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LEIR IMPEDANCE MODEL AND COHERENT BEAM INSTABILITY OBSERVATIONS

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Abstract

The LEIR machine is the first synchrotron in the ion acceleration chain at CERN and it is responsible to deliver high intensity ion beams to the LHC. Following the recent progress in the understanding of the intensity limitations, detailed studies of the machine impedance started. In this work we describe the present LEIR impedance model, detailing the contribution to the total longitudinal and transverse impedance of several machine elements. We then compare the machine tune shift versus intensity predictions against measurements at injection energy and summarize the coherent instability observations in the absence of transverse feedback.

INTRODUCTION

The LEIR machine is the first ion synchrotron accelerator along the CERN ion accelerators chain and it was conceived in order to deliver high brightness bunches to the LHC [1]. The machine is equipped for this purpose, with an electron cooler that, together with the 2.5 planes stacking injection mechanism (transverse phase spaces and longitudinal momentum space), allows for accumulation of high intensity beams at the injection plateau of 4.2 MeV/nucleon.

Once injected and accumulated, the coasting beam is captured by the RF system [2], accelerated to 72 MeV/nucleon and sent to the PS ring.

During the capture process, high losses were systematically observed for high intensity beams, leading to performance degradation in terms of delivered bunch intensity [3, 4]. At the end of 2015 an extensive beam study program was started in order to understand the underlying mechanism and the main driving source was identified as direct space charge effects in combination with the lattice sextupolar resonances [5, 6]. Thanks to special shaping of the longitudinal line density during the RF capture and optimized resonance compensation, the LIU/HL-LHC design intensity goal of $8.1 \cdot 10^8$ ions/bunch has been reached in 2016 [6, 7].

In order to ensure a stable LEIR machine performance with enough margin with respect to the LIU baseline, further studies are presently ongoing [8] (working point and electron cooling optimization, resonance compensation, bunching factor increase, etc.). Among these, the development of the transverse impedance model is taking place in order to improve the general understanding of the machine with respect to collective effects.

In this work we will detail the development status of the LEIR transverse impedance model, we will compare the measured transverse tune shift versus intensitv with the corresponding predictions and summarize the transverse coherent instabilities that are observed in coasting beam mode in the absence of the transverse feedback.

LEIR TRANSVERSE IMPEDANCE MODEL

The process of developing an impedance model for an accelerator has been recently summarized in [9]. Concerning the LEIR machine, the vacuum envelopes of the following elements have been considered so far for the impedance calculations [10–12]: dipoles, quadrupoles, vacuum drift tubes, septa, beam position monitors, electron cooler main and transition pipes (computed with IW2D [13] considering the corresponding flat or round stainless steel beam pipe), kickers (modeled with the Tsutsui formalism [14]), stripline pick-up (computed using Ng formulae [15]). The total integrated length calculated so far is 68.37 m, i.e. ≃ 87% of the total machine circumference (78.54 m).

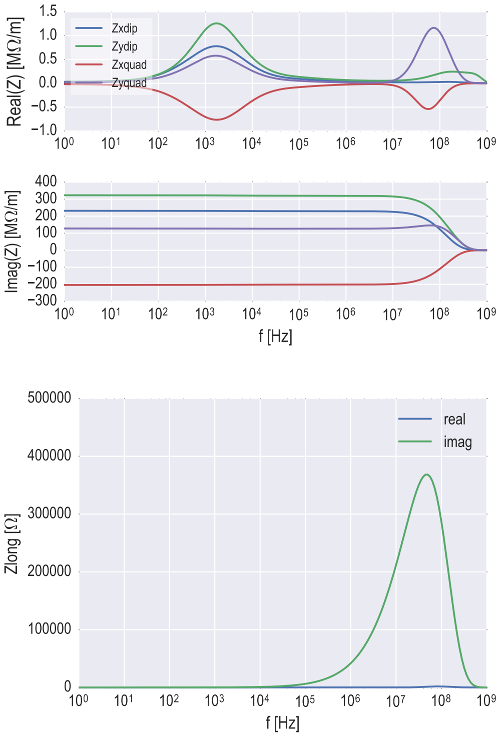

Figure 1: Left: Real and imaginary part of the dipolar (driving) and quadrupolar (detuning) LEIR impedance model. Right: Real and imaginary part of the longitudinal LEIR impedance model.

