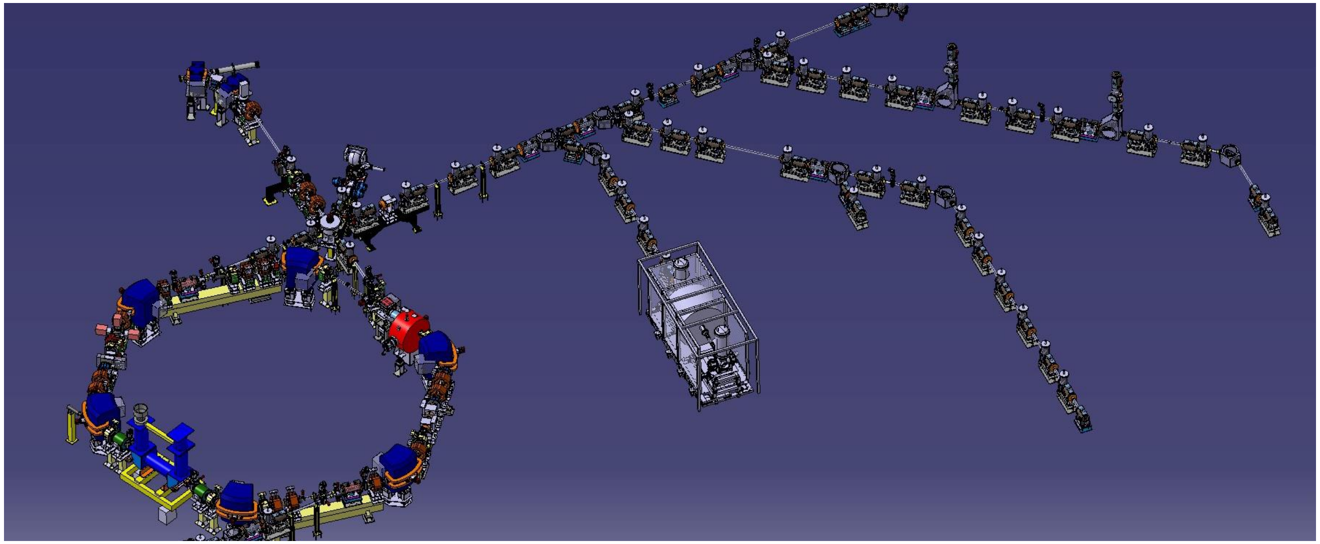
ELENA Decelerator and Proton electric Dipole Measurement

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

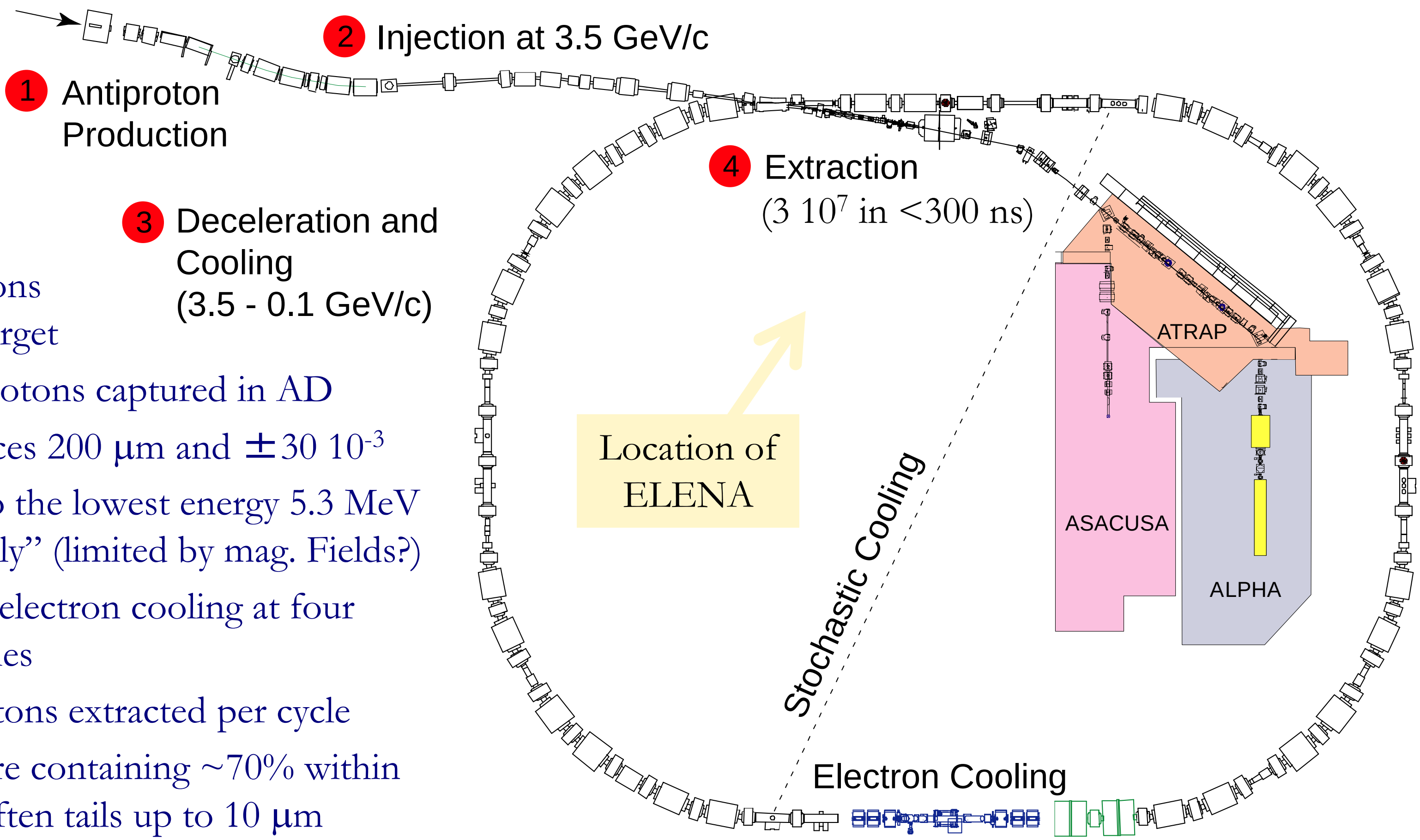
Workshop on Impact of Stray Fields, 4th October 2017



- ELENA
  - Introduction
  - ELENA Overview and Layout
  - Selected Features and Challenges
  - ELENA Commissioning
  - Impact of Stray Fields
- Proton EDM Measurements
- Summary and Outlook

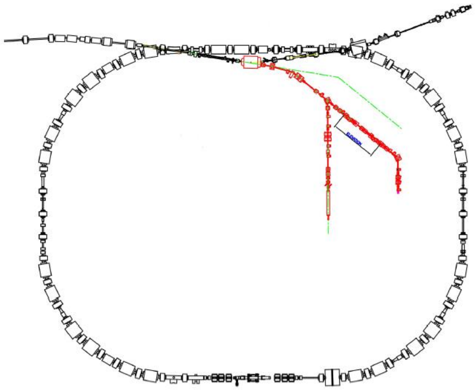
Introduction: Antiproton Decelerator AD – a unique facility providing 5.3 MeV antiprotons

- ~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?)
- Stochastic and electron cooling at four different energies
- ~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
- Cycle length about 100 s



