PERFORMANCE OF LEAR

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The CERN Low Energy Antiproton Ring has been running in its stretcher mode during six physics runs, between July 1983 and December 1984. It has delivered pure and intense beams of antiprotons to sixteen experiments at five different momenta in the range of 200 to 1500 MeV/c. This paper summarizes the machine performance during these runs and gives a preview of the latest improvements achieved with protons and H^- ions during machine development periods.

Introduction

LEAR [1] is a strong focusing synchrotron/storage ring 78.5 metres in circumference. The design range of operating momenta is 0.1 to 2.0 GeV/c and its present role is to provide intense, pure beams of low energy antiprotons. It has a separated function lattice BODFOFDOB and is a symetric four period machine with 4 bending magnets and 8 focusing doublets. The result is a very strong focusing machine, with a phase advance per period of ≈ 250° and a betatron wavelength of ≈30 metres. $\gamma_{transition}$ is imaginary for the standard working points. This leads to a large value for $|\eta|$,

$$\text{where } \frac{\Delta F}{F} \Big/ \frac{\Delta P}{P} = \eta = \frac{1}{\gamma_T^2} - \frac{1}{\gamma^2}$$

which favours good mixing for the stochastic cooling process and helps the ultraslow stochastic extraction. Since η is always negative, the machine operates below transition over all of its large momentum range, thus avoiding negative mass effects and the problems associated with operating close to the transition energy.

Chromaticity correction is performed using 18 sextupoles (14 normal and 4 skew). The closed orbit is controlled using 8 backleg windings and 4 dipoles in the horizontal plane and 6 dipoles in the vertical plane.

	1983 (Nov./Dec.)	1984
Machine experiment and setting-up	360* hours (protons) 32** hours (antiprotons)	836* hours (protons) 546* hours (antiprotons)
Physics running time	352** hours (antiprotons)	1320* hours (antiprotons)
Number of antiproton pulses used for physics	233***	815****
Approximate number of antiprotons used for physics (not including setting-up, etc.)	0.7×10^{12}	2.4×10^{12}

* Continuous running mode (i.e. 24 x 24 hours)
** Alternate running mode (i.e. 16 x 24 hours)
*** 15 minute + 1 hour spills
**** All 1 hour spills

Table 1 : LEAR running statistics

The essential features of the machine are phase-space cooling to improve beam quality, ultraslow stochastic extraction with spill times of up to 60 minutes, a flux of around 5×10^5 extracted antiprotons per second and a duty factor approaching 90%. Possible future running schemes for the machine include operation with co-rotating beams of H^- ions and antiprotons, an internal hydrogen target, operation as a mini proton-antiproton collider, and various post-deceleration schemes to reach momenta well below 100 MeV/c.

To date the machine has delivered antiproton beams at 200, 310, 610, 1480 and 1510 MeV/c. All 16 experiments, presently installed, have received beam at one or more of these momenta. Figure 1 shows the layout of the machine and experimental area and Table 1 gives a breakdown of the running between November 1983 and December 1984. More detailed information on the machine parameters can be found in references [1, 2, 3].

