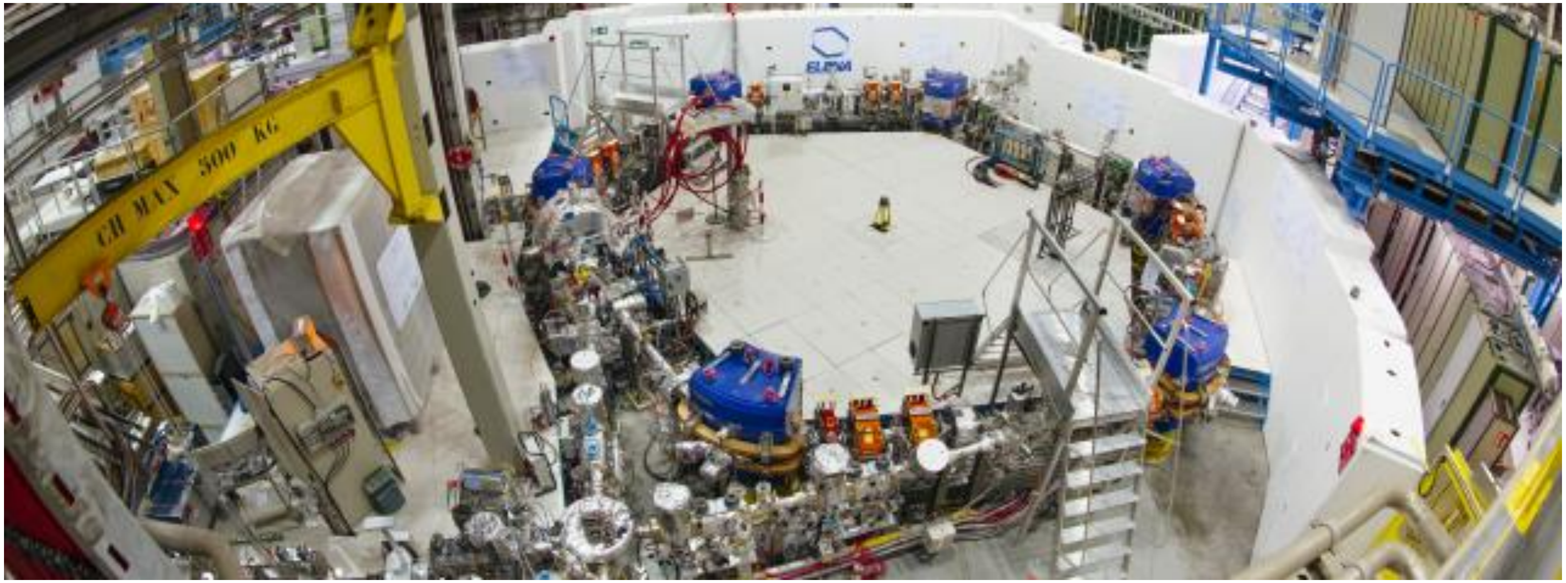
Extra Low ENergy Antiproton ring ELENA

C. Carli on behalf of the AD/ELENA team(s)

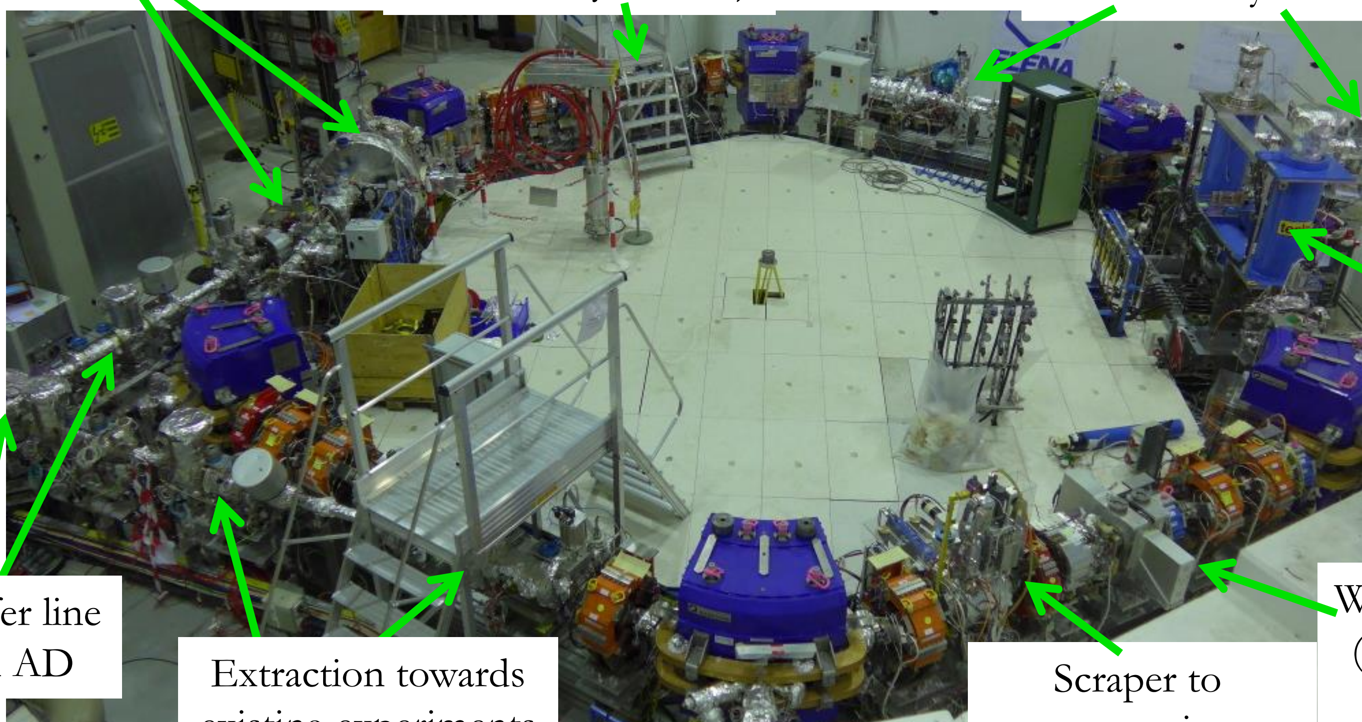
LEAP 2018, 12th March 2018



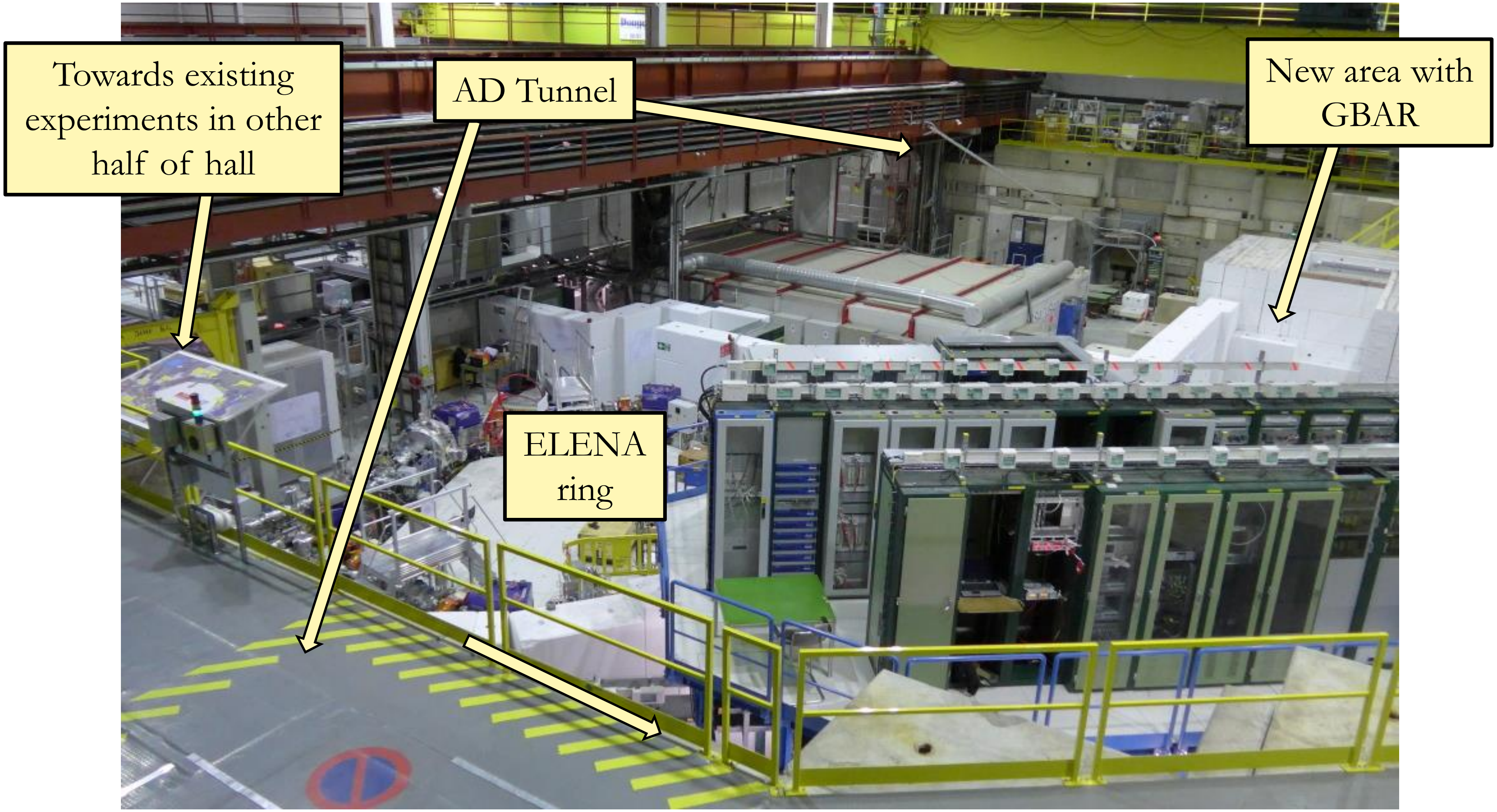
- Introduction
- Selected Features and Challenges
- Status of ELENA Ring Commissioning
- Status of Electron Cooler
- Plans for 2018
- Summary and Outlook

Introduction

- Controlled deceleration of 5.3 MeV Antiprotons from AD down to 100 keV and electron cooling