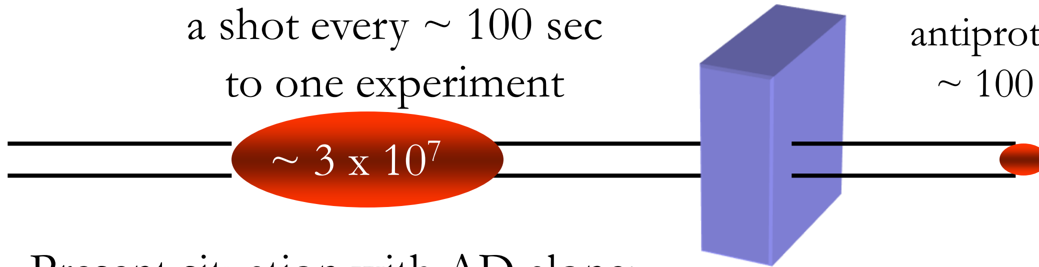
Sketch of the present AD – circumference 182 m
- In addition experiments AEGIS and BASE
- Experiment Gbar being installed in new experimental area

Introduction: Efficiency for capturing antiprotons in traps without and with ELENA



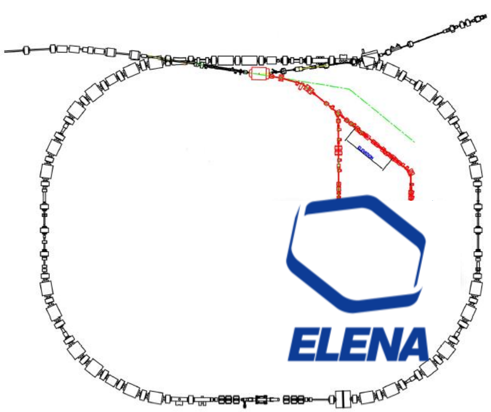
5.3 MeV antiprotons
a shot every ~ 100 sec
to one experiment

~4 keV
antiprotons/
~ 100 sec

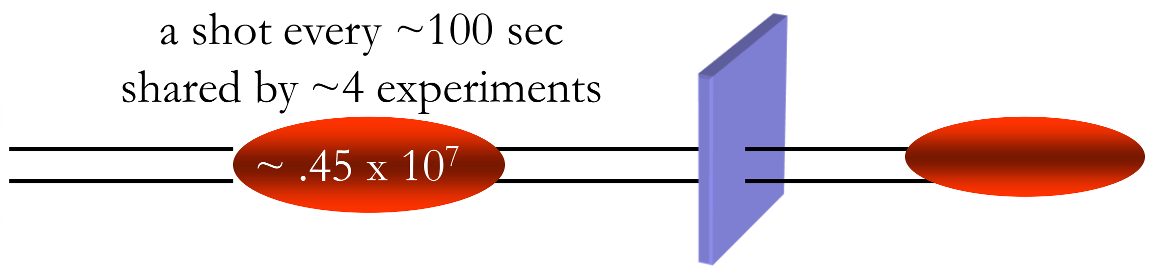


Present situation with AD alone:

- Most experiments slow antiprotons down by "degrader"
  => very inefficient – most (>99%) antiprotons lost
  (one experiment uses an RFQ for deceleration with higher efficiency)



100 keV antiprotons
a shot every ~100 sec
shared by ~4 experiments



Future situation with AD and ELENA decelerating to 100 keV:

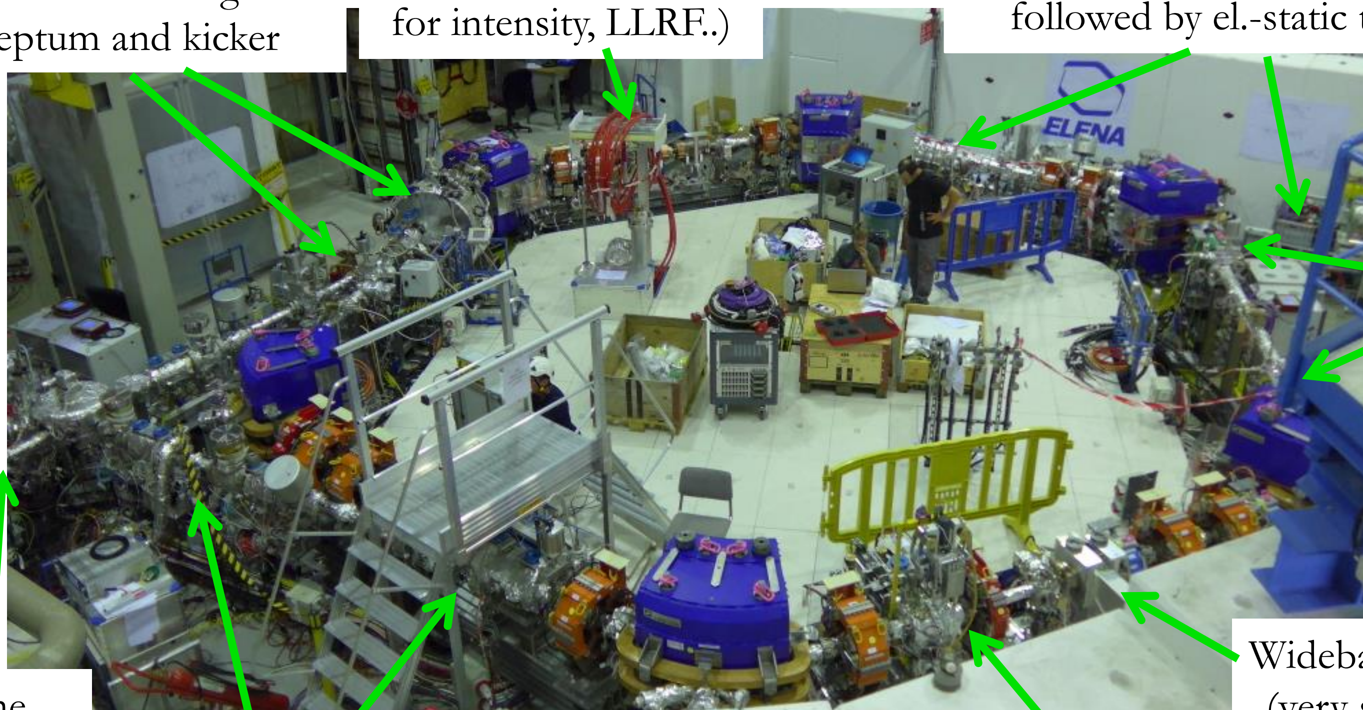
- thinner "degrader" and increased trapping efficiency
  (some experiments use other means to decelerate the beam)
- Intensity shared by four exp's allows longer periods with beam

ELENA Overview and Layout

High sensitivity magnetic Pick-up (Schottky diagnostics for intensity, LLRF.)

