EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

*Large Hadron Collider Project*

**LHC Project Report 936**

# LEIR LATTICE

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## Abstract

The Low Energy Ion Ring (LEIR) is a low energy ion cooling and accumulation ring and serves to compress long ion pulses from Linac3 into high density bunches suitable for LHC ion operation. Issues of the LEIR lattice are to fulfil all constraints with a small number of quadrupoles and compensations of perturbations due to an electron cooler and gradients seen by the beam in the bending magnets during the ramp. Furthermore, experimental investigations via orbit response measurements will be reported

*Presented at*
*EPAC'06, Edinburgh, UK,*
*June 26-30, 2006*

CERN,
CH-1211 Geneva 23,
Switzerland
Geneva, June 2006

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### *Abstract*

The Low Energy Ion Ring (LEIR) is a low energy ion cooling and accumulation ring and serves to compress long ion pulses from Linac3 into high density bunches suitable for LHC ion operation. Issues of the LEIR lattice are to fulfil all constraints with a small number of quadrupoles and compensations of perturbations due to an electron cooler and gradients seen by the beam in the bending magnets during the ramp. Furthermore, experimental investigations via orbit response measurements will be reported.

## INTRODUCTION

The LEIR ring, whose commissioning was recently completed [1], is an essential part of the ion beam injector chain of the Large Hadron Collider (LHC) at CERN. It accumulates several Linac3 $Pb^{54+}$ pulses at 4.2 MeV/u by multiturn injection and electron cooling. It extracts short and dense ion bunches at 72 MeV/u towards the PS (Proton Synchrotron). The main machine parameters related to optics are given in Table 1.

Table 1: Nominal LEIR lattice parameters

| $(Q_H, Q_V)$ | (1.82, 2.72) |
|---|---|
| Circumference | 78.54 m |
| D at cooler | 0 m |
| D at injection | 10.3 m |
| $\beta_H$, $\beta_V$ in cooler | 5 m |
| $\beta_H$, $\beta_V$ at injection | about 4 m |
| Bρ | 1.12 – 4.8 Tm |
| $Pb^{54+}$ energy | 4.2 – 72 MeV/u |
| Acceptance H/V | 60/40 μm |
| Momentum acceptance | $\pm 4 \quad 10^{-3}$ |

Operation of LEIR sets several requirements on optics:

- Injection: A relatively large normalized dispersion $D/\beta^{1/2}$ is needed for the elaborate multiturn injection [2] with stacking in momentum and both horizontal and vertical phase spaces. The value obtained ($D/\beta^{1/2} \approx 5$) is a bit smaller than the one desired.
- Electron cooling: Betatron functions of about 5 m were found optimal for fast electron cooling [3]. Although a finite dispersion of a few meters was found beneficial for a fast cooling, it has been decided to have zero dispersion for easy overlap of ions (with large momentum spread at injection) with electrons. In addition, the extraction installed in the opposite SS40 will profit from the zero dispersion.
- Working point far from ($Q_H - Q_V = -1$) resonance and clear from other dangerous resonances to obtain good multiturn injection efficiency and avoid emittance blow-up.
- Sufficient momentum and transverse acceptances.

## LEIR OPTICS

### *General Layout and "Bare" Machine*

LEIR inherits its "square" shape (see Fig. 1) from the former LEAR (Low Energy Antiproton Ring). Quadrupole doublets are installed in the injection Straight Section 10 (SS10) and opposite in SS30. Triplets are used in SS20 on both sides of the electron cooler and in the opposite SS40 suited for extraction. The basic focusing is defined by five quadrupole families, which surprisingly is sufficient to yield a lattice satisfying all the requirements given above.

### *Compensation of the Electron Cooler*

The cooler introduces a strong source of coupling due to the longitudinal magnetic field of the main solenoid. The electron cooler magnet system has no azimuthal symmetry in the toroids. Thus, the cooler cannot be modelled as pure solenoid, but additional field components must be taken into account. In particular dipolar and skew quadrupolar components are estimated from magnetic field measurements (see Fig. 2).

The coupling introduced by the electron cooler is compensated mainly by two solenoids placed symmetrically on either side of the cooler. In order to compensate the small skew quadrupole components in the toroids and the residual coupling of the machine, skew quadrupoles are used. They are located symmetrically within the triplets (due to lack of space in the proximity of electron cooler).

