AD/ELENA electron cooling experience during and after CERNs Long Shutdown (LS2)

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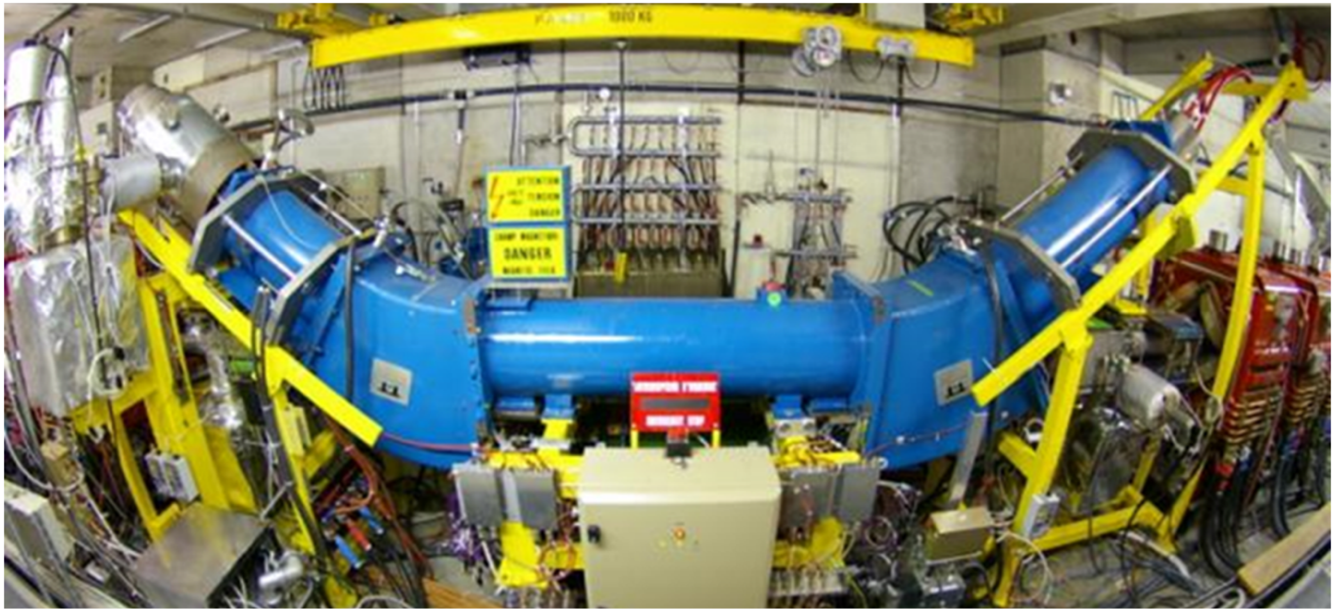

- Introduction
- Status of AD/ELENA cycles after restart in 2021
- Optimization tools and highlight observations of e-cooling
- Work in progress

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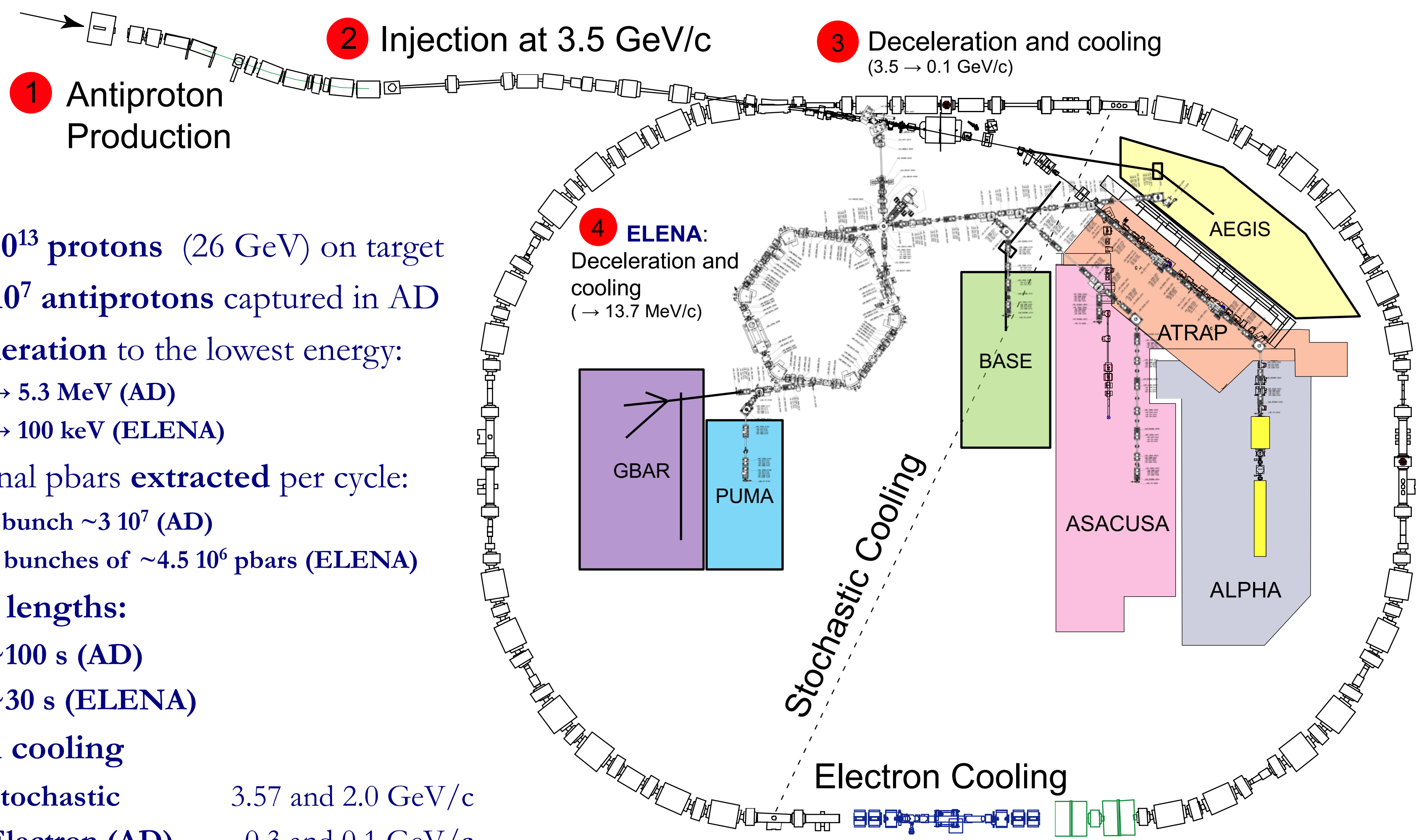
AD/ELENA – introduction

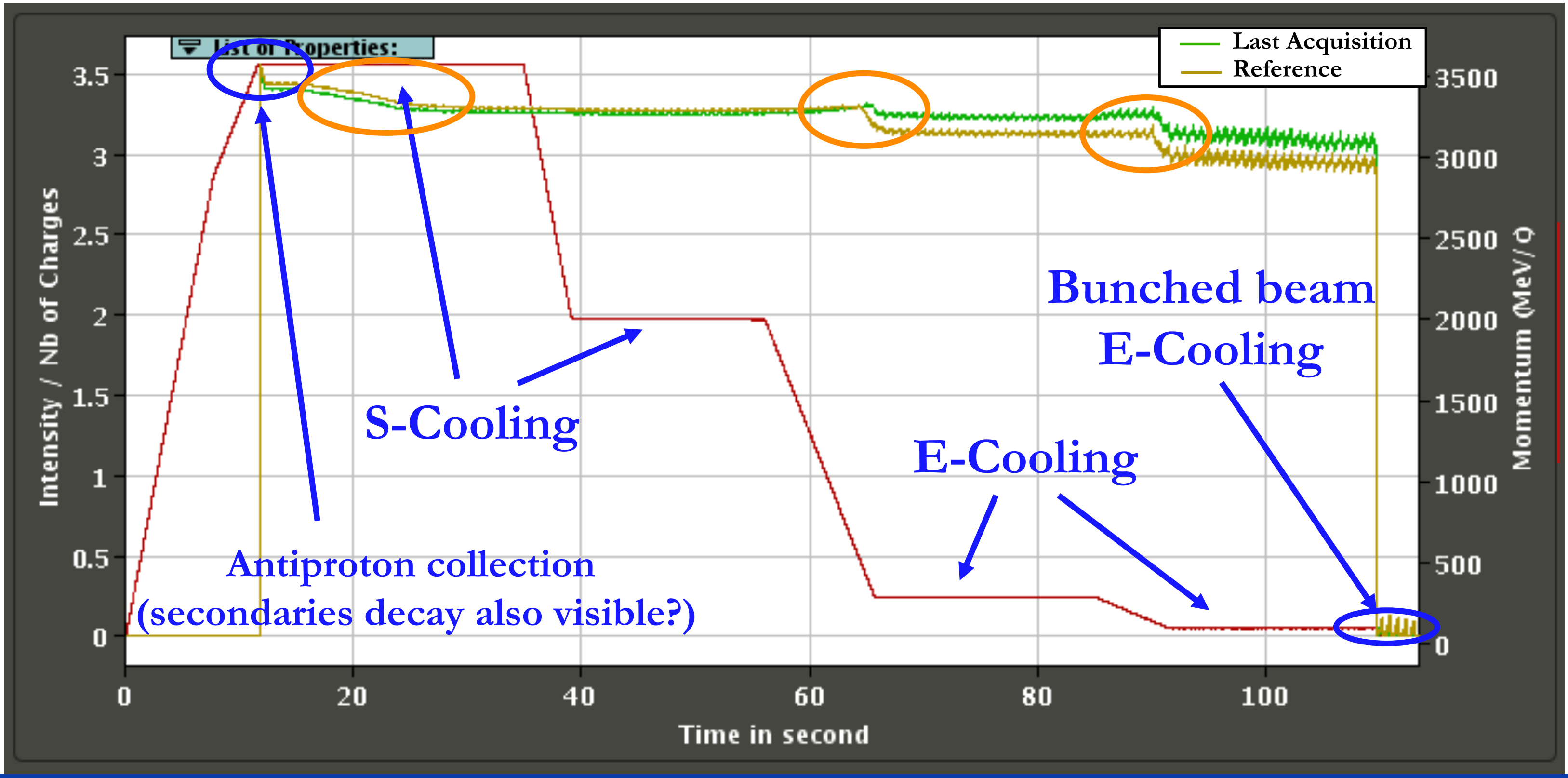
- **~1.5 10^{13} protons** (26 GeV) on target
- **~3.5 10^{7} antiprotons** captured in AD
- **Deceleration** to the lowest energy:
  - **→ 5.3 MeV (AD)**
  - **→ 100 keV (ELENA)**
- Nominal pbars **extracted** per cycle:
  - **1 bunch ~3 10^{7} (AD)**
  - **4 bunches of ~4.5 10^{6} pbars (ELENA)**
- **Cycle lengths:**
  - **~100 s (AD)**
  - **~30 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



Sketch of the AD (**circumference 182 m**)
ELENA (**circumference 30.4 m**)
AD/ELENA experiments

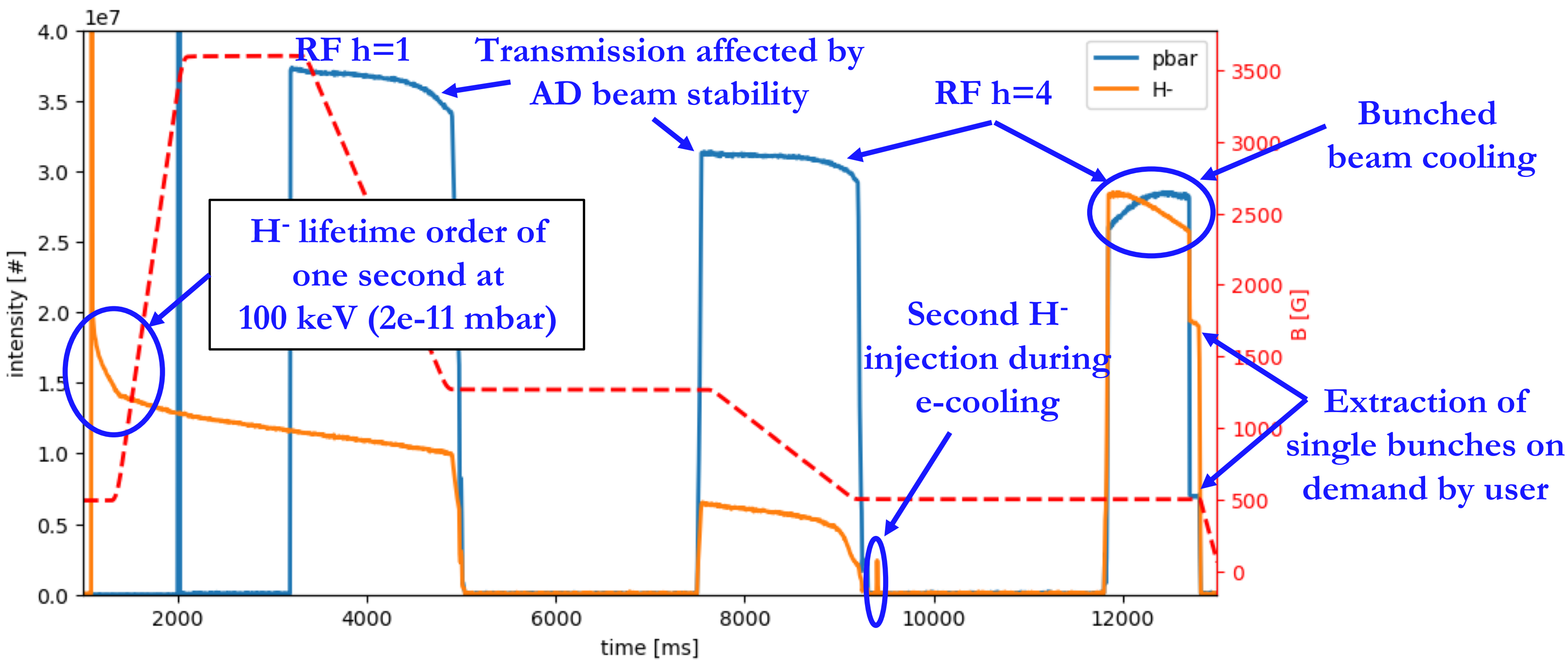
Typical AD cycle in 2021

- **Slightly longer** cycle than in **2018** (but still being optimized)
- Using **h=1** for the **whole cycle** (h=3 for 300 → 100 MeV/c ramp pre-LS2)
- Using **bunched-beam cooling** before extraction (was bunch rotation pre-LS2)
- Most **losses** still **during injection plateau** and on **300 → 100 MeV/c ramp**
  - **2 GeV/c → 300 MeV/c also "touchy"** in terms of transmission stability



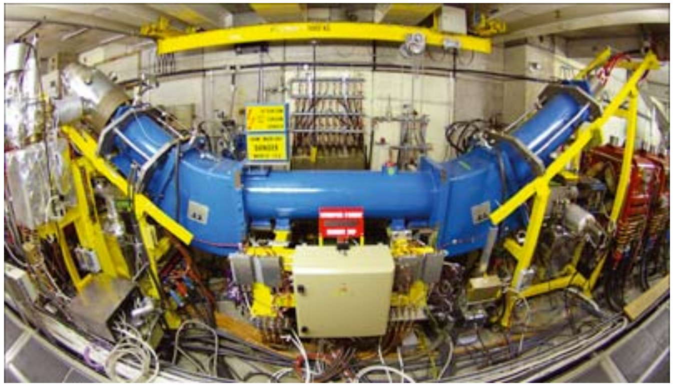
Typical ELENA cycle in 2021

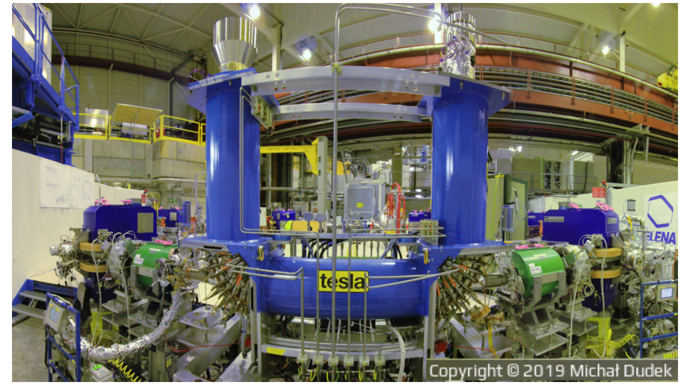
- Beam **intensity estimated by LLRF** system (only when beam is **bunched**)
  - (not very accurate as it does not take into account bunch length)
- Running with two (magnetically-equal) ~**15 second-long** cycles:
  - **pbar** (repetition rate limited by AD to about **one shot every 2 minutes**)
  - **H$^-$** with beam generated by **local source** at **100 keV** kinetic energy
    - **2nd injection** during 100 keV e-cooling to better mimic pbar-intensities at extraction



