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LEIR LONGITUDINAL STUDIES

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Abstract

Towards the end of 2015 and during 2016 there were extensive studies of longitudinal beam dynamics in LEIR aimed at improving extracted intensities. As the driving source of losses early in the ramp was shown to be transverse space charge tune spread a significant improvement came from flattening the beam profile to increase the bunching factor by offsetting the RF frequency from the beam revolution frequency. Further benefits were provided by modulating the RF frequency during capture, leading to emittance blow-up and improved reproducibility. The use of two RF cavities during operation was studied to try and further increase the captured emittance, however after careful alignment of the RF it was found that a hard limit in the bunch heigh of approximately 7 MeV exists. Due to the acceptance limit there was no operational benefit to using both cavities simultaneously.

INTRODUCTION

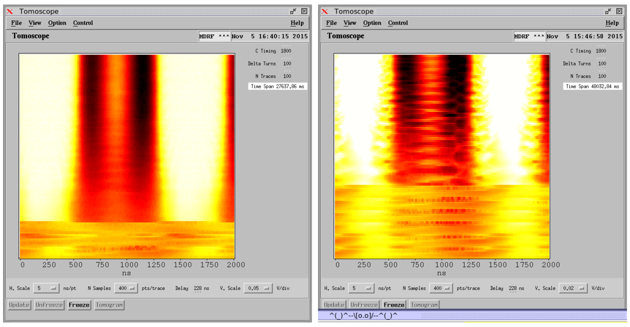
This paper sumarises the studies that were carried in the longitudinal plane in LEIR at the end of 2015 and during 2016. The paper comprises three sections, the first related to line density reduction, the second to two cavity operation, and the third to longitudinal acceptance limitations.

LINE DENSITY REDUCTION

The RF frequency in LEIR is calculated based on the measured B-Train, however during capture an additional offset can be used to correct for differences between the design frequency and the revolution frequency of the coasting beam. Under the assumption that the revolution frequency is constant an offset can therefore be used to center the bucket on the center of the coasting beam. However, it was found in operation that having an offset between the RF and the beam during capture lead to reduced losses.

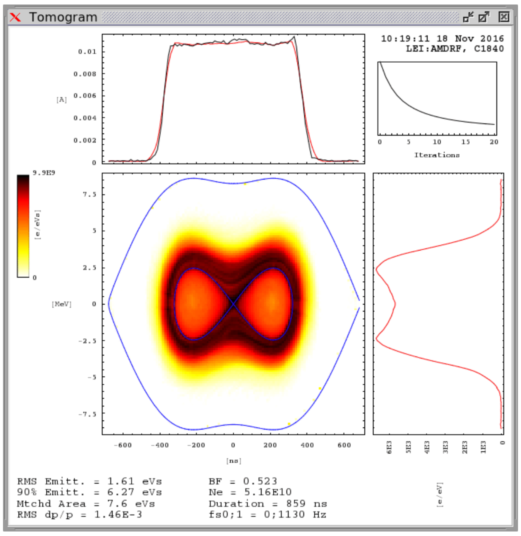
Figure 1 shows the capture process with the RF frequency (F_{RF}) equal to the coasting beam revolution frequency (F_{beam}), and with an offset between them. Whilst the centered case (Fig. 1a) is clearly smooth and much neater the transmission is better in the case where $F_{RF} \neq F_{beam}$ (Fig. 1b).

After further optimising the voltage function and frequency offset the capture process was designed such that the coasting beam was captured in such a way as to produce hollow bunches, dubbed the "Lone Ranger" effect shown in Figure 2 [1]. The Lone Ranger phase space distribution shows a low density part of the beam within the inner seperatrix, with the majority of the particles on the outer edge of the inner separatrix. The difference between the beam and RF frequencies must be chosen carefully, if the core is too dense or the outer part of the beam too far from the inner separatrix the profile will not be flat, thus increasing the line density.