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The left side of Fig. 1 shows, as an example, the total impedance budget in the transverse planes for real and imaginary part of dipolar (or driving) and quadrupolar (or detuning) impedances. A typical bunched beam in LEIR has a rms bunch length of $\sigma_\tau^{rms} \simeq 200$ ns corresponding to $\sigma_f^{rms} \simeq 1$ MHz considering a Gaussian profile. Considering tune shift calculations, for example, only the inductive part of the impedance would be relevant. The machine total impedance budget (i.e. dipolar plus quadrupolar) is 442 MΩ/m in the vertical plane and 27 MΩ/m in the horizontal plane [1].

Due to the low machine energy, the indirect space charge impedance is dominant and mainly driven by the vacuum chamber in the dipoles (60%) and the quadrupoles (20%).

TUNE SHIFT MEASUREMENTS

The impedance model presented in the previous section was used to predict the tune shifts in coasting and bunched beam regimes. The coasting beam angular frequency shift $\Delta\omega_n$, from Laclare's theory [16] can be evaluated in the (vertical) plane, as

$$\Delta\omega_n = \frac{Q}{A}\frac{j\beta c^2 I_0}{4\pi Q_y f_0 C E_t/e} Z_y^{dip}(n), \qquad (1)$$

where the number of ion charges over the number of mass ratio Q/A is 0.26 for Pb^{54+}, $I_0 = Nef_0$ is the beam current with N total number of charges, e the elementary charge and f_0 the revolution frequency, β the relativistic factor ($\simeq 0.1$ at injection and 0.37 at extraction), c the speed of light in vacuum, Q_y the betatron tune, C the machine circumference, E_t the total beam energy per nucleon, Z_y^{dip} the dipolar impedance sampled at the coasting beam spectral lines given by

$$f_n = (n + Q_y)f_0, \quad \text{with } n \in (-\infty, +\infty). \qquad (2)$$

When the coasting beam is kicked, coherent betatron oscillations build up and the coherent frequency shift is proportional to the total transverse impedance $Z_y^{tot} = Z_y^{dip} + Z_y^{quad}$.

The predicted tune shift and growth rate for a coasting beam of $N = 10^{10}$ charges calculated for the vertical plane (most critical) with reference to the working point $Q_x = 1.82$, $Q_y = 2.72$ are respectively of $2.75 \cdot 10^{-4}$ and $0.25\ \mathrm{s}^{-1}$, the latter corresponding to the spectral line f_{-3} driven by the resistive wall impedance.

Tune shift versus intensity measurements were done in the machine during 2016 with both coasting and bunched beams following a first assessment done in [10]. High intensities available in LEIR allow for several injections from Linac3 followed by electron cooling. The electron cooler introduces an average momentum shift which depends on the intensity and may lead, by itself, to a tune shift trough chromaticity. As it is difficult to set chromaticity exactly to zero, a different approach was followed in order to perform a coasting beam intensity scan: once the maximum intensity is accumulated into the machine to about 10^{10} charges, the vertical damper is turned off for an adjustable time in order to let the coherent instability (see next section) develop and scrape the beam onto the vacuum chamber. Figure 2 on the left shows measured and predicted tune shifts in agreement within 80%.

