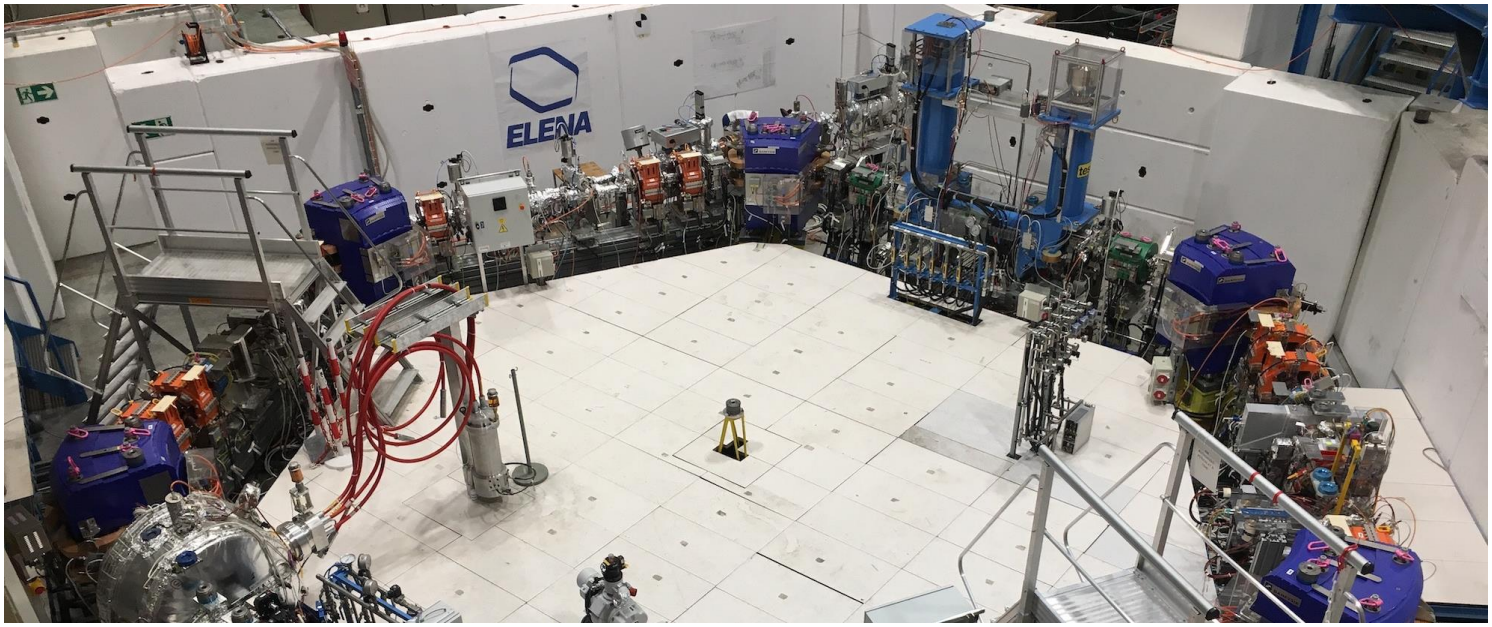
Status of E-cooling at 100 keV in ELENA

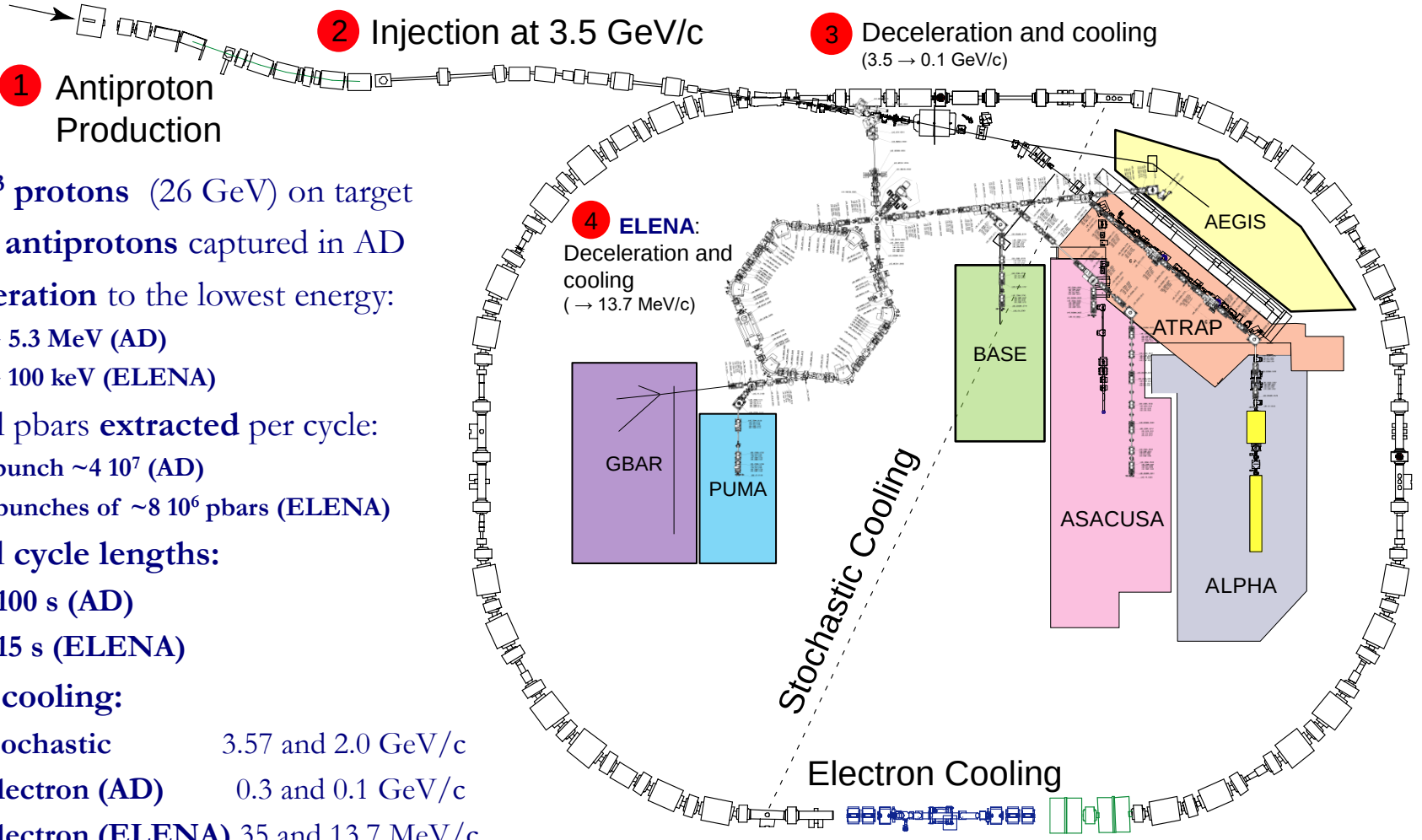
COOL2023 Workshop – Montreux – Oct 2023

D. Gamba for the AD/ELENA team



- Introduction of the AD/ELENA facility and performance status
- Tools and methods available for e-cooling studies in ELENA
- Some recent, yet preliminary, results at 100 keV

AD/ELENA – introduction

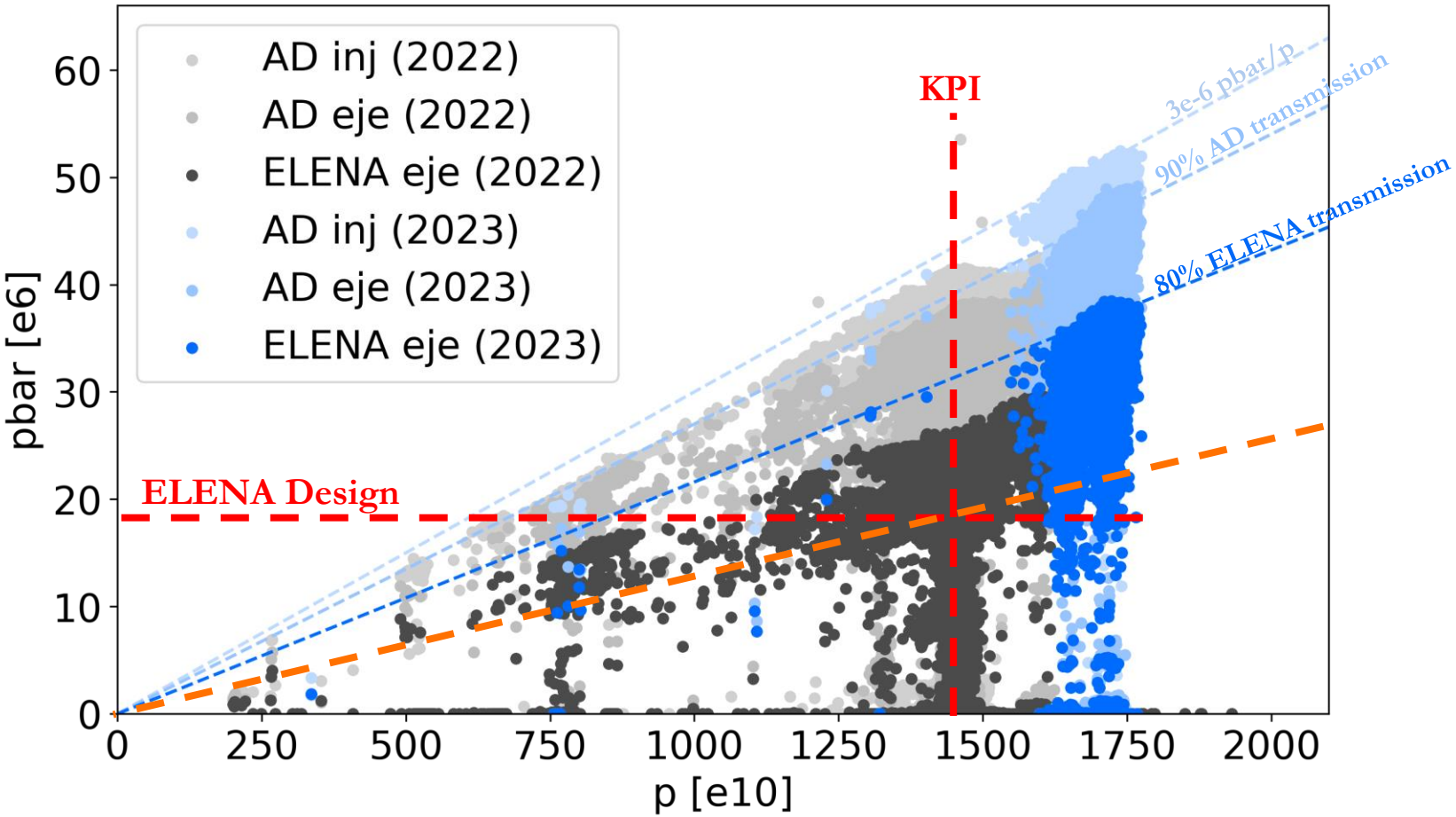


- **~2 10^{13} protons** (26 GeV) on target
- **~5 10^{7} antiprotons** captured in AD
- **Deceleration** to the lowest energy:
  - **→ 5.3 MeV (AD)**
  - **→ 100 keV (ELENA)**
- Typical pbars **extracted** per cycle:
  - **1 bunch ~4 10^{7} (AD)**
  - **4 bunches of ~8 10^{6} pbars (ELENA)**
- Typical **cycle lengths:**
  - **~100 s (AD)**
  - **~15 s (ELENA)**
- **Beam cooling:**
  - **Stochastic** 3.57 and 2.0 GeV/c
  - **Electron (AD)** 0.3 and 0.1 GeV/c
  - **Electron (ELENA)** 35 and 13.7 MeV/c
- **Beam Revolution Frequency:**
  - **AD injection: 1.6 MHz; β_{rel}=0.967**
  - **ELENA ejection: 144 kHz; β_{rel}=0.015**

