

# The CERN Antiprotons factory: performance and perspective

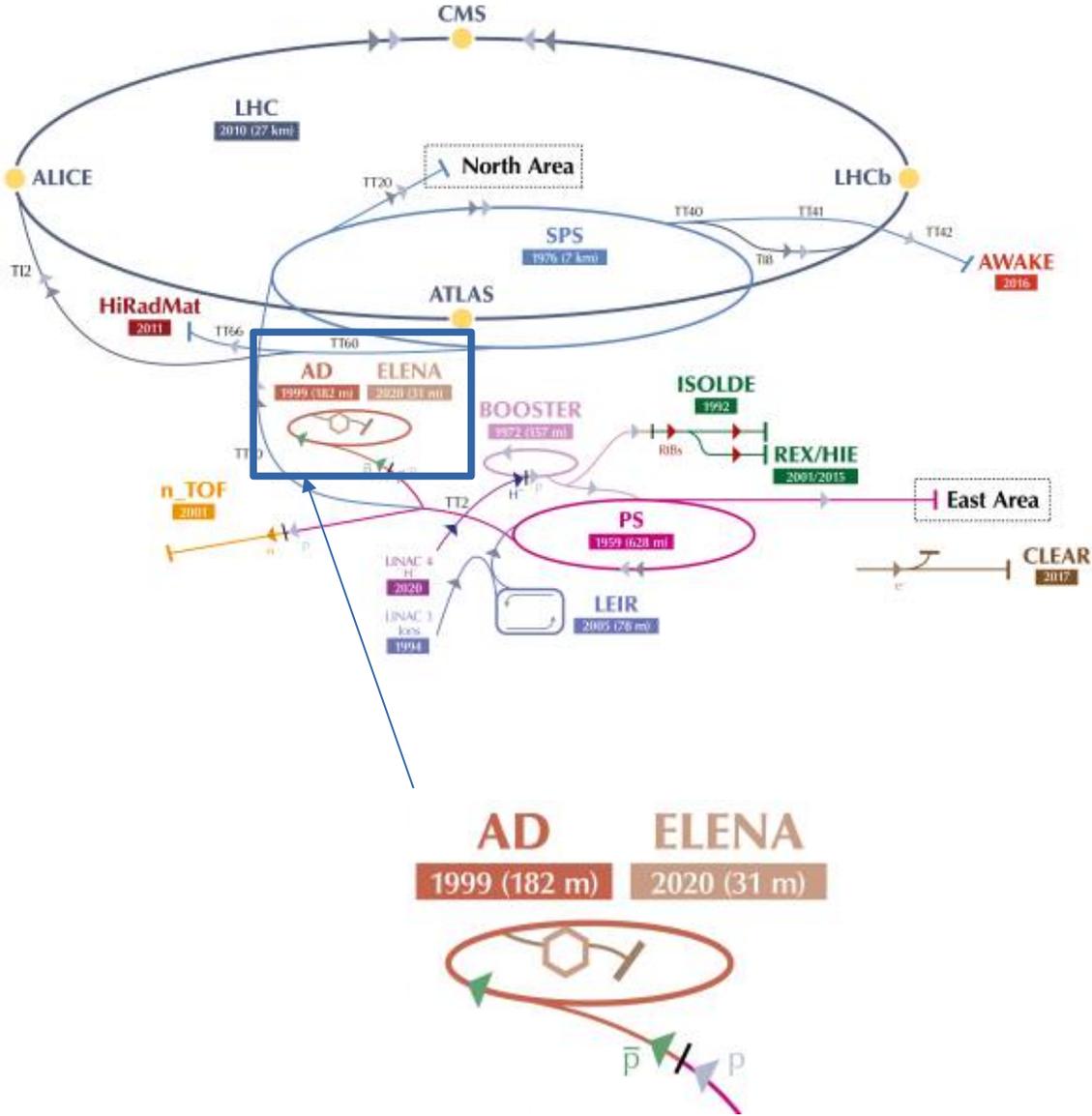
L. Ponce on behalf of the AD-ELENA operation and experts team

ACKNOWLEDGEMENT: M.E. Angoletta, L. Bojtar, C. Carli, J. Cenede, B. Dupuy, Y. Dutheil, A. Frassier, P. Freyermuth, D. Gamba, W. Hofle, L. Joergensen, G. Kathri, B. Lefort, O. Marquversen, S. Rey, D. Sittard, G. Tranquille



# Outline

- Introduction
- Machines performance
- Challenge: setting-up of the coolings
- Perspectives of the complex

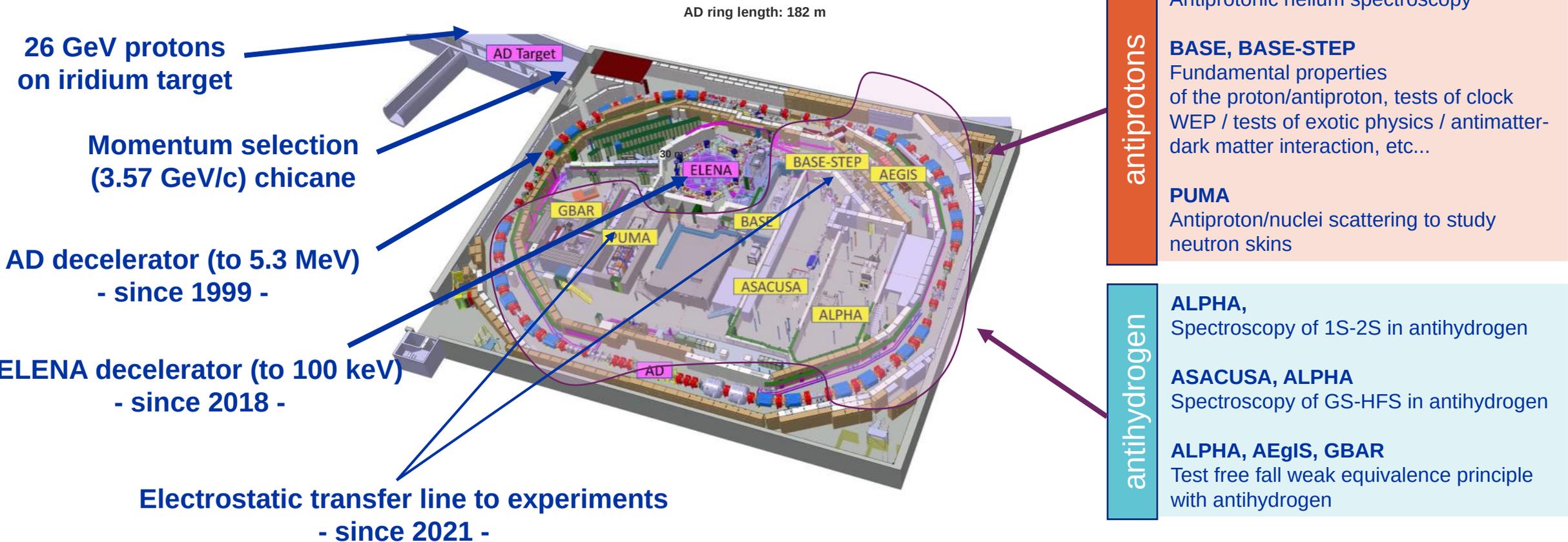


# The AD/ELENA-Facility today

The only place in the world with low energy pbars in a synchrotron!

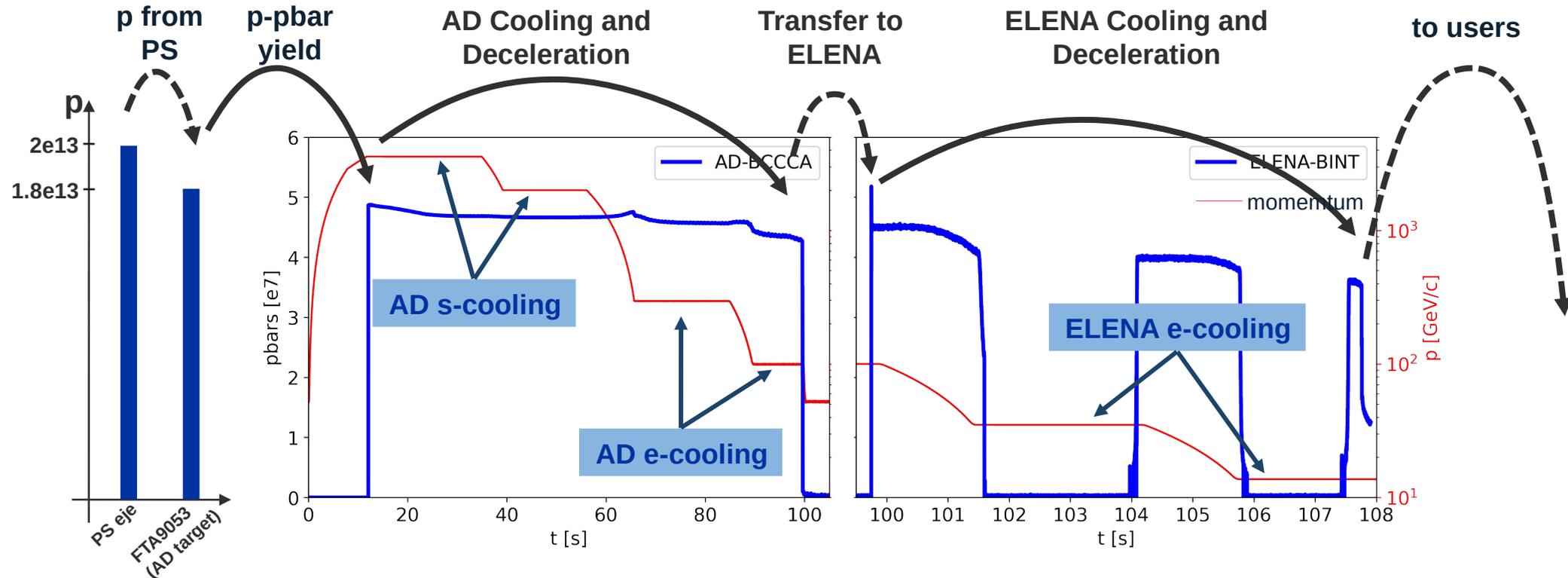
It seems unlikely to have similar capabilities elsewhere for the next 10-20 years

Serving 60 Research Institutes/Universities – 350 Scientists – 6 Active Collaborations



