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5. Beam intensity, polarization, collective effects

R&D and risk factors

Technical risk: 1

Polarized proton beam parameters needed for injection into EDM ring are close to what is presently available from Booster/AGS. Increase of polarization to 90% is expected within the next few years after source upgrade, while 80-85% is available already. Needed transverse emittance is significantly smaller than presently available but due to very small needed bunch intensity required small emittance may be produced with scraping. An experimental study at AGS injection to verify what values of emittance could be achieved is needed. A careful RF manipulation in the EDM ring will be needed to preserve small longitudinal momentum spread within the beam.

Level of effort: A

As design of the ring and lattice progresses, careful beam dynamics estimates of various effects and some simulations will be needed.

Beam parameters

For present parameters of EDM Ring it is desired to have small horizontal beam size in the location of the plates. Presently, full distance between the plates is 20 mm. Ring lattice is presently under development. For this report we assume June 2009 version of the lattice. For maximum dispersion function of D_x=3.88 m, rms momentum spread 2.5e-4, maximum horizontal beta function of β_h=20m, and emittance of 3 mm mrad (95%, unnormalized), horizontal rms beam size is 3.3 mm. The horizontal aperture between the plates can thus accommodate 3 σ of the beam. Such transverse acceptance may be sufficient for beam injection from the AGS. Required beam lifetime in EDM ring is relatively short since the beam will be constantly lost on the target as part of the experiment. As a result, requirement on maximum allowed horizontal emittance of the beam is 3 μm (95%, unnormalized), which corresponds to 2.2 μm (95%, normalized) for this energy. The values of normalized emittance are obtained by multiplication of unnormalized value by the relativistic factor $\beta\gamma$.

Booster ring will be used to prepare required bunches for transport in the EDM ring. These bunches will be then transported through the AGS with AGS being used simply as transport channel. Required kinetic energy for protons is 232 MeV which is slightly above present injection energy in the Booster, which is 200 MeV. At such energy expected polarization is given by the source performance and is presently 80-85%. After planned upgrade of the source in 2012, it is expected that polarization will be increased to about 90%.

Beam parameters needed for injection into EDM ring are:
Single bunch intensity: 1e10
Horizontal emittance (95%, normalized): 2 mm mrad
Vertical emittance (95%, normalized): 7 mm mrad
Rms momentum spread: 2.5e-4

Presently available beam parameters from Booster:
Bunch intensity: 2e11
Transverse emittances: 5-6 mm mrad
Rms momentum spread: 5e-4

Available horizontal emittance from the Booster is factor of 3 larger than needed for the EDM ring. However, as will be explained later, maximum allowable intensity in single bunch due to collective effects in EDM ring is about one order of magnitude smaller. Thus, Booster will be used to collimate bunches to the required emittance of 2 μm (95%, normalized). Momentum spread will be also reduced to required value at the expense of beam intensity. This seems to be doable since we are allowed to loose about factor of 20 in single bunch intensity. Experimental verification would be useful to understand what emittance will be possible to achieve for different bunch intensities in the Booster. If needed, as it was studied in the past, electron cooling of proton bunches in EDM ring prior to the start of experiment can be done as well. However, we presently do not anticipate the need for cooling since required beam parameters can be produced by scraping.

After long bunches of necessary intensity, emittance and momentum spread will be prepared in the Booster, they will be transported through the AGS ring and injected in the EDM ring. Bunches in the EDM ring will be captured either by barrier bucket RF or by low-frequency RF system. To produce high values of synchrotron tune bunches will be then captured adiabatically into the high frequency RF. At the start of the experiment there will be 50 short bunches rotating CW and 50 short bunches rotating CCW. Individual bunch intensity is presently 2×10^8 or the total intensity of 100 bunches 2×10^{10}.

At the start of the experiment in EDM ring desired parameters of an individual bunch are given in Table 5.1. However, some increase in momentum spread due to adiabatic capture in high-frequency RF is expected which will be taken into account. For example, initial momentum spread of bunch from the Booster can be made smaller to account for momentum increase due to adiabatic capture in the EDM ring.

Table 5.1 Needed parameters of single bunch in EDM ring with high-frequency RF.

