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FEEDBACK SYSTEMS FOR MULTIBUNCH BEAM DIAGNOSTICS AND INSTABILITIES SUPPRESSION*

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Abstract

Transverse instabilities in storage rings can limit both beam and single bunch currents. The vacuum chamber impedance can be a source of instabilities for stored beams of positive and negative charges. Furthermore, parasitic e-clouds can produce other undesirable effects to stored beams of positive charges. Transverse bunch-by-bunch feedback systems are implemented in storage rings as active devices for instability suppression and for state of art beam diagnostics.

In this paper the following topics are discussed: basics on bunch-by-bunch feedback for lepton storage rings; beam diagnostics by using feedback; a new feedback design proposed for the electron-positron Future Circular Collider (FCC-ee).

INTRODUCTION

Transverse instabilities in storage rings can limit both beam and single bunch currents.

The vacuum chamber impedance, by means of producing wake-fields at the bunch passage, can be a source of instabilities for positively and negatively charged stored beams. Moreover, also parasitic e- clouds in the vacuum chamber can give undesired or destructive effects for positively charged stored beams.

Transverse bunch-by-bunch feedback systems are implemented in storage rings as active devices for instability suppression and for state of art beam diagnostics.

A FEEDBACK SIMPLE MODEL

As beginning we propose a very simple model of the bunch motion that can be easily studied by writing a software simulator, and that could be interesting from an academic/educational point of view too. This model is fitting to be implemented by using the state-space formalism, for example.

Bunch-by-bunch feedback systems work in the time domain kicking each bunch of particles (considered as a charged rigid body).

Following this approach, the classic harmonic oscillator equation describing small oscillations can be used as a model. For the n-th bunch the formula will be:

$$\ddot{x}_n + 2d_r\,\dot{x}_n + \omega_v^2 x_n = c_f * (V_n^{fb} - V_n^{wf})$$

where

x_n = position displacement in the horizontal (or vertical) plane from the equilibrium orbit of n-th bunch;

d_r = natural damping rate;

ω_v = resonance angular frequency (betatron_fractional _tune * 2 * π * revolution_frequency);

c_f = conversion factor (note that c_f it is not a pure number);

V^{fb}_n = kick voltage applied by the feedback to the n-th bunch (correction signal computed for the n-th bunch);

V^{wf}_n = kick voltage produced by the wake-fields and applied to the n-th bunch (i.e. voltage produced by the vacuum chamber impedance).

It is interesting to note that by using this formula, the feedback correction kick (V^{fb}_n) behaves as the opposite of the term (V^{wf}_n) generated by the ring impedance.

This simple model can be used to evaluate the effect of the bunch-by-bunch feedback with different setups. In order to build a real time system, very fast analogue and digital electronics are necessary to implement a correction kick algorithm for each bunch [1,2,3]. Furthermore, by using a special technique tested in the longitudinal plane, it is possible to control the quadrupole (head-tail) motion by using the same feedback that implements a more complicated system setup [4]. The most common algorithm is based on a Finite Impulse Response (F.I.R.) filter computing for each bunch per turn an individual correction signal as in the following formula:

$$y_n = k * \sum_i c_i * x_{i,n}$$

where y_n is the correction value, k is the gain, c_i is the i-th filter coefficient and $x_{i,n}$ is the i-th acquired value of the n-th bunch.

It is important to note that some parts of the feedback system itself add impedance to the ring: the pick-up, often made by steel buttons, and the kickers, usually made by two copper striplines or, in the longitudinal case, by a cavity in aluminium or copper.

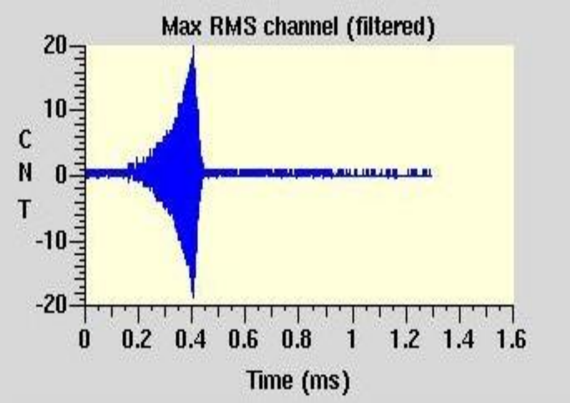

Figure 1: Horizontal oscillations of 500 mA e+ beam (feedback turned off for 0.4 ms). The vertical scale is in arbitrary counts (CNT).