Injection with magnetic septum and kicker

Extraction towards new experimental zone (fast deflector) followed by el.-static transfer lines



Compensation solenoids for (not yet Installed) cooler

Line From AD

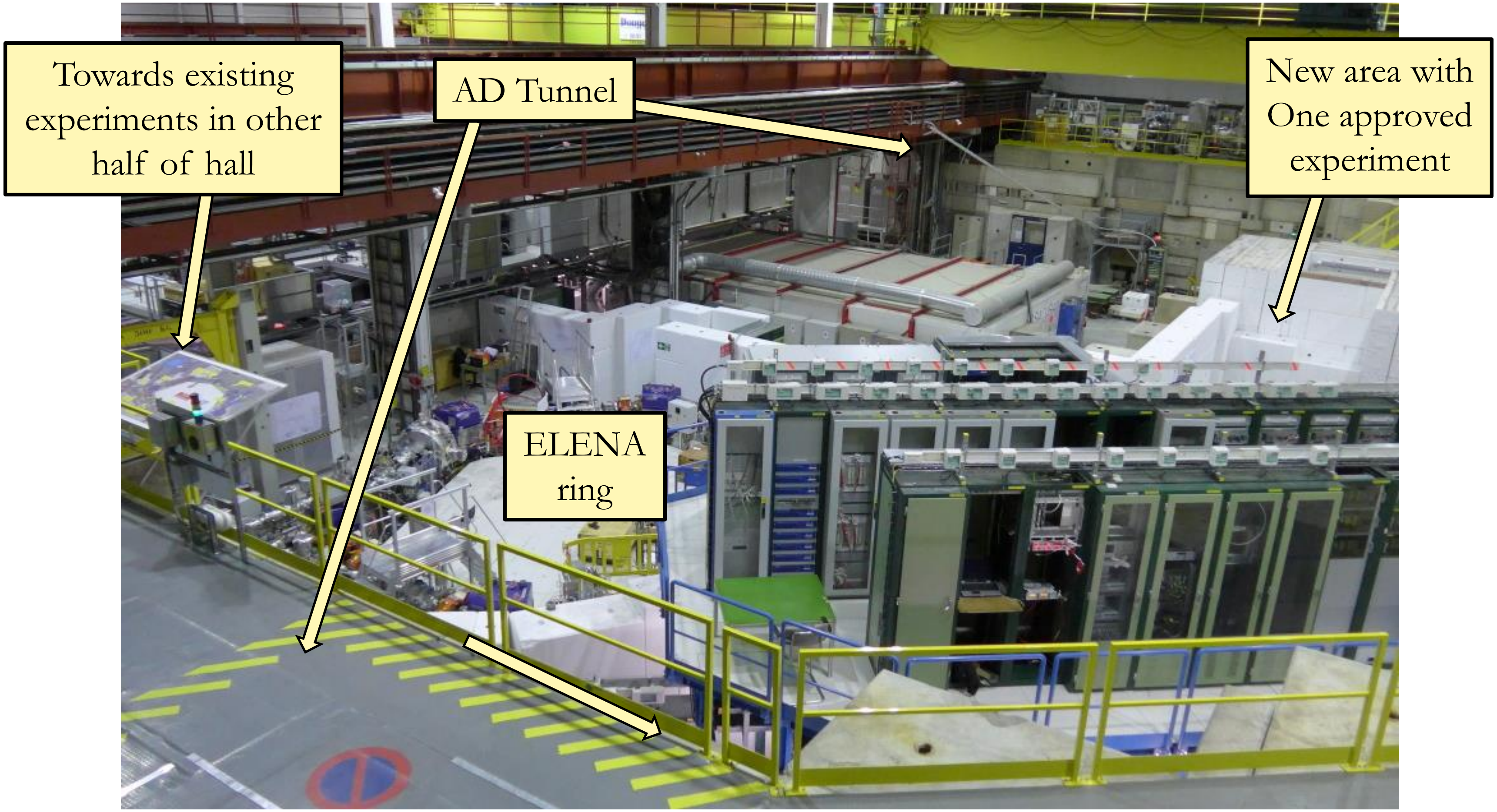
Extraction towards existing experiments

Scraper to measure emittance

Wideband RF cavities (very similar to new PSB cavities)

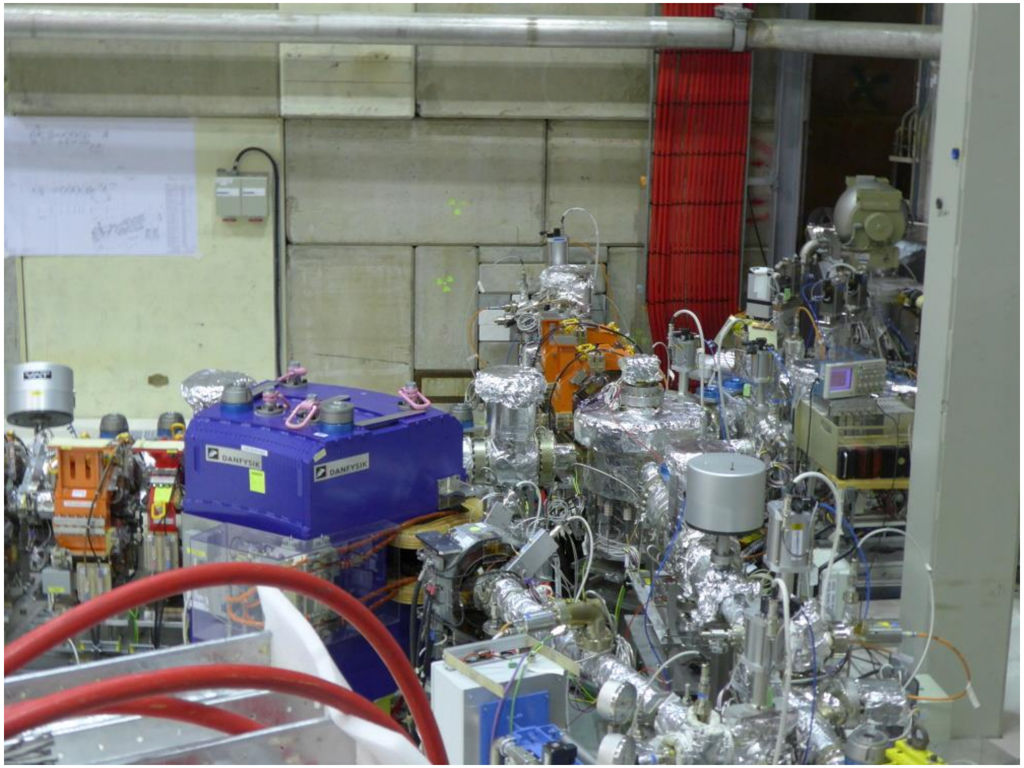
- Deceleration of antiprotons from 5.3 MeV to 100 keV to improve efficiency of experiments
- Circumference 30.4 m (1/6 the size of the AD), magnetic ring and electrostatic extraction lines
- Challenges related to low energy as field quality of magnets operated with very low fields

