LHC Injectors Upgrade

e-Cooling measurements at LEIR 2018

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Cooling Meeting, 13th March 2019

Motivation

Electron Cooler is an essential component of LEIR:

- To enable beam storage: reduce the transverse and longitudinal emittances of the ion beam (high charge state: Pb 54+, low injection energy: $\beta_{rel} = 0.094$)
- To enable beam accumulation: drag mean energy of each injected pulse to accommodate next injection

Several measurements during 2018

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Several measurements during 2018

- to characterize the cooling force and benchmark simulations of new code
  - Already discussed in the previous meeting (https://indico.cern.ch/event/774322/contributions/3217585/attachments/1776825/2889336/Ecool_and_Elens_2019_01_10.pdf)

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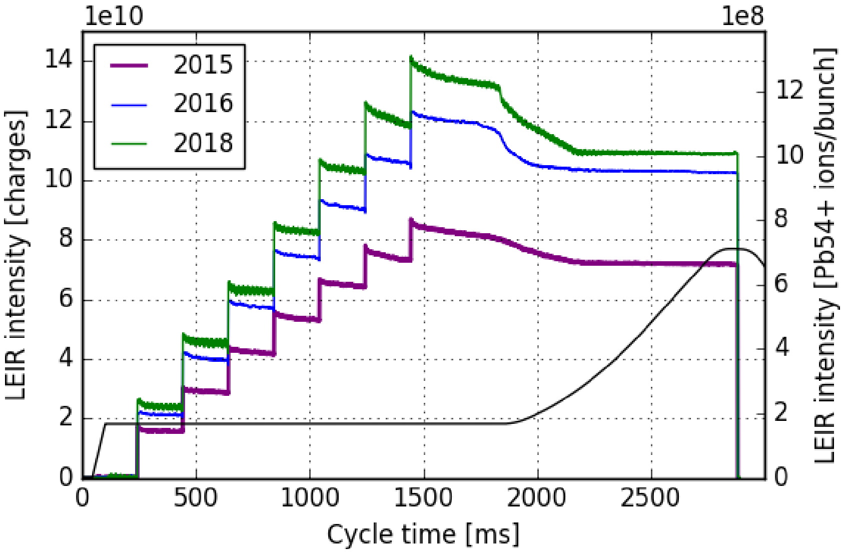
- to try to overcome intensity limitations
  - Ion-acceleration with Ecooler
  - Cooling of bunched beams
  - Studies of equilibrium emittances



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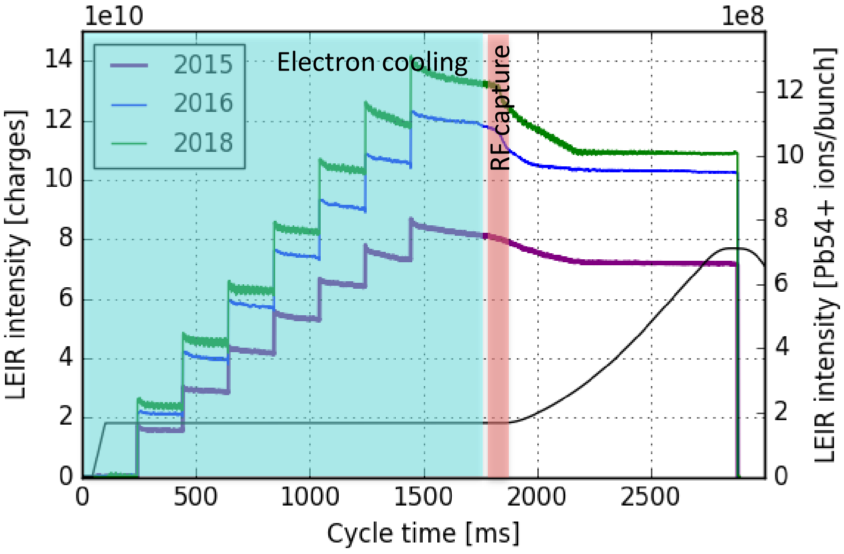

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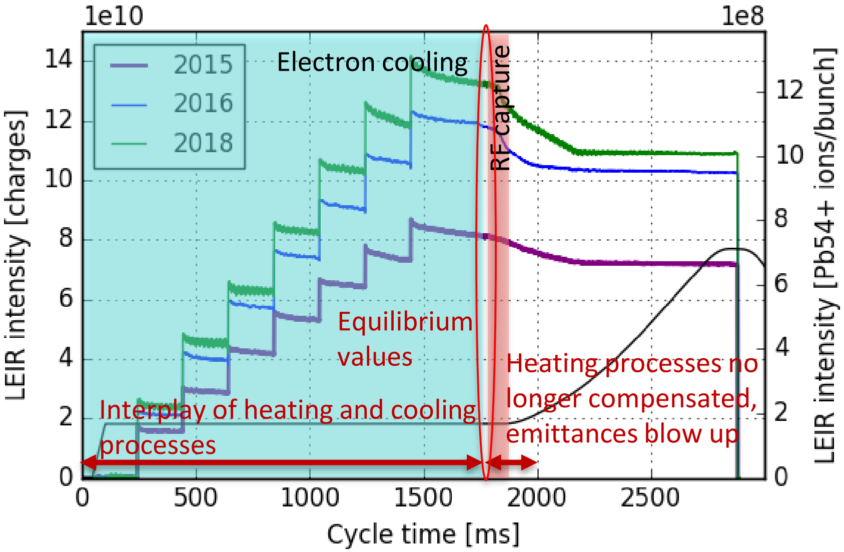

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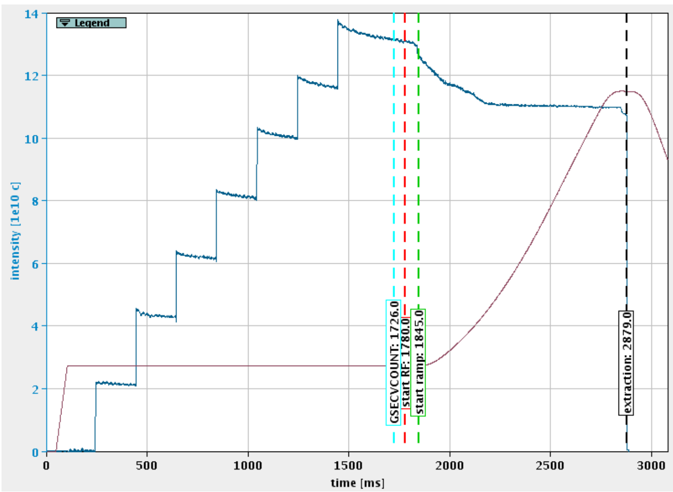
* Discussion on measurable parameters:

- We pretty much cannot measure any e- beam parameter… at least directly
- Instead we can measure its effects on the ion beam!
  - Intensity: Beam Current Transformer (BCT)
  - Position: Beam Position Monitors (BPM)
  - Beam size (→ emittances) : Ionization Profile Monitor (IPM)
  - Revolution Frequency (→ momentum): longitudinal Schottky
  - Longitudinal profile (when bunched): tomoscope

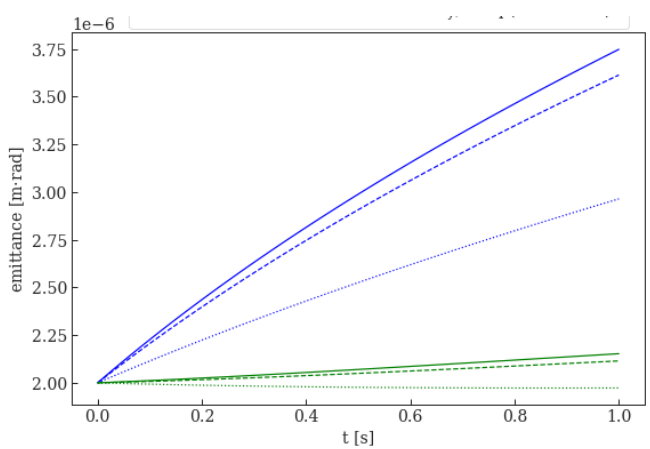
- Measurements along full cycle
- Sampling rate: BCT → 1ms, IPM → 5ms, schottky, tomo → variable, ms order
- Measurement resolution depends on beam intensity
- No clear limitations from this side

Ion acceleration with the Electron Cooler

Losses after RF capture, stabilized after t ≈ 2100 ms



p(t=2100 ms) ≈ 1.4 p(flat bottom)



Hypothesis: assume losses are caused by IBS, how much would the emittance blow-up decrease for a higher p?
(arbitrary inputs)

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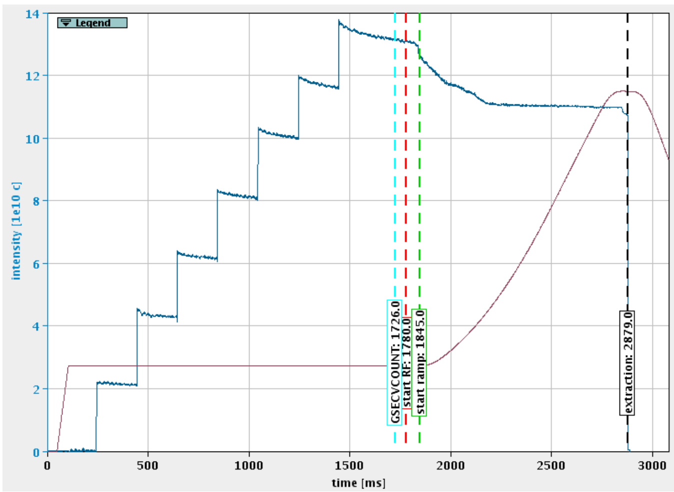
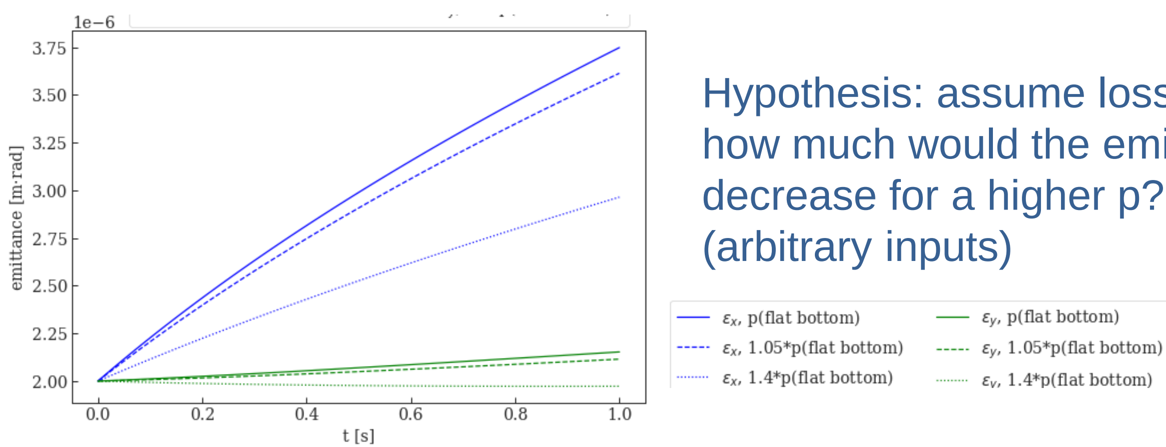


p(t=2100 ms) ≈ 1.4 p(flat bottom)

Could we do the RF-capture at a higher p?