(a) $F_{RF} = F_{beam}$ (b) $F_{RF} \neq F_{beam}$

Figure 1: Waterfall plots of capture with the RF centered on the coasting beam, and with an offset.



```
RMS Emitt. = 1.61 eVs        BF = 0.523
90% Emitt. = 6.27 eVs        Ne = 5.16E10
Mtchd Area = 7.6 eVs         Duration = 859 ns
RMS dp/p = 1.46E-3           fs0;1 = 0;1130 Hz
```

Figure 2: The Lone Ranger phase space distribution.

Whilst the Lone Ranger effect was able to provide lower line densities than otherwise achievable the sensitivity to changes in coasting beam revolution frequency meant regular adjustment was necessary. Along with slow changes in the average revolution frequency, which were corrected by regular tuning, there is also shot to shot variations that cannot be compensated for. An alternative method of capture using frequency modulation during the capture process was found to greatly improve the reproducibility of the captured bunch.

Modulating the RF frequency during capture causes the bucket to sweep through the coasting beam giving a more reproducible and uniform distribution than otherwise possible. Compared to fixed frequency capture this produces significantly improved reproducibility, unfortunately the intensity

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in initial studies was not as high. The Full Width at 25% Maximum of the captured bunch is shown in Fig. 3, the flat frequency data was taken before Lone Ranger became the operational norm.

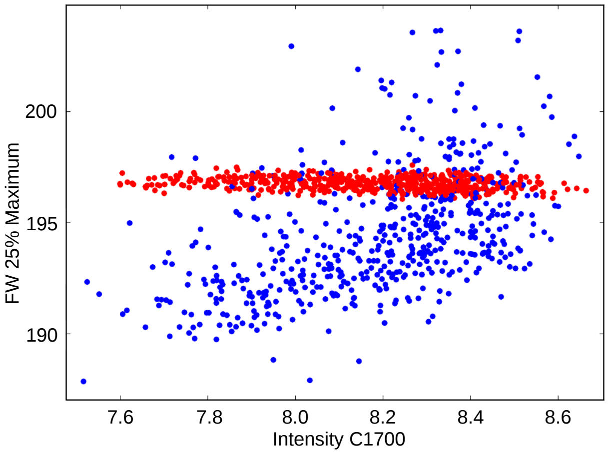
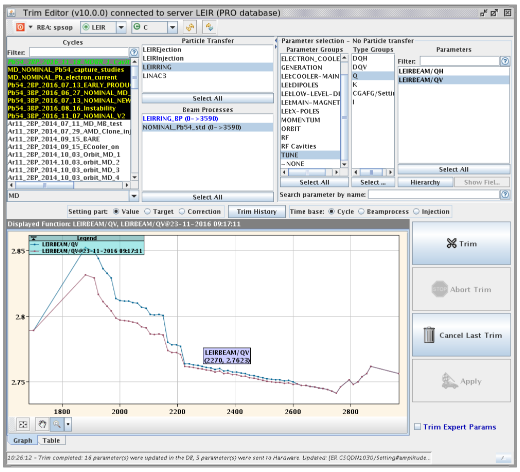


Figure 3: A comparison of captured Full Width at 25% Maximum vs intensity with modulated RF frequency (red) and flat RF frequency (blue) during capture.

As modulated capture provided larger longitudinal emittances and lower line densities it was expected that the transmission would be higher, however this was not the case. After a significant amount of optimisation and study it was found that modifying the working point in the vertical direction throughout the cycle was needed to capitalise on the benefits as shown in Fig. 4. The need for a modified working point was put down to a shift in the density of the tune foot print, which changed the density in tune space near resonance lines.


Trim Editor (v10.0.0) connected to server LEIR (PRO database)

RBA: spsop

Setting part: ● Value ○ Target ○ Correction

Time base: ● Cycle ○ Beamprocess ○ Injection

Parameter selection – No Particle transfer

Displayed Function: LEIRBEAM/QV, LEIRBEAM/QV@23-11-2016 09:17:11

10:26:12 - Trim completed: 16 parameter(s) were updated in the DB, 5 parameter(s) were sent to Hardware. Updated: [ER.GSQDN1030/Setting#amplitude...

