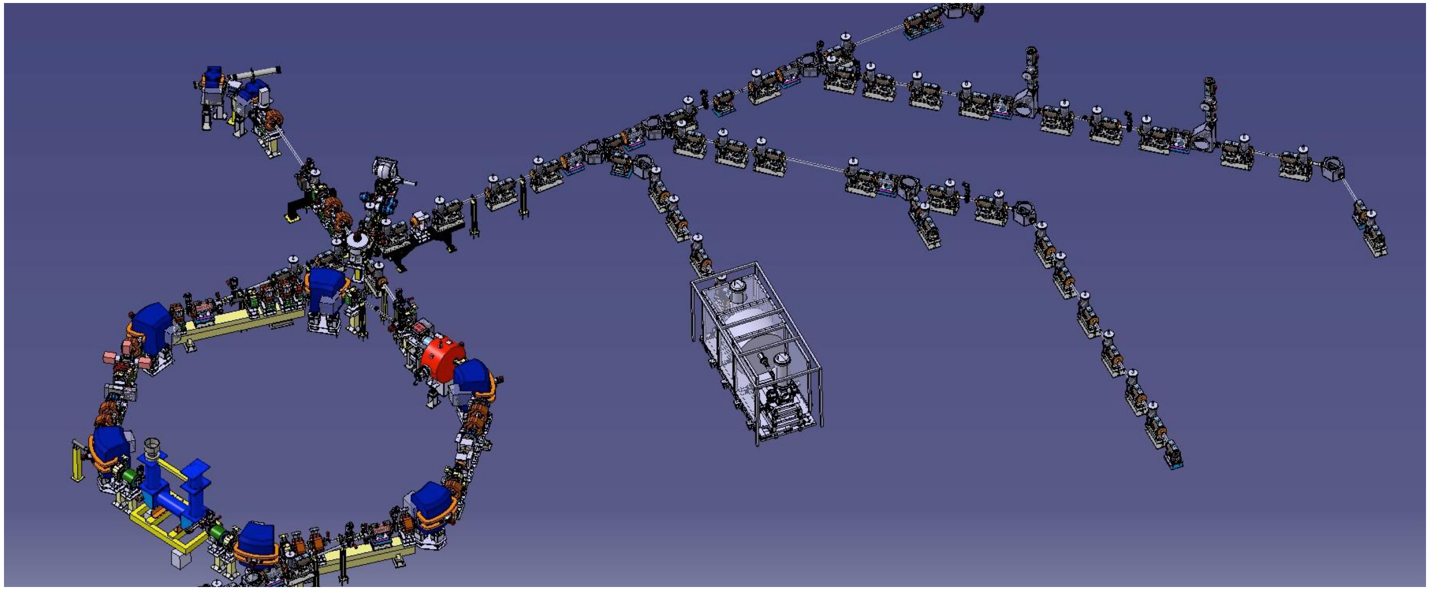
Experience with e-cooler at ELENA and requirements for optimisation of future applications

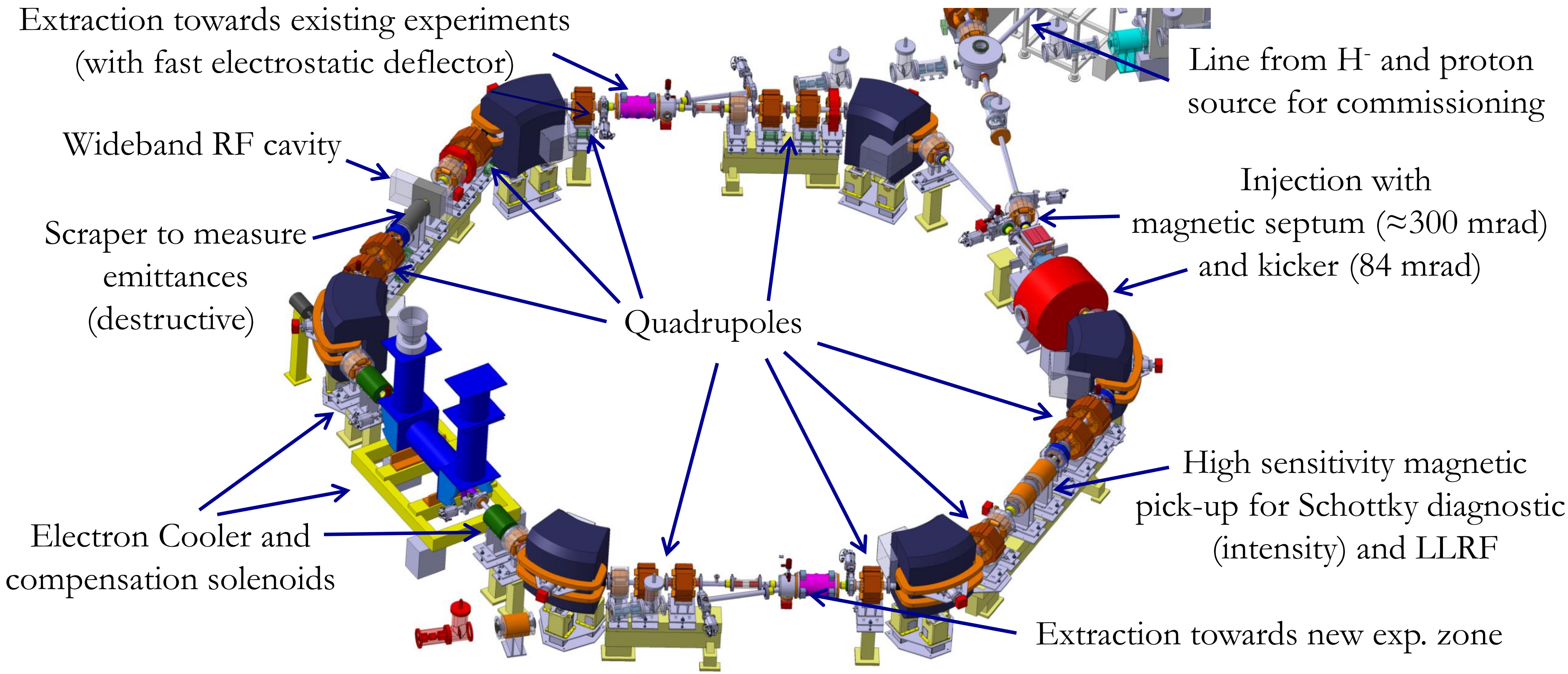
D. Gamba on behalf of the AD/ELENA teams