Linac3 could not inject at a higher energy, so we would need to accelerate the ions without RF during the (no-longer) flat bottom by means of the Electron Cooler



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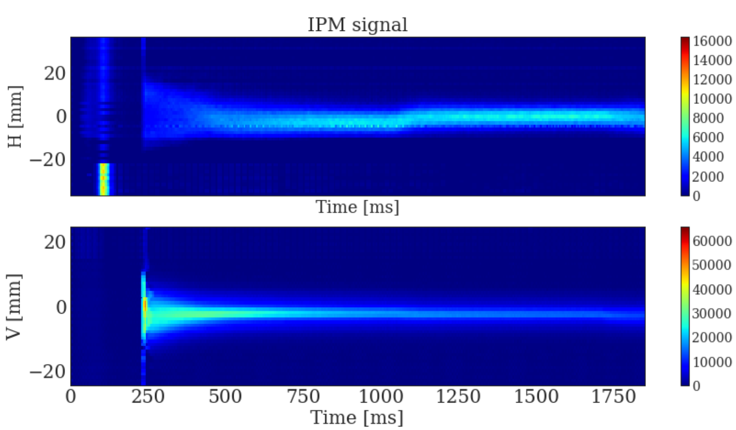
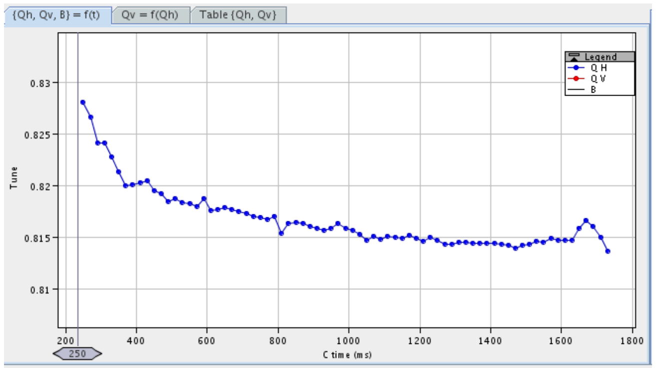
Ion acceleration with the Electron Cooler

How to?

- increase e- gun voltage → increase e- velocity → via momentum exchange drag the ion beam to higher momentum
- Measurements from cooling force useful for optimum settings
- synchronize momentum and Bfield, and also quadrupoles, sextupoles, and dipole correctors. Ensure ion beam stays cooled, orbit centered and tune constant → trick: use LSA-knob Brho_dot + fine tuning



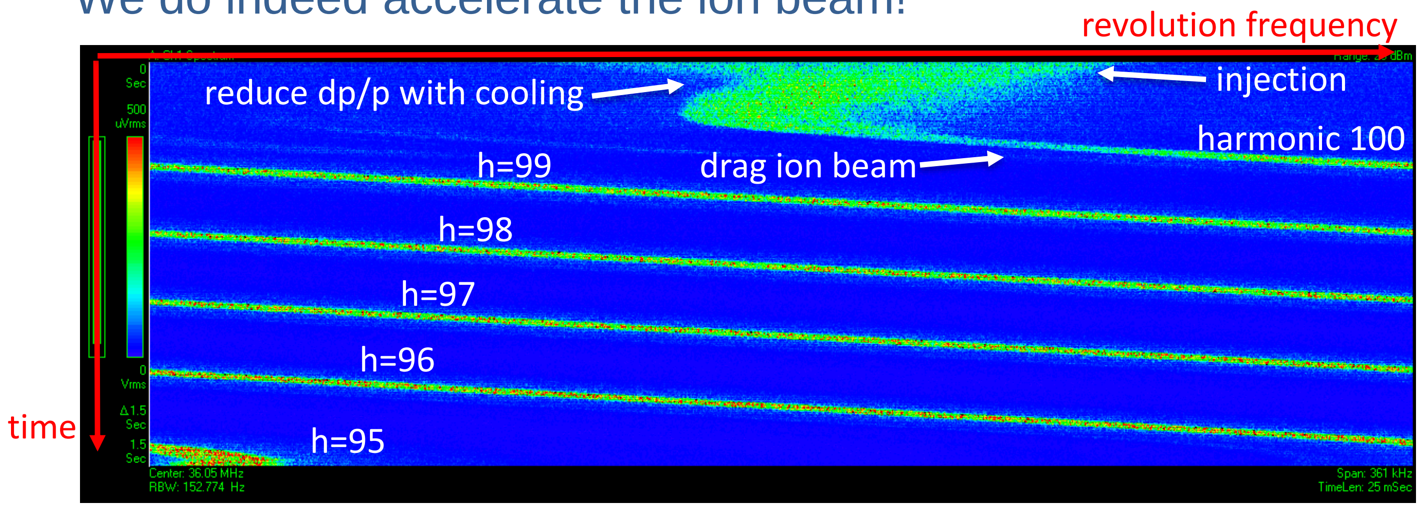


tune measured during cooling-acceleration
→ additional correction needed

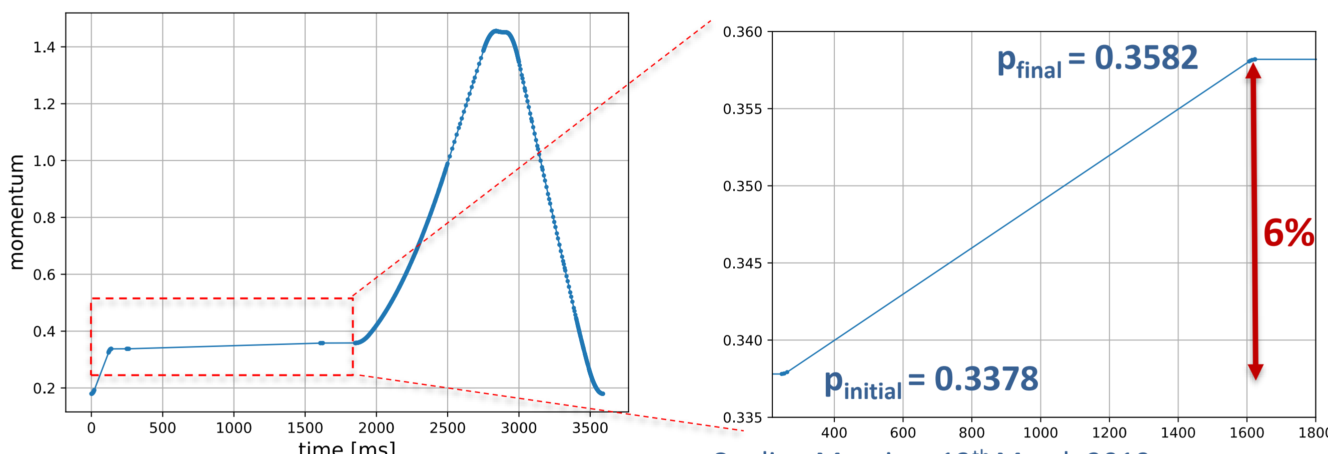
Ion acceleration with the Electron Cooler

Results

We do indeed accelerate the ion beam!



Longitudinal Schottky



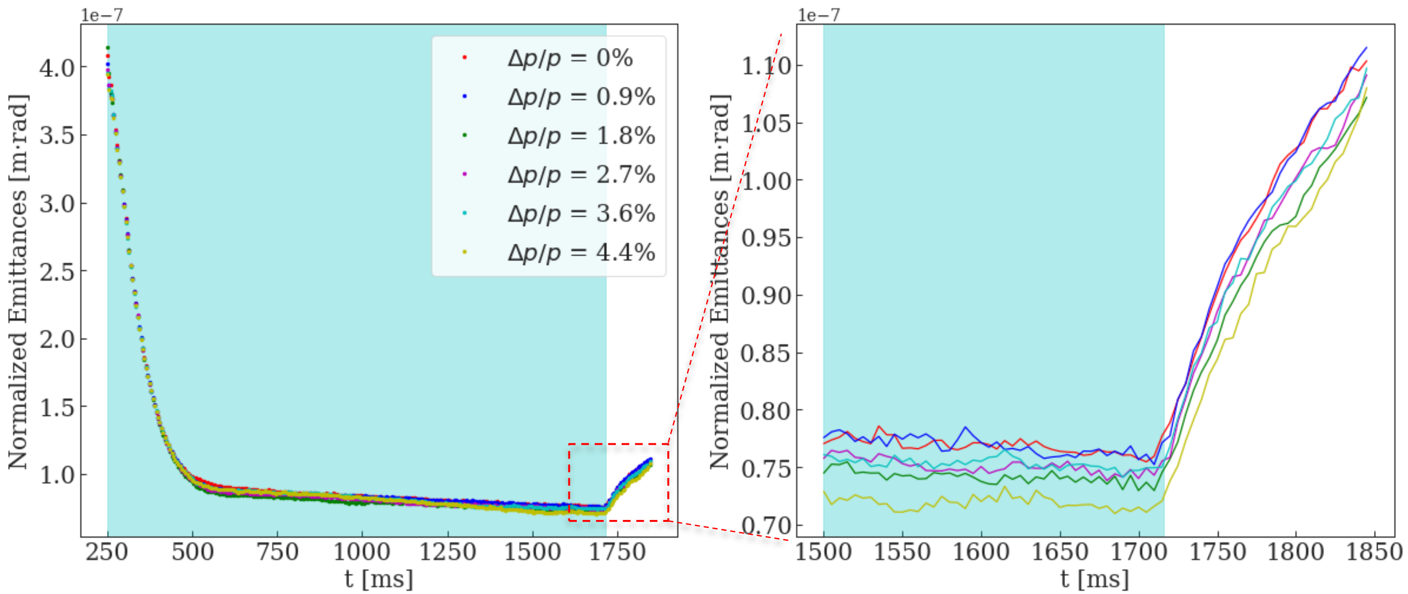
Limit comes from duration of “injection plateau” and slow thermalizing process

Ion acceleration with the Ecooler

Results

- No losses during cooling-acceleration
- No losses during RF-capture by simply adjusting RF
- No losses during RF acceleration, but ramp had to be adjusted
- Beam could be extracted

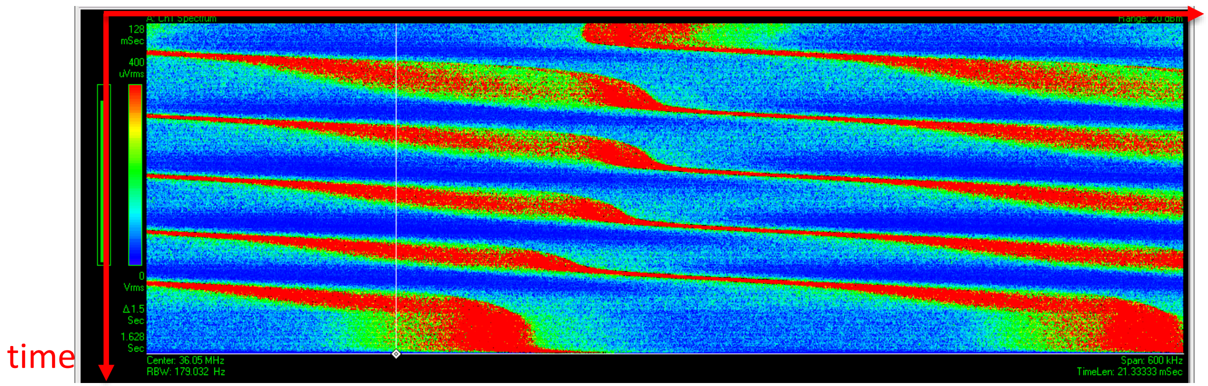
However: similar emittance blow-up for higher final p
→ Too small p increase!



Ion acceleration with the Ecooler

That simple? well...