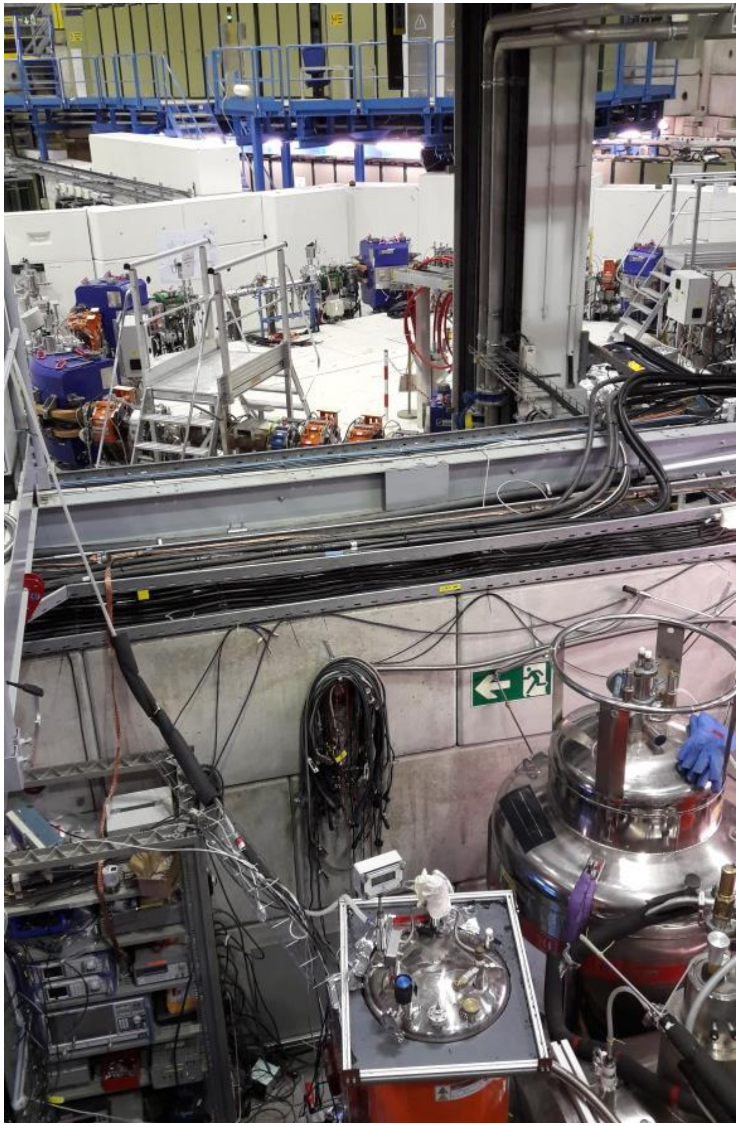
ELENA Overview and Layout



- 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

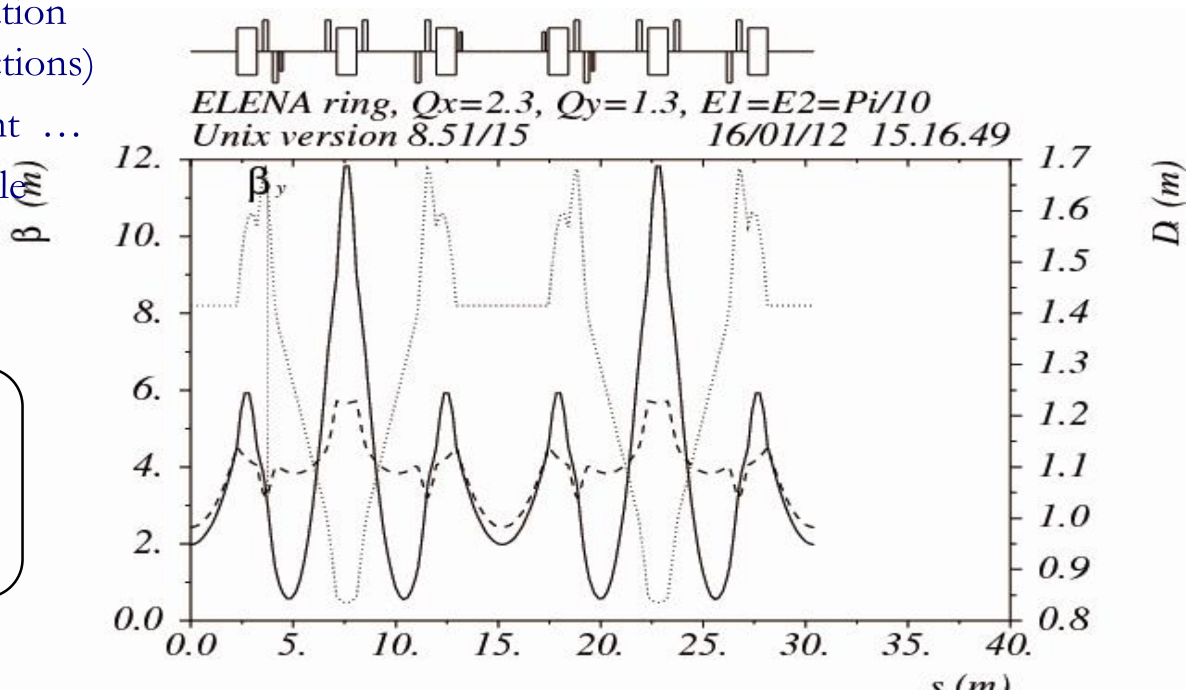
ELENA Overview and Layout





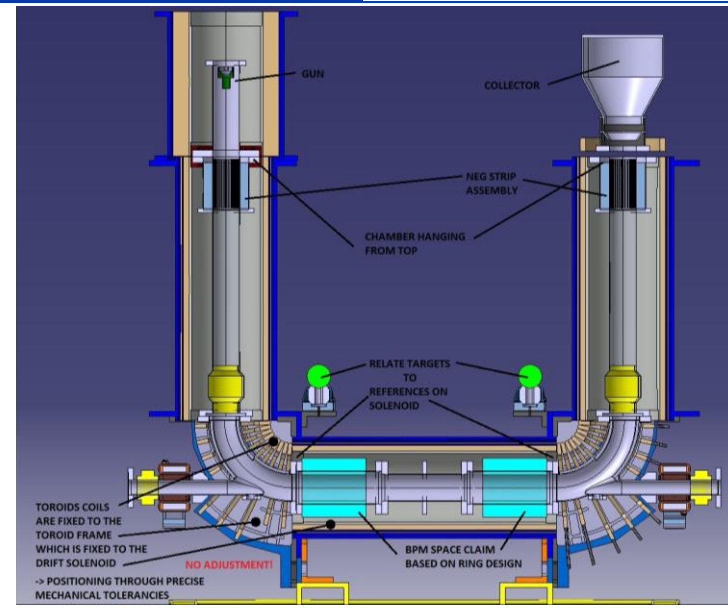
Selected Features and Challenges

- 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)

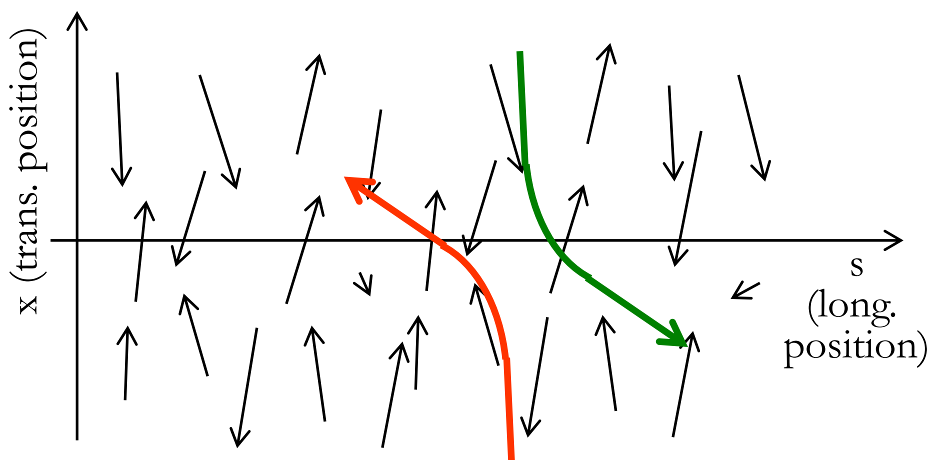


Selected Features and Challenges

- 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 and under discussion
  - Mounting within the next weeks