BE-ABP/BE-BI Joint Meeting 10th Jan 2019



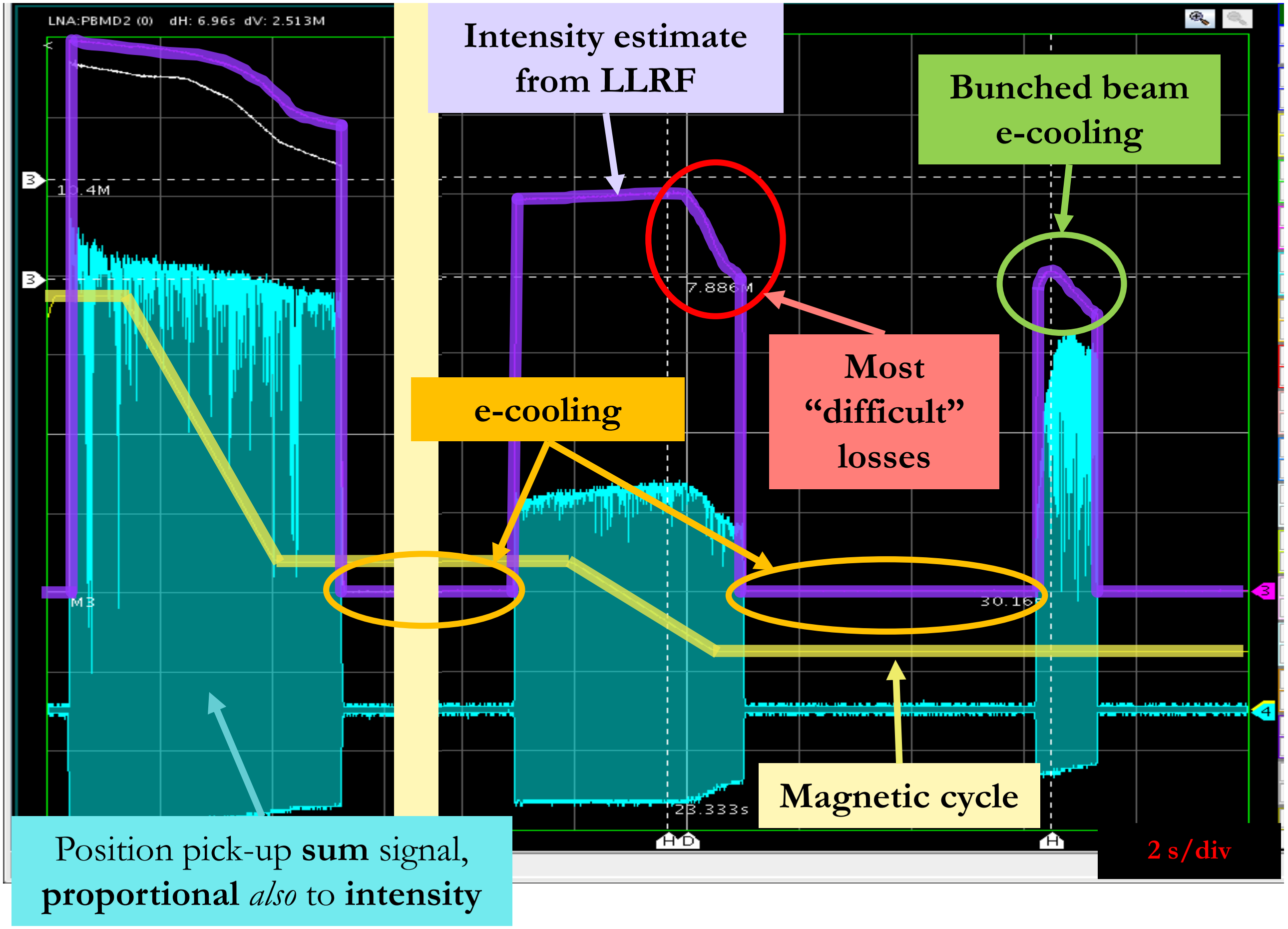
- ELENA **layout** and **beam status** at the end of the run (9 Nov 2018)
- Hints about **e-cooling performance**
- **Desiderata** for future optimisation
- **Conclusions**

ELENA Overview and Layout



- Deceleration of antiprotons from 5.3 MeV to 100 keV to improve efficiency of experiments
- Circumference 30.4 m (1/6 the size of the AD)
  - Fits in available space in AD hall and allows installing all equipment without particular efforts
  - Lowest average field (beam rigidity over average radius) $B\rho/R$ = 94 G (smaller than for AD 115 G)

Status End of Run 2018

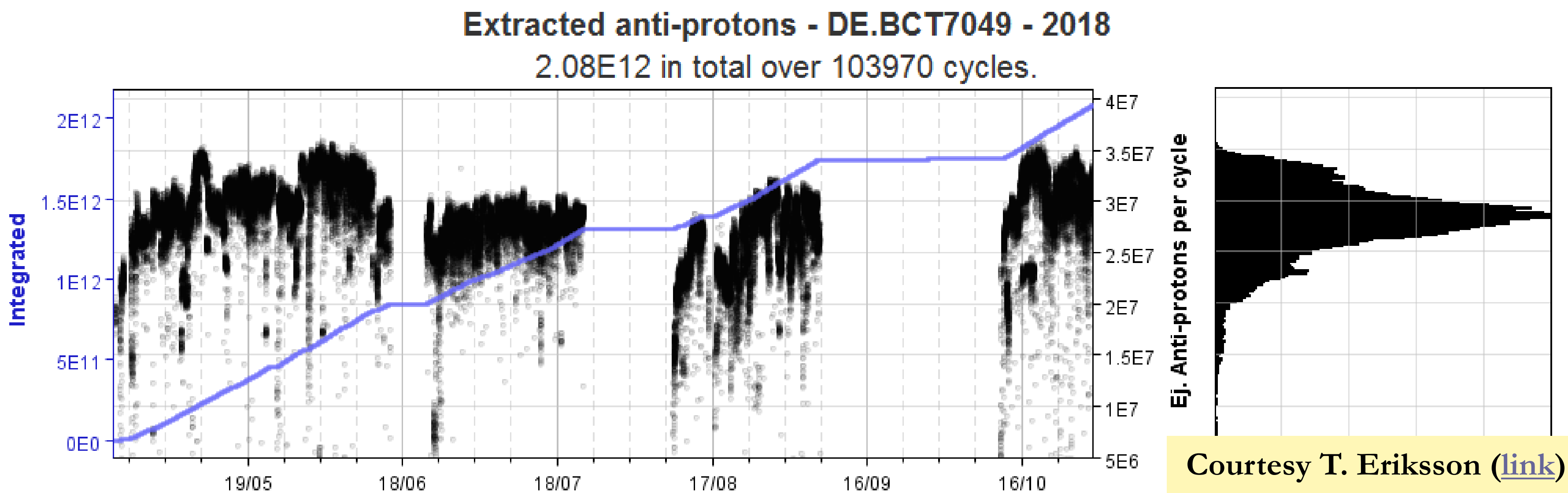


- Almost nominal cycle:
  - Injection 100 MeV/c
  - Deceleration to **35 MeV/c** (**h = 1**)
  - De-bunching and **e-cooling**
  - Deceleration to **13.7 MeV/c** (**h=4**)
  - De-bunching and **e-cooling**
  - Re-bunching (with e-cooler on) on **h=4** and **extraction to experiment**
    - GBAR only user so far.
- If we trust LLRF intensity estimate we have **about 50% deceleration efficiency**
- Still quite some **losses** at the end of **second ramp**
  - **Still to be understood…**

(Almost) Ready and looking forward to send beam to all other AD experiments after LS2!

Important Facts: beam time

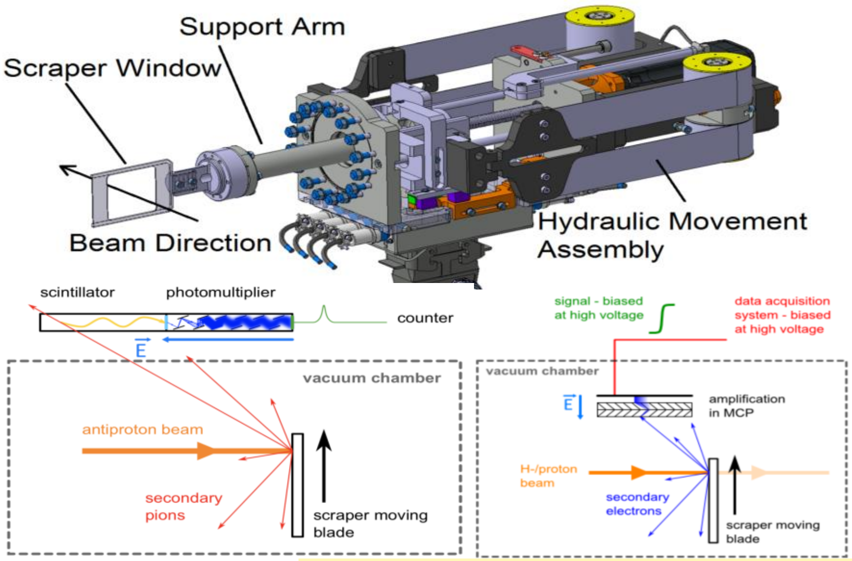
- E-cooler **studies** (so far) **only possible with *pbars***
  - **Unavailability** of ***p*** beam from **source; limited attempts** with **H-**
- AD cycle length ~110 s; MD shift of 8 h
  - About **33 shots/hour**; **260 shots/MD shift**
  - Typically **2/3 MDs per week ≈ 10% of time**
  - **Unfortunate year for AD** (about 62% availability = 4400h)
    - **i.e. about 15000 shots (upper boundary) for ELENA MDs** in **2018**