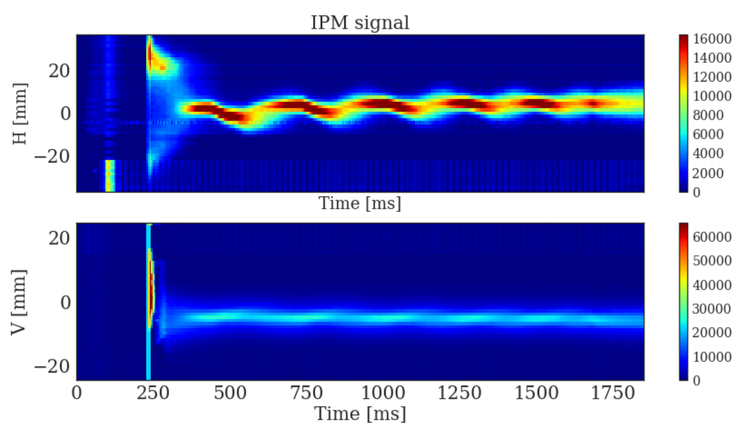
- Actually quite fast to set up.
- However first tests with very fast and large gun voltage increase failed to drag the full beam. Implemented as step – plateau – step

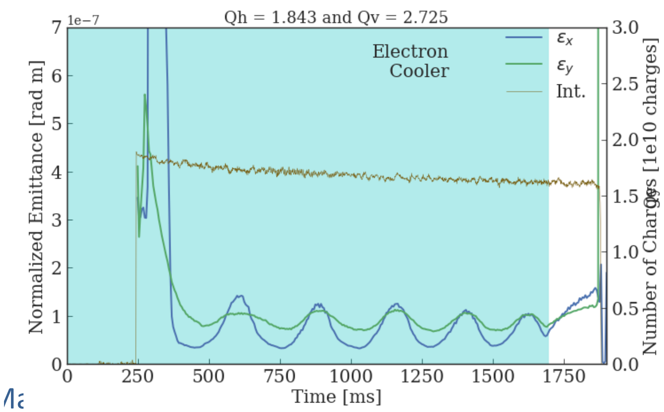


revolution frequency

Longitudinal Schottky

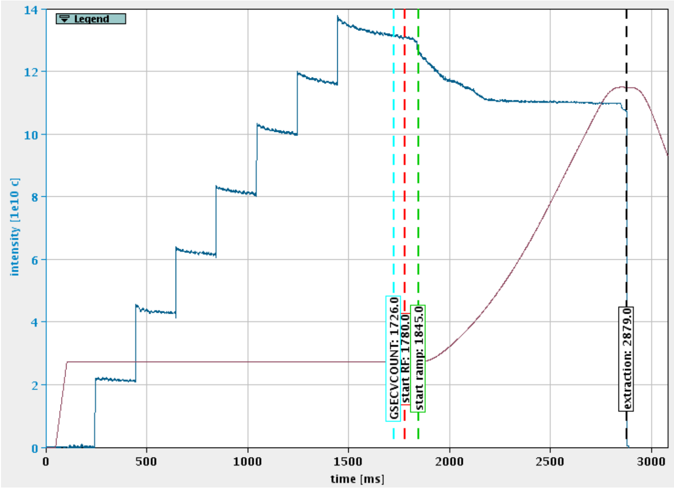
No losses, however large momentum spread and emittance increase





Cooling of bunched beams

Losses after RF capture, electron cooler switched off earlier…



Better if we do the RF-capture earlier and switch Electron Cooler off later?

Pros:

Compensate heating effects (IBS, space-charge), which create losses

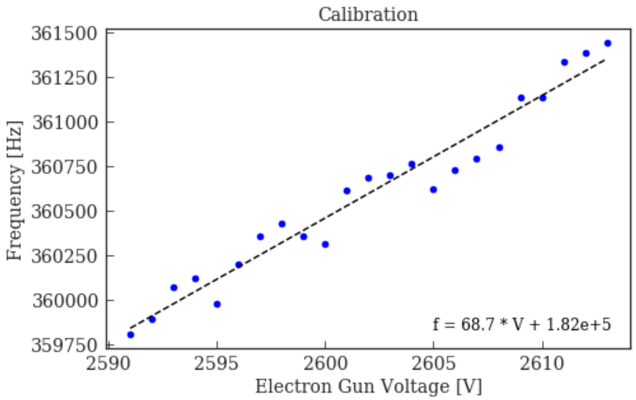
Cons:

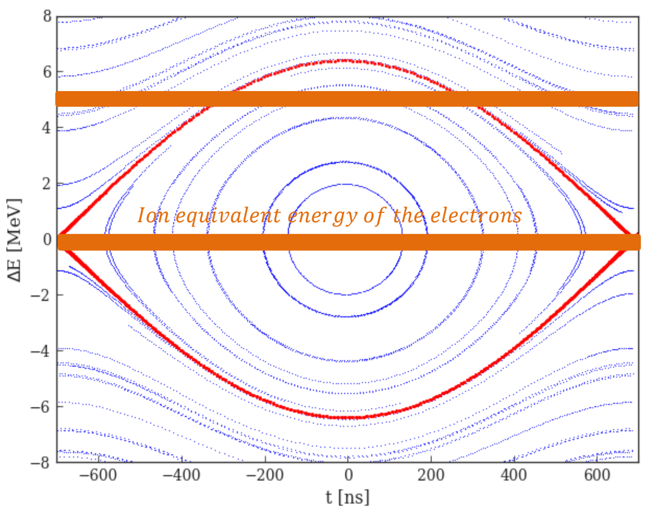
Cooling a bunched beam instead of a coasting one → damping in all 3 planes → more compressed beam, may create even stronger heating effects

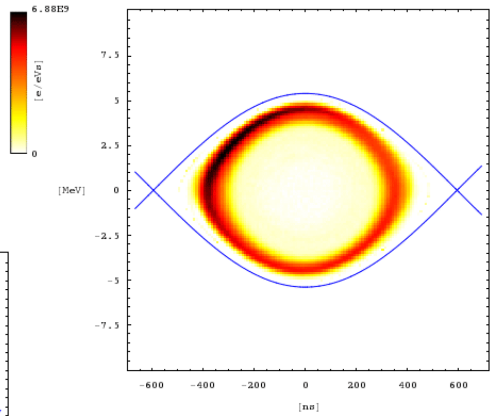
Cooling of bunched beams

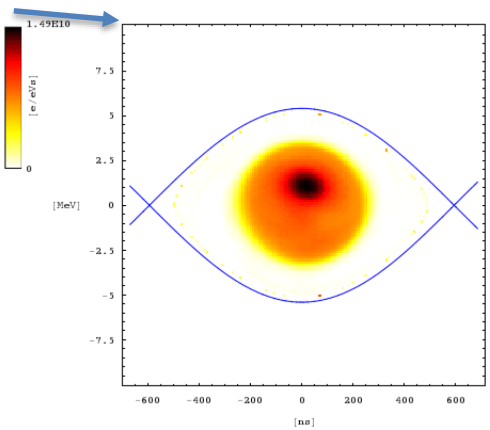
By changing the e^- gun voltage, we can drag the ion beam to a frequency which has an offset with the RF frequency.

$\Rightarrow$ longitudinal distributions can be varied between parabolic, flat and hollow



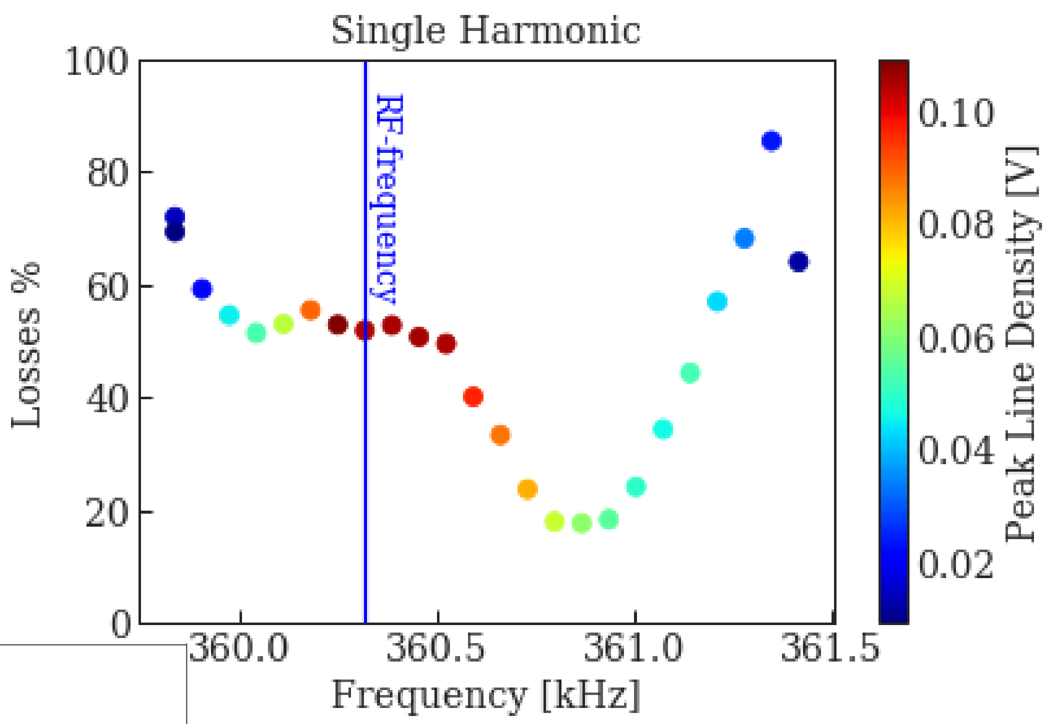


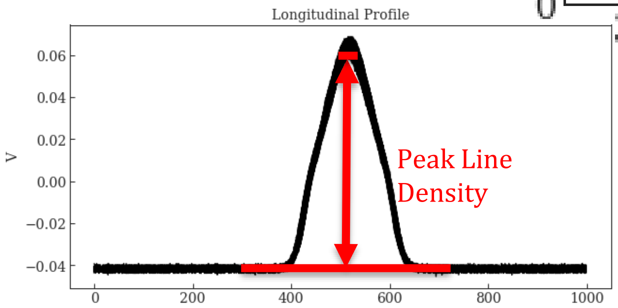




Cooling of bunched beams

We measured the losses between the start of RF and the start of ramping (400 ms), as a function of rev. frequency set by the Ecooler