- Improved capture efficiency of (typical) existing experiments and new types of experiments (GBAR)
- Magnetic ring and injection line, electrostatic ejection lines (effective at low energies)
- Challenges related to low energy (e.g. magnetic field quality) and intensity



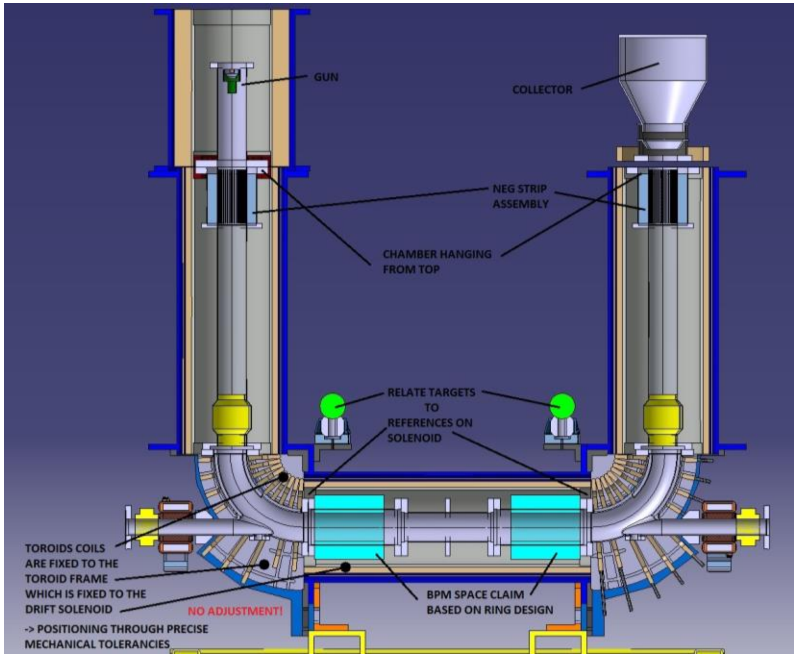
Introduction



- 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!)
  - Challenges mainly a consequence of the low energy
- 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
  - See dedicated slides on status



