EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PERFORMANCE UPDATE ON LEAR

The LEAR Team[1]

ABSTRACT

This paper reviews the performance of the CERN Low Energy Antiproton Ring (LEAR) in its first 3 years of operation and gives a preview of the requirements for the next 3 years with the second generation of LEAR experiments in the post-ACOL era. ACOL is the Antiproton Collector ring being built at CERN as an upgrade to the Antiproton Accumulator (AA) facility. The "LEAR consolidation program", which is necessary to meet the needs of the new experiments, will be described, and finally some ideas for future options will be discussed.

[1] : D. Allen, E. Asseo, S. Baird, J. Bengtsson, M. Chanel, J. Chevallier, R. Giannini, P. Lefèvre, F. Lenardon, R. Ley, D. Manglunki, E. Martensson, J.L. Mary, C. Mazeline, D. Möhl, G. Molinari, J.C. Perrier, T. Pettersson, P. Smith, G. Tranquille, H. Vestergård.

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The LEAR Team[1]
CERN
CH-1211 Geneva Switzerland

Introduction

This paper reviews the performance of the CERN Low Energy Antiproton Ring (LEAR) in its first 3 years of operation and gives a preview of the requirements for the next 3 years with the second generation of LEAR experiments in the post-ACOL era. ACOL is the Antiproton Collector ring being built at CERN as an upgrade to the Antiproton Accumulator (AA) facility. The "LEAR consolidation program", which is necessary to meet the needs of the new experiments, will be described, and finally some ideas for future options will be discussed.

Present performance

The main mode of LEAR operation for experimental physics has been as a variable momentum antiproton beam -^retcher ring. The essential features of the machine e phase space cooling to improve beam quality, ultra-slow extraction with spill times ranging from 15 minutes to 5 hours and a variable extraction momentum from 105 to 1700 MeV/c. Figure 1 shows the general layout of LEAR and its associated transfer lines.
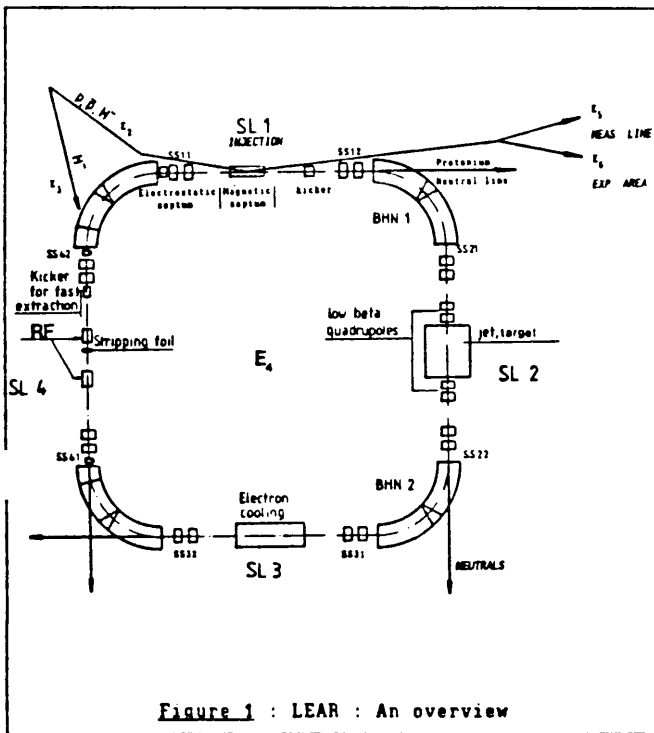

