Review of Beamloading and Compensation in Synchrotrons

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1. Introduction

Longitudinal focusing and acceleration are performed by RF electric fields in cavity resonators. The topic of "Beam Loading" denotes all the phenomena encompassed by "the cavity is driven by two current sources: (i) the generator and (ii) the beam". One attempts to control the beam using the generator components; but our ability to control the generator's effect is compromised by strong perturbations from the beam.

The longitudinal emittance and ellipse aspect ratio, and acceleration rate, dictates the voltage per turn. Qualitatively, the system follows demand values when the generator current is greater than the beam current component. If this ideal beam-load ratio ($I_g/I_b \gg 1$) is not possible, then compensation is required.

The range of "beam loading" phenomena includes: steady-state phase and amplitude shift of voltage due to reactive beam-component (compensated by detuning), periodic transients (if empty buckets), injection/accumulation transients, coupled-bunch instabilities (due to fundamental and HOMs), and power-limited (i.e. Robinson) instability. A review [1, 2] of theory and state-of-art applications was given at 7th ICFA Mini-Workshop held at KEK–Tanashi in February 1998. There was also some reporting [3] of phenomena at 9th ICFA Mini-Workshop held in Geneva. I shall speak about developments in three areas after the 1998 workshop.

- Introduction of Magnetic Alloy (e.g. Finemet) cores and adoption of low Q cavities.
- e^+e^- factories with very large beam current (e.g. KEKB, PEP II).
- Developments at p,p factories (e.g. LHC), and simulation codes.

The reason to include e^+e^- in a talk ostensibly about proton machines is that lepton machines represent the present beamload frontier. The territoy pioneered and conquered by e^+e^- will be settled by future hadron machines. One other development is worthy of mention: the decision of the neutron-source type machines (SNS, ESS, etc.) to adopt full energy injection via a SC linac into a storage ring; thereby avoiding many of the beamload problems of rapid cycling synchrotrons. This note is a precis of [4].

2. MA-loaded Cavities

Historically, booster-type proton synchrotrons have used low RF (say, < 100 MHz); and, in addition, the fast-cycling machines have desired high acceleration gradients. Often these machines have used long bunches to reduce space-charge effects. Low frequency structures are traditionally loaded with material of high relative permeability (such as ferrite) so as to shorten them (dramatically) compared with the free-space wavelength. At yet lower RF (say, < 10 MHz) micro-grained magnetic alloys have been considered as an alternative to ferrites since *circa* 1995. Impetus mostly from the JHF team [5, 6, 8, 10]. The advantages/disadvantages of these materials are tightly coupled, and listed as follows (in rough order of importance). Shunt resistance independent of RF flux density; small shunt resistance; high Curie temperature; longitudinally compact

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structures; tuner not required; variable quality factor; reduced coupled-bunch instability; less severe transient beam-loading; barrier bucket and multi-harmonic RF operation.

The shunt resistance of a coaxial resonator is given by $R_{\mathrm{shunt}} = \mathrm{length} \times \ln[OD/ID] \times \mu Q f$ where OD, ID denote outside,inside diameter. For FT3M (FineMet), when excited in the range of a few MHz, the product of permeability and quality factor and drive frequency, $\mu \times Q \times f$, remains constant up to high magnetic flux (2kGauss) whereas for Ni-Zn ferrites (e.g. 4M2, N5C, SY2) the product falls quickly for RF magnetic fields above 100 Gauss. Thus, much higher RF fields may be sustained leading to higher effective gradient. Finemet in the form of a amorphous metallic tape can be wound into a core over 1 m in diameter. C.f. $\ln(OD/ID)$ term in R_{shunt}. Contrarily, ferrite is ceramic in nature, is manufactured by baking in an oven and large cores are difficult to produce. The ≈ 10 times higher (than ferrite) relative permeability of MA may allow for even more compact structures. However, relative permeability of MA drops above 2 MHz, unless cut-cores are used.