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BEAM DIAGNOSTICS BY USING FEEDBACK

To understand if the feedback performances are adequate, it is necessary to evaluate the fastest modal growth rate of the instabilities. The feedback itself can be used to make this measurement. In order to accomplish the goal, it is necessary to turn off the feedback for a short period of time or, in other words, to open the loop.

In Figure 1 the horizontal oscillation of the DAFNE positron beam with 500mA is shown. The signal shows the most oscillating bunch of the train. The feedback is turned off for 0.4 ms. The off period has to be carefully chosen based on the (foreseen or observed) growth rate of the instability. The instability growth is exponential.

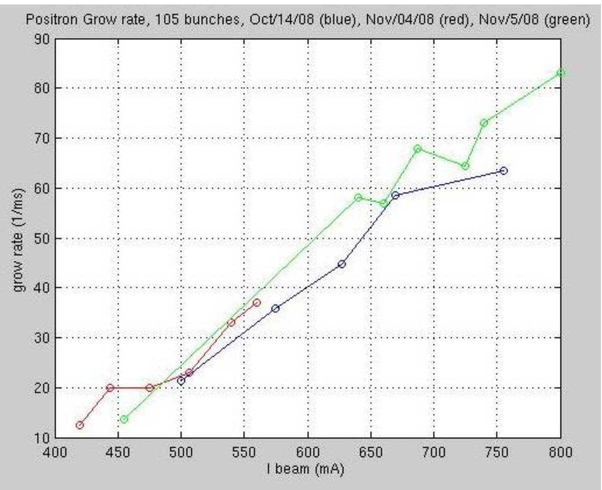

Figure 2: Growth rates (1/ms) of the fastest horizontal e+ mode vs. the beam current (mA)

In Figure 2 the e+ horizontal mode growth rates are reported for DAFNE. The measures are collected in 2008 by using the diagnostic capability of the feedback and recorded in three different days (indicated by three colours). Data are coherent versus beam current if the ring parameters do not change. From the theory [5,6] we expect a linear behaviour versus beam current. A precise error estimate is difficult to obtain because this kind of measurement is extrapolated after a long processing of the raw data and it strongly depends on the human operator skill. Nevertheless, the error seems reasonable because the linear behaviour appears evident. The horizontal growth rates are plotted versus DAFNE e+ beam current between 400 and 800 mA [7,8].

To mitigate instability caused by the presence of the e-clouds, twelve clearing electrodes have been installed in the positron ring in the year 2011. The distance of the electrodes from the beam axis is 8 mm in the four wigglers and 25 mm in the eight bending magnets. How can we evaluate the correct working of the clearing electrodes? A very good method (but not the only one) to evaluate their performance is by measuring the growth rates (by means of the feedback system) versus different voltages applied to the electrodes at various beam currents [9,10], as shown in Figure 3. In this case the behaviour linearity is much less evident. This fact can be motivated by the observation that changing the electrode voltage has also the collateral effect to slightly influence the beam trajectory and optics, that are important ring parameters. After these measurements the voltage has been raised up to 500 V, changing in the meanwhile the polarity too, to find the best use of the electrodes.

