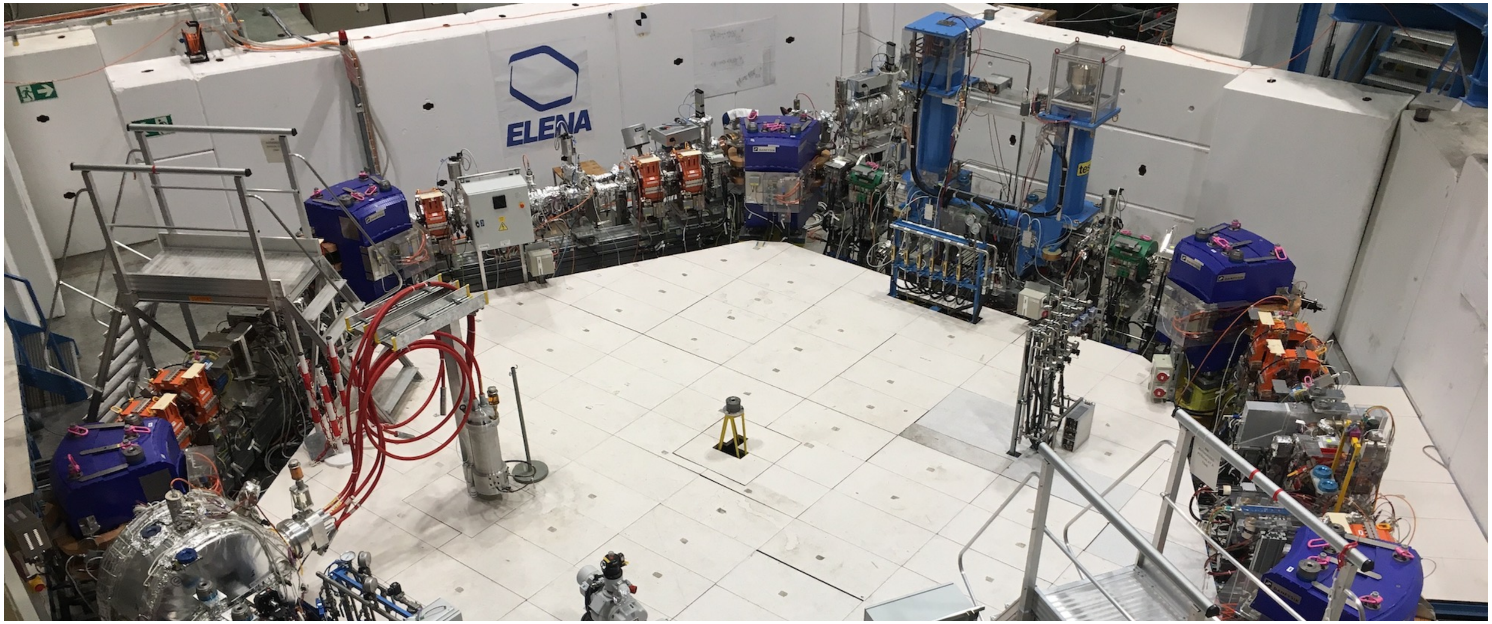
ELENA COMMISSIONING

D. Gamba* on behalf of the AD/ELENA collaboration

COOL2019 – 25th Sep 2019



- From AD to ELENA: an **overview**
- Status of **H$^-$, pbar, electron cooler commissioning**
- **First beam extracted** to experiments (**GBAR**)
- **Current Activities and Plans** for **CERN Long Shutdown 2 (LS2)**

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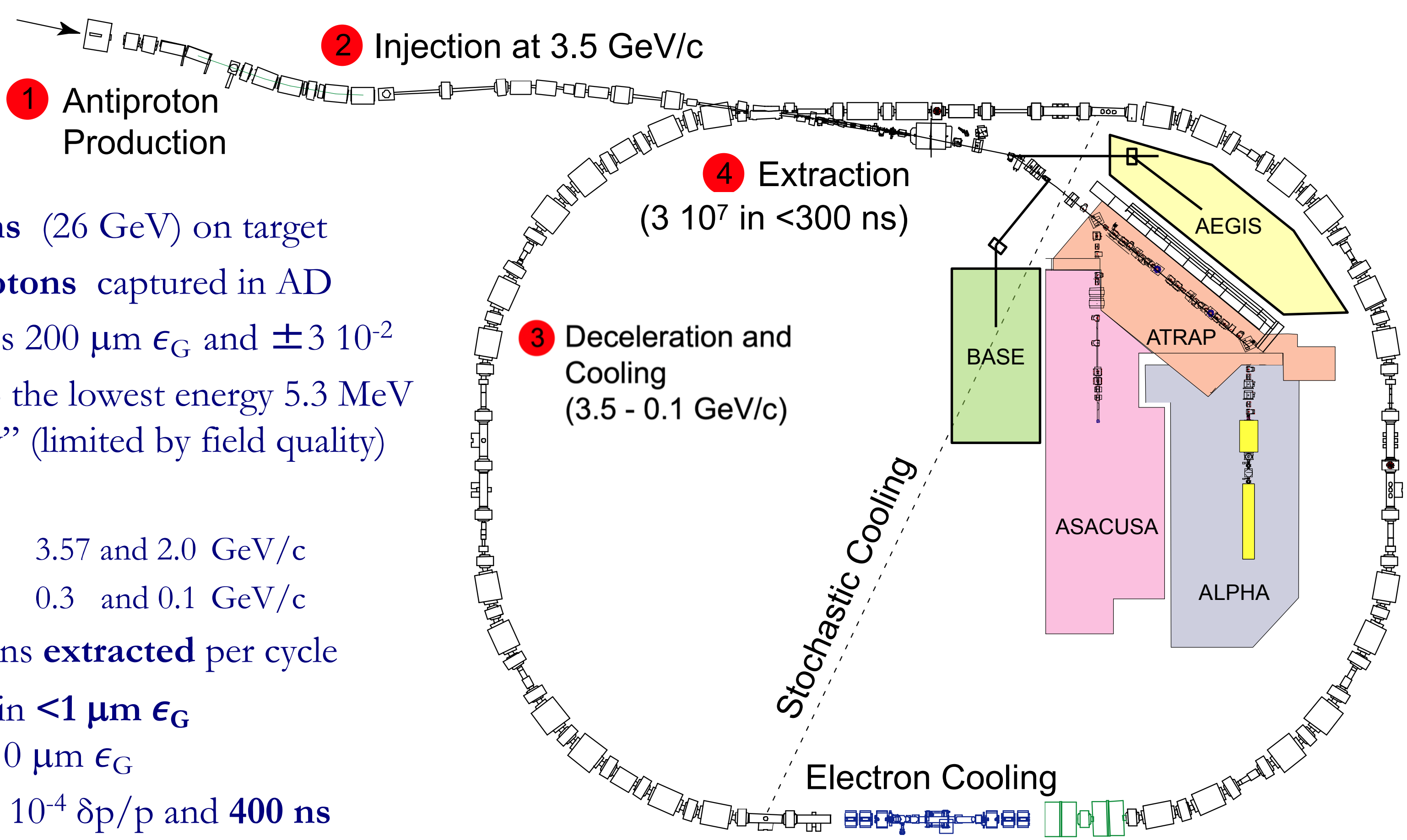
AD – a unique facility providing 5.3 MeV antiprotons

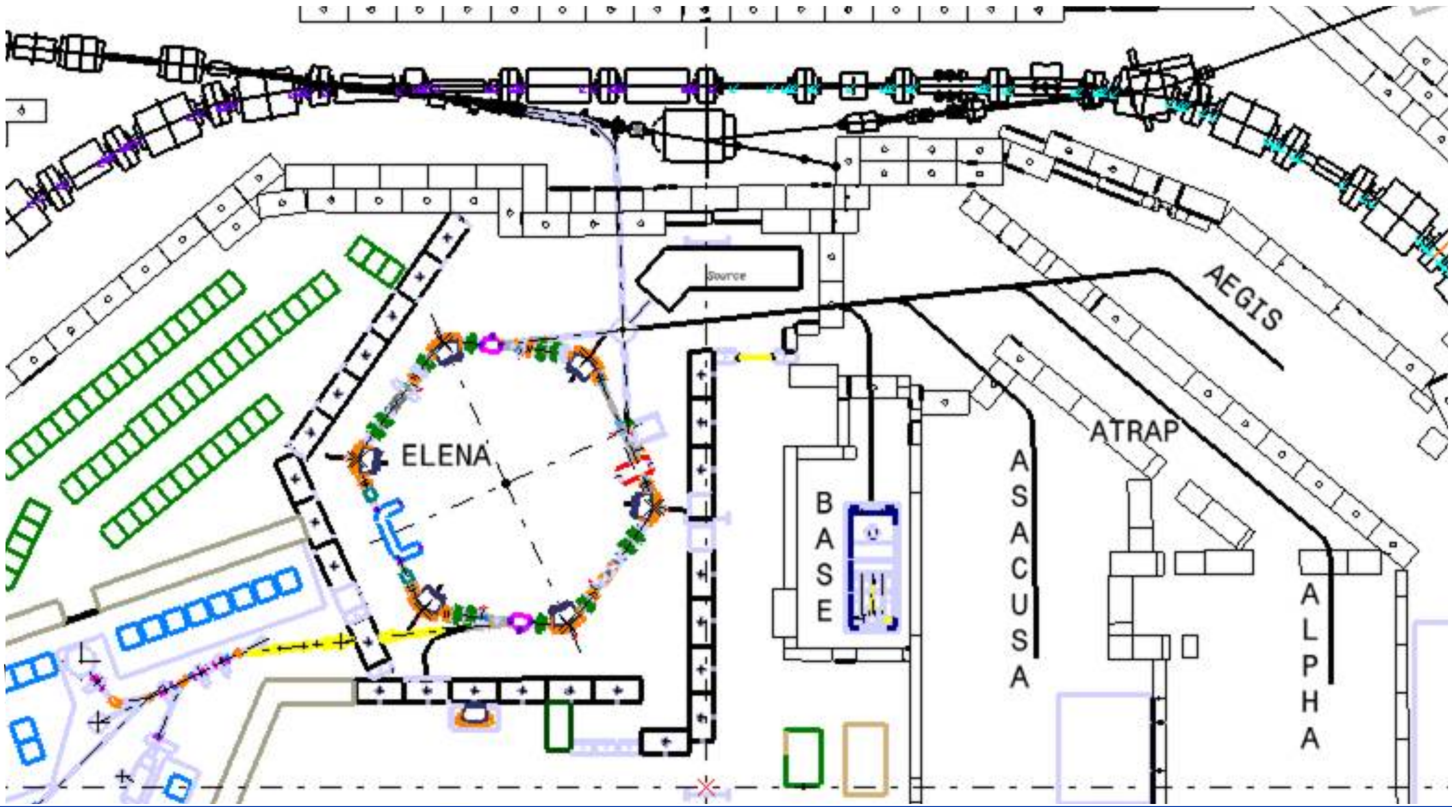


- **~1.5 10^{13} protons** (26 GeV) on target
- **~3.5 10^{7} antiprotons** captured in AD
  - Acceptances 200 µm ϵ_G and ±3 10^{-2}
- **Deceleration** to the lowest energy 5.3 MeV reachable "safely" (limited by field quality)
- **Beam cooling**
  - **Stochastic** 3.57 and 2.0 GeV/c
  - **Electron** 0.3 and 0.1 GeV/c
- **~3 10^{7}** antiprotons **extracted** per cycle
  - ~70% within **<1 µm ϵ_G**
    tails up to 10 µm ϵ_G
  - 95% within 10^{-4} δp/p and **400 ns** (before bunch rotation)
- **Vacuum pressure: ~10^{-10} mbar**
- **Cycle length ~100 s**

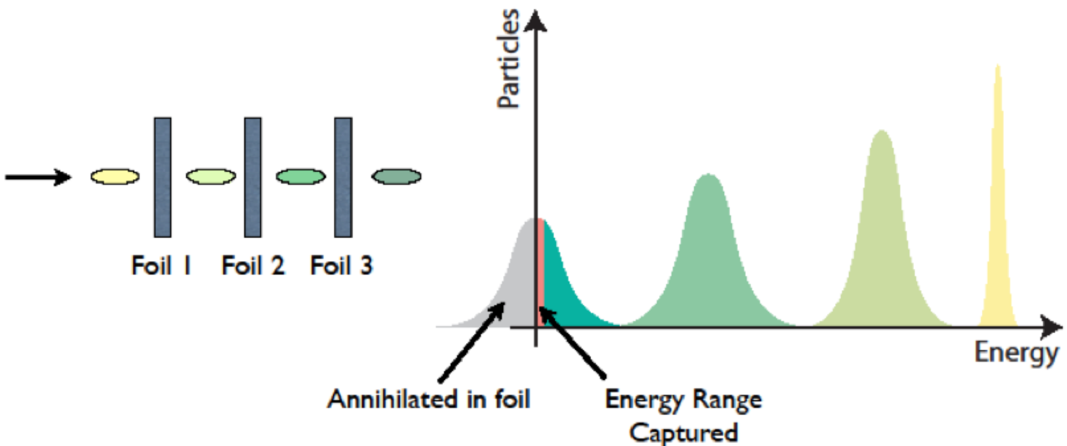
Sketch of the "present" AD
circumference 182 m

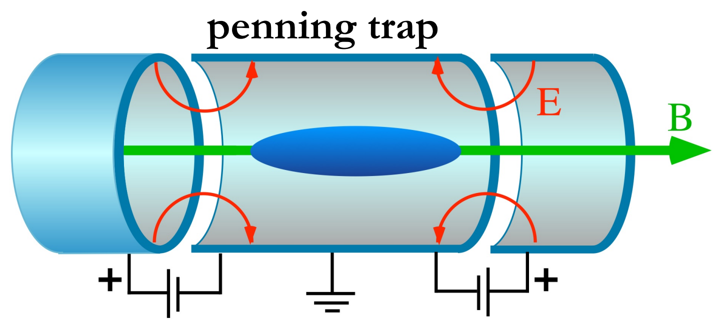
First ELENA proposal

- Since **Villars (Aug 2004)** the **SPSC** has **supported** the **implementation** of the **ELENA** decelerator ring **for AD**
  - **Pbar deceleration down to 100 keV** to increase pbar trapping efficiency
  - (**First ideas** for such a ring **for LEAR** were proposed in **1982 - CM-P00059041**)
- **CERN Research Board approved construction in June 2011**



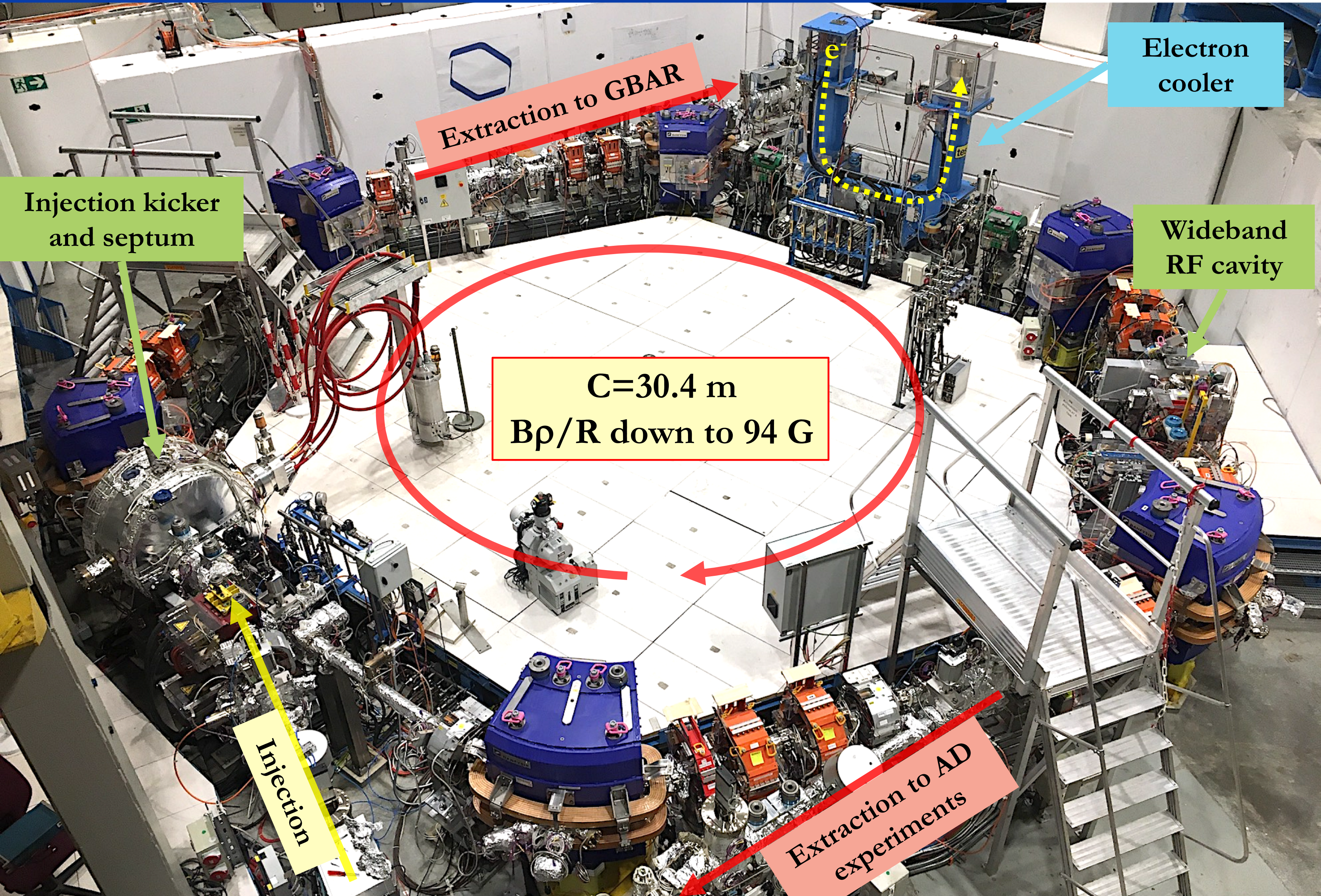
Why ELENA ?
= Extra Low ENergy Antiproton ring



