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LEAR PERFORMANCE

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Abstract

This report retraces the performances of LEAR during its life, the contribution to accelerator physics made at LEAR. It shows also the successful tests on ion accumulation that promises a new life of LEAR

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LEAR PERFORMANCES

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Introduction

In what it is a natural continuation of the talk by Dieter Möhl on LEAR history, I will talk about statistics, which is essentially what LEAR has really provided to low-energy antiproton physics. I will then make a review of the daily machine operation and show some of the contributions of LEAR to accelerator physics, with some emphasis on slow extraction, the heart of LEAR operation. The fun we have had with the filling of the trap experiments, the record antiproton transfer for the internal gas-jet target and the invention of $\bar{H}_0$ is also reported. Some of the studies on different ions and the contributions to physics knowledge are recalled. Part of the test results on accumulation of lead ions for LHC that premised a new life for LEAR are shown.

Overall statistics

During the fourteen years of LEAR operation from July 1983 to December 1996, the statistics [1] in terms of number of spills, number of antiprotons used to set-up the machine or for physics, number of hours of operation and efficiency have been recorded (Figures 1 to 3).

The number of hours scheduled gradually increased during the whole period culminating with 5450 hours in the last year. The efficiency in terms of number of spills used for physics relative to the number of fillings remained around 90% and always above 85% even during 1993/1994 when an instability sometimes developed during slow extraction. This instability was never fully understood and cured. We suspected an ion instability due to the stacking of ions, coming from the ionisation of the residual gas, in the potential well of the antiproton beam. Another possibility could have been charged dust traversing the beam and making losses by single scattering. Neither of these two hypotheses was corroborated by clear observations on the beam behaviour.

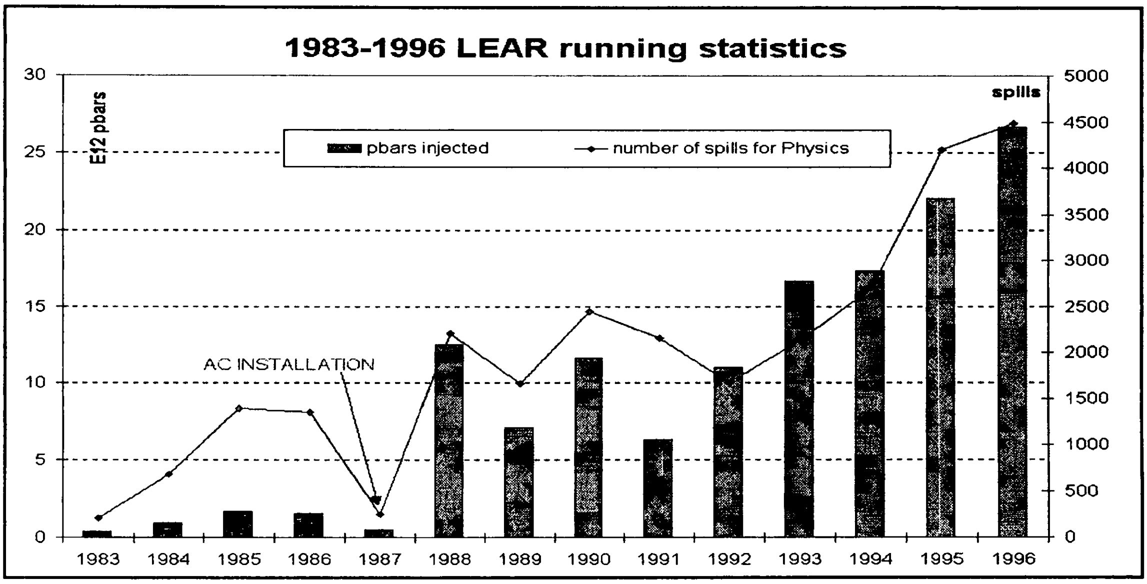

Figure 1: The number of antiprotons injected (bars) in LEAR and the number of spills (squares) is drawn for each year of LEAR operation

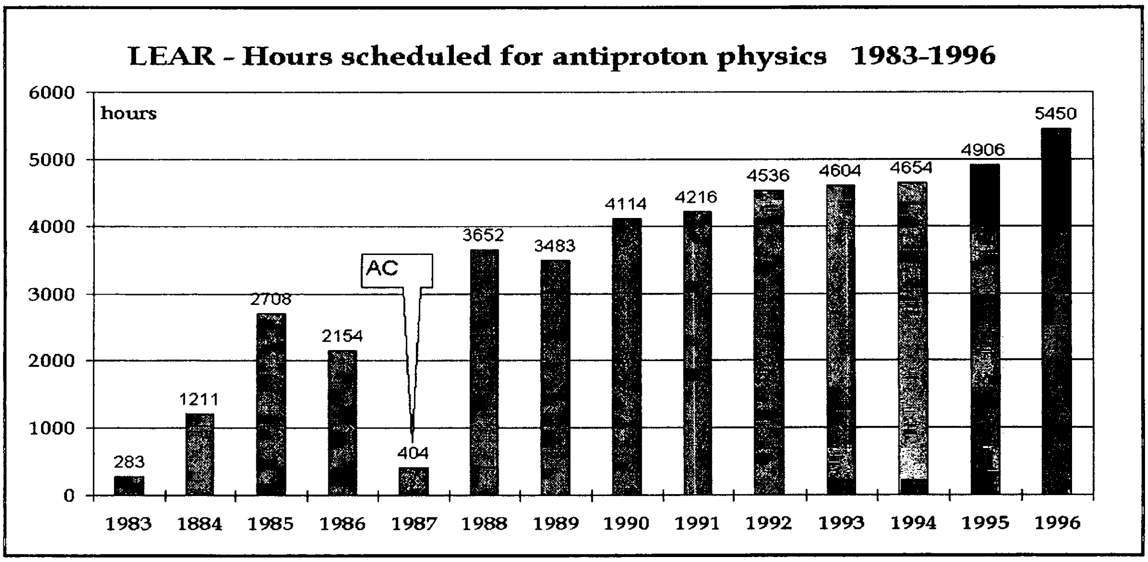

Figure 2: The number of scheduled hours is presented for each year of operation. This takes into account the setting-up time, the physic times and the time necessary for machine development.

The time needed for deceleration below 300MeV/c was decreased for the last five years by the use of the electron cooling system. This gave between 30 minutes and one hour more for physics each day.

The number of antiprotons used has also increased during this period. After the addition of the AC machine [2] in the AA complex in 1987 (ACOL project) a large step in the antiproton consumption by LEAR is observed. When the second generation of LEAR experiments was fully in operation, and the Spp̄S stopped, the gain factor was more then 10 and mainly limited by the flux of antiprotons accepted by the experiments. It is also important to notice that the number of antiprotons per spill increased after the AC start-up. The antiproton stack was larger in the AA leading to more antiprotons transferred to LEAR. A longer spill time was then possible at the optimum flux in the experiments. This had the advantage of increasing the ratio of spill time to cycle time.