How we got there (focus on e-cooling)
- tools used -

AD/ELENA E-Coolers

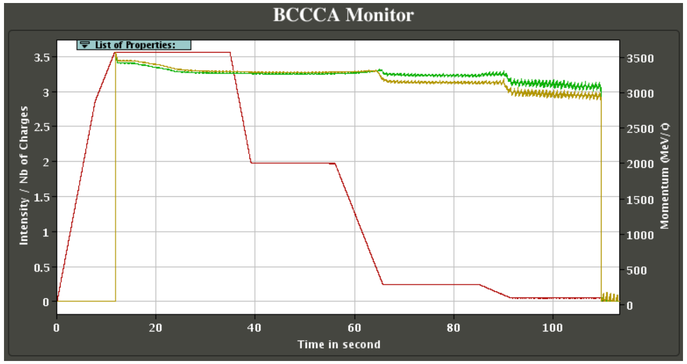




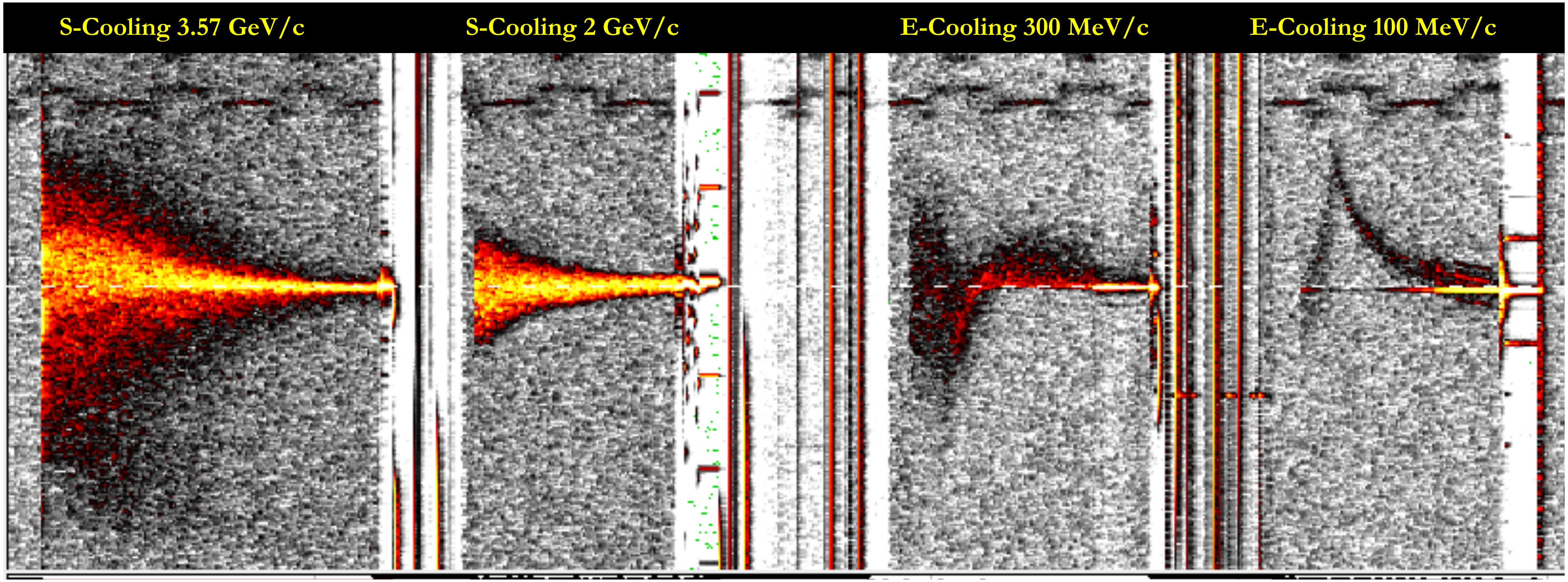
	AD		ELENA	
(Main) Ion particle	pbar	pbar	Pbar/H^-	pbar/H^-
Ion momentum	300 MeV/c	100 MeV/c	35 MeV/c	13.7 MeV/c
Electron kinetic energy	25.5 keV (<35 keV)	2.9 keV	355 eV	55 eV
Relativistic beta	0.305	0.106	0.037	0.015
Electron current	2.5 A	100 mA	5 mA	1 mA
Cooling length	1.5 m		1 m	
Ring length	182.43 m		30.41 m	
Gun magnetic field	590 G		Up to 1 kG	
Drift magnet field	590 G		100 G	
Electron beam radius (drift)	25 mm		8 to 25 mm	

Main AD instrumentation: BCCC and Schottky

- **Beam Cryogenic Current comparator (CCC)**
  - **beam intensity all along the cycle (also un-bunched)**
    - **Extremely useful was to have "live" acquisition of "losses"**
  - only a few days downtime in 2021

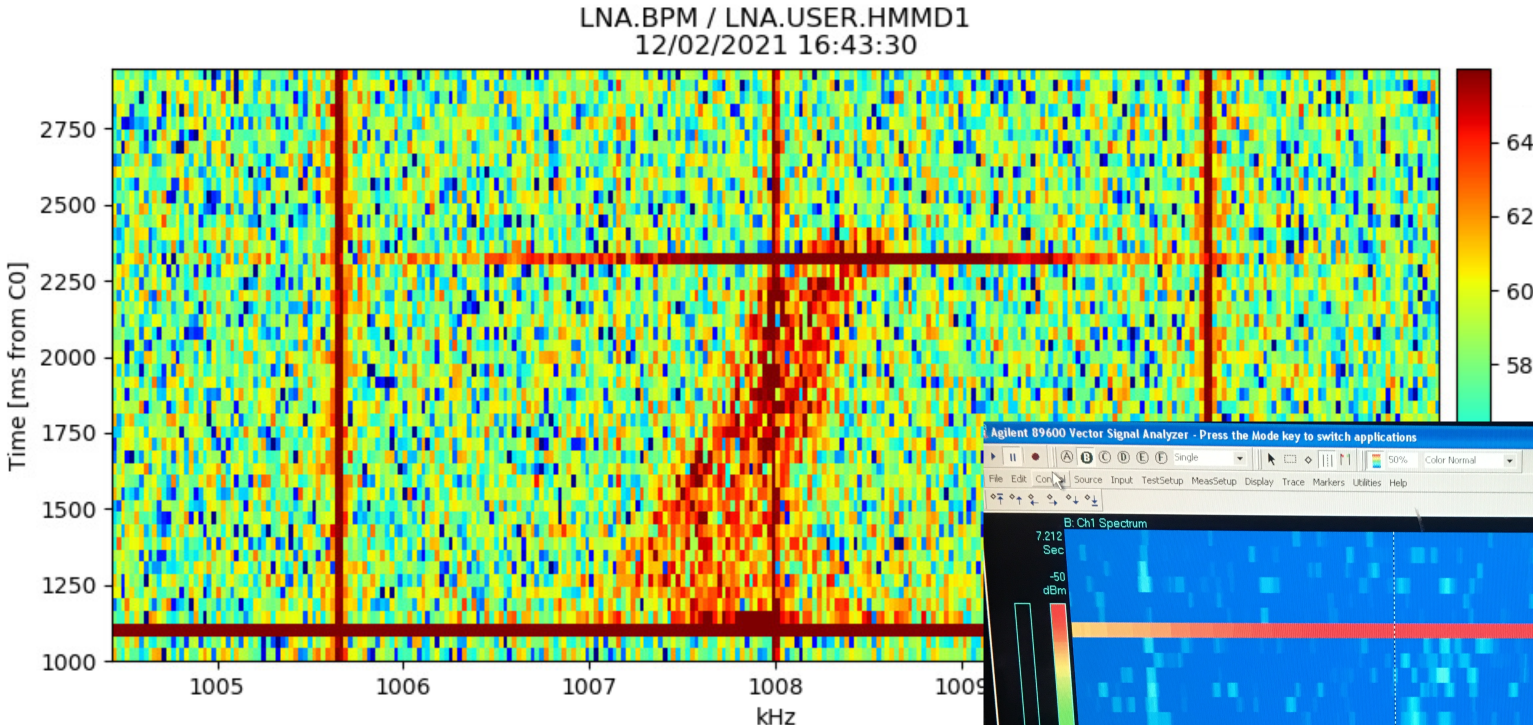


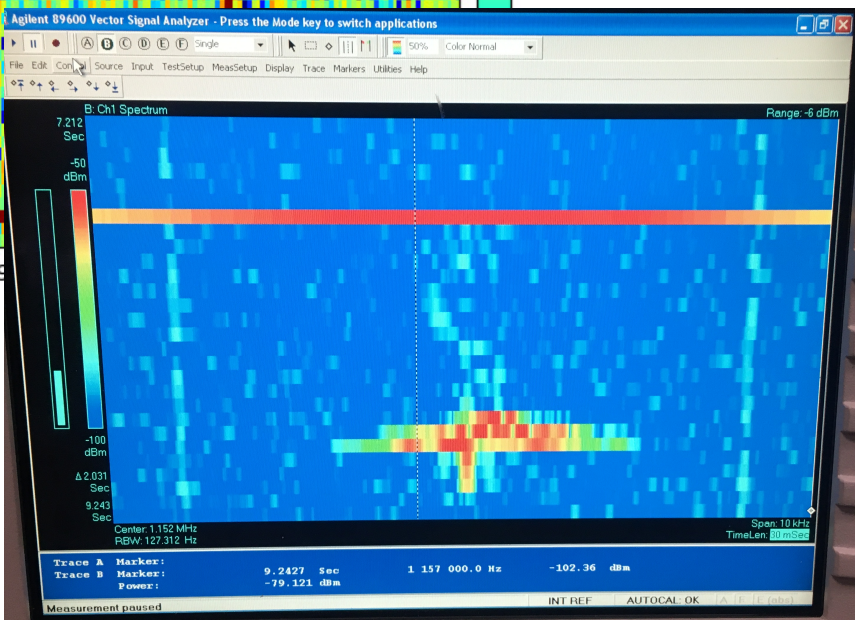
- **Schottky**
  - Downmixed to around 50 kHz on all cooling plateaus
  - gives a **real time information on cooling efficiency**



Schottky in ELENA

- Schottky signal (with cooling) by **combining several BPMs**
  - See O. Marqversen and S. Jensen at IBIC2021 – WEPP04



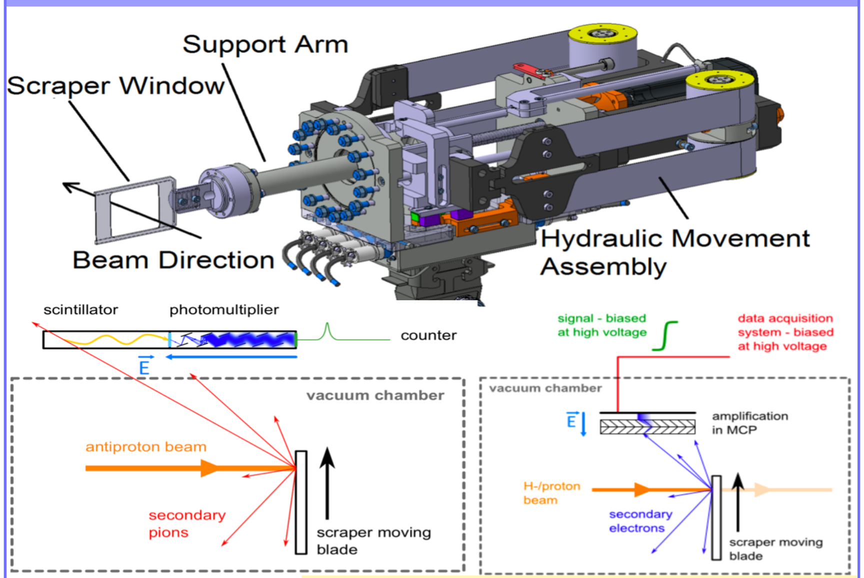


To be compared with the little signal seen using standard spectrum analyzer with a single BPM sum signal

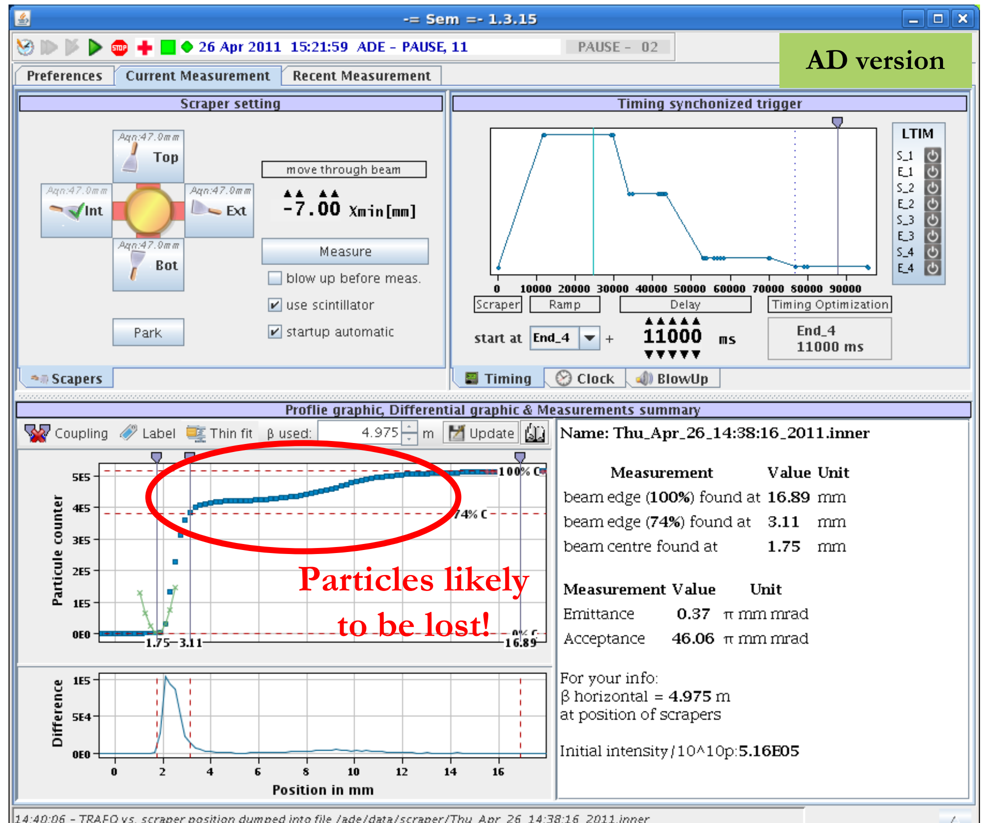
Transverse emittance measurements

- **Only actually 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**! (AD cycle ~120 seconds)

ELENA version

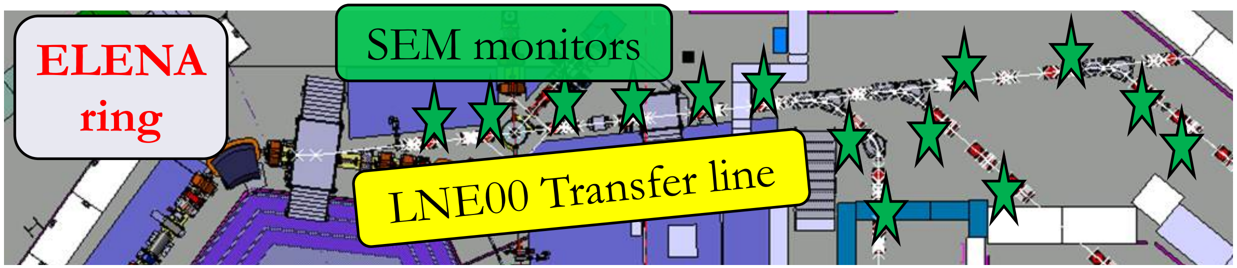


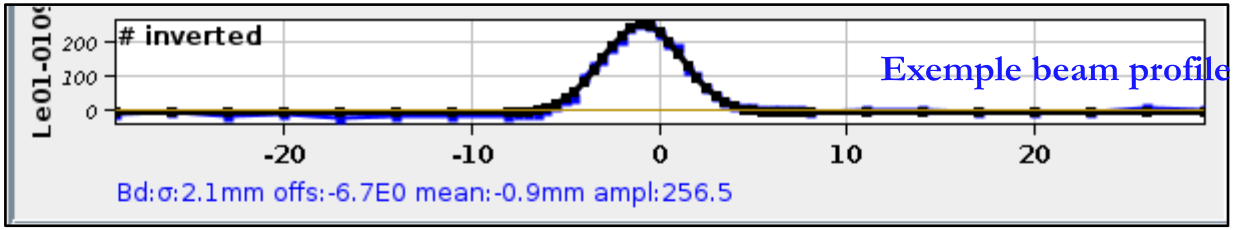
Courtesy P. Grandemange (link)