Figure 1 : LEAR : An overview

The antiprotons for LEAR, typically a bunch of up to 3.0×10^9 particles, is unstacked from the AA and transfered to the PS, where the beam is decelerated from 3.5 GeV/c to 0.609 GeV/c, before being ejected towards LEAR. After about 3 minutes of stochastic cooling in LEAR at the injection momentum (609 MeV/c) the beam is either accelerated or decelerated to the required ejection momentum. At present, for ejection

momenta above 609 MeV/c no further stochastic cooling is applied, however, for ejection momenta below 609 MeV/c, further beam cooling is necessary to maintain high beam quality, and to counteract the adiabatic emittance increase. During the deceleration cycle the beam is held on a series of fixed momentum "flat-tops" (309, 200 and 105 MeV/c) for several minutes of intermediate cooling. At each stage the emittances are restored to their previous levels. Under normal operating conditions, the minimum emittances obtained are around 10π mm.mrad transversely and $dp/p = \pm 1.0 \times 10^{-3}$ longitudinally (emittances containing 95% of the beam).

The transverse stochastic cooling system consists of a limited number of pick-ups and kickers. A set of coaxial relays, which commute between different cable delays, are used to compensate for the changing particle velocities over the range of operating momenta. There are several sets of preadjusted delays, which allow "fast" cooling on each of the fixed "flat-tops", with cooling time constants of the order of one minute for 10^9 particles. In addition a second series of relays and cables can be set to provide a slow transverse cooling at any intermediate momenta. This slow cooling is used to maintain beam quality during the long extraction process.

The longitudinal cooling system is again made in two parts, each using the same pick-up. One, for use at 609 MeV/c, uses a line filter of fixed electrical length, and the other, for all momenta below 609 MeV/c, uses a line filter of variable electrical length from 70 to 700m. The present LEAR stochastic cooling system is shown in Figure 2 and described in detail in Ref. [1]. Table 1 summarises the present "fast" cooling system.
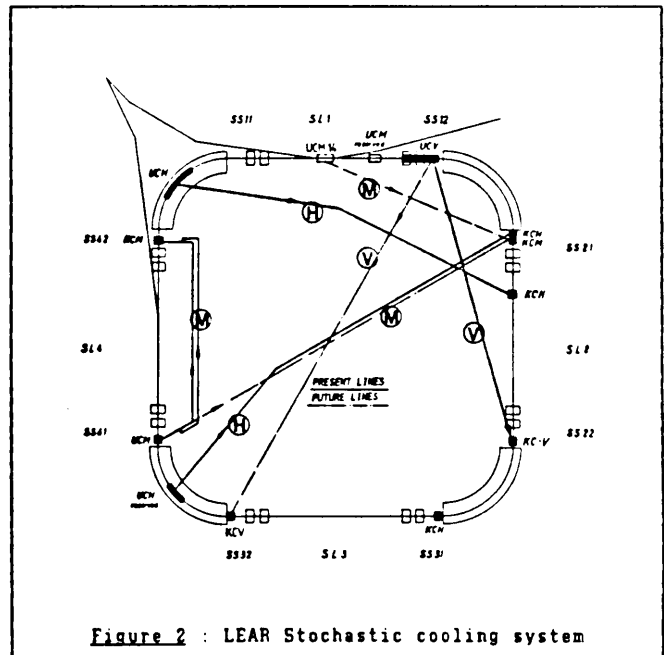

Figure 2 : LEAR Stochastic cooling system

The ultra-slow stochastic extraction process has been described in detail in Refs. [2,3] and only a brief description will be given here. Once the required momentum has been reached, the longitudinal beam

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distribution is made rectangular, using an RF noise signal with a well defined bandwidth applied at a harmonic of the revolution frequency. Once this "shaping" is complete, and the relevant betatron tune and chromaticity adjustments have been performed, a second RF noise signal is swept into the coasting beam. The particles, under the influence of this noise, diffuse slowly onto the extraction resonance ($3Qh = 7$), and are extracted using a thin electrostatic septum together with a magnetic septum. The power of this second noise signal and the speed at which it is displaced into the beam control the rate at which particles diffuse onto the extraction resonance and thus the spill rate. In order to reduce the time modulation of the spill rate, due principally to power supply ripple, a third stronger noise "chimney" is applied around the extraction resonance itself. In this way continuous spills with an 80% duty factor, intensities ranging from 2.0×10^{6} antiprotons/sec to over 1.0×10^{6} antiprotons/sec, and varying from 15 minutes to 5 hours in length, are routinely obtained.