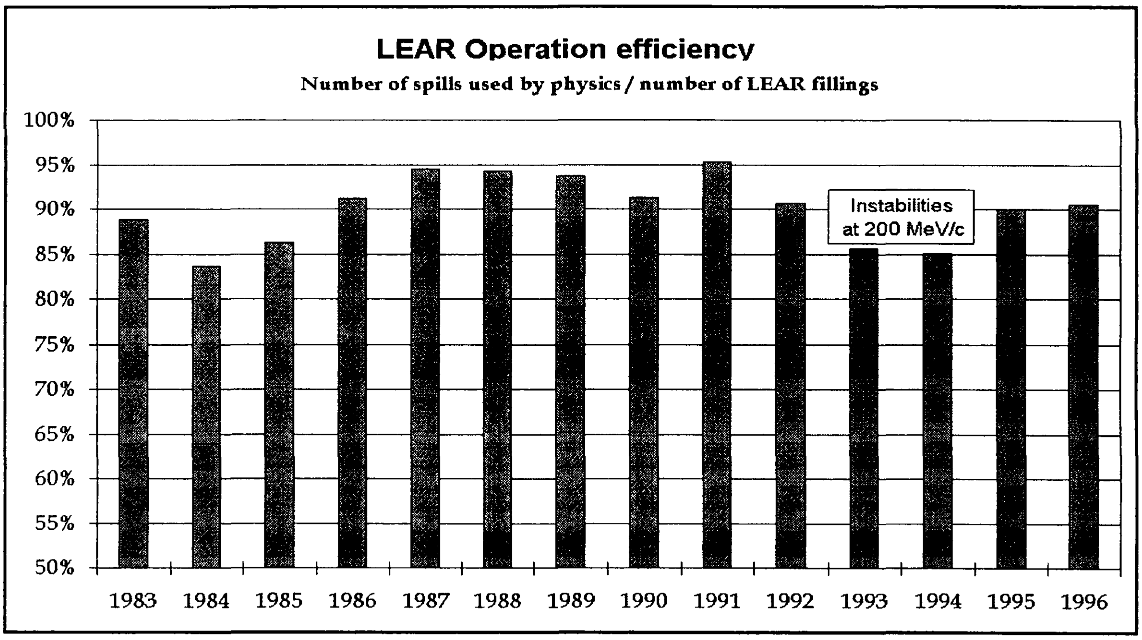

Figure 3: The efficiency defined as the number of spills used by physics over the number of LEAR fillings is drawn for each year of operation.

During the final years of operation, the AA complex used a horn [3] to focus the antiprotons into the AC acceptance instead of a lithium lens. This simplified operation and improved reliability despite a 30% loss for the antiproton collection efficiency. Nevertheless, the stacking was stopped most of the time, to save electricity consummation, as the antiproton stacking rate possibility was larger than the antiproton consumption (Figure 4).

The number of antiprotons used by the LEAR experiments amounted to 1.3 10^{14} dispatched over 26000 spills and 14 years. This represents only 0.2 nanogram of antimatter. The corresponding annihilation energy is 40 Joules, which is the energy consumed by a lamp of 40 W during 1s!

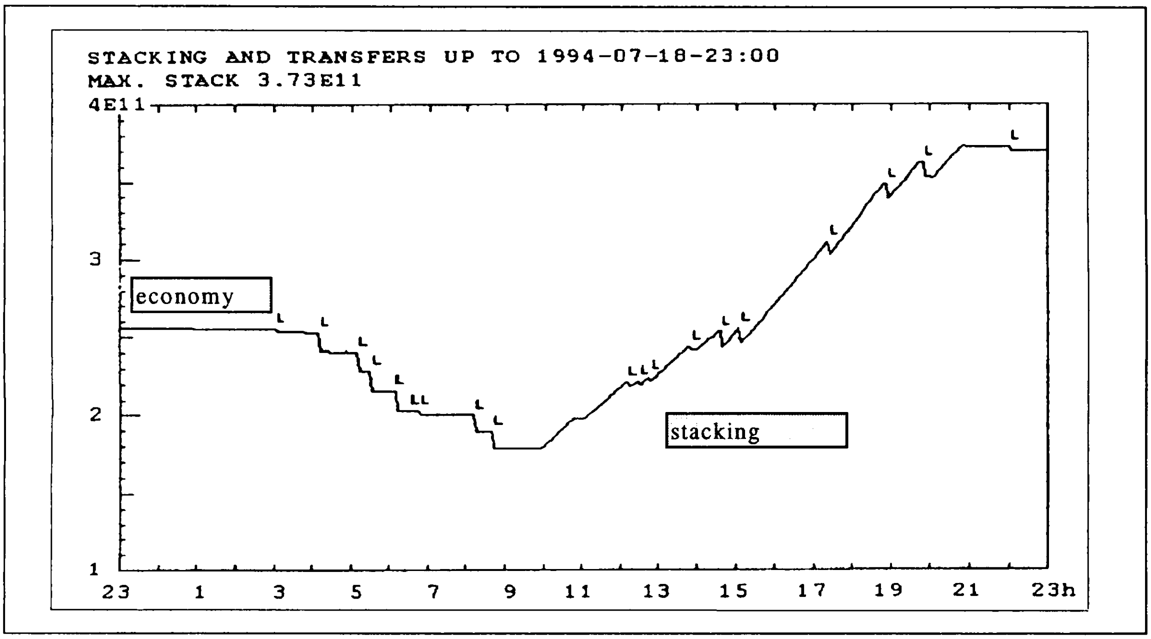

Figure 4:The typical evolution of the AA stack during one day. “L” means LEAR transfer. At the beginning of the day the AA complex is in economy mode (no stacking and AC at low field). As soon as the stack decreases to 2 10^{11}, stacking is re-started.

