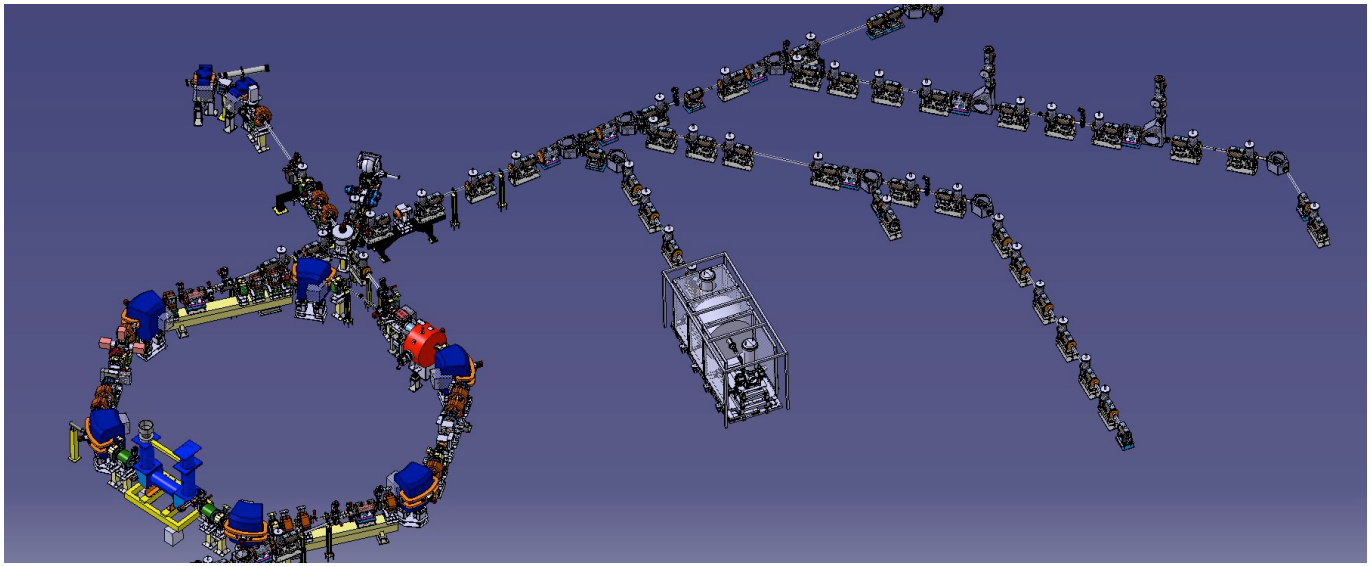
ELENA: CERN and Extremely Low Energy Cooling

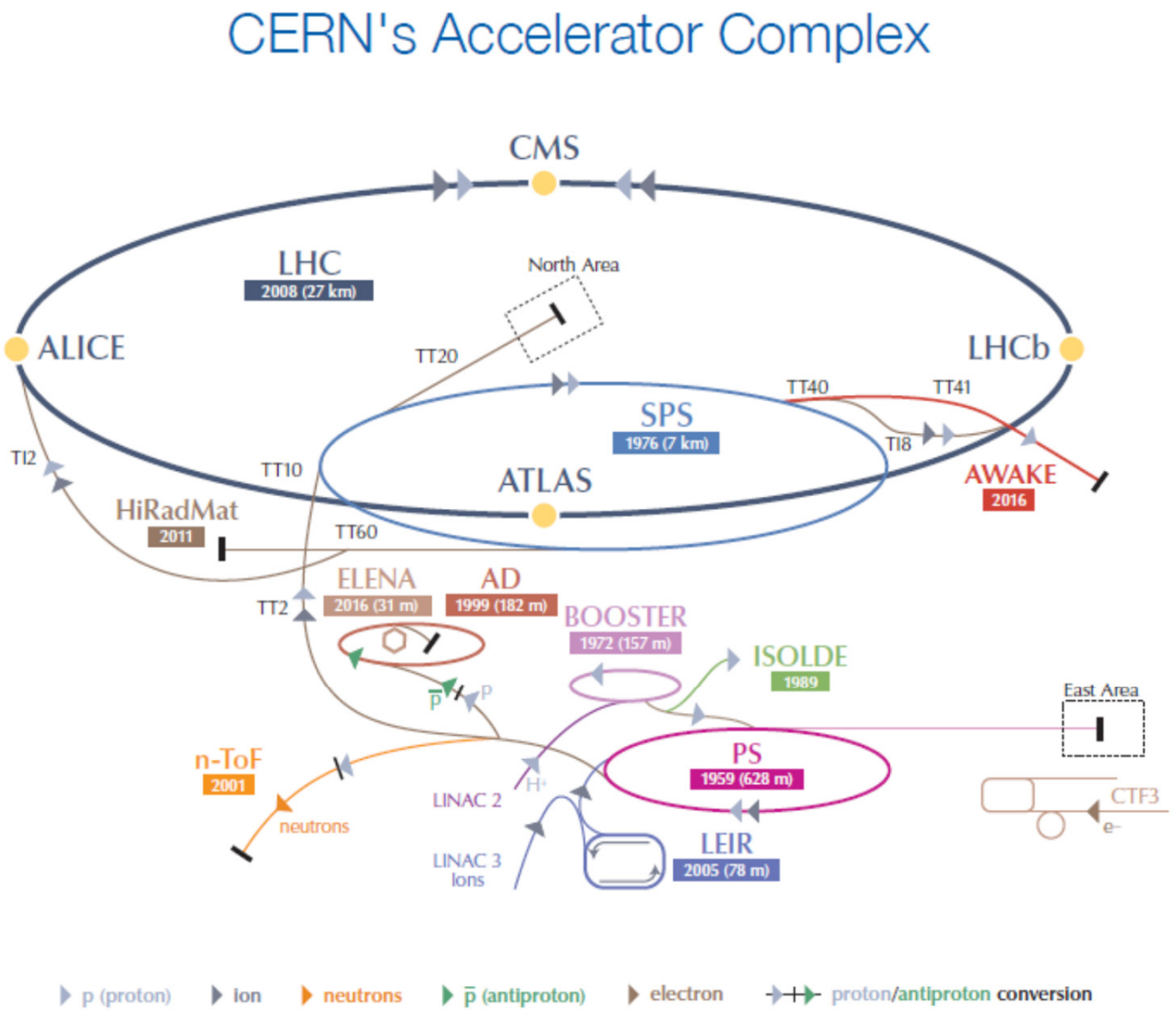
L. Jorgensen on behalf of the AD/ELENA team(s)

COOL 2017, 21 Sept. 2017



- Introduction and overview of ELENA and Layout
- Selected Features and Challenges
- Very Low Energy Electron Cooling
- ELENA Commissioning with H-
- ELENA commissioning with pbars
- Summary and Outlook

ELENA at CERN

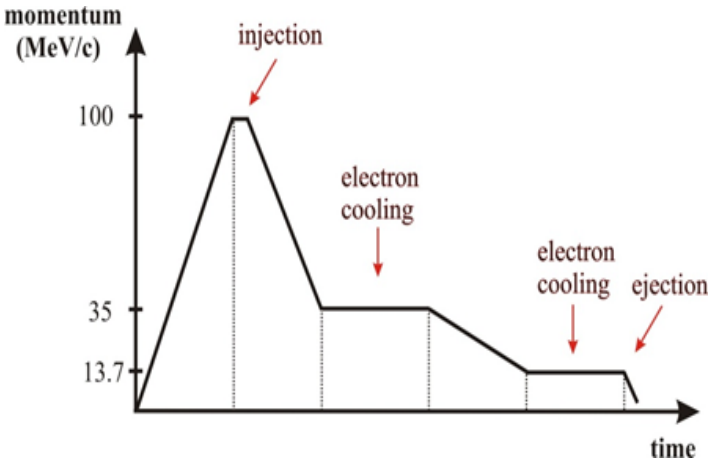


ELENA – A Brief Introduction

- The AD delivers antiprotons at 5.3 MeV. This is too high energy for the experiments, so >99.7% of antiprotons are lost.
- Solution: ELENA (Extra Low Energy Antiprotons) – new ring to decelerate the antiprotons further down to 100 keV.

