LEIR NOMINAL beam commissioning step by step

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SPS/LEIR Training
Objectives

Large improvement of LEIR performance in the past 3 years thanks to the synergy of LEIR/SPS-OP + LEIR/Linac3 teams.

In 2021, we will need to recover 2018 performance, i.e. steady delivery of \( \geq 9\times10^9 \) extracted charges from the machine.

In this lecture: we will try to gather the most important steps learned from the past experience and required for LIU performance achievement.
Our target

Accumulation  Capture  Acceleration
Steps for NOMINAL commissioning

- First injection setup
- First turn
- Linac3/LEIR Energy matching
- Orbit correction
- Acceptance optimization
- Injection optimization
- Orbit along the ramp
- Extraction
- Tune/Chromaticity setup
- Cooler setup for high intensity
- Accumulation
- RF modulated capture
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First injection setup

For the 2021 restart (and already by end of 2020), LEIR ITE to EI lines will be equipped with 9 BPMs allowing to check both position and pulse quality, also for low (~4uA) current.
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1. w/o energy ramping: check the quality of the 200us pulse (Intensity/Position), e.g. at EI.BPMI30.
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2. w/ energy ramping: check ramping effect ($\frac{\Delta p}{p} \sim \pm 0.2\%$), e.g. in EI.BPMI30.
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3. w/ energy ramping: check position and correct to reference.

H - trajectory

V - trajectory
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First turn

- LEIR injection process foresees stacking in longitudinal and transverse planes.
- 200 us pulse ramped from $\frac{\Delta p}{p}$ -2e-3 (low energy) to +2e-3 (high energy).
- Low energy pulse comes first from transfer line to the inner circumference.
- High energy pulse travels towards outer circumference.
- Collapsing bump allows for same on momentum orbit.

$$\text{Linac3}$$

$$200\text{us}$$

$$x = x_b + D_x \frac{\Delta p}{p}$$
First turn

Injection efficiency determined by:

- Injected beam position at the septum \((x,x',y,y')\), mean energy and energy ramp extent
- Closed orbit injection bump settings \((x,x',y,y')\), transverse tunes \((Q_x, Q_y)\)

Terrain for optimizers! But still to early… check first turn… first!

- New mode of operation available for first turn observation / debug.
- Only indicative positions available due to noisy trace.
- Signal should look like a derivative of the pulse.
First turn

Once the beam circulates, it is also possible to monitor the fast-bumpers rise and fall and the corresponding accumulation slope via OASIS.

Pulse along EI

FBCT in LEIR

Bumpers voltage
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Energy matching

Once the beam manages to circulate, the Schottky monitor can be used to check the mean energy of the injected beam, even at weak current.

Observe the $100^{th}$ rev. harmonic at 36 MHz

Example: no ramping, no cooling
Energy matching

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Example: ramping, no cooling
Energy matching

Cooler can be setup in a first rough manner to allow for beam cooling and RF capture.

Cooler setup (335 mA):

\[ v_{el} = 99.8\% v_{ions} \]

- \( V_{CONT} \): 480V
- \( V_{GRID} \): 1550V
- \( V_{GUN} \): 2588V

Cooler bump:

- \( X = 10 \) mm
- \( X' = 0 \) mrad
- \( Y = 0 \) mm
- \( Y' = 0 \) mrad

Example: ramping, cooling
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Orbit correction

Even with low intensity we can proceed in correcting the orbit.
To decouple from the complex injection bump gymnastics, we can split the plateau in two segments.
Orbit correction

Even with low intensity we can proceed in correcting the orbit.
To decouple from the complex injection bump gymnastics, we can split the plateau in two segments. We capture and correct the orbit at the radial loop (RL) pickups with a bare correction (PU 31 & 32).
Orbit correction

On the Schottky we can see that, when RL is still not on (immediately after capture) the expected frequency is different from the one with RL on $\rightarrow$ RL tries to correct an off momentum orbit.
Orbit correction

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We can avoid this “jump” trimming the value of Btrain received by the RF with the ER.TRAIN/CCV parameter: (27217 for NOMINAL)
Orbit correction

The correction can now be extended all over the cycle, restoring the previous makerule (all flat bottom). Iterations on Btrain correction might be required to center back the RF frequency at capture.
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Acceptance optimization

The injected beam can be put slightly off momentum w.r.t. RF capture frequency (+0.1% mean momentum). This can be achieved trimming the machine BRHO (reference set to 1.127 Tm, design 1.142 Tm).