Courtesy T. Eriksson (link)

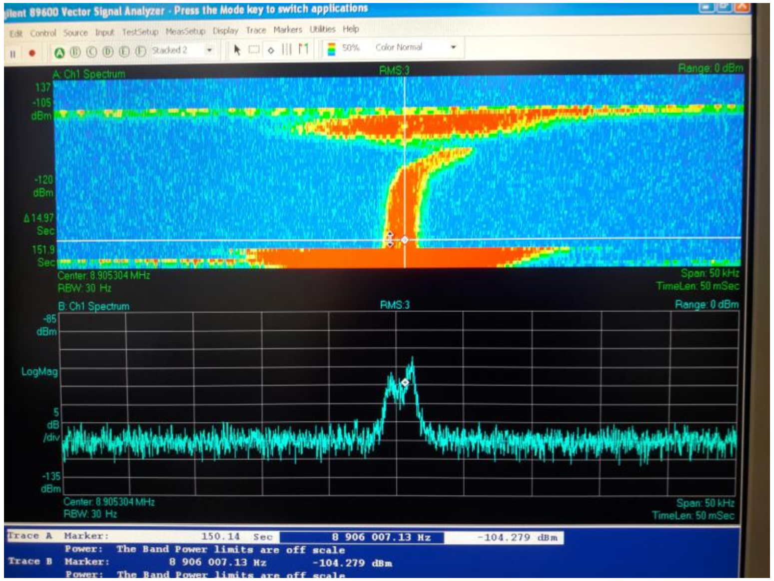
Important Facts: Beam Instrumentation

- **Scraper** measurement
  - **Destructive**
  - **Integrated** in control system



Courtesy P. Grandemange (link)

- **Schottky diagnostic** (LPU or **TPU**)
  - **Non-destructive**
  - **Not fully integrated** in CO

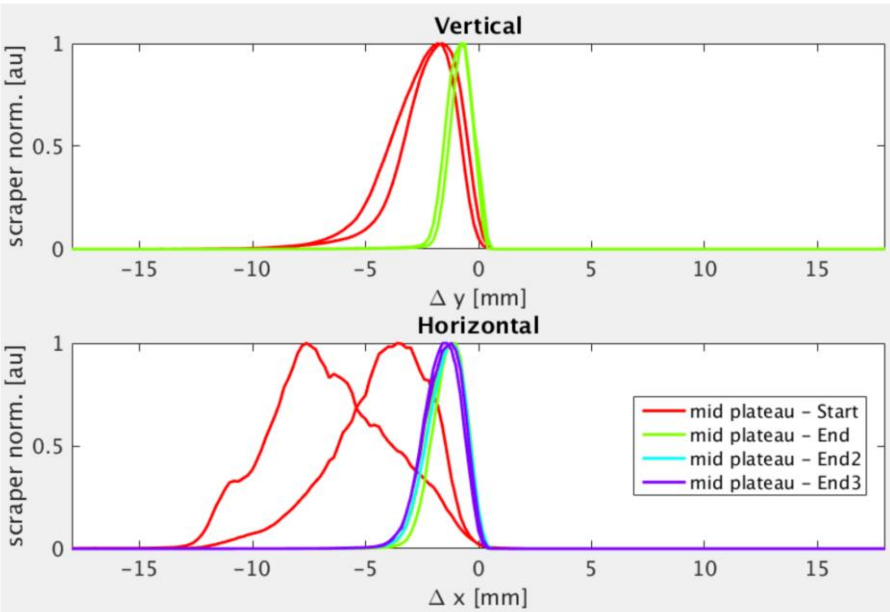


Also available:

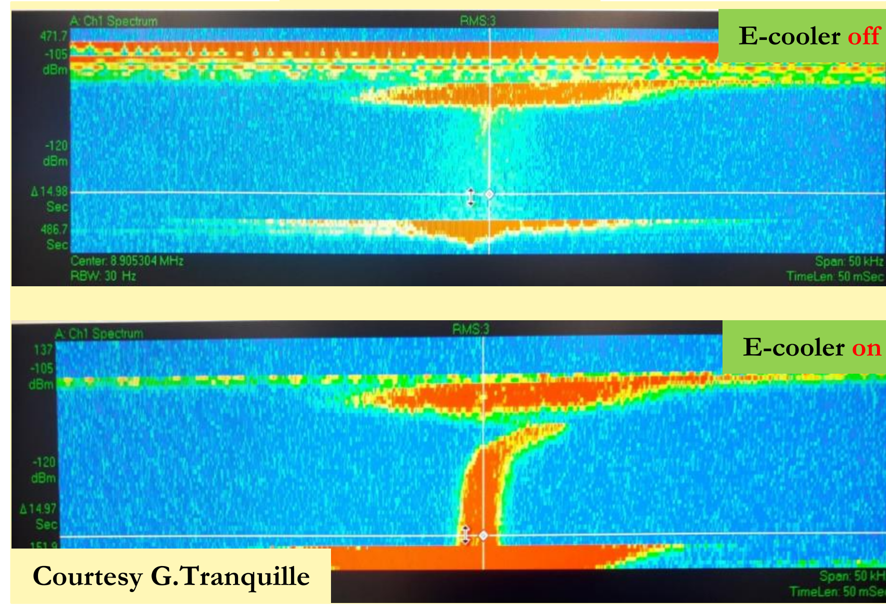
- 2 **BPMs** in e-cooler section, but **only used to measure ions** **(no tests with e-, isn't it?)**
- **Recombination Monitor** only for e- beam optimisation with H- and p **(not exploited)**

E-cooler in action - 35 MeV/c plateau

~half profile measured with "scraper"

