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IMPEDANCE AND INSTABILITIES IN HADRON MACHINES

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Abstract

Coherent beam instabilities related to impedance effects represent one of the main limitations to increasing beam intensity in circular accelerators.

This contribution was presented at the ICFA mini-workshop on impedance and beam instabilities in particle accelerators on 18-22 September 2017 in Benevento, and aimed at providing a brief overview of the situation in circular hadron machines at the moment of the workshop.

INTRODUCTION

In his report on the CERN Intersecting Storage Rings (ISR), B. Zotter (1932-2015) highlighted that “already during the earliest ISR development runs it was found that part of the beam was lost suddenly when a certain current level was reached during stacking. This phenomenon repeated itself again and again at the same level, and was called ‘brickwall’ in the first moment of despair” [1]. As in this case, the performance reach of several machines has been limited by such collective phenomena, either in the longitudinal or transverse plane(s), and mitigations had to be found.

The case of lepton machines is dealt with in a contribution at the same workshop [2] and this contribution focuses on the specific case of hadron machines. The theory of instabilities and in particular impedance related instabilities was developed and summarised in great detail for instance in Ref. [3-9], and this contribution will start with listing the specificities of hadron machines, before attempting to give an overview of the instabilities experienced by hadron machines. The focus will be put on the main instability issues at the moment of the workshop (Rutherford Appleton Laboratory ISIS, GSI SIS18 and CERN LHC as CERN PS and SPS are covered in other contributions at this workshop [10-13]).

This contribution does not cover linear accelerators, since the beam break-up instability in proton and ion Linacs is generally above the space charge limit and can be efficiently mitigated by adding betatron frequency spread between the head and the tail of the bunch with a Radio Frequency Quadrupole (RFQ) or an adequate choice of bunch phase with respect to the RF (BNS damping) [14].

SPECIFICITIES OF HADRON MACHINES

Hadrons are made of protons and neutrons, whose rest mass is 1836 times that of the electron. It therefore requires much more force to accelerate and bend hadrons than electrons. As a consequence, the potential relativistic factor γ reach is much lower for hadrons for similar machine size. At lower γ synchrotron radiation plays a smaller role (both quantum excitation and damping), which means that hadron machines would typically operate with larger beam emittance and bunch length with similar focusing forces. This is even worse for heavy ions, for which the accelerating and guiding forces scale with the ratio of the atomic charge Z to the atomic number A, which is always lower than unity due to the presence of neutrons. For collective effects the forces scale with Z^2/A.

Another consequence of the larger hadron mass is the much larger beam power for the same relativistic factor, and the impact of beam losses can be much more dramatic. This may lead hadron machines to require a collimation system to localize losses, and these collimators can represent a large contribution to the machine impedance (due to the current technology that requires having robust material with low atomic number close to the beam). The lower relativistic factor also means that space charge should have a stronger impact.

For stability purposes, operating with larger emittance means more tune spread available for Landau damping, stronger impact of octupoles on damping instabilities and that collimators and apertures should remain far from the beam, which reduces impedance.

Historically, the synchrotron tune – a critical parameter for stability – was typically much larger for lepton machines (of the order of 10^{-1}) than for hadron machines (of the order of 10^{-3}) [15]. Nevertheless, the synchrotron tunes of ESRF, SOLEIL, CERN SPS and LHC are for instance within the same order of magnitude (2 to 5 10^{-3}).

The longer bunch length requires less bandwidth for feedback systems to be effective on intra-bunch motion. In addition, the frequency spectrum excited by the beam does not reach very high frequencies, which are difficult to reach with simulations and measurements. The excited beam spectrum is typically lower than the beam pipe cut-off frequency in hadron machines, which is very good news for performing 3D numerical impedance simulations, but also means that resonant modes do not propagate in the beam pipe and remain trapped in the device: this is bad news for the device itself as it could be damaged, but good news for the neighbouring accelerator components.

It has to be noted that the energy reach of energy frontier hadron machines like LHC is now such that hadrons are also experiencing significant synchrotron radiation effects, and the transverse emittance (not normalized) is now in the same ballpark as light sources.

Most hadron machines operate in the strong space charge regime, with the notable exception of LHC, even though the impact of space charge at injection is still expected to be significant [16].

Finally, the vast majority of hadron synchrotrons use positively charged ions, and electron cloud phenomena should be accounted for.