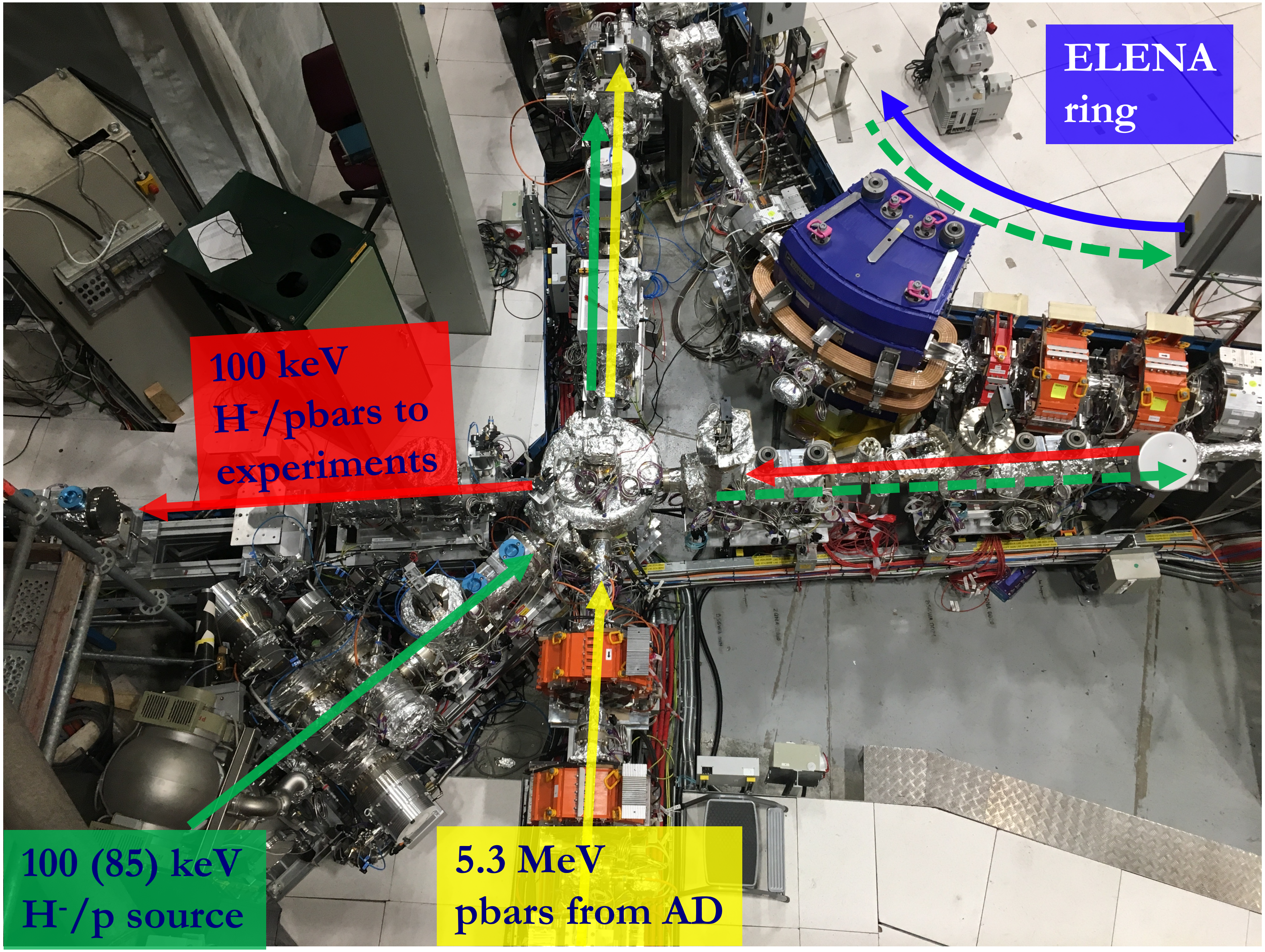


- To be able to **capture antiprotons in penning traps**, **most experiments** **use degrader foils** to further **decelerate** the **5.3 MeV** antiprotons coming from AD **to a few keV**.
- Energy straggling increases energy spread such that **only a few antiprotons can be captured (< 1%)**; even with optimized foil thickness
  - Almost **half of the incoming pbars** are **stopped in foil**, where they annihilate
  - Almost **half of the incoming pbars** are **too energetic** to be trapped
- **ASACUSA decelerates antiprotons** with an **RFQ**
  - they achieved about **one order of magnitude higher trapping efficiencies**
- **ELENA** will provide **100 keV antiprotons** (**over 4 bunches** => serving 4 experiments)
  - **Expected two order of magnitude higher trapping efficiency**
- Other **requirements from experiments:**
  - **Beam size** on foil small enough (rms size **<1 mm**); full **bunch length** less than **<300 ns**

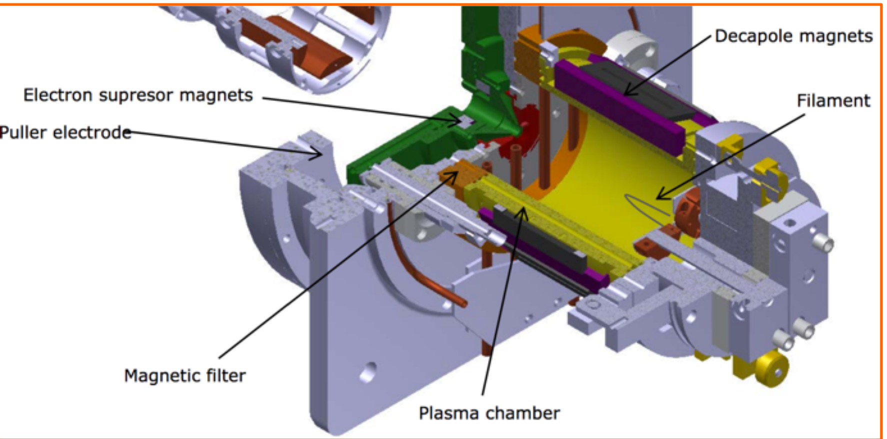
ELENA Ring – 2018



ELENA Injection/Extraction



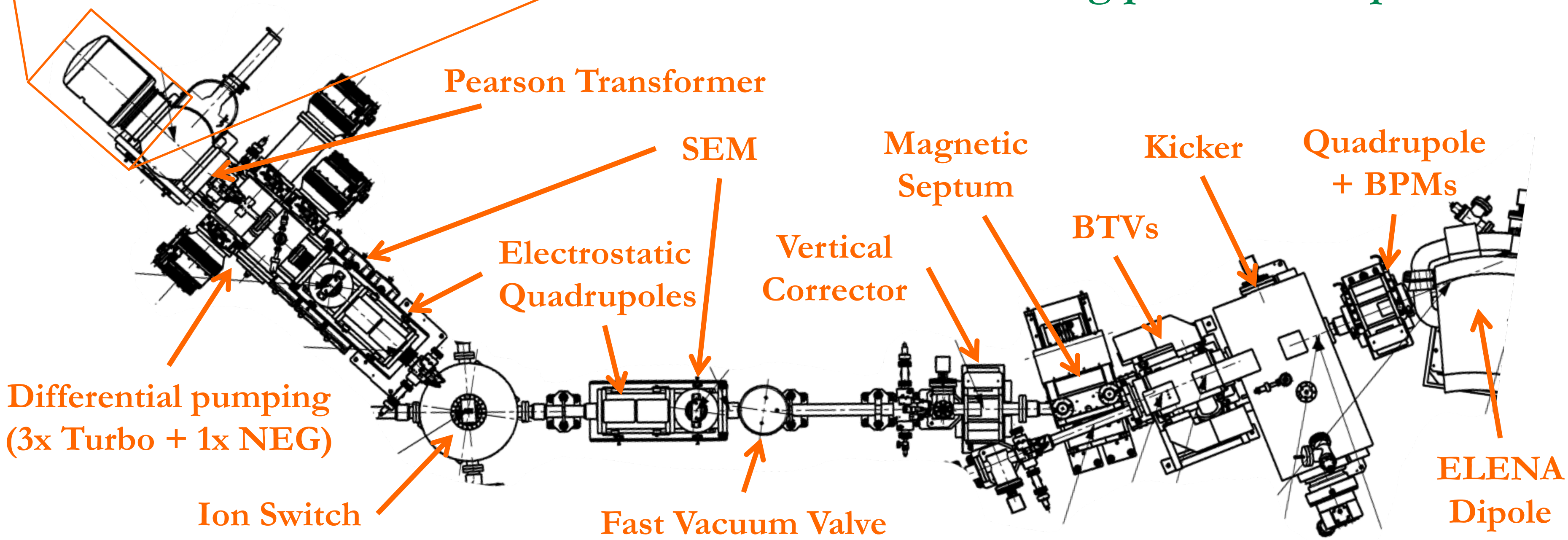
H$^-$ (or p): from Source to Ring



Only DC Power Supplies control via PLC in Faraday Cage

Wish list:

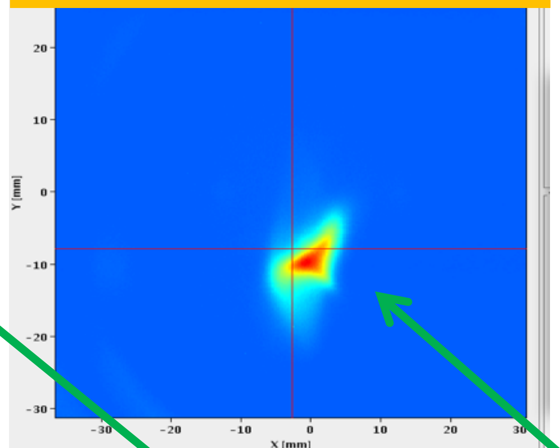
- ~100 uA; ~1 us; ~square pulses
  - Only 650 ns-long pulses injectable by kicker
- Good Stability/Repeatability
  - order ~1% for intensity and beam shape
  - order ~0.1% better for energy
- Aim: progress as much as possible without taking precious antiprotons



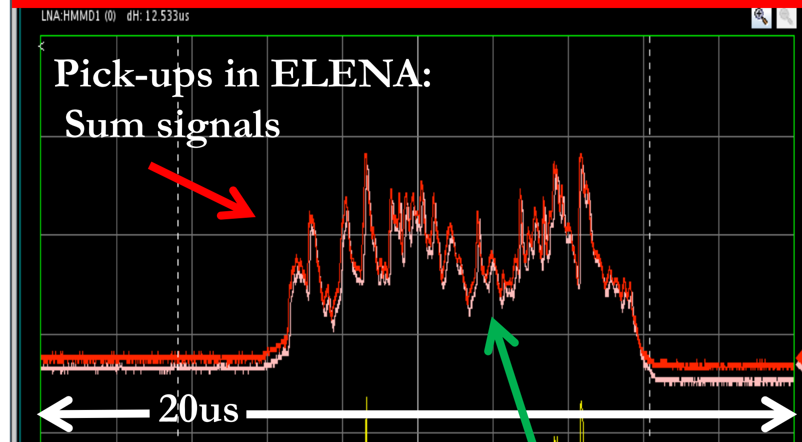
Beam observations

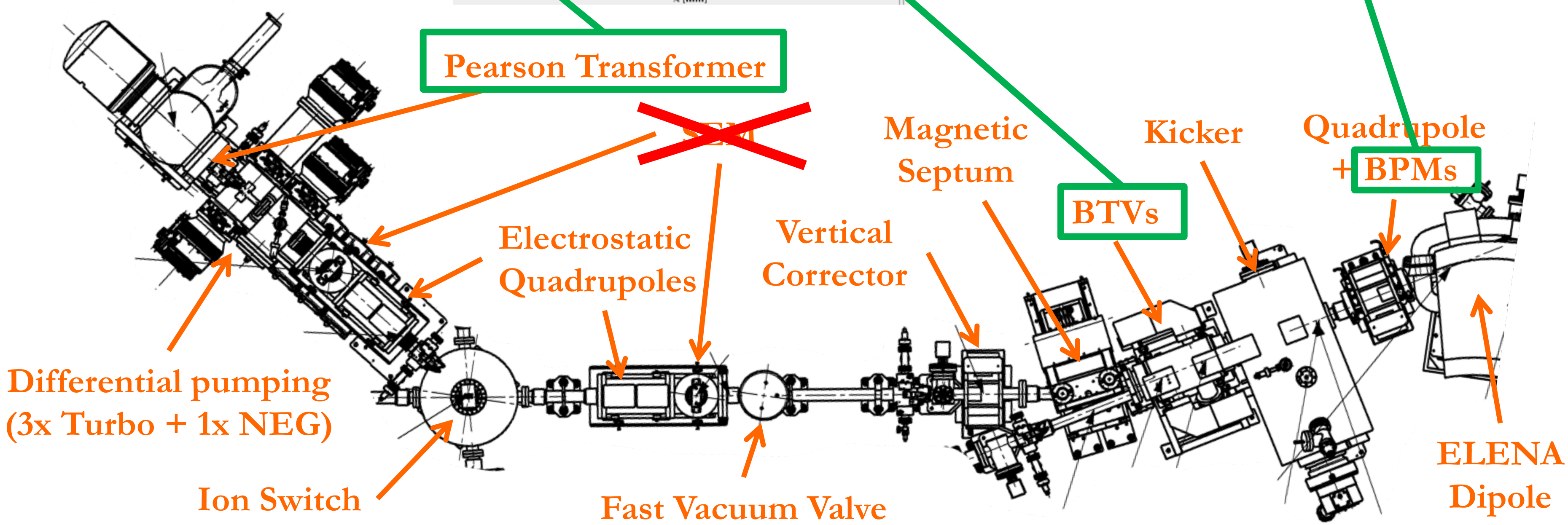
Possible to make ~100 uA beams @source

Poor pointing stability after some time, sometimes



Shot-to-shot, Intra-pulse, Intensity Instability in ELENA

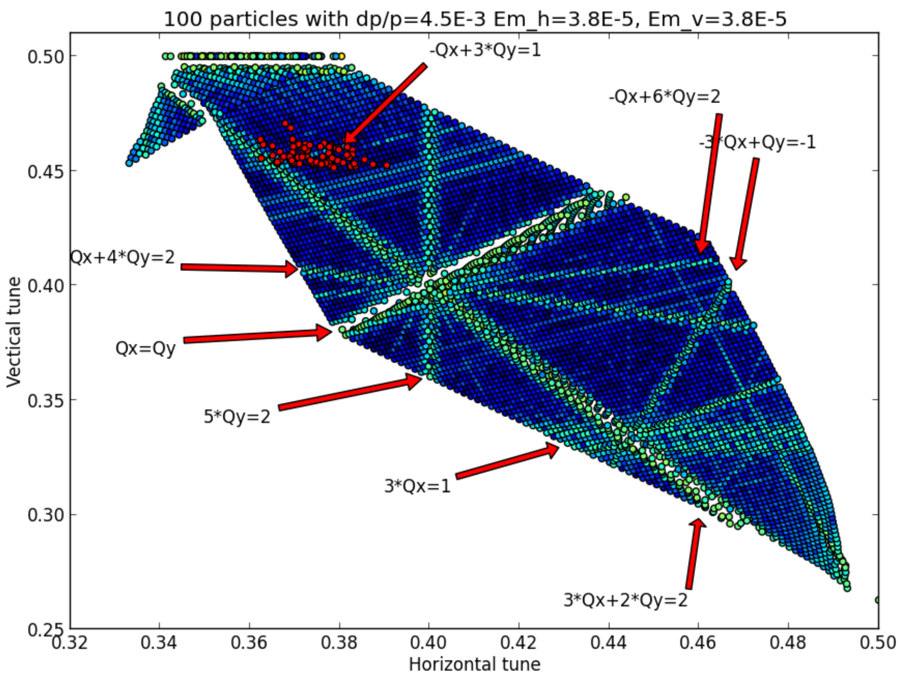




Exploring tune diagram with H-

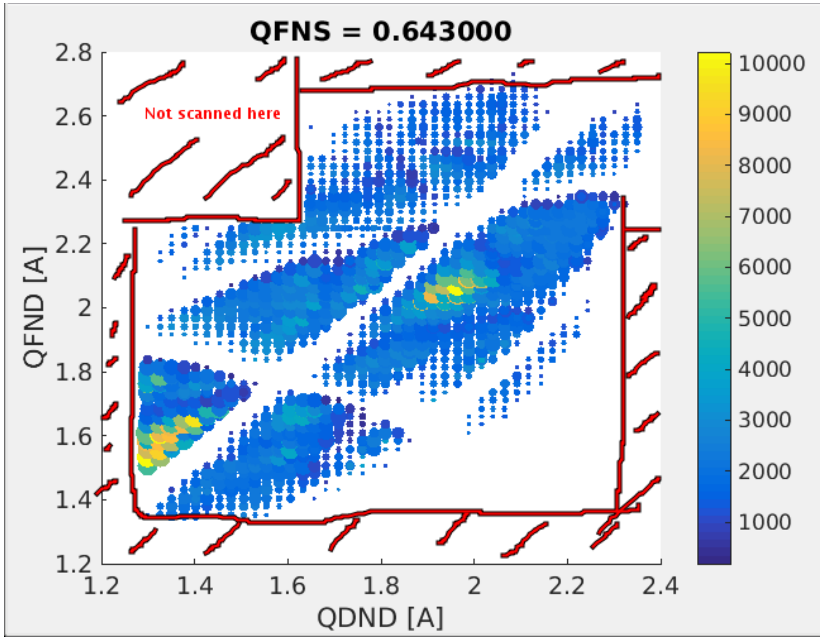
Simulations

- **Custom-made code** to study tune diagram by L. Bojtar
  - Detailed magnetic field map of full ring
- Machine model predicts **strong resonances**/small portion of tune diagram "available" for beam.

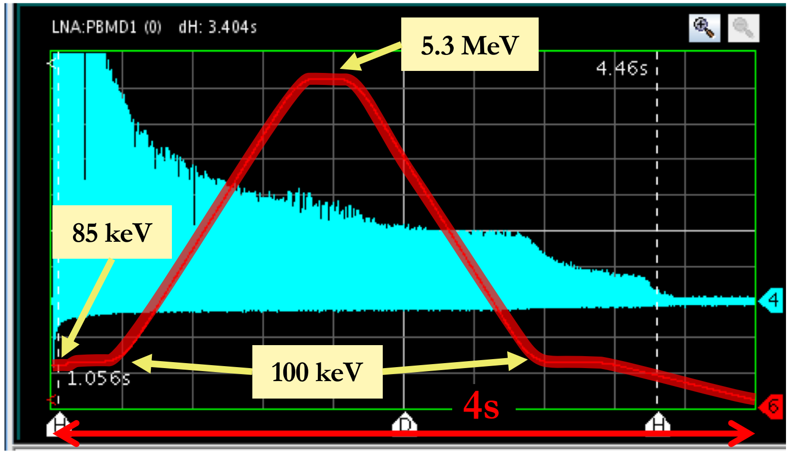


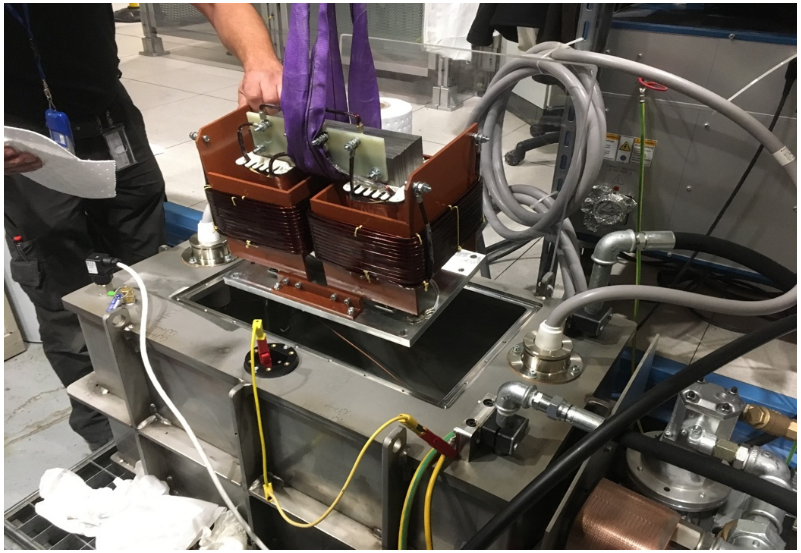
Measurements

- Profiting of "fast" and "cheap" H- cycles to **explore tune diagram with beam**
- Here an example of **measured "lifetime"** as a function of different quadrupole settings at 85 keV
  - **Preliminary data analysis**



H- Status: a "full cycle"





- Accelerating cycle:
  - From 85 keV to 100 keV
  - From 100 keV to 5.3 MeV
  - Back to 100 keV.
- **H^-** also used for **GBAR commissioning**
  - **First experiment taking ELENA beam**
- **H^- lifetime (~a few s) main limitation** for long cycles, and/or e-cooling studies
  - **Somewhat shorter than expectation** from rest-gas interaction, but not too far…

