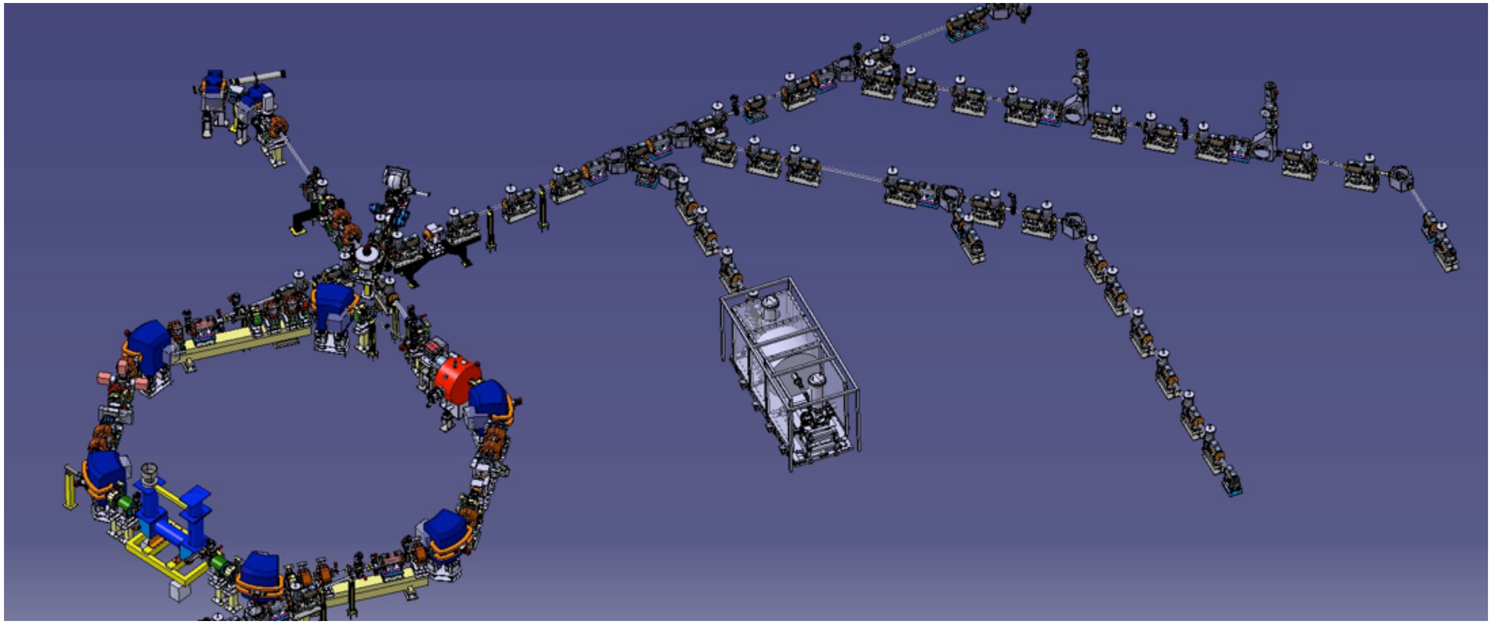
Operational aspects of ELENA and AD commissioning

D. Gamba on behalf of the AD/ELENA collaboration

AVA Topical Workshop GSI - 6th Feb 2019



- From AA to AD (to ELENA): some history
- AD main features and challenges
- Toward ELENA: why and how
- Results from ELENA Commissioning in 2018

A bit of History

- Antiprotons have been used at CERN since ~1980, in the beginning mainly for high energy proton-antiproton experiments in the **SPS**
- 1980-1986 **AA**
  - **3.57 GeV/c** Antiproton Accumulator ring
- 1986-1996 **AAC (AA+AC)**
  - Large acceptance Antiproton Collector ring added to increase capture
  - Production rate increased 10-fold to **$6*10^{10}$ pbars/h**
  - **10^{12} pbars stored (peak)**. p/pbar collisions in SPS
  - \+ low energy experiments in LEAR
- 1998 - 2017 **AD**
  - AC converted from fixed energy storage ring to Decelerator. **~$5*10^{7}$ pbars** slowed down to **100 MeV/c** (**5.3MeV** kinetic). Local experimental area.
- 2018 - ? **AD + ELENA** (Extra Low ENergy Antiproton ring)
  - Addition of a smaller ring for further, controlled deceleration with beam cooling. Much more antiprotons can be captured with cool **100keV pbars**.

Antiproton Decelerator (AD)

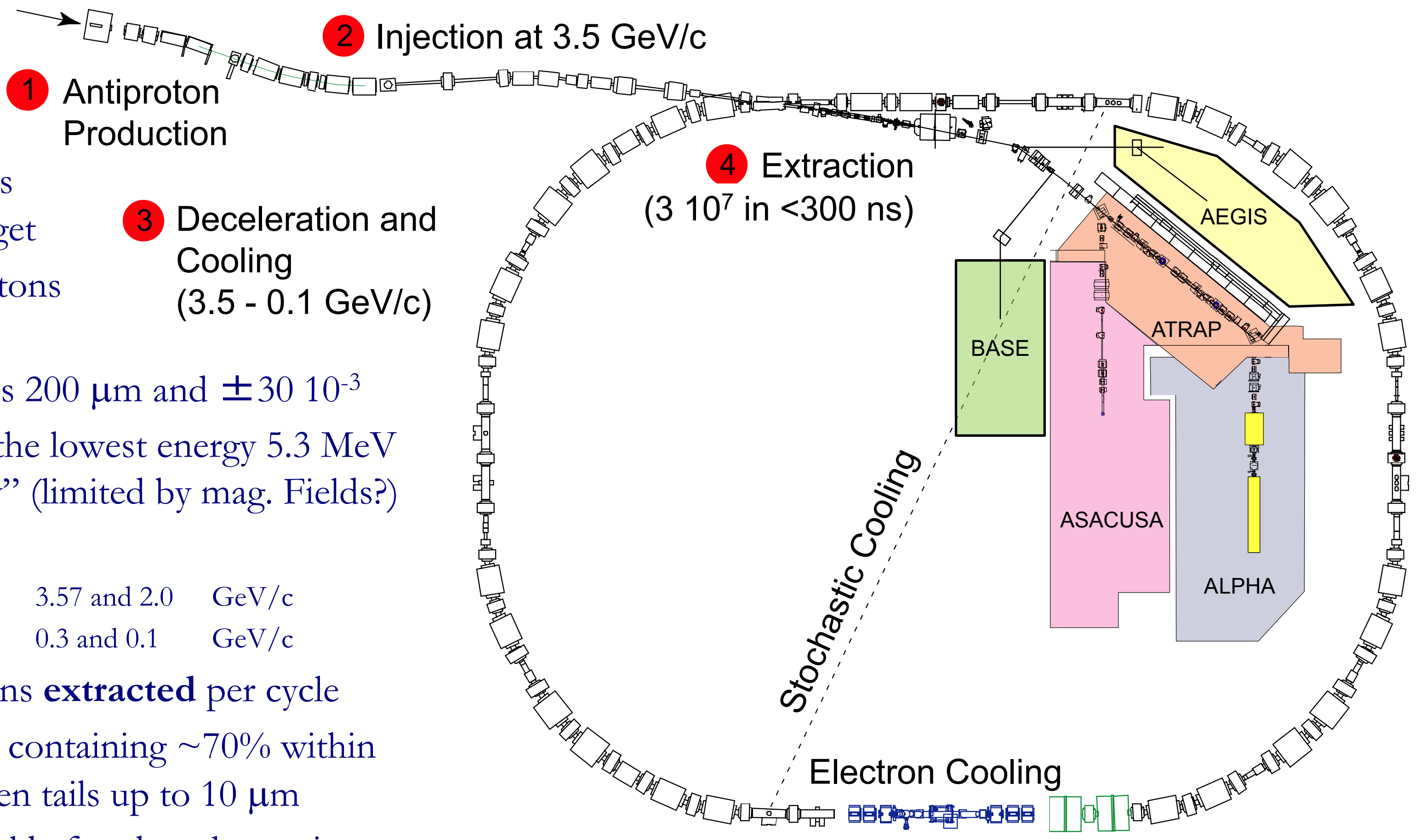
Historical picture of Antiproton Accumulator (**AA**) with no shielding

Historical picture of AAC: Antiproton Collector (**AC**) and Accumulator (**AA**) rings with shielding roof removed

The outer ring was retained and converted into AD

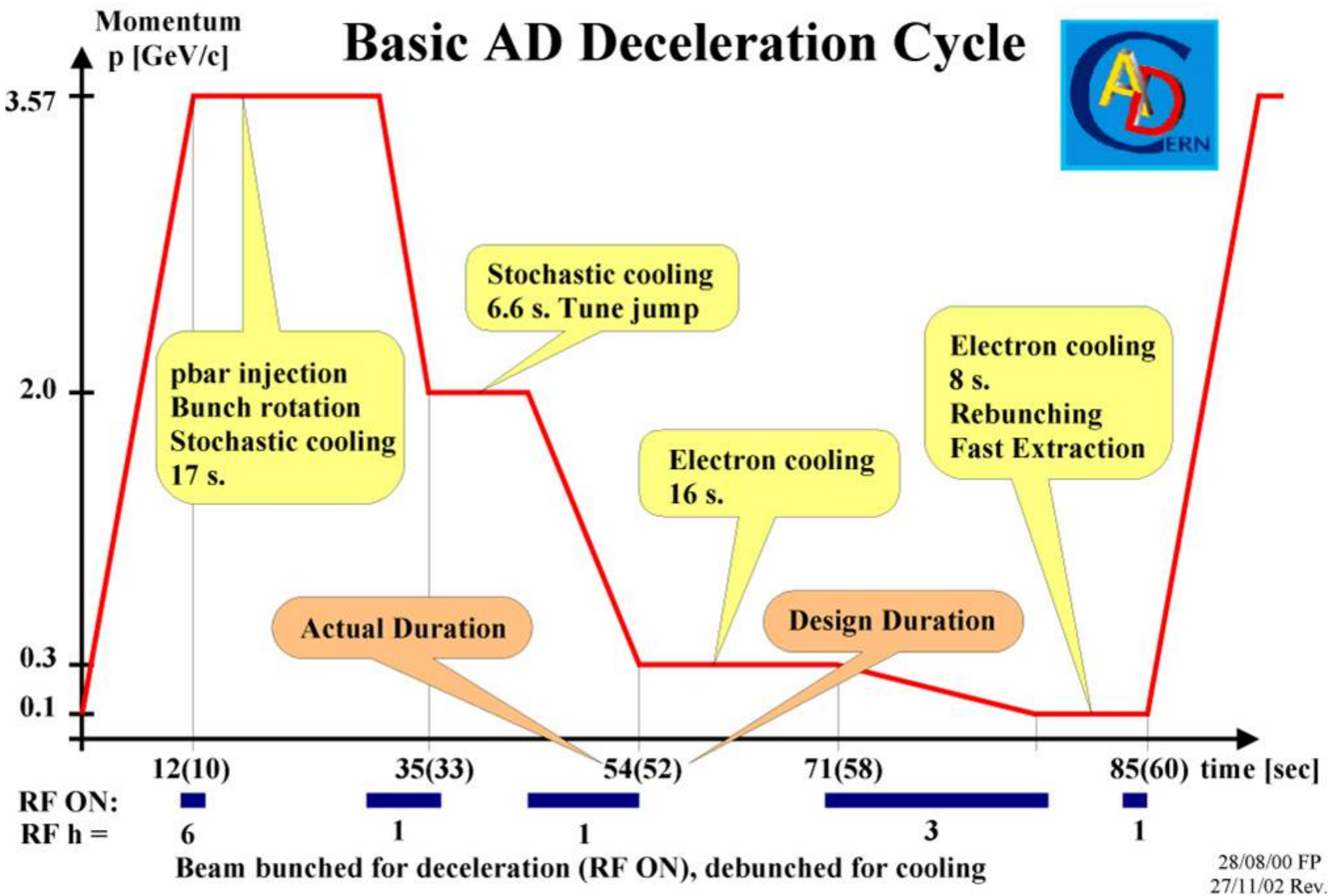
AD – a unique facility providing 5.3 MeV antiprotons

- **~1.5 10^{13}** protons (26 GeV) on target
- **~3.5 10^{7}** antiprotons captured in AD
  - Acceptances 200 μm and ±30 10^{-3}
- Deceleration to the lowest energy 5.3 MeV reachable "safely" (limited by mag. Fields?)
- **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
  - Dense core containing ~70% within <1 μm, often tails up to 10 μm
  - Longitudinal before bunch rotation 95% within 10^{-4} and 400 ns
- **Vacuum pressure: ~4*10^{-10} mbar**
- Cycle length ~100 s



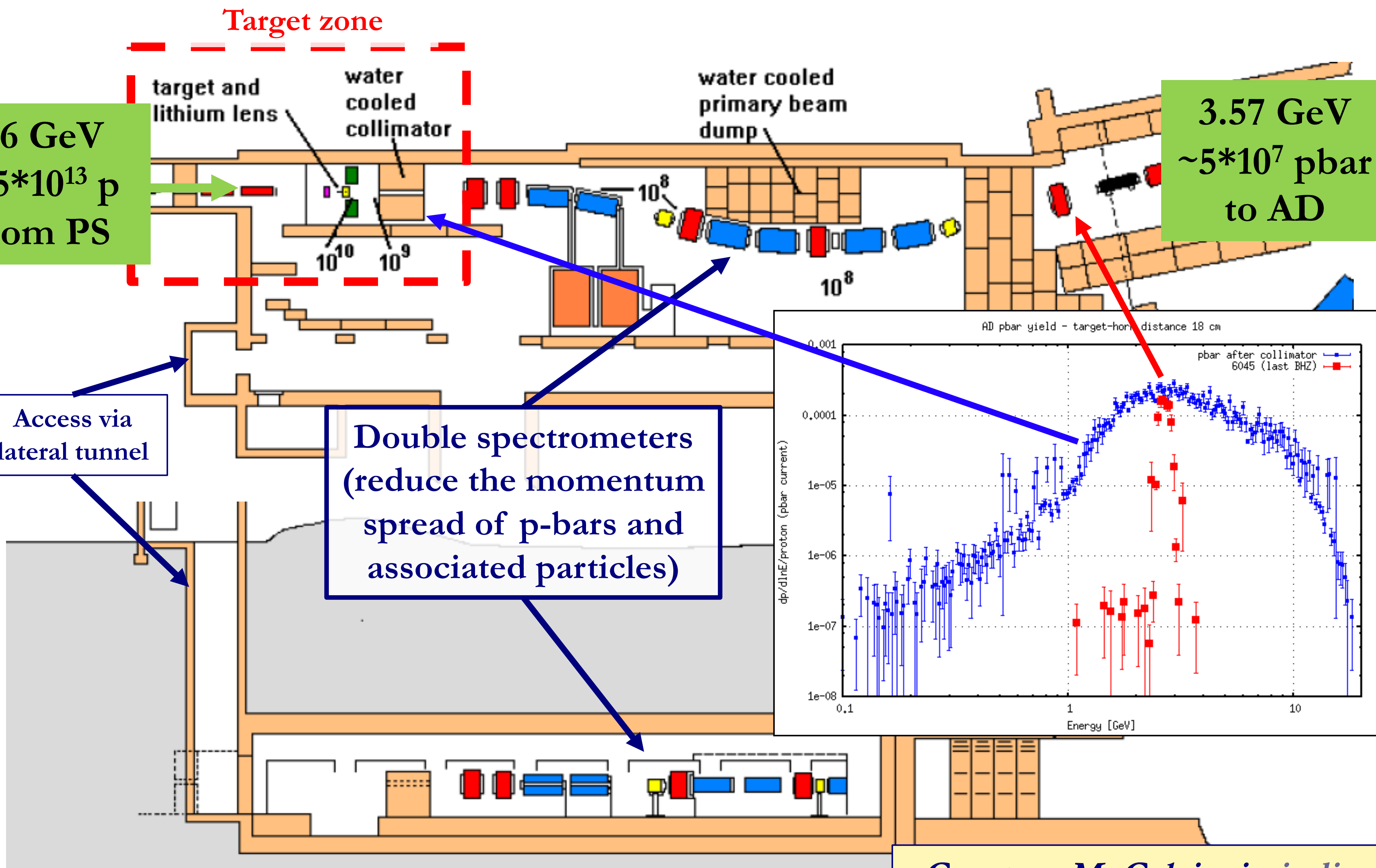
Sketch of the "present" AD
circumference 182 m

AD cycle



Basic AD Deceleration Cycle
Momentum
p [GeV/c]
3.57
2.0
0.3
0.1
pbar injection
Bunch rotation
Stochastic cooling
17 s.
Stochastic cooling
6.6 s. Tune jump
Electron cooling
16 s.
Electron cooling
8 s.
Rebunching
Fast Extraction
Actual Duration
Design Duration
12(10)
35(33)
54(52)
71(58)
85(60)
time [sec]
RF ON:
RF h =
6
1
1
3
1
Beam bunched for deceleration (RF ON), debunched for cooling
28/08/00 FP
27/11/02 Rev.

Pbars generation: AD-target area



26 GeV
$1.5*10^{13}$ p
from PS

3.57 GeV
~$5*10^{7}$ pbar
to AD

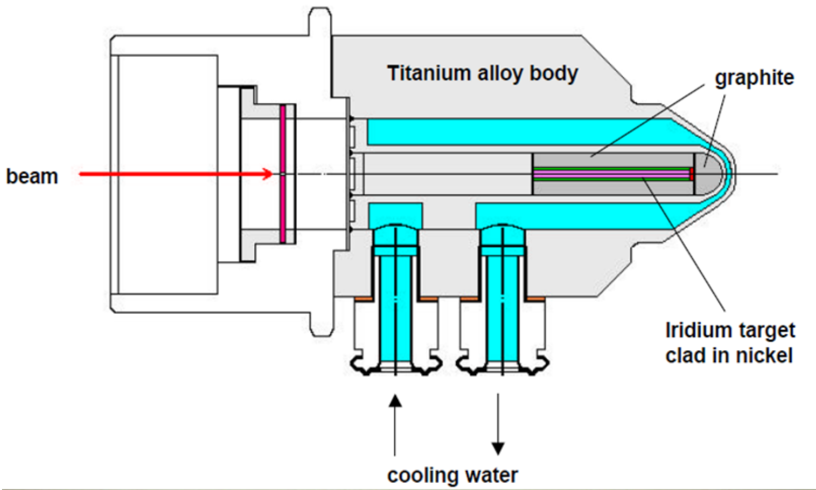
Access via lateral tunnel

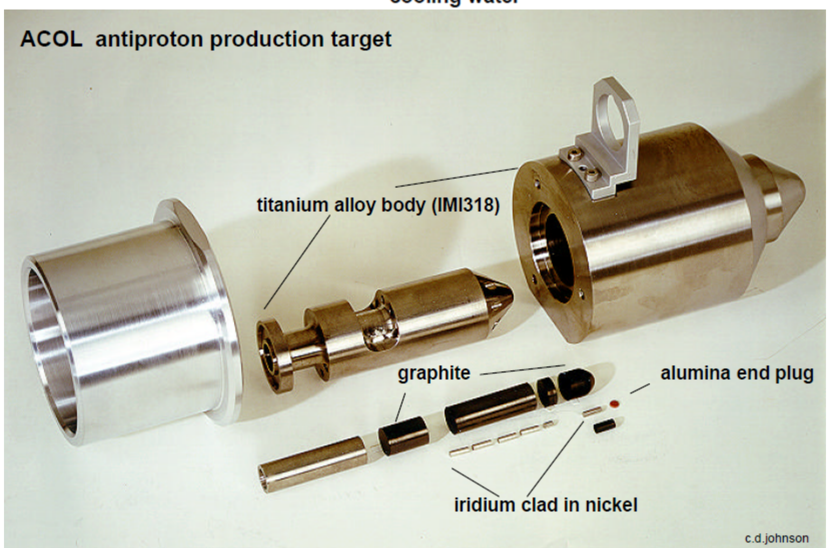
Double spectrometers (reduce the momentum spread of p-bars and associated particles)