- **Main purpose is to provide 100 keV pbar beams** to (typically trap-based) experiments!
- **Kay parameter: INTENSITY** (for ~100s rep period)

AD/ELENA Overall Performance

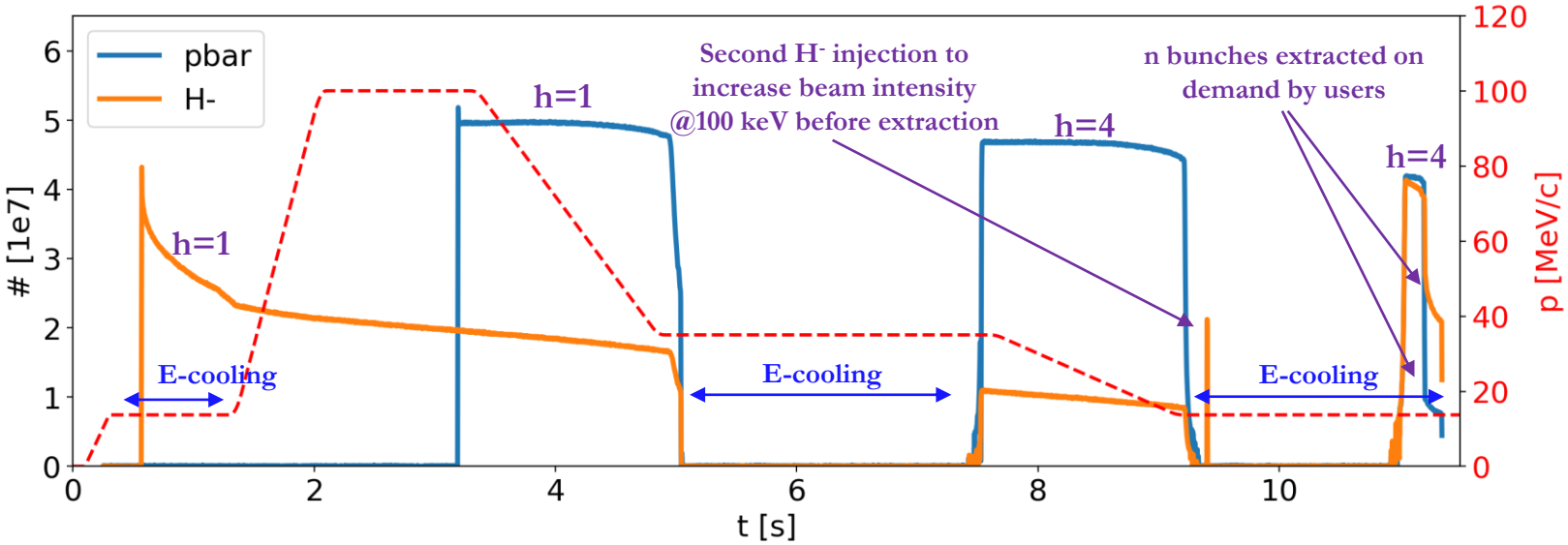
- **Overall performance** can be expressed as **delivered pbar per proton on target**
  - Looking **at about ~20 days** of operation in **2022** and **2023**



- **Overall: another excellent year for AD/ELENA with performance improvements!**
  - **Still need to work on stability, repetition rate, and transmission…**
  - **More details in L. Joergensen presentation**

The ELENA cycle

- Running with two (magnetically-equal) ~**15-second-long pbar/H-** cycles

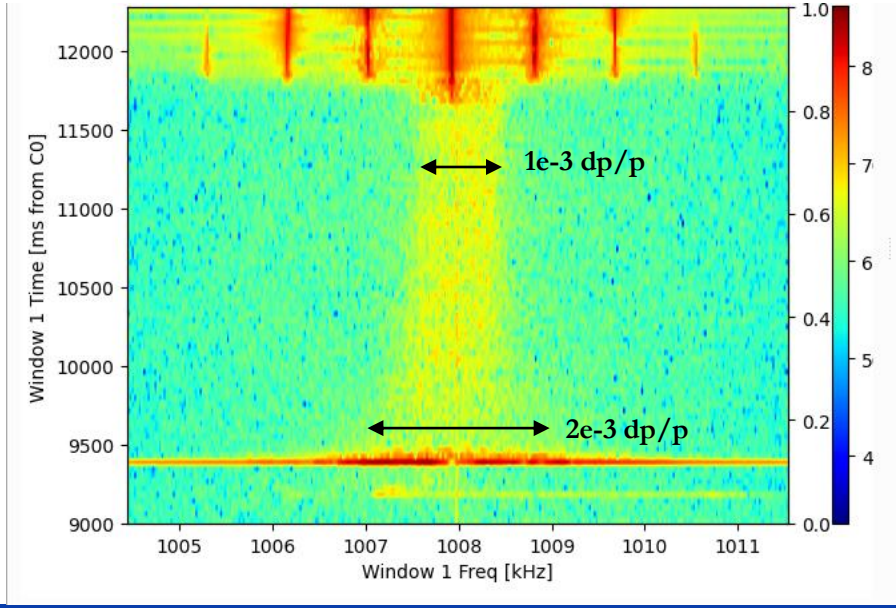


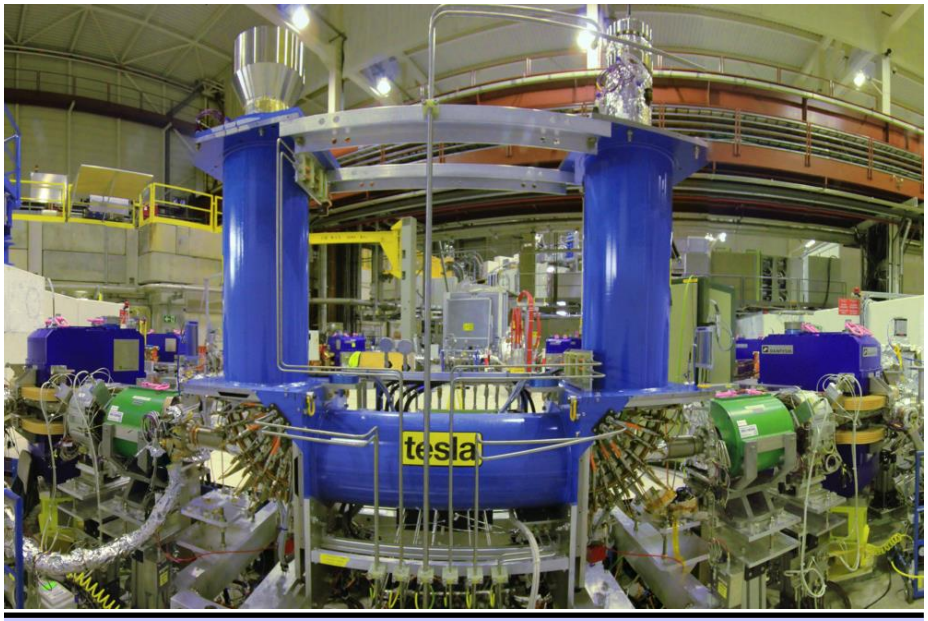
- **We are providing 4 equal bunches to serve 4 experiments in contemporary**
- **Margin of improvement:**
  - **Transmission**: today at up to **~20% losses**,
  - **Cycle length:** not important if we run in the shadow of AD (baseline), but **relevant if we wait for ELENA extraction before restart AD** (as **today**!)
- **Repetition rate is very slow for any study/setup with pbar**
  - **Good news: No H- lifetime degradation observed with e-cooling! We can use H- for most studies!**
  - **Bad news: H- source reliability** questionable, known to be prone to hardware faults…
  - **Bad news: H- lifetime strongly affected by vacuum levels in the ring** (typically 10^{-11} mbar)

The ELENA e-cooler

- **Designed by G. Tranquille** (see for example IPAC2016, IPAC2018)
- In operation since 2018, **no major hardware issues** observed so far
- First measurements and **characterisation of cooling** already done in 2018 (see J. Hunt thesis)

- **Here an example of 100 keV H^-**

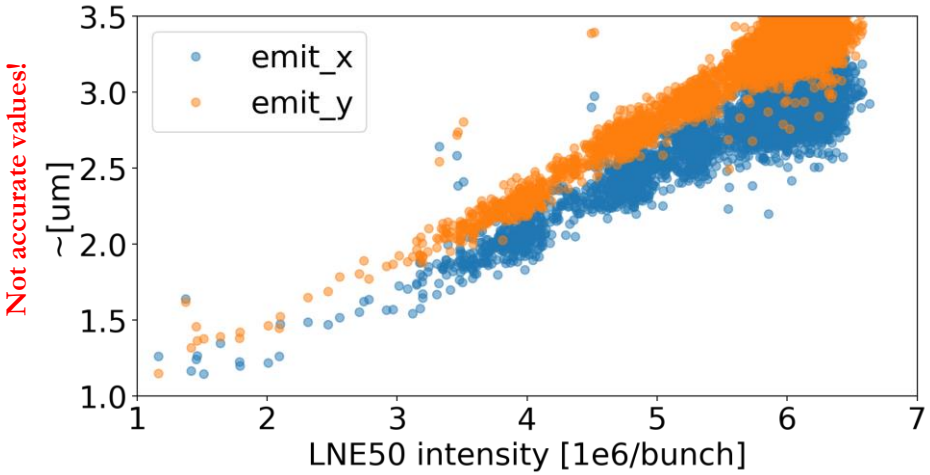




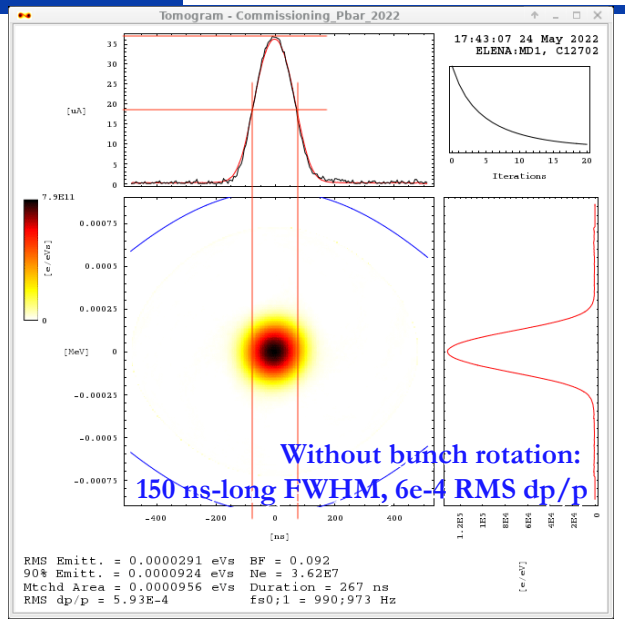
pbar momentum	35 MeV/c	13.7 MeV/c
Electron kinetic energy	355 eV	55 eV
Relativistic beta	0.037	0.015
Electron current	~5 mA	~1 mA
Cooling length	~1 m	
Ring length	30.41 m	
Gun magnetic field	Up to 1 kG	
Drift magnet field	100 G	
Field quality $B_{perp}/B_{parallel}$	<5e-3	
Electron beam radius (drift)	8 to 25 mm	