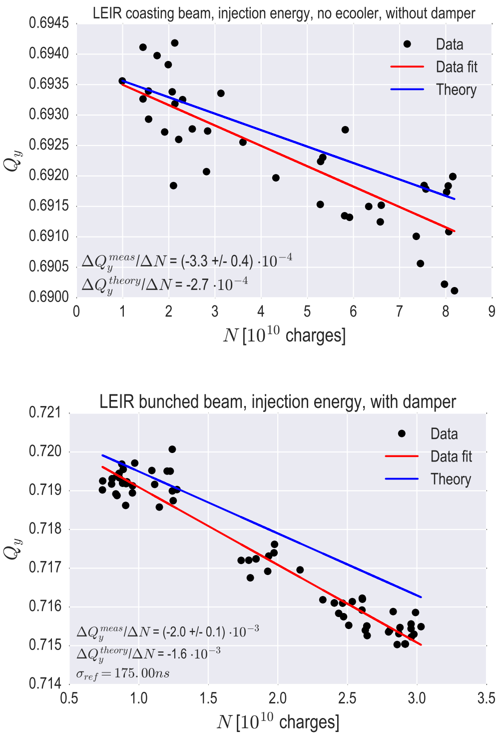

Figure 2: Coasting beam (left) and bunched beam (right) transverse tune shift versus intensity.

The measurements with bunched beams were performed after capturing the coasting beam using a double harmonic RF system. Despite the losses at capture described in the introduction, a maximum intensity of $3 \cdot 10^{10}$ charges within $\sigma_\tau^{rms} = 175$ ns bunch length was achieved. This produces a tune shift versus intensity of $-2 \cdot 10^{-3}$ (per 10^{10} charges) to be compared with $-1.6 \cdot 10^{-3}$ predicted scaling Eq. (1) by the inverse of the bunching factor $B_f = \sqrt{2\pi}\sigma_\tau^{rms} f_0 = 0.16$ between coasting and bunched beam measurements. The measurement results are shown in Fig. 2 on the right and are in agreement with prediction within 80%, in line with the coasting beam measurements.

INSTABILITY OBSERVATIONS

When the transverse feedback is not in operation, a fast vertical instability is observed in coasting beam, still unexplained by the impedance model outlined so far. We present here a characterization of the instability in terms of resonator impedance based on beam measurements.

Figure 3 shows the instability observed analyzing the turn-by-turn data acquired with a wide band pick-up of the trans-

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[1] We accounted for an additional $1/\beta$ factor multiplying the impedance of IW2D in order to be compatible with the theory of [16] used later.

verse feedback system. A single line growth can be observed at ≃ 1.9 MHz which corresponds to the coasting beam spectral line f_{-8} . The growth rate is ≃ $40\text{s}^{-1}/10^{10}$ charges and according to Eq. (1) would correspond to a transverse impedance with a real part of 28 MΩ/m, larger than the impedance model predictions of ≃ 0.1 MΩ/m in this range of frequencies. In the hypothesis of having a localized resonant mode in the machine at this frequency, we performed a Q-factor characterization studying the variation of growth rate with respect to a change in the machine tune Q_y. This can be seen as a frequency scan as the unstable mode line f_{-8} will move according to Eq. (2). As shown in Fig. 4 for different chromaticities [2], a resonator with a $Q \simeq 50$ can describe the observations within the accuracy of the measurement.

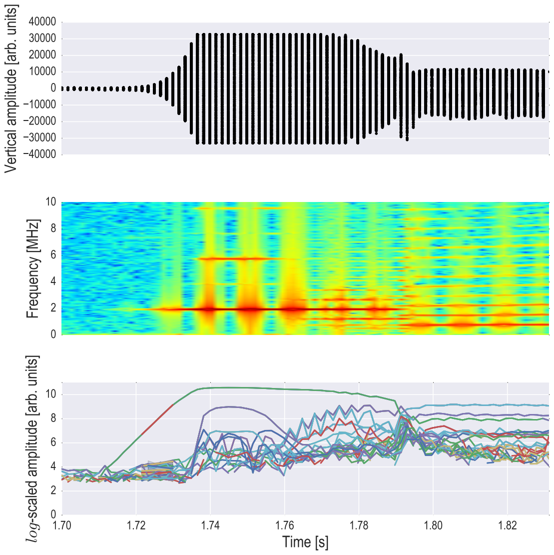

Figure 3: Turn-by-turn data (top) with moving window FFT (middle) and amplitude growth per coasting beam spectral line of the observed vertical instability: the linear growth (in log scale) corresponds to the f_{-8} spectral line.