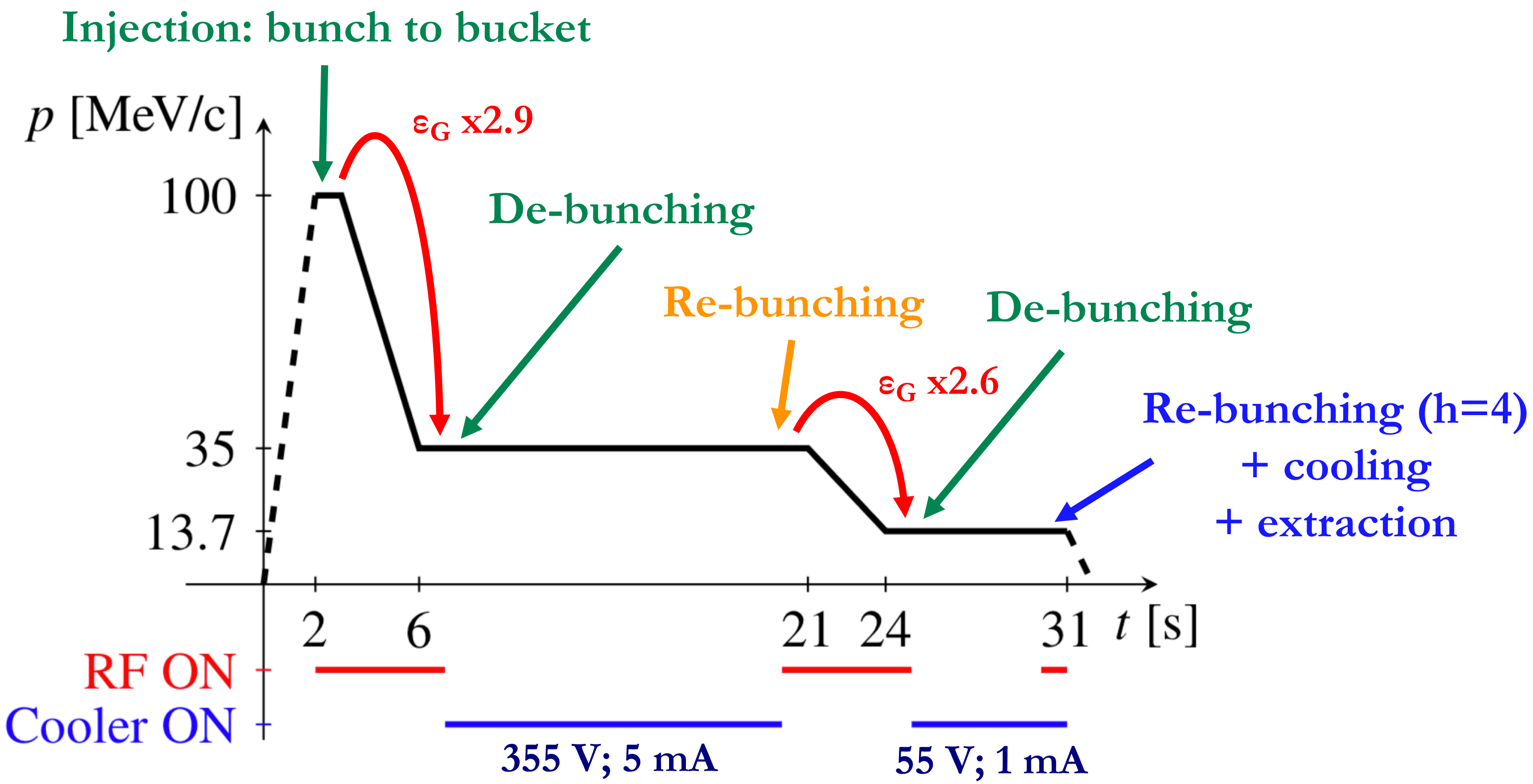
- Unfortunately we had many **issues** with **HV insulation transformer**
- **Only a few month operations in 2018 at 85 keV instead of nominal 100 keV**

- **H^- only used for sub-system (e.g. RF, timing) commissioning, ELENA optics, and transfer line to GBAR experiment.**

Commissioning With Pbars

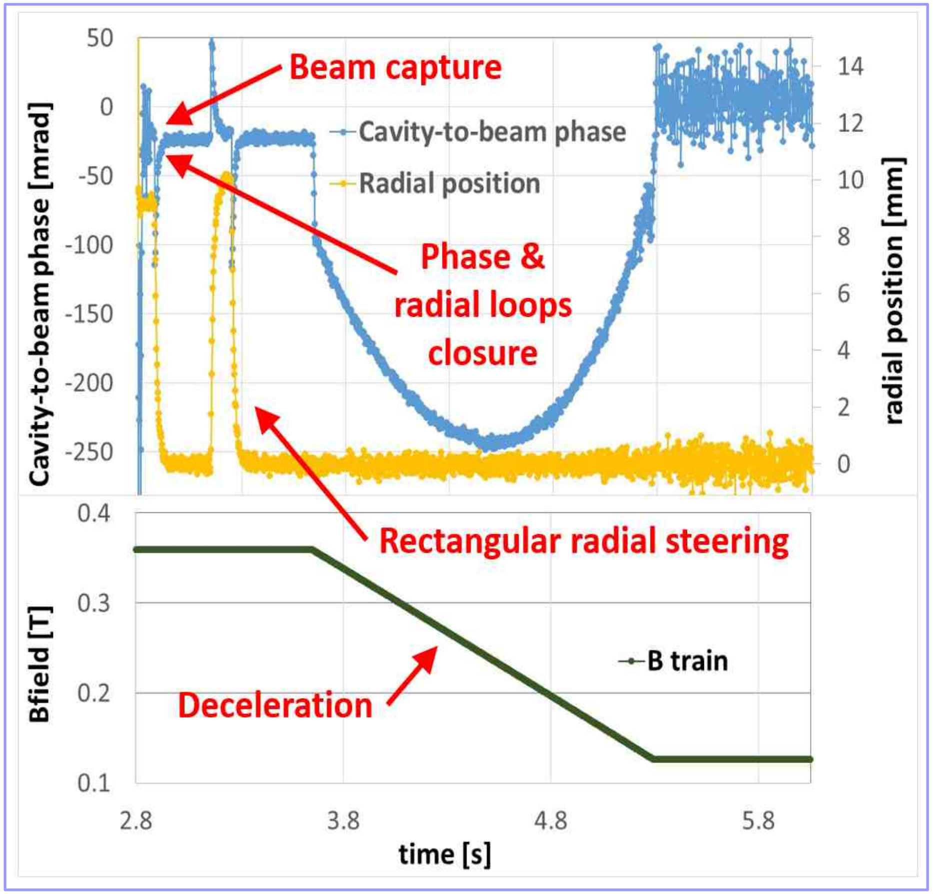
ELENA Decelerating Cycle

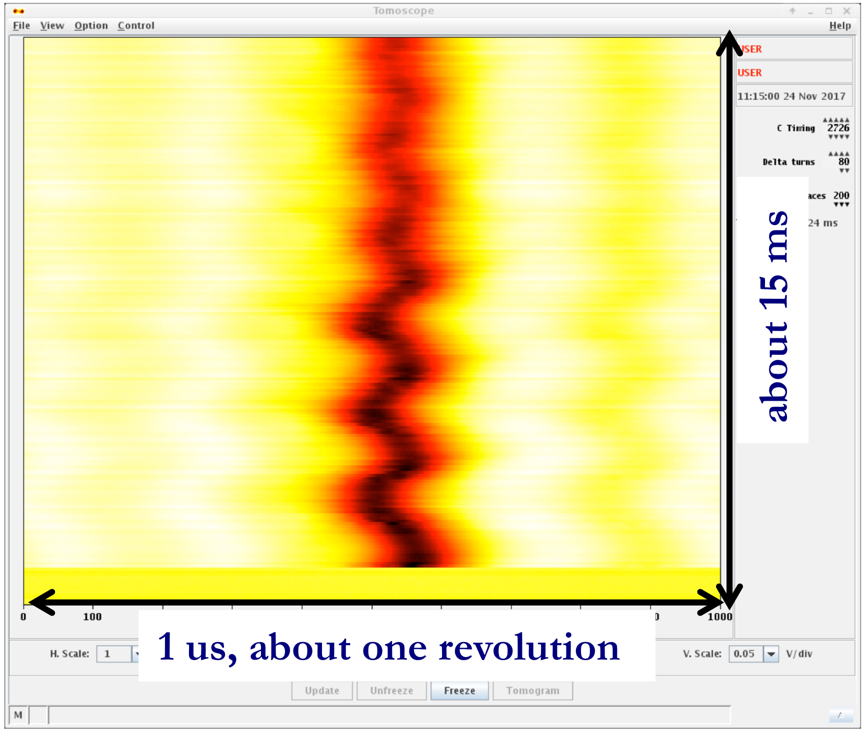
- **Beam arrives** already "**cooled**" from AD ($\varepsilon_G \approx 1\ \mu m$)
  - Deceleration starts "immediately".
- **Two deceleration steps** with cooling to compensate for adiabatic blow-up
- **Extraction of 4 bunches** ($\sigma_t \approx 75$ ns, $\varepsilon_G \approx 1\ \mu m$, $\sigma_p = 5e\text{-}4$, $\#_{pbar/bunch} = 4.5e6$)



Injecting Antiprotons from the AD

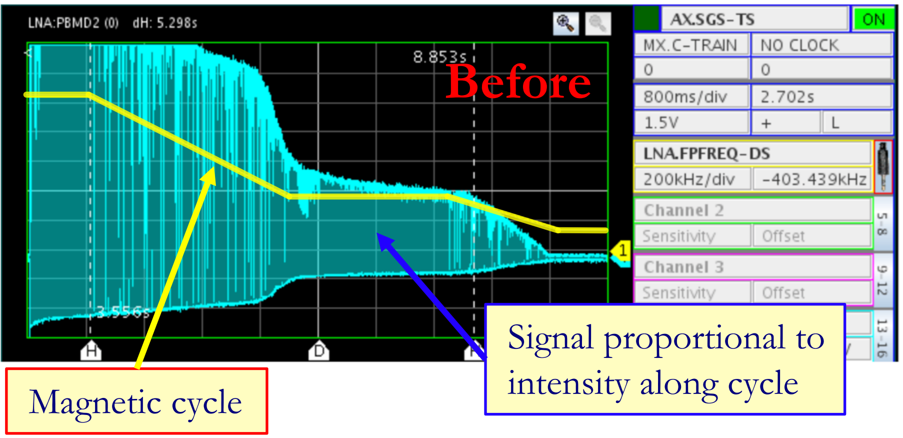
- **Bunch to bucket** transfer between **AD** and **ELENA** (~ 3.2E7 pbars) and deceleration with **phase** and **radial loops**

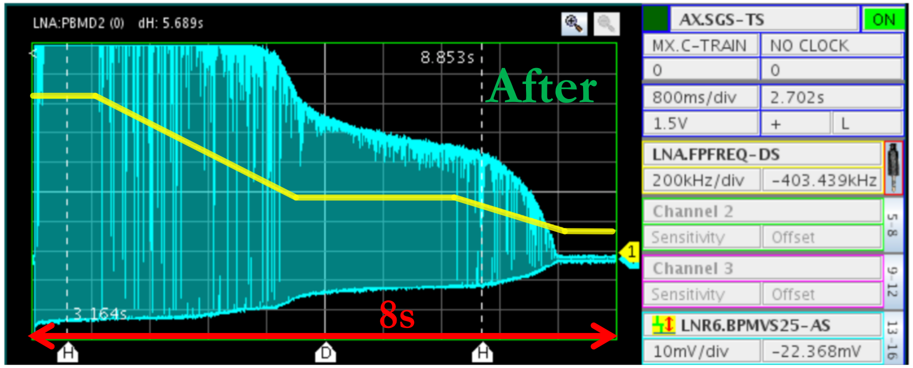




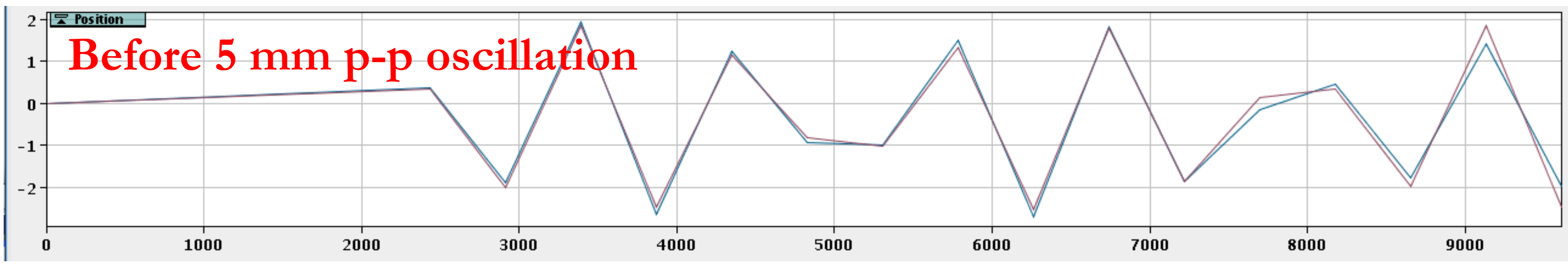
Bunch transferred into ELENA waiting bucket - Phase loop damps synchrotron oscillations

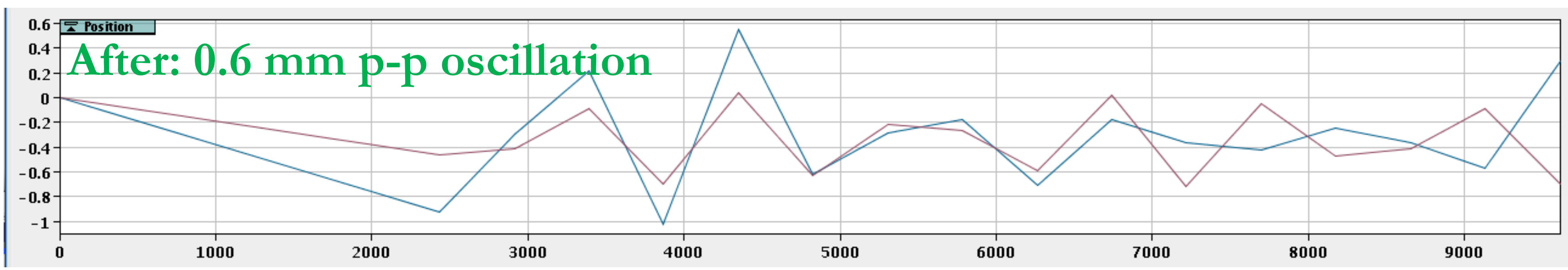
First decelerating cycles:
Impact and correction of injection orbit





- **Orbit correction** in injection transfer line to **match** ELENA **closed orbit**

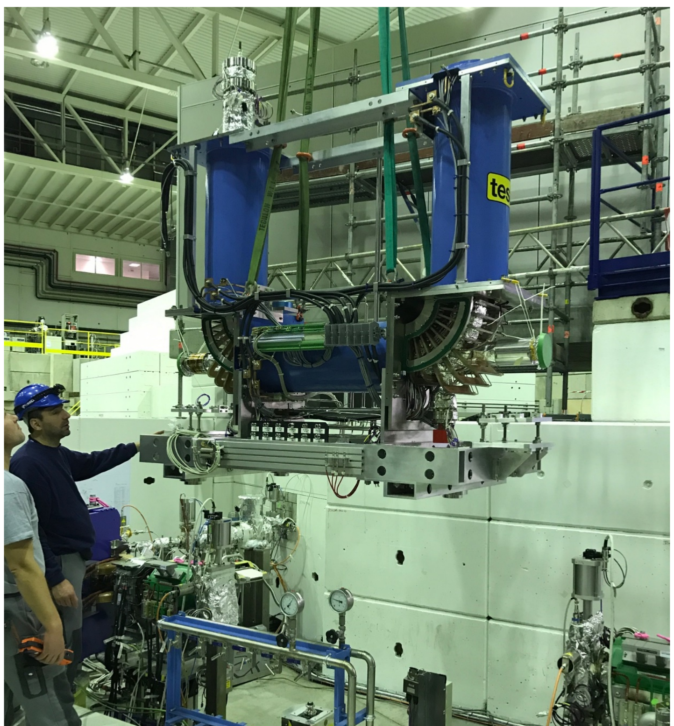




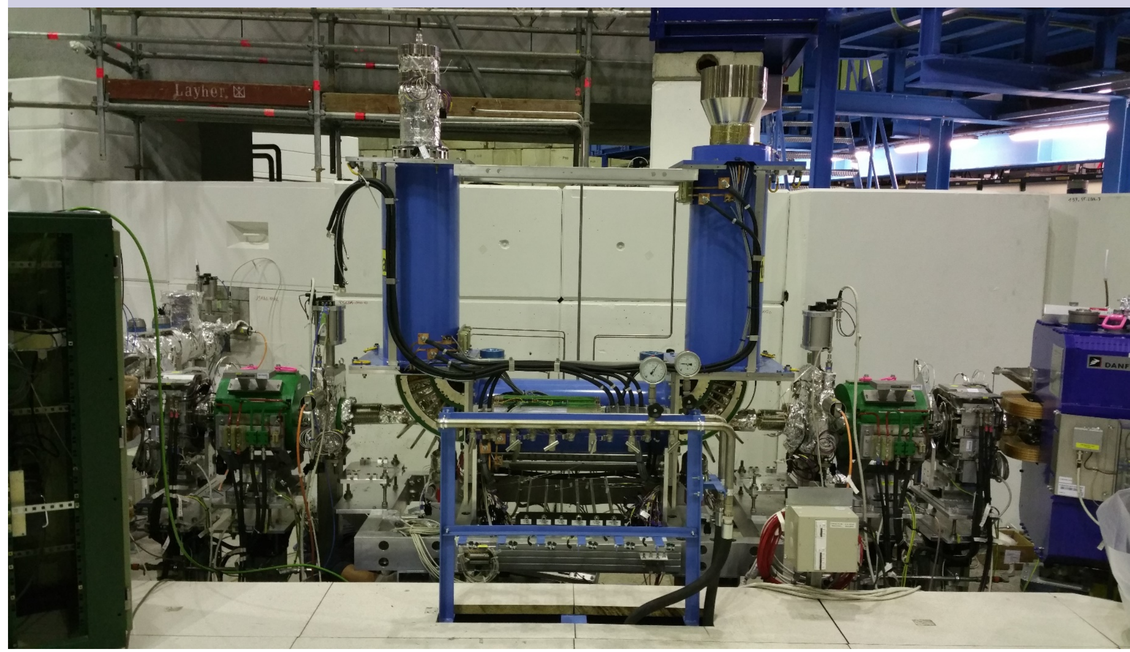
From B. Lefort (link)

ELENA Electron Cooler

- Design based on L-LSR e-cooler (Kyoto)
- Cooler **installed** beginning of **December 2017**
  - Unfortunately, a **vacuum leak** developed after first bake-out
- Cooler **taken out** for dismounting and repair at the beginning of 2019
  - **ELENA restarted delayed to April 2018**