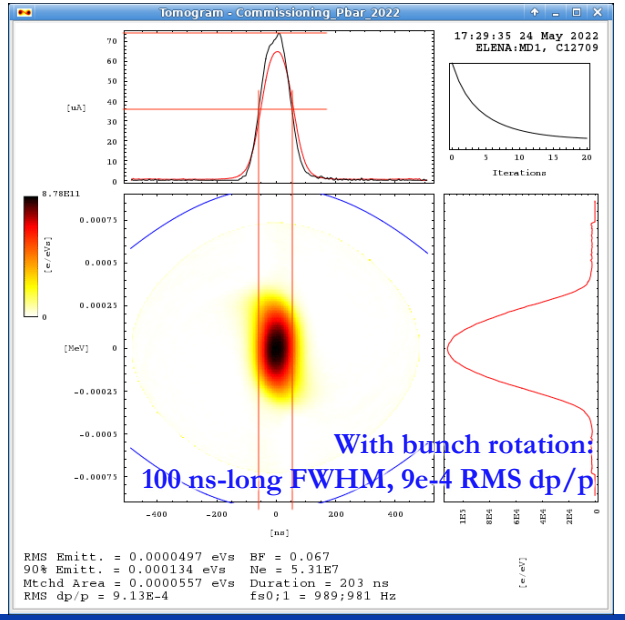
Charactheristics of beams delivered to users

- In **longitudinal**, normally **meeting user needs**
  - **Thanks to flexibility** provided by **bunched beam cooling**, and **bunch rotation**
- **Transverse emittances too large!**
  - **Design values: ~1 um**
  - **~linear dependance with beam intensity**



- **Users do not seem to have strong requirements on emittance** and/or **energy spread…**
- Still, **worth investigating reasons for discrepancy!**

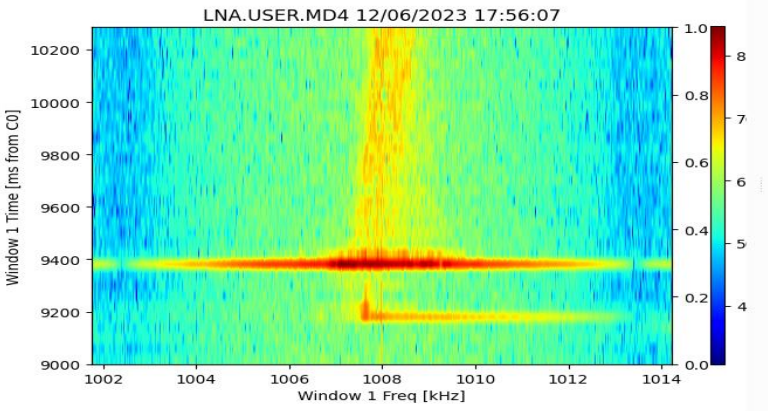


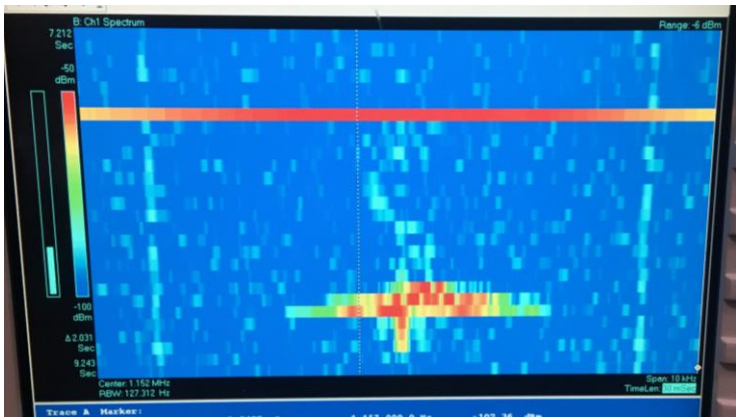


Investigations Tools and Methods

Longitudinal: Schottky using BPMs

- Schottky by **combining several BPMs**
  - See O. Marqversen et al. at IBIC2021
  - **Characterisation** of the full system **still ongoing,** but certainly **good enough for e- energy adjustments**
- **Too little signal** seen using standard spectrum analyzer **with a single BPM**
  - Tests ongoing to see if we can amplify the signal…
- **In principle, dedicated LPU should give us more SNR than all BPMs,**
  - **so far, never seen any usable Shottky** (to my knowledge) using the **LPU**
  - Tests also ongoing to see if we can amplify the signal…

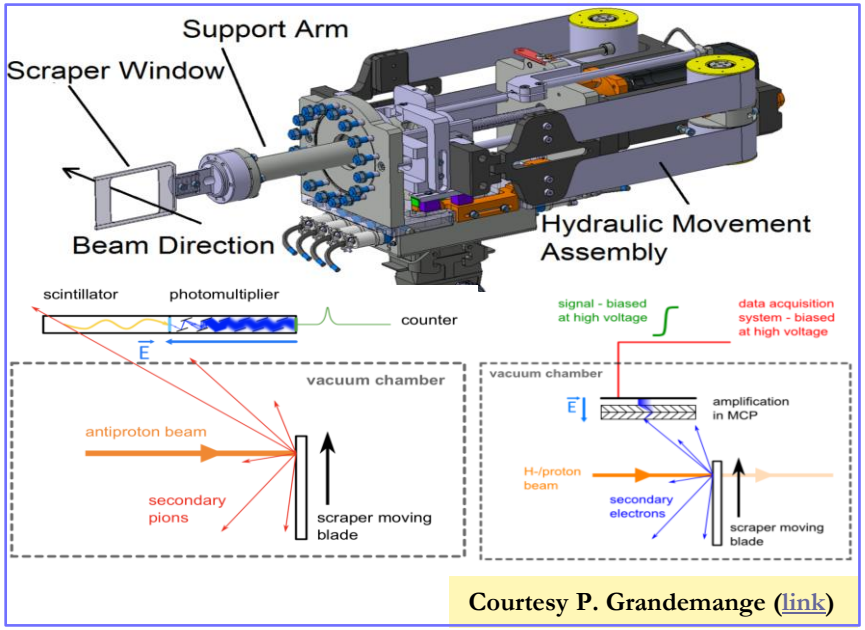




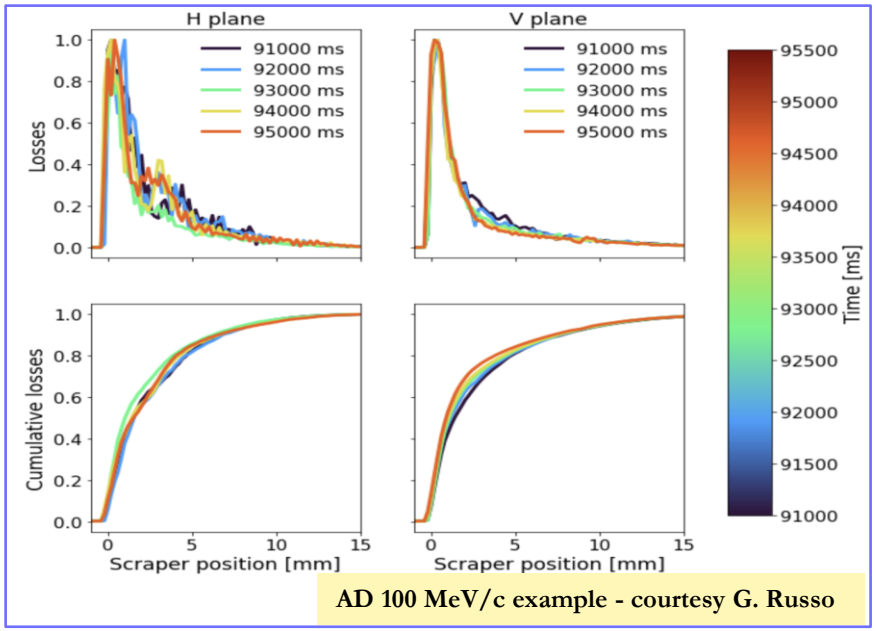
LPU Schottky?

Transverse: Scraper Measurements

- **Only available system** to measure transverse **beam profiles**
  - Similar system (different hardware) for both AD and ELENA
  - **Destructive measurement:** any optimization is a **very lengthy process**!
- Reliability of **signal retrieval** and **interpretation** sometimes **difficult**
  - **Work ongoing** for better data treatment – **see** G. Russo @ HB2023
  - So far, **limited time invested on ELENA**
    - In-vacuum MCPs for H- detection too noisy



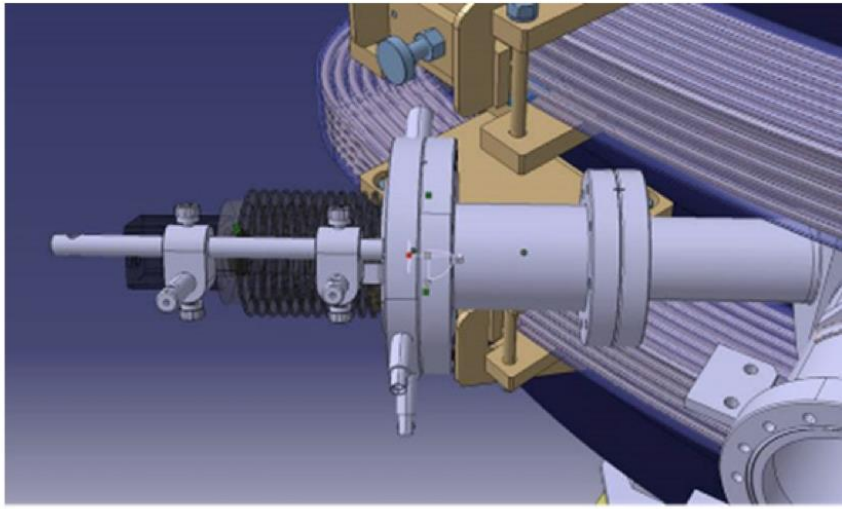
Courtesy P. Grandemange (link)