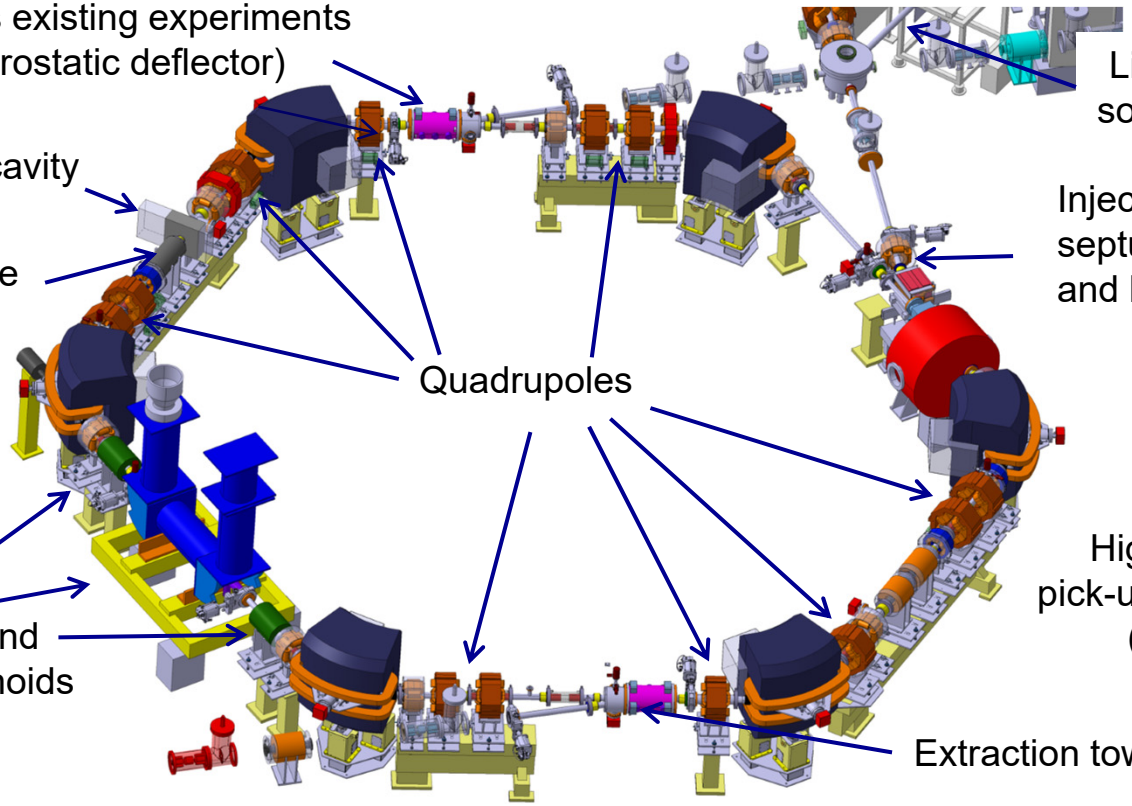
Very challenging !!!

Momentum range, MeV/c	100 - 13.7
Energy range, MeV	5.3 - 0.1
Circumference, m	30.4
Intensity of injected beam	3×10^7
Intensity of ejected beam	1.8×10^7
Number of extracted bunches	1 to 4
Emittances (h/v) at 100 KeV, π·mm·mrad, [95%]	4 / 4
Δp/p after cooling, [95%]	10^{-3}
Bunch length at 100 keV, m / ns	1.3 / 300
Required (dynamic) vacuum, Torr	3×10^{-12}

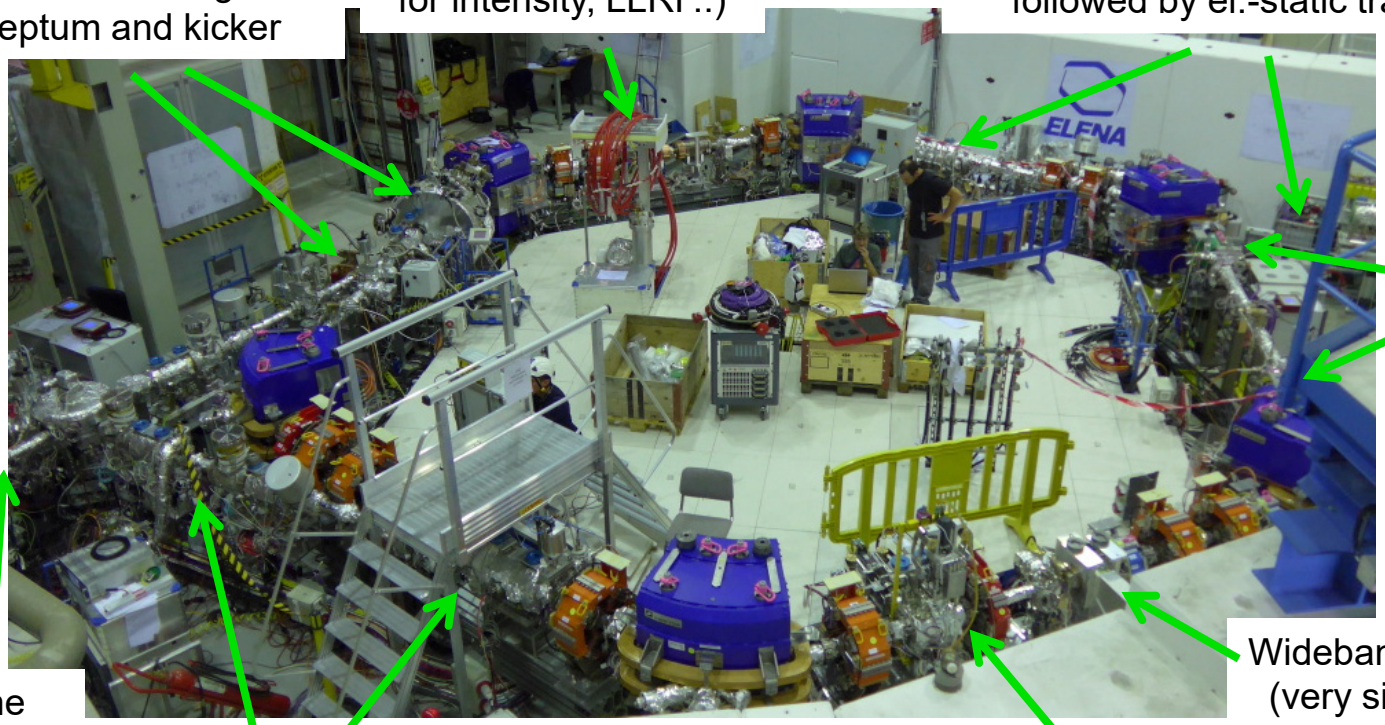


ELENA Overview and Layout

- Deceleration of antiprotons from 5.3 MeV to 100 keV to improve efficiency of experiments
- Circumference 30.4 m (1/6 the size of the AD)
  - Fits in available space 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)

