ELECTRON COOLING OF Pb^{54+} IONS IN LEIR

G. Tranquille, CERN, Geneva, Switzerland

Abstract

Electron cooling is central in the preparation of dense bunches of lead beams for the LHC. Ion beam pulses from the Linac3 are transformed into short high-brightness bunches using multi-turn injection, cooling and accumulation in the Low Energy Ion Ring, LEIR. The LEIR cooler was the first of a new generation of coolers utilising high-perveance variable-density electron beams for the cooling and accumulation of heavy ion beams. It was commissioned in 2006 at the same time as the LEIR ring and has since been used to provide lead ions for the commissioning of the LHC injector chain.

We report briefly on the status of the LHC ion injector chain and present results of measurements made to check and to better understand the influence of the electron beam size, intensity and density profile on the cooling performance. Future plans to improve the performance of the device will also be presented.

IONS FOR LHC

The LHC physics program with heavy ion (lead-lead) collisions at luminosity of 10^{27} $cm^{-2}s^{-1}$ will be achieved by upgrading the ion injector chain: Linac3-LEIR-PS-SPS [1]. The main part of the modifications is the conversion of the Low Energy Antiproton Ring (LEAR) to a Low Energy Ion Ring (LEIR), which transforms long pulses from Linac3 to high-density bunches by a multi-turn injection and an accumulation with electron cooling. The conversion of LEIR included new magnets and power converters, high-current electron cooling system produced by INP Novosibirsk, broad-band RF cavities, upgraded beam diagnostics and vacuum equipment to achieve 10^{-12} mbar. The complete accelerator chain for LHC ion operation indicating the major hardware changes that have been made on the different machines is shown in Fig. 1.

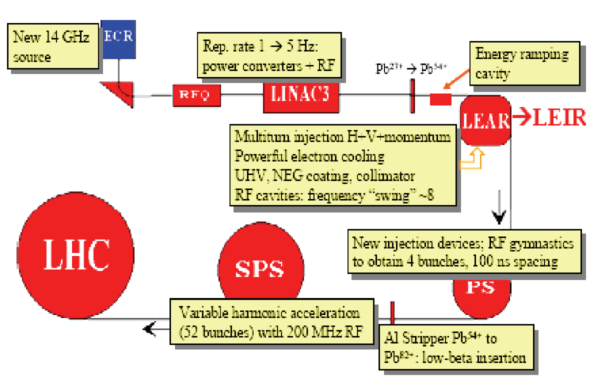

Figure 1: Hardware upgrades in the LHC injector chain.

In the nominal scheme, the injector chain will provide the LHC with 592 bunches of $9x10^{7}$ ions in each ring. This beam may be subject to limitations in the injectors and also in the LHC. These effects are difficult to predict, so it has been decided to start with a beam whose characteristics allow the limitations to be explored with reduced risk. The "early beam" (Table 1) has a reduced number of bunches (60 per LHC ring with 1.35 µs bunch spacing) but with the same bunch intensity as in the nominal scheme, yielding a luminosity of $5x10^{25}$ $cm^{-2}s^{-1}$. This beam will allow the study of fundamental limitations in the LHC rings without the risk of damaging the equipment and will also enable early physics discoveries.

Table 1: Beam Parameters along the Injection Chain for "early" LHC Ion Operation

	ECR Source →	Linac 3 →	LEIR →	PS →(4, 2)	SPS →(12)	LHC
Output energy	2.5 KeV/n	4.2 MeV/n	72.2 MeV/n	5.9 GeV/n	177 GeV/n	2.76 TeV/n
^{208}Pb charge state	27+	27+ → 54+	54+	54+ → 82+	82+	82+
Output Bρ [Tm]		2.28 → 1.14	4.80	86.7 → 57.1	1500	23350
number of bunches			1 (1/8 of PS)	1	4, 2	62/ring
ions/pulse[1,2]	$9\ 10^{9}$	$1.15\ 10^{9}$	$2.25\ 10^{8}$	$1.2\ 10^{8}$	$\leq 3.6\ 10^{8}$	$4.3\ 10^{9}$
ions/LHC bunch	$9\ 10^{9}$	$1.15\ 10^{9}$	$2.25\ 10^{8}$	$1.2\ 10^{8}$	$9\ 10^{7}$	$7\ 10^{7}$
bunch spacing [ns]					1350	1350
ε*(nor. rms) [µm][3]	~0.10	0.25	0.7	1.0	1.2	1.5
ε (phys.rms) [µm][3]	50	2.5	1.75	0.14	0.0063	0.0005
Repetition time [s]		2.4	2.4	2.4	18	~5'fill/ring
total bunch length [ns]			200	3.9	1.65	1

