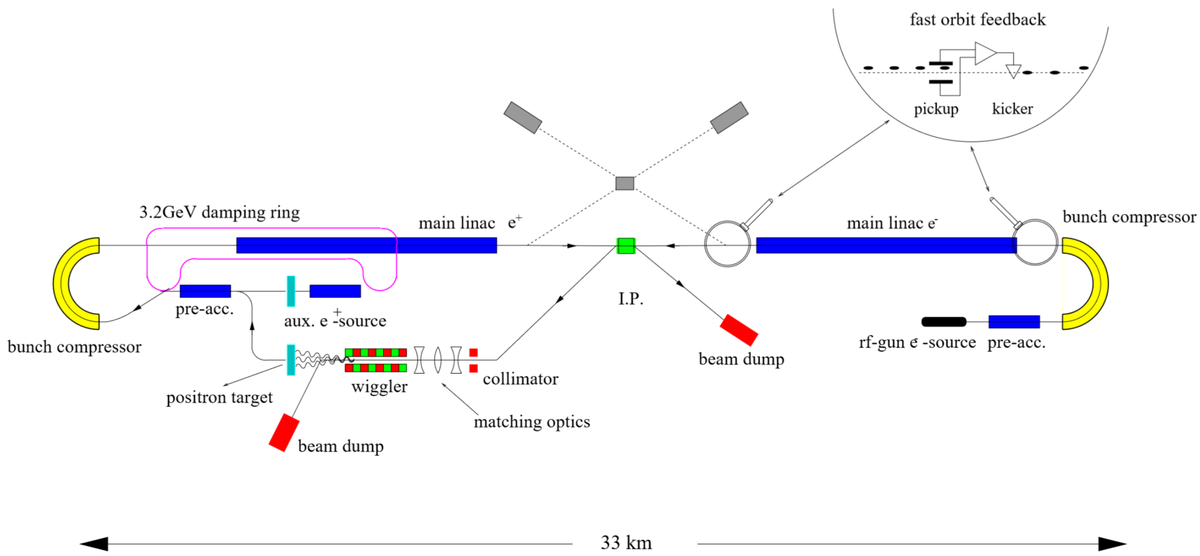


Figure 5: TESLA superconducting linear collider overview

#### 2.2.3.1 Development project of MBK prototyping

Chin promoted the joint MBK development for TESLA, with the BINP team using the know-how accumulated through the X-band PPM Klystron. A. Larionov developed GUN and magnetic focusing, V. Teryaev developed cavity positions, beam dynamic, and magnetic focusing, and one of the authors V. Vogel was in charge of the environment and klystron testing. Based on these initial design results, KEK decided to promote the joint development of the TESLA project with Toshiba in the spring of 2002. One of the authors S. Miyake was appointed as an MBK responsible person in Toshiba, as in the X-band PPM development. The requirement parameters for MBK are shown in Table 1.

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Frequency | 1300 MHz | Efficiency | 60 % |
| Output Power | 10 MW | RF Pulse Width | 1.5 ms |
| Average Output Power | 150 kW | Repetition Rate | 10 pps |
| Beam Voltage | 150 kV | Gain | 45 dB |
| Beam Current | 132 A | | |

Table 1: Requirement Parameters for TESLA MBK

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Toshiba and KEK collaborated on the verification of electrical design parameters based on the KEK/BINP team's basic design. In the summer of 2002, Toshiba made an interest announcement to DESY for the TESLA project. After some negotiation and the agreement with DESY and KEK, it was approved, and preparatory work officially started in Toshiba and KEK. Several improvements were made to the basic design, and after identifying manufacturing risks, MBK's proposed specifications were compiled, and a formal development proposal was made to DESY in the spring of 2003. Table 2 shows the proposal specification to DESY. These series of proposals and local meetings were all conducted and supported by Chin in KEK, and we have to say it would not have been possible for Toshiba alone.

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Frequency | 1300 MHz | Gain | 47 dB |
| Output Power | 10 MW | Number of Beam | 6 |
| Average Output Power | 150 kW | Cathode Loading | $< 2.1$ A/cm$^2$ |
| Beam Voltage | 150 kV | Structure | 6 Cavities |
| Beam Current | 132 A | RF Window | Pill Box |
| Efficiency | $> 60$ % | Tube Length | 2270 mm |
| RF Pulse Width | 1.5 ms | Solenoid Power | $< 4$ kW |
| Repetition Rate | 10 pps | Prototype (diode) | 15 months |

Table 2: Proposal Parameters of Toshiba, KEK/BINP MBK

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The MBK proposal of Toshiba and KEK/BINP was a 6-beam with an independent drift tube and ring-shaped TM010 mode common cavities (Figures 5, 6). All these designs were successfully intertwined, reducing the cathode loading to less than 2.1 A/cm$^2$ and reducing the risk of discharge, which improves cathode life expectancy. In the case of other companies, the cathode loading of Thales was 5.5A/cm$^2$, which was a significant improvement by Toshiba MBK. From the manufacturing point of view, in order to make six beams behave evenly, it was necessary to fine-tune cavity frequency during operation, so it was one of the very difficult klystrons to manufacture. The first prototype, #0 MBK, was successfully built at Toshiba factory and approved by DESY with 10-MW, 1 ms, 115 kV, 105 A, and 68.4% (Figures 8 and 9) [7].

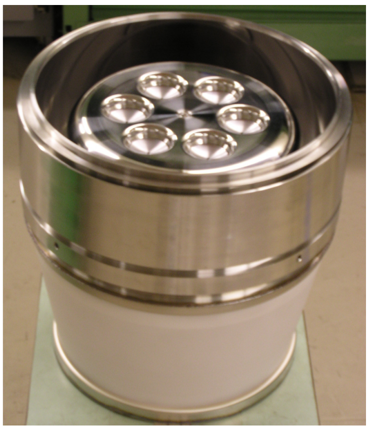

Figure 6: MBK cathode

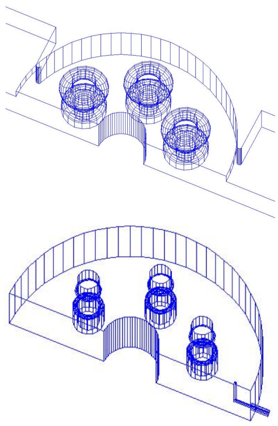

Figure 7: output and input cavities

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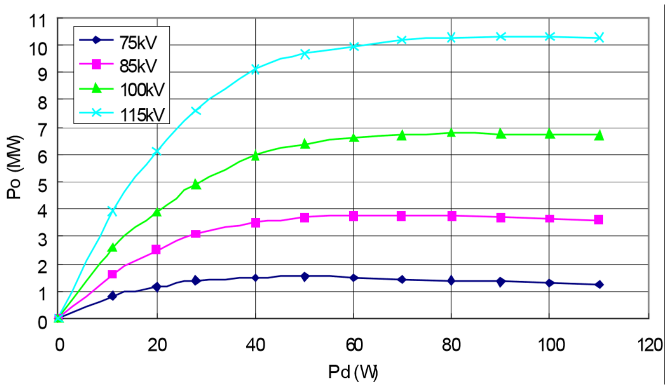


Figure 8: Measurement Output Power vs drive power

Figure 9: MBK E3736

Following the successful production of prototype #0 MBK, prototype #1 MBK design started with some modifications resulting from the collaboration between Toshiba and KEK. The points of improvement were mainly minor modifications in the size around the electron gun and the cavity, as well as reduction in the Q value of the second cavity to achieve the 3-MHz bandwidth. So the production of prototype #1 started. Although there were some manufacturing problems along the way, the FAT was passed to full-rated continuous operation at Toshiba factory in March 2006. In June of the same year, it was delivered to DESY for the final approval test with strong support from Choroba in DESY. The data are shown in Table 3, and Figures 9 and 10 [8].

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Frequency | 1300 MHz | Gain | 49 dB |
| Output Power | 10.2 MW | Number of Beam | 6 |
| Average Output Power | 150 kW | Cathode Loading | 2.1 A/cm$^2$ |
| Beam Voltage | 115 kV | Structure | 6 Cavities |
| Beam Current | 132 A | RF Window | Pill Box |
| Efficiency | 66.5 % | Tube Length | 2270 mm |
| RF Pulse Width | 1.5 ms | Solenoid Power | $< 4$ kW |
| Repetition Rate | 10 pps | Band width | 4.1 MHz |

Table 3: Vertical Model of Toshiba MBK E3736 Data

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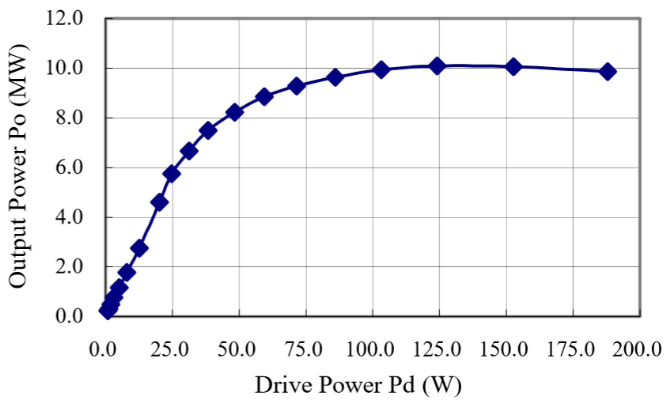


Figure 10: The transfer curve at a beam voltage of 115kV

Figure 11: MBK test at DESY

#### 2.2.3.2 Horizontal MBK E3736H for the European-XFEL project

In mid-2000, TESLA-FEL started as a European project and was renamed as European-XFEL. In this project, MBK is designed to be installed horizontally, so Toshiba started developing a horizontal MBK in collaboration with Chin in KEK. In addition to mechanical rigidity, which was essential for lateral installation, the cooling structure was modified to be compatible with lateral installation. The first horizontal MBK E3736H was delivered to DESY in 2008, and it was successfully completed in DESY. All the performances and tests were accomplished. Figures 11 and 12 show the horizontal MBK E3736H and waveforms of the parameters with 10.1 MW, 118.8 kV, 129.5 A, and 1.5 ms [9].

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Figure 12: Horizontal MBK E3736H

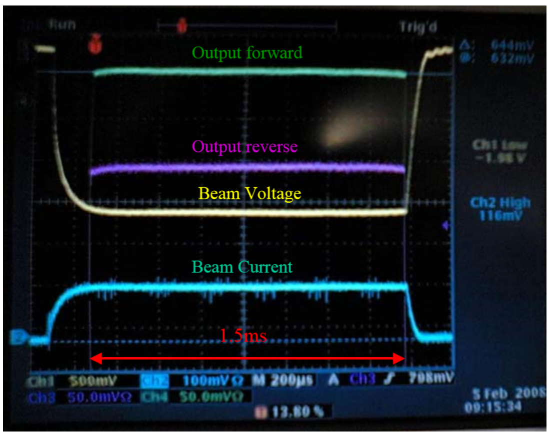


Figure 13: Waveforms of beam voltage and beam current output power

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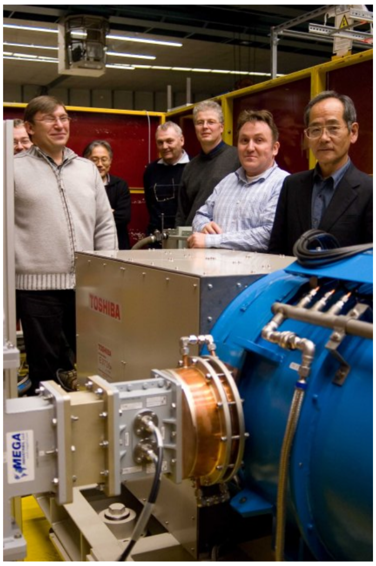


Figure 14: Final acceptance test with DESY, KEK, and Toshiba

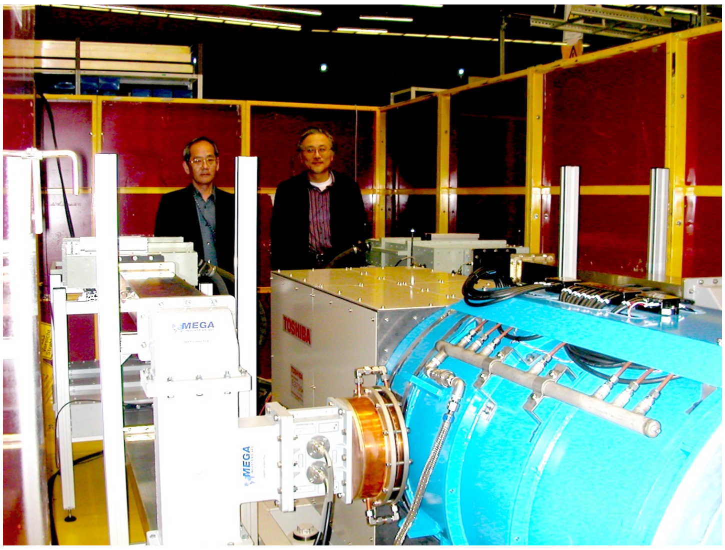


Figure 15: Y.H. Chin (right) and S. Miyake (left) at the DESY test stand with the horizontal MBK E3736H

### 2.2.4 Conclusions, Remarks

The background of Toshiba's successful development of MBK was great help, advice, and encouragement by Chin from KEK. Toshiba's MBK was approved as a candidate for an RF source in the European-XFEL project and was later included in the project. We cannot forget the joyous look on his face when we reported to Chin that Toshiba was able to make a successful bid after the tender. We are grateful to Chin, who left us too early.

Finally, we would like to conclude that one of the authors S. Miyake succeeded in developing the X-band PPM Klystron and MBK with the team at Toshiba.

## References

[1] JLC Design Study, KEK, April 1997

[2] Y. Toge, Y. H. Chin *et al.*, JLC project `https://ilc.kek.jp/MechWS/2002/Toge.pdf`

[3] Y. H. Chin, K. Takata *et al.*, "The 120 MW X-Band Klystron Development at KEK"

[4] Y. H. Chin, "Worldwide Progress in X-band Power Sources", LINAC02, Gyeongjn, Korea

[5] K. Yokoya presentation, "The road to ILC" KEK, January 2005

[6] Capter 3 "TESLA Superconducting Linear Collider" `https://flash.desy.de/.../e1545/infoboxContent1750/TESLA.pdf`

[7] Y. H. Chin *et al.*, "Toshiba/KEK MBK for TESLA", TTC meeting, Sep, 2003

[8] Y. H. Chin, S. Miyake *et al.*, "The Toshiba E3736 Multi Beam Klystron", TTC meeting, April 2004

[9] Y. H. Chin *et al.*, "Design and Performance of L-band and S-band MULTI BEAM KLYSTRONS", LINAC08 conference at Victoria, BC, Canada.

## 2.3 Progress on intra-bunch GHz bandwidth beam feedback and applications for future accelerators

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### 2.3.1 Introduction

Beam instabilities and techniques to study, model and control them have been an active research topic for decades. Beam instabilities from impedance-driven mechanisms, or from electron cloud or ion mechanisms, can limit performance for both electron and hadron machines. In the last 25 years coupled-bunch feedback methods have been widely applied to light sources and almost all modern facilities incorporate coupled-bunch instability control as a requirement for operation. The most recent generations of B and $\Phi$ factory colliders have required coupled-bunch instability feedback to reach their design luminosities. Hadron facilities have used feedback for decades as well, to damp injection offsets, coupled bunch motion and intra-bunch motion.

The HL-LHC upgrade motivated a technology development and machine physics effort in feedback stabilization of intra-bunch modes. The plans for increased bunch currents were foreseen to drive instabilities via several possible mechanisms in the injector chain and the main collider [1]. Machine design choices in optics and RF system configurations can be important means to mitigate instabilities. The Ecloud mechanisms can also be addressed by machine surface coatings or blazing to reduce photo-electron yield, in some machines external magnetic solenoids have been used to mitigate photoelectrons. The instability feedback control research goal was to explore new techniques to mitigate intra-bunch transverse motion driven by electron cloud or transverse mode coupling (TMCI) mechanisms. The feedback methods offer a complementary approach to stability via optics configurations, RF configurations and surface treatments. Active feedback methods were seen as potentially allowing higher currents without the dynamic aperture and lifetime tradeoff of high chromaticity and potentially advantageous in cost and longevity compared to surface coating.

The DOE sponsored LHC Accelerator Research program (LARP) supported a wideband feedback effort to explore GHz bandwidth systems applicable to intra-bunch motion for ns scale bunches. The effort supported US national lab staff, University postdoctoral researchers and graduate students, and allowed a robust collaboration between US researchers and efforts at CERN and LNF-INFN. This effort spanned 2010-2017 and included extensive simulation models to predict Electron-cloud impacts, technology development of a Demonstration transverse wideband intra-bunch feedback system, and machine studies at CERN to understand the performance of the technology. The SPS, as part of CERN's LHC Injector Upgrade (LIU) project, offers configurations with beam instabilities and the capability of exploring high currents required for the HL-LHC planned operations. A wideband feedback Demonstration system was commissioned at the SPS as a testbed for hadron machines with potential for electron-cloud and TMCI instabilities.

The wideband feedback and instability control work has been reported in numerous accelerator conference proceedings, as progress talks at workshops and as progress reports at collaboration meetings [2–4, 15]. This newsletter is an opportunity to highlight some of the challenges and results, with the goal of putting the broad effort in some perspective. It is also an opportunity to suggest where these new techniques and technology might be applicable in future facilities.

### 2.3.2 Overview of Instability Feedback Challenges

Wideband intra-bunch feedback is technically very challenging for ns scale bunches. The JPARC facility has commissioned intra-bunch feedback on long 100 ns scale bunches (implemented using systems and technology patterned from coupled-bunch systems) [5] but the SPS case was estimated to require GHz bandwidths. This GHz closed loop bandwidth required development of completely new signal processing hardware with roughly a factor of 8 - 16 times faster data rates than the 500 MHz sampling rate systems in common use at the lepton facilities.

Besides the issue of bandwidth and sampling rates, the nature of the dynamics of TMCI and Ecloud intra-bunch instabilities presents challenges in the design of control methods. While this work started by using similar control methods to that used in coupled-bunch feedback, the work has explored the use of model-based control techniques that can help achieve wide bandwidth and targeted damping of selected modes. These new control methods may be valuable for future applications. A related use of the model-based techniques provides an interesting path to compare non-linear time domain simulations to actual data taken in an operating accelerator and validate the fidelity of the simulation [6].

### 2.3.3 SPS Wideband Feedback Demonstration System

To allow machine studies and validate critical new technical functions a Demonstration Wideband Feedback system was developed by a collaboration of researchers from US and European labs. The approach was to identify possible technical challenges, and implement a rapid prototype system of limited functionality but with 1 GHz closed loop control bandwidth capable of controlling 1 - 64 bunches.

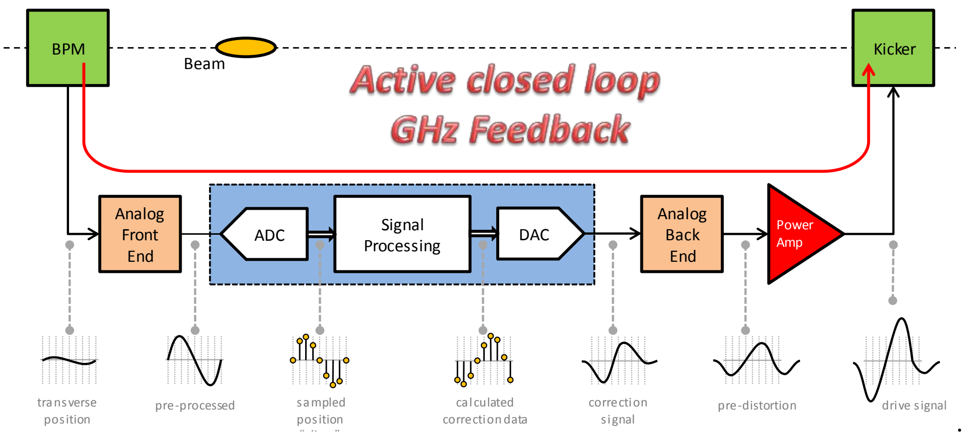


Figure 1: Block diagram of the intra-bunch feedback channel. The demonstration system used a single exponentially-tapered pickup and an array of two stripline and one slotline kicker to close the loop on the beam vertical motion signal. The digital processing operates at 3.2 - 4 GS/sec. with 16 samples across each controlled bunch. Figure from G. Kotzian

The block diagram of this system (Figure 1) looks very much like any contemporary coupled-bunch instability feedback system based on 1 pickup, digital signal processing and high power correction amplifier and kickers. What is unique, and new in this work is the technology to implement the sampling of coordinates within a ns scale bunch, the linear group delay in the processing loop required by the GHz closed loop bandwidth, the kicker technology for the 1 GHz bandwidth and some new ideas on processing filters and model-based control methods. It is the need for the 4 GS/sec sampling rate and 1 GHz closed loop bandwidth that makes this a research project.

The system uses a wideband tapered stripline pickup with 4 electrodes, and a conventional hybrid-based analog receiver to produce an analog vertical moment signal. The digital signal processing is implemented with 4 GS/sec. rate system reconfigurable to allow evaluation of various control algorithms and expandable to control of roughly 64 bunches with the core FPGA platform. The baseband back end correction signal is applied to the beam through an array of wideband GHz bandwidth power amplifiers via stripline kickers as well as a novel slotline kicker structure.

The 1 GHz system closed loop bandwidth is particularly challenging and the A/D, D/A and digital processing system can operate at up to 4 GS/sec. As seen in Figure 2, this allows 16 samples to be taken of the transverse displacement of sections of the SPS bunch (4 sigma length of 3.2 ns at injection). The fill pattern in the SPS has 5 bucket periodicity of filled 200 MHz RF buckets in trains of 72 bunches reflecting the injection from the PS machine. This wideband sampling system is structured to process 16 samples across each controlled bunch, and not process samples from empty buckets. System features and analysis codes grew over time, the original FPGA implementation processed 1 bunch and later upgrades expanded the control functions to process 64 bunches in a train, as well as special pattern of 32 doublet scrubbing bunches used to condition the vacuum chamber. The flexibility of the architecture was exploited by later additions of numerous beam diagnostic functions, and an output upconverter digital modulator that could transfer the baseband correction signal to a higher revolution harmonic in the output band to get better use of the amplifier power to apply signals to the lowest controlled mode [7].

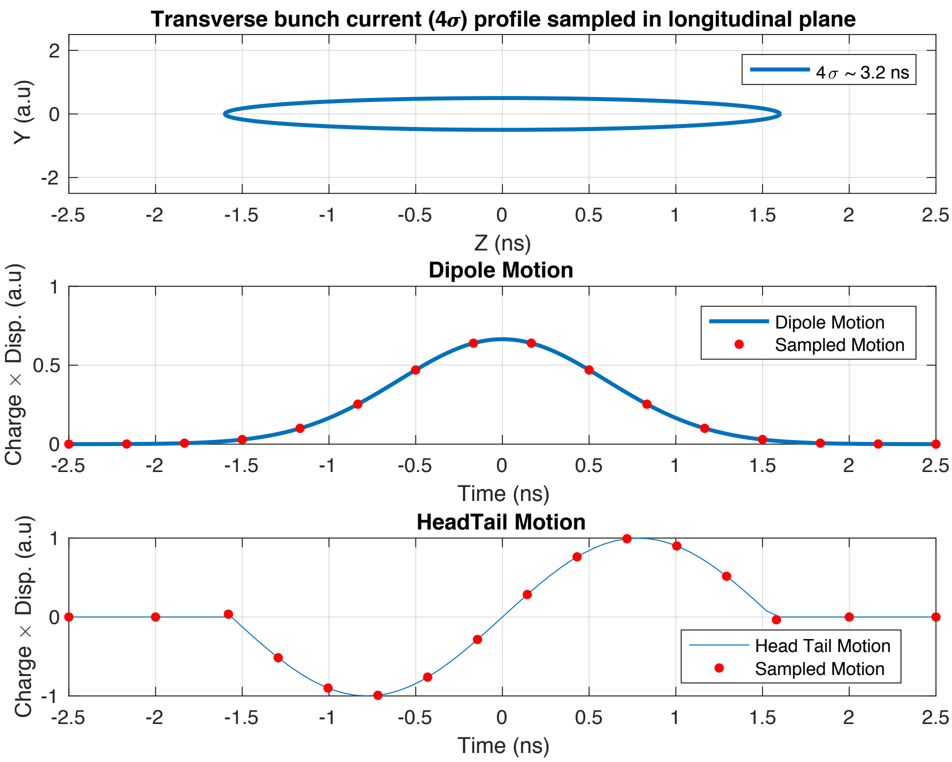


Figure 2: Sampling grid of 16 samples taken at 3.2 GS/sec. The motion of a bunch is represented in these 16 samples which measure charge*displacement. Example pickup signals are shown for a barycentric (mode 0) displacement and a head-tail (mode 1) displacement. The actual bunch motion can be a superposition of many internal modes, represented in the 16 consecutive time samples.

The unique challenges of this bandwidth require wideband pickups, power amplifiers and kickers. The pickup signal was taken from an existing exponentially-tapered diagnostic pickup, this pickup (originally developed by Trevor Linnecar) has a non-linear group delay with the 1500 MHz bandwidth. A special wideband active equalizer was implemented to compensate for the pickup and the dispersive cable response to recreate at the A/D input the time structure of the transverse displacement of a bunch [8]. The kicker functions were implemented in two bands, a relatively conventional 500 MHz bandwidth stripline (designed by S. De Santis at LBL), and a novel slotline (Faultin) style 1 GHz bandwidth transverse structure (Figure 4). The slotline kicker was designed by a collaboration from US and Europe [9] [10] and fabricated by CERN. These back end kickers and cable plant also require active equalization for kicker response and cable dispersion [11]. The necessary time response and linearity of the power stages is technically very challenging. More than 8 commercial RF power amplifiers with GHz bandwidth were evaluated and the most promising was re-engineered in conjunction with the amplifier manufacturer to improve the transient response and phase linearity over an operating range of 20 MHz - 1 GHz. Four 250 W amplifiers were installed in the SPS tunnel requiring remote operation and monitor control.