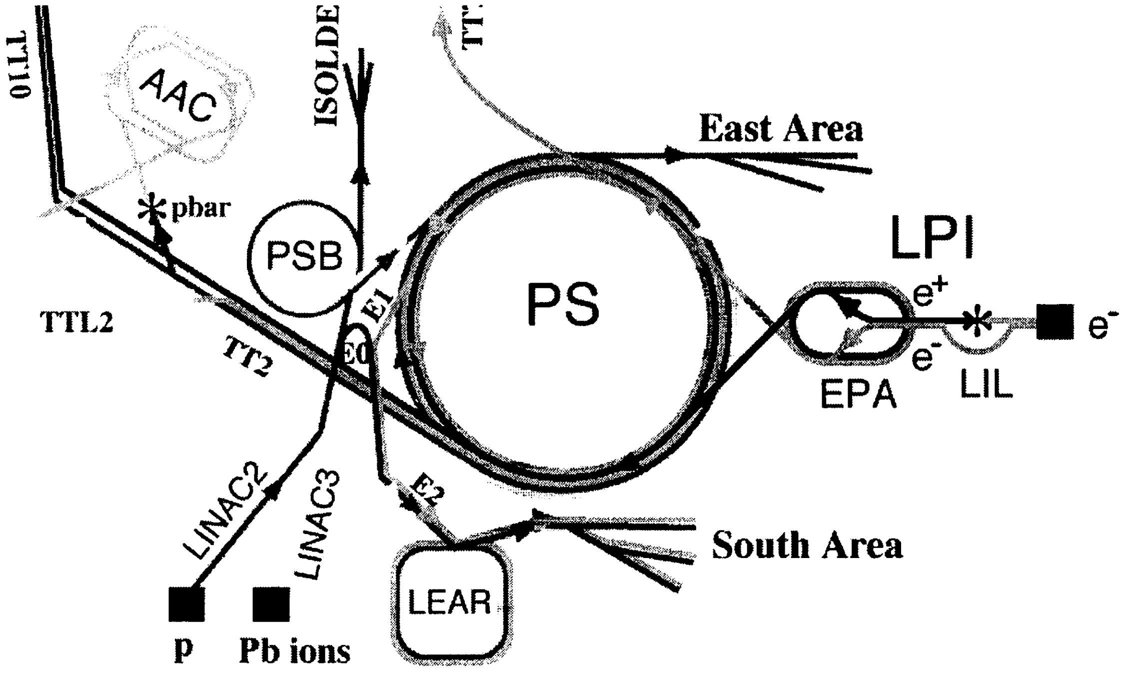

Figure 5: The PS complex at the time of the LEAR operation.

Machine operation

The antiproton transfer from the AA(Figure 5).

From the AA stack (at 3.5 GeV) a batch of some 10^9 antiprotons is taken by creating a bucket of maximum 0.25 eVs, decelerated to change its orbit in the machine and finally extracted via TTL2 loop. The number of antiprotons requested by LEAR and the stack density defined the size of the bucket, the bunching frequency and even the amount of frequency swing during the bunching itself. With a stack of 10^{12} obtained during the Sp$\bar{p}$S operation, a small batch of 10^9 antiprotons could nevertheless be transferred to LEAR efficiently. From the TTL2 loop, the beam was injected into the PS, decelerated to 609 MeV/c (~180 MeV) and transferred to LEAR via the E1-E2 lines. Due to the change of momentum by a factor 6, the beam emittances increased by at least the same factor.

The proton test beam

To test LEAR without using the expensive antiprotons, the LINAC 1 proton beam and later on the LINAC 2 proton beam was injected at 309 MeV/c (50 MeV) through the E0 loop and E2 line.

The machine cycles

The LEAR cycle had to cope with two different momenta at injection and some specific momenta for extraction. One has to note here that all 'front-porches' of the cycle were always and improperly called 'flat-tops' by the LEAR teams. Two types of cycles were defined:

-One for acceleration (Figure 6) up to 2 GeV/c with an intermediate at 1.5GeV/c, just before the main magnet begins to saturate, but also just above the $\Lambda-\bar{\Lambda}$ production threshold. In fact, due to power limitation of the electrostatic and magnetic septa, the slow extraction was never performed at 2 GeV/c but at a maximum of 1.94 GeV/c.

- One for deceleration (Figure 7) with 'flat-tops' at 309 MeV/c, 200 MeV/c, 105 MeV/c, 61.2 MeV/c and 20 MeV/c. As the beam is decelerated, the beam dimensions increase and it is necessary to perform cooling to increase the deceleration efficiency. At the beginning, only stochastic cooling was available. Later on, electron cooling was applied to 'flat-tops' at and below 309 MeV/c.

These two cycles use different power supplies for the main magnets (bending and two families of quadrupoles) to increase the precision of the control of the current at low energy and decrease the ripple on the current, otherwise introduces too much ripple on the extracted flux of particles. After deceleration and prior to debunching, the frequency of the RF was automatically and carefully settled to predefined values in such a way that the longitudinal cooling systems had little to do in terms of mean momentum. This was done by controlling the amount of bdot pulses (each 0.1Gauss) sent to the frequency generation system for each deceleration.

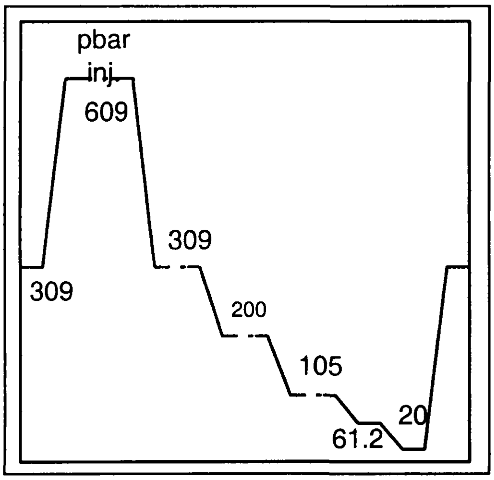

Figure 6: "Low Energy" cycle for the operation down to 61.2 MeV/c. The 20 MeV/c flat-top is only set for main magnet magnetisation reproductibility.

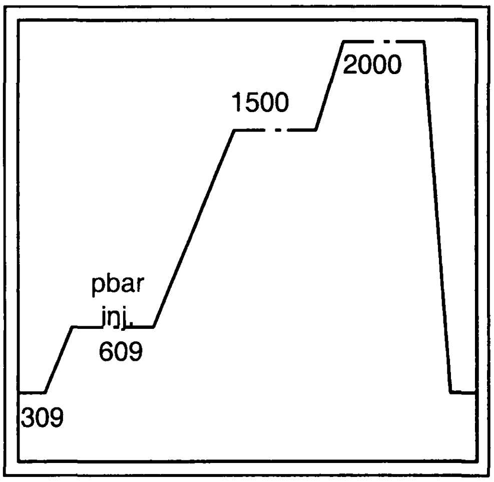

Figure 7: "High energy" cycle for the operation up to 2 GeV/c.

The machine control

Due to the number of 'flat-top' s [4] covering a factor 30 in momentum, all the magnetic elements have been controlled individually through function generators (GFA) and power supplies. These GFAs were sequenced by a powerful timing system permitting:

- Cycles length of up to 120 hours with a resolution of 1 ms.
- Cycle stop on request on each 'flat-top'.
- Abort cycle to compress the cycle time when the beam was lost.

The cycle editor allowed the connection of all the events needed in a tree sequence. The links between events were all easily programmable giving the possibility of having a main trunk sequence and some other local sequences linked to it

The GFA [5] was in fact a digital function generator (the DAC being in the power supply itself) which can be started and stopped from the timing system. The function was then only activated when necessary during the cycle.