Table 1 : Present LEAR stochastic cooling system

	Longitudinal		Vertical	Horizontal
	609 MeV/c	309, 200 MeV/c	609, 309 200, 100 MeV/c	609, 309 200, 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
Bandwidth (Hnz)	20-300	15-200	50-500	50-500

In order to be capable of ejecting beam at any momentum within the LEAR operating range (at present 105 to 1700 MeV/c), an online procedure has been developed, which will calculate the power supply values and cycle timing necessary to create the new ejection momentum, by interpolation or "scanning" between existing ejection settings. All existing values for cycles with different extraction momenta are stored using an archive and retrieval system on the LEAR control computers, Refs. [4,5]. In this way it is possible to recall a previously used cycle or create an entirely new machine cycle in a few minutes.

A similar technique is used to "scan" the values for the transfer lines to the physics experiments, and to calculate new settings for the tranverse stochastic cooling. The time needed to change the extraction momentum is less than 1 hour, if recalling a previously used cycle, and about 2 hours for a completely new "scanned" ejection momentum. This scanning procedure is now a routine part of machine operation, but considerably more development is needed both in the hardware and software domains to meet the demands of future experiments, as will be seen in the following sections.

Table 2 gives a breakdown of the antiproton running statistics from November 1983 to August 1986.

Post-Acol performance requirements

The addition of the Antiproton Collector (ACOL) to the CERN Antiproton Accumulator (AA) coincides with the installtation of the second generation of LEAR experiments. These are, in general, bigger and more complex than the first generation, and more demanding in terms of machine performance Refs. [6,7]. Some of the problems posed by the new experimental demands on LEAR are outlined in this section. The proposed final layout of the new LEAR experimental area is shown in Figure 3.

Table 2 : LEAR running statistics

Year	Number of different extraction momenta	Hours of operation exp physics	total	Antiprotor pulses used
1983	2	352	712	233
1984	5	1320	2444	815
1985	24	2651	3837	1612
1986	36	2254	3370	1480

The most obvious effect of ACOL on LEAR operation will be the increase in AA stack intensity. This increase in the antiproton stack density will mean a possible increase in stack emittance, therefore, in order to profit fully from the higher antiproton fluxes available, the acceptance of the PS-LEAR transfer line needs to be increased. The optics of this transfer line have been redesigned and two new quadrupoles added in order to reduce the beam dimensions in the transfer channel. At the same time seven horizontal and vertical beam position pick-ups are being installed at critical points down the line. These pick-ups are copies of the pick-ups developed for the ACOL machine, and they will cover a range of bunch intensities from $1.0 \ 10^{9}$ to $1.0 \ 10^{11}$ particles for bunch lengths ranging from 20 to 200 nsecs. The estimated position resolution is $\pm$ 1 mm.

Several approved LEAR experiments require ultra-low beam momenta, even below the 100 MeV/c design figure already attained. The different experimental methods impose varying constraints on the form of the LEAR extracted beam. Some need slow extraction of the type already performed at higher momenta, others need extraction times of between 100 msecs and a few seconds, and finally the "antiproton trapping" experiments need fast extraction of small antiproton bunches of around 200 nsecs in length.

One of the principle problems at low momenta has been the excitation of systematic machine resonances by the machine sextupoles. These sextupoles are primarily used for chromaticity adjustment and excitation of the extraction resonance, $3Qh = 7$. However in mid-1986 a series of machine experiments were started in order to compensate, using the existing sextupoles, the resonance $Qh + 2Qv = 8$ at 309 MeV/c. This compensation was found semi-empirically by placing the machine working point very close to the resonance in question and adjusting the compensation until the maximum beam intensity was injected Ref. [8]. The resulting optimum compensation was used at all momenta below 609 MeV/c, but only partially applied at momenta above 609 MeV/c, due to lack of available sextupole power.