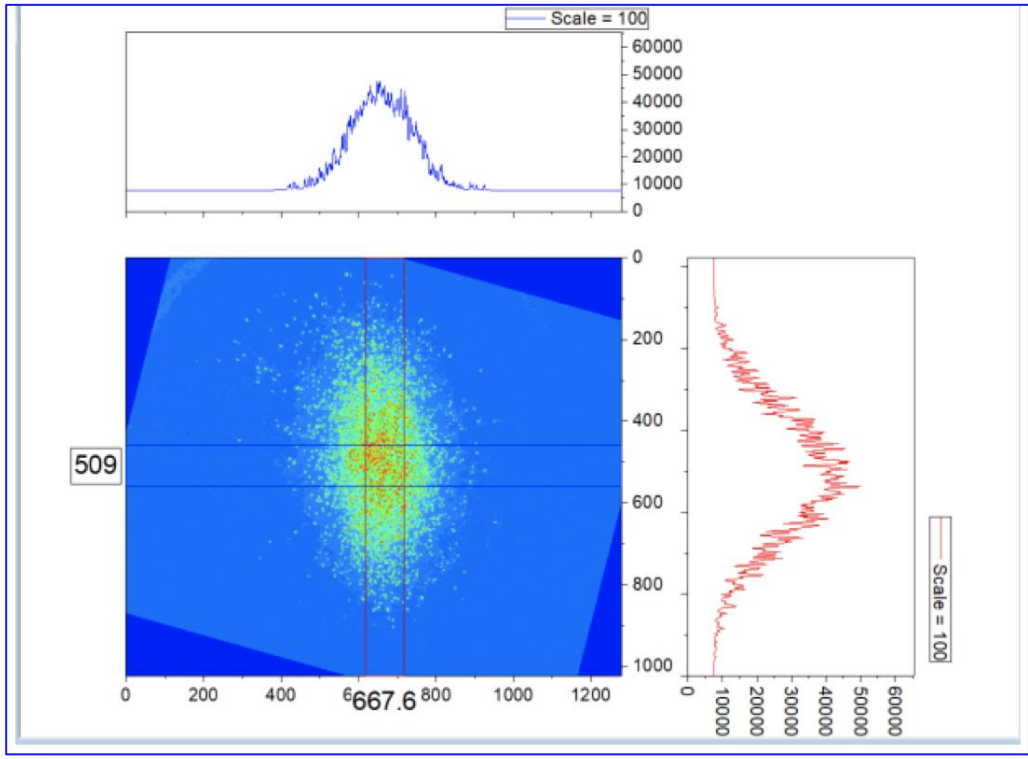


AD 100 MeV/c example - courtesy G. Russo

Neutrals Monitor

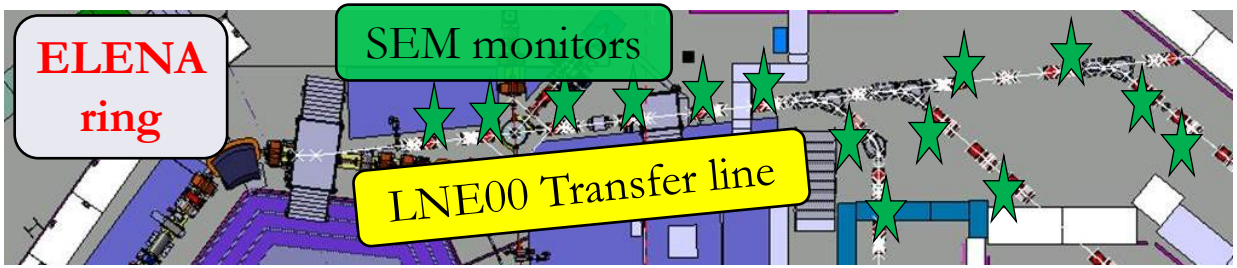
- **System installed** at the end of e-cooler section in ELENA
- **Great potential** for cooling (but not only!) studies **with H^-**
- **Work ongoing to interpret the measurements obtained so far:**
  - Source of the **signal might not be (only) due to H^--e^- interaction**
  - **System not yet fully exploited**
  - **See G.Tranquille at COOL23**

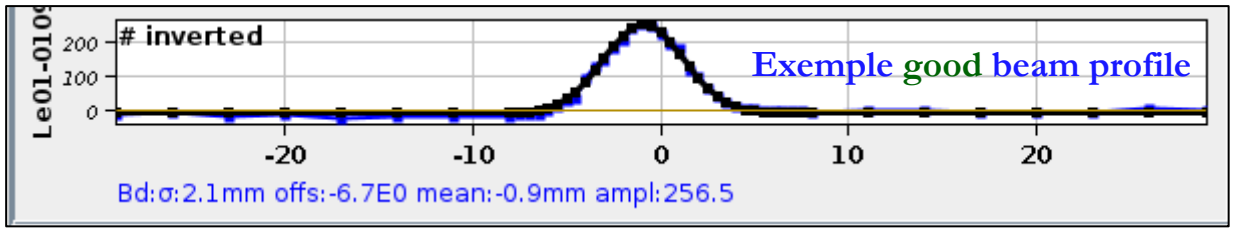


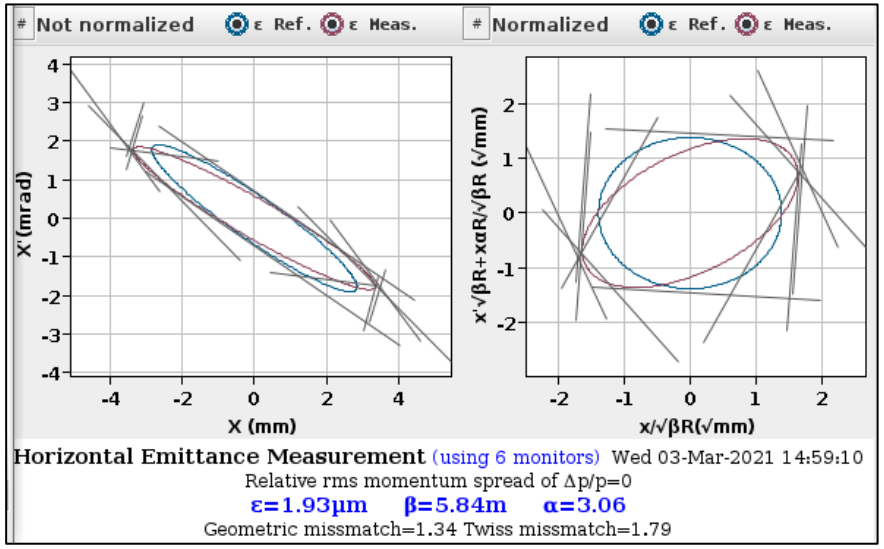


SEM: single shot optics measurement

- **ELENA transfer lines** are **equipped** with **multi-wire profile monitors** (SEM)



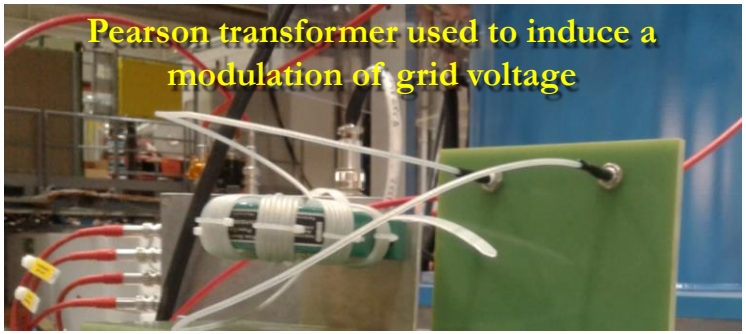


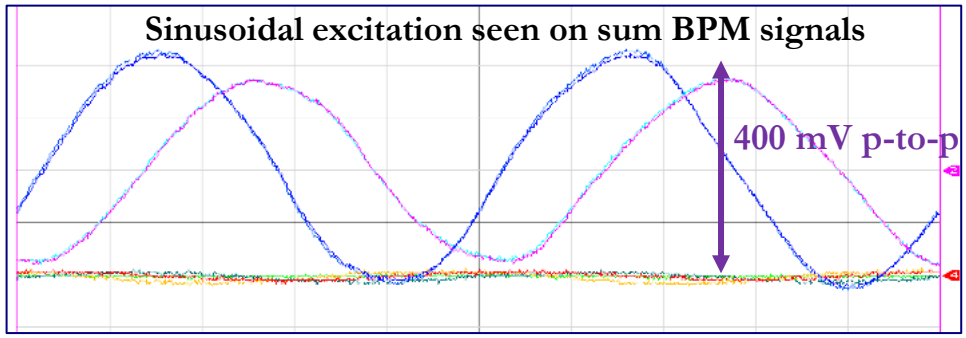


- By **combining the information of several SEM** one can perform a multi-screen **beam Twiss parameter** measurement
- **Extremely useful diagnostic!!**
  - **but loss of intensity as** SEM are **semi-interceptive** device (about **10% beam loss per SEM** in the beam)
- **Often using a single SEM for e-cooling optimization…**

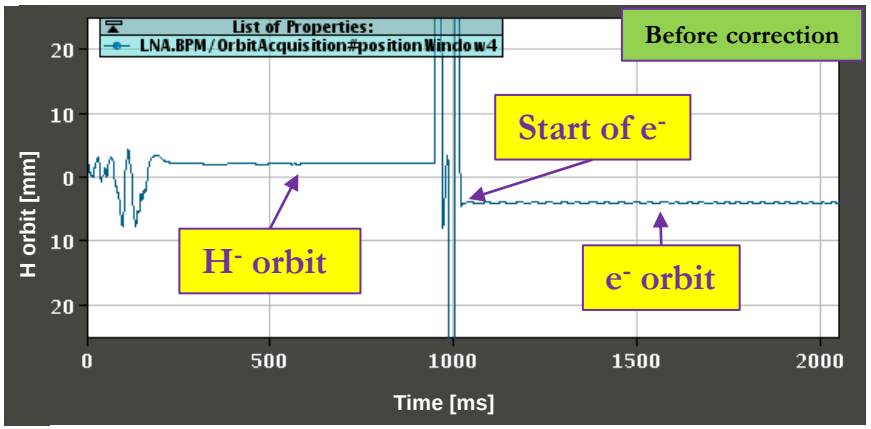
pbar (or H-)/e- orbit matching

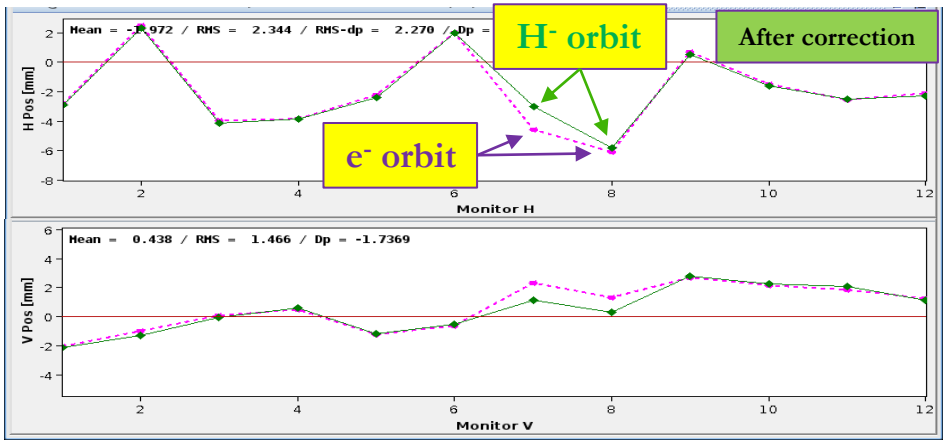
- All **CERN cooler** have **two BPMs** in the **cooling drift solenoid** that "see" both ions and e- beams.
  - **One needs to induce an e- beam intensity modulation** in order to see a signal with those BPMs





- **Using BPM acquisition system** for both generating **e- excitation and signal processing**
  - **it allowed to integrate this new tool with standard orbit correction tools** (e.g. YASP steering program widely used at CERN)
  - **Accuracy on H-(pbar)/e- alignment of the order of 1 mm: enough for first cooling setup!**