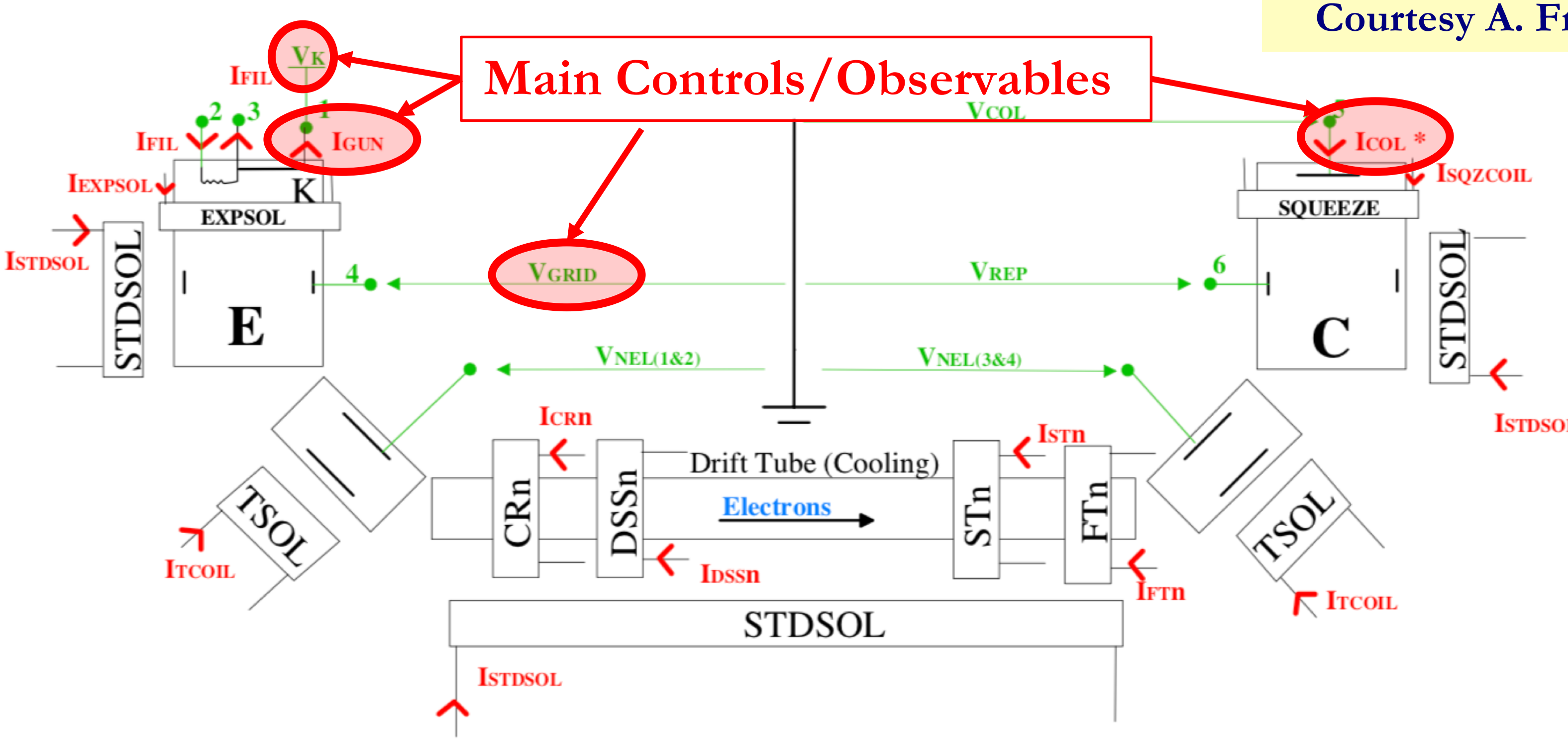


e-cooler fully available in July 2018



ELENA Electron Cooler

Courtesy A. Frassier



pbar p/β_{rel} [MeV/c]/[c]	35/0.037	13.7/0.015
e− current (mA)	5	1
B gun/drift (G)	1000/100	
Cathode radius (mm)	8	
e- beam radius (mm)	25	
Twiss parameters (m)	β_x=2.1, β_y=2.2, D_x=1.5	

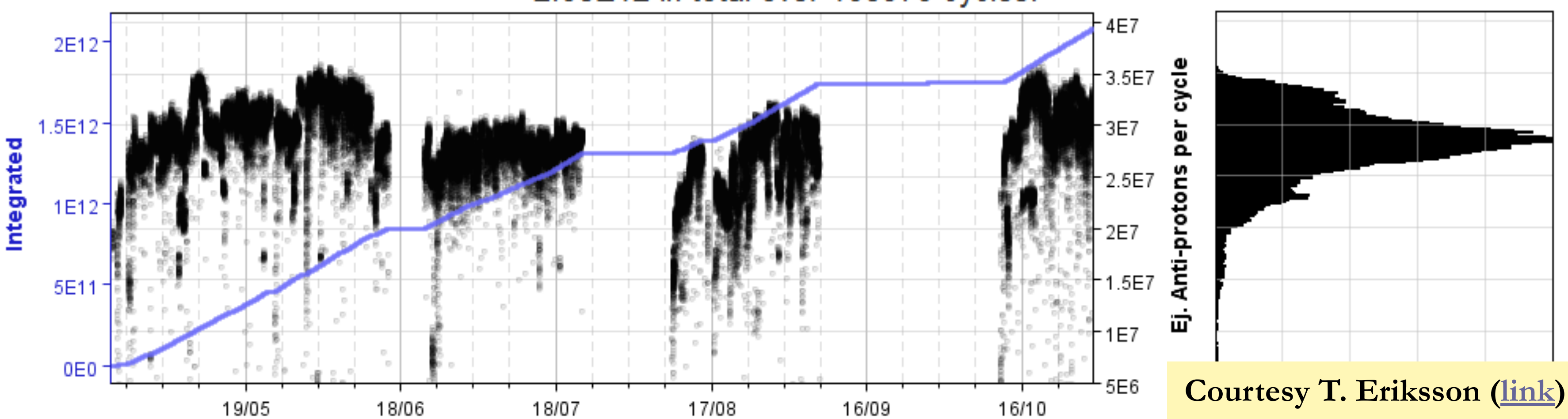
- Complex/flexible design with **many correctors** needed to achieve **specifications:**

$$B_\perp / B_\parallel \leq 5 \times 10^{-4}$$

  - Magnetic field carefully measure and corrected before installation
- Most **PC referred** to **ground**

Beam availability in 2018

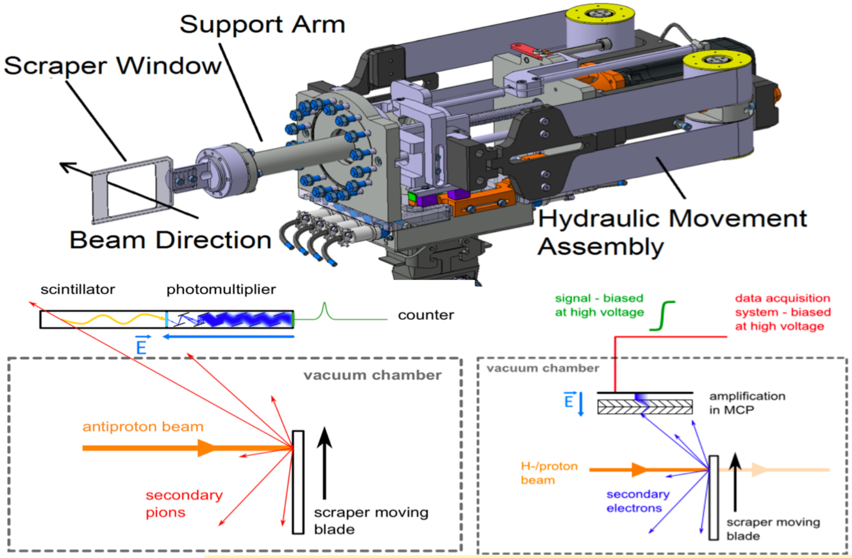
- E-cooler **studies** (so far) **only possible with *pbars* from AD**
  - **No attempt** of ***p*** beam from **source; limited attempts** with **H⁻**
- AD cycle length ~110 s; MD shifts of 8 h each
  - About **33 shots/hour**; **260 shots/MD shift**
  - Typically **2 to 3 MDs per week ≈ 10% of time**
  - **Unfortunate year for AD** (about 62% availability = 4400h)
    - **i.e. only a few thousand shots for ELENA MDs** in **2018**
    - **ELENA e-cooler fully operational only from July**



Courtesy T. Eriksson (link)

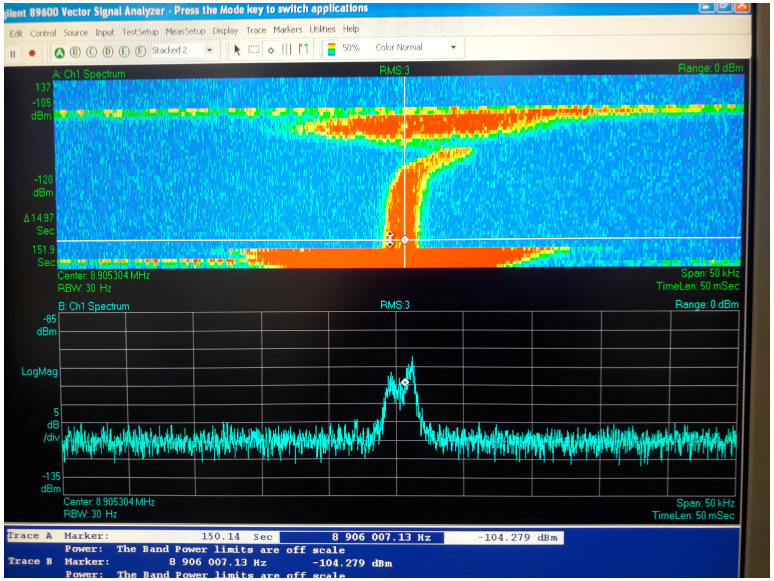
Beam Instrumentation for Cooling Studies

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



Courtesy P. Grandemange et al. (link)

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

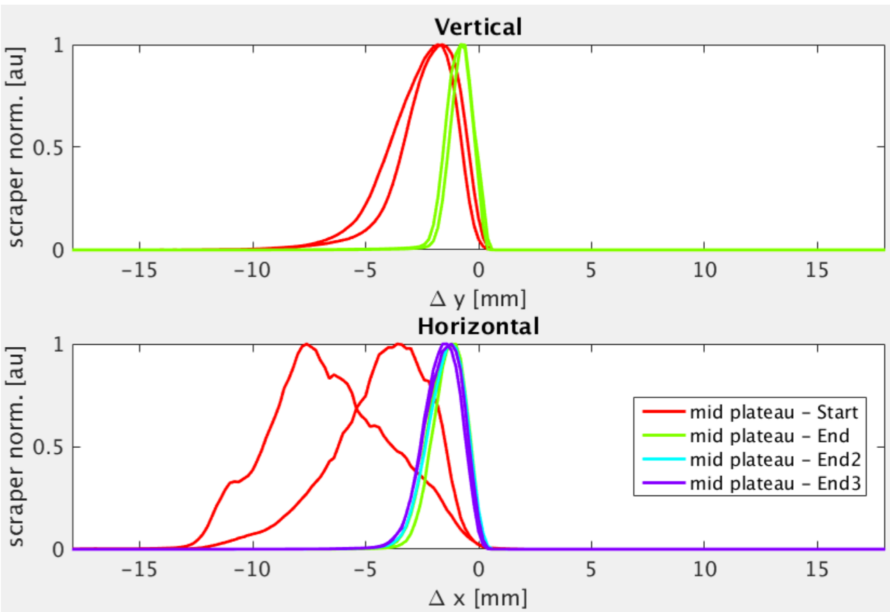


Also available:

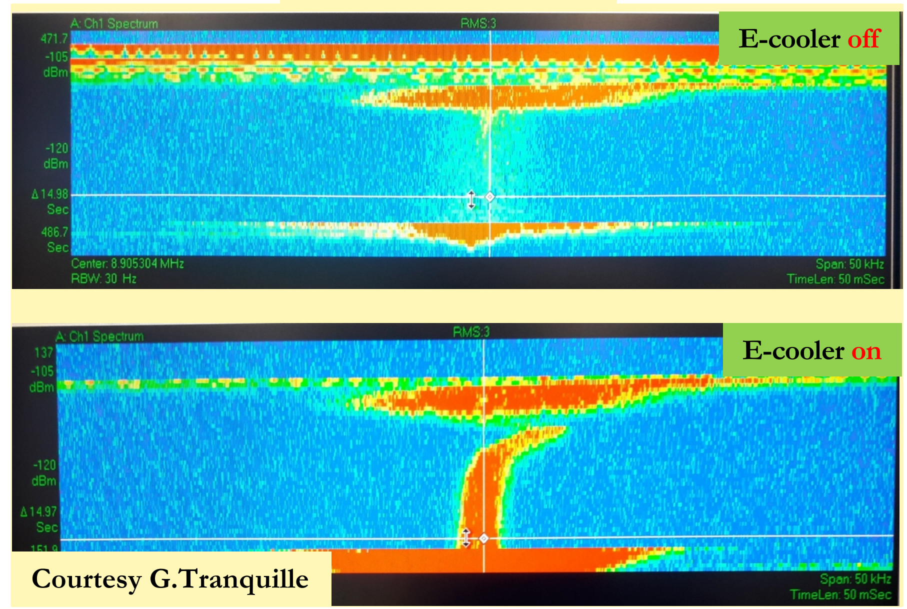
- 2 **BPMs** in e-cooler section, but **only used to measure ions (no tests with e⁻ so far)**
- **Recombination Monitor** only for e⁻ beam optimisation with H⁻ and p **(not exploited)**

E-cooler in action (35 MeV/c plateau)

~half profile measured with "**scraper**"

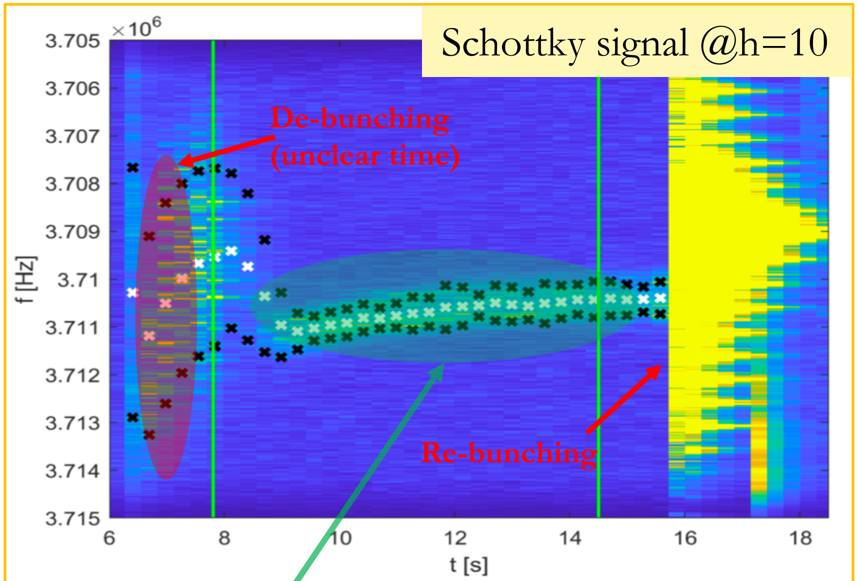


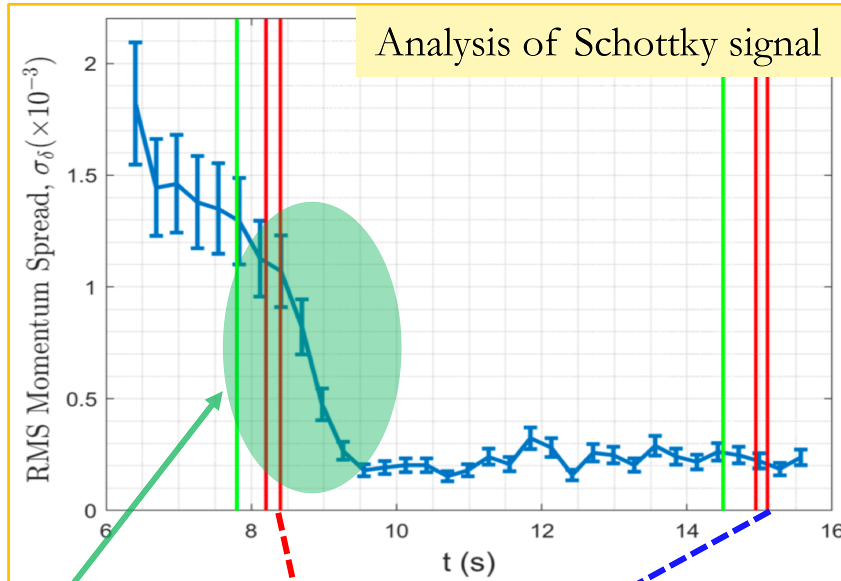
Schottky signal



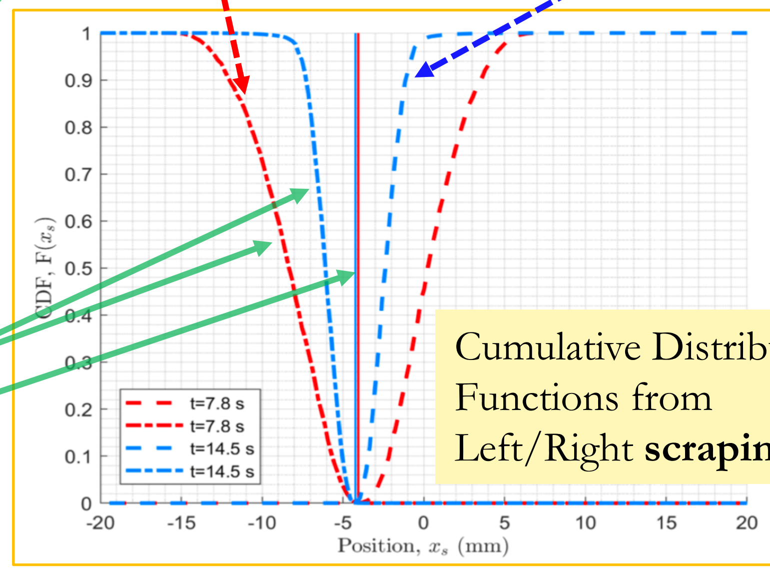
- **Clear qualitative transverse** and **longitudinal emittances reduction** observed
- **Only limited amount of time** on systematic optimization of cooling (**lack of time**)
  - **Some optimisation with ion orbit bumps/angles in e-cooler**
  - **Surely(?) margin** for improvements

Some details (35 MeV/c plateau)