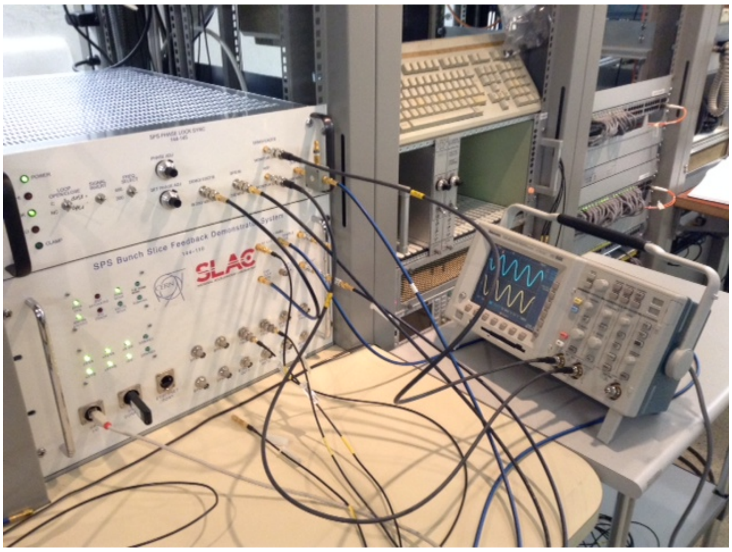


Figure 3: Photo of signal processing system in the SPS Faraday cage

The digital processing system was built as a rapid prototype using commercial evaluation boards for a Virtex 5 FPGA, and incorporated interleaved 2 GS/sec. A/D functions with over 1.5 GHz analog bandwidth. A custom design PC card implemented a 4 GS/sec D/A system with associated GHz logic for synchronization. Synchronization to the SPS RF system and associated timing system requires a synchronized master oscillator which generates the high speed digital clocks at harmonics of the SPS RF (at 400 and 1600/2000 MHz). Figures 3,5 and 6 show the main processing chassis installed in the SPS "Faraday cage", two stripline kickers, the slotline kicker on the SPS beamline, and the remotely operated power amplifiers installed on the beam line.

One of the early design considerations was the choice of feedback control filter. The first implementation was patterned after the diagonal FIR or "all-mode" controllers commonly used in the 500 MHz systems from the light sources and B ($\Phi$) factories. This approach is computationally efficient, and easily programmed via the FIR coefficients to adapt to machine lattice and tune variations. In this approach each bunch is treated as 16 independent "slices", and a FIR filter processes N turns of past oscillation coordinates from each slice, computing a new correction kick for that slice every turn. There are no cross-terms in this diagonal filter, which

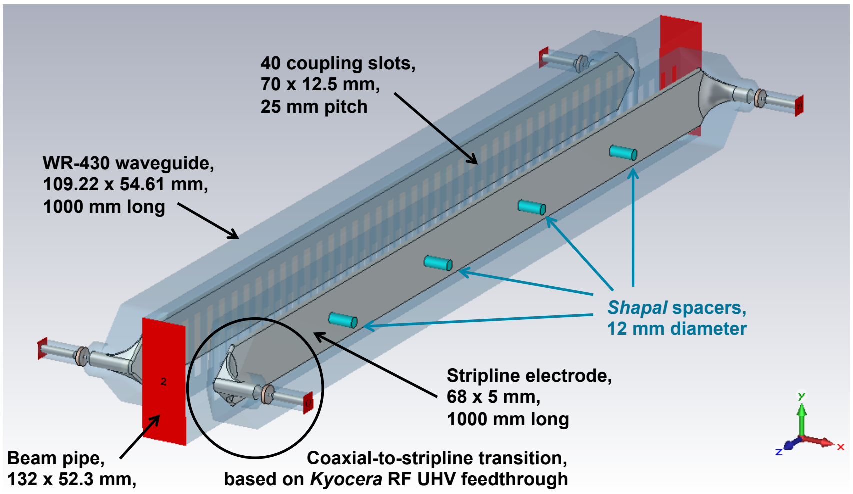


Figure 4: Transverse slot line ( Faultin style) kicker with 1 GHz bandwidth. In this style of kicker the beam and the drive signal co-propagate along the beam direction, unlike traditional stripline devices where the kick signal counter-propagates. This means the long structure can have both bandwidth and high shunt impedance.

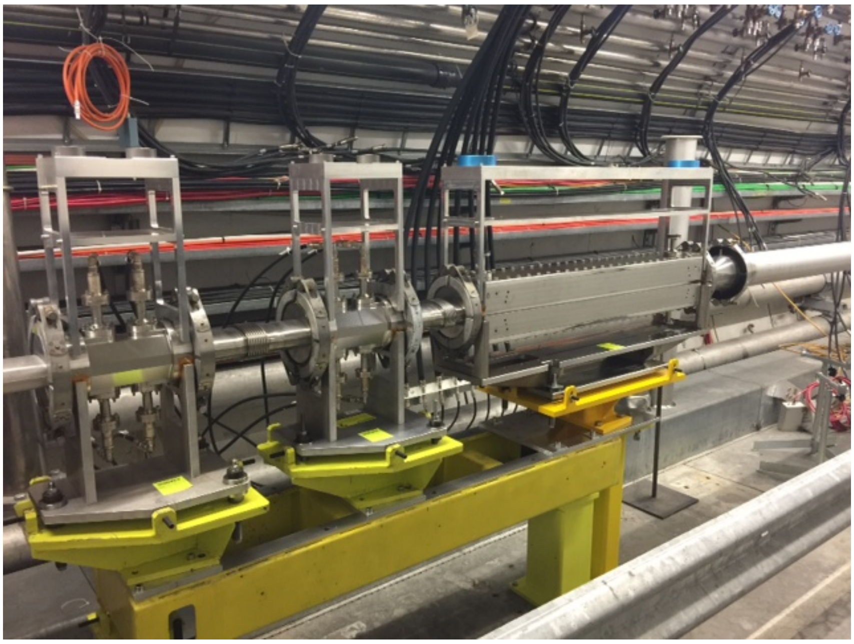

Figure 5: Photo of installed kickers on SPS beam Line, two 500 MHz bandwidth stripline kickers and one 1 GHz bandwidth slotline structure

allows parallel processing architectures to simplify the data rates in the numeric computations. With this diagonal controller the computational load scales by the number of taps N, and the number of slices and bunches. The time-domain sampling formalism and filter act in the frequency domain as bandpass filters at the aliased betatron tune, rejecting DC orbit offset and signals away from the bandpass center frequency. The necessary phase shift for damping at the tune frequency is implemented in the design of the filter coefficients.

The use of the all-mode diagonal FIR control filter for these first studies was a pragmatic choice but there are some operational disadvantages to this control approach. As seen in Figure 7, the slope of the filter phase in the vicinity of the operating tune means that for control

Figure 6: Photo of amplifiers in tunnel. 1 kW of 1 GHz bandwidth power amplifiers are available in this demonstration configuration to drive the beam. The amplifiers are located in the tunnel to minimize power loss in the cable plant

of many widely spaced modes, the filter can only be truly resistive for a few modes, and at the edges of the operating band the filter phase has reactive components. This leads to limitations on possible gain and tradeoffs in control of all modes. The various modes are spaced in frequency separated by the synchrotron tune, so for lattice configurations with low synchrotron tunes, the impact of the group delay slope in the control filter is manageable. But for some of the configurations considered for operations, particularly lattice designs that have relatively high synchrotron frequencies, model-based control methods, that can more usefully control all potential modes, and also target the limited output power to particular modes, became an active research effort.

Because of the time-domain sampling formalism it is very important for the signal sampled at the A/D, and the correction signals applied via the high power kickers properly align with the beam structure. This requires care in the control and equalization of dispersive elements, such as the cable plant, and equalization of any non-linear group delay in the pickups, kickers or power amplifiers. There are also subtle effects that require synchronization of the sampling clocks to the accelerator RF signal, particularly as the RF frequency ramps during acceleration, so that the overall processing can faithfully transfer information from one “slice” of the bunch at the pickup to the corresponding “slice” of the bunch as it passes through the kickers.

The impact of any possible coherent synchrotron oscillations on the transverse control can be understood in the time domain by considering the longitudinal motion of the bunch relative to the number of turns it takes to compute the transverse correction signal for a particular slice. The impact of synchrotron motion in this controller is minimal if the bandwidth of the control filter is chosen carefully - if the number of “taps” in the control filter is a small fraction of the synchrotron period, the synchrotron motion oscillates the beam centroid slowly across the 16 samples of control, with the control filter computing the betatron correction signals for the vertical coordinate. In this scheme the correction computed for slice N is driven in time synchronism with the passage of slice N in the kicker, while the bunch motion in the longitudinal plane or sampling grid occurs slowly and slice signals are sensed and kicks applied to the appropriate corresponding slice in the kicker.

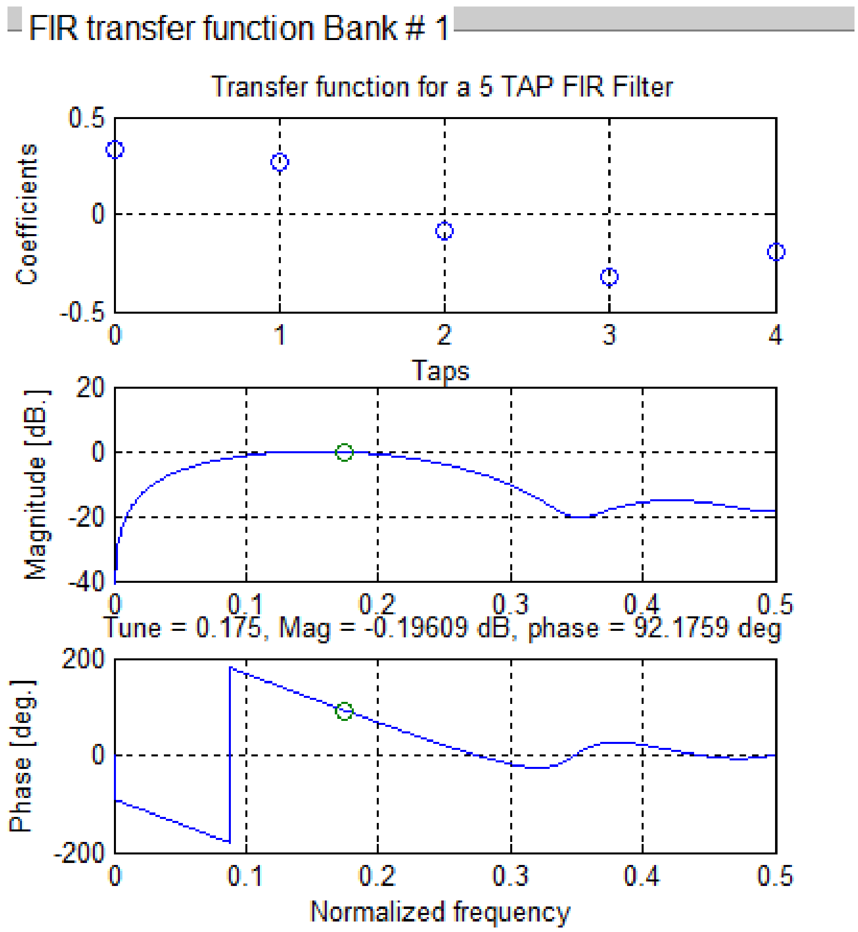


Figure 7: 5 tap FIR filter frequency response

Figure 7 shows a typical control filter in time and frequency domains, this is a 5 tap example for the 0.185 betatron tune. The action of the diagonal control creates an all-mode control filter that has gain for the barycentric mode (where all "slices" move together) as well as head-tail or higher frequency internal modes. One downside to this diagonal processing is that it is an all-mode controller with identical gain on every possible mode. All-mode processing is attractive in the sense of being complete, but the barycentric mode oscillation from injection or other disturbances can saturate the power stages, which "blinds" the system to control of higher frequency internal modes that can grow while the large barycentric mode damps.

An essential part of the processing system is a diagnostic memory which can record samples of beam motion over many turns, and can also play out in a controlled and synchronized manner an excitation signal which can be driven through the processing and kicker system on the beam. The synchronization of this diagnostic memory to machine injection and the use of internal timing markers allows the system to excite beam motion, record the response, use time varying feedback control (e.g. allow the filter coefficient sets to be changed during the store in synchronism with injection and subsequent turns). The data set of time-domain samples can then be processed offline to resolve beam information in the frequency domain, compute system transfer functions and extract the beam transfer function in the frequency domain.

One very significant aspect of the receiver and equalizer functions is the control of the system noise floor and management of the noise floor consistent with the A/D converter quantizing noise. As implemented, the system has a noise floor of roughly 3 microns of vertical motion for the nominal bunch current of 1.5E11 p/bunch. This level is the effective limit on the damping of unstable beam motion - it can be damped to this system noise floor. The conference and workshop literature have extensive details on the dynamic range and noise floors achieved in the system. The impact of the number of bits in the A/D converter and in the computation does not impact the noise floor or equilibrium damped motion of the beam, instead this parameter impacts the dynamic range of beam motion that can be sensed in conjunction with a static orbit offset. A more practical concern is that a high design gain, necessary to control a fast growth rate, can easily saturate the output stage with limited kicker power and shunt impedance. This operation with saturated output stage is a particular concern at injection.

### 2.3.4 Beam Studies

The approach to quantify and validate this sort of instability control on an operating accelerator is very challenging. Just "doing feedback" on unstable beams is not very possible or particularly productive. One aspect is that the studies are done with a demonstration system of limited kicker power, which limits the impact of the kick signals on the beam and allowed range of unstable motion in terms of growth rates (achievable gains). Another factor is that the studies were done on the operational SPS machine, before some upgrades that would be necessary to reach the Hl-LHC intensities, so with beam conditions that are not yet unstable in routine operation. A significant aspect of these studies was the creation of special test beams that could be unstable with growth rates and modal structure useful to validate the control methods. The goal in these dedicated feedback tests is to explore intensities and lattice configurations in the SPS which elicit intra-bunch effects, and can be operated in machine lattice configurations similar to those anticipated for the ultimate operational state.

The need to is have good understanding of the beam conditions, via simulations or physical experiments, apply signals through the demonstration system, measure the changes in the beam response with and without feedback- and decide if the system and beam behave as anticipated. Only though the validation of system responses through experiments and models can the behavior at future intensities be confidently predicted.

The approach taken went in steps as the hardware was developed over time and as machine conditions and lattices were also in development. The early studies were driven beam studies, where the back-end functions of the feedback path are used to drive the beam, and the motion is studied open-loop. These studies show the stability of the beam system and the effective bandwidth and kick strength of the system. A second class of studies can be done on stable beams, but using the feedback to de-stabilize the motion via positive feedback. This method can be time-varying in feedback gain or phase, via Grow-Damp studies. The final approach taken is with a beam that is unstable after injection, and where the feedback system is used to stabilize the beam and keep the intra-bunch motion damped up through extraction or in a store configuration. All of these methods provide vital information on the capabilities of the system, and are necessary to understand the performance and predict the capabilities of a fully engineered system with a future high-current beam.

### 2.3.5 Open-Loop driven studies

An example of a driven study of a single bunch is shown in Figure 8. This example uses a chirped excitation signal from the internal excitation memory that is spatially structured to excite intra-bunch modes, while the frequency content is slowly varied over 20,000 turns, moving slowing in tune as the beam is present in the machine. The beam motion is recorded during this process, and offline analysis can then show the beam response in time or frequency domains at multiple intra-bunch modes.

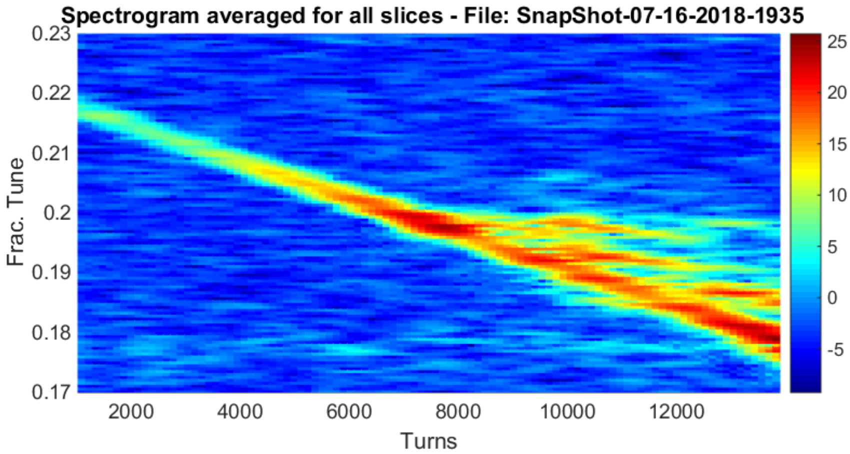


Figure 8: Spectrogram of beam motion in response to a descending excitation chirp, revealing 4 internal modes of motion excited by the drive signal

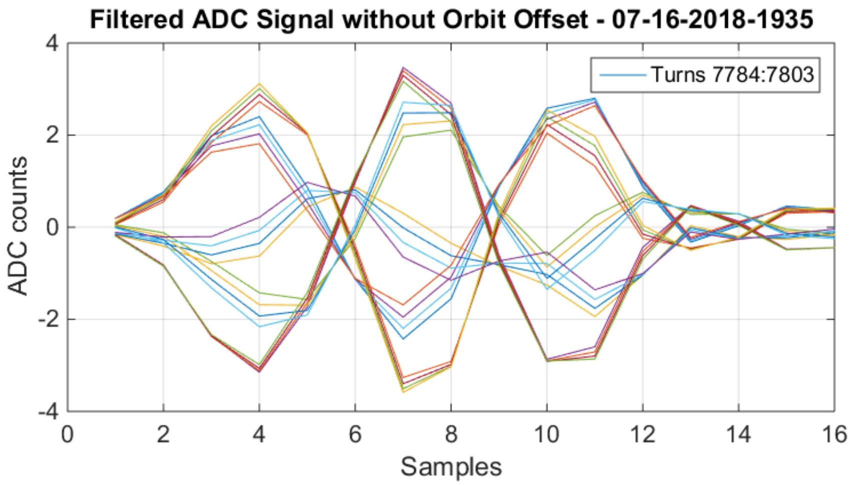


Figure 9: 20 consecutive turns showing beam motion and modal pattern at turn 7784

Figure 8 shows a descending chirp in tune applied to the stored beam, starting at a tune of 0.22, descending over 15,000 turns to a final tune of 0.17. The figure is sliding window spectrogram, which is calculated from the time-domain recording of the vertical coordinates of the 16 samples across the bunch every turn. The nominal mode zero betatron tune in this example is 0.178 to 0.180, with a nominal synchrotron tune of 0.012, so we expect each synchrotron sideband away from the betatron tune to show higher modes of intra-bunch motion. The nominal mode zero or barycentric response at tune 0.178 is seen at the end of the chirp with a very strong response. This study is very insightful in revealing the effective bandwidth of the kicker and amplifier system as well as the free response of the damped or undamped beam modes. We can see in the spectrogram clear excitation of 4 internal modes, and the natural damping present as the motion continues to ring in each mode as the chirp passes through the resonance.

The modes are cleanly resolved in the frequency domain of the spectrogram - it is also interesting to look at the time-domain motion of the beam at various points of the chirp. The system records 16 samples across the bunch each turn (the nominal bunch length 1 sigma is 1.8 ns, the sampled interval is 16 samples at 3.2 GS/sec., or 5 ns total).

Figure 9 shows the envelopes of 20 consecutive turns taken as the chirp passes through mode 2 and then mode 1 - we can see the clear head-tail motion present as different sections of the

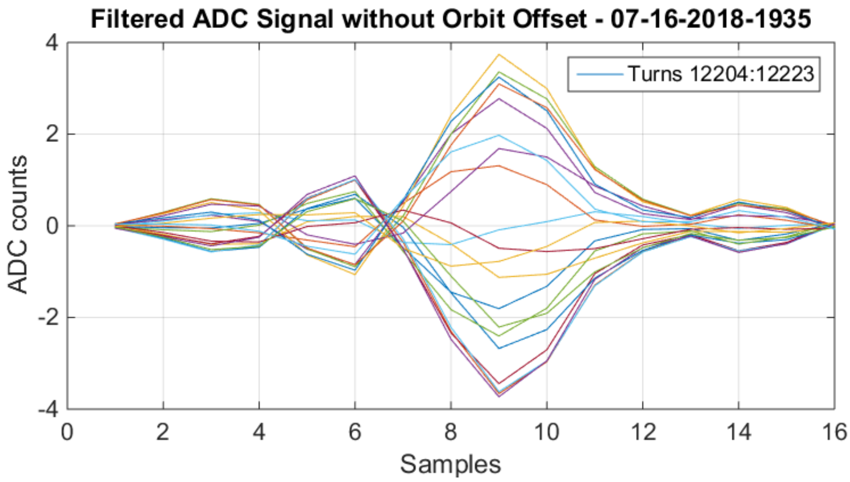


Figure 10: 20 consecutive turns of beam motion samples at turn 12204, showing the larger mode 0 component as well as smaller residual ringing in the beam at modes 1 and 2. The descending chirp excites the higher modes before hitting the strong barycentric mode 0.

beam oscillate at unique betatron phases. At the end of the chirp, the barycentric mode zero motion is very clear in Figure 10, with smaller motion of the higher modes still present. These studies, taken during the commissioning of the slot-line kicker, help quantify the bandwidth of the kicker and amplifier system. As seen the system can clearly excite 3 or 4 internal cycles across the 16 samples of the beam, reflecting a system with the Gigahertz bandwidth.

### 2.3.6 Grow-Damp Studies

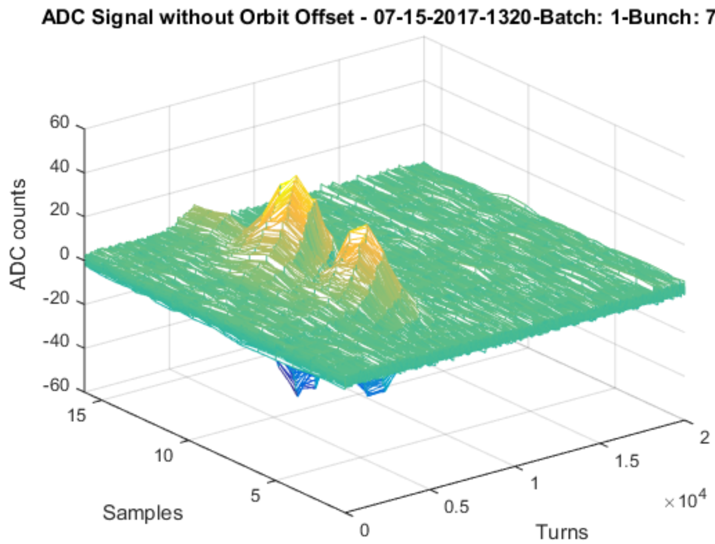


Figure 11: Time domain envelope of motion for 16 slices over 20,000 turns after injection. The beam develops a head-tail instability in the 6000 turns after injection

Another form of beam study is a type of grow-damp transient, where the feedback properties are manipulated during a study to allow naturally unstable motion to grow and then be captured as the feedback is switched to a damping state. It is also possible to use these methods on a stable beam, where a stable beam is excited via positive feedback for a defined time interval, after which the beam can be allowed to freely decay, or decay under the action of damping

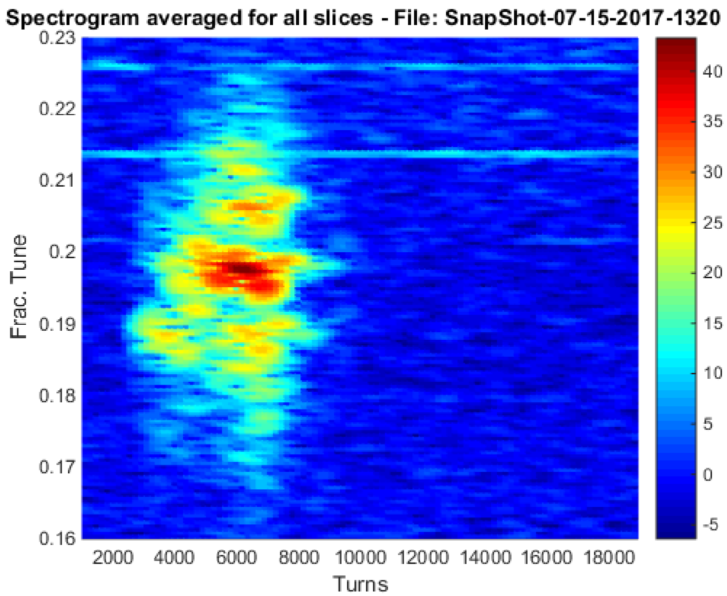


Figure 12: Spectrum of the data in Figure 11, showing the largest mode is mode 1 ( head-tail) with smaller barycentric motion (mode 0) as well as mode 2

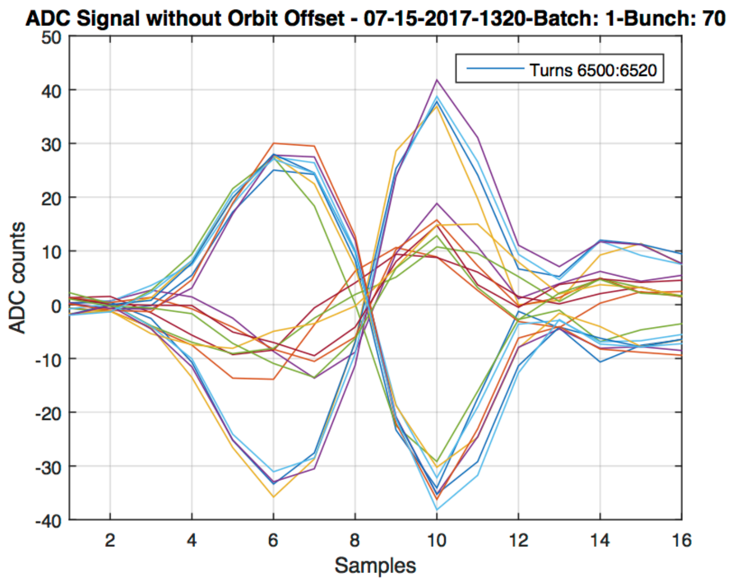


Figure 13: Time domain snapshot of 20 consecutive turns at turn 6500, showing the clear signature of the head-tail (mode 1) motion. Data set is the same as Figures 11 and 12

feedback. These studies help quantify the damping rate that the feedback system can achieve. If the study is done for a family of damping gains, the effective closed loop gain of the system, and fastest controllable growth rate, can be estimated. It also is useful to study the noise within the closed loop system through recordings of beam motion after a damping transient. One aspect of this method is that it tends to most strongly excite the least stable mode, as seen in Figure 11, a time domain envelope of beam motion during the 20,000 turn grow-damp study. In this study, positive feedback is applied after injection for 5000 turns, after which the feedback filter is switched to a damping phase with adjustable gain. The spectrogram in Figure 12 shows the growth of internal modes 0 and 1 excited by the positive feedback. Figure 13 shows 20 turns of vertical motion at turn 5000, just before the excitation stops. The vertical time domain signals show a large mode 1 component as well as excitation of mode zero. After turn 5000 the wideband feedback is turned on with moderate gain, and the beam motion damps to the system noise floor. Without feedback, the natural damping in the beam takes roughly 10,000 turns to get to the noise floor. With the feedback active, the motion is damped to the system noise floor in roughly 1200 turns.