[1] 200 eµA x 200 µs (Pb^{27+}) from ECR source, 50 eµA$_{e}$ x 200 µs (Pb^{54+}) from Linac3 after stripping
[2] Pessimistic assumptions on losses in LEIR. Optimistically LEIR can produce up to 4.5 10^{8} Pb ions per cycle with a single Linac3 pulse.
[3] Same physical emittance as protons. ε*(normalized) = β γ ε (physical) invariant if no blow-up

⋮ Stripping foil

LEIR beam commissioning started in summer 2005 with a short run with oxygen ions. In 2006 lead ions were used to fully commission the machine and to start delivering beam to the PS ring. This confirmed the ability for LEIR to routinely produce the "early" ion beam for the LHC. 2007 was devoted to sending beam to the SPS and to initiate studies on the "nominal" beam. Unfortunately, the "nominal" LEIR beam has not yet been fully demonstrated; although sufficient intensity could be accumulated on the low energy plateau, the nominal intensity of $4.5x10^{8}$ Pb^{54+} ions per bunch was never attained due to losses at the beginning of the ramp. Understanding the reasons for this loss will be the main focus of investigations this year. The performance achieved for the "early" and "nominal" beams in LEIR is summarized in Table 2 and the LEIR cycle showing the evolution of beam intensity can be seen in Fig. 2.

Table 2: Performance of early and nominal LEIR Beams

	Early	Nominal
N [10^8 Pb^{54+} ions/bunch]	2.2	3.7
I [10^{10} charges/bunch]	1.2	2.0
ε^*_H [µm]	0.5	0.5
ε^*_V [µm]	0.2	0.2
$\varepsilon_{//}$ [meVs/u]	40	50
τ_B [ns]	200	200

In the PS ring a number of RF issues were solved before the 2007 run such that the required intensity of 1.2×10^8 Pb^{82+} ions per bunch could be delivered to the SPS. The sensitivity of the head amplifiers of the radial loop was increased by 6 dB curing the beam loss that occurred at the start of the accelerating ramp and a 30 dB attenuation was introduced in the synthesizer signal to reduce the crosstalk with the phase pick-up signal at injection energy.

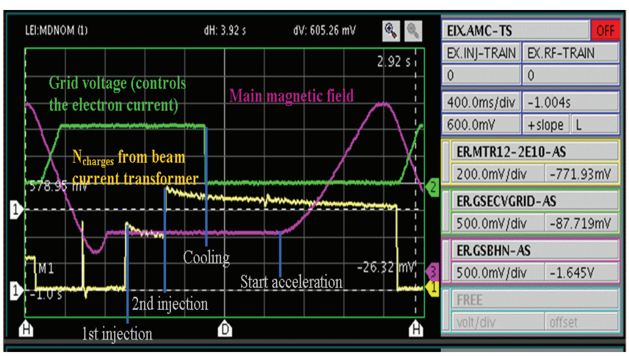

Figure 2: A standard 3.6 s LEIR cycle during which 2 LINAC pulses are cooled-stacked in 800 ms at an energy of 4.2 MeV/n. After bunching the Pb ions are accelerated to 72 MeV/n for extraction and transfer to the PS.

In addition a stand-alone frequency programme was implemented for the ion beam control as the system used for protons was too coarse resulting in the beam being shaken at each B-train pulse at low energy.

An accurate re-matching of the PS to SPS transfer line (TT2) was also necessary in order to take into account the change in the optical functions due to Coulomb scattering of the ions as they pass through the stripping foil.

Much time was devoted in the SPS to study the behaviour of bunches at the injection plateau. This is a source of concern for the "nominal" beam where the bunches will have to wait up to 40 seconds and will be subject to space-charge and intra-beam scattering. The measurements confirmed that, despite a space-charge detuning as high as $\Delta Q_{sc} = 0.092$, there is no transverse blow up of the beam over periods of the order of one minute. Up to 4 single bunch injections were performed into the SPS and they were accelerated to the 450 GeV/c/u flat top required to fill the LHC. After optimisation of the tunes and the chromaticity, up to 81% transmission was achieved. A short session devoted to the extraction of the ion beam towards the LHC through the TT60 transfer channel was also performed at the end of the 2007 run. Transverse emittances were measured with secondary emission grids and were found to be in agreement with the expected values of 1.2 µm.