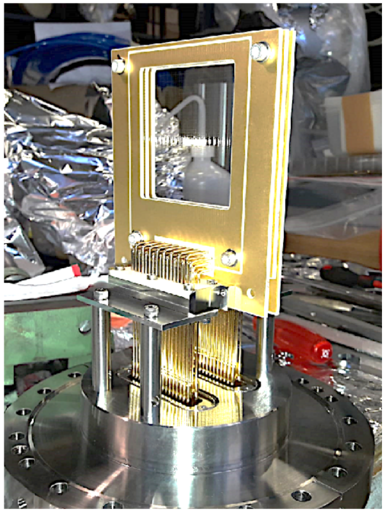


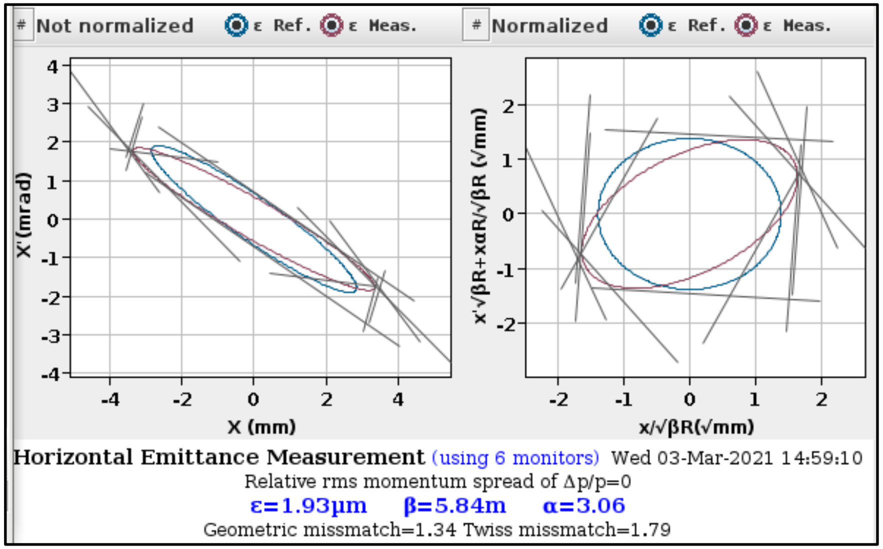
Single shot optics measurement

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





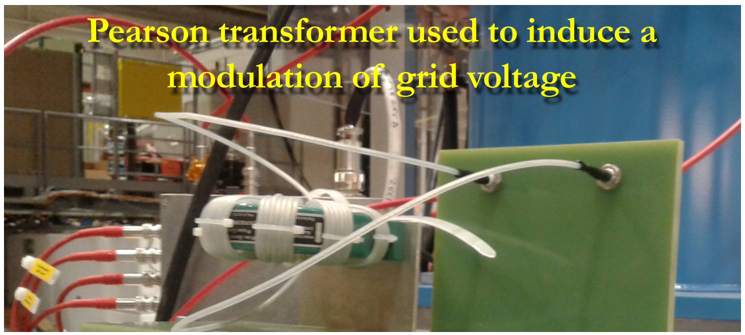


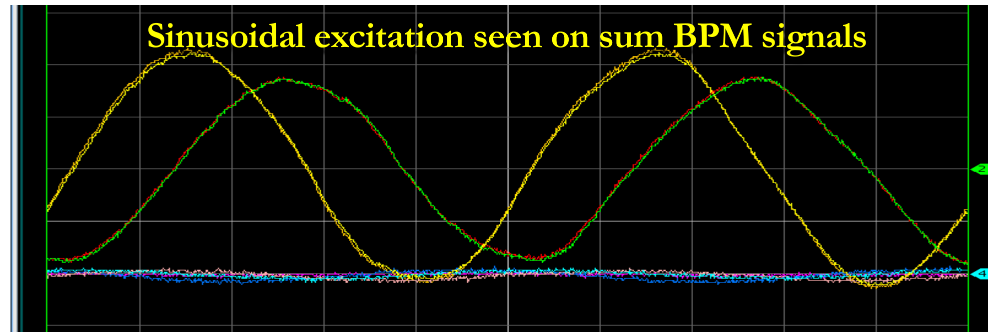


- SEM are **semi-interceptive** device (about 10% beam loss per SEM)
- By **combining the information of several SEM** one can perform a multi-screen **beam Twiss parameter** measurement in a **single beam shot**

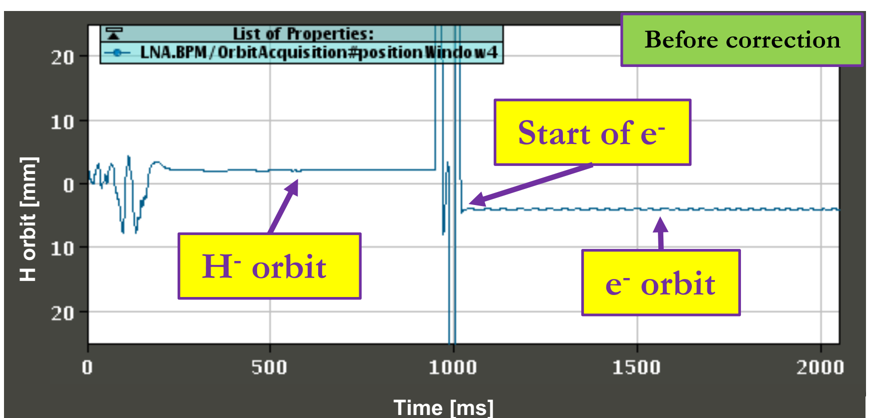
pbar/e$^-$ orbit matching

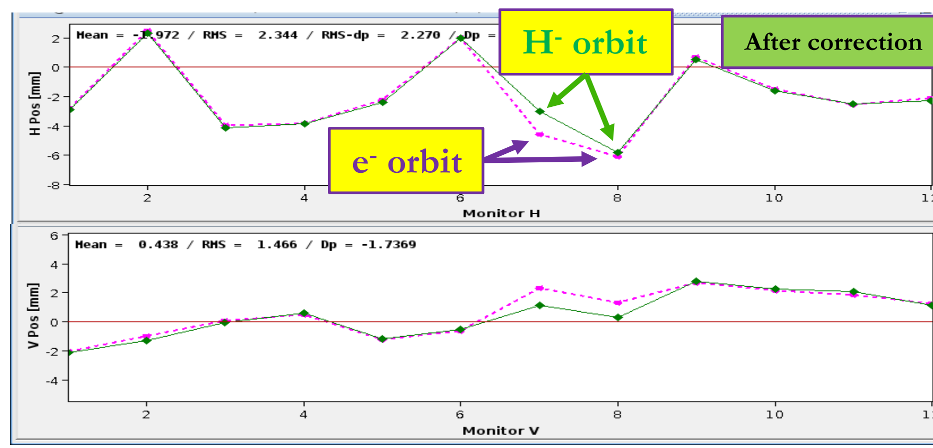
- All **CERN cooler** have **two BPMs** in the **cooling drift solenoid** that “see” both ions and e$^-$ beams.
  - **One needs to induce an e$^-$ beam intensity modulation** in order to see a signal with those BPMs
  - **Tests performed** in ELENA in **2019**, and this **system** put **in operation** on all CERN e-coolers **during LS2**





- **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)





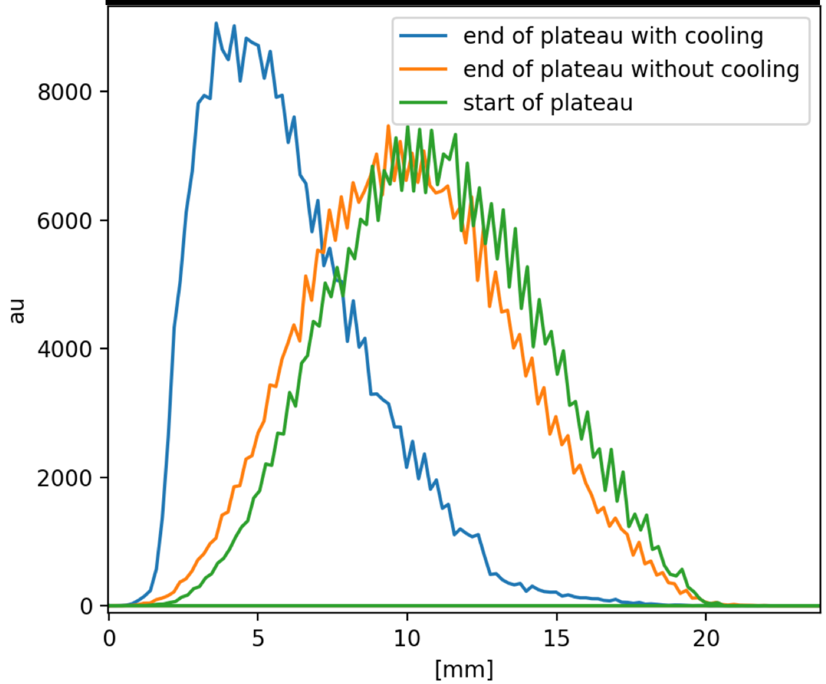
Special thanks to A. Frassier and B. Galante

How we got there (focus on e-cooling)
- observations highlight -

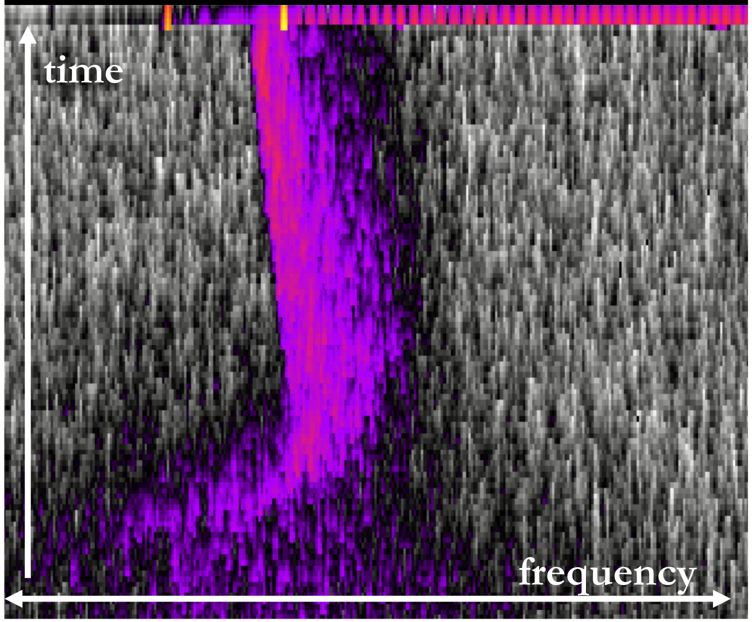
Example: setup of e-cooling at 300 MeV/c

1. Using **e-/pbar orbit** reading to **match offset/angle** (within a few mm)
2. Watch **Schottky** for **adjusting electron energy**
3. Using **scraper** measurements while **scanning pbar angle** in the **e-cooler**
   - **Some doubts** on the **scraper accuracy** and/or **interpretation** of the data
   - **Note:** scraper data give "**half beam profile**" assuming no Dispersion at cooler.

Horizontal scraper measurements



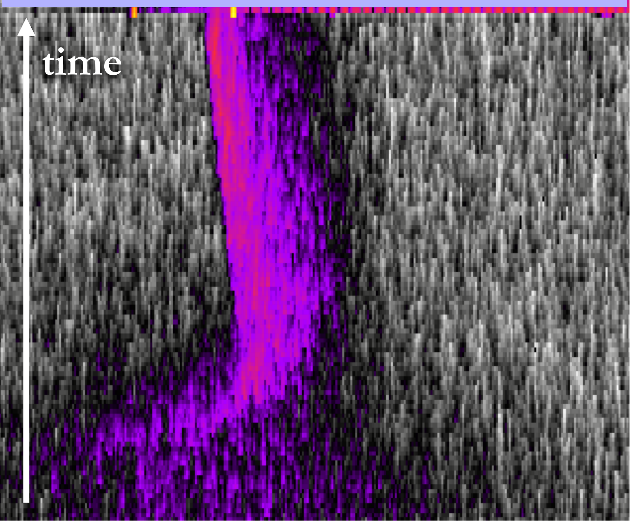
Longitudinal Schottky measurement



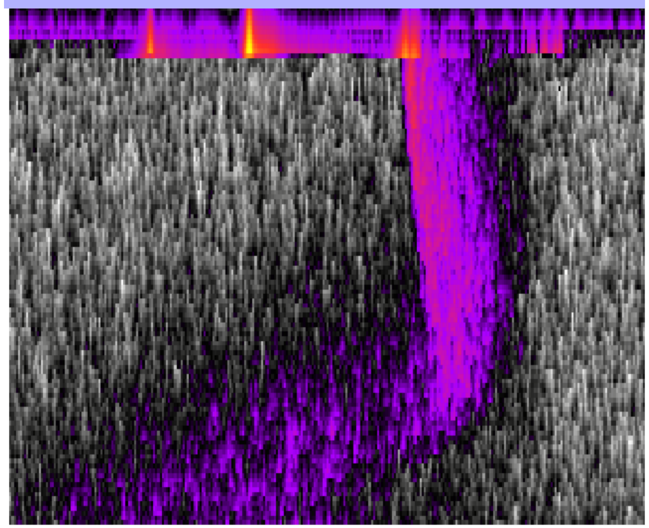
Note: longitudinal beam profile

- Initial observation of "**sharp low-energy edge**" in Schottky profile **cured** with **pbar orbit offset** in the **e-cooler**.