The hardware system, shortly described above, fully controls all of the physical parameters (tune, orbit correction and orbit bumps, chromaticities, compensation or excitation of the resonance's...) of the machine on each of the 'flat-tops' and ramps. The physical parameters measured were corrected through high level programs, which can modify the corresponding GFAs at the right time in a fully automatic way. This required the building of a database containing all the characteristics of the machine (Twiss parameters), of all the machine elements (current versus field...). The way the control system was build also allowed the momentum scanning (see below).

Cooling systems

Since the beginning of LEAR, stochastic cooling systems [6] were implemented to reduce the beam size and momentum spread after each deceleration. They were mainly used at the standard 'flat-tops' defined above. It was also possible to use them for every momentum between 200 and 2000 MeV/c as all the delays where built in a binary way (next delay equals twice the previous one). About 700 wide band and reliable relays where necessary. The useful frequency bandwidth (linear phase and flat gain curves) was properly adjusted between 10 and 1000 MHz. A special system was built for 105 and 61.2 MeV/c using travelling wave pick-ups. All these systems had a cooling time of about 200 s. The cooling is defined as the time to reach the equilibrium between cooling and heating (Intra Beam Scattering for example)

In 1987, the refurbished old ICE electron cooling was installed [7] and later on put into operation. It was then possible to reduce the cooling time to 20 s for each of the low energy 'flat-tops'. It was operated [8] in a pulsed way to avoid non-linear effects introduced by the solenoid and toroïd magnets during slow extraction.

Beam diagnostics

The instrumentation systems were all built to measure beams of some 10^9 particles and even below. The 32 electrostatic pickups were able to measure the orbit with a precision of 0.5 mm. The capability of the Schottky pickups was even better as we could measure beams of 10^7 particles at 105 MeV/c with a $\Delta p/p$ of about 2‰.

The measurement of the tune (and consequently the measurement of the chromaticities and the phase advance between pickups) was an important tool at LEAR. Two methods were developed:

- One used the residual oscillation of the beam at injection or the oscillation provoked by a kick to the beam. A bunch synchronisation system was developed to provide pulses centred on the bunch, which allowed to measurement of the beam position turn by turn. A Fast Fourier Transform was applied on the 1024(or less) turns recorded, and using the frequency finding algorithms [9] developed by E. Asseo the tunes could be measured with high precision despite the bad signal over noise ratio specially if the beam was partially lost. This system was very useful when the beam was lost during deceleration to very low energy.

-The second one was the Beam Transfer Function (BTF): using a network analyser, the beam was excited successively at two consecutive transverse modes (n+q, n+1-q) and the response, captured from a resonant pickup,was compared to the excitation. With these two measurements, the tune and accessory the revolution frequency can be determined on a 'flat-top' . By changing the momentum of the beam we could also measured the chromaticities. This was essential for the slow extraction.

Ultra slow extraction

The ultra slow extraction is an extension of the slow extraction well described in the literature. The main difference is in the way the particles are driven to the third order resonance. Contrary to the conventional slow extraction schemes, the tune of the main part of the beam is not changed, only some particles are driven to the resonance [10]. The upper part of the beam distribution is heated by adding some noise around a harmonic of the revolution frequency. The particles that see this noise diffuse by acceleration to the resonance. The diffusion in tune is obtained by a careful setting of the chromaticity. The noise distribution should always cover the frequency mode corresponding to the resonance and the upper side of the beam distribution. The carrier frequency, which supports the noise distribution, is then moved slowly toward the beam frequency distribution, heating particles at the upper edge of the beam distribution. During the LEAR era, two ways of creating the noise distribution were used:

-At the beginning (Figure 8), a simple low-frequency noise (bandwidth Δf) was mixed with a carrier frequency f_0, making a noise bandwidth $2\Delta f$ around f_0. The bandwidth $2\Delta f$ was very large (from the resonance frequency to the frequency of the lower edge of the beam distribution). Then at the beginning of the spill, for low-energy slow extraction, the noise was also heating the beam transversally as it was covering one of the transverse modes. During that period, prior to extraction, the beam distribution was shaped to a uniform distribution by applying noise heating around a longitudinal frequency mode. With that uniform distribution, the carrier frequency of the extraction noise was changed quasi linearly with time, making it easier to control the uniformity of the spill over time. When the number of antiprotons present at extraction increased, this well shaped distribution had a tendency to diffuse (external noise, IBS...) and it became more and more difficult to control the spill.

-To overcome these inconveniencies, it was decided to keep the beam under cooling during extraction, to have a noise generation system such that the upper side of the noise distribution stays fixed during extraction and the lower part moved (Figure 9). A feed back system (piece of software) which used the counting rate measured by the physics experiments and compared it to a defined value and acted onto the noise advancement. This system [14] proved to be so powerful that it permitted long and constant spills, making life easier for the operation team and saving time since the beginnings and the ends of the spills were sharper.

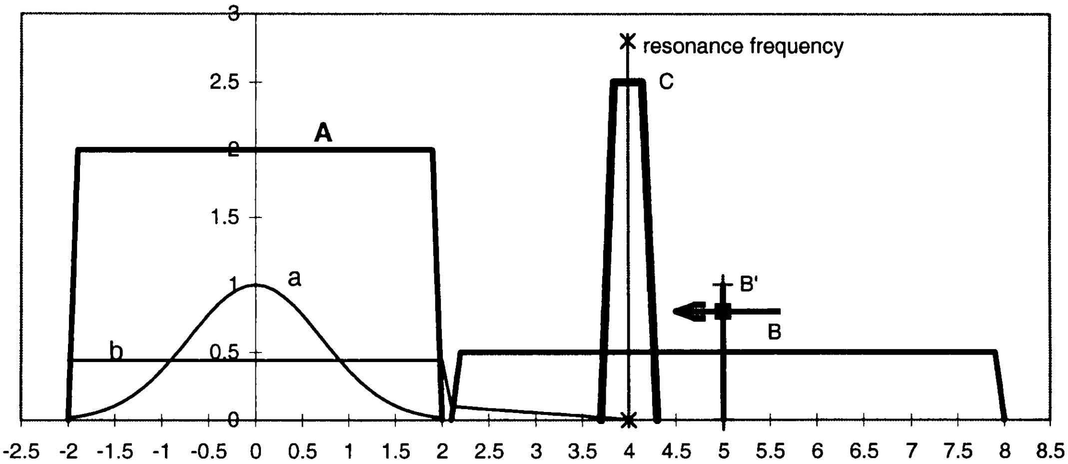

Figure 8 Scheme of the noise arrangement for the slow extraction at the beginning of LEAR. The noise A was applied first to make a uniform beam distribution b, then the noise B was applied. The carrier frequency of the noise B is moving toward the beam distribution. In addition a strong noise power C but with narrow bandwidth was applied around the resonance frequency to decrease the ripple on the extraction flux. Note that the horizontal axis is frequency, tune, radial position or momentum deviation (adopted here).

