HH/fn
20/11/81

CERN/PSCC/82-3
PSCC/P52 Add.1
28 January, 1982

A Small Deceleration Ring for Extra Low
Energy Antiprotons (ELENA)

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INTRODUCTION

CM-P00059041

On completion of LEAR, experiments with low energy antiprotons may be carried out for the first time using well defined antiproton beams in the energy range from 1270 MeV down to 5 MeV. As some experiments demand antiprotons even below 5 MeV, several devices for deceleration have been discussed, such as degraders, cyclotrons or RF-cavities. However, all these devices have the disadvantage that, due to the phase space blow up during deceleration, the intensity for a given (small) acceptance of the experiment decreases in this energy range roughly with the 3rd power of the difference of the particle velocity before and after deceleration. We would therefore like to propose a small and inexpensive deceleration ring equipped with an electron cooling¹ device, which can provide an antiproton beam as low as 200 KeV having at least a similar momentum spread and emittance as the beam extracted from LEAR at 5 MeV.

THE DECELERATION RING

Figure 1 shows the layout of the ring called hereafter ELENA (EXTRA LOW ENERGY ANTIPROTONS). It consists of four 90° bending D-magnets and four straight sections of 1.40 m length each. The circumference of the ring is 7.85 m which corresponds to 1/10 of LEAR. To allow a fine tuning of the machine all magnets are equipped with pole face windings. A summary of the ring parameters is given in table 1. The corresponding lattice functions are shown in fig. 2.

The fast extracted beam from LEAR at 5 MeV will have an emittance $\epsilon_{H,V}$ between 10π and 20π mm mrad and a momentum spread of $\pm 2 \times 10^{-3}$.

At 200 KeV the cooled beam in ELENA will have an emittance $\epsilon_{H,V}$ of $\sim 7\pi$ mm mrad and a momentum spread of $\pm 2 \times 10^{-3}$. Depending on the extraction system, these values may be smaller either in the horizontal or in the longitudinal direction for the extracted beam.

The number of particles to be decelerated in ELENA must be limited to $\leq 10^8$ antiprotons because of the maximum acceptable tune shift at 200 KeV due to space charge for the quoted emittances.

The antiproton beam from LEAR will be injected into ELENA in one of the straight sections using an electrostatic inflector. This inflector has the advantage that the pulse fall time can be made smaller than 50 nsec. As the revolution time at 5 MeV is 250 nsec, a 200 nsec long bunch from LEAR can be injected in 1 turn.

After deceleration the antiprotons will be ejected by means of a slow resonance extraction and an electrostatic septum. Due to the experience gained in the PS with such systems, adjustable spill lengths between ~ 1 -100 msec can be expected. However, a careful calculation has to be made to check these values.

A vacuum of $\sim 10^{-11}$ Torr in the deceleration ring is desirable to restrict particle losses at 200 KeV.

THE ELECTRON COOLING DEVICE

The electron cooling device is located in one of the straight sections of the ring. It consists of:

- an electron gun for the creation of a "cold" electron beam of 1 cm ϕ
- a dipole magnet to bend the electron beam into the straight section of the ring and
- a set of 2 solenoids and 1 toroid for the creation of a longitudinal magnetic field from the gun to the end of the cooling section, which is used to limit the transverse motion of the electrons.

As the electrons have nearly the same mean velocity as the antiprotons the latter can transfer in the straight section their "heat" to the "cold" electron beam by Coulomb interactions.

The parameters of the electron cooling device are summarized in table 2. The voltages and currents needed can be easily supplied by a standard FLUKE photomultiplier supply which fulfils all requirements for a low ripple and stability. The construction of the electron gun is facilitated by the low acceleration voltages needed. Furthermore, it should be pointed out that due to the small power of max 57 watt in the electron beam, it is not necessary to recuperate this energy.

COOLING AND DECELERATION TIMES

For the calculation of the cooling times and the maximum "drag" force which the electrons can apply on the antiprotons for deceleration, it is at first necessary to consider the rms divergence θ^{HV} and the momentum spread θ^L of the antiproton and the electron beam.

