Coasting Beam Instability Calculations for the MEIC Proton Ring

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This note is a rough set of calculations for MEIC hadron collider ring coasting beam instabilities. The intent is to establish order of magnitude (or better) requirements for momentum spread and longitudinal impedance for beam stability as inputs to detailed evaluation of hadron beam high-frequency bunch formation.

1 Background

The current baseline design for MEIC as of January 2015 calls for rebucketing of beams in the hadron collider ring from a "low-frequency" $h = 9$ acceleration system ($f_{\mathrm{RF}} \approx 1.25$ MHz) to a "high frequency" $h = 6832$ collision system ($f_{\mathrm{R}F} \approx 952.6$ MHz) (Table 10.1 of [1]). The baseline approach described in that document and others is a debunch/rebunch scheme [2], in which the beam is adiabatically debunched from the low-frequency RF and adiabatically (or quasi-adiabatically) recaptured in the high-frequency RF.

Longitudinal coasting beam stability criteria are well-described in the literature. This note evaluates the proposed MEIC coasting beam that occurs in a debunch/rebunch scenario against these criteria to develop rough, order-of-magnitude requirements for this coasting beam stability. Since the collider cooling system is designed for bunched beam [1], this note assumes that no cooling is available during the debunch/rebunch process; other studies including 952.6 MHz bunched-beam cooling in the context of rebucketing without coasting beam are not examined here.

This note does not consider the issues of beam loading of the RF system during the debunch/rebunch, which has created problems for several other facilities attempting a debunch/rebunch scheme (e.g. CERN PS, BNL AGS). Beam loading is inversely proportional to the applied RF voltage, and RF control issues must be investigated to ensure that they can address the expected beam loading of a 0.5 A design MEIC ion beam.

It should also be noted that a debunch/rebunch scheme for the MEIC collider ring will likely have to include a barrier bucket to maintain an abort gap, since the total stored energy of the 0.5 A hadron beam (3.6×10^5 J at 100 GeV) is likely enough to create substantial damage in the superferric magnets if not aborted properly. The impact of a barrier bucket on these coasting beam calculations is likely to be small since the stability criteria used here are generally applicable for a quasi-coasting beam that is much longer than its abort gap.

2 Negative Mass/Microwave Instability

An early derivation of coasting beam instability criterion against the negative mass instability was provided by Neil and Sessler, Eq. (4.19) of [3].

$$\Delta\omega_s > 2\sqrt{2\pi\left(f\frac{df}{dE}\right)\left(\frac{Ne^2}{R\gamma^2}\right)\left(2\ln\frac{b}{a}+1\right)} \tag{2.1}$$

A similar derivation by Chao derives the negative mass instability stability requirement for a synchrotron in Eq. (5.129) of [4]:

$$\frac{\Delta\omega}{\bar{\omega}_0} > \sqrt{\frac{N r_0 \eta}{\gamma^3 C}\left(2\ln\frac{b}{a}+1\right)} \tag{2.2}$$

where N is the total number of particles in the coasting beam, r_0 is the classical radius of the beam particle (here protons), C is the circumference of the synchrotron, and b/a is the ratio of the average beampipe size to beam RMS size. This criterion is derived for a beam with a Lorentz spectrum, which is typical of a debunched Gaussian beam, and provides a criterion for Landau damping of this instability by a spread in longitudinal revolution frequency.

From [1], we have

$$\begin{aligned}
I = 0.5\,\mathrm{A} \qquad f_{\mathrm{rev}} = 139.19\,\mathrm{kHz} \qquad &\Rightarrow & N &= 2.24\times 10^{13} & (2.3)\\
&& C &= 2153.89\,\mathrm{m} & (2.4)\\
&& r_0 &= 1.231\times 10^{-15}\,\mathrm{m} & (2.5)\\
\gamma_{\mathrm{T}} = 12.46 \qquad \gamma = 106.579 \qquad &\Rightarrow & \eta &= \frac{1}{\gamma_{\mathrm{T}}^2}-\frac{1}{\gamma^2} = 6.35\times 10^{-3} & (2.6)\\
\frac{b}{a}\approx 40 \qquad &\Rightarrow & \left(1+2\ln\frac{b}{a}\right) &= 8.4 & (2.7)
\end{aligned}$$