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

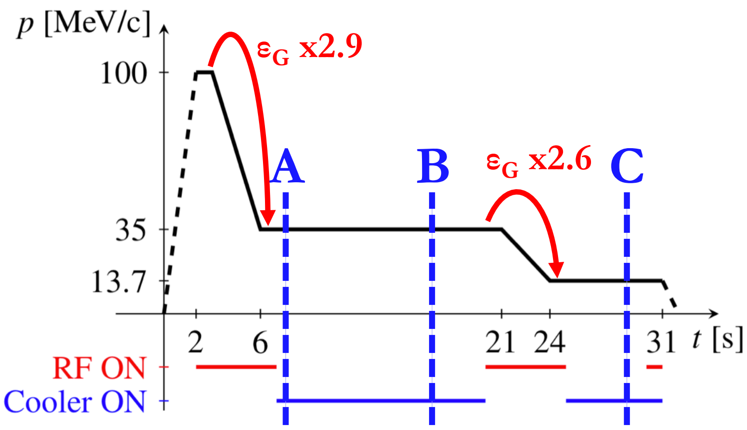


Cumulative Distribution Functions from Left/Right **scrapings**

From J.Hunt Ph.D thesis

Transverse cooling performance

- **Analysis** of **scraper measurements** at (only) three times along cycle



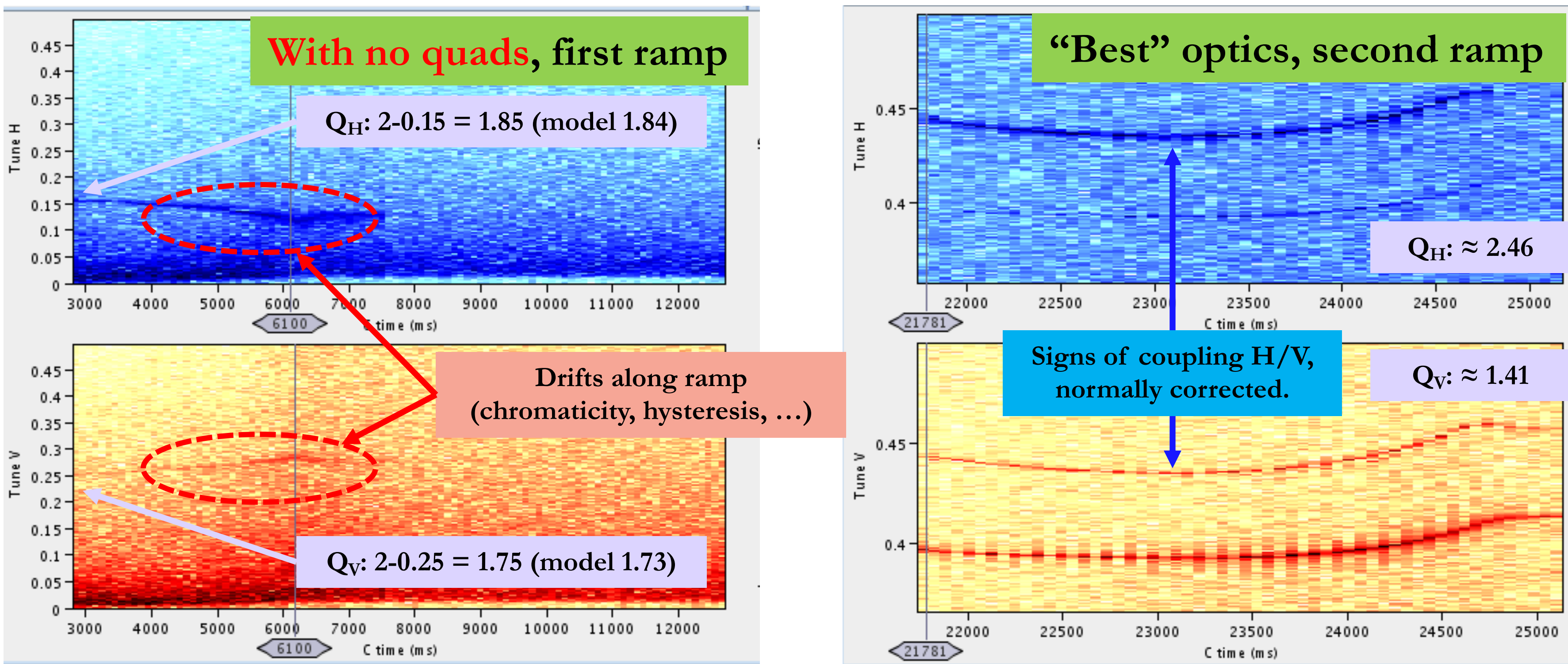
T [s]	E_k pbar [keV]	ε_{XG} [μm]	ε_{YG} [μm]
~8 (**A**)	650	3.6	**1.6**
~15 (**B**)	650	0.7	1.2
	Reduction to	**20%**	**75%**
~28 (**C**) (no cool)	100	2.5	2.6
~28 (**C**)	100	0.6	0.5
	Reduction to	**24%**	**19%**

- A few more measurement available, but scattered in time/beam condition
  - **More systematic measurements to come in the next run**
- No big tails seen, but detailed analysis to do.
- Obtained values here about **x2 worst than design** (0.3/0.2 μm ϵ_G for **coasting beam** with cooling on)
  - Good enough for emittance blow-up compensation

From J.Hunt Ph.D thesis

Tune optimization

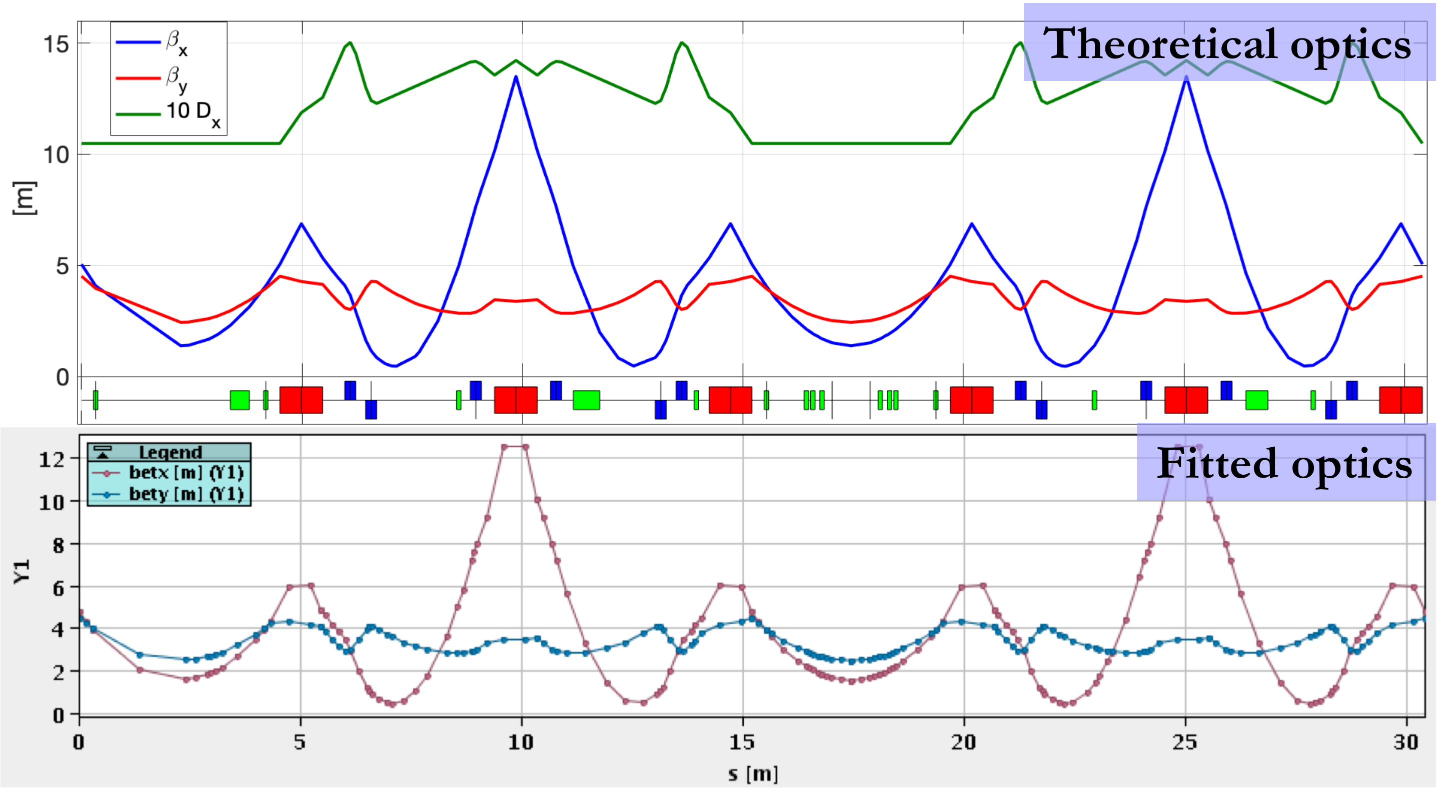
- Machine was **designed** to allow for a **broad range of tunes** (around **2.3/1.3**)
- Several **tune measurements** taken at different time with **different optics**
  - Mainly **empirical adjustments** / **trial-and-error** approach
  - The main observable for **optimization** was the **transmission** along cycle



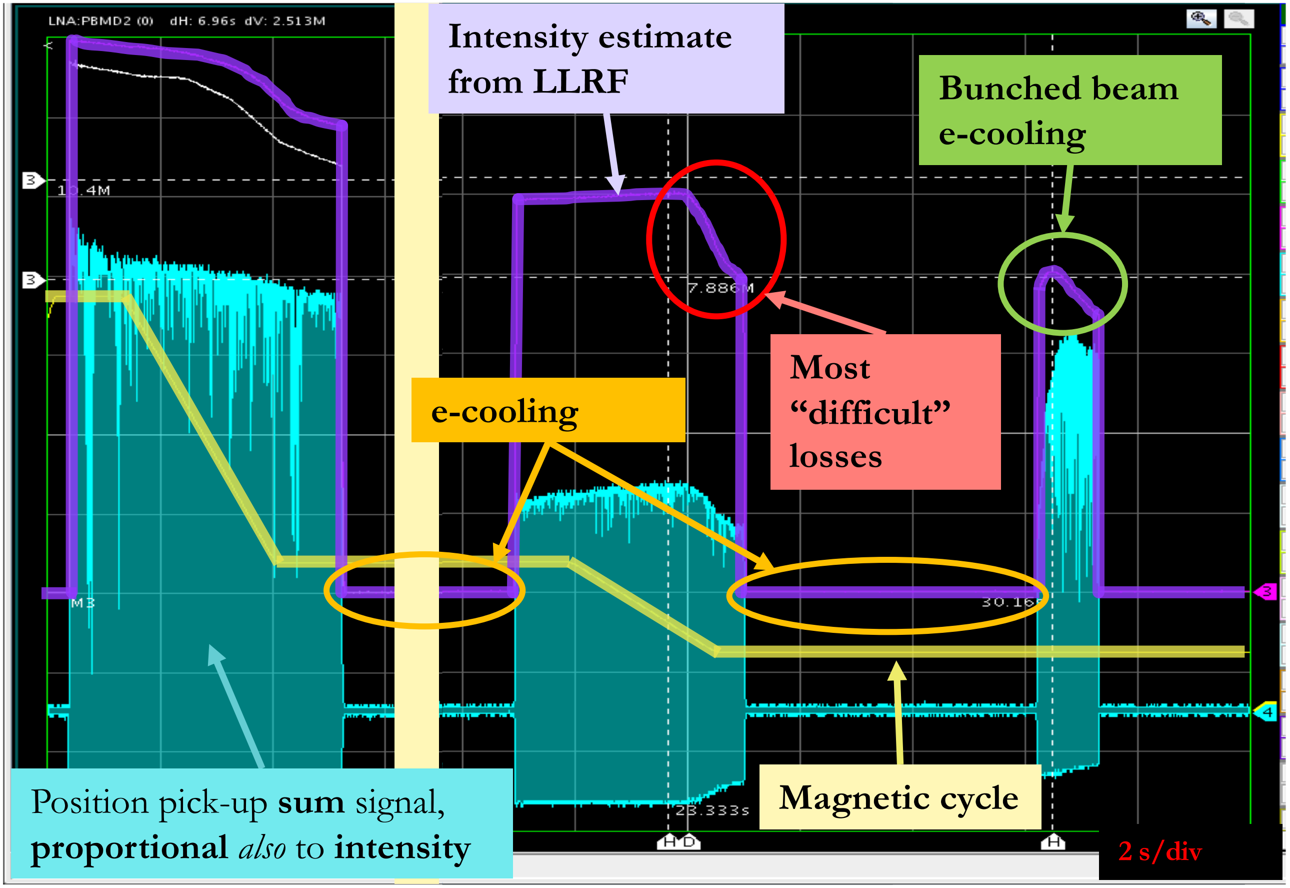
- **Finally able to control tune better than ΔQ < 0.02**
  - Mainly **limited by beam time** and **control system** restrictions (being solved)

Kick response matrix analysis

- **Discrepancies** between **machine model** and **measurements** have been observed
  - Discrepancy **varies along** magnetic **cycle**, pointing to possible **hysteresis effects**
- A possible way to investigate is via **kick response matrix analysis**
  - **(Preliminary) Overall agreement between theoretical optics and fitted optics**
    - **More data and analysis needed**



Status End of Run 2018



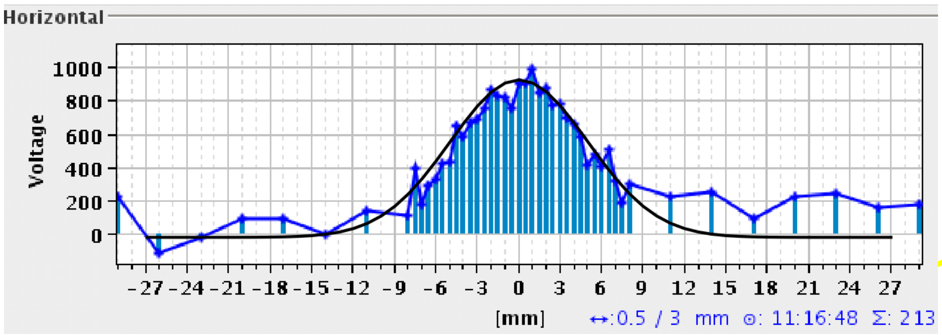
- Almost nominal cycle:
  - Injection 100 MeV/c
  - Deceleration to 35 MeV/c (**h = 1**)
  - De-bunching and **e-cooling**
  - Deceleration to 13.7 MeV/c (**h=4**)
  - De-bunching and **e-cooling**
  - Re-bunching (**with e-cooler on**) on **h=4** and **extraction to experiment**
    - GBAR only user 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…**

Not far from design parameters

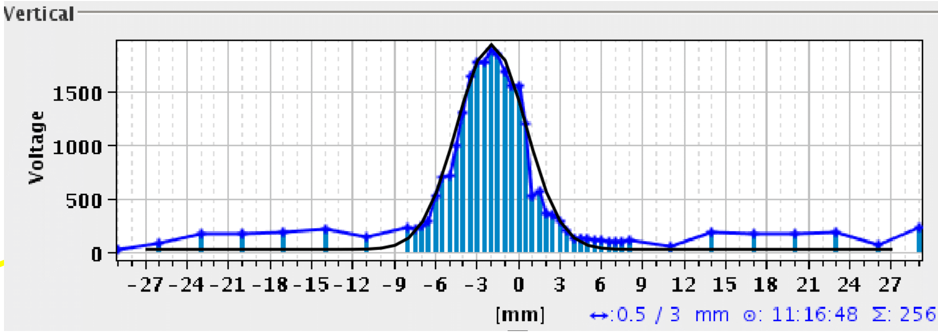
Connection of ELENA to AD experiments approved at the end of 2018

Bunches extracted to GBAR

- Beam profiles in measured on **Microwire monitors** installed in **GBAR line**

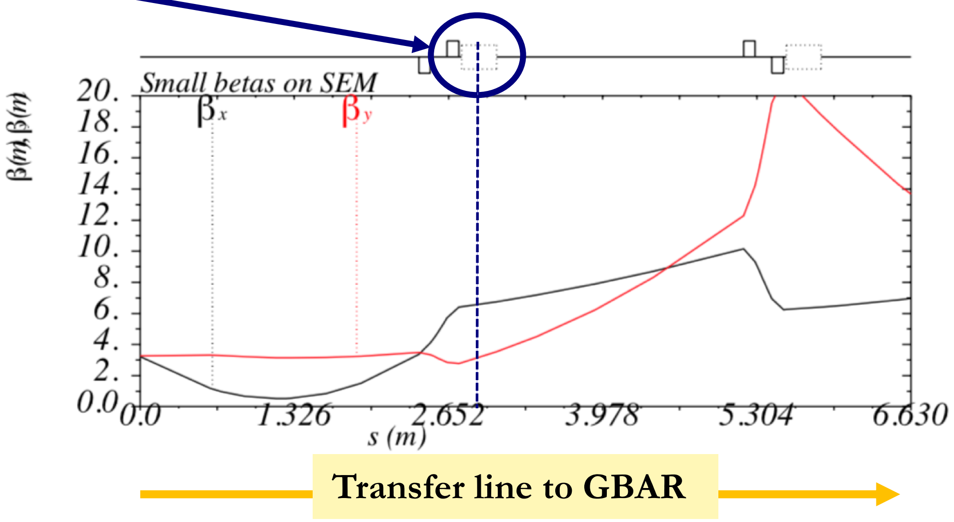


Gaussian fit by hand with σ_H = 5 mm

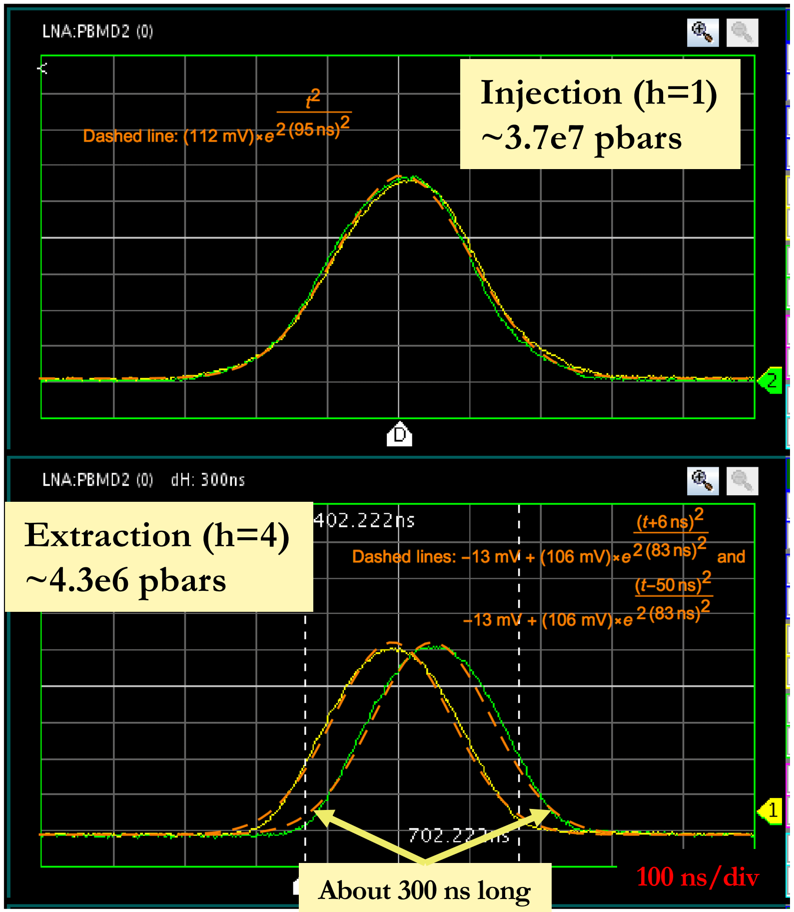


Gaussian fit by hand with σ_V = 2.5 mm

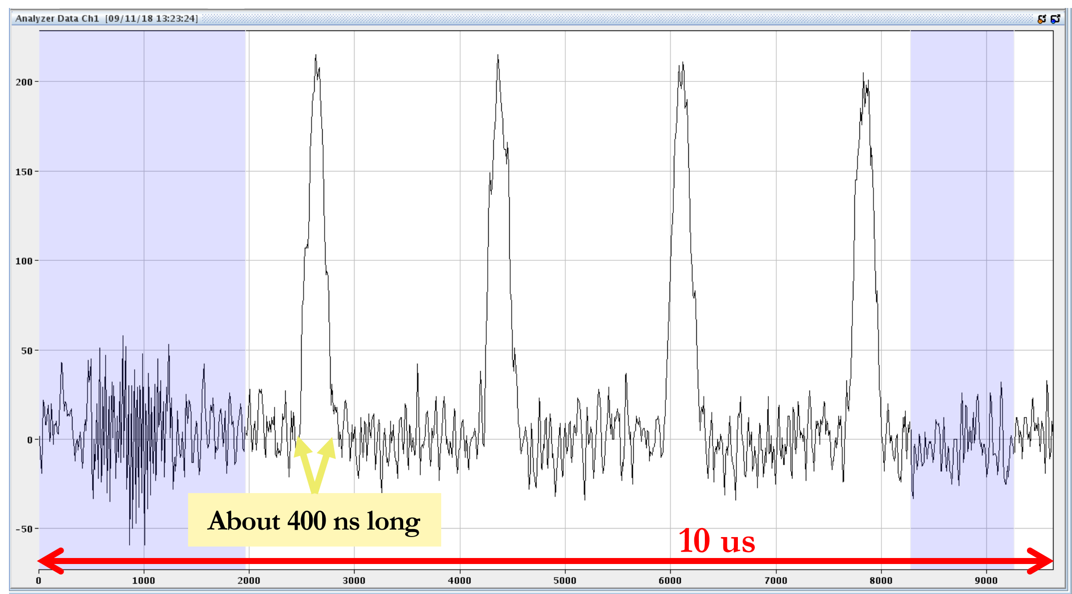
- Acquisitions with second monitor LNE.BSGWA.5020 in GBAR line
- Beam sizes with voltages of first two quads of line set to zero
  - β_H = 6 m gives rms emittance: **ε_H = 4.1 µm** (without taking dispersion into account) **(design 1.2 µm)**
  - β_V = 4 m gives rms emittance: **ε_V = 1.5 µm (design 0.75 µm)**