THE LEIR ELECTRON COOLER

The LEIR electron cooler (Fig. 3) is based on a design previously used for the construction by BINP of the two electron cooling devices for IMP Lanzhou in China. Taking into account recent improvements tested on various electron coolers during the last decade, it uses a high-perveance, variable-density gun followed by an adiabatic expansion provided by an additional solenoid.

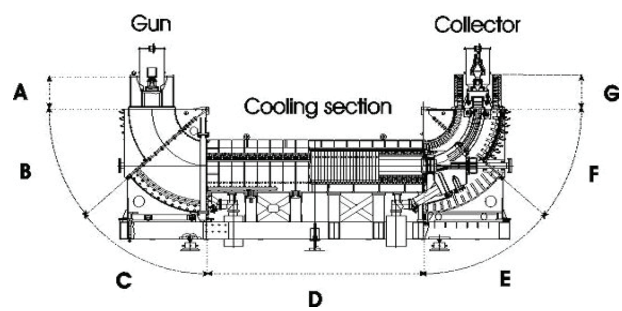

Figure 3: Schematic view of the LIER electron cooler.

The high perveance aims at providing an electron beam with a high density in order to decrease the cooling rate. However, increasing the electron density induces first an increase of the recombination rate (ions may capture an electron from the cooler and, finally be lost hitting the vacuum chamber), which is detrimental to the ion beam lifetime, and secondly increases the electron azimuthal drift velocity and thus increases the cooling time. For these reasons the electron gun has a "control electrode" used to vary the density distribution of the electron beam. In this manner the lifetime of the cooled ion beam will be increased by a reduction of the recombination rate of the ions with the electron beam. The electron beam profile is adjusted in such a way that the density at the centre where the stack sits is smaller and thus the recombination rate is reduced. At larger radii, the density is large and allows efficient cooling of the injected beam executing large betatron oscillations.

The cooling time is influenced by a number of machine and cooler parameters [2]. The electron current, I_e, and the relative angle difference between the ions and the electrons, θ, are two parameters that are easily accessible for experiments. The new electron gun also opens up the possibility to investigate the influence of the electron beam size and density profile on the cooling process.

ELECTRON GUN PERFORMANCE

The high perveance gun provides an intense electron beam in order to reduce the cooling time. However, with the higher electron density an increase of the recombination rate (capture by the ion of an electron from the cooler) and the electron azimuthal drift velocity is observed. Increased recombination is detrimental to the ion beam lifetime and the larger drift velocity will lengthen the cooling time. To contrast the increase in electron-ion recombination, the electron gun has a "control electrode" used to vary the density distribution of the electron beam. The beam profile is adjusted in such a way that the density at the centre, where the cold stack sits, is smaller and thus the recombination rate is reduced. At larger radii, the density is large and allows efficient cooling of the injected beam executing large betatron oscillations.

Fig. 4 shows the measured electron beam intensity as a function of the control to grid voltage ratio. As the control electrode voltage is increased, the electron beam distribution changes from a parabolic beam ($V_{cont} < 0.2\ V_{grid}$) to a completely hollow beam ($V_{cont} = V_{grid}$). The maximum design current is 600 mA but for the normal operation of the cooler only 200 mA is used.

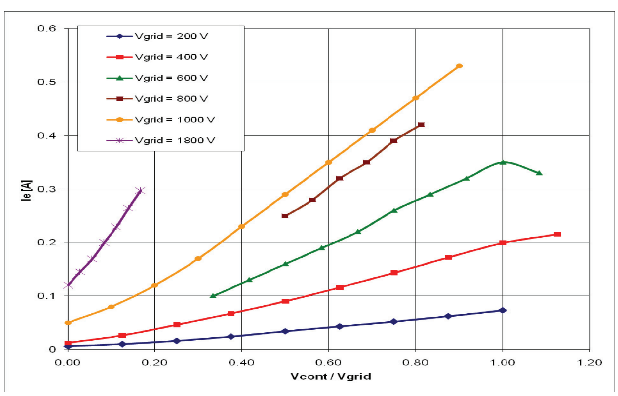

Figure 4: Electron beam current as a function of the ratio V_{cont}/V_{grid} , for an electron beam energy $E_e = 2.3$ keV.