In order to compensate for the changes of the working point and the betatron functions caused by the cooler and other coupling elements, corrections to the five quadrupole families and to the setting of the triplet quadrupoles in SS20 via trim power supplies are programmed. The corrections depend quadratically on the ratio between the solenoidal field and the beam rigidity, and are reduced during acceleration.

### *Eddy Current Compensation*

The LEIR bending magnets are C-shaped and the vacuum chamber is connected to ground at various locations. As a consequence, a net eddy current flows along the chamber during the ramp resulting in a gradient experienced by the beam. It produces strong tune shifts, especially in the horizontal plane, where the working point moves below the half-integer resonance. This perturbation (together with the distortion of betatron functions around the ring) has to be compensated by adding appropriate corrections to the five main quadrupole families.

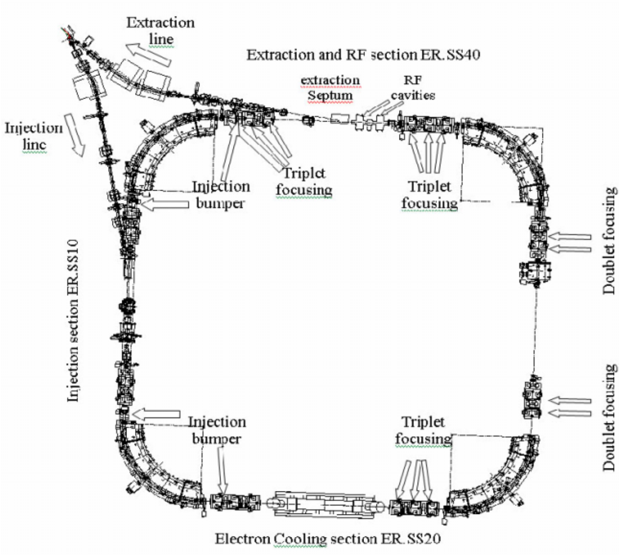

Figure 1: Layout of LEIR ring.

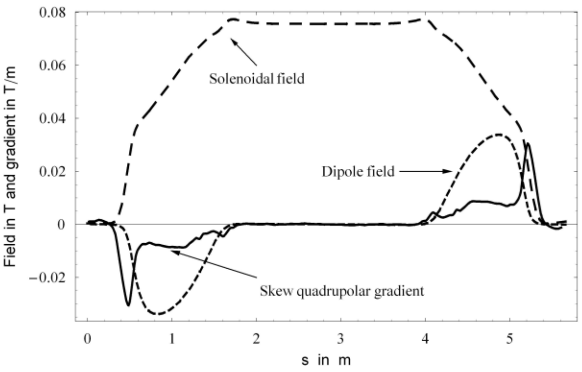

Figure 2: Magnetic field components in the electron cooler found from measurements.

## ORBIT RESPONSE ANALYSIS

### *Method Description*

In order to check the LEIR optics at various times during the cycle, orbit response measurements [4, 5] were performed. They consist of orbit acquisitions measured with 16 horizontal and 16 vertical BPMs (Beam Position Monitors), when 14 horizontal and 14 vertical correctors are excited separately one by one. Typically the correctors are excited to positive and negative kicks (1 mrad) in order to reduce nonlinear effects . The measurement was repeated three times for each setting in order to reduce the effect of noise. Several conditions have to be met in order to obtain useful data:

- Bunched beam circulating with decent intensity for the good BPMs read-out.
- Machine pulse by pulse stability.
- Low noise in BPMs.

The difference between measured data $X^D_{ij}$ (i,j are BPM and corrector numbers respectively) and values $X^M_{ij}$ found from a model is the subject for analysis. Keeping only linear terms in the expansion of model with respect to the machine parameters, one can solve the following equation for this difference:

$$X^D_{ij} - X^M_{ij} = \frac{\partial X^M_{ij}}{\partial p_k} \Delta p_k \ . \qquad (1)$$

This is done in the form of a least square minimization. Here $p_k$ are parameters which define machine optics and have to be found from the fit (quadrupole strength errors, BPM gains, corrector strengths etc.)

The $\chi^2$ function is defined as:

$$\chi^2 = \sum_{ij} \frac{(X^D_{ij} - X^M_{ij})^2}{\sigma_i^2} \ , \qquad (2)$$

where $\sigma_i$ is rms noise of a given BPM. The figure of merit (penalty function) of the model is the ratio between $\chi^2$ and the sum of the number of data and the number of fitted parameters. For the perfect machine model its value should be close to one.

