BEAM LOSS IN THE LOW ENERGY ION RING (LEIR) IN THE LIGHT OF THE LHC INJECTOR UPGRADE FOR IONS (LIU-IONS)

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Abstract

For the LHC injector upgrade for Ions (LIU Ions), the Low Energy Ion Ring (LEIR) is requested to deliver twice the intensity per extraction compared to the last Pb^{54+} ion run in 2013 [1]. As the number of injected ions has been increased into LEIR, a fast loss is observed during the RF-capture of the electron cooled ion beam, and this loss today leads to an effective saturation of the available ion intensity at extraction.

Based on chromaticity measurements with Pb^{54+} beam in LEIR with bunched beam and during acceleration in February 2013 [2], we suspected the chromaticity of the LEIR machine to be wrong in the vertical plane. To investigate the stationary behavior of the LEIR machine, we have developed a new method to measure the machine chromaticity on the low energy flat bottom of LEIR during a single cycle, where the ion beam is un-bunched and coasting. The new method controls the ion beam momentum by the LEIR electron cooler beam rather than the LEIR RF-system. The new method uses the LEIR Schottky system to measure the applied momentum change rather than the radial beam position offset in dispersive regions. The existing tune measurement system is used to measure the tune in the same way as in the classic way involving the RF-system and bunched ion beam. The new method allows a single-cycle-chromaticity measurement of coasting and un-bunched beam with high accuracy and no dependency of cycle-to-cycle machine variation.

INTRODUCTION

LEIR has accumulated, cooled and stacked ion beams of Oxygen (O^{4+}), Lead (Pb^{54+}) and Argon (Ar^{11+}). For LIU, LEIR is requested to deliver $1.6x10^9$ ions in 2 bunches, which is 50% more intensity compared to the last Pb^{54+} ion run in 2013. The number of injected lead ions into LEIR has been increased during several machine development studies (MDs) in late 2012 and early 2013. Total intensities of up to $1.8x10^9$ lead ions have been observed during the coasting beam phase before RF capture. An ion beam loss is then observed during and after the RF-capture. Today, this loss leads to an effective saturation of the available ion intensity at extraction. Fig.1 shows a typical Pb^{54+} NOMINAL cycle as it is used for LHC injections. Fig.2 shows that with two bunches per extraction up to $5.9x10^8$ ions per bunch have been measured.

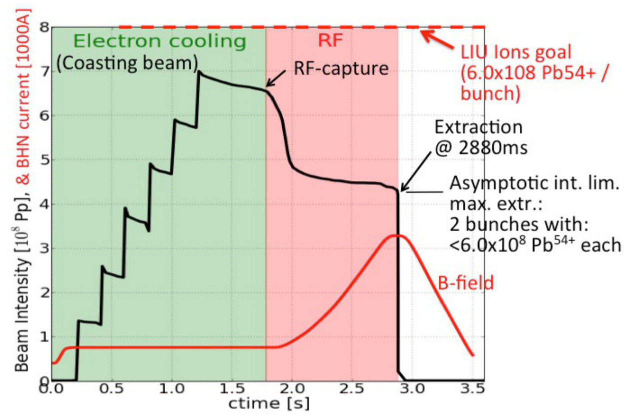

Figure 1: A typical LEIR NOMINAL cycle, 3.6s in length with main magnet current, proportional to particle momentum in red and ion beam intensity in black versus cycle time.

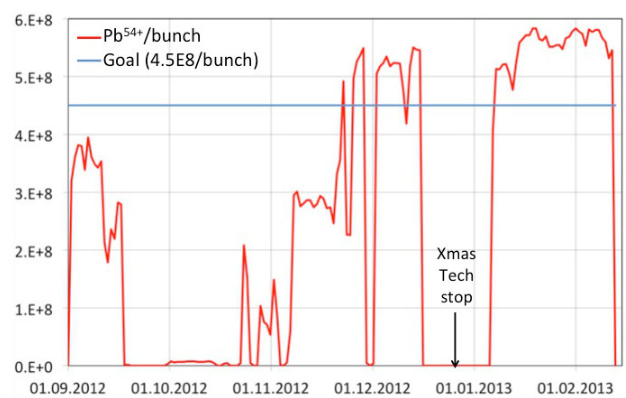

Figure 2: Extracted ions per bunch from LEIR from September 1st 2012 until February 1st 2013. The intensity goal of the LHC ion run for LEIR was $4.5x10^8$ ions per bunch, which was achieved in January 2013.

However, with respect to the LIU Ions beam parameter goals, the extracted beam intensity, which was achieved during the last ion run in early 2013, is not sufficient. In fact, $8x10^8$ ions per bunch are required for LIU Ions [1].

BEAM LOSS SYMPTOMS IN 2013

The LEIR Pb^{54+} low energy beam loss has been analysed in the past [2, 3]. The chromaticity of LEIR with Pb^{54+} was measured to be positive in the vertical plane (Fig.3) in February 2013, and as such, was found to be inconsistent with the machine design [4] and beam stability needs, both requiring at first order negative chromaticity for the horizontal plane and for the vertical plane.