EXPERIMENTAL SETUP

The cooling of ion beams was studied in parallel with the commissioning of the ions for LHC injector chain [3]. As it was difficult to obtain long cycles dedicated to electron cooling studies, most of our measurements were performed on the standard magnetic cycle lasting 2.4 or 3.6 seconds during which 2 to 5 linac pulses are cooled and stacked at 4.2 MeV/u. Schottky diagnostics, ionisation profile monitors (IPM) and the beam current transformer (BCT) were used to measure the phase-space cooling characteristics and to investigate the ion beam lifetime. The electron beam position was also measured during our measurements to ensure that the two beams were always correctly aligned [4].

COOLING EXPERIMENTS

The short duration of the injection plateau imposed that we used the momentum spread and the transverse beam size after 400 ms as the parameters to characterise the cooling performance. LEIR uses a multi-turn injection in all three planes and the injected beam has a transverse emittance of about 2.5 µm and a momentum spread of 4×10^{-3}. After cooling, the beam emittance is reduced by a factor of 10 and the longitudinal momentum is a few 10^{-4}.

Influence of Beam Expansion

The beam size can be varied by applying a stronger longitudinal field in the gun region. A maximum expansion factor, k, of 3 is available thus making it possible to vary the electron beam radius up to 24 mm. Fig. 5 shows the result of a series of measurements made for two electron beam distributions (uniform for Vc/Vg = 0.2 and hollow for Vc/Vg = 0.5) with similar currents (~150 mA) whilst varying k from 0.86 (r = 13 mm) to 2.57 (r = 22.4 mm).

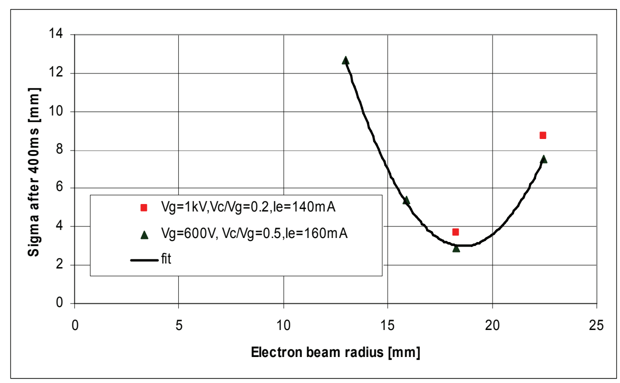

Figure 5: Beam size 400 ms after first injection as a function of the electron beam radius.

What one sees is that beam expansion becomes less useful when the electron beam radius is greater than 20 mm, roughly the size of the injected beam. Another phenomenon that was observed with larger electron beams is the relatively bad cooling of the first injected beam. In all our measurements, regardless of the number of injections, the first beam was never fully cooled to make space for another injection when the electron beam radius was greater than 20 mm. Subsequent injections were cooled to dimensions almost twice smaller than on the first injection.

Influence of the Electron Intensity and Density

As explained earlier, the electron beam intensity and density distribution can be varied by applying voltages to the grid and control electrodes. Roughly speaking, the grid determines the intensity whilst the control electrode changes the density distribution by enhancing the emission from the edge of the cathode.

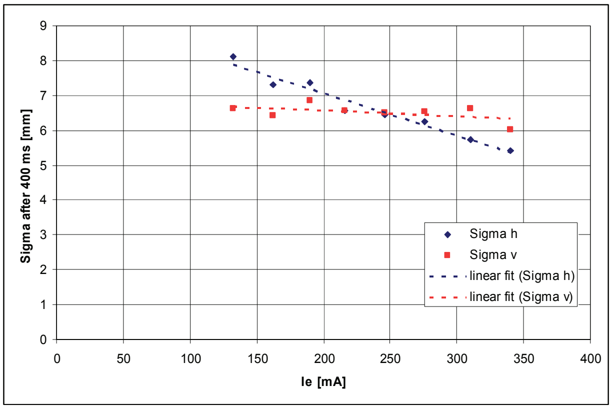

Figure 6: Ion beam size as a function of the electron cooler current (V_{grid} = 1.1 kV, k = 2.57, r = 22.4 mm).