Using the new sextupole configuration several improvements in beam behaviour have been observed, which are particularly important for ultra-low energy operation.

The dependance of Qh or Qv on the betatron amplitude was reduced effectively to zero, contributing to a large increase in the dynamic transverse acceptance of the machine. E.g. at 309 MeV/c the loss-free horizontal acceptance passed from around 40π mm.mrads to 100π mm.mrads. This is important both at injection and during stochastic extraction, when the particles excecute very large amplitude horizontal betatron oscillations on the last few turns before leaving the machine.
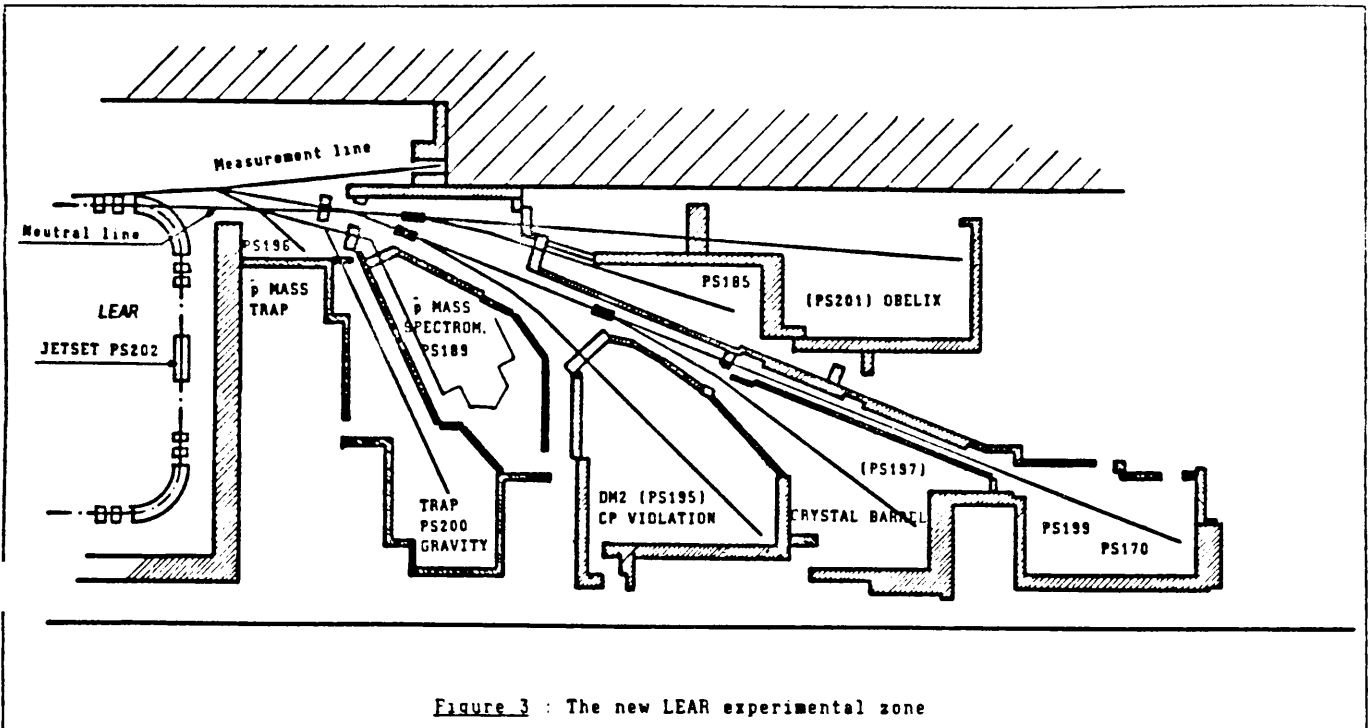
Figure 3 : The new LEAR experimental zone

The beam lifetime at 105 MeV/c, with the stochastic cooling on, was increased from 13 to 50 minutes, which made spills of 1 hour feasible at 105 MeV/c and quadrupled the extraction efficiency. Indeed the first evidence of genuine transverse cooling at 105 MeV/c was seen after compensation of this coupling resonance. It was also possible to reduce the losses during deceleration from 200 to 105 MeV/c from 50% to 30%.