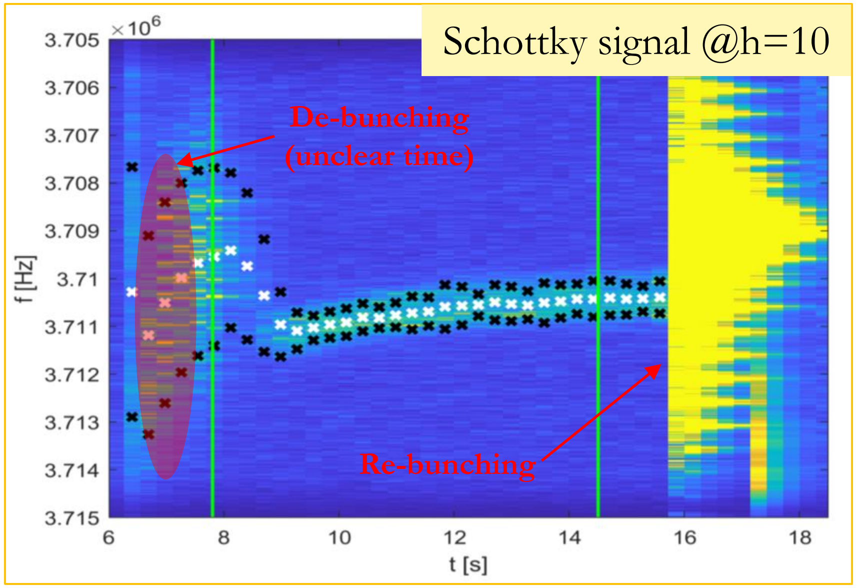


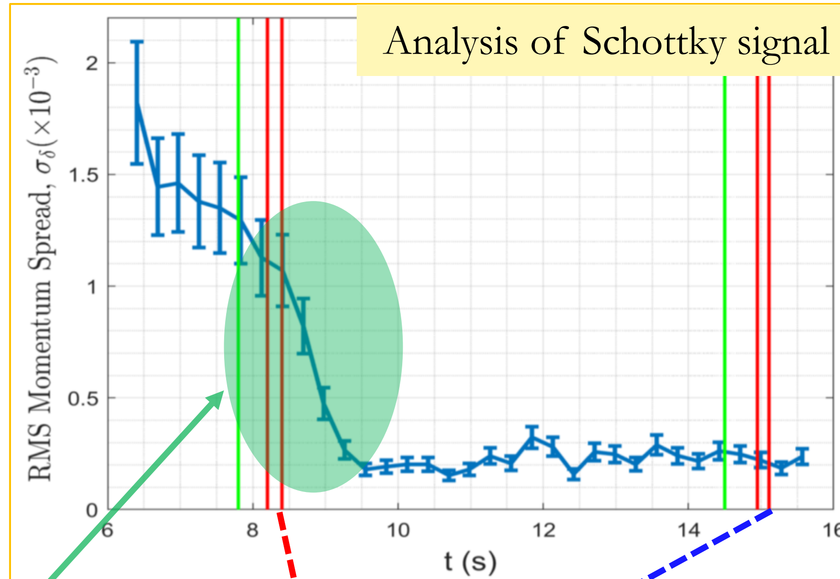
Schottky signal



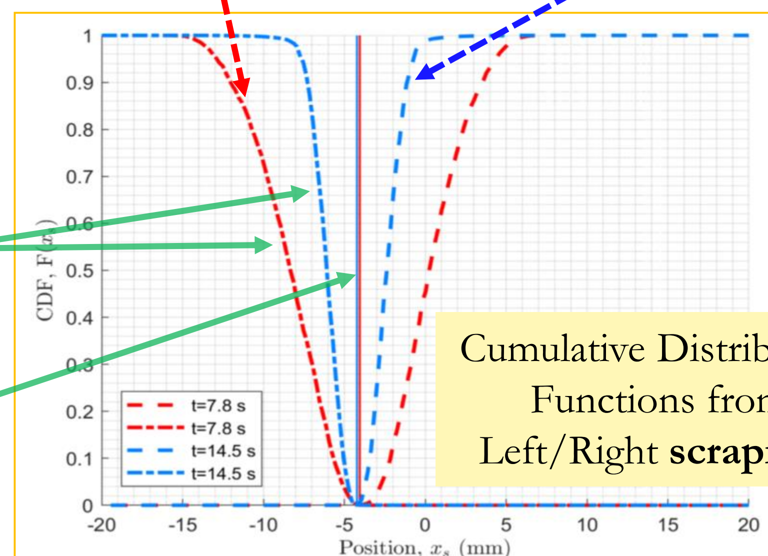
- **Clear transverse and longitudinal emittances reduction observed**
- **Only limited amount of time** on systematic optimization of cooling (**lack of time**)
  - **Some optimisation with orbit bumps/angles in e-cooler**
  - **Surely(?) margin** for improvements

Some details *by J.Hunt*





- **Longit. cooling time** of the order of **1 s**
  - **Momentum spread ~2.5e-4 compatible with expectations**
- Clear **reduction** of transverse **beam size**
- Some **drift** of **mean energy**
  - **e- beam energy drift?**
- No sizable variation of beam mean transverse position



Cumulative Distribution Functions from Left/Right **scrapings**

Cooling time

$$\frac{1}{\tau} = \frac{1}{k}\frac{q^2}{A}\eta_c L_C r_e r_p \frac{j}{e}\frac{1}{\beta_\gamma^4 \gamma^5 \Theta^3}$$

k = 0.16(?)

L_C = Coulomb logarithm

≈ 10 typically

j = e⁻ current density

$j = N_e \beta_\gamma c e$

$N_e \approx 1.4 \times 10^{12} [m^{-3}]$

Q = -1; A = 1 for ELENA

$r_e = 2.8 \times 10^{-15}$

$r_p = 1.54 \times 10^{-18}$

r.m.s. ion/electron "angular" spread

$\Theta_\parallel \approx \Delta p_{ion}/p_{ion} \approx 2 \times 10^{-3}$

$\Theta_\perp \approx \sqrt{\epsilon \gamma_{Twiss}} \approx 1.4 \times 10^{-3}$

$\eta_c = \frac{L_{cool}}{L_{ring}} \approx 0.023$

$\gamma \approx 1$

$\beta_\gamma \approx 0.038 - 0.015$

from: ELENA Design Report (CERN-2014-002)

- Putting everything together, to be expected cooling time of **$\tau < 1$ s**
  - **Compatible with observations.**

Transverse performance *by J.Hunt*

TABLE 6.8: Intermediate plateau summary table. Note: changes in emittance are expressed as percentages of initial emittance.

	t=7.8	Error	t=14.5	Error	Change	Error
ϵ_y(mm mrad)	1.59	0.02	1.15	0.02	28%	2%
y_0 (mm)	-2.88	0.03	-2.89	0.03	-0.01	0.06
ϵ_x (mm mrad)	3.6	0.27	0.70	0.05	81%	10%
x_0 (mm)	-4.05	0.04	-4.22	0.04	-0.17	0.08

TABLE 6.9: Ejection plateau summary table. "e^-C. Off" and "e^-C. On" refer to the status of the electron cooler. Note: changes in emittance are expressed as percentages of initial emittance.

	e^-C. Off	Error	e^-C. On	Error	Change	Error
ϵ_y (mm mrad)	2.55	0.03	0.53	0.01	79%	2%
y_0 (mm)	-2.08	0.03	-2.03	0.03	0.05	0.06
ϵ_x (mm mrad)	2.5	0.20	0.55	0.04	78%	10%
x_0 (mm)	-3.67	0.04	-3.91	0.04	-0.24	0.08

still, about **x2 worst than design** values (0.3/0.2 μm)