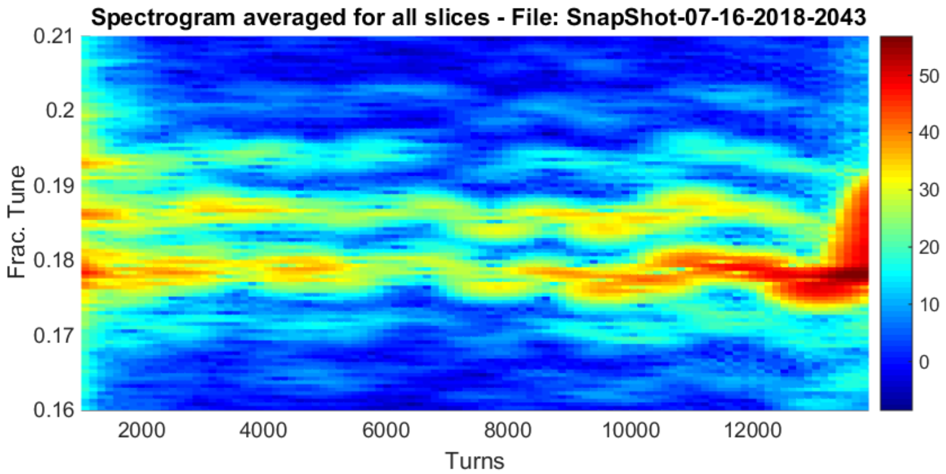


Figure 14: An unstable bunch which exhibits growing vertical motion at modes 0 and 1 after injection, leading to beam loss. No feedback is applied in this case.

### 2.3.7 Control of unstable beams

Control of an unstable beam requires that the system filter be well-specified for damping and that the system gain is carefully chosen to not saturate the power stage during the injection and damping process. We have studied single bunch cases as well as bunch trains of 4 injected trains ("stacks") of 72 bunches. An interesting single bunch study is shown from a beam that exhibited TMCI motion at the available operating current of 1.5e11 P/bunch. This beam is unstable after injection, with growing motion of modes zero and 1 over roughly 14,000 turns.

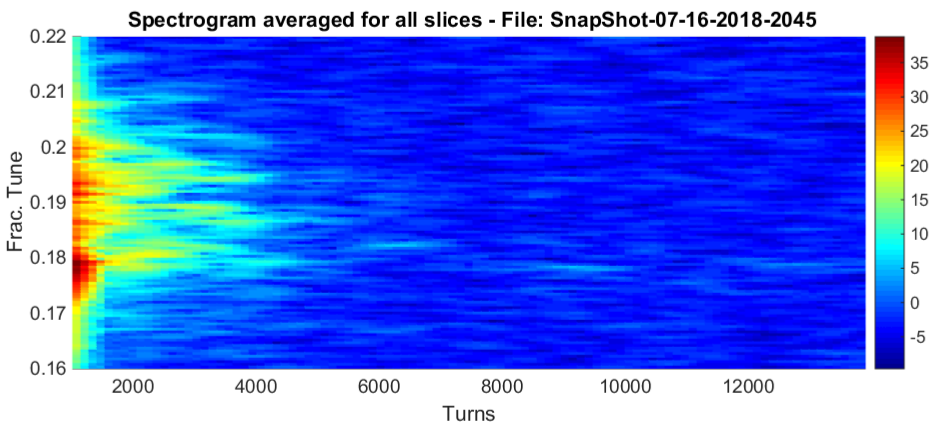


Figure 15: Similar beam conditions as figure 14, with wideband vertical feedback applied after injection. The injection transient and excited motion is damped to the noise floor of the feedback system.

Figure 14 shows the spectrogram of this case with no feedback applied, with growing motion after injection. In contrast Figure 15 shows the behavior with the negative feedback gain applied starting from turn 1000 - we see the damping of all modes down to the noise floor. A series of these studies, each taken with different damping gains, reveals the net damping achieved by the system, and is important in understanding the capabilities of a more complete operational system with more kickers and more output power. The system has achieved damping times of roughly 200 turns when operated at the gain limits of the Demonstration system with limited kicker power.

Numerous studies have been made in 2016, 2017 and 2018 looking at cases of unstable beams, stabilized after injection, and then switching off the feedback to show the growth of unstable motion without feedback. Train studies have also shown that without the wideband feedback, high current bunches at the tail of a train of 72 break into instability without feedback. These studies show the effectiveness of the wideband system in controlling what the last bunches in a train even when extra current is added to these otherwise unstable bunches.

### 2.3.8 Injection Efficiency Studies

A very interesting study was performed at CERN by Kevin Li to quantify the transfer efficiency of the SPS as part of the LHC injection system [12]. In this study, the wideband demonstration feedback was configured for negative feedback, and the SPS beam behavior was studied in terms of injection charge from the PS, the capture of the charge, and the possible losses in the machine during the store of the study. In this study the SPS configuration showed a clear threshold limit on stored charge, as seen in Figure 16 the injection of more than 1.6E11 particles shows losses during the store. The action of the SPS Injection damper (a barycentric 20 MHz bandwidth system, case “feedback”) helps raise the threshold, but the action of the wideband feedback (case “WBFB”) is seen to allow roughly 30% higher charge to be stable and remain in the machine.

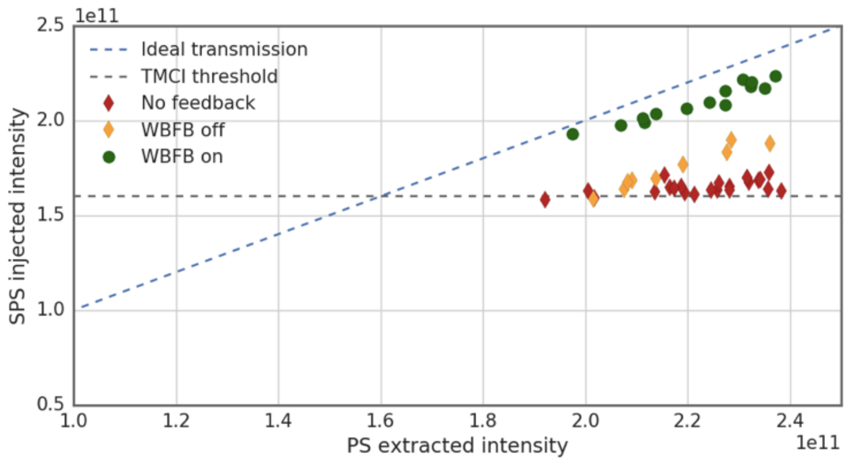


Figure 16: Injection efficiency showing capture of charge from the PS into the stored beam of the SPS. With increasing injection intensity, the SPS loses charge above about 1.6e11 unless the wideband feedback is on. This increases the stored charge by nearly 30%. From Kevin Li, et al

It is also interesting to look over time at the total transmission efficiency of charge from PS injection, through store in the SPS. As each injection cycle is unique, with unique injected charge, a study over time with many cycles is particularly interesting. As some injections are below the instability threshold, some above, this study over time highlights the improved transfer behavior. In this study (Figure 17) the wideband feedback was alternately active or inactive in 5 minute intervals, and by looking over the time intervals is easy to see how the wideband feedback consistently allows greater stored charge and extraction efficiency, in this example roughly 20% increase in stored charge injection and capture efficiency is seen.

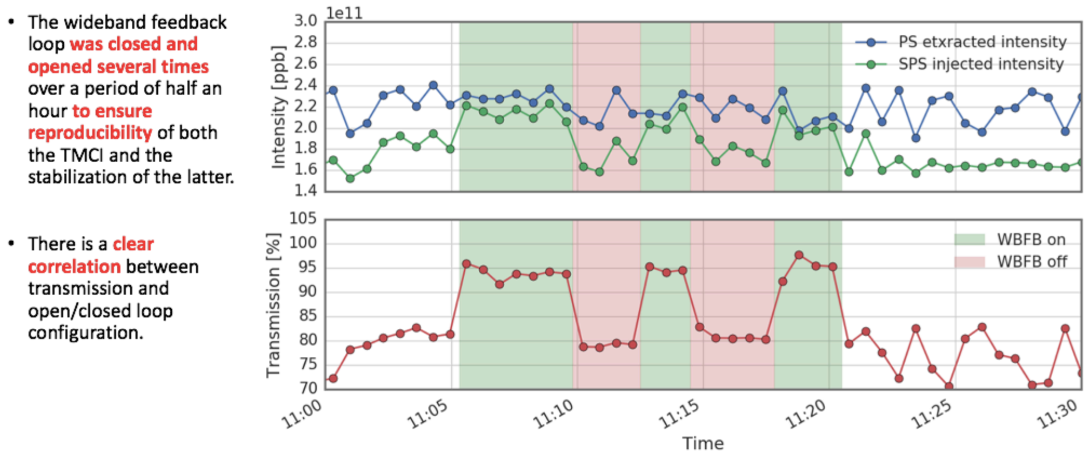


Figure 17: A time study tracking injection efficiency from PS to SPS showing the intervals with wideband feedback ON, and OFF. The increase in transmission is clearly seen. From Kevin Li

### 2.3.9 Summary and the Path Forward

The technology effort of the demonstration system, and the series of machine studies, is an exciting start to explore the possibilities of this wideband instability control. These first studies, though done with limited kicker power, clearly show the applicability of this approach to stabilizing HL-LHC style beams in the SPS. The path to designing and commissioning a practical or production wideband instability feedback for the SPS is clear, the author thinks this engineering could be confidently done now on the basis of this demonstration system.

Looking forward, these techniques may be applicable to future facilities. One attractive aspect of achieving stable beams via feedback is the option to choose lattice and RF parameters for operational flexibility, large dynamic aperture and beam lifetime, rather than accept compromises in operational parameters to help with the stability issue. The Slotline kicker concept can be scaled in operating frequency to address shorter bunches, and is possible with technology available today to imagine the signal processing being implemented with sampling rates of 8 - 16 GS/sec. From this early work at the SPS we think it entirely feasible to develop a system for HL-LHC application, which would might require closed loop bandwidths of 2 - 4 GHz [13].

The CERN injector upgrade plan is underway, the SPS began a long shutdown in December 2018. Future beam studies with the demonstration system, or an upgraded version of the system, must wait till 2020 or later. In 2017 US DOE funding decisions terminated the US contributions to this collaboration, and the skilled US team on this program has dispersed from a mix of employment layoffs, transfers to other technical areas outside of accelerator physics, and the completion of the University degree programs.

These first series of measurements have been successful in demonstrating the possibilities of this wideband approach to instability control, and have produced technical examples of the processing, pickup and kicker technologies. This work was the focus of a recent Stanford Ph.D. thesis that applied new ideas in model-based control to the accelerator physics community [14]. The model-based control may be very helpful in a future application where it can target the wideband power to selected modes and not exhibit the saturation impact from large mode zero motion.

The LARP-funded effort did more than produce hardware and take data, it also provided a dynamic collaboration between European and US labs, and trained a cohort of graduate students and a postdoctoral scientist in this mix of technology and accelerator physics. In many ways, the development of these young scientists and engineers, and the intellectual collaboration fostered between the labs, is the most important and enduring contribution of the work.

## Acknowledgements

Work supported by DOE contract DE-AC02-76SF00515, the US LARP program, the FP7 High Luminosity LHC project, the CERN LIU project, and the US-Japan Cooperative Program in High Energy Physics. J. Fox is especially grateful to the CERN LIU program for travel support to CERN in 2017 and 2018, and the ARiES WP6 program and the LNF-INFN laboratory for travel support to the 2018 APEC workshop. The US-Japan High luminosity Collaboration supported C. Rivetta's CERN travel in 2018. Many researchers contributed throughout this project, and this note must acknowledge the numerous contributions from J. Cesaratto, J. Dusatko, C. Rivetta, O. Turgut, S. Uemura (SLAC), and A. Bullitt, J. Goldfield, J. Platt, K. Pollock, N. Redmon (Stanford). We thank S. Verdu (Brookhaven), S. De Santis (LBL), D. Agiulera (CERN) and M. Wendt (CERN) for their contributions on the kicker technology through LARP and CERN LIU support. We owe thanks to H. Bartosik, E. Bjorsvik, W. Höfle, K. Li, E. Metral, B. Salvant , T Levens , G. Kotzian, D. Valouch, U. Werhe, G. Zhu (CERN) for consistent MD participation, Slotline Kicker efforts and enthusiasm. D. Alessini, A. Drago, S. Gallo, F. Marcellini and M. Zobov contributed numerous important ideas via LNF-INFN. The author also wants to specially acknowledge the longstanding collaborations with W. Hofle, D. Teytelman, M. Tobiyama and M. Serio who were central to developing numerous ideas in instability control for so many facilities.

## In Memoriam

This note was composed after the passing of Yong Ho Chin of KEK, and the passing of Albert Hoffmann of CERN. This author wants to add a personal acknowledgement to the memory of both, for their many contributions to the field as well as the warm personal connections they brought to our community. They will be greatly missed.

## References

[1] E. Shaposhnikova, "Intensity upgrade plans for CERN-LHC injectors", CERN-AB-2008-065.

[2] W. Höfle *et al.*, "Impact of a Wideband Feedback Prototype System on TMCI in the SPS", doi:10.18429/JACoW-IPAC2018-TUZGBD4

[3] J. Fox *et al.*, "Control of Intra-Bunch Vertical Motion in the SPS with GHz Bandwidth Feedback", J. Phys. Conf. Ser. **1067**, no. 7, 072024 (2018). doi:10.1088/1742-6596/1067/7/072024, 10.18429/JACoW-IPAC2018-WEPAL079

[4] J. Fox *et al.*, "Control of Intra-Bunch Vertical Instabilities at the SPS - Measurements and Technology Demonstration", doi:10.18429/JACoW-IPAC2017-TUPIK119

[5] K. Nakamura, Y. H. Chin, T. Obina, M. Okada, M. Tobiyama, T. Koseki, T. Toyama and Y. Shobuda, "Transverse Intra-bunch Feedback in the J-PARC MR", doi:10.18429/JACoW-IPAC2014-THOAA03

[6] O. Turgut, J. Dusatko, J. Fox, C. Rivetta and S. Rock, "Identification of Intra-bunch Transverse Dynamics for Model-Based Control Purposes at CERN Super Proton Synchrotron", doi:10.18429/JACoW-IPAC2016-THOAA01

[7] J. Dusatko, E. Bjørsvik, J. Fox, W. Höfle, C. Rivetta and O. Turgut, "The SPS Wideband Feedback Processor: A Flexible FPGA-Based Digital Signal Processing Demonstration Platform for Intra-Bunch Beam Stability Studies", doi:10.18429/JACoW-IBIC2017-WE1AB1

[8] K. Pollock et al., “Signal Equalizer for SPS Ecloud/TMCI Instability Feedback Control System”, TUPA32, Proceedings of IBIC’12, Tsukuba, Japan, 2012.

[9] J. M. Cesaratto *et al.*, “SPS Wideband Transverse Feedback Kicker: Design Report”, SLAC-R-1037.

[10] M. Wendt, I. Alonso Romero, S. Calvo, W. Höfle, O. R. Jones and E. Montesinos, “A Broadband Transverse Kicker Prototype for Intra-Bunch Feedback in the CERN SPS”, doi:10.18429/JACoW-IPAC2017-TUPIK053

[11] J. Platt, W. Höfle, K. Pollock and J. Fox, “Equalizer design techniques for dispersive cables with application to the SPS wideband kicker”, Nucl. Instrum. Meth. A **868**, 93 (2017). doi:10.1016/j.nima.2017.06.029

[12] K. Li *et al.*, “Recent Results from the Wideband Feedback System Tests at the SPS and Future Plans”, doi:10.18429/JACoW-HB2018-MOP2WA04

[13] J. Dusatko and J. Fox, “Ultra-Wideband Transverse Intra-Bunch Feedback: Beginning Development of a Next Generation 8GSa/s System”, doi:10.18429/JACoW-IPAC2018-WEPAF073

[14] O. Turgut, “Identification of Intra-Bunch Dynamics for Model-based Beam Instability Control in the CERN Super Proton Synchrotron”, Ph.D. Thesis Stanford University, Department of Aeronautics and Astronautics, April 2019 `https://searchworks.stanford.edu/view/13250248`

[15] The LARP collaboration meetings have many progress reports for this effort `http://www.uslarp.org/`

## 2.4 SPring-8 Bunch-by-bunch Feedback System

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### 2.4.1 Introduction

Digital bunch-by-bunch feedback systems for damping of betatron or synchrotron oscillations of storage rings are now indispensable devices for suppression of beam instabilities. At SPring-8, the 8-GeV electron storage ring for a light source, several digital feedback processors and feedback schemes were developed, and, in this report, we will show the progress of them and related topics.

### 2.4.2 Feedback System

#### 2.4.2.1 Concept of Feedback System

The conceptual diagram of a feedback system [1] is shown in Fig.1. A digital feedback system is composed of a beam position monitor (BPM), a RF front-end circuit (FE), a digital feedback signal processor, and kickers.

In the FE, a 180deg hybrid produces the difference signal (BPM signal) and the sum signal (BPM sum signal) of BPM electrodes facing each other across a beam. The BPM signal is proportional to both the position and the bunch current of a bunch, and the BPM sum signal is proportional to the bunch current. The FE amplifies the BPM signal to adjust its signal level for the input of the processor following the FE.

The digital feedback signal processor is the core component of a feedback system and it converts the turn-by-turn history of the position data detected by the BPM to the kick signals. Most feedback signal processors employ an FIR filter as the algorism to calculate a kick signal from position data. The bunch-by-bunch feedback is the feedback operated on a bunch-by-bunch basis and used at most rings.

#### 2.4.2.2 First version of Feedback Processor

We developed three types of the feedback signal processors for the SPring-8 storage ring of bunch (RF bucket) rate 508.6MHz. The first version of a feedback signal processor [2] was developed in 2003 and put into user operation in 2004. This processor was the one of the world's first FPGA based digital bunch-by-bunch feedback processor for ∼500MHz bunch rate. The processor was composed of six FPGA boards and an analog signal multiplexer. Each FPGA had two 12-bit 105MS/s ADCs and two 14-bit 125MS/s DACs: one for the feedback and one for diagnostics and was operated with the sampling rate of 85MS/s, one sixth of the bunch rate of 508.6MHz. The analog signal multiplexer was also an FPGA based system with ADCs and DACs, and converted six 85MS/s DAC output signals of the FPGA boards to a 500MS/s analog signal that drives kickers.

In the FE circuit, a position signal from a BPM (BPM signal) was split to six signals and each signal was down-converted to the baseband of kHz to 250MHz range with an analog demultiplexer, and distributed to six ADCs of the processor. The sampling timing of the ADCs were interleaved to obtain 500MS/s effective sampling rate. The processor was compact, cost

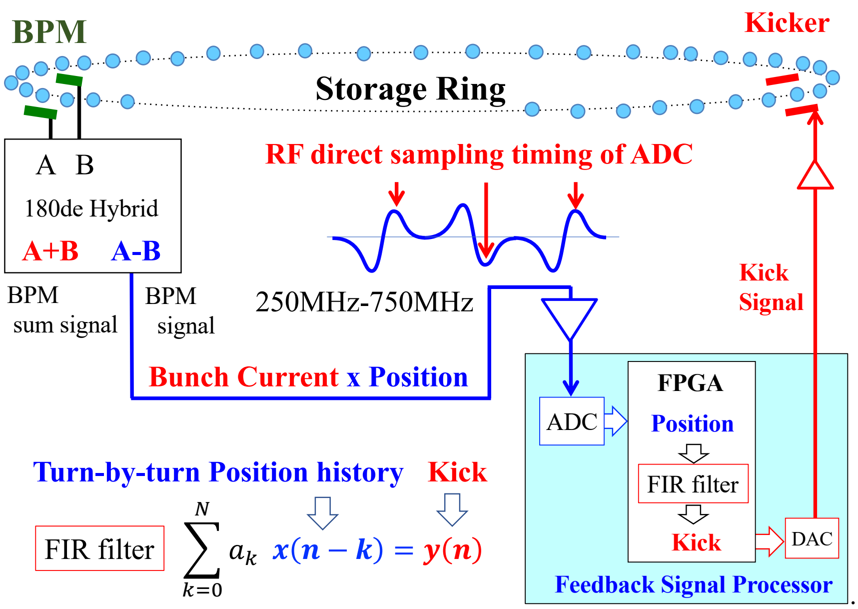


Figure 1: Digital feedback system.

effective, and with higher resolution compared with the processors operated at several rings at that time, which was composed of a number of DSP boards, an 8-bit ADC board, and a DAC board [3].

We also analyzed the effect of the noise of a BPM signal [2,4] on the beam size and a high-resolution BPM [5] was developed to suppress it. However, we met a signal coupling in the beam pipe between the BPM and the kicker placed side-by-side and this coupling made the feedback unstable even without a beam. This coupling was produced by the induction from the kicker to the BPM because the frequency of the feedback kick was much lower than the cut-off frequency of the beam pipe. Using the induced signal on the extra BPM between the BPM and the kicker, this coupling was canceled, and the instability of the feedback was suppressed [5].

#### 2.4.2.3 Second version of Feedback Processor

The second version of the feedback processor [6] was developed short after the first version was put on user operation. In the second version, one FPGA, six 125MS/s 12-bit ADCs for a BPM signal and four 1GS/s 12-bit DACs for a feedback kick signal were integrated on one single board. The sampling timing of the six ADCs were again interleaved to achieve the effective sampling rate of 500MS/s. The analog bandwidth of the ADC was 750MHz which covered the frequency range of the BPM signal: 250MHz-750MHz. Therefore, the RF direct sampling method [7] was adopted to sample the peak voltage of the BPM signal as in Fig.1. With the RF direct sampling, we eliminated the frequency down convertor stage for the BPM signal to the baseband signal of the kHz to 250MHz and this simplified the system and reduced the cost of the system compared with the system with the version 1.

With this processor, we collaborated with tens of storage rings: light sources (PF [8], TLS [9], HLS [10], SOLEIL [11], PLS, PLS-II [12], . . . ), proton bunched beam (KEK-PS [13]), and ion coasting/bunched beams [14,15], for the operation at user mode or for test of the feedback.

The single-loop two-dimensional feedback with a single version 2 processor was performed at several rings [8,9,11,12]. With two FIR filters in the processor, we drove the all four electrodes of a skewed position to kick two dimensionally.

#### 2.4.2.4 Fast Variable Attenuator System for Hybrid Filling

As in most light sources, the popular bucket filling modes of the ring was shifted from multi-bunch filling to so called "hybrid filling" that are composed of singlets with high bunch current and bunch trains with low bunch current as shown in Fig.2.

In the hybrid filling, the feedback system has to suppress multi-bunch instabilities of the bunch trains driven by its high average current, and single-bunch instabilities of singlets driven by its high bunch current.

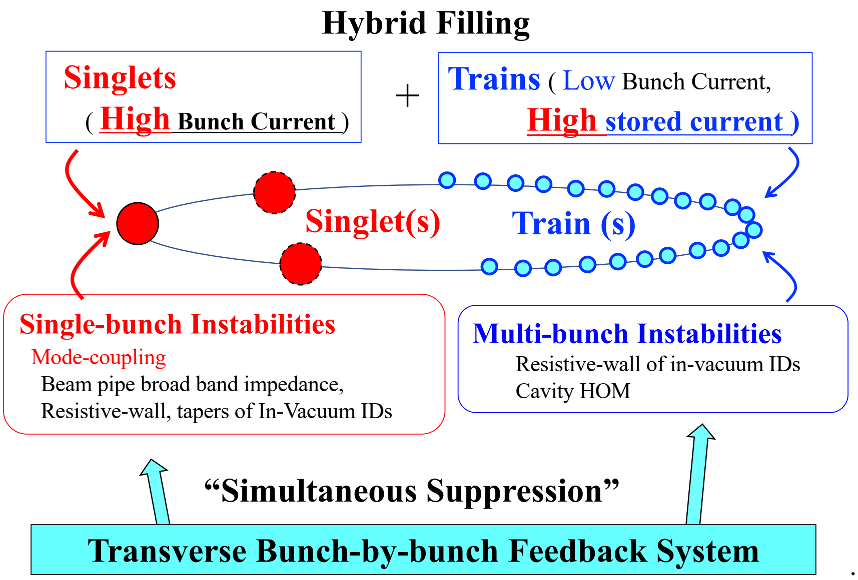


Figure 2: Hybrid filling

For the SPring-8 ring, the ratio of the bunch current of the singlets and the trains is about ten to fifty. This high contrast of the bunch current makes the processing with a single FE circuit difficult. A FE circuit has an amplifier that amplifies the BPM signal for adjustment of the signal level to the ADC input range of the processor. If the amplifier gain is optimized for low current bunches, the BPM signal level of high current bunches is so high, causing the amplifier to saturate, or the high feedback gain to be too high. If the gain is optimized to high current bunches, the BPM signal level of the low current bunches is so low and the resolution of ADC and the gain of the feedback are lost. Therefore, it is difficult to handle the high ratio of the bunch current with a single FE circuit.

To overcome the problem of the high ratio of bunch current, we first developed a simple bunch current sensitive two-step attenuator system [16] to equalize the two signal levels of "high" and "low" current bunches. The bunch current was measured using the BPM sum signal, and when the bunch current exceeds certain threshold, the attenuation increased to "high" to equalize the signal levels of "high" and "low" bunch current. However, its use was limited to some specific hybrid fillings.

In 2009, we developed new bunch current sensitive attenuator system [17] in Fig.3 to equalize the level of the BPM signals of multiple ranges of bunch current for the wire range of the hybrid filling modes. The attenuator system was based on the bunch-by-bunch feedback processor, and it detected bunch current of each RF bucket using the BPM sum signal and controlled a step attenuator by a digital signal output of the processor and a variable attenuator controlled by the analog voltage created by a DAC of the processor.

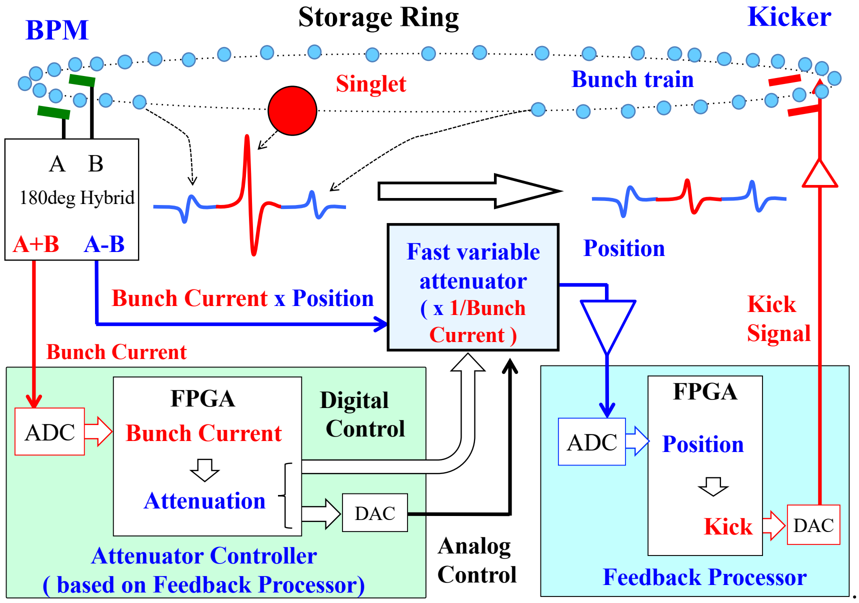


Figure 3: Bunch current sensitive automatic fast variable attenuator for RF front-end.