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OVERVIEW OF CIRCULAR HADRON MACHINES

Circular hadron machines have been located mainly in 8 countries (see Fig. 1):

- Canada (TRIUMF)
- France (CERN and GANIL)
- Germany (DESY, GSI and Julich)
- Japan (JPARC)
- Russia (IHEP)
- Switzerland (CERN and PSI)
- UK (RAL)
- USA (BNL, Fermilab, LANL and ORNL)

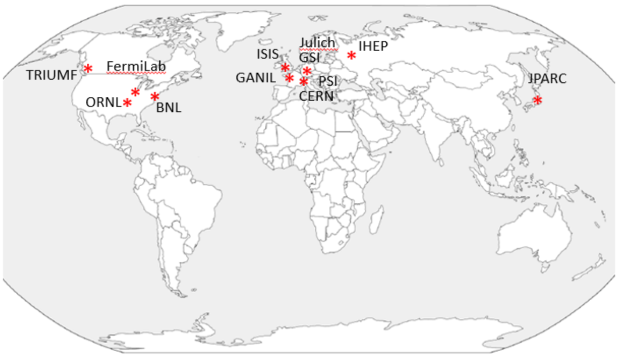

Figure 1: Location of circular hadron machines.

Instabilities were observed in most of the currently running machines (see Tab. 1). Looking at the "instabilities" column of this table, one can observe that instability issues are currently concentrated in RAL ISIS, GSI SIS 18, as well as CERN PS, SPS and LHC.

Table 1: status of instabilities in circular hadron machines. As shown in the legend below the table, a white box means that there is no observation of instability; a green box means that instabilities are observed and mitigated; an orange box means that instabilities are observed and are a worry for performance reach; and finally a red box means that instabilities currently limit performance. FB refers to presence of "feedback", while "HH" to the presence of "higher order harmonic cavity", and "chroma" to the use of chromaticity to help damping the relevant instabilities.

Laboratory	Machine	instabilities	longitudinal	transverse	ecloud	TMCI	microwave	loss of landau damping	vacuum instability	unexplained	heating
BNL	AGS	[green]		FB [green]	[green]						
	RHIC	[green]	HH [green]					damped by 21st order cavity [green]			
CERN	ELENA										
	AD										
	LEIR	[green]		FB [green]							
	PSB	[green]		FB [green]						[green]	
	PS	[orange]	FB [orange]	FB [green]	[green]	[green]	[green]	[green]			
	SPS	[red]	HH [red]	FB [green]	[green]	[green]	[orange]	[orange]			[orange]
	LHC	[red]	no HH [green]	FB [red]	[orange]			[green]	?	[red]	[orange]
Fermilab	Booster	[green]	FB [green]	FB [green]				[green]			
	MI	[green]		FB [green]				[green]			
	recycler	[green]		FB [green]	[green]						
GANIL											
GSI	ESR	[green]	[green]					[green]			
	SIS18	[orange]	[green]	no FB [orange]				[green]	[orange]		
IHEP	U-70	[green]		FB [green]				[green]			
JPARC	RCS	[green]		chroma [green]				[green]			
	MR	[green]		FB [green]				[green]			
Juelich	COSY	[green]		FB+chroma [green]	cooler [green]						
LANL	PSR	[green]	[green]	FB [green]	[green]			heating the ferrite! [green]			
ORNL	SNS	[green]		FB [green]	[green]						
PSI	HIPA										
RAL	ISIS	[red]		no FB [red]				[red]			
TRIUMF	MC	[green]									

[white]	no observations
[green]	observation and mitigation
[orange]	worry
[red]	limits performance

With the "longitudinal" column, one can see that machines use a feedback system or a higher order harmonic cavity as active damping methods. In the "transverse" column, one can notice that almost all machines have implemented an active damping for the tranverse plane, and that SIS-18 and ISIS have transverse instability issues because a feedback system was not installed. Colleagues present at the workshop from RAL and GSI confirmed that a feedback system is planned to be installed.

The "electron cloud" column of Tab. 1 shows that electron cloud instabilities is an issue mainly in LHC for the injection of certain beams (e.g. the doublet beam used for beam scrubbing).

The following columns of the table ("TMCI" (Transverse Mode Coupling Instability), "microwave" instability, "loss of landau damping" instability, "vacuum instability") show if such instabilities were observed and are considered as threats to the machine performance. TMCI and microwave instabilities are observed in very few machines, while loss of Landau damping instability in longitudinal and/or transverse plane is observed in almost all machines, in particular when the feedback is switched off. Vacuum instability is only observed in SIS18, while the recent transverse instabilities in LHC were still not fully understood at the moment of the workshop.

Finally heating issues are concentrated in SPS and LHC.

The impact of the parameters planned for the major upgrades foreseen for the hadron machines modifies Tab. 1 into Tab. 2.

Table 2: status of instabilities for parameters planned for major upgrades of circular hadron machines. Same legend as Tab. 1.