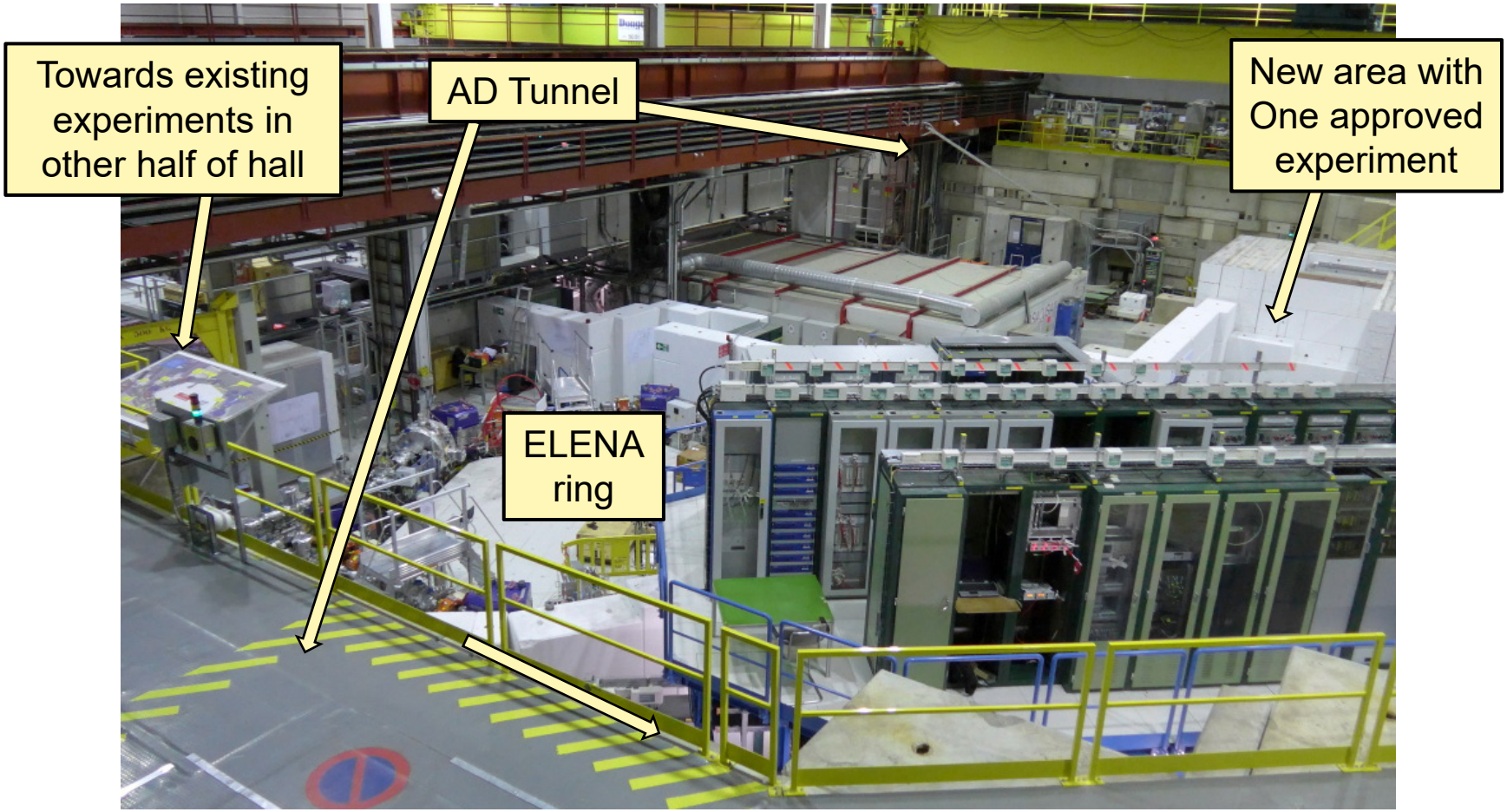


ELENA Overview and Layout



- Deceleration of antiprotons from 5.3 MeV to 100 keV to improve efficiency of experiments
- Circumference 30.4 m (1/6 the size of the AD), magnetic ring and electrostatic extraction lines
- Challenges related to low energy as field quality of magnets operated with very low fields

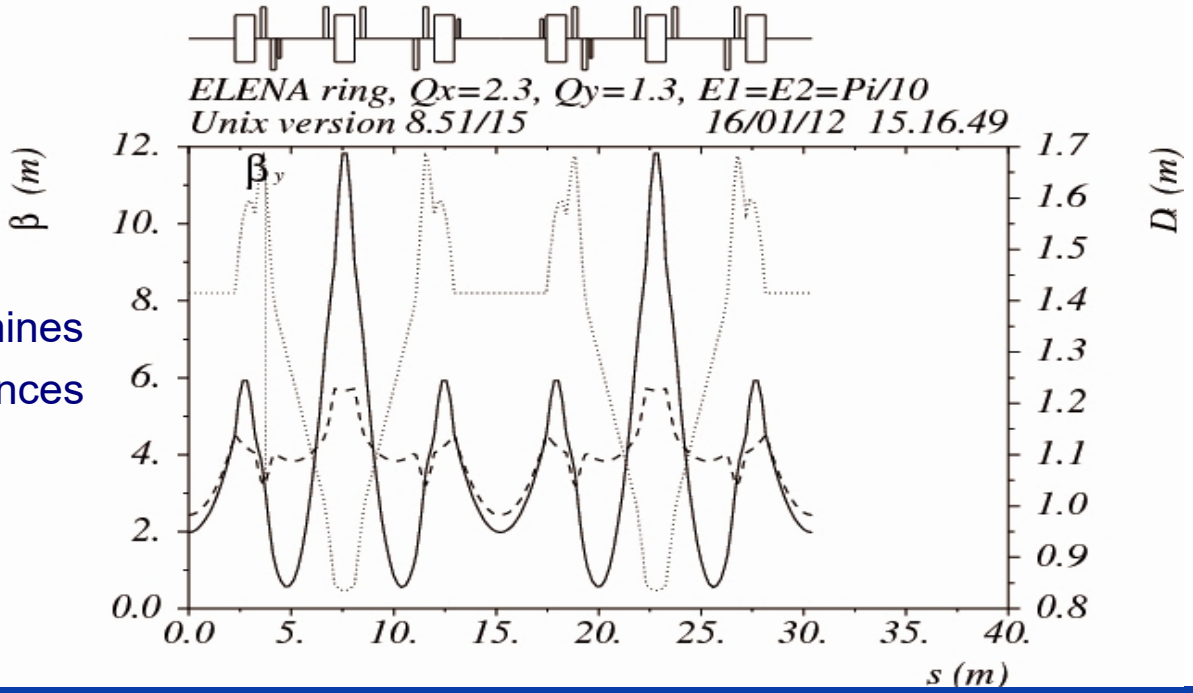
ELENA Overview and Layout



- ELENA in AD hall with existing (AD experiments) and new experimental area
  - Seen from the door to the new small annex building (for kicker generators and storage)
  - Cost effective with short transfer line from AD and no relocation of existing experiments

Selected Features and Challenges

- Energy Range
  - Machine operated at an unusually low energy for a synchrotron (down to 100 keV!)
  - Many points below a consequence of the low energy
- Lattice
  - 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)
- IBS
  - Emittance blow-up – determines together with cooling emittances of available beams
- Transverse direct space charge defocusing



Selected Features and Challenges

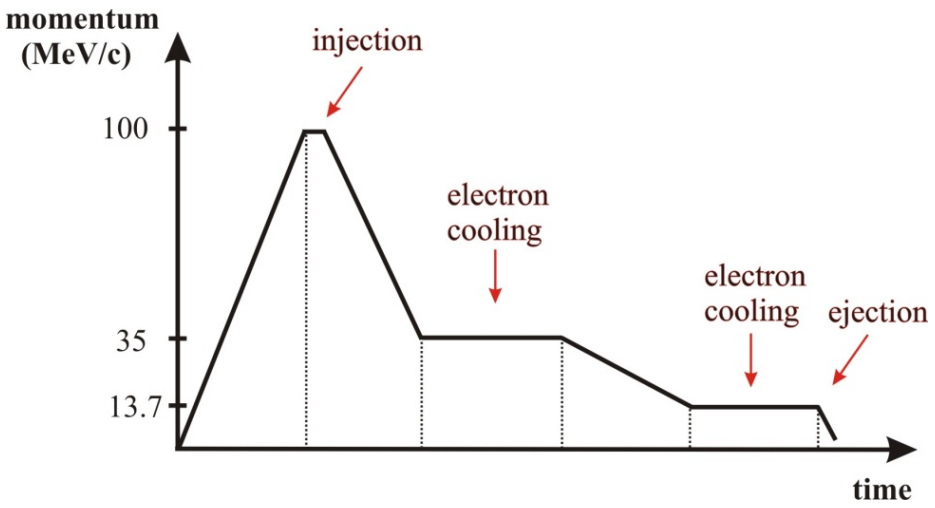
- Rest gas interactions and vacuum system
  - 3 10^{-12} Torr nominal pressure - fully baked machine with NEGs wherever possible
  - Interactions of beam with rest gas to be evaluated with care, not the dominant limitation
- Beam diagnostics with very low intensities and energy
  - E.g.: Beam currents down to well below 1 μA far beyond reach standard slow BCTs
  - ➠ Intensity of coasting beam measured with Schottky diagnostics

➠ 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
- H^- and proton source (and electrostatic acceleration to 100 keV) for commissioning as much as possible
  - Higher repetition rate but start commissioning at the difficult low energy part of the cycle
  - Antiprotons needed to complete ELENA ring commissioning … and already taken during the last months

The Need for Electron Cooling

- Electron cooling essential in ELENA to counter emittance blow-up caused by the deceleration process.
- To prepare bunches with sufficiently low emittance for extraction to the experiments via the long electrostatic extraction lines.
- Cooling needed at 2 momenta: 35 MeV/c and 13.7 MeV/c.
- Expected emittances prior to cooling:
  @ 35 Mev/c:
  $\varepsilon \sim 50\ \pi$ mm mrad
  $(\Delta p/p) = \pm 2 \times 10^{-3}$
- Needed emittances at extraction
  $\varepsilon \leq \sim 3\ \pi$ mm mrad
  $(\Delta p/p) \leq \pm 1 \times 10^{-3}$