#### 2.4.2.5 Longitudinal Feedback with Resonant Stripline Kicker

For longitudinal feedback, we developed a resonant strip-line type kicker [18, 19], a new type of energy kicker with high shunt impedance per unit length, which is required to produce high kick strength at the limited space for the kickers in the large and high energy ring of SPring-8. The drive frequency of the kicker was set to 13/4 of the RF frequency ($f_{RF}$) to make the kicker drive circuit simpler [18,19] than the QPSK modulator based drive circuit for widely used over-damped cavity kickers of the frequency of 11/4 $f_{RF}$.

The longitudinal feedback with a feedback processor of the second version and the triplet of the resonant strip-line kickers was tested at the SPring-8 ring at 6-GeV operation and the feedback suppressed a longitudinal instability driven by a higher order mode of acceleration cavities [20].

#### 2.4.2.6 Third Version of Feedback Processor

The feedback signal processor version 3, BBFSIG3 [21–23] was developed with recent advances of digital technology of FPGAs, ADCs and DACs, in collaboration with SOLEIL and PAL, and is in operation at the SPring-8 ring since 2015. Figure 4 shows the feedback system with BBFSIG3. BBFSIG3 has multiple 500 MS/s ADCs; one ADC can sample all the bunch signals in the BPM signal. Each ADC has its own FE circuit with different amplifier gain optimized for some range of bunch current. The position signal from a BPM is split and is distributed to the FE circuits. The processor has another ADC to measure the bunch current using the BPM sum signal and the processor choose one ADC of which FE circuit has adequate gain for the measured bunch current on bunch-by-bunch basis.

With this processor BBFSIG3, the feedback system for hybrid filling is simplified and the signal-to-noise ratio (SNR) for high current bunches is improved, compared with the previous variable attenuator system. With high SNR, the gain of the feedback for high current bunches can be increased without the emittance increase by the feedback noise [2, 4], and the signal of the bunch motion is distinct from noise and is easily observed.

The first FPGA program for the processor is for eight ADCs as shown in Fig.4 to cover the various hybrid filling modes of the SPring-8 ring, as shown in Fig.4. Then, the FPGA program was converted to handle two feedback loops for the horizontal and vertical directions in a single BBFSIG3 as shown in Fig.5, in the collaboration with PAL to apply the processor to the hybrid filling of PLS-II at PAL.

The feedback processor BBFSIG3, has several functions shown in Fig.6:

**1)** "Selector": For bunch-by-bunch selection of sets of ADC and FE corresponding to bunch current with anti-chattering function, to compensate the bunch current dependence of the BPM signal at hybrid filling.

**2)** "Stretcher": Stretching the pulse length of a kick signal for selected ADCs of specific bunch current ranges. To kick in bunch-by-bunch basis, the kick pulse length is just one clock length for a bunch and is rather shorter than the kicker filling time, which leads to the reduction of kicker efficiency. However, isolated bunches like singlets do not have constraint on the kick pulse length, therefore, the kick pulse length for those bunches are increased to several clock length in the processor to obtain kicker's full efficiency.

**3)** "FIR 11"-"FIR 22" : FIR filters of 500MHz RF bucket/bunch rate for compensation of the response of kickers and power amplifiers.

**4)** "Signal switchyard": to convert the horizontal and vertical signals to the signals for skewed position kickers.

**5)** Bunch-by-bunch base switching between the feedback signal and the signal from an internal signal source ("NCO") for tune measurement during user operation by exciting oscillation just one bunch in a ring. This function is based on the collaboration with SOLEIL.

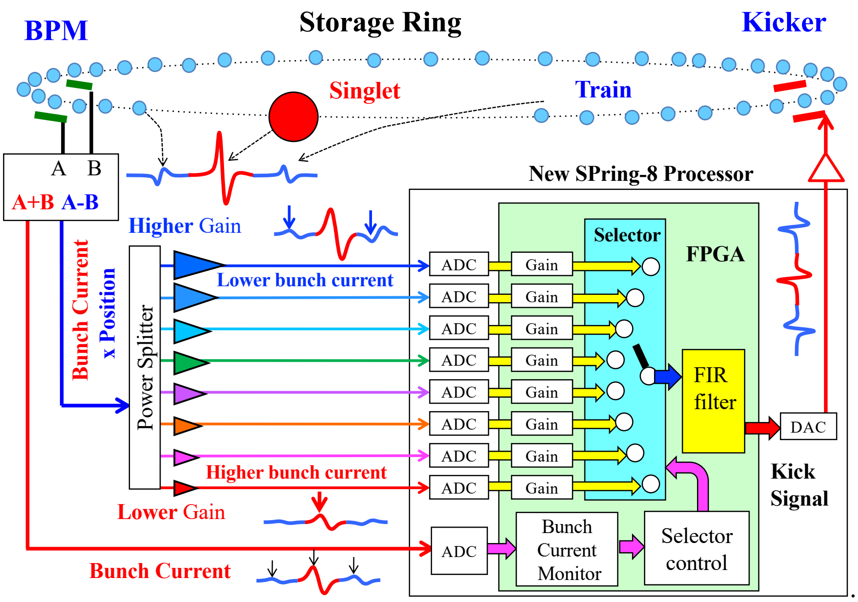


Figure 4: Feedback for hybrid filling with SPring-8 signal processor version 3 (BBFSIG3).

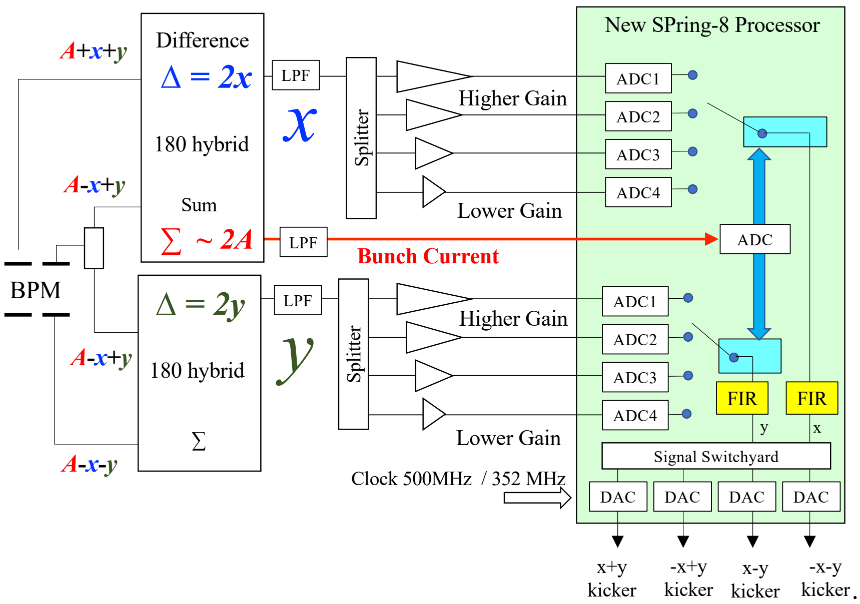


Figure 5: Two-dimensional signal processing by one BBFSIG3 processor for hybrid filling at PLS-II.

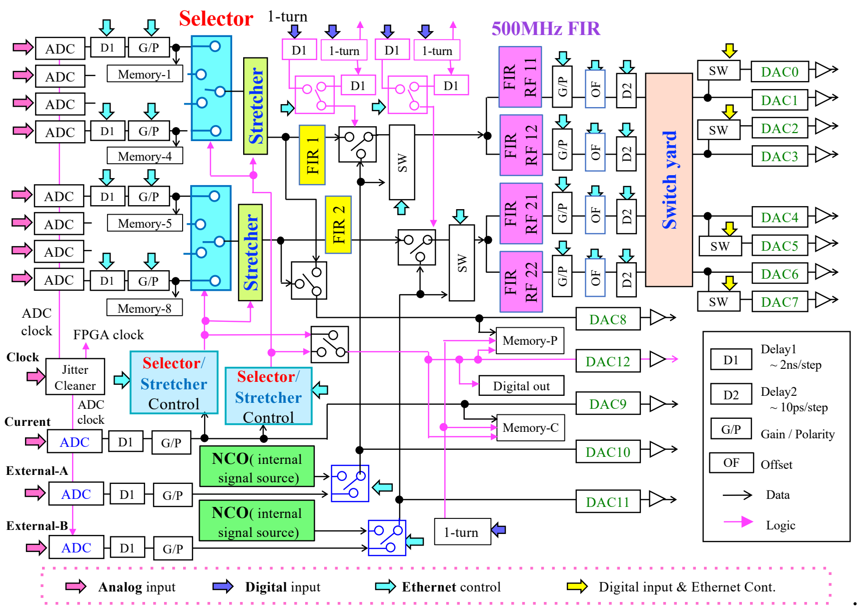


Figure 6: Block diagram and functions of SPring-8 signal processor version 3 (BBFSIG3) in Fig.5.

### 2.4.3 New Feedback Scheme: Multiple BPM Feedback

At hybrid filling, the high bunch current in singlets is required by users. However, the bunch current is limited by single bunch instabilities and a feedback system is applied to suppress the instabilities to increase the bunch current to some value. To increase the bunch current further, we proposed two types of feedback scheme: multiple BPM feedback [24] and head-tail feedback [25–27].

#### 2.4.3.1 Limitation on Feedback Gain

Usual transverse feedback systems calculate the required feedback kick from the history of turn-by-turn positions of a single BPM to damp the oscillation. However, at high gain, the feedback itself drives an instability, or the beam is fragile for the noise kick if the gain is close to the threshold of this instability [1, 24]. This instability of the feedback is driven by the coupling between the feedback kick and the turn-by-turn position history used to calculate the feedback kick because the feedback kick affects the turn-by-turn position of later turns, and this coupling produces large tune shift to drive the tune to unstable region [1, 24].

#### 2.4.3.2 Multiple BPM Feedback and Feedback Processor

To eliminate the coupling between the bunch position and the kick, multiple BPM scheme [1,24] shown in Fig.7 is proposed. In this scheme, the multiple BPMs are distributed in a ring and a feedback kick is calculated from the beam positions of them at the same turn as the kick, as in analog feedback systems. For this scheme, two FIR filters, FIR-M and FIR-T, are introduced as shown in Fig.7. With FIR-M, the position data of the multiple BPMs is converted to a feedback kick signal, and FIR-T subtract the offset in the feedback kick signal of FIR-M using the turn-by-turn data from FIR-M. The function of the FPGA program of BBFSIG3 for this scheme is shown in Fig.8 and the program was developed based on the program for Fig.6. In principle, just one BPM with adequate betatron phase relation between the BPM to the kicker is enough for this feedback. However, with multiple BPMs, the condition on the betatron phase advance from the BPMs to the kicker is relaxed with FIR-M as in analog feedback with two BPMs, where FIR-M is a two-tap analog FIR filter and no FIR-T.

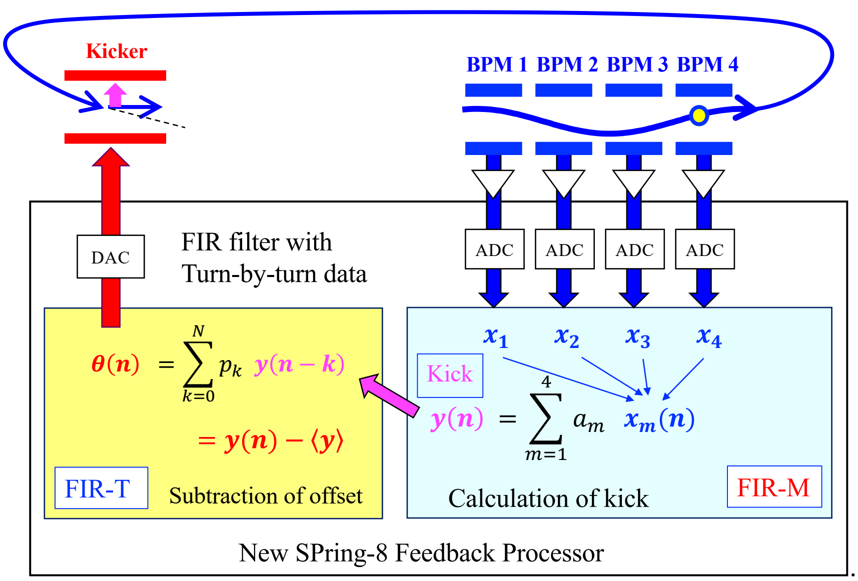


Figure 7: Multiple BPM feedback.

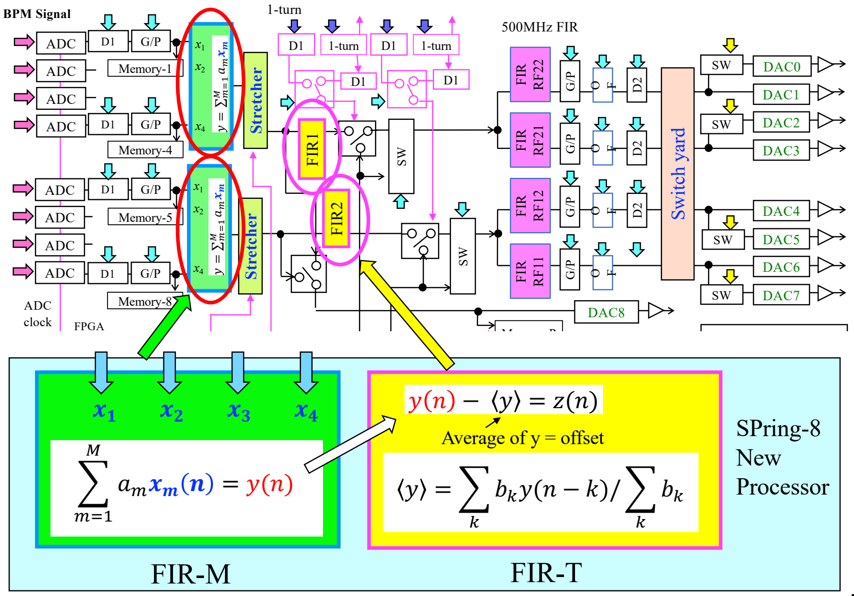


Figure 8: BBFSIG3 with FPGA program for Multiple BPM feedback with two feedback loops.

### 2.4.4 New Feedback Scheme: Head-tail Feedback

#### 2.4.4.1 Head-tail Motion inside Bunch and its Feedback

In single instability [28], the oscillation of the head of a bunch produces the oscillating wake field and this wake field kick the tail of the bunch and excite the oscillation of the tail as shown in Fig.9. By a synchrotron motion, electrons in the head move to the tail and those in the tail move to the head. Then the oscillation of the “new” head that is excited by the initial oscillation kicks of the electrons in the “new” tail, excites the oscillation of the “new” tail and the loop is closed. At some condition, this loop is unstable and drive single-bunch instabilities.

The feedback systems previously mentioned are for the center of mass (CM) of bunches (CM feedback) which detects the position of the CM (CM position) and adds the kick with the same amount for all electrons in the bunch (CM kick). However, at the single-bunch instabilities, the oscillation phases of the head and the tail usually have some difference and there are two oscillations: the oscillation of the CM position and of the relative position between the head and the tail (head-tail position) as shown in Fig.9, and the effect of the CM feedback on head-tail position is indirect.

To enhance the damping of the single-bunch instabilities, head-tail feedback [25–27] was proposed. The head-tail feedback directly detects the angle of a bunch produced by the head-tail motion and kick the head and the tail of the bunch with different kick strength (head-tail kick) as shown in Fig.9.

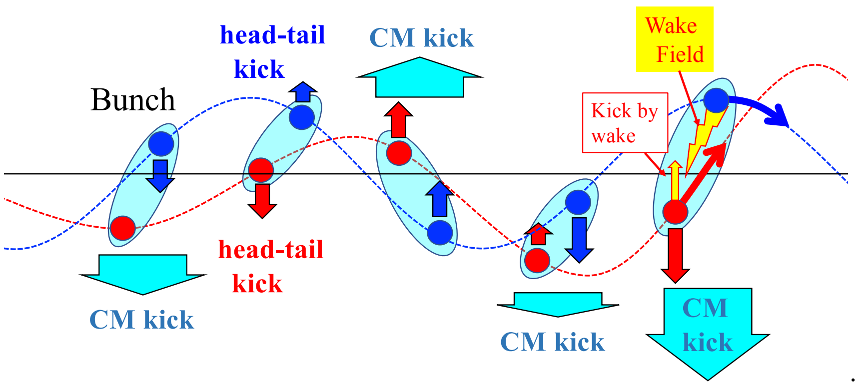


Figure 9: Single-bunch instability, CM feedback and head-tail feedback.

#### 2.4.4.2 Detection of Head-tail Motion

The idea of the direct detection of the angle of a bunch is shown in Fig.10. The BPM signal shapes of a usual button type BPM for a CM position (CM signal) and for an angle (angle signal) are shown in Fig.10, using the BPM signal obtained with MAFIA simulation for a short bunch as a Green function.

The shape of the CM signal is the derivative of the timing distribution of a bunch, and the shape of the angle signal is similar to the derivative of the CM signal, therefore, the parity of the CM signal and the angle signal are opposite; odd for the CM signal and even for angle signal. The BPM sum signal has the same shape as the CM signal and has odd parity. Therefore, by differentiating the CM signal with a simple high pass filter, we have the similar shape signal as the angle signal with even parity; if the bunch shape is the Gaussian, they have the similar shape. After the multiplication with a mixer with this signal, the CM signal is converted to high frequency signal with small low frequency component and the angle signal is to a signal with low frequency component. Using a low pass filter, we can enhance the angle signal compared with the CM signal, and the parity of those signals are still opposite, therefore, we can sample with an ADC at adequate timing where the CM signal is low, and the angle signal is high. In this case of Fig.10, the value of the angle is assumed as that the transverse position at the timing shift of the bunch length in r.m.s. is the same as the CM position.

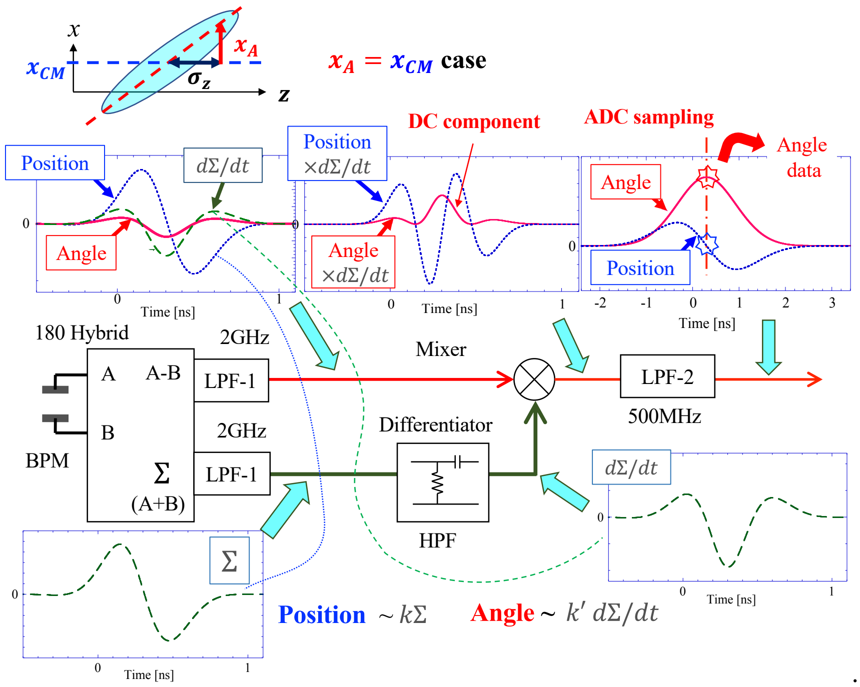


Figure 10: Concept of monitor for head-tail motion detection.

### 2.4.4.3 Head-tail Kicker

A kicker with high kick gradient in time (head-tail kicker) is required to kick the head and the tail of a bunch with different kick strength. Based on the structure of the SPring-8 longitudinal kicker with slit [18], we designed a high Q cavity transverse kicker [26] in Fig.11 for isolated bunches to produces almost one-order higher kick gradient than usual stripline kickers.

For a bunch-by-bunch head-tail kicker on bunch-by-bunch basis, we proposed a low Q transverse cavity kicker [27] in Fig.12 with short longitudinal length. The kicker creates two times more kick gradient than the simple stripline kickers, and with its short length, two or three times more kickers can be installed to a space for kickers than usual stripline kickers.

Also, we propose a series of short stripline kickers [27] driven by a pulse train with 100% duty to enhance the total kicker efficiency.

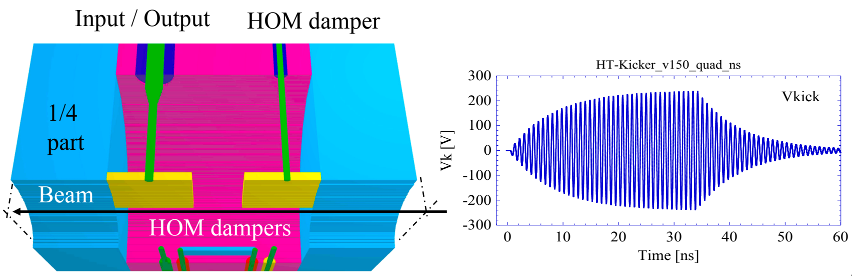


Figure 11: High Q resonant stripline type head-tail kicker (1/4 shape). Left: Shape, Right: Growth of kick voltage by resonance. The cavity length is ~100mm.

### 2.4.4.4 Simulation

The simulation of the head-tail feedback was performed [25, 27] with the home-made code SISR [29, 30] for single-bunch instabilities. The signal processing for head-tail feedback in the processor

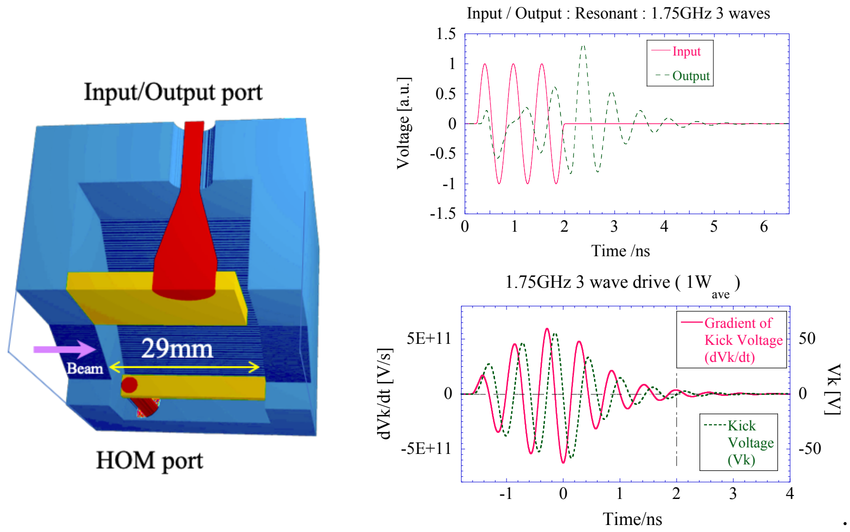


Figure 12: Low Q resonant stripline type head-tail kicker. 1/4 shape with point symmetry in cross-sectional plane for the beam axis.

is the same FIR filters as for CM feedback that the phase shift of the feedback kick from the beam oscillation at the kicker is -90 degree. For the wake fields and beta functions for the simulation, we used the wake field calculated with MAFIA based on the shape of the beam pipe components of SPring-8 (SPring-8 wake) and beta functions at the components, and a constant wake field that is just the step function with the step at the particle that produces wake (constant wake). The strength of the constant wake times beta function is set to show the same threshold current with the CM feedback only as with the SPring-8 wake case. We assumed that the head-tail feedback and the center-of-mass feedback were both in operation as shown in Fig.13.

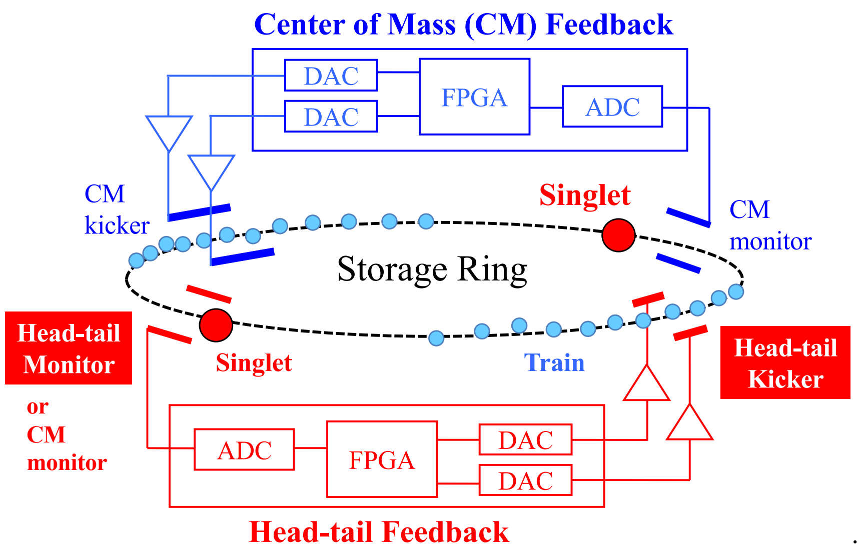


Figure 13: Head-tail feedback with CM feedback.

The preliminary results [25, 27] show that, with the SPring-8 wake, the bunch current increased 50% with both the head-tail feedback and the CM feedback compared with the CM feedback only, and with the constant wake, the bunch current increased 250%.

Also we found that the relative phase of the CM oscillation and head-tail oscillation is rather constant during the growth of the instability, therefore, the feedback that detects the CM position of a bunch and kick with head-tail kicker shows the suppression of the single bunch instabilities and increases the bunch current, but less than the head-tail feedback. The FIR filter for this feedback was -180 degree phase shift.

For both feedbacks and both wake cases, the bunch motion above the bunch current of the stability limit shows higher order oscillations inside of the bunch as in text books [28] and the both effect of the CM feedback and the head-tail feedback should be small for those instabilities.