Laboratory	Machine	instabilities	longitudinal	transverse	ecloud	TMCI	microwave	loss of landau damping	vacuum instability	unexplained	heating	
BNL	AGS			FB								
	RHIC		HH					damped by 21st order cavity				
CERN	ELENA											
	AD											
	LIU-LEIR			FB								
	LIU-PSB			FB								
	LIU-PS		FB	FB				CBI				
	LIU-SPS		HH	FB								
	HL-LHC		no HH	FB					?			
Fermilab	Booster		FB	FB								
	MI			FB								
	recycler			FB								
GANIL												
GSI	ESR											
	SIS18			no FB								
IHEP	U-70			FB								
JPARC	RCS			chroma								
	MR			FB								
Juelich	COSY			FB+chroma	cooler							
LANL	PSR			FB				heating the ferrite!				
ORNL	SNS			FB								
PSI	HIPA											
RAL	ISIS			no FB								
TRIUMF	MC											

The push of performance required by the upgrades means that instabilities become more critical. This is clearly the case for the High Luminosity LHC (HL-LHC) and LHC Injectors Upgrade projects at CERN as well as in GSI and SNS.

For these upgrades, the requested increase in performance leads to reduce beam coupling impedance and/or damping mechanisms (higher harmonic cavities, feedback systems, improvement of optics to gain margin with respect to instability thresholds by reducing betatron tune shifts [10] or increasing betatron tune spread).

In this context, it is important to note that hadron circular machines require a significant investment and most were built a long time ago and upgraded. In fact, as Sophie Marceau [17], impedance theory was very young at the time of designing many of these machines, and impedance reduction was not an integral part of the design, as it is nowadays for instance for GSI SIS-100, JPARC rings, CERN LHC and HL-LHC. Many accelerator elements from the 1970s to 1990s are still present and a replacing all of them with impedance-optimized components would be very costly. A significant effort to patch these existing machines is therefore underway in view of heavy upgrades (see for instance [18]).

FOCUS ON TWO CURRENT INSTABILITY ISSUES

Headtail instabilities

Transverse Headtail instabilities were observed in both GSI SIS-18 and RAL ISIS, both from single bunch loss of Landau damping (see Fig. 2) [19, 20]. These instabilities could be issues for the foreseen upgrades, but common damping techniques have not yet been installed and exploited (in particular feedback systems for both machines and even chromaticity control for ISIS since sextupoles had been removed to free space). Both labs therefore plan to install transverse feedback, as well as octupoles in SIS18 and in SIS100.

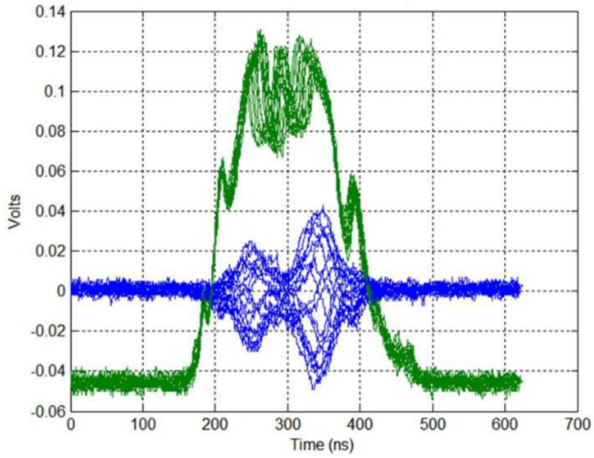

Figure 2: Sum (green) and delta (blue) vertical Beam Position Monitor (BPM) signals over several turns around 1 ms through the ISIS acceleration cycle. Courtesy Williamson et al [19]. A Headtail instability with 1 node is visible on the delta signal.

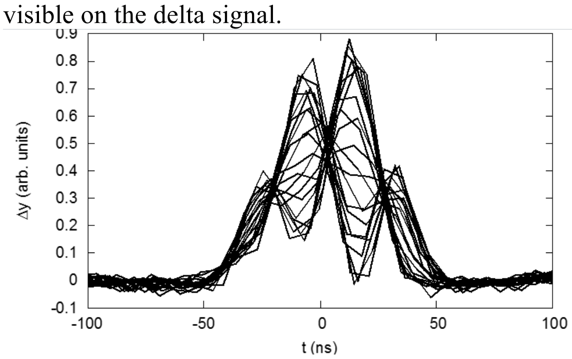

Figure 3: superimposed delta vertical BPM signals over several turns in SIS-18. Courtesy V. Kornilov [20]. A Headtail instability with 3 nodes is visible on the delta signal.

LHC: a testbed for beam instabilities

Since 2010, there has been many different types of beam instabilities observed in LHC (see Tab. 3). The evolution of beam parameters since 2010 (in particular of the bunch intensity, bunch spacing, number of bunches and beta function at the colliding points) as well as the mitigations put in place to avoid these instabilities and the improvement of diagnostics that allow catching more instabilities explain the staged occurrence of these instabilities.