Z	1
A	1
γ	1.25
β	0.598
N, intensity in single bunch	2×10^8
Rms momentum spread dp/p	0.00025
Rms bunch length, m	0.4
Horizontal emittance (unnormalized, 95%), μm	3
Vertical emittance (unnormalized, 95%), μm	10

Space-charge tune shift

Space charge is the simplest and most fundamental of the collective effects. The charge and current of the beam create self-fields and image fields due to beam surroundings which alter beam dynamics. The direct space charge leads to defocusing in either plane. Thus particles within the beam will experience lowering of their betatron tune $Q_{x,y}$ by ΔQ. Such tune-shift for individual particles is also called incoherent tune-shift. For a beam with non-uniform density distribution such defocusing becomes betatron-amplitude dependent. The small-amplitude particles have the largest tune shift.

For a Gaussian transverse and longitudinal distribution, maximum incoherent tune shift due to space charge self-fields in a bunched beam can be estimated using the following formula:

$$\Delta Q_{x,y} = -\frac{3N_b Z^2 r_p}{\pi A \beta^2 \gamma^3} \frac{1}{\varepsilon_{x,y}\left(1+\sqrt{\dfrac{\varepsilon_{y,x} Q_x}{\varepsilon_{x,y} Q_y}}\right)} \frac{C_r}{\sqrt{2\pi}\sigma_s},$$

where N_b is the number of particles per bunch; Z and A are the charge and atomic mass of ion, r_p is the classical radius of particle, $\varepsilon_{x,y}$ are 95% unnormalized horizontal and vertical emittances, σ_s is the rms bunch length, $Q_{x,y}$ are the horizontal and vertical tunes of the ring, and C_r is ring circumference.

For beam parameters given in Table 5.1 and present ring circumference of 240m horizontal and vertical tune shifts are 0.012 and 0.007, respectively. Such space-charge tune shifts can be considered small for beam lifetime of 100-1000 sec needed for the EDM experiment. Note that even with an equal beam emittance and thus round beam cross section, space-charge tune shift is still sufficiently small.

Fields from the beam are modified by the beam surrounding represented by vacuum chamber, etc. and act back on the beam. This influences the motion of the individual particles (incoherent effect) as well as of the beam as a whole (coherent). The simplest effect is again the influence on betatron tunes, and is typically referred to as an effect of images. This results in correction to the incoherent tune shift due to self-fields given above as well as introduces tune shift of coherent betatron oscillation. For beam parameters in Table 5.1, correction to the incoherent tune shift due to images is negligible compared to the direct self-field contribution. The coherent tune shift due to images is comparable in magnitude to the incoherent correction due to the images, which is small.

Intra-beam scattering

Charged particles within the beam can scatter via Coulomb collisions. In general, one can distinguish large-angle single scattering events and multiple small-angle scattering events. When scattering angles are sufficiently small, addition at random of such collisions causes beam dimensions to grow. In accelerator community, this effect of small-angle multiple Coulomb collisions is called Intra-Beam Scattering (IBS). The growth rates of beam dimensions are linearly proportional to the phases-space density of beam distribution. Thus, setting limits on beam emittances and having requirement on needed beam lifetime due to IBS, provides the limit on maximum number of particles in the bunch.

IBS simulations were performed using the BETACOOL code. We used the Martini's model of IBS. In the future, we will benchmark it vs. Bjorken-Mtingwa model and will explore accuracy of these models for such non-relativistic energies. Resulted acceptable single bunch intensity is about 2×10^8. In simulations we used the lattice of pEDM ring shown in Fig. 5.1 and beam parameters from Table 5.1.