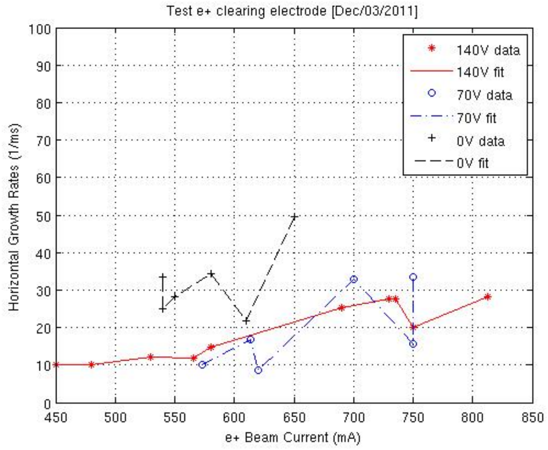

Figure 3: Growth rates (1/ms) of the fastest mode vs. the beam current (mA) with different voltages applied to the clearing electrodes

In addition, there are other beam diagnostic measures implemented at DAFNE by using the feedback systems that, as a matter of principle, could also be made by other tools. First of all, synchronous phase spread measurements along the bunch train have been taken by acquiring data from the front end phase shifter of the longitudinal feedback.

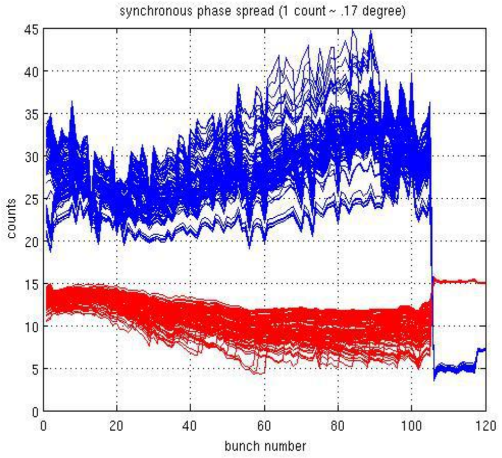

Figure 4: Synchronous phase spread (counts) versus the bunch number for electron (blue) and positron beam (red). Note that the signal acquisitions are plotted with infinite persistence on the display.

In Figure 4 the synchronous phase spread (in counts) is acquired versus bunch number with beam currents up to 1.4 A for the e-, and up to 1 A for the e+. One count corresponds to ~0.17 degree. The spread measured is 2.72 degrees for e- and 1.7 degrees for e+. See for example [11], a recent reference, for a comparison.

Moreover, by using feedback it is possible to get real time fractional tune measurements for the beam and also for each bunch separately. This method for tune measuring can be used when the other colliding beam (if any) does not produce tune shift or Landau damping [12-16].

After converting the beam motion recorded by the feedback in the frequency domain by an FFT routine, it is possible to get a rejection negative peak resultant by the feedback response at the frequency where the tune is located and where the S/N ratio is highest. If the feedback gain is large enough, the rejection negative peak will be evident [17]. This approach has been confirmed by frequent comparisons with the traditional measurement technique by using spectrum analyser and white noise excitation.

By following this approach, the bunch-by-bunch fractional tune diagnostics can be implemented without turning off the feedback and by using the transverse system to record long data streams for each bunch. As example for the e- beam with 1 A stored in 90 bunches, the betatron fractional tune spread is ~0.001 for both horizontal and vertical oscillations (close to the error threshold). On the contrary, for the e+ beam with 0.7 A stored in 90 bunches the betatron fractional tune spread is as follows:

0.008 (from .106 to .114), with clearing electrodes off;
0.004 (from .109 to .113), with clearing electrodes on.

For the positron the effect of the e-clouds is evident from the large tune spread, and hence, this is another technique to evaluate if the clearing electrodes are working well.

R&D FOR FCC-EE FEEDBACK

As an interesting R&D case, a new feedback design proposed for FCC-ee is presented in the following.

The bunch-by-bunch feedback systems for FCC-ee should be designed on the basis of the experience acquired working on the lepton circular colliders in the last two decades. Along the past years a common way to approach these systems has been carried on for PEP-II, KEKB, DAFNE, and, later, for SuperB and SuperKEKB. Feedback systems for circular light sources are only apparently very similar, nevertheless they have to cope with different performance requirements and beam currents.