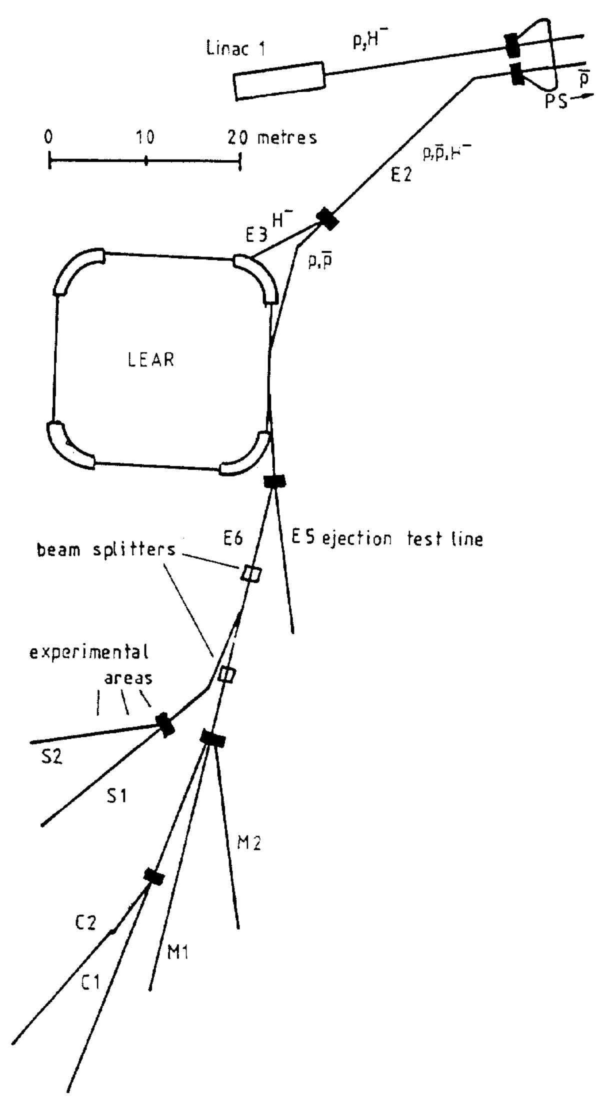

Figure 1 : Layout of LEAR, machine transfer lines and experimental area.

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	Typical	Best
AA to PS	95-100%	100%
PS to LEAR	70%	92%
Overall to LEAR	65%	92%
LEAR to Users	50%	70%

Table 2 : Overall antiproton transfer efficiencies

Presentday operation as an antiproton beam stretcher

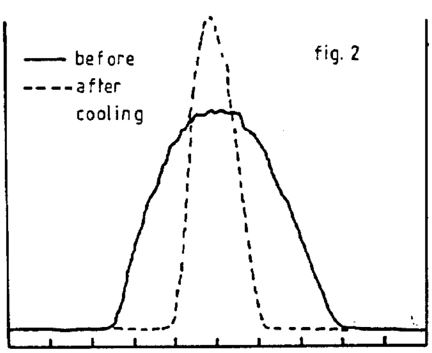
The antiproton beam destined for LEAR, typically a bunch of 3×10^9 particles is unstacked from the Antiproton Accumulator, AA, and transferred at 3.5 GeV/c to the Main Proton Synchrotron, PS. Here it is decelerated to 0.6 GeV/c for injection into LEAR. Table 2 shows typical transfer efficiencies. After injection into LEAR, the beam is stochastically cooled prior to acceleration or deceleration. The results of this cooling are shown in Figures 2, 3 and 4. However, an improved AA unstacking technique, adapted to low intensity antiproton transfers, coupled with "bunch to bucket" injection, followed by adiabatic debunching in LEAR means that a total momentum spread of $\pm 1 \times 10^{-3}$ on the injected beam is obtainable. In this case, only transverse cooling is needed at 0.6 GeV/c.

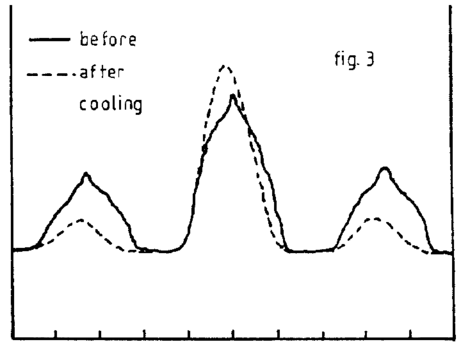
Figures 2, 3 and 4 show the result of 5 minutes stochastic cooling of 2.5×10^9 particles at 609 MeV/c.

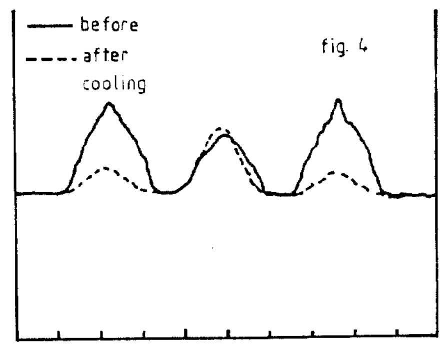
Figure 2: Longitudinal Schottky scan, taken at the 20th harmonic of the revolution frequency (centre frequency = 40.56 MHz, frequency span = 300 kHz). The curves show the square root of the particle density against momentum. The momentum spread is reduced from 5.5‰ to 2‰.