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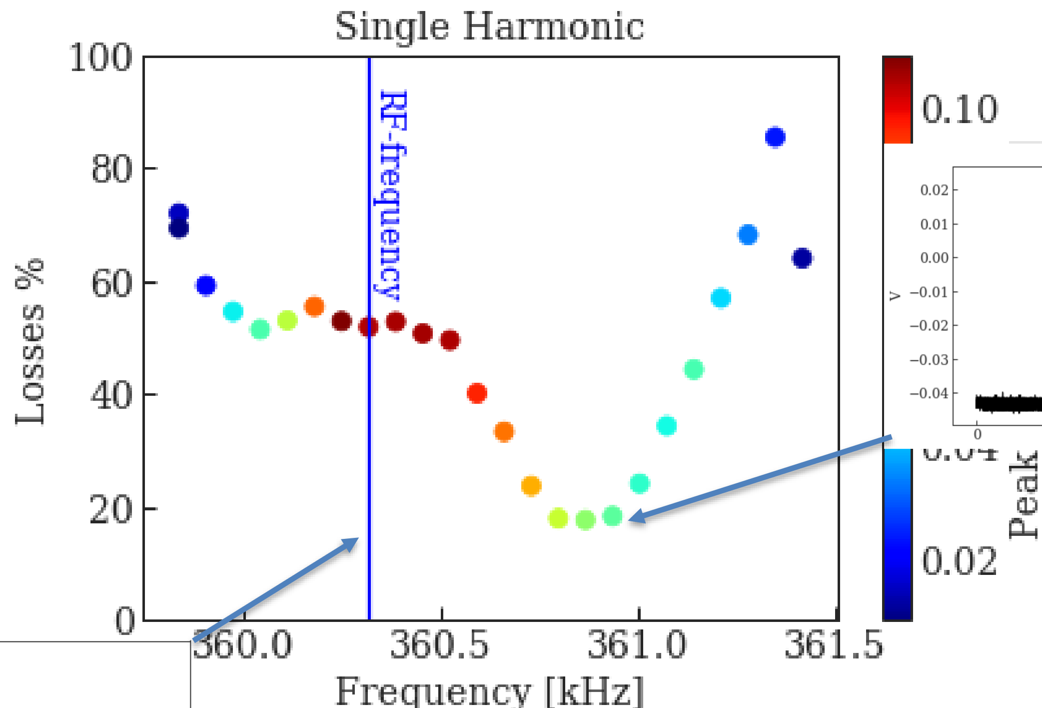
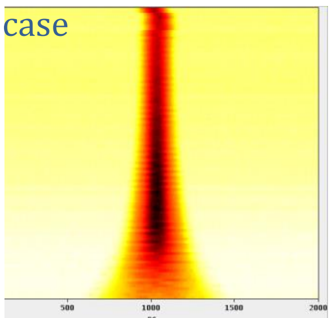
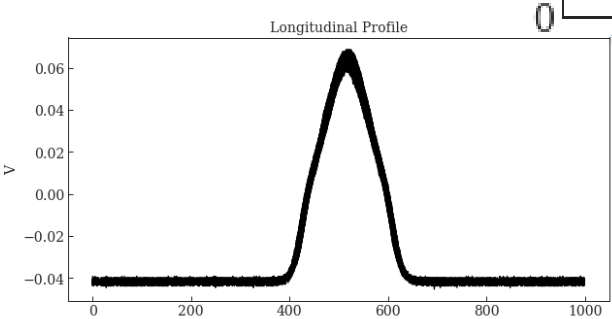
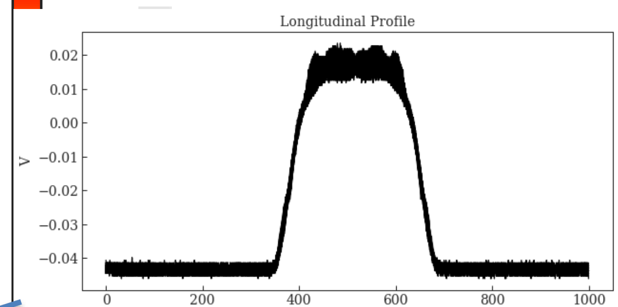


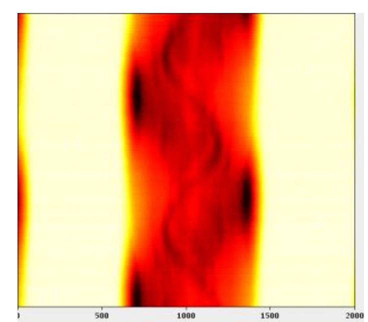
Profiles for central case





Profiles for minimum losses





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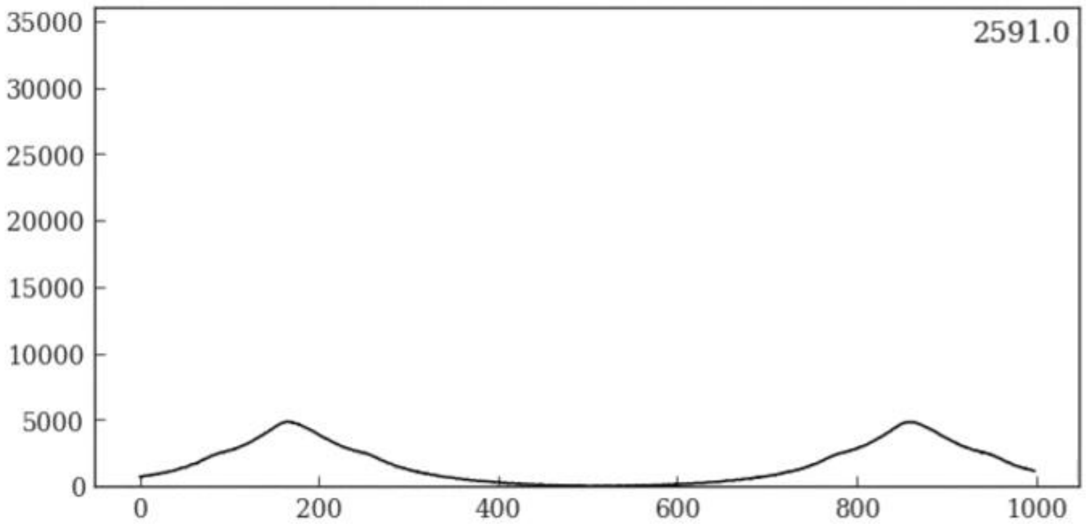
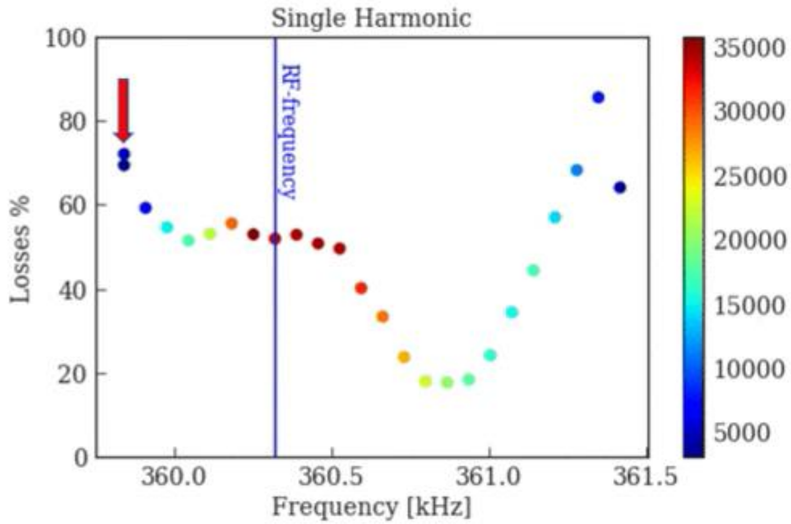
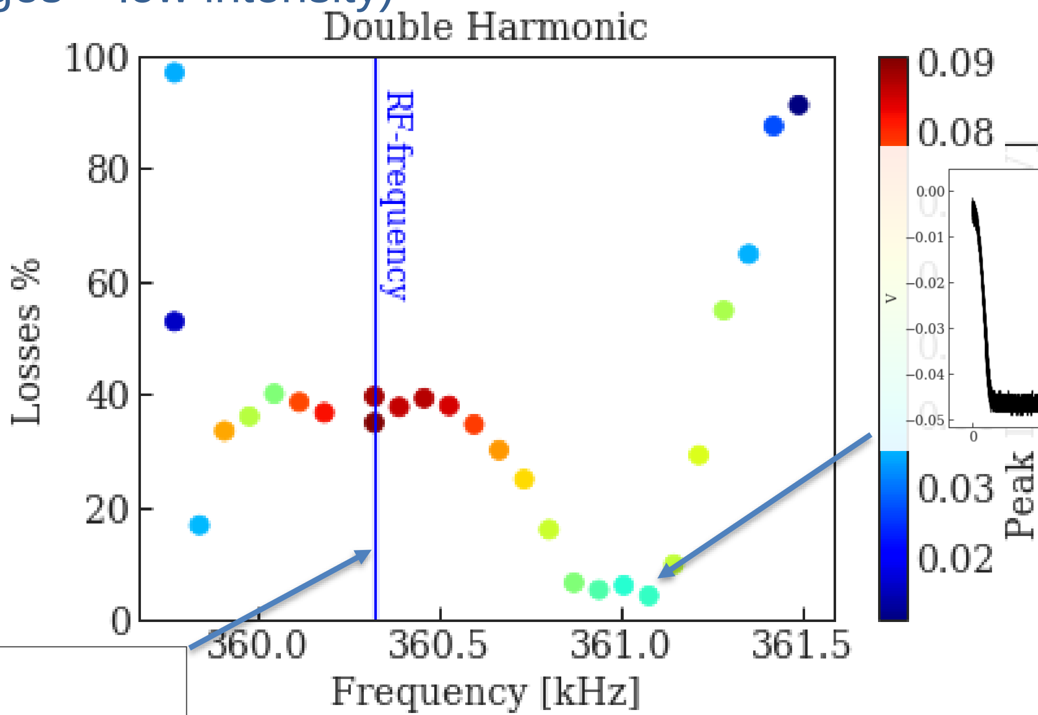




**Colorbar not calibrated.*

Cooling of bunched beams

Same measurements setting the RF cavity to h2+4 settings: minimum losses < 4% → similar to standard case for equivalent intensities (~3e10 total charges = low intensity)



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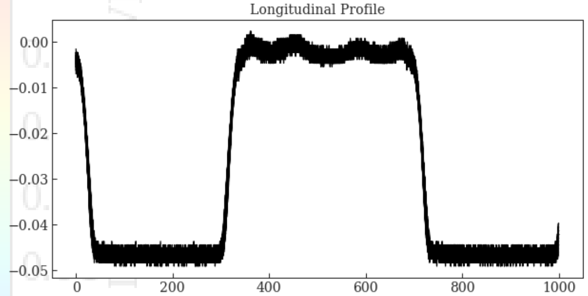

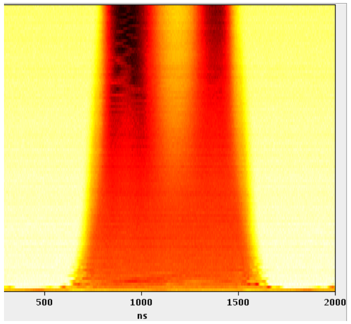

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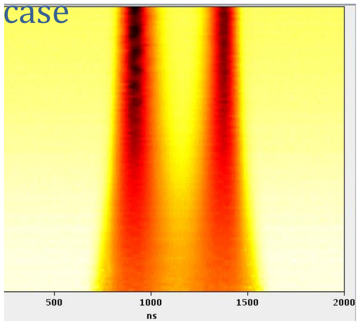