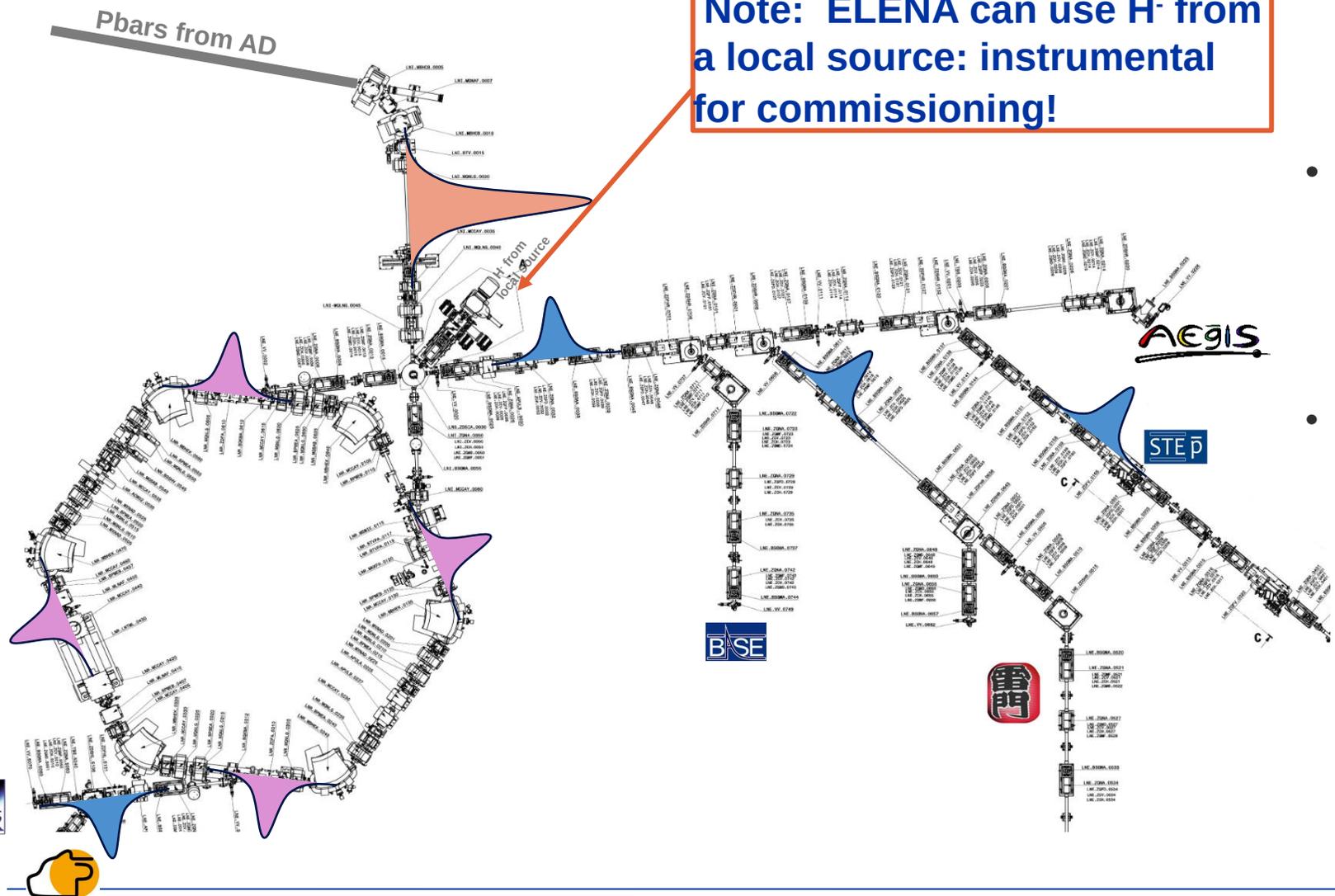
# The AD and ELENA cycles today

- Generating **pbars** from **26 GeV/c** protons (yield of the order of  $3e-6$  pbar/p)
- Up to **80% deceleration efficiency** from **2.75 GeV** ( $3.57$  GeV/c) to **100 keV** ( $13.7$  MeV/c)
  - Thanks to **several stochastic and electron cooling steps**
- Up to  **$5e7$  pbars every 2 minutes** delivered to experiments

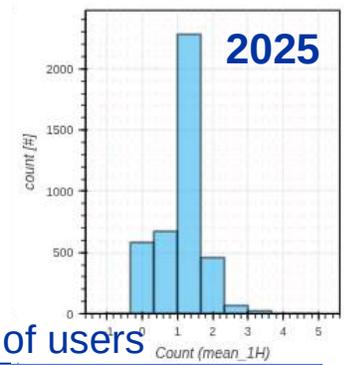
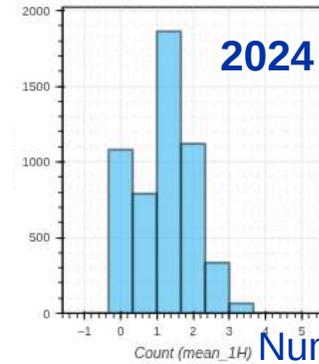


# Beam Delivery to Users today

Note: ELENA can use H<sup>-</sup> from a local source: instrumental for commissioning!



- AD produces 1 bunch at 5.3 MeV
- ELENA 4 bunches at 100 keV
  - <150 ns FWHM
  - <6e-4 RMS dp/p
  - <2.5 um emittances
- Up to 4 experiments served at the same time with up to 1.3e7 pbars/bunch
- 24/7 beam availability was the key game changer for AD users
- bunches “wasted” when less than 4 users requesting at the same time:
- Installation of beam test line TELMAX

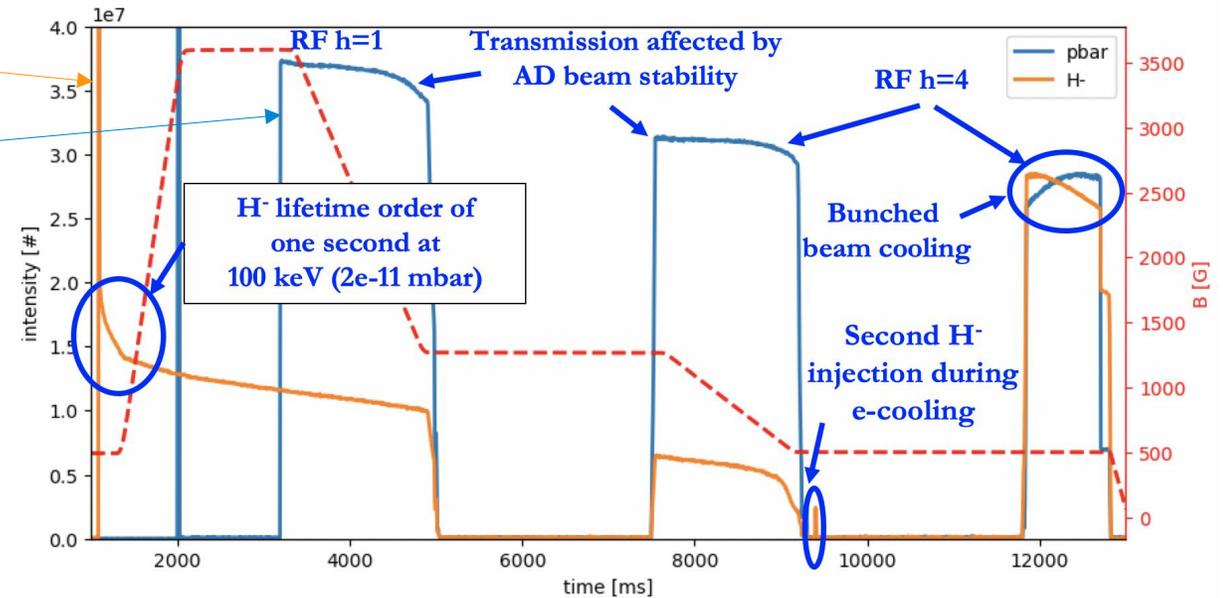
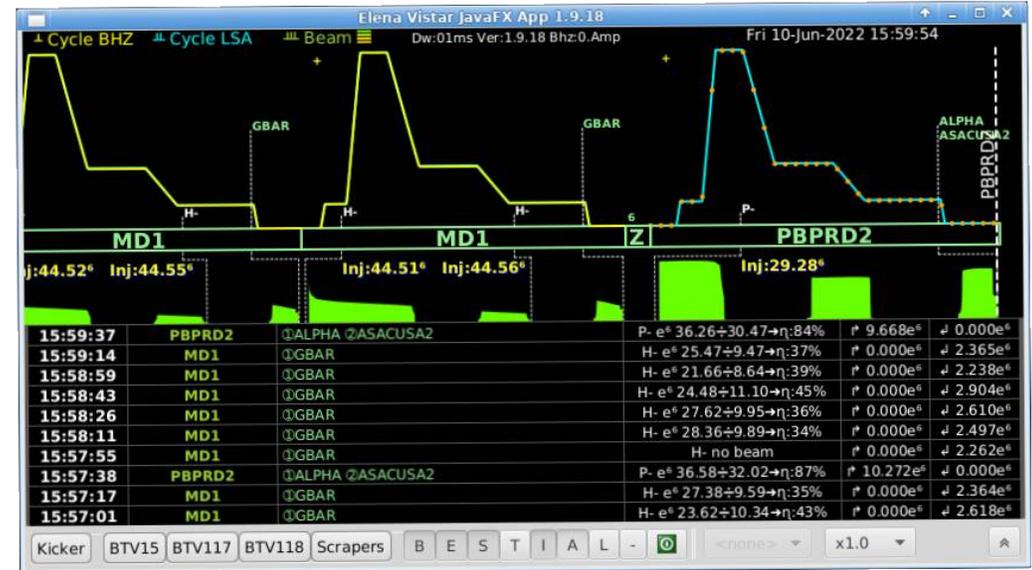


# ELENA operation with H<sup>-</sup> ions

- ELENA cycle short compare to AD cycle (~2min)
  - H<sup>-</sup> cycles possible between antiproton cycle
- Pbars cycle is **magnetically equal** to the cycle with H<sup>-</sup> ion beam to ease the setting-up:
  - Including e-cooling set-up
- Operational deceleration cycle is **15 s long**:

- 13.7 MeV/c plateau for H<sup>-</sup> injection
- Acceleration to 100MeV/c
- 100 MeV/c plateau for Pbars injection
- Deceleration to 35 MeV/c on RF h=1,
- Electron cooling of debunched beam at 35 MeV/c
- Rebunching and deceleration to 13.7 MeV/c on h=4
- Electron cooling of debunched beam at 13.7 MeV/c
- Re-bunching on h=4 with e-cooling on