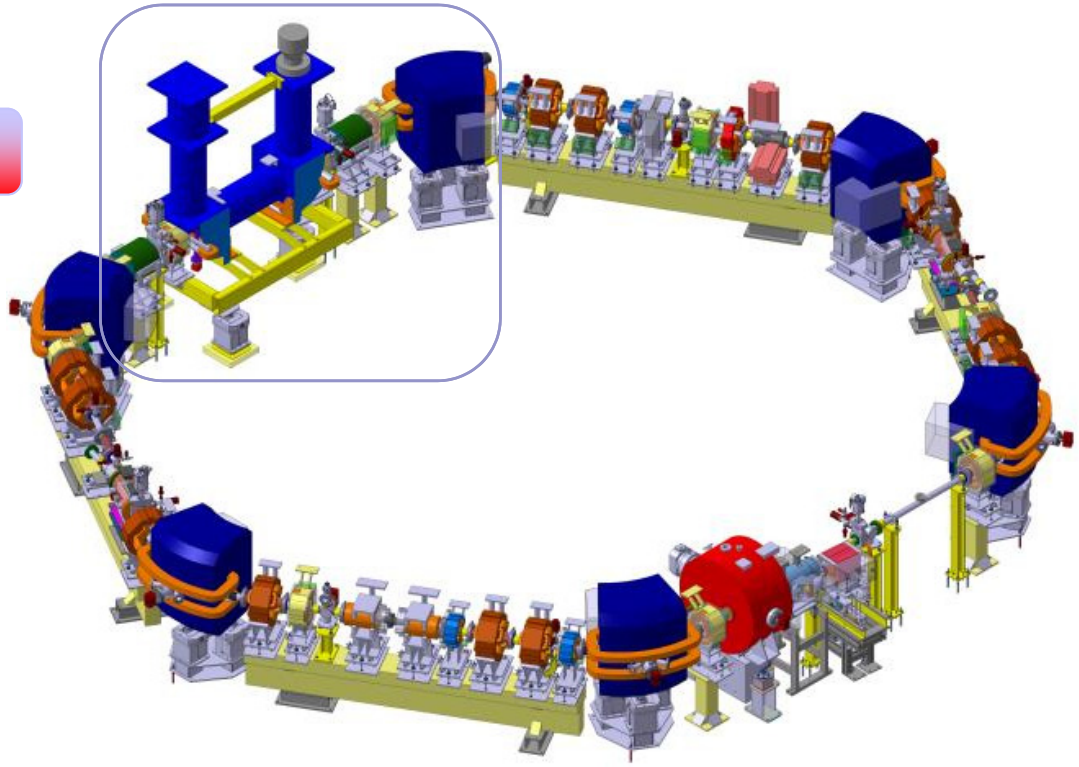
General Requirements

- Operate at very low electron energies (down to 55 eV).
- Operate at very low magnetic field to minimize disturbance to circulating low energy antiprotons – we have chosen 100 Gauss in the cooler.
- Have extremely good vacuum.
- Adiabatic expansion of electron beam to reduce transverse temperatures.
- Very good field quality – especially in the cooler solenoid ($B_{\perp}/B_{\parallel} < 5 \times 10^{-4}$).
- Orbit correctors and compensation solenoids

ELENA requirements

Must be very compact!

Section 4



Must fit in Section 4 incl. solenoid compensators and correctors.

~ 2 meters available for the electron cooler.

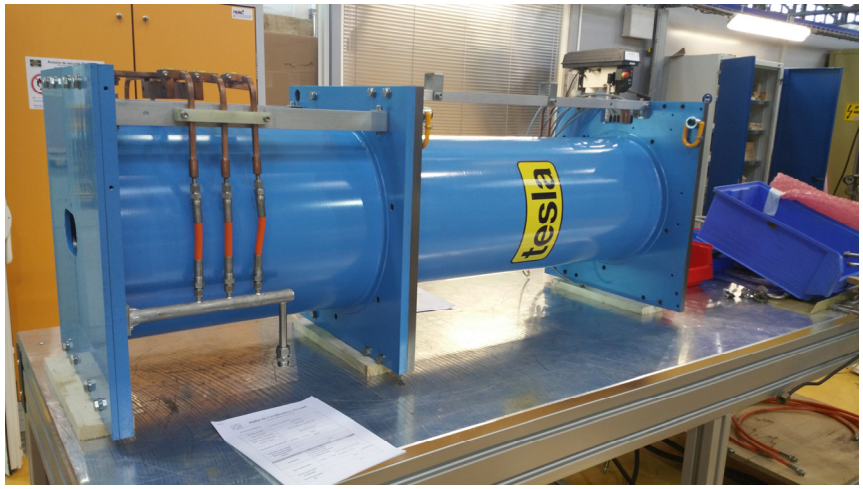
Space constraints also necessitate 90° bends on relatively small radius (25 cm)

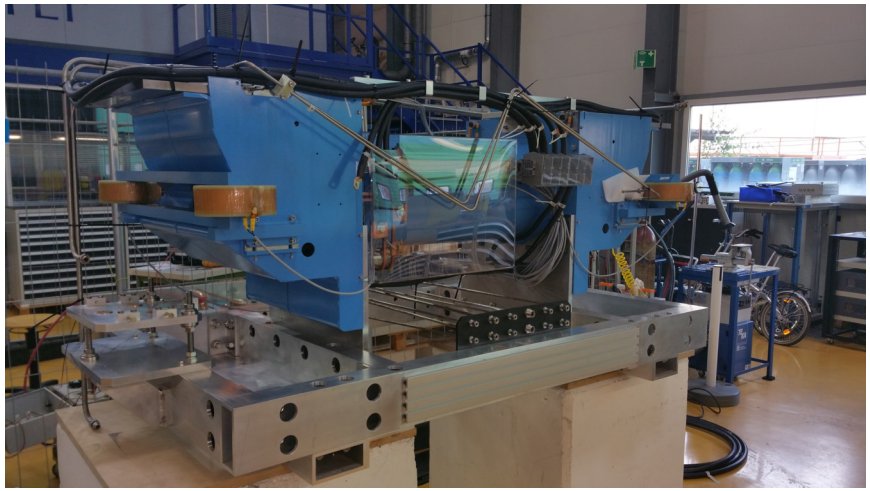
Electron Cooler parameters

Momentum (MeV/c)	35	13.7
β	0.037	0.015
Electron beam energy (eV)	355	55
Electron current (mA)	5	2
Electron beam density (m^{-3})	1.38×10^{12}	1.41×10^{12}
B_{gun} (G)	1000	
B_{drift} (G)	100	
Expansion factor	10	
Cathode radius (mm)	8	
Electron beam radius (mm)	25	
Twiss parameters (m)	β_h=2.103, β_v=2.186, D=1.498	
Flange-to-flange length (mm)	2330	
Drift solenoid length (mm)	1000	

Status of the Electron Cooler

- Magnetic system at CERN since about a month

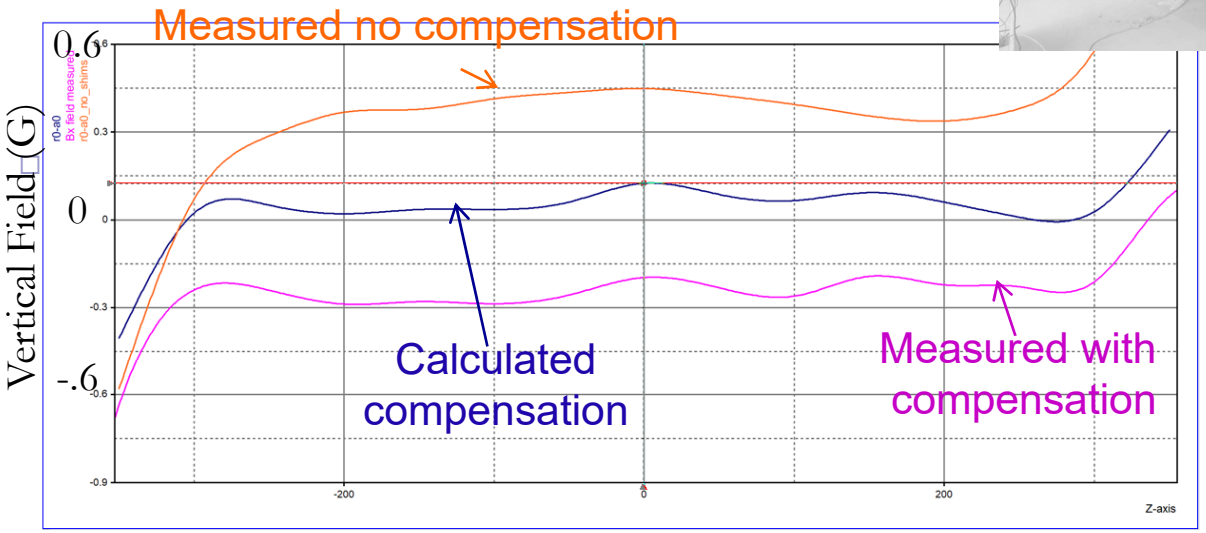




  - Now with Magnet Group for “Certification” (standard tests done with magnets)
  - Some issues with magnetic measurements done by company (some details on next slide)
- Issues with NEG coating of Vacuum System (recurrent problems for several ELENA Chambers)
  - All chambers (and electrodes) coated, acceptance tests still to be completed
  - Depending on progress this autumn or during CERN YETS (end-of year shutdown)
- Installation to be coordinated with other activities and in particular, first beam for GBAR