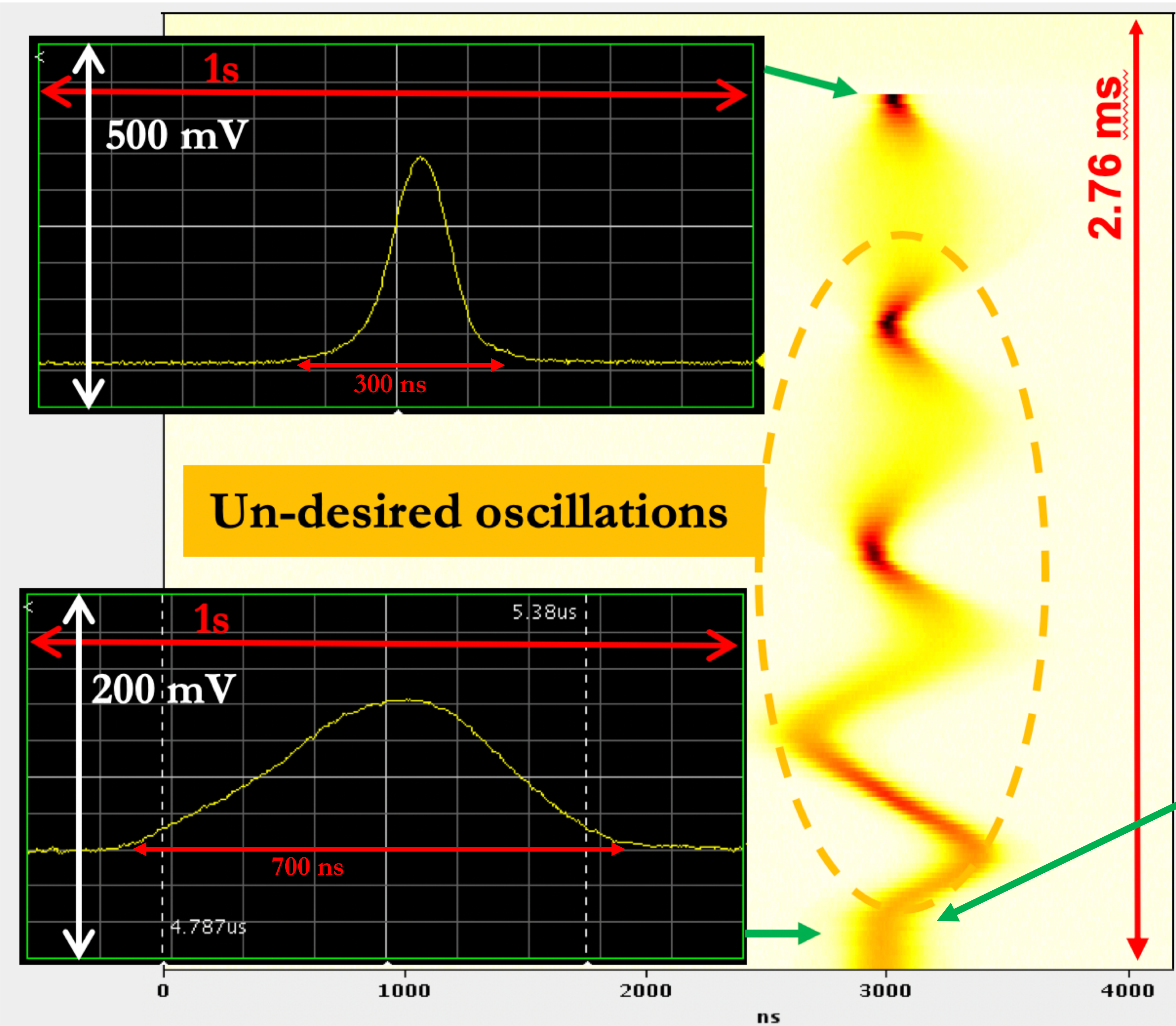
Bunches extracted to GBAR



- According to <u>Transverse Pickup</u> signals:
  - After injection 3.7e7 pbars
  - Before extraction 4x4.3e6 = 1.7e7 pbars
- According to <u>Magnetic Pickup</u> in extraction line we see about 1e7 pbars extracted (over all 4 bunches)
  - **Unrealistic** to think we are **loosing 0.7e7 pars at extraction…** Probable some **calibration error**!



"Bunch rotation" (h=1)

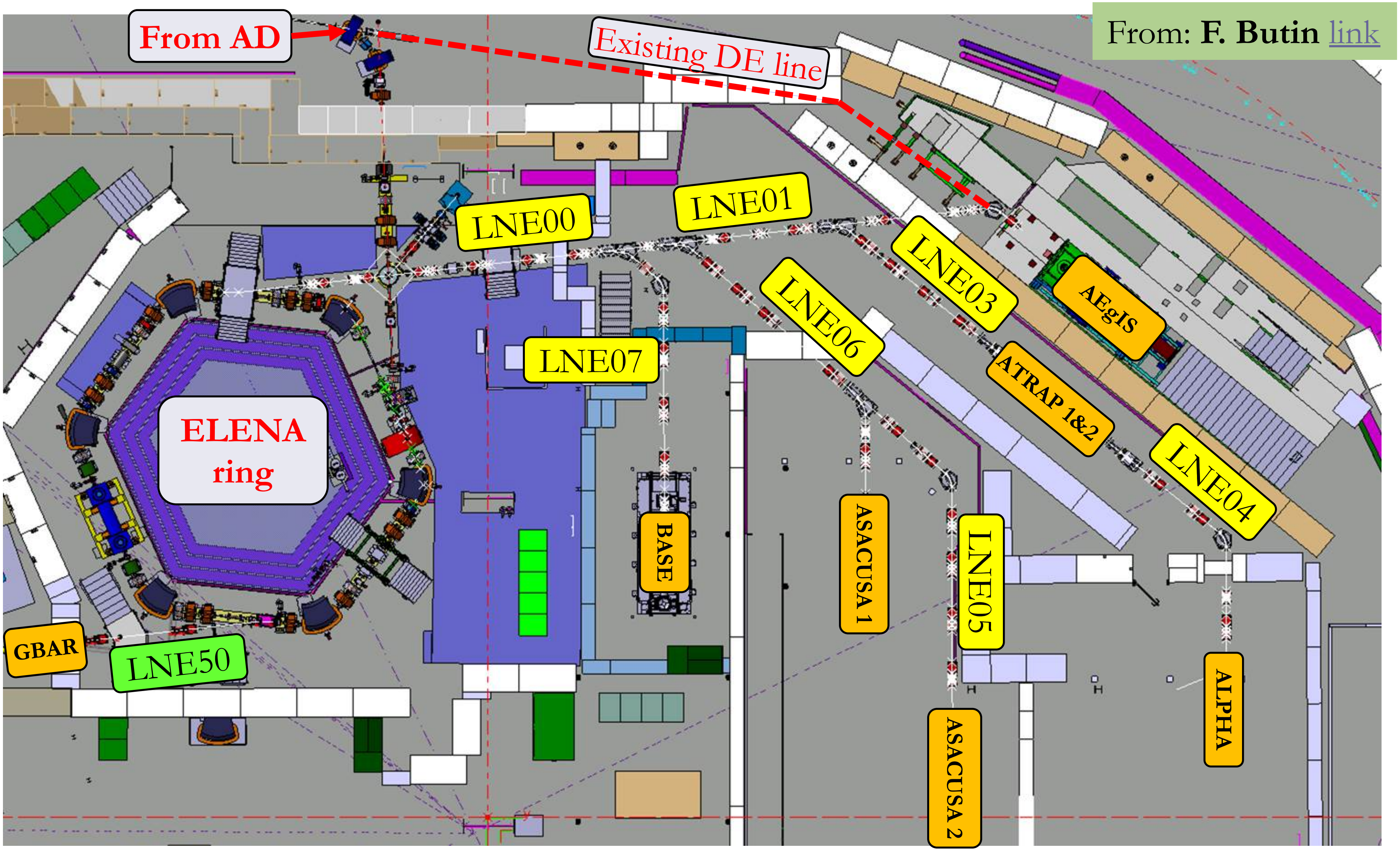


Possible to shorten the bunches (but higher energy spread) with **bunch rotation** (not baseline) for **h=1** operation (**100 keV**)

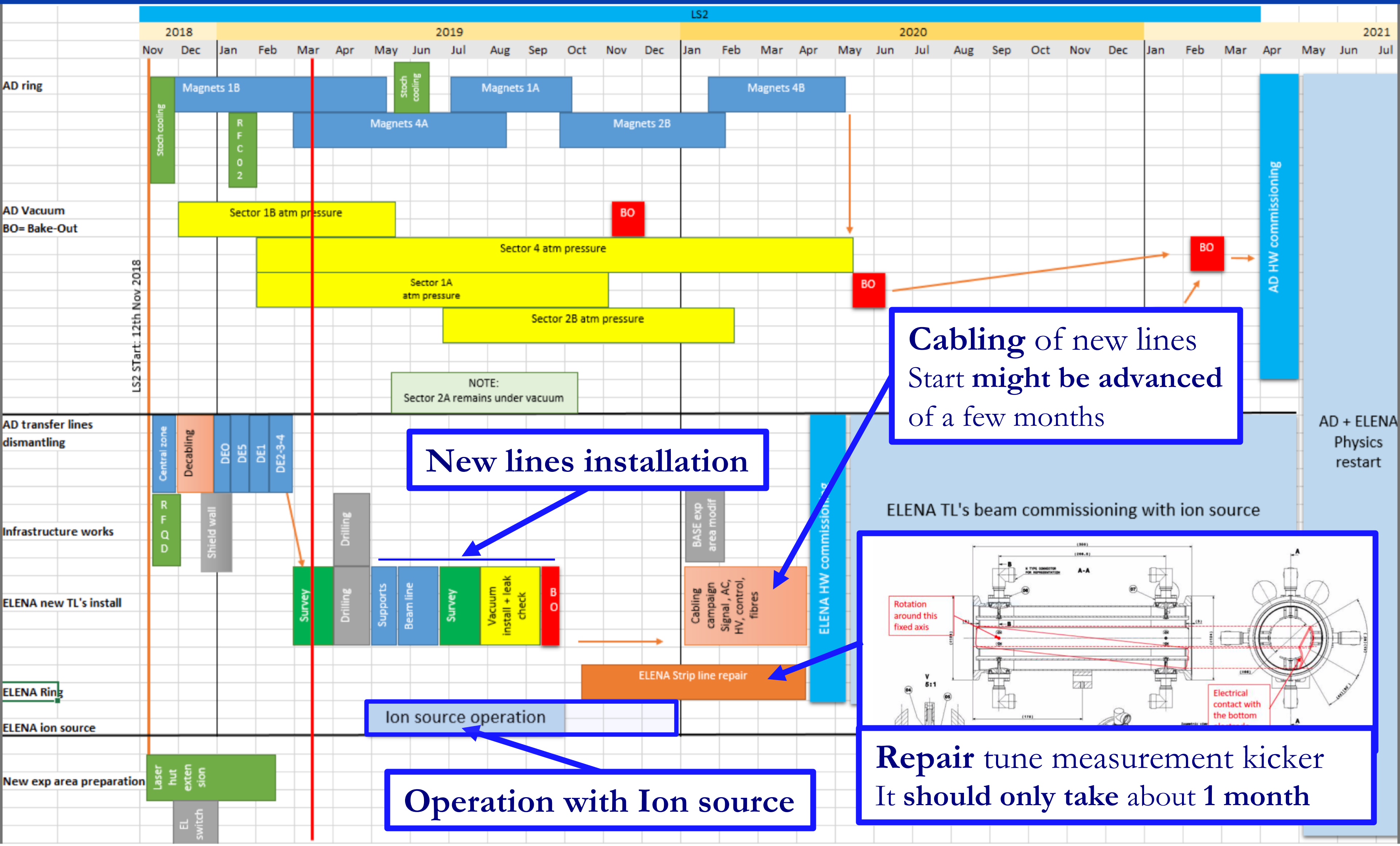
Jump programmed in RF Voltage

Current Activities and Plans for LS2

LS2: Electrostatic lines being installed



In the contexte of AD consolidation



New lines installation

Cabling of new lines
Start **might be advanced** of a few months

Operation with Ion source

Repair tune measurement kicker
It **should only take** about **1 month**

Master planning of activities in the AD hall during LS (by **Francois Butin** who follows up all these activities) link

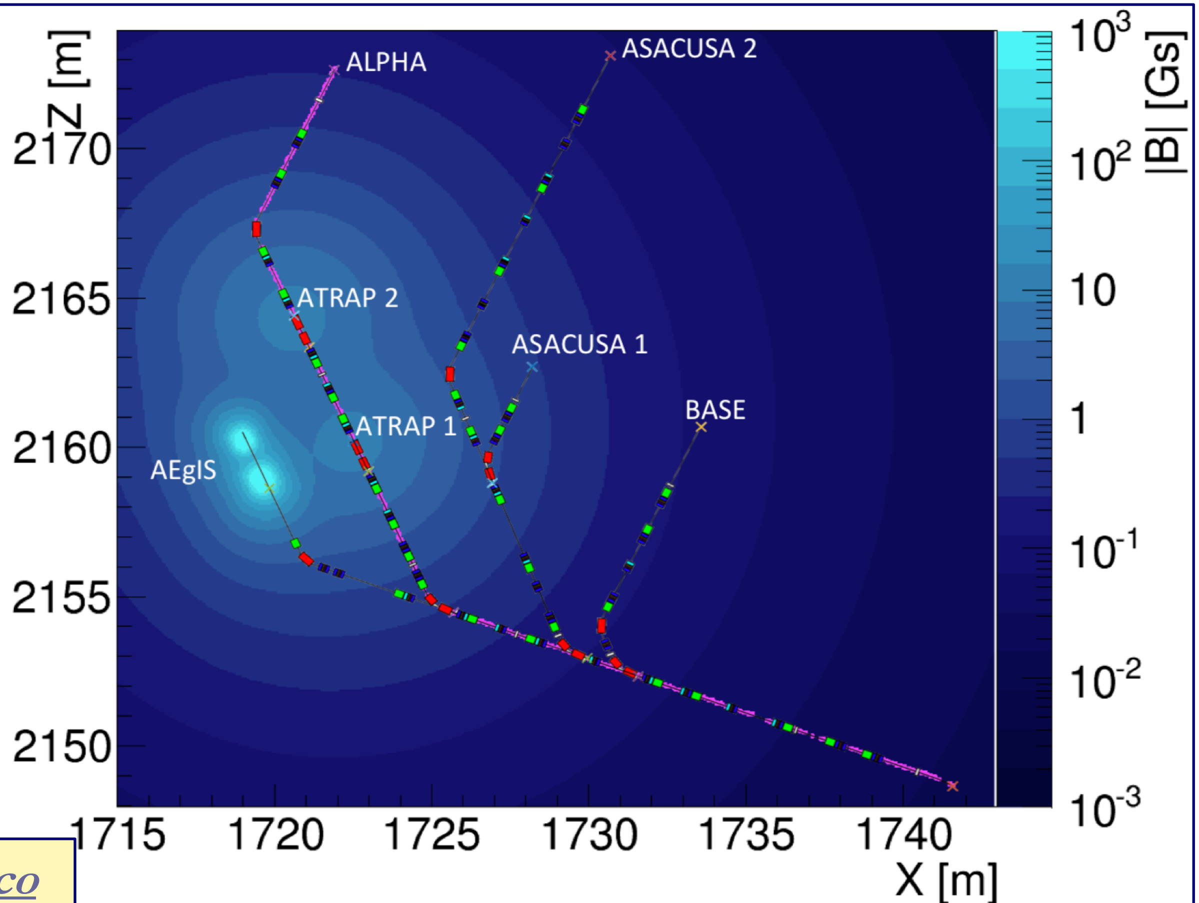
Some concern:
Profile monitors availability for transfer lines

- **Complex** design
  - **Initially** foreseen as **in-kind collaboration**, now being taken care more and more by BE-BI
- Parts coming for **Japanese collaboration**, assembly made at CERN by BE-BI
  - **Limited documentation**
  - **Many issues found during assembly** (vacuum leaks, mechanical problems, broken wires, poor cleaning) had to be addressed at CERN
- **Slow reception of parts**
  - Looking for "local" supplier for spare parts
- Final version of **head amplifier** being finalized
  - Also with supervision from CERN BE-BI

- **First prototypes demonstrated to work**, but more beamtime needed to finalize their commissioning!