**Setting-up with H<sup>-</sup> is instrumental in the success of ELENA**

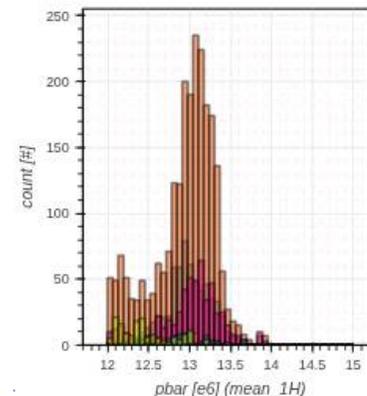
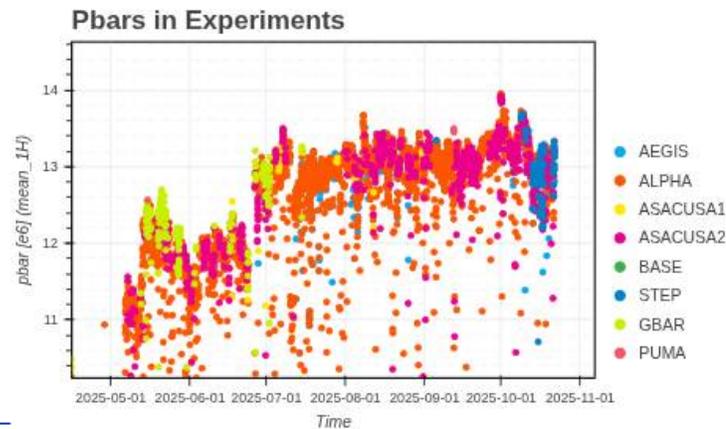
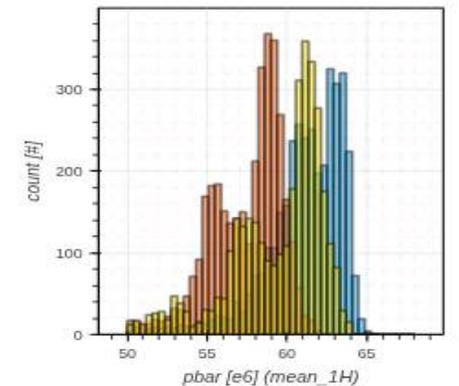
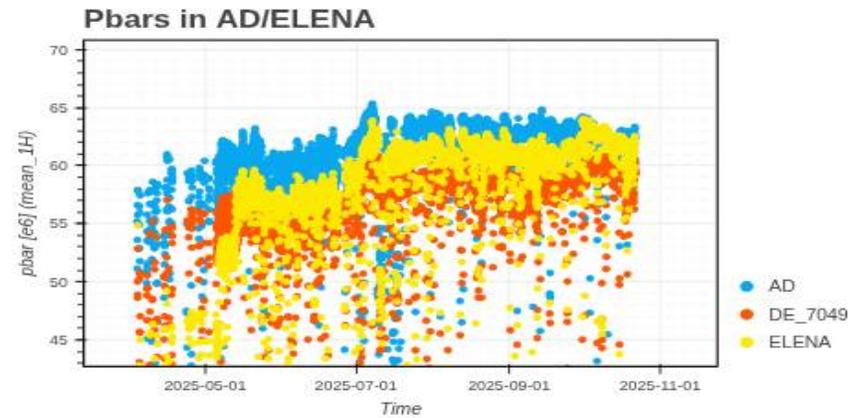
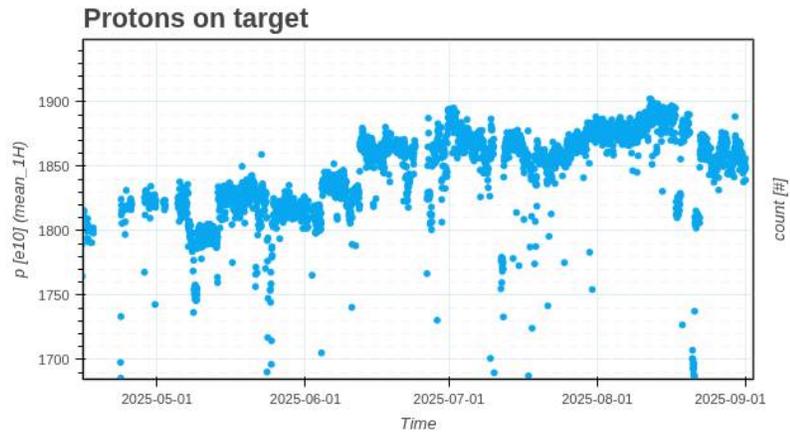


# AD/ELENA Performances

# 2025 at a glance

- Main numbers:

- Cruising around  $6.4e7$  pbars injected in AD with  $1.85e13$  protons on target
- With deceleration efficiency around 94% in AD and 85% in ELENA, delivering  $1.3e7$  pbars per bunch to the users with a very good reproducibility along the year

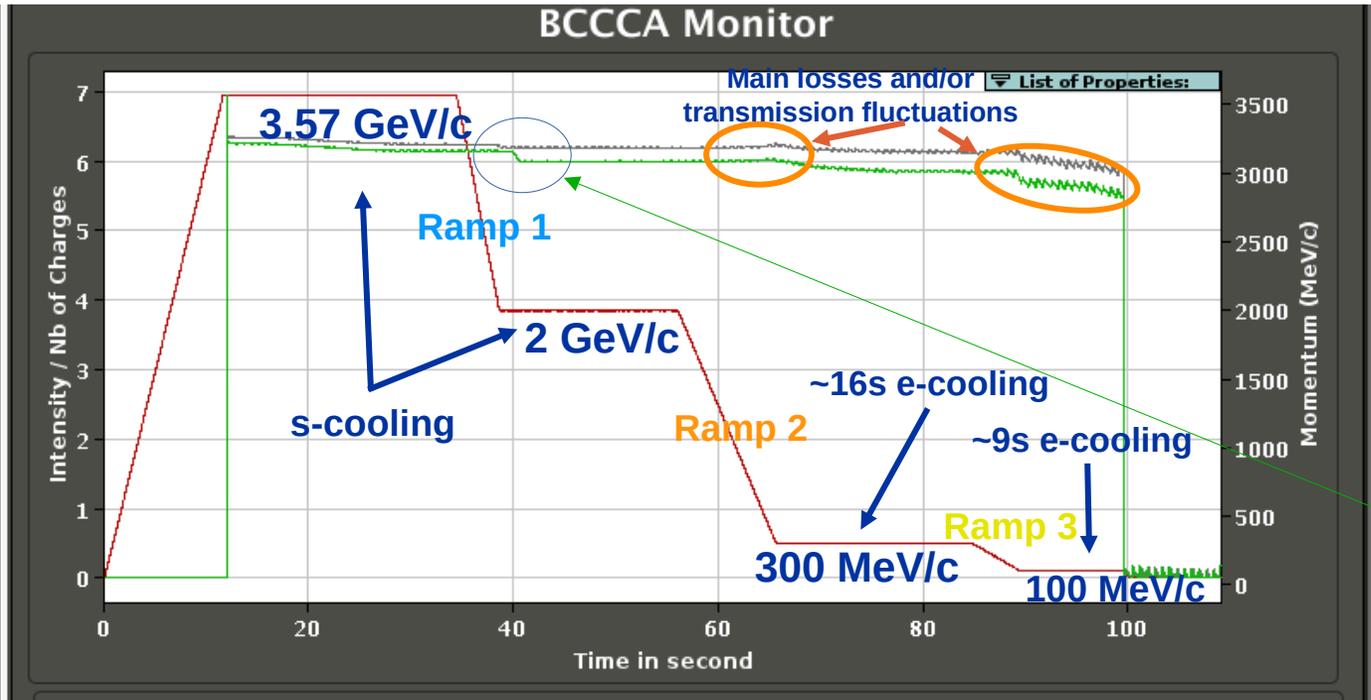


# Records all along the path

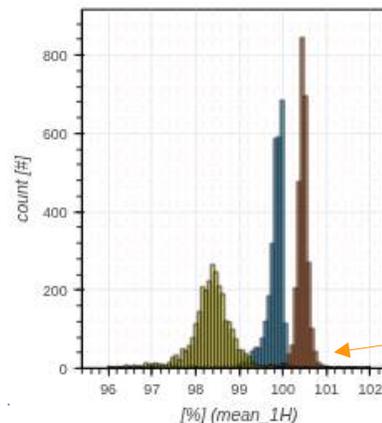
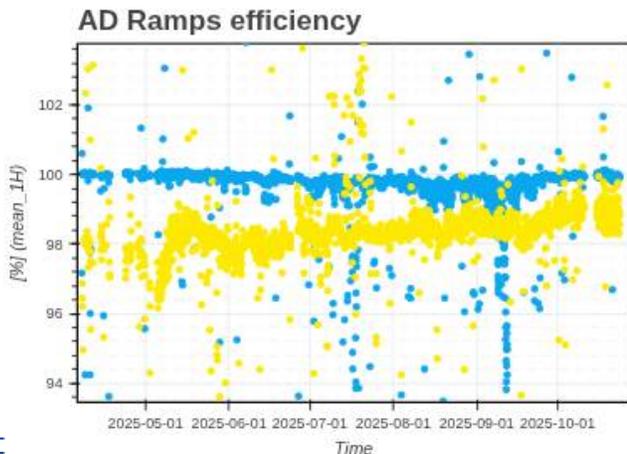
- › New records established for:
  - Injected intensity in AD:  $6.5e7$  pbars
  - Extracted intensity from AD :  $6.3e7$  pbars (+50% compared to 2018)
  - Intensity per bunch extracted from ELENA:  $1.37e7$  pbars per bunch (more than twice the design value)