From the emittance and the average β -function in the straight section we find for the antiproton beam

$$\theta_{\overline{p}}^H \approx 1.2 \times 10^{-3} \quad \theta_{\overline{p}}^V \approx 2.5 \times 10^{-3} \quad \theta_{\overline{p}}^L = 2 \times 10^{-3}$$

For the electron beam it can be shown that at these low energies the divergences are mainly created by the cathode temperature T_K .

Due to the acceleration to the energy W in the gun the longitudinal energy spread of the electrons is reduced:

$$T_L = \frac{T_K^2}{4W}.$$

Assuming a cathode temperature of 0.1 eV one finds

$$T_L = 8.7 \times 10^{-7} \text{ eV (5 MeV)} \quad T_L = 2.2 \times 10^{-5} \text{ eV (200 KeV)}$$

As the electron flux near the cathode is well described by a Maxwellian distribution, one finds for the transverse temperature, which stays unchanged by the electrostatic acceleration

$$T_T = 0.1 \text{ eV}$$

The divergence of the electron beam is given by

$$\theta_e^T = \sqrt{\frac{T_T}{2W}}$$

$$\theta_e^T = 4 \times 10^{-3} \text{ (5 MeV)} \quad \theta_e^T = 2 \times 10^{-2} \text{ (200 KeV)}$$

As the divergence of the electron beam is always bigger than the divergence of the antiproton beam the cooling time is independent of the amplitude of the antiproton oscillations. Furthermore, the longitudinal temperature of the electron beam is always several orders of magnitude smaller than the transverse temperature, which corresponds to a "flattened" velocity distribution in the electron beam. Under these conditions the cooling time is given by

$$\tau = 0.16 \frac{\beta^4 \gamma^5 e (\theta_e^T)^3}{r_p r_e \eta j L}$$

with r_p , r_e the classic radii for the two particles, η the ratio between the length of the cooling straight section and the circumference of the ring, j the electron current density and $L \sim 10$ the Coulomb logarithm.

With a cooling length of 1.1 m and an electron current of 20 (0.16) mA at 5 MeV (200 KeV) one finds:

$$\tau_c = 0.13 \text{ sec (5 MeV)}$$

$$\tau_c = 3.25 \text{ sec (200 KeV)}$$

Ideally, the cooling process will stop when antiprotons and electrons have the same temperature. At 200 KeV this corresponds to a minimum antiproton beam emittance of $\sim 1\pi \text{ mm mrad}$.

In reality, however, the emittance will be bigger because cooling is counteracted by a blow up of the antiproton beam mainly due to the following effects:

- multiple scattering on the rest gas in the ring
 - multiple scattering of the antiprotons within the beam (intra-beam scattering) and
 - resonances and ripple in the guiding and focussing fields of the ring.
- The effect of multiple scattering on the rest gas at a vacuum of 10^{-11} Torr is very small even at 200 KeV. At this energy cooling and blow-up will be balanced for an emittance of $\sim 1.5\pi \text{ mm mrad}$ which is close to the limit given by the electron cooling.

The effect of intra-beam scattering² is more difficult to evaluate. Depending on the local lattice functions of the deceleration ring, this effect will lead either to an equal temperature distribution within the beam or to a continuous "heating" by the transfer of energy from the translational motion of the beam. For this effect the dispersion function of the lattice plays an important role.

Computer calculations, which investigate the effect of intra-beam scattering in small steps around the ring, show that "heating" will occur in the middle of the straight sections due to the small beam dimensions and the dispersion. As there is no dispersion in the vertical plane the "heating" of the beam is much smaller in this plane. At equilibrium between cooling and heating the vertical emittance is therefore in principle smaller. However, due to the coupling between horizontal and vertical planes by the solenoid needed for electron cooling, the emittances of both planes will be nearly equal. The equilibrium value for the emittance depends furthermore on the number of stored particles as intra-beam scattering depends linearly on the beam intensity.

The beam blow-up due to resonances depends on the working point of the machine and on the width of the stopbands which is given by imperfections of the guiding and focussing fields. In a well-tuned and aligned machine the effect should be small. However, while the beam dimensions decrease during cooling the tune shift produced by space charge in the antiproton beam will increase, bringing the working point closer and closer to a stopband and exciting the betatron oscillations. The corresponding beam blow-up will counteract cooling until both effects are in equilibrium. For the maximum tune-shift we assume a limit of 5×10^{-3} , adopting the same single beam tune shift limit in this case as for the linear beam-beam tune shift in p-p($\bar{p}$) storage rings.