## References

[1] For example, T. Nakamura, “Transverse and Longitudinal Bunch-by-bunch Feedback for Storage Rings”, in Proc. of IPAC2018, TUZGBD2, `http://accelconf.web.cern.ch/AccelConf/ipac2018/papers/tuzgbd2.pdf`

[2] T. Nakamura, S. Date, K. Kobayashi, and T. Ohshima, “Transverse Bunch-by-bunch Feedback System for the SPring-8 Storage Ring”, in Proc. of EPAC2004, THPLT068, `https://accelconf.web.cern.ch/accelconf/e04/PAPERS/THPLT068.PDF`

[3] D. Bulfone, V. Forchi’, M. Lonza, L. Zambon, and M. Dehler, “The ELETTRA Digital Multi-bunch Feedback System”, in Proc. of EPAC2002, THPRI035, `https://accelconf.web.cern.ch/accelconf/e02/PAPERS/THPRI035.pdf`

[4] T. Nakamura, “Residual Beam Motion Driven by the Noise at Transverse Feedback”, in Proc. of NANOBEAM2005, KEK Proceedings 2005-20, p. 401, `https://lib-extopc.kek.jp/preprints/PDF/2005/0525/0525020.pdf`

[5] T. Nakamura, “Beam Position Monitor and Kicker for the SPring-8 Transverse Bunch-by-bunch Feedback”, in Proc. of DIPAC2005, POW027, `http://accelconf.web.cern.ch/AccelConf/d05/PAPERS/POW027.PDF`

[6] T. Nakamura, K. Kobayashi, “FPGA Based Bunch-by-bunch Feedback Signal Processor”, in Proc. of ICALEPCS2005, PO2.022-2, `http://accelconf.web.cern.ch/AccelConf/ica05/proceedings/pdf/P3_022.pdf`

[7] T. Nakamura, K. Kobayashi, and Z. Zhou, “Bunch-by-bunch Feedback by RF Direct Sampling”, in Proc. of EPAC2008, THPC128, `https://accelconf.web.cern.ch/accelconf/e08/papers/thpc128.pdf`

[8] T. Nakamura, K. Kobayashi, X. W. Cheng, T. Honda, M. Izawa, T. Obina, and M. Tadano, “Single-Loop Two-Dimensional Transverse Feedback for Photon Factory”, in Proc. of EPAC2008, THPCH092, `http://accelconf.web.cern.ch/AccelConf/e06/PAPERS/THPCH092.PDF`

[9] K.H. Hu, C.H. Kuo, P.J. Chou, Demi Lee, S. Y. Hsu, Jenny Chen, C.J. Wang, K.T. Hsu, K. Kobayashi, T. Nakamura, A.W. Chao, and W.T. Weng, “Commissioning of the Digital Transverse Bunch-by-bunch Feedback System for the TLS”, in Proc. of EPAC2006, THPCH097, `http://accelconf.web.cern.ch/accelconf/e06/papers/thpch097.pdf`

[10] Z.R. Zhou, J.H. Wang, B.G. Sun, L.J. Huang, K. Zheng, Y.L. Yang, Y.B. Chen, T. Nakamura, and K. Kobayashi, “Development of Digital Transverse Feedback Bunch-by-bunch Feedback System of HLS”, in Proc. of PAC2007, MOPAN056, `http://accelconf.web.cern.ch/AccelConf/p07/PAPERS/MOPAN056.PDF`

[11] R. Nagaoka, L. Cassinari, J.C. Denard, J.M. Filhol, N. Hubert, M.P. Level, P. Marchand, C. Mariette, F. Ribeiro, R. Sreedharan, T. Nakamura and K. Kobayashi, “Transverse Feedback

Development at SOLEIL", in Proc. of DIPAC2007, WEPC04, https://accelconf.web.cern.ch/accelconf/d07/papers/wepc04.pdf

[12] E.-H. Lee, D.-T. Kim, J.-Y. Huang, S. Shin, T. Nakamura, and K. Kobayashi, "A Transverse Bunch by Bunch Feedback System for Pohang Light Source Upgrade", Review of Scientific Instruments 85, 125102 (2014).

[13] With the first version, T. Toyama, S. Igarashi, T. Obina, T. Miura, T. Nakamura, and K. Kobayashi, "Transverse Feedback Damper at the KEK-PS MR", in Proc. of the 3rd Ann. Meet. of Part. Acc. Soc. of Japan (2006), TP57, http://www.pasj.jp/web_publish/pasj3_lam31/Proceedings/T/TP57.pdf

[14] T. Nakamura, K. Kobayashi, T. Shirai, S. Fujimoto, A. Noda, T. Toyama, S. Shibuya, and K. Torikai, "Digital Feedback for Transverse Coasting Beam Instability at S-LSR", in Proc. of the 3rd Ann. Meet. of Particle Accelerator Society of Japan (2006), TP56, http://www.pasj.jp/web_publish/pasj3_lam31/Proceedings/T/TP56.pdf

[15] T. Shirai, K. Mizushima, S. Ojima, T. Furukawa, Y. Iwata, M. Kanazawa, K. Noda, S. Shibuya, K. Torikai, K. Kobayashi, T. Nakamura, "Fast Extraction of Electron-Cooled Ion Beam at HIMAC", in Proc. of 5th Ann. Meet. of Part. Acc. Soc. of Japan, (2008), WP050, https://www.pasj.jp/web_publish/pasj5_lam33/contents/PDF/WP/WP050.pdf

[16] T. Nakamura, T. Fujita, K. Fukami, K. Kobayashi, C. Mitsuda, M. Oishi, S. Sasaki, M. Shoji, K. Soutome, M. Takao, and Y. Taniuchi, "Filling of High Current Singlet and Train of Low Bunch Current in SPring-8 Storage Ring", in Proc. of EPAC2008, THPC127, http://accelconf.web.cern.ch/AccelConf/e08/papers/thpc127.pdf

[17] K. Kobayashi and T. Nakamura, "New Automatic Bunch Current Sensitive Fast Attenuator for RF Front-end of Bunch-by-bunch Feedback System at SPring-8", in Proc. of ICALEPCS2009, THB006, https://accelconf.web.cern.ch/AccelConf/icalepcs2009/papers/thb006.pdf

[18] T. Nakamura, "Resonant Strip-line Type Longitudinal Kicker", in Proc. of IPAC2011, MOPO007, http://accelconf.web.cern.ch/AccelConf/IPAC2011/papers/mopo007.pdf

[19] M. Masaki, T. Fujita, K. Kobayashi, T. Nakamura, M. Oishi, H. Ohkuma S. Sasaki, and M. Shoji, "Development of a Highly Efficient Energy Kicker for Longitudinal Bunch-by-bunch Feedback", in Proc. of IBIC2013, TUPC18, http://accelconf.web.cern.ch/AccelConf/IBIC2013/papers/tupc18.pdf

[20] M. Masaki, T. Nakamura, K. Kobayashi and T. Fujita, "Test of Longitudinal Bunch-by-bunch Feedback at the SPring-8 Storage Ring", in Proc. of the 12th Ann. Meet. of Part. Acc. Soc. of Japan (PASJ2015), WEP088, https://www.pasj.jp/web_publish/pasj2015/proceedings/PDF/WEP0/WEP088.pdf

[21] K. Kobayashi, T. Nakamura, M. Masaki, and T. Fujita, "Development of a New Bunch-by-bunch Feedback Signal Processor at the SPring-8 Ring", Proc. of the 12-th Ann. Meet. of Part. Acc. Soc. of Japan (PASJ2015), WEOL03, https://www.pasj.jp/web_publish/pasj2015/proceedings/PDF/WEOL/WEOL03.pdf

[22] T. Nakamura, K. Kobayashi, M. Masaki, T. Fujita, H. Dewa, T. Asaka, S. Sasaki, and H. Ohkuma, "Bunch-by-bunch Feedback System for Hybrid Filling and Recent Topics in SPring-8", Topical Workshop on Instabilities, Impedance

and Collective Effects 2014 (TWIICE2014), Synchrotron SOLEIL, Jan. 16-17, 2014, https://indico.cern.ch/event/277919/contributions/626964/attachments/506954/699891/02-TWIICE2014_Nakamura.pdf

[23] T. Nakamura, K. Kobayashi, T. Fujita, M. Masaki, H. Dewa, R. Sreedharan, R. Nagaoka, LEE Jaeyu, KIM Dotae, and SHIN Seunghwan, "New SPring-8 Bunch-by-bunch Feedback Processor for Hybrid Filling", The Joint ARIES Workshop on Electron and Hadron Synchrotrons: Next Generation Beam Position Acquisition and Feedback Systems, ALBA Synchrotron, Nov. 12-14, 2018, https://indico.cern.ch/event/743699/contributions/3112134/attachments/1747270/2840473/SP8_BBF_ARES_WS_181114.pdf

[24] T. Nakamura, "Stabilization of High Gain Transverse Feedback by Multiple BPMs", in Proc. of 14th Ann. Meet. of Part. Acc. Soc. of Japan, (PASJ2017), TUP090, http://www.pasj.jp/web_publish/pasj2017/proceedings/PDF/TUP0/TUP090.pdf

[25] T. Nakamura, "Challenge to Head-tail Feedback for Mode-coupling Instability", in Proc. of 15th Ann. Meet. of Part. Acc. Soc. of Japan, (2018), THP089, https://www.pasj.jp/web_publish/pasj2018/proceedings/PDF/THP0/THP089.pdf

[26] T. Nakamura, "Proposal of Head-tail Kicker for Feedback to Cure Head-tail Instabilities", the 70-th annual meeting abstracts of the Physical Society of Japan, 24aDE-5 (2015), https://doi.org/10.11316/jpsgaiyo.70.1.0_547

[27] T. Nakamura, "Bunch-by-bunch Head-tail Kicker for Head-tail Feedback for Single-bunch Instabilities", in Proc. of 16th Ann. Meet. of Part. Acc. Soc. of Japan, (2019), WEPI031.

[28] For example, A. Chao, "Physics of Collective Beam Instabilities in High Energy Accelerators", Wiley Series in Beam Physics and Accelerator Technology (1993). ISBN: 9780471551843. Electronic version available on https://www.slac.stanford.edu/~achao/wileybook.html

[29] T. Nakamura, "Simulation of Beam Instabilities in SPring8", Workshop SAD2006, KEK, Sept. 5-7, 2006, http://acc-physics.kek.jp/SAD/SAD2006/Doc/Slide/Nakamura.pdf

[30] T. Nakamura, "The Simulation Study of the Single-bunch Instabilities in the SPring-8 Storage Ring", in Proc. of EPAC1996, WEP104G, http://accelconf.web.cern.ch/AccelConf/e96/PAPERS/WEPG/WEP104G.PDF

## 2.5 Transverse Intra-bunch Feedback System in J-PARC Main Ring

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### 2.5.1 Introduction

Japan Proton Accelerator Research Complex (J-PARC) comprises three proton accelerators: a 400 MeV linear accelerator [1], a 3 GeV Rapid-Cycling Synchrotron (RCS) [2] and a 30 GeV Main Ring synchrotron (MR) [3]. The RCS accelerates the proton beam up to 3 GeV in 25 Hz and supplies it to the Material and Life Science Facility and the MR. The MR accelerates the beam further up to 30 GeV and extracts it to the neutrino beam line with fast extraction (FX) and the hadron beam line with slow extraction (SX). The main parameters of the MR are summarized in Table 1.

Table 1: Main parameters of J-PARC MR.

| | |
|---|---|
| Circumference | 1567.5 m |
| Injection Energy | 3 GeV |
| Extraction Energy | 30 GeV |
| Repetition Period | 2.48 s (FX), 5.2 s (SX) |
| RF Frequency | 1.67 - 1.72 MHz |
| Number of Bunches | 8 |
| Synchrotron Tune | 0.002 - 0.0001 |
| Betatron Tune (Hor. / Ver.) | 21.35 / 21.45 (FX), 22.33 / 20.8 (SX) |

The MR impedance is dominated by the transverse resistive-wall impedance of the stain-less steel (later one third of that was replaced by the titanium chamber) and the horizontal kicker impedance [4]. The fast extraction (FX) kicker impedance has sharp peaks at about 1MHz and 10MHz. The injection kickers has peaks at about 3 MHz and 70 MHz. It is almost halved after kickers were replaced by parasitic-impedance-free new models with HOM dampers. The FX kickers were replaced in 2010 summer shutdown and injection kickers in December 2012.

The beam instability evaluation before the commissioning of MR started predicted that beam instabilities would start to hurt beam operation from the beam power of 100-200kW. Although, the necessity of a damper system has been recognized, the actual development has been delayed due to financial constraints. After the commissioning of MR started, the careful inventory of the existing hardware revealed that we already have some key components necessary to compose the damper system: several unused Single-Pass Monitor (SPM) [5] and the exciters for tune measurements that can be exploited as damper kickers. It was found that only remaining component to be developed is a signal processing circuit to filter and process SPM data and then to produce kick signals. The whole project costs only less that 100k USD.

The MR beam power is steadily upgraded (Figure 1) and timely introduction of the damper system has been indispensable for the steady upgrade.

Figure 2 sketches the transverse bunch by bunch feedback system (BxB FB) introduced in December 2010. The beam position signals are sampled at an RF frequency times 64 rate (107.0MHz at 3GeV). The signal processing and digital filtering circuits consist of two LLRF4 boards with four 14-bit ADCs and two 14-bit DACs. They extract the betatron oscillation signals using 8-tap FIR filters. Its system integration and firmware development including EPICS interface was done by the Dimtel Inc [6]. The kick signals are sent to the stripline damper kickers

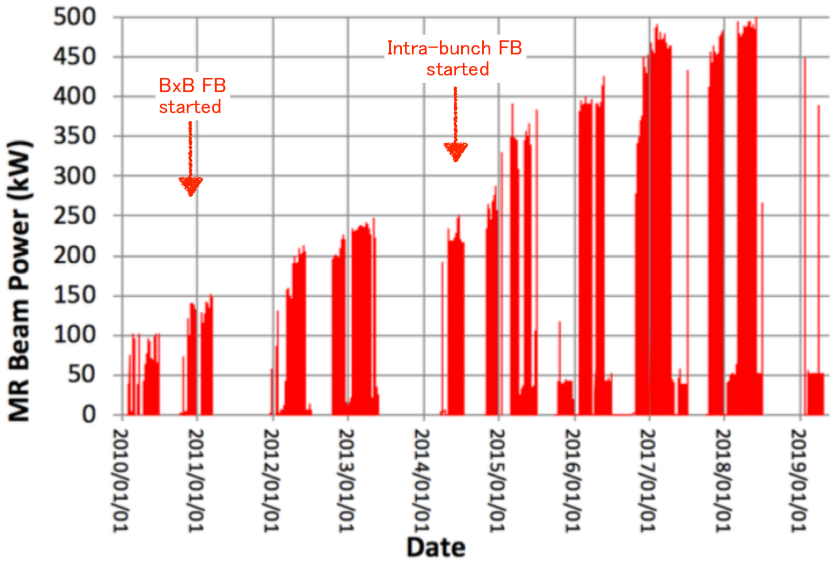


Figure 1: History of MR beam power.

through the power amplifiers (four 500W/ 10kHz-250MHz ones for the horizontal plane and two 1kW/100kHz-8MHz ones for the vertical plane, later replaced by the same ones as horizontal) to provide a single kick per bunch per passage for the both directions. This BxB FB was effectively suppressing transverse dipole oscillations, allowed attaining the 230 kW beam power [7]. But the BxB FB can damp only the center of mass motions of the whole bunches. Even with the BxB FB on, internal bunch oscillations have been still observed, which is causing additional particle losses, especially around the 250 kW beam power [8]. To suppress intra-bunch oscillations, a more wideband and elaborate feedback system (named the intra-bunch feedback system) has been developed (Figure 3) [9].

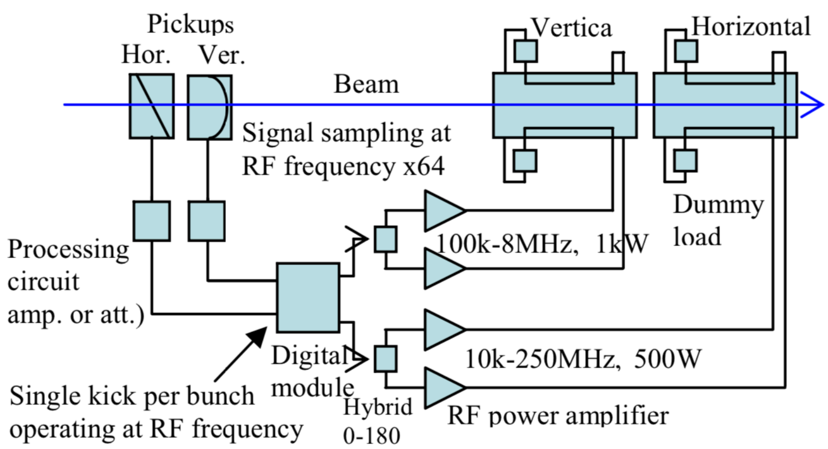


Figure 2: Schematic view of the transverse bunch-by-bunch feedback system.

#### 2.5.1.1 Tapered-coupler BPM

The new stripline BPM has been designed and fabricated based on Linnecar's electrode design [10] (Figure 4). It is equipped with the exponentially tapered electrodes which, in principle, allow a flatter and wider frequency response (the green line in Figure 5) than the conventional

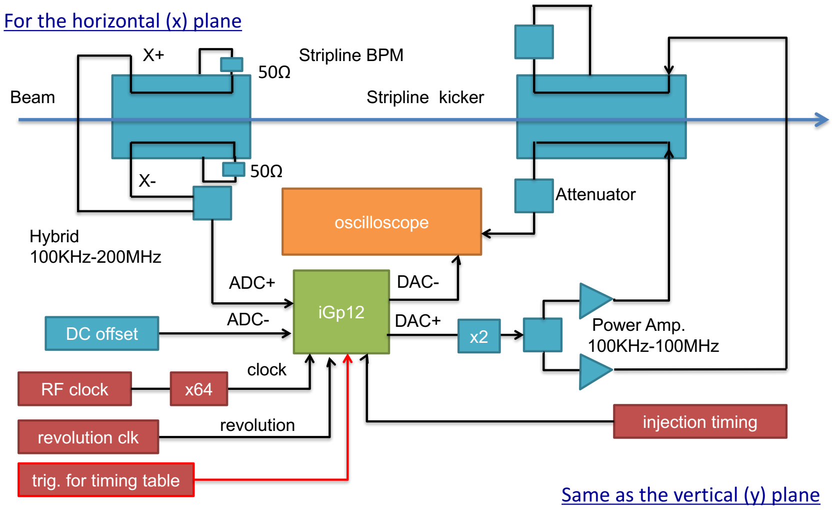


Figure 3: Schematic view of the transverse intra-bunch feedback system.

rectangular ones (the blue line in Figure 5). The diameter of the beam pipe is 148 mm, and the length of the electrodes is 300mm. The electrodes are placed 67mm from the center of the beam pipe. The height of the electrodes from the chamber surface needs to be gradually reduced (proportional to its width) toward their tips for the impedance matching. The BPM characteristics were measured by the stretched wire method. The measured frequency response is shown by the red line in Figure 5. It can be seen that the new BPM has a good frequency response up to 1GHz. The position sensitivity is also measured and it is found to be fluctuating around 0.027 by 0.002.

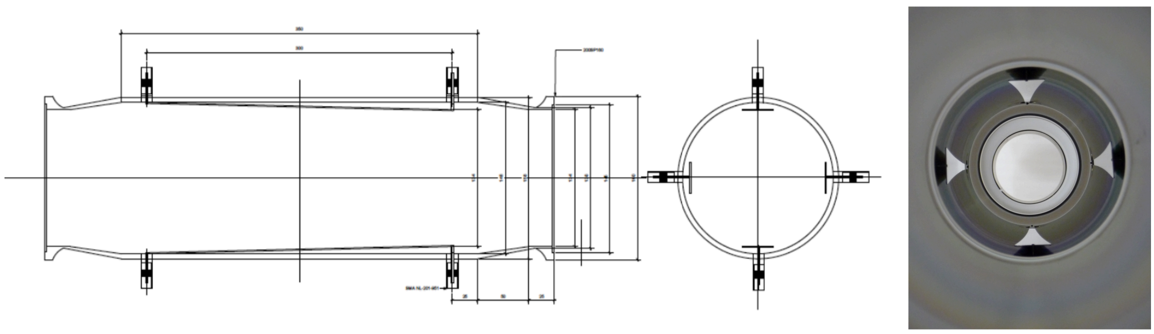

Figure 4: Drawings of side (left), front (center) views, and the photograph (right) of the BPM.

#### 2.5.1.2 Stripline Kickers and Power Amplifiers

The new stripline kickers were also fabricated (Figure 6). The electrodes are 750mm long and they are put on the circle of the diameter 140mm. They are coated with the Diamond Like Carbon (DLC) to suppress the electron multipacting [11]. The power amplifiers have 3kW capability. Their bandwidth is 100kHz-100MHz, which limits the bandwidth of the whole system now. The kick angle at 3 GeV when used with the two 3kW amplifiers is estimated to be 3.2 $\mu rad$ at 0.263 MHz [12].

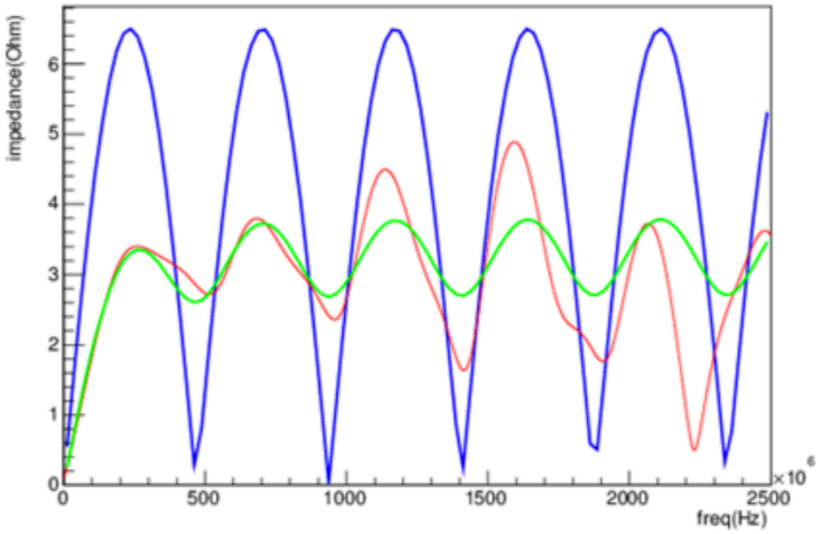


Figure 5: Theoretical and measured frequency responses of the BPM.

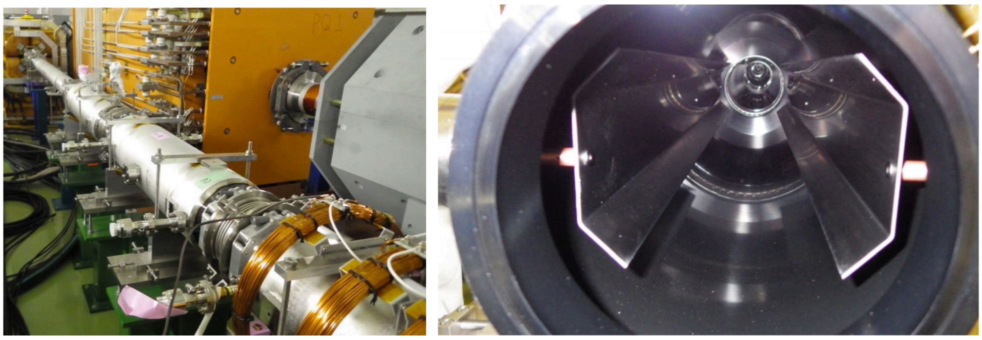

Figure 6: Stripline kicker with DLC coating.

#### 2.5.1.3 Signal Processing by iGp12

We adopt the iGp12 signal processing module developed by Dimtel Inc. [6]. It samples BPM signals (through the hybrid coupler) at the rate of 64th harmonic of the RF frequency (107-110MHz). It divides each RF bucket into 64 bins (slices). It extracts betatron oscillation signals by using the n-tap FIR ($n \leq 16$, n=8 in early-stage and 4 in later-stage is used) filter on each slice, and feedbacks kick signals to each slice. As seen in Figure 5, the frequency characteristic of the BPM is approximately linear in the low frequency region (up to 200 MHz). Thus, the beam position can be reconstructed by integrating the differentiated signals from the BPM.

### 2.5.2 Commissioning of the intra-bunch feedback system

Trial of the intra-bunch feedback damping had started in October 2012. The processing circuit, iGp12-H, was first set in the same auxiliary building as the BxB FB (D1 building). In Figure 7 the photograph taken by M. Tobiyama shows four experimenters right to left, T. Obina, Y. H. Chin, Y. Shobuda, and T. Toyama. In autumn of 2013, K. Nakamura joined our group as a master candidate from Kyoto University. He designed, bench-tested and installed the above mentioned BPM. In May 7 and 9 of 2014, we commissioned the intra-bunch feedback system, starting with the number of FIR filter taps 8 and reduced down to 4 in May 9 for faster damping. The beam parameters during the commissioning study is tabulated in Table 2.

Figure 8 shows the 3-D view of the time evolutions (top) and FFTs (bottom) of the oscillation amplitude of the horizontal dipole moment in the following three conditions: (left) both the intra-bunch and the BxB FB systems are off, (center) only the BxB FB system is on, and (right) only the intra-bunch FB system is on. The X-and Y-axes show the oscillation amplitudes of the bunch-slices and the revolution turn, respectively. The large horizontal oscillations are excited around the 262th turn due to the mismatching field of the injection kicker magnets. The horizontal oscillation decays even without the feedback systems, indicating that it is not instability. It can be clearly seen that the intra-bunch FB system damps the horizontal oscillations much quicker than the BxB FB system. The slow change of the dipole moment amplitude (300 turns) is due to the change in the longitudinal profile of the bunch, not the horizontal oscillation amplitude itself. A possible cause of this longitudinal profile change is a quadrupole oscillation of the bunch in the longitudinal phase space due to mismatching between the bunch and the bucket shapes. In the FFTs plots the Y-axis is the frequency. Even when the BxB FB system is on, the betatron sidebands are clearly visible at around 76kHz. But, they disappear when the intra-bunch FB system is turned on.

Figure 9 shows the evolution of the bunch signals at every 100 turns after the large perturbation at the 262th turn. In each plot, signals are superimposed on 10 consecutive turns. It can be seen in the bottom figure that the intra-bunch oscillations are almost completely damped by the intra-bunch FB system after the first 100 turns.

Table 2: Beam parameters during the commissioning in May 2014.

| | |
|---|---|
| Beam intensity | $2.7 \times 10^{12}$ ppp |
| Beam Energy | 3 GeV |
| Bunch Length | 150 - 200 ns |
| Chromaticity (Hor. / Ver.) | +0.5 / +1.2 |

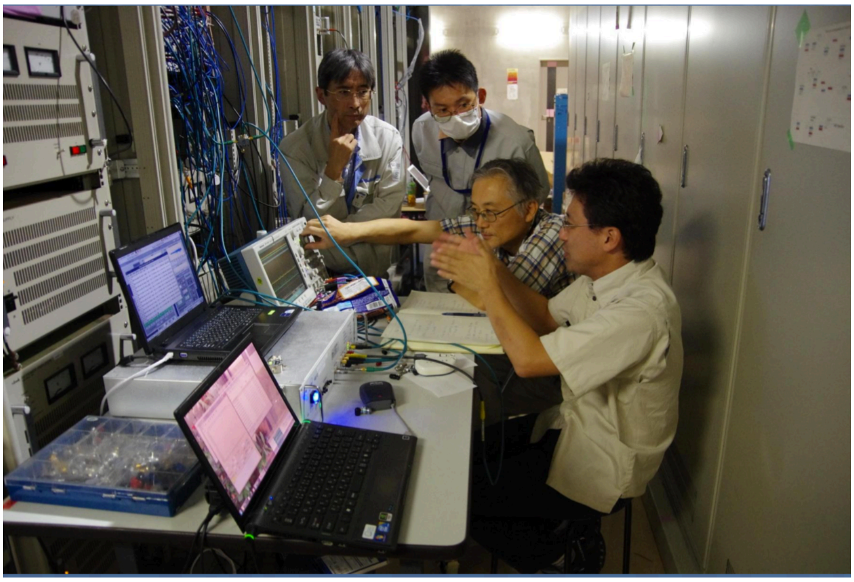

Figure 7: First trial of the intra-bunch feedback damping in Oct. 2012. The photograph was taken by M. Tobiyama, shows experimenters right to left: T. Obina, Y. H. Chin, Y. Shobuda, and T. Toyama.