Great emit. improvement

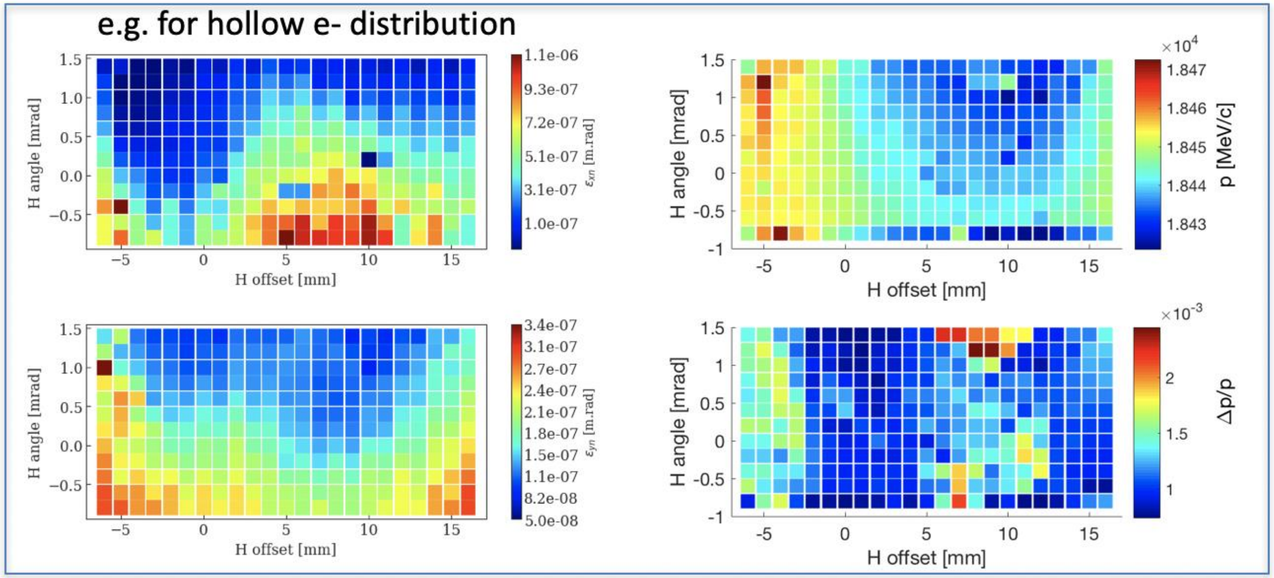
Desiderata: looking at LEIR

from: A.Saa Hernandez (indico)

Studies of equilibrium values

As a function of the ion beam position in the electron cooler (i.e. on the e-ion overlap)

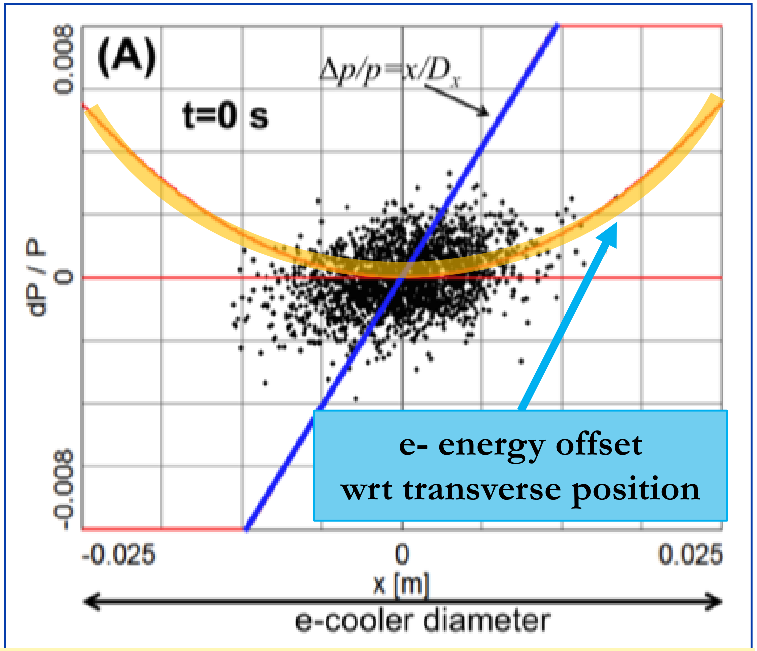
- For different electron currents: 200, 300 and 400 mA
- For different transverse beam profiles: parabolic, flat, hollow



- **Each scan** contains about **260 points = 1 ELENA pbar MD shift**
- **Only destructive emittance measurement in ELENA**

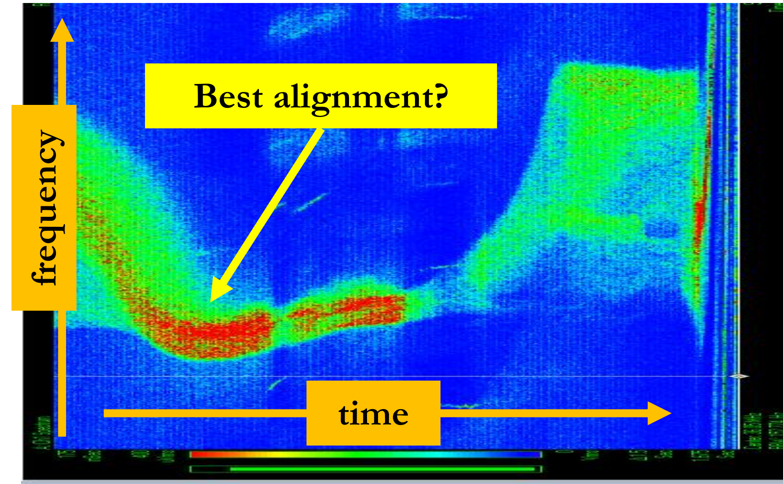
Scan using a single cycle?

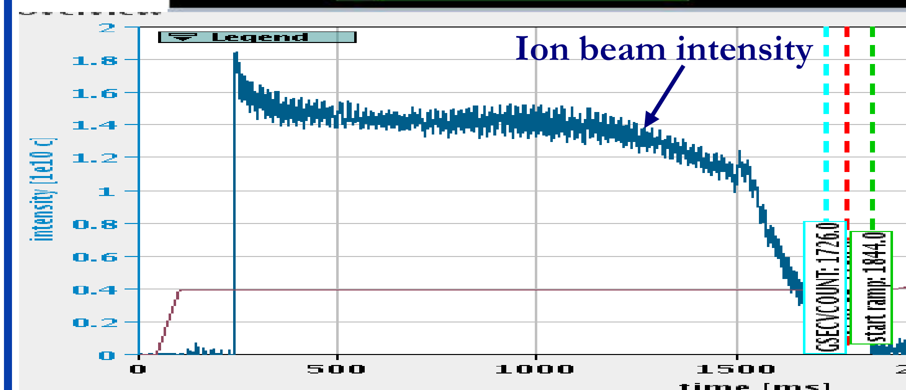
- **We can profit of space-charge effect on e- beam energy distribution:**

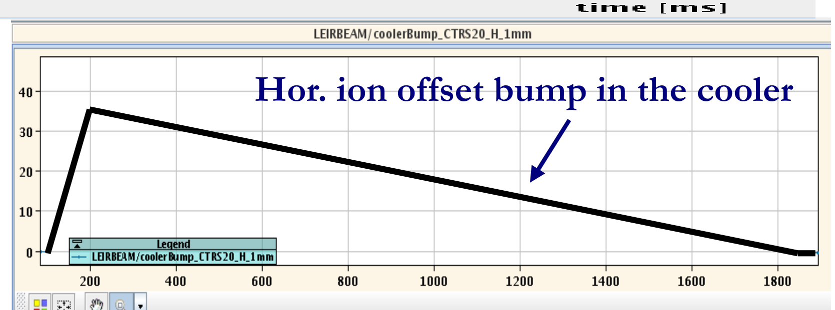


from: J. Resta-López *et al* 2015 *JINST* **10** P05012 (link)

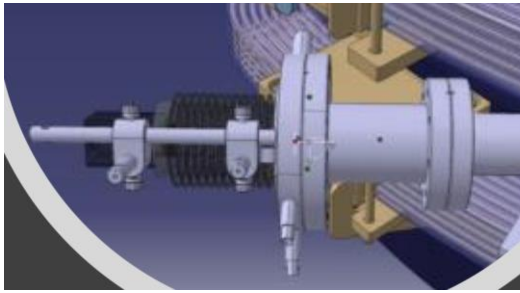
- To the **right**, a **quick test at LEIR**
  - **Requires new tooling/flexibility of ELENA control system**