Figure 4: Original (red) and new (blue) vertical tune used to maximise transmission with modulated capture.

After implementing the new working point a comparison of modulated capture with Lone Ranger capture (Fig. 5) showed that better, and more reproducible, transmission could be achieved. As a result modulated capture was used operationally for approximately the last half of the 2016 p-Pb run.

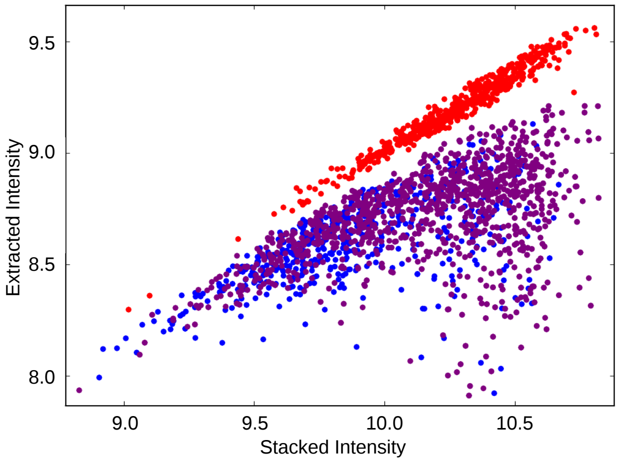


Figure 5: Extracted versus stacked intensity with modulated capture (red) and Lone Ranger (purple and blue).

TWO CAVITY OPERATION

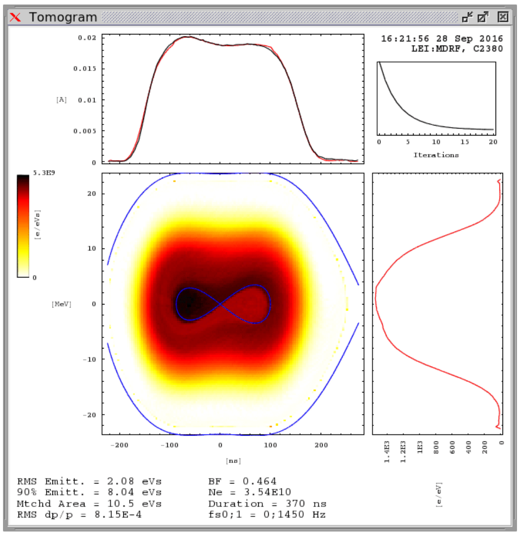
In LEIR there are two Finemet cavities, with one used operationally and the other maintained as a hot spare. After it was demonstrated that frequency modulated capture could be used to provide reproducible longitudinal emittance blow-up it was decided to try using both cavities simultaneously. By using both cavities the RF acceptance would be increased, potentially allowing even larger bunches to be produced.

To use both cavities they must first be phased correctly relative to each other. The first coarse tuning brought the phases very close to correct alignment without beam, afterwards a fine tune with beam made a small additional correction. Using modulation during capture allowed for a highly reproducible distribution in phase space, it was therefore possible to use bunch profiles and tomography to adjust the LLRF and bring the harmonics into alignment.

To align the cavities using the beam an initial measurement was taken with both harmonics in a single cavity, shown in Fig. 6a. The h=2 voltage was then set to 0 in the first cavity and set to the operational program in the second cavity. The conditions prior to fine tuning are shown in Fig. 6b, whilst the result is very close to the single cavity case there is a visible difference. Fine tuning of the alignment of the cavities resulted in a near identical bunch as can be seen in Fig. 6c.