Figure 3: Horizontal Schottky scan, taken at the 100th revolution harmonic (centre frequency = 207.8 MHz, frequency span = 1.87 MHz). The height of the betatron sideband is a measure of the transverse emittance. Cooling decreases the emittance by a factor of 3.5.

Figure 4 : Vertical Schottky scan, taken at the 100th revolution harmonic (centre frequency = 207.8 MHz, frequency span = 2.078 MHz). The vertical emittance is reduced by a factor of 5 during the cooling.







The present LEAR stochastic cooling set-up, which is shown in Figure 5 and Table 3, consists of one horizontal and one vertical system, each with pre-measured, preset delay settings for 100, 200, 309 and 609 MeV/c. The longitudinal system is in two parts, one of which is for cooling at 609 MeV/c with two 144 metre coaxial line fixed notch filters and the other of which covers the range 450 to 100 MeV/c with variable synthesized notch filters. It was found necessary to add an horizontal kicker to the longitudinal cooling gaps to eliminate the transverse blow-up caused by the momentum cooling system. This was due to a non zero derivative of the dispersion function at the cooling gaps.

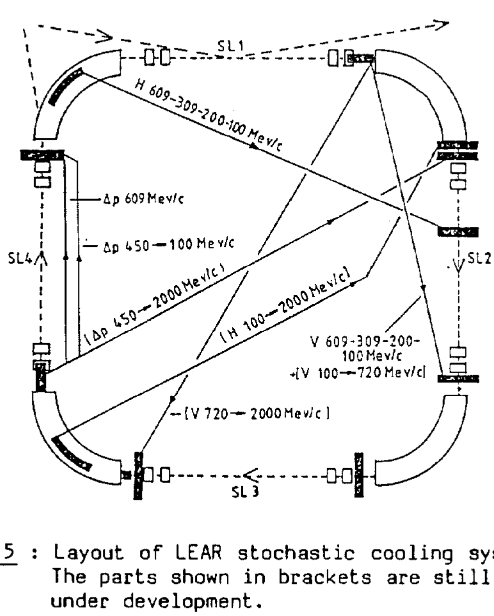


Figure 5 : Layout of LEAR stochastic cooling systems. The parts shown in brackets are still under under development.

	Momentum		Vertical	Horizontal
	609 MeV/c	309, 200 MeV/c	609, 309 200, 100 MeV/c	609, 309 100 MeV/c
Pick-ups	24 gaps	24 gaps	8 loop pairs	12 loop pairs
Noise figure amplifiers	2.5 dB	2.5 dB	2.0 db	2.0 dB
Kicker	8 gaps	8 gaps	1 loop pair	1 loop pair
Available power	2x20 W	2x20 W	1 W	1 W
Bandwidth	20-220 MHz	15-100 MHz	150-650 MHz	150-650 MHz

Table 3: Present LEAR stochastic cooling system

After 5 minutes cooling, the beam is accelerated or decelerated to the required momentum. For momenta above 600 MeV/c, no further cooling is applied, as the beam damps adiabatically during acceleration. For deceleration to 200 MeV/c, an intermediate cooling, in all three planes, for a further 5 minutes, is performed at 300 MeV/c.