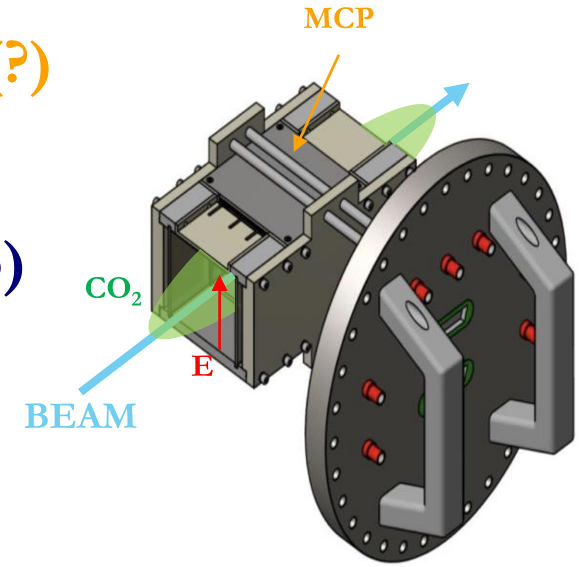




Overcome scraper limitation



- Use of available **recombination monitor**
  - **Only** for **H-/p** operation
  - **Still to be exploited**
  - How to translate information to pbar operations?
- Use of **Transverse Resonant Schottky Pickup** to estimate emittances
  - **Previous attempts** in AD **not successful (?)**
- **Installation** of **dedicate IPM**
  - **Proposal available (e.g. EDMS #1754985)**
  - **Impact** on **vacuum** and **beam dynamics still to be fully evaluated (?)**
  - **No short term plans (?)**



Conclusions

- **2018** a very **fruitful year** for ELENA commissioning
  - Many **sub-systems** (RF, BI, e-cooler) (almost) fully **commissioned**
  - Nominal **beam performance** (almost) **established**
- **E-cooling** is doing what it has promised
  - **Emittance reductions of ~80% down to ~0.5** μm (nominal ~0.3 μm)
  - **Results obtained with limited-empirical studies "by hand"**
- **Could not** fully **profit** of the **H^-/p source => being fixed**
  - Use of ***p*** **beam envisaged for e-cooling studies (higher rep rate)**
- **After LS2 all pbars** will need to go **through ELENA**
  - **More pbar** "shots" **available**, eventually for **parasitic observations**
  - Hopefully, **more time** for well-thought, **systematic measurements**
- Still, **limited emittance-measurement capabilities**
  - We probably **need to discuss** what are the **options** (e.g. IPM?)

Thanks for your attention, comments and questions …

Backup

Cooling time

Optional [1] — **Cooling Time (Contnd)**

For estimates by order of magnitude one can use *approximate cooling time Formula*. Besides, a practical application requires to find cooling time value in Lab. Reference Frame. Then one needs to make Lorenz transformation of all parameters from PRF to Lab. Ref. Frame. One needs to introduce the following parameters:

$$\theta_{ion\perp} = \frac{\Delta p_{ion\perp}}{p_{ion}}, \qquad \theta_{ion\parallel} = \frac{\Delta p_{ion\parallel}}{p_{ion}},$$

$$\theta_{e\perp} = \frac{\Delta p_{e\perp}}{p_e} = \frac{1}{\gamma\beta}\sqrt{\frac{T_{e\perp}}{mc^2}}, \qquad \theta_{e\parallel} = \frac{\Delta p_{\parallel}}{p_e} = \frac{1}{\beta}\sqrt{\frac{T_{e\parallel}}{mc^2}},, \qquad \eta_{cool} = \frac{l_{cool}}{C_{Ring}}.$$

Here $\Delta p_\perp$ ($\Delta p_\parallel$) are transverse (longitudinal) components of ion or electron momentum spreads in Lab. Ref. Frame, l_{cool} is cooling section length. Using The "Parkhomchuk Formula" one can derive Formula for cooling time:

$$\tau_{cool} = \frac{A_i}{Z_i^2} \cdot \frac{\beta^4\gamma^5}{4 r_p c L_c} \frac{I_0}{J_e} \left(\theta_{i\perp}^2 + \frac{\theta_{i\parallel}^2 + \theta_{e\parallel}^2}{\gamma^2} + \theta_B^2 \right)^{3/2}.$$

Here r_p is electron classic radius, J_e is electron beam density (A/cm²) , θ_B is angular amplitude of solenoid magnetic field deviation.

$$L_c = ln\left(1 + \frac{\rho_{max}}{\rho_{L\perp} + \rho_{min}}\right), \qquad I_0 = \frac{mc^3}{e} \approx 17000\ A,$$

$\rho_{max} = [(\gamma\theta_{ion\perp})^2 + (\theta_{ion\parallel})^2]^{1/2}\, l_{cool}$, $\rho_{min} = Z_i r_e / \beta^2[(\gamma\theta_{ion\perp})^2 + (\theta_{e\parallel})^2]^{1/2}$, $\rho_{L\perp} = \beta\gamma\theta_{e\perp} mc^2/eB$ - electron "transverse" Larmor radius .

from: Beam Cooling Techniques – I. Meshkov (indico)

Some interesting slides from A.Saa Hernandez (indico):

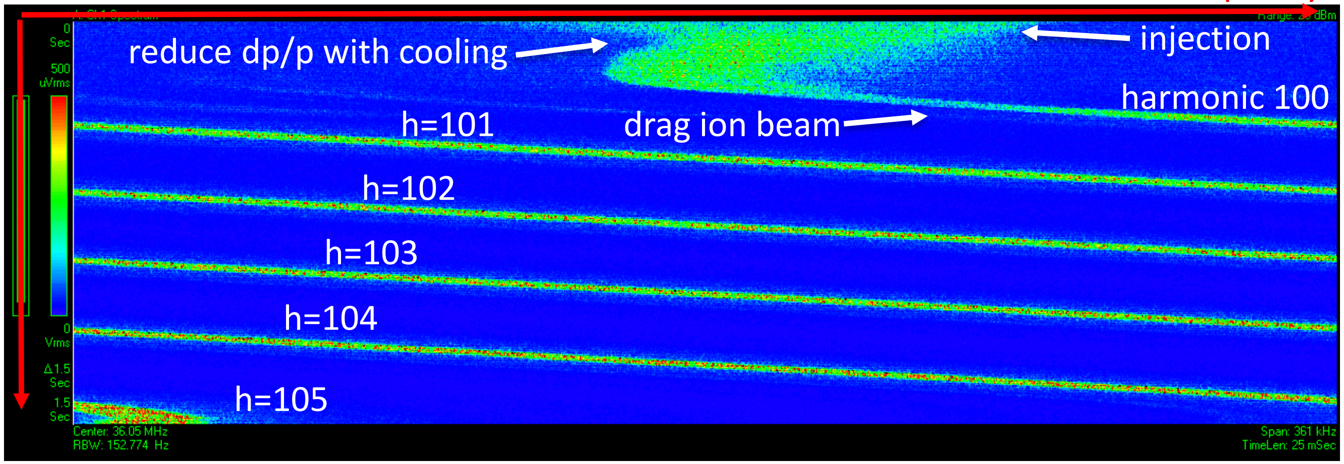
Overview of 2018 MD studies in LEIR

Can we capture at a higher momentum?