Since the 1998 workshop there has been an explosion of MA-activity led by the JHF group; and several MA-cavities working in machines have demonstrated that both the high effective gradients and the large frequency swings are achievable. 1997 JHF: operated cavity with 10 kV, 30 kW, Q=0.6, R=83 ohm. 1998 JHF: bench tested Q=1, R/Q=600 ohm resonator. 1999 BNL AGS [7]: Barrier cavity with Q=0.6, R/Q=1500 ohm, $f_{\mathrm{res}} = 1$ MHz, 10kV/gap and 4 gaps developed total 40 kV. Employed 1-turn delay feedforward to compensate beam-induced voltages at three harmonics. HIMAC (PAC 99) accelerated light ions through a huge frequency change 1-8 MHz, with gradient 50 kV/m. HIMAC and the Wakasawan ERC have demonstrated dual harmonic.

There are definitely niches where the MA-loaded type of cavity has definite advantages over parallel biased ferrites, but their use is not a panacea. Given the coupling of benefits and detractions, careful anlaysis [11] has to be made for each particular application. For example, despite low RF, the lack of frequency swing led SNS to choose 4M2 ferrites for its dual harmonic RF [9]. It is dangerous to generalise, but it is the authors personal opinion that MA-loaded cavities are suited to low frequency applications involving: requirement for high effective gradient; large frequency swing; large beam load ratio, i.e. beam power dominates consumption; avoidance of coupled bunch instabilities. However, these benefits come at the cost of higher power (c.f. ferrites) and or requirement to compensate beam components by multi-harmonic feed-forward. Finally, do not forget *perpendicular bias* ferrite.

e^+e^- Colliders for factories

The B-Factory proposals (KEKB, PEP-II) date from *circa* 1992. These factory machines absolutely require beam-loading compensation, *and* Higher Order Mode (HOM) damping, *and* coupled-bunch feedbacks for their operation. There was significant R&D performed in 94-96 and preliminary commissioning of beams in July 1998. At the time of the 7th ICFA Mini-workshop, it was not known whether the very complex RF and F/B systems would deliver desired performance. (Though the CB feedbacks had been demonstrated at DAΦNE and ALS.) Beam currents approaching design values were achieved in 1999 (PEP-II) and 2000 (KEKB) [17, 18].

As a generality, KEKB has taken a strategy of passive measures (use of SC and ARES cavities) to combat the usual beamload problems, whereas PEP-II adopted active measures using multiple-level cavity feedbacks relying heavily on digital electronics. The full difficulty of setting up all the cavity loops, adjusting the group delays, nulling out the steady-state phase offsets of cables and of bunch positions (modulated by periodic transients) compared with references, can be appreciated from reading of [13]. The “datum” problems in “active measures” are also encountered in CB F/B [16]. No doubt, future e^+e^- ring-colliders will combine passive and active measures to attain yet higher beam current and luminosity. We take our list of *beam loading* topics from the review “RF Issues for High Intensity Factories” by K. Akai in EPAC 96. The topics are: (i) instability driven by the accelerating mode; (ii) bunch gap transients; (iii) NC versus SC cavities; (iv) high-power handling.

Detuning of the cavity for reactive beamload compensation automatically stabilizes the m=0 CB-mode. However, if the revolution frequency is comparable with the detuning, then low order CB-modes with large growth rates may be excited. There are two strategies to tame this instability. (1) Cavity with large stored energy. A super-conducting (SC) cavity operated at high voltage, e.g. KEKB SCC, or the normal conducting (NC) ARES: a 3-cavity system where an accelerating cavity is resonantly coupled with a large energy storage cavity operating in a high-Q mode, [12]. (2) A 1-turn delay comb filter feedback at revolution harmonics. e.g. PEP-II comb filter F/B gives up to 17dB impedance reduction across 30 harmonics.

A 5% gap is introduced into the bunch trains of PEP-II and KEKB. This periodic transient causes phase and amplitude modulation of the RF train. In KEKB, the problem is addressed with large stored energy by the use of SC and ARES cavities. A disadvantage of the ARES system is the need to tune 3 cavities and to adjust the coupling between them, which leads to quite complicated servo-loops and complicated tuning-dynamical response. In PEP-II, the modulation causes difficulty for the cavity feedbacks; the steady state offsets must be rejected. The gap-voltage feed-forward module [14], a master-piece of control engineering, generates reference phases (using a DSP) without which the direct vector feedback would drive the klystron into saturation.