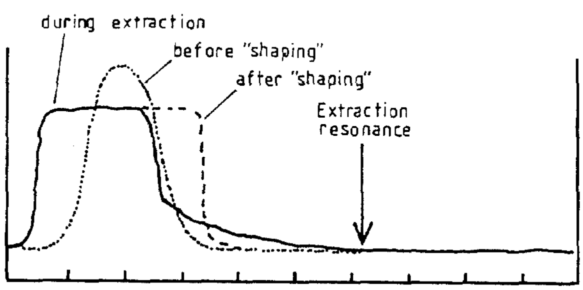


Figure 6 : Longitudinal particle distribution during "shaping" and extraction

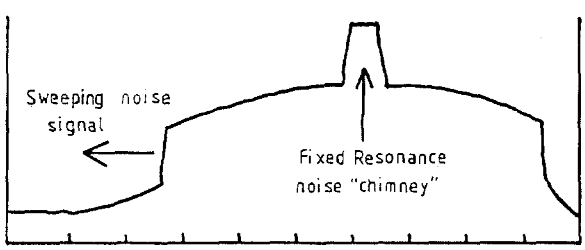


Figure 7 : Form of swept RF noise used for ultraslow extraction

Once the required momentum has been reached, the stochastic extraction process [4] is initiated. Firstly, the beam is "shaped", i.e. the longitudinal distribution is made rectangular, Figure 6, by applying an RF noise signal to the beam, with a well defined bandwidth around an harmonic of the revolution frequency between 15.5 and 17.5 MHz. This shaping takes 30 seconds and is done to ensure a constant spill rate. During acceleration or deceleration, the betatron tune and chromaticity ($\xi = \Delta Q/Q \;/\; \Delta p/p$) are kept at or very close to $Q_H=2.305$, $Q_V=2.725$, $\xi_H=\xi_V = 0$. After shaping, the machine quadrupoles and sextupoles are adjusted to give $Q_H=2.325$, $Q_V=2.725$, $\xi_H=0.6$ and $\xi_V=0.0$, and at the same time drive the extraction resonance $3Q_H=7$. Figure 8 shows the various working points used during acceleration and extraction. Simultaneously, a local orbit bump is applied to move the beam close to the electrostatic and magnetic extraction septa. Finally, an RF noise signal is swept slowly into the beam, again at around 16 MHz, as shown in Figures 6 and 7, and the particles diffuse slowly towards the extraction resonance. The length of the spill is determined by the rate of sweeping of the extraction noise. Table 4 gives further details of the shaping and extraction process.

This extracted beam is then split into 3 different experimental lines, shown in Figure 1, using 2 beam splitters [6]. In this way, three different experiments can receive particles simultaneously. Figure 9 shows the extracted beam intensity variation during a typical spill.

Early spills were 15 minutes long, but this was increased to 1 hour to improve the overall machine duty factor and reduce the number of antiproton transfers from the AA. Recent proton tests have shown that spills of 3 hours are feasible at momenta above 600 MeV/c. At momenta well below 200 MeV/c, it may be necessary to work with 15 minute spills due to beam intensity and lifetime limitations.

a) Shaping			
	Bandwidth	60	kHz
	Power	0.15	mW/Hz
	Time	28.0	s
	Centre frequency	17.340	MHz
b) Extraction			
	Bandwidth	140	kHz
	Power	0.02	mW/Hz
	Time	3600	s
	Centre frequency	17.458	MHz
	Sweep	85	kHz
c) Resonance "chimney"			
	Bandwidth	10	kHz
	Resonance frequency	17.433	MHz
	Resonance power	0.2	MW/Hz

Table 4 : Parameters for ultraslow extraction at 350 MeV/c

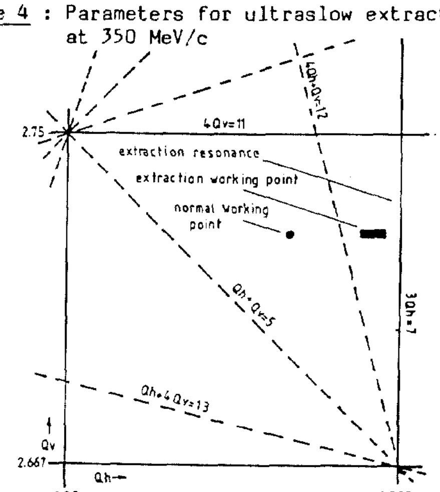


Figure 8 : Typical machine working points

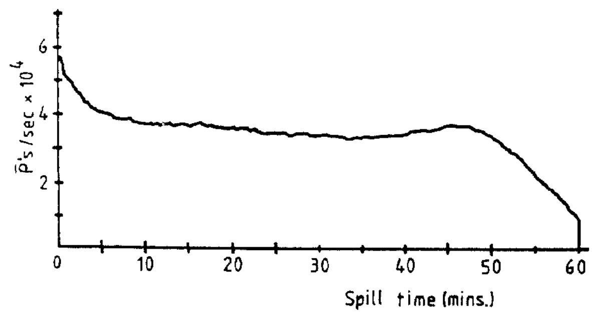


Figure 9 : Extracted beam intensity seen by one experiment over a 60 minute spill