Taking into account intra-beam scattering and the above discussed limit of the tune shift the following emittances were found at 200 KeV:

$1 \times 10^8 \bar{p}$	$\epsilon = 7 \text{ mm mrad}$	$\Delta p/p = 1.9 \times 10^{-3}$
$5 \times 10^7 \bar{p}$	$\epsilon = 5 \text{ mm mrad}$	$\Delta p/p = 1.7 \times 10^{-3}$
$1 \times 10^7 \bar{p}$	$\epsilon = 2.5 \text{ mm mrad}$	$\Delta p/p = 1.2 \times 10^{-3}$

This shows clearly that the effect of multiple scattering on the rest gas is negligible and the beam dimensions are determined by intra-beam scattering and the tune shift limit. As cooling can always balance the beam blow-up the lifetime in the machine is only limited by single scattering, which means processes where the angle of a single scattering is bigger than the aperture of the machine. For 200 KeV one finds a lifetime of ~ 1000 sec.

To calculate the minimum deceleration time which is possible due to electron cooling only, one has to calculate the "drag" force, which the electrons apply on the antiprotons. Under the above discussed conditions, this is given by

$$F_e = 4\pi n_e r_e^2 (m_e c^2)^2 \cdot L / T_{eT}$$

with n_e being the electron density.

Integrating over the forces corresponding to the different velocities during deceleration gives a minimum deceleration time of 65 sec.

As this might be too long a small RF-cavity working on the first harmonic of the revolution frequency can be used to shorten the deceleration time.

In this case cooling will be applied before deceleration for about 1 sec. With RF voltages less than 60 volt deceleration times of ~ 1 sec are possible. After this the beam can be cooled again. By this procedure the deceleration time can be reduced to ~ 5 sec, which is less than 1/10 of the time needed for deceleration by electron cooling only.

DIAGNOSTICS

To check the correct injection position 2 TV screens are foreseen, one at the end of the transfer line from LEAR and a second just behind the inflector, being used also for beam dumping. A set of pick-ups is used to measure orbit distortion and the tune of the machine.

The number of circulating particles can be measured by a beam current transformer, which can be used also for life time measurements and for monitoring the beam during deceleration.

A longitudinal resonant pick up for Schottky noise³ working at ~ 300 Mhz allows the measurement of the momentum spread before and after deceleration.

The beam dimensions will be measured by a set of horizontal and vertical scrapers, which also give information about the betatron oscillation cooling.

OPERATIONAL SCHEME LEAR - ELENA

To allow a single turn injection into ELENA, the beam in LEAR at 5 MeV is bunched by an RF-cavity working at the 6 harmonic of the revolution frequency. Using an RF voltage of ~ 2.5 kV the bunch length will be about 200 nsec. One bunch will then be ejected and transferred to ELENA. For this purpose the existing cavity in LEAR is adequate. Some changes are needed, however, on the fast extraction system of LEAR.

After the injection into ELENA the beam will be cooled for ~ 1 sec to reduce the betatron oscillations and the momentum spread. Then the field of the bending magnets will be lowered, while the position of the antiproton beam is monitored by a pick-up. A displacement of the beam causes a reduction of the electron gun voltage, of the magnetic guiding field for the electron beam and - if the deceleration is supported by RF - the change of the RF-frequency, which corresponds to the first harmonic of the revolution frequency.

After deceleration the beam is sent to the experiment using resonance extraction from ELENA. As stated before, spill length between 1-100 m sec seems to be feasible.

This procedure can be repeated 6 times before reloading LEAR with antiprotons. Figure 3 shows schematically the above discussed operational scheme.

TESTS

The use of a small proton source mounted on a 200 KeV accelerating column will allow testing of the whole set-up independent from LEAR. To provide 10^8 p for ELENA a proton pulse of 1.2 μ sec and a peak current of ~ 13 μ A is used. Injected into ELENA and accelerated, it allows the study of cooling and deceleration. It seems to be possible to construct such a source partially from spare parts used for PS ion sources.