A first set of measurements were made to confirm that the increase in electron current did improve the cooling efficiency. This is shown in Fig. 6 where the ion beam size is plotted as a function of the electron current with a fixed grid voltage of 1.1 kV. The decrease in the beam size as the current is increased is a clear sign of better cooling even though the effect was less pronounced in the vertical plane.

With the grid voltage fixed we were able to explore the influence of the electron beam distribution on the cooling performance by simply increasing the control voltage. Fig. 7 shows the result of one set of measurements where the grid voltage was held at 600 V and the control voltage was increased to 85% of the grid value. The beam size decreases as expected as the current is increased, but as the beam distribution becomes hollower the increase in electron current is no longer beneficial and the cooling is less efficient.

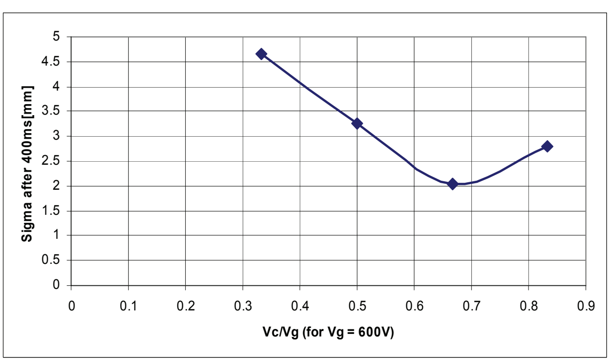

Figure 7: Beam size after 400 ms as a function of the electron beam distribution for a constant value of 600 V on the grid electrode (k=1.7, r=18 mm).

To further understand the influence of the density distribution, measurements were made where the electron current was kept constant and the density distribution modified. The results (see Fig. 8) clearly show that the determining parameter for obtaining small beam sizes is the electron current and not the density distribution.

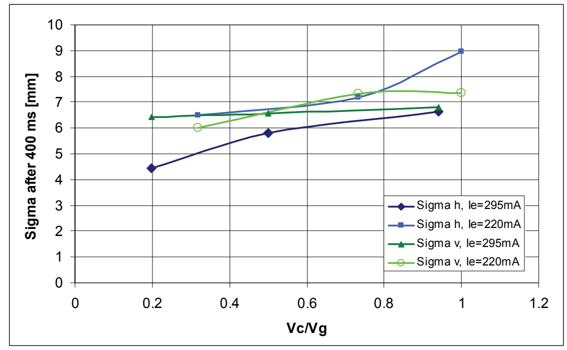

Figure 8: Ion beam size as a function of the density distribution for a constant electron current (k = 2.57, r = 22.4 mm).

Longitudinal Cooling

The momentum spread after 400 ms of cooling was measured using a down-mixed longitudinal Schottky signal captured with a fast ADC and treated mathematically to produce the spectral density distribution as a function of time. The results show the usual decreasing momentum spread as the electron current is increased.

The influence of the density distribution of the electron beam on the longitudinal cooling was also investigated. The Schottky spectrum was recorded during the cooling/stacking process for three electron density distributions. One sees, from the plots below, that the best cooling is obtained with a uniform electron beam density. As the electron beam becomes hollow the cooling time increases and fewer particles are dragged into the stack.

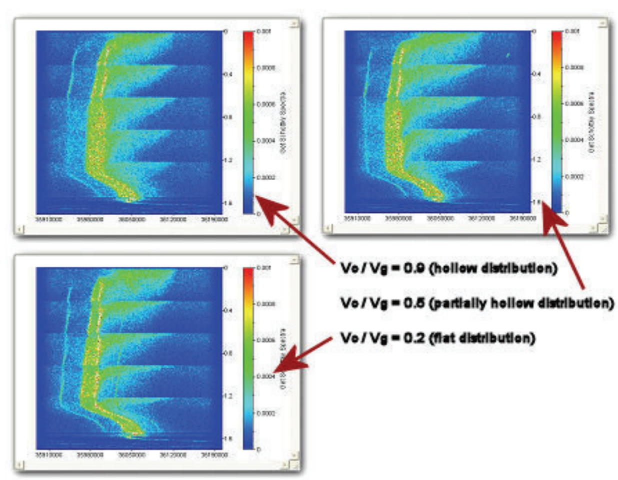

Figure 9: Evolution of the momentum spread during the cooling/stacking process with a constant electron current of 295 mA. The density distribution is changed from a flat distribution (V_{cont}/V_{grid} = 0.2) to a completely hollow one (V_{cont}/V_{grid} = 0.9).