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 Ecooler

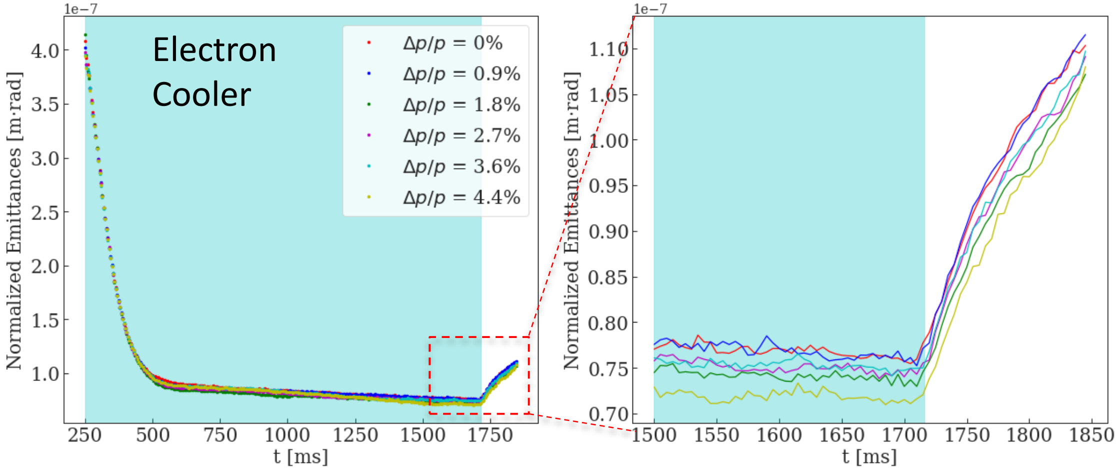
We do indeed accelerate the ion beam

Longitudinal Schottky



And could afterwards capture and ramp with minor modifications (adjust RF at capture and correct ramp)

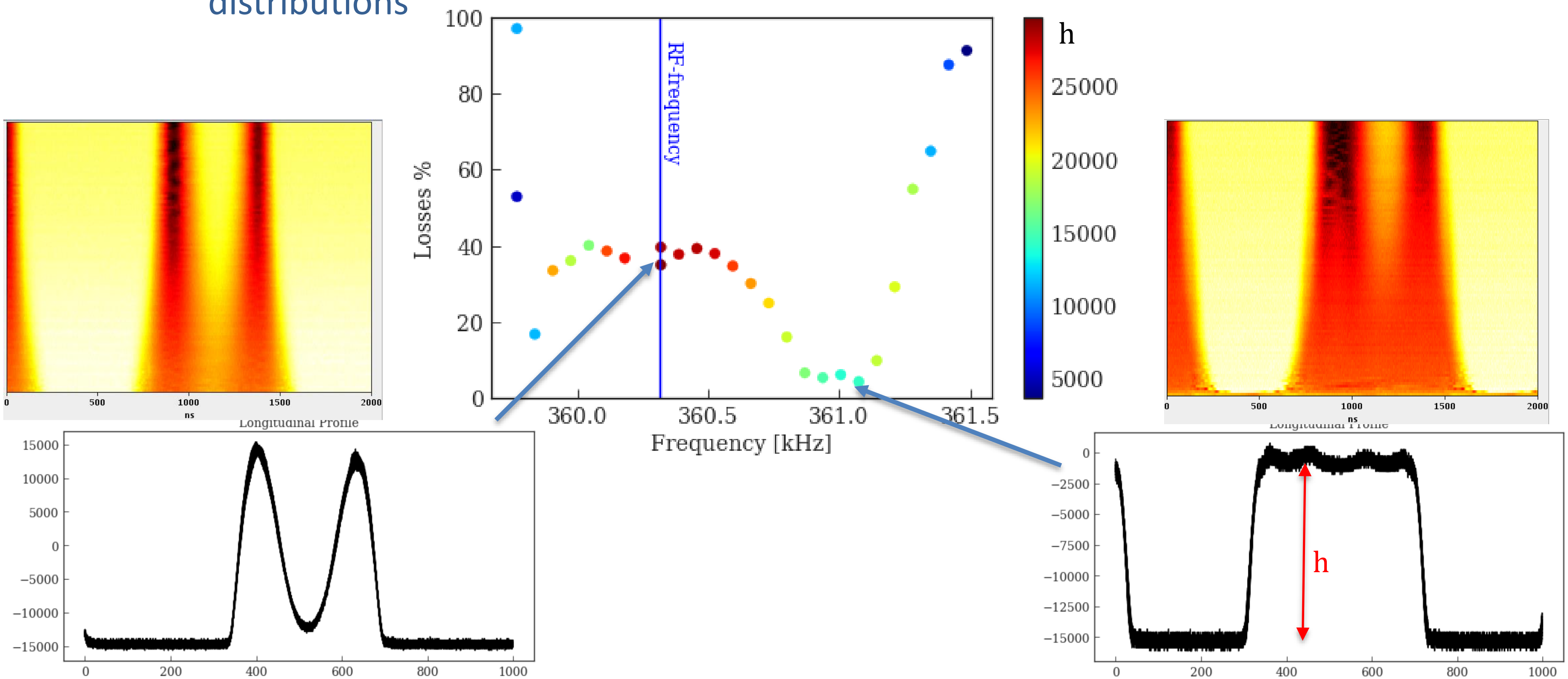
However:
same emittance blow-up for different final momentum



And if we cool a bunched beam?

At capture, losses and a emittance blow-up associated to SC and IBS always observed
What if we extend cooling time to after RF capture?

- Beam damped in all 3 planes
- By adjusting the electron cooler gun voltage, we drag ion beam to a frequency which has an offset with the RF frequency, creating hollow/flat distributions

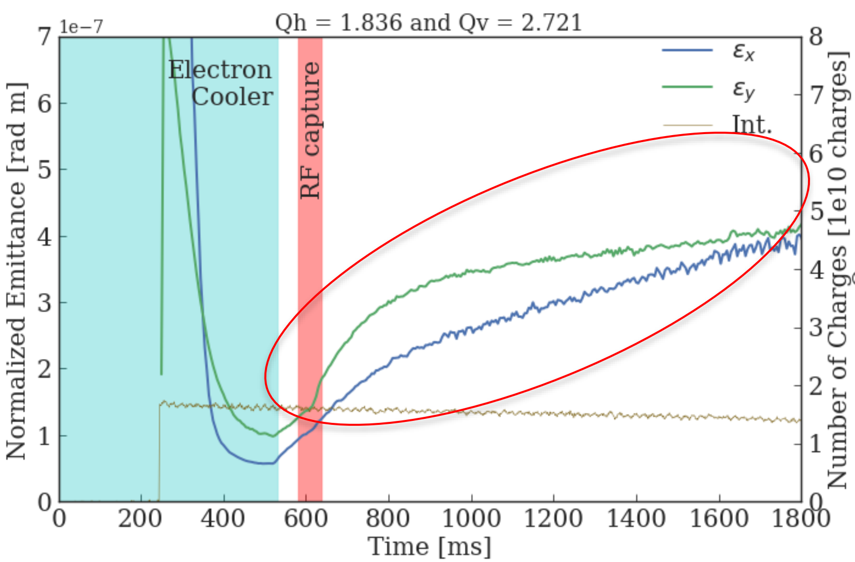


Heating processes: dominated by IBS or Space Charge?