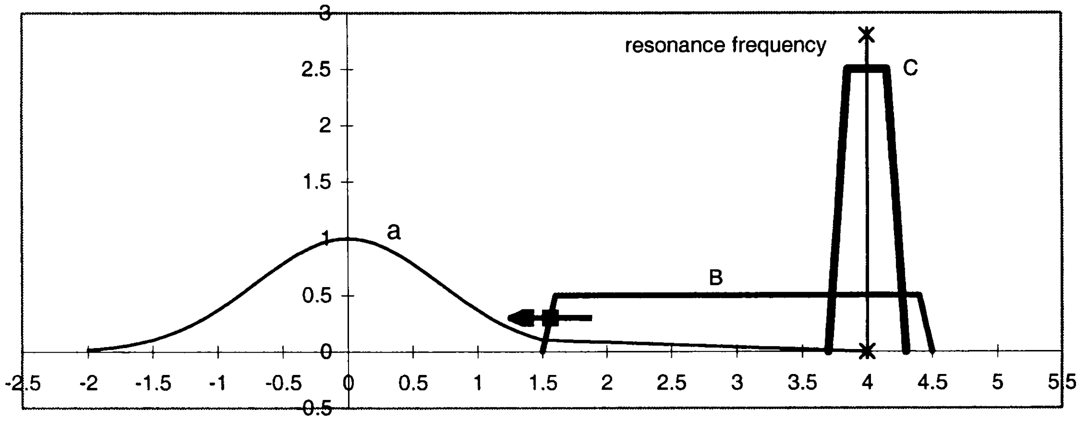

Figure 9: Scheme of the noise arrangement in the second part of the LEAR era. Longitudinal (and transverse) stochastic cooling was continuously applied. The low frequency edge of the noise B distribution is moved slowly into the beam. A strong noise C is applied at the resonance frequency.

Not only did W. Hardt propose the way of driving the particles into the resonance (following a first proposal of S. Van der Meer [11]) but also he proposed to align the outgoing separatrices in transverse phase space. This alignment means that all the separatrices going to the electrostatic septum were superimposed independent of the original amplitude of oscillation of the particles. The horizontal emittance of the extracted beam is then theoretically zeroed and particles have the lower possible interception on the electrostatic septum. But it imposes a relation between the horizontal chromaticity and the amplitude and phase of the sextupolar resonance. This had to be applied for the set-up of the extraction and it implied the development of sophisticated and precise methods to measure the chromaticity, to compensate the natural force of the resonance of the machine, and to measure at least the phase of the resonance when excited.

After the start-up of the machine, it was found that the horizontal emittance was not as low as originally tough and that the sextupole strength required drove a systematic sextupolar resonance strongly, which was close to the working point. Two additional sextupoles where added to compensate this resonance. The extraction went more efficient but also the lifetime of the beam increased especially at low energy (from 15 to 50 minutes at 105 MeV/c). The addition of these two sextupoles gave a strong second-order chromaticity. When the internal target experiment was approved (JETSET), further sextupoles were added together with vertical dipoles as pole face windings on each of the extremity blocks of the main dipoles where the dispersion function vanishes.

During LEAR commissioning, it took a long time to have the first proton beam slowly extracted at 309 MeV/c . In the evening of the 19th of April 1983, the first 1 minute spill was observed at 20h40 at the end of the measurement line (Figure 10) on a CsI scintillation screen. The next spill lasts for 5 minutes, the third one for 15 minutes (the design value [12]). While drinking Champagne, we could contemplate a thirty minutes spill, later nobody remembered the first one hour spill (even not written in the logbook!). This was a great achievement as prior to LEAR the longest spills were of some seconds only. Very soon after the start up, the one-hour spills became the most popular and were used at many momenta. At the end of the LEAR era, the number of transfers per day was minimised as it was chosen to transfer from the AA the maximum number of particles compatible with an efficient operation, leaving free the spill length

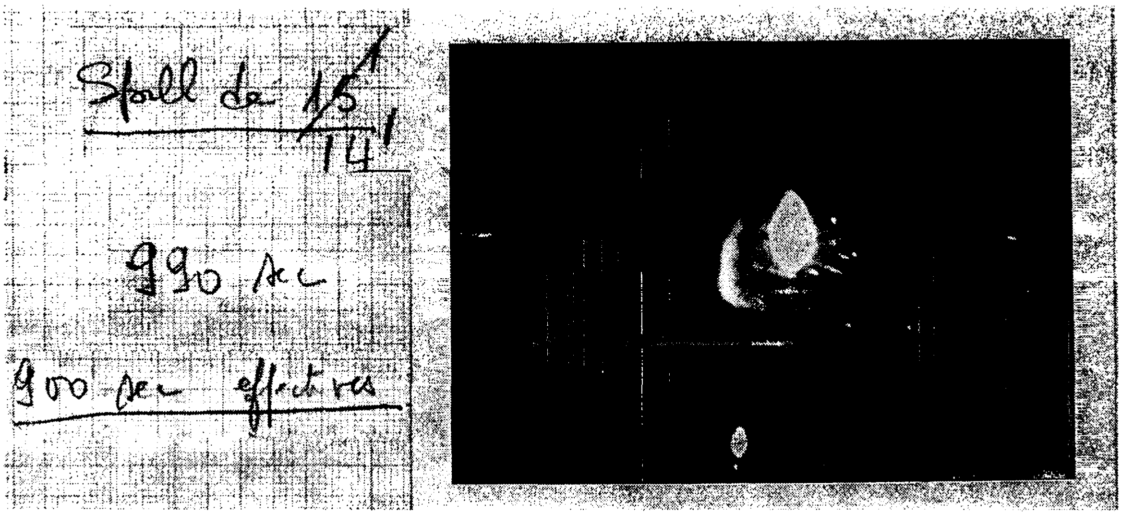

Figure 10: Part of the page of the logbook of 19th of April 1983 showing the "LEAR candle".

but controlling the flux asked by the physicists. In that way, we could contemplate spills of many hours (Figure11) at 309 MeV/c while serving two experiments in parallel at 30000 antiprotons per second. The maximum spill length ever observed last for 14 hours. Probably the most delicate spills were delivered in parallel (Figure 12) to CPLEAR (900000 antiprotons/second but not more otherwise their wire chambers would drive too much current) and CRYSTAL BARREL (less than 50000 antiprotons/second).