LIFETIME STUDIES

In previous tests the maximum accumulated intensity was a factor 2 lower than that required for the nominal

LHC ion beam ($1.2x10^9$ ions). This was in part attributed to a short lifetime due to the recombination of ions with the cooling electrons and also to the limited electron current that could be obtained for effective cooling with the old electron gun.

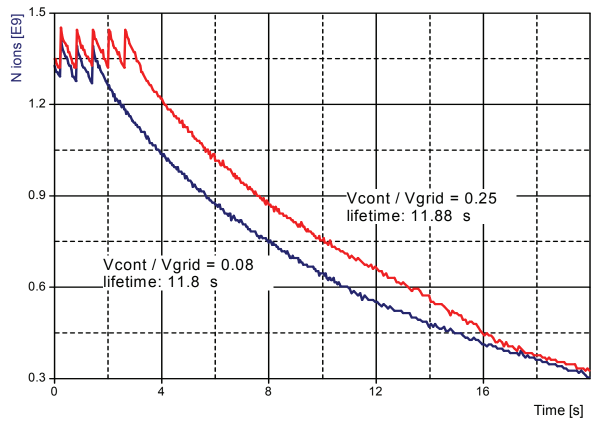

Figure 10: Beam lifetime for a parabolic (blue) and a slightly hollow (red) electron beam distribution.

In our measurements intensities well above $1.2x10^9$ ions could easily be accumulated with an injection repetition rate of 1.6 Hz. If the repetition rate is increased, the maximum number of stacked ions decreases proportionally.

The lifetime of the cooled ion beam was measured by recording the evolution of the BCT signal as a function of time. Comparing for a parabolic and a hollow electron beam distribution (Fig. 10), we see that this parameter does not significantly influence the lifetime, indicating that recombination may not be after all the main cause of the short lifetime measured in the 1997 tests [5]. Other processes related to the vacuum conditions or the injection scheme could be more dominant.

A compilation of all our lifetime measurements for different intensities and density distributions is shown in Fig. 11. The slope of the curves gives the lifetime due to the electron beam whilst the intersection with the y-axis gives the vacuum lifetime. Compared with measurements made in 1997, a gain by a factor of 2 in the vacuum lifetime is observed but the lifetime due to the electron beam is only slightly improved and is not influenced by the electron beam distribution.

CONCLUSION

The LHC lead ions injector chain is ready to deliver the "early" beam as soon as it is required. The characteristics of this beam will enable the LHC to explore any limitations in the ring without the risk of damaging any equipment. Despite the lower luminosity, early physics discoveries will also be possible.

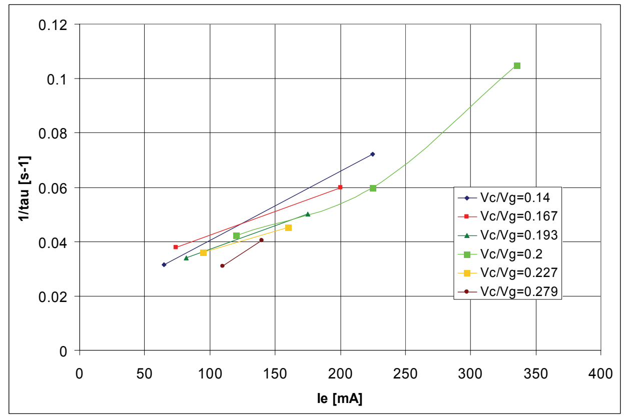

Figure 11: Inverse lifetime of Pb^{54+} ions as a function of electron current and density distribution.

Our cooling experiments on LEIR have shown that the main parameter that enhances the process is the electron beam current. Up to 600 mA of electron current can be obtained with the new gun, but the interplay between the electron beam size, density distribution and intensity is such that the best cooling is obtained with an electron beam having approximately the same size as the injected ion beam, a flat density distribution and an intensity less than 300 mA. It is clear that systematic measurements need to be continued and dedicated machine time is needed to explore the full potential of the device.

After a stop of nearly 18 months, the focus of the next lead ion run (which will start in July) will be the generation of the "nominal" beam for the LHC. In parallel the cooling process will be further investigated in order to optimise the lead ion beam characteristics in LEIR. In particular, it may be necessary to introduce a variation in the electron beam size during the cooling/stacking cycle. This has the potential to obtain faster cooling rates, thus enhancing the total number of ions that can be accumulated.

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