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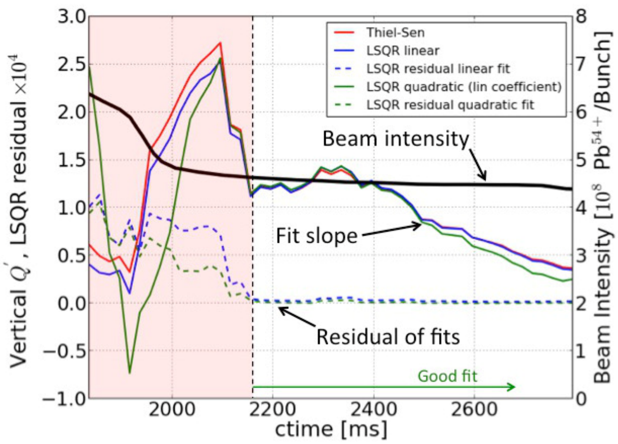

Figure 3: Fitted slopes to measured [2] chromaticity (Thiel-Sen fit in red, linear LSQR fit in blue and quadratic LSQR fit in green), residuals of described fits and beam intensity versus cycle time.

However, advancing the RF-capture in the magnetic cycle by 200 ms before the magnetic ramp, positioning it on the flat bottom has shown that the critical beam loss is advancing together with the RF-capture. This revealed that the low energy beam loss occurs with the machine optics of the flat bottom (see Fig.4) and that the machine optics has to be analysed in more detail, especially with respect to its chromatic behaviour.

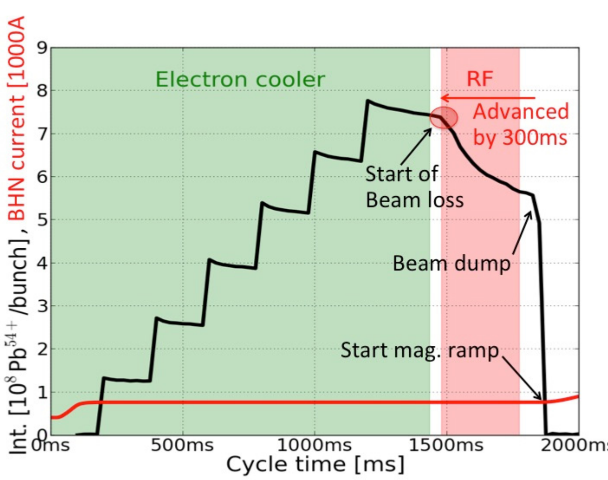

Figure 4: LEIR ion beam intensity with advanced RF-capture and main bending magnet current versus cycle time.

However at low energy, the ion beam is coasting. This denies access to chromatic information via the LEIR RF-system, which would produce bunched beam, but also would introduce transient effect during the bunching itself making the measurement not possible. Hence, another method, not relying on an RF-captured ion beam, is required to analyse the chromatic behaviour of LEIR.

A NEW METHOD

The Classic Chromaticity Measurement

So far, the chromaticity in the LEIR machine was determined by correlating a tune change due to a controlled energy change imposed by the RF-system on the already bunched beam. A radial beam offset was programmed in one of the two dispersive regions in the LEIR machine. The LEIR RF-system would then accelerate or decelerate the ion beam in order to meet the desired radial beam offset. The resulting change in beam momentum induces a tune change, and thus reveals the chromatic behaviour of the machine. Furthermore, it requires a large number of LEIR cycles to span the desired interval of momentum offsets.

Electron Cooling in the LEIR Machine

In LEIR, un-bunched ion beam is injected by Linac3 with a $\Delta p/p = 4x10^{-3}$ momentum ramp (see ref [4] for the details of the injection process). The ion beam remains on a flat and low energy plateau for up to 1.6s for electron cooling and for further multi-turn injections before it is bunched and accelerated. During the beam-cooling phase, the LEIR electron cooler is used to shrink the 6D-phase space emittance and to increase the phase space density of the coasting ion beam without significant beam loss.

The electron beam of the LEIR electron cooler also has the ability to drag the ion beam in momentum space. This feature is used to park the ion beam on a low momentum orbit and makes room for up to 7 additional 70 turn (multi-turn) injections. This way LEIR can stack up to 8 multi-turn injections in a 3.6 second NOMINAL cycle. Fig.5 shows the most common cycle setup with 7 multi-turn injections, with momentum dragging to a cooled stack and the momentum dragging to the RF-capture at the end of the diagram.

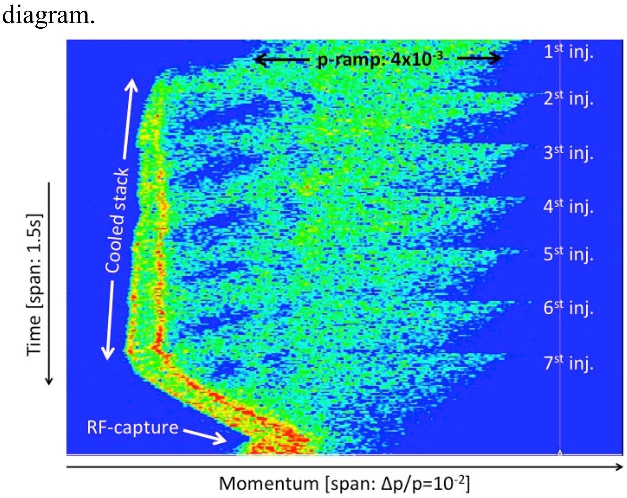

Figure 5: Schottky spectrum in momentum space of the Pb^{54+} ion beam in LEIR in a waterfall diagram (time versus beam momentum).