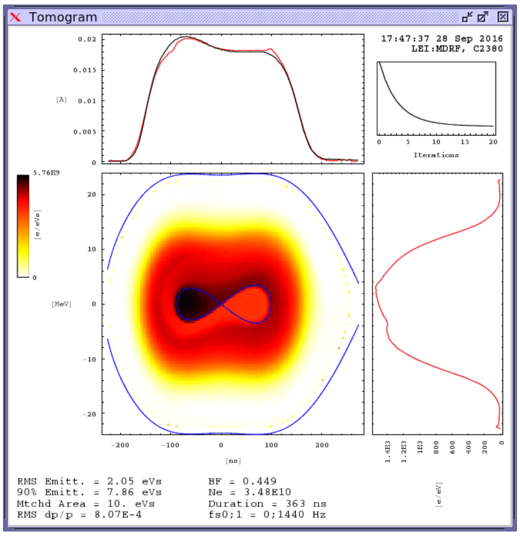
LONGITUDINAL ACCEPTANCE LIMITATION

After dual cavity operation was shown to be effective frequency modulation was used to try and further increase the captured emittance, taking advantage of the increased longitudinal acceptance. It was discovered that the emittance could not be increased past a hard limit, at which point losses were unavoidable with no further blow-up. As it was not



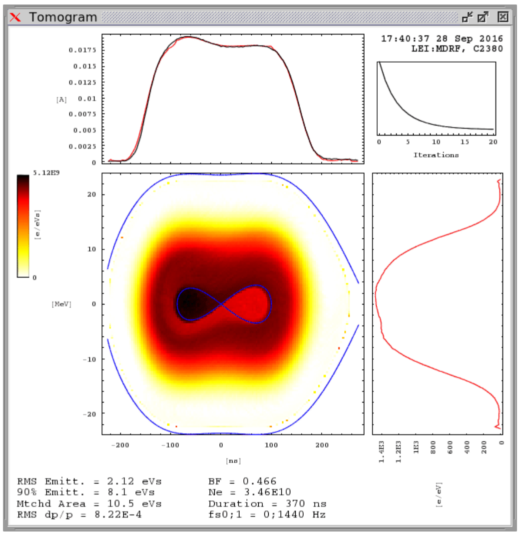
```
RMS Emitt. = 2.08 eVs       BF = 0.464
90% Emitt. = 8.04 eVs       Ne = 3.54E10
Mtchd Area = 10.5 eVs       Duration = 370 ns
RMS dp/p = 8.15E-4          fs0;1 = 0;1450 Hz
```

(a) Single Cavity



```
RMS Emitt. = 2.05 eVs       BF = 0.449
90% Emitt. = 7.86 eVs       Ne = 3.48E10
Mtchd Area = 10. eVs        Duration = 363 ns
RMS dp/p = 8.07E-4          fs0;1 = 0;1440 Hz
```

(b) Dual Cavity Initial



```
RMS Emitt. = 2.12 eVs       BF = 0.466
90% Emitt. = 8.1 eVs        Ne = 3.46E10
Mtchd Area = 10.5 eVs       Duration = 370 ns
RMS dp/p = 8.22E-4          fs0;1 = 0;1440 Hz
```

(c) Dual Cavity Final

Figure 6: Phase spaces produced with single cavity (6a), two cavities before fine tuning (6b) and two cavities after fine

clear if the losses were due to an acceptance limitation or related to the transition from the flat bottom to the ramp the capture was first moved earlier in the cycle to allow distinguishing the end of capture from the start of the ramp.

Separating capture from the ramp allowed two distinct losses to be seen as shown in Fig. 7. First a fast loss can be seen at C1780, the end of capture, and a second larger loss is seen at the start of the ramp at C1850. The localisation of losses at capture appeared to indicate that the longitudinal momentum spread was responsible for lost beam, this was shown to be the case by capturing a fixed emittance and then increasing the voltage to stimulate losses.

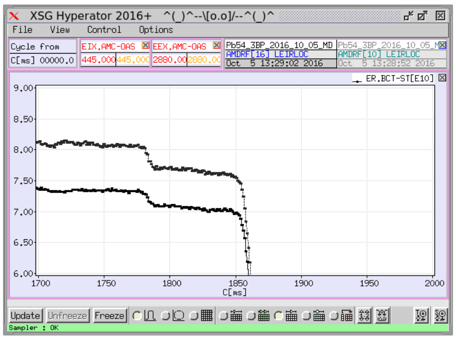


Figure 7: Distinct losses at the end of capture and the start of the ramp.

