SELECTIVE RESONANT EXTRACTION FROM THE FERMILAB MAIN INJECTOR USING ELECTRON LENS

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Abstract

We propose to use an electron lens for slow extraction of proton bunches from the Fermilab Main Injector. Negatively charged electron beam colliding with protons causes positive tune shift proportional to the electron current. If the resulting tune satisfies resonance condition, protons move to larger betatron amplitudes as in conventional slow extraction systems. Time variation of the electron current allows slow extraction from particular batches or even slow extraction from a single bunch.

1 INTRODUCTION

The Main Injector at Fermilab [1] is designed to provide beams to many areas, including the Tevatron collider, antiproton production, fixed target experiments. It is possible to extract the beam from a portion of the Main Injector (MI) circumference using fast (single turn) extraction and then extract slowly (with resonant extraction) the remaining beam. It some scenarios it is useful to invert the order, namely, to use slow extraction on a portion of the circumference while retaining some of the beam for later extraction. This scenario can become a reality if a high bandwidth quadrupole (risetime much less than a turn) is available. An electron lens provides a suitable technology for this application.

The first operational electron lens has been installed in the Tevatron collider for the purpose of compensation of beam-beam effects. The TEL (Tevatron Electron Lens) with 3A current of some 8 kV electrons has shifted the betatron tune of a selected 980 GeV proton bunch (bunch spacing is 400 ns) by dQ=+0.007 [2] – in a good agreement with theory.

2 MAIN INJECTOR ELECTRON LENS

Standard way of the resonant extraction in the MI employs two families of magnets. Octupole magnets distributed around the ring introduce an amplitude dependent tune spread into the 150 GeV proton beam $dQ \propto x^2$. Particles with large betatron amplitudes have tunes closer to half-integer resonance of 26.5 than those of small amplitude. Consequently, the phase space splits into stable and unstable areas, thereby providing a means for manipulating the extraction rate through control of the stable region in the phase space. Slow extraction from the MI proceeds as follows. The horizontal tune is raised towards the half-integer from its unperturbed value of Q_x=26.425 to 26.485 using a family of quadrupole magnets. The strength of the octupoles is chosen such that the stable phase space area equals to the emittance of the circulating beam $\varepsilon_N \approx 20\pi$ mm mrad (95% normalized emittance). The proton beam is just marginally stable staying just ΔQ=0.015 from the resonance. Finally, in the standard procedure, quadrupole magnets shift the tune onto the resonance and, thus, the slow extraction takes place.

If an electron lens is used to make the final tune shift of ΔQ=0.015, then its current can be easily modulated in such manner, that the resonant extraction would occur only from particular batch(es) of proton bunches. In different operational modes, the MI accelerates 4 to 6 batches of 84 proton bunches from 8 GeV to 150 GeV with the cycle period of 1.5s to 4s. The bunch spacing is 19 ns, so the duration of one batch is about 1.6 µs. Batches are separated by 532 ns gaps (28 bunches). Therefore, the electron current in the ELMI (Electron Lens for Main Injector) should have following waveform: less than 532 ns risetime, at least 1.6µs of the flat top (maximum current) and shorter then 532 ns fall time. The ELMI must act on the choosen batch every turn (revolution frequency f_o=88 kHz) for few seconds required for the slow extractions. Let’s consider the electron beam parameters in detail.

According to [3], a perfectly steered round electron beam with a constant current density distribution will shift the proton betatron tune by:

$$dQ_{x,y} = +\frac{\beta_{x,y}}{2\pi}\cdot\frac{1+\beta_e}{\beta_e}\cdot\frac{J_e L_e r_p}{e\cdot c\cdot a_e^2\cdot\gamma_p} \tag{1}$$

where the sign + reflects focusing effects, $\beta_e = v_e/c$ is the electron beam velocity, β_X=60 m and β_Y=28 m are beta functions at the location of the lens (we take typical values in the 15 m long MI straight sections), a_e , J_e and L_e stand for the electron beam size, current and effective interaction length, r_p is the classical proton radius, γ_p=160 is relativistic Lorents factor for 150 GeV protons. Factor (1+β_e) reflects the fact that when electron beam collides with the protons – the direction which requires less electron current for the same dQ – the magnetic focusing *adds* to the stronger electric focusing force. In order to have the same tune shift for more than 99% protons, the electron beam radius has to be at least three times the rms proton beam size

$$a_e = 3\sigma_x \tag{2}$$

that is 3*1.1=3.3 [mm] - for $\varepsilon_N \approx 20\pi$ mm mrad and β_X=60m. The maximum current of the electron beam with such radius is limited by space-charge deceleration in the beam pipe, and for 70 mm diameter beam pipe it depends