# Beam performance: AD deceleration efficiency

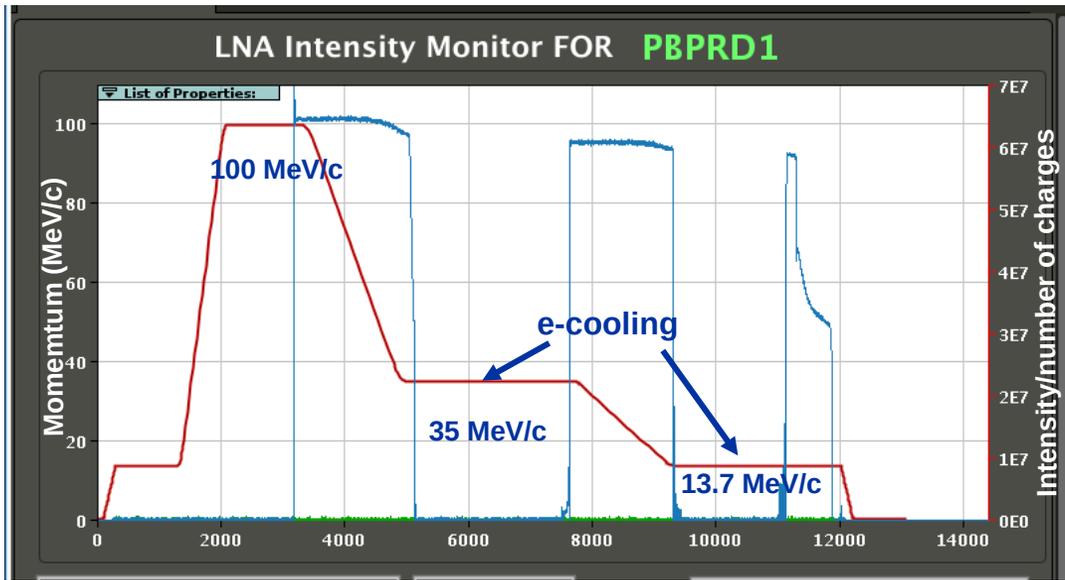


- **AD Deceleration efficiency above 90%**
  - Losses mainly during low energy part of the cycle:
    - Regular sublimation of AD ring to improve vacuum => allow to recover 3-5% in transmission
  - Strong dependance on coolings efficiencies:
    - Tuning of the coolings systems triggered by loss of transmission



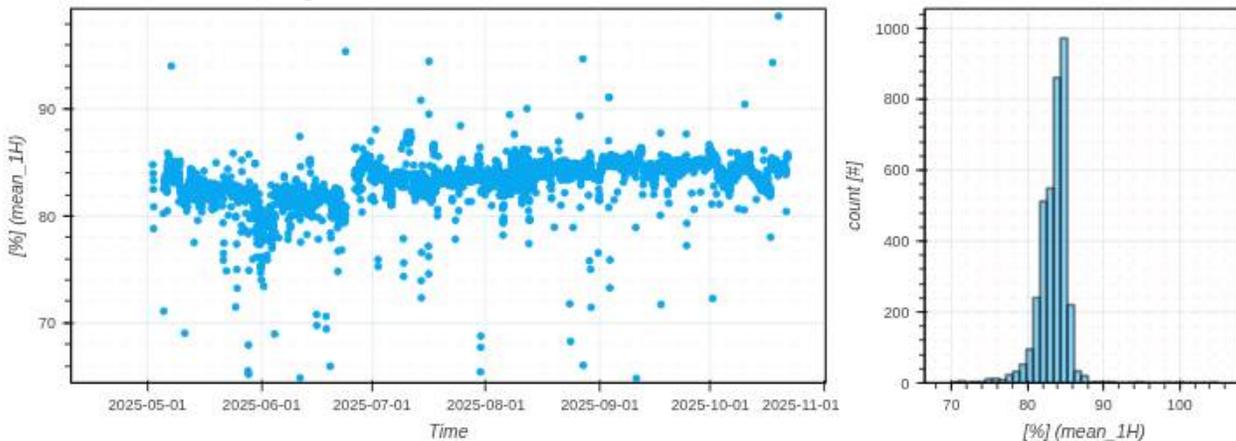
Note: artefact in the BCCCA data causing overestimated data for ramp2

# Beam performance: ELENA deceleration efficiency

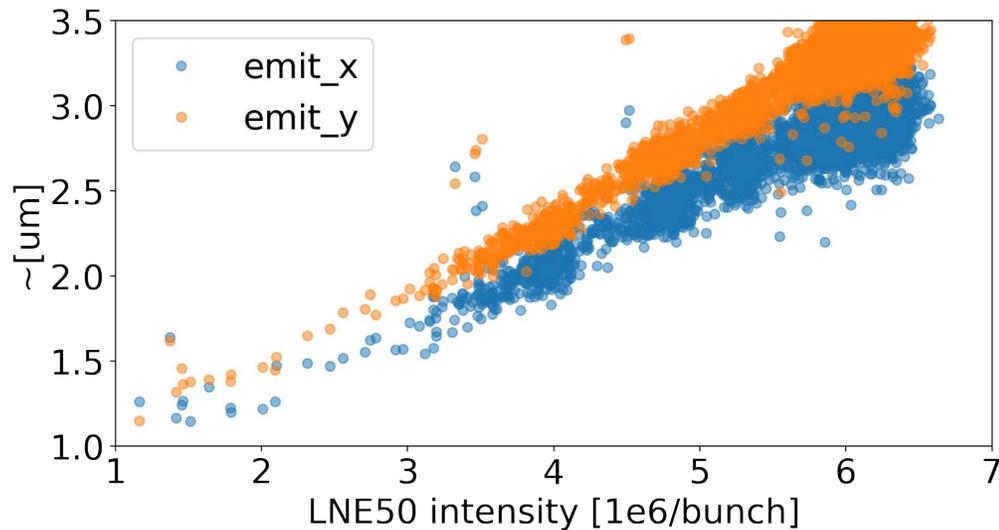
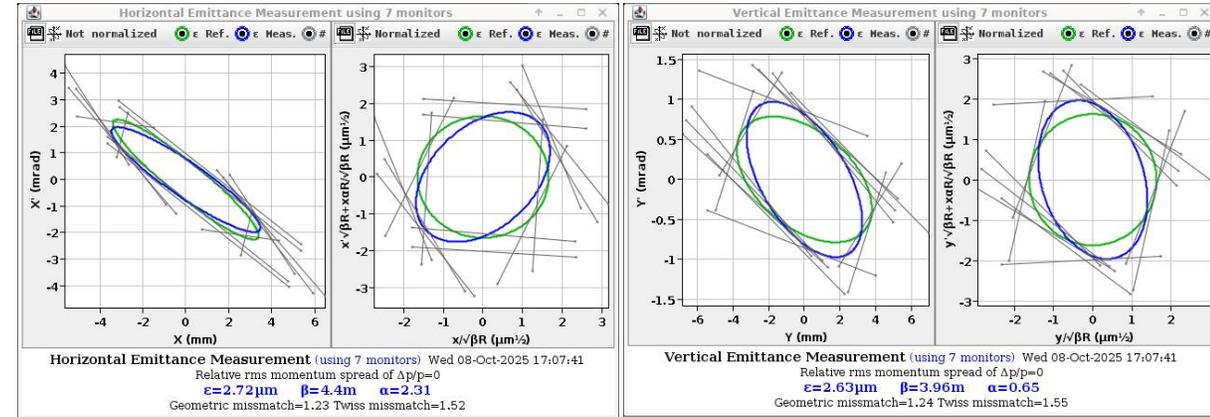
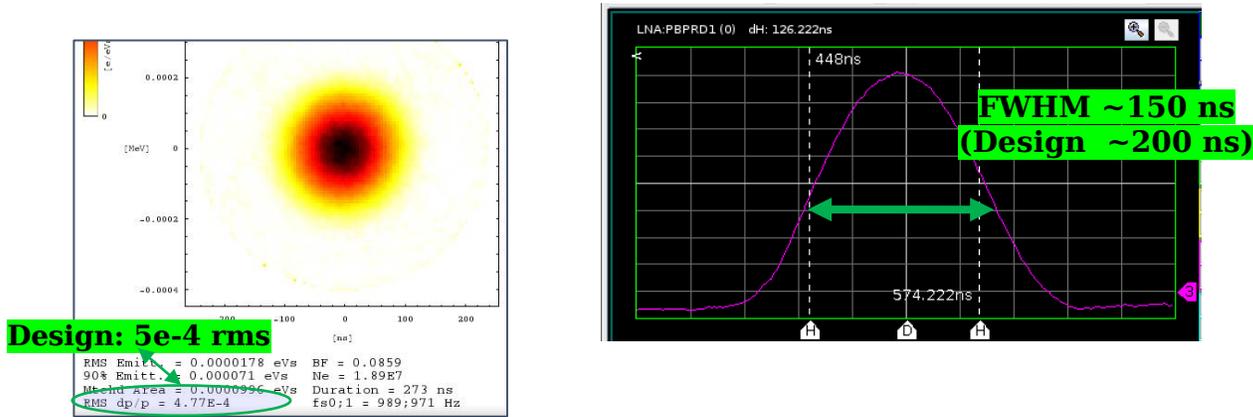


- **ELENA deceleration efficiency around 85%**
  - Main source of losses during first ramp linked to injected beam parameters (and so cooling in AD)
  - Stability improved with injection oscillation correction tools
- **Cycle optimized with H- source allowing machine development during physics time:**
  - Change of working point
  - New extraction scheme for TELMAX