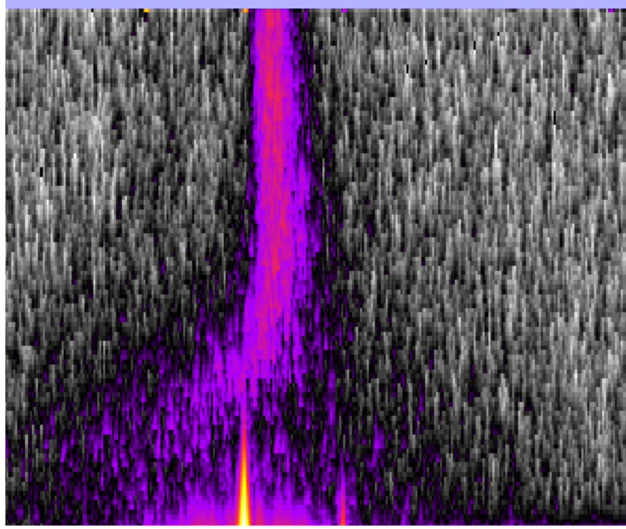
After orbit alignment

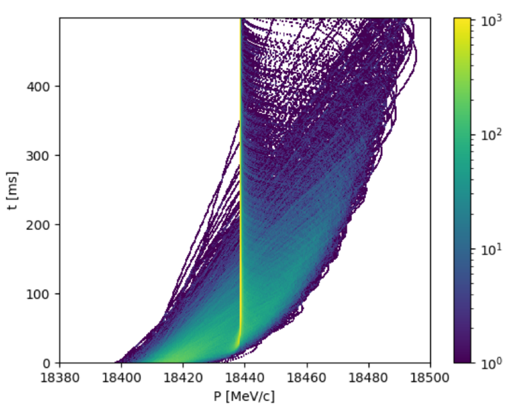


+ e^- energy shift



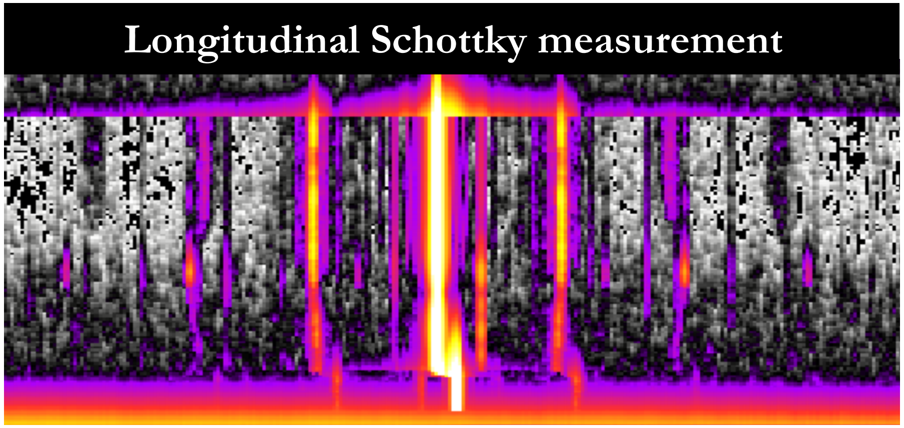
+ pbar orbit offset

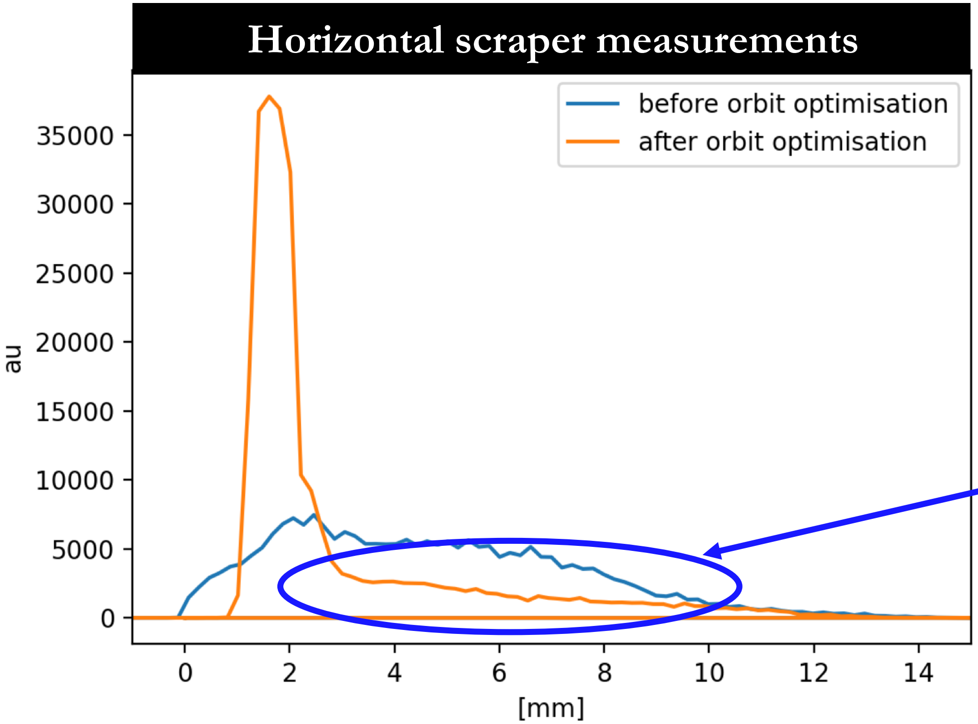




- Simulations shows that this could be due to **e^- space-charge effects** (see also **poster P1005 on Friday**)
- **Presently, running with sharp edge visible** in the Schottky, i.e. with **pbar beam centered in e^- beam**
  - It **seems** like it give **better** stability, but **difficult to judge**

Bunched beam cooling at 100 MeV/c

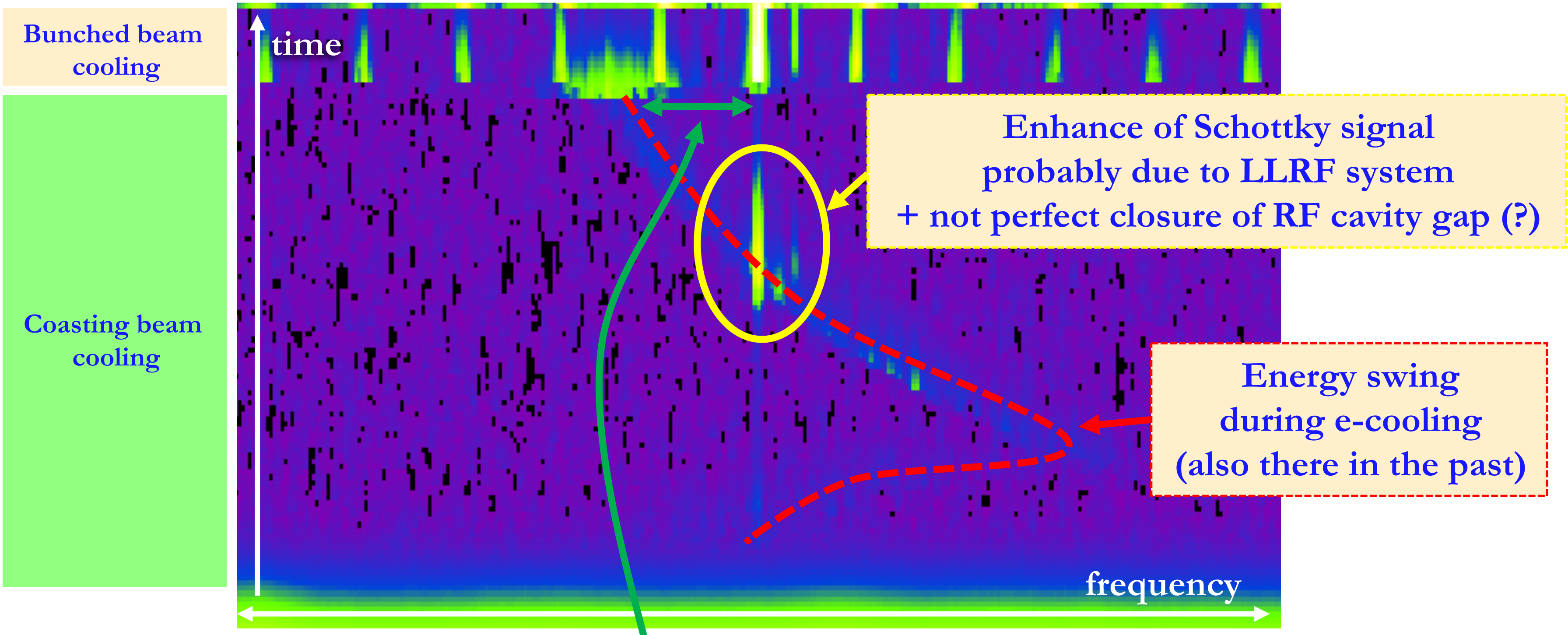




- **Initially found beneficial** to keep the beam bunched on **100 MeV/c plateau** and therefore implement **bunched beam cooling**
  - Main **drawbacks: Schottky is blinded** by bunch structure, i.e. difficult to spot drift of e^- energy
- Optimization of **transverse cooling** mainly **watching profiles in AD-ELENA transfer lines** and **confirmed** by **scraper measurements**
  - **Long tails visible** in scraper measurement, but not evident elsewhere: **are they real**?

Coasting + bunched beam cooling at 100 MeV/c

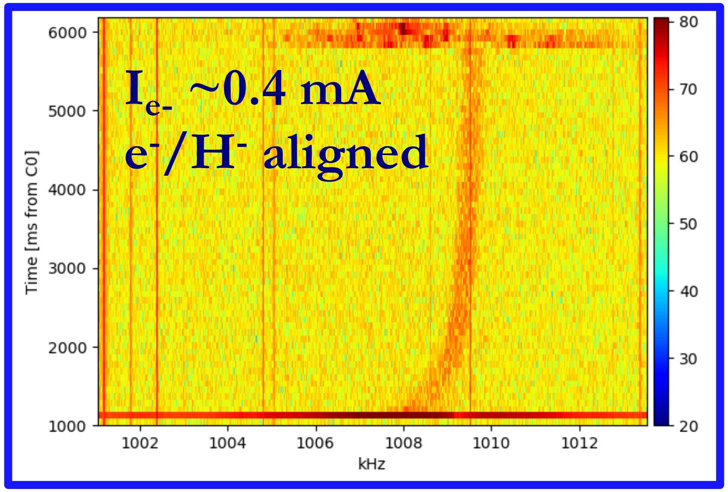
- Moved back to **coasting beam** during physics run while **keepking about 2 s-long bunched beam cooling** to **improve ELENA injection efficiency**

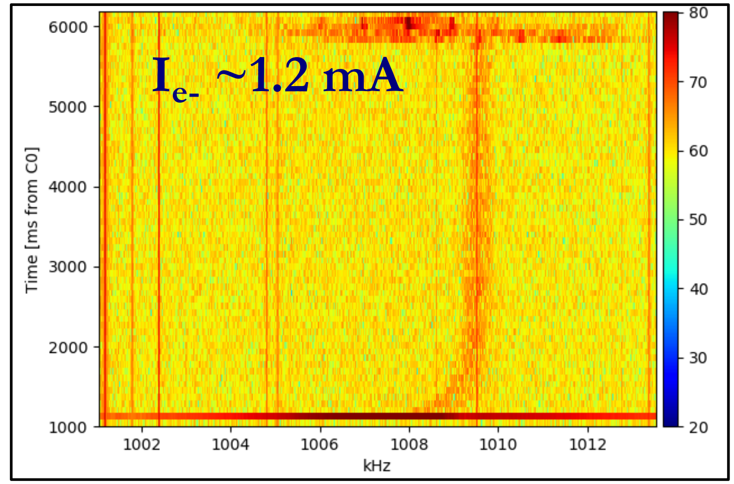


- **Observed** sudden/slow **e$^-$ energy drifts** up to 0.5%, only(?) at **100 MeV/c**
  - Linked to **vacuum activity ($10^{-11} \rightarrow 10^{-9}$)** generated by nearby bunch rotation cavities and/or stochastic cooling cryogenic pickups

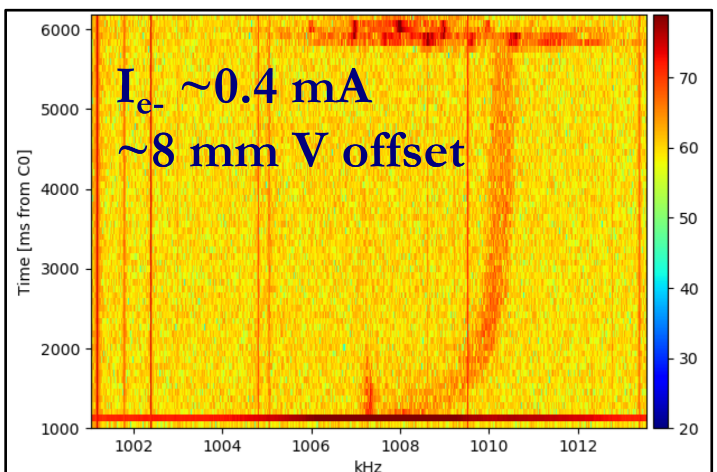
ELENA: H^- e-cooling at 13.7 MeV/c

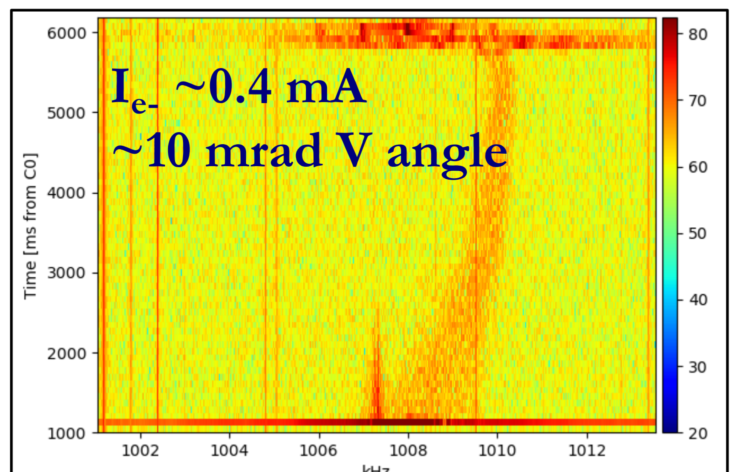
- Easy to see **effect** of **e^- current** on longitudinal **cooling speed**





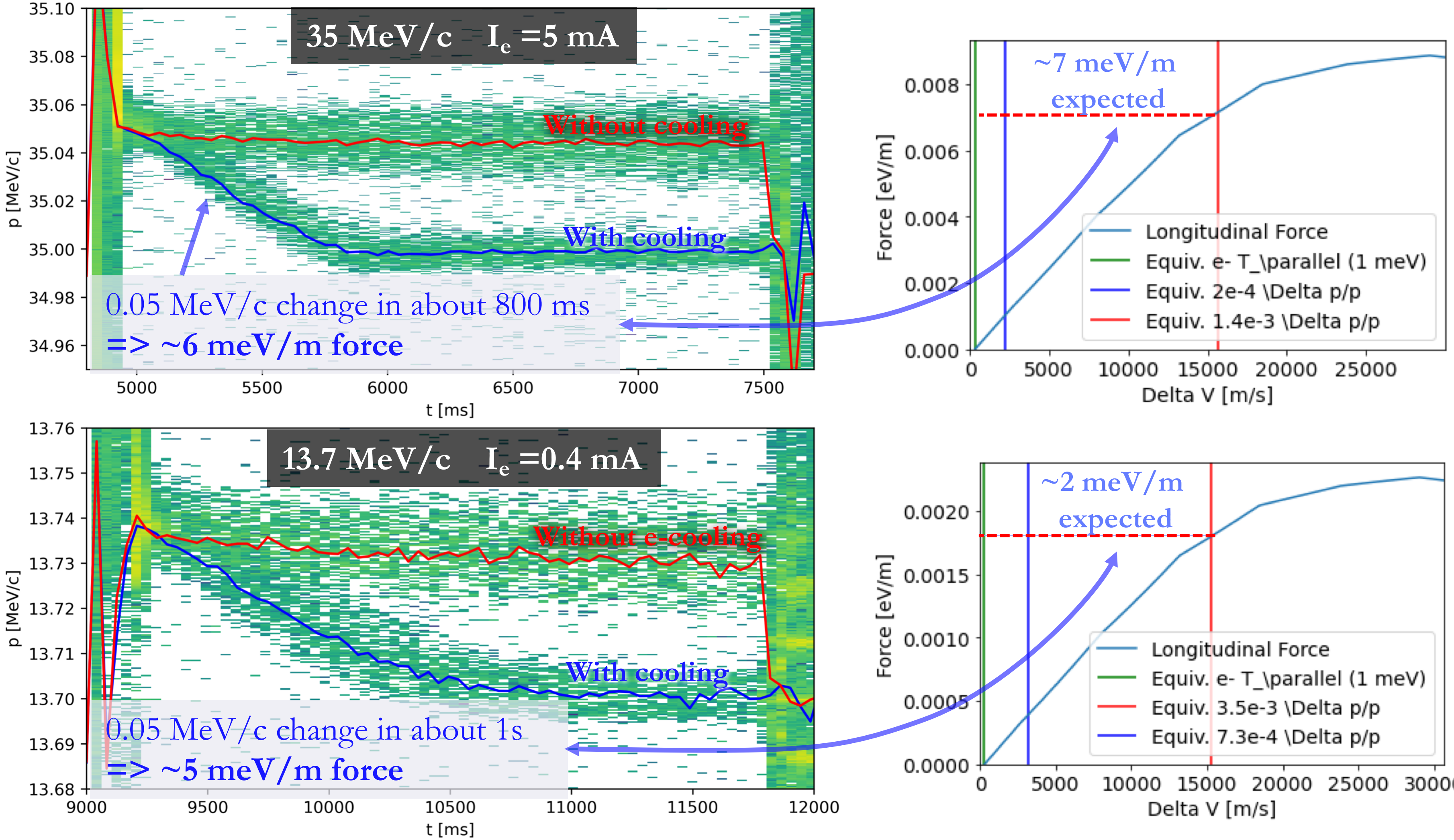
- Effect of **H^-/e^- orbit alignment**





Cooling of pbars at 35 and 13.7 MeV/c

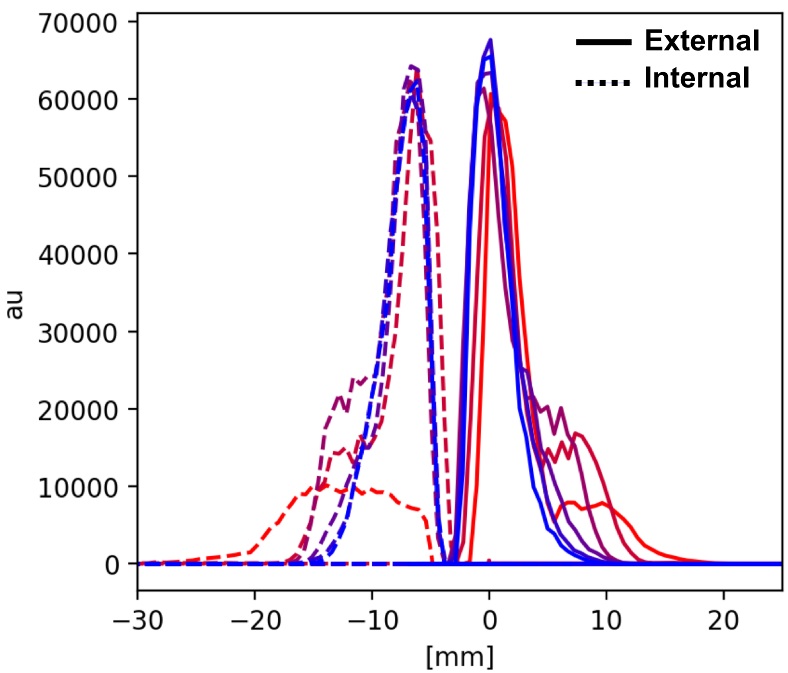
- Preliminary check of **longitudinal cooling force** with respect to expectations
  - (using **RF-Track – see poster P1005 by A. Borucka on Friday**)