Having in mind the approach developed for the previous lepton colliders, what is necessary to damp the beam oscillations in FCC-ee, is "simply" getting the position displacement (in the horizontal, vertical or longitudinal plane) for each bunch in every turn, and, after computing the correction signal, applying it to the selected bunch as soon as possible. The systems will be designed to work in the time domain without considering in detail the modes which are actually acting in the ring. Of course a bunch-by-bunch feedback leads to a system design that is mainly digital. Considering the difference between transverse and longitudinal feedback systems, the digital processing unit (DPU) is identical while the analogue parts (front end and back end), the power amplifiers and the kickers are quite different. Another difference is the expected tune value that is usually much lower for the longitudinal plane as compared to the transverse ones.

Analysing the FCC-ee characteristics and taking into account the beam dynamics point of view, three possible cases can be considered as feedback design strategies [18,19,20]:

a) slow or very slow instabilities (growth rates slower than 10 revolution turns)

b) fast instabilities (growth rates up to 3 revolution turns)

c) extremely fast instabilities (growth rates around 1-2 turns or even less).

These three approaches are based on the experience acquired with several lepton colliders showing that one feedback system cannot damp growth rates faster than 10 turns. As consequence different approaches must be studied to achieve more challenging goals.

Before discussing how to proceed to cope with the different cases, there are some preliminary requirements to consider. First of all, it is necessary a very good β function at the pick-up to have a decent signal-to-noise ratio before processing it. Also a good β at the kicker is required to have the best performance for the voltage applied to each bunch. Regarding the fractional tune value, it is important to note that if it is too small (<.10) the correction signal computing will become slower, because more acquisitions are necessary to fill the F.I.R. filter response, worsening the feedback damping time.

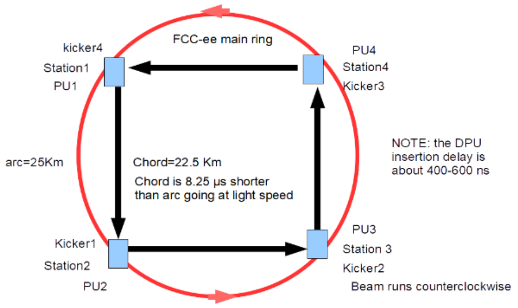

Figure 5: proposed feedback sketch for option c). Note that PU is for pick-up and DPU for digital processing unit

Let's now discuss the three cases described above, with the goal of maintain the standard mixed analogue and digital technologies developed for the feedback in the past. Only the a) case can be based on the usual well known approach, in which many parts are commercially available. Indeed, increasing the gain over a certain limit has only the effect to saturate the feedback. Moreover, the present feedback systems can process up to a few thousand buckets. As a consequence, new and more powerful digital processing units (DPU) have to be built for the a) case as well to cope with a very high harmonic number (of the order of 100k). Another possible issue can arise due to the possible very low frequency of the modes that have to be damped. Indeed, the kickers and the power amplifiers feeding the correction signal must have the appropriate bandwidth. Moreover, even if power amplifiers are commercial devices, they have to be checked carefully to work in pulse mode at low frequencies, too. A similar feature is necessary for the kickers. As said above, this "usual" feedback design is foreseen to have a damping rate of 10 revolution turns, as the experience acquired in the past and present colliders has showed.

Analysing the b) case, that considers instability growth rates up to 3 revolution turns, a different and more powerful scheme has to be implemented. Indeed, only one feedback system does not guarantee to manage correctly enough power to damp the oscillations without system saturation. The experience made at DAFNE in 2007 by implementing two complete feedback systems in the same horizontal plane as described in [21], clearly highlights that the damping rate is mainly limited by the noise coming from the pick-up and not by the noise generated inside the feedback itself. A high beam current makes worse the signal-to-noise ratio leading to a feedback saturation. Moreover, saturation or excess of feedback gain can induce an enlargement of the bunch dimension. This effect is more dangerous in the vertical plane and it can also be amplified by the kick given by beam-beam collisions. Implementing four co-operative systems spaced by a distance of a quarter of the main ring can overcome the gain saturation limit with the benefit to achieve a feedback damping rate of the order of 10/4=2.5 revolution turns.