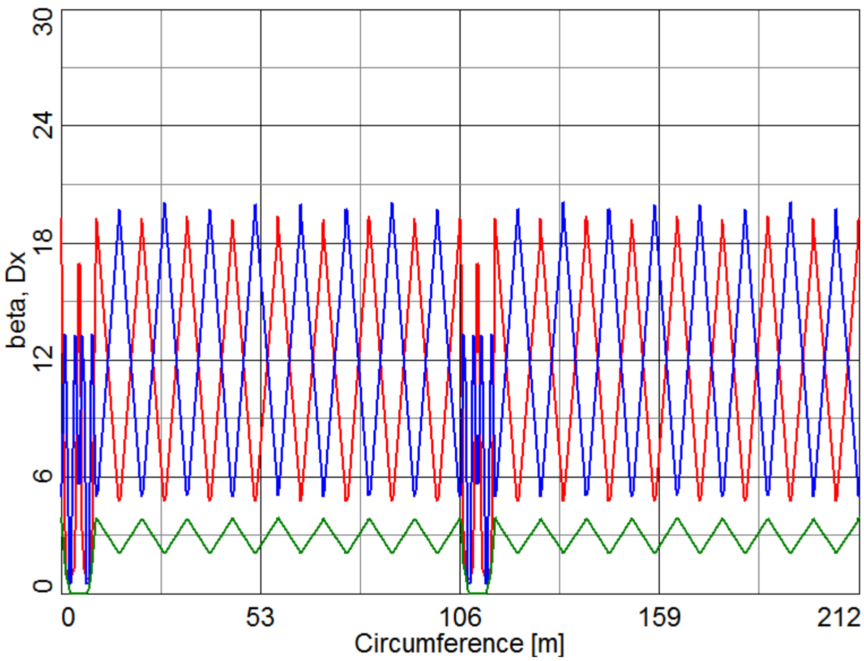

Figure 5.1 Lattice of pEDM ring used in IBS simulations. Blue and red are horizontal and vertical beta functions; green – dispersion function.

At present, exact RF voltage needed is under discussion. Smaller RF voltage results in bunch which fills in RF bucket completely, which in turn results is a significant initial intensity loss from the RF bucket. Higher RF voltage will result in shorter bunches but this in turn will result in stronger space charge and IBS growth rates, as well as it will result in larger synchrotron tune. When lattice for new ring is optimized, IBS simulations will be done taking into account optimization of RF voltage and losses from the RF bucket. Here results of IBS simulations are shown for older (June 2009) version of the lattice and small RF voltage which corresponds to the rms bunch length of 40 cm and rms momentum spread of 2.5e-4. In simulations shown, the only beam loss which was included was loss on the target with the beam lifetime of 500 sec. The corresponding loss of bunch intensity during storage in EDM ring is shown in Fig. 5.2.

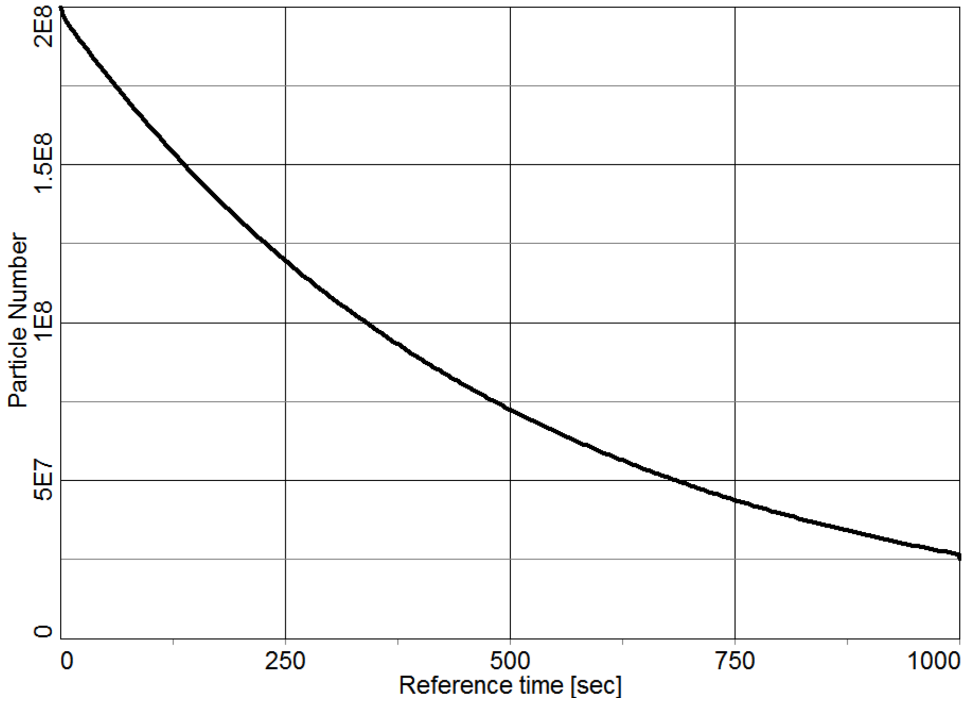

Figure 5.2. Bunch intensity due to loss on target with 500 sec beam lifetime.