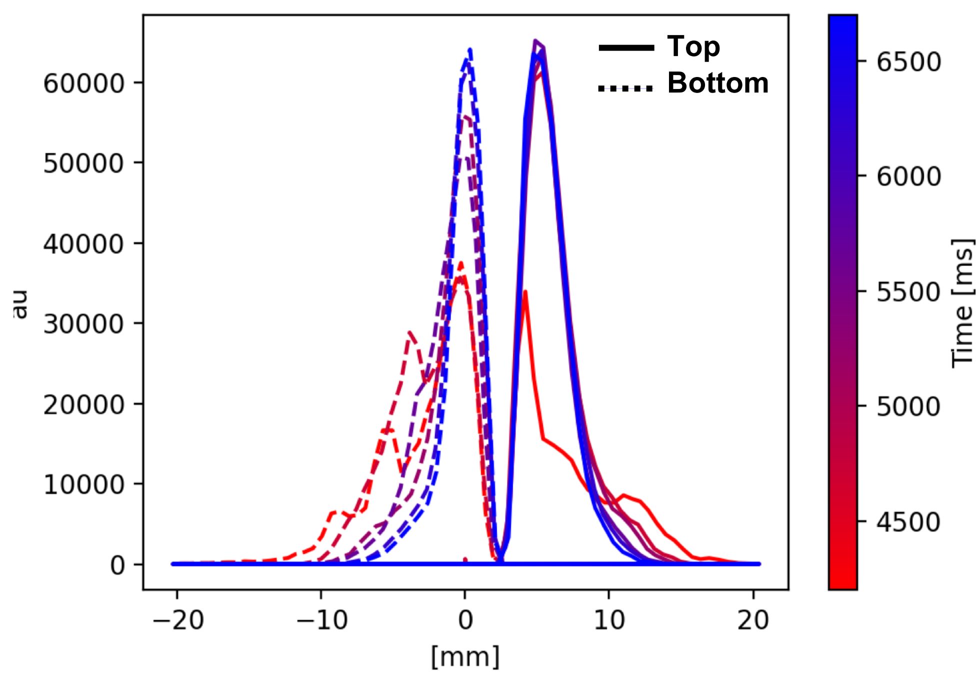
Transverse cooling at 35 MeV/c

- **Scraper** of **pbars** at different times **during cooling plateau**
  - **Transverse cooling visible** in both planes
  - **Quickly** getting into **equilibrium** (after about 1 second)
  - **Accuracy** of the measurement **still to be investigated**
    - **Acquisition/interpretation** with **H⁻ even more difficult**

Horizontal scraper measurements

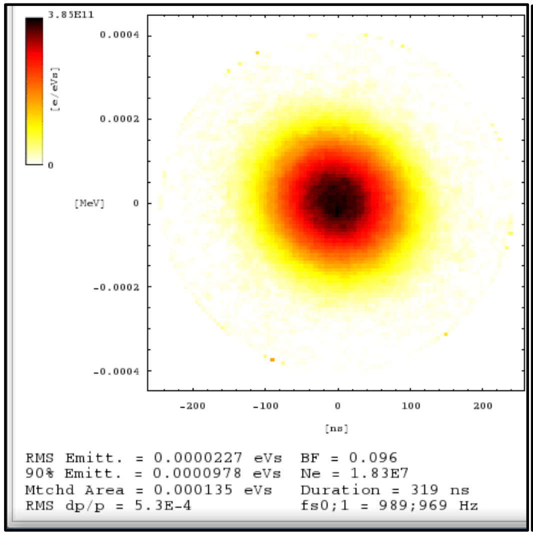


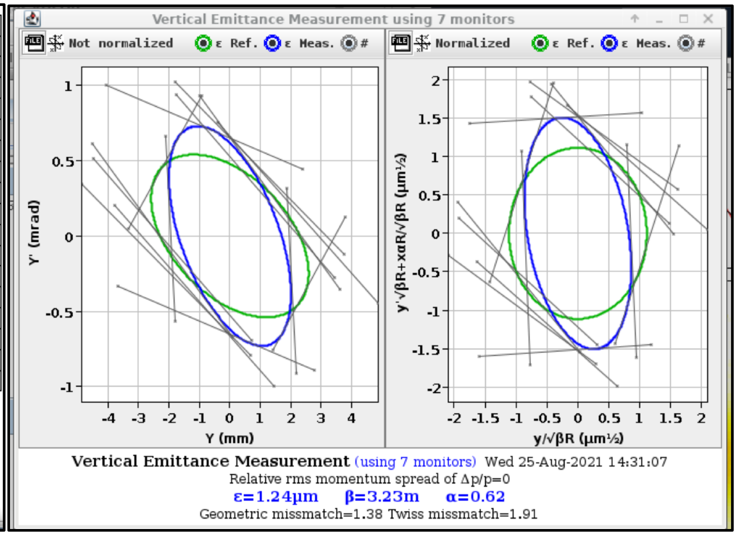
Vertical scraper measurements



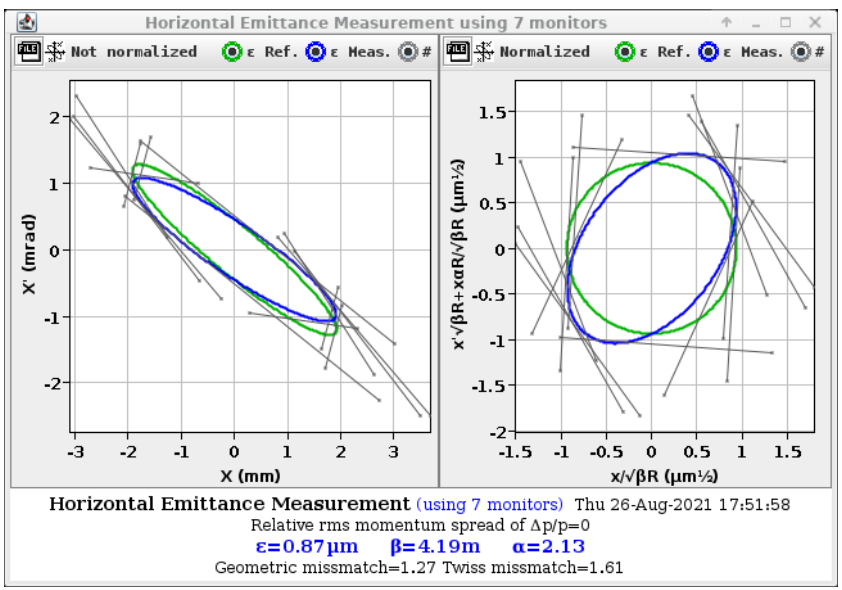
What we are working on

User beam optimisations





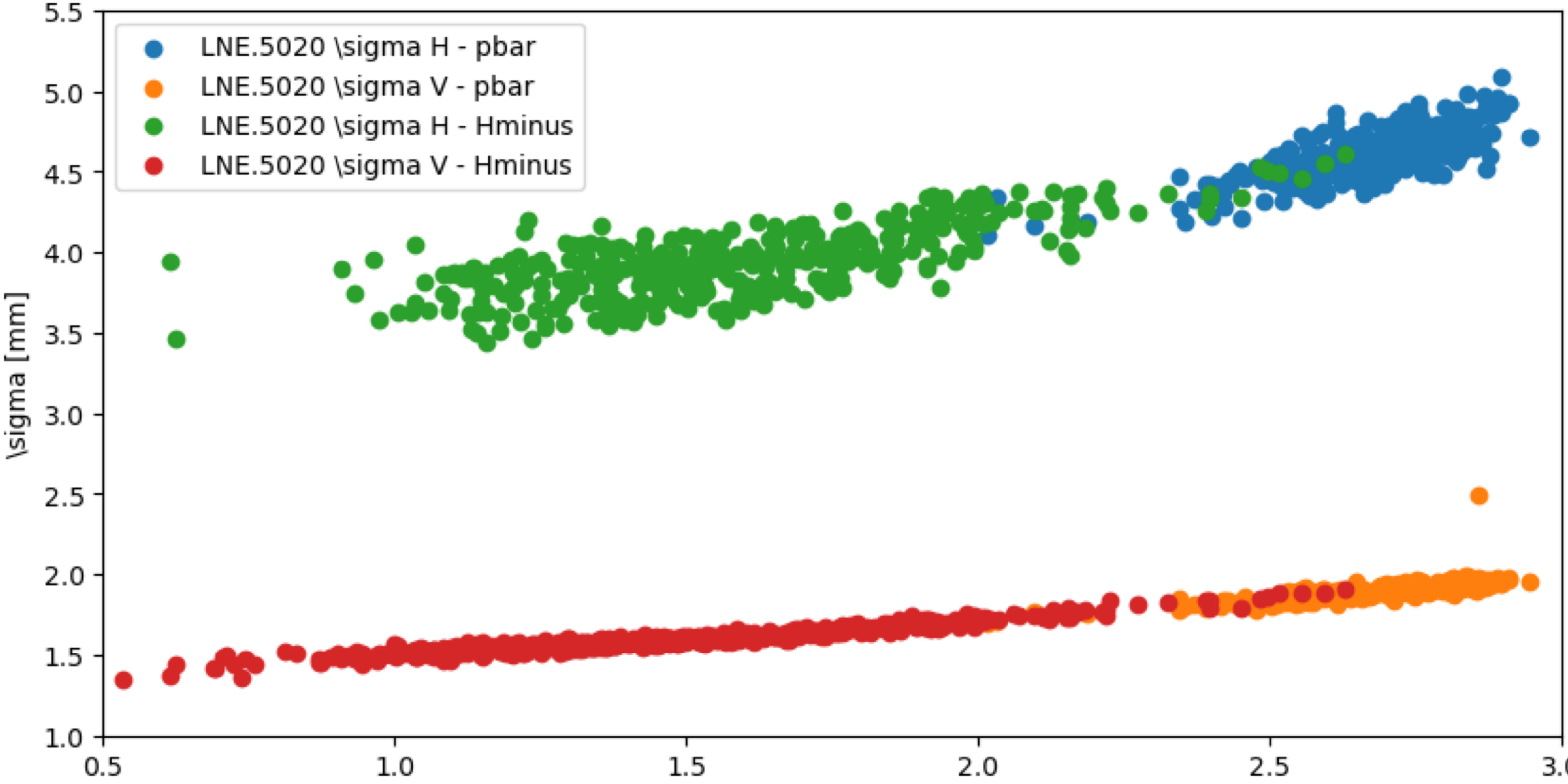
Possible to obtain smaller emittance (at the expenses of higher longitudinal one) playing with **length of bunched beam cooling** before extraction in **ELENA**



- Also possible to obtain **smaller emittance** working on **e- H- alignment.**
- So far this was **not possible to reproduce with pbars**:
  - **Intensity dependance?**

Emittance intensity dependence?

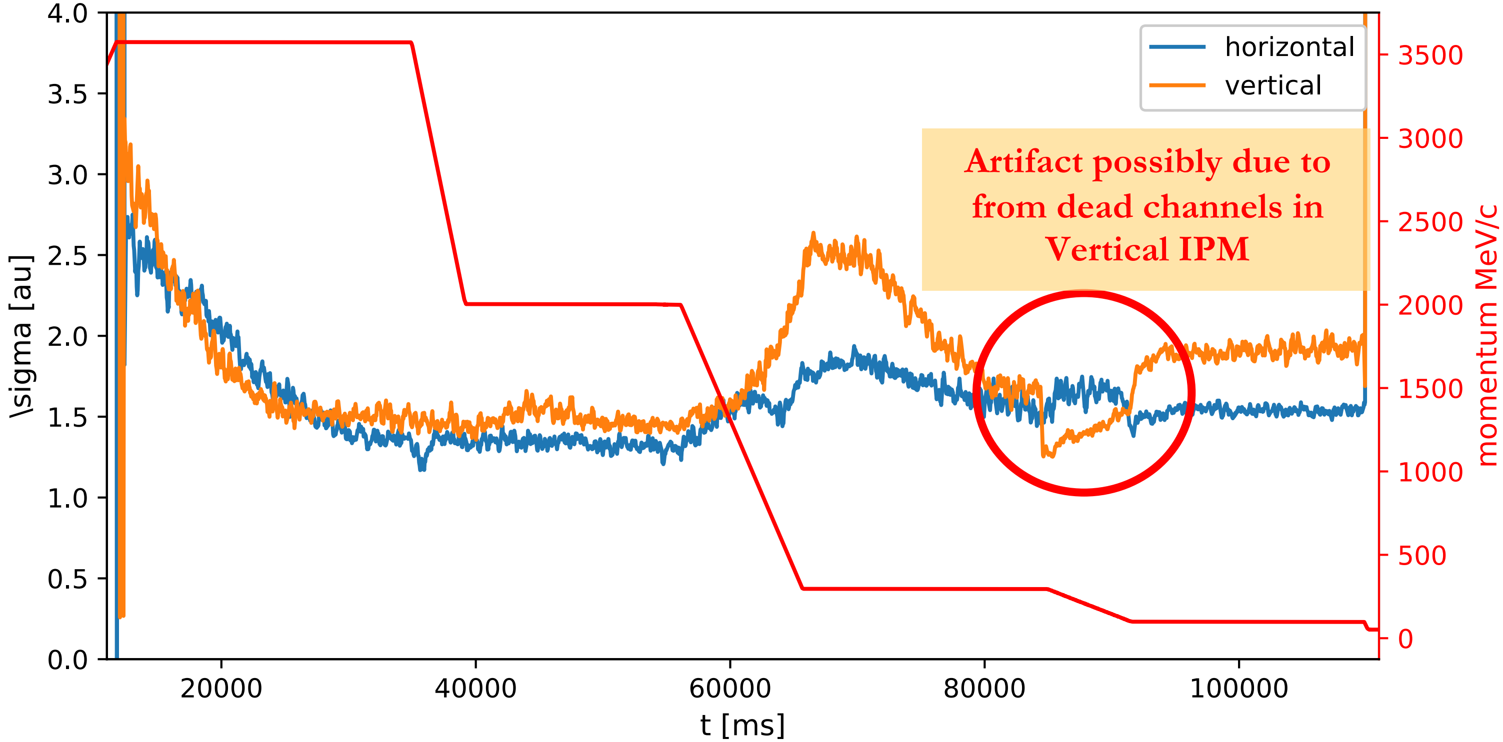
- Measuring **beam size** at a single **SEM** in ELENA transfer line **over one day**
  - Profiting of intrinsic **instability of H^- source** to span **wide range of extracted intensity**
  - Clear **beam size-intensity dependence:** **to be investigated!**
  - **No striking difference between H^- and pbars** (but intensity)
    - **We can use H^- to optimize and study cooling in ELENA!**



(for 4 bunches)

IPM: a first raw acquisition

- **AD** equipped with **Ionization Profile Monitor (IPM)**
  - **Typically not used because requires injecting gas in the ring**
- **"double MCP"** installed **to allow measurements without gas injection**
  - Here one of the very first acquisition of H and V profiles all along the cycle
  - Some **cooling effect observed**, but **accuracy** of the instrument still **to be understood**

