LEIR COMMISSIONING

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Abstract

After reporting on already completed phases of LEIR commissioning, an outlook and tentative schedule until completion aiming at providing the beam needed for first LHC ion runs will be given. Expected and unexpected problems and actions to tackle them are highligthed.

INTRODUCTION

The role of the LEIR ring, as a central part in the ion injector chain for the LHC, is well documented in [1,2,3,4]. It transforms several long Linac 3 pulses into short bunches, with high density needed for LHC ion operation.

Since nominal LHC ion operation is very demanding for both the LHC and the injector chain, first LHC ion operation will take place with a lower luminosity and less bunches using the so-called "early scheme" [1,5]. The aim of LEIR commissioning described in this paper is to provide the beam for this early scheme and to transport it as far as possible towards the PS (observation at the last TV station ETP.MTV10 in front of the PS ion injection).

LEIR commissioning follows a schedule with alternating commissioning and installations phases [6] proposed in the wake of discussions at the Chamonix XII workshop. LEIR injection line has taken place as planned between May and very beginning of July; LEIR ring commissioning has started almost on time at the beginning of October 2005 (instead of August).

The first phase of LEIR ring commissioning until December 2005 (and injection line commissioning as well) has been carried with O^{4+} ions instead of the nominal Pb^{54+} beam. The reason is that, extrapolating from observations with O^{8+} and O^{6+} beams in LEAR, a much longer vacuum life-time (lower cross section for charge exchange processes with rest gas molecules) had been expected and that the beam rigidity is very close (only small re-adjustments needed to switch to Pb^{54+} operation).

It is planned to complete LEIR commissioning early (end of April) in 2006 in order to free the operations team for the AD run (due to manpower restrictions only one operations team is available for LEIR and AD). LEIR will be stopped during the AD run and be restarted towards the end of the summer and provide the beam needed for commissioning the early LHC ion beam in the PS.

The fact, that LEIR controls are to a large extent based on developments for LHC, implies that getting LEIR the control system fully operational was expected to be a challenge. The resulting "teething problems" and lessons learnt will be reported in [7,8]. It is an achievement that, thanks to the work of many people involved, a working (although not yet perfect) LEIR control system is available now and allows LEIR commissioning.

LEIR COMMISSIONING UP TO NOW

General comments

Commissioning of the Linac 3 to LEIR transfer line (for a layout, see Fig. 1) has taken place as scheduled between May and beginning of July 2005. The very first phase has been dominated, as described in detail in [7,8], by "teething problems" and debugging of the control system, largely based already on developments for LHC. Later-on, coordination has been rendered complicated due to the fact that several activities took place in parallel: installation of the last part of the line, hardware tests and controls debugging, and already commissioning with beam of the first part of the line. Actual progress of commissioning with beam has taken place in rather sharp steps with longer preparation phases in-between:

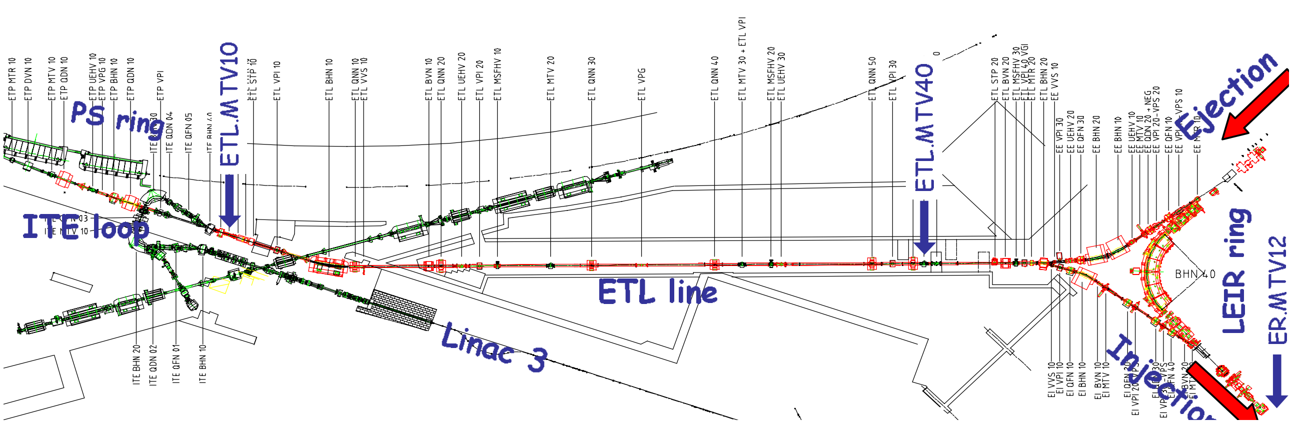


Fig.1 : Layout of the LEIR transfer lines and LEIR ring

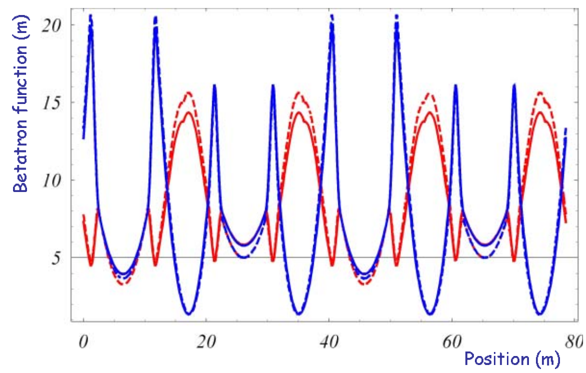
- "Loop" ITE on June 6th until the TV station ETL.MTV10: Note that the digitized acquisitions of TV stations (both the FESA based front-end and the application), the main beam diagnostics for this transfer line, have been operational already at the very beginning.
- Most of the ETL line (until the last TV station ETL.MTV40) during week 25 (starting on June 20th): A few days were necessary to find empirically settings of two bending magnets. One out of these two bendings had coils connected in parallel and not as expected in series, a fault repaired in between. Once the right settings were found, the beam could be easily brought up to the last TV station ETL.MTV40 of the ETL line.
- Last part of the line until the TV station ER.MTV12 on July 6th: Commissioning of this last part of the line, located already inside LEIR enclosure, has been carried out in evenings in order to allow for installations during normal working hours. The beam has been brought up to a TV station ER.MTV12 installed already in the ring after the injection (magnetic and electric) septa.

During this first part of LEIR commissioning, it has been shown that the beam can be transported with good efficiencies until the very end of the injection line. It should be noted that difficulties in understanding the optics along the line (both the initial conditions at the end of Linac 3 and the optical properties of the line itself are unclear) have been encountered and will be described in more detail below.

During the summer 2005, LEIR commissioning has been on hold as scheduled. During that time, LEIR ring installations have been completed as planned.

LEIR ring commissioning could restart almost on schedule at the beginning of October 2005. After again some lengthy controls debugging [7,8] and polarity tests, first injection and circulating beam, have been achieved very quickly on October 6th. After a two weeks interruption (preparations, bake-out, re-installations ….) due to a vacuum leak caused by friction of a TV support on its bellow (problem understood and support modified to avoid such problems in the future), a period with very fast progress took place. A few highlights of this phase were:

- First bunching (with a conventional analogue -and not yet the definite DSP based- low level RF system) of the beam and orbit acquisitions have been set up very quickly.
- Longitudinal and transverse Schottky diagnostics allowed observing the beam and to measure momentum spreads and tunes and estimating chromaticities. Note that vertical chromaticities rather different from expectations have been measured.
- Setting-up of the momentum ramping (increase of the momentum of the beam delivered by Linac 3 between the beginning and the end of the pulse by ~0.4%) allowed increasing the injection efficiency to the nominal 50% (the elaborate LEIR injection aims at injecting high intensity, accepting deliberately some losses).



Courtesy : P. Beloshitsky and J. Pasternak

Fig 2: First results [9] from orbit response measurements on the accumulation plateau. Solid and dashed lines correspond to "measured" and expected betatron functions along the accelerator. Red and blue lines are for the horizontal and vertical phase space, respectively.