- Intra Beam Scattering IBS
  - Coulomb scattering between beam particles
  - Emittance blow-up due to transfer of heat (unordered motion) between phase spaces (long. & transverse)
- Characteristics of beam sent to experiments given by the equilibrium between
  - Electron cooling
  - IBS increasing emittances

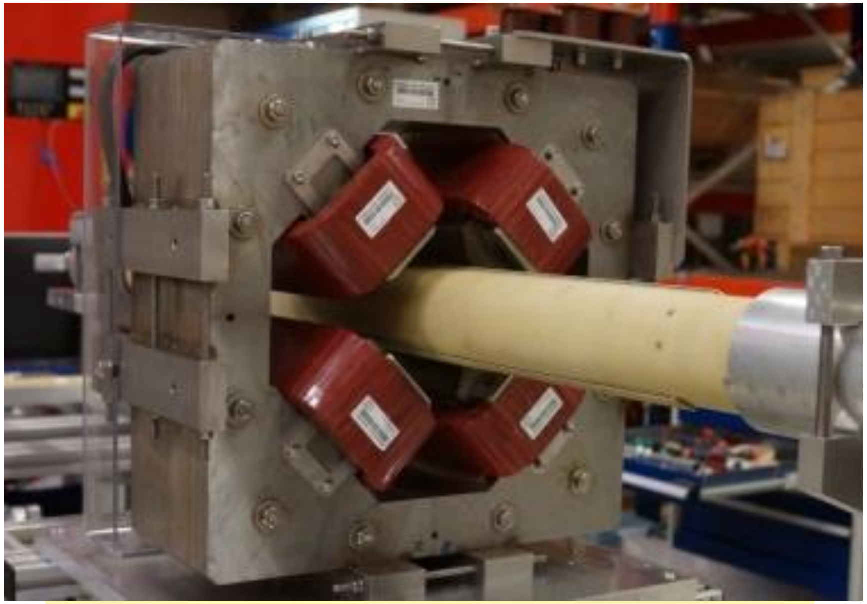
Selected Features and Challenges

- Direct space charge effect
  - Coulomb force between beam particles generate non-linear defocusing force
  - Initial reason to split available intensity into 4 bunches
- Sensitivity to magnetic stray fields
- Magnets operated with very low fields
  - Possible imperfections due to hysteresis
  - "Thinning" (mixing of stainless steel and magnetic laminations) had been foreseen initially and expected 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
- H^- and proton source (and electrostatic acceleration to 100 keV) for commissioning
  - ELENA 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 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

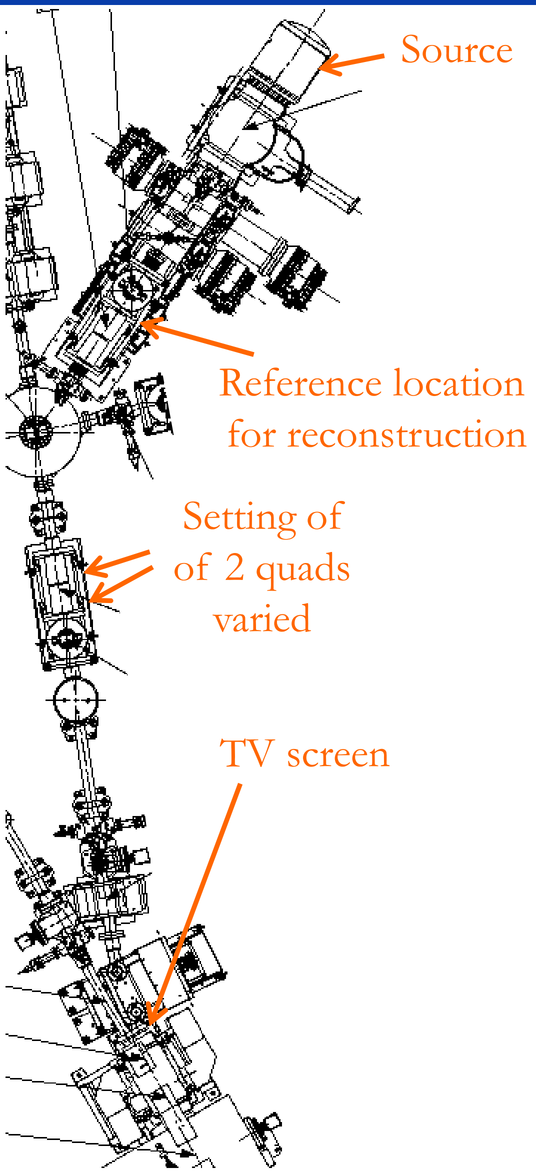
b) Increase of voltage from 16 V at transfer to 100 V on ramp