During 1983, the machine operated in so-called "alternate mode", i.e. 8 hours of continuous antiproton production followed by 16 hours of particle transfers to LEAR. In 1984, it was possible to operate in a "continuous mode", with antiproton transfers every 70 minutes and antiproton accumulation inbetween the transfers. This was mainly due to improvements in the AA beam cooling and beam extraction systems. As the AA can produce 5 x 10^9 antiprotons per hour, LEAR - which needs 3 x 10^9 antiprotons per hour - can run continuously.

In the first nine months of operation, a strong 50 Hz modulation was seen on the extracted beams. This was found to be caused by a ripple of some 10^{-3} on the sextupole power supplies and some 10^{-4} on the quadrupole and main bending magnet power supplies. This problem has been solved by a power supply improvement programme and by modifying the extraction noise[5]. This noise level is reduced between the circulating beam and the extraction resonance and increased around the resonance itself. See Figure 7 and Table 4.

The control system

The LEAR control system consists, at present, of two linked microcomputer systems (PDP 11's) and a parallel-serial Camac hardware interface, with a number of dedicated microprocessors distributed around the Camac crates. The control system has a link to the main PS control system, this is in preparation for the future routine operation of LEAR from the PS Main Control Room.

The basic control system functions, such as setting parameter values and switching power supplies, are handled by one microcomputer, whilst the second is used to control the timing and autonomous function generator software. The autonomous function generators control the magnet power supplies during the machine cycle, under the direction of the timing system.

The control system will shortly be augmented by the addition of a micro VAX computer that will handle large programs such as the energy scanning program, which is described in the following section, and the editing programs for the function generators. This will free one of the existing PDP11's, which will then be used for general alarm and status surveillance of all important machine parameters and systems.

This type of general survey program is especially important for a machine, which operates with antiprotons that are both expensive and difficult to produce. Indeed, for remote operation of LEAR from the PS Main Control Room, it will be indispensable.

Recent developments and future plans

Machine studies are normally conducted using protons injected directly into LEAR at 300 MeV/c, via the E2 transfer line (see Figure 1), from the old PS Linac, Linac 1. As the protons rotate in the same direction as the antiprotons, the polarity of the machine has to be inverted. This practice of setting up the machine using protons and then inverting for antiproton operation is very reliable. After a polarity reversal, field levels are reproducible to within a precision of about 5 x 10^{-4}, so that only fine tuning of the machine remains to be done with the precious antiprotons. However, efficient extraction demands reproducibility down to the 1 x 10^{-4} level.

Since October 1984, it has been possible to inject H^- ions, again from Linac 1, into LEAR either via the normal antiproton line E2, or via a second reverse injection line E3, see Figure 1. H^- ions can be injected via the E2 line directly into the machine with antiproton polarity. The H^- lifetime at 300 MeV/c was about 10 seconds, which agrees with the predictions for stripping via multiple Coulomb scattering on the residual gas in the machine for a vacuum (80% H_2) of 5 x 10^{-12} Torr (N_2 equivalent pressure). It is also possible to fully strip the H^- ions in the E2 line and inject protons into LEAR, without dismantling the Linac source. In this way, long lifetime tests, such as slow extraction, which would not be possible with the H^- beam, can be carried out in the usual way with protons.

H^- ions injected in the reverse direction, via the E3 line, can be stripped just after injection to become protons circulating in the opposite direction to normal. Figure 10 describes this injection procedure. Just before injection, a two dipole horizontal bump corresponding to half one betatron wavelength is applied, and a 200 ug cm^{-2} Aluminium stripping foil is introduced as shown in Figure 10. During the injection two fast deflectors steer both the injected H^- beam and the circulating proton beam through the stripping foil. At the end of the injection process (about 20 turns), the foil is removed and the two dipole bump switched off to recentre the proton beam in the vacuum chamber. Various diagnostic pick-ups are used to observe slow and fast electrons stripped from the H^- ions or ejected from stripping foil itself during the injection, and to detect the neutral hydrogen atoms, created due to incomplete stripping in the foil.