Some concern:
stray fields from experiment magnets

- |B| @ common beam level
- 5 exp. magnets simulated:
  - AEgIS (1T)
  - AEgIS (4.46T)
  - ATRAP 1 (5T)
  - ATRAP 2 (1T)
  - ATRAP 2 PBAR (2T)
- Based on analytical calculations and numerical field maps inside the magnets



Courtesy J. Jentzsch - indico

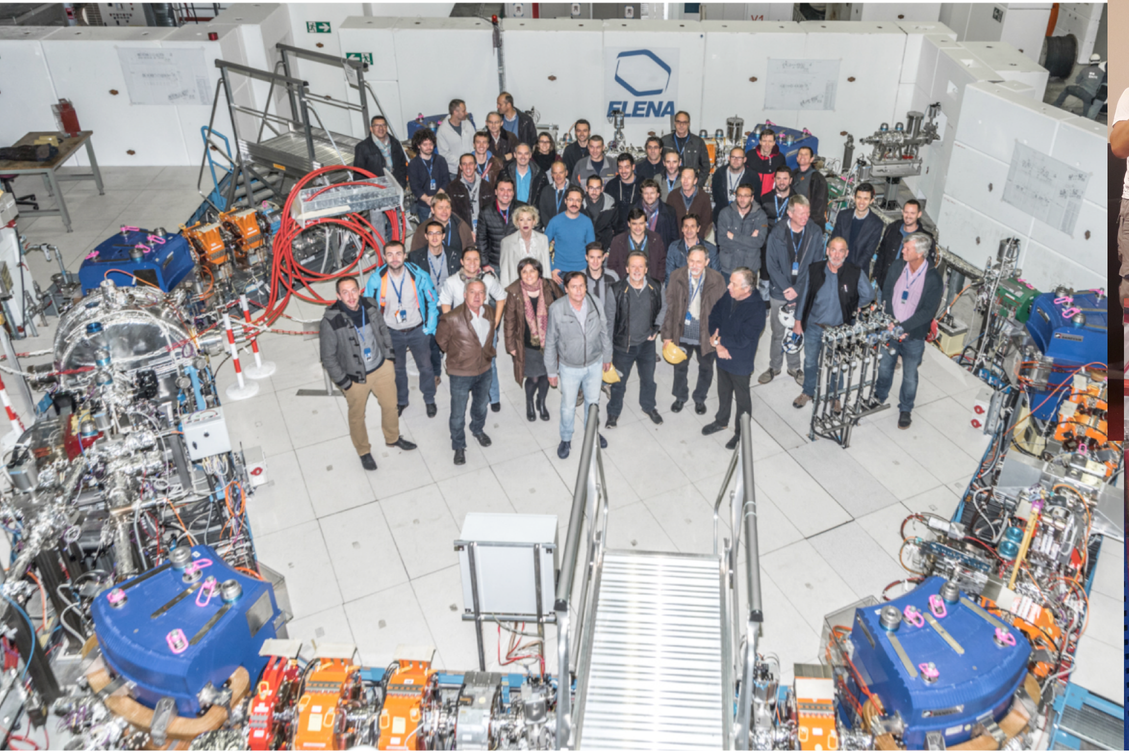
- From preliminary studies, **transfer line design should be able to cope with static fields**
  - **How to cope** with **experiments going on/off** while others are taking beam?
    - Additional **shielding** and/or **"online" orbit correction** knobs **possible**
  - **Plan** is to **start sending beam** to **first assess** the actual **impact on** the **beam**

Summary

- **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% (even at 100 keV)**
  - **Longitudinal** beam **specifications** met with **bunched beam cooling**
  - **Results obtained with limited/empirical studies → room for improvement?!**
- **Could not** fully **profit** of the **H^-/p source => being fixed**
  - Use of **H^-/*p* beam envisaged for e-cooling studies (higher rep rate)**
- **Plans for LS2**
  - **Installation** of the **ELENA transfer lines** to the “old” experimental zone
  - **Fix ion source** and **Improve** its **reliability** and **stability**
  - **Continue commissioning activities** with **H^-/p in 2019/2020**
  - **Commissioning** of **electrostatic transfer lines** in **2020 with H^-**
  - **Physics with pbars mid 2021**

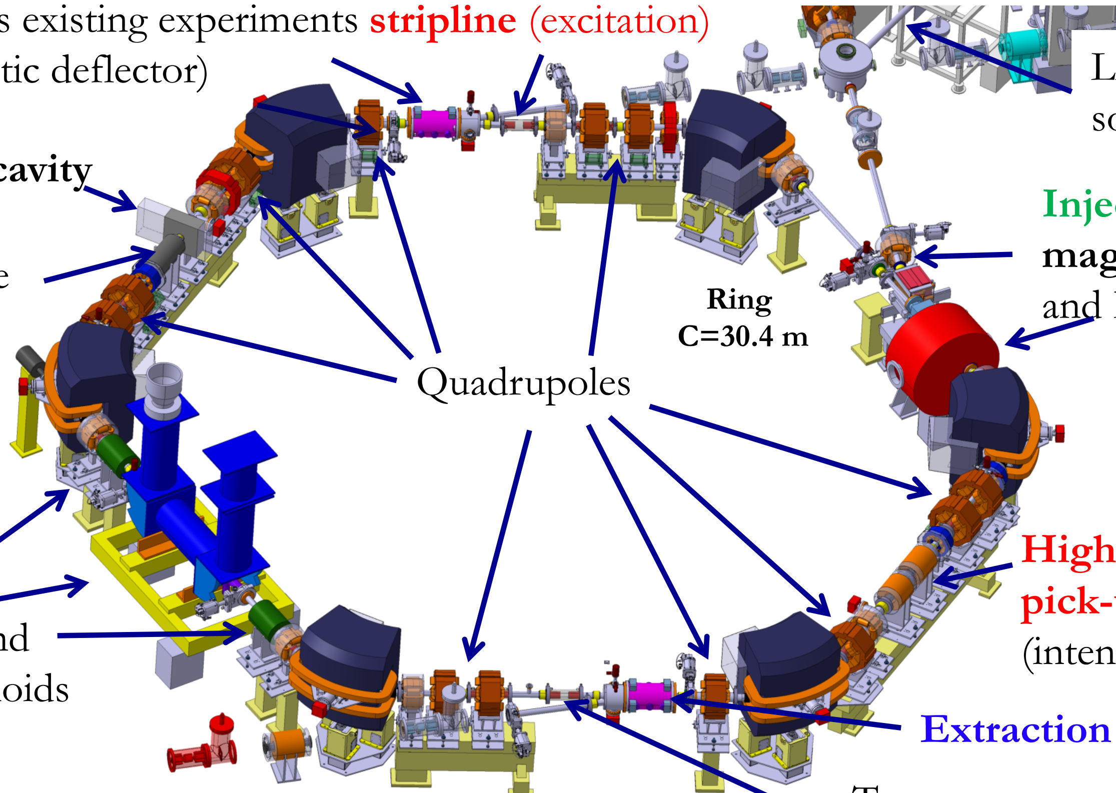
Thanks!

- Wolfgang Bartmann
- Pavel Belochitskii
- Lajos Bojtar
- Francois Butin
- Christian Carli
- Marco Calviani
- Fritz Caspers
- Bruno Dupuy
- Tommy Eriksson
- Miguel Fernandes
- Matthew Alexander Fraser
- Alexandre Frassier
- Pierre Freyermuth
- Pierre Grandemange
- Lars Varming Joergensen
- Bertrand Lefort
- Stephan Maury
- Sergio Pasinelli
- Flemming Pedersen
- Laurette Ponce
- Gerard Alain Tranquille
- *… + many other colleagues to whom I apologies!*



Backup

ELENA Overview and Layout



- **Longitudinal pickup in the ring too noisy: being revisited by BE/RF**
- **Tune measurement excitation stripline broken**
    - **planned to be repaired in 2019 by BE/BI (need to break vacuum)**

Expected 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

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

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

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

$$\gamma \approx 1$$

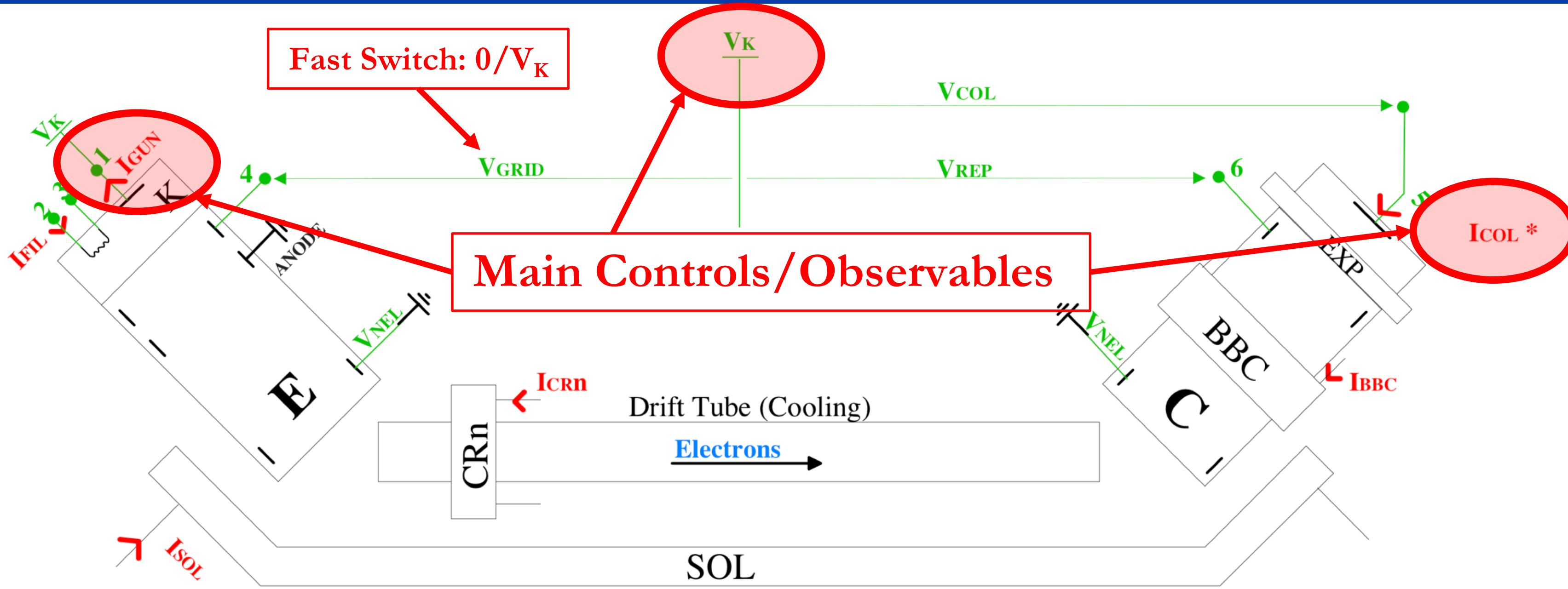
$$\beta_\gamma \approx 0.038 - 0.015$$

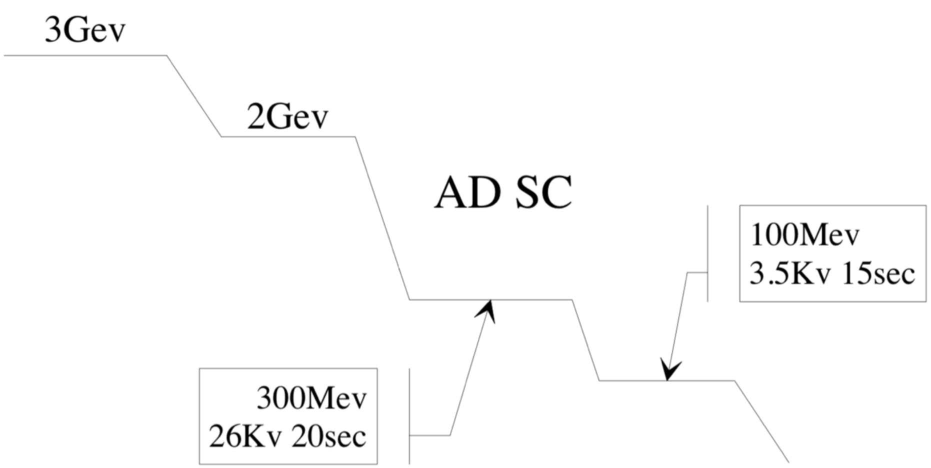
from: ELENA Design Report (CERN-2014-002)

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

AD

AD e-Cooler





- Some useful formulas

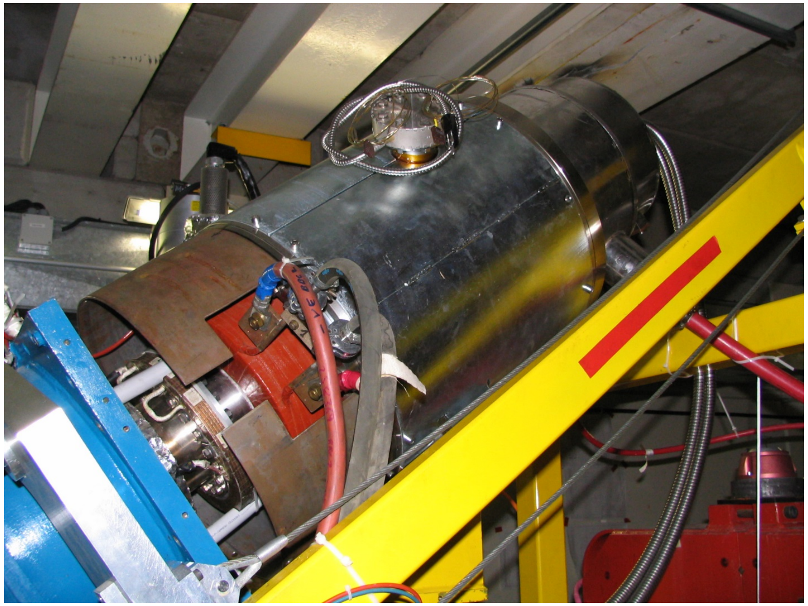
$$E_k = eV_K$$

$$I_e = PV_K^{\frac{3}{2}}$$

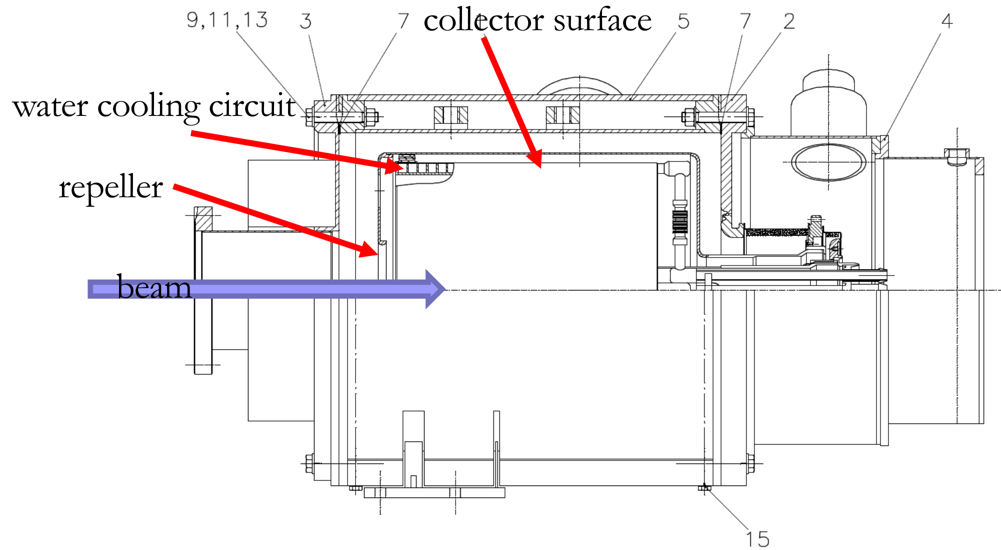
$$P = 0.58 \times 10^{-6}$$

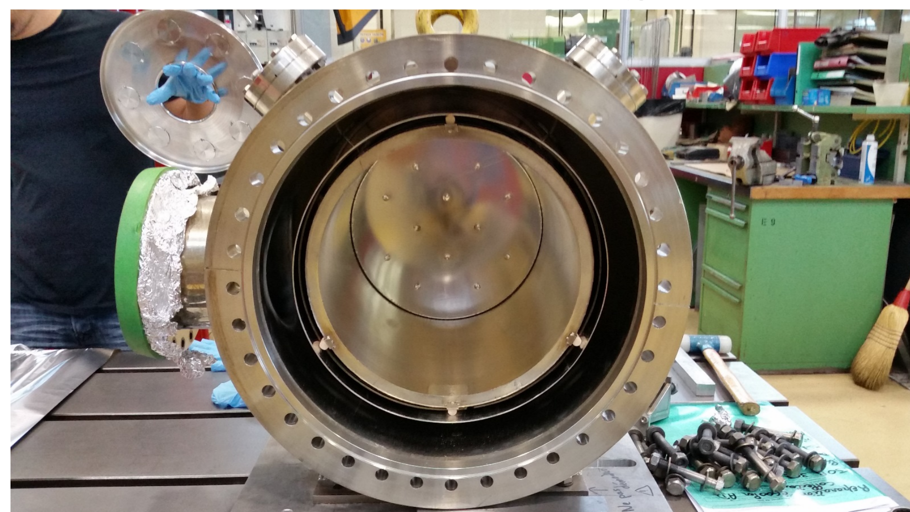
Courtesy A. Frassier

AD cooler issues in 2018



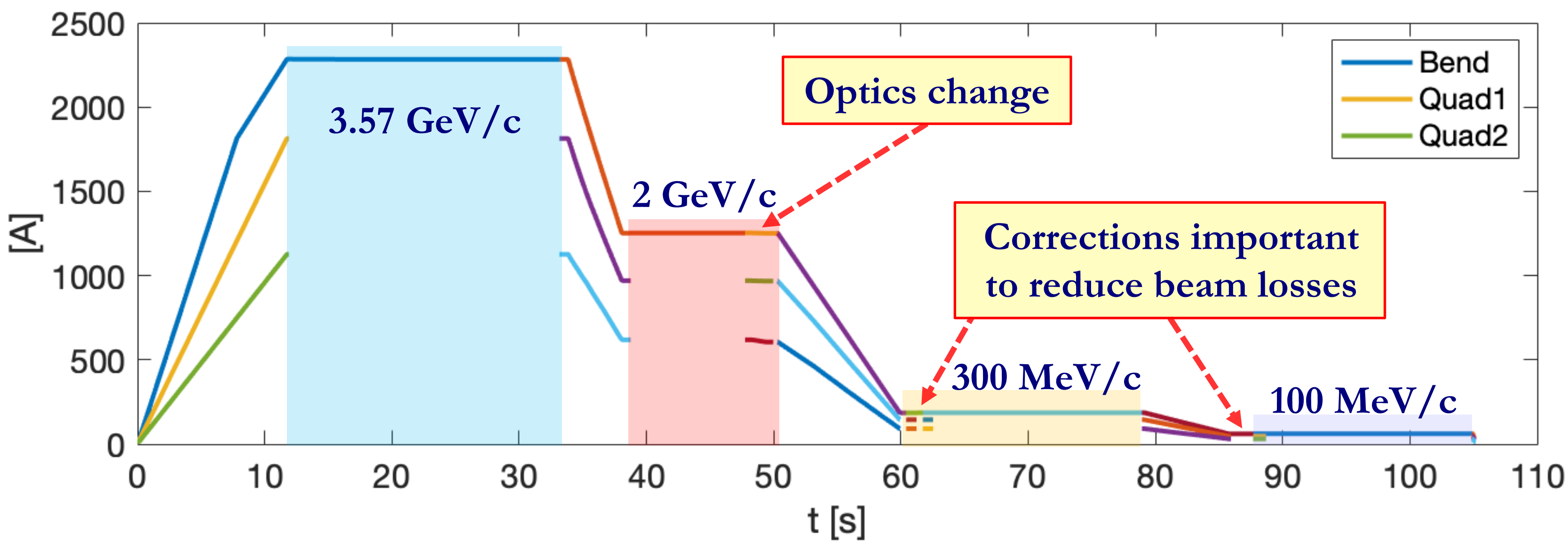
- Leak detection performed on the electron cooler
- Leak traced to the collector cooling circuit





From G. Tranquille (link)

