BLOW-UP DUE TO INTRA BEAM SCATTERING DURING DECELERATION IN ELENA

C. Carli, M. Martini, CERN, Geneva, Switzerland

Abstract

Intra Beam Scattering (IBS) is expected to be the main performance limitation of the Extra Low Energy Antiproton ring (ELENA), a small synchrotron equipped with electron cooling under construction at CERN to decelerate antiprotons from 5.3 MeV to 100 keV. Thus, the duration of the ramps must not be too long to avoid excessive blow up due to IBS. On the other hand, the bending magnets are C-shaped and the vacuum chambers are without insulated junctions, which are difficult for fully baked machines; thus, the ramps must not be too short. The evolution of transverse and longitudinal emittances along the ramps have been estimated assuming that IBS is the main phenomenon leading to blow-up. The blow-up due to IBS found along the ramps have been found to be acceptable.

INTRODUCTION

The Extra Low ENergy Antiproton (ELENA) [1–5], is a small 30.4 m circumference synchrotron equipped with an electron cooler to decelerate antiprotons coming from the Antiproton Decelerator (AD) with a kinetic energy of 5.3 MeV down to 100 keV. This will allow existing low energy antiproton experiments, typically capturing the antiprotons in traps, to increase their efficiency and will make new types of experiments on gravitational effects with antimatter possible. The ELENA ring has been installed and commissioning has started recently [6].

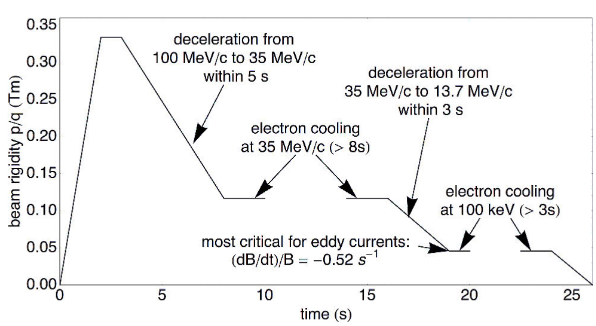

Figure 1: Expected ELENA cycle.

A sketch of the expected magnetic cycle is shown in Fig. 1. After injection with a momentum of 100 MeV/c (kin. energy of 5.3 MeV), the beam is decelerated to an intermediate plateau at about 35 MeV/c and debunched for electron cooling. Thereafter the beam is bunched again and further decelerated to the final momentum of 13.7 MeV/c (kin. energy of 100 keV). At this low energy plateau, the beam is again cooled by electron cooling. During the first part of the low energy electron cooling plateau, the beam is debunched. During a second part of this low energy plateau, the beam is bunched to obtain small longitudinal emittances. The total duration of a cycle depends on the time needed for electron cooling on the two plateaus and is expected to be around 25 s.

Two phenomena have an impact on the minimum and maximum duration of the ramps:

- Eddy currents induced by the ramp and their impact on beam dynamics and optics.
- Intra-Beam Scattering (IBS): IBS will lead to emittance blow-up along the ramps without electron cooling. To limit the impact, the ramps should not be too long.

Both effects have been estimated assuming durations of the two ramps of 5 s and 3 s, respectively. Perturbations of the optics and blow-up due to IBS have been found to be acceptable.

EDDY CURRENTS INDUCED BY THE RAMP AND RESULTING OPTICS PERTURBATIONS

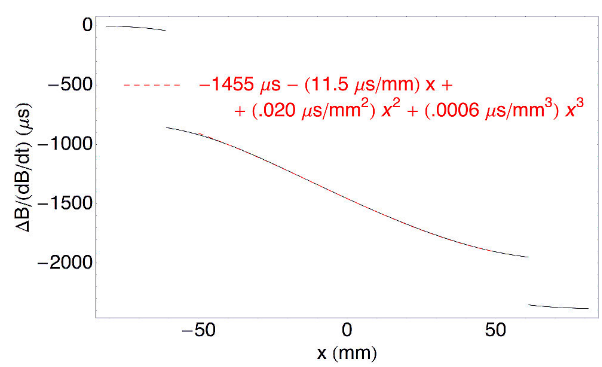

Figure 2: Estimate for the magnetic field ΔB due to the ramp normalized to the ramp rate as a function of the horizontal position. The dashed red line is a fit.