ELENA Efficiency



# Beam performance: extracted beam parameters

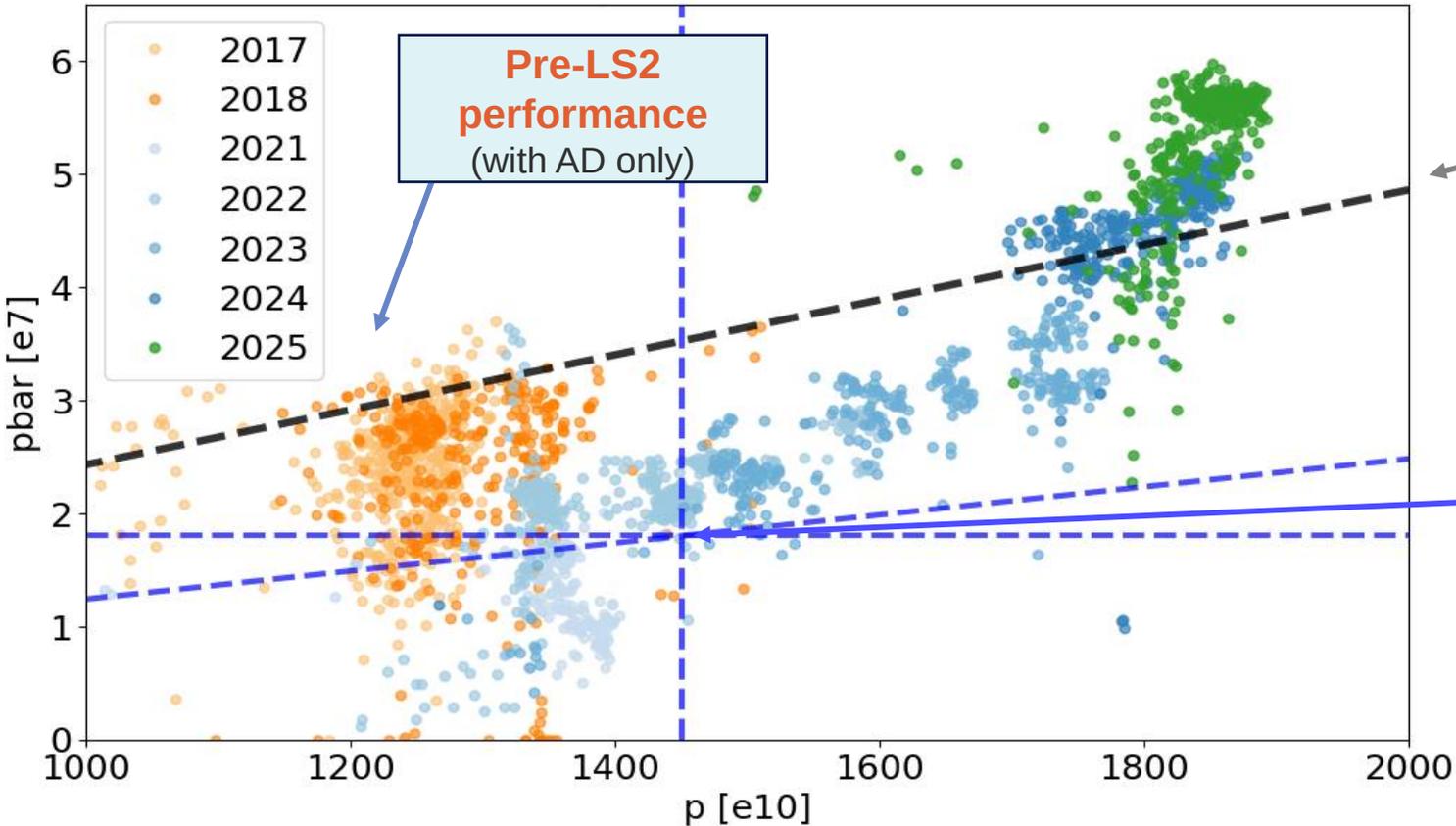


- Energy spread and bunch length within or better than design
  - Bunch length reduced for GBAR experiments with bunch rotation at expense of energy spread
- Typical transverse emittances of 2.5  $\mu\text{m}$  rms are about factor 2 larger than design
  - Change of working point in 2024 allowing to reduce by a factor 2
  - But clear emittance-intensity dependance and we are running at more that 2 times the design values

**=> Overall reached close to nominal beam characteristics with more than twice the design intensity**

# Overall performance of AD/ELENA Facility: pbars vs protons on target

- Enhancing reliability, operability, and overall pbar flux
  - Enabled by Injectors upgrades (p intensity), and AD/ELENA investments (pbar yield and efficiency)



**New targeted parameters:**  
 $3e-6$  p-to-pbar yield  
 90% deceleration efficiency in both AD-ELENA

**ELENA Design Expectations:**  
 $1.45e13$  ppp on target  
 $1.8e7$  pbars from ELENA

**Note:** Each point in the graph is the mean pbar/p intensity over 12 h periods

**2024:  $\sim 2.7e18$  p  $\Rightarrow$   $\sim 6e12$  pbars (10 pg of pbars!) in  $1.5e5$  shots  $\Rightarrow$  the highest integrated #pbars ever!**

# Challenge for operation team: setting-up of cooling systems

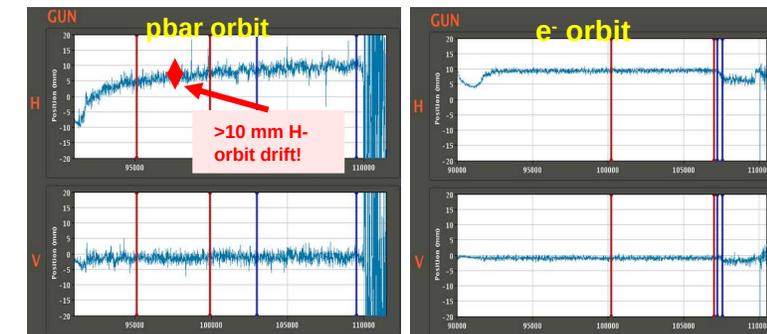
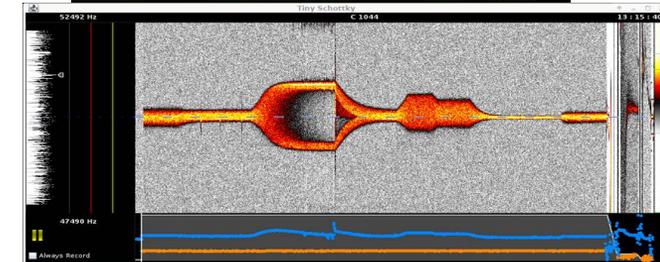
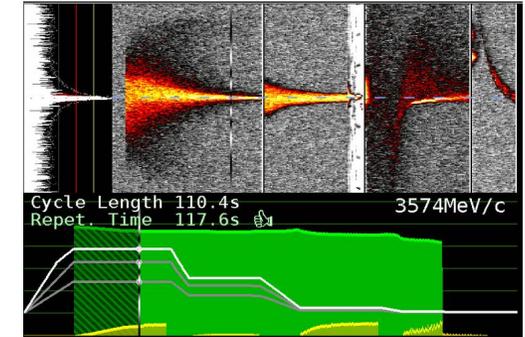
# Tedious setting-up of Coolings = key of the success

Schottky and Intensity (BCCCA) in AD

See L. Joergensen JACoW-COOL23-WEPAM1r3

- **Challenge in Beam Diagnostics** in measuring very low intensity and low energy beams
  - Mainly relying on Schottky and Intensity measurements
    - i.e. indirect measurement of many possible faults/effects
  - Only destructive transverse beam profile measurements
- **Lengthy setting-up of cooling systems: Crucial for machine performances**
  - Beam Transfer Function measurements on the plateaus for stochastic cooling:
    - Dedicated time for measurement in « pause » mode
  - Adjustment of pbars/e- overlap for e-cooling in both AD and ELENA:
    - Pbars orbit controls in offset and angle
    - ELENA can profit of the H<sup>-</sup> cycle
- **Improved methodology and stability:**
  - BTF automatic tool : reduce setting-up time from several hours to 30min
  - New Optical notch filter design with better temperature regulation, more parameters control

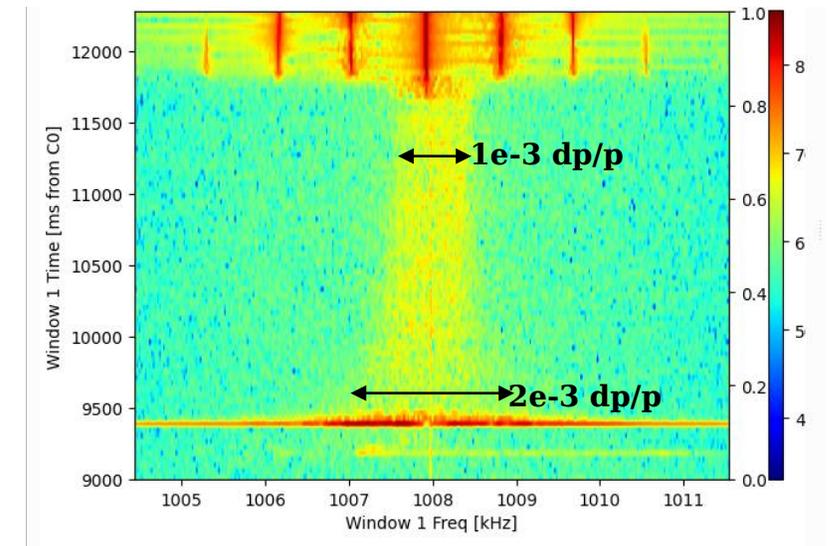
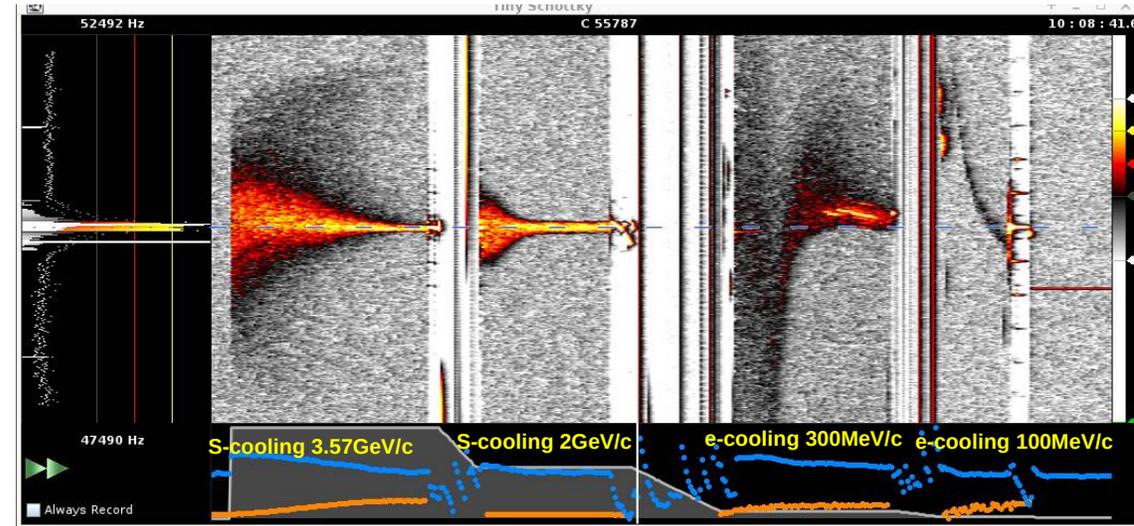
See W.Hofle JACoW-COOL2021-S302



See poster S.Rey JACoW-COOL2023-THPOSRP22

# Instrumentation: Schottky signals

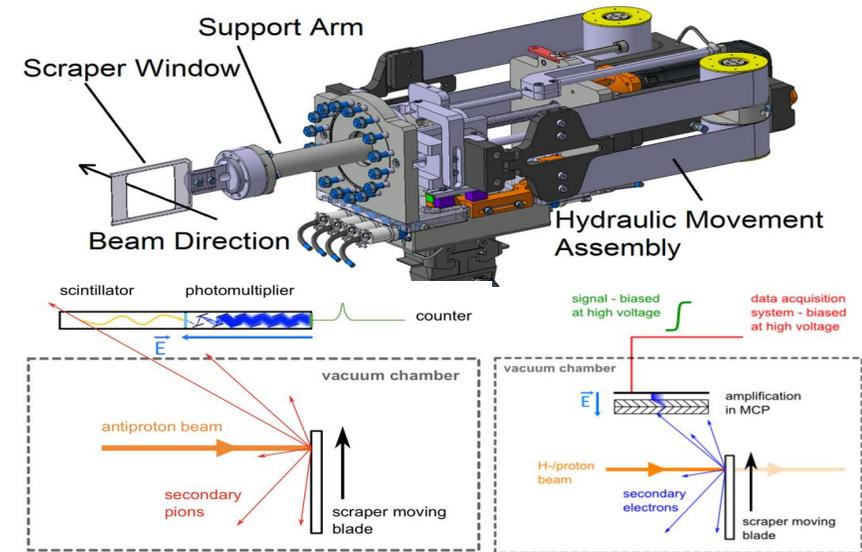
- Gives **real time information** on the coolings performances:
  - Main instrument for setting-up and diagnostics
- AD Schottky system:
  - Based on RF longitudinal pick-up
  - Spectrum analyser downmixed to around 50kHz on all cooling plateaus
- ELENA Schottky System:
  - Combining several Beam Position Monitors signal
    - See O. Marquversen et al. at [IBIC2021-WEPP04](#)
  - Same input signal as the radial loop, not used during physics production