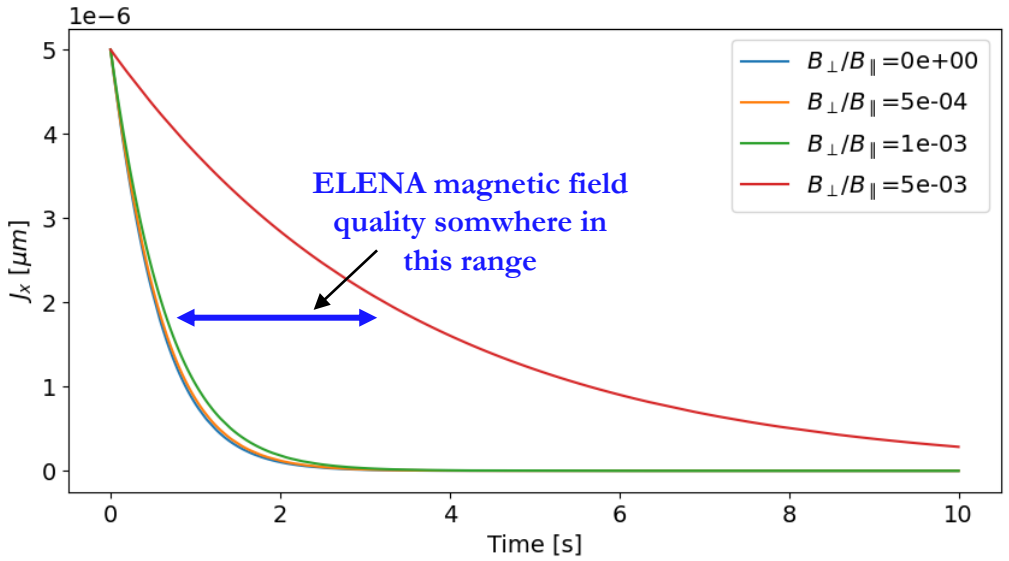


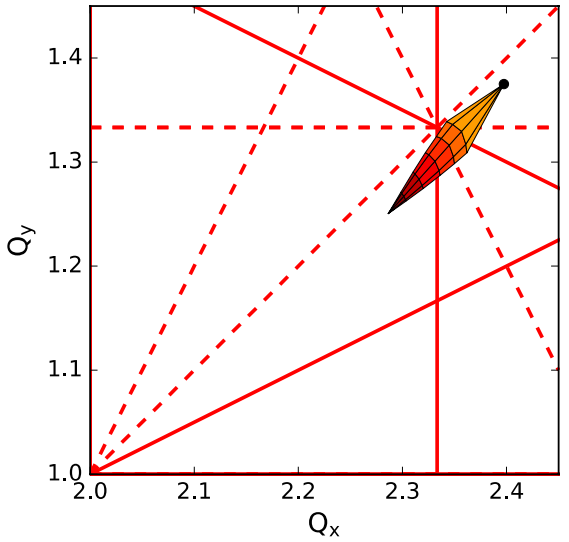


Special thanks to A. Frassier and B. Galante

Simulations Tools Development

- Trying to overcome **limited availability** of **e-cooling simulation codes:**
  - Exploring the **e-cooling module in RF-Track** (see work by A. Boruka @COOL21)
  - Implementation of **e-cooling module in Xsuite** (see work by P. Kruyt @COOL23)
    - E.g. study impact of **solenoid field straightness on cooling time**



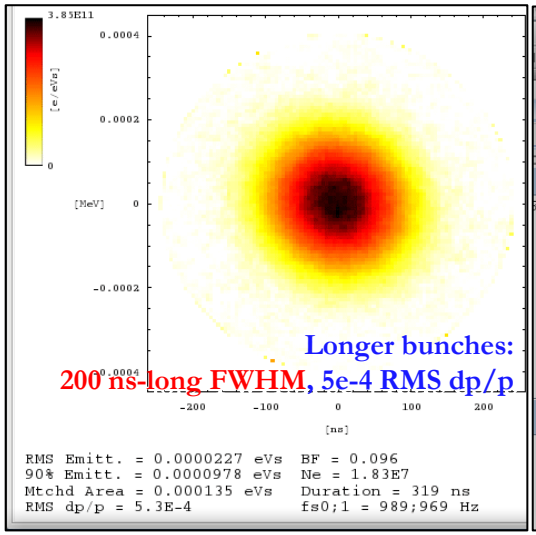


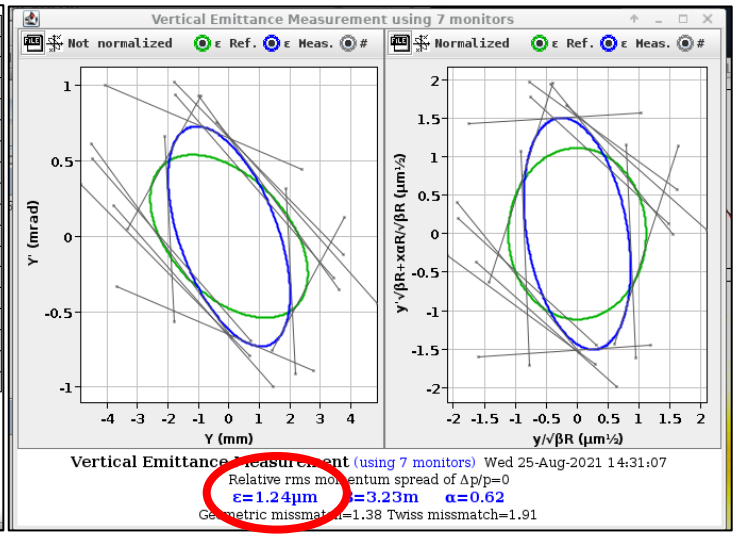
Present wp:
- 1e7 pbars
- 100 keV
- 65 ns rms
- 2 um rms

- Investigate in tools/methods typically used in **space-charge-dominated machines** (e.g. see F. Asvesta studies in CERN injectors)
  - **Space-charge induced tune spread at ELENA extraction is right on top of a third order resonance!**

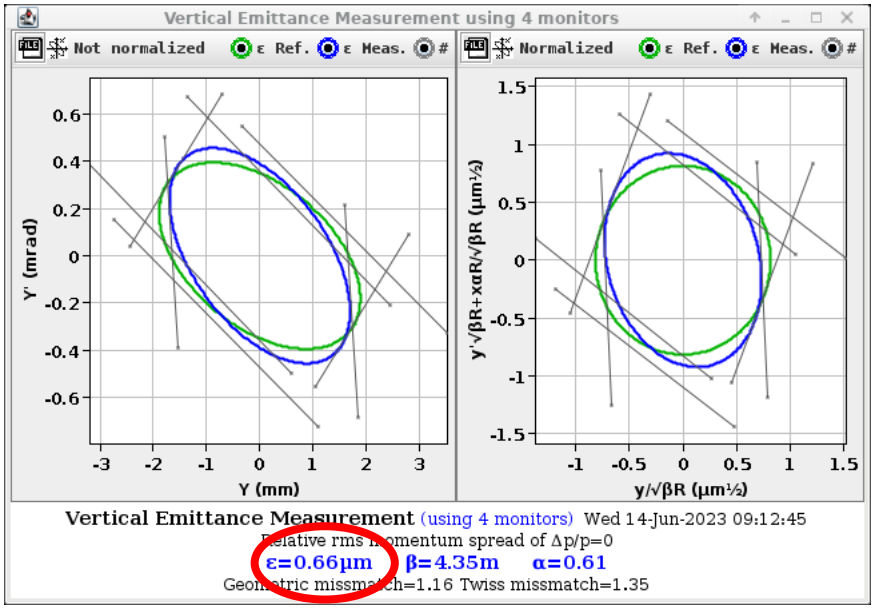
Some Recent (yet preliminary) Results

Is space charge our limiting factor?

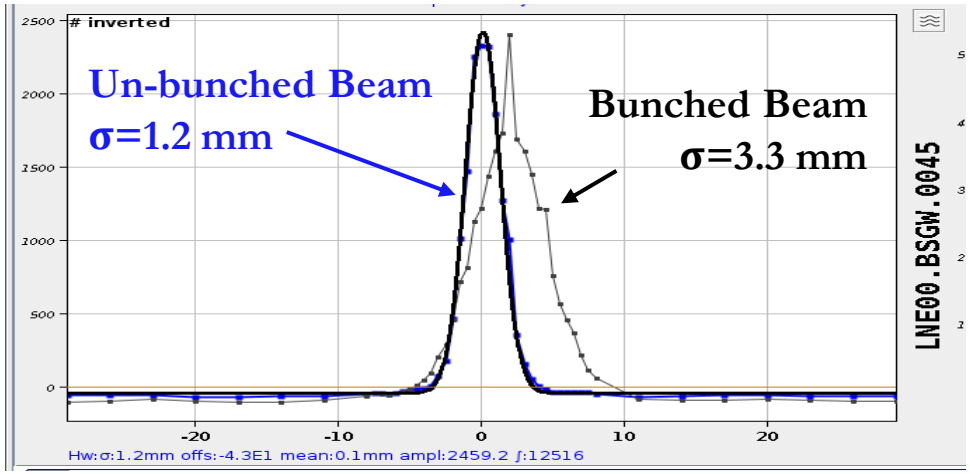




Possible to obtain smaller emittance (at the expenses of higher longitudinal one) playing with **length of bunched beam cooling** before extraction in **ELENA**



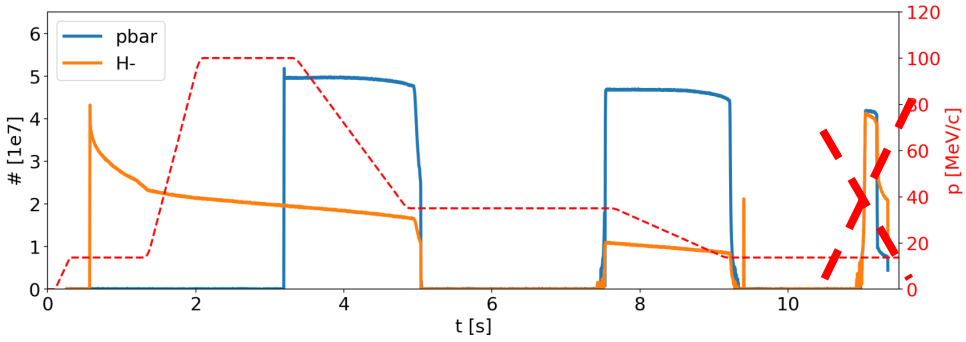
Or even smaller emittances if **extracting the beam un-bunched!**



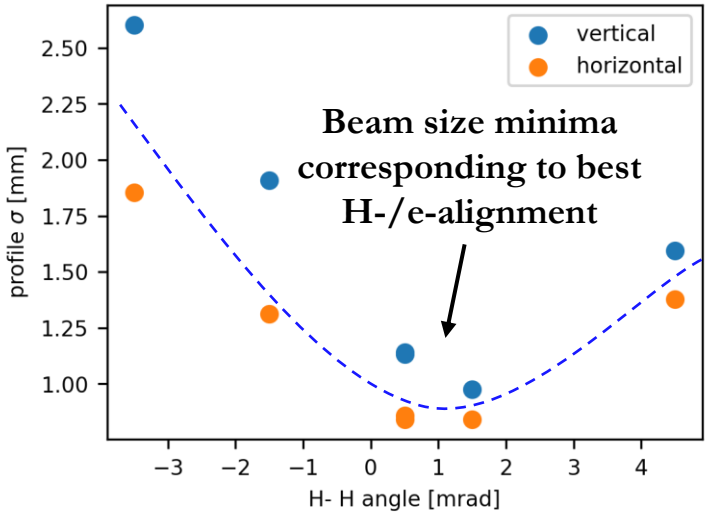
New 100 keV e-cooling Optimisation Procedure