ELENA bending magnets are C-shaped for simple access to the vacuum chamber to install vacuum equipment and there are no isolated junctions between vacuum chambers, as these are difficult to implement for a fully baked vacuum system designed to reach a pressure in the low 10^{-12} Torr range. Thus, a total current (and not only Eddy currents flowing in one direction on one side of the chamber and in the opposite direction on the opposite side) is driven by the ramp leading as well to quadrupolar components of the field. Figure 2 shows an estimate for the resulting change of the magnetic field. The parameters $(\mathrm{d}\Delta B/\mathrm{d}x)/(\mathrm{d}B/\mathrm{d}t) = -0.0115$ s/m and $(\mathrm{d}^2\Delta B/\mathrm{d}x^2)/(\mathrm{d}B/\mathrm{d}t) = 0.020$ s/m^2 lead to perturbations to the circulating beam. With a bending

ISBN 978-3-95450-182-3

radius of $\rho = 0.927$ m and at the most critical point of the cycle (arrival at the low energy plateau with $(\mathrm{d}B/\mathrm{d}t)/B = -0.52\ \mathrm{s}^{-1}$ indicated in Fig. 1), this results in an additional gradient and sextupolar coefficient of:

$$\Delta k = \frac{1}{\rho}\frac{\mathrm{d}B/\mathrm{d}t}{B}\frac{\mathrm{d}\Delta B/\mathrm{d}x}{\mathrm{d}B/\mathrm{d}t} = 0.0064\mathrm{m}^{-2}$$

$$\Delta k' = \frac{1}{\rho}\frac{\mathrm{d}B/\mathrm{d}t}{B}\frac{\mathrm{d}^2\Delta B/\mathrm{d}x^2}{\mathrm{d}B/\mathrm{d}t} = -0.011\mathrm{m}^{-3}$$

Both these quadrupolar and sextupolar components generated by currents induced by the ramp lead only to small and acceptable perturbations of the lattice.

BLOW-UP DUE TO IBS ALONG RAMPS

Formalism

Typical algorithms to estimate IBS of bunched beams describe the beam by the transverse physical rms emittances ϵ_H and ϵ_V , the rms relative momentum spread σ_p/p and the rms bunch length σ_z. We introduce a longitudinal emittance $\epsilon_L = (\sigma_p/p)\sigma_z$ and $\beta_L = \sigma_z/(\sigma_p/p)$ in analogy to the transverse emittances[1]. The rms relative momentum spread and bunch length become $\sigma_p/p = \sqrt{\epsilon_L/\beta_L}$ and $\sigma_z = \sqrt{\epsilon_L\beta_L}$. Standard algorithms for IBS estimates assume that the average beam energy is constant and can be brought into a form where the time derivatives of the transverse emittances are given by $\frac{\mathrm{d}\epsilon_H}{\mathrm{d}t} = \dot\epsilon_{H,IBS}\left(\beta_r\gamma_r, \epsilon_H, \epsilon_V, \sigma_p/p, \sigma_z\right)$, and $\frac{\mathrm{d}\epsilon_V}{\mathrm{d}t} = \dot\epsilon_{V,IBS}\left(\beta_r\gamma_r, \epsilon_H, \epsilon_V, \sigma_p/p, \sigma_z\right)$ and $\frac{\mathrm{d}\epsilon_L}{\mathrm{d}t} = 2\sigma_z\dot\sigma_{p,IBS}\left(\beta_r\gamma_r, \epsilon_H, \epsilon_V, \sigma_p/p, \sigma_z\right)/p$ with β_r and γ_r the relativistic factors. As for ELENA the relativistic $\gamma_r \approx 1$ throughout the whole cycle and the RF voltage is kept constant for a ramp, one can approximate $\beta_L = \beta_r\gamma_r\,\beta_L^*$ with β_L^* approximately constant for a ramp (but depending on the RF voltage).

For IBS simulations along a ramp with varying energy, it is suitable to consider normalized emittances $\epsilon_H^* = \beta_r\gamma_r\epsilon_H$, $\epsilon_V^* = \beta_r\gamma_r\epsilon_V$ and $\epsilon_L^* = \beta_r\gamma_r\epsilon_L$ and their time derivatives:

$$\frac{\mathrm{d}\epsilon_H^*}{\mathrm{d}t} = \beta_r\gamma_r\dot\epsilon_{H,IBS}\left(\beta_r\gamma_r, \frac{\epsilon_H^*}{\beta_r\gamma_r}, \frac{\epsilon_V^*}{\beta_r\gamma_r}, \frac{\sqrt{\epsilon_L^*/\beta_L^*}}{\beta_r\gamma_r}, \sqrt{\epsilon_L^*\beta_L^*}\right)$$