For a given emittance an increase in the RF voltage will lead to a larger dp/p and a smaller bunch length. After capture the two harmonics were increased to a peak and then decreased (peak at 100ms shown in Fig. 8) causing an increase in the bunch height and the losses shown in Fig. 9 with no fast loss at the start of the ramp.

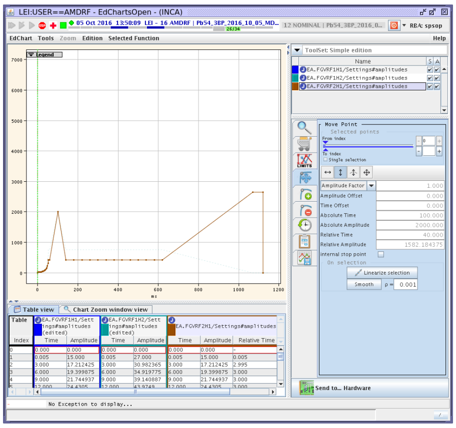


Figure 8: Voltage spike used to increase bunch height.

Figure 10 shows the phase space reconstructions at C1800 (Fig. 10a), C1820 (Fig. 10b) and C1830 (Fig. 10c), where the emittance decreases with approximately constant $\frac{dp}{p}$. The constant $\frac{dp}{p}$ shows that there is a hard limit in the maximum energy deviation, which therefore causes the emittance to be reduced with increasing voltage due to losses.

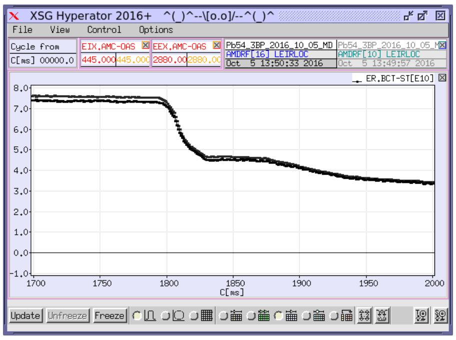


Figure 9: Losses during voltage spike.

The acceptance limitation demonstrated that the maximum bunch height after capture must be less than 7 MeV, as a result the use of two cavities would not be able to improve transmission. Working with a single cavity the voltage program was adjusted such that the ratio $V_{h=2} : V_{h=1}$ maximised $\frac{A_B}{h_B}$, where A_B is the bucket area and h_B is the bucket height. The maximum of $\frac{A_B}{h_B}$ on the flat bottom was found to be at approximately 1.1 : 1 voltage ratio.

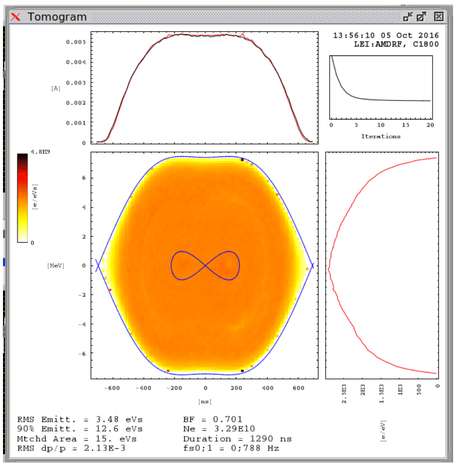
CONCLUSION

There were extensive studies in the longitudinal plane of LEIR during 2016. A series of studies and developments are summarised in this paper, which resulted in highly reproducible beams with large emittances being produced through frequency modulation during capture.

Initially a constant offset between the RF frequency and the design frequency was used to increase the captured emittance. Further improvements to this lead to the production of the “lone ranger” distribution, in which the beam is smeared around the edge of the inner separatrix giving a high bunching factor and very flat profile. Later it was shown that modulating the frequency offset during the capture process lead to larger emittances and improved reproducibility, combined with an adjustment to the working point this then allowed better and more reproducible transmission.