Severity of many beam-loading effects is proportional to $(I_b/V)(R/Q)$. One usually favours low R/Q. High Q implies large stored energy. Large R means that both beam and generator could induce large voltages. However, R/Q is not the whole story, voltage V is also relevant. SC cavities typically have high R/Q *and* can sustain very high field gradients allowing large gap voltages. The large stored energy reduces the effects of transients, allows one to use few cavities and lower the machine impedance. Further, operation with large voltages leads to $I_g \gg I_b$. The KEKB SCC has $Q = 8.9 \times 10^4$, R=8.3 Mohm, and power coupler rated at 500 kW. The low Q, c.f. conventional SC cavities, eases required tuning precision.

The beamload ratio is reduced when there are a small number of cavities with large voltages. Thus, each cavity should provide several hundred kW of beam power. This challenges the thermal and electrical performance of input couplers, RF windows, etc., and also the junction between cavity and HOM waveguides, and the absorbers. Despite successes, this is an area where more R&D is still needed (see H. Padamse [15]).

3. Transient compensation in LHC

Although injection and periodic transient beam-loading is still the dominant factor in the design of the LHC RF systems, plans have changed from the 1995 “Yellow Book” description [19]. Because the bunch emittance and phasing will be inferior to values presumed in 1995, the scheme has grown to accomodate a greater effort in correcting injection/transfer errors [20, 21, 22]. Uncertainty of the LHC injection field due to “snap back” leads to energy errors up to 50 MeV. SPS-LHC synchronization will have a residual static error of $\approx 15^\circ$ at 400 MHz. Because of the long gap (70%), periodic transient beam-loading across the SPS batch leads to a dynamical phase error from head to tail of the batch. A similar effect occurs in the LHC. Furthermore, as additional SPS batches are added to LHC the transient voltage patterns will change regularly. The worst case error is anticipated to be $\approx 15^\circ$ at 400 MHz. Grossly simplified, the present strategy is to accept the 200 MHz SPS bunches into 200 MHz combined-capture-damper buckets in the LHC before adiabatic transformation to 400 MHz.

SPS (for LHC) will use four 200 MHz travelling wave NC cavities for acceleration, delivering bunches of emittance 1 eV.sec. Beam current RF component 1.2 A leads to significant beamload; a factor 10 reduction in severity is accomplished by combination of feedback of V_g and feedforward of I_b. LHC will use four (per beam) 400 MHz single-cell single-mode super-conducting (SC) cavities each capable of 2 MV/gap for acceleration. The high stored energy of SC cavity reduces the effect of transient beamloading by an order of magnitude compared with a NC cavity. Direct vector F/B of the gap voltage is used to reduce the apparent impedance of the fundamental mode. Further, 1-turn delay feedback reduces the impedance at revolution harmonics. Due to the lengthy beam-gap, the cavities will be “half-angle detuned” to minimize power.

Four NC single-cell multi-mode 200 MHz standing wave cavities will be used in the LHC to capture and damp the injected bunches. 0.75 MV per cavity is used for acceptance and 25 kV is used for damping. The cavity is optimised for the accelerating mode. Compensation of reactive beamloading is by half-angle detuning. The cavities have direct vector feedback (gain=8) of the gap voltage, supplemented with a 1-turn delay comb-filter feedback (gain of 32) which further reduces the impedance. The LHC 200 MHz cavities must damp the static m=0 mode phase error at injection and reduce the dynamical error across each batch to acceptable levels before filamentation causes significant longitudinal emittance increase. The LHC 400 MHz system is used to linearize the applied RF waveform, allowing the feedback to do useful work for up to 3000 turns.

In the subsequent 1000 turns, the 400 MHz is ramped to 8 MV/beam, and during a further 1000 turns, the 200 MHz capture system is ramped to zero. The LHC 200 and 400 MHz sub-systems are operated under various conditions during different stages of an LHC fill. Both sub-systems strongly interact with the beam and are thus coupled together. A simulation program has been written by J. Tückmantel to evaluate in the behaviour of the LHC RF [20, 23]. This offers the possibility of runing "machine development studies" to examine many parameters and to find the best settings and the limits of the system. The author wishes to thank Tückmantel for permission to show a QuickTime movie of the LHC injection process, as excerpted from [22].

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