However, due to the non-symetric distribution of sextupole power used to compensate the systematic resonance $Q_h + 2Q_v = 8$, and the location of the sextupoles in non-zero dispersion regions, a strong dependance of Q_v on $(dp/p)^2$ is now observed. This dependance has been measured $\delta Q_v = 700(dp/p)^2$. Although relatively unimportant at high momenta, where dp/p is small, this effect becomes enormous during deceleration wards 60 MeV/c, where dp/p approaches 1%. Studies are derway to try and reduce this sextupolar asymmetry even more, but this task is complicated by the lack of space, and the fact that at least one sextupole has to be moved from its present postion to make way for a gas-jet target Ref [9]. Any reduction in beam momentum spread at 100 MeV/c would significantly reduce the machine sensitivity to this sextupole asymmetry, and considerable effort is being invested into the developement of stochastic cooling pick-ups for use at or below 100 MeV/c.

In order to continue this work of resonance measurement and compensation a system for Q measurement by Fast Fourrier Transform analysis of the beam response to a transverse kick has been installed at LEAR Ref [10]. It is now possible to measure accurately the amplitude and phase of a resonance and thus correctly compensate or excite it. Refs [11,12]. This method has been used during machine experiments to study resonances $Q_h + Q_v = 5$ and $3Q_h = 7$.

The fast extraction process, which is required by two approved experiments, has already been tested and used for some initial trapping trials using a Penning trap, supplied with 200 MeV/c antiprotons, which are subsequently degraded down to the KeV energy range. This work culminated in the trapping and storing, for upto 10 minutes, of 3 KeV antiprotons Ref. [13]. The extraction method is a standard fast extraction of a bunched beam using a kicker module, similar to the injection kickers, placed a quarter of a betatron wavelength upstream of the magnetic septum. One of the important requirements of the trapping experiment was the possibility to set-up the experimental apparatus with slow extracted beam before receiving the fast extracted pulses. This meant that not only did the machine have to be capable of switching rapidly from one mode of ejection to the other, but also that the momentum of the fast extracted pulses had to be the same as that the slow spills. However, during stochastic extraction the particles, prior to ejection, are diffused across the machine aperture and their momentum increases, therefore the momentum of the slow ejected beam is $5\ 10^{-3}$ higher than the coasting LEAR beam.

The solution to these problems was in fact relatively simple. Firstly the same magnetic machine cycle is used for both processes, making switching extraction modes very quick and simple. Secondly, instead of using a local radial orbit bump to move the circulating beam close to the extraction septum, as is done for stochastic extraction, the entire beam is accelerated to the momentum of the slow extracted particles, which corresponds to a fractional momentum increase of $5\ 10^{-3}$, prior to fast extraction. This acceleration displaces the beam at the magnetic septum by almost the same amount as the normal dipole extraction bump, and ensures that the fast extracted bunches have exactly the same momentum as the slow extracted beam.

The whole fast extraction process lasts less than 1 sec, and can be performed at any time during the LEAR cycle. The beam is decelerated to the required momentum and the stochastic cooling switched on. When fast extracted beam is requested the coasting LEAR beam is bunched at the 4th RF harmonic, accelerated to the ejection orbit, and one bunch out of the four is ejected by sychronising the ejection kicker with one of the circulating bunches. Then the remaining 75% of the beam is decelerated back to the centre of the machine and debunched, ready for the next beam request. Between

fast and slow extraction a small correction, at the magnetic septum, is needed, as the trajectories upon which the particles leave the machine are not the same in the two cases, but apart from this diference the settings for the experimental beam line are identical for either fast or slow extraction.