- First results (see Fig. 2) of orbit response measurements taken at the accumulation plateau showed that the ion optics of the bare LEIR machine (no perturbations due to the electron cooler and acceleration) is close to expectations [9] from the theoretical model of the ring.
- Compensations of the strong perturbations on the lattice due to the electron cooler (first the very strong orbit distortions, later coupling and distortions of the betatron functions).
- Discovery of pick-up cable damage (see details and actions to cure below) due to currents on the ramp.

After this period, a phase with less visible and fast progress followed until the scheduled interruption at the end of the year. Some of the highlights and observations of this phase are:

- More time than expected has been necessary to complete installations of the cooler and to commission the cooler with electron beam only.
- A FFT based system, which had been in use [10] already in the former LEAR machine, allowing to observe evolution of longitudinal and transverse (important, since ionization profile monitors were not yet available) Schottky spectra has been set up. First results obtained with this system are shown in Fig. 3.
- Setting-up of the fully digital RF system [11] and acceleration tests with both low level RF systems: Convincing results have been obtained with both the analogue and then new fully digital low level RF systems. With both systems, beam (without cooling)

has been accelerated up to a plateau with half the design magnetic field at ejection.

- First orbit response measurements at the beginning of the ramp (with almost the nominal $(\partial B/\partial t)/B$) have been taken and are evaluated at present. The only actions taken to compensate lattice perturbations (see below) were many adjustments ("trims") of the working point.
- First cooling studies showed a clearly visible action of the electron cooler on the ion beam. Despite some evidence (see Fig. 3) of beam cooling, the results are difficult to interpret. Fig. 3 shows the time evolution of longitudinal Schottky spectrum. Just after injection at time $t = 1$ s, the full relative momentum spread is given by the momentum ramping set to about $4\text{x}10^{-3}$. After about 1 s (note that with O^{4+} longer cooling times than for Pb^{54+} are expected), the momentum spread is reduced and the density (slightly) increased, i.e. clear signs of cooling have been are observed. However, the total decrease in momentum spread after long cooling and the increase in density are only small. Thus, further investigations and optimizations (with Pb^{54+}) will be necessary at resumption of LEIR ring commissioning. More details on electron cooler commissioning are given in [12].

Expected and unexpected difficulties

Various difficulties expected and encountered are reported in a chronological order:

- Controls debugging: The ambitious decision to deploy many LHC developments already for LEIR [7] implied a significant effort for controls debugging [6]. Thanks to the dedication and the work of CO experts and the commissioning team, a working (although not yet perfect) control system is available [6]. In addition, validations of solutions developed for the LHC [7] have been carried out.
- Understanding of the Linac 3 to LEIR transfer line: Extrapolating from experience with the old transfer line during the LEIR ion accumulation tests between 1995 and 1997, injection line commissioning had been expected to be smooth. However, during commissioning, significant discrepancies (observing shapes of the beam on TV stations along the line) between expectations and observations have been found. For systematic investigations, trajectories have been measured by exciting correction dipoles at the beginning of the line and compared to computations [13]. Based on these measurements, the optics model of the line is improved. Results of such comparisons using an already improved model are shown in Fig. 4.
- First injections: Since circulating beam is necessary for proper diagnostics in the LEIR ring, first injections and circulating beam had been expected to be a critical milestones. Finally, it turned out that circulating beam could be established very quickly without significant difficulties.
- Position pick-up damage: An unexpected problem, discovered during the first phase of LEIR ring commissioning, is that currents induced by the ramp damage the (outer conductor of) cables (see fig. 2) connecting pick-ups installed inside the bending magnets with their head amplifiers. This problem has been cured temporarily by reducing the ramp to a maximum magnetic field of half the nominal one. After testing several options during the end of the run last autumn, a definite cure [14] implemented at present is to insulate the head amplifier box from the magnet yoke. Thus, the current loop (via the local LEIR control room) to close the circuit becomes longer and has a higher resistance and, thus, the current is reduced.