Courtesy M. Calviani - indico

Target main components

Target: pbar production

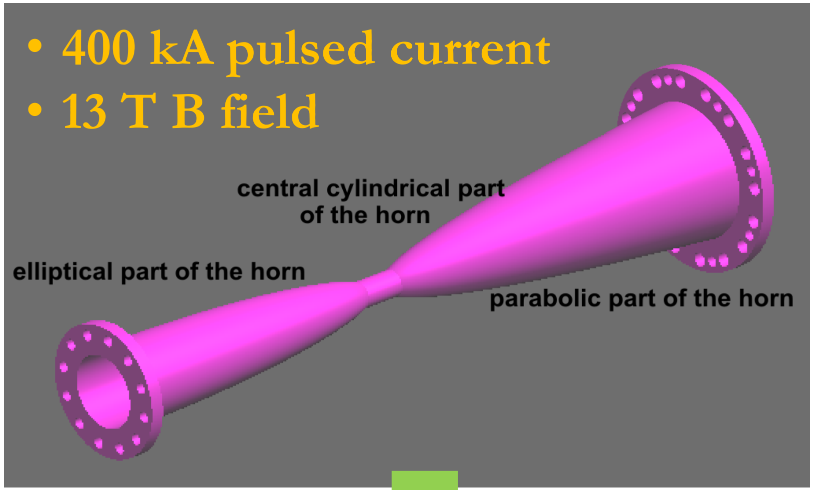


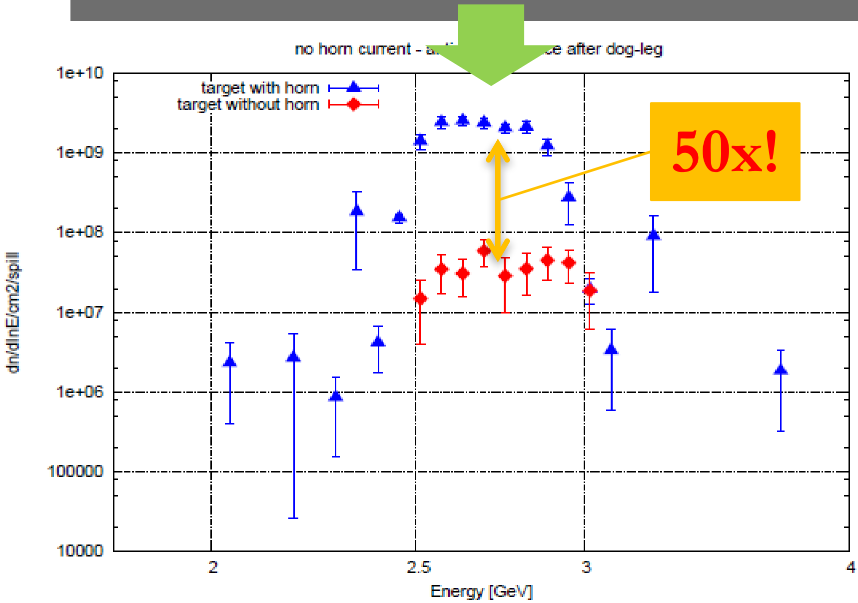


>11 different designs from 1982 to 1990

Magnetic Horn: pbar focusing

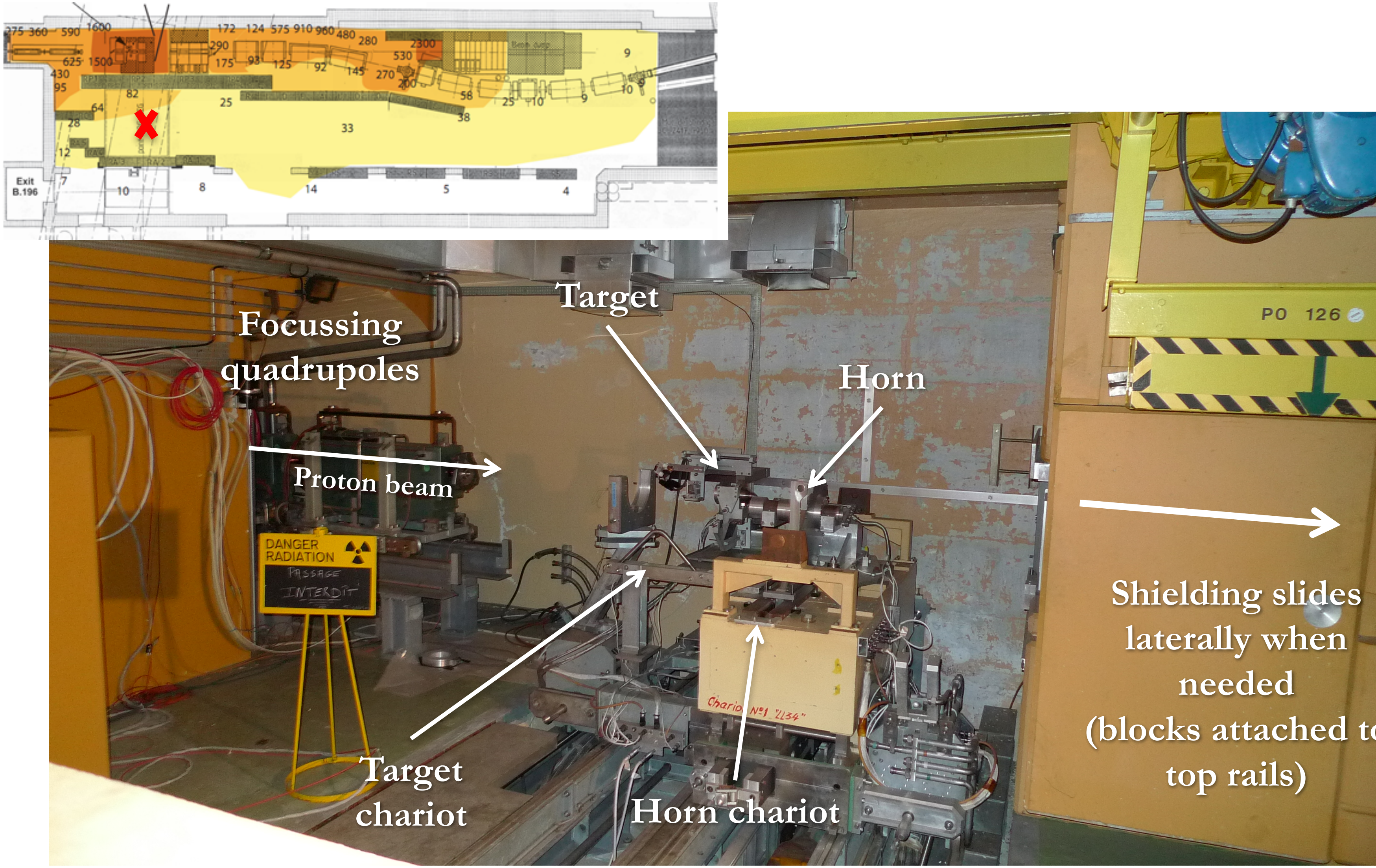
- 400 kA pulsed current
- 13 T B field





Courtesy M. Calviani - indico

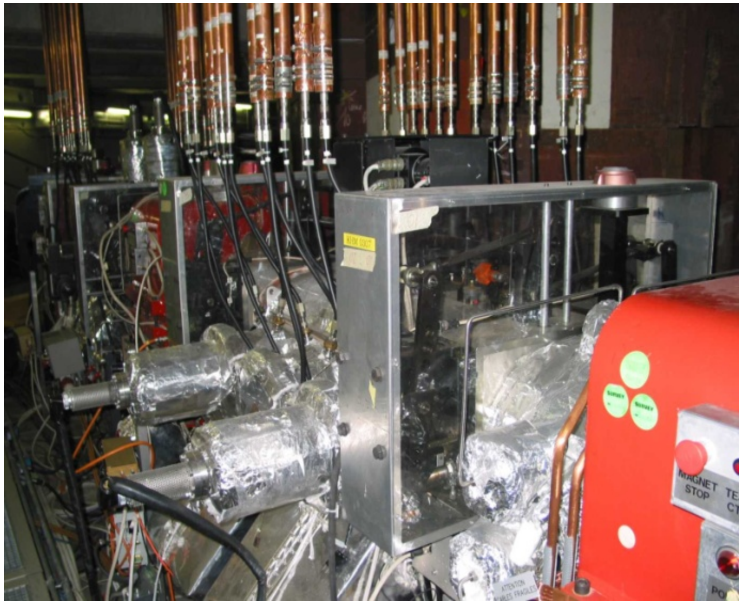
Target zone

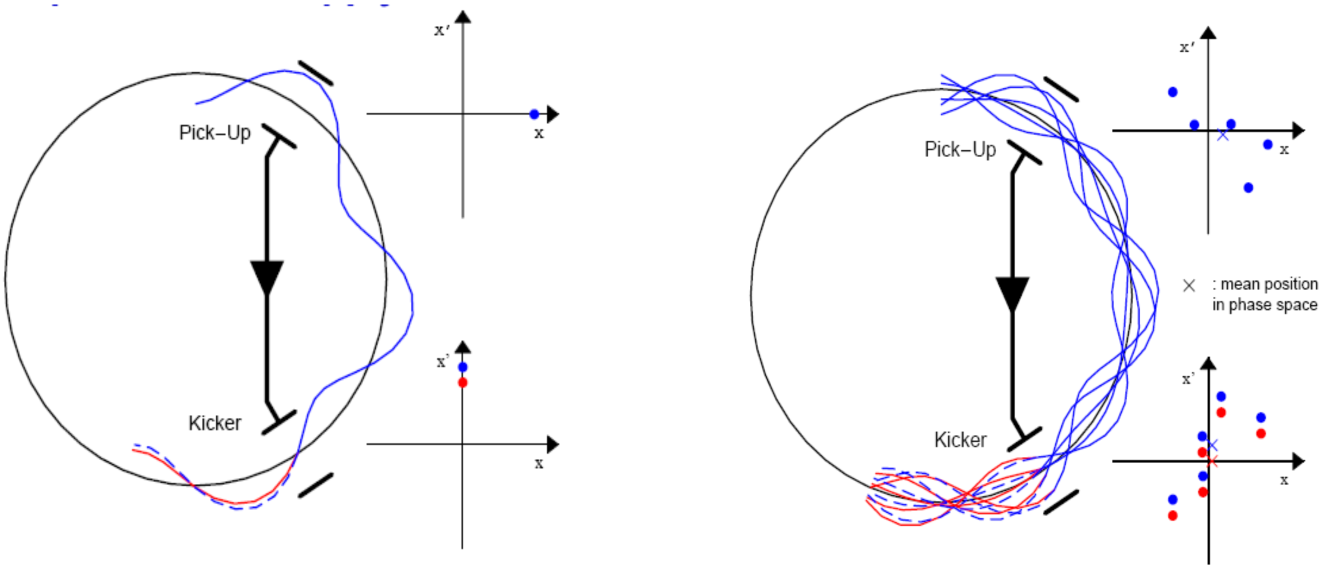


Courtesy M. Calviani - indico

Stochastic Cooling

- Invented by **Simon Van der Meer** (Nobel Prize 1984)
- Aim of cooling:
  - Reduction of transverse and longitudinal emittances
  - Increase of phase space density
- **Pickup and kicker must be correctly placed** re. phase advance and mixing
- Large system bandwidth
  - **1–1.6 GHz** (0.9 – 3.2 GHz in AC)
- **Cryogenic** cooling of certain components to **reduce thermal noise**
- **Moving p/u and kicker** follow beam size for optimum gain and S/N





Stochastic cooling in the AA

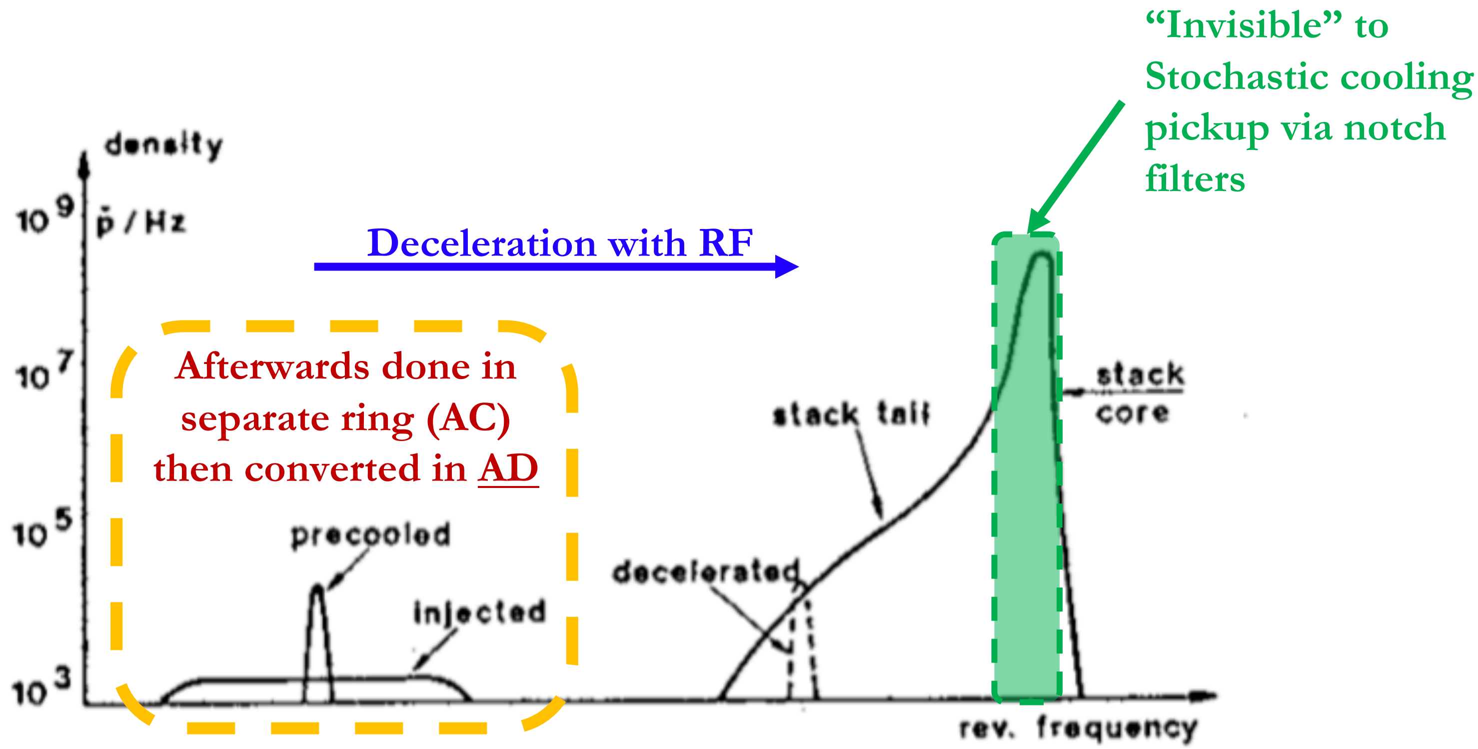
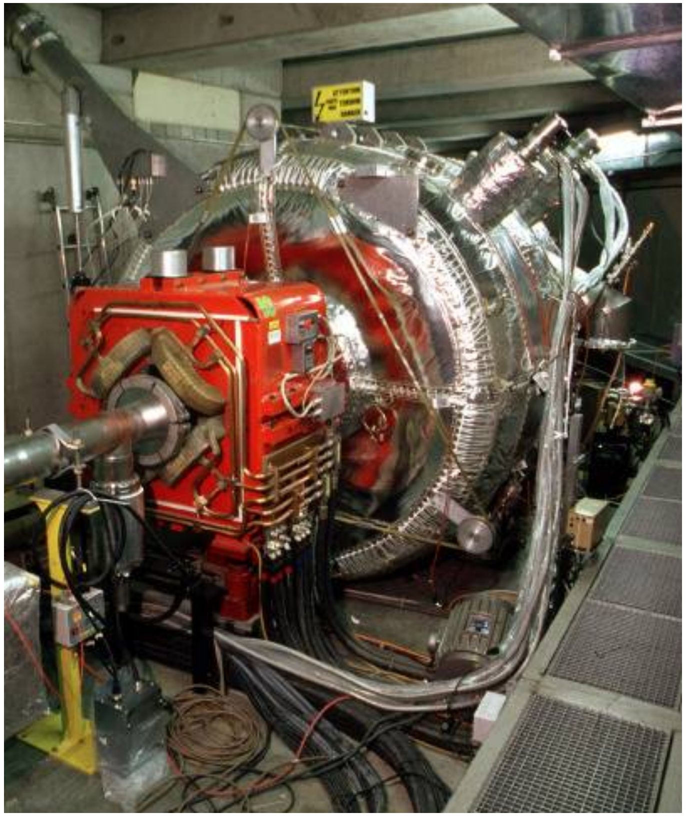


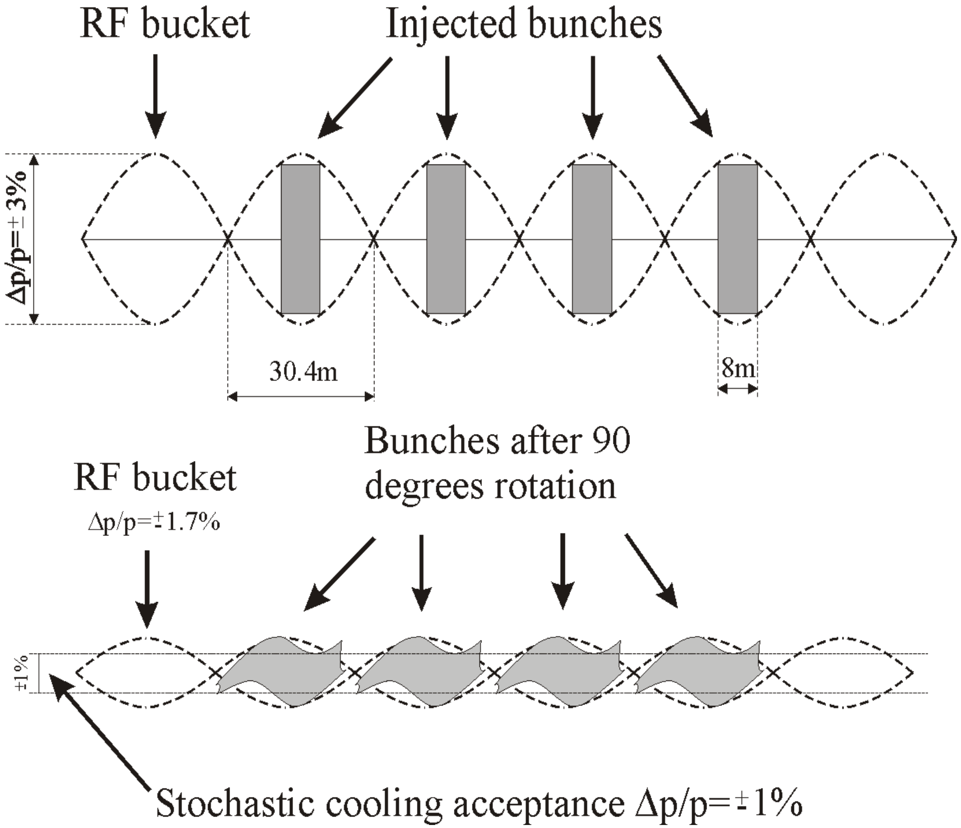
Figure 7 - Stochastic stacking in the AA. The density distribution is shown with the injected p̄ beam at the left and the stack at the right.

From S. Van Der Meer - An introduction to stochastic cooling CDS

AD – beam compression

- **Reduction of energy spread to fit** **Stochastic cooling acceptance**
- **Bunch rotation in longitudinal phase-space** reduces dp/p from 6% to 1.7%
- 9.5 MHz 1.2MV RF-system
- Efficiency of bunch rotation + cooling very sensitive to length and structure of primary bunches !!!





Electron Cooler in AD

Means to increase the phase space density of a stored ion beam.

- **Mono-energetic cold electron beam is merged with ion beam** which is cooled through Coulomb interaction.

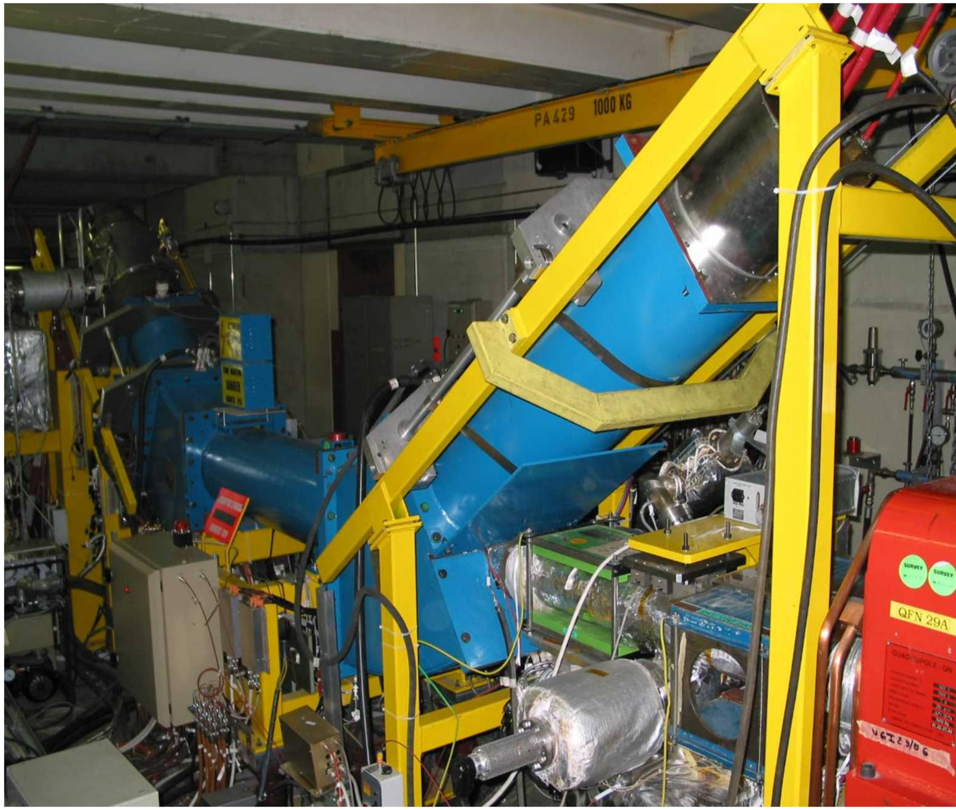
Cooling time:

$$\tau \propto \frac{\theta^3}{\eta \cdot I_e}$$

- where θ is the relative difference in angle between the ions and electrons

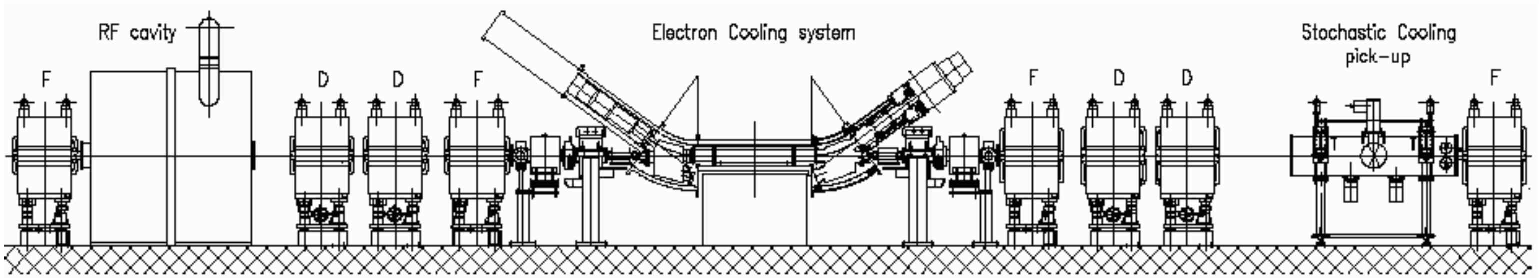
$$(\theta_i - \theta_e); [\theta_i = \sqrt{(\varepsilon/\beta)}]$$

- $\eta = L_{cooler}/L_{machine}$
- I_e is the electron current.



Electron Cooler in AD

- The electron cooler (**ex-ICE, ex-LEAR**) is still in operation!
- Gun, collector, and corrector coils upgraded during the LEAR era, but some parts still original ICE components.
- **Minimum upgrade after removal from LEAR**: mechanical support, change from S-configuration to U-configuration, orbit correction.



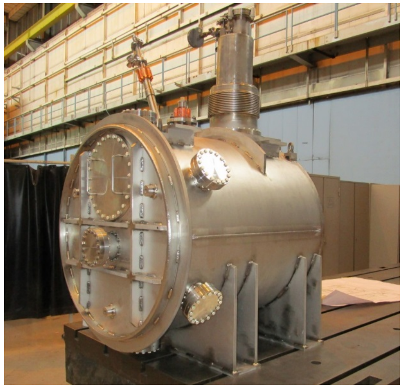
- In 1999 we suffered from ***poor alignment*** of e-cooler (~20 mm misalignments)
- **Orbit kicks** from toroids guide field could not be corrected due to *inadequate strength of compensating correctors*: power supplies upgraded in 2000.
- **Coupling** introduced by e-cool solenoid is compensated by separate power supplies for compensating solenoids and two skew quads.
- Cooling is ***much slower* than anticipated**.
  - AD cycle about 85-110 s instead of 60 s of design.

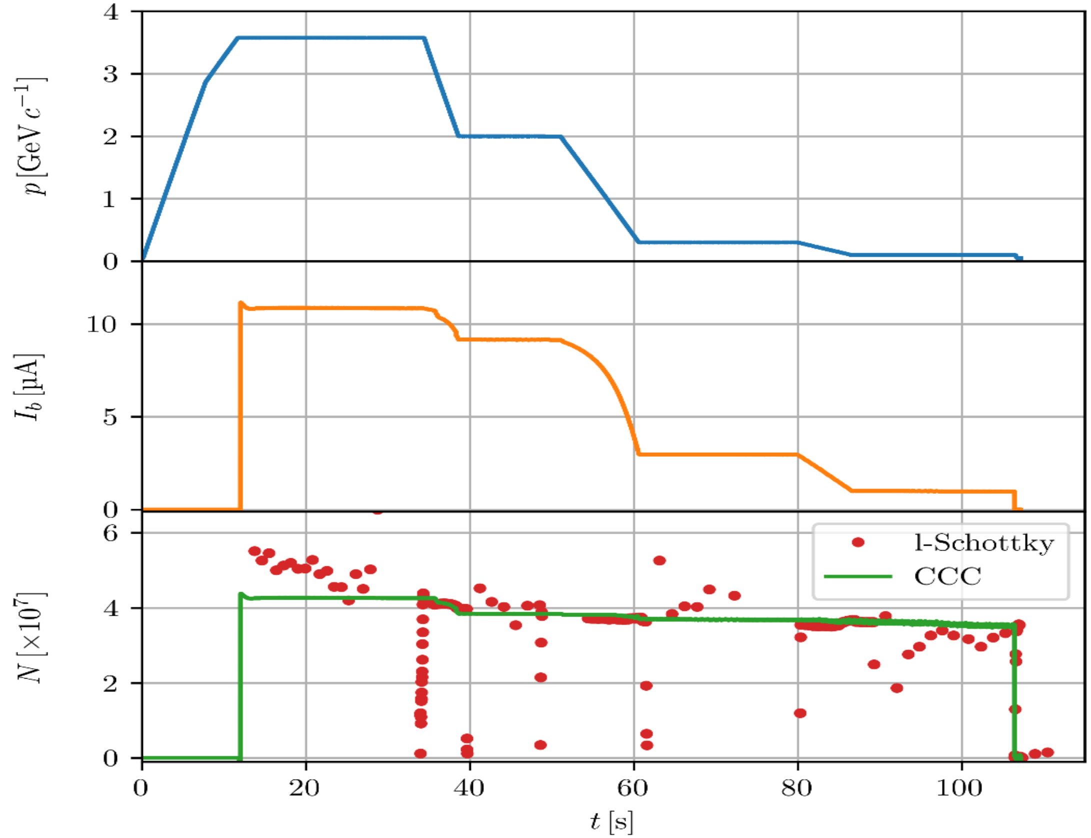
Beam Diagnostics

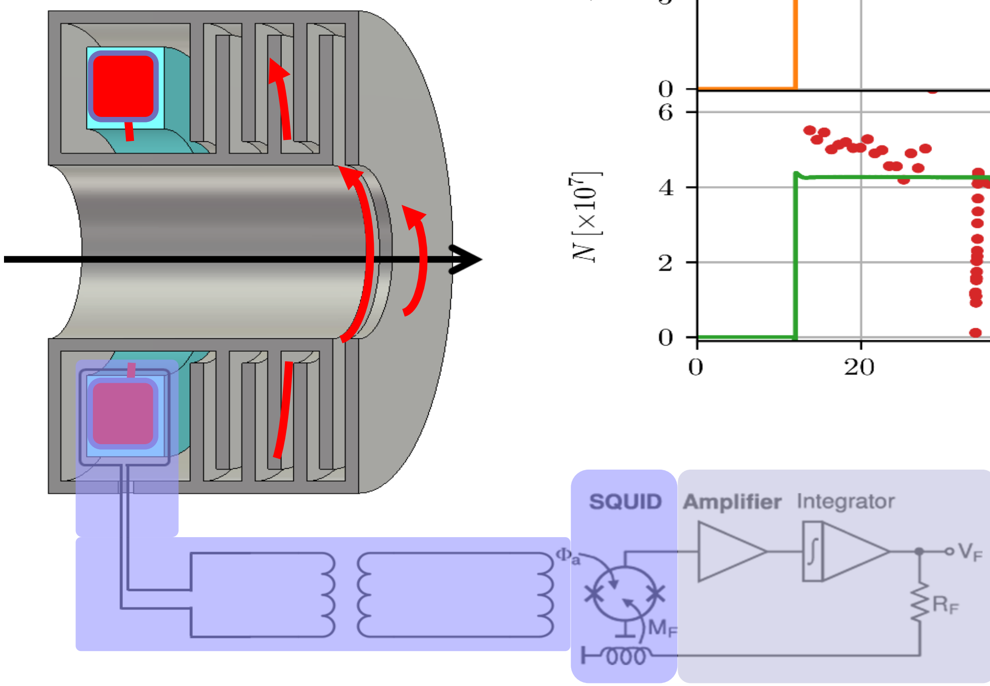
AD project **challenges due to low intensity and energy**.

- New low frequency (0.3 - 30 MHz) ***longitudinal Schottky*** pick-up, performance as expected ~20 dB S/N improvement [**Schottky intensity and momentum distribution, RF phase loop, bunched beam intensity,…**]
- New low frequency (5 - 7 MHz) ***transverse Schottky*** pick-up, achieved performance approx. ~10 dB S/N ratio at normal pbar intensities
  - => **unable to observe passively tunes** and emittances, but OK with beam excitation
- **Scrapers** and scintillators recuperated from AC:
  - ***destructive*** transverse profile measurements
- ***Beam Ionisation Profile Monitor*** [BIPM]
  - **requires gas injection which spoils the beam quality**
  - => ***no passive, non-destructive emittance observation avaliable.***
- **Closed orbit measurement system** upgraded with ultra low noise head amplifiers.
  - After EMC upgrade: ~$\mathbf{2 \times 10^7}$ **pbars [+/- 0.2 mm] at 100 MeV/c.**
- **DC beam transformer** used for **intensity calibration** of Schottky system (bunched / unbunched) **with** higher intensity **proton** beams.