- Intra Beam Scattering IBS
  - Coulomb scattering between beam particles
  - Transfer of heat (unordered motion) between phase spaces (long. & transverse)
  - Emittance blow-up – determines together with cooling emittances of available beams



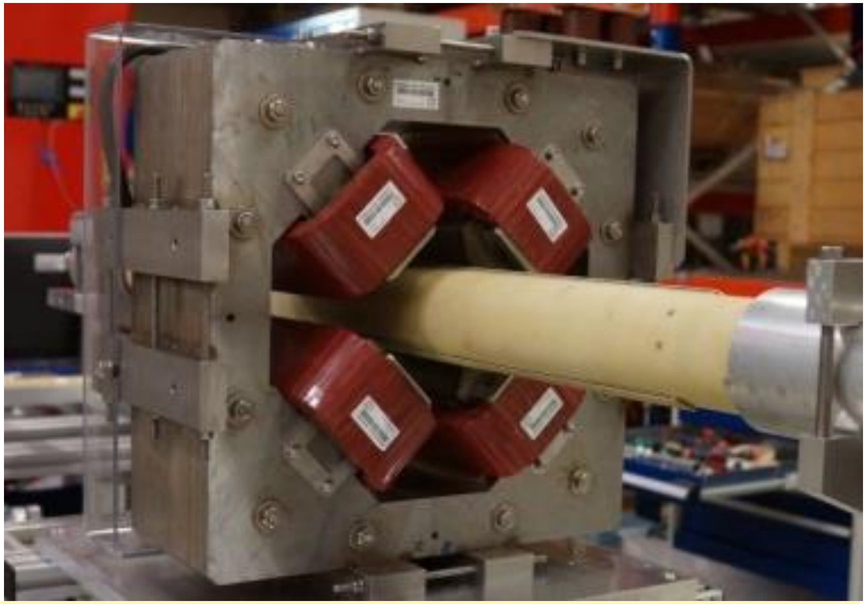
Intra Beam Scattering IBS – co-moving coord. system

- Equilibrium between Cooling and IBS determines properties of beams for experiments

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

- 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
  - 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 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 weeks

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

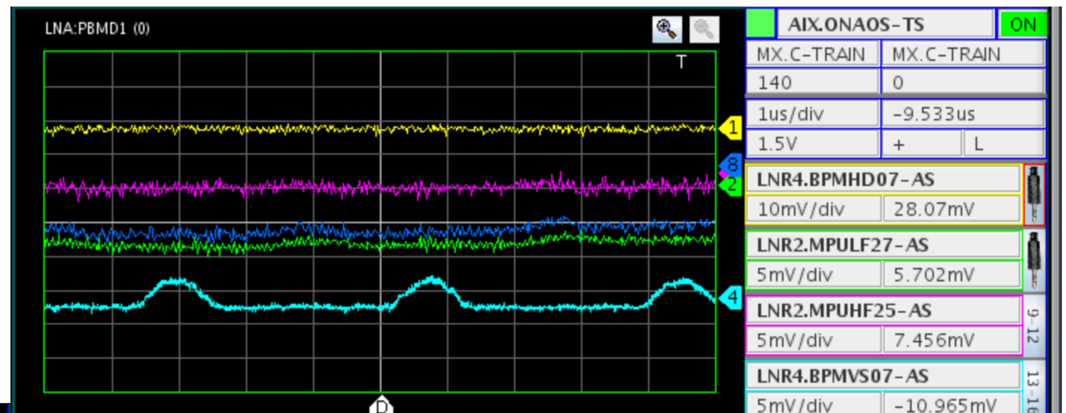
c) Simulations of IBS on ramp

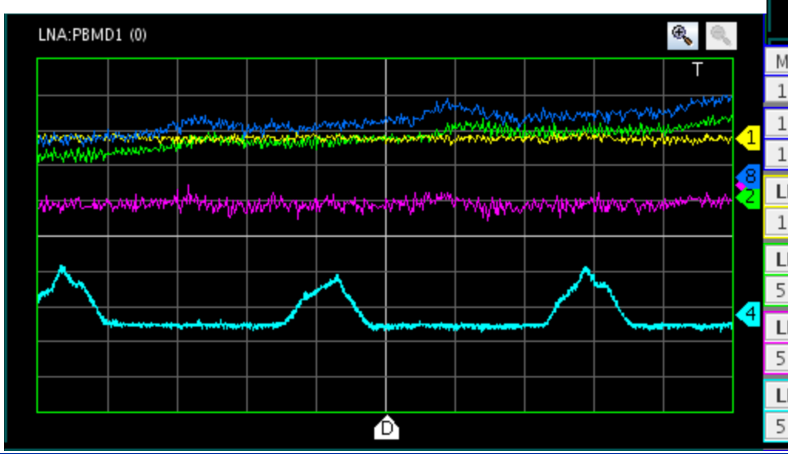
d) Debunching/bunching with 50% blow-up (bunched with LHC def. $\varepsilon_L = 4\pi\,\sigma_E\,\sigma_T$, coasting $\varepsilon_L = 4\,(2/\pi)^{1/2}\,\sigma_E\,T_{rev}$)

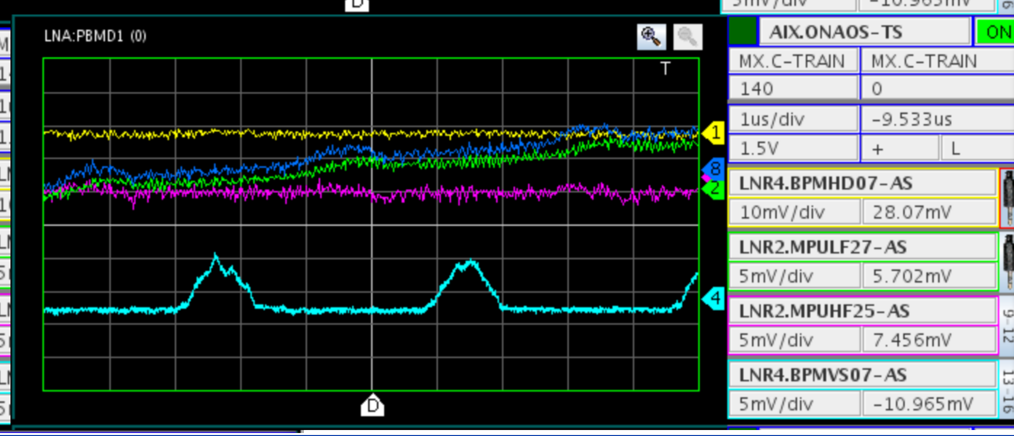
e) From ELENA technical meetings with presentations by G.Tranquille and P. Beloshitsky