Table 3: list of instabilities observed in LHC with their year of occurrence, plane, rise time and criticality for operation.

Instability type	Year observed	Longitudinal	Transverse	Rise time (for transverse instabilities)	Critical?
Single bunch loss of Landau damping instabilities	Since 2010	X			Not for LHC, but limits bunch length for HL-LHC
Longitudinal oscillations of colliding pairs	2016	X			No
Transverse loss of Landau damping	Since 2010 in various forms		X	1 to 10 s	Yes, requires high chromaticity, high octupole current, low linear coupling and large damper gain
Mode coupling instability with colliding beams	2012		X	~ 1 s	No
Electron cloud instabilities	Since 2011		X	~ 1 s	Yes for certain special beams
"16L2" instabilities	Since 2017		X	~ 0.1 s	Yes

Transverse Loss of Landau damping instabilities have been a concern since 2012, and have required increasing chromaticity, octupoles current, damper gain and damper bandwidth. A major breakthrough came in 2016 when linear coupling was identified as a critical machine parameter to keep under control along the LHC cycle to avoid Headtail instabilities [21] (see an example of such a Headtail instability in Fig. 4).

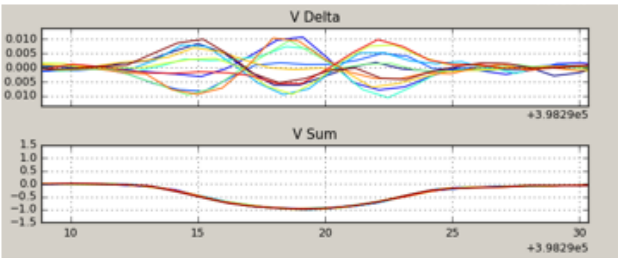

Figure 4: superimposed delta signals (top) and sum signals (bottom) from a vertical BPM (arbitrary units). Courtesy T. Levens. A Headtail instability with 2 nodes is visible on the delta signal.

The latter "16L2" instability has significantly affected the 2017 LHC run and is described in detail in [22]. It is believed that an accidental air inlet into the LHC beam vacuum with beam screen at 20 K has caused condensation and solidification of a significant amount of gas on the beam screen surface in and around the beam plug-in-module [23]. The interaction of the LHC proton beam with flakes of these frozen gases is believed to lead to the following sequence of events [24, 25]:

(1) Desorption of frozen nitrogen/oxygen flakes could be stimulated by electron multipacting.
(2) The proton beam interacts with the flakes, generating a loss spike.
(3) The flake undergoes phase transition to a gas and is ionized, generating a plasma of high density of electrons and ions in the beam path, both generating a very fast instability affecting mainly the tail of the LHC bunches (see Fig. 5).

Such fast instabilities were not observed before in LHC, and the complicated mechanism requires simulating the proton beam in presence of both electrons and ions.

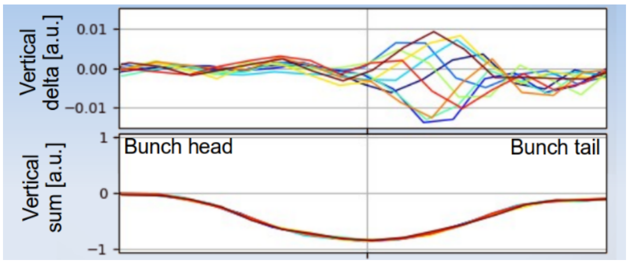

Figure 5: superimposed delta signals (top) and sum signals (bottom) from a vertical BPM (arbitrary units). Courtesy T. Levens and N. Biancacci. An instability with travelling wave pattern is visible on the delta signal and affects only the tail of the bunch.

LESSONS LEARNT FOR FUTURE HADRON MACHINES AND UPGRADES

Avoiding transverse feedback is not an option for high intensity operation and a combination with wideband feedback, octupoles, electron lens and/or RFQ should be investigated.

Proper control of chromaticity, amplitude detuning and linear coupling is crucial.

Electron-cloud suppression is critical and technical solutions include surface treatments that can have an impact on impedance contributions and therefore beam stability.

Impedance now drives major aspects of machine design, when we run at the limit of stability: beam screen aperture for the CERN FCC-hh project (Future Circular hadron Collider), collimator materials and gaps for HL-LHC, anti-electron cloud coatings, kicker shielding, bellow and pumping port shielding.

Finally, the experience of CERN PS, SPS and LHC shows that safe operation requires significant margins (e.g. factor of 2 for LHC) from predicted instability thresholds.

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