Intensity effects for mu2e project

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Stable operation of the Accumulator and Debuncher rings has been established during many years of the Pbar source operation. Most of the beam physics issues have been understood and addressed. In this chapter we discuss high intensity effects that are new to these machines. Since the time of original experiment proposal [1] the beam delivery scenario has been improved, substantially reducing the intensity of the circulating beams. However, intensity effects still need to be specially considered.

Beam stability is analyzed for the following set of parameters in the Accumulator and Debuncher:

	Accumulator	Debuncher
Number of protons	1.2E13 (3×4E12 coasting)	3E12
Number of bunches	4	1
Bunch length, rms	40 ns	40 ns
Energy spread, rms	25 MeV (3×1.8 MeV coasting)	25 MeV
Slippage factor	0.014	0.006
Emittance, normalized, 95%	20 π mm mrad	20 π mm mrad
Duration	480 ms	160 ms
Synchrotron tune	5.0E-4	1.1E-4
Max space charge tune shift	0.01	0.01

Incoherent space charge tune shift is one of the main parameters governing the transverse beam stability. For a Gaussian bunch, its maximal value can be expressed as

$$Q_{\mathrm{sc}} = \frac{N_b r_p T_{.0}}{2(2\pi)^{3/2}\gamma^2 \varepsilon_n \tau_b},$$

with N_b as the bunch population, r_p as the classical proton radius, T_0 as the revolution time, γ as the relativistic factor, ε_n as the normalized rms emittance and τ_b as the rms bunch lengh in time units. For the specified parameters, it gives $Q_{\mathrm{sc}} = 0.02$. This assumes that the beam is round and its size is dominated by the betatron oscillations. Given dominant dispersive contribution in the arcs, actual tune shift is about factor of 2 lower in the both machines. Increased footprint of the beam in the tune space sets limitations on the choice of the operation point.

Transverse stability of a single bunch in the Accumulator and the Debuncher rings for mu2e requires space charge to be taken into account: as it is clear for the table above, the space charge tune shift significantly exceeds the synchrotron tune for the both machines. For zero chromaticity, the bunch is stable up to the transverse mode coupling instability (TMCI) threshold. According to Ref. [4], for the resistive wake in a round chamber with conductivity σ and radius b, this happens at

$$K \equiv \frac{N_b r_p \beta_x R_0 Q_{\mathrm{sc}} \eta_{\mathrm{occ}}}{4\pi^2 \gamma Q_s^2 b^3 \sqrt{\sigma \tau_b}} \approx 100$$

With the average beta-function β_x=12 m, σ=1.3E16 s^{-1}, taking into account that the main contribution to the impedance goes from the dipole area occupying $\eta_{\mathrm{occ}} = 0.25$ of the entire circumference, with the vertical aperture b=2.6 cm (the remaining 75% of the ring is a round chamber with 6.4 cm radius), this yields K≈2 (Accumulator) and K≈10 (Debuncher), significantly smaller than the threshold value. Thus, under the specified parameters, the beam should be well below the TMCI onset.

If the chromaticity is not zero, weak head tail instability may be possible. Does the resistive head-tail instability allow arbitrary chromaticity? Maximal growth rate of the weak head-tail instability is given by [4]:

$$\Gamma T_0 = 0.1 \frac{N_b r_p \beta_x R_0 \eta_{\mathrm{occ}}}{\pi \gamma b^3 \sqrt{\sigma \tau_b}} \ \ [\mathrm{turn}^{-1}]$$

This yields $\Gamma T_0 N_t$ =1 for the Debuncher, so the weak head tail should not be an issue there. A small chromaticity may need to be introduced in the Accumulator, as for the last bunch the growth rate condition reaches $\Gamma T_0 N_t$ =3.

As for the electron cloud, the bunch is too short and zero-current time is too long for any visible cloud to be built [3].

Without feedbacks in RF cavities, the coasting beam in the Accumulator would be unstable against longitudinal instabilities on the fundamental harmonics in 2.5 and 53 MHz cavities. Assuming shunt impedance Z/n=1 kOhm for the both of them, it yields that the current is 20 times higher Keil-Schnell threshold. The growth times are calculated as 0.5 ms for 53 MHz and 10 ms for 2.5 MHz cavities. However, the active feedback is supposed to be effective for 2.5 MHz cavities, which should preclude the longitudinal instability at that frequency. Special care is needed for stability at 53 MHz.

The bunched beam should not be affected by the space charge or resistive wall longitudinal impedances. The space charge synchrotron tune shift is estimated as small as ~ 1% of the synchrotron tune itself, while for the resistive wall tune shift this number is even smaller.

The coasting beam stage in the Accumulator is stable against the longitudinal microwave instability when (see e. g. Ref.[5], Eq. (5.133)):

$$\frac{N_c r_p \ln(b/\sigma_\perp)}{C_0 \eta \gamma^3 \sigma_p^2} \le 1 .$$

Here $N_c = 4 \cdot 10^{12}$ is the number of particles in a single coasting beam, $\sigma_\perp$ is the transverse beam size, C_0 is the ring circumference and σ_p is the relative rms momentum spread. For the given parameters, the beam intensity is an order of magnitude below this threshold.

Analysis of the IBS shows that it is too slow to be seen for rather short time of the beam existence.

[1] Proposal to Search for muN->eN with a Single Event Sensitivity Below 1.0e-16, mu2e Collaboration. Mu2e document 388.
[2] C. Bhat, Mu2e Document 797, with recent revisions by S.Werkema.
[3] K. Y. Ng, FERMILAB-CONF-09-128-AD .
[4] A. Burov, Phys. Rev. ST Accel. Beams 12, 044202 (2009).
[5] A. Chao, “Physics of collective beam instabilities in high energy accelerators”, 1993.