ELENA Commissioning – Results with H⁻ Beams from Source

- Aim: progress as much as possible without taking precious antiprotons
- Source operated now at 85 keV instead of 100 keV because of technical problems
- Transport from source to ring and injection end of 2016, beam life-time unclear without RF system
- Reasonable life-time observed with RF on, setting up of instrumentation …..
- Poor reproducibility (shot-to-shot fluctuation and long term drift) had been an issue for long
- From yesterday
  - Two bunches with about 1 to 2.10^6 H^- ions each after 140 ms
  - (no reasonable situation)
  - Ready to continue commissioning of systems as RF, tune measurement …

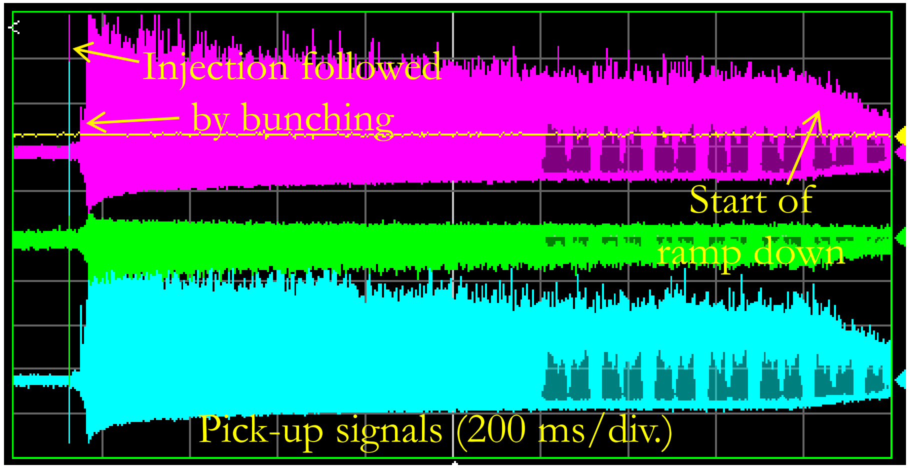


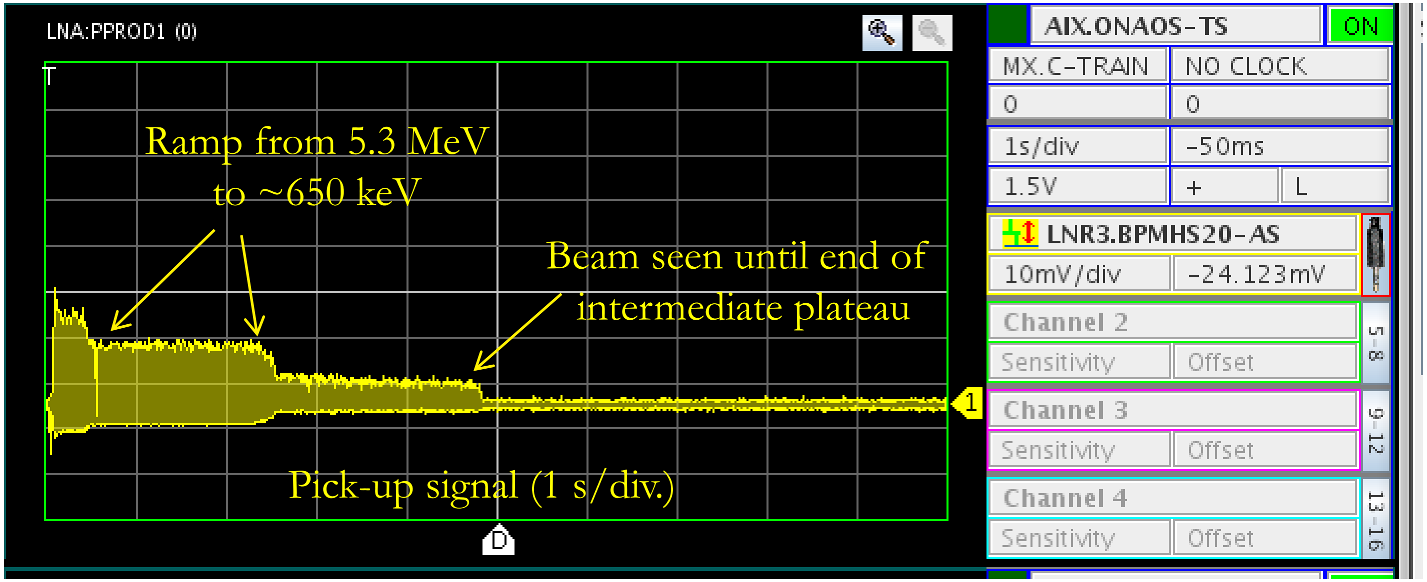




ELENA Commissioning – Results with Antiprotons from the AD

- Successfully set up:
  - Transfer from the AD to ELENA still with large injection mis-steering
  - Injection, some instrumentation as tune and orbit system (commissioning of scraper started)
  - RF system with beam capture, phase and radial loops, but not yet “bunch-to-bucket transfer”

