EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN - PS DIVISION

CERN/PS 93-05 (OP)

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LEAP'92, Courmayeur (Aosta) - September 14-19 1992

Geneva, Switzerland
20/1/93

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Abstract

Limitations to the antiproton beam intensities that are decelerated and stored in LEAR are examined, and expectations for machine performance in the momentum range at and below 105 MeV/c are given. These estimates are compared with the current machine performance. The various modes of beam extraction at low momentum are reviewed and some estimations are given for fast extraction efficiencies.

1. DEFINITION OF EMITTANCE AND BUNCHING FACTOR

1.1 Emittance

All emittances are defined as surfaces in either longitudinal or transverse phase space, and all the relevant distributions are taken to be Gaussian. Longitudinal emittance is defined as:

$$\varepsilon_{\parallel} = \pi . 2\sigma_{\Delta p/p} . 2\sigma_s \quad \text{(m)} \tag{1}$$

Where $\sigma_{\Delta p/p}$ and σ_s are the rms fractional momentum spread and bunch length (m).

Transverse emittance is defined as:

$$\varepsilon_{\perp} = \pi . 2\sigma_x . 2\sigma_{x'} = (2\sigma_x)^2/\beta_x \quad \text{(mm.mrad)} \tag{2}$$

Where σ_x and $\sigma_{x'}$ are defined as the rms width for the distributions of position and angle respectively.

The quantities $\varepsilon_{\parallel}$ and $\varepsilon_{\perp}$ are non-normalised emittances i.e. they vary with changing beam momentum. In the absence of beam cooling the emittance increases as the beam momentum decreases. Normalised emittances, which do not vary with momentum, are defined as:

$$\varepsilon_{\parallel}^{*} = \pi.2\sigma_{\Delta E}.2\sigma_{t} = (E_{0}/c).\beta\gamma.\varepsilon_{\parallel} \quad (\mathrm{eV.s}) \qquad (3)$$

$$\varepsilon_{\perp}^{*} = \beta\gamma.\varepsilon_{\perp} \quad (\mathrm{mm.mrad}) \qquad (4)$$

Where $\beta = v/c$, $\gamma = E/E_0$, $\beta\gamma = cp/E_0$
$\sigma_{\Delta E}$ is the rms energy spread
σ_t is the rms bunch length (secs).

1.2 Bunching factor

The bunching factor indicates the change in the longitudinal density due to bunching, and is defined as the average beam current divided by the peak instantaneous beam current. Again for a Gaussian longitudinal distribution the bunching factor is given by:

$$Bf = (\sqrt{(2\pi)}/4).(\sigma_t.m/T_{rev}) \qquad (5)$$

Where m is the number of bunches, assuming bunches equally spaced around the ring, and T_{rev} is the revolution time.

For a coasting beam Bf = 1, and for a bunched beam Bf < 1. The bunching factor will get smaller and smaller for more strongly bunched beams i.e. for shorter bunches.

2. LIMITATIONS TO STORED LEAR BEAM INTENSITY

Ultra-low momenta are taken to mean momenta at or below 105 MeV/c. The original design [1] specified that the minimum momentum in LEAR would be 100 MeV/c. This range has since been extended to 61 MeV/c, and in this paper we examine some of the fundamental limitations to stored beam intensity in this momentum range. A review of intensity limitations and instabilities in cooled beams is given in [2]. Some of the major limitations to the beam intensity that can be stored in LEAR at low momenta are given below:

2.1 Physical size of the vacuum chamber

It is obvious that in any particle storage ring the actual transverse beam size, the beam emittance, must be kept somewhat smaller than the machine acceptance. The upper limit to the machine acceptance is given by the size of the vacuum pipe in which the beam circulates. This leads automatically to the requirement that the beam emittances be kept small to maintain a good beam lifetime.

2.2 "Dynamic aperture"

The transverse aperture, within which particles will circulate without being lost, may be rather smaller than the physical acceptance of the vacuum chamber. This is due to chromatic effects in the particle focusing, because of unwanted higher order multi-pole fields, and possible defects in some or all magnetic elements. The resulting higher order terms in the equation of motion will mean that above a certain transverse oscillation amplitude single particle motion becomes unstable and the particle is lost. The emittance corresponding to this limiting amplitude defines the so-called dynamic acceptance of the accelerator or storage ring. As the beam momentum is reduced the field errors tend to become more important and hence the dynamic aperture limitation becomes more pronounced. There is a second contribution to this dynamic limitation. During deceleration and/or acceleration, the storage ring magnets are ramped and the changing magnetic flux will in itself introduce unwanted multi-pole components. These induced fields will certainly modify the particle behaviour and limit the dynamic acceptance of the storage ring. The dynamic aperture limits lead to the requirement that beam emittances be kept small to keep the transverse oscillation amplitudes small.