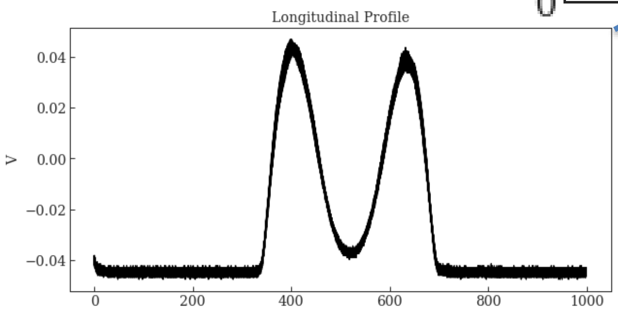

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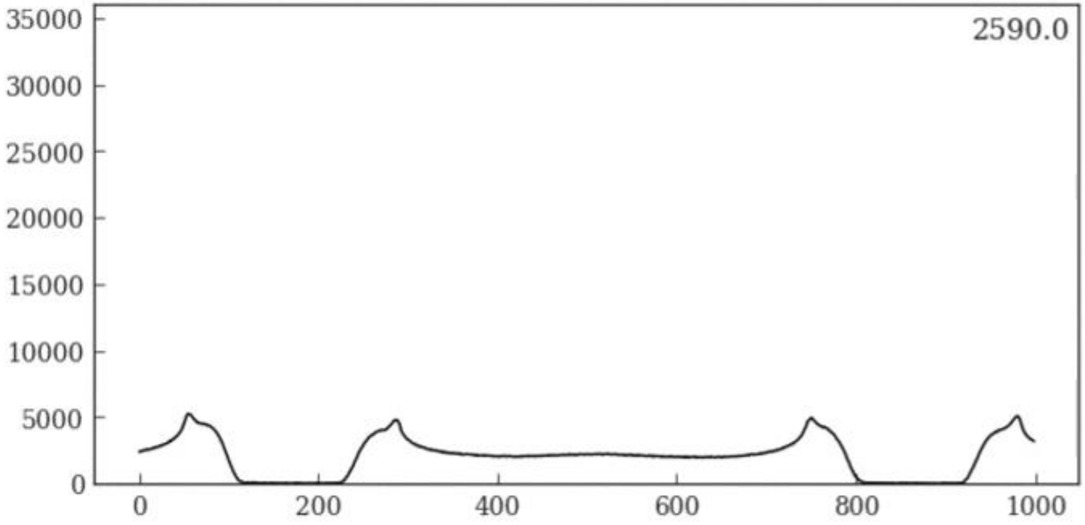
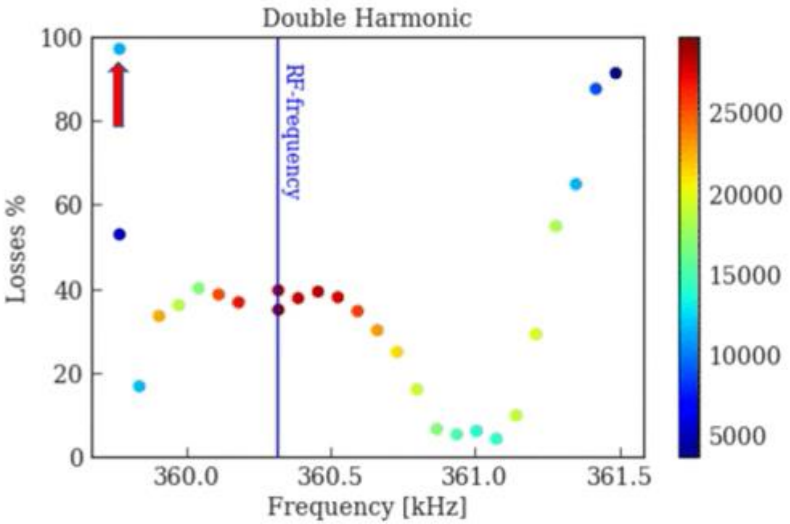
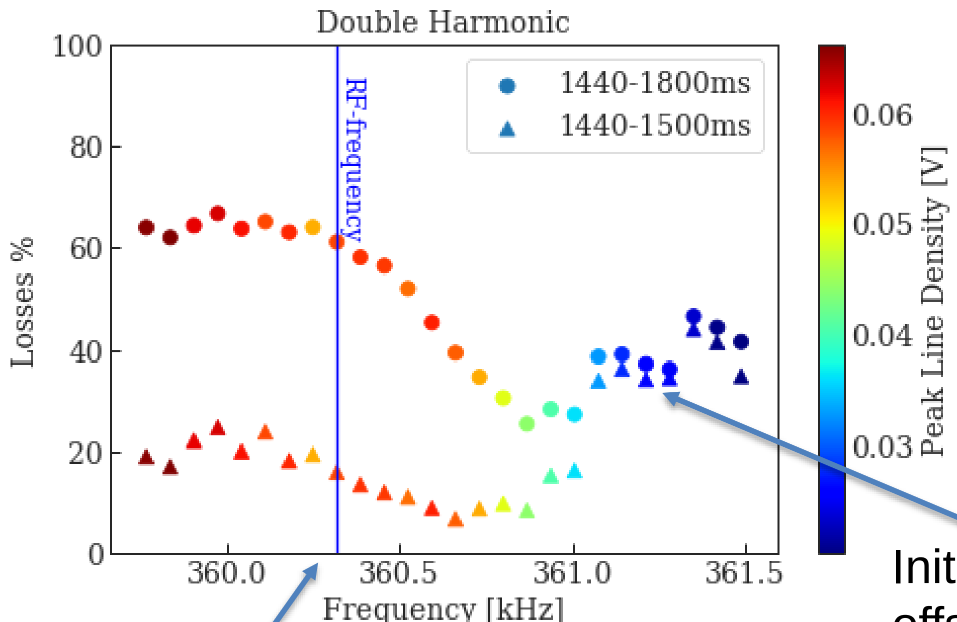


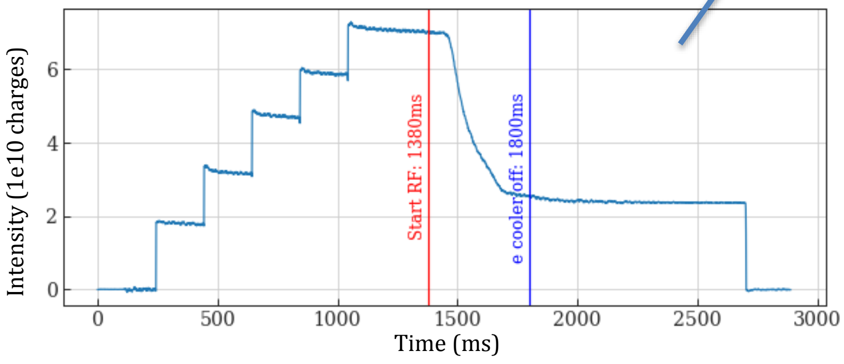


Cooling of bunched beams

For higher intensities (~6.5e10 total charges)



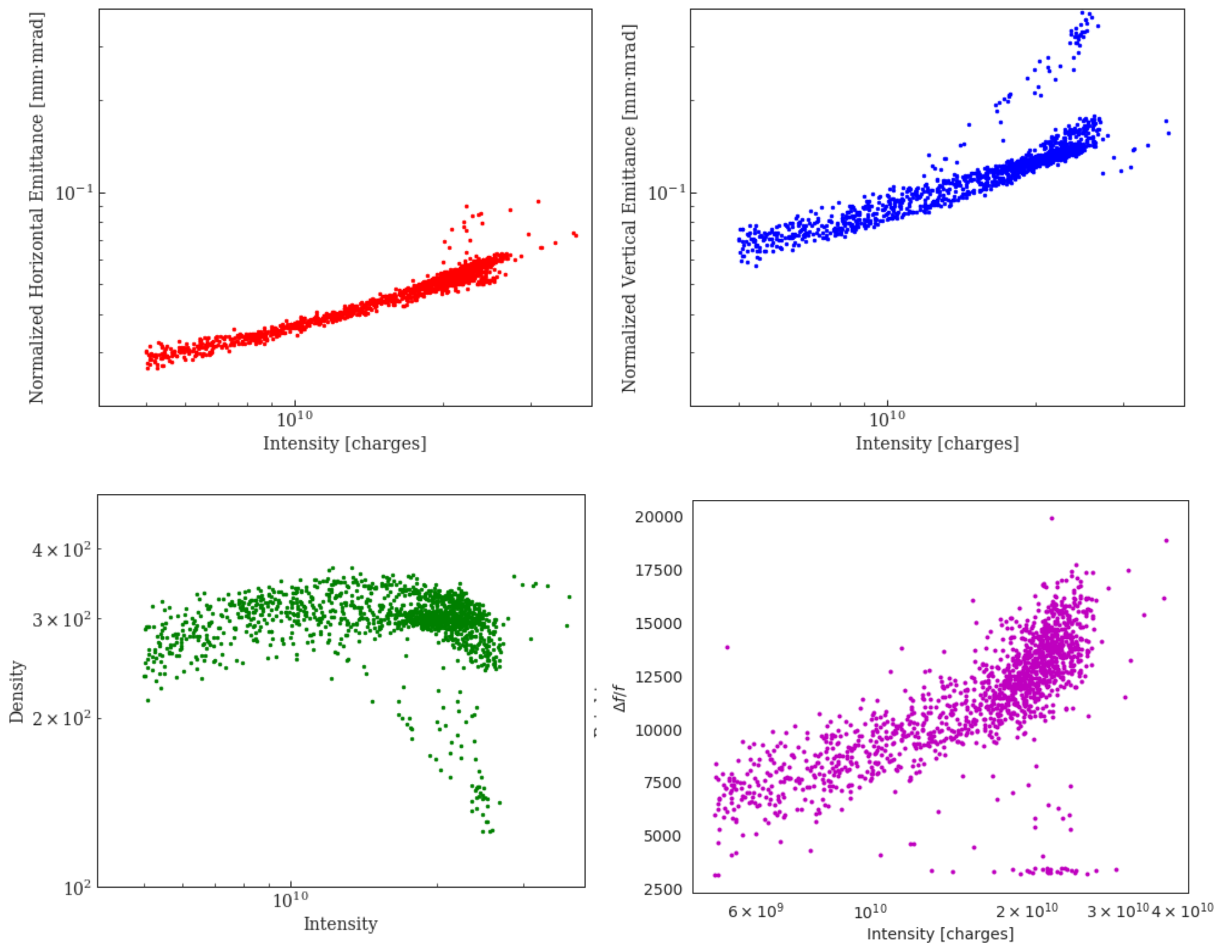
Initial losses during offset capture of a high intensity beam



Well-centered beam during capture very compressed ⇒ more losses!

Studies of equilibrium values: as a function of intensity

Vary ion beam intensity by mis-steering a corrector (BHN10) in the transfer line



Studies of equilibrium values: as a function of intensity and tune

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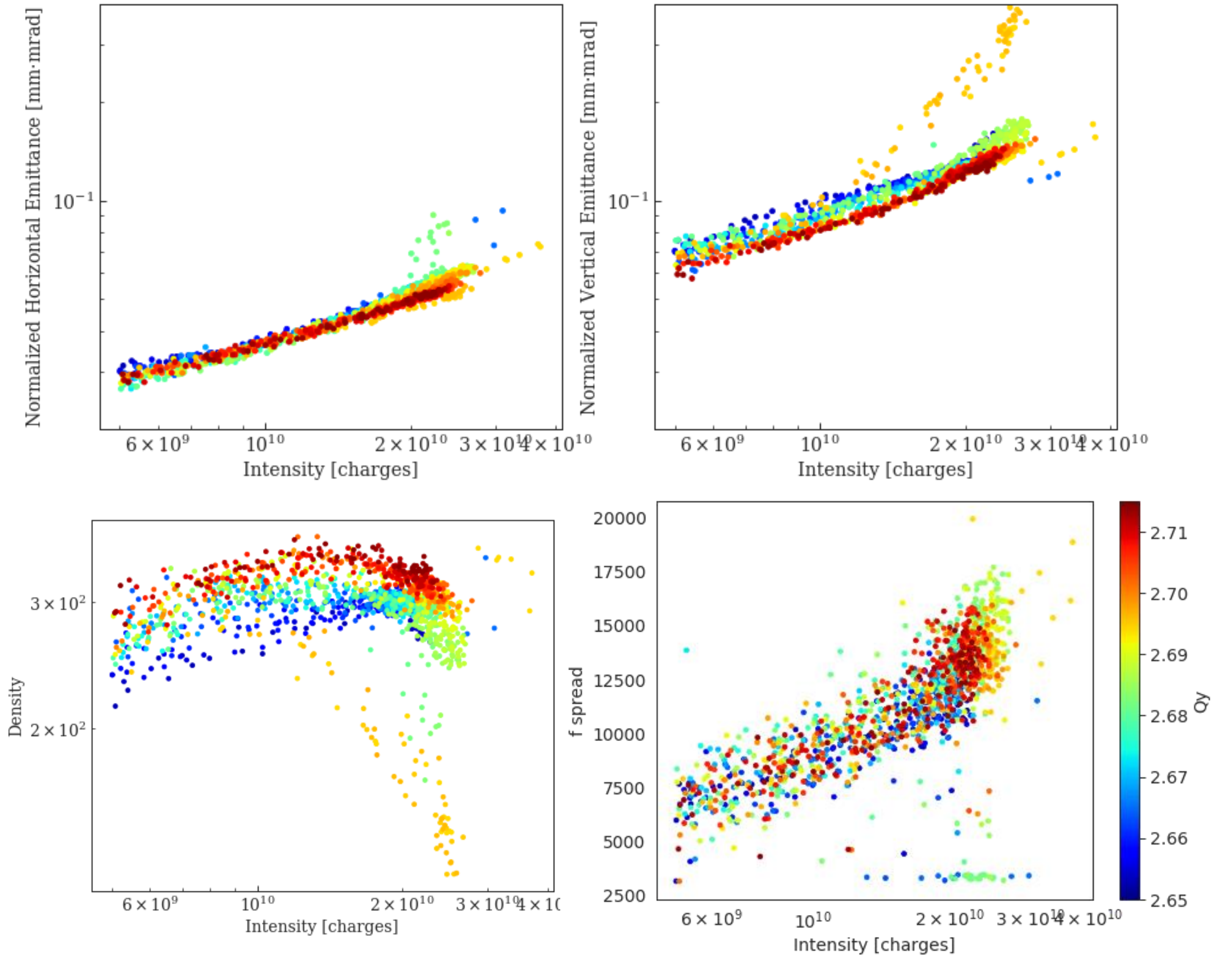
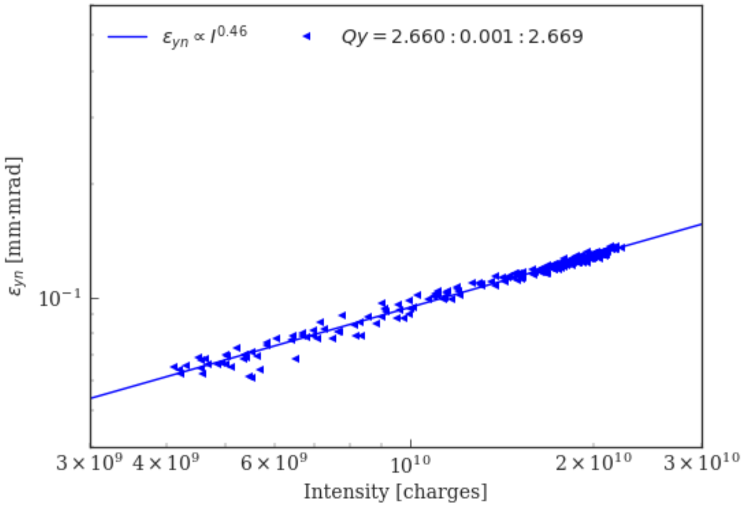