More recent diagnostic: CCC







Superconducting

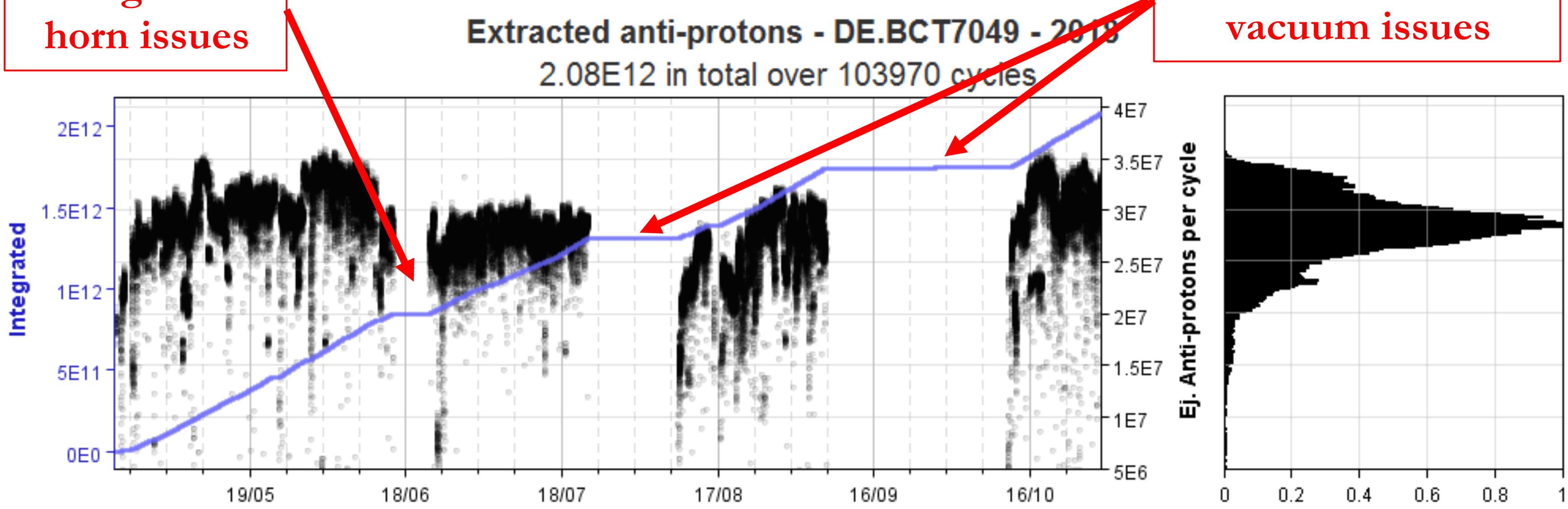
Room temperature

From ***M. Fernandes*** **- Operation of a CCC for continuous beam intensity measurements in AD** (indico)

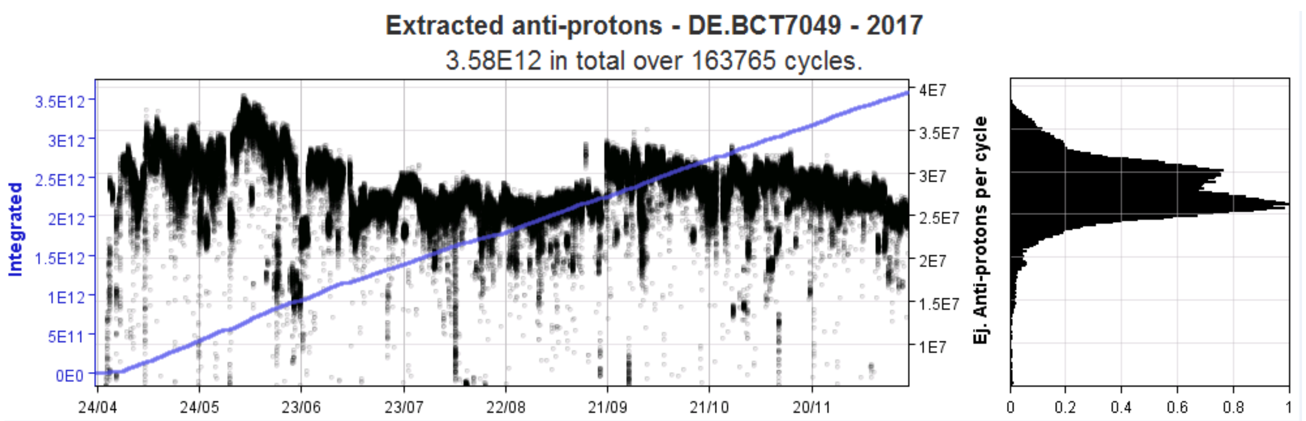
AD Ejected beam intensity in 2018

Magnetic horn issues

e-cooler collector vacuum issues



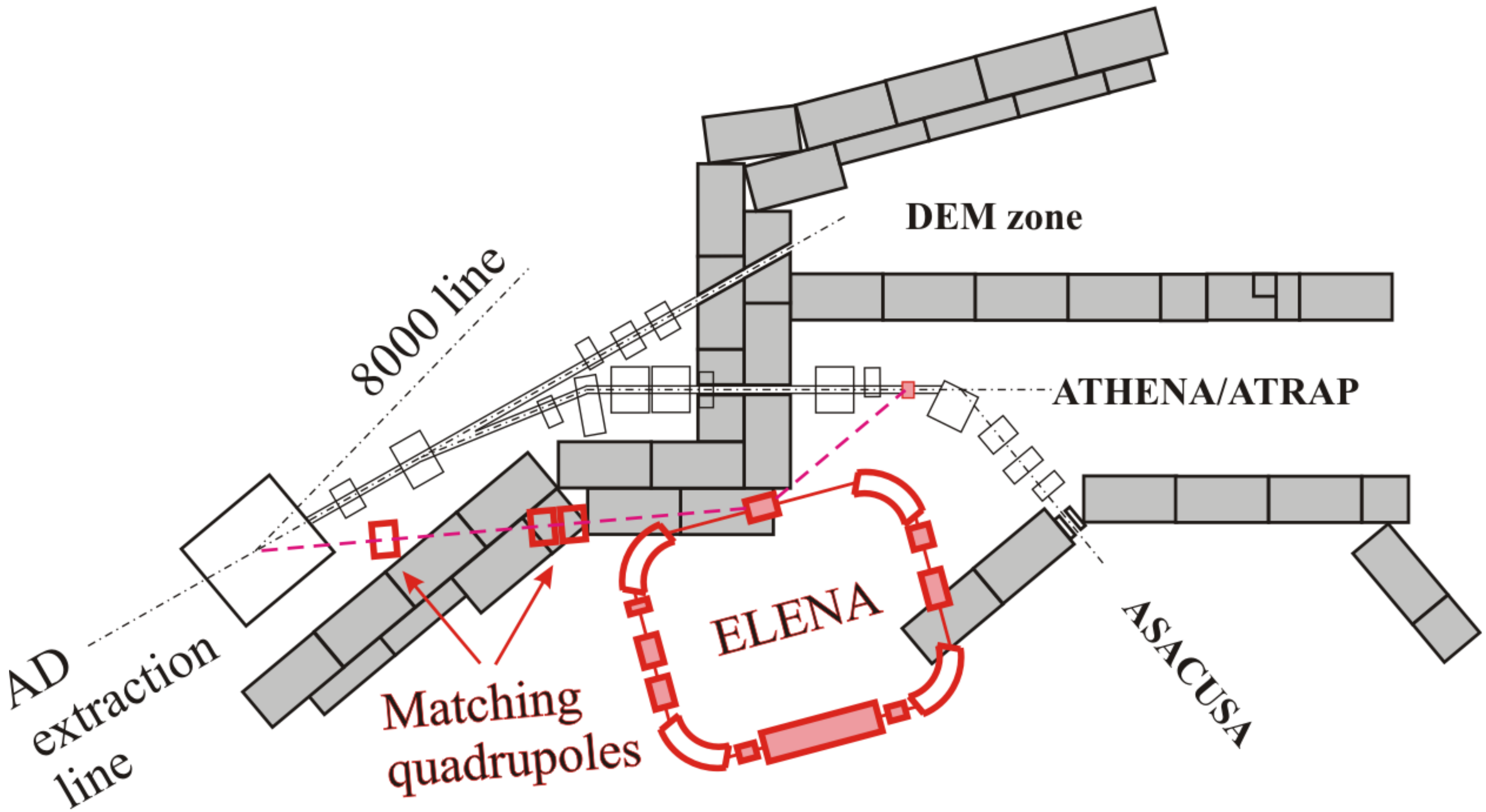
For comparison: 2017



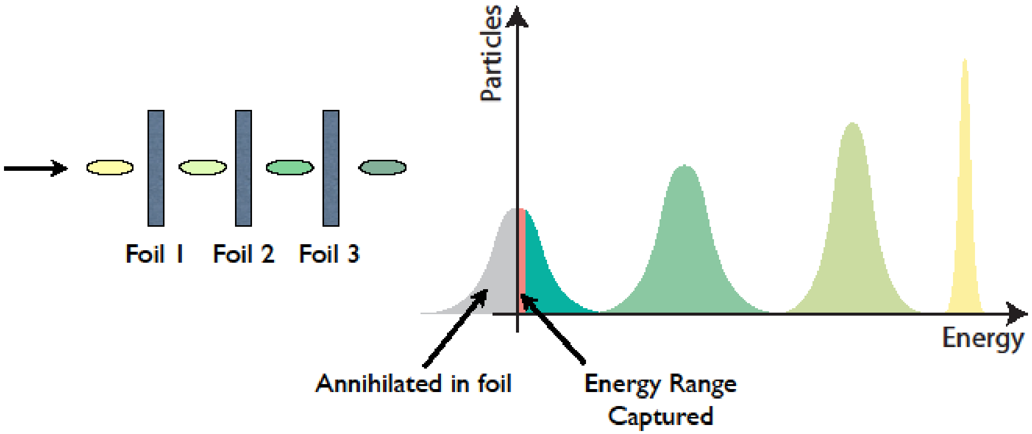
Courtesy T. Eriksson (link)

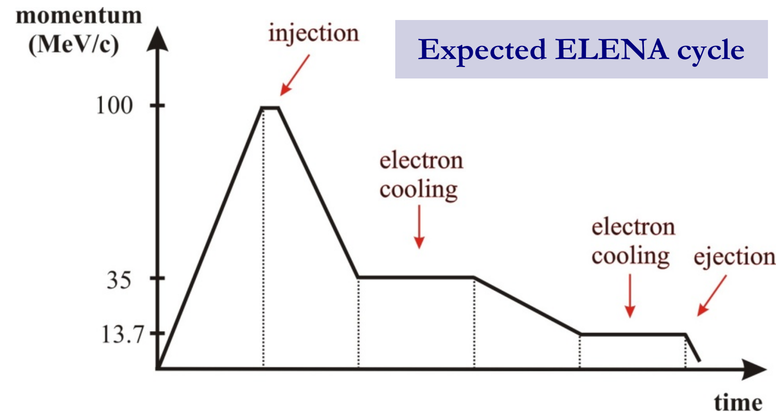
History: first ELENA proposal

- **At Villars (Aug 2004) the SPSC has supported the implementation of the ELENA decelerator ring**
- **Further deceleration from 5.3 MeV to 100keV** will increase pbar trapping efficiency



What is ELENA ?
= Extra Low ENergy Antiproton ring

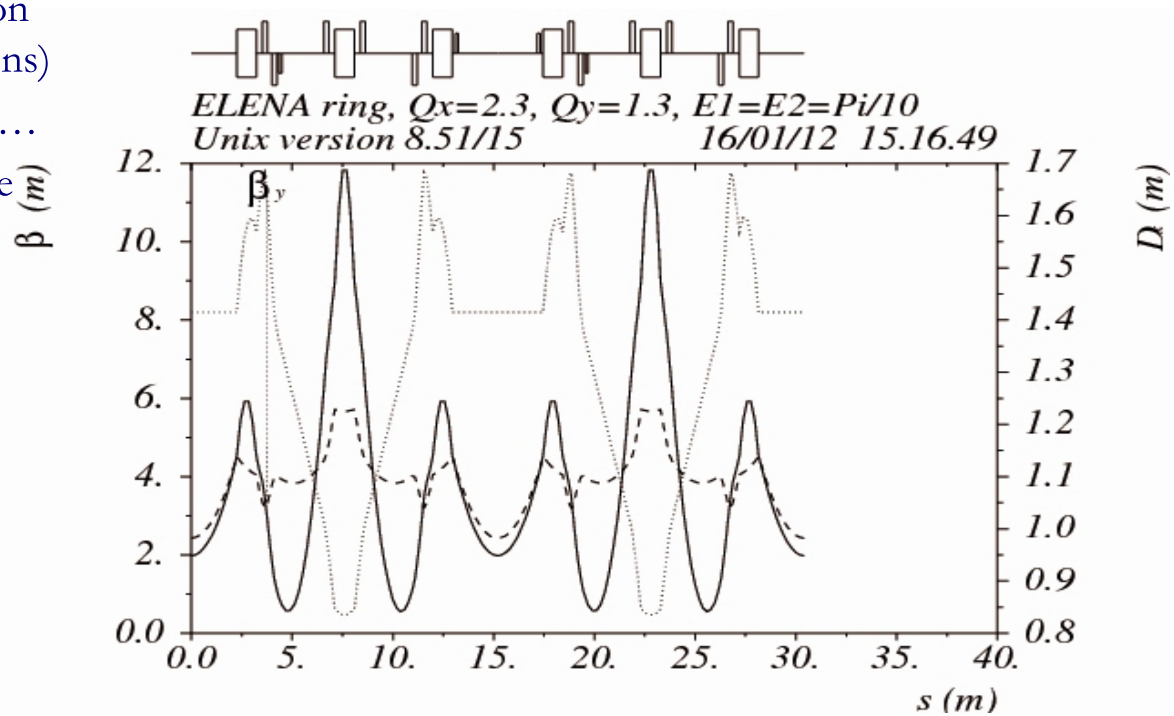




- To be able to **capture antiprotons in penning traps**, **most experiments** **use degrader foils** to further **decelerate** the 5.3 MeV antiprotons coming from AD **to a few keV**.
- Energy straggling increases energy spread such that only a few antiprotons can be captured; even with optimized foil thickness
  - Almost **half of the incoming pbars** are **stopped in foil**, where they annihilate
  - Almost **half of the incoming pbars** are **to energetic** to be trapped
- (**Note:** there are AD experiments not using degraders as e.g. **ASACUSA decelerating antiprotons with an RFQ** – they achieve about one order of magnitude higher trapping efficiencies)
- Other requirements from experiments
  - Beam size on foil small enough (rms size <1 mm)
  - Full bunch length less than 300 ns

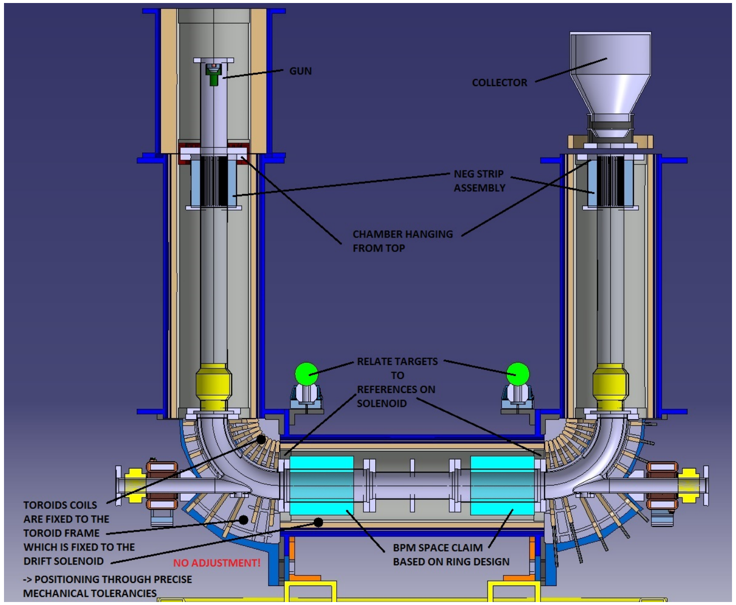
Selected Features and Challenges

- **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)



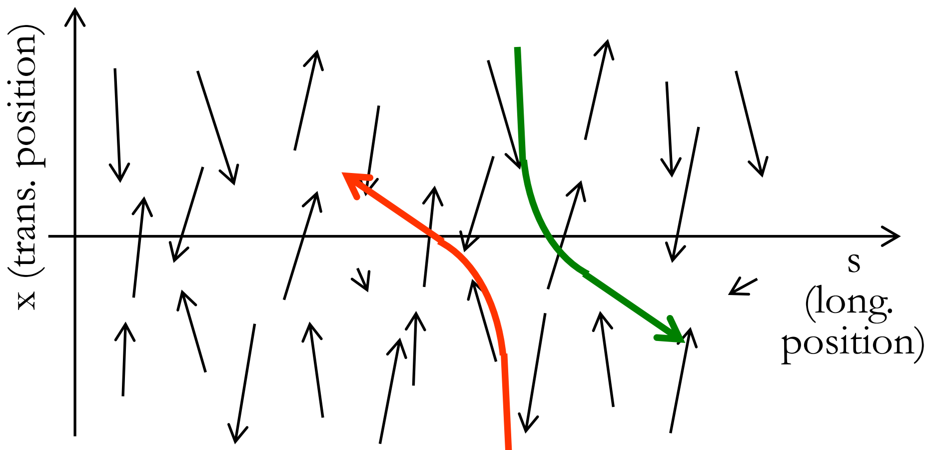
Selected Features and Challenges

- 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
  - Electron cooling
  - IBS increasing emittances



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

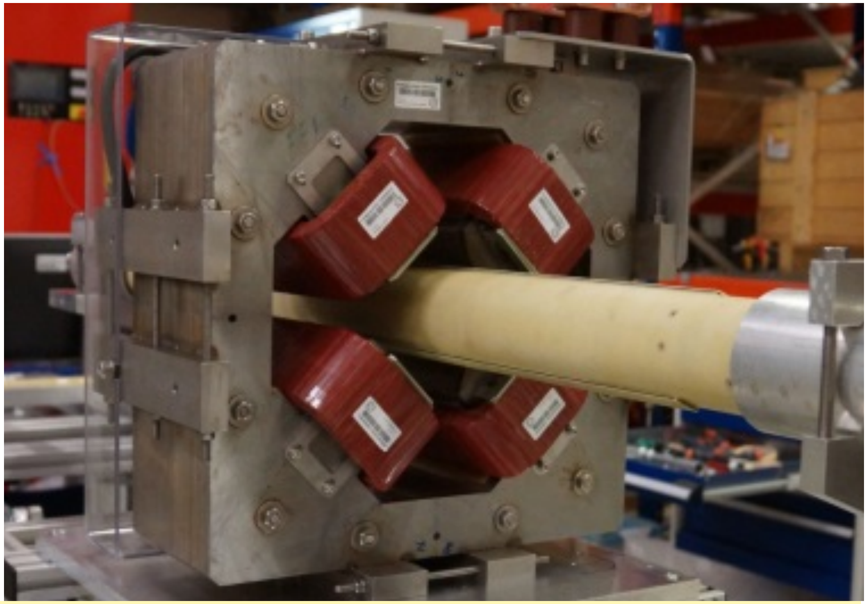
$$\Delta Q = -\frac{G_T r_p N_b}{2\pi\varepsilon_x \beta^2 \gamma^3} \frac{G_L C}{l_b}$$

- **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

⇒**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)

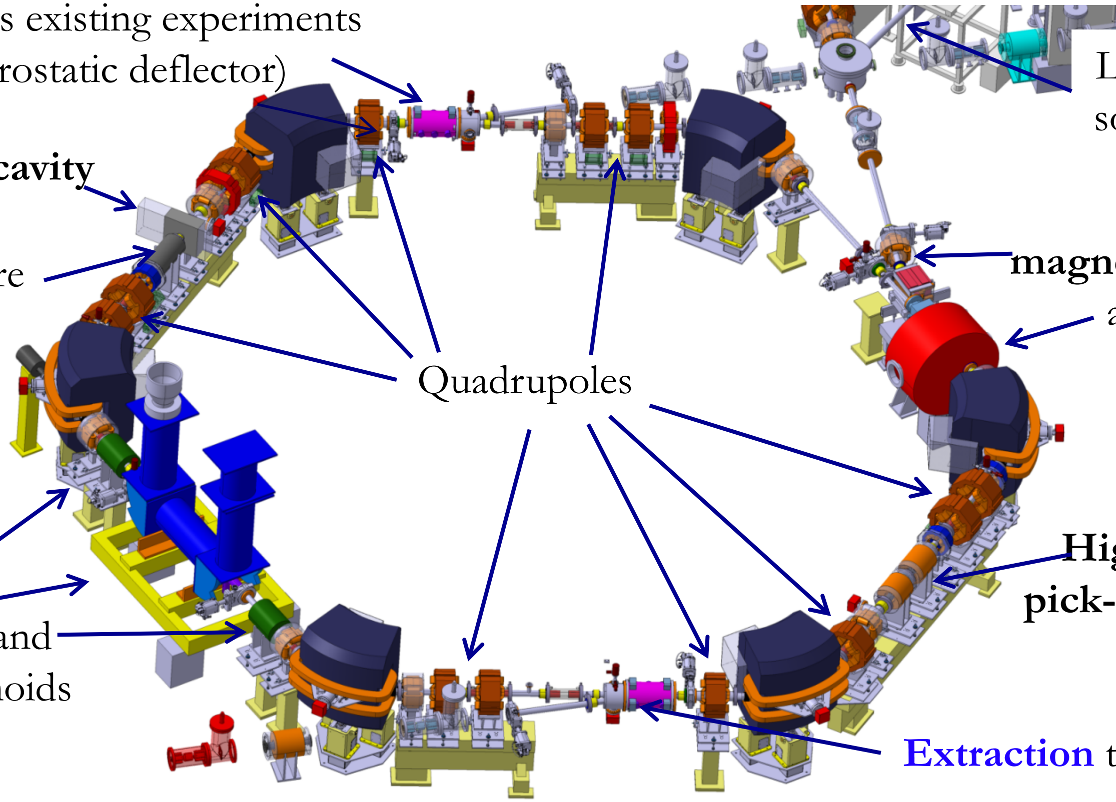


Prototype quadrupole to investigate magnet "thinning" on the measurement bench

Selected Features and Challenges

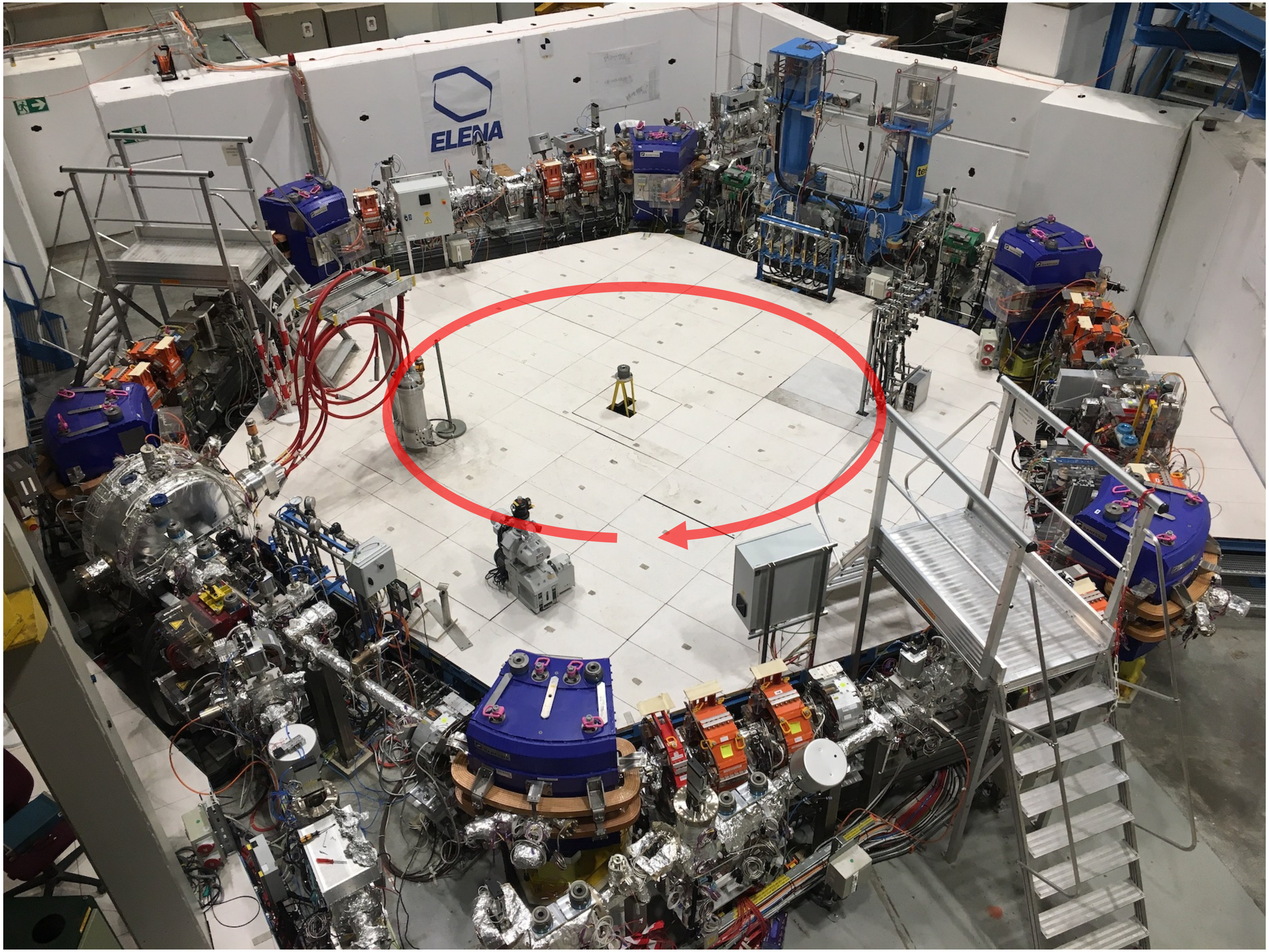
- **Rest gas interactions** and vacuum system
  - 3 10^{-12} Torr nominal pressure - **fully baked machine with NEGs** wherever possible (technical problems as peel-off with NEG coating of stainless steel chambers)
  - Interactions of beam with rest gas to be evaluated with care, not the dominant limitation
- **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, precious antiprotons kept as much as possible for experiments
  - Higher repetition rate but start commissioning at the difficult low energy part of the cycle
  - Antiprotons needed to complete ELENA ring commissioning