2.3 Space charge detuning

In any charged particle beam the individual particles are electrostatically repelled by all the other charged particles in the beam. This leads directly to a defocusing effect, which reduces the number of betatron oscillations per turn for each particle. For low momentum, cooled beams, if the beam is considered as a uniformly charged cylinder [2], then the resulting incoherent tune shift can be calculated as follows:

$$\Delta Q = r_p . Z^2/A.(N/[\varepsilon_{h,v}(1+\sqrt{(\varepsilon_{h,v}/\varepsilon_{v,h})})\beta^2\gamma^3.Bf]) \qquad (6)$$

Where r_p is the classical proton radius
Z, A are the charge and mass of ion.
ΔQ is the total Q shift for small amplitude particles
Bf is the bunching factor (see 1.2)
  1 for a uniform coasting beam
  <1 for a bunched beam
$\varepsilon_{h,v}$ is the horizontal or vertical beam emittance (see 1.1)

However, the beam is not a uniform cylinder of charge and the above expression is correct for a small amplitude betatron oscillation, which only samples the centre of the beam distribution. For large amplitude oscillations the incoherent tune shift will be smaller as the particle will spend a sizable proportion of its time out in the lower density tail regions of the beam. This introduces an amplitude dependent spread of around $\Delta Q/2$ in the final tune shift, ΔQ. In a storage ring the transverse betatron tunes are chosen and controlled very carefully to avoid resonances up to very high orders. Consequently, only very small tune spreads can be accommodated before the beam falls outside the stable area in tune space, and particles are lost. Estimations of this effect for the ISR, from Eq. (6), suggest that an acceptable tune shift is 0.01 or less. For LEAR the acceptable tune spread is probably higher due to the presence of the electron cooling, which will compensate some of the resonant blow-up. Therefore a reasonable estimate of the tolerable tune shift may be 0.02. In the CERN Antiproton Accumulator this incoherent tune shift is negligible, for 10^{12} antiprotons stored at 3.5 GeV/c, ΔQ is only 0.001. Once the maximum tune shift has been estimated it is simple to calculate the maximum beam intensity that can be stored. It is now apparent, from Eq. (6), that this maximum possible beam intensity will decrease at lower momenta, as β is reduced. It will decrease even further if the transverse emittance (ε_h or ε_v) is reduced, i.e. the beam density is increased, and finally, it will decrease still further if the beam is bunched. This incoherent tune spread due to space charge defocusing is a very severe limitation on beam intensity at low momenta and leads to the conclusion that it may be desirable to maintain larger rather than smaller transverse beam emittances, during beam deceleration in LEAR when the beam is bunched. This is a major intensity limitation during the deceleration of beam in LEAR.

2.4 Intra-beam scattering

Coulomb scattering between particles in the circulating beam leads to beam blow-up and ultimately to particle loss. The rate of blow-up is a complicated, non-linear function of beam momentum, lattice parameters, beam emittance and beam intensity [4,5]. The variation of this blow-up rate with these various parameters is given by:

$$1/\tau = F.[N.c.r_p^2.(Z^2/A)^2]/[\beta^3.\gamma^4.\varepsilon_h.\varepsilon_v.\varepsilon_\parallel] \qquad (7)$$

Where N is the number of particles (per bunch for a bunched beam)
c is the velocity of light
F is a constant between 1 and 10 depending on beam conditions

Intra-beam scattering gets worse, i.e. the blow-up gets faster, at lower momenta and for smaller emittances. Expressed in terms of normalised emittances (ε_h^*, ε_v^*, $\varepsilon_\parallel^*$), see 1.2, Eq. (7) becomes:

$$1/\tau = F.[N.r_p^2.(Z^2/A)^2]/[\gamma.\varepsilon_h^*.\varepsilon_v^*.\varepsilon_\parallel^*/E_0] \qquad (8)$$

At low energy, $\gamma \approx 1$, and Eq. 8 does not depend on the beam momentum, provided the normalised emittances remain constant. Therefore the blow-up due to intra-beam scattering will not increase during the deceleration process, but will only become more important if the beam emittances are reduced by beam cooling. The equilibrium beam emittances at low energies under a strong cooling are obtained when the cooling rate equals the blow-up rate. In this way intra-beam scattering will limit the beam emittances but will not cause additional beam losses during deceleration.