Studies of equilibrium values: as a function of intensity and tune

Let's look in more detail:

$\varepsilon \sim I^n$ consistent with measurements at other labs (Ti^{22+}, Kr^{36+}, Xe^{54+}, Au^{79+}, U^{92+} measured at GSI) for IBS dominated regime…

but then emittance blow up and losses should be similar for all tunes and we had already observed that was not the case



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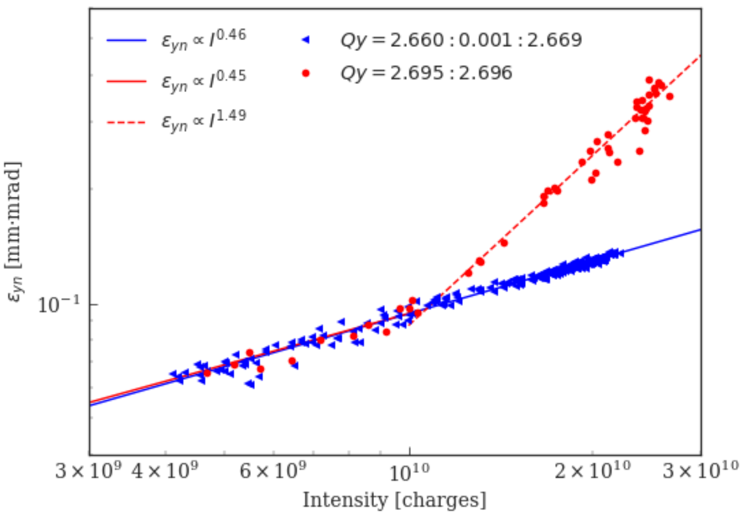
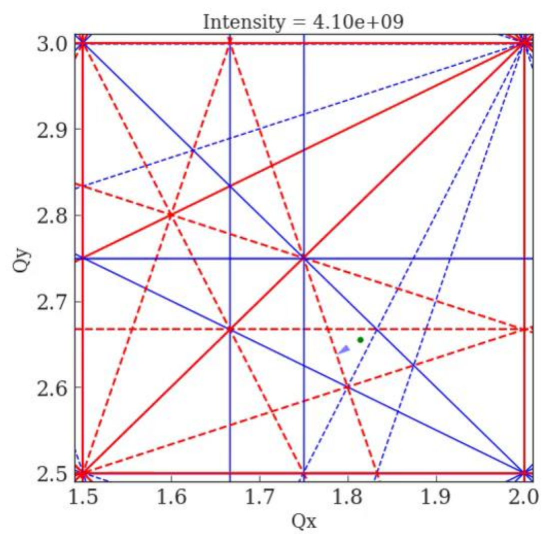
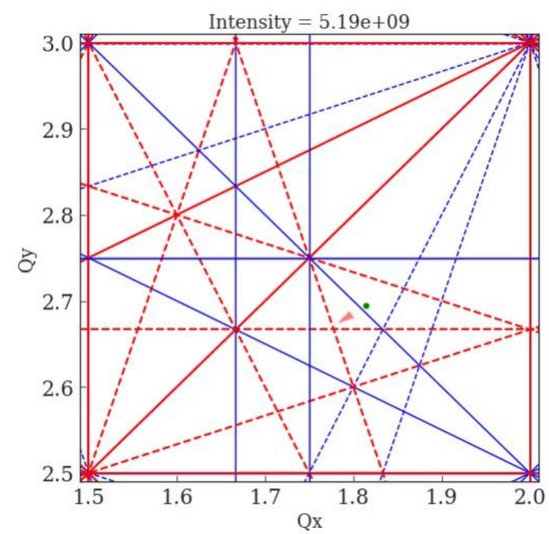
emittance dependence on WP, above a threshold intensity!
→ Space charge dominates for certain tunes and intensities (ongoing studies)







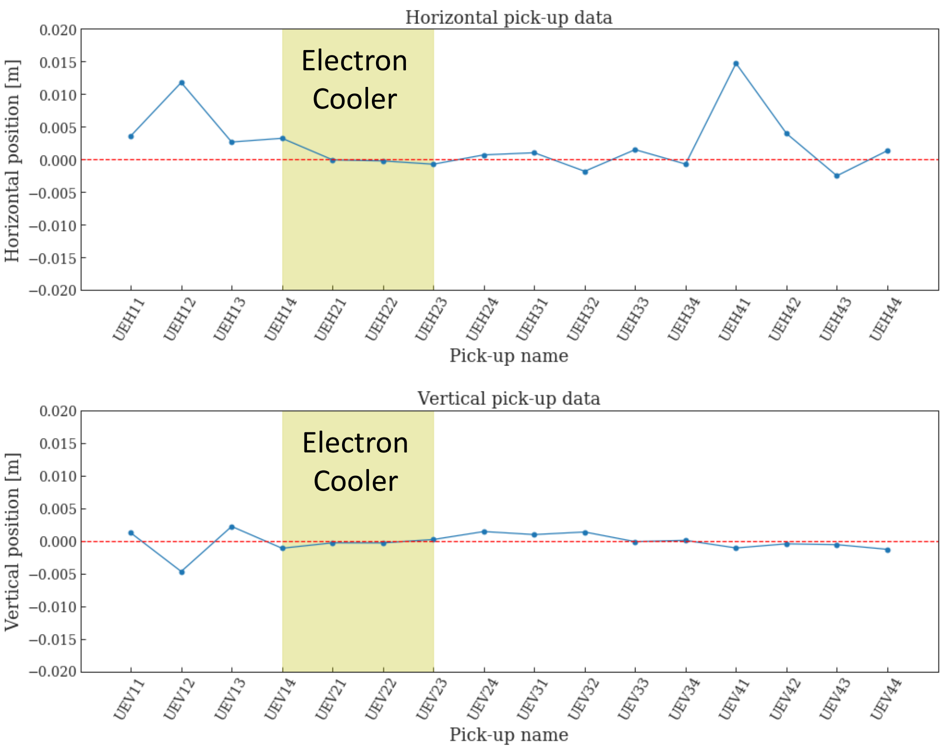
Equilibrium values studies not only to characterize cooling process but also dominant heating processes!

Studies of equilibrium values: as a function of ion beam position

Scan equilibrium emittances as a function of orbit bumps (offset/angle)

- Indirect measurement of e-beam position
- Create “cooling maps” to guide us in the preparation of beams with certain specifications

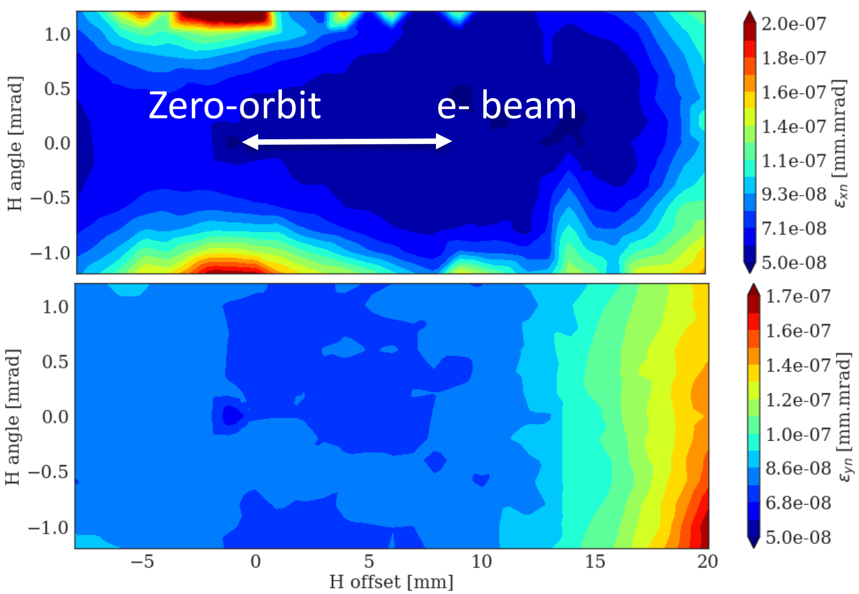
Calibrate bump knob
(here H_offset=0, H_angle=0)

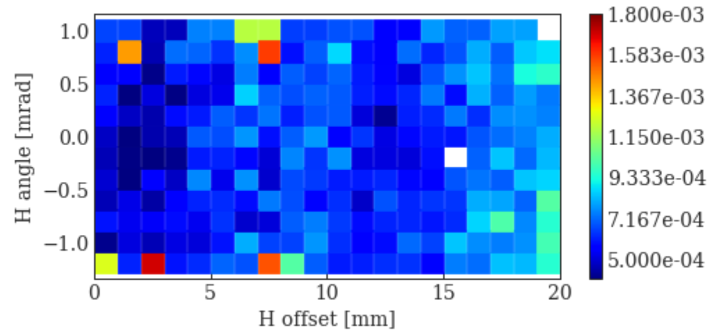


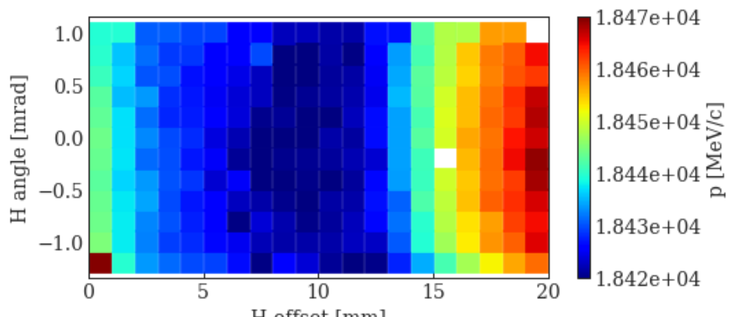
Studies of equilibrium values: as a function of ion beam position