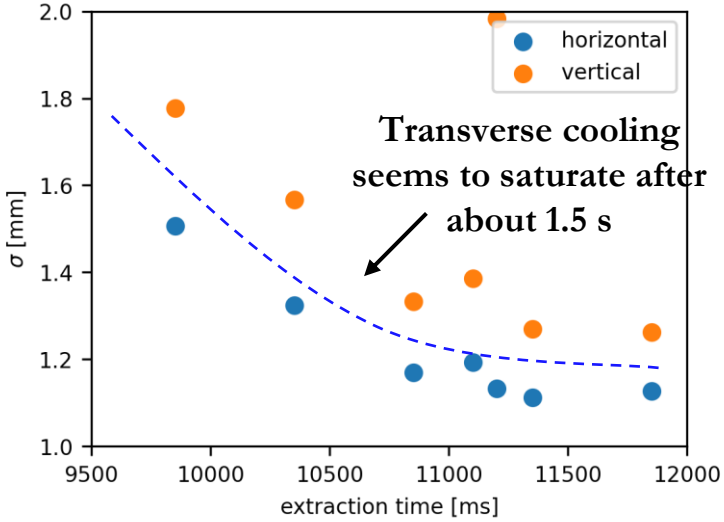
Bunching masks most of e-cooling performance, hence, relying on **beam profile measurement** of extracted beam in a **single SEM:**

1. **Remove RF** before extraction
   - **focus on e-cooler performance** and not on re-bunching/space charge dynamics
   - But… we are **blind on intensity measurement**…



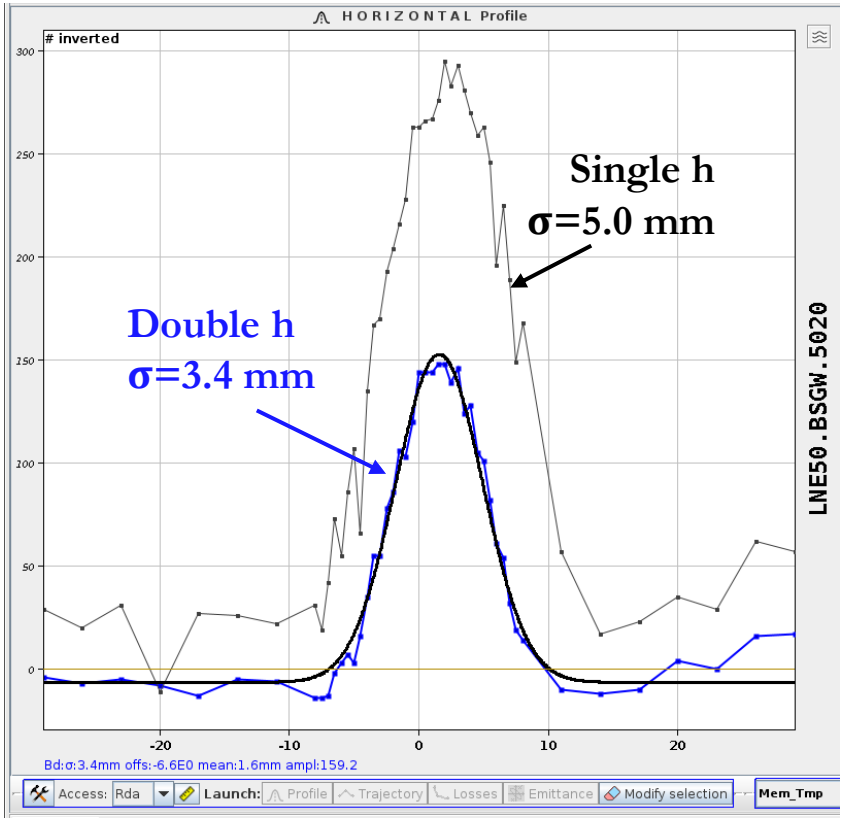
2. **Vary H- (pbar) angle in e-cooler** and minimise observed beam size
3. **Extract the beam at different times** to see when cooling "stops" begin effective

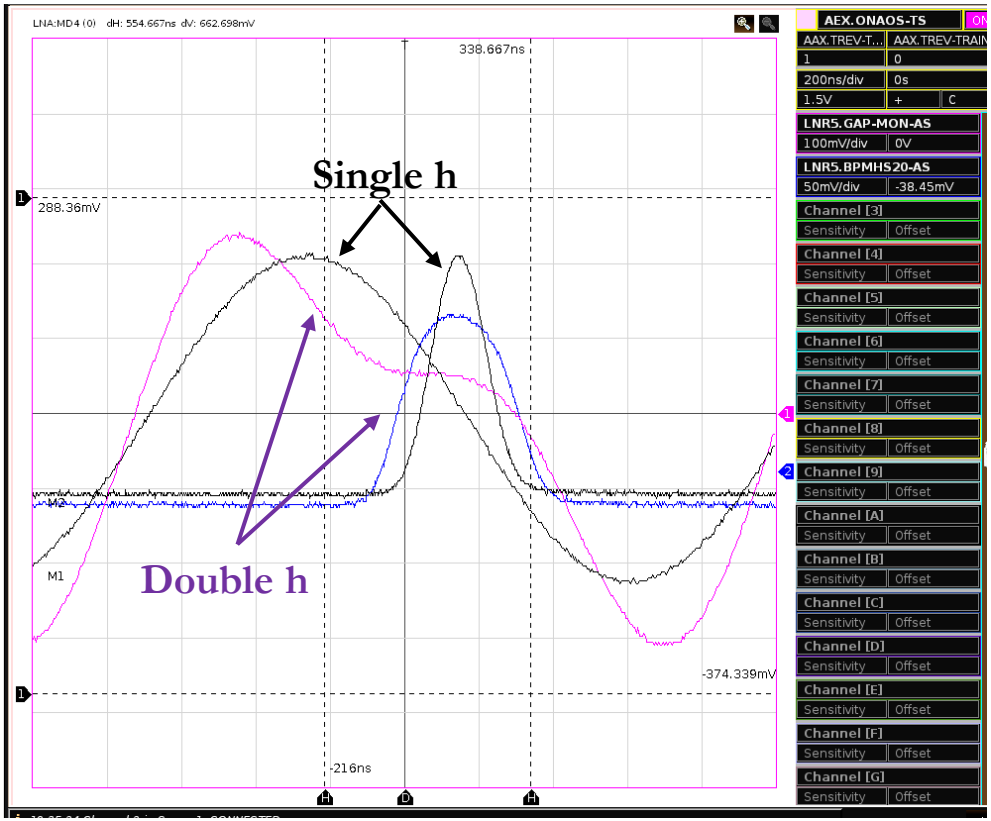




Using double h RF for SC minimisation?

- Profiting of **flexibility of ELENA RF system** with **double harmonic**
  - Possible to reduce beam size (hence emittance), but **not-acceptable bunch length** (300 ns FWHM) for experiments using drift tubes to stop the beam



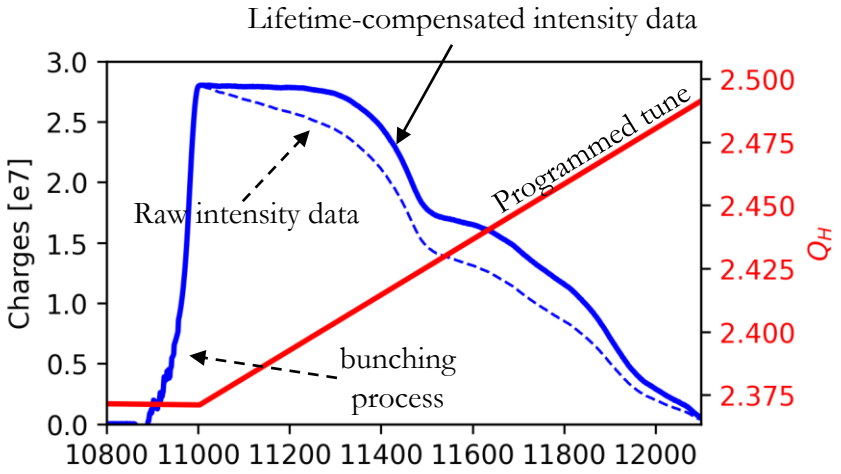


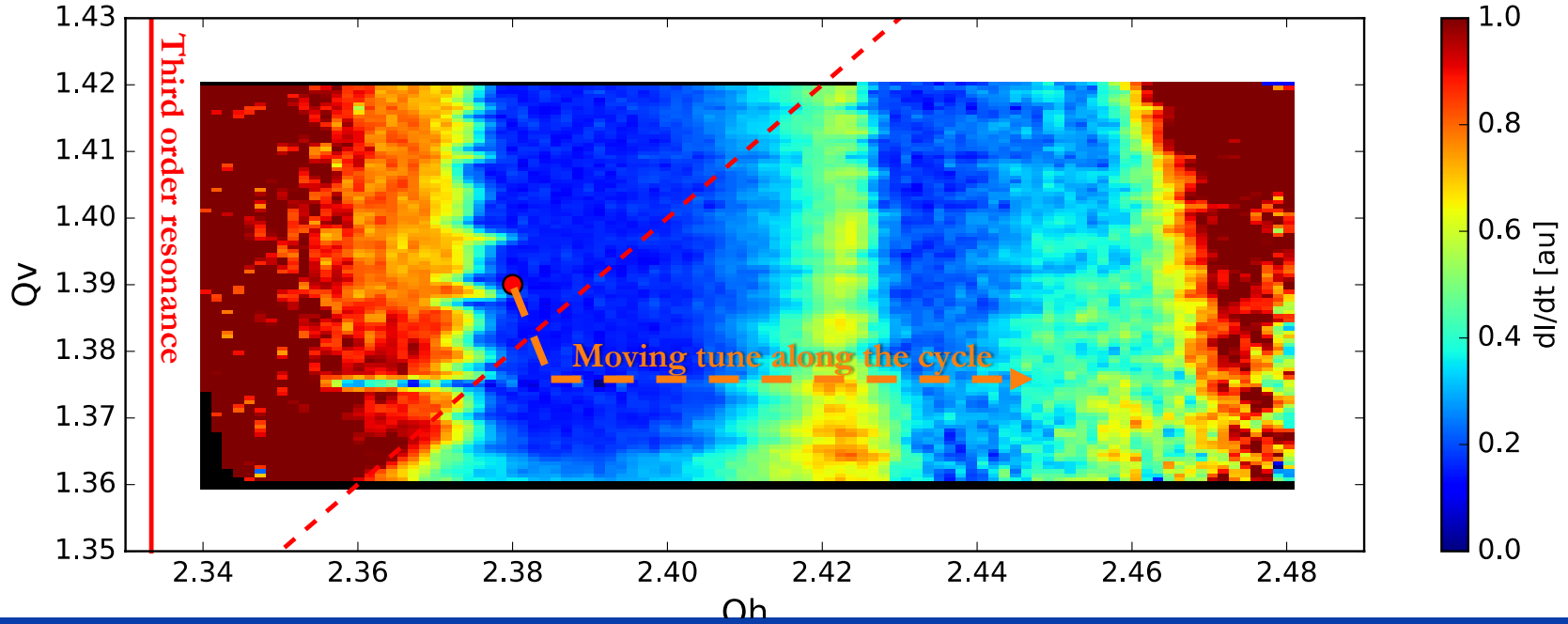
Exploring nearby Working Point

Idea of looking at **loss rate** as a function of working point variation

- **Inpractical with pbar** (too few cycles!)
- Using H-, but **require lifetime compensation**
  - One should be careful interpreting the data, as **space-charge tune shift varies with time**!