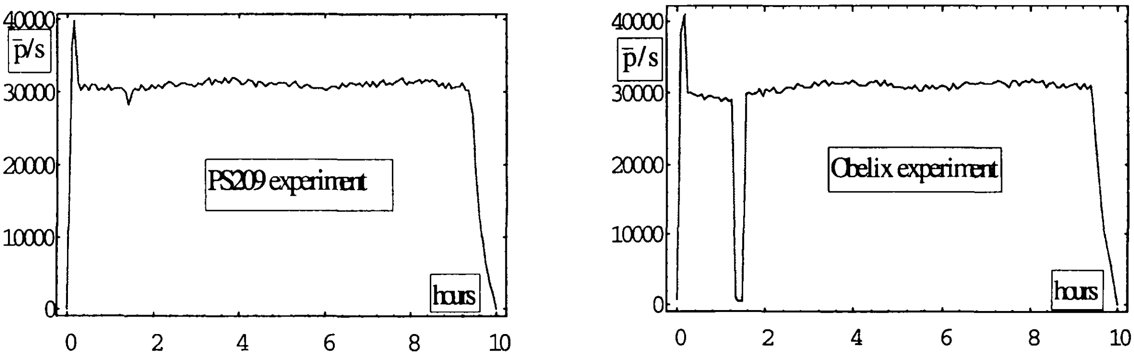

Figure 11: A typical spill, which lasts for 10 hours for two experiments, served in parallel. For this picture one measurement point represents the integration of the counting rate for 10 seconds

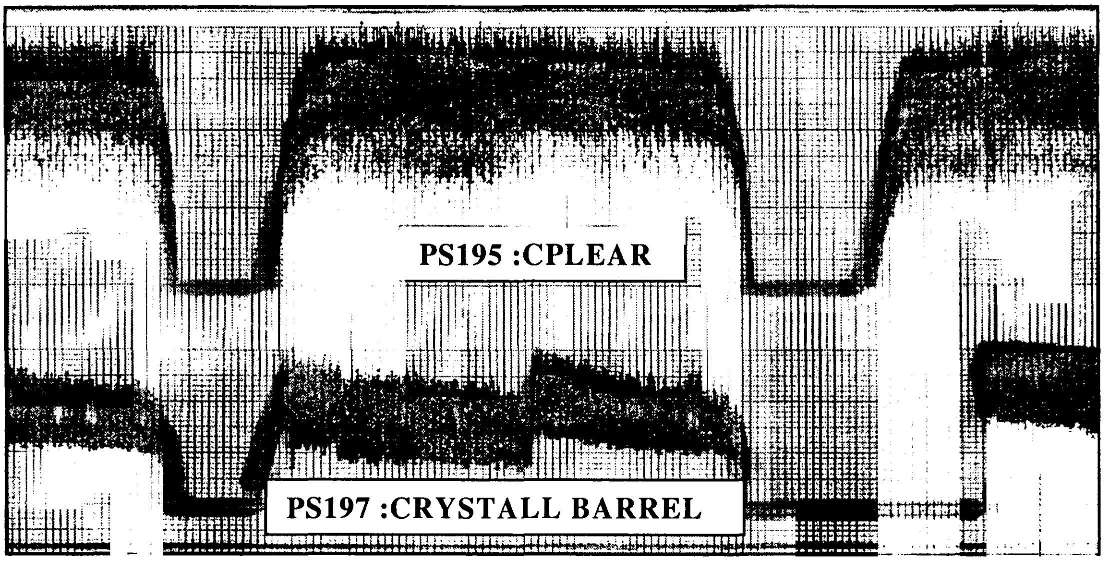

Figure 12: One of the numerous spills delivered to CPLEAR and CRYSTALL BARRELL in parallel. It lasts for 70 minutes. The counting rate (counting for 100 ms) is transformed to a voltage which is filtered (band pass 10 Hz) and recorded.

One of the main problems the LEAR team had to face was the ripple in the spill. Low harmonics of the power line were present. W. Hardt proposed a first solution. It consisted of applying a strong noise [13] power just around the resonance frequency. When there is ripple on the tune coming from the power supplies, we can consider that the tune of the particles is fixed but the frequency of the resonance is wobbling. Applying a strong noise called "the chimney" around the resonance frequency provides a fast diffusion of the particles approaching it. If the diffusion of the particles is faster than the movement of the resonance the ripple on the spill is decreased. It can be compared to the constant flux exiting a funnel even if its filling is slow. This was applied successfully but the power needed implied very linear power amplifiers. Later on it was found that the phase and amplitude of the ripple was constant with time (even days and months). Then an air core quadrupole was installed into the machine to compensate the tune ripple. An HiFi amplifier controlled by a GFA generating the appropriate frequencies (amplitude and phase) synchronised on the mains powered it. In this way, the ripple on the spill was greatly reduced and then "the chimney method" worked more efficiently (less noise power needed). The golden events recorded by

CPLEAR increased from 20 to 30 per second (from 200 to 300 tapes per day!) when the quadrupole was properly set-up.

During the operation, we have very often verified that the extraction was stochastic by two methods:

-The distribution of time intervals between two extracted particles was a decreasing exponential.

-The distribution of particles arriving in a short time interval was close to a Poisson distribution except when the spill ripple was too large.

Extraction lines

There were two different arrangements [15,16] of the experimental area during the LEAR era. While during the first 5 years only six areas were accommodated to serve about 16 experiments, there were up to eight areas during the last years (Figure 13). Some of them were devoted to big experiments, others were shared by different smaller experiments. It was possible to distribute the slow extracted beam to a maximum of 3 experiments in parallel by splitting the beam using vertical magnetic splitters with limited beam losses. This proved to be an efficient way of using the expensive antiproton beam. The most difficult gymnastic turned out to be the sharing of 5% for CRYSTAL BARREL and 95% for CPLEAR due the vertical beam dimension evolution along the spill time. Collimators controlled the final flux to CRYSTAL BARREL.

Fortunately, it was not very often that we had to serve 3 experiments in parallel, as the momentum requests were different.

The optics of the line was adapted to each of the experiments and it proved to be efficient. The difficulties came mainly from the scattering of the measurement systems installed in front of the targets. The experimentalists through INTERNET could control the last elements of the lines.