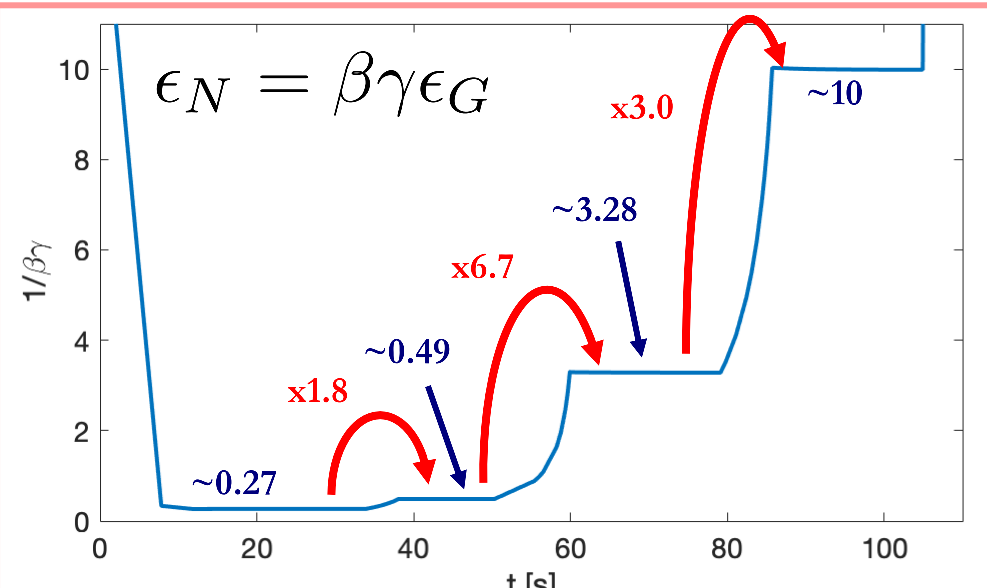
AD Cycle end of 2018



Not much time for looking at AD cycle in 2018:

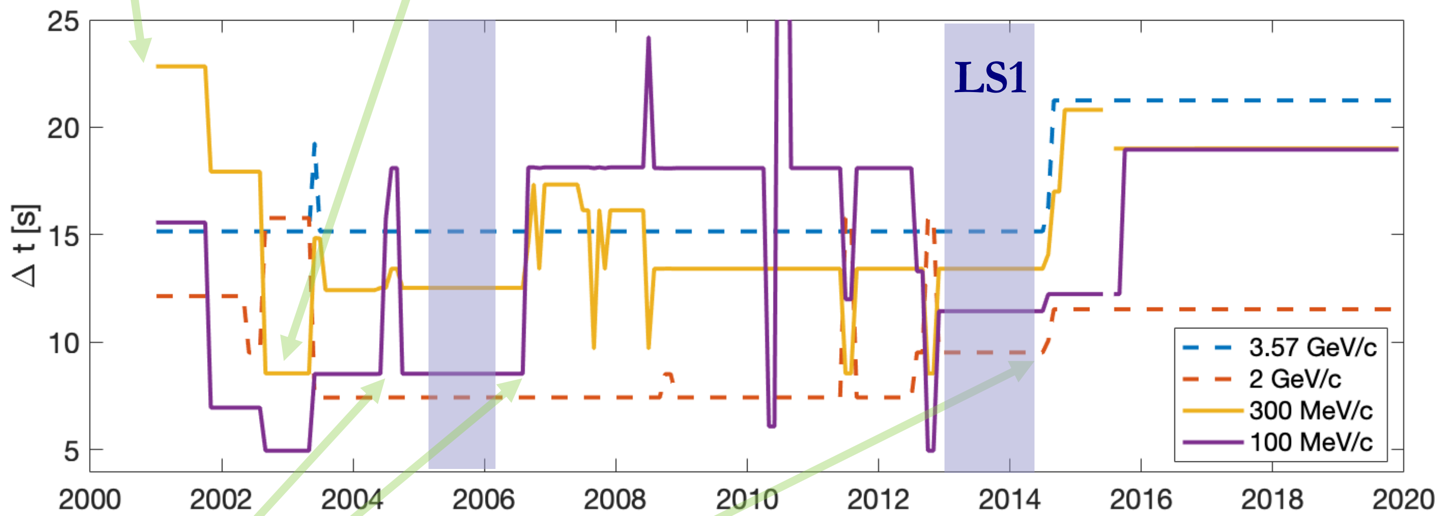
- Hardware issues
- ELENA commissioning

Expected adiabatic emittance blow up at each



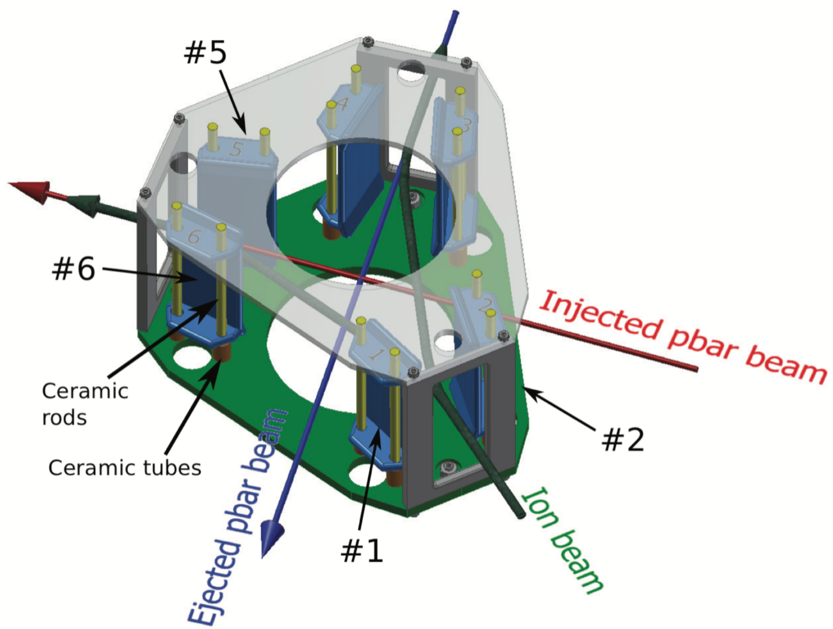
AD Cycle Evolution

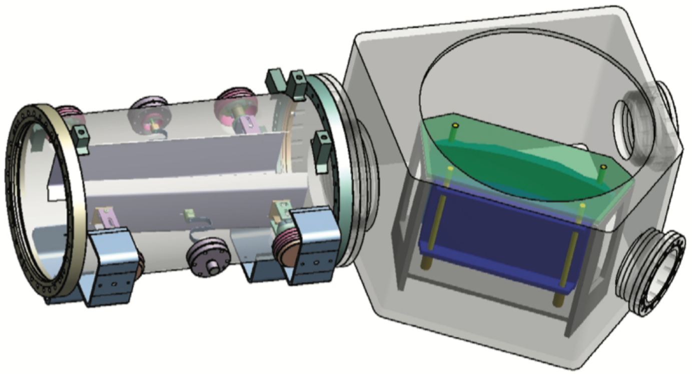
- Length of different plateaus (T. Eriksson - link)
  - 2000, end of the year: 2.0 10^7 pbars/bunch, 110s cycle length
  - 2003, end of the year: 3.0 10^7 pbars/bunch (routine operation value), 85s cycle length

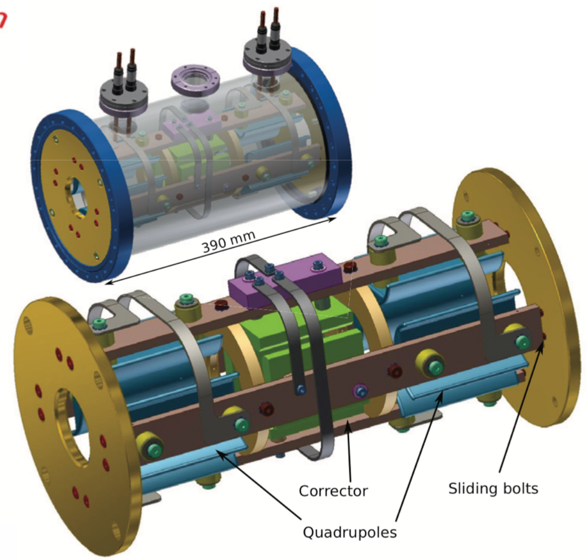


- Major faults (T. Eriksson - link):
  - 2004: >200h e-cooler downtime due to water system & collector replacement
  - 2006: Re-start after 2005 shutdown problematic due to **various machine issues**. E-cooler problems with water circuit and HV stability. 5 weeks total delay => physics start rescheduled
  - 2014: Difficult start-up: **Orbit issues** and e-cooler HV stability
  - 2018: Cathode/vacuum fault(s),

Transfer line elements





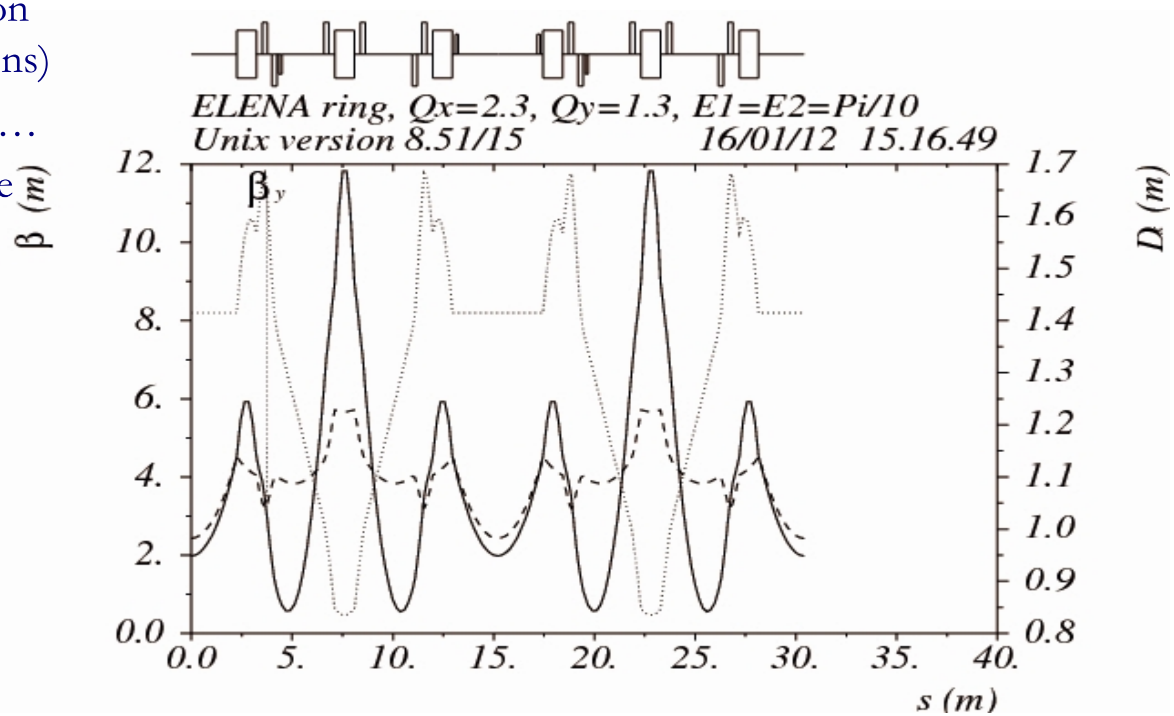


From D. Barna et al. – IPAC2014 - MOPRI101

ELENA Design – some features

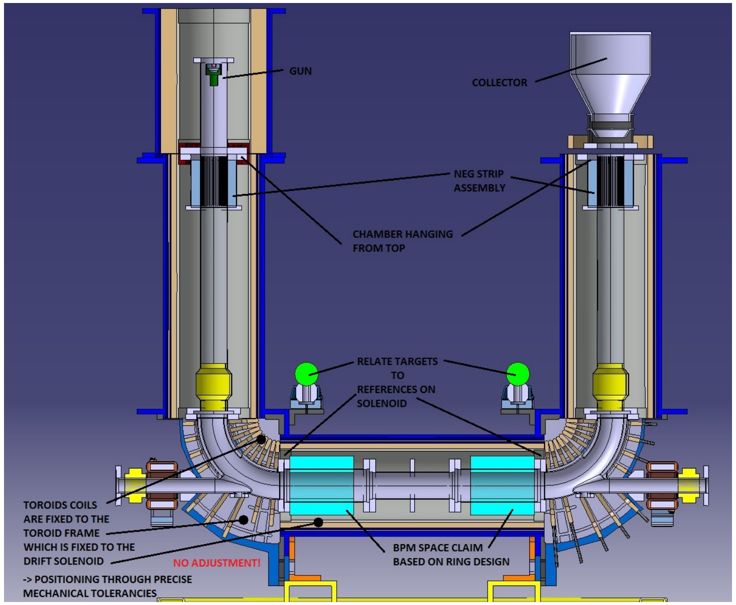
Selected Features and Challenges

- **Energy Range**
  - Machine operated at an unusually low energy for a synchrotron (down to **100 keV**!)
  - **Challenges mainly a consequence of the low energy**
- **Lattice**
  - Geometry of ring with position and strength of magnets
  - **Constraints**
    - Long straight section with small dispersion for **electron cooling**
    - Geometry in **AD hall** (location of injection and two extractions)
    - Acceptances, working point …
  - **Many geometries** and quadrupole locations **investigated**
  - Hexagonal shape and optics with periodicity two
  - Tunes : $Q_X \approx 2.3$, $Q_Y \approx 1.3$ (e.g. $Q_X = 2.23$, $Q_Y = 1.23$)
  - Acceptances: about 75 µm (depends on working point)



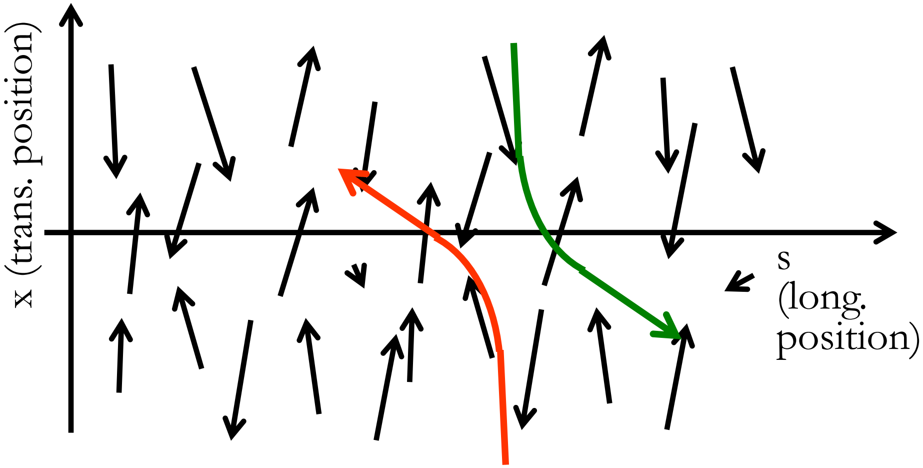
Selected Features and Challenges

- **Electron cooling**
  - **Essential ingredient of concept**
  - Cooling at intermediate plateau to **reduce losses** and the final energy 100 keV to **provide dense bunches**
  - **Bunched beam cooling at 100 keV** to reduce momentum spread of short bunches
  - Perturbations of magnetic system on circulating beam difficult to assess



- **Intra Beam Scattering IBS**
  - Coulomb scattering between beam particles
  - Transfer of heat (unordered motion) between phase spaces (long. & transverse)
  - **Emittance blow-up**

- **Characteristics of beam sent to experiments given by the equilibrium between these two effects**



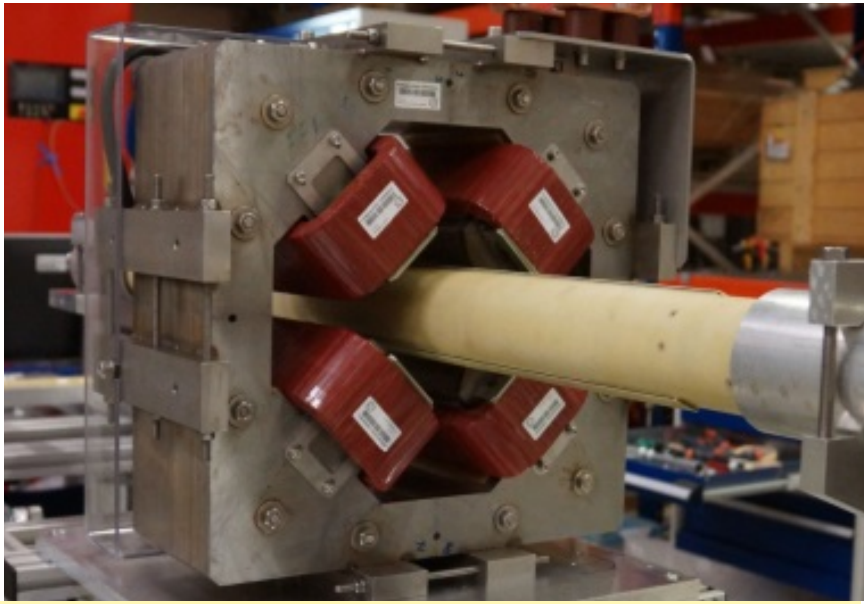
Intra Beam Scattering IBS – co-moving coord. system

Selected Features and Challenges

- **Direct space charge effect**
  - Coulomb force between beam particles generate **non-linear defocusing force**
  - **Initial reason to split available intensity into 4 bunches**

$$\Delta Q = -\frac{G_T r_p N_b}{2\pi \varepsilon_x \beta^2 \gamma^3} \frac{G_L C}{l_b}$$

- **Magnets with very low fields**
  - Low energy beam sensitive **stray fields** and magnet imperfections due to **hysteresis** & **remanence**
  - "**Thinning**" (mixing of stainless steel and magnetic laminations) **had been foreseen initially to improve**
  - Careful magnetic measurement with pre-series quadrupoles showed smallest remanence with conventional yoke (no thinning)
  - Observation confirmed with bending magnet prototype and understood now



Prototype quadrupole to investigate magnet "thinning" on the measurement bench

⇒**Magnet thinning does NOT improve field quality at low fields**, but rather increases remanence effects

⇒ELENA bending magnets, quadrupoles and sextupoles made with conventional yokes

- (Corrector magnets without yokes)

Selected Features and Challenges

- **Rest gas interactions** and vacuum system
  - $3\ 10^{-12}$ Torr nominal pressure - **fully baked machine with NEGs** wherever possible (technical problems as peel-off with NEG coating of stainless steel chambers)
  - Interactions of beam with rest gas to be evaluated with care, **not the dominant limitation**
- **Beam diagnostics** with very **low intensities and energy**
  - E.g.: beam currents down to well below 1 μA far beyond reach standard slow BCTs
  - ➠ Intensity of coasting beam measured with **Schottky diagnostics** (observing noise generated by coasting beam on a pick-up, special pick-ups design to limit background noise)
- **Electrostatic transfer lines to experiments**
  - **Cost effective** at very low energies
  - **Many quadrupoles** allow a design with small “betatron functions” and large “betatron phase advance” (small beam sizes) **limiting impact from stray fields**
  - **Easier for shielding against magnetic stray fields**
- **RF system** with modest voltages, but very large dynamic range **(1.04 MHz – 144 KHz f_{rev})**
- **H^- and proton source** (and electrostatic acceleration to **100 keV**) for **commissioning**
  - **Commissioning independent of AD**, antiprotons kept as much as possible for experiments
  - **Higher repetition rate** but start commissioning at the difficult low energy part of the cycle
  - Still, antiprotons needed to complete ELENA ring commissioning