We made very simple simulations to see if they can qualitatively reproduce the experimental results of the intra-bunch FB system. Macro particles of 6400 are used. Wake fields, space charge

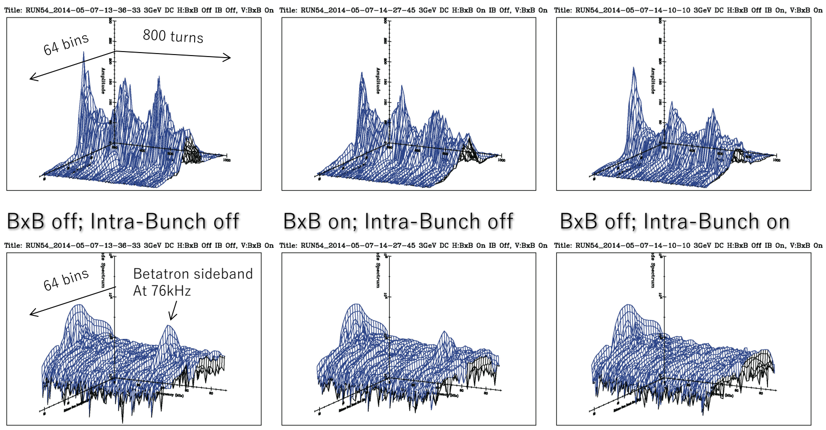


Figure 8: Time evolutions (top) and FFTs (bottom) of the horizontal dipole moment amplitude after excited at 262th turn. (Left) Both the intra-bunch and BxB FB systems are off. (Center) Only the BxB FB system is on. (Right) Only the intra-bunch FB system is on.

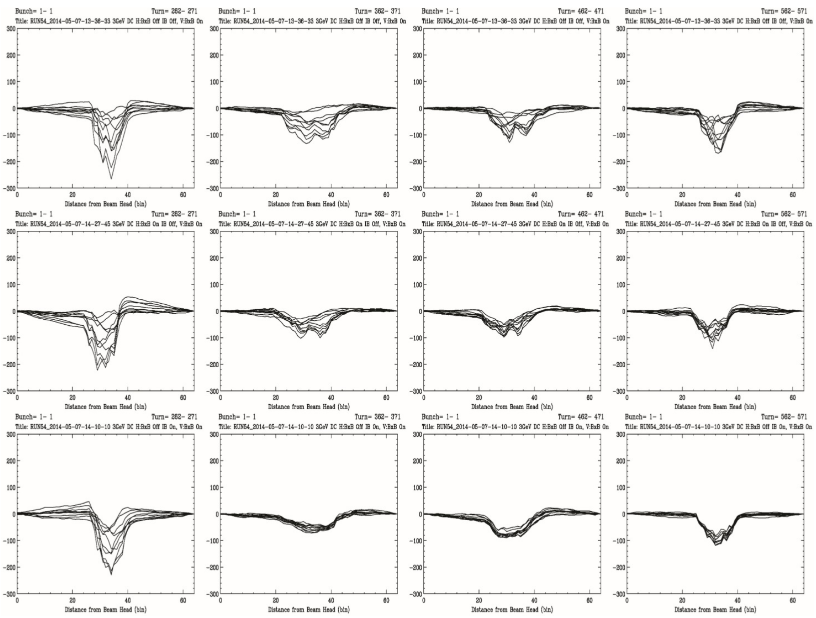

Figure 9: Time evolution of the bunch signals at every 100 turns after the large perturbation at the 262th turn. In each plot, signals are superimposed on 10 consecutive turns. (Top) Both the intra-bunch and the BxB FB systems are off. (Middle) Only the BxB FB system is on. (Bottom) Only the intra-bunch FB system is on. The 1st row corresponds to 262th turn, the 2nd row to 362th turn, the 3rd row to 462th turn, and the 4th row to 562th turn, respectively.

effects and nonlinear effects are not included in these simulations. We are proceeding with more effects such as wake fields, the space charge and the multi-bunch effects for more accurate evaluations. Figure 10 shows the time evolution of center slice of the bunch. The left figures are for experimental results and the right ones are for simulations. It can be clearly seen that the intra-bunch FB system damps oscillations faster than the BxB FB system. This tendency qualitatively agrees with the experiments. At the maximum gain configuration, the damping time is about 2000 turns and 40 turns when only the BxB FB is on and when only the intra-bunch FB is on, respectively. The experimental results when both the feedback systems are turned off shows damping of signals, indicating the existence of additional damping mechanisms, such as non-linear effects or wake fields. More elaborate simulation models are needed for accurate evaluations.

In Figure 11, the Δ-signal motions are plotted every 5 turns after the 200th turn from the perturbation kick. In simulations, arbitrary offsets are added to match with the initial perturbations of the experiment. Good qualitative agreements are seen between the simulations and the experiments.

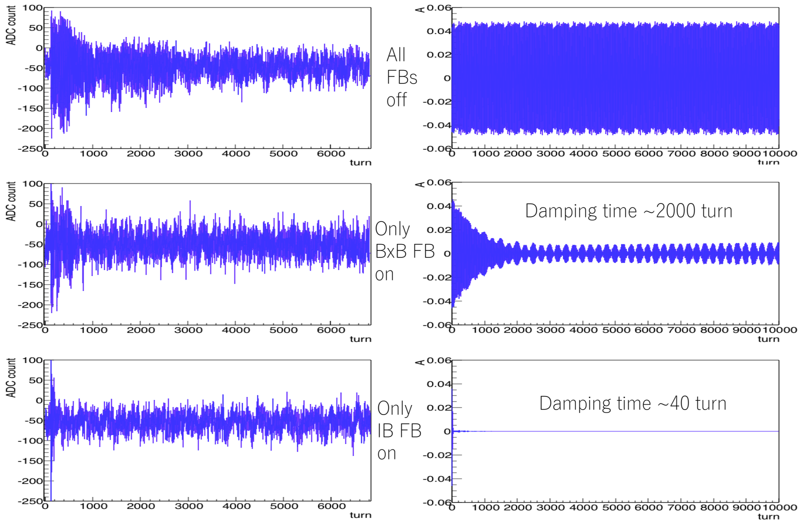


Figure 10: Time evolution of the center slice of the bunch (the 30th slice). The left figures are the experimental results (Top: all FBs off, Middle: only BxB FB on, Bottom: only intra-bunch FB on) and the right ones are the simulations (Top: all FBs off, Middle: only BxB FB on, Bottom: only intra-bunch FB on).

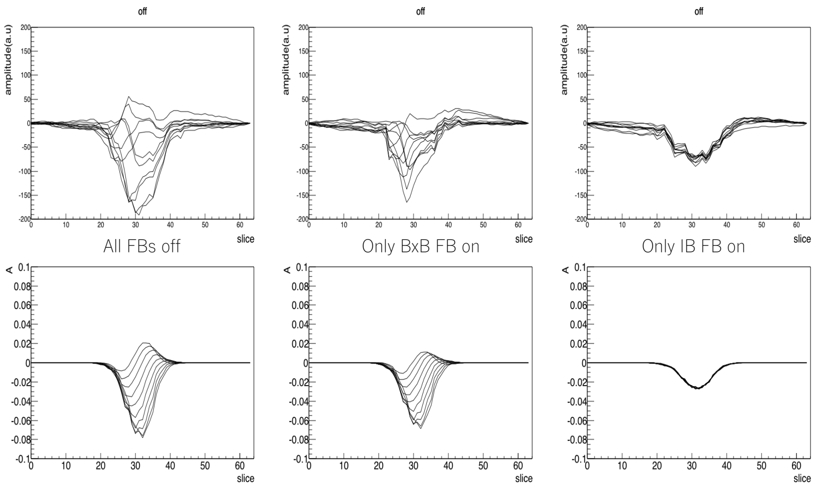


Figure 11: The Δ-signal motion around 250th turn after a perturbation kick. The top figures are for the experimental results (Left: all FBs off, Middle: only BxB FB on, Right: only intra-bunch FB on) and the bottom ones are for the simulations (Left: all FBs off, Middle: only BxB FB on, Right: only intra-bunch FB on).

### 2.5.3 Operation

After the commissioning during 3 GeV injection flat bottom, the intra-bunch FB system entered in operation. The utility during acceleration was started in June 25, 2014. The delay tuning was performed comparing the iGp12 data with markers on at, e.g. slice #5 and #570, to the returned signal from the kicker (Figure 12). The sum signal from the kicker shows the bunch distribution and the RF power from the FB system including the artificial delta-function-like markers. The delay clock can be adjusted so as to match the marker position and the beam distribution (Figure 13). After this adjust we successfully suppressed the instability (Figure 14).

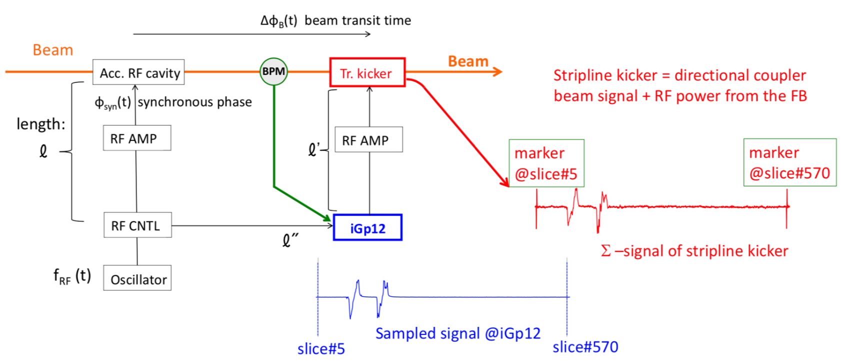


Figure 12: Waveform of the beam and the markers from the iGp12.

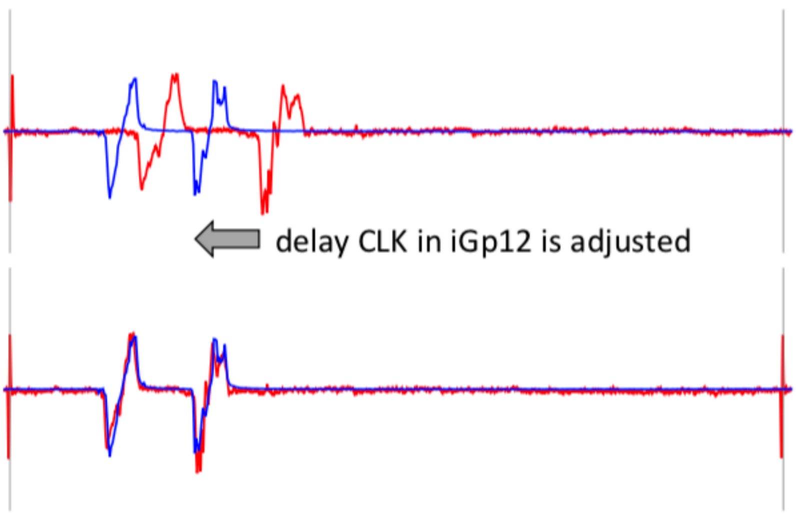


Figure 13: Delay clock adjust.

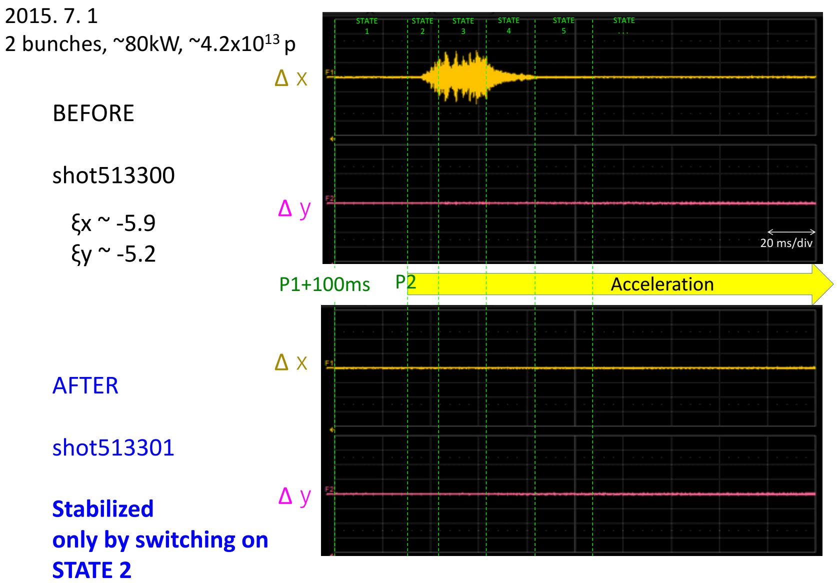


Figure 14: Instability suppression during acceleration with delay clock adjust. (Top) Δ-signals in horizontal and vertical plain without FB at STATE2, (bottom) FB of STATE2 is on with appropriate delay setting. The instability on the horizontal plain is successfully suppressed.

### 2.5.4 Summary

The transverse intra-bunch feedback system has been well suppressing the instabilities up to nearly 500 kW beam power with the careful optimization of betatron tune and chromaticity. But at higher beam power instabilities appear again. The upgrade of the intra-bunch feedback system is foreseen.

This article is mainly based on Yong Ho Chin's paper [13] and added small modifications. He led the "impedance and instability group" of J-PARC for nearly 20 years. Success of this work is largely indebted to him.

## References

[1] M. Ikegami, "Beam commissioning and operation of the J-PARC linac", Prog. Theor. Exp. Phys. 2012, 02B002.

[2] H. Hotchi *et al.*, "Beam commissioning and operation of the Japan Proton Accelerator Research Complex 3-GeV rapid cycling synchrotron", Prog. Theor. Exp. Phys. 2012, 02B003.

[3] T. Koseki *et al.*, "Beam commissioning and operation of the J-PARC main ring synchrotron", Prog. Theor. Exp. Phys. 2012, 02B004.

[4] Y. H. Chin *et al.*, "Impedance and Beam Instability Issues at J-PARC Rings", HB2008, Nashville, August 2008, WGA01, p.40 (2008).

[5] T. Toyama *et al.*, "Stripline BPM at the J-PARC MR", Proc. of the 7th Annual Meeting of Particle Accelerator Society of Japan (August 4-6, 2010, Himeji, Japan), p. 638.

[6] Dimtel, Inc., San Jose, USA, `http://www.dimtel.com`.

[7] Y. Kurimoto *et al.*, "Bunch by bunch feedback system in J-PARC MR", DIPAC2011, Hamburg, May 2011, p. 482 (2011).

[8] Y. H. Chin *et al.*, "Analysis of transverse instabilities observed at J-PARC MR and their suppression using feedback systems" NA-PAC2013, Pasadena, September- October 2013, p.27 (2013).

[9] K. Nakamura *et al.*, "Transverse intra-bunch feedback in the J-PARC MR", IPAC14, Dresden, June 2014, p.2786 (2014).

[10] T. Linnecar, "The high frequency longitudinal and transverse pick-ups used in the SPS", CERN- SPS/ARF/78-17 (1978).

[11] M. Okada *et al.*, "Development of the DLC coated beam exciter", Proc. of the 11th Annual Meeting of Particle Accelerator Society of Japan, August 9-11, 2014, Aomori, Japan, p.242.

[12] T. Toyama *et al.*, "The kick angle calibration of the exciter in the J-PARC MR", Proceedings of the 13th Annual Meeting of Particle Accelerator Society of Japan August 8-10, 2016, Chiba, Japan, p.1081.

[13] Y. H. Chin *et al.*, "Performance of transverse intra-bunch feedback system at J-PARC MR", Proc. of HB2014, East-Lansing, MI, USA, p.384.

## 2.6 A tribute to Yong Ho Chin on behalf of the collaboration, his JACoW Family

Christine Petit-Jean-Genaz
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CERN(retired), Geneva, Switzerland

Dear Yong Ho,

Your JACoW family was terribly saddened to learn you left us so suddenly. Taken at the outset of the JACoW 2008 Team Meeting at KEK, the above picture captures so well your gentle and courteous disposition that we will all miss.

Our collaboration goes back many years. You were one of the original group of completely inexperienced individuals confronted more than two decades ago with the task of introducing electronic publication of conference proceedings to the field of accelerator science and technology.

Thinking back to those exciting times, the accelerator field's first effort at electronic publication was for PAC'95 in Dallas, promoted by Robert Siemann of SLAC as the SPC Chair. Bob later went on to found the first peer reviewed open access electronic journal in accelerator science and technology, now known as Physical Review Accelerators and Beams (PR-AB) [1].

In spite of the gloom that hung over the PAC'95 venue and event caused by the closure of the SSC project, there was a rather optimistic atmosphere in the Proceedings Office which was collecting the conference papers on 1.44 MB diskettes to be shipped later to SLAC for processing.

CERN's John Poole, who was to become JACoW's first Chairman, and I as Scientific Secretary and Editor for EPAC'96, joined the PAC'95 proceedings office to get a foretaste of what we might expect the following year. We then went on to SLAC to test the quality of the diskettes. This was so painful we realized we would have to re-think the process if we were to spare ourselves a year's effort to publish. We were not exactly panicking, but perhaps certainly a little nervous at times...

We came up with what was to become the “JACoW model”:

- comprehensive templates and guidelines for the authors and editors alike,
- a group of editors would be in situ during the conference to process the papers, and learn from each other to build “editor education”, and to interact directly with the authors to provide “author education”
- editors from APAC, EPAC and PAC needed to remain helping each other through several event cycles in order not to lose the experience, and provide sustainability via continuity.

The proceedings of EPAC’96 were published around three months after the conference, which was quite an achievement with the tools and software available at the time.

The EPAC’96 editorial team in Sitges included the editors of the coming accelerator conferences: Martin Comyn of TRIUMF for PAC’97 in Vancouver, Leif Liljeby of the Manne Siegbahn Laboratory for EPAC’98 in Stockholm, and you Yong Ho, designated editor of APAC’98, the first in the APAC series, to take place in Tsukuba.

Yes, Yong Ho, in your quiet, courteous and unassuming manner, you joined the small team of pioneers back in 1996 in Sitges. Strong friendships were formed during those days and you became a firm supporter of JACoW during the following years. Japanese by birth with a Korean heritage, besides your outstanding professional background in accelerator science and technology, you contributed so much to our cosmopolitan group. When not talking about electronic publication we were talking physics, accelerators, gastronomy, history, culture, etc.

In Sitges our small group of editors learned together, laughed and cried together at our own experience and what authors had submitted to us on those diskettes. Some submitted one diskette with text, plus an envelope full of the diagrams and figures they did not know how to produce electronically ... But through long days (and it has to be admitted several evenings spent enjoying Spanish hospitality, wine and food, but always animatedly discussing our experience in the proceedings office), we pulled off the achievement of processing all 800 or so contributions during the week of the conference, communicating the processing status to the authors via several panels onto which I, as the first official “dotting lady”, stuck on physical green, yellow and red dots to indicate the processing status.

Following the publication of the EPAC’96 proceedings on a website at CERN, the APAC, EPAC and PAC Organizing Committees enthusiastically embraced the proposal from Ilan Ben-Zvi (BNL) to publish all accelerator conference proceedings on the same website, thus giving birth to the Joint Accelerator Conferences Website, JACoW, together with the JACoW Collaboration [2].

As one of the original editors doing “hands on” in the EPAC’96 Proceedings Office, you gained that essential in depth knowledge of all of the nitty gritty of conference proceedings production, not only careful attention to detail processing the papers, but the important role of IT, and having experienced editors and problem solvers on hand for the inevitable soft- and hardware issues, not to mention the “brown” dots ....

You organized the electronic publication of APAC’98 proceedings and since those days remained a staunch supporter of JACoW. You were very early on instrumental in setting up the JACoW mirror site at KEK, and promoting the installation of the Oracle software for the SPMS installations there for the Asian conferences. You welcomed the first JACoW Team Meeting to take place in Asia, at KEK, in 2008 where you were a wonderful and thoughtful host. The meeting was well organized, but to me even more memorable were the special social events you personally oversaw with such attention to detail. I particularly remember the unforgettable experience of the Tsukiji fish market in Tokyo early on a Saturday morning, and a very exceptional marriage in a Buddhist Temple ...

Twenty years on from its inception, the JACoW Collaboration counts 18 conference series, including the International Committee for Future Accelerators (ICFA) Beam Dynamics Workshops. Since 2016 you chaired the ICFA Beam Dynamics Panel in your methodical and thorough way, always listening carefully to colleagues and striving to improve organization and policies for the future.

I have been so happy to meet up with you regularly over the years at different conferences where you often took younger colleagues under your wing. You took on a more active role in the overall organization of conferences and workshops and their scientific programmes in recent years, always communicating closely with JACoW on all aspects of programme management and editing of proceedings. Since I retired from CERN, you on several occasions managed to find sponsorship for me to join various JACoW teams at Asian events, and thereby allow me to continue to be personally active within the JACoW Collaboration, for which I will always be grateful. JACoW is based on good will, which you so well understood.

When we met up in Shanghai and Beijing last year you were particularly excited to be joining PR-AB as Associate Editor - just over 20 years after Bob Siemann introduced PR-STAB and electronic publication to our accelerator conferences community. Frank Zimmermann who succeeded Bob Siemann as Editor was delighted to have you join the team. We were looking forward to seeing you play this very important role.

I personally, and your JACoW family, will miss you dear Yong Ho. Our Collaboration will miss one of its staunchest friends and closest ties to Asia.

## References

[1] `https://journals.aps.org/prab/`

[2] `http://jacow.org`

[3] `http://www.jacow.org/html/TM_2008_KEK/default.html`

An Afterword

For those interested in how JACoW works and the life of the Collaboration, it is worth taking a look at the JACoW.org site [2], and in particular at the 2008 Team Meeting Programme [3] as well as the photos published there by JACoW's current Chair, Ivan Andrian, and myself. There are some photos of a younger Yong Ho (including the one included in this tribute) and a number of JACoW long standing editors one may still catch glimpses of staring at their screens during JACoW conferences.

# 3. WORKSHOP AND CONFERENCE REPORTS

## 3.1 The 4th ICFA Mini Workshop on Higher Order Modes in Superconducting Cavities, HOMSC2018, 1-3 October 2018

. Matthias Liepe[1], Cornell University, Ithaca, NY

The 4th ICFA Mini Workshop on Higher Order Modes in Superconducting Cavities (HOMSC18, `https://indico.classe.cornell.edu/event/185/overview` ) was held at Cornell University, Ithaca, NY, USA from October 1 to 3, 2018. HOMSC18 was the most recent workshop in a very successful series on the topic of Higher Order Modes in superconducting RF cavities (HOMSC12 at the Cockcroft Institute and ASTeC, HOMSC14 at Fermilab, and HOMSC16 hosted by University of Rostock at Warnemünde). The objective of these workshops is to bring together researchers studying high order mode (HOM) suppression in superconducting RF cavities for applications ranging from energy recovery linacs and light sources to linear colliders. HOMs excited by a beam in superconducting cavities can create excessive heat load on the cryogenic system and dilute beam quality, giving rise to beam break up instability in the worst case.

Over the course of the 21 talks during the two-and-a-half-day workshop, 27 participants from Europe and USA discussed the current status of both experimental and theoretical work in this area. The scientific program of the workshop was set up by the Scientific Program Committee, chaired by M. Liepe (Cornell University), and was structured in four serial working groups: (1) High-current accelerators and HOM damping requirements, convened by E. Jensen (CERN); (2) Numerical simulation/modelling approaches and tools, convened by U. van Rienen (University of Rostock); (3) Design of SRF cavities and HOM damping schemes, convened by M. Liepe (Cornell University); and (4) HOM measurements, beam effects, and diagnostics, convened by N. Baboi (DESY). The program included tours of the Cornell Superconducting RF lab and of the CBETA Energy Recovery Linac (ERL) test accelerator. The detailed program and talks are available via the workshop website.

[1]Mail to: MUL2@cornell.edu

Figure 1: Participants of the HOMSC2018 Workshop.

## 3.2 ARIES-ICFA Workshop on 'Beam Test and Commissioning of Low Emittance Rings' at the Karlsruhe Institute of Technology (KIT), 10-20 February 2019

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Sara Casalbuoni, Anke-Susanne Müller, Karlsruhe Institute of Technology (KIT), Germany
and
Frank Zimmermann, European Organization for Nuclear Research (CERN), Switzerland

Figure 1: Group photo in front of the Karlsruhe palace (also see instagram photo by @kitkarlsruhe https://www.instagram.com/p/BvPFH3LBFhZ/?utm_source=ig_web_button_native_share)

From 18-20 February 2019, more than 80 world experts gathered at the Karlsruhe Institute of Technology (KIT) for the "ARIES-ICFA Beam Test and Commissioning Workshop" to discuss the best methods for running-in an utterly complex modern research facility: the low emittance storage ring. Figure 1 shows many of the 84 workshop participants. The host institute KIT operates the accelerator test facilities FLUTE and KARA (http://www.ibpt.kit.edu), both available to accelerator scientists within the framework of ARIES Transnational Access WP11.

This particular ARIES workshop, which was organized under the auspices of the International Committee for Future Accelerators (ICFA), featured 37 presentations and 7 summary talks distributed over 8 sessions: 1. Motivations, lessons and projects overview; 2. Injectors and injection; 3. Insertion devices; 4. Diagnostics, controls, automation, and feedbacks; 5. High current effects; 6. Low emittance; 7. Optics design, measurements and correction; and 8. Summary. Researchers hailing from 29 scientific laboratories in 16 countries (Germany: 26, France: 13, Switzerland: 8, USA: 7, Italy: 6, China: 5, Russia: 5, UK: 3, Japan: 2, Poland: 2, Sweden: 2, Australia: 1, Canada:1, Denmark: 1, Korea: 1, Spain: 1) discussed suitable technologies and procedures to master the rising complexity of particle accelerators, in view of the advent of new large-scale facilities with ever-increasing demands on stability and efficiency. Over the next 10 years, most synchrotron light sources around the world will carry out expensive upgrades, and close international networking is becoming increasingly important in this area of science.