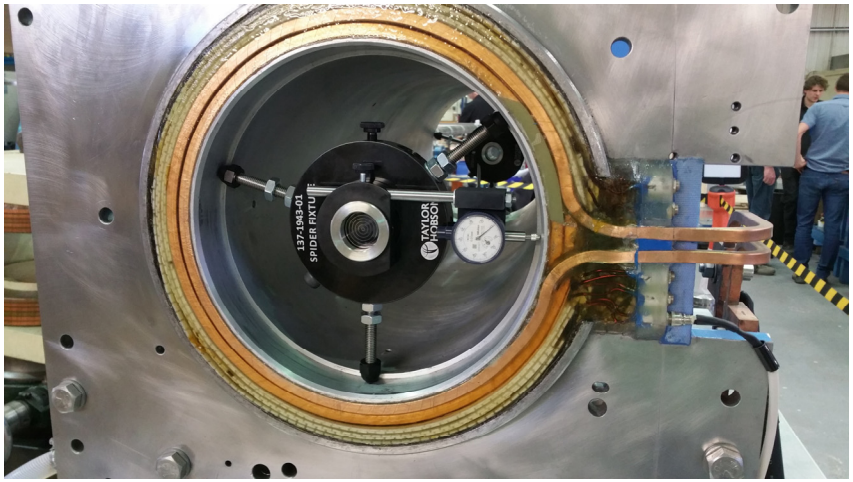
Status of the Electron Cooler

- Aim of magnetic measurements
  - Field quality of single solenoids ($B_t/B_{\parallel} \leq 5x10^{-3}$) and in center of drift solenoid (where beams interact) of assembled system ($B_t/B_{\parallel} \leq 5x10^{-4}$)
  - Check magnetic model
- Issues:
  - Unexpected behavior between “toroid” and corrector
  - Non-reproducible offsets of transv. field measurements

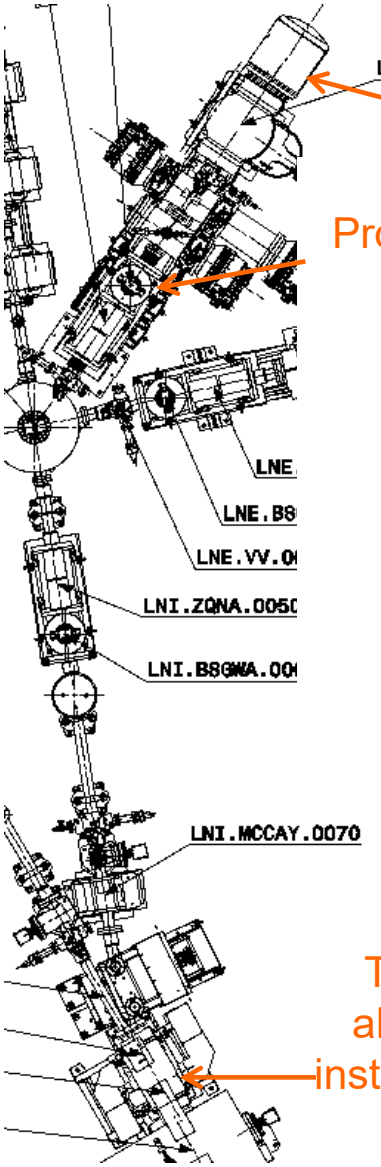


- Plan:
  - Compensation scheme combining info. from measurements of single solenoids and assembled system
  - Try to understand (simulations and/or measurements?) unexpected field and evaluate possible impact

Status of the Electron Cooler

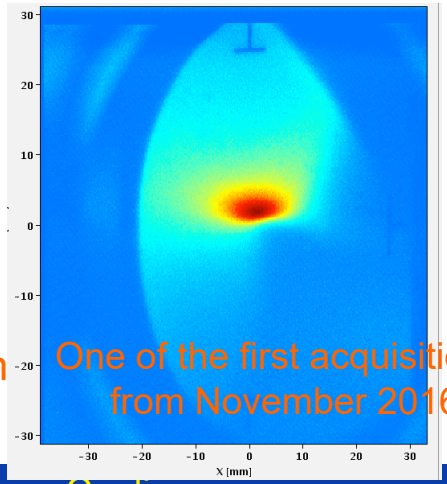


ELENA Commissioning – Ion Source and Line from Source to Ring



- 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

  => Now running with fixed isolation transformer at 85 keV
- Limited beam diagnostics
  - Only one profile monitors with temporary electronics available

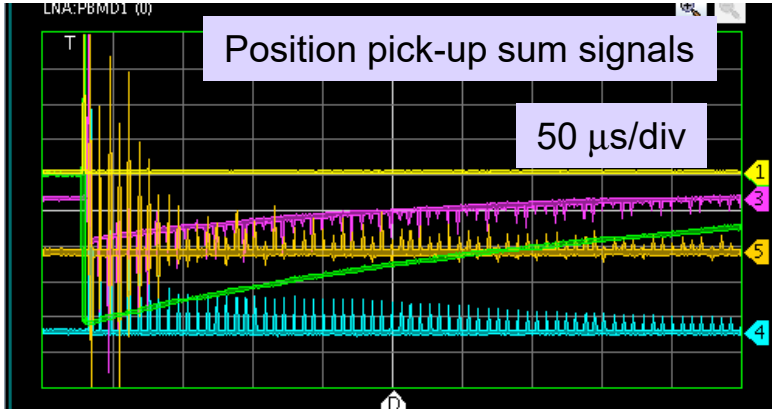


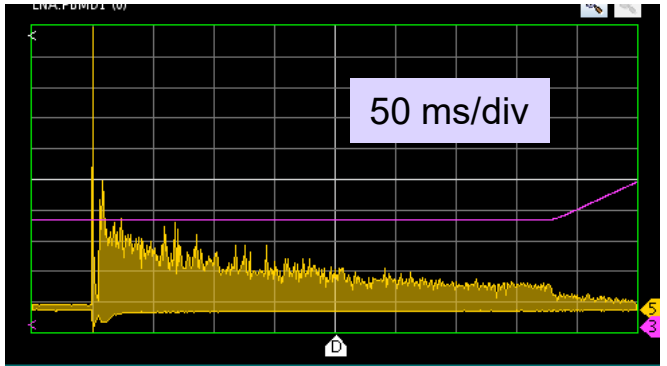
One of the first acquisitions from November 2016

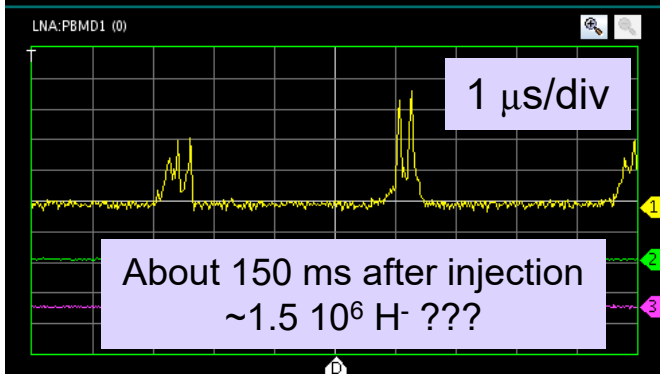
Thanks a lot to the teams providing the source and monitors as in-kind contribution
In-kind contributions important for the project!!