c) Simulations of IBS on ramp

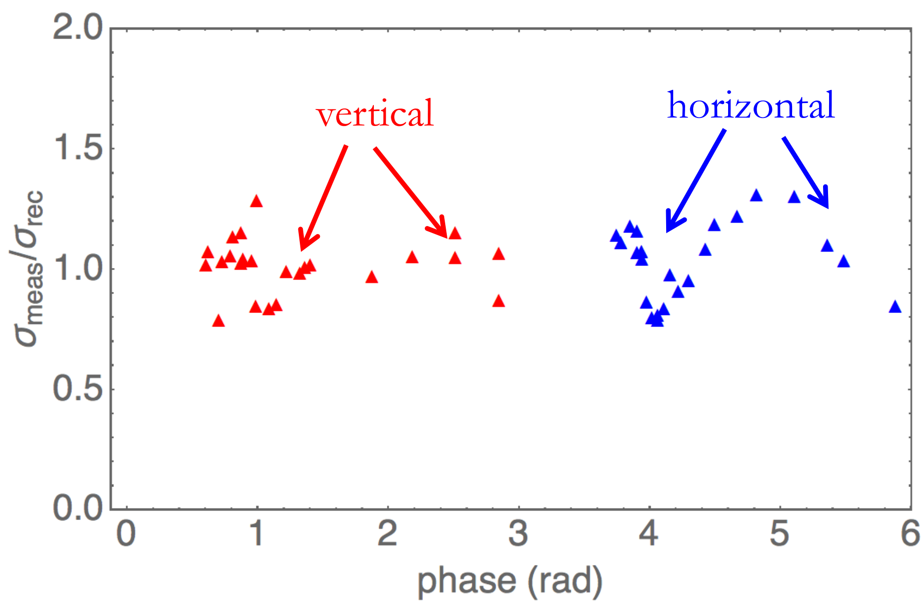
d) Debunching/bunching with 50% blow-up (bunched with LHC def. $\varepsilon_L = 4\pi\, \sigma_E\, \sigma_T$, coasting $\varepsilon_L = 4\,(2/\pi)^{1/2}\, \sigma_E\, T_{rev}$)

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

Results from ELENA Commissioning – Ion Source and Line from Source to Ring



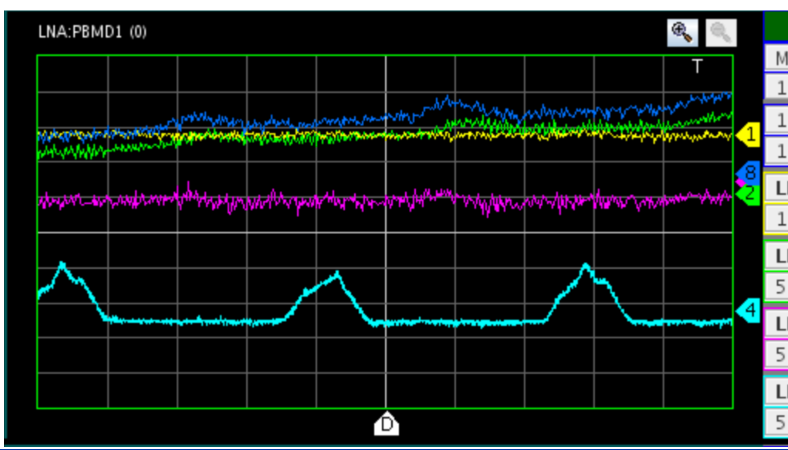
- Technical issues despite serious preparations and early testing
- Energy lowered from 100 keV to 85 keV for 2017
- Quadrupole scan to measure beam characteristics:
  Variation of the setting of (two) quadrupoles and observation of beam sizes with a monitor (TV screen between septum and kicker)
  - Reconstructed characteristics at the reference location
    Hor.: $\varepsilon_{x,rms}$ = 4.71 μm, β_x = 1.4151 m and α_x = -3.0061
    Vert.: $\varepsilon_{y,rms}$ = 5.08 μm, β_y = 0.8381 m and α_y = -2.6142
- Improved setting of line not (yet) tested