\[ f_{\text{ref}} = 36.047 \text{ MHz} \]

\[ 36.083 \text{ MHz} = 1.001 \times f_{\text{ref}} \]
Acceptance optimization

As well, the stacked beam should be dragged to -0.1% w.r.t. the RF central momentum.

\[ f_{\text{ref}} = 36.047 \text{ MHz} \]

\[ 36.01 \text{ MHz} = 0.999 \times f_{\text{ref}} \]

\[ 36.083 \text{ MHz} = 1.001 \times f_{\text{ref}} \]
Centering capture

As the stacked beam is off momentum, it needs to be dragged back with ecoolwer voltage once the accumulation process is ended.

$$f_{ref} = 36.047 \text{ MHz}$$
Centering capture

Increasing (decreasing) the voltage of the red point (last in high gun voltage) we accelerate (decelerate) the beam

$$f_{ref} = 36.047 \text{ MHz}$$
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Injection optimization

At this point, we can aim for more intensity injected in the ring:
Run the optimizer on the injection line (ETL/EI) and/or the injection bump optimizer.

- EI line steering
- ETL corrector steering
- Injection bump steering
Injection optimization

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We went even above 75%! 😊
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Orbit along the ramp

With one injection we can already start to correct the orbit along the cycle using the skeleton points available or adding other ones according to the correction needed.
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Extraction

Three independent kicker modules are available to kick the beam towards the extraction septum SMH40.
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The extraction bump can be optimized together with the ETL/ETP lines to extract the beam to the PS.

Orbit at 2875ms (before extraction)
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Tune setup

Using Qmeter + AutoQ we can correct the tunes to be flat along the cycle at $Q_x, Q_y = 1.82, 2.72$. 
The machine operates below transition: \( Q' \) is setup small and negative \( (Q'_{x,y} = -1) \).
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- Accumulation
- RF modulated capture
Cooler setup for high intensity

- In order to allow better lifetime and stability margins, cooling rate can be adjusted mainly by changing the orbit bump in the cooler.
- From the cooling maps performed in 2018/2019, the electron cooler has maximum cooling rate when the ions travel with an horizontal offset of 10mm.

\[ \propto \frac{\text{Re}(Z)N}{\sigma_p} \]

\[ \propto \frac{\text{Im}(Z)N}{\sigma_p} \]

A: close to boundary
B: more margin!

See also 28 May 2019, SPS-LEIR OP training on LEIR intensity limitations
https://indico.cern.ch/event/822753/
Cooler setup for high intensity

- In order to allow better lifetime and stability margins, cooling rate can be adjusted mainly by changing the orbit bump in the cooler.
- From the cooling maps performed in 2018/2019, the electron cooler has maximum cooling rate when the ions travel with an horizontal offset of 10 mm.
- A negative H angle helps to gain lifetime and stability.
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- **Accumulation**
- RF modulated capture
Accumulation

The standard NOMINAL cycle allows for 7 injections spaced by 200ms.

The number of injections can be changed from the LSA trim editor.
Accumulation

This is what you could see on the new and old Schottky monitor.

NB: a small “tilt” is visible on the stacked beam → correction for B-field decay à-la-radial loop.
More corrections

During accumulation the intensity in the machine is larger and collective effects change the machine parameters (e.g. tune, frev, etc..)

- Tune might need further minor touch in order to keep it constant.
- The electron gun voltage can also be adjusted to keep the beam momentum aligned.

E.g. Increasing (decreasing) the voltage of the red point (before velocity dragging) we accelerate (decelerate) the beam.
More corrections

A “vacuum bump” is needed in accumulation to avoid pressure rise (due to beam loss and consequent outgassing in S4) that would reduce beam lifetime.

The bump has non-unique shape: here an example.
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RF-Modulated capture

In order to flatten the line density and reduce the space charge tune shift, a modulated capture is used.
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Values of frequency and amplitude modulation on the \( f_{rev} \) correction can be set in the LSA trim editor in the RF BEAM CONTROL panel or through working set:

- EA.FGMODAMPLI
- EA.FGMODFREQ
And there you go..!
And there you go*..!

*and fingers crossed that it stays like that!
Thanks for your attention!
Questions*?