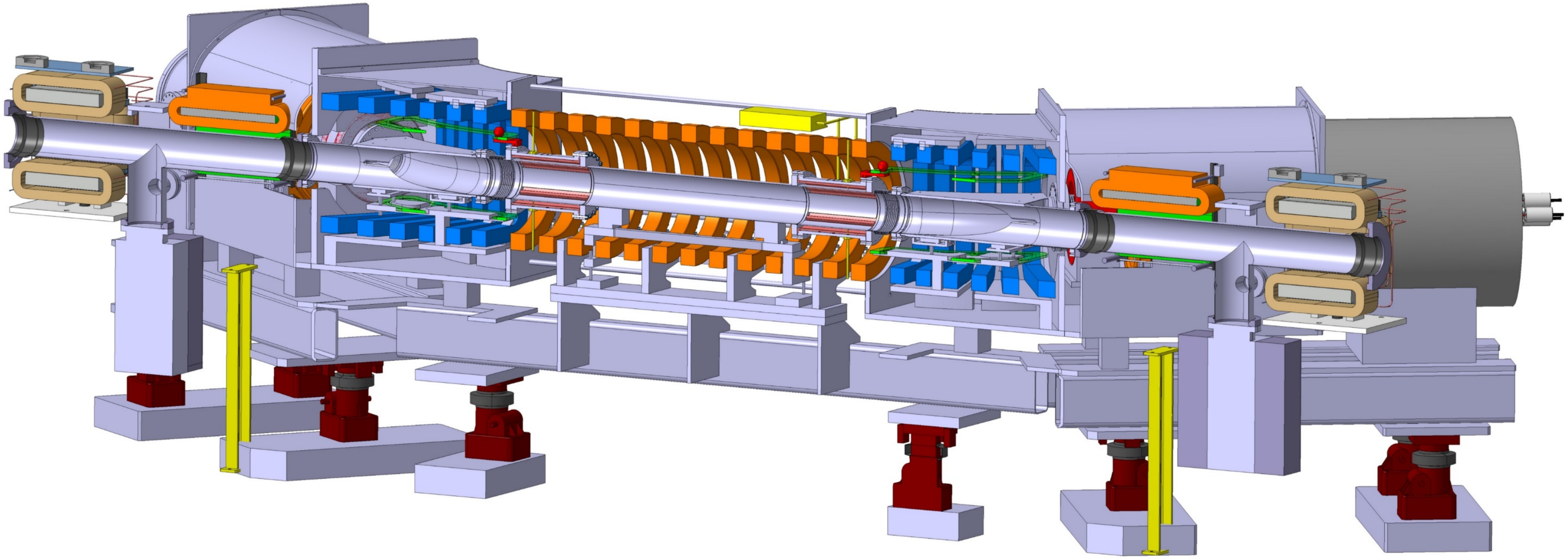


- No gas injection; $\beta_{H/V}$ about 10 m; spacing between MCP wires of 1 mm

A New E-Cooler for AD

- **Time to retire the oldest e-cooler at CERN** (with critical spare situation)
  - **Design** of a new e-cooler **ongoing**. **Installation** planned for ~**2025**.
- **Profit** to of **this unique opportunity** to:
  - **increase maximum energy** (from 300 MeV/c to 500 MeV/c, i.e. from 27 to 68 keV e-)
  - **improve cooling performance** by implying a better magnetic system and gun/collector
    - B_T/B_L from 1e-3 to 1e-4; e^- expansion; 4x higher I_e at 100 MeV/c; 4x better vacuum

See paper P2004 by G. Tranquille on Friday!



Summary

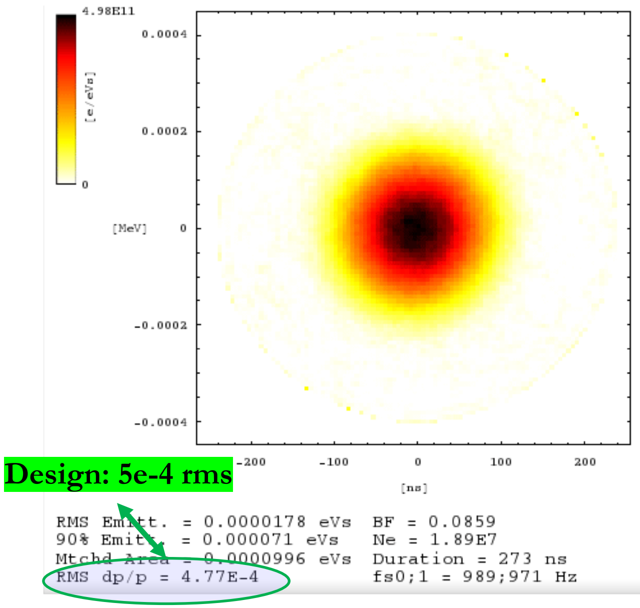
- **AD** and **ELENA** have been **successfully re-commissioned**
  - **New era for antimatter physics:** 100 keV pbar beams delivered to all experiments
- **E-cooling** with **pbars** in **AD** was setup with **no major issues**
  - **No** major **hardware intervention** done **during LS2**
  - Introduction of **e-** (and pbar) **orbit reading** was useful to **quickly find cooling** and **guide the orbit overlap optimization**
  - Availability of **live** (during the cycle!) **Schottky** and **Intensity** measurement **was instrumental** (note: only about 700 pbar shot/day)
  - **Scraper measurement are lengthy** and of **difficult interpretation**
    - **Investigating** on having the AD **IPM back in operation**
- **ELENA** profited of **extensive preparation** with **H^-**
  - **E-cooling of H-** was observed with **no degradation of lifetime**
  - **No evident differences** in **cooling performance** between **H^-** and **pbars**
    - (but lower H^- beam intensity and, consequently?, lower equilibrium emittances)
- **E-cooling performance characterization** and **comparison** with latest **simulation** tools started, but **still a lot of work to be done**.

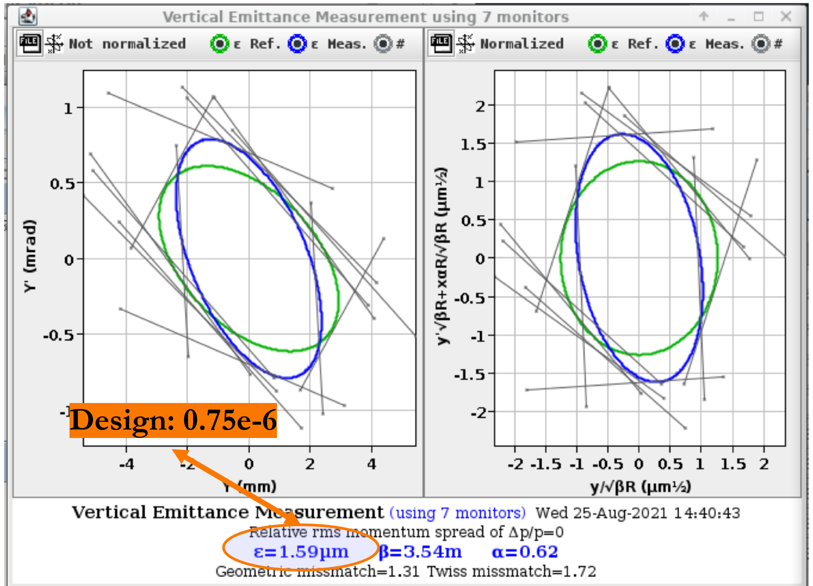
Thanks for your attention and to the many colleagues who contributed!

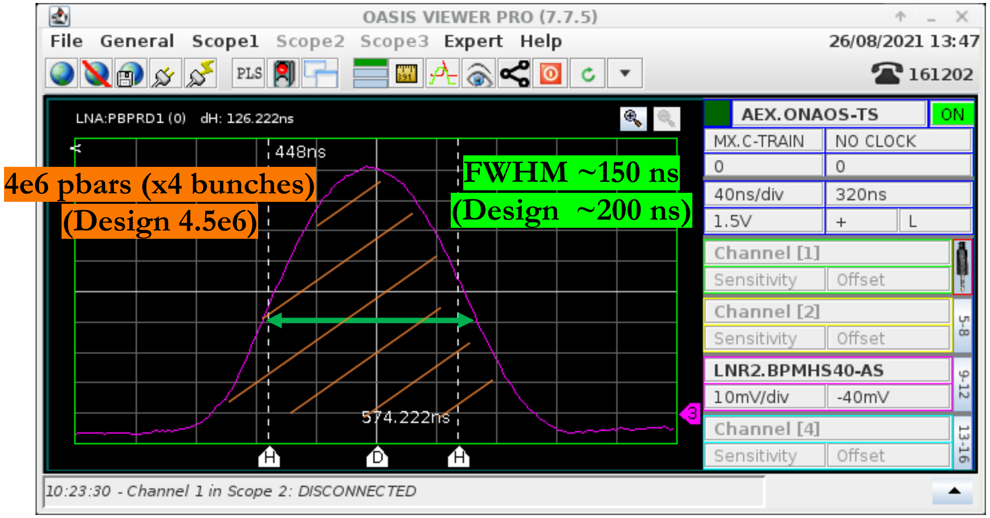
Backup

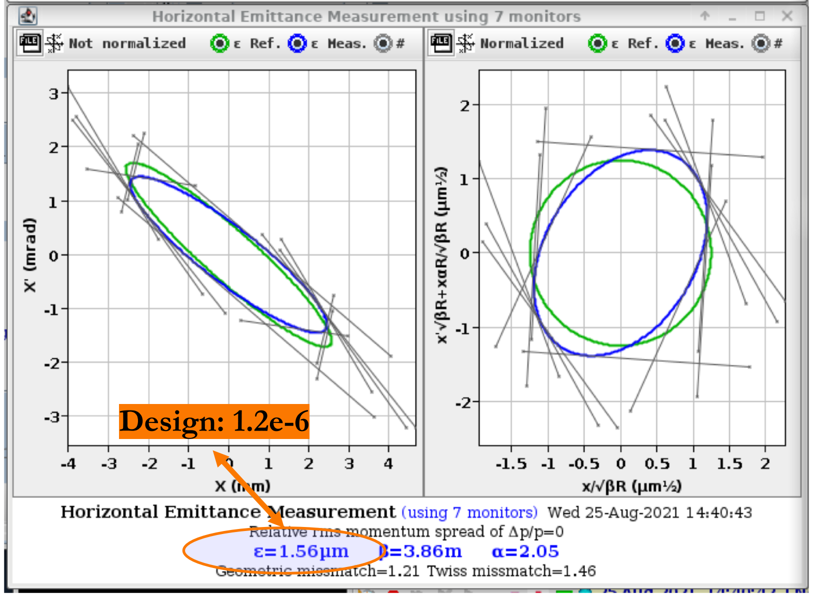
Extracted pbar beams parameters

(at start of physics run in Aug 2021; design values from ELENA Design Report)