ELENA Overview and Layout

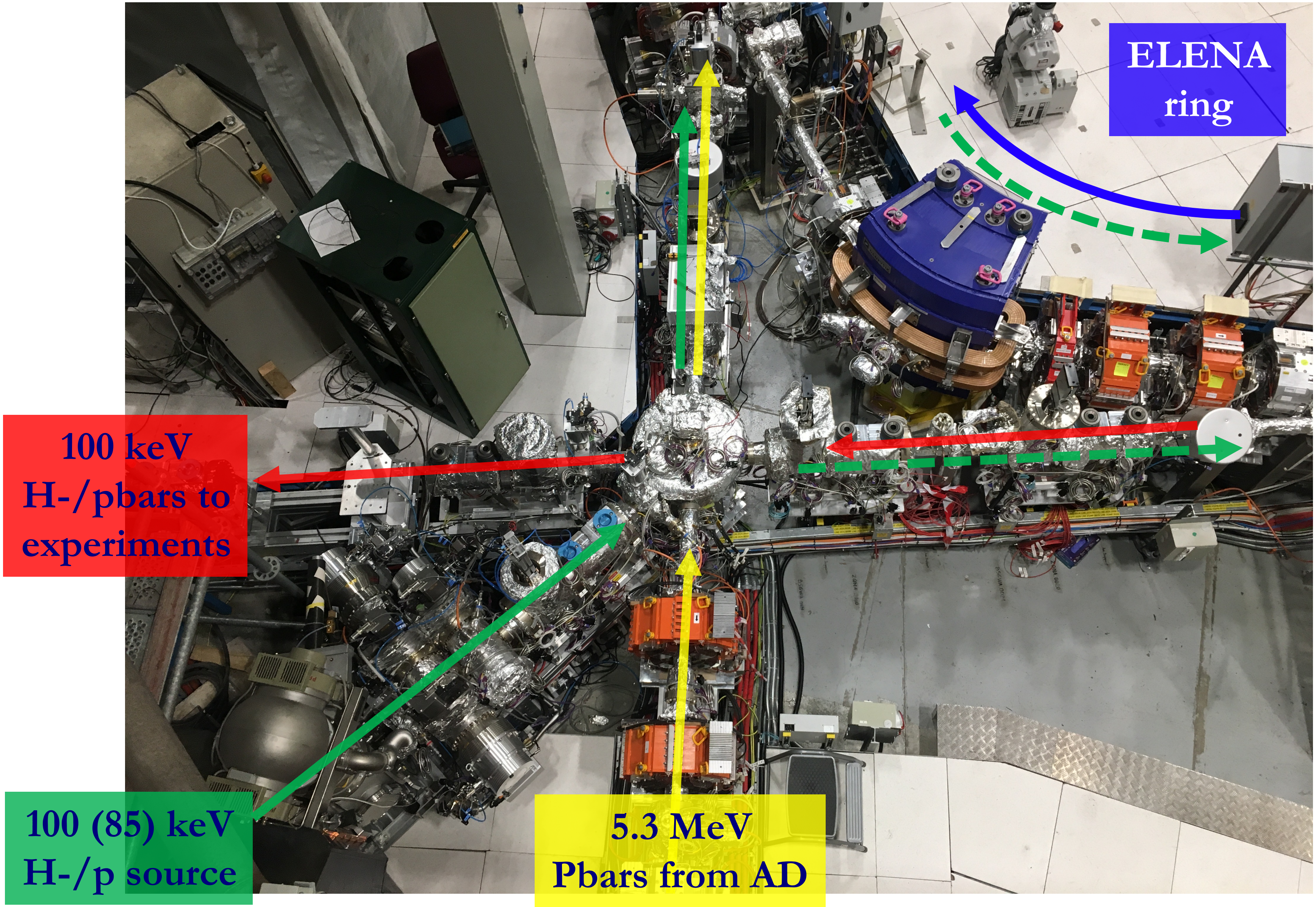


- **Circumference 30.4 m** (1/6 the size of the AD)
  - Fits in AD hall and allows installing all equipment without particular efforts
  - **Lowest average field** (beam rigidity over average radius)
    - **Bρ/R = 94 G (smaller than for AD 115 G)**

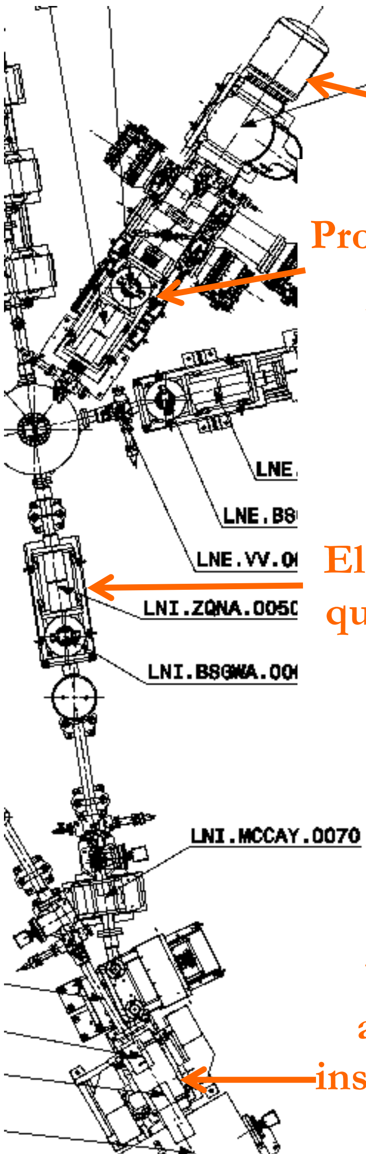
ELENA Ring – 2018



ELENA Injection/Extraction

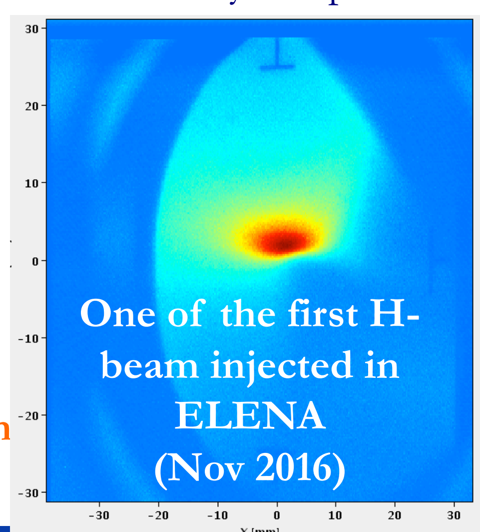


ELENA Commissioning – Ion Source and Line from Source to Ring



- Aim: **progress as much as possible** without taking precious antiprotons
- **Source available and tested well in advance**
  - 100 keV (post-acceleration), source a few meters from Faraday cage with HV cables in between
  - First tests with source mounted in Faraday cage
- **Technical issues despite serious preparations**

  => **Running most of the time at 85 keV**
- **Empirical adjustments** led to unexpected settings
- **Limited beam diagnostics**
  - Only one profile monitors with temporary electronics

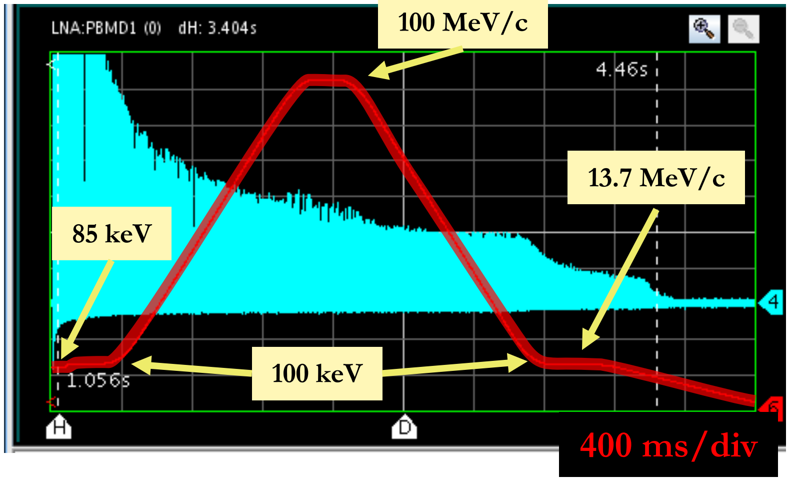


One of the first H- beam injected in ELENA (Nov 2016)

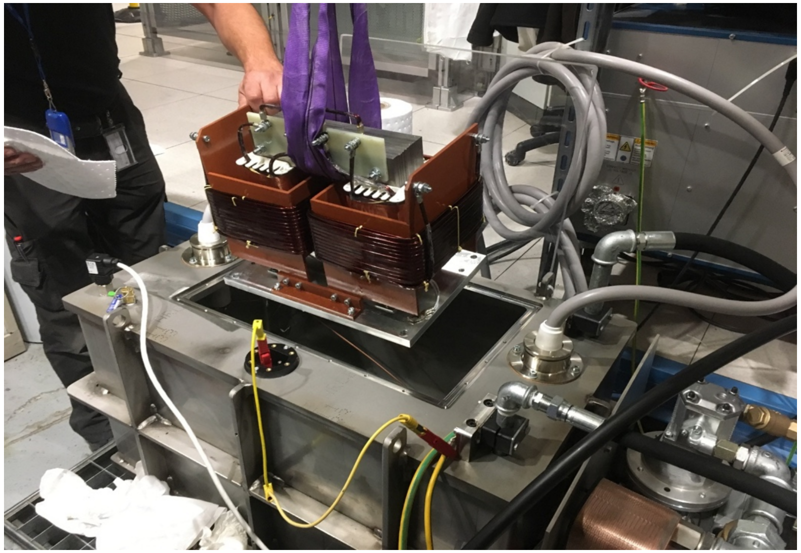
Source and profile monitors are in-kind contributions to ELENA

Thanks a lot to all teams contributing!

H- Status: a "full cycle"



- **Accelerating cycle:**
  - From 85 keV to 100 keV
  - From 100 keV to 100 MeV/c
  - Back to 100 keV.
- Possible to have beam even for energies lower than 85 keV on the "other" side of the acceleration…

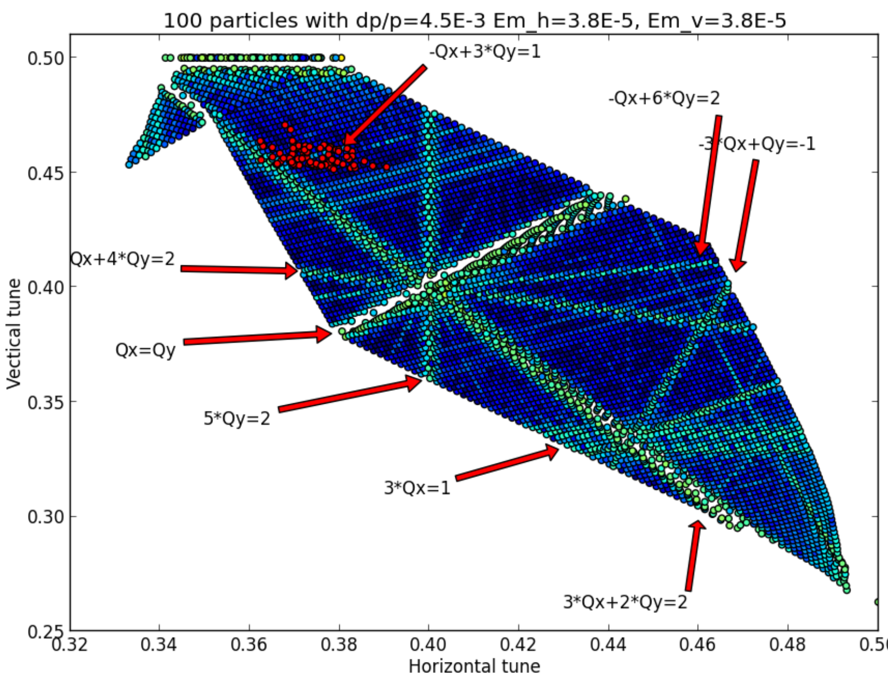


- Unfortunately we had many **issues** with **HV insulation transformer**
- **Only a few months of operations in 2018 mainly at 85 keV instead of 100 keV.**

Exploring tune diagram

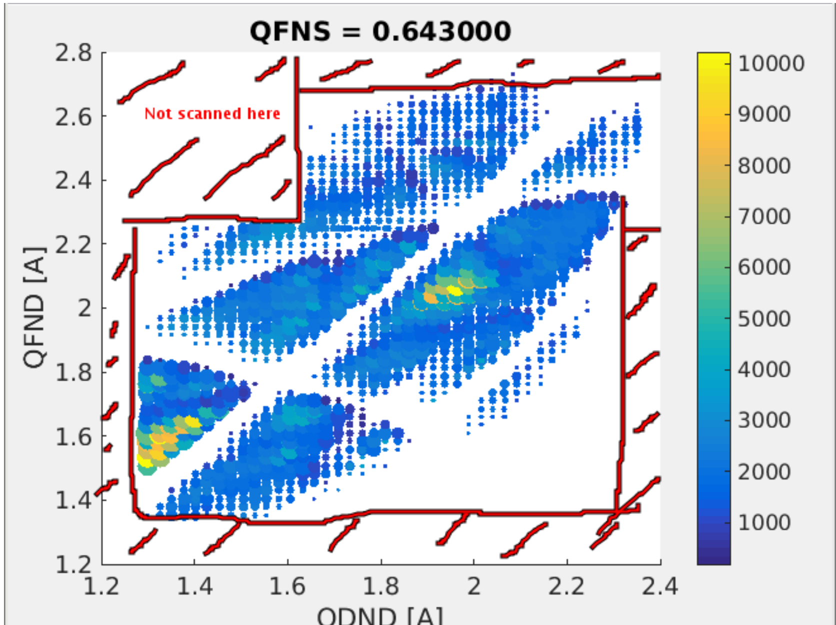
Simulations

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



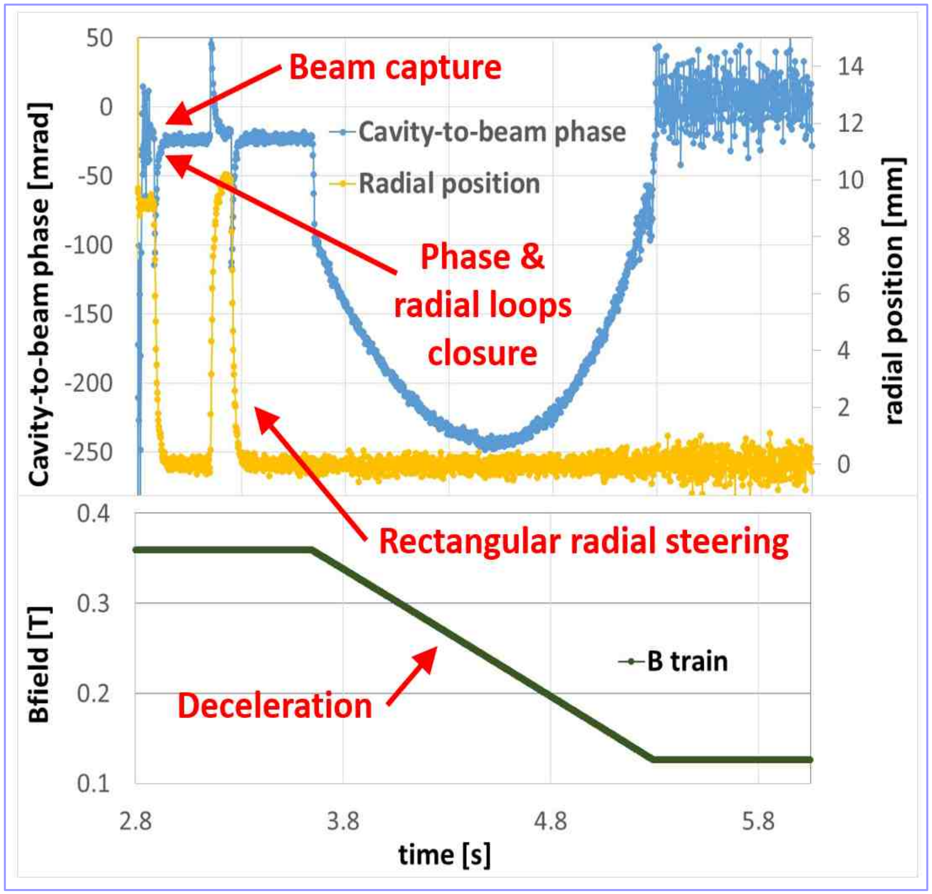
Measurements

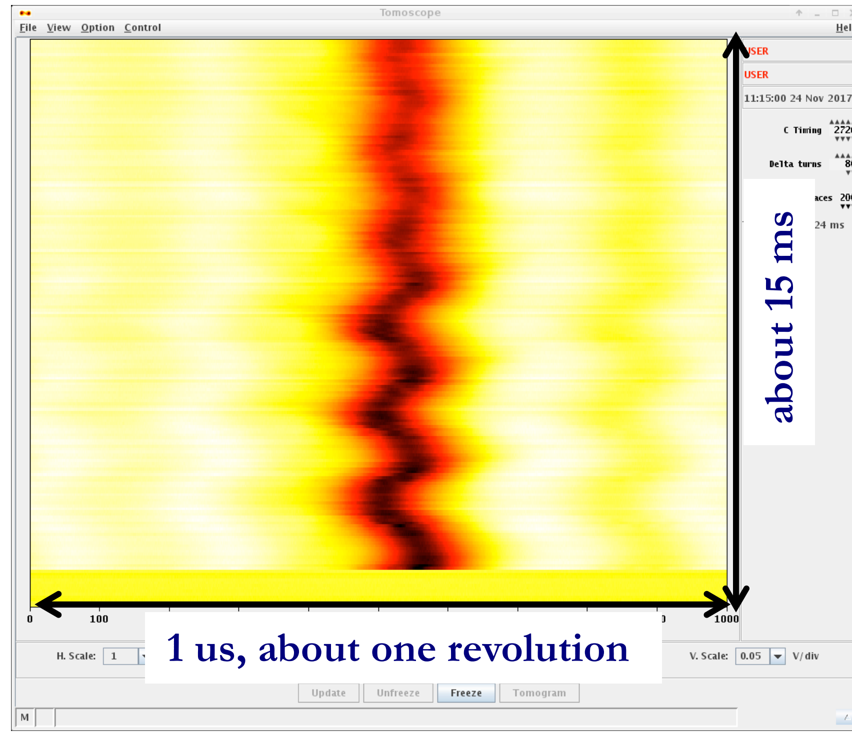
- Profiting of "fast" and "cheap" H- cycles to **explore tune diagram with beam**
- Here an example of **measured lifetime** as a function of different quadrupole settings at 85 keV
- **Data still to be analyzed.**



Results from ELENA Commissioning – with Antiprotons from the AD

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

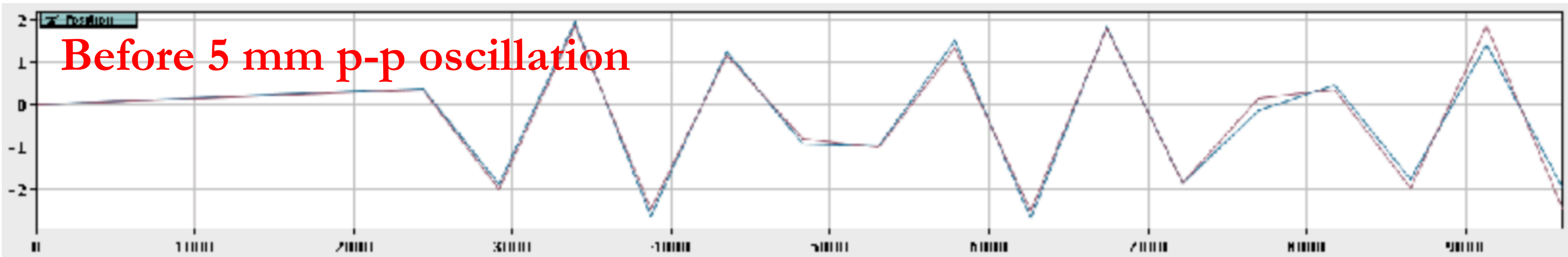


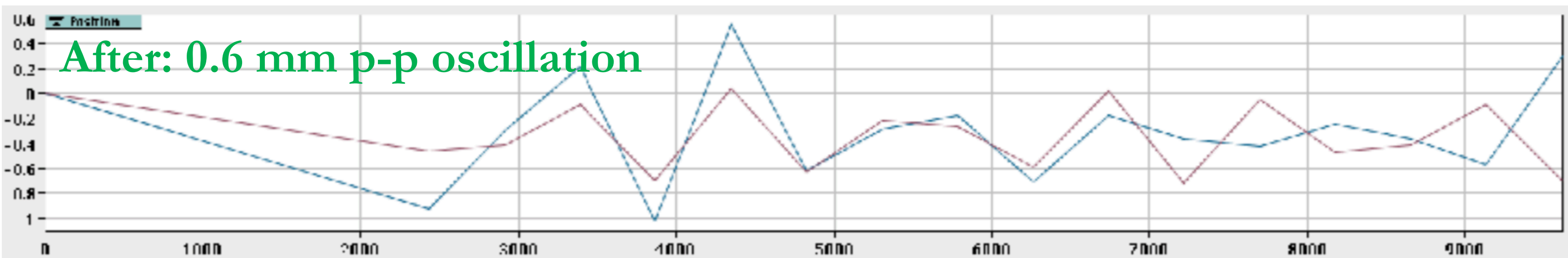


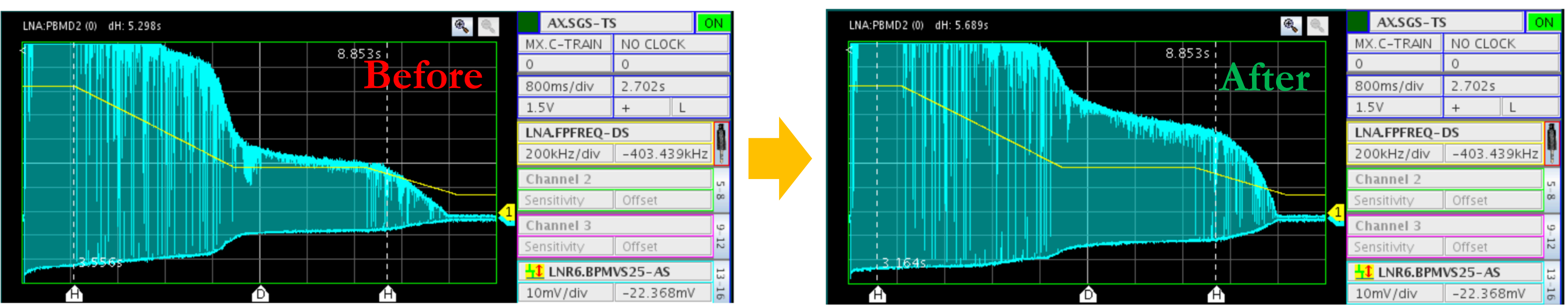
Bunch transferred into ELENA waiting bucket - Phase loop damps synchrotron oscillations

Injection oscillation correction

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



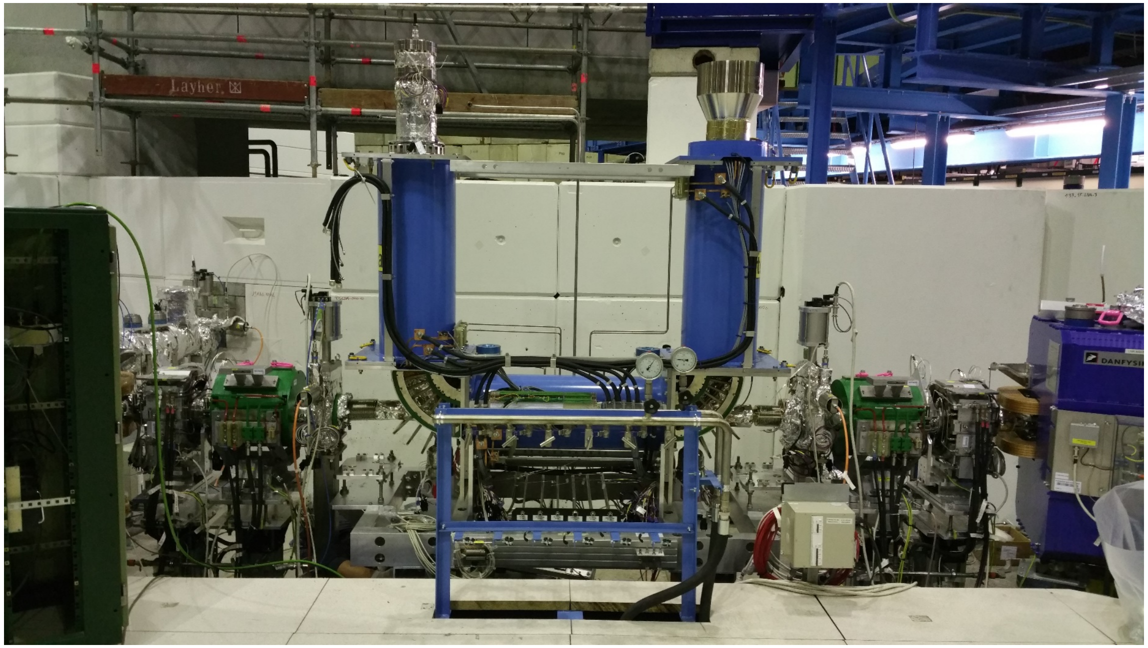




From B. Lefort (link)

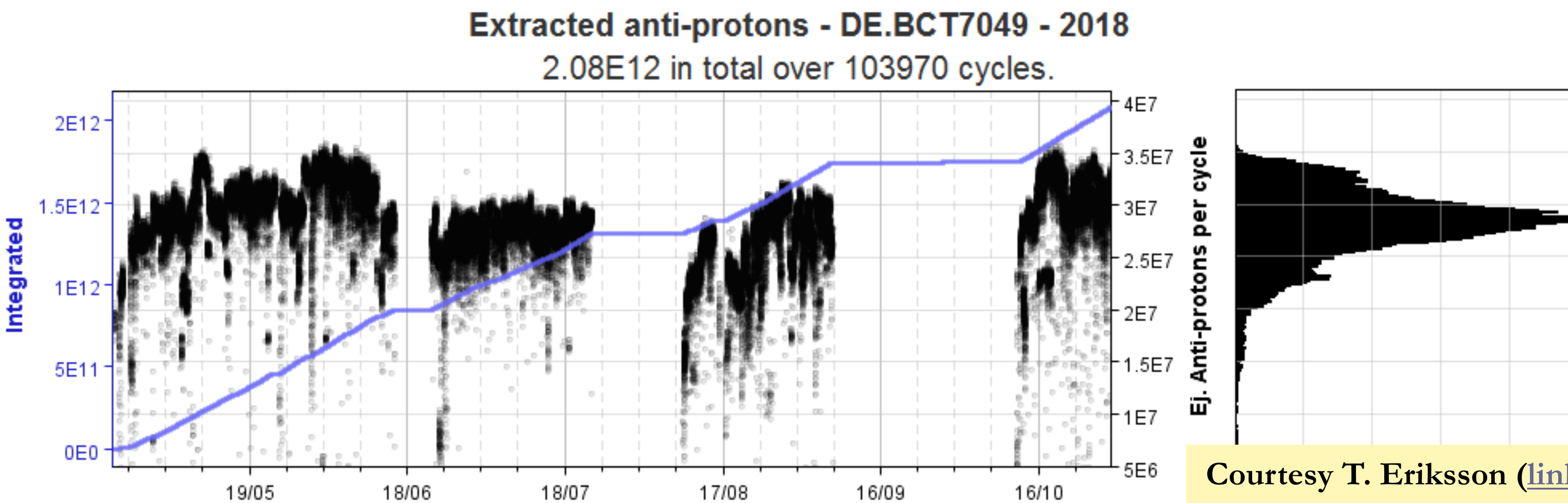
ELENA Electron Cooler

- Cooler **installed** beginning of **December 2017**
  - Unfortunately, **vacuum leak** after first bake-out
- Cooler taken out for dismounting and repair. **ELENA restarted in April 2018**.
  - **e-cooler fully available in July 2018**