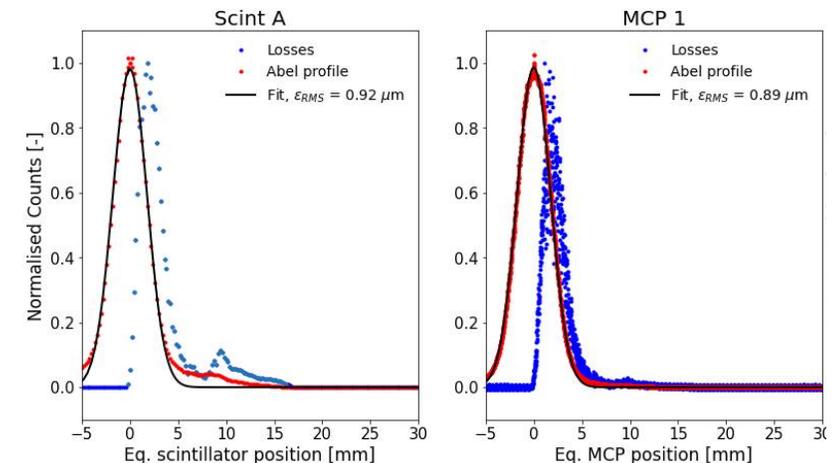
# Instrumentation: transverse beam profiles

- Mainly **destructive measurements** available based on scrapers:
  - Similar system with different Hardware in both AD and ELENA machines
  - Discrete measurements along the cycle, one plane at a time:
    - **Any optimization is very lengthy process** with an AD cycle length of 110s!
- **Reliability of signal** retrieval and interpretation sometimes **difficult**:
  - Controls issues, synchronisation
- A lot of beam time invested to develop operator independent measurement method to characterize the emittance evolution in AD

see [G. Russo @ HB2023](#)



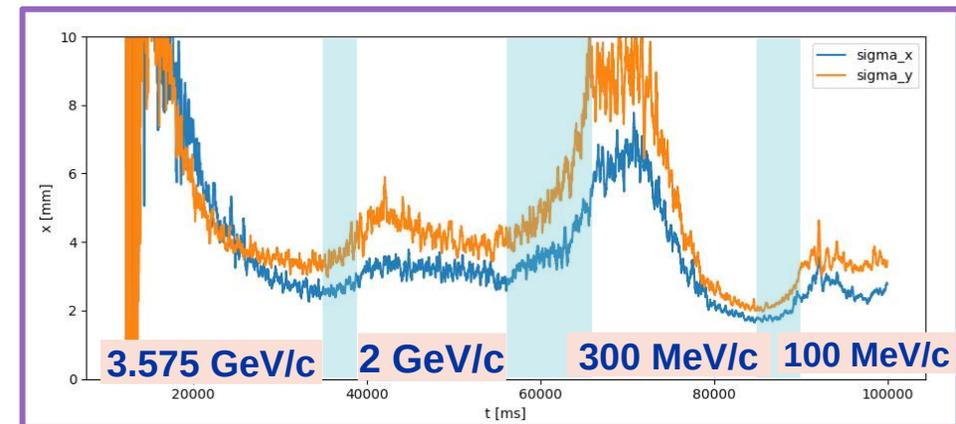
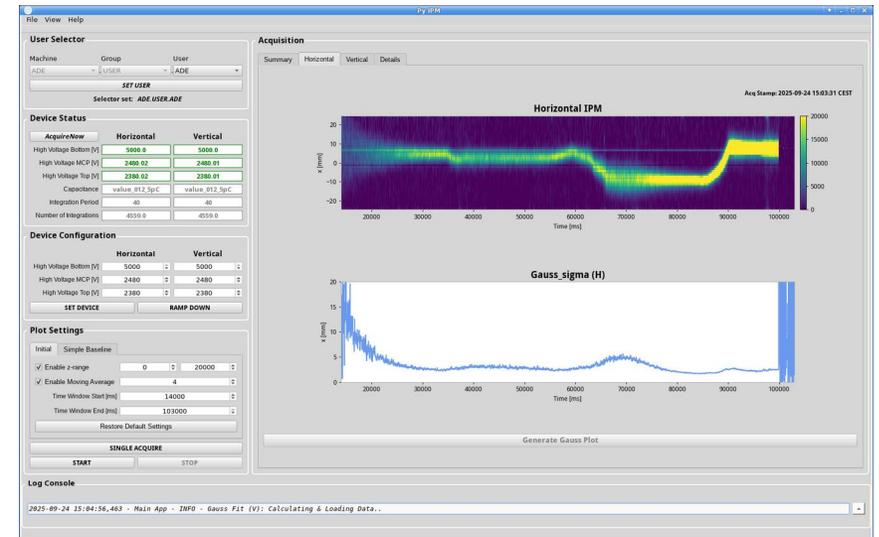
Courtesy P. Grandemange ([link](#))



# Instrumentation: transverse beam profiles

- On-going development in **non destructive method** to be used in during physics production as alternative to the scrapers method
- **Ionization Profile Monitor in AD:**
  - Gives both planes profiles all along the cycle, enhanced signal with gaz injection (affecting pbars lifetime)
  - Affecting trajectory of circulating beam => Need self-compensated devices or compensation scheme to be used during physics production
- **Neutral monitor** installed at the end of e-cooler section in ELENA:
  - Only for H<sup>-</sup>

See presentation G. Tranquille at COOL25 (THC1)

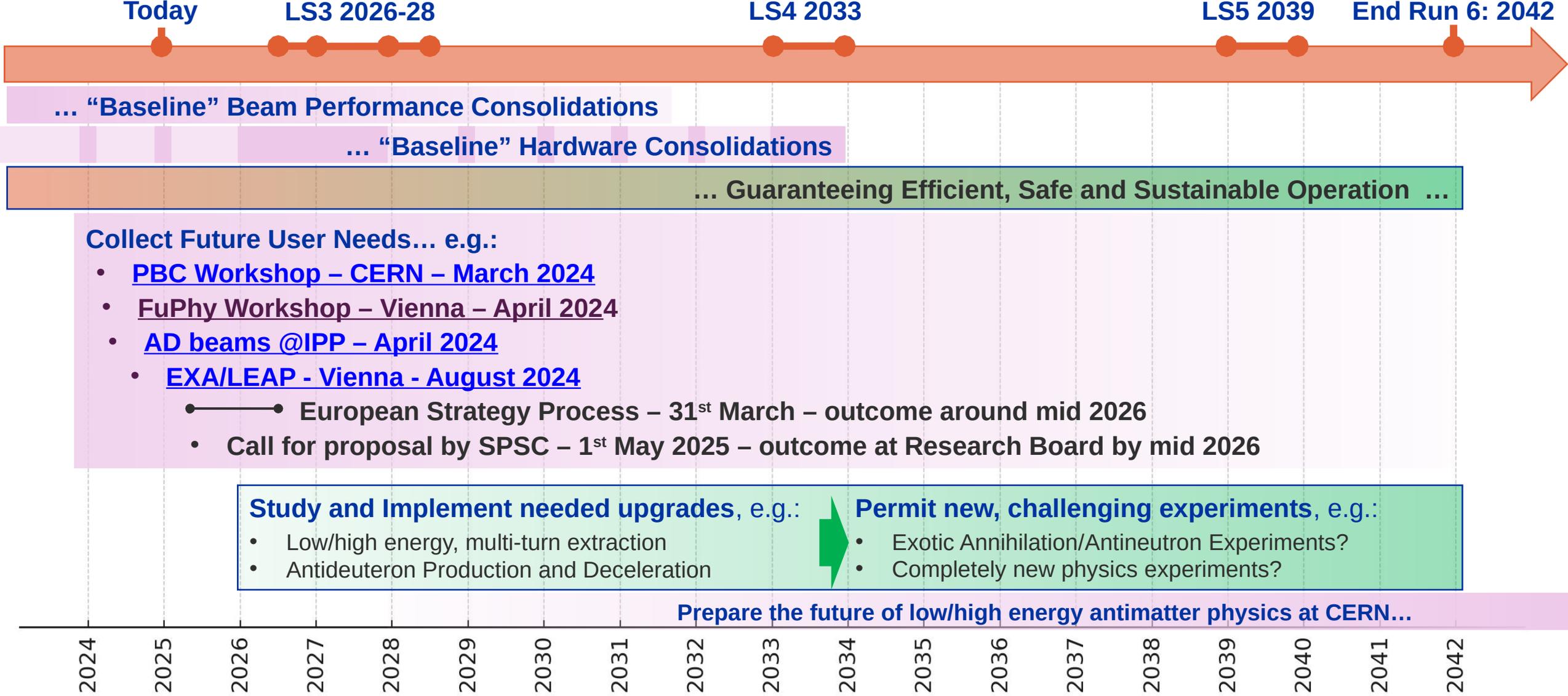


# What's the future of the complex?

# Current Facility perspectives: preparing the future

- **Hardware Aging, especially the AD!**
  - AD made from hardware recycled from the Antiproton Collector (AC) constructed in 1986
  - Ongoing **consolidation efforts** since the facility's early days
- **Looking beyond the horizon**
  - **Present experiments** have certainly another **10+ years of “things to do”** with present pbar beams and physics program
  - **Longer term: new (beam) requirements** should come early 2026 based on letters of intent submitted by the user community to the SPSC
    - **Higher pbar flux** for faster pbar/Hbar accumulation
    - **Higher(/lower) extraction energy** and/or **slow extraction** for antineutron production, hexaquark investigations, **Pontecorvo** reaction investigation
    - **Other types of particules to decelerate:** completely new experiments