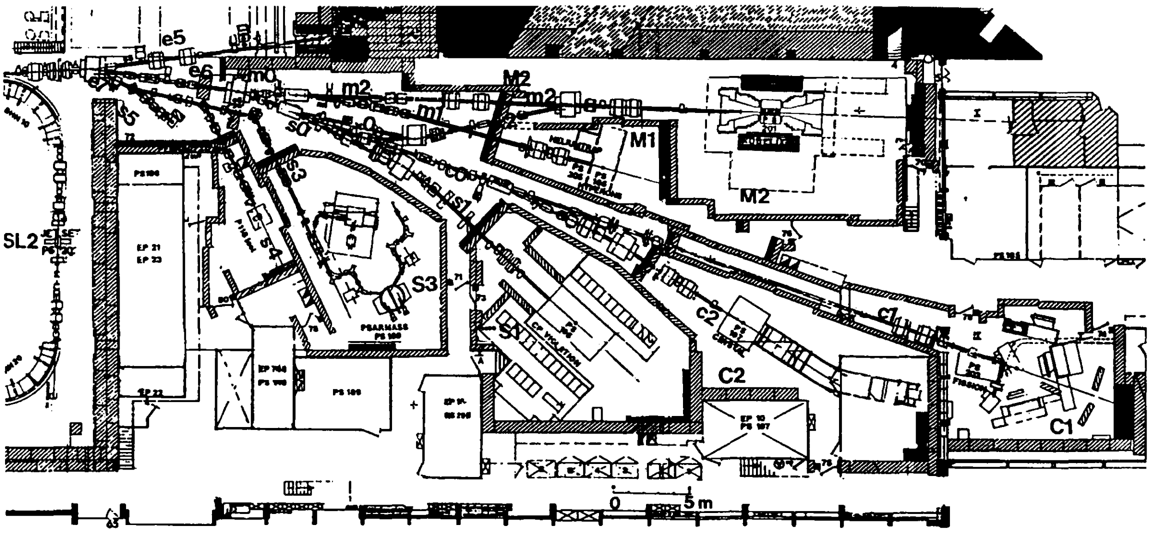

Figure 13: The experimental area during the last year of LEAR running.

Momentum scanning

The goal was to change the slow extraction [17] to a new momentum in less than 2 hours. If a new momentum was requested between two 'flat-tops', the second 'flat-top' was moved earlier (Figure 14). A learning process was implemented in the following way:

-First, a slow extraction was performed on the first 'flat-top' then on the second one. The controlled values of the sixteen GFAs were saved (both the values on the cooling 'flat-top' and on the extraction 'flat-top' module).

-Second, a linear interpolation was made to compute the expected values foreseen for the new momentum requested. All the 70 GFAs and their associated timings were modified and sent to the hardware. The stochastic cooling settings were computed as well.

-Third, a beam was taken, the machine parameters verified and adjusted (tunes, orbit...), the stochastic cooling adjusted, the ejection noise generation system settled.

-Fourth, in the same way the controlled current of the magnetic elements of the line were computed and sent to the hardware.

-Finally, when the beam was extracted, fine-tuning of the extraction parameters occurred. In the same way the extractions lines were adjusted. The controlled parameters obtained were saved for further scanning. The next scan can then be made by higher order interpolation, becoming easier and faster.

This method proved to be efficient, especially when the experiments asked for one or even for two scans per day. The main momentum scanning campaigns were:

-The systematic scans from 309 to 609 MeV/c every 10 MeV/c for s-meson search. Unfortunately it was not found.

-The systematic scans around and above 1436 MeV/c to study the $\Lambda-\bar{\Lambda}$ production behaviour above threshold. The scans between 1500 and 1940 MeV/c for Σ physics. The latter appeared to be the most difficult due the non-linearity of the main bending field approaching saturation

-The scans from 400 MeV/c to 1940 MeV/c for polarisation measurements.

- The scans for JETSET experiment for $\Phi-\Phi$ study.

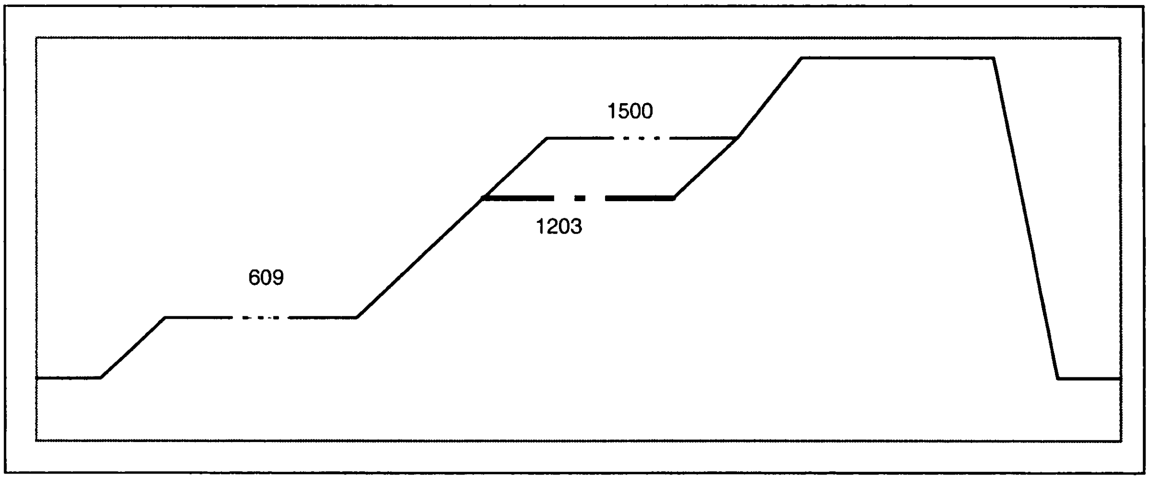

Figure 14: The way the cycle was modified during momentum scanning is shown (from 1500 to 1203MeV/c).

Fast extraction

In 1985 G. Gabrielse(PS196) proposed to stack antiprotons in a magnetic trap [18]. It was decided to extract a part of the LEAR circulating beam at 105 MeV/c, to further decelerate the beam by degradation through foils and/or through gas and then kept the antiprotons which have the matched energy of the trap (0 to 2 keV). Soon afterwards, PS196 experiment was followed by PS200, which used a larger capture voltage (30 keV). Part of the coasting beam was extracted using a kicker. This was not a clean operation as the rise and fall parts of the kicker pulse give losses. But generally we used a 100 ns pulse (over 2.5 μs of revolution time) to serve the experiments. With the same circulating beam, many pulses can then be sent to the experiment at their request. This operation was much more efficient when the electron cooling system came into operation. The beam size was smaller (Figure 15) and it matched the small extraction channel. When working a 200 MeV/c slow extraction, we interrupted the slow extraction towards the end, kept and cooled the remaining antiprotons, decelerated them to 105 MeV/c and serve the trap experiments. In this way, fast extraction for the "trap experiments" could be done parasitically and time was saved.