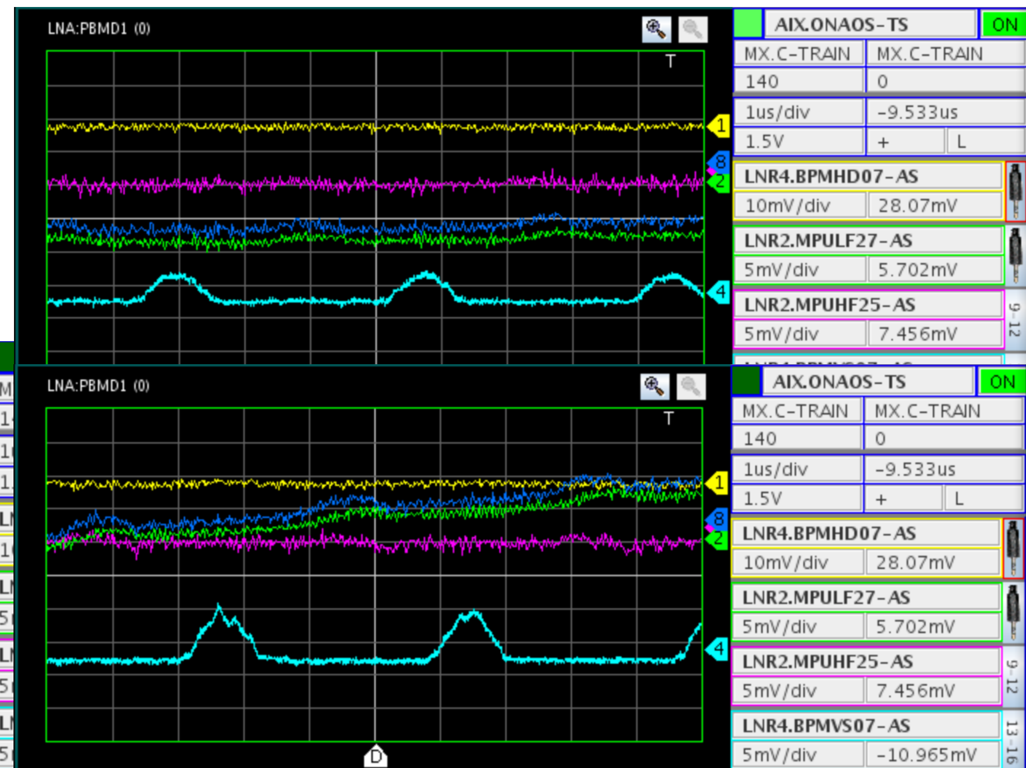


Ratio between measured beam size and beam sizes from reconstruction

Results from ELENA Commissioning – with H⁻ Beams from Source

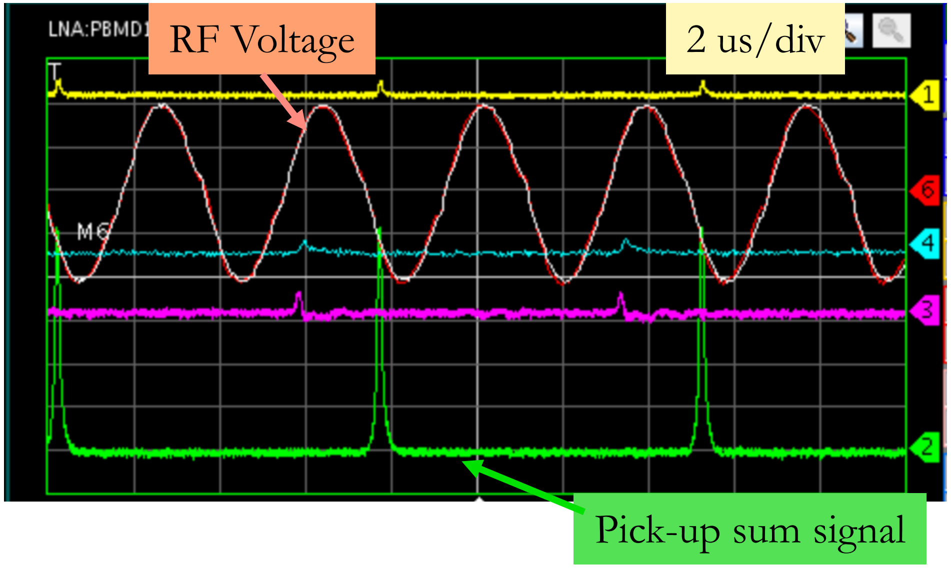
- Beam energy 85 keV instead of 100 keV because of problems with the source isolation transformer
- Few 100 ms life-time observed with RF (very basic functionalities) since spring
- Successful commissioning of orbit system, orbit correction, partly tune system, scraper ..
  => confidence in "lattice" with working point and orbit correction behaving about as expected
- Issues during summer: poor reproducibility (shot-to-shot fluctuation and long term drift) of H^- injection, sometimes technical problems with source, more time than expected to install GBAR line
- Improved reproducibility of injection from around September (Why? Just careful tuning?)
- Two long bunches with about $1\ 10^6$ to $2\ 10^6$ H^- ions each after 140 ms
  - Improved reproducibility (similar bunches for several cycle), but still low intensity
  - With RF capture after filamentation (injection with RF off)

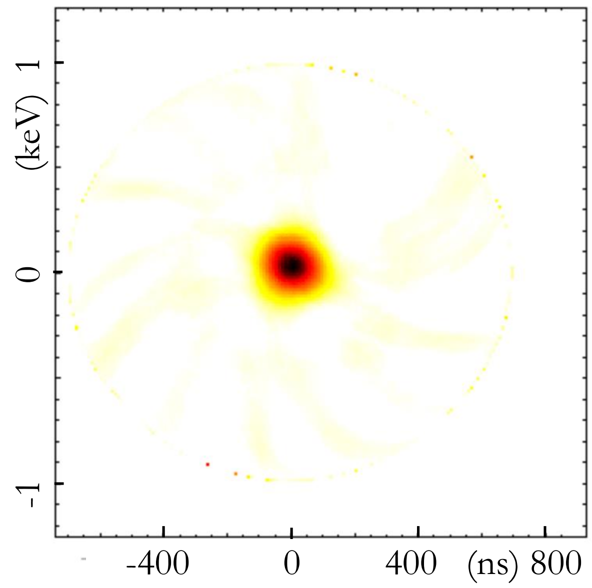




Results from ELENA Commissioning – with H⁻ Beams from Source

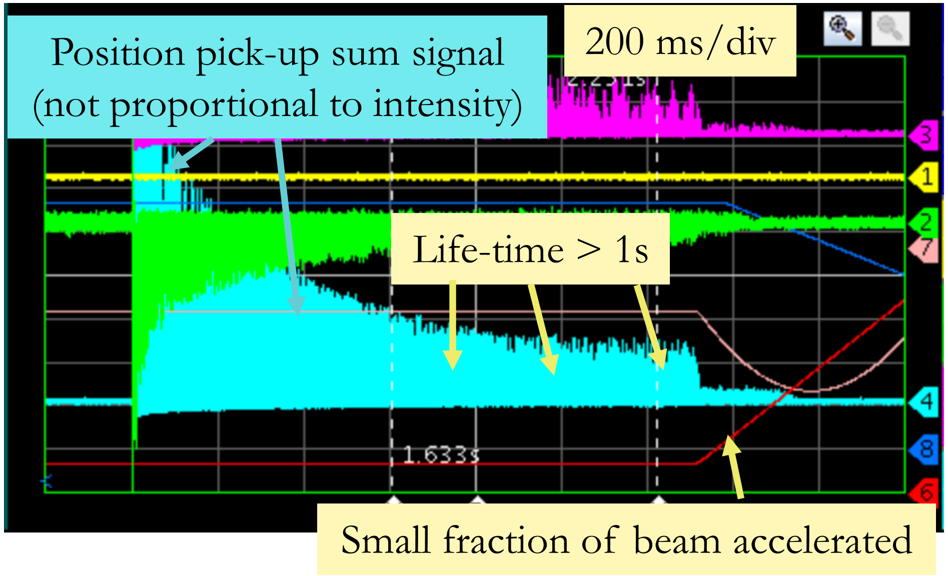
- H⁻ extraction into LNE50 line towards GBAR
  - Aim: preparation of first beam for an experiment – transfer to GBAR now planned for April
  - Modification of timings system: revolution train generated by the Low Level RF system (LLRF) to trigger source and fast deflector for extraction
  - Possible to inject with RF on (into "buckets") to keep small longitudinal emittances and short bunches (had not been foreseen initially)
  - Fast deflector for extraction synchronized with RF
  - Signals clearly due to beam on monitors in line, but impossible to interpret in terms of beam position and width