Finally considering the c) case with instability growth rates of the order of 1-2 turns or even slightly less, a very different design scheme is necessary. Indeed, the solution found for the b) case is not sufficient. To achieve a faster damping rate, it is necessary to apply the correction signal earlier than in the previous scheme (able to kick only after one revolution period). Again, four systems are proposed but they are not enough. The way to implement a new faster design consists in putting the kicker with a distance of a quarter of the ring downstream the feedback pick-up. To be effective the correction signal has to arrive at the kicker before the bunch, in a sort of "*feeding forward*". This is possible because the path along the chord (for the signal) is shorter than the path along the arc (for the beam), as shown in Figure 5. A signal transmission system with about the speed of light is of course necessary. The new hollow optical fibre technology [22] is a state-of-art for cabled transmission and it seems in this moment the best solution to the problem. Otherwise, a standard radiofrequency transmission system can be used. With this scheme the feedback damping rate should be pushed up to 0.625 revolution turns (10/4/4=0.625).

Note that in both the b) and c) cases the author has proposed *four* systems (and not *two, three, or five*, etc.) just for practical reasons but, of course, a different number of systems can also be also evaluated.

In conclusion, instability growth rates of the order of one revolution turn require a very strong R&D program to implement the above proposed innovative feedback design. Less critical instability growth rates can be solved by a more moderate R&D program.

Now analysing the feedback systems from the ring impedance point of view, it is noteworthy to underline that the three feedback design options have different impacts. The first option requires just one cavity kicker for the longitudinal case and two stripline kickers for the transverse planes, whereas both the b) and c) options need four cavity kickers and eight stripline kickers thus increasing consequently the ring impedance. However, for each feedback (horizontal, vertical, longitudinal) system, the more suitable solution can be implemented by the design option that is best fitting to cope with the instability grow rate.

CONCLUSION

Transverse instabilities can limit both beam and single bunch currents. Source of instabilities are vacuum chamber impedance and (for positive charge stored beams) parasitic e- clouds. Bunch-by-bunch feedback systems are extremely useful tools for both beam diagnostics and instabilities suppression in storage rings. A simple feedback model is proposed for a software simulator based on state-space formalism.

Bunch-by-bunch feedback systems are implemented in storage rings as active devices for instability suppression and for state of art beam or bunch-by-bunch diagnostics.

For FCC-ee, the feedback systems should be based on the designs developed for other previous e+/e- colliders (PEP-II, KEK, DAFNE, SuperB, SuperKekB) able to achieve damping rates up to 10 revolution turns.

By implementing multiple co-operative feedback systems and maintaining the usual design scheme it will be possible to damp instability growth rate up to 3 revolution turns, if necessary.

Damping in about 1 revolution turn or slightly less will be possible only by changing the usual feedback strategy. An innovative bunch-by-bunch "*feeding forward*" system is proposed for this challenging goal.

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REFERENCES

[1] J.Fox, et al. “Observation, Control and Modal Analysis of Coupled-Bunch Longitudinal Instabilities”, EPAC’96 Proceedings, 1996.

[2] S.Prabhakar, “New Diagnostics and Cures for Coupled-Bunch Instabilities”, Stanford Univ. PhD thesis, SLAC-R-554, August 2001.

[3] D.Teytelman, “Architectures and Algorithms for Control and Diagnostics of Coupled-Bunch Instabilities in Circular Accelerators”. Stanford Univ. PhD thesis, SLAC-R-633, June 2003.

[4] A.Drago, et al. "Longitudinal Quadrupole Instability and Control in the Frascati DAFNE Electron ring", PRST-AB, 6, 052801-1-11, 2003.

[5] J.L. Laclare, “Bunched Beam Coherent Instabilities”. Cern Accelerator School 1985. CERN 87-03, 21 April 1987.

[6] M. Zobov et al., “Collective Effects and Impedance Study for the DAFNE F-Factory”. LNF-95/041 (P), 31/7/1995.