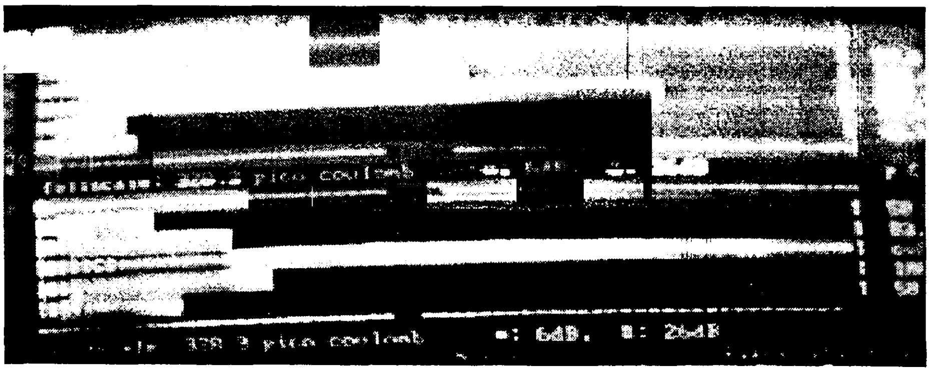

Figure 15: Example of the horizontal and vertical beam profile observed at the entrance of PS196. One bin is 3mm wide.

Internal target and $\bar{H}_0$

The internal gas-jet target [19], part of the experiment PS202, was installed in the LEAR straight section 2. This implied a major modification [20] of LEAR (sextupoles and vertical dipoles, reshuffling of the straight section, addition of strong vacuum pumps....). It was also an every day excitation to transfer a large number of antiprotons (up to 7.4 10^{10} in coast), to keep them cool at the right momentum with the stochastic cooling. Most of the time we observed transfer around 5 10^{10} antiprotons and their lifetime was of the order of 50 hours with a hydrogen target of 3 10^{12} atoms/cm^2.

Knowing the ideas of Munger, Brodsky and Schmidt [21] to produce $\bar{H}_0$ on an internal target, some of us have tried to measure them at the exit of a thin window installed in an extension of the straight section 2. But our inexperience was obvious and during a coffee break in the PS cafeteria we proposed to Walter Oelert and Kurt Kilian to study the possibility of observing these $\bar{H}_0$. This led to some preliminary experiment and the final acknowledgement of the PS210 experiment using a Neon target to improve by a large factor the $\bar{H}_0$ production. After the nine or eleven $\bar{H}_0$ detected, the LEAR machine was invaded by the media proving that the fundamental physics can be a matter of public interest.

OTHER SUDIES AT LEAR

During the LEAR era, many other subjects have been studied:

-The electron cooling was extensively used and tested. the neutralisation [22] of the electron beam, the stability of the well-cooled proton or antiproton beam, the computation of the tune shift of a well-cooled beam using quadrupole Beam Transfer Function measurement [23] and the cooling tests on different ions (O^{6+},O^{8+},Pb) are all worthy of note.

- H^- beams were injected from the old LINAC to study their lifetime [24] and to prepare the foreseen experiment with co-rotating antiprotons and H^-. There was the surprise of the influence of light (particularly switching off the gauges, which use hot filament) that improved their lifetime from 7 s to 70 s and the measurement of the intra-beam stripping cross section that are two major results.

-The charge exchange injection was also tested to anticipate the use of LEAR as a proton-antiproton collider at low energy.

-For one experiment, we set up a “fast-slow” extraction at 61.2 MeV/c (2 MeV) lower than the design limit of 100 MeV/c. The beam was kept under electron cooling, at a tune close to third order resonance. We kicked it outside the stable area defined by its emittance and the force of the resonance. We then obtained an extraction of 0.5 ms long matching the time acceptance of the Radio Frequency Quadrupole linac (RFQ) installed downstream in the line. The RFQ should decelerate the beam down to 200 keV. Although we have verified that the extraction was efficient, and synchronised on the PS supercycle and on the mains, the experiment never saw a good beam at the exit of the RFQ.

FUTURE OF LEAR

To improve the LHC ion luminosity by a factor 100, it was proposed to use LEAR as an ion accumulator [25] profiting of the electron cooling system. Extensive tests have been done during the last years of LEAR running. The large charge exchanged cross section [26] measured between Pb^{53+} and the electrons of the electron cooling led to the use of Pb^{54+} (its cross section is 6 times lower). Encouraging results were then obtained:

-Combined longitudinal multiturn injection was successfully tested.

-The large size injected beam was cooled in less than 400 ms.

- Up to 6 10^8 Pb^{54+} ions were stacked (Figure 16) instead of the 12 10^8 required for LHC.

This is encouraging for the use of LEAR for LHC even if a factor 2 in stacking time and a factor 2 in the number of ions stacked are missing in these tests.

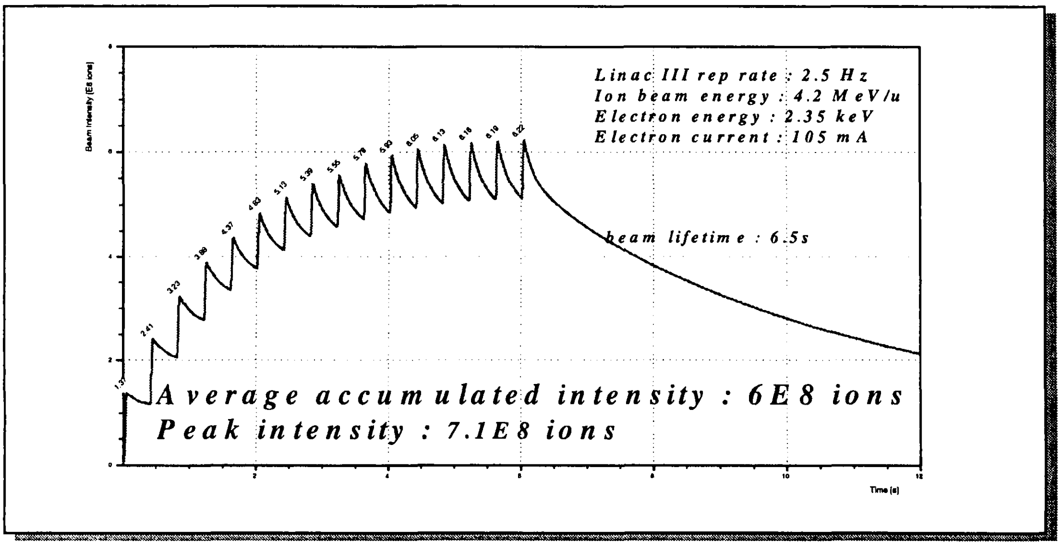

Figure 16: Accumulation by multi injection of Pb54+ ions.

CONCLUSION

LEAR was a very exciting machine that was close to being all things to all men. It was an accelerator, a decelerator, a storage ring, a cooler ring and also a heater ring, Sometimes it was dominated by space charge effects, and often operated rare and costly particles of low and high energy. They were distributed to experiments most of the time one by one using ultra slow extraction, in a packet by fast extraction or as a whole beam interacting with gas target.

After 15 years of fantastic physics progress, what can you enjoy more? Life surely?

Et quel ne fut pas mon plaisir de travailler avec Pierre et Dieter?

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