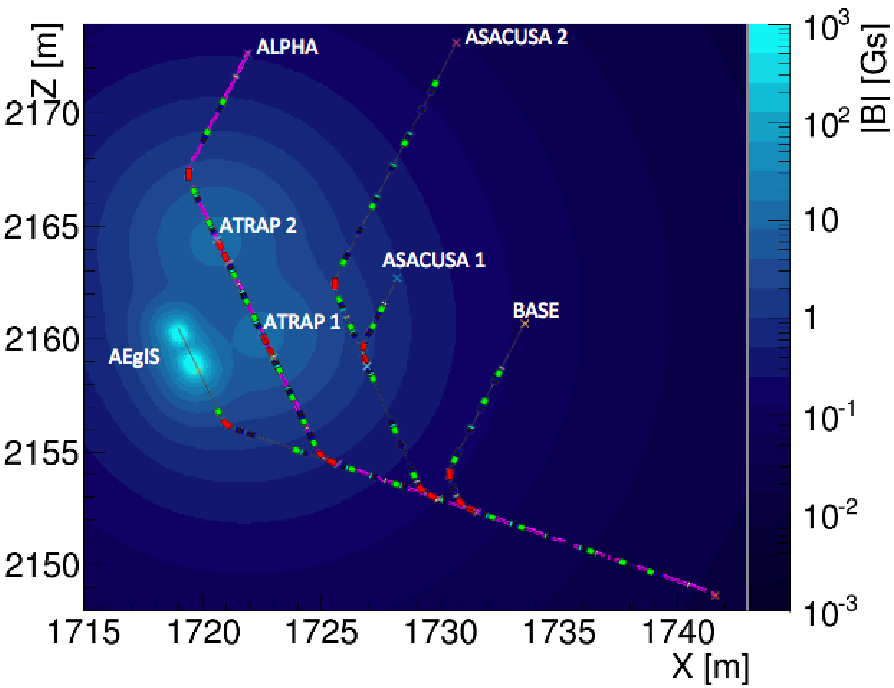




Impact of Stray Field on ELENA

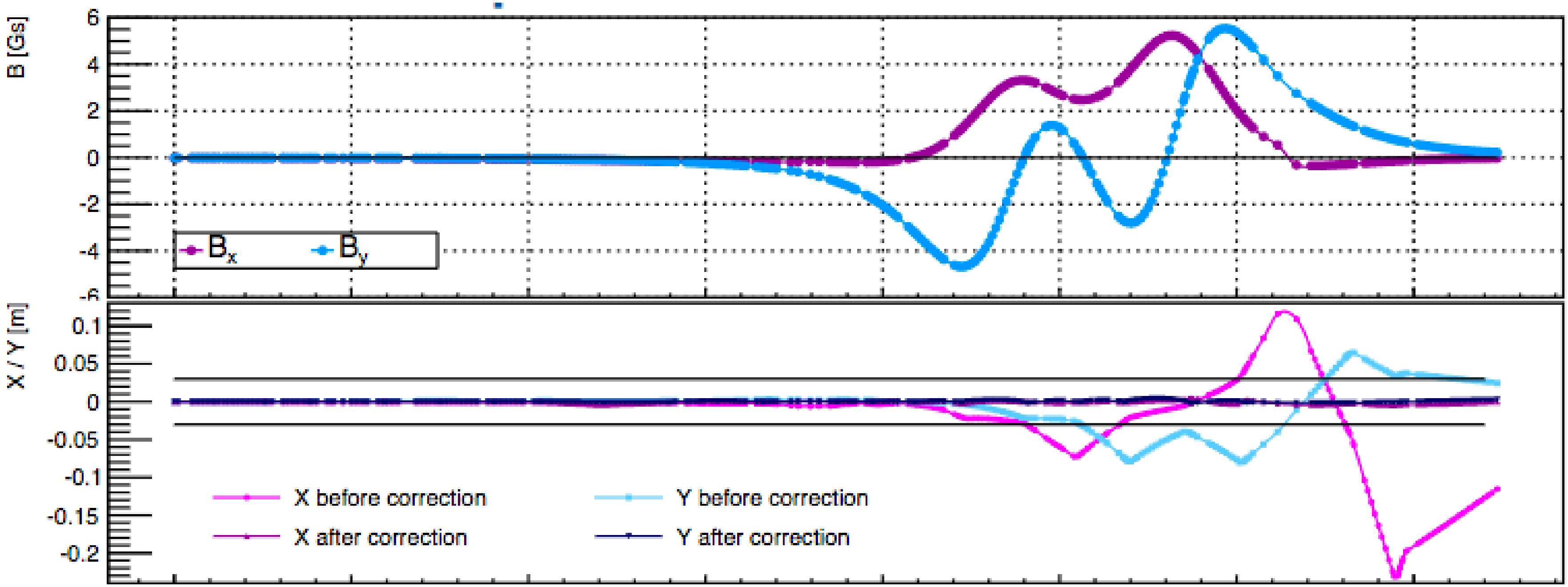
- Beam rigidity at the lowest energy 100 keV
  Bρ=457 Gm
  - Earth magnetic field of 0.5 G deflects beam by about 1 mrad (to be compared to typical divergence of a few mrad)
  - Leads to significant perturbations of the closed orbit (beam not centered any more in the chamber)

- Transfer lines bringing beam to experiments come close to other experiments with fields up to a few G
  - Experiments may switch on/off their solenoids



Impact of Stray Field on ELENA

- Steering (many deflectors available along the line) essential to keep beam in vacuum and chamber and bring it to the experiments



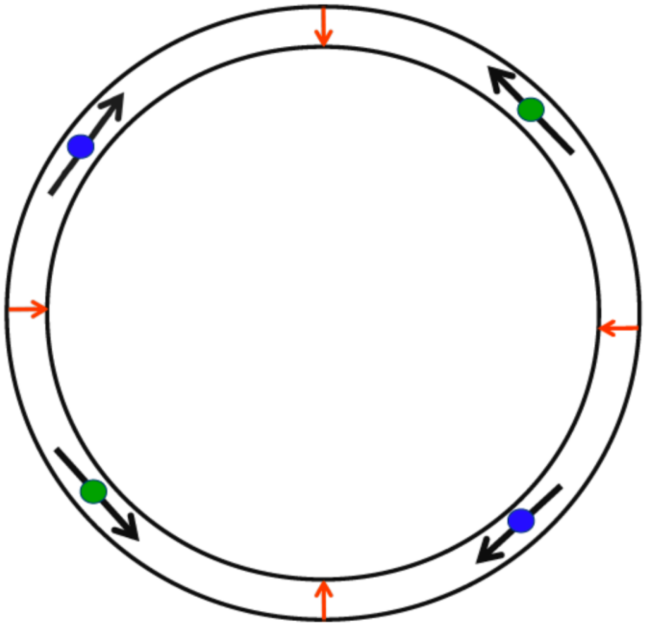
Magnetic field from solenoids of experiments (earth magnetic field neglected) and trajectories without and with correction (steering)

- Magnetic shielding close to experiments under envisaged
  - Perturbation with future electric lines difficult to evaluate (different “magnetic” environment)
  - Reduces required steering to bring beam to experiment
  - Mitigation of perturbations due to switching of experimental solenoids

Proton Electric Dipole Measurement (pEDM)

- Significant effort underway worldwide (BNL, Juelich, Cornell, CAPP/IBS …) since several years on the measurement of the electric dipole moment of protons or deuterons
  - Difficulty: achieve high sensitivity with the given magnetic moment of these particles coupling to the magnetic field
  - Precursor experiment for deuterons using COSY prepared in Juelich (spin not "frozen")
  - CERN being interested since less than a year within the Physics Beyond Collider (PBC) study group (identify possible programs, which could be realized at CERN in addition to the high energy program)

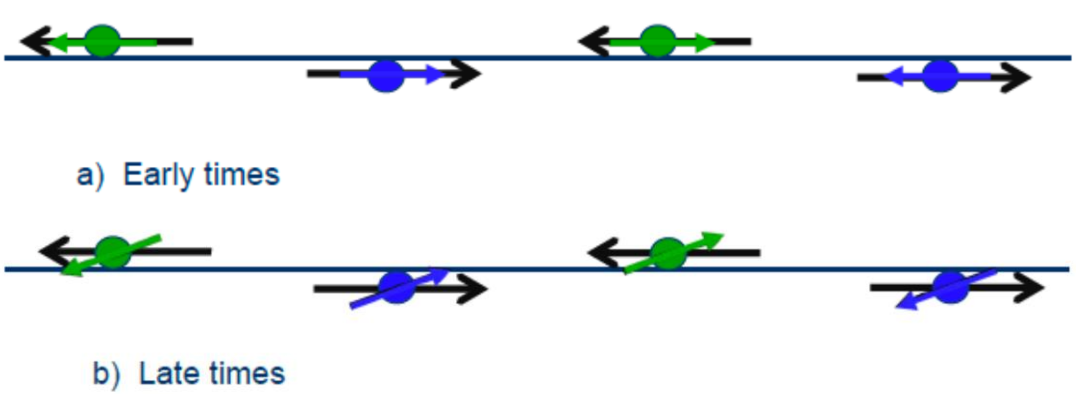
- CERN effort (still at the very beginning) concentrates on fully electric ring for pEDM
  - Fully electric ring to guide and focus the beam
  - Spin frozen in longitudinal direction
    - At the "magic" energy of 233.8 MeV
    - In the absence of magnetic fields
    - Without an electric dipole moment
  - (no such magic energy for deuterons)
  - An electric dipole moment couples to the horizontal electric field (torque in vertical direction)
    - Spin moves into the vertical direction (order of magnitude for practical ring nrad s^{-1} only for the expected sensitivity)



Principle of fully electric pEDM ring (image from BNL proposal)

Proton Electric Dipole Measurement (pEDM)

- The challenge of an pEDM ring is to control systematic effects such that the sensitivity aimed at of 10^{-29} e.cm can be reached
  - Main issue in a practical machine (~500 m circumference) with the given proton magnetic moment: average radial magnetic fields of around 10 aT generate the same effect (spin moving into vertical direction) than the EDM one is looking for
    - Suppression of magnetic fields by shielding (reason to go for "magic energy" proton ring) to say 1 nG
    - Average radial field smaller than typical absolute value
    - Local field measurement and correction not foreseen .. to be looked at?
    - Radial magnetic field generates orbit difference of counter-rotating



Orbit difference generated by radial magnetic fields (image from BNL proposal)

    ⇒ precision measurement of orbit difference to quantify and correct average radial magnetic field (feasibility of measurement at the pm level in a machine with week vertical focusing optimized for this purpose?)