Opening speaker Emanuel Karantzoulis from ELETTRA, Trieste, recalled that some experts had thought that the 4th generation light sources would be the FELs. He stressed that no prediction could have been wronger! FELs are complementary but, for the moment, they do not have the high repetition rate, reproducibility and stability required, and they cannot simultaneously serve many beam lines. A whole range of experiments requiring low intensity at the sample and high-repetition rate brought about a renaissance of storage ring light sources. It took 26 years from the pioneering proposal of a multibend achromat lattice to the commissioning of the first of these novel machines - see Fig. 2.

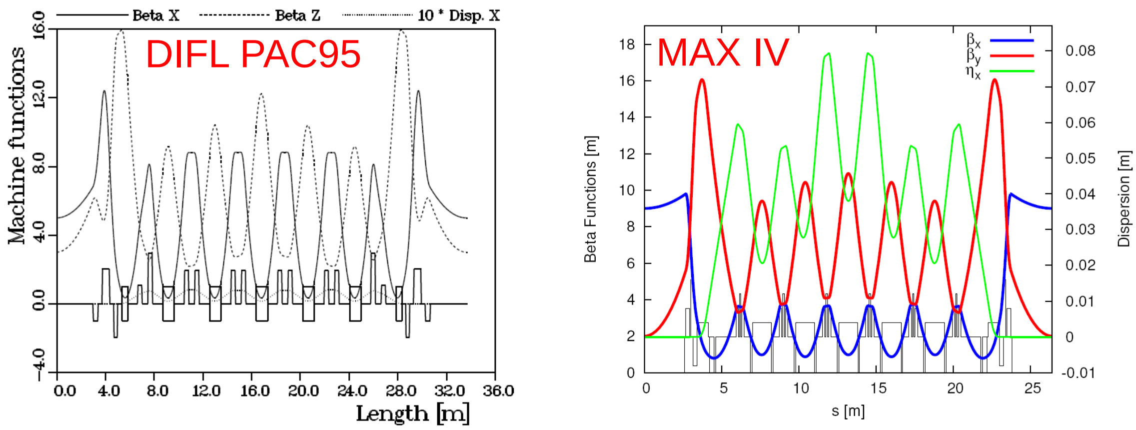


Figure 2: Optics design of a diffraction limited light source proposed in 1993 by D. Einfeld (NIM A 1993 and PAC1995, left) and the actual optics of MAX-IV presented by M. Eriksson at IPAC2016 (E. Karantzoulis).

The new light sources offer higher brilliance (implying a smaller emittance), higher transverse coherence, small photon beam size, small photon beam divergence, and cleaner spectral flux. In addition they might provide short electron pulses (for time resolved measurements) and round beams.

New technologies include high gradient magnets small apertures (100 T/m 12.5 mm), longitudinal gradient dipoles and strong gradient dipoles, advanced short period undulators, NEG pumping (no harm seen for impedance!), fast pulsed kickers and on-axis injection (feedbacks, higher-harmonic cavities, ...). A lot of design and technology synergies were evidenced between the next generation of ultralow emittance storage rings, and future low-emittance ring colliders like FCC-ee and FCC-hh. Figure 3 illustrates that their energy-normalized “invariant optical emittances” are indeed quite comparable.

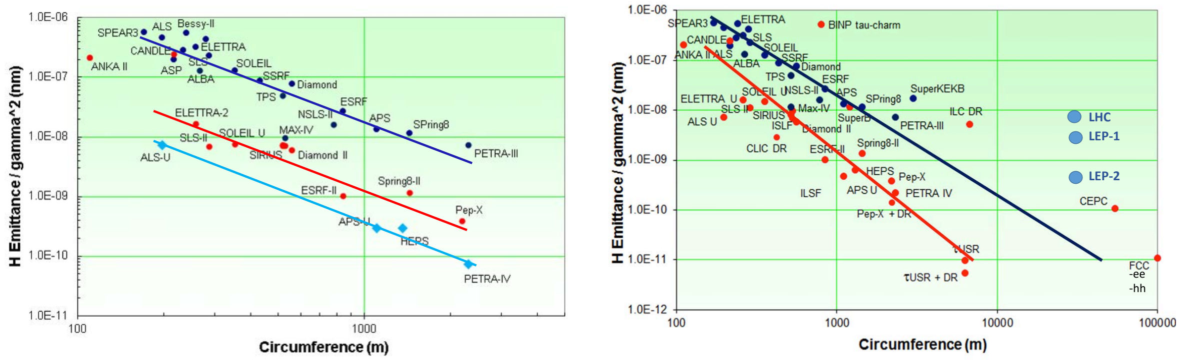


Figure 3: Normalized emittances in present, next and next-next generation storage ring light sources (R. Bartolini and E. Karantzoulis, left) and an extension including the low-emittance rings of high-energy colliders (R. Bartolini - 2016, right).

## 3.3 IPAC2019, 19-24 May 2019, quoted from (`https://ipac2019.vrws.de/papers/preface.pdf`)

. Rohan Dowd, (ANSTO), Chair of the IPAC'19 Local Organising Committee, Australia

The tenth International Particle Accelerator Conference, IPAC'19, took place at the Melbourne Conference and Exhibition Centre, Melbourne, Victoria, Australia from Sunday to Friday, May 19 to 24, 2019. IPAC'19 was attended by 1,186 delegates from 32 countries on all continents. The total includes 146 industry and exhibitor delegates. Hosted by the Australian Nuclear Science and Technology Organisation (ANSTO). ANSTO was established in 1953 (originally as the AAEC) and is the home of Australia's most significant landmark and national infrastructure for research. ANSTO's infrastructure incudes the nuclear research reactor, OPAL; neutron beamlines; the National Imaging Facility Research Cyclotron; the Centre for Accelerator Science and in 2016 the Australian Synchrotron was integrated as a division of ANSTO. The Local Organising Committee (LOC) consisted of 12 staff from ANSTO as well as representatives from Industry and the University of Melbourne.

167 young scientists from all over the globe attended the conference. 79 of these students received travel grants thanks to the sponsorship of societies, institutes and laboratories worldwide. The Americas region grants were sponsored by APS-DB. The Europe region sponsors are: EPS-AG, GSI, CNRS/IN2P3, INFN/LNL, CERN, DESY, PSI, CEA Saclay, ELETTRA, CELLS/ALBA, HZB, ESS, Cockcroft Institute, KIT, SOLEIL, ESRF, STFC/DL/ASTeC, MAX IV, and FZJ. The Asian region was sponsored by IPAC'19 and the Victorian State Government. The organisers of IPAC'19 are grateful to all sponsors for their valued support of students.

The conference was opened by Mark Boland (CLS), Chair of the Organising Committee (OC), The Hon. Martin Pakula, Victorian State Minister for Jobs, Innovation and Trade, and Adi Patterson CEO of ANSTO, who all made welcoming remarks.

Suzanne Sheehy (JAI/UoM) and Massimo Ferrario (INFN) opened the scientific program with presentations, respectively, on 'Meeting Future Challenges in Accelerators: Innovation, Collaboration and Communication' and 'From Dream to Reality: Prospects for Applying Advanced Accelerator Technologies to Next Generation Scientific User Facilities'. The other plenary talks on Monday morning were presented by Susumu Igarashi (J-PARC/KEK), Denis Kostin (DESY) and Lucio Rossi (CERN), respectively, on 'Challenges to Higher Beam Power in J-PARC: Achieved Performance and Future Prospects', 'SRF Operation at XFEL: Lessons Learned after More than One Year' and 'Progress with the LHC Programme at CERN'.

The program was closed with illuminating presentations by Henry Chapman (DESY), 'X-ray Imaging: Faster, Smaller and Brighter'; Leonida Gizzi (INO-CNR), 'Lasers for Novel Accelerators'; and Dong Wang (SINAP), 'Overview of Light Source Developments in Asia'.

36 invited and 51 contributed oral presentations of very high quality were made during the week. The regional distribution of talks was 33% from Asia, 31% from Europe, and 33% from the Americas. The gender ratio for oral presentations was 76% male and 24% female.

The scientific program was developed by the 16-member IPAC'19 Scientific Program Committee (SPC) comprising 8 leads from Asia and 4 deputies each from the Americas and Europe under the leadership of Hitoshi Tanaka (RIKEN). Valued suggestions for invited talks were contributed by the 92-memberScientific Advisory Board (SAB) representing accelerator laboratories world-wide. Oral sessions were grouped according to the eight IPAC Main Classifications, with Poster Sessions Grouped according to Sub Classifications. The conference program spanned four and a half days, with plenary talks on Monday and Friday mornings and on Thursday afternoon for the Accelerator Awards Ceremony. All other sessions were composed of two invited or contributed talks in parallel.

Four Poster Sessions were held each afternoon on Monday through Thursday, during which

1341 posters from 215 institutions were scheduled for presentation. 167 students from 72 institutions, representing 17 countries, attended IPAC'19, with 79 students supported via the student grant programme. The Sunday afternoon student poster session was again a successful event and saw 130 student posters presented and was judged by a team of 28 judges, organised by Toshiyuki Mitsuhashi (KEK).

These proceedings (`http://accelconf.web.cern.ch/AccelConf/ipac2019/`) contain the reports of 1441 total contributions. The regional breakdown is 30% Asia, 26% Americas and 44% Europe. The breakdown by Main Class is as follows: MC1 Circular and Linear Colliders, 105 contributions; MC2 Photon Sources and Electron Accelerators, 289 contributions; MC3 Novel Particle Sources and Acceleration Technologies, 120 contributions; MC4 Hadron Accelerators, 181 contributions; MC5 Beam Dynamics and EM Fields, 202 contributions; MC6 Beam Instrumentation, Controls, Feedback, and Operational Aspects, 198 contributions; MC7 Accelerator Technology, 279 contributions; MC8 Applications of Accelerators, Tech Transfer and Industrial Relations, 50 contributions.

The scientific program was supplemented by a variety of special sessions and events.

A special session on Diversity in Accelerator Physics was held on the Wednesday evening. This event saw two great presentations by Dr. Robert Appleby (UMAN) and Prof. Cordelia Fine (UoM) on different aspects of Diversity and the importance of public engagement in increasing diversity in our field. This was followed by an introduction to a Wikipedia based 'Edit-a-thon' project set up to increase the visibility of our diverse community of accelerator physicists and their contributions to science. Approximately 100 delegates participated in this event.

The Industry Session was held on Wednesday and was based on the theme of building successful partnership between industry and academia. Presentations were given by Lucia Sabbatini (INFN), 'The LATINO Project - An Italian Perspective on Connecting SMEs with Research Infrastructures'; Chris Philpott (Buckley Systems), 'The light at the end of the tunnel: Light Source lessons learned'; Brian Jurczyk (Starfire Industries), 'Developing a Deployable 4-MeV Deuteron RFQ Linac for Industrial and Security Applications: Insights from a Small Business Perspective' and Michelle Shinn (US Department of Energy), 'DOE, Office of Nuclear Physics' Small Business Innovative Research (SBIR) Program'.

The APS again offered a "breakfast and learn" tutorial for aspiring authors and referees on Tuesday morning which was well attended, as well as its traditional 'Meet the editors' event on Wednesday evening, providing delegates with a chance have discussions about the Physical review journals directly with the editors.

The industrial exhibition took place from Monday to Thursday. Industrial exhibitors (62 companies) occupied 67 booths at which they presented their high technology products and services to the delegates. This industrial exhibition area featured a central networking lounge to facilitate discussion and was co-located with the poster areas. It must be acknowledged that the conference would not be possible in its present format without the generous support of the IPAC industry exhibitors and sponsors. 5 learned societies exhibited at desks during the same 4-day period.

IPAC'19 hosted a range of satellite meetings, including SPC meetings of LINAC'19 and IPAC'20 as well as the ARC Imaging CoE, XFEL serial Crystallography workshop 2019 and the NST 4 Health Conference.

The 2019 Asian Committee for Future Accelerators (ACFA) and IPAC'19 were honoured to announce the following awards during the awards session:

The Xie Jialin Prize for outstanding work in the accelerator field, with no age limit was awarded to Prof. Vittorio Giorgio Vaccaro "For his pioneering studies on instabilities in particle beam physics, the introduction of the impedance concept in storage rings and, in the course of his academic career, for disseminating knowledge in accelerator physics throughout many generations of young scientists."

The Nishikawa Tetsuji Prize for a recent, significant, original contribution to the accelerator field, with no age limit was awarded to Prof. Vladimir Shiltsev, "For his original work on electron lenses in synchrotron colliders, his outstanding contribution to the construction and operation of high-energy, high-luminosity hadron colliders and for his tireless leadership in the accelerator community."

The Hogil Kim Prize for a recent, significant, original contribution to the accelerator field, awarded to an individual in the early part of his or her career was awarded to Dr. Xueqing Yan, "For his demonstration of new experimental technique of phase-stable laser acceleration of protons and ions, in overcoming the challenges to producing high-quality beams and leading the way to realising future medical accelerators."

The Mark Oliphant Prize for a student registered for a Ph.D. or diploma in accelerator physics or engineering, or to a trainee accelerator physicist or engineer in the educational phase of his or her professional career was awarded to James MacArthur, "For his contribution to free electron laser electron beam dynamics, especially the analysis of the self-modulation mechanism, and experiments leading to sub-femtosecond pulse generation."

The prizes for best student posters were awarded to Daniel Bafia, (Fermilab & Illinois Institute of Technology) for "Understanding and Pushing the Limits of Nitrogen Doping"; and Nazanin Samadi, (CLS, University of Saskatchewan): "Application of a Phase Space Beam Position and Size Monitor for Synchrotron Radiation".

Two special awards were presented at IPAC'19 in remembrance of Greg LeBlanc, Head of accelerator science at the Australian Synchrotron and LOC chair, who sadly passed away in December 2018. The two awards are for a significant and original contribution to IPAC'19: by an individual in the early part of his or her career (up to five years after their terminal degree); and by a technical staff and/or operator. They were awarded to Dr. Tessa Charles "For her research in the theory and analysis of the first measurements of the caustic nature of trajectories in bunch compressors." and Dr. Filippos Toufexis. "For his work in radio-frequency devices, including crab cavities, radio-frequency undulators, and W-band parallel-coupled power extraction structures."

The proceedings of IPAC'19 are published on the JACoW site (`www.jacow.org`). The processing of the electronic manuscripts was achieved on-site by the 30 strong JACoW team from 24 different institutions prior to, and during the conference. The team, led by David Button (ANSTO), and Volker RW Schaa (GSI), includes "seasoned experts" who also trained less experienced volunteers.

The JACoW Collaboration is formed by electronic publishing experts and technicians volunteered by laboratories worldwide. Tasks performed by the proceedings office include: author reception, processing of contributions and transparencies, checking that references are formatted to journal standards, and cross-checking of titles and authors. Setting up the computers and internet network, presentations management and poster session management were a collaborative effort between the LOC and JACoW. Thanks to the work of this dedicated team, a pre-press version with all on time author's submissions published totalling more than 1,200 contributions by the last day of the conference. The final version was published at the JACoW site just weeks after the conference. This is yet another impressive record set by the JACoW Collaboration, which is sincerely grateful to the supervisors of each of the team members for releasing them from their usual duties.

IPAC'19 would also like to acknowledge the brilliant contribution of two new tools developed by ANSTO, to assist authors and editors. These tools allowed the search and generation of JACoW paper references from a complete database of all JACoW papers, and the identification of technical and formatting errors in Word DOCX contributions. These tools are now known as the JACoW Reference Search & Generation Tool, and the JACoW Cat Scan Editor Tool. These tools have both been made available to the entire JACoW conference community, educating authors and assisting editors, and to further improve the sustainability of the conferences and JACoW. We believe these tools will have a bright future.

A new feature of IPAC, introduced on a trial basis at IPAC'17, is light peer review of a limited number of papers for publication in a volume of an Institute of Physics conference proceedings. A white paper defining the review criteria and process was developed by Koscielniak & Bogacz. Papers are reviewed by the SAB, while the SPC under the leadership of the Scientific Publication Board chair, performed the function of editorial board. Due to the untimely death of the Scientific Publication board chair, Yong Ho Chin, early in the year, Alex Bogacz once again stepped into the role, aided by members of the SPC. Candidate papers were submitted two weeks in advance of the normal deadline to allow a cycle or review, revision, and final review. Over 237 papers were submitted, many were revised, and 220 were approved. Todd Satogata managed the review process within the JACoW SPMS database.

The success of IPAC'19 was due in great part to the strong collaboration between the international teams of the OC, SPC and the LOC. Membership of the LOC included the following:

Rohan Dowd (ANSTO): LOC Chair and SPMS Administration
Eugene Tan (ANSTO): LOC Co-chair and Student Programme manager
Nicole White (Nicole White Projects): Event Project Support and Scientific Secretary
David Button (ANSTO): Proceedings Manager
Alan Cowie (ANSTO): IT Manager
Nick Hauser (ANSTO): IT Manager
Mike Lafky (ANSTO): Technical Tour Manager
Jaye Muir (ANSTO): Public Affairs
Kerry Hayes (ANSTO): Industry and Sponsorship
Dieter Pelz (RFCURRENT): Industry and Sponsorship
Dean Morris (ANSTO): Conference Support
Roger Rassool (UoM): Conference Support

It is clear that on this tenth conference of the series that IPAC remains a focus for the coming together of the worldwide accelerator community and the fruitful exchange of ideas, unbounded by nationality, experience or background. Being the first of this conference series to be hosted in the Southern hemisphere, it was especially pleasing to see a strong participation from the international community, despite the extra distance.

The eleventh IPAC will return to the Northern Hemisphere in the European super-region and will take place in Caen, France.

## 3.4 The 19th International Conference on RF Superconductivity SRF2019, 30 June - 5 July 2019

. Peter Michel[1], Helmholtz Center Dresden-Rossendorf and University of Rostock, Germany

Superconducting radiofrequency accelerators are traditionally used not only for nuclear and particle physics, but also as drivers for modern high-power radiation sources such as the European X-ray FEL in Hamburg or the comparatively compact ELBE Center for High-Power Radiation Sources at Helmholtz-Zentrum Dresden-Rossendorf (HZDR). Regardless of the size, SRF accelerators play a significant role for several Helmholtz facilities with a large number of international users. Therefore, it is natural that the SRF2019 Conference took place in Dresden and was hosted by the HZDR.

The conference is held every two years and rotates around the continents of Asia, Europe, and North America. This conference last took place in Germany in 2009 (HZB, Berlin), and returned to Germany for 2019 with the award going to the HZDR in Dresden. Immediately preceding the conference, the HZDR hosted three days of tutorials that are traditionally held together with this conference. 89 students and young scientists from all over the world participated in these tutorials, which covered wide-ranging aspects of SRF technology. The conference itself saw 332 participants from 16 countries convene at the Hilton Hotel, in the beautiful historic center of the city of Dresden. There were 67 oral presentations in the categories of: Facilities, Fundamentals, SRF Technology and Cavities. There were also keynote lectures on significant topics related to certain scientific applications of and competing technologies for SRF accelerators. In addition, a hot topic session on the fundamental barriers to achieving maximum achievable field strength in SRF accelerator cavities. In addition, scientific and technological results were presented and actively discussed on about 300 posters. In particular focus for the scientific program were questions of the fundamental understanding of the physical processes in superconducting radiofrequency cavities, the investigation and evaluation of novel materials such as e.g. Nb3Sn, and groundbreaking technological developments covering a wide range, from accelerator cavity design, tuners, cryomodules, to digital control systems.

The conference was opened with a student poster session specifically for young scientists who presented 40 posters. G.D.L. Semione (DESY, Hamburg) was awarded the Best Poster Prize from this session. In addition, B. Giaccone (Fermilab and Illinois Institute of Technology) and R.D. Porter (Cornell University) were honored for the best oral presentations by young researchers. Also, 28 students were selected by the organizers for financial support based on review of their applications. During the conference, 12 international industrial exhibitors were stationed at their booths where they held discussions with the participants during the breaks and poster sessions. The publications and presentation slides of the conference were published in advance on the website `https://srf2019.vrws.de/`.

As is customary for this conference, the participants were treated to a boat trip, which this year took place on the Elbe River despite low water level limitations. The boat trip and onboard banquet culminated in a firework display and will remain in the memory of the participants for years to come.

Peter Michel was the conference and program committee chairman and André Arnold was the local organization chairman. More details about the conference can be found at `www.srf2019.org`.

The conference was financially supported by the Deutsche Forschungsgemeinschaft, the HZDR, the HZB, and DESY.

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## 3.5 The 3rd Workshop on Slow Extraction, 22-24 July 2019

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Vladimir Nagaslaev [1], FNAL, USA

Slow Extraction (SE) is employed in many accelerator experimental facilities with users ranging from the apparatus beam tests to the fixed target experiments, and the medical facilities running proton and ion beams for the patient cancer treatment. As the beam intensities are constantly growing and requirements to the spill quality are expanding, this field is constantly experiencing new challenges and creating new ideas and methods to address those challenges. Collaboration in this field is very important to make this effort of many individuals, labs and universities coherent and focused. This has been demonstrated by the success of recent Slow Extraction Workshops at Darmstadt (2016) and CERN (2017). This series has been continued in July of 2019 with the next Slow Extraction Workshop #3 (2019) at Fermilab.


Figure 1: The 3rd Slow Extraction Workshop Poster

Fermilab has a history of SE spanning over many decades, which brought it to the discoveries of bottom quark in 1977. Currently there are several fixed target beam lines with the Switchyard, running the SE beam of 120 GeV protons from the Main Injector. A new facility, the Mu2e experiment is coming to the scene very soon, starting beam commissioning in 2020, which employs the slow extraction with extremely demanding performance requirements. The SE Workshop 2019 was a part of preparations for the Mu2e beam commissioning. It was held under the auspices of ICFA and was supported by the Fermi Research Alliance (FRA). The workshop convened to address the most important current issues of the slow extraction and to provide a forum for discussions between experts in this field. It was attended by 56 participants from USA, Europe and Japan, representing 10 institutions and Universities around the world. The scientific program of the workshop was set up by the International Organizing Committee, which was chaired by V. Nagaslaev (Fermilab) and comprised M. Bai (GSI), K. Brown (BNL), G. Franchetti (GSI), M. Fraser (CERN), B. Goddard (CERN), S. Ivanov (IHEP), T. Kroc (FNAL), D. Morris(FNAL), K. Noda(QST), M. Pullia(CNAO), H. Stockhorst and M. Tomizawa (KEK). Efficient Local Organization was provided by G.Annala (FNAL) and C.Kachel (FNAL). There was the total of 40 presentations by the participants in the 10 sessions. Some of the sessions were subdivided in two parts to accommodate the abundancy of contributions. The workshop started with the Welcome and Motivation session, followed by the presentations of the progress status from the major SE facilities, including the two nice overviews of the medical

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machines in Europe and Japan. These two introductory sessions were followed by detailed sessions devoted to the Beam Loss Reduction, Spill Quality, Dose and Activation Issues and Machine Protection, and the Special Topics of the SE. The new initiatives presented in this Workshop were the additional session on Tutorials and a parallel Engineering session. Most of attention was attracted to the Efficiency and Beam Losses session, where numerous success stories have been presented with recent machine demonstrations of significant improvements in the extraction efficiency. The effort lead in the past two years by the CERN colleagues brought a number of successful developments: Constant Optics SE (COSE), Diffusers, Crystal Shadowing of the septum, Octupole separatrix folding, Advanced simulations. Matthew Fraser called this in his talk "the Renaissance in SPS SE". This effort allowed CERN to justify the required tunnel activation levels suitable for the SHIP experiment with the projected 4 times increase in beam power. There was also a significant public interest for these presentations and M.Fraser was asked to make a special presentation at the Fermilab general seminar.

It would be not possible to list here the most appetizing highlights of the remaining contributions - the list would be too long. Instead, we encourage the reader to review the list of talks at the Workshop website `https://indico.fnal.gov/event/20260/`.

Figure 2: The Workshop Participants gathering in the Fermilab Main Control Room for the site tour.

There was a consensus of the participants that both the Engineering session and the Tutorials are very useful tools and are strongly recommended for the next workshops. The most active discussions from the sessions were continued in the dedicated Discussions session. The list of topics was compiled by the session conveners and everyone could bring up his own concern, criticism or even a confusion for the clarification. The Follow up discussion was led by Brennan Goddard (CERN), the Chair of the previous workshop, V. Nagaslaev and M. Tomizawa. Many practical issues of the common glossary, common bank of the most important performance data and its mutually agreed format, threads for collaboration and directions of the main effort were discussed and some adjustments were in order compare to the previous Workshop. It was a strong feeling of the Workshop participants, that this trend of the workshops plays a big role in defining the focus, communication and collaboration between labs and centers and needs to be continued. It has been proposed that the next site for the workshop would be the KEK/J-PARC facilities in Japan and the suggested time is October 2021.

## 4. RECENT DOCTORAL THESES

### 4.1 Development of X-Ray Beam Size Monitor for the SuperKEKB Rings

CANDIDATE: Emy Mulyani, SOKENDAI, Tsukuba, Japan
SUPERVISOR: John Flanagan (KEK)
GRADUATION: September, 2018

Emy Mulyani has developed an X-ray beam size monitor applying coded apertures (CA). By using the CA monitor, the brighter image and the higher resolution is expected than the usual pinhole monitor. She optimized the design of the CA, and optical components based on simulations. At the commissioning stage of SuperKEKB, the beam size could be quantitatively evaluated for both High Energy Ring and Low Energy Ring. She has also established a beam profile reconstruction technique applying uniformly redundant array (URA) and succeeded in showing the possibility for bunch-by-bunch or turn-by-turn measurement of the X-ray beam size monitors.

### 4.2 Study on Properties of Plastic Scintillators for Designing a Tissue- Equivalent LET Spectrometer

CANDIDATE: Tran Nguyen Thuy Ngan, SOKENDAI, Tsukuba, Japan
SUPERVISOR: Shinichi Sasaki (KEK)
GRADUATION: September, 2018

Tran Nguyen Thuy Ngan has developed a tissue equivalent LET (linear energy transfer) spectrometer capable of equivalent dose measurements in environments such as space radiation and radiation fields around accelerators including heavy ions and high energy neutrons. Plastic scintillators (PLS) were selected as materials for the tissue-equivalent LET spectrometer because of the close density to living tissues or water, and excellent time response and sensitivity. Fundamental characteristics of PLS were determined first by devised experiments, and a configuration of PLS-based dosimeter has been proposed. Her doctoral thesis received the Dean's Award of the School of High Energy Accelerator Science, Sokendai.

### 4.3 Space-charge driven transverse beam instabilities in synchrotrons

CANDIDATE: Yao-shuo Yuan, Technische Universität, Darmstadt, Germany
SUPERVISOR: Prof. Dr. Oliver-Boine-Frankenheim
GRADUATION: November, 2018

Intense proton or ion beams are of fundamental importance for many research areas, which relay on such beams, such as spallation neutrons or radioactive beams. The main subject of this thesis is the detailed investigation of the intense beam motion and instability in synchrotrons, based on two approaches: particle-in-cell (PIC) simulations and the numerical methods for calculating the beam's envelope motion. In the former approach, the accelerator simulation code pyORBIT is employed. In the latter, the widely-used two dimensional (2-D) beam envelope model is extended with a dispersion equation, to describe the beam's coherent motion under the combined effect of space charge and dispersion in circular accelerators. Full numerical solution of the extended envelope model reveals that a new coherent mode, namely, dispersion mode, exists besides the well-known envelope modes. It is shown in this thesis that for a phase advance larger than 120° and sufficiently high intensity, the dispersion mode becomes unstable, and induces the "120° dispersion instability".