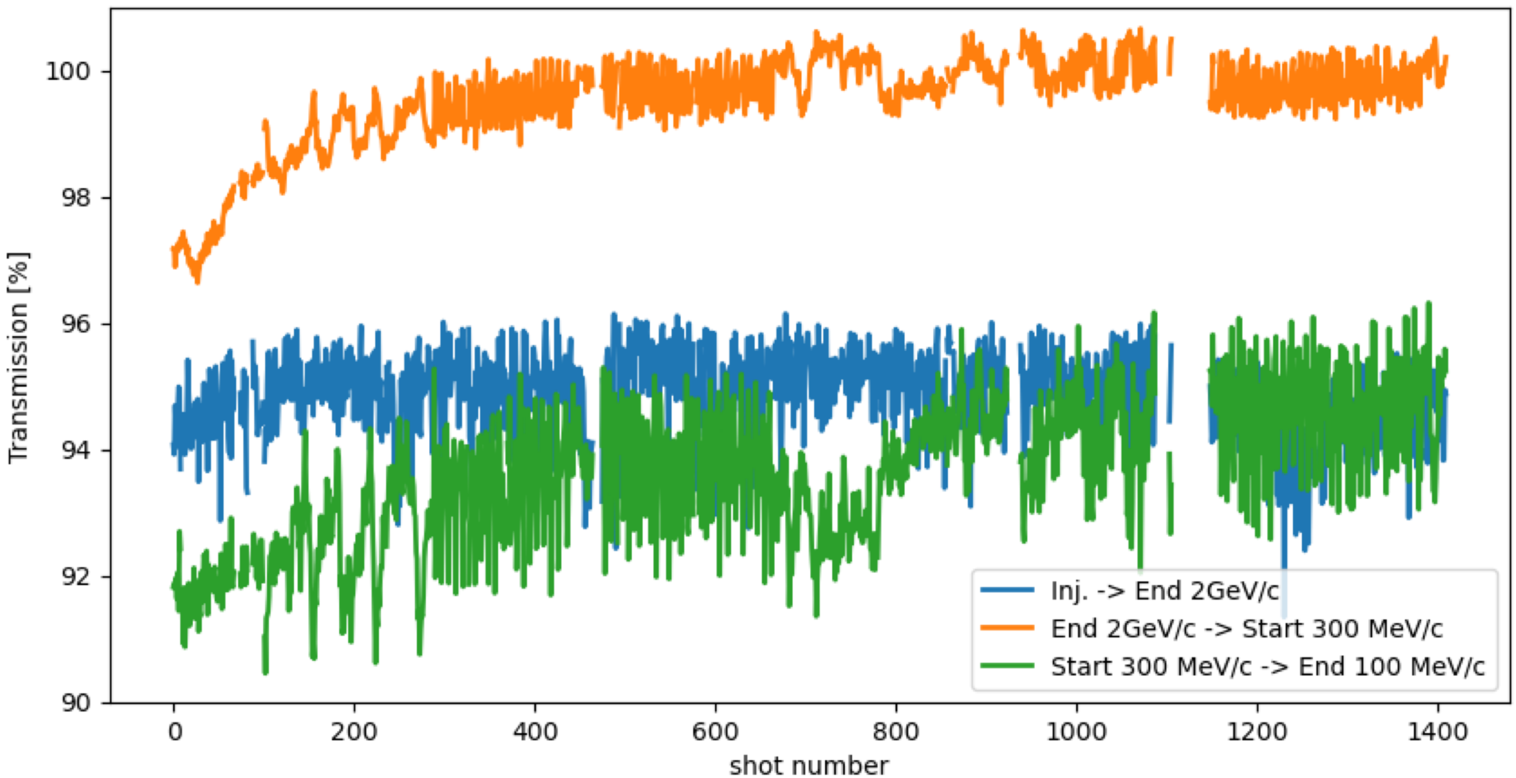






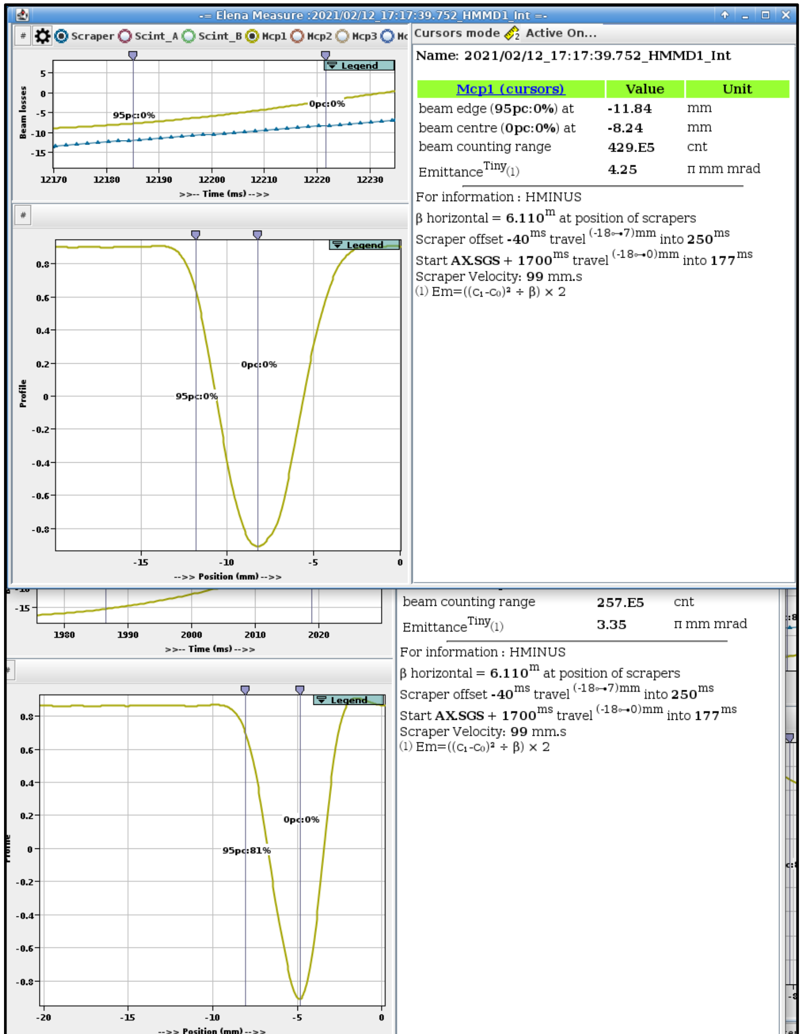
AD transmission stability

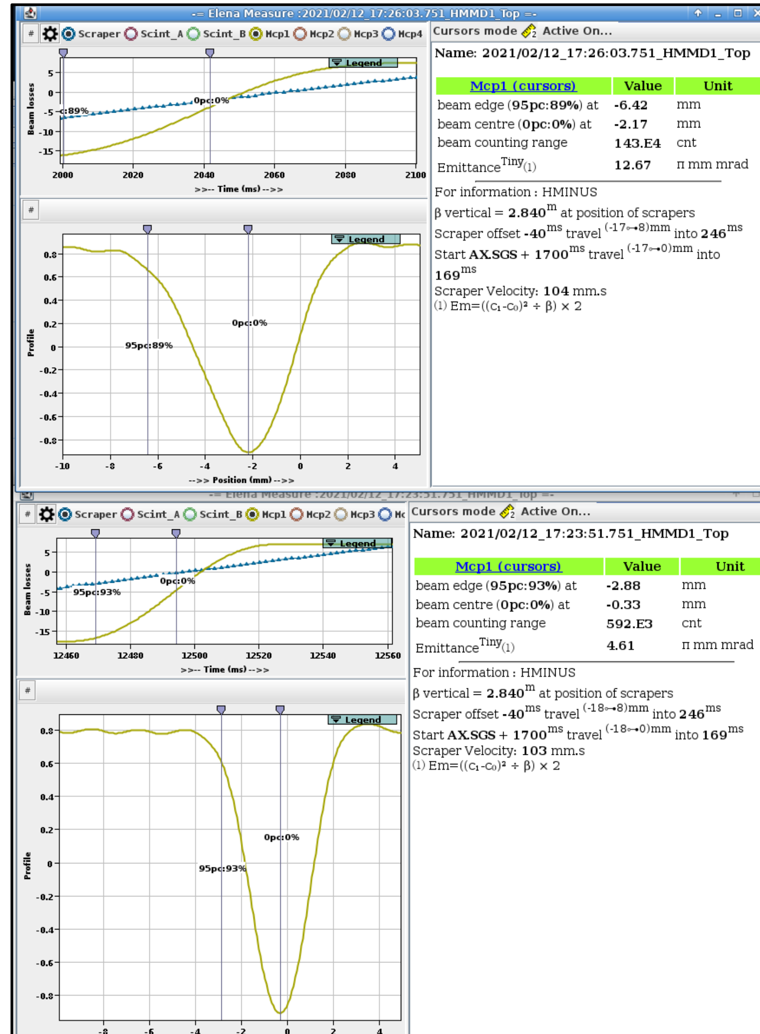
- Transmission in AD over one weekend (about 3.4e7 pbars injected)
  - S-cooling-related losses mainly on **injection plateau** (limited SC acceptance)
  - **Possible to have very little losses between 2 GeV/c (SC) and 300 MeV/c (EC)**
  - **E-cooling**-related "**transmission efficiency**" **comparable** to **s-cooling** one, but:
    - **Not considering here ELENA!** heavily affected by e-cooling at 100 MeV/c!
    - **E-cooling** is typically the **most sensitive to drifts** (here probably vacuum activity)



Cooling of H^-: transverse

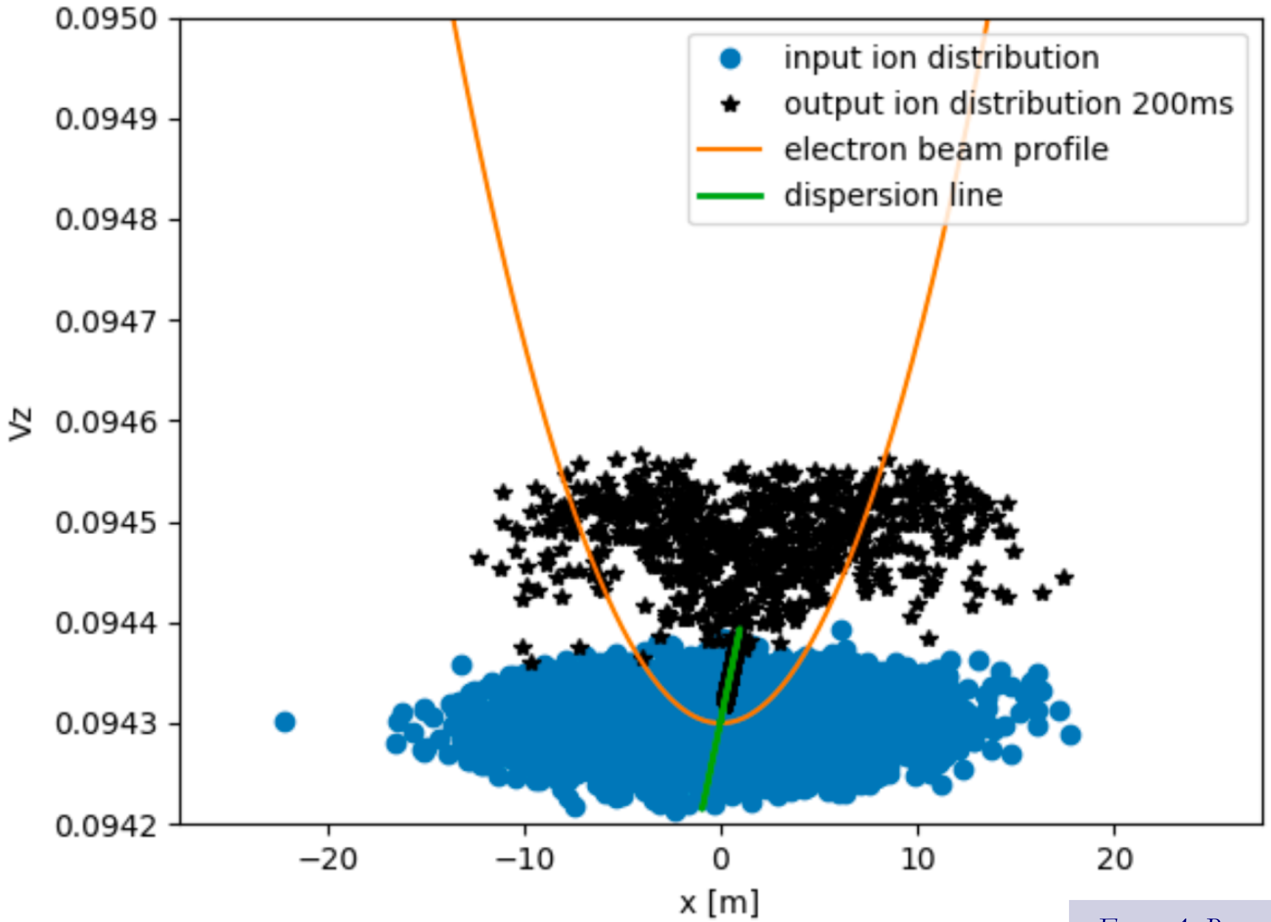
- Horizontal and vertical **scraper measurements** before bunching without/with e^- using Bruno's acquisition and analysis application





On dispersive e-cooling:

- Interplay between **ions dispersion**, Twiss functions and **e- distribution** (e- space charge! - might be linked to vacuum)



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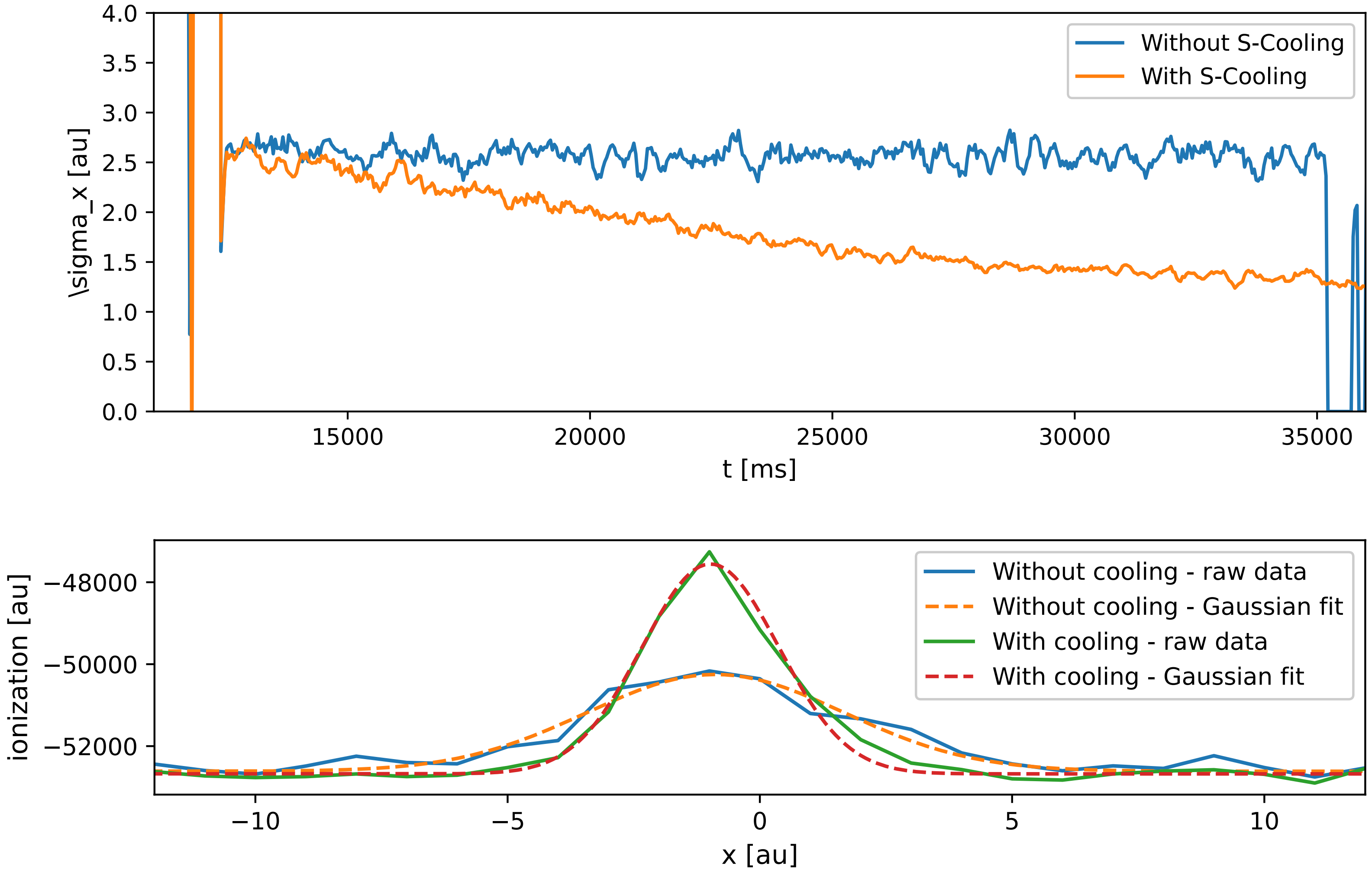
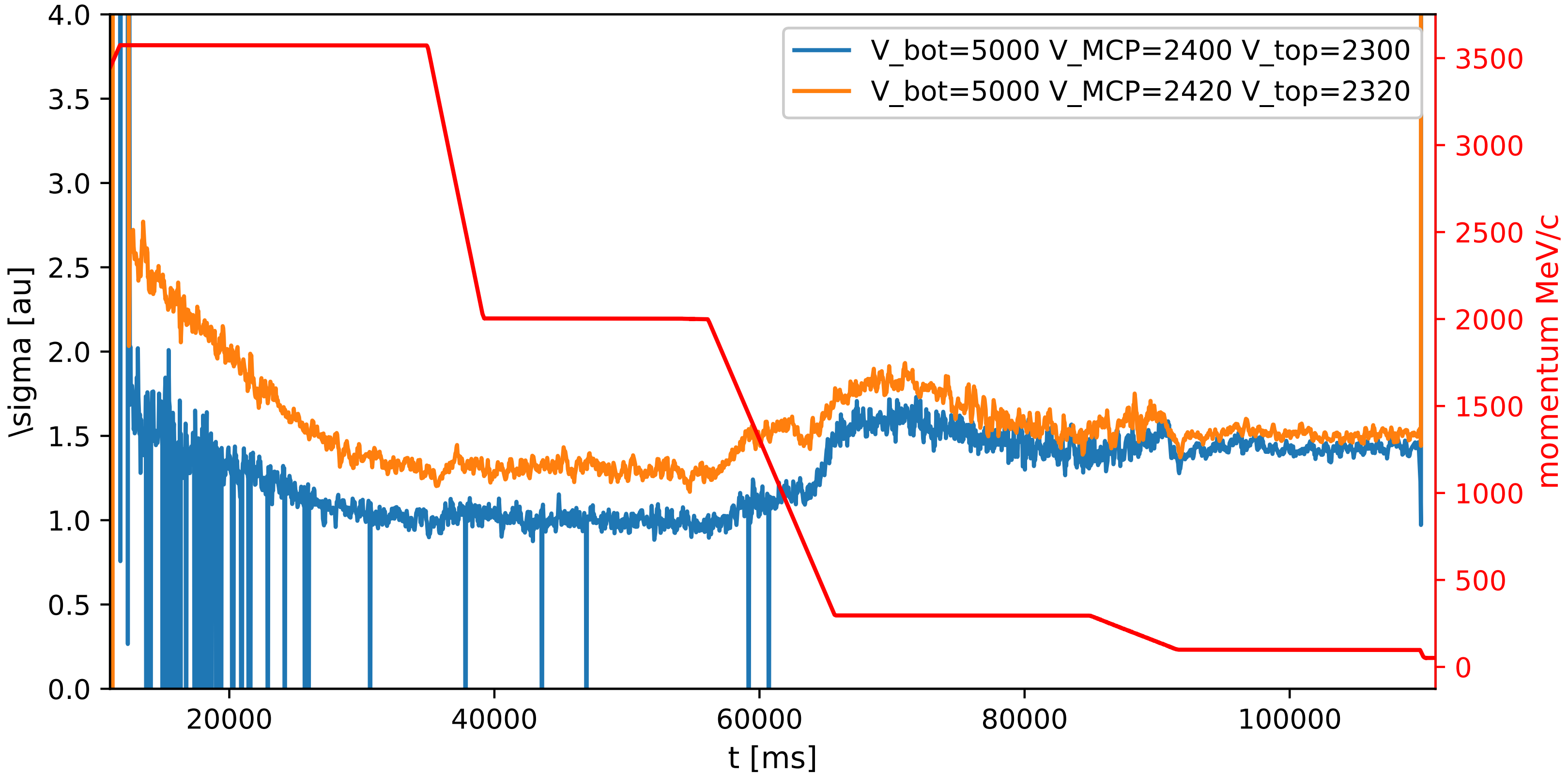
IPM: zoom in on S-cooling plateaus

- Clear effect of s-cooling at 3.5 GeV/c



IPM: different voltage settings

- Note that voltages are not yet “optimal”: beam size depends on MCP settings…



Some (little) history/references

- 1996: **Design Study of the Antiproton Decelerator: AD** - S. A. Baird et al. - link
  - Main description of the AD at time of design.