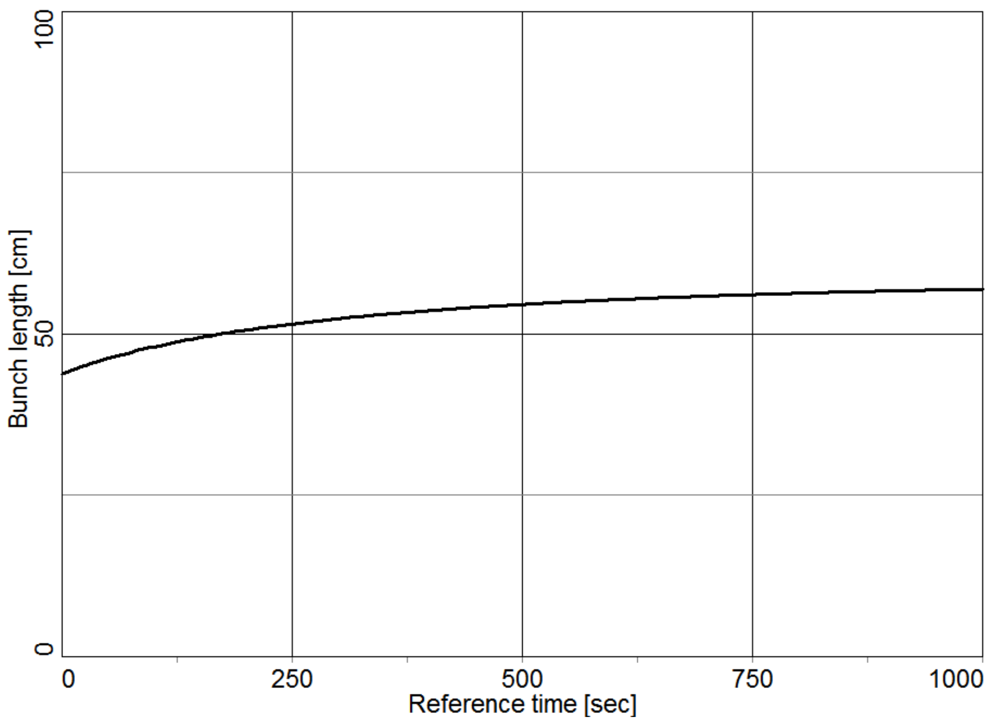

Figure 5.3. RMS bunch length growth due to IBS.

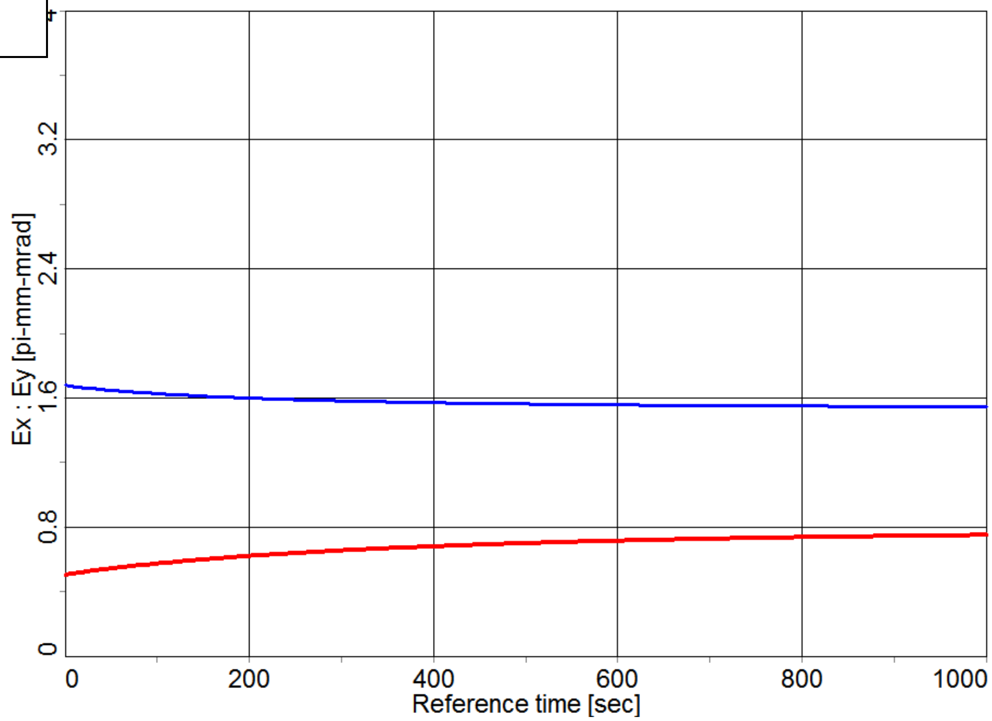

Figure 5.4. Evolution of horizontal (red) and vertical (blue) rms unnormalized emittances due to IBS (95% emittance=6×rms emittance).