Bunch compression achieved via a fast bunch rotation in longitudinal phase space is a well-accepted scheme to generate short, intense ion bunches for various applications. In this thesis, the set of transverse envelope equations including dispersion are coupled with the longitudinal envelope equation to describe the three dimensional (3-D) beam motion during bunch compression. An analysis of the relevant space-charge driven beam instability and the particle resonance phenomena during bunch compression is presented. The agreement between the envelope and PIC results indicates that the stop band of the 120° dispersion instability should be avoided during bunch compression.

This work also investigates the stability of all possible second order coherent modes of beams, with a complete set of second-moment oscillation equations. Results are compared with results on mode frequencies obtained from the linearized Vlasov-Poisson equation. Excellent agreement is found in the case of the "tilting instability" in constant focusing, and the "sum envelope instability" in periodic focusing structures, which completes the picture of second order coherent modes in 2-D high intensity beams.

## 4.4 Study of tunable narrow-band THz and high-intensity channeling radiation sources with a 50 MeV class photo-injector

CANDIDATE: Jibong Hyun, SOKENDAI, Tsukuba, Japan
SUPERVISOR: Mitsuhiro Yoshida (KEK)
GRADUATION: March, 2019

Jibong Hyun has developed terahertz and hard x-ray sources using the 50-MeV class injector Linac. His work was done at the Accelerator Physics Center of Fermilab under Dr. Tanaji Sen. Narrow-band terahertz radiation was generated by coherent transition radiation of a micro bunch. Energy chirped electron bunch made by the off-crest acceleration in a superconducting cavity, and the micro bunch was formed by a laterally spread bunch passing through a slit. He also planned the generation of hard X-rays in the range of 100 keV as channeling radiation using diamond crystals and aimed to obtain high brightness and flux by generating a low emittance electron beam at the Linac. He was honored for the 2nd SOKENDAI Award to commend the students who have accomplished their outstanding research and have been conferred their degrees with the excellent doctoral thesis.

## 4.5 Studies on Neutron and Photon Response of a Fluorescent Nuclear Track Detector for Developing a Neutron Personal Dosimeter

CANDIDATE: Takuya Hashizume, SOKENDAI, Tsukuba, Japan
SUPERVISOR: Toshiya Sanami (KEK)
GRADUATION: March, 2019

Takuya Hashizume investigated the performance of fluorescent nuclear track detectors (FNTD) to develop a new neutron personal dosimeter. Plastic nuclear track detector (PNTD) widely used as a neutron dosimeter has drawbacks that it takes time to process after measurement and cannot be reused, but the disadvantages can be solved if we can use FNTD instead of PNTD. He analyzed the image data of the FNTD tracks to quantitatively evaluate the detection efficiency and the effect of gamma irradiation on the count loss of particle tracks. He also demonstrated first the possibility of using FNTD in the treatment room of the iBNCT facility for neutron beam cancer treatment and succeeded in defining the calibration coefficient and the lower detection limit of the FNTD.

## 4.6 A novel approach to Landau damping of transverse collective instabilities in future hadron colliders

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| CANDIDATE: | Michael Schenk, EPFL, Lausanne, Switzerland |
| SUPERVISOR: | Prof. Leonid Rivkin (EPFL), Dr. Kevin Li (CERN) |
| GRADUATION: | March 2019 |

Transverse collective instabilities induced by the beam-coupling impedance of the accelerator structure pose a major limitation to the machine performance. Landau damping, a powerful stabilising mechanism employed against various types of instabilities, is present in the transverse planes when there is a betatron frequency spread among the beam particles. Traditional approaches use octupole magnets to introduce an incoherent betatron tune shift with the transverse particle oscillation amplitudes. Their damping efficiency depends on the transverse geometric beam emittances which decrease with increasing beam energy and brightness. Within the framework of this PhD thesis a novel approach to Landau damping is studied from the theoretical, numerical, and experimental points-of-view. The novelty of the method is to introduce the betatron frequency spread through detuning with the longitudinal instead of the transverse amplitudes. This is motivated by the fact that in high-energy proton machines the longitudinal emittance is typically several orders of magnitude larger compared to the transverse ones. Two equivalent detuning schemes are considered: a radio-frequency (rf) quadrupole cavity and nonlinear chromaticity. The first achievement of the project is the development of the Vlasov theory for nonlinear chromaticity. The formalism is successfully validated against a circulant matrix model and the PyHEADTAIL tracking code. Second, the first numerical proof-of-concept of an rf quadrupole for Landau damping is realized in PyHEADTAIL. It is shown that the required active length of the proposed device is indeed significantly shorter compared to octupole elements. Third, the numerical models and the theory are validated against measurements in the Large Hadron Collider (LHC) and the Super Proton Synchrotron (SPS) at CERN. In the two machines, the second-order chromaticity is successfully enhanced and the measured nonlinear optics parameters are shown to be consistent with MAD-X calculations. The stabilization of single bunches by means of a betatron frequency spread produced by nonlinear chromaticity is demonstrated in the LHC which marks the first experimental proof of the novel Landau damping method. The measurements are in good agreement with detailed PyHEADTAIL simulations. In particular, effects predicted by the theory are consistently observed in both experiments and simulations confirming a thorough understanding of the involved beam dynamics.

## 4.7 Nonlinear Beam Physics

CANDIDATE: Benjamin Folsom, Lund University, Lund, Sweden
SUPERVISOR: Emanuele Laface (ESS)
GRADUATION: April 2019

A condensed treatment of conventional beam physics (both linear and nonlinear) is given for the non-expert; this constitutes a minimum knowhow for constructing simulations of rudimentary beamlines. The criteria for an ideal nonlinear charged-particle simulation algorithm are then presented, leading to the derivation of a symplectic, explicit, Lorentz-covariant integrator. Space charge (inter-particle interaction) is addressed next, with a first-principles approach based on the Liénard-Wiechert potentials. A cumulative chapter follows, applying the developed simulation methods to multipole magnets (sextupoles, octupoles, and higher-order) which have inherently nonlinear potentials. A concluding chapter proposes applications for nonlinear simulation of neutron particle dynamics in terms of magnetic dipole moment steering.

## 4.8 Study of Some Key Beam Dynamic Problems in the Recirculating Proton Linac

CANDIDATE: Yue Tao, Institute of Modern Physics, CAS, China
SUPERVISOR: Prof. Yuan He (IMP), Dr. Ji Qiang (LBNL)
GRADUATION: June 2019

The beam dynamic issues of the recirculating proton linac such as two bunches overtaking collision space charge effects, robustness of the linac design under imperfect realistic conditions, correction of two different energy bunches, and multi-pass recirculating proton linac synchronization condition need to be carefully studied.

This thesis studies the interbunch space-charge effects of two proton bunches transporting through the linac in the proposed double-pass recirculating proton linac using both analytical estimate and self-consistent multi-particle simulation with the IMPACT code suite. Compared with analytical estimated results, the numerical simulation space-charge interaction effects are somewhat small. The difference of beam parameters with and without interbunch space-charge effects are less than 1%. At the end of the double-pass recirculating proton linac (with 10 times of interbunch space-charge effects), the RMS emittance growth is less than 7%, the transverse and longitudinal RMS beam size growth are less than 15%.

The static and dynamic errors from RF cavities and magnetic focusing elements are considered in the double-pass linac error study. One thousand random lattices were used. The results show that the average particle loss is 2.13E-6, the average beam power loss is 5.88 W. A new correction method, Optimization Correction Method (OCM), is proposed to correct the error effect of low and high energy beams. With correctors, simulation results show that the centroid shift, RMS beam size, RMS emittance, maximum beam size are smaller than before, and no particle loss.

For the multi-pass sections of the recirculating linac, a variable field phase-shifter between two cavities is needed to shift time delay between multiple passes to meet the synchronous condition. The conceptual design of the phase-shifter that varies the path length with different energy ranges in the four-pass linac section were carried out. Under the maximum fields gradient 5 Tesla, the phase-shifter maximum length is 8 meters, the magnet filed gradient changed range is less than 0.2 Tesla.

Finally, some perspectives on the future work of the recirculating proton linac are given.

## 4.9 The Study on the Fringe Field Effects of Magnets in the Rapid Cycling Synchrotron of CSNS

CANDIDATE: Jianliang Chen, Chinese Academy of Science, Beijing, China
SUPERVISOR: Professor Sheng Wang, Associate Professor Shouyan Xu
GRADUATION: July 2019

The Rapid Cycling Synchrotron (RCS) is a key component of accelerators of China Spallation Neutron Source (CSNS). In order to suppress the space charge effect, CSNS/RCS employs large aperture quadrupoles to provide a large acceptance for painting injection. For CSNS, with the design acceptance of $540\pi$ mm-mrad, the apertures of quadrupoles are quite large, which are comparable to the effective length of quadrupoles. In this case, the fringe field effect cannot be neglected. For some quadrupoles, the interval between the core and the adjacent magnet is comparable to the aperture of quadrupole, and the effect of field interference needs to be taken into account. The fringe field effects and interference effects of quadrupoles will lead to the additional tune-shift of RCS and may cause serious beam loss. At present, all the research work on the fringe field of magnet are concentrated in the static magnetic field, but the research on the dynamic fringe field of rapid-cycling magnet is still blank in the world. For CSNS/RCS magnets, the results of magnetic measurements show that the static magnetic field processing is inaccurate for rapid-cycling magnetic field. For rapid-cycling magnets, the magnetic field is asynchronous with excitation current at different locations of the magnet caused by eddy current effect, and results in changes in the distribution of the fringe field of the magnet, which leads to the additional tune shift of RCS in the process of acceleration. In order to achieve the design target of 100 kW beam power, it is necessary to further increase the beam current, which requires the optimization of parameters of RCS, especially optimization of tunes.

A thorough study on the fringe field effects and field interference effects has been done. Firstly, based on the measured magnetic data of quadrupoles, the linear fringe field effects and fringe field interference effects at DC mode are studied by slicing model and Lie algebra. In addition, in order to correct the fringe field effects and fringe field interference effects, the Lattice of RCS is optimized. The optimized parameters are verified in the actual operation of the machine, which makes the beam commissioning of RCS at DC mode go smoothly. Secondly, based on the magnetic measurement data of quadrupoles at AC mode, the dynamic fringe field effects of quadrupole magnet caused by eddy current effect in the rapid-changing process are investigated. By improving Enge equation, the distribution of the variable fringe field is fitted in the whole period, and the fringe field effect at any time can be calculated by Lie algebra method. On the other hand, the fringe field effect at different energy points (time points) is calculated by slicing model. The measured tunes which are consistent with theoretical expectations are obtained in the process of beam commissioning at AC mode. Finally, using particle tracking code ORBIT, the beam with design mode and other different modes of quadrupoles of RCS under slicing model is simulated and tracked, and the effects of different tunes on beam emittance and loss are analyzed. In addition, the tunes under two kinds of painting scheme are optimized by simulation.

## 4.10 The Theoretical and Simulation Study on the Transverse Collective Instabilities in the HIAF/BRing

CANDIDATE: Jie Liu, Chinese Academy of Science, Beijing, China
SUPERVISOR: Jiawen Xia, Jiancheng Yang
GRADUATION: July 2019

Booster Ring (BRing) which is the main accelerator in the High Intensity heavy ion Accelerator Facility (HIAF) can accelerate high intensity beams with a wide range of heavy ion species from proton to uranium (proton $2 \times 10^{12}$ ppp, $Kr^{19+}$ $3 \times 10^{11}$ ppp, $U^{34+}$ $1 \times 10^{11}$ ppp). The research on the transverse collective instabilities stimulated by the coupling impedances plays a significant role in reaching the required intensity or keeping the high beam quality in the BRing. It is also the fundamental work for the design of octupole magnets for Landau damping or feedback systems. Compared with other accelerator facilities, like colliders, synchrotron light sources or spallation neutron sources, the operations are very complicated in the BRing. So, three transverse dipole collective instabilities should be analyzed under proton and heavy ion operation modes with complicated beam manipulations, which is also very complex. In this thesis, the Vlasov mode approach and the numerical approach for these transverse dipole collective instabilities are studied. A code, named Simulation Platform for Collective Instabilities (CISP) is developed in order to simulate all these instabilities. Both two methods are used to analyze the transverse collective instabilities in the BRing with three typical beams including proton beam, $Kr^{19+}$ beam and $U^{34+}$ beam.

Firstly, Vlasov mode approach is employed in this thesis to study the frequency shifts due to transverse dipole collective instabilities under a general condition in the proton and heavy ion beams. And the general method of analyzing transverse dipole collective instabilities in the proton and heavy ion beam is reproduced. Meantime, based on the general results, the thresholds or growth rates of transverse mode-coupling instability, transverse coupled-bunch instability and transverse unbunched beam instability have been obtained and they are used in the calculations with the parameters of the BRing. The Vlasov mode approach shows that transverse mode-coupling instability can limit the intensity of the proton beam to $8 \times 10^{11}$ ppp which is much less than the required intensity $2 \times 10^{12}$ ppp. However, the $Kr^{19+}$ beam and the $U^{34+}$ beam are not influenced by this instability. The growth times of transverse coupled-bunch instability and transverse unbunched beam instability are less than the corresponding duration times, which shows that both two transverse collective instabilities can influence all typical beams.

As to the numerical approach, there are some codes for several specific transverse collective instabilities in some heavy ion beams, but no one for all these instabilities. They cannot cover all transverse collective instabilities in the BRing. In this thesis, the numerical models for wake, 6D tracking, nonlinear magnets and space charge are studied. And with these numerical models, the simulation code CISP is developed. It can simulate all these transverse collective instabilities now. CISP simulations show that the intensity of the proton beam is limited to $6 \times 10^{11}$ ppp by transverse mode-coupling instability. And transverse coupled-bunch instability can introduce the beam loss which is about 95% in the $Kr^{19+}$ beam and increase the normalized emittance of the proton beam and the $U^{34+}$ beam by $3 \sim 4$ times. Besides, transverse unbunched beam instability can also increase the normalized emittance of the three typical beams by about 40%. With the comparisons, simulation results and theoretical results agree with each other, which tests the validity of both two methods.

How to stabilize these transverse dipole collective instabilities is also an important issue. In this thesis, the stabilization from chromaticity, octupole magnets and feedback systems is discussed. The difference of physics among different methods is also analyzed. The research shows that chromaticity $-0.04$ can stabilize the transverse mode-coupling instability in the BRing very well. And chromaticity $-2$, an octupole magnet whose integral strength is 1.8 $\mathrm{m}^{-3}$ or a bunch-by-bunch feedback system can stabilize transverse coupled-bunch instability very easily. However, for transverse unbunched beam instability, introducing a feedback system with large bandwidth is the best way to stabilize it. This research is the fundamental work for the design of the stabilization systems related to these transverse dipole collective instabilities.

# 5. FORTHCOMING BEAM DYNAMICS EVENTS

## 5.1 Workshop devoted to the Accelerator Tracking Code Zgoubi, Boulder, 26-30 August 2019

. CONTACT: Dan T. Abell, dabell@radiasoft.net

A workshop devoted to the particle accelerator code Zgoubi will take place in Boulder, Colorado,USA from 26th-30th August 2019.

The particle tracking code Zgoubi evolved from a tool for modeling spectrometers in 1972to what it is today: one of the most complete single-particle dynamics codes. Used by labs worldwide for a wide range of particle accelerator modeling tasks, Zgoubi is especially valued for studies of polarization in electron-ion colliders, as well as for studies of the complex dynamics in fixed-field accelerators (FFAs) and medical synchrotrons.

The goal of the Zgoubi Workshop is to promote an exchange of knowledge about the Zgoubi code. Presentations on important scientific applications will motivate the associated practical tutorials. Bringing together both developers and scientist users will facilitate coordinated development that will leverage expertise from both groups and result in new tools and interfaces having consistent approaches.

* Please visit the conference website:`https://zgoubi-workshop.com/`

* If you are interested in giving a talk or tutorial, please contact us: zgoubi-workshop@radiasoft.net

* If you are unable to attend, but are interested in being on the mailing list, please let us know: zgoubi-workshop@radiasoft.net

## 5.2 63rdICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs (ERL2019), Berlin-Adlershof, 15-20 September 2019

. CONTACT: Atoosa Meseck, (workshop chair)

The 63rd ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs (ERL2019), organized by Helmholtz-Zentrum Berlin, will take place from Sunday, September 15th, to Friday, September 20th, 2019 on the Science & Technology Campus, Berlin-Adlershof, Germany.

ERL'19 is the eighth in the series of biennial international workshops covering the accelerator physics and technology of Energy Recovery Linacs. The workshop will serve as a forum for scientists and engineers from around the world to review and discuss the latest developments in ERL physics, technology and applications. Among the issues to be addressed are: ERL facilities, beam dynamics and instrumentation, electron sources and injectors, superconductingRF, ERL applications, etc. The talks will cover commissioning and operations experience, ERL applications and status presentations from different projects. There will be plenary sessions and the possibility to display posters.

Important dates and other useful information are available on the workshop website: `https://www.helmholtz-berlin.de/events/erl19/index_en.html`

The website will be updated (regularly) in the course of preparation for the workshop.

Early registration is currently open and will end on June 30th, 2019. Regular registration starts July 1st, 2019

## 5.3 22nd International Conference on Cyclotrons and their Applications (CYC2019) , Cape Town, 22-27 September 2019

. CONTACT: Lowry Conradie, CYC2019 International Organizing Committee Chair, and Muneer Sakildien, CYC2019 Local Organizing Committee Chair

The 22nd International Conference on Cyclotrons and their Applications (CYC2019) will be hosted in Cape Town, South Africa from the 22nd of September to the 27th of September, 2019.

The conference takes place every three years with the most recent events being held in-Zurich/Switzerland (2016), Vancouver/Canada (2013) and Lanzhou/China (2010). The conference returns to the African continent after being hosted here in 1995 and opened then by one of the greatest sons of our continent, Dr. Nelson Rolihlahla Mandela.

Cape Town is located on the southwest coast of South Africa at the foot of the majesticTable Mountain. The city is world-renowned for its breath-taking scenery and attractions such as the Kirstenbosch Botanical Gardens, Stellenbosch Wine Routes and the splendid beaches.

CYC2019 will offer plenary sessions of invited and contributed oral presentations from Monday morning through Friday noon. Poster sessions are scheduled for the Monday and Tuesday afternoons. The scientific program will cover six themes namely:

* Cyclotron Technologies
* Theory, Models and Simulations
* Operations and Upgrades
* Cyclotron Applications
* Cyclotron Concepts, FFA and New Projects
* Session for Young Scientists

The conference website is now online at:`https://indico-jacow.cern.ch/event/14/`

The deadline for abstract submission is Saturday, June 15th, 2019 (GMT+2).

The early bird registration deadline is Friday, May 31st, 2019 (GMT+2).

For more information and assistance, contact: cyc2019@tlabs.ac.za.

## 5.4 ICFA mini-Workshop on Mitigation of Coherent Beam Instabilities in Particle Accelerators (MCBI2019), Zermatt, 23-27 September 2019

. CONTACT: Elias Métral, Tatiana Pieloni and Giovanni Rumolo,
IOC Chairs MCBI2019

Following the ICFA mini-Workshop on “Electromagnetic Wake Fields and Impedances in Particle Accelerators” held in April 2014 in Erice, Sicily, and the ICFA mini-Workshop on “Impedances and Beam Instabilities in Particle Accelerators”, held in September 2017 in Benevento, Italy, a third workshop in the series will be organized jointly between CERN and EPFL and will take place from September 23rd to 27th, 2019 in Zermatt, Switzerland.

This workshop will focus on mitigation methods for coherent beam instabilities, reviewing in detail the theories (and underlying assumptions), simulations and measurements on the one hand, and on the other hand trying to compare the different mitigation methods (e.g. with respect to other effects such as beam lifetime) to provide the simplest and most robust solutions for day-to-day operation of the machines.

Further details are available at the workshop web-site: `https://indico.cern.ch/e/MCBI2019` which will be regularly updated to include the latest information as it becomes available.

## 5.5 Workshop on design of synchrotron light source, Mexico City, 28-30 October 2019

. CONTACT: Laman Carranza Ramirez [1], Victor del Rio [2], Robert Hettel [3], Herman Winick [4] , Workshop organizers and Co-Chairs

New synchrotron light sources are in design or planning in many places around the world.

A first step for Mexico, and other places where this is the first such facility, is to decide on the design parameters of the electron storage ring. Work is underway in Mexico about the best design for the first light source for the country.

At this workshop, this preliminary Mexican design, and other designs already underway or decided elsewhere, will be presmeted for criticism and discussion.

New groups will be encouraged to work together to select a common design so that orders for components can be placed with savings in time and money.

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## 5.6 ICFA Mini-Workshop on Space Charge, CERN, 4-6 November 2019

. CONTACT: Hannes Bartosik (CERN), Alexander Huschauer (CERN) and Frank Schmidt (CERN), Workshop organizers

The series of Space Charge Workshops has been started in 2013 in collaboration between GSI and CERN: `https://indico.cern.ch/event/221441/` as an ICFA Mini workshop. It has been followed by: - Oxford Space Charge Workshop in 2015 `https://www.cockcroft.ac.uk/events/SpaceCharge15/` and - Darmstadt Space Charge Workshop in 2017 `http://indico.gsi.de/event/5600/`.

Topics are:

A) Preliminary Results from Space Charge experimental studies of the LHC pre-accelerators of Run II. This concerns substantial Space Charge studies at LEIR, PSB, PS & SPS in view of the LIU upgrade program.

B) Space Charge Experiments at other Labs (2019 Fermilab Booster experiments, GSI, others)

C) Tools (benchmarking, status, medium & long-term plans)

D) Methods (Symplectic PIC codes, noise, balance coherent & incoherent Space Charge effects, 3D symplectic Space Charge kick with Sigma Matrix analysis)

E) Progress on Space Charge tools and analysis for Linacs

## 5.7 Fixed Field Alternating Gradient Workshop (FFA2019), Paul Scherrer Institute, 19-22 November 2019

. CONTACT: Andreas Adelmann, Chair of FFA2019

The latest in the series of annual workshops devoted to the study of FFAs will be hosted by the Paul Scherrer Institute in Switzerland from November 19th to 22nd 2019. The workshop will provide an opportunity to hear about operational discoveries on the existing FFA machines in Japan, progress in construction and commissioning of the FFA sections of the new CBETA project in the U.S.A. and the latest in theoretical studies being carried out in laboratories and universities around the world. As many aspects as possible of FFAs will be addressed over the period of the workshop, from applications and modelling codes through to magnets, rf and proposals for future FFA projects. Depending on the program and time available, we hope to include a session on the two main codes used to model FFAs - Zgoubi and OPAL - as well as at our of the accelerator facilities at PSI.

Further details will be available on the workshop websitehttps://indico.psi.ch/event/7313/.

# 6. ANNOUNCEMENTS FROM THE BEAM DYNAMICS PANEL

## 6.1 ICFA Beam Dynamics Newsletter

### 6.1.1 Aim of the Newsletter

The ICFA Beam Dynamics Newsletter is intended as a channel for describing unsolved problems and highlighting important ongoing work, and not as a substitute for journal articles and conference proceedings that usually describe completed work. It is published by the ICFA Beam Dynamics Panel, one of whose missions is to encourage dissemination of information and international collaboration in beam dynamics. Normally the Newsletter is published every April, August and December. The deadlines are 15$^{\text{th}}$ March, 15$^{\text{th}}$ July and 15$^{\text{th}}$ November, respectively.

### 6.1.2 Categories of Articles

The categories of articles in the newsletter are the following:

1. Announcements from the panel.
2. Reports of beam dynamics activities carried out by an ICFA-BD group.
3. Reports on workshops, meetings and other events related to beam dynamics.
4. Announcements of future beam dynamics-related international workshops and meetings.
   - Those who wish to use a newsletter to announce their workshops are welcome to do so. Articles should typically fit within half a page and include descriptions of the subject, date, place, web site and other contact information.
5. Review of beam dynamics problems.
   - This is a place to bring attention primarily to progress in solving problems or developing a field rather than just to report about completed work. Clear and short highlights on the problem are encouraged.
6. Letters to the editor
   - A forum open to everyone, anybody can express his/her opinion on beam dynamics and related activities, by writing to one of the editors. The editors reserve the right to reject contributions they judge to be inappropriate, although they have rarely had cause to do so. The editors may request an article following a recommendation by panel members. However anyone who wishes to submit an article is strongly encouraged to contact any Beam Dynamics Panel member before starting to write.

### 6.1.3 How to Prepare a Manuscript

The editors' preference is to prepare the Newsletter in LaTeX, although articles in Microsoft Word will also be accepted. Contact information for the Editor-in-Chief and the Issue Editor is provided on the Beam Dynamics Panel web site:

http://www.icfa-bd.org

Articles in LaTeX can be prepared using any standard class file or using the template for authors on the web page. The text and associated figures should be in separate files and sent to the editors together with a PDF file to indicate how the finished article is expected to appear.

Those using Word should download the appropriate template from the web site. Send the article to the editors as above, also including a PDF indicating how the finished article should appear.

In both cases the templates will evolve with time, so please make sure you use the latest version.

Each article should include the title, authors' names and affiliations. If agreeable the e-mail address of the lead author will also appear. However, personal data is subject to the provisions of data protection laws and it is within the rights of authors to request that details (such as their email address) are not published in the Newsletter.

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### 6.1.4 Distribution

The Newsletter is published in both html and (downloadable) PDF format. Readers who sign-up to the electronic mailing list via `http://www.icfa-bd.org` will receive an email notification whenever a new issue is released.

The Panel's web site provides access to the Newsletters, information about future and past workshops, and other information useful to accelerator physicists.

An archive of issues of this newsletter from 1987-2016 is available at

http://icfa-usa.jlab.org/archive/newsletter.shtml.

Except in a few exceptional cases, printed copies of the ICFA Beam Dynamics Newsletters are no longer issued.

### 6.1.5 Regular Correspondents

The Beam Dynamics Newsletter particularly encourages contributions from smaller institutions and countries where the accelerator physics community is small. Since it is impossible for the editors and panel members to survey all beam dynamics activity worldwide, we have some Regular Correspondents. They are expected to find interesting activities and appropriate persons to report them and/or report them by themselves. We hope that we will have a "compact and complete" list covering all over the world eventually. The present Regular Correspondents are as follows:

| | | |
|---|---|---|
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| Sameen Ahmed Khan | Rohelakhan@yahoo.com | Middle East and Africa |
| Suzie Sheehy | suzanne.sheehy@unimelb.edu.au | Australasia |

Additional volunteers as Regular Correspondents would be welcome.

## 6.2 ICFA Beam Dynamics Panel Members

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