Similar nature: Coulomb force

IBS: particle collisions as they perform betatron and synchrotron oscillations → redistribution of momenta within the bunch → increase emittances

Space charge: derived from the E-field generated by the distribution of charged particles, creates tune shift and can excite resonance → increase emittances



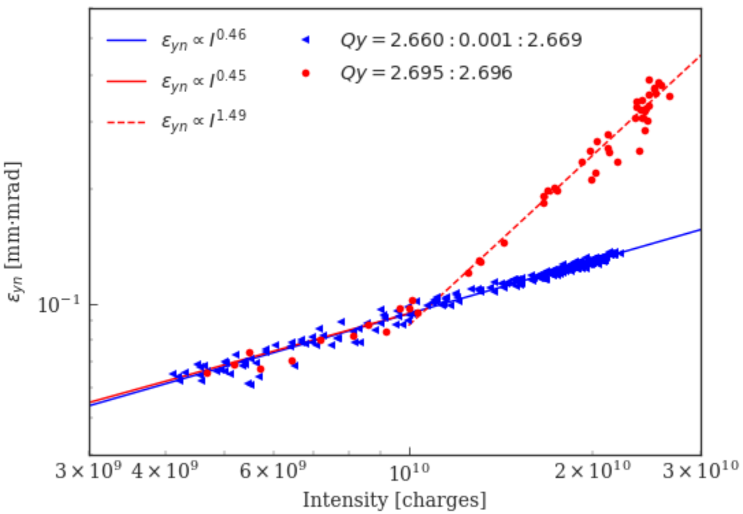
What happens here?
Depends on intensity? On WP? On resonance excitation? Does it cause losses?

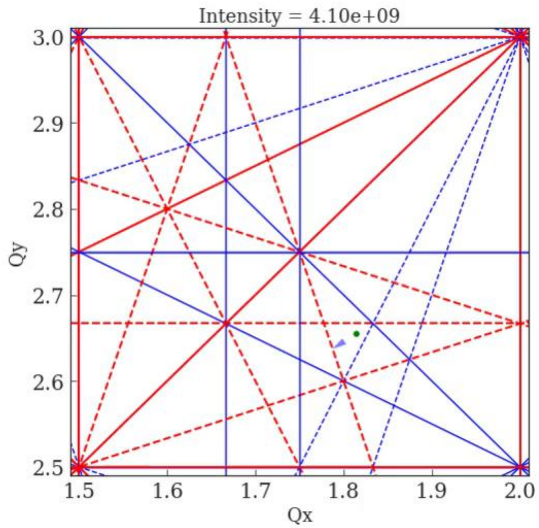
Simulations ongoing for both IBS and space charge, separately. Qualitative agreements found, we needed to get lots of data for further understanding

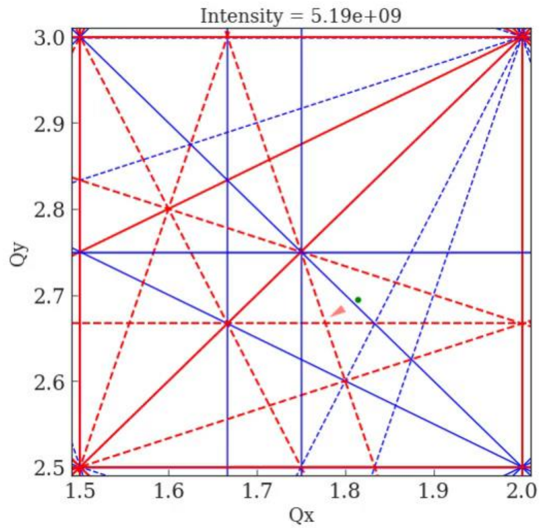
Equilibrium emittance vs Intensity vs Qy

For IBS dominated regime $\varepsilon \sim I^n$ (with n ~ 0.6 for ions of Ti^{22+}, Kr^{36+}, Xe^{54+}, Au^{79+}, U^{92+} measured at GSI)…
but then emittance blow up and losses should be similar for all tunes and we had already observed that was not the case

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



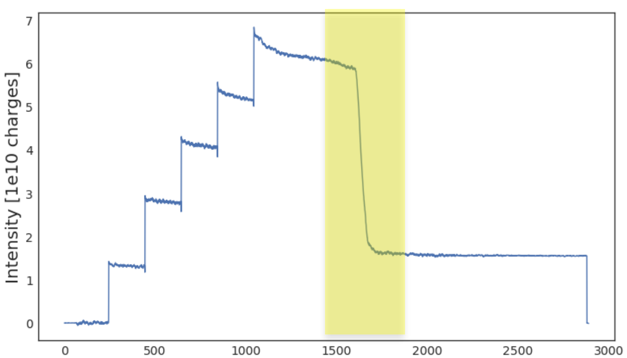


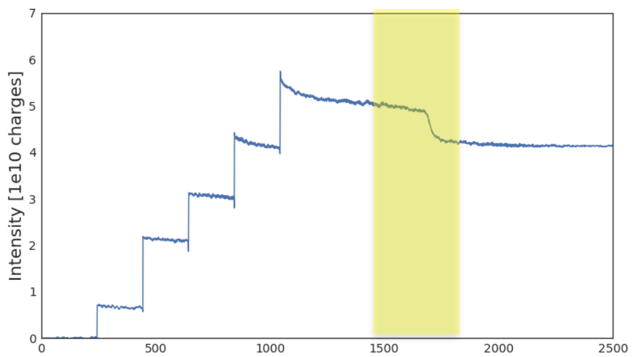


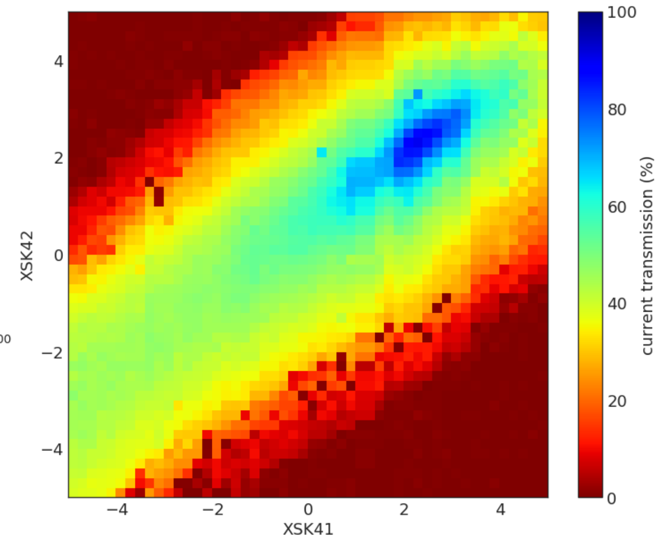
Can we compensate this resonance?

Yes, if excited by the magnetic errors, it should be possible by means of a pair of skew sextupoles with a phase advance $3\Delta Q_y = 90°$ → Only XSF41 and XSF42 available, with $3\Delta Q_y = 133°$

- do a dynamic resonance crossing as a function of the current in the sextupoles and measure losses





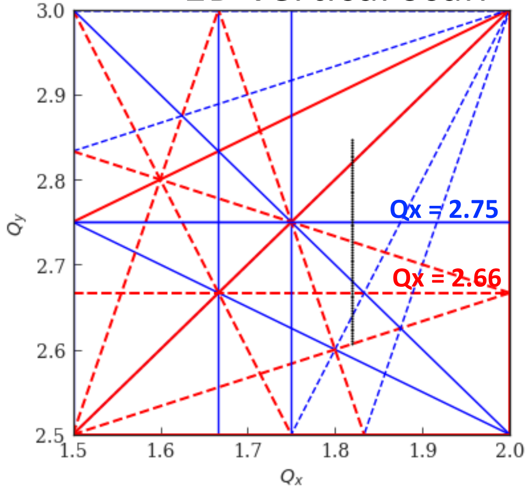


Sextupole settings found that compensate losses up to 90% when crossing the resonance dynamically

Measurements for beams with low and high intensity, compensating on flat bottom and during ramp. Studies also for static (nominal) WP.

Tune Scan: compensated vs. uncompensated

1D vertical scan



No compensation of resonance at Qy=2.66

With compensation of resonance at Qy=2.66 using skew sextupoles

cycle evolution for different Qy