$$\frac{\mathrm{d}\epsilon_V^*}{\mathrm{d}t} = \beta_r\gamma_r\dot\epsilon_{V,IBS}\left(\beta_r\gamma_r, \frac{\epsilon_H^*}{\beta_r\gamma_r}, \frac{\epsilon_V^*}{\beta_r\gamma_r}, \frac{\sqrt{\epsilon_L^*/\beta_L^*}}{\beta_r\gamma_r}, \sqrt{\epsilon_L^*\beta_L^*}\right)$$

$$\frac{\mathrm{d}\epsilon_L^*}{\mathrm{d}t} = 2\beta_r\gamma_r\sqrt{\epsilon_L^*\beta_L^*}\,\frac{\dot\sigma_{p,IBS}}{p}\left(\beta_r\gamma_r, \frac{\epsilon_H^*}{\beta_r\gamma_r}, \frac{\epsilon_V^*}{\beta_r\gamma_r}, \frac{\sqrt{\epsilon_L^*/\beta_L^*}}{\beta_r\gamma_r}, \sqrt{\epsilon_L^*\beta_L^*}\right)$$

Results using the Piwinski Model

Initial emittances at the beginning of the ramps have been estimated from measurements at low energy in the AD for the first ramp and from simulations of electron cooling [4] for the second one. As the beams had significant transverse tails, it was difficult to estimate rms emittances describing the beam and, thus, IBS simulations have been made for different initial emittances. Other basic parameters used for the simulations are given in Table 1.

[1] A more common, but less suitable for this study, definition of longitudinal emittance is $\epsilon_{L,\mathrm{con}} = 4\pi\sigma_z\sigma_p = 4\pi p\epsilon_L$.

Table 1: Parameters for IBS Simulations for the Two Ramps

Parameter	1st Ramp	2nd Ramp
Intensity	$3\ 10^7$	$3\ 10^7$
RF Voltage (V)	100	25
β_L^* (m)	32 000	65 000
Kin. energy start of ramp (MeV)	5.3	0.65
Kin. energy end of ramp (MeV)	0.65	0.100
$\beta_r\gamma_r$ start of ramp	0.107	0.037
$\beta_r\gamma_r$ end of ramp	0.037	0.0146

Results obtained with the latest model by Piwinski [7] based on classical Coulomb scattering, and which takes the details of the lattice into account and could in principle take coupling fully into account, are shown in Figs. 3 and 4 for the first and second ramp, respectively.

Results using the Bjorken-Mtingwa Model

For benchmarking, a different approach, based on the Bjorken and Mtingwa theory [8–12], is taken to evaluate the blow-up caused by IBS during the deceleration. As for the Piwinski model, the added effects of deceleration on beam sizes are joined with those of the IBS. However, the emittance changes during the slowing down of the beam are worked out using a procedure slightly different from the

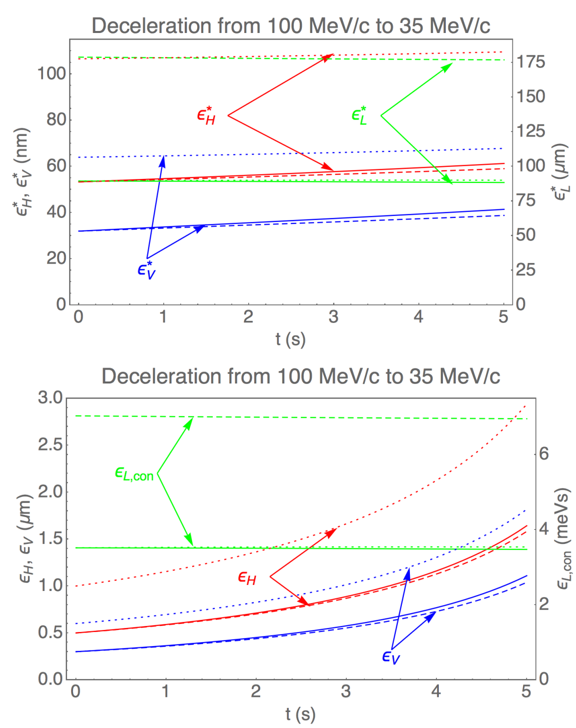

Figure 3: Evolution of emittances along the first ramp estimated using the Piwinski model. Solid lines are for the nominal initial values of the emittances at the beginning of the ramp. Dashed and dotted lines are for beams with larger longitudinal and transverse emittances at the beginning of the ramp.