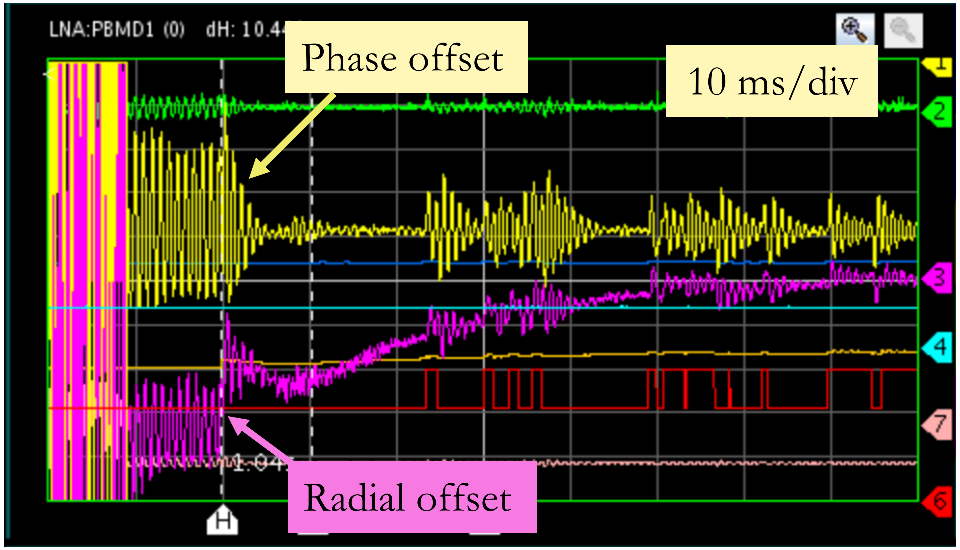
Results from ELENA Commissioning – with H- Beams from Source

- Results from the very end of beam time in 2017
  - Improved life-time with phase loop of RF system
  - Allowed further increase of life-time to > 1s by adjustments of quadrupole currents
  - Small amount of beam accelerated (was not aim at that time)



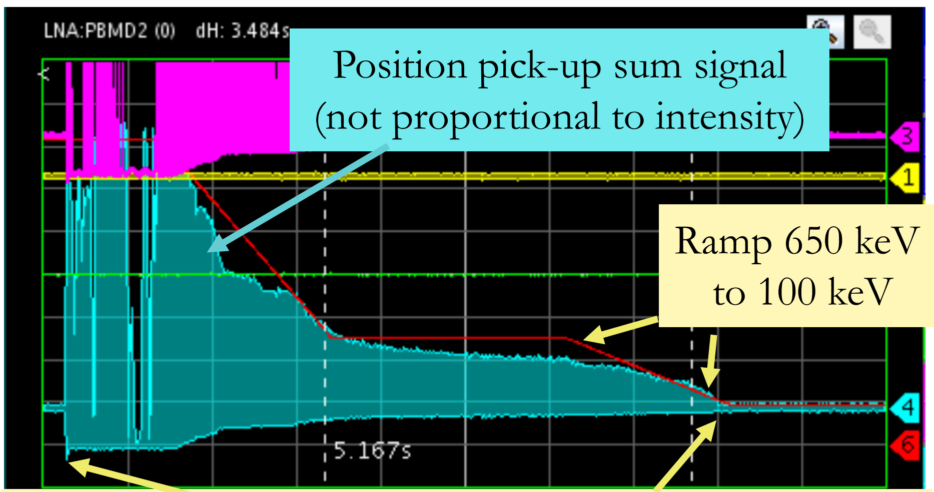
- RF System
  - Issues with noise on magnetic pick-up and low intensity

  => RF system uses sum signal of position pick-up to detect beam phase
  - Phase and radial loop operational
  - Indications for improved life-time with phase loop
  - Sometimes sudden jumps of frequency from "B-train" excite synchrotron oscillations

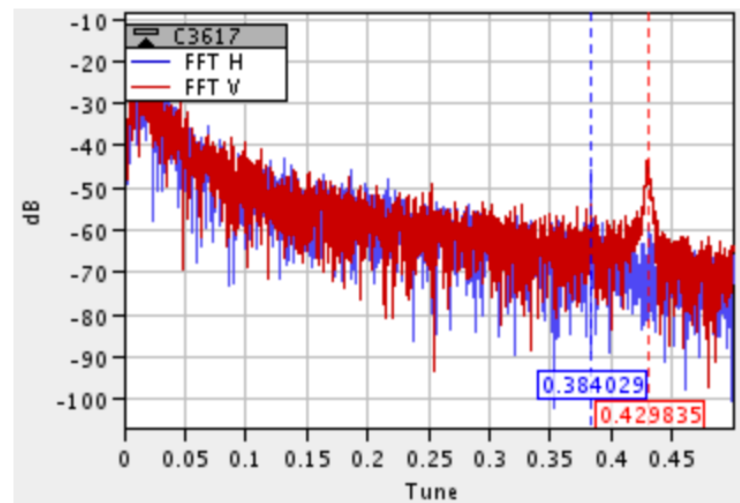


Results from ELENA Commissioning – with Antiprotons from the AD

- With Antiprotons from the AD (typically one or two 8hr-shifts per week)
  - Successful transfer from the AD, injection with bunch-to-bucket transfer, correction of injection oscillations tested, tests of instrumentation ….
  - Some antiprotons (fraction of injected beam) decelerated until end of ramp without electron cooling (lost at 100 keV arriving at the low energy plateau)