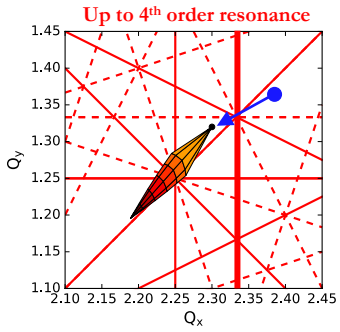
We are operating in a narrow region!

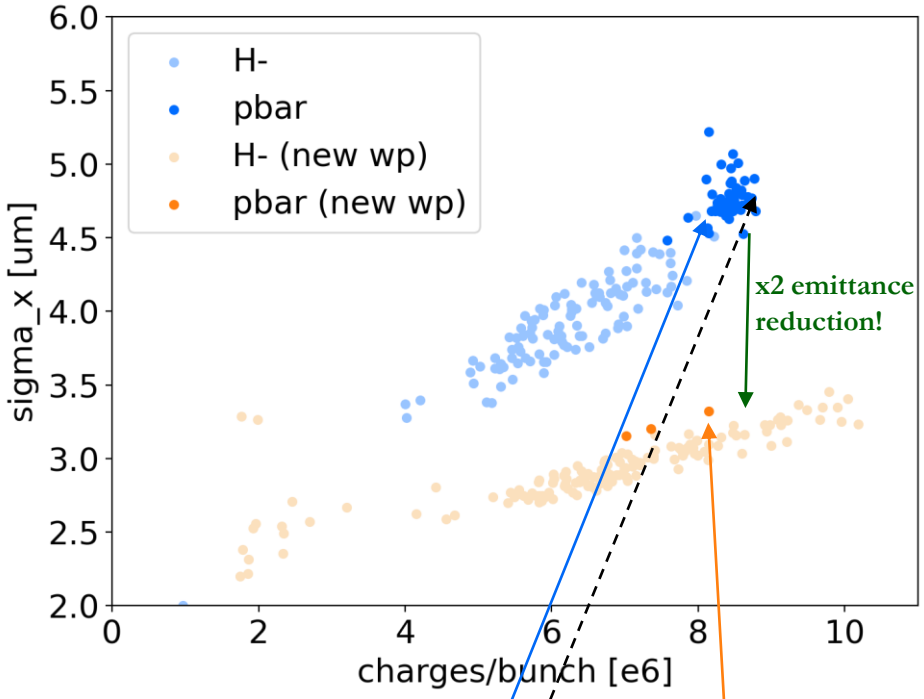


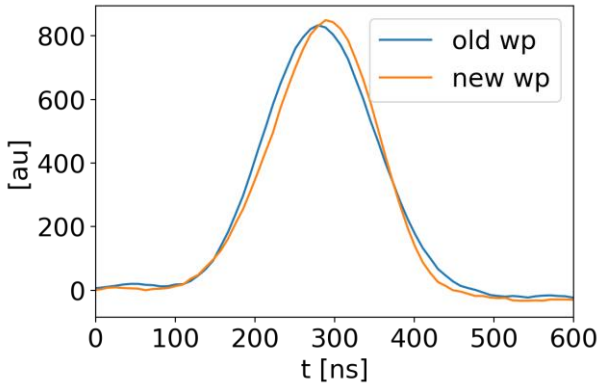


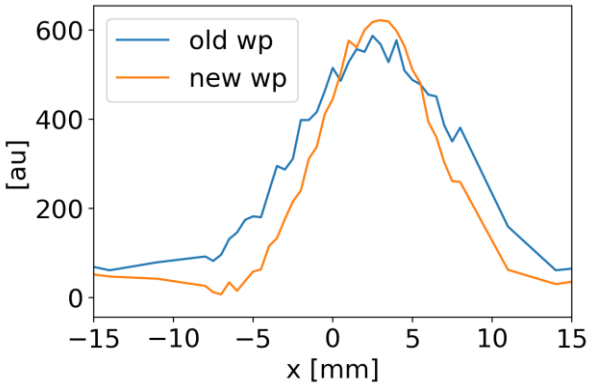
Exploring a New Working Point

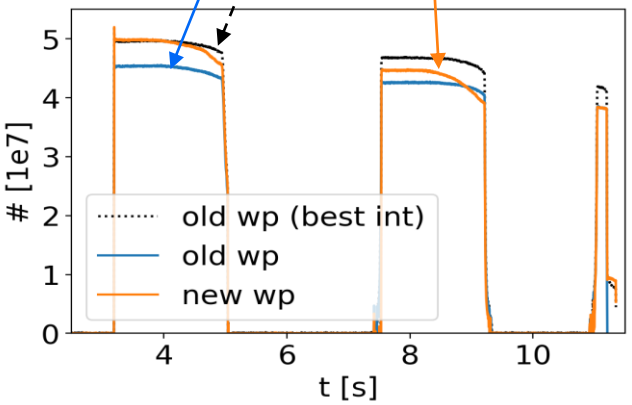
- **Moving below third order resonance** requires to change whole ELENA cycle…
- **Tested first with H-**
  - Advantage of **injecting beam already on new working point at 100 keV**
  - **Clear reduction of beam size observed** for **equivalent bunch length**
- **Promising preliminary results confirmed with pbar (but losses along the cycle)**











Outlook and Conclusions

- **ELENA and its e-cooler are performing within expectations**
  - **Delivered beam intensities x2 higher than design!**
  - **Procedures and tools** for e-cooling setup and optimisation are **in place**
    - Regularly applied for **correcting drifts** and **recovery from incidents**
  - **Space-charge** might be **defining beam parameters at extraction**
    - **Short bunch length typically requested/favoured by experiment**
    - Investigations on **different working point show promising results**
- **Ongoing activities:**
  - Improving understanding of **beam instrumentation** (scrapers, Schottky,…)
  - Improving **ring optics** understanding/control
  - Implementing **complete simulation** of e-cooling process including **Space Charge** and **Intra Beam Scattering** effects
    - Aim at **measuring+simulating** impact of **magnetic field quality** and **cooling force** on e-cooling performance

Thanks to all the AD/ELENA team and for your attention !

Appendix

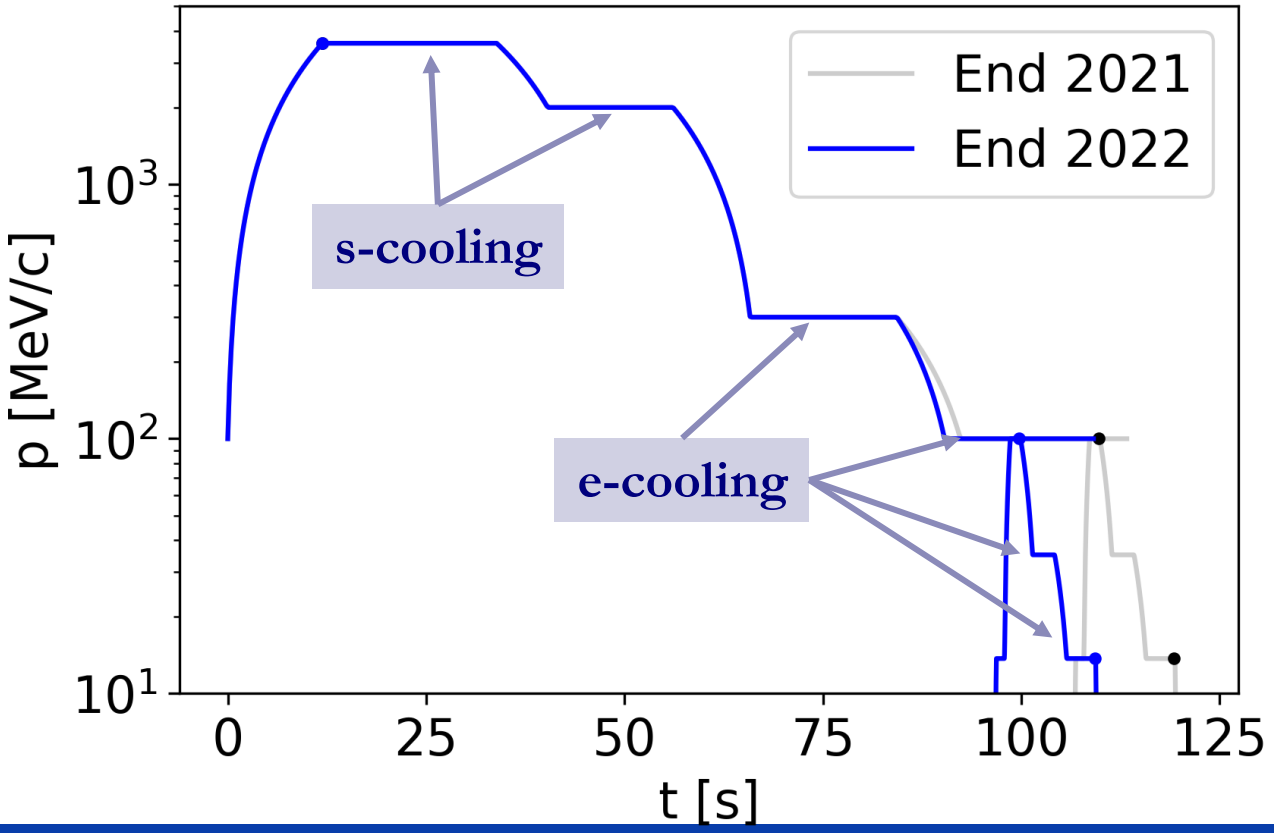
User wishes

Based on recent survey sent to all AD/ELENA users

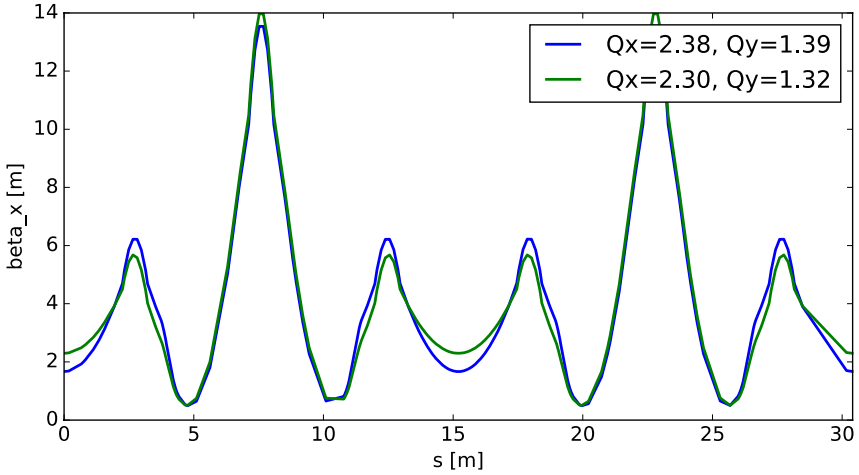
- **Repetition time** and **stability**:
  - **~110s** (mainly driven by BASE: shorter cycles can be a problem for them!)
  - Ideally requiring **back-to-back cycles** (optimum for stability and intensity flux).
    - If not (as today) we should **aim for 5% rep-rate stabilty**
- **Delivered bunch properties**:
  - **>7.5e6 pbars/bunch** (driven by AEgIS design)
  - **Rms emittance <2um.** No strong desire for lower (but GBAR, short term)
  - **Rms dp/p <1e-3.** No strong desire for lower
  - **Trajectory stability <0.1 mm**
  - **100 ns FHWM bunch length**
    - Today's 150 ns FWHM without bunch rotation sufficient for most experiments, but GBAR.
  - **100 keV fixed extraction energy**
    - But keep open the possibility to explore 50-500 keV (up to 5.3 MeV for ASACUSA1)
- Beam **availability**:
  - Present **yearly schedule (days of pbar physics)** and **injectors availability** typically good enough
    - Both could be improved with **equal importance**
  - **4 bunches extracted from ELENA all the time** seems to statisfy most use cases
    - More **dynamic scenarios don't seem to be interesting**