Performing this calculation gives

$$\frac{\Delta\omega}{\bar{\omega}_0} > 7.5\times 10^{-7} \tag{2.8}$$

Assuming this frequency spread is entirely from a spread of revolution frequencies of a coasting beam gives a momentum spread (σ_{p}/p) criterion for stability against the negative mass/microwave instability:

$$\frac{\sigma_{\mathrm{p}}}{p} = \frac{\Delta\omega}{|\eta|\bar{\omega}_0} > 1.2\times 10^{-4} \tag{2.9}$$

Though it may look reasonable at first when one is used to momentum spreads of longitudinally focused beams, this is a concerning value. A coasting beam of this momentum spread in the full MEIC ring ($T_{\mathrm{rev}} = 7.18\ \mu$s) has a longitudinal emittance of about 86 eV-s, nearly two orders of magnitude larger than longitudinal emittance measurements of RHIC ions at a similar energy in 2011-14 [5] of order 1 eV-s.

3 Keil-Schnell Transverse Coasting Instabilities

The Keil-Schnell criterion is a reasonably simplified analysis of the stability of a coasting beam interacting with the longitudinal impedance $Z_{\|}$ of the accelerator. The treatment in [4] is a bit cumbersome; for computational simplicity I use the result quoted in Eq. (1) of Schnell [6],

$$\frac{|Z_{\|}|}{n} < F\frac{\beta^2\gamma E_0}{e}\frac{|\eta|}{I}\left(\frac{\sigma_{\mathrm{p}}}{p}\right)^2 \tag{3.10}$$

Here F is a form factor of order 1 (indeed, it is equal to 1 for Gaussian beams), E_0 is the beam energy, I is the total beam current, and e is the proton charge.

From [1], we have

$$\begin{aligned}
&& E_0 &= 100\,\mathrm{GeV} & (3.11)\\
&& I &= 0.5\,\mathrm{A} & (3.12)\\
\gamma_{\mathrm{T}} = 12.46 \qquad \gamma = 106.579 \qquad &\Rightarrow & \eta &= \frac{1}{\gamma_{\mathrm{T}}^2}-\frac{1}{\gamma^2} = 6.35\times 10^{-3} & (3.13)\\
&& \left(\frac{\sigma_{\mathrm{p}}}{p}\right) &\approx 1.2\times 10^{-4} & (3.14)
\end{aligned}$$

where the momentum spread is taken as a lower bound from the previous result. Combining these gives

$$\frac{|Z_{\parallel}|}{n} < 18\ \Omega \tag{3.15}$$

This is a more reasonable result. For example, recent measurements of longitudinal impedances in the RHIC rings [7] gave impedances in the RHIC rings of

$$\frac{|Z_{\parallel}|}{n} \approx 1.5 - 5.5\ \Omega \quad \text{(RHIC)}$$

However it should be noted that this is only an order of magnitude difference between these simple calculations, and the calculation of the MEIC impedance requirement depended on a large coasting beam momentum spread. Hence careful longitudinal impedance management will be necessary if a rebunching scheme is investigated that lowers momentum spread by more than a factor of $\approx$3.

4 Conclusions

This note presents some fairly straightforward evaluations of coasting beam instability thresholds for MEIC collider hadron beams, based on simplified criteria. These evaluations indicate concerns over required momentum spread and longitudinal emittance for the current baseline scheme of debunch/rebunch, driven by negative mass instability. More detailed calculations and simulations should be done in the future to evaluate alternative rebucketing scenarios (perhaps avoiding coasting beams entirely), evaluate the impacts of barrier buckets on potential coasting beam instabilities, and evaluate the impacts of beam loading on RF controls for this scenario.

References

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[7] M. Blaskiewicz, J.M. Brennan, and K. Mernick, "Longitudinal Impedance of RHIC", MOPMN020, Proc. of IPAC'15, 2015.