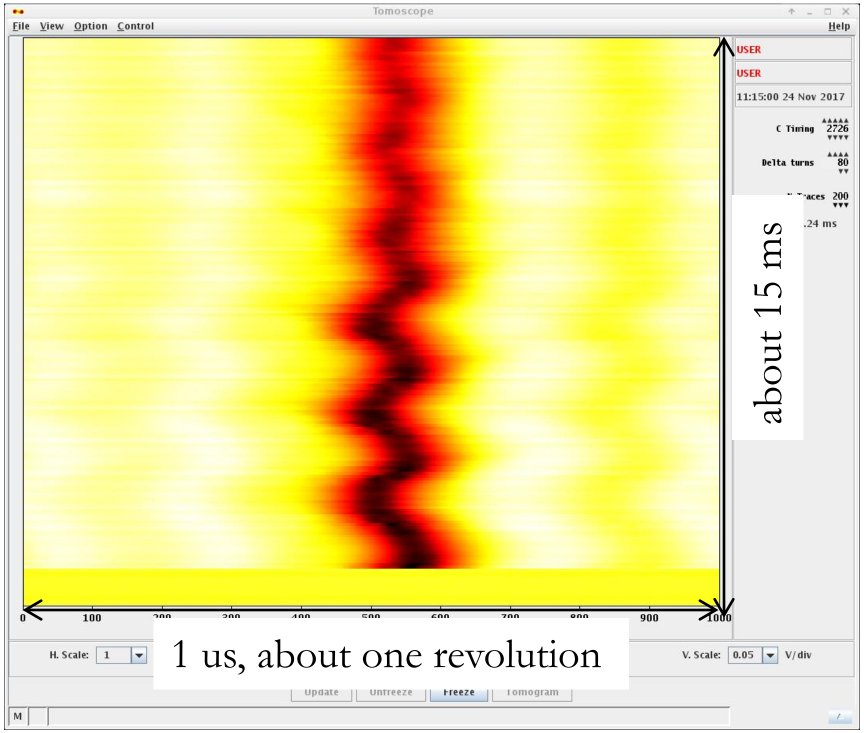


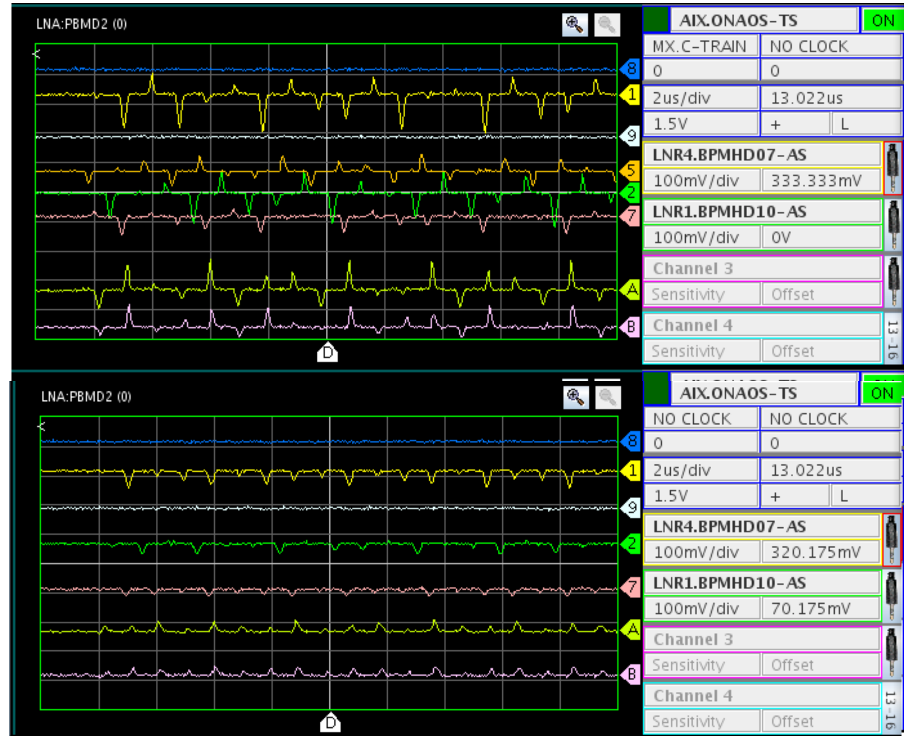
Beam in machine during ~6.5 s until end of 2nd ramp (not yet nominal cycle, longer plateaus)



Test of the "Q-meter":
- vertical plane excited
- horizontal tune seen without excitation
- verification of excitation required to have final version for restart 2018

Results from ELENA Commissioning – with Antiprotons from the AD





- Evolution of bunch shape after “bunch to bucket” transfer – RF in ELENA and synchronized w.r.t. AD
  - “Phase loop” damps synchrotron oscillations

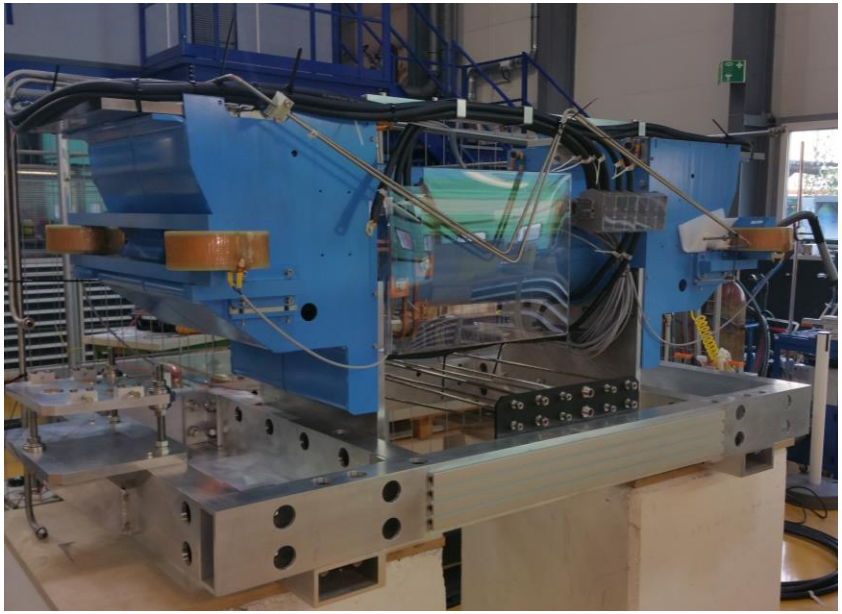
- Transverse pick-up signals before and after correction of mis-steering
  - Use pick-up sum and difference signals to detect turn-by-turn positions
  - Quantification and correction of injection mis-steering