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Measurement of the Chromaticity by the Electron Cooling Velocity Shift Method

Due to its beam cooling and momentum shifting capabilities, the LEIR electron cooler, in conjunction with the LEIR Schottky-system, can be used to precisely move and measure the coasting beam in momentum space (see Fig.6).

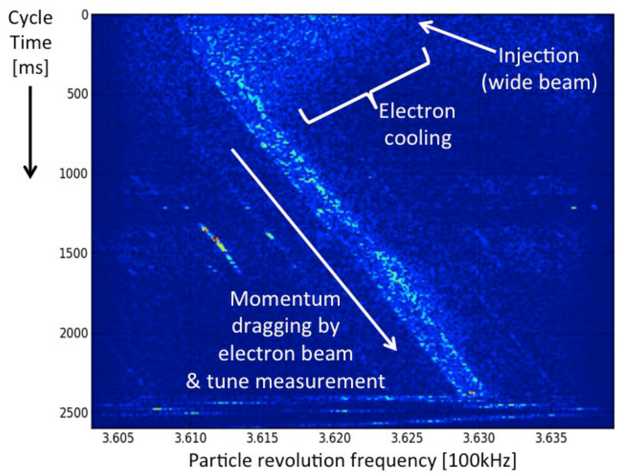

Figure 6: Schottky spectrum of the Ar^{11+} beam as it is used for the new method of chromatic measurement.

At the same time, the LEIR tune measurement system can determine the machine tune thanks to a Base-Band Q (BBQ) Measurement with Direct Diode Detection [5], which does not need a fully bunched beam to identify betatronic oscillations. We then correlate the measured tune with the measured momentum offset, apply linear least square fits and, then infer the machine chromaticity (see Fig.7).

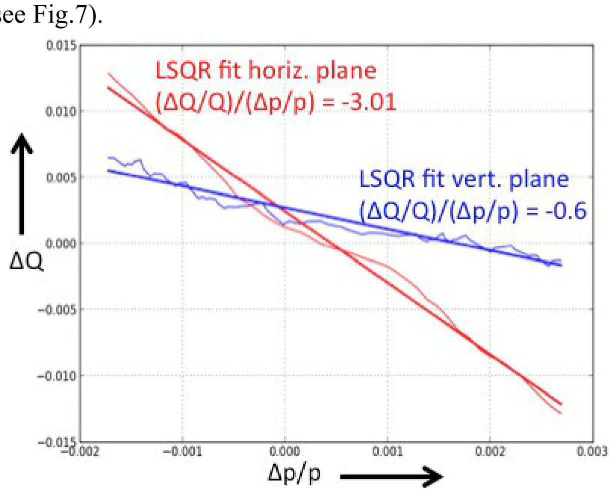

Figure 7: Measured machine tune deviation versus measured ion beam momentum deviation

The new method leads to a measured horizontal chromaticity of -3.01 and a vertical chromaticity of -0.6 with the Ar^{11+} ion beam. It has done so in a single cycle with a length of 4.8s, or 4 basic periods of the LHC injector chain timing system. The time resolution of the tune acquisition system was limited to 40ms and the one of the Schottky system was capable of a time resolution of 12.7ms.

To produce this measurement, we have injected into LEIR ion beam from Linac3 with a momentum ramp of $\Delta p/p = 4x10^{-3}$ across a ramp duration of 200µs. The LEIR electron cooler then cools the ion beam within 400ms to $\Delta p/p = 4x10^{-4}$. The velocity of the electron beam is then linearly changed during a period of 1800ms, momentum-dragging the ion beam accordingly. The dragging of the ion beam covers half the momentum acceptance of LEIR, which is $\Delta p/p = 10^{-2}$.

The measurement accuracy is limited by the extent of the longitudinal momentum distribution of the ion beam. This extent is determined by the effectiveness of the longitudinal electron cooling and is currently limited at $\Delta p/p = 4x10^{-4}$.

CONCLUSION

The new method made accessible the horizontal and the vertical chromaticity of the LEIR machine on the low energy plateau with coasting Ar^{11+} beam. Earlier measurements with Pb^{54+} ion beam in February 2013 have revealed a positive vertical chromaticity during a noisy beam loss period after RF-capture and at the beginning of the momentum ramp.

This electron cooler method requires a sufficiently long plateau of constant magnetic field, where the LEIR electron cooler has sufficient time to shrink to a sufficiently small extension the longitudinal momentum distribution of the coasting ion beam before the chromaticity measurement can start. Due to the single cycle required for the measurement, it is immune to the large cycle-to-cycle variations, which we observe in LEIR. This makes it a very useful new tool in better understanding the low energy beam loss in LEIR.

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