In 1988 this procedure will be reused at 105 MeV/c for the same experiment, and later a similar ejection will be required at 60 MeV/c for another trapping experiment, which uses an inverted RFQ to decelerate the extracted beam, rather than a simple energy degrader foil, Ref. [14]. The expected characteristics of this rather specialised fast extracted beam are shown in Table 3.

Table 3 : Fast extracted beam for RFQ deceleration

Momentum = 61.3 MeV/c, Kinetic energy = 2 MeV
Eh = Ev = 5 to 10π mm.mrad.
Dp/p = 2 to 4 x 10^{-3}, Energy spread = 8 to 16 KeV
Bunch length = 250 to 500 nsec

The installation and operation of a gas-jet target, Ref. [9], inside LEAR is also an integral part of the approved experimental program. The expected maximum luminosity is around 3.0×10^{30} cm^{-2} sec^{-1}, which is determined by the antiproton production rate. However, the maximum available target density may limit this figure to 1.6×10^{30} cm^{-2} sec^{-1}. As well as the obvious consequences for the machine vacuum, and severe space limitations for the experimental apparatus, this installation will pose several specific problems for LEAR, Ref. [15].

Stochastic cooling will be necessary over the whole LEAR momentum range in order to combat the beam blow-up caused by repeated traversals of the gas-jet, as well as longitudinal cooling as a method for fine tuning of the final beam momentum. At present, stochastic cooling is only available at or below 609 MeV/c.

For an internal target it is advantageous to increase the acceptance angle of the machine by reducing the β values at the interaction point. This is especially true for momenta below 800 MeV/c, where the loss rate due to single Coulomb scattering in the gas-jet, without a reduced β at the interaction point becomes comparable with the strong interaction rate. For this reason a low β insertion has been designed for operation with the gas-jet Ref. [16]. The experiment requires continuously variable beam momentum, in order to scan a wide mass range in the proton/antiproton formation channel. With this in mind a considerable revision of the control system hardware and software has been undertaken, which is dealt with in the following section.

Machine upgrade for the new experiments

In order to be able to satisfy the needs of the new generation of experiments, the LEAR consolidation program has been approved and started.

The effective range of the stochastic cooling system is being extended. In one direction, the system must be capable of operation up to 2 GeV/c, for the gas-jet operation, and in the other direction cooling at and below 100 MeV/c is essential for efficient deceleration towards 60 and even 20 Mev/c! For high momentum cooling the problem is one of space for new kickers, as the increasing particle velocity means that the cooling signals have to take bigger and bigger short-cuts with respect to the beam. The proposed

layout of these new lines is shown in Figure 3. At low momenta the small beam intensities and the low revolution frequency mean that a very poor signal-to-noise ratio is the major difficulty, and a range of new pick-ups are being developed to try and overcome this problem. Two existing transverse pick-ups have been connected in 'travelling wave' mode in order to coherently sum the beam signals. They have also been equiped with cryogenically cooled pre-amplifiers and terminating resistors. In this way the thermal background noise is reduced by a factor of four. This system has been used with some success at 105 MeV/c.

The same longitudinal cooling system used at 200 MeV/c has been tried at 105 MeV/c, but very little effective cooling has been observed. Two new designs of travelling pick-ups for stochastic cooling of 60 MeV/c beams are at present being tested. The pick-ups must have a high coupling impedance up to 50 Mhz, above which the Schottky bands overlap. For betatron cooling a pair of 20 cm long 'meander couplers' have been built, the meander line and the copper ground plane are electroplated onto the surface of ceramic plates. The phase velocity of the induced signal is designed to be as close as possible to the beam velocity, about 6.5% of the velocity of light. Proton beams of 100 and 200 MeV/c have been used to estimate the coupling impedance of one coupler. The measured impedance is about one half of the theoretical prediction at 100 MeV/c. This reduction in coupling impedance is thought to be caused by unwanted signals induced at the ends of the pick-up. The available beam current at 60 MeV/c in LEAR is not yet high enough at present to permit measurements of the coupling impedance at the pick-up design momentum.