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on the electron beam energy as J_e =4.4[μA/V$^{3/2}$] $U_e^{3/2}$. Thus, requesting dQ_x=+0.015 we immediately get from Eq.(1) the following approximate equation for the minimum required electron beam energy:

$$U_e\ [\text{kV}] \approx 1.7\varepsilon_N[\pi\ \text{mm mrad}]/\ L_e[\text{m}] \qquad (3)$$

For example, taking comfortable values of L_e[m]=3.5 m and $\varepsilon_N \approx 20\pi$ mm mrad one gets electron beam energy of U_e =10 kV and peak electron current required (and allowed) J_e =4.4A. These electron beam parameters are very close to the Tevatron Electron Lens [2] which is depicted in Fig.1. As we know from the TEL experience, a convex thermionic cathode with 2a_c =10 mm diameter can provide such a current [4]. A 10 kV HV pulser based on RF tetrode similar to described in [5] can be used for modulation of the electron gun anode voltage (and, consequently, the electron current) with as fast as 400 ns rise/fall time.

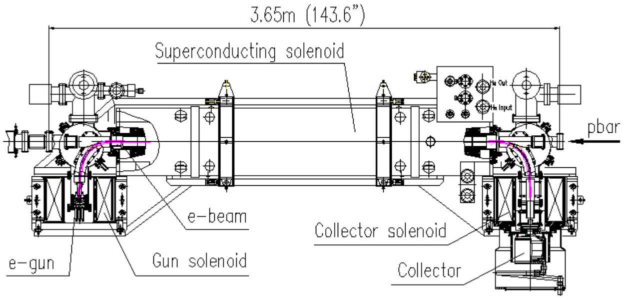

Figure 1: Layout of the Tevatron Electron Lens [1], similar to the proposed Electron Lens for Main Injector.

The electron beam in the ELMI will be strongly magnetized and follow the magnetic field line from the gun to the electron beam collector. The beam size in the main solenoid is defined by condition Eq.(2), therefore, if the cathode radius a_c =5mm is chosen to provide the needed current, then the ratio of the magnetic fields in the gun and main solenoid comes from adiabaticity condition:

$$B_{Main} / B_{Gun} = [a_c / a_e]^2 \qquad (4)$$

For the given current density at the cathode one needs B_{Gun} =2-3 kG, thus, from (4) one gets B_{Main} =4.5-7 kG. Using beam dynamics analysis as in [3], one finds that such field strength is more than enough to avoid the Transverse Mode Coupling Instability in the proton beam due to electrons, to have a minimal electron beam distortions due to interaction with elliptic proton beam and introduce a very minimal coupling due to the electron current. Because of a larger electron beam size, the magnetic field straightness requirement is very loose – some 0.3 mm rms field line deviation over 3.5 m length of the interaction region. Another simplification compared to the TEL is that the current stability tolerance is also very loose - even 2% fluctuations on the turn to turn time scale would not cause a significant emittance growth over the few seconds of the ELMI operation. The electron gun and collector can be copied from the TEL design [4].

The field in the main solenoid of ELMI is much less than the maximum field of 65 kG in the TEL main SC solenoid [6]. There are two equally feasible options: to build the main solenoid of water cooled copper conductor or make it of SC wire and use locally operated cryogen free cryocoolers [7]. The gun and collector solenoids for the ELMI can be made the same as for the TEL.

Finally, we compare parameters of the ELMI and the TEL in Table 1

Table 1: Main parameters of ELMI vs TEL

	ELMI	TEL
electron beam energy, kV	10	6-12
maximum peak electron current, A	4.4	2-3.5
repetition rate, kHz	88	48
magnetic field in main solenoid, kG	7	35
in gun solenoid, kG	3	3.7
e-beam radius in main solenoid, mm	3.3	1.75
cathode radius, mm	5	5
e-pulse risetime, ns	~500	~400
current stability, peak-to-peak, %	<2	< 0.1
effective interaction length, m	3.5	2.0
rms *B*-field line straightness, mm	0.3	0.05
valve-to-valve length, m	5.4	3.65

3 CONCLUSION

We have considered the electron lens with current modulation for the slow resonant extraction from a portion of the 150 GeV MI proton beam. We have found that the lens for one batch extraction is feasible, and even less demanding in design and operation parameters than the Tevatron Electron Lens, which has been recently successfully tested at Fermilab. A single bunch resonant extraction from the MI is also possible, though it would require more powerful high voltage pulser - 40 kV 20ns pulse width and 88 kHz repetition rate - high-voltage which is still quite feasible technically.

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4 REFERENCES

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