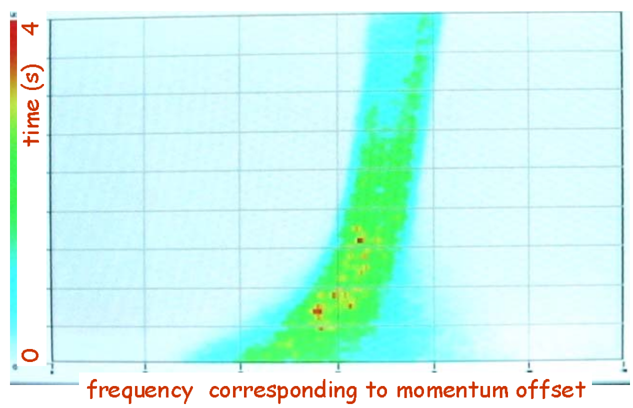
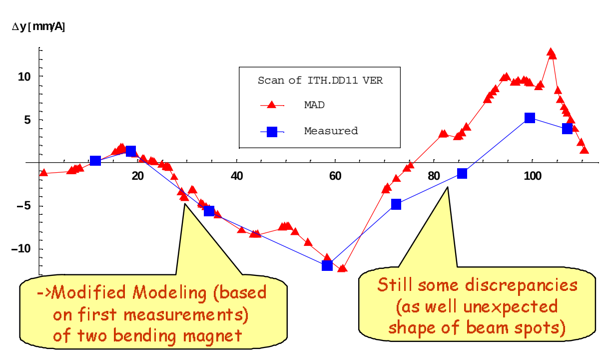


Figure 3: First electron cooling results. Time evolution of longitudinal Schottky spectra indicating some cooling.



Courtesy : F. Roncarolo

Figure 4: Vertical trajectories along the Linac 3 to LEIR transfer line. Blue boxes have been measured on TV stations and red triangles are computed with a model taking results of previous measurements into account.

- Short life-time and fast losses have been observed and hampered systematic investigations on electron cooling. Probably, this was the result of the superposition of several phenomena:
  - Almost perfect exponential decay of the circulating has been observed at many occasions, especially with low intensities. These losses may be well explained by interaction with rest gas molecules. On the one hand, one concludes that that the anticipated gain in life-time (extrapolated from experience with O^{8+} and O^{6+} in LEAR) was not that significant. Observation of relatively high pressures in LEIR section 40 (part of vacuum sector 5) especially during periods with regular injections correlated well with short life-times. Explanations are a few vacuum leaks (e.g. on recuperated bellows) and beam loss induced outgassing. In particular, kapton (with an unknown but possibly high beam loss induced outgassing rate) insulated wires (signal read-out and supplies for HV electrodes with insulating of unknown, but possibly high s materiel) of the vertical ionization profile monitor, showed traces of ion impact [12]. During the present short "shutdown", the vacuum system has been opened in order to repair the small leaks (and for other upgrades, e.g. a modified support of a TV station and a larger horizontal beam ionization profile monitor). Au coated (lower ion loss outgassing yield) coated plates intercepting ions, before they can hit the vertical ionization profile monitor, have been added.
  - In addition to above losses with almost exponential decays of the intensity, fast losses have been observed. From Schottky signals, transverse "activity" could be observed in good correlation with these losses. Hypotheses explaining these fast losses are transverse instabilities excited by coupling impedances or ions trapped in potentials created by the electron beam of the cooler. Although instabilities due to coupling impedances are expected only for small momentum spreads after efficient electron cooling, the transverse dampe
  - r has been commissioned at the end of the run. Care will be taken to connect properly all electrodes of the electron cooler (also the electrostatic bends not yet during operation last year) in order to avoid potentials trapping ions.
- Investigations on electron cooling have been difficult to interpret. This is on the one hand related to losses reported above. In addition, it is unclear how well the electron beam and circulating ion beam trajectories have been adjusted with respect to each other. Careful preparation of the cooler and related diagnostics will render systematic investigations of electron cooling more efficient.