Start of ELENA Commissioning – Ring

- Beam observed over several 10s of turns (probably a few ms) in November ‘16 after less than 2 weeks
  - Beam lost quickly or just not visible any more due to debunching?
  - Commissioning of RF system as next under preparation, when source broke (insulation transformer)
- With 85 keV H^- after commissioning of RF system
  - Beam shown to survive at least until start of ramp
  - Only very basic RF functionalities, no phase loop
  - Poor reproducibility a serious issue
    - Slow drifts and shot-to-shot
    - Difficult to work on setting-up systems as RF
- Synchrotron oscillation, debunching seen with OASIS





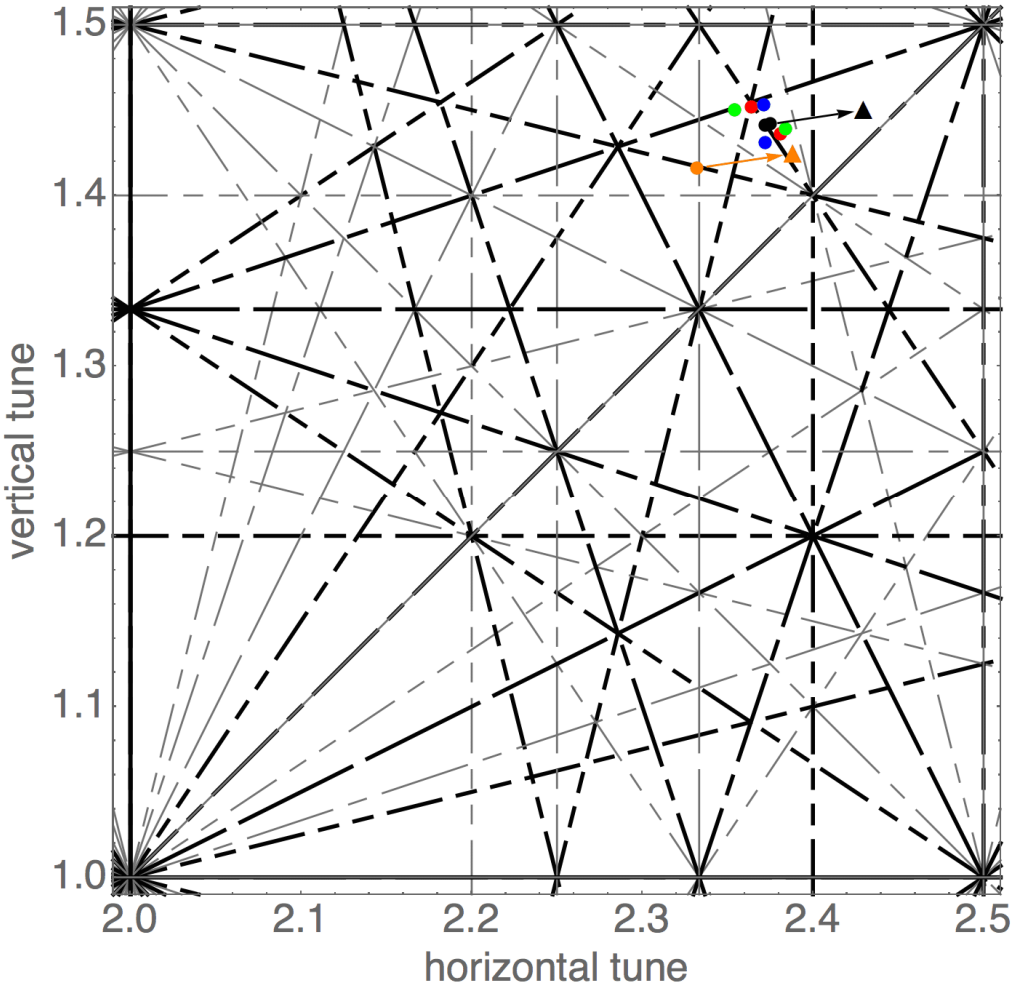


Working points

- Tune: number (average) of transverse oscillations per revolution (two tunes for the horizontal and vertical plane)
- Working point is the combination of the two tunes – must avoid “resonances”

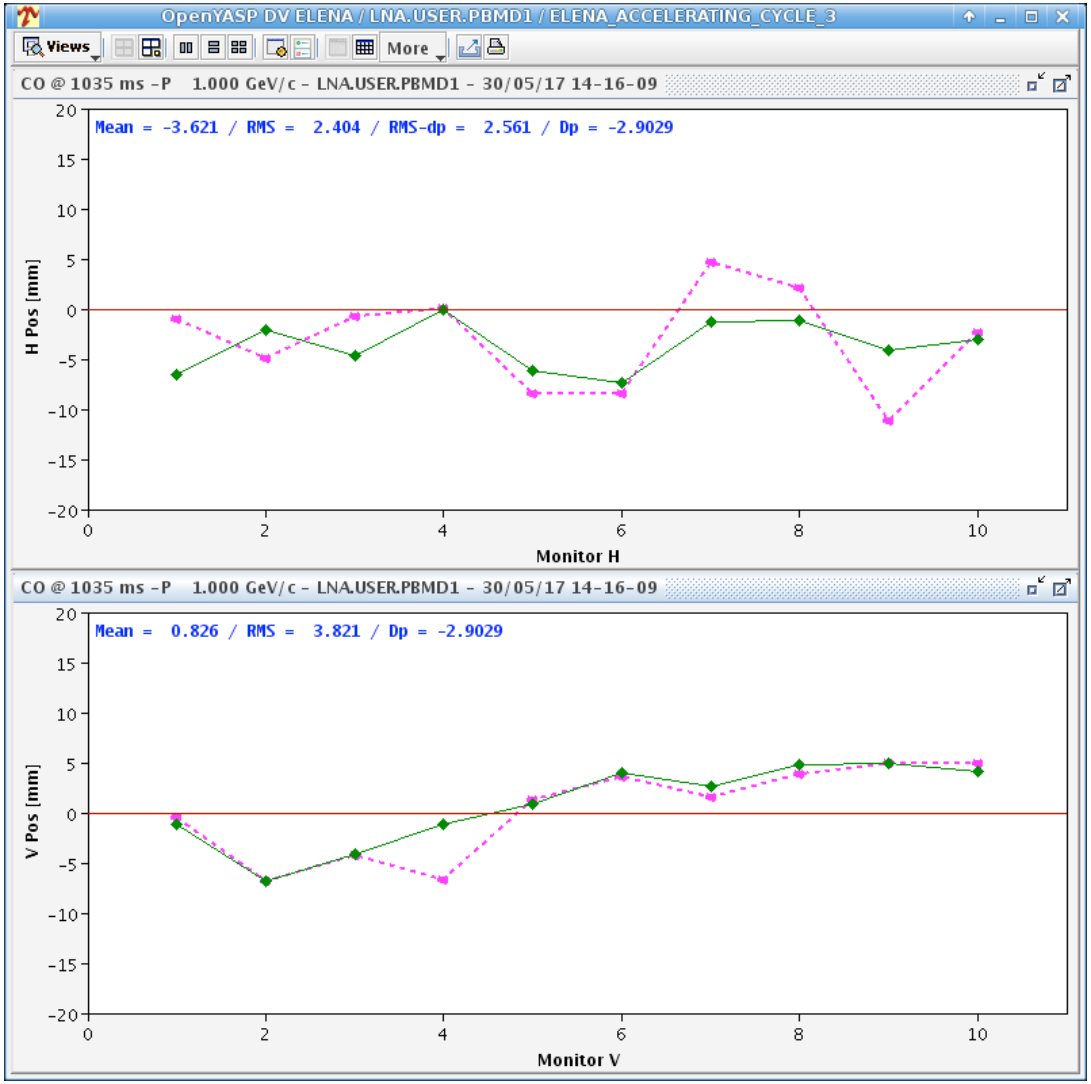
- Black: measured working point with initial quadrupole currents
- Red, blue and green: current of one of the three quadrupole circuits changed by ±0.05 A
- (Orange: working point from model with programmed quad currents)