In order to damp the instability, it is possible to enhance the transverse Landau damping by means of increasing chromaticity [16]. For this purpose, a scan in Q' was done for a fixed value of the vertical tune. Figure 5 shows the growth rate of the instability for different values of Q': the frequency f_{-8} is unstable for $Q' \in (-10, 4)$ whereas for $Q' > 4$ only higher order lines are observed to be unstable.

As the stabilizing betatron spread from chromaticity S is

$$S_n = \left(f_n - \frac{Q'}{\eta} f_0\right) \eta \Delta p/p, \tag{3}$$

with $\eta = -0.87$ the slip factor at injection and $\Delta p/p \simeq 10^{-3}$ momentum spread, S_{-8} cancels for $Q' = 4.5$. On the contrary, the threshold effect observed in Fig. 5, is still under investigation and could be related to the effect of direct space charge [18].

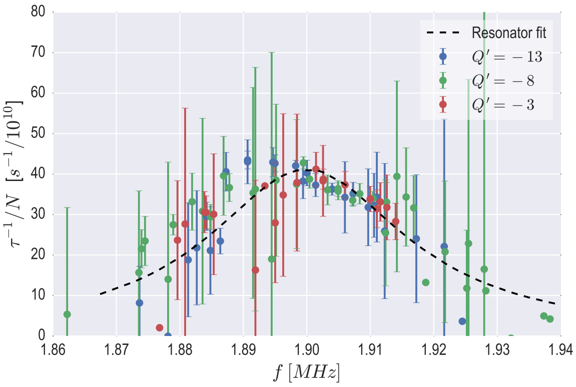

Figure 4: Instability growth rate versus frequency (i.e. Q_y) for Q' values of -3, -8, -13. The fit with a resonator model is done at the frequency of 1.9 MHz with $Q \simeq 50$ and growth rate of $40\text{s}^{-1}/10^{10}$.

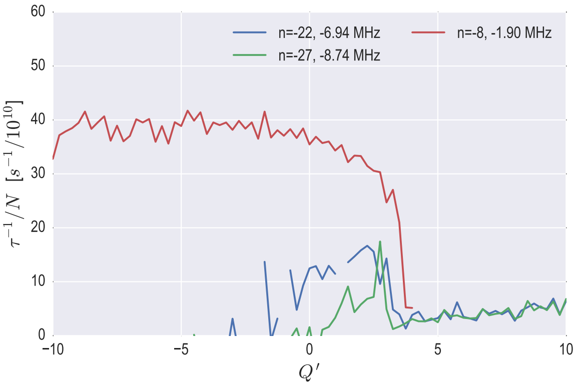

Figure 5: Instability growth rate versus Q': the f_{-8} line is unstable for $Q' < 4$.

CONCLUSIONS

The LEIR impedance model has been largely developed and accounts for ≃ 87% of the total machine elements. Studies are ongoing in order to include the remaining elements and update the tune shift predictions that are, so far, in agreement within 80% with coasting and bunched beam transverse tune shift measurements.

The vertical coherent instability observed in coasting beam without damper is not yet predicted by the model and studies are ongoing in order to localize possible sources of resonant modes (cavities, kickers, electron cooler, etc.).

By means of tune and chromaticity parametric scans it was possible to derive the parameters of an equivalent resonator describing the instability having shunt impedance of 28 MΩ/m, a resonant frequency at 1.9 MHz, corresponding to the f_{-8} coasting beam line, and a Q-factor of ≃ 50.

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[2] The ones indicated are programmed chromaticities corrected with -3 units to account for the difference between real and programmed values [17].

The stabilization of the instability is measured for $Q' > 4$ revealing a threshold effect in contrast with theory compatible with a local reduction of Landau damping. Further measurements, in particular of the beam transfer function in coasting, will help clarifying the role of space charge in the stabilizing mechanism and defining the corresponding stability margins for possible future intensity upgrades.

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