Proper transfer between the two machines

Good conditions to work seriously on deceleration once beam is back

Status of Electron Cooler

- Coordination and first design by CERN
  - Vacuum system constructed by CERN workshop
  - Magnetic system from company (including design and measurements)
    - Many correction circuits to compensate for imperfections and to obtain straight field lines
    - Issue with magnetic – very challenging – measurements and unexpected behavior around "toroids"
  - Cooler was mounted in autumn 2017 and installed a first time in December

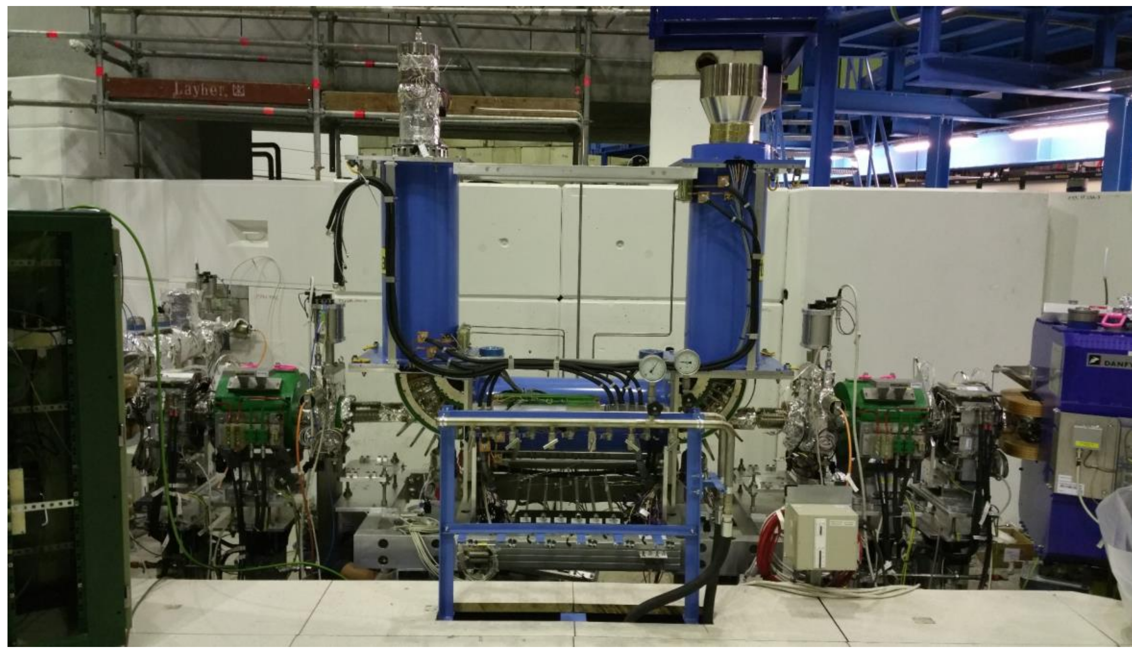


Magnetic system during "acceptance tests"

Electron cooler mounting

Status of Electron Cooler

- Installed a first time in December, vacuum leak after first first bake-out in January
- Cooler taken out and dismounted to access and repair leak
- Re-installation last week, about four weeks for bake-out and other preparations
- Restart of ELENA Commissioning delayed by about 1½ months to beginning of April



Plans for 2018

- Consolidation of injection line and injection into ring
  - Increase of H^- injection efficiency and consolidation of improved reproducibility
    - Injection matching and empirical improvements
  - Setting up of proton injection and cycle: expect similar issues than for H^-
- Acceleration of H^- and possibly proton beams
  - For machine studies without taking precious antiprotons
- Commissioning of electron cooling
  - Behavior of 100 keV beam with magnetic system of cooler on?
  - Observe cooling preferably with beams from the source
    - Probably cooling studies to be done with protons (short H^- life-time due to stripping)
- Further consolidation of instrumentation and corrections (orbit, tune)
  - Final version of profile monitors in transfer lines!
- New isolation transformer for source and 100 keV H^- and proton beams in spring
- Setting up of complete antiproton cycle to complete ELENA commissioning
  … highest priority to gain confidence before the installation of the new lines!
- First beams to GBAR
  - Coordination with cooling studies using protons and inversed polarity
  - H^- beams in spring, antiprotons probably later

Summary and Outlook

- ELENA ring installed and commissioning started
  - Progress H^- with beams from source and antiprotons from the AD, setting-up and testing of most systems – no showstopper
  - Less progress than expected at the beginning of the year due to various problems (e.g. poor reproducibility of the injection)
  - Electron available at the end of the year, but not yet for commissioning
- Aim for 2018
  - Completion of ELENA ring commissioning with cooler from April on
  - Get confidence that machine works properly by having an operational antiproton cycle with deceleration, cooling and extraction
  - First beams for GBAR
- Plans for after 2018
  - Installation and commissioning of electrostatic lines to old experimental are during CERN Long Shutdown 2 (LS2 scheduled in 2019 and 2020 mainly for LHC)
  - 100 keV antiprotons for all experiments after LS2 from 2021 on

Contributors to the ELENA Project