*even later on ;) → nicolo.biancacci@cern.ch
Backup
The LEIR machine

<table>
<thead>
<tr>
<th></th>
<th>Injection</th>
<th>Extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C$</td>
<td>$25\pi$ m</td>
<td></td>
</tr>
<tr>
<td>$K$</td>
<td>4.2 MeV/n</td>
<td>72.2 MeV/n</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.094</td>
<td>0.37</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>1.005</td>
<td>1.07</td>
</tr>
<tr>
<td>$Q_x, Q_y$</td>
<td>1.82, 2.72</td>
<td></td>
</tr>
<tr>
<td>$Q_x', Q_y'$</td>
<td>-2.19, -3.74</td>
<td></td>
</tr>
<tr>
<td>$\gamma_{tr}$</td>
<td>2.87</td>
<td></td>
</tr>
<tr>
<td>$\eta$</td>
<td>-0.87</td>
<td></td>
</tr>
<tr>
<td>$\alpha_c$</td>
<td>0.1241</td>
<td></td>
</tr>
<tr>
<td>$f_{rev}$</td>
<td>360 kHz</td>
<td>1.42 MHz</td>
</tr>
<tr>
<td>$\varepsilon_{nH,V}$</td>
<td>$\sim$ 0.4 um (after cooling)</td>
<td></td>
</tr>
<tr>
<td>$4\sigma_{t,rms}$</td>
<td>800 ns (h=2)</td>
<td></td>
</tr>
</tbody>
</table>
Frequency program

\[ m_u = 1.66009 \cdot 10^{-27} \]

\[ C = 25\pi \]

\[ Q = 54 \]

\[ A = 208 \]

\[ e = 1.60217 \cdot 10^{-19} \]

\[ c = 299792458 \]

\[ f_{rev} = \frac{c}{C} \sqrt{1 - \frac{1}{(\frac{B\rho Qe}{cm_uA})^2 + 1}} \]

LEIR measured

LEIR LSA

0.6% difference?
Injection bump/ injection trajectory optimization

- ETL optimization procedure:
  1. First injection optimized for high efficiency with optimizers
  2. Additional function steps corrected looking at BPM orbit to achieve same position (assumes this as main knob).
Orbit in the cooler optimization for best distribution

- Cooling maps in H/V produced by A. Saa Hernandez et al. (to be presented)
- Island of strong H cooling confirmed.
- Optimal bump settings are not necessarily the “coolest” ones:
  - Small beam size -> ok for aperture, may lead to poor lifetime or instabilities.
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- Island of strong H cooling confirmed.
- Optimal bump settings are not necessarily the “coolest” ones:
  - Small beam size -> ok for aperture, may lead to poor lifetime or instabilities.
- Operational settings for accumulation:
  - Fast cooling in V (due to tighter aperture): straight bump through the cooler.
  - Weak cooling in H (larger aperture): achieved with non-zero angle in cooler bump.
Momentum correction during accumulation (radial loop -like)

- Effect of Bfield drift can be seen removing radial loop (RL) after early capture.
- RL changes frev to ensure no orbit drifts
- Cannot be used in accumulation phase: no bunch structure at RL pickups.
Momentum correction during accumulation (radial loop -like)

- Momentum increased in accumulation to compensate Bfield drift.
- So far we give the same order of frev correction needed as if the RL were on…
• Due to B field decay at injection, H injection bump drift can be as high as 5mm
• Compensation can be done on the function
• Clear gain on efficiency of last injections.
Orbit bump in SS4 to minimize vacuum pressure
• One single un-optimized cycle, can affect the global vacuum pressure to extreme levels -> impact on lifetime of all cycles.
Injected pulse energy distribution optimization

- Injection efficiency depends also on the beam energy distribution coming from Linac3.
- Mean energy offset or large energy tails are eventually lost if out of acceptance.
- The stripper foil is also affecting the “mean” energy.
- Currently being optimized with help of Linac3 team looking at:
  - Tank 3 output energy (defines LEIR mean energy)
  - Ramping/Debunching cavities settings (define energy spread along pulse)
Cooling + dragging + impedance

Toy model simulation parameters:

**Impedance**
- $R_s = -1M\Omega$
- $n_{fr} = 1000 f_0$
- $Q = 1.$

**Cooler**
- $n_{e} = 4e_{13}$
- $B = 0.07 \text{ T}$
- $T_{\perp} = 0.01 \text{ eV}$
- $T_{\parallel} = 0.001 \text{ eV}$
- $L_e = 3 \text{ m}$
- $\Delta v_{offset} = -2e^{-3}$

**Beam**
- $n_{mp} = 50k/\text{inj}$
- $n_{bins} = 1850$
- $\Delta p/p_0 = +/-1e^{-3} \text{ uniform}$
- $N_{c/inj}=2e10 \text{ charges}$
- $\Delta T_{inj}=4000 \text{ turns}$

![Schottky spectrum at $n_h = 100$](image)

![Schottky spectrum log amplitude](image)