### *Results for the Injection Plateau*

Several orbit response studies were done on the injection plateau around 1850 ms from the start of the cycle, which was enough to accumulate and cool 3 linac pulses, and then bunch the beam.

The minimization of $\chi^2$ function was performed by varying the following parameters of the machine model:

- 5 quadrupole families.
- 3 trims in SS20.
- Longitudinal magnetic field in the cooler and compensation solenoids
- Skew quadrupole strengths
- BPM gains and corrector strengths

The immediate result was the verification of the BPM and correctors polarity. Then the parameters governing the optical properties of the machine were used to fit the data. The optics on plateau was found to be close to the nominal and the quadrupole families are close to the programmed values except for one. This quadrupole family is located in the proximity of the bending section, and the relative discrepancy was found to be about 14%. The result of the fit for the coupling elements was far from the expected values. The value of the penalty function was 2.8. Both facts together may indicate that the machine model is not complete. The lattice functions calculated for the theoretical model and with parameters found in the orbit response analysis are shown in Fig. 3.

### *Results for the Ramp*

The primary goal of the orbit response analysis during acceleration was to find, with the beam, the gradients induced by the eddy current flow in the bending magnets and their effects on the machine optics. The measurements were taken in the middle of the ramp at 2400 ms from the beginning of the cycle. In addition to the parameters used in the analysis on plateau a quadrupolar gradient $g_{EDDY}$ in bending magnet was used to fit the data. The result yielded (assuming equal $g_{EDDY}$ in all bending magnets) a conversion coefficient from d(Bρ)/dt to a gradient of -0.004 (T/m)/(Tm/s). The pessimistic estimate calculated assuming perfect connection of the vacuum chamber to ground is -0.006 (T/m)/(Tm/s). The value of the penalty function was 9.2, which is much bigger compared with that for the plateau.

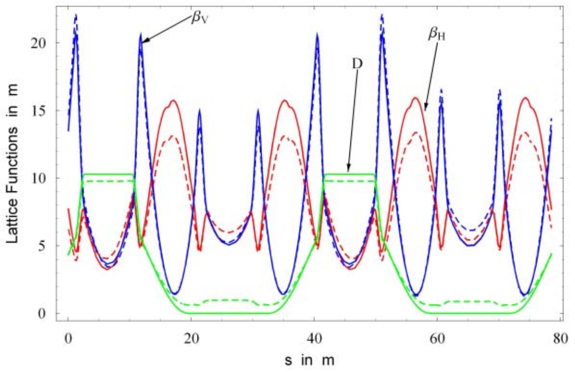

Figure 3: Lattice functions on injection plateau assumed in the design (full) and obtained in the orbit response analysis (dashed).

The next step to improve the model was to allow $g_{EDDY}$ to be fitted independently in each bending section. The penalty function was reduced to 5.4 and the fit result was quite different between the bending blocks. The lattice functions for this case are shown in Fig. 4.

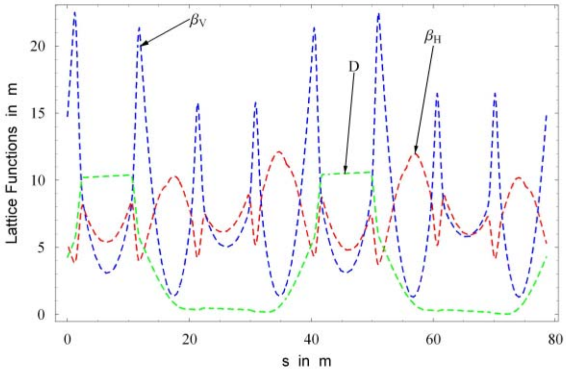

Figure 4: Lattice functions on ramp with gradient induced by eddy currents fitted independently in every bending block.

## CONCLUSIONS

During commissioning the LEIR optics was found to be sufficiently close to what was expected and provides good machine performance. It is not far from the design on the injection plateau and works properly for efficient electron cooling and accumulation. The orbit response analysis was a very efficient tool for the optics check and improvement. It was especially effective for optics correction on the ramp, providing the value of the quadrupolar component in the bending blocks. As a result, beam acceleration was done without losses. The information from the measurements are still under analysis with possibly better understanding of the LEIR optics and improvement of the machine model.

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