- Reassuring that behavior about as expected



Resonance diagram with working point(s) close to 5th order resonance

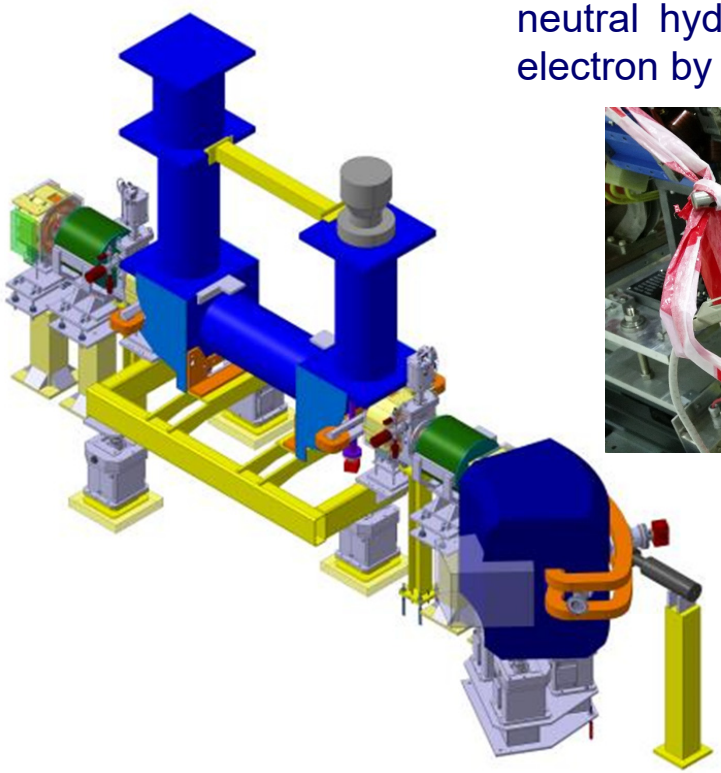
First orbit corrections

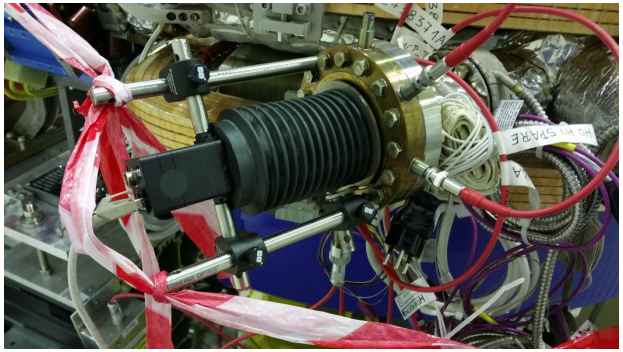


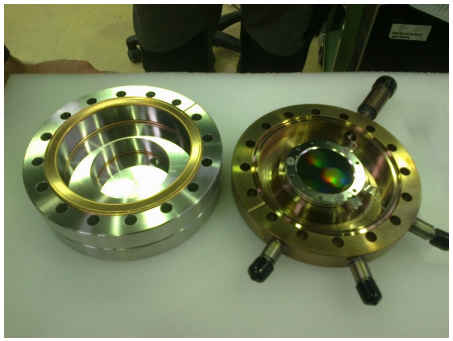
Recombination monitor

For commissioning at 100 keV with the proton source, optimisation of the electron cooler can be performed by measuring the recombination of electrons with the circulating protons.

In H^- mode the circulating beam profile can be determined from the neutral hydrogen atoms created by the stripping of the loosely bound electron by the residual gas.



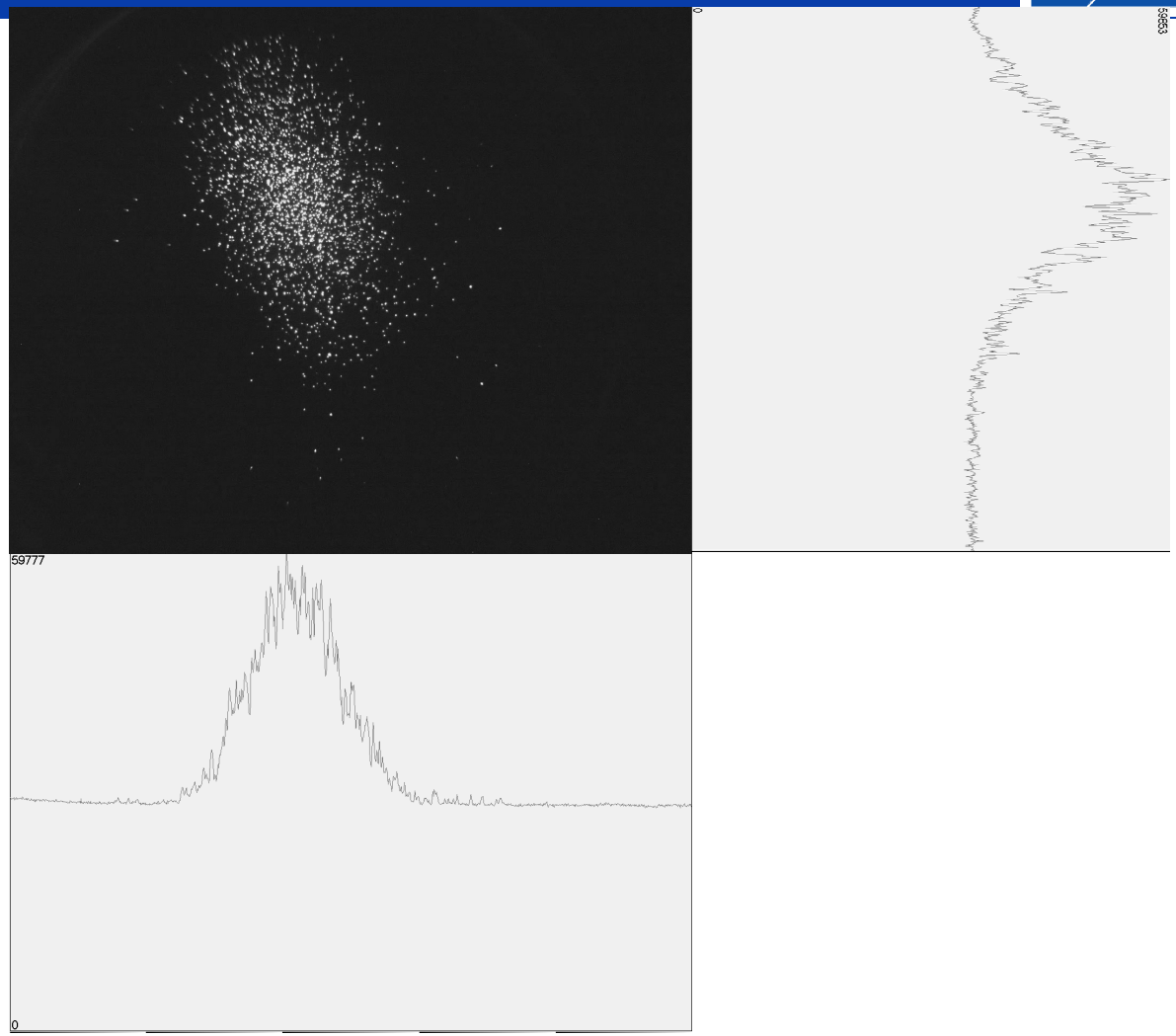




- Chevron mounted MCP detector
- MgO coating
- Fibreoptic phosphor screen with P43
- Direct image of cooled beam on CMOS camera on a PC