	STOCHASTIC COOLING					ELECTRON COOLING				
p [GeV/c]	ε_i [π mm·rad]	ε_f	$\Delta p/p_i$ [%]	$\Delta p/p_f$	t [s]	ε_i [π mm·rad]	ε_f	$\Delta p/p_i$ [%]	$\Delta p/p_f$	t [s]
3.5	200	5	1.5	0.1	20					
2.0	9	5	0.18	0.03	15					
0.3	33	10	0.2	0.1	20	33	2	0.2	0.1	6
0.1	30	7	0.3	0.1	40	6	1	0.3	0.01	1
0.1 bunched	–	–	-	-	-	6	1	0.3	0.1	1

- 2001: **Optics for the Antiproton Decelerator at CERN** - P. Beloshitsky et al. - link
  - **Main reference about the AD optics**, with detailed explanations of why and what
- 2004: **The CERN antiproton decelerator (AD) in 2002** [...] - P. Belochitskii et al. - link
  - Successful **tests for better cooling** by **adding dispersion in cooler on 300 MeV/c**
  - **No mention about those ideas later, maybe too unstable or difficult to operate?!**
- 2007: **Status of the Antiproton Decelerator** [...] - P. Belochitskii - link

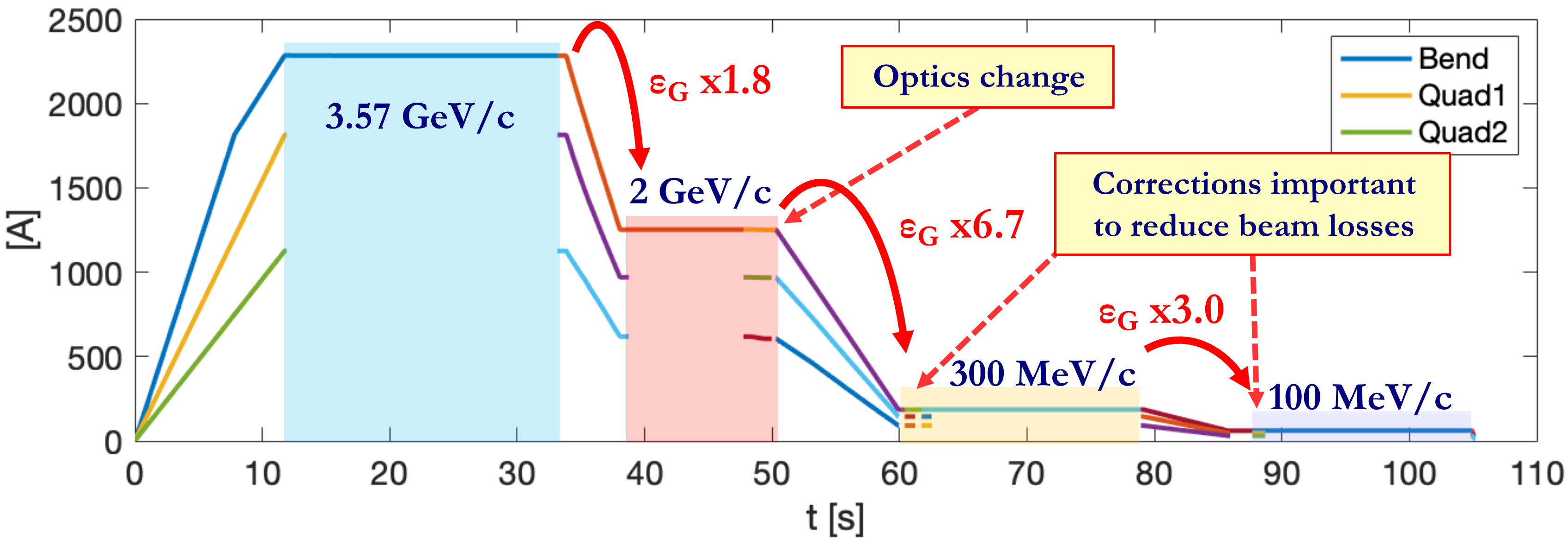
Table 1: Performance of stochastic cooling system

Momentum, GeV/c	3.57	2.0
Duration, sec	17	6
$\varepsilon_x/\ \varepsilon_y$, π mm mrad	3 / 3	4 / 5
$\Delta p/p$	$1\cdot10^{-3}$	$2\cdot 10^{-4}$

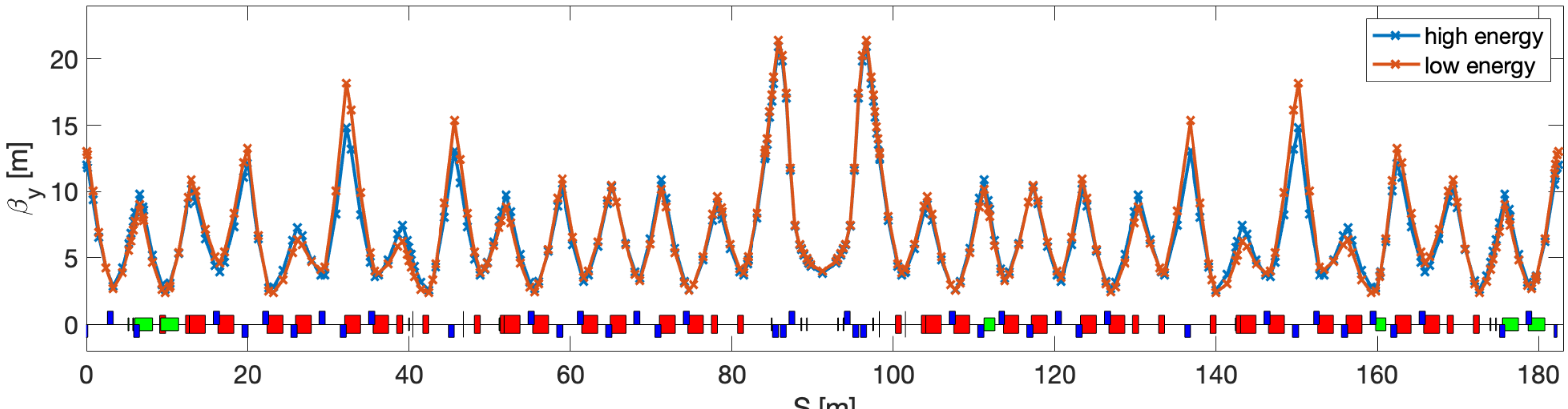
Table 3: Performance of electron cooling

Momentum, MeV/c	300	100
Duration, sec	16	15
$\varepsilon_x/\ \varepsilon_y$, π mm mrad	1.6 / 2.4	<0.5 / <0.5
$\Delta p/p$	$8\cdot10^{-5}$	$1.2\cdot 10^{-4}$

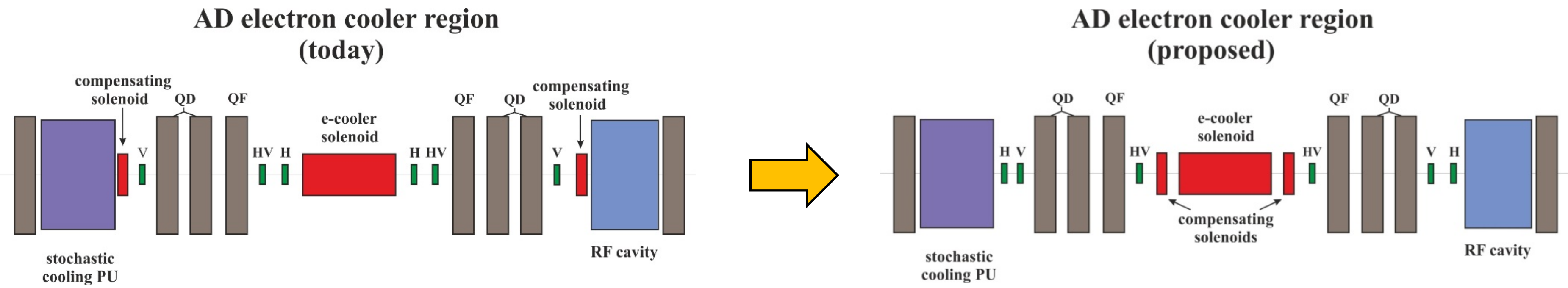
AD cycle at the end of 2018



- **A bit worst cycle length than in 2007 (<100 s)**
  - but it looks mainly due to stochastic cooling and deceleration ramp lengths
- **Two optics, mainly to improve dynamic aperture** (Q_x: 5.385 → 5.45 Q_y: 5.37 → 5.42)



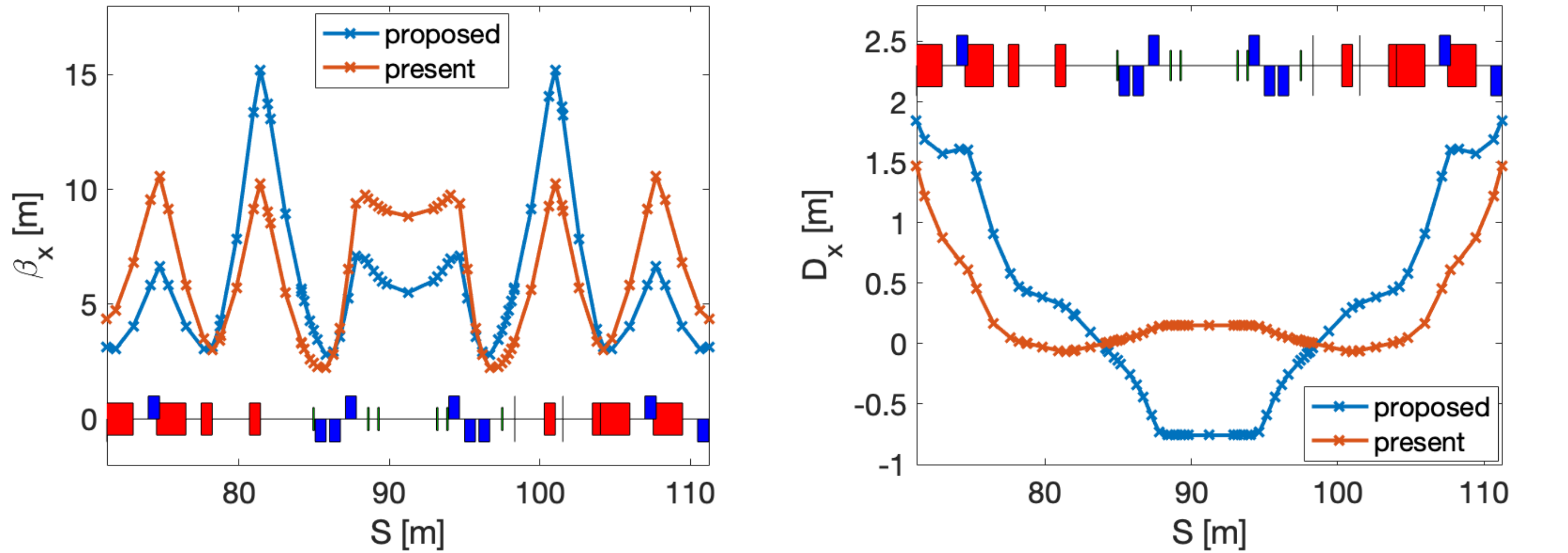
Other possible hardware improvements



- Proposal by Pavel (see AD e-cooler cons. review)
- **Two main reasons:**
  - **Minimize coupling**: e-cooler solenoid effect immediately compensated by closer compensating solenoids
    - Promise for an **easier optics**, possibly with **bigger acceptance**
    - **Actual gain could be investigated in simulations**
  - **Increase orbit correction strength** for e^-/pbar orbit alignment
    - Partially, **already proposed in 2002** - CERN-PS-2002-046-OP
    - Stated several times to be the **main limitation for cooling optimization**
    - **Impact of orbit excursion in solenoids to be investigated**
    - With an **"horizontal" cooler,** this **problem needs to be re-addressed:** in the **present scenario**, **we will "miss" one horizontal corrector**.

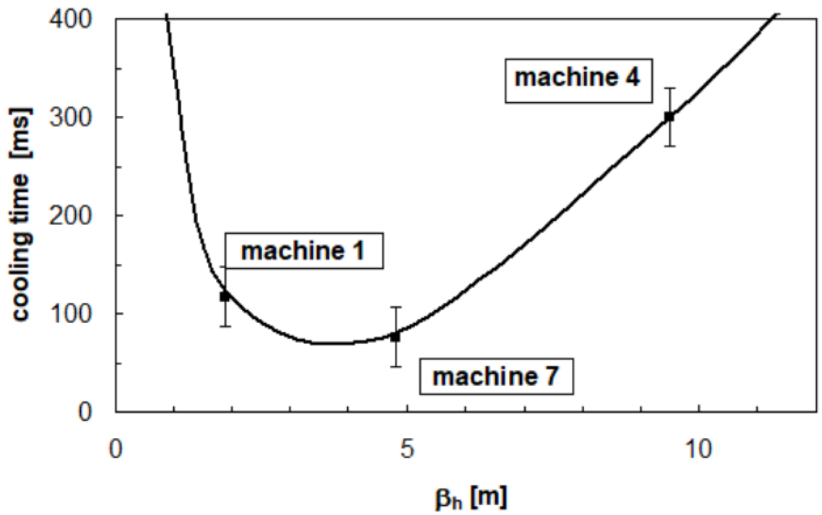
Possible optics improvement

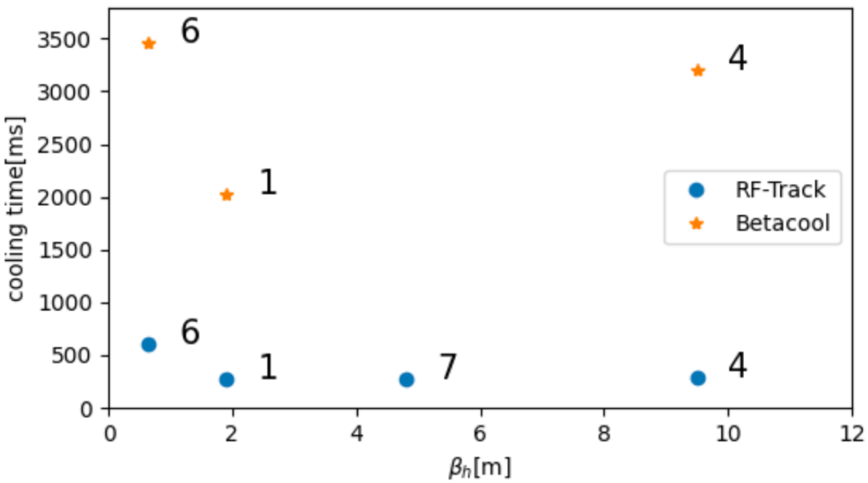
- Proposal by Pavel (see AD e-cooler cons. review)
  - **Based on experience from 2002-2004 (link) ?**
- **No need for hardware changes**
- Keep the **same working point** (Qx: 5.45; Qy: 5.42), but:
  - **lower betas** ($\beta_{x,y}$= 5.5 m / 3.2 m instead of $\beta_{x,y}$ = 8.7 m / 4.1m),
  - **non zero dispersion** D_x=-0.75m instead of 0.15 m
  - **Promise** for **faster cooler** and **smaller final emittances emittances**



Question: how does optics affect cooling?

- **Dependence** of cooling performance and optics functions is **not trivial**
- Studies in the past have shown **some dependence**, but always **explanation not always clear/reproducible**
  - E.g.: trying to match past experience in LEAR with Betacool/RF-Track simulations :





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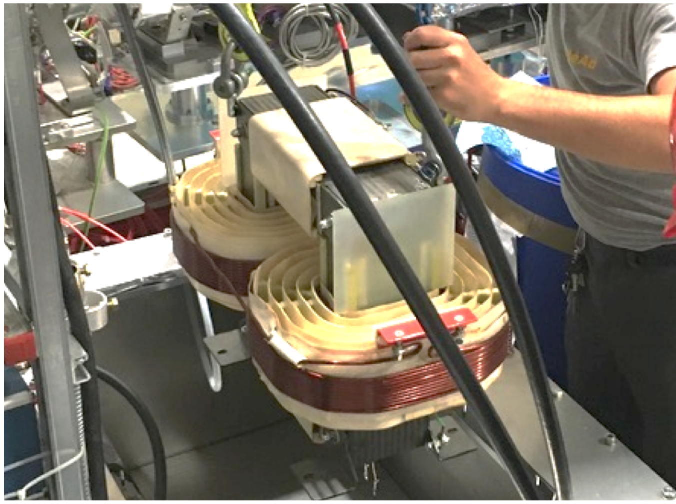
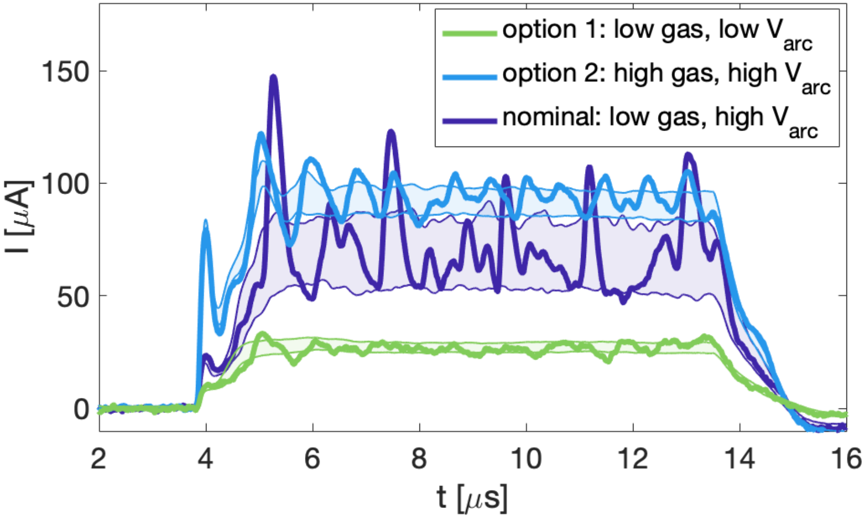
- ***Some references:***
  - *1999: Optimum dispersion for e-cooling (LEAR) – [CERN-PS-99-045-OP]*
  - *2003: Dispersive electron cooling experiments at TSR - link*

ELENA Ion Source Status

- **Always suffered of reliability issues**
  - Main issue: **HV insulation transformer** breakdown
  - Now running with a **new design** in **pulsed mode**
    - ~60kV to 100kV in about 1 second before each beam



- **Still open issues:**
  1. **H^- intra-pulse intensity instability**
     - Two possible, but not optimal, **workaround** found



  2. **Suffering from beam position drift over time:**