For momentum cooling, a helix coupler is being fabricated, which will be installed in LEAR in May 1987. The structure is similar to that used in TARN, Ref [17,18]. The pick-up will be located in the straight section used for injection and has an aperture 32 cm wide by 6 cm high. The coupler is divided into three pieces, which are connected in series for 60 MeV/c operation, and give a theoretical coupling impedance of 500Ω at 100 Mhz. With 100 MeV/c beam the couplers can be connected in parallel, and in this way a reasonable coupling impedance at 100 MeV/c can be obtained. The expected maximum is about 200Ω at 70 Mhz.

As part of the overall improvement in low energy performance a series of new more stable power supplies are being installed for the LEAR start-up in June 1987. All of these supplies will be bipolar, i.e. able to change polarity during a machine cycle. Upto now this has not been the case, which has, for example, proved to be a limiting factor in the optimum use of the horizontal dipoles for closed orbit correction and in the sextupolar excitation of the extraction resonance.

As was mentioned earlier, it will be necessary to scan the beam momentum for gas-jet target operation. Until now the momentum scanning process has been restricted to producing one new momentum flat-top in any one machine cycle, but, in this case, momentum scanning has to be possible, whenever requested by the users, and without the injection of a new beam. With the old control system this would not be possible, as the Function Generators, which controled the power supplies could only be updated at the end of a complete cycle. A new series of Digital Function Generators are being developed, which will be updatable on-line. This will make the continuous momentum tuning possible, as well as considerably speeding up the present momentum scanning procedures, since the results of requested changes will be immediately measurable, without the necessity of recycling and injecting a new antiproton pulse.

Continued software effort is required to make effective use of the new hardware, and new programs for the momentum scanning procedure as well as the new Digital Function Generators are under development. Software and hardware development is also continuing in the area of machine surveyance and fault-finding. A new CAMAC unit has been developed to memorise all the cycle timing events as they occur, and make timing system faults easier and quicker to diagnose. It is hoped to simplify the control of the stochastic cooling system, by the use of local intelligence, in the form of several 6809 uprocessors, installed in the local G64 interface.

Work on the machine vacuum system is also underway, to try and push the overall vacuum towards $1\ 10^{-12}$ Torr, by the installation of several new NEG pumps to isolate the machine vacuum from that of the transfer lines. In addition the installation of the gas-jet and the electron-cooler both pose very particular vacuum problems, which have to be solved in order to fully integrate these devices into LEAR. This vacuum improvement is an essential part of the quest for lower and lower momenta, and has made possible some of the sts, which have been performed with H⁻ ions and will __ discussed in the following section.

Studies for future options

The installation of an electron cooler, Ref [19], developed from the original ICE test device, has started and a series of experiments aimed at running-in the device with proton beams are scheduled to take place this summer. In this way we will be able to study the electron cooling itself and the possible combination of electron and stochastic cooling (Ref. [20]), for use with internal targets in the low momentum range (<300 MeV/c).

The availability of H⁻ ions, from Linac 1, has made possible a series of measurements of H⁻ beam lifetimes and stripping mechanisms. A variety of stripping processes have been studied, including intra-beam stripping, beam-gas stripping and photon-induced stripping. For the first time it has been possible to make accurate measurements of the cross-sections for these processes at LEAR energies, and the results show the stripping cross-sections to be somewhat lower than previously estimated, Refs [21,22]. This could open the / to the storage and use of beams of H⁻ ions for perimental physics purposes, e.g. the storage of co-rotating H⁻ and antiproton beams.

Conclusions

The first generation of LEAR experiments have already pushed the machine performance beyond the goals set in the initial machine design, and the second generation promise to extend still further the possibilities of the machine. This extension is possible due to the "consolidation program", which is underway, and the first part of which should be finished in time for the restart of the machine in June 1987. The years to come will see LEAR far beyond its initial role as a low momentum beam stretcher, and rather come of age as a multi-purpose storage and decelerator ring.

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