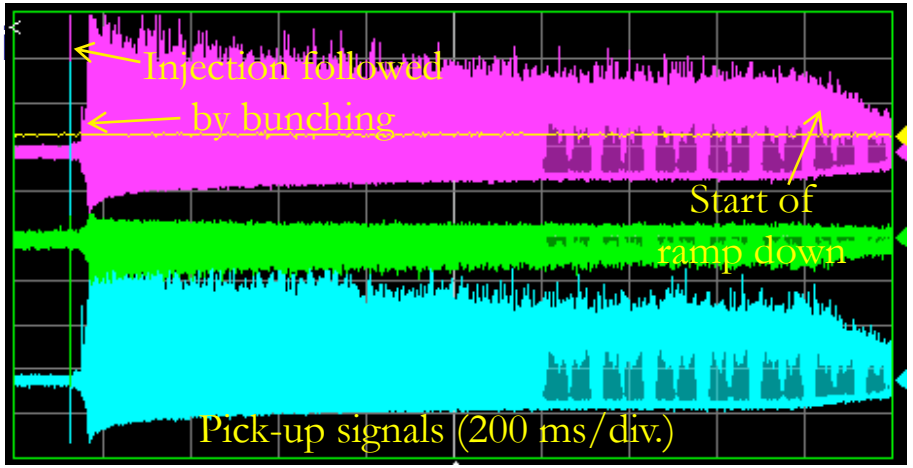
Recombination monitor

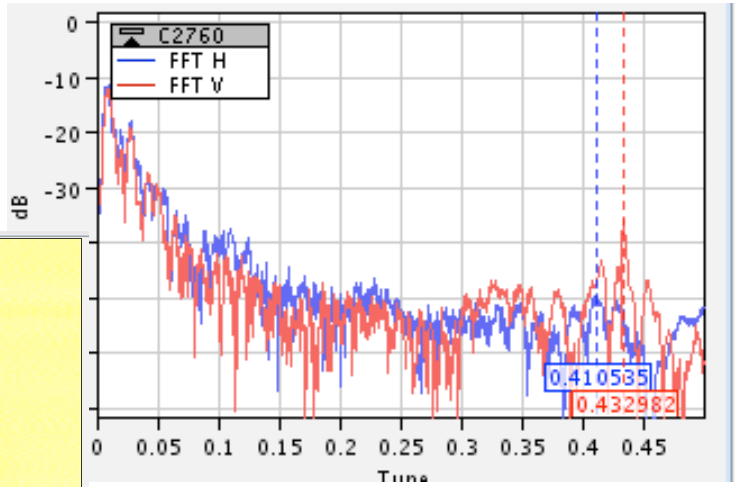
Recombination monitor

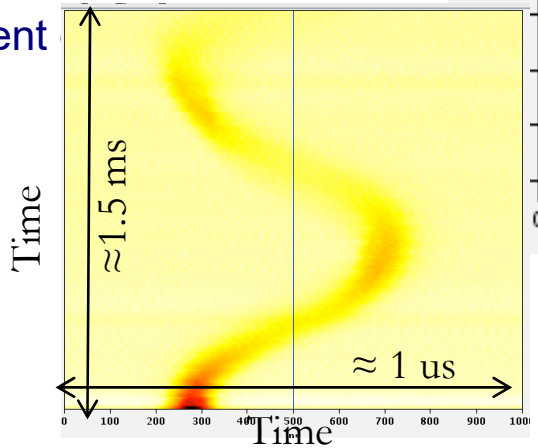


ELENA Commissioning Progress with Antiprotons

- Antiprotons injected followed by bunch
  - Phase and radial loops and “Bunch to Bucket” transfer to be set-up
  - Large transverse missteering (leading to emittance blow-up) to be corrected
  - Good life-time
- Commissioning of the scraper
  - Emittance measurement by observing losses, when a scraper is moved into the beam
- Tune measurement with the system
  - So far “only” using the coherent from injection
- Synchrotron oscillation with RF on at injection



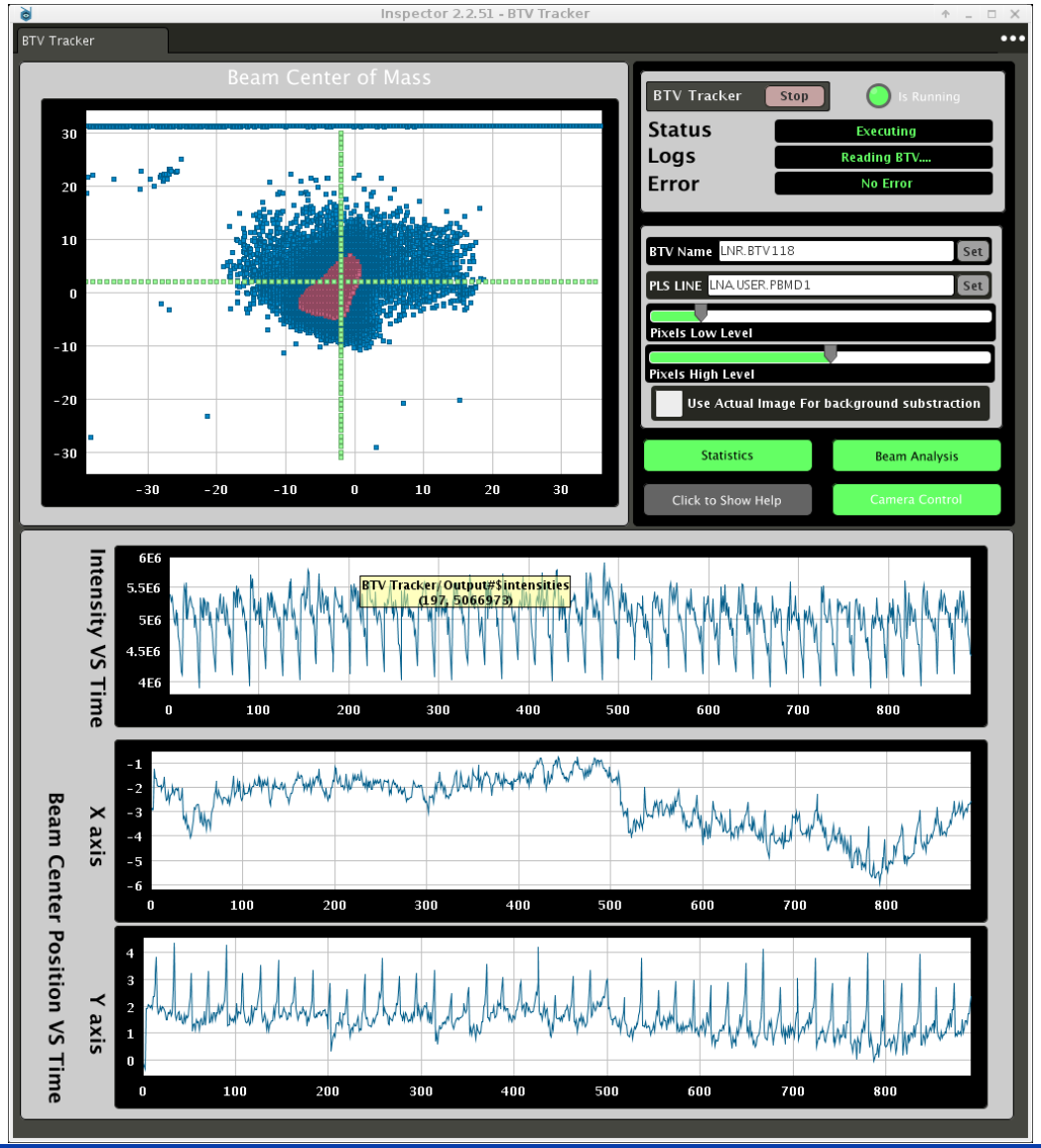




Issues

- Poor reproducibility at 85 keV slowing down progress
  - Unclear reason – attempts to correlate with possible perturbations (AD cycle, crane …) not successful
  - Improvement with 100 keV and/or better setting of transfer line?
- Ion source
  - No spare isolation transformer available, solutions under discussion
- Profile Monitors
  - Three monitors installed and a few more under preparation
  - First version of acquisition electronics hopefully coming soon (for transfer to GBAR)
- Electron cooler
  - Magnetic system now at CERN and with the magnet group
  - All chambers coated with NEGs, last vacuum acceptance tests still to take place
- Magnetic pick-ups for extraction lines
  - Everything ready now to mount them
- Internal leak of injection kicker tank – new tank under preparation

H- source instability



Summary and Outlook

- ELENA Ring installed and Commissioning started
  - Circulating H^- beam from source for several 100 ms at 85 keV (limited by flat bottom)
  - Commissioning of system (RF, instrumentations, …) slowed down by poor reproducibility of injection of 85 keV H^- beam
  - Commissioning with antiprotons started (circulating beam with decent life-time …)
- Short Transfer Line Towards GBAR installed recently
- Next Steps
  - Continuation of ELENA Commissioning with H^- (protons?) and antiprotons
    - Further setting up of RF and other systems, acceleration/deceleration
    - Completion of commissioning of orbit system and correction, tune measurements, scraper …
    - Quantification and correction of antiproton injection oscillations
    - Efforts to understand and cure poor reproducibility of H^- injection (transfer line?)
  - First beam (probably H^- or protons) to GBAR this year
  - Installation of cooler in autumn or during YETS (end-of-year shutdown)
  - Completion of ELENA ring commissioning (electron cooling and finally setting-up of operational antiproton cycle)
  - Until CERN Long Shutdown 2 (LS2) GBAR will be the only user with the connection of old experimental area to ELENA during LS2 only

Contributors to the ELENA Project

Thanks!