Note: beam time

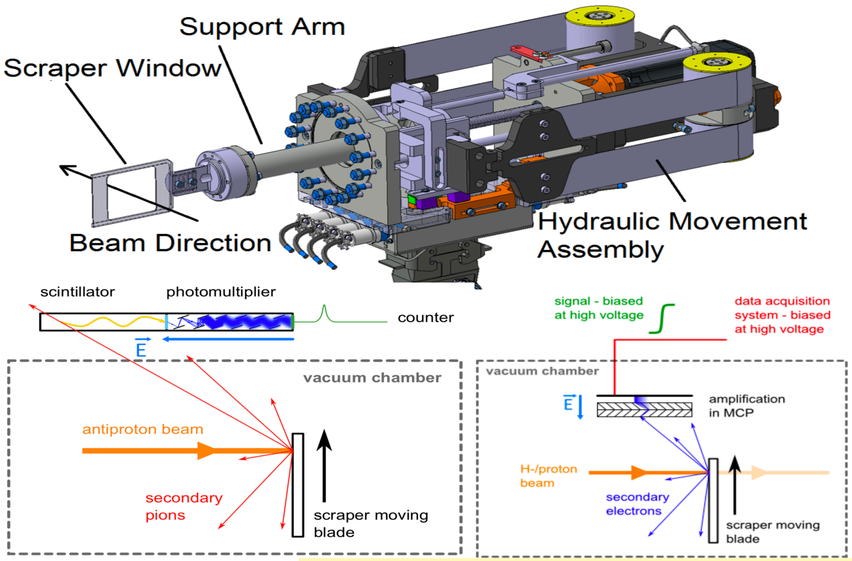
- E-cooler **studies** (so far) **only possible with *pbars***
  - **Unavailability** of ***p*** beam from **source; limited attempts** with **H-**
- AD cycle length ~110 s; MD shift of 8 h
  - About **33 shots/hour**; **260 shots/MD shift**
  - Typically **2/3 MDs per week ≈ 10% of time**
  - **Unfortunate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



Courtesy T. Eriksson (link)

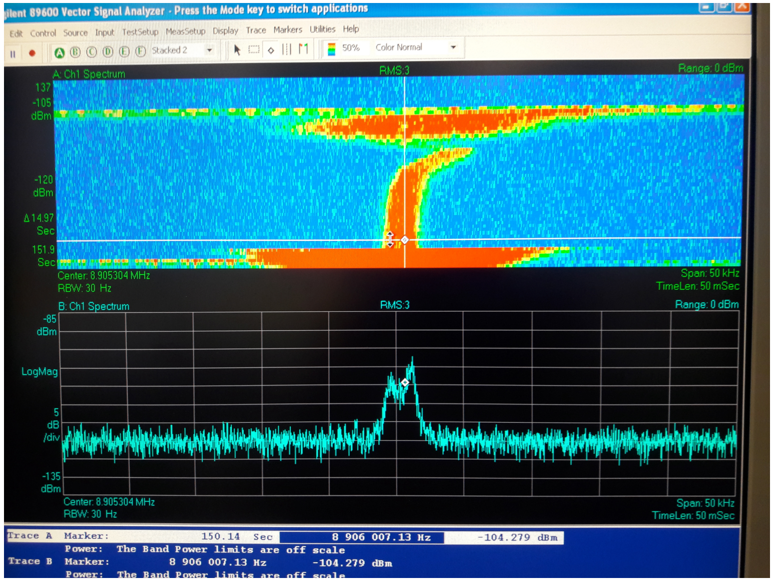
Note: Beam Instrumentation

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



Courtesy P. Grandemange (link)

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

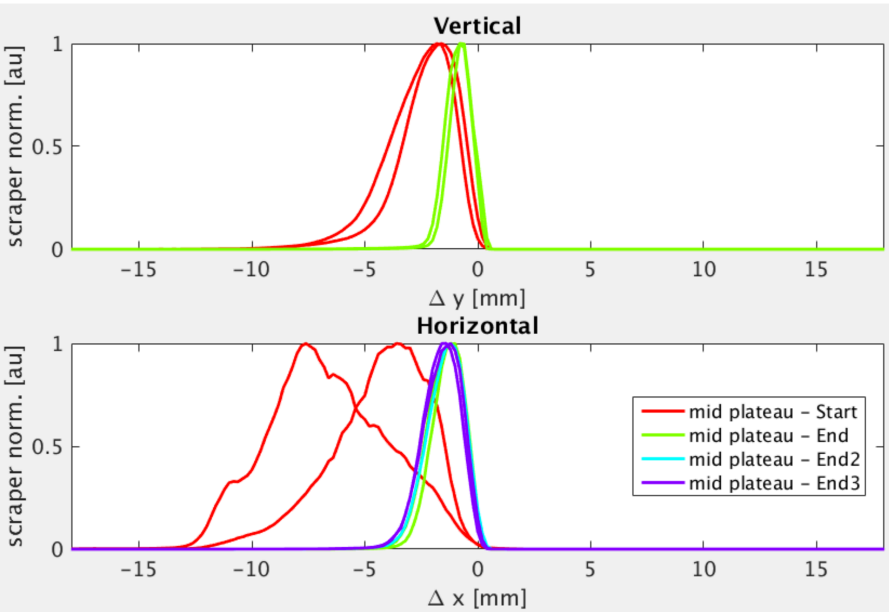


Also available:

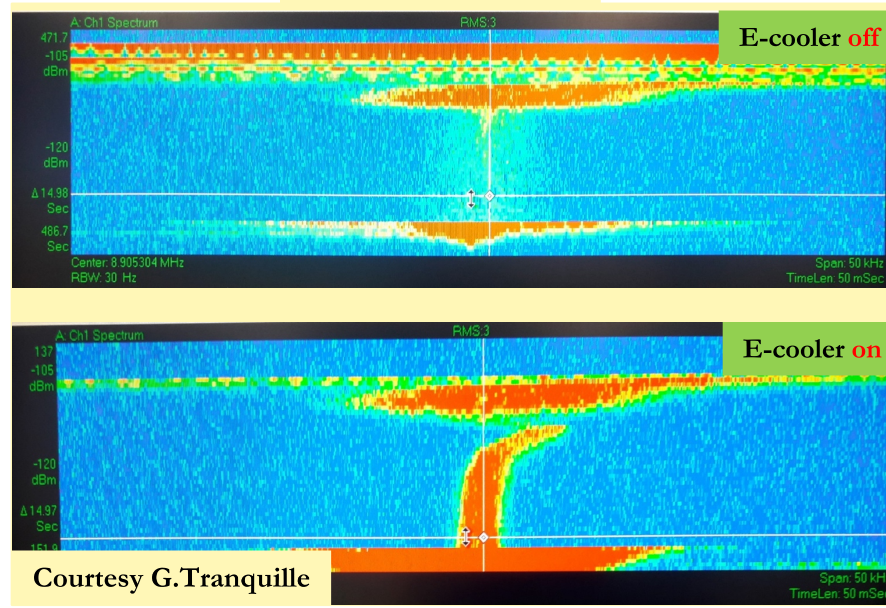
- **2 BPMs** in e-cooler section, but **only used to measure ions** **(no tests with e-, isn't it?)**
- **Recombination Monitor** only for e- beam optimisation with H- and p **(not exploited)**

E-cooler in action - 35 MeV/c plateau

~half profile measured with "scraper"

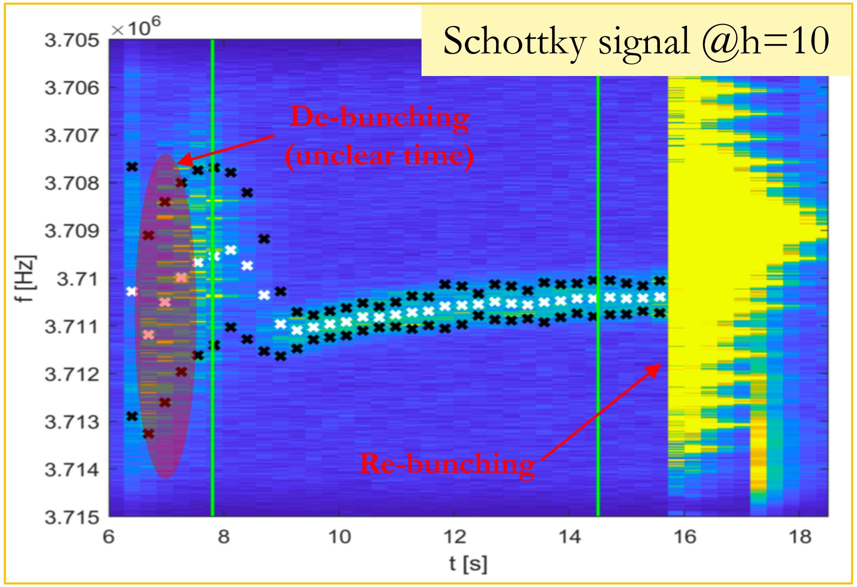


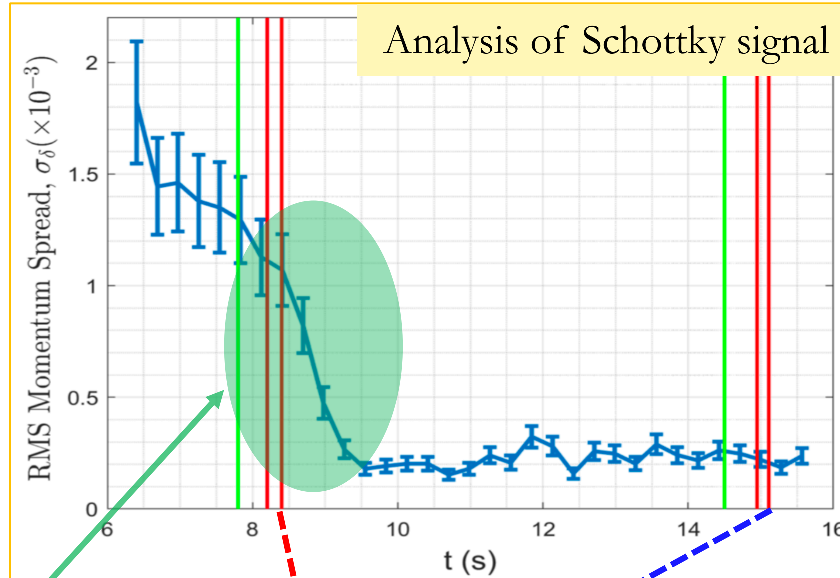
Schottky signal



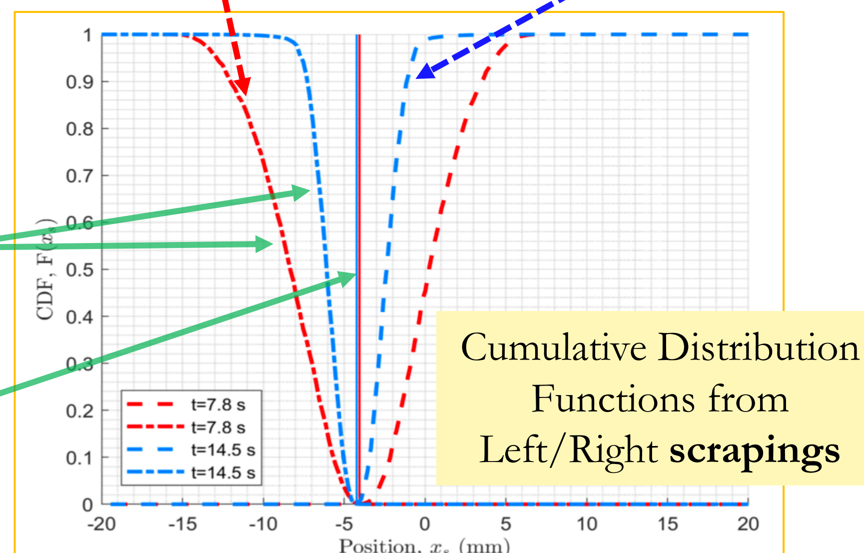
- **Clear transverse and longitudinal emittances reduction observed**
- **Only limited amount of time** on systematic optimization of cooling (lack of time)
  - **Some optimisation with orbit bumps/angles in e-cooler**
  - **Surely(?) margin** for improvements

Some details





- **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**
- Some **drift** of **mean energy**
  - **e- beam energy drift?**
- No sizable variation of beam mean transverse position



From J.Hunt Ph.D thesis

Transverse performance

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

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

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

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

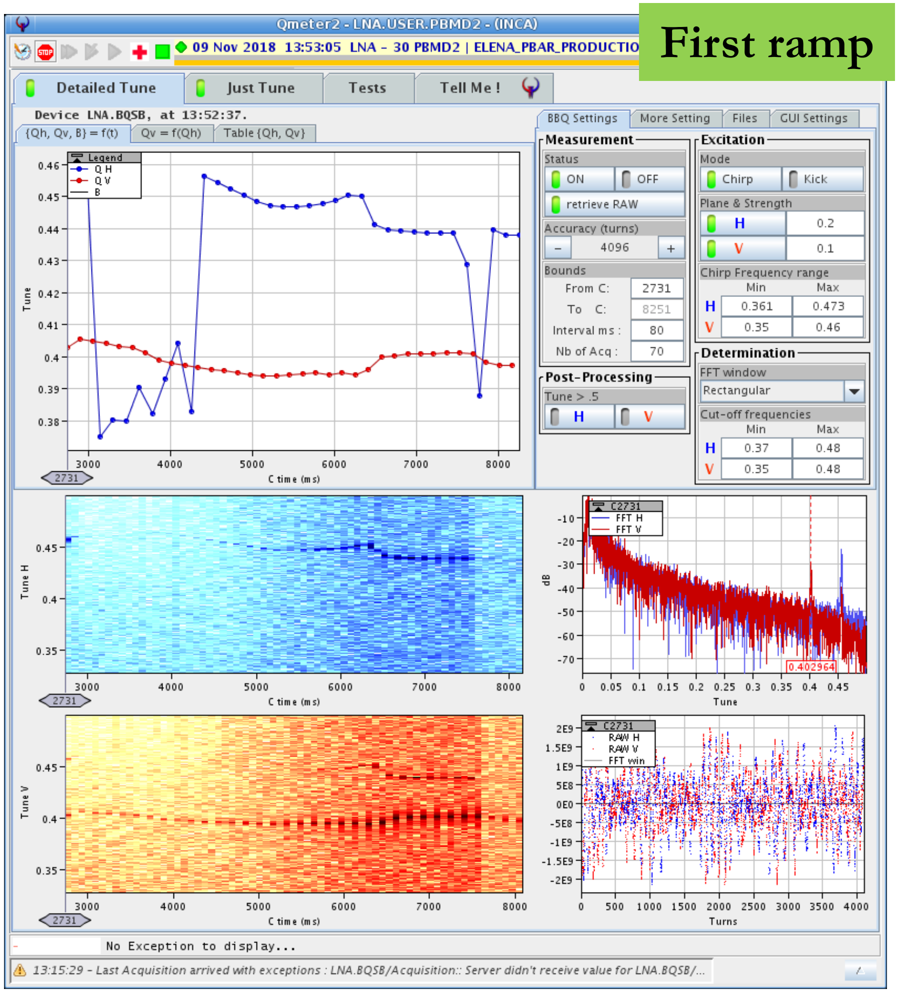
still, about **x2 worst than design** values (0.3/0.2 μm)

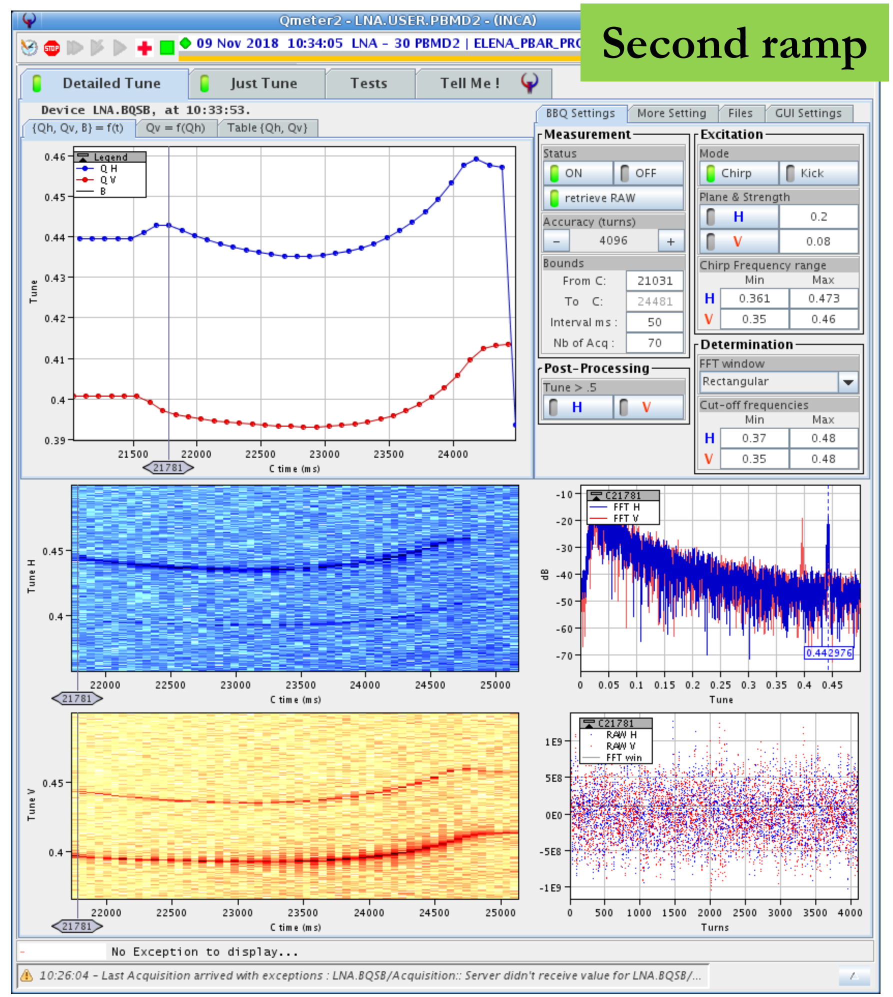
Great emit. improvement

From J.Hunt Ph.D thesis

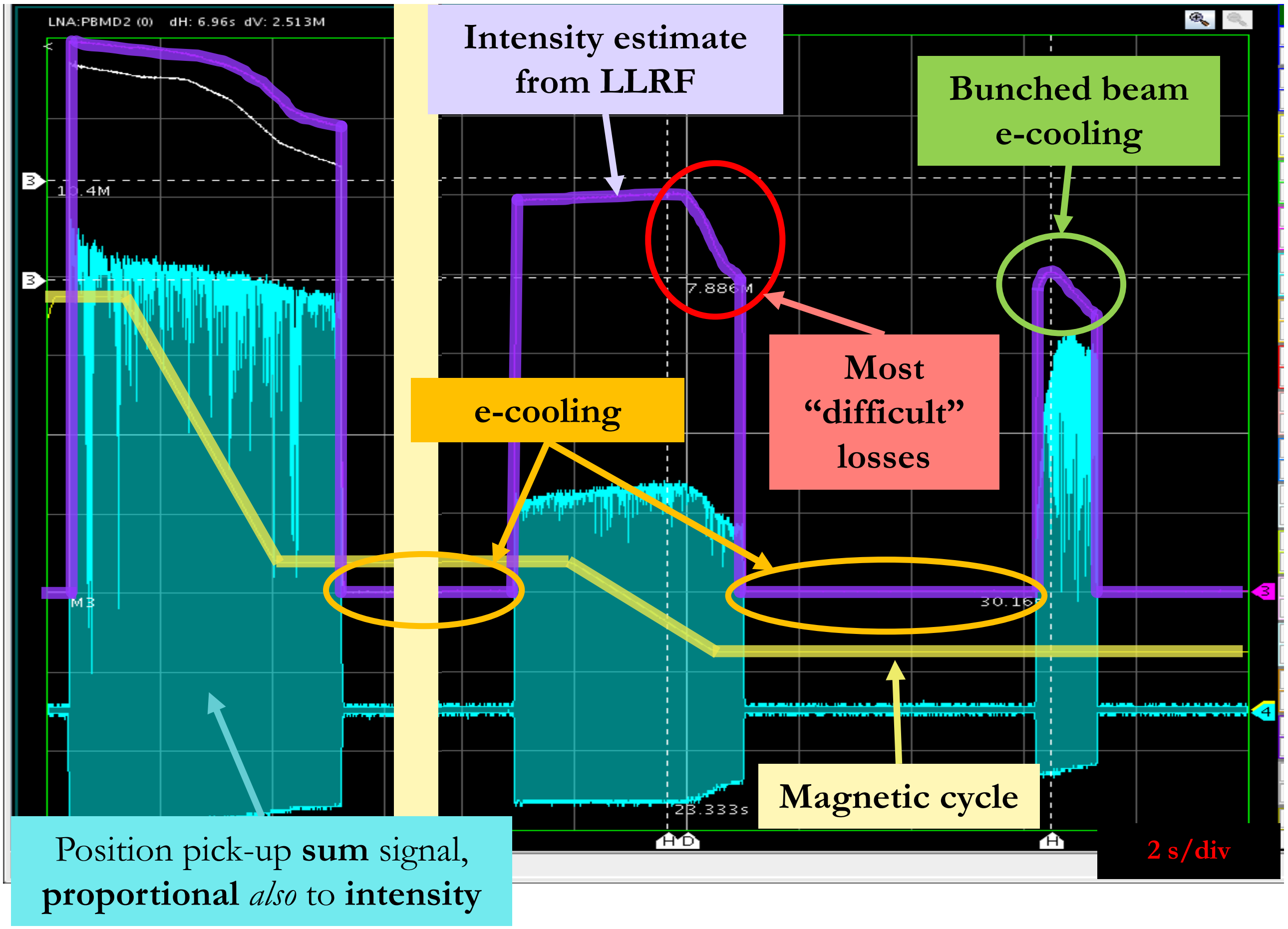
Optics validation

- Several tune measurements taken at different time with different optics
  - Under analysis by L. Ponce





Status End of Run 2018



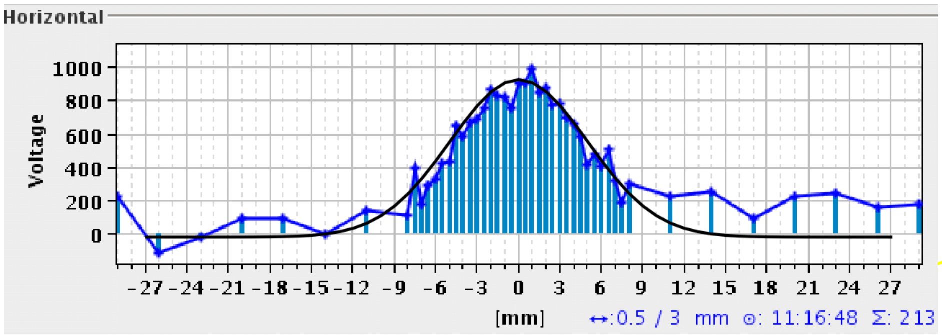
- Almost nominal cycle:
  - Injection 100 MeV/c
  - Deceleration to 35 MeV/c (**h = 1**)
  - De-bunching and **e-cooling**
  - Deceleration to 13.7 MeV/c (**h=4**)
  - De-bunching and **e-cooling**
  - Re-bunching (with e-cooler on) on **h=4** and **extraction to experiment**
    - GBAR only user so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

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

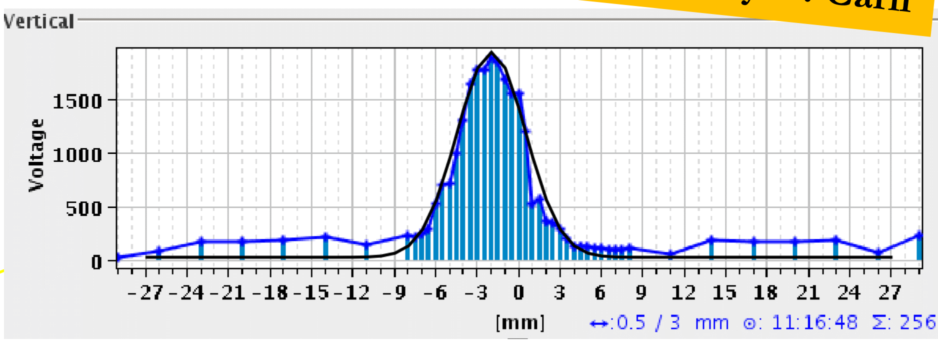
Bunches extracted to GBAR

- Beam profiles in measured on SEM installed in GBAR line

Preliminary estimate by C. Carli



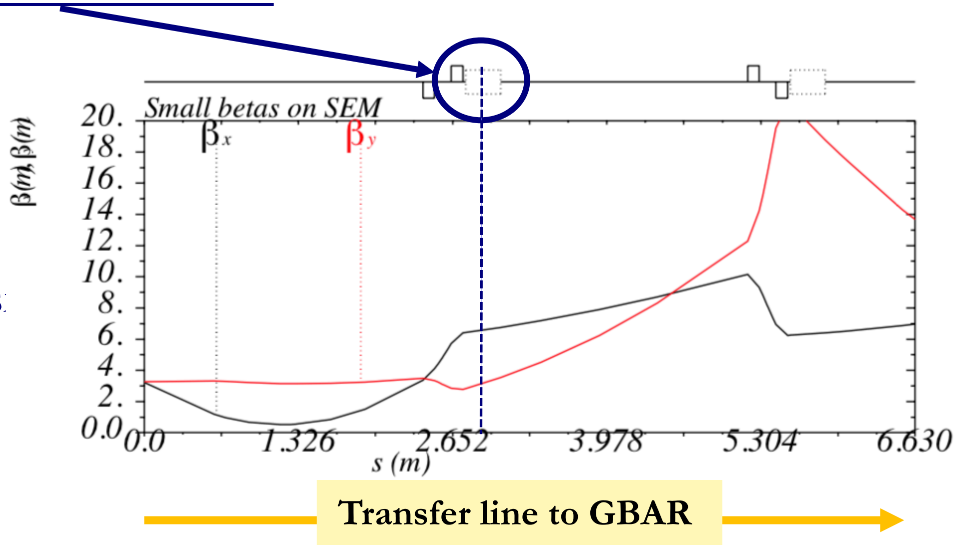
Gaussian fit by hand with $\sigma_H = 5$ mm