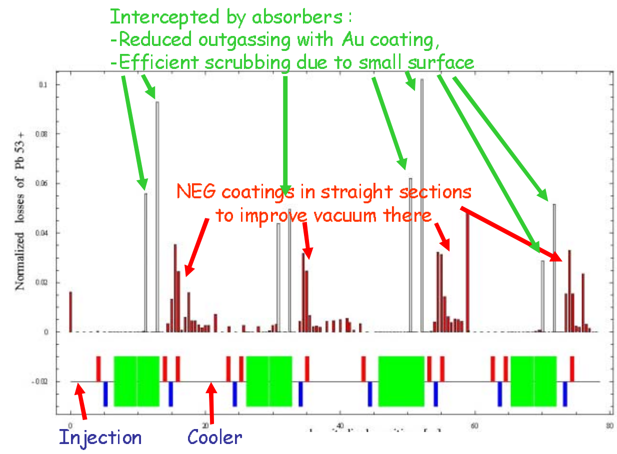


Figure 5: Simulation [10] of the LEIR collimation system to remove Pb^{53+} ions (Pb^{54+} having captured an electron from a rest gas molecule).

COMPLETION OF LEIR COMMISSIONING AND BEYOND

What remains to be done

Main milestones up to completion of LEIR commissioning are:

- LEIR restart with Pb^{54+} implies re-adjustments for the slightly lower beam rigidity and setting up of the collimation system (see below under expected problems).
- Completion of electron cooling studies.
- Completion of acceleration to the design ejection magnetic field.
- Ejection necessitates creating an orbit bump (due to the limited strength of the dipoles, more than four dipoles are needed) moving the beam towards the ejection septum and setting up ejection kickers and septum.
- The last step to complete LEIR commissioning is setting-up of the ejection line and checking the emittance (and betatron matching) with secondary emission monitors (SEM) in the ETL line. Since the first part of the ejection line EE is delicate (strong quadrupoles needed due to space and geometry constraints), some readjustments based on measurements on the SEMs in the ETL line may be necessary.

Expected difficulties

Following problems and difficulties and actions to tackle are expected until completion of LEIR commissioning:

- The "dynamic vacuum" with beam, causing additional outgassing due to ions hitting the chamber in the machine, must be controlled. To this purpose, a collimation system (see Fig. 5) [15,16], based on results of systematic investigations on ion loss impact induced outgassing [17,18] has been installed and must be commissioned. Most ions hit absorbersblocks installed at appropriate locations in the bending magnets. Au coatings and perpendicular incidence reduce the beam loss induced outgassing rate. Most ions not intercepted by the absorbers are lost in the straight sections and are pumped efficiently by NEG coatings installed wherever possible in these regions.

- Optics perturbations due to gradients seen by the beam during the ramp inside the bending magnets: During the ramp, a net current flows along the vacuum chamber inside the C-shaped bending magnets and excites quadrupolar fields. Corrections of the resulting very strong lattice perturbations have been implemented in the magnetic cycle generation software. The fact, that it has been possible to take first orbit response measurements on the ramp only applying "trims" of the working point, is a good sign that these lattice perturbations can be brought under control.

Beyond LEIR Commissioning

If LEIR commissioning can be completed as planned until April 21st, 2006, the machine will be stopped during the summer and the operations team will work for the AD. In the late summer, LEIR will be restarted in order to provide the beam for commissioning the early LHC ion beam in PS in autumn 2006. This schedule leaves just enough time to provide first LHC ion operation with the "early beam" on time [1].

SUMMARY AND CONCLUSIONS

Thanks to the work of many people from several departments involved in the I-LHC project, LEIR installations have been completed almost on time and allowed to start LEIR injection line commissioning as scheduled and LEIR ring commissioning almost on time.

Significant progress of LEIR commissioning has been achieved up to now. Still, many commissioning milestones remain to be completed. After re-adjustment for Pb^{54+} ions and setting up of the collimation scheme, electron cooling studies and optimization will be completed. Then, setting up of acceleration, together with corrections of lattice perturbations during the ramp, will be completed. Finally, ejection and transfer to the PS will be commissioned. For the moment, no showstopper ruling out completion of LEIR commissioning until end of April has been identified. Completion of LEIR commissioning until the target date (April 21st) looks very challenging, but feasible.

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