TIME SCHEDULE AND PRICES

The estimated time for design, construction and installation will be about 30 months from authorization up to initial tests.

An estimation of the prices for the different items is summarized in Table 3.

ACKNOWLEDGEMENTS

I would like to thank M. Bell, W. Hardt, P. Lefevre, D. Möhl and G. Petrucci for many helpful discussions and encouragement.

REFERENCES

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- 2) A. Piwinsky, Intra-beam scattering, Proc. 8th Int. Conf. on High Energy Acc. (1974).
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Table 1 RING PROPERTIES

Kin. energy range	T = 5 MeV	T = 200 KeV
Momentum range	p = 100 MeV/c	p = 20 MeV/c
Circumference	C = 7,85 m	
Bending radius	$\rho = 0,37$ m	
Magnetic field	B = 0.9 T	B = 0.18 T
Gradient	K = 3.36 m ⁻²	
Length of straight section	L = 1.40 m	
Tune	$Q_H/Q_V = 1.63/1.43$	
Tune shift due to space charge for 10 ⁸ antiprotons	$\Delta Q \sim 2 \times 10^{-4}$	$\Delta Q \sim 5 \times 10^{-3}$
Required vacuum	P $\sim 10^{-11}$ Torr	
Size of vacuum chamber	$\sim 10 \times 5$ cm	
Beam lifetime (1/e)		
Uncooled	4000 sec	~ 30 sec
Cooled	35 H	~ 1000 sec

Table 2 ELECTRON COOLING PARAMETERS

$\bar{p}$ kinetic energy	5 MeV	200 keV
e^- -gun voltage	2870 V	113 V
Cathode ϕ		1 cm
$\bar{p}$ beam size in straight section		~ 0.8 cm
e^- current	20 mA	0.16 mA
Cooling length		1.1 m
Magnetic guiding field	380 Gauss	76 Gauss
Potential depression in the e^- beam	5.7 V	0.23 V
Tune shift to $\bar{p}$ beam	3.8×10^{-3}	3.8×10^{-3}
Cooling times	0.13 sec	3.25 sec

Table 3 COSTS

MAGNETS

Iron, coils, pole face windings power supplies	150 000.-
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VACUUM

Pumps, vacuum chambers, manifolds, gauges	100 000.-
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ELECTRON COOLING

Gun, solenoid, toroid, power supply	50 000.-
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INJECTION

Deflection kicker, switch (partially recuperated)	30 000.-
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DIAGNOSTICS

Beam current transformer, scrapers, Tu-screens, Schottky pick-up	50 000.-
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CONTROLS

Electronic for deceleration, RF	50 000.-
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EXTRACTION

Electrostatic septum, HV, Correction elements (partially recuperated)	30 000.- <hr/> 460 000.- <hr/>
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Fig.1

POS	S	QX	QY	BX	BY	AX	AY	X	DX	Y	DY	DS
0	0.0000	0.00000	0.00000	.30293	.48690	-.00000	.00000	.69078	.00000	0.00000	0.00000	0.00000
1 LI	.6900	.18416	.15220	1.87460	1.46472	-2.27779	-1.41712	.69078	.00000	0.00000	0.00000	.54254
2 B	.9817	.20401	.17869	2.62388	1.92252	-.00000	-.00000	.69078	.00000	0.00000	0.00000	1.08508
3 B	1.2735	.22386	.20519	1.87460	1.46472	2.27779	1.41712	.69078	.00000	0.00000	0.00000	1.08508
4 LI	1.9635	.40802	.35739	.30293	.48690	.00000	.00000	.69078	.00000	0.00000	0.00000	1.08508
R=	1.25000	TGAM=(. 1.34519, 0.00000)										
				THETX= 6.28319229				THETY= 0.00000000				1.42955
				QX= . 1.63207				QY=				
MAXIMA	BETAX(2)=	2.62388	XEQ=(4)=	.69078	BETAY(2)=	1.92252	YEQ(4)=	0.00000				
MINIMA	BETAX(4)=	.30293	XEQ=(3)=	.69078	BETAY(4)=	.48690	YEQ(4)=	0.00000				

Fig.2

OPERATIONAL SCHEME LEAR – ELENA

Fig.3