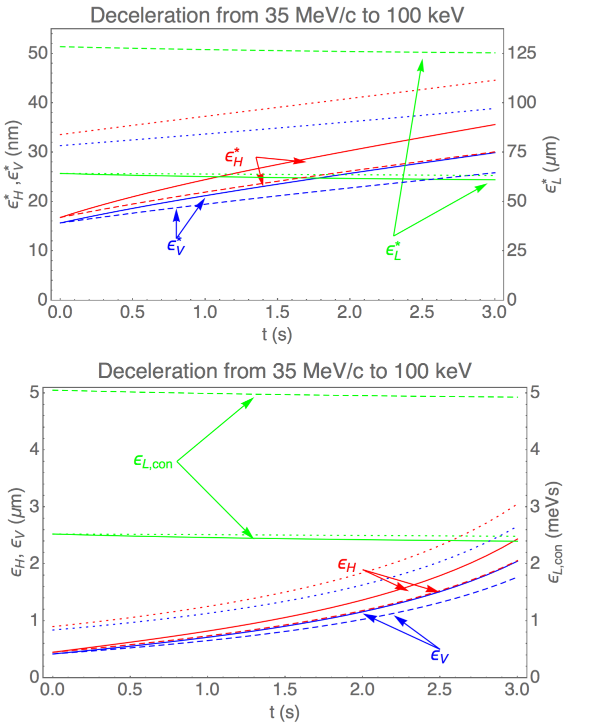

Figure 4: Evolution of emittances along the second ramp estimated using the Piwinski model.

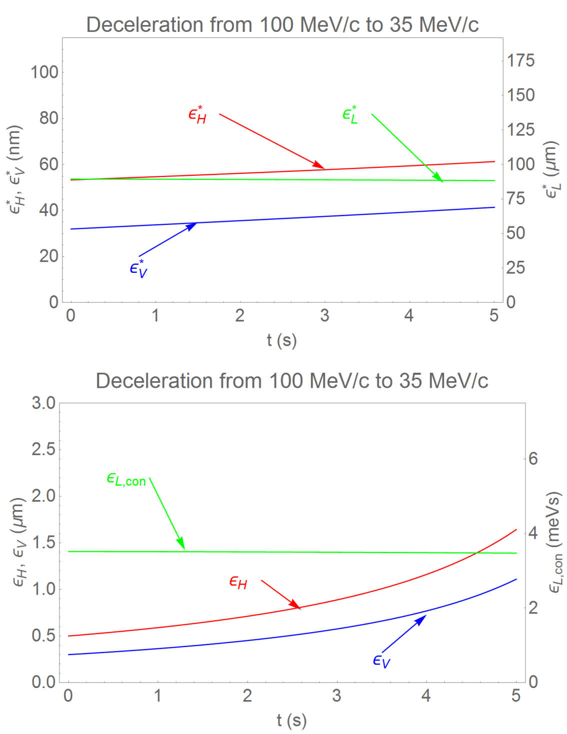

Figure 5: Evolution of emittances along the first ramp from a simulation based on the Bjorken-Mtingwa model.

one described and used above. Physical (non-normalized) emittances are used to describe the beam. The blow-up due to a change of the reference momentum $p_0^i = (\beta_r\gamma_r)^i mc$, with m is the particle mass, between two deceleration steps i and $i+1$ is taken into account by a multiplication with