Scan equilibrium emittances as a function of orbit bumps (i.e. on the e-ion overlap)

Scan range: limited by intensity losses < 20%







Some observations:

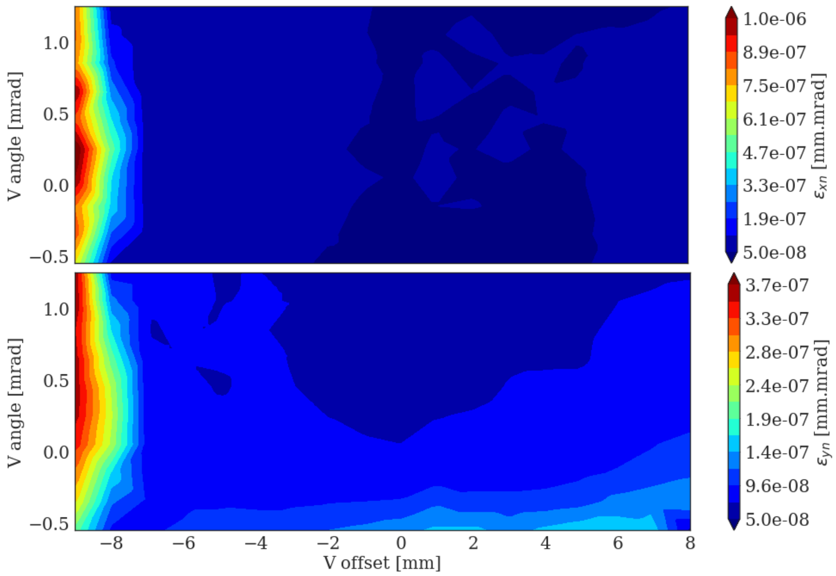
- Increasing emittance with abs(angle) → expected
- 10 mm offset between center of e-beam and zero-orbit ion beam
- Vertical emittance independent of H-angle → expected
- Vertical emittance increases as e-ion overlap decreases
- Momentum dependence with e-ion overlap
- Momentum spread not that sensitive (further analysis may be required)

Studies of equilibrium values: as a function of ion beam position

Scan equilibrium emittances as a function of orbit bumps (i.e. on the e-ion overlap)

Scan range:
limited by intensity losses < 20% and by vertical correctors strength (smaller than in H plane)

(horizontal orbit set to maximum cooling: H_offset = 10 mm, H_angle = 0 mrad)



Some observations:

- Horizontal emittance independent of V-angle → expected
- Vertical emittance not very sensitive to vertical bump, except for very large offsets

Measurements repeated:

- For different electron currents: 210, 340 and 430 mA
- For different transverse beam profiles: parabolic, flat, hollow

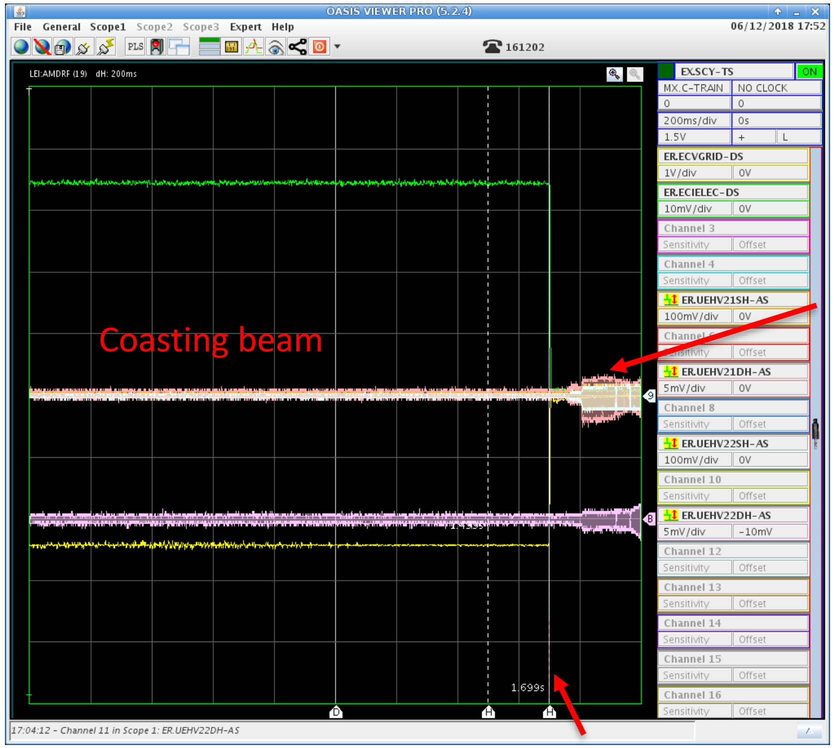
Conclusions

- **Very successful year from the point of view of the MDs in LEIR (performed many cooling-related measurements, quite some data still to be analyzed).**
- **"Exotic" ideas tested to try to overcome intensity limitations in LEIR. Successfully implemented, did not help overcoming limitations, but better characterized (SC, IBS).**
- **Detailed characterization of e-cooling as a function of ion beam position that helped us preparing beam with given specifications.**

Extra: tests to measure directly the e-beam position with a scope

Measurements of the electron beam position?

Monitor with a scope the signal from gun and grid voltage from e-cooler and sum and difference signals from a pick-up inside e-cooler



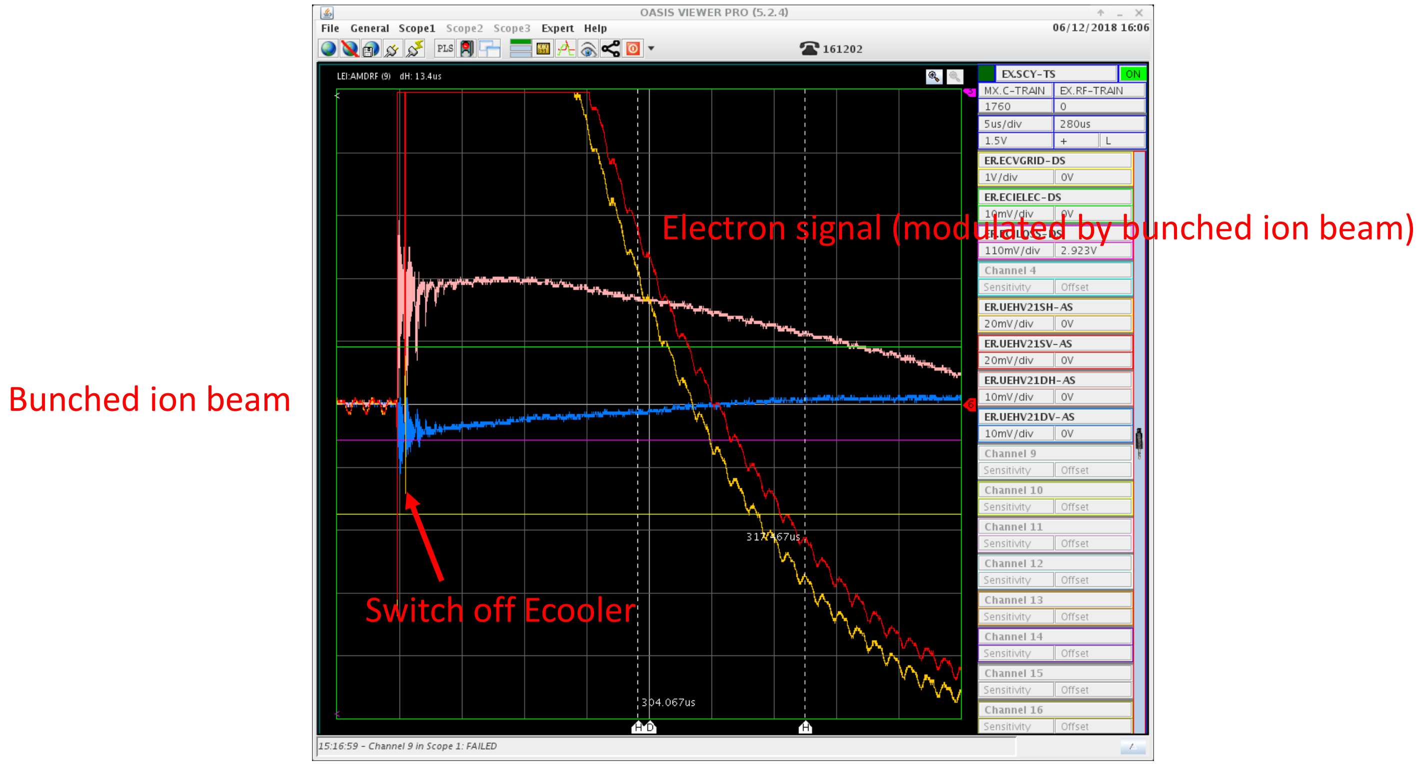
RF capture, bunched beam

Switch off Electron Cooler:
Use "switch" to avoid decaying gun voltage
→ Measure signal not present for e- dc-beam

Measurements of the electron beam position?

Advance RF capture to get signal from bunched beam

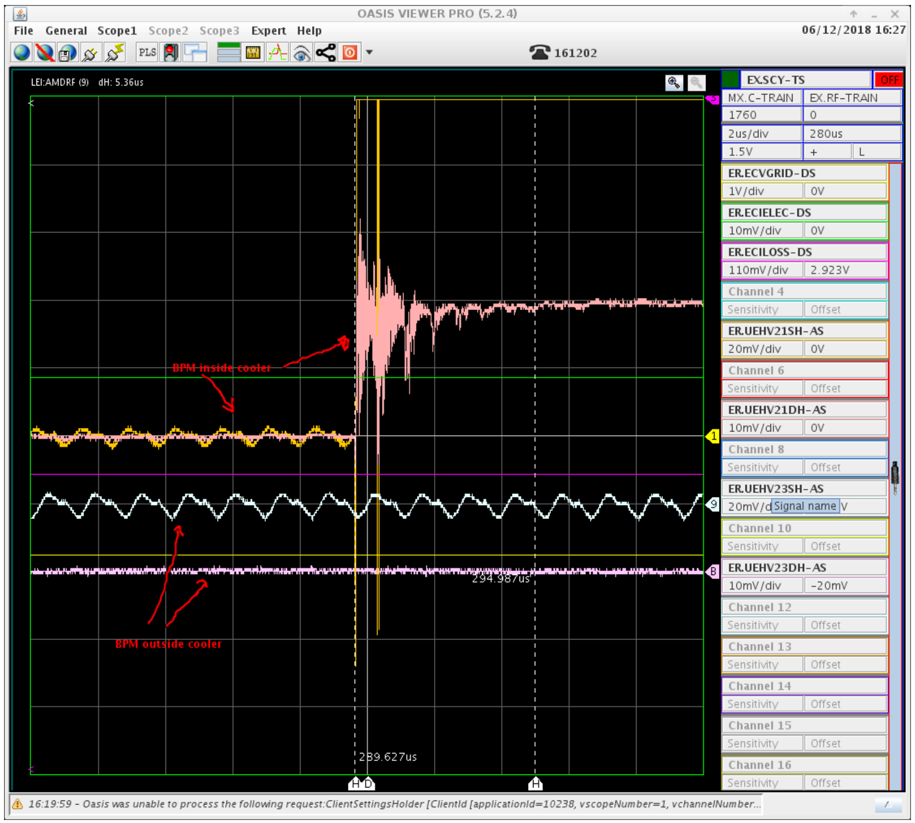
Zooming in to 5us/div to look in detail at the signal