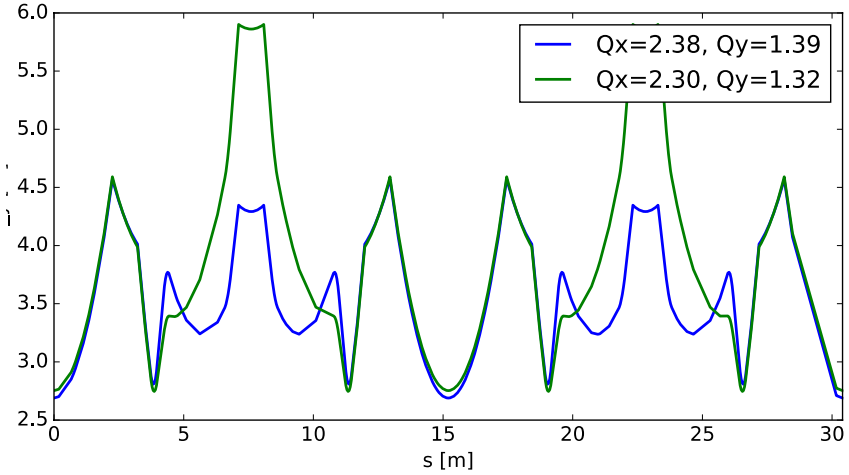
AD/ELENA Cycles

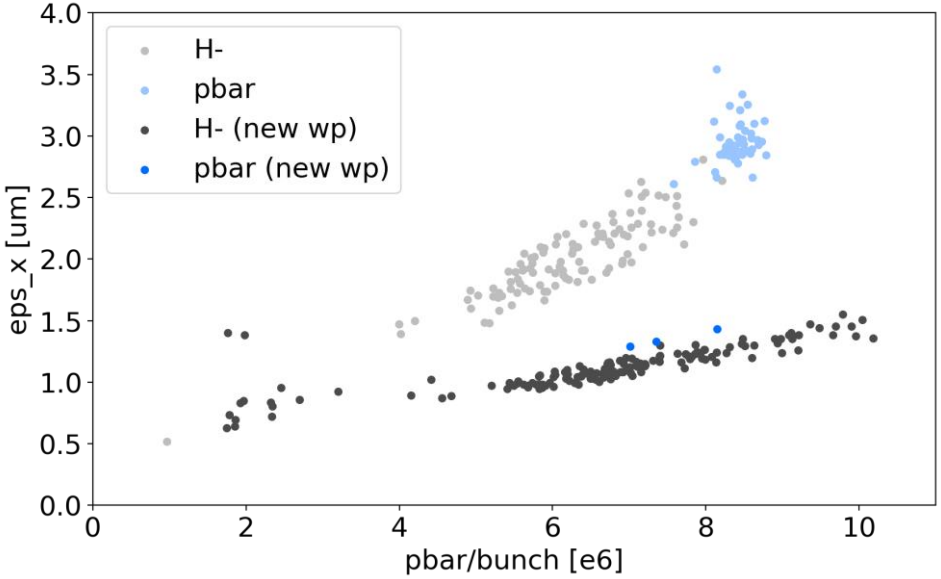
- Cycles basically un-changed since after LS2, but some minor shorthening of AD cycle thanks to better control of e-cooling.
- Total cycle time dominated by AD cycle: about 2 minutes per shot!
  - Very few cycles for machine setup… and studies with pbar
  - Likely, possible to use H- directly injected in ELENA for studies

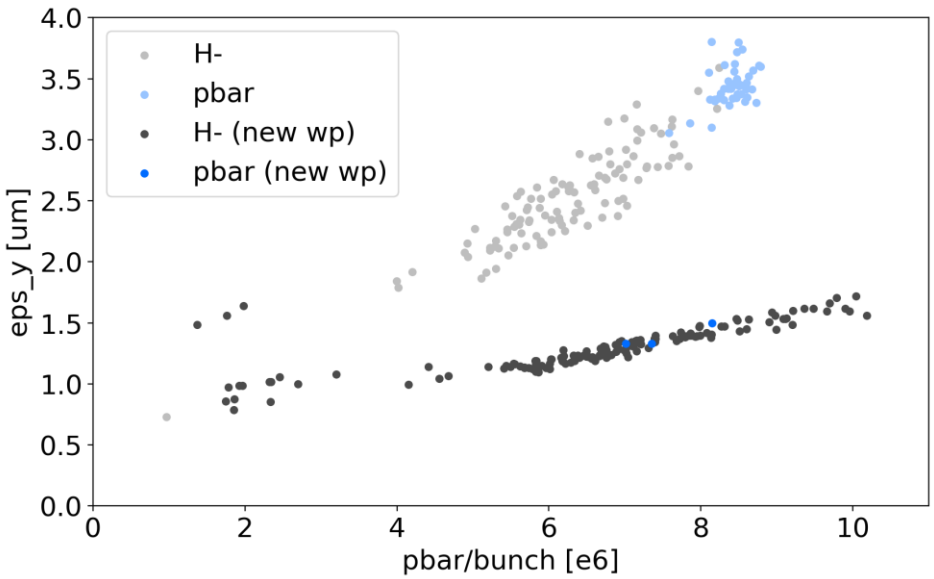


Exploring new working point



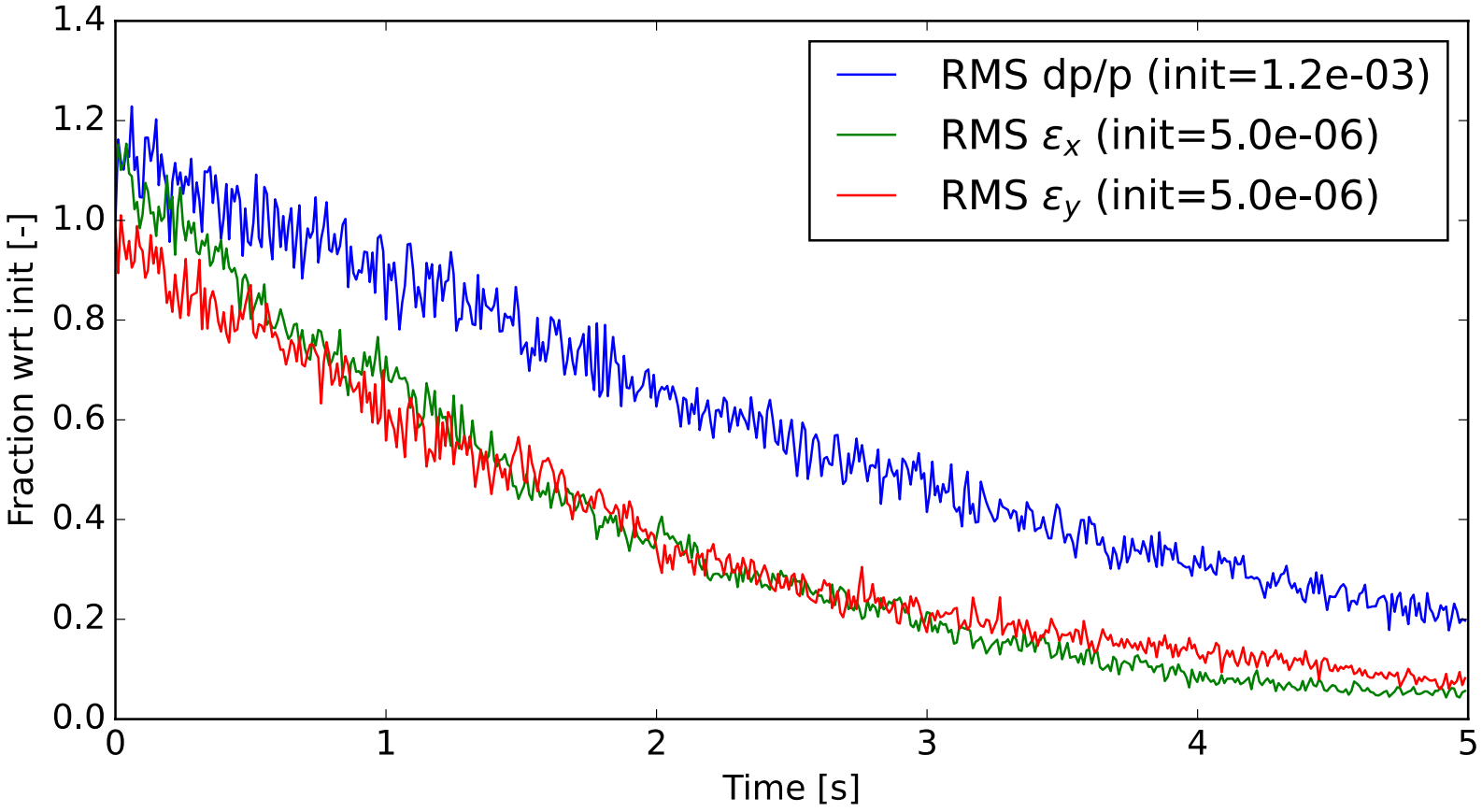






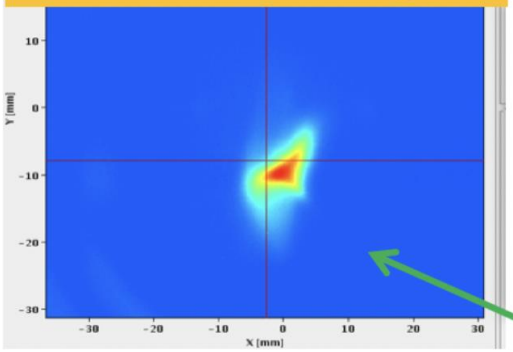
First simulations in Xsuite with space–charge and cooling

- Only few particles tracked
- Frozen model of space charge (assuming bunched beam, 1e7 pbar/bunch)



On ELENA Source (2020)

Beam spot only measurable in the ELENA ring



H⁻ intensity instability visible on several pickup on a long pulse magnetically injected in the ring