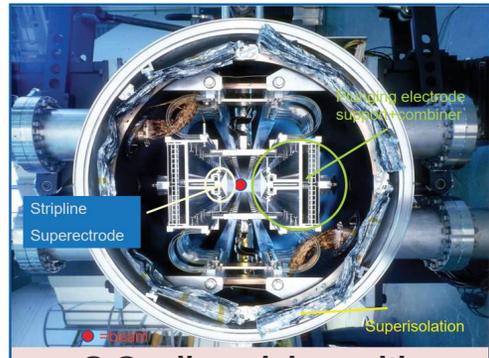
# Overall Long-Term Timeline for AD/ELENA (being discussed)



# Hardware: Most Critical/Aged Items



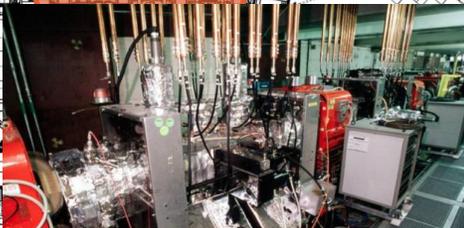
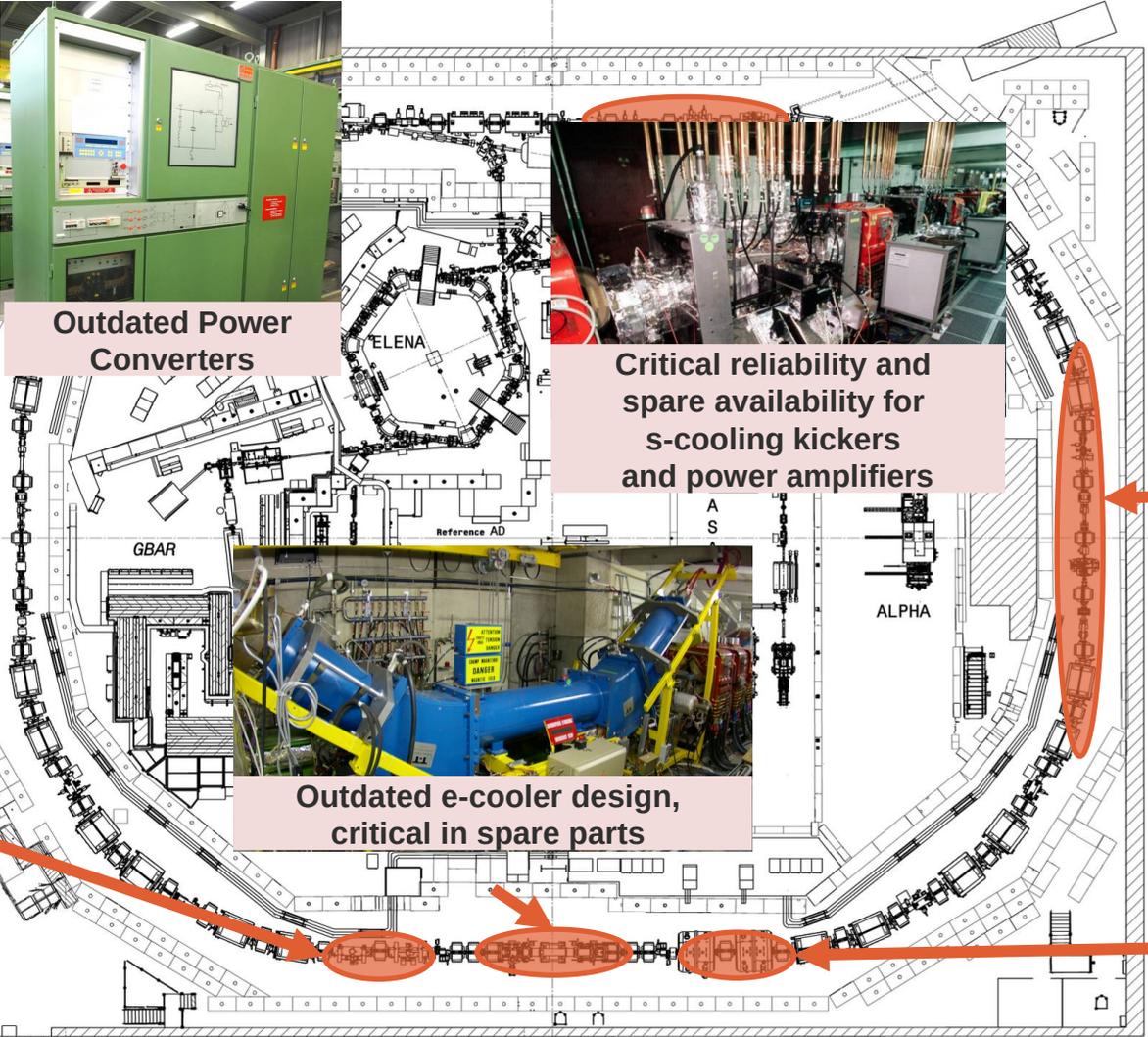
Injection line magnets with high risk of breakdown and no spare



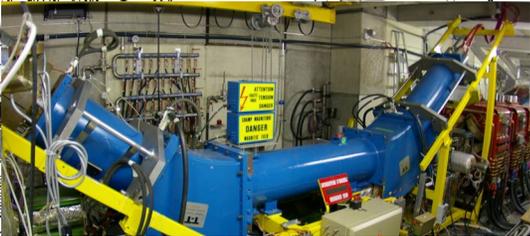
S-Cooling pickup with no spares, limited know-how



Outdated Power Converters



Critical reliability and spare availability for s-cooling kickers and power amplifiers



Outdated e-cooler design, critical in spare parts



Outdated (and not very "green") cooling and ventilation systems



AD magnets consolidation being finalised



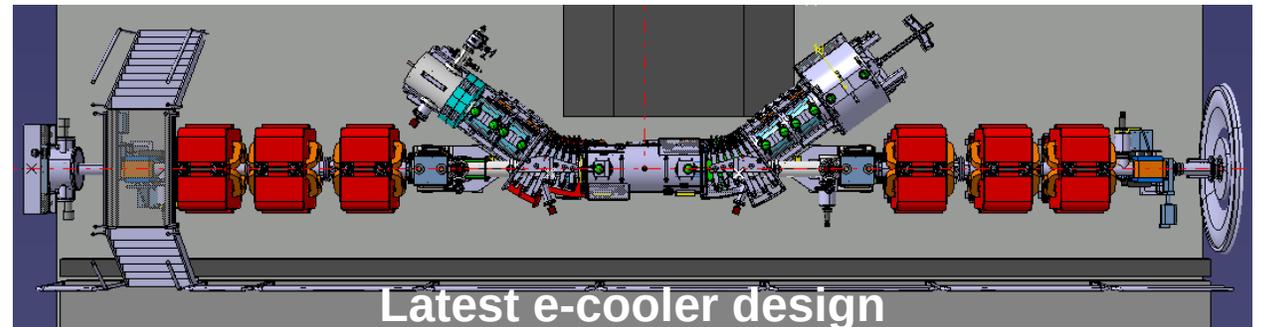
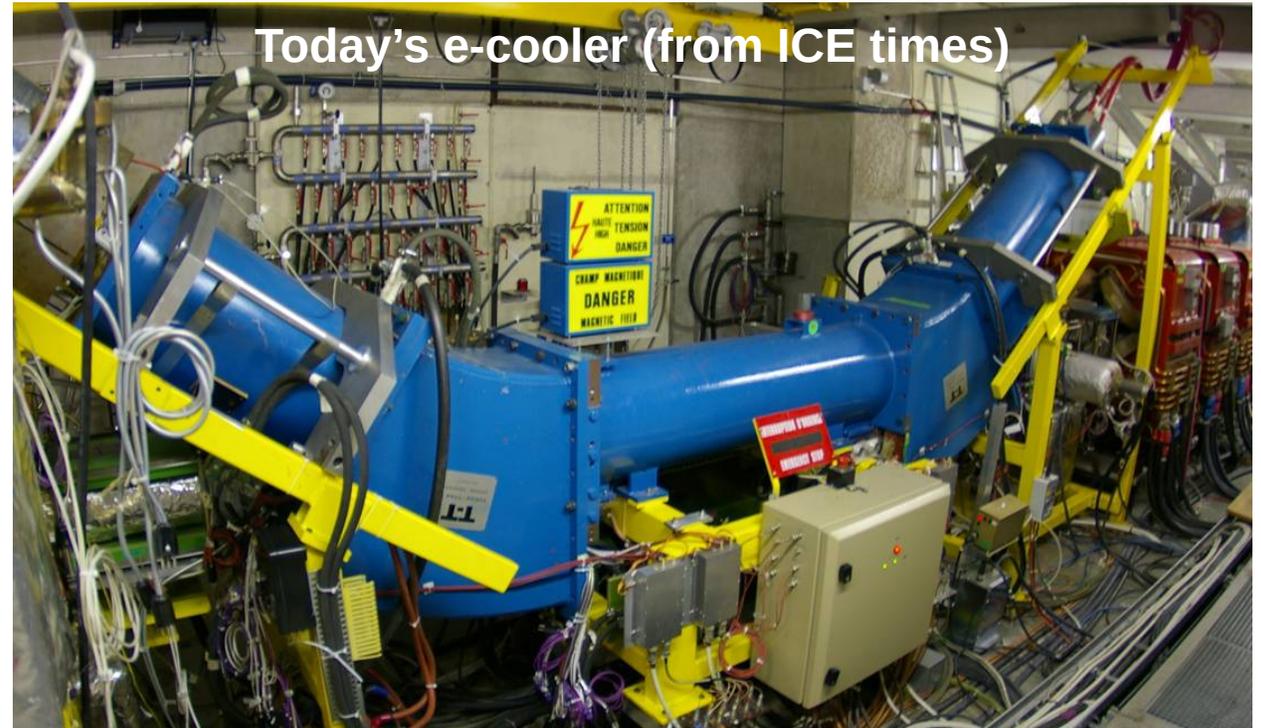
Outdated LLRF and HLRF for C10 cavities

# AD E-cooler Replacement during next Long Shutdown

- **Aims at:**
  - Improve reliability and solve critical spare situation
  - Improve the current performance to aim at :
    - 20% cycle length reduction
    - Reduce beam losses
    - Increase the max. e-cooler energy to 500 MeV/c
- **Several iterations on design to:**
  - improve magnetic field quality
  - Electron beam magnetic expansion
  - Better control over beams relative trajectories
  - Faster switching of the electron beam on/off
- **Installation foreseen for 2027-2028:**
  - Design is finalized
  - Gun and collector prototypes are being tested