2.5 Multiple scattering on the residual gas

The transverse beam emittance increases as a result of Coulomb scattering of the circulating particles on the residual gas. The rate of emittance increase can be estimated as follows [6].

$$d\varepsilon/dt = 0.61.\beta_{av}.P/(\beta^3.\gamma^2) \qquad (9)$$

Where β_{av} is the ring averaged beta function
P is the gas pressure in N_2 equivalent.

The rate of emittance blow-up due to scattering on the residual gas is independent of the beam intensity and the initial emittance. However, it is strongly momentum dependent, and increases rapidly at lower momenta.

2.6 Transverse and Longitudinal instabilities

These are coherent effects, in which the beam responds as a whole rather than as individual particles [7]. The circulating beam induces an image current in the accelerator vacuum pipe. Any change of material or cross section, as well as properties like resistivity, will present some "impedance" to this current, which will result in a voltage acting back on the beam. Both transverse and longitudinal cases must be considered, and can be described by transverse and longitudinal impedances. A small change in the beam position or density will induce a change in the transverse and longitudinal forces acting back on the beam. If these forces amplify the initial change this leads to instability and ultimately beam loss. Since the beam motion is coherent, the unstable motion of the beam can be detected via a pick-up and this signal can be used to damp the motion. Such a transverse feedback system is installed in LEAR and is essential to decelerate beam to 105 MeV/c and below. If the feedback system is functioning correctly then coherent transverse instabilities do not limit the LEAR beam intensity at low energies. Under present operating conditions longitudinal instabilities do not yet pose problems during beam deceleration, therefore no longitudinal feedback is needed at the moment.

In conclusion, the limitations to beam intensity become dramatically worse at lower and lower momenta, Taking into account all of the above factors it is possible to estimate the maximum intensity that can be stored in LEAR as a function of beam momentum, emittance and bunching factor. The results of these calculations are shown in Table 1. The critical limitations will be at small transverse emittances and for bunched beams. A bunching factor of 1/3 has been used, this corresponds to an RF bucket of twice the longitudinal bunch area. As the beam is bunched for each deceleration, the intensity figures for bunched beams must be taken as the realistic limits, rather than the unbunched limits, which are higher. The principle intensity limitation is the incoherent space charge tune shift that LEAR can tolerate. Therefore the maximum beam current is obtained for larger, rather than smaller, transverse emittances.

Table 1: Estimations of maximum beam intensity as a function of beam momentum and emittance.

Momentum (MeV/c)	200	200	105	105	61	61
Kinetic Energy (MeV)	21.1	21.1	5.9	5.9	2.0	2.0
$\varepsilon_h, \varepsilon_v$ (mm.mrad)	10π	2π	10π	2π	10π	2π
$\Delta p/p$	0.001	0.0005	0.001	0.0005	0.001	0.0005
IBS time constant (s)	360	35	196	20	98	11
Max beam intensity (debunched) ①	$38\ 10^9$	$7.6\ 10^9$	$10\ 10^9$	$2.0\ 10^9$	$3.5\ 10^9$	$0.7\ 10^9$
Max beam intensity (bunched) ①②	$12\ 10^9$	$2.4\ 10^9$	$3.3\ 10^9$	$0.7\ 10^9$	$1.1\ 10^9$	$0.2\ 10^9$

① Maximum incoherent tune shift (ΔQ) = 0.02 ② bunching factor = 1/3

3. PRESENT LEAR "BEST" LOW MOMENTUM PERFORMANCE

Table 2 shows the maximum beam intensities that are obtained during normal LEAR antiproton deceleration. Electron cooling is used to reduce emittances at several momenta during the deceleration cycle (309, 200, 105 and 61 MeV/c). The intensities shown are for debunched beams at the given momenta.