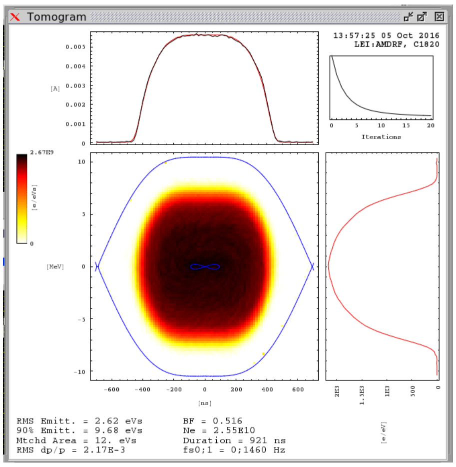
There are two cavities in the LEIR ring, with only one used in operation. The use of two cavities was studied as a possible way to further increase the longitudinal acceptance, allowing greater emittance blow-up during capture. After careful alignment of the voltage in the cavities it was found that a limit in the longitudinal acceptance existed due to the energy spread of the beam, rather than the bucket area. Since the maximum energy deviation on the flat bottom was approximately 7 MeV, corresponding to an RMS $\frac{dp}{p}$ slightly above 2×10^{-4} there was no operational benefit to using two cavities.

Finally in the second half of the LHC p-Pb run frequency modulated capture with a single cavity and voltage functions designed to maximise the bucket area within the acceptance limit became the operational norm.



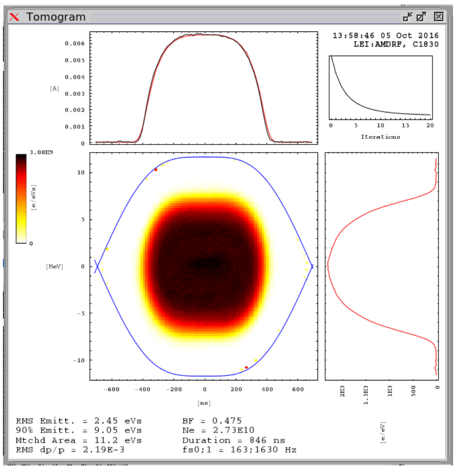
```
RMS Emitt. = 3.48 eVs        BF = 0.701
90% Emitt. = 12.6 eVs        Ne = 3.29E10
Mtchd Area = 15. eVs         Duration = 1290 ns
RMS dp/p = 2.13E-3           fs0;1 = 0;788 Hz
```

(a) C1800, ε_l =15 eVs, $\frac{dp}{p} = 2.13 \times 10^{-4}$



```
RMS Emitt. = 2.62 eVs        BF = 0.516
90% Emitt. = 9.68 eVs        Ne = 2.55E10
Mtchd Area = 12. eVs         Duration = 921 ns
RMS dp/p = 2.17E-3           fs0;1 = 0;1460 Hz
```

(b) C1820, ε_l =12 eVs, $\frac{dp}{p} = 2.17 \times 10^{-4}$



```
RMS Emitt. = 2.45 eVs        BF = 0.475
90% Emitt. = 9.05 eVs        Ne = 2.73E10
Mtchd Area = 11.2 eVs        Duration = 846 ns
RMS dp/p = 2.19E-3           fs0;1 = 163;1630 Hz
```

(c) C1830, ε_l =11 eVs, $\frac{dp}{p} = 2.19 \times 10^{-4}$

Figure 10: Phase spaces during an increase in the RF voltage showing an approximately constant $\frac{dp}{p}$ with decreasing longitudinal emittance (ε_l) demonstrating the existence of a longitudinal acceptance limitation indepent of RF voltage.

ACKNOWLEDGEMENTS

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REFERENCES

[1] the New LEIR Digital Low-Level RF System, M. E. Angoletta et al, *IPAC2017, THPAB144*