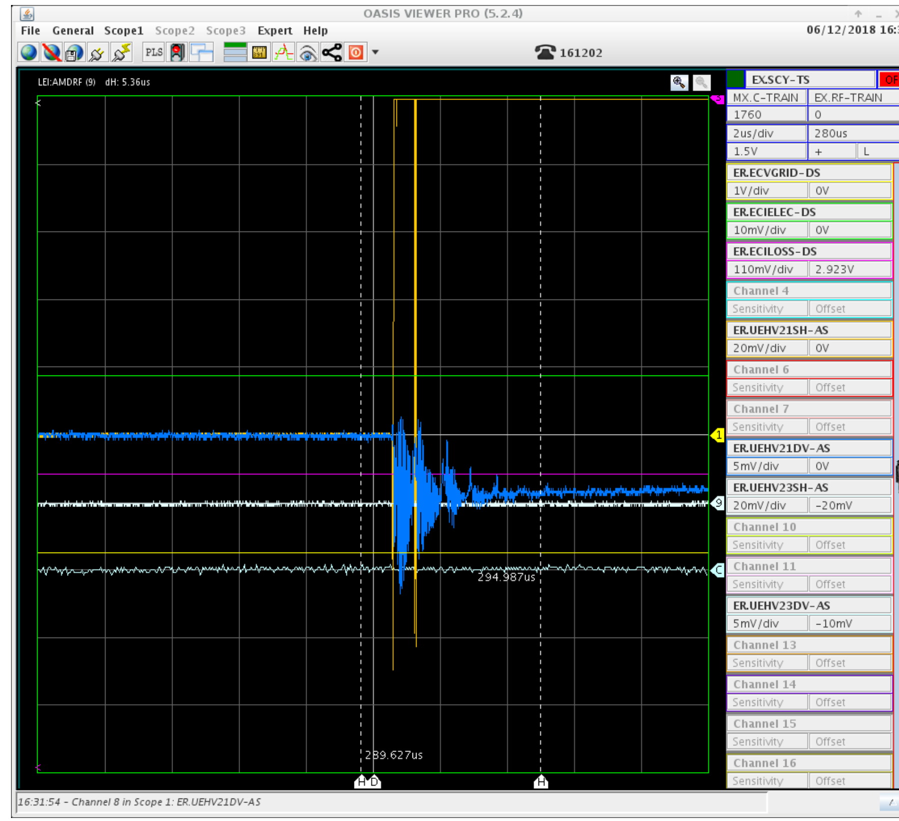
Measurements of the electron beam position?

Compare signals from a pick-up inside e-cooler and one outside

With ion beam



Without ion beam

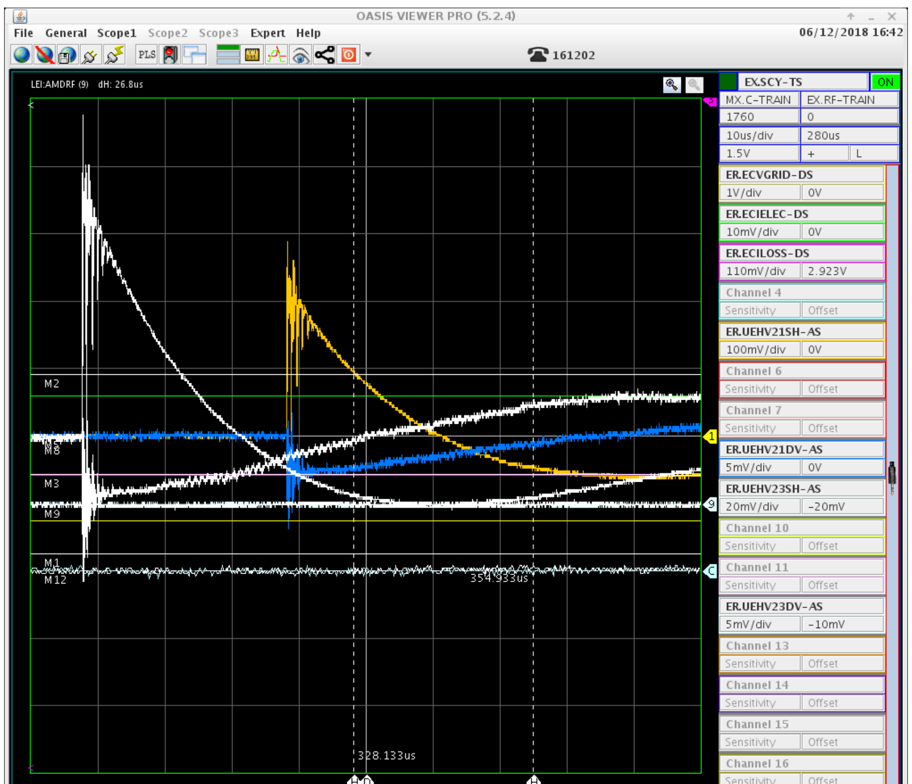


Measurements of the electron beam position?

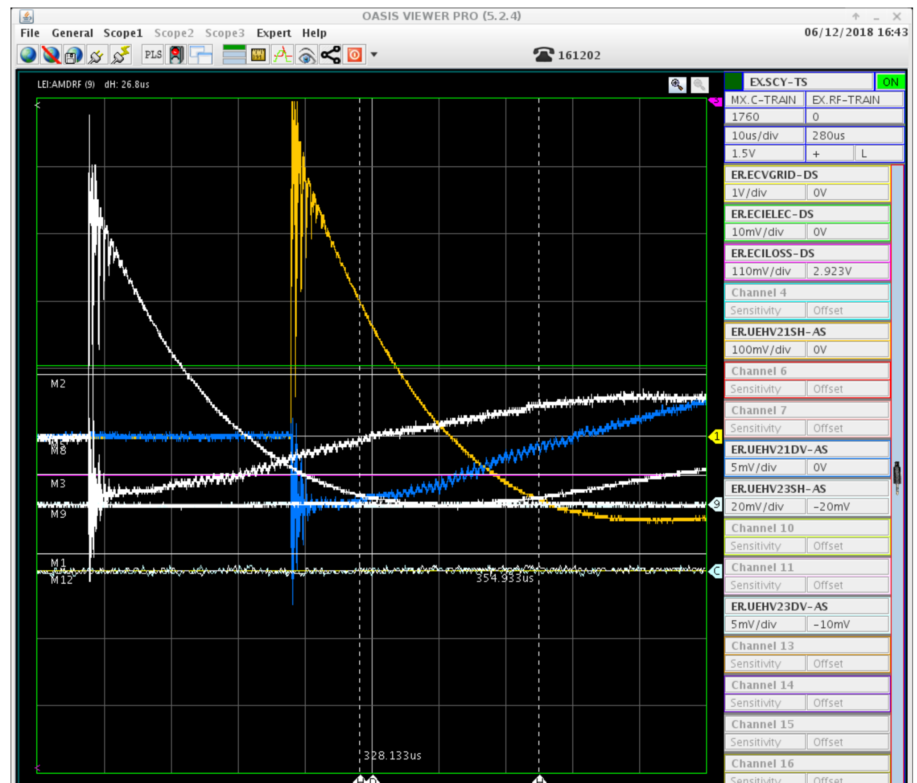
Different amplitude proportional to electron beam current?

White signals: reference for 340 mA default case

Reducing current from e-cooler to 210 mA



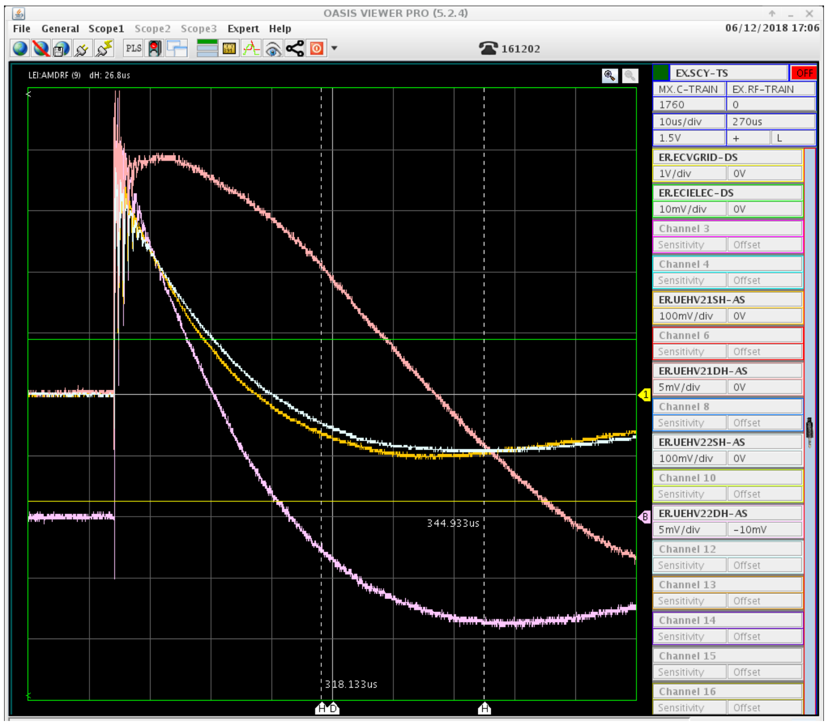
Increasing current from e-cooler to 430 mA

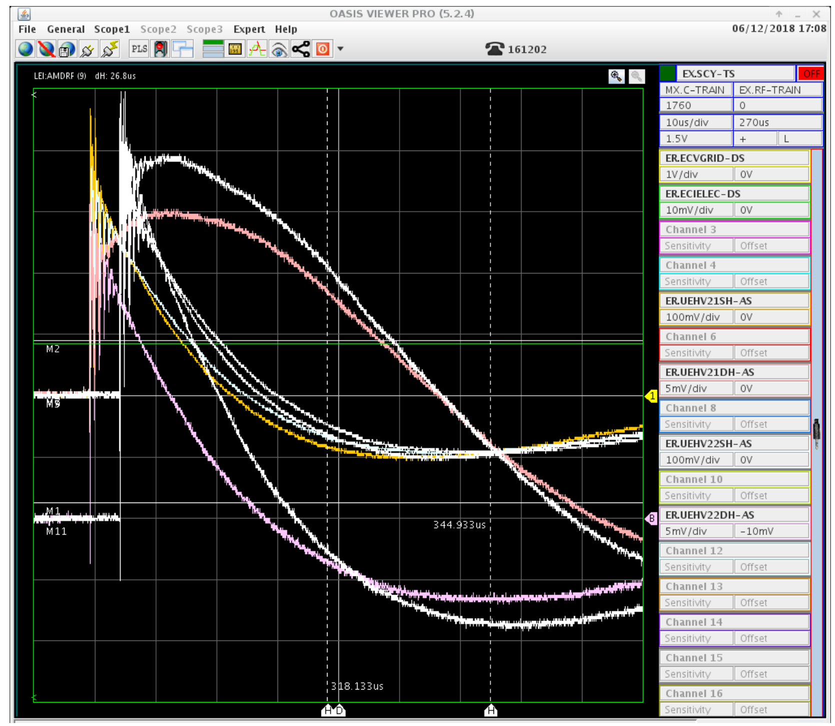


Measurements of the electron beam position?

Sum and difference signals of the two Horizontal pick-ups inside Ecooler

Changing (slightly and very carefully!) a coil inside the cooler: 3A → 2A





Additional: measurements while switching OFF filament by A. Frassier (at beginning of shut down) confirm measured signal from e-beam

Measurements of the electron beam position?

Conclusions:

Signal from e-beam when Electron cooler switched off, proportional to beam current and varies with coil current

- Can it be calibrated?
- Any other measurement possible?

Crazy idea (just for discussion):
Retractable screen inside electron cooler for e- position + distribution measurements?

- Could stand high e-current? If only for smaller e-currents, should we expect same results?
- Space between solenoid sections? Otherwise: screen just outside + let e-beam go through? High radiation levels in open hall?

LHC Injectors Upgrade

Thank you for your attention!

CERN