    ⇒ (Proposal for vertical focusing by octupoles to increase orbit separation)
  - Systematic errors of polarization measurement an issue with the small effect expected
  - Polarization to be kept for "long"durations of say 1000 s … sextupoles for longitudinal dynamics
  - Field fluctuations at the 1 mG level a potential issue?

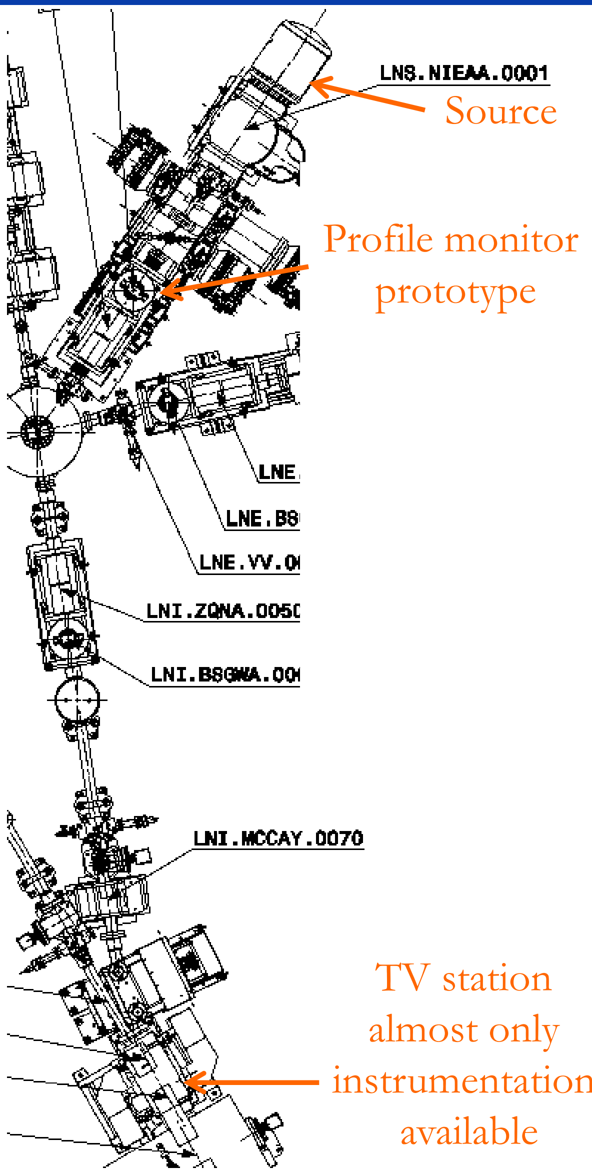
Summary and Outlook

- ELENA Ring installed and Commissioning started
  - Small very low energy ring with electron cooling to decelerate antiprotons from 5.3 MeV to 100 keV to allow experiments to increase efficiency
  - Commissioning has started with both injection of <100 keV H^- beam from dedicated source and 5.3 MeV antiprotons from the AD
    - Encouraging results (beam circulating with less than 100 keV ..), but still a lot of work ahead
  - Due to the low energy, perturbation due to the earth magnetic field and stray fields are significant and corrections are required
  - First beam (85 keV H^- from source) to GBAR for equipment tests within the coming weeks
  - Installation of cooler likely during end of year shutdown with tests next year
  - Operation only for GBAR until LS2, for other experiments only after LS2 from 2021 on

- Electric Dipole Measurement (EDM)
  - Significant effort over several years in various labs around the world (BNL, Juelich, Cornell, CAPP/IBS …) to study such facilities and to prepare a precursor experiment in Juelich
  - CERN interested since less 1year with a proton EDM ring considered as one of the options within the Physics beyond Colliders study
  - One of the challenges (.. probably the main challenge) is to avoid systematic measurement errors due to uncontrolled radial (.. to a lesser extent vertical and longitudinal) magnetic fields (average of 10 aT giving similar effects than the quantity to be measured)

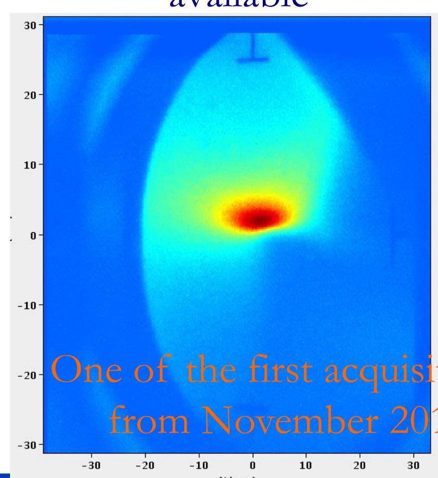
Contributors to the ELENA Project

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
- Empirical adjustments led to unexpected settings
- Limited beam diagnostics
  - Only one profile monitors with temporary electronics available



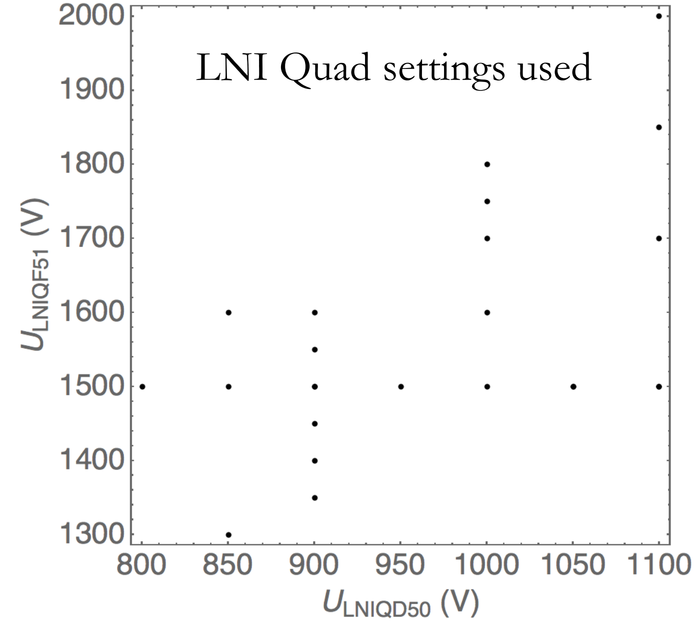
One of the first acquisitions from November 2016

Source and profile monitors are in-kind contributions to ELENA