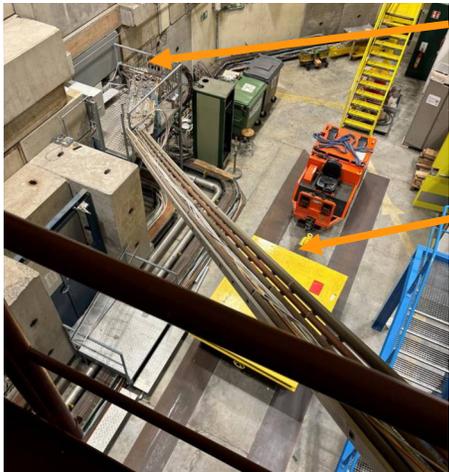
See presentation COOL25-WEA2 from G. Kathri

=> **challenging beam commissioning after LS3**



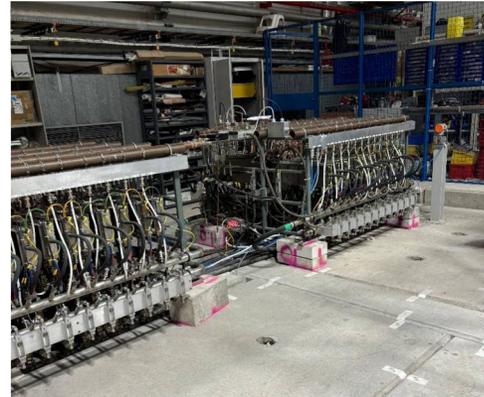
# Stochastic cooling consolidation: from AC to AD

- AC operated at fixed momentum (3.5 GeV/c) converted to a decelerator (AD)
  - In AC featured stochastic cooling at three frequency bands, habitually designated band I, II and III:
    - Band I covering 800 MHz to 1.6 GHz for initial part of cooling with the high frequency band II and band III system switched on later in the cycle
  - from the initial stochastic cooling system only the band I was retained => **slower cooling**
  - Adaptation also included making the band I system to **operate at 2 GeV/c, with some limitations**
- Stochastic cooling equipment needed to be adapted to the new higher standard vacuum requirements of AD due to deceleration of beam to low momentum



Fritz's platform close to the AD stochastic cooling pickups

Transmission lines going thru the middle of the Antimatter Factory



Rack containing 24 power amplifiers each

A kicker is fed with RF power by 24 coaxial transmission lines



# Possible future upgrades and improvements

- **Lowlevel consolidation**

- improved noise figure with new set of LNAs (keep these at ambient temperature)
- shape correctly bandwidth to limit effect of noise at lower frequency limits of the system
- roll-out and optimization of optical delay line notch filters series production for both energy plateaus

- **Power system**

- consolidate power system for higher operational efficiency and better power usage

- **New kicker design**

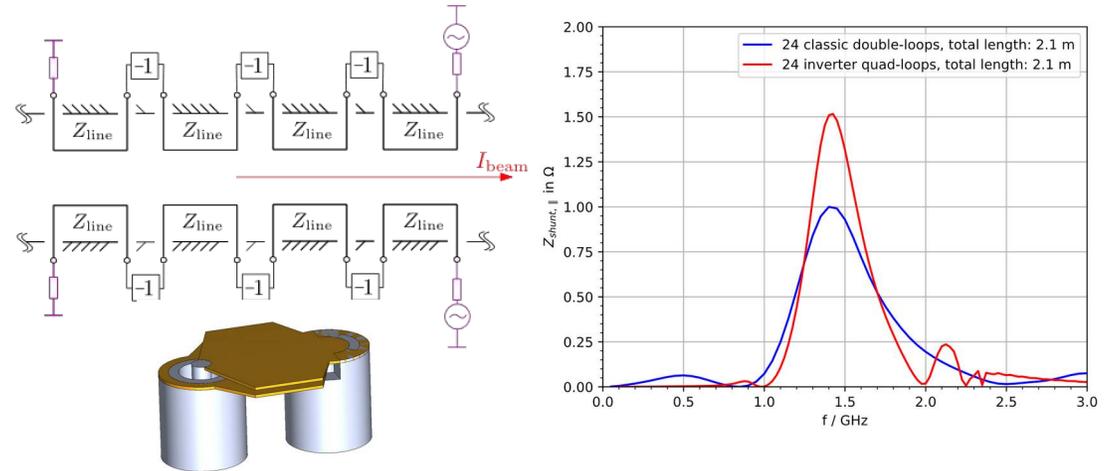
- fixed aperture
- inverter or multi-cell design

- **Operational improvements**

- explored optimization of gain during cooling to balance transverse and longitudinal cooling
- commission time of flight cooling to reduce losses between handover of bunch rotation system and stochastic cooling at 3.5 GeV/c
- profit from new flexible electronic phase shifter

- **Need to (re)-Establish a Beam Dynamics simulation framework**

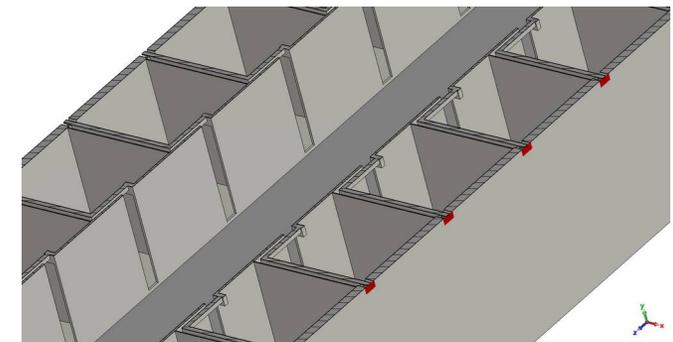
See presentation COOL25 (FRA2) from D. Gamba



Multi-electrode design with inverter

Thesis from **D.Sittard** <https://repository.cern/records/w1p7v-5y637>

Optical notch filter



slotted kicker design (**L. Thorndahl**)

# Summary

- Continuous increased performances for both AD and ELENA since the start of ELENA physics era in 2021:
  - AD/ELENA is the unique facility worldwide
  - Consistently delivering **1.3e7 antiprotons per bunch at 100 keV bi-minute to 4 users** at the same time within designed beam parameters (except transverse emittance)
  - **High satisfaction across the physics user community**
- Regular progress on performances stability thanks to improved diagnostics and setting-up methods
  - Regular machine development time dedicated for systems tests/developments
  - Importance of the **H<sup>-</sup> operation of ELENA for efficient setting-up**
- Preparing the future of the facility:
  - Collecting possible future experimental requirements to **intercept upgrade needs** while pursuing the **consolidation of aging hardware** in both machines
  - Profiting of the consolidation to **resolve longstanding limitations and improve performances**

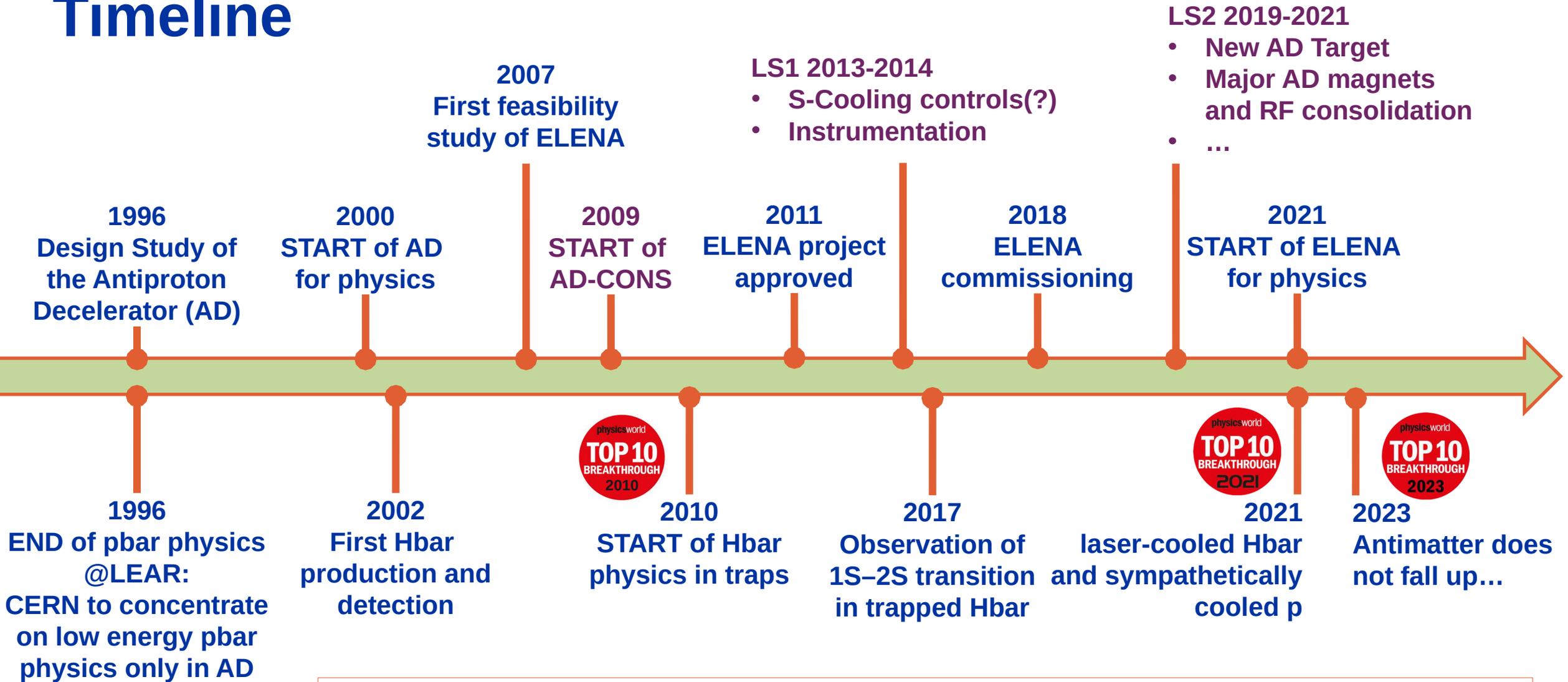
# Spares



# ELENA beam parameters summary

Parameter	design	Achieved in 2025
$Q_x/Q_y$	~2.3/~1.3	2.295/1.315
Cycle duration [s]	20	13
Injected intensity [pbars]	3e7	>6e7
Deceleration efficiency [%]	60	85
Extracted bunches	4	4
Bunch population [pbars]	4.5e6	> 1.3e7
$Dp/p_0$	5e-4	4.5e-4
Bunch length (rms) [ns]	75	<75
Transverse emittances x/y [ $\mu\text{m}$ ]	1.2/0.75	~2.7/~2.6

# Timeline



**Timestep between major results/changes: ~5-10 years**