The successful direct H^- injection means that tests can now begin on the possible storing of co-rotating H^- ions and antiproton beams. Using the H^- ion stripping injection tests and setting up of the machine and injection system directly in antiproton polarity can be carried out using protons circulating in the reverse direction. This form of injection is also needed if any sort of proton-antiproton collisions inside LEAR are to be considered.

Until now, only five well defined momenta have been available from LEAR, but in December 1984 a preliminary scanning procedure, to enable the machine to supply beam to the experimental area at a range of

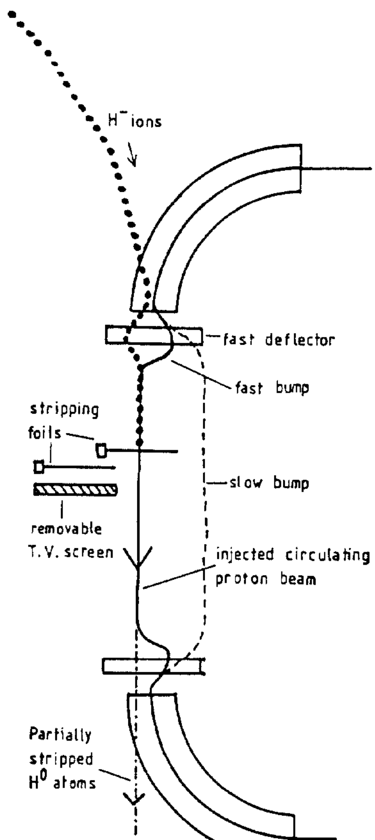


Figure 10 : Schematic representation of H^-stripping injection

intermediate momenta, has been tested. The scanning is a software process, which interpolates between the fixed "standard" LEAR energies of 100, 200, 309, 609 and 1500 MeV/c. This is a very complicated procedure, which involves the on line modification of around 50 functions, power supplies, RF, etc. and 100 timing instructions for the machine alone, plus the stochastic cooling and ultraslow extraction systems. To date proton beams have been extracted from the machine at 350, 450 and 550 MeV/c, and it is hoped to begin using this technique during antiproton physics runs in 1985.

In conjunction with the scanning, an improvement program has been started on the stochastic cooling systems. The idea is to split the system into two parts: a "strong" system to provide fast cooling at each of the standard LEAR momenta, and a "weak" system with variable delays to provide slow cooling at any intermediate momenta, with the possibility to cool the beam during extraction. Figure 5 shows the existing system and proposed improvements.

An electron cooler[7] based on the Initial Cooling Experiment, ICE, is being developed for LEAR. It would be especially useful in conjunction with an internal target at momenta below 600 MeV/c, where fast cooling times, a few seconds, would combat the fast beam blow-up due to multiple Coulomb scattering on the target. However, it is hoped to be able to cool antiproton beams at momenta up to 780 MeV/c, which would cover the 609 MeV/c injected antiproton beam. Studies are under way regarding the possible installation of an internal hydrogen gas jet target inside the machine.

Finally, there are various ideas being studied to provide beams with momenta considerably below the 100 MeV/c (5 MeV kinetic energy) planned for LEAR. These include fast ejection from LEAR into a smaller post-decelerating ring or slow ejection, between 100 ms and 1 s, into a radio-frequency quadrupole, which would be used to decelerate the extracted beam. This second option would require some sort of time structure to be imposed on the extracted beam to fit with the bucket of the post decelerator.

Conclusion

The Low Energy Antiproton Facility is a successful part of the CERN Antiproton complex, serving at present 16 different experiments installed around the machine. It is a machine which is evolving rapidly and although no major difficulties have yet been encountered, there remain many problems to be overcome, both in the present beam stretcher mode and for possible future options. One of the most demanding problem is that of power supply stability, brought about by the large momentum range that the machine has to cover (0.1 to 2.0 GeV/c). For an ultraslow extraction at 100 MeV/c, a current charge of 5×10^{-3}, i.e. 2.5×10^{-6} of maximum current in one of the machine quadrupoles, would reduce the extraction efficiency by 50%.

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