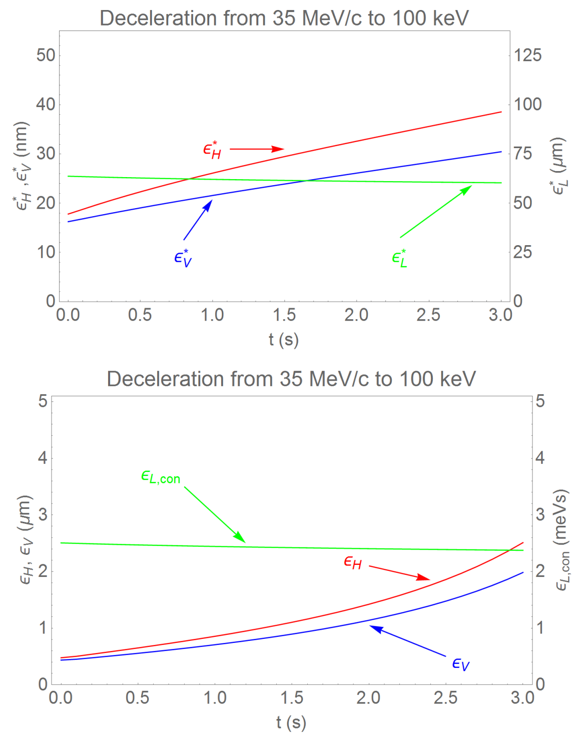

Figure 6: Evolution of emittances along the second ramp from a simulation based on the Bjorken-Mtingwa model.

the ratio of the momenta at the two integration steps. The emittances are computed iteratively using:

$$\epsilon^{i+1}_{H,V,L} = \frac{(\beta_r\gamma_r)^i}{(\beta_r\gamma_r)^{i+1}}\left(\epsilon^i_{H,V,L} + \Delta t\frac{\mathrm{d}\epsilon^i_{H,V,L}}{\mathrm{d}t}\right)$$

where $\epsilon^i_{H,V,L}$ denotes the emittances at the i-th integration step, $(\beta_r\gamma_r)^i$ the factor $\beta_r\gamma_r$ and Δt the integration step. Figures 5 and 6 show the results of the IBS simulations for the nominal case of initial emittances and for the first and the second ramp.

CONCLUSIONS

Perturbations of the lattice due to currents induced by the ramp and IBS effects have estimated for the two ramps foreseen in the ELENA cycle. The perturbations of the optics are small and do not compromise the performance of the machine.

The emittance blow-up due to IBS along the ramps has been estimated using two different models, namely the latest one by Piwinski taking details of the lattice, as dispersion, Twiss parameters and coupling into account and the one by Bjorken and Mtingwa. A fairly small and acceptable increase of the transverse emittances has been found with both models.

One notes that the agreement of emittance growth obtained with the two different methods applied is excellent for the very low energy case studied here.

ISBN 978-3-95450-182-3

REFERENCES

[1] W. Bartman *et. al*, “Progress in ELENA Design”, *Proc. 4th Int. Particle Accelerator Conf. (IPAC’13)*, Shanghai, China, May 2013, paper WEPEA062, pp. 2651-2653.

[2] P. Belochitskii, “ELENA Project Status”, *Proc. of the International Workshop on Beam Cooling and Related Topics 2013 (COOL’13)*, Murren, Switzerland, June 2013, paper THPM1HA02, pp. 192-196.

[3] W. Bartman *et. al*, “Extra Low ENergy Antiproton ring ELENA: from the Conception to the Implementation Phase”, *Proc. 5th Int. Particle Accelerator Conf. (IPAC’14)*, Dresden, Germany, May 2014, paper TUOAA003, pp. 910-912.

[4] V. Chohan (editor) *et. al*, “Extra Low ENergy Antiproton (ELENA) ring and its Transfer Lines Design Report”, CERN-2014-002.

[5] W. Bartmann *et. al.*, “ELENA: Installations and Preparations for Commissioning”, in *Proc. 7th Int. Particle Accelerator Conf. (IPAC’16)*, Busan, Korea, May 2016, paper MOPOY009, pp. 860-863.

[6] T. Eriksson *et. al.*, “ELENA - From Installation to Commissioning”, in *Proc. 8th Int. Particle Accelerator Conf. (IPAC’17)*, Copenhagen, Denmark, this conference.

[7] A. Piwinski, “Intra-Beam Scattering in Presence of Linear Coupling”, DESY 90-113.

[8] J. Bjorken and S. Mtingwa, “Intrabeam scattering”, *Part. Accel.* 13 (1983) 115.

[9] F. Antoniou and F. Zimmermann, “Revision of intrabeam scattering with non-ultrarelativistic corrections and vertical dispersion for MAD-X”, CERN-ATS-2012-066 (2012).

[10] A. Wolski, *Beam dynamics in high energy particle accelerators*, Imperial College Press, March 2014.

[11] M. Martini, F. Antoniou, Y. Papaphilippou, "Intrabeam Scattering", *ICFA Beam Dynamics NewsLetter* # 71, 2016.

[12] M. Martini, “Intrabeam scattering: Anatomy of the theory”, *Proc. of the CERN Accelerator School “Intensity Limitations in Particle Beams”*, Geneva, November 2015, to be published.