[7] A.Drago, “Fast Horizontal e+ instability measurements in DAFNE”, PAC’09, TH5RFP057. Vancouver, Canada, 2009.

[8] A.Drago, C.Vaccarezza, M.Zobov: "Analysis of Mechanisms Driving the Horizontal Instability in the DAFNE Positron Ring", G-67, 25/5/2006.

[9] A. Drago et al., “Mitigation and control of instabilities in DAFNE positron ring”. Apr 2012. 3 pp. e-Print: arXiv:1204.5016 [physics.acc-ph]. Presented at 2012 Beam Instrumentation Workshop (BIW12), April 15-19, 2012, Newport News, USA. Task 2.4 meeting, CERN, 13/06/2012: http://emetral.web.cern.ch/emetral/Task2point4OfHLLHCWP2/3rdMeeting_05-09-12/TUPG001_talk_r1.pdf

[10] D.Alesini, A.Drago, A.Gallo, S.Guiducci, C.Milardi, M.Zobov, LNF-INFN; S.De Santis, LBNL; T.Demma, LAL; P. Raimondi, ESRF, “Experimental Measurements of e-Cloud Mitigation using Clearing Electrodes in the DANE Collider”, IPAC2012 Proceedings, 2012.

http://accelconf.web.cern.ch/AccelConf/IPAC2012/papers/tuobc03.pdf

[11] W.Cheng et al.,“Precise Synchronous Phase Measurements”. Proceedings of IPAC2017, MOPAB152, Copenhagen, Denmark, 2017.

[12] M. Migliorati et al., “Landau Damping of Longitudinal Multi-Bunch Instabilities in DAΦNE”, DAΦNE Technical Note G-21, 13 September 1993.

[13] P. Raimondi and M. Zobov, “Tune Shift in Beam-Beam Collisions with a Crossing Angle”, DAΦNE Technical Note G-58, 26 April 2003.

[14] M. Zobov and D. Shatilov, “Synchrotron Tune Shift and Tune Spread Due to Beam-Beam Collisions with a Crossing Angle”, DAΦNE Technical Note G-72, 04 March 2010.

[15] A.Drago et al., “Synchrotron Oscillation Damping Due to Beam-Beam Collisions”, THOBRA01, oral talk presented at the first IPAC, Kyoto, Japan, May, 23-28, 2010.

[16] A.Drago, P. Raimondi, M. Zobov, (INFN/LNF), D.Shatilov, (BINP), “Synchrotron Oscillation Damping by Beam-Beam Collisions in DAFNE”, PRST-AB, 14, 092803 (2011).

[17] A. Drago, “Tune measurements”, talk presented at "Beam Dynamics meets Diagnostics" Workshop, 4-6/11/2015, Florence,Italy. https://indico.gsi.de/event/3509/session/3/contribution/12

[18] A.Drago, "Feedback Systems for FCC-ee". Oral presentation at FCC Week 2016, Rome, Italy.

[19] A.Drago, "Feedback Systems for FCC-ee". Oral presentation at eeFACT2016, 58th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e-Colliders, 24-27 October 2016. Daresbury (UK). Slides & proceedings:

https://eventbooking.stfc.ac.uk/uploads/eefact/dragotut3ah9.pdf.

http://accelconf.web.cern.ch/AccelConf/eefact2016/

https://doi.org/10.18429/JACoW-eeFACT2016-TUT3AH9

[20] A.Drago, "Fast Feedback System Design Update". Oral presentation at the FCC Week 2018, Amsterdam, the Netherlands, April 9-13, 2018. https://indico.cern.ch/event/656491/contributions/2918510/attachments/1628585/2594686/FCC-week-2018-Drago.pdf

[21] A. Drago, "Fast feedbacks for diagnostics and mitigation of e-cloud instability". Oral presentation at the International Linear Collider Workshop 2008, LCWS08 & ILC08. University of Illinois, Chicago, November 16-20, 2008.

[22] F.Poletti et al., “Toward high-capacity fibre-optic communications at the speed of light in vacuum”, Nature Photonics 7, 279-284 (2013).