Table 2: Maximum stored antiproton intensities obtained in LEAR as a function of beam momentum

Momentum (MeV/c)	200	105	61
Maximum Intensity	$9\ 10^9$	$3\ 10^9$	$1\ 10^9$
$\varepsilon_h, \varepsilon_v$ (mm.mrad)	$<5\pi$	5π	$5\text{-}10\pi$
$\Delta p/p$	0.0005	<0.001	0.001
Transverse cooling time (s)①	10	10	10
Longitudinal cooling time (s)①	3	3	3

① using electron cooling

The figures given are very close to the space charge limits given in Table 1 for bunched beams with transverse emittances of 10π mm.mrad. This seems reasonable as the critical intensity limitation will be at the end of deceleration when the beam is still bunched at the new low momentum. These figures suggest that LEAR is already approaching the maximum intensity levels that can be achieved at ultra low energies. However these limitations are strongly density dependent, and are therefore strongly affected by the beam emittance and the bunching factor during deceleration. Further study is needed of these intensity limitations as a function of beam emittance and density. In January 1993 the existing electron cooling device will be upgraded by the addition of a variable perveance electron gun, which means that it will be possible to vary the cooling time constant. This will give, in principle, much greater control over the beam emittance during the deceleration cycle. However, it appears likely that any gains in intensity at low energy will not exceed a factor of two above the present performance.

4. EXTRACTION MODES AT LOW MOMENTA

Three different methods of extraction are used at low momenta. The beam characteristics currently obtained in each case are summarised in Table 3. The ultra-slow and the semi-slow extraction are both multi-turn resonant extractions, where the horizontal oscillation amplitude of the circulating particles is increased using a third order betatron resonance until the individual particles are extracted by the ejection septa. The fast extraction is a single turn extraction, in which a fast kicker ejects one bunch of antiprotons from the machine. For the semi-slow and the fast ejections it is possible to extract the circulating beam in one or several ejections depending on the needs of the users.

Table 3. Extraction modes at low momenta

Momentum (MeV/c)	200	105	61
Ultra-slow extraction	yes	yes	yes
Maximum spill length (s)	7200	7200	1200
Best extraction efficiency (%)	75	60	≈30
Semi-slow extraction	no	no	yes
Spill length (ms)	-	-	0.2 ⇒ 5.0
% of circulating beam ejected in each spill	-	-	20 ⇒ 100
Fast extraction	yes	yes	yes
Ejected pulse length (ns)	100 ⇒ 500	100 ⇒ 1200	100 ⇒ 3500
% of circulating beam ejected in each pulse	50 ⇒ 100	10 ⇒ 100	5 ⇒ 100

Until now there has been no real user demand to increase dramatically the intensity of the fast extracted beam. However, this will probably be requested in the near future if tests aimed at accumulating large numbers of antiprotons in Penning traps begin. There are two major constraints on the intensity available in the fast ejection process. The LEAR extraction channel has a relatively small transverse acceptance and this requires small beam emittances for reasonably efficient extraction. The Penning traps themselves are limited in the length of the antiproton pulse that they can accept, and therefore require short high intensity bunches of particles. This means that small emittances and small bunching factors are needed. In section 2 it was shown that these requirements will severely limit the stored beam intensity in LEAR. Table 4 shows some estimations of beam intensities available from LEAR for fast ejection, under various conditions.

Table 4. Estimation of maximum fast extracted beam intensities at low momenta.

Momentum (MeV/c)	105	105	105	61	61	61
Number of ejected bunches	2	4	2	4	8	8
Bunch length (ns)	200	200	500	500	255	200
Bunching factor	0.11	0.21	0.27	0.31	0.31	0.25
Transverse emittance (mm.mrad)	5π	5π	5π	5π	5π	5π
Beam Intensity (10^{9})	0.55	1.10	1.38	0.54	0.55	0.43
Intensity per ejected bunch (10^{9})	0.27	0.27	0.69	0.14	0.07	0.05
Transverse emittance (mm.mrad)	10π	10π	10π	10π	10π	10π
Beam intensity (10^{9})	1.10	2.20	2.76	1.08	1.10	0.86
Intensity per ejected bunch (10^{9})	0.54	0.54	1.38	0.28	0.14	0.11

It should be emphasised that the ejected intensities given in Table 4 should be multiplied by an overall extraction and transport efficiency. A reasonable guess at such an overall efficiency is 50%. The numbers given in Table 4 are estimations based on current machine performance, and further study is needed before these first estimations can be turned into realistic predictions. In particular, work on the long-term behaviour and stability of a bunched beam under electron cooling is needed, to allow the ejection of several equal high intensity bunches. If the stored beam intensity in LEAR can be increased above the present levels, see section 3, then the fast extracted beam intensities would also increase correspondingly. However, Table 4 does give indications of the relative intensities available as a function of bunch length and extracted beam momentum, and indicates that the ejected intensity will increase for "longer" Penning traps.

5. REFERENCES

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