Gaussian fit by hand with $\sigma_V = 2.5$ mm

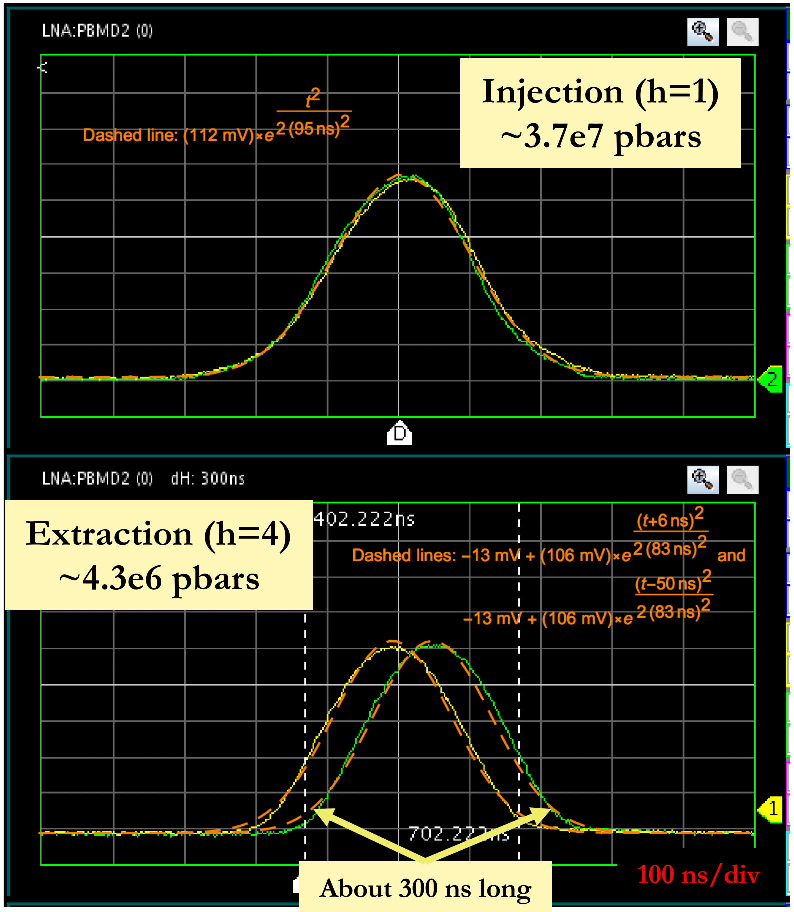
- Acquisitions with second monitor LNE.BSGWA.5020 in GBAR line

- Beam sizes with voltages of first two quads of line set to zero
  - $\beta_H = 6$ m gives rms emittance **ε_H = 4.1 um** (without taking dispers into account)
  - $\beta_V = 4$ m gives rms emittance **ε_V = 1.5 um**

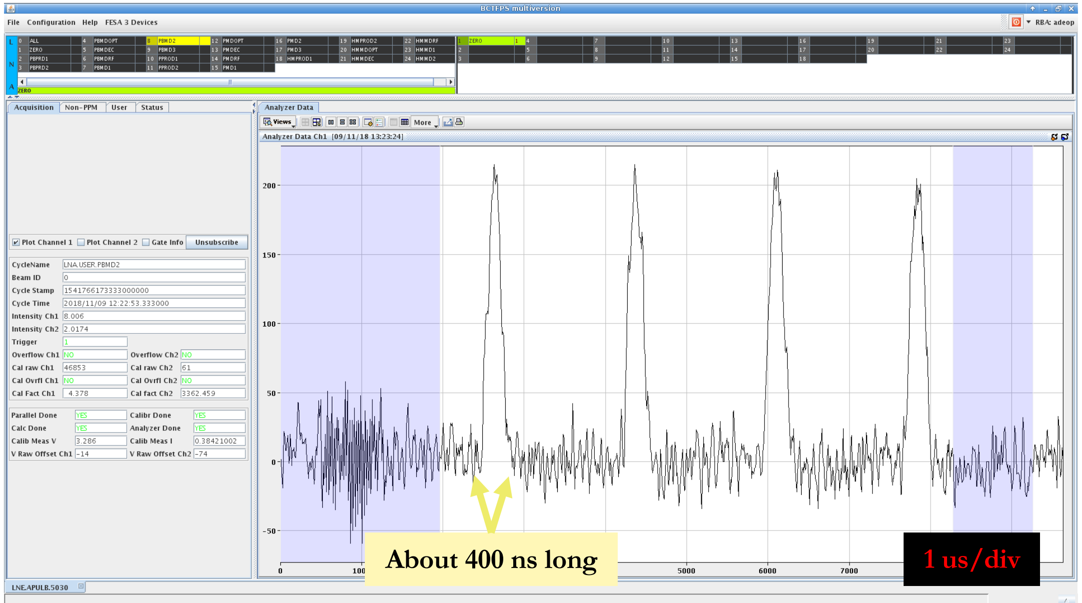


Bunches extracted to GBAR

Preliminary estimate by C. Carli

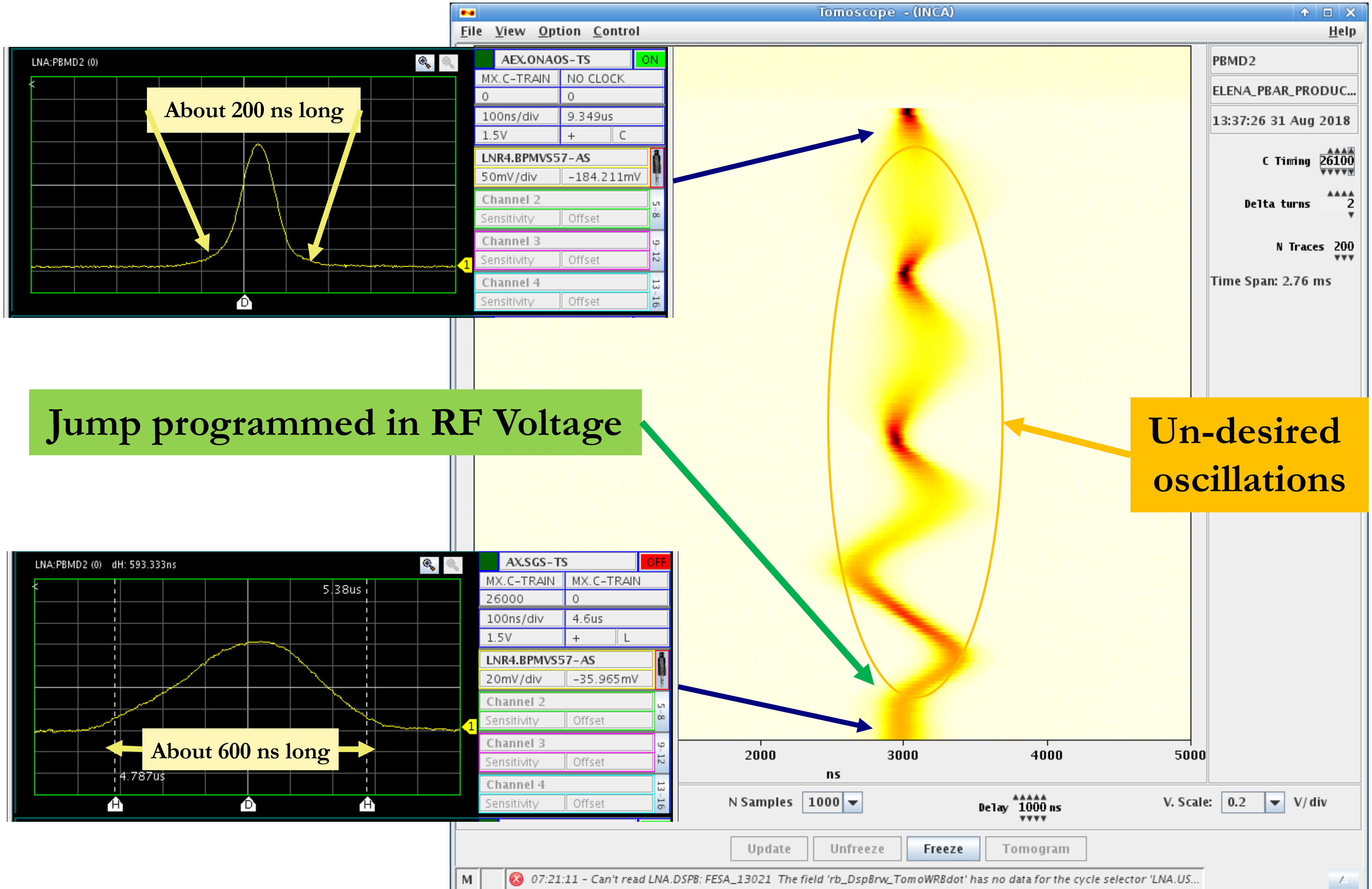


- According to Transverse Pickup signals we injected about 3.7e7 pbars and we extract 4x4.3e6 = 1.7e7 pbars
  - Compatible with LLRF intensity estimate along cycle
- According to Magnetic Pickup in extraction line we see about 1e7 pbars extracted (over all 4 bunches)

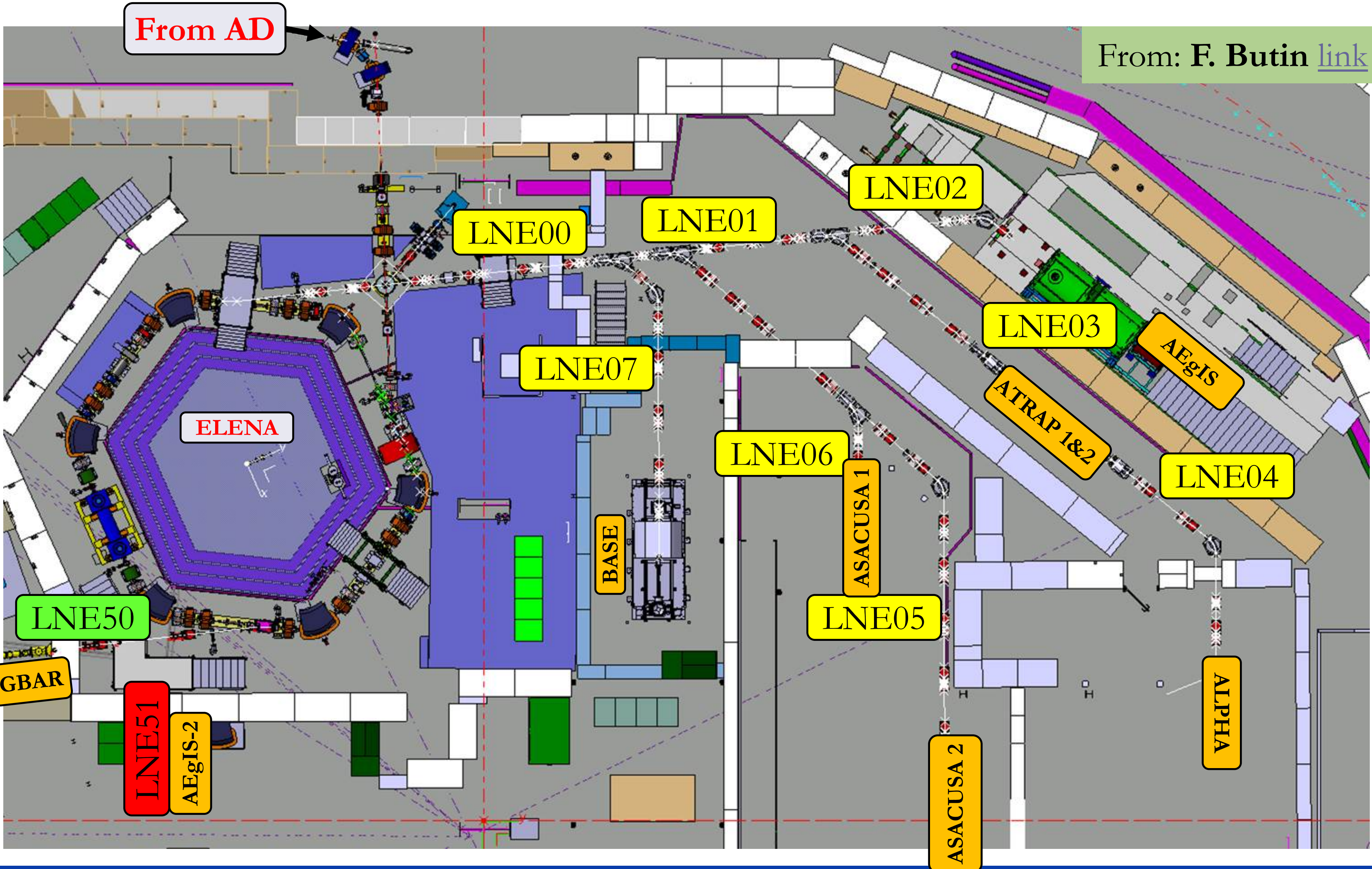


Bunch rotation (h=1)

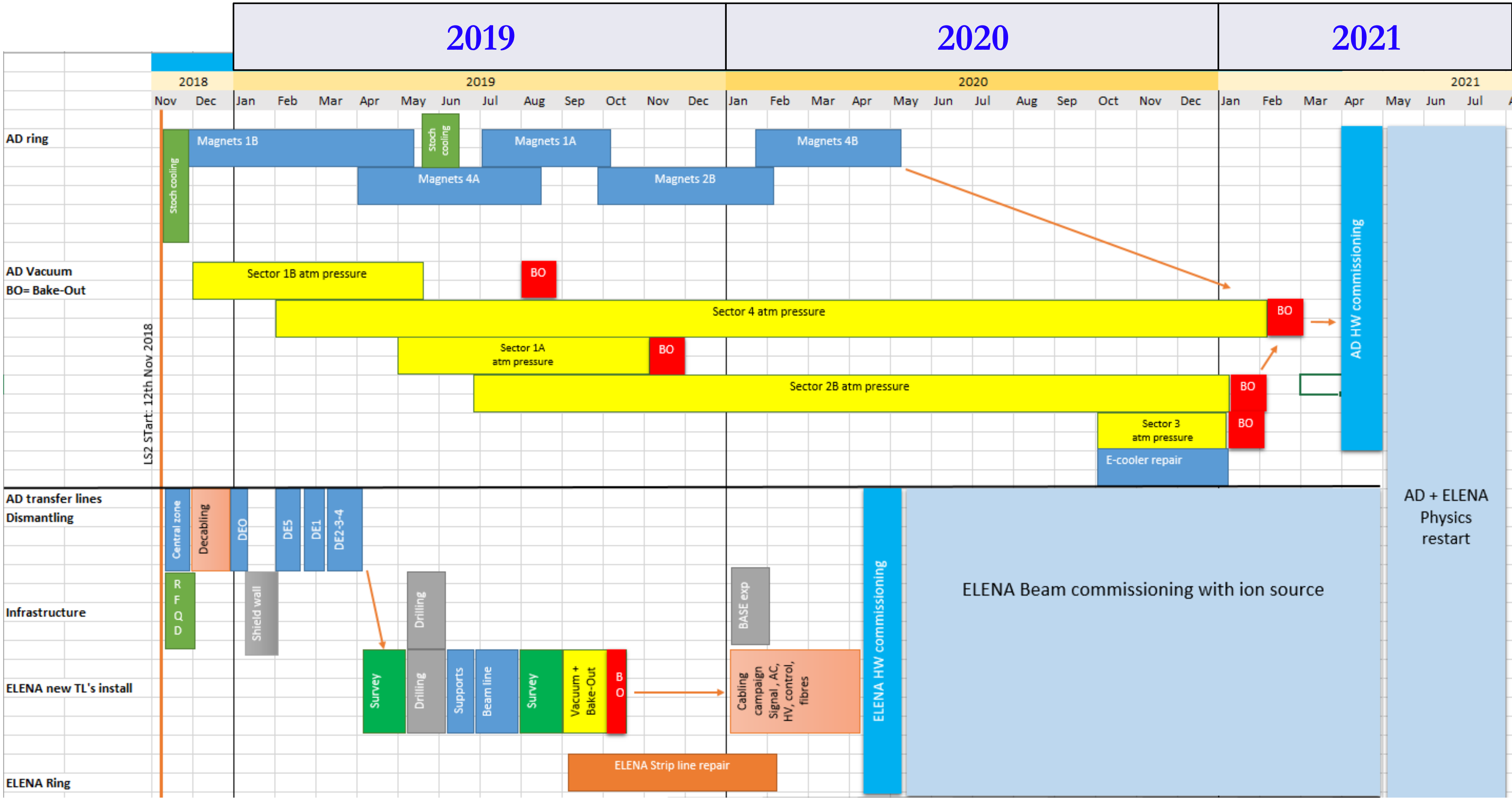
- Possible to shorten the bunches (but higher energy spread) with bunch rotation (not baseline) for h=1 operation.



LS2: Electrostatic lines to be installed



In the context of AD consolidation…



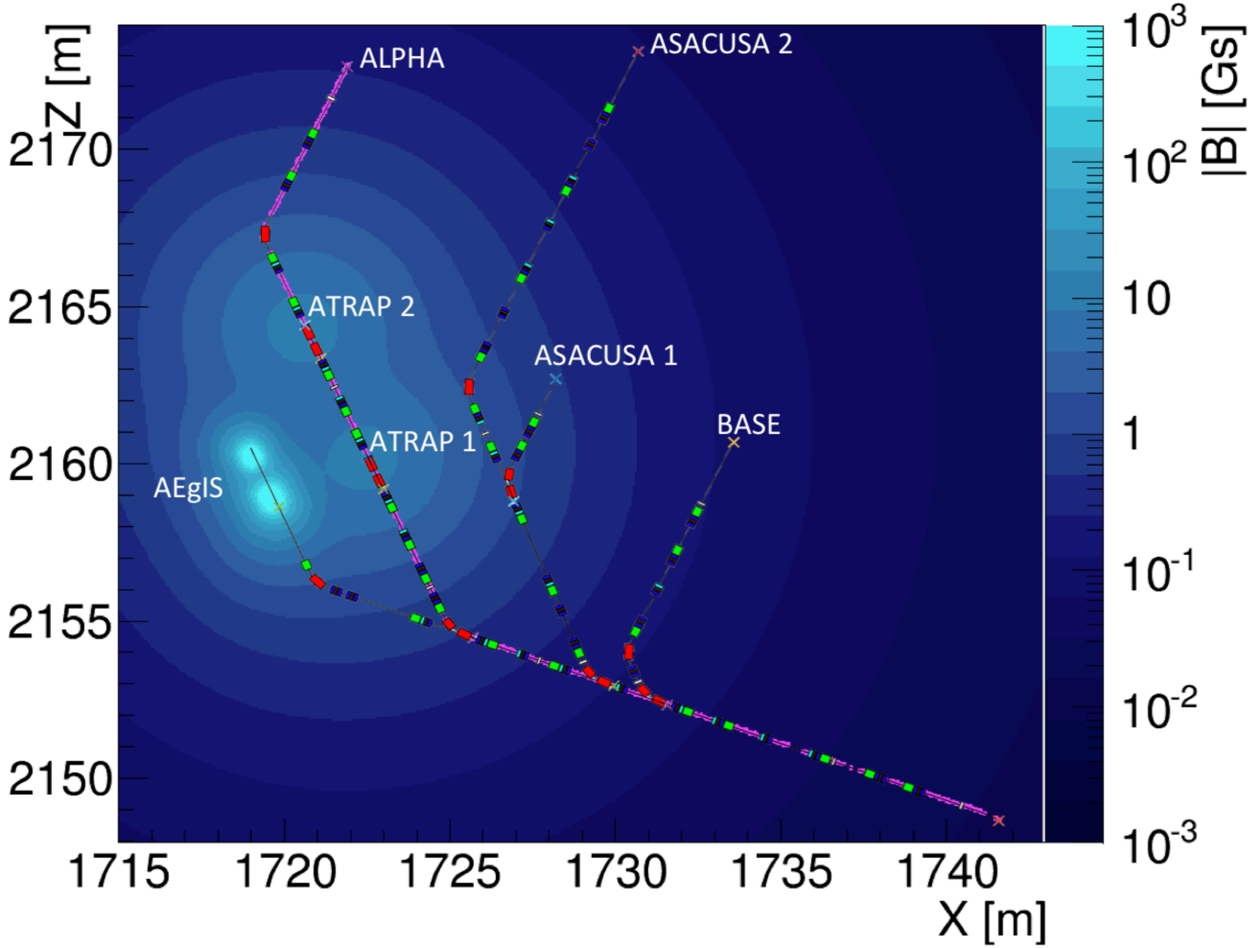
From: **F. Butin** link

Main “concern” to stay within schedule

From: **M. Hori** link

Other 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



BPPC 12 May 2016

Courtesy J. Jentzsch - indico

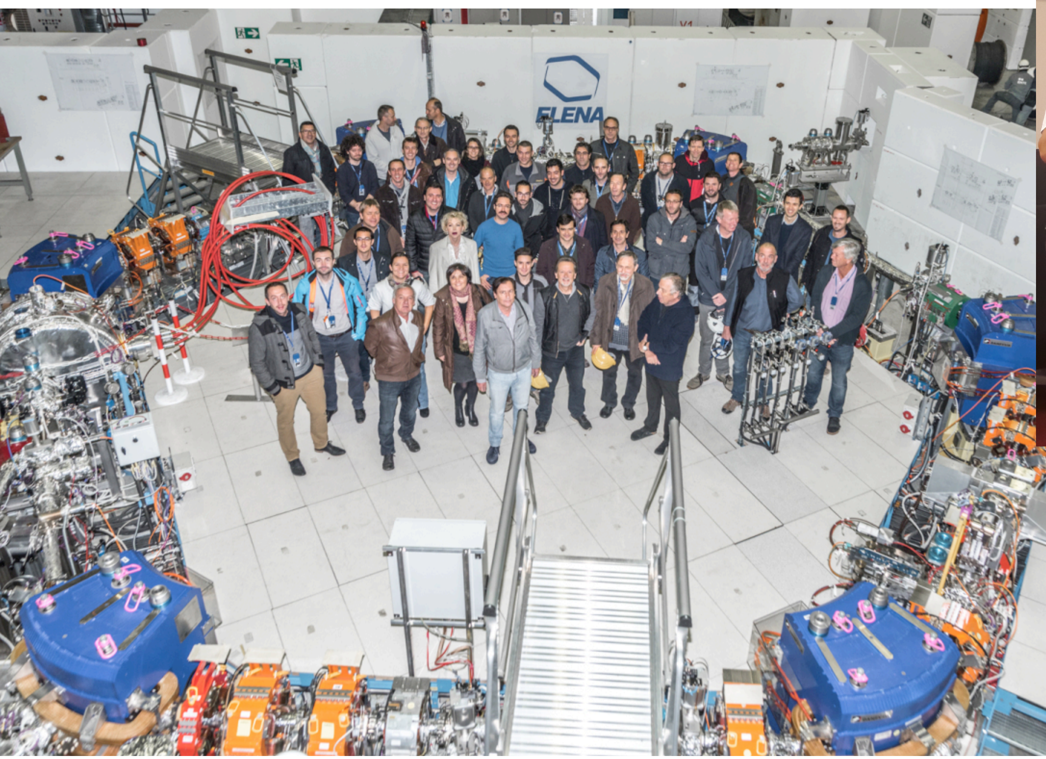
- From preliminary studies, **transfer line design should be able to cope with this..**

Conclusions

- Long life for AC -> AD
  - Despite many challenges and age, **providing pbars for excellent physics**
- 2018 a very **fruitful year** for **ELENA** commissioning
  - Many **sub-systems** (RF, BI, e-cooler) (almost) fully **commissioned**
  - Nominal **beam performance** (almost) **established**
- **E-cooling** is doing what it has promised
  - **Emittance reductions of ~80% down to ~0.5** μm (nominal ~0.3 μm)
  - **Results obtained with limited-empirical studies "by hand"**
- **Could not** fully **profit** of the **H^-/p source => being fixed**
  - Use of ***p* beam envisaged for e-cooling studies (higher rep rate)**
- **Plans for LS2**
  - **Consolidation of AD** (Target, Magnets, Coolers, Instrumentation, …)
  - **Installation** of the **ELENA transfer lines** to the "old" experimental zone
  - **Resume commissioning activities** with **H-/p** in **early summer 2020 (or 2019)**

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!*



Thanks for your attention, comments and questions …

Backup

AD: Design Basic Parameters

Circumference	182	m
Production beam	$1.5*10^{13}$	protons/cycle
Injected beam	$5*10^{7}$	pbars/cycle
Beam momenta max-min	3.57 – 0.1	GeV/c
Momenta for beam cooling		
Stochastic	3.57 and 2.0	GeV/c
Electron	0.3 and 0.1	GeV/c
Transverse emittances h/v	200 – 1	pi.mm.mrad
Momentum spread	$6*10^{-2} – 1*10^{-4}$	dp/p
Vacuum pressure, average	$4*10^{-10}$	mbar
Cycle length	100	s
Deceleration efficiency	90	%

AD - challenges

- Efficient Pbar production
- Deceleration: Beam compression required to combat adiabatic blow-up
- Beam diagnostics with beams of a few 10^7 particles
- Stability (orbit, trajectories) problems at low energies, ramping speed etc. – ring was designed for fixed energy
- Vacuum system – required ring pressure 10^{-10} Torr
  - Beam lifetime at low energies

Performance reached in 2001

Extracted Beam	Obtained		Design
Momentum	100 MeV/c	☺	100 MeV/c
Injected intensity (peak)	5.7×10^{7}	☺	5×10^{7}
Extracted intensity (peak)	4.5×10^{7}	☺	1.2×10^{7}
Cycle time	110 secs	☹	60 secs
E_H	<1 π [80%]	☺	1 π [95%]
E_V	<1 π [80%]	☺	1 π [95%]
Δp/p [95%] debunched	1.1×10^{-4}	☺	1.0×10^{-4}
Δp/p [95%] bunched	1.1×10^{-3}	☺	1.0×10^{-3}
Bunch length [95%]	390 ns	☺	500 ns
With bunch rot. [95%]	205 ns	☺	200 ns

Commissioning Challenges (1)

Problems during commissioning :

- Quality control problems during installation:
  - **e-cooler (mis-)alignment**
  - **pick-up alignment** relative to quads
  - intermittent triggering of key timing pulse: restart all magnet GFA's (many receivers, many sources).
- Transverse LF Schottky pickup 6-8 dB higher noise than anticipated (cause unknown).
  - **Transverse Schottky below noise threshold**.
- Inadequate strength of e-cool horizontal correctors
- **Inadequate number/strenght of orbit correctors**
- **Coils moving in wide quadrupoles** => cooling water pipes broken
- Orbit fluctuations: bad contacts of dipoles in electron cooler section
- **Field lag compensation of slow eddy current effects**
  - (10 - 20 seconds) on flat tops required
- **Poor tracking of QDC53** with respect to other QDN's: QTRIM5 supply introduced
- New AD managing system (cycle editor) needed a lot of debugging

Commissioning Challenges (2)

Good surprises:

- **Ultra-low noise orbit measuring system** has been improved to +/- 0.2 mm precision at 2×10^7 after EMC clean-up (50 dB immunity gained during 1999/2000 shutdown).
- **Longitudinal LF Schottky pick-up** (0.3 - 30 MHz) permits to measure the bunched beam intensity of 2×10^7 particles.
- **Response matrix measurements** very useful in identifying ring optics and deviations from expected nominal optics and suggest corrections.
- **Improvements in beam diagnostics** (orbits, tunes, coupling, intensities, response matrices) for typical pbar intensities (2×10^7) made it **possible to make *setting up with pbars.***

Stochastic Cooling: basic cooling rate equation

- The basic cooling rate (1/τ) equation is given as

$$\frac{1}{\tau} = \frac{W}{N}\left[2g(1-\tilde{M}^{-2}) - g^2(M + \frac{U}{Z^2})\right]$$

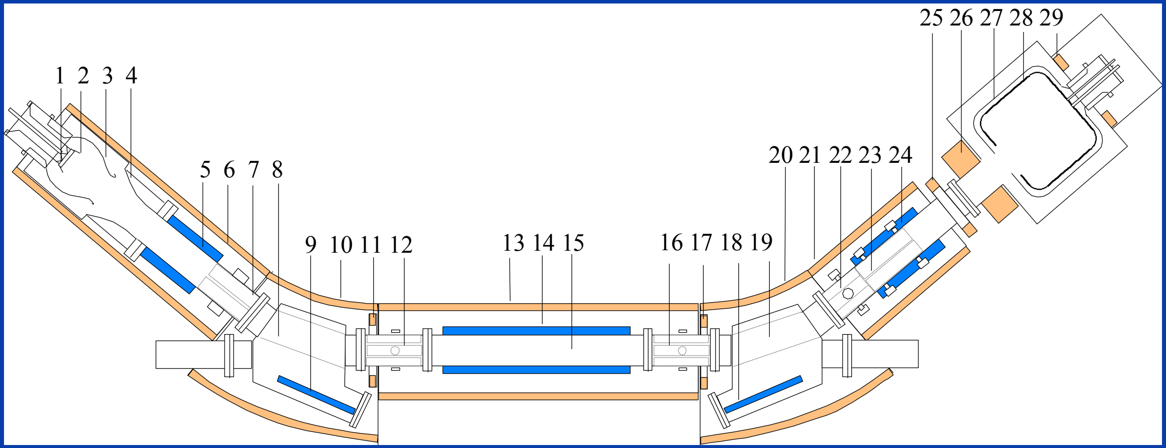
- N = number of particles
- W = cooling system bandwidth [Hz]
- g = gain parameter (not to be confounded with electronic gain); [g < 1]
- M = desired mixing (between kicker and PU); [M>1]
- $\tilde{M}$ = undesired mixing (between PU and kicker)
- U = noise to signal (power) ratio [U>0] for Z=1
- Z = charge number of particle

From F. Caspers **Techniques of Stochastic Cooling** - Bad Honnef, Germany, May 2001

AD Stochastic Cooling

- Only minor modifications and upgrades
- Only band I *(1 - 1.6 GHz)* from AC used (2 pickup tanks and 2 kicker tanks).
- Momentum cooling by *notch filters* (3.57 & 2.0 GeV/c)
- Factor ~2 loss in pickup sensitivity at 2 GeV/c ($\beta = 0.905$) as pickup *combiner boards are fixed* and optimised for $\beta = 0.967$
- *Dynamic real time control of gain* (+PU movements)
- Low noise pickup *cryogenic pre-amplifier* replaced by *low noise amplifier at ambient* temperature.
- Cryogenic system used for the complete PU structure.
- Initial commissioning with protons (ring polarity inversed)
- Design performance quickly achieved (speed, emittances)

AD – electron cooling



•Electron gun: thermocathode, Pierce shield, accelerating anodes

•30 kV 2A electron beam

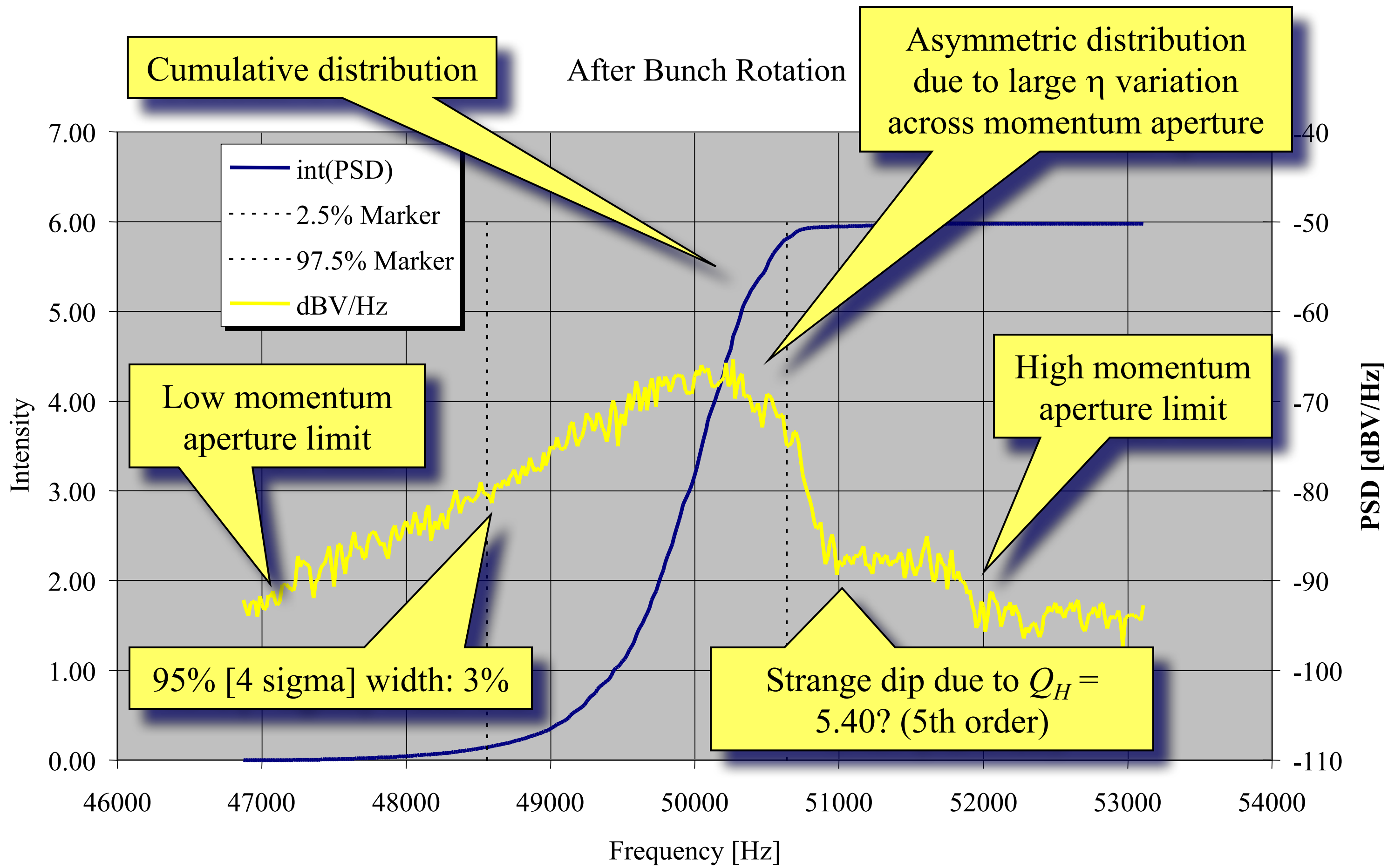
•Interaction section

•Collector

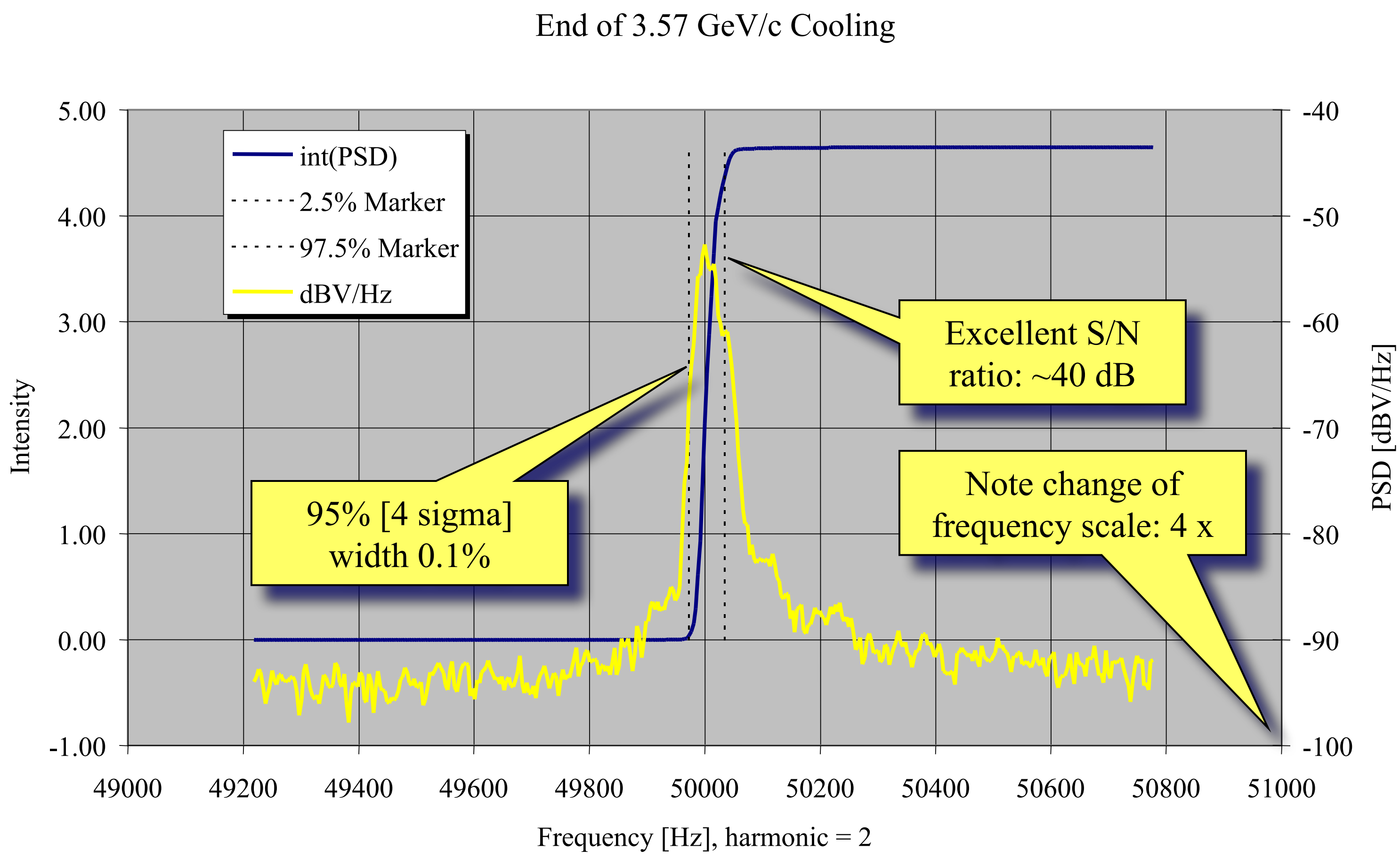
•The whole system is immersed in a longitudinal field

•Well suited for lower beam energies in AD

Longitudinal Schottky

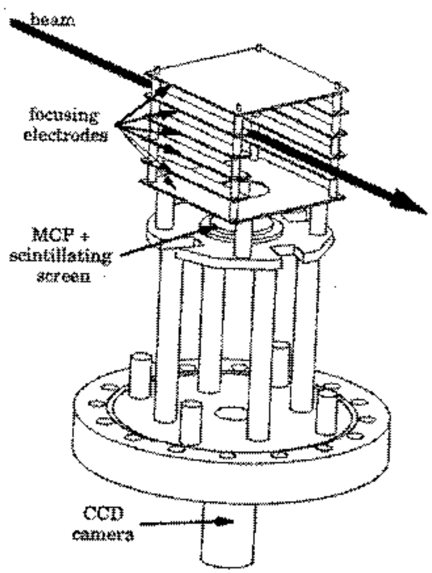


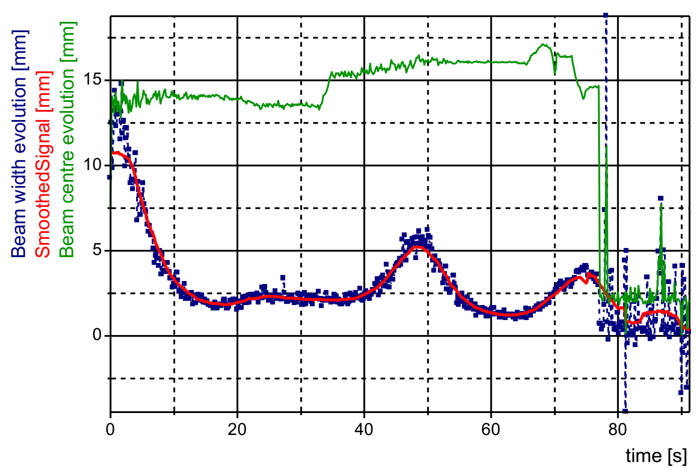
Longitudinal Schottky

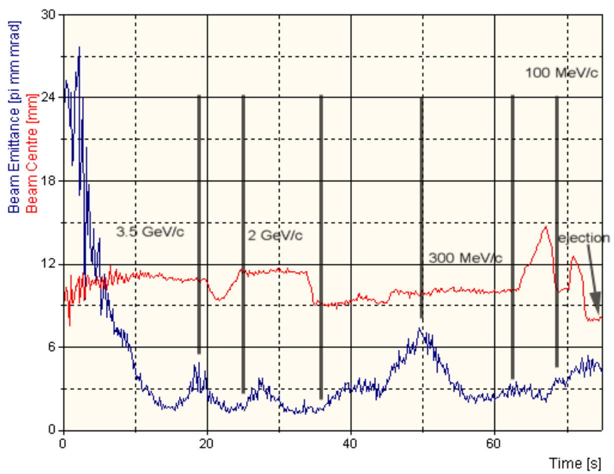


Beam Ionization Profile Monitor (BIPM)

- A new Beam Ionization Profile Monitor system is used for non-destructive monitoring of beam emittances and beam center throughout the cycle. The charged particle beam ionizes residual gas molecules in the vacuum tube. Ions (or electrons) that are produced are then accelerated towards a detector by an electric field where the generated signal is acquired for analysis
- Initial tests have been done with promising results, but more work is necessary before regular use is possible.

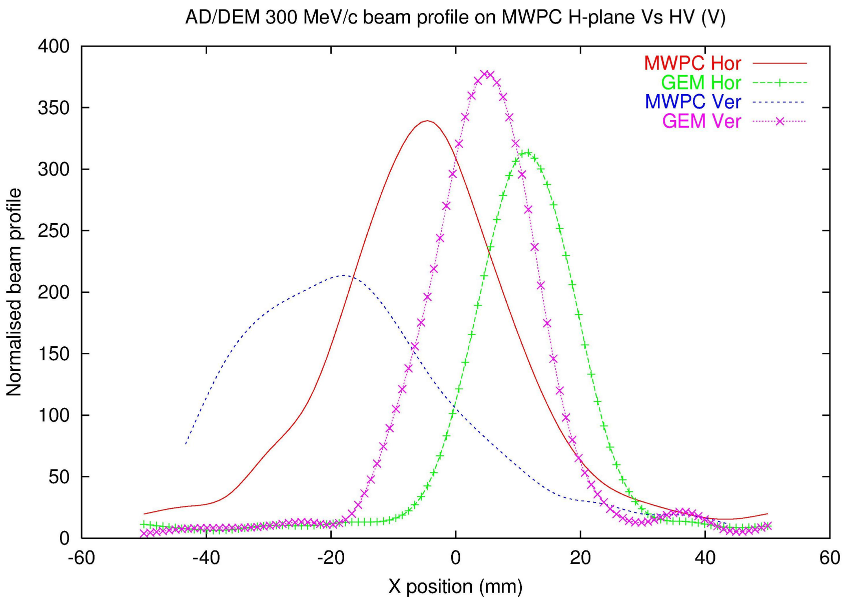


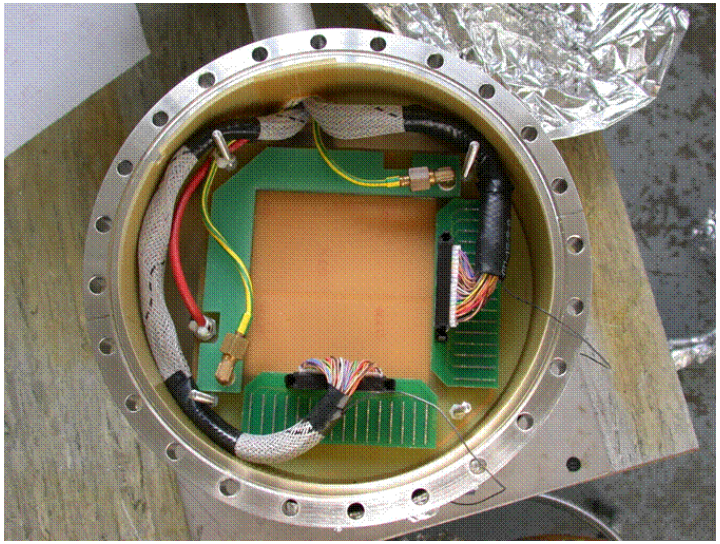


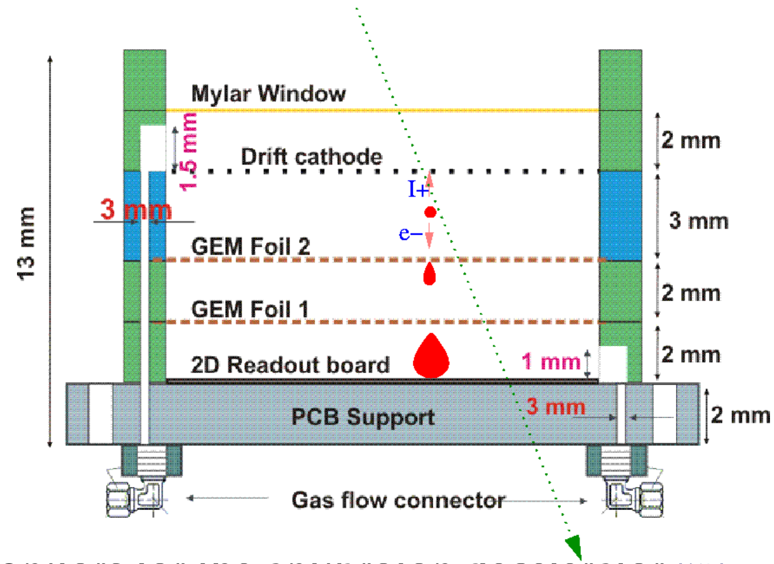


GEM

- Used to measure transverse beam size and position in AD transfer lines.
- Upgrade with respect to Multi Wire Proportional Chamber (MWPC) previously used
  - Destructive effect on beam
  - Impossible to reconstruct both transverse profiles







S. Durante Pinto et al. **GEM-based beam profile monitors for the antiproton decelerator** link

S. Durante Pinto et al. **Gas Electron Multipliers versus Multiwire Proportional Chambers** link

MWPC vs GEM

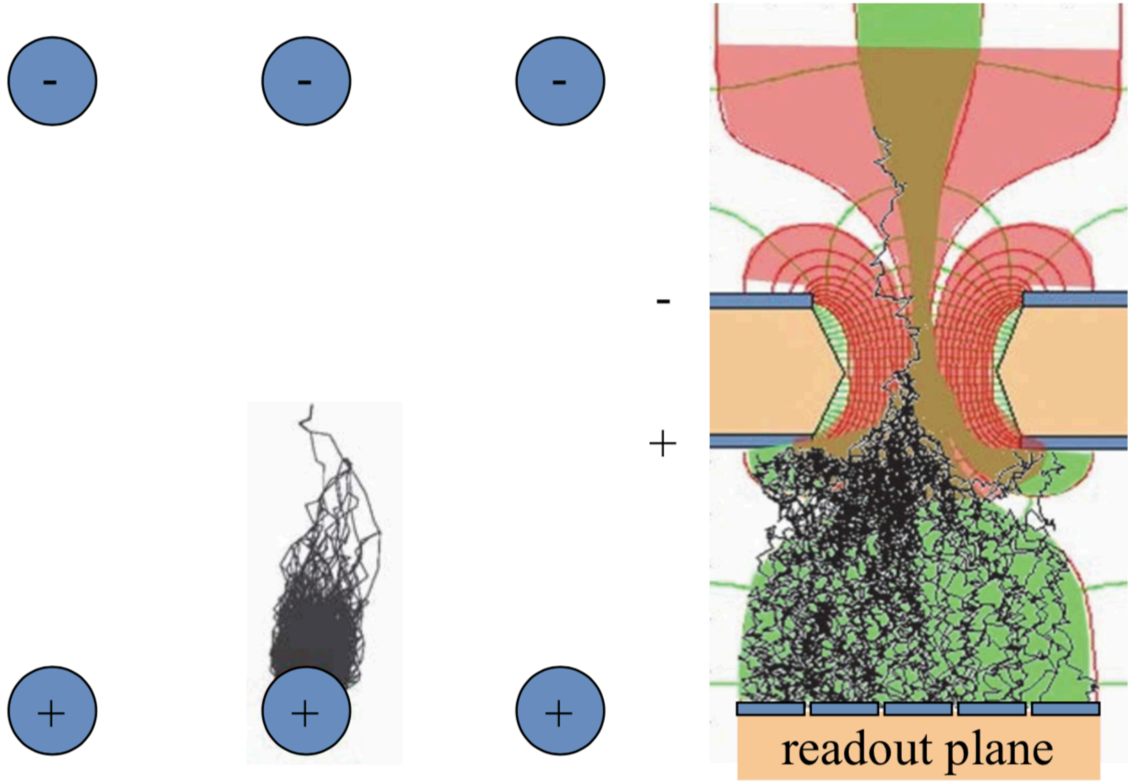


Figure 1: Working principle of MWPC (left) and GEM (right) illustrated. Electron avalanches as simulated by Garfield† are shown for both technologies; black paths are electron trajectories, the drift of ions is not indicated.

Limitation due to space charge

- Incoherent tune shift

$$\Delta Q_z \propto \frac{N}{\varepsilon \beta^2 \gamma^3 B_b}$$

most severe conditions are at ejection momentum 100 MeV/c, especially when beam is bunched (after electron cooling right before ejection)

- For AD parameters (N=3 10^7 pbars in bunch, 1 π mm mrad emittances, bunching factor B=1/60) it is about 0.07
- Estimate for stacking mode: with pbar flux 2 times bigger than now factor 4 in number of particles is expected -> ΔQ ≈ 0.3: *too much for AD!*

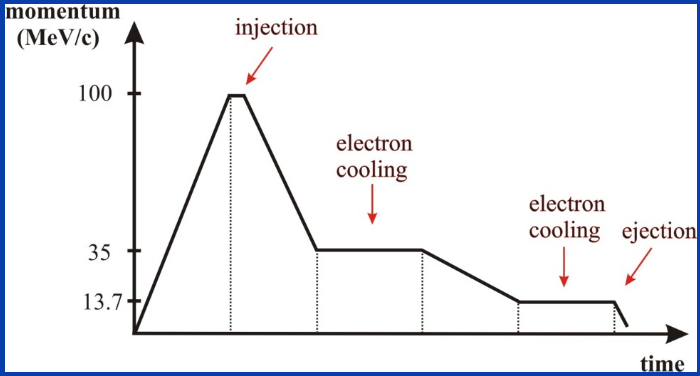
Limitation due to Vacuum

- The different effects of the **residual gas** which have an influence on the quality of the antiproton beam are:
- losses caused by nuclear scattering and single Coulomb scattering with an angle larger than the acceptance,
- blow—up of the beam emittance due to multiple Coulomb scattering.
- Both the single scattering loss and the blow-up scale with beam momentum as $(p^2 beta\_rel)^{-1}$ and thus become very important at low momenta. The nuclear scattering has a much weaker energy dependence and can be neglected at low momenta.

ELENA basic Parameters & cycle

Parameter	Value	Comment
Basic shape	Hexagonal	Two long straights for injection and cooling
Periodicity	Two periods	neglecting the electron cooler
Circumference	30.4055 m	1/6 the AD
Max. beta functions $\beta_{H,max}$/ $\beta_{V,max}$	≈12 m/≈ 6m	
Working point Q_H/Q_V	≈2.3/≈1.3	Some tuning range to choose working point
Relativistic gamma at transition	≈2	
Energy range	5.3 MeV – 100 keV	
Momentum range	100 MeV/c – 13.7 MeV/c	
Transverse acceptances	75 μm	
Cycle length	>25 s	Deceleration and cooling
Repetition rate for pbar operation	≈100 s	Limited by AD operation
Injected intensity	3 10^7 antiprotons	
Efficiency	60%	Conservative guess
Parameter at ejection[a)]		For Baseline with four bunches
Number of bunches	4	
Bunch population	0.45 10^7 pbars	
Rel. mom. spread	0.5 10^{-3}	Rms value
Bunch length	75 ns	Rms value
Hor. emittance	1.2 μm	Rms, physical
Vert. emittance	0.75 μm	Rms, physical

Cycle length estimated at ~ 25s – much shorter than AD



Expected ELENA Beam Parameters

Present best guess combining different Sources

Step in cycle	ε_L (meVs)	σ_p/p (10^{-3})	σ_E (keV)	σ_T (ns)	$\varepsilon_{H,rms}$ (μm)	$\varepsilon_{V,rms}$ (μm)
Injection[+,a)]	3.5	0.25	2.8	98	0.5	0.3
Start 1st ramp[+,b)]	3.5	0.49	5	53	0.5	0.3
End 1st ramp[c)]	3.5	1.4	1.8	150	1.8	1.1
Start plateau 35 MeV/c[d)]	5.2	0.46	0.6	coasting	1.8	1.1
End plateau 35 MeV/c[e)]	1.7	0.15	0.20	coasting	0.45	0.42
Start 2nd ramp[d)]	2.5	0.84	1.1	180	0.45	0.42
End 2nd ramp[c)]	2.4	2.1	0.42	455	2.2	2.5
Start plateau 100 keV[d)]	3.6	0.81	.16	coasting	2.2	2.5
Cooled coasting 100 keV[e)]	1.1	0.25	.050	coasting	0.3	0.2
Cooled bunched 100 keV[f)]	4 x 0.12	0.60	.120	75	1.2	0.75

$\varepsilon_{rms} = \sigma_\beta^2/\beta_T$ with σ_β the rms betatron beam size and β_T the Twiss betatron function

+) difficult to determine due to (i) dense core and long tails, (ii) variations with time

a) Typical values measured with AD – some reduction of long. Emittance with bunched beam cooling

b) Increase of voltage from 16 V at transfer to 100 V on ramp

c) Simulations of IBS on ramp

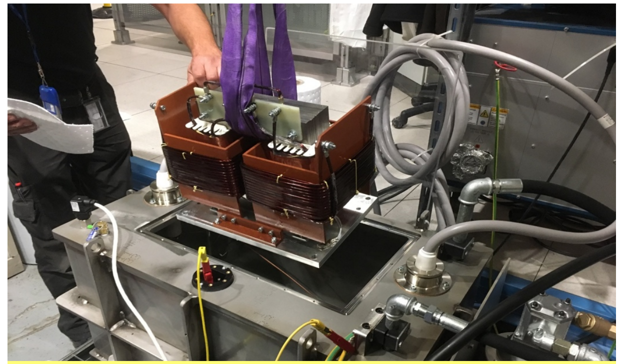
d) Debunching/bunching with 50% blow-up (bunched with LHC def. $\varepsilon_L = 4\pi\,\sigma_E\,\sigma_T$, coasting $\varepsilon_L = 4\,(2/\pi)^{1/2}\,\sigma_E\,T_{rev}$)

e) From ELENA technical meetings with presentations by G.Tranquille and P. Beloshitsky

Issues with H^- source

- Last (repaired) isolation transformer operated at 85 kV failed on **Friday 21st September**

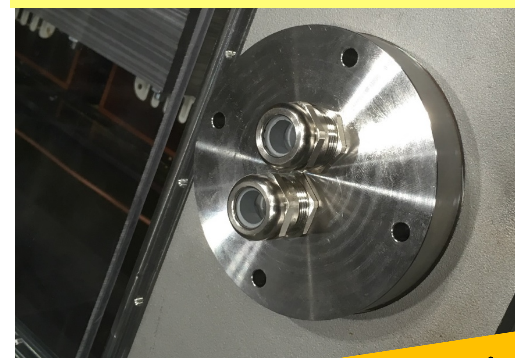
Oil tank for new isolation transformer completed on 26th September

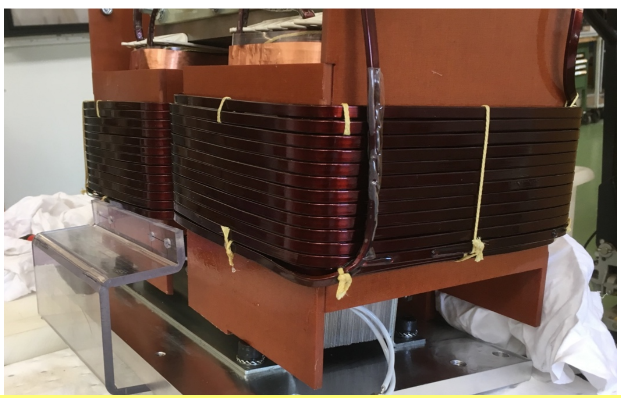


1st mounting of transformer

Broken HV connector…

…replaced by cable feedthrough





New support for secondary coils

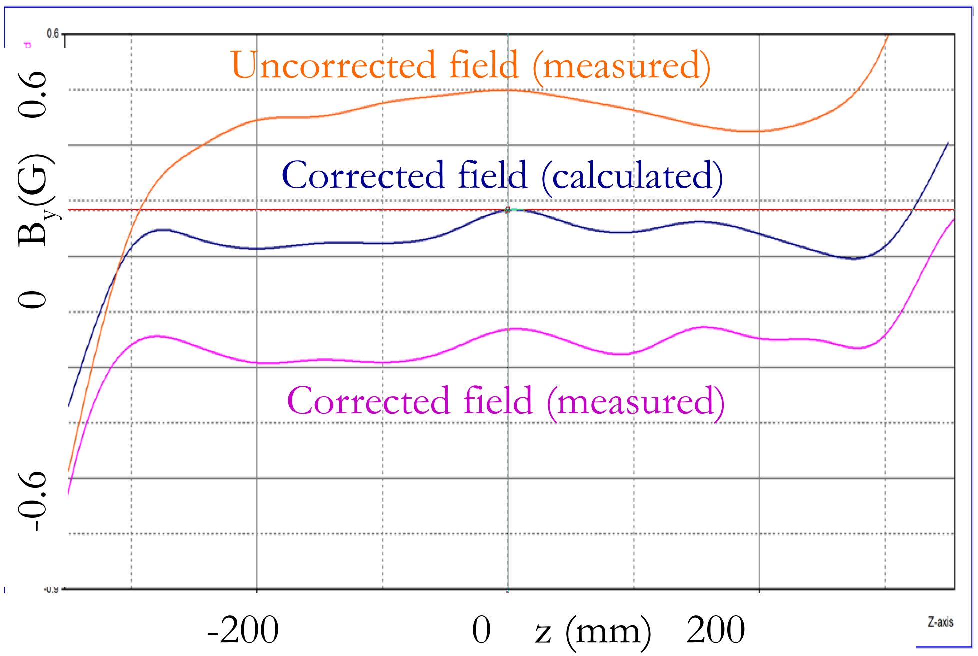
Winding new secondary coil

Thanks a lot for the high priority and efforts by several groups and many people

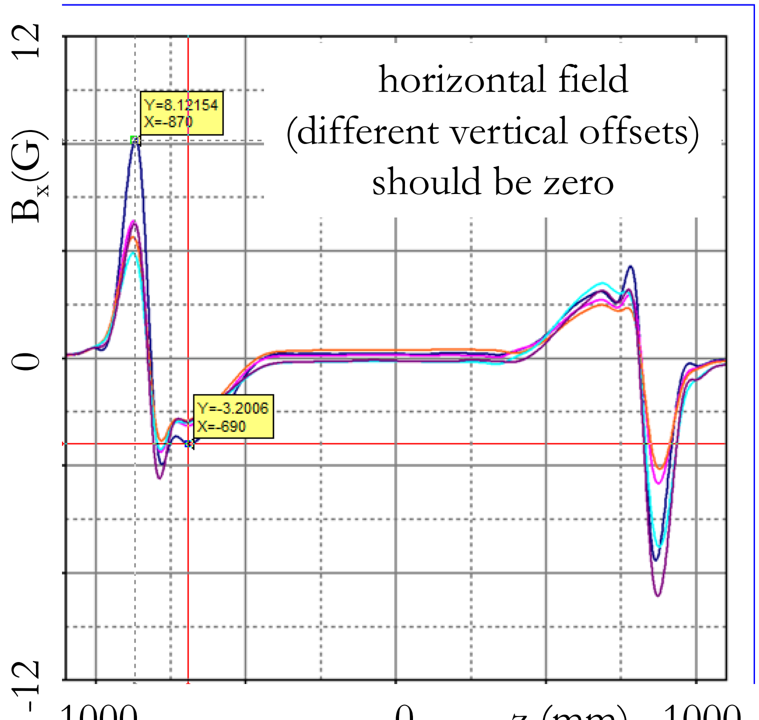
Despite high priority by CERN groups, beam available only a few hours since…

Electron Cooler Challenges

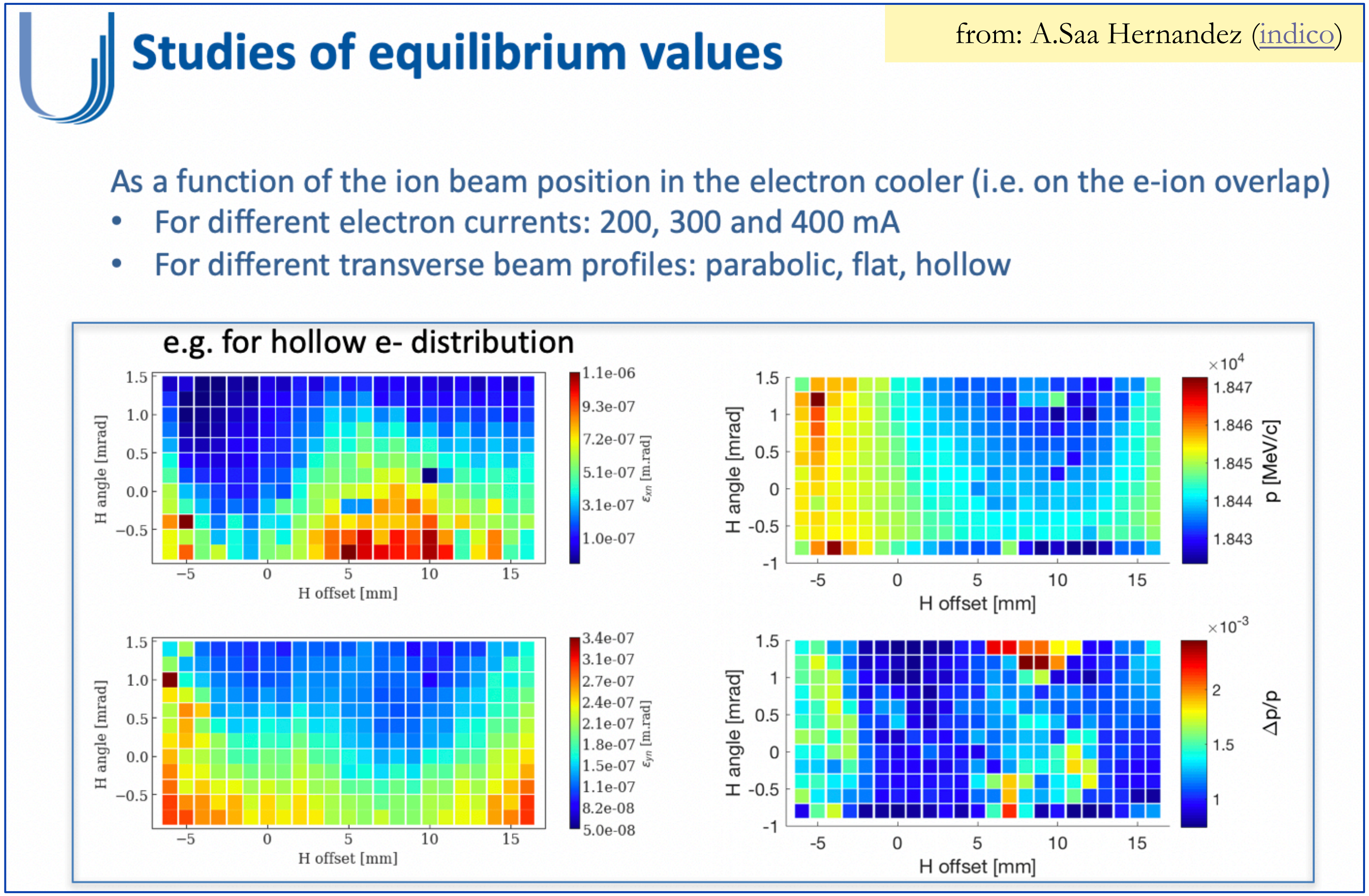
- Some issues with (challenging) magnetic measurements
  - Non-reproducible offsets of transverse fields makes compensation more tricky
    - Strong currents for “fine-tuning” coils for local corrections proposed
    - Improved compensation setting under discussion
  - Unexpected horizontal field components measured around “toroids”



Vertical field component along axis



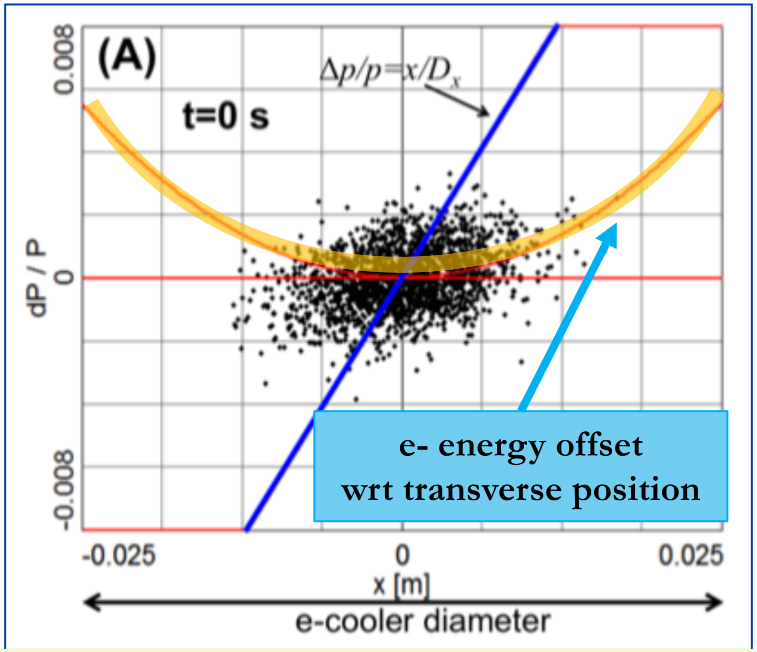
Further optimization desiderata: looking at LEIR



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

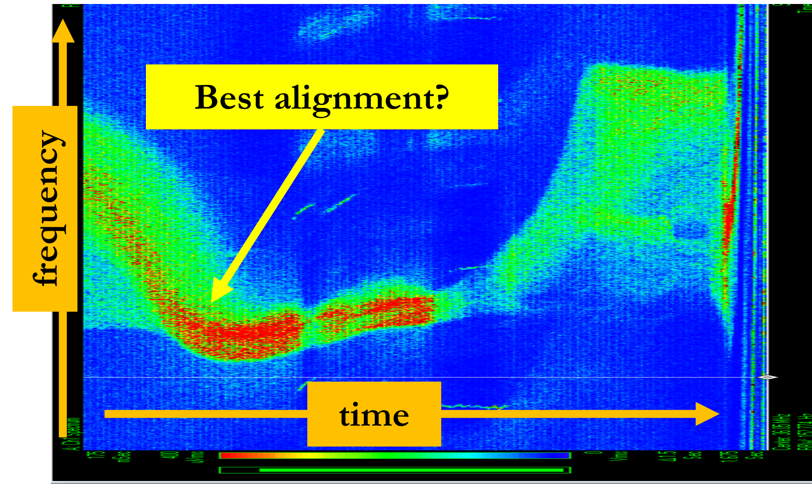
Scan using a single cycle?

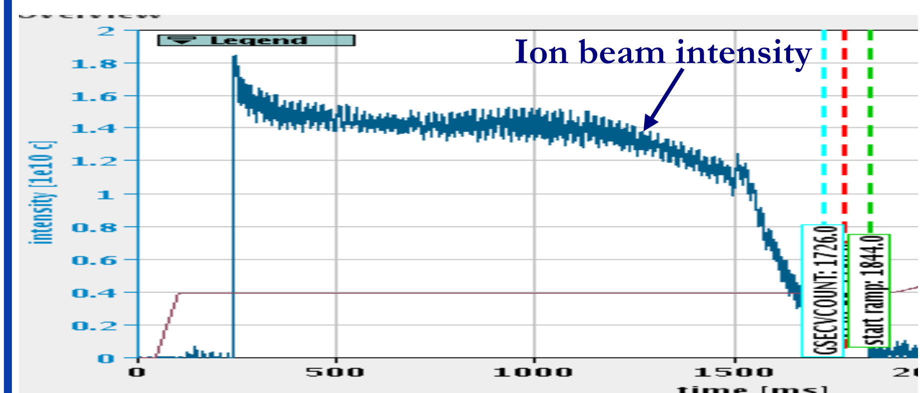
- **We could profit of space-charge effect on e- beam energy distribution:**

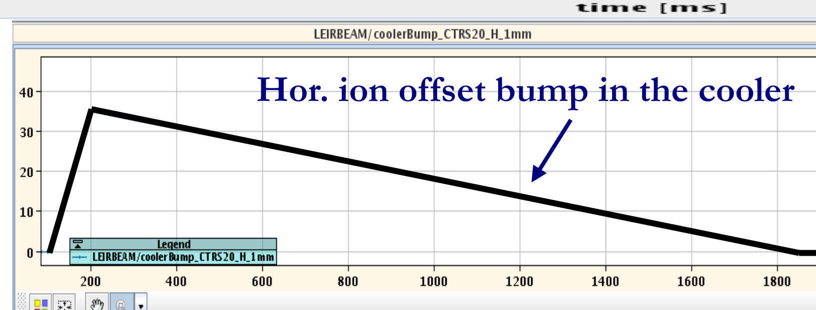


from: J. Resta-López *et al* 2015 *JINST* **10** P05012 (link)

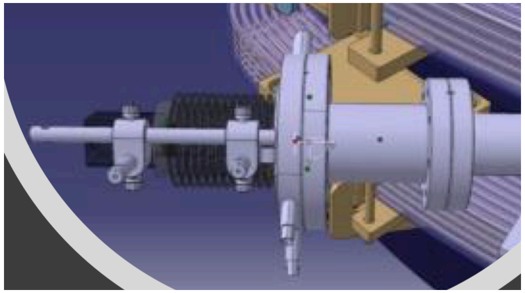
- To the **right**, a **quick test at LEIR**
  - **Requires new tooling/flexibility of ELENA control system**



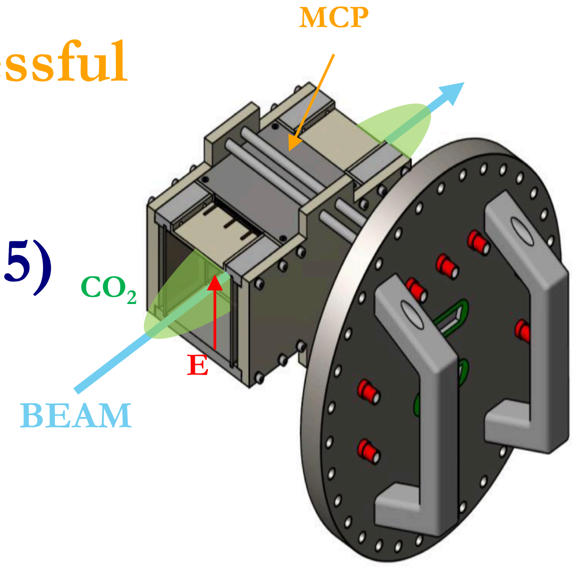




Overcome scraper limitation



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



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

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

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

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

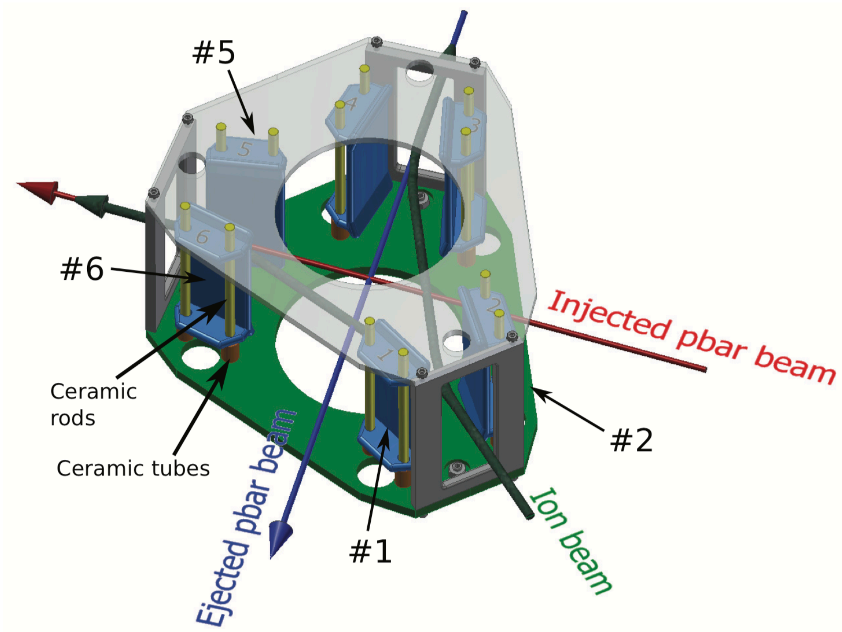
$$\gamma \approx 1$$

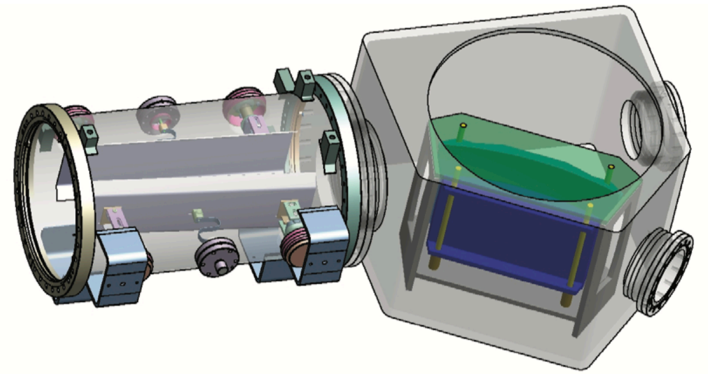
$$\beta_\gamma \approx 0.038 - 0.015$$

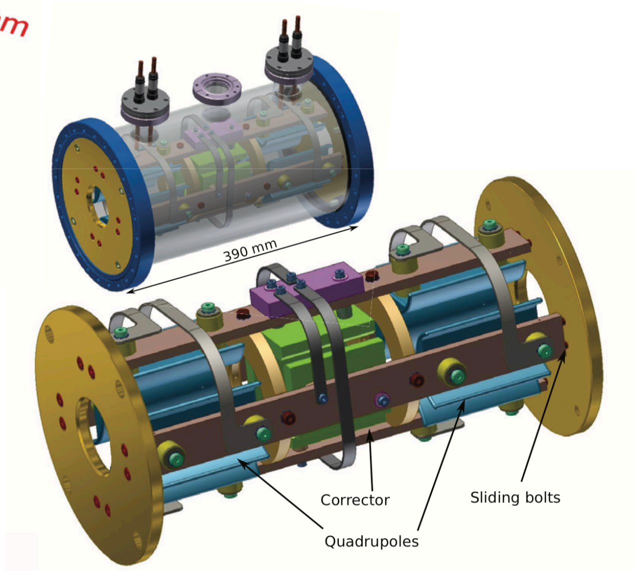
from: ELENA Design Report (CERN-2014-002)

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

Transfer line elements

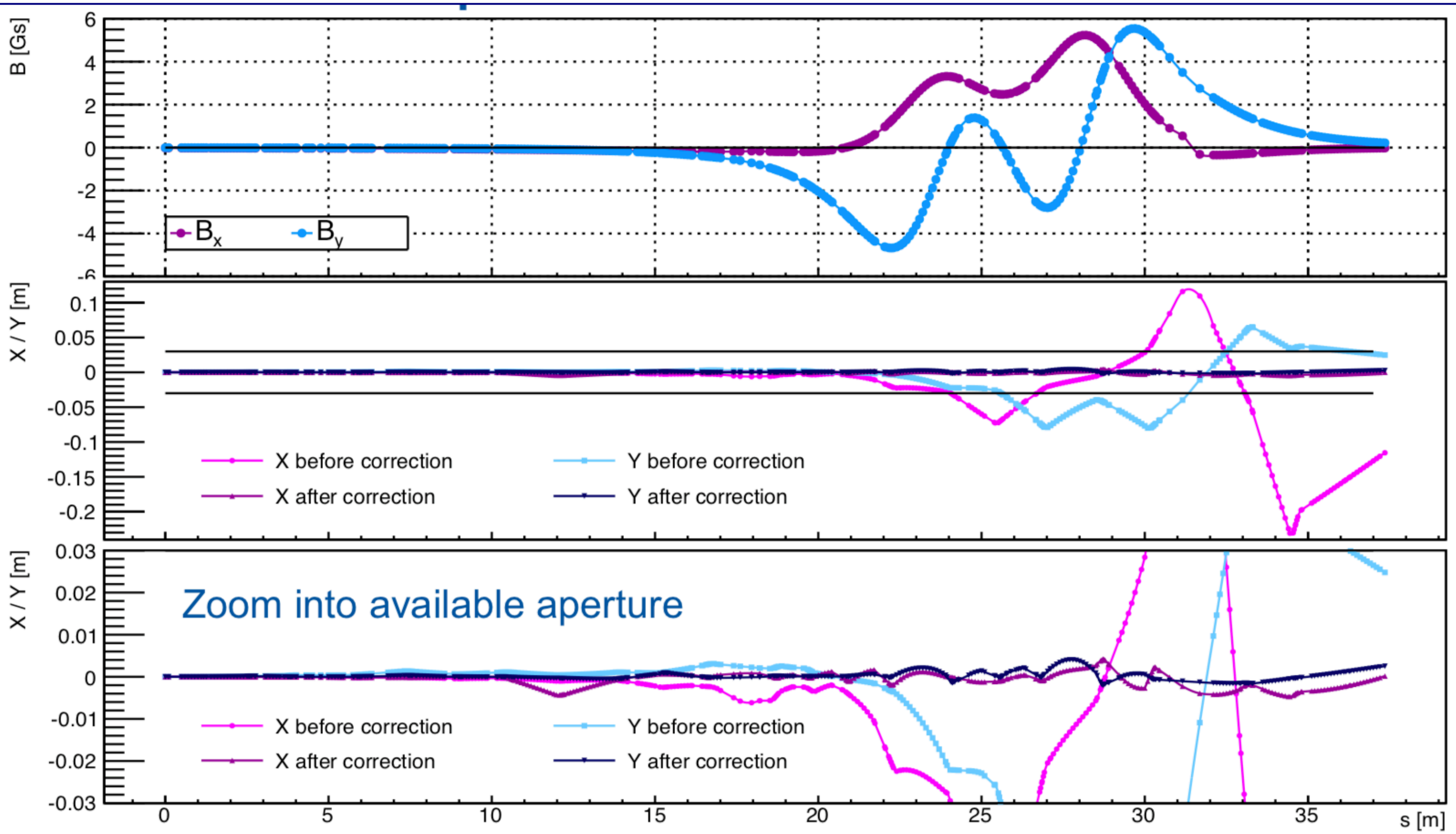






From D. Barna et al. – IPAC2014 - MOPRI101

Stray fields: effect on antiproton beam



- In total, 21 horizontal and 21 vertical correctors available
- MADX MICADO technique, aiming to limit RMS values along the line to 10^{-5} m

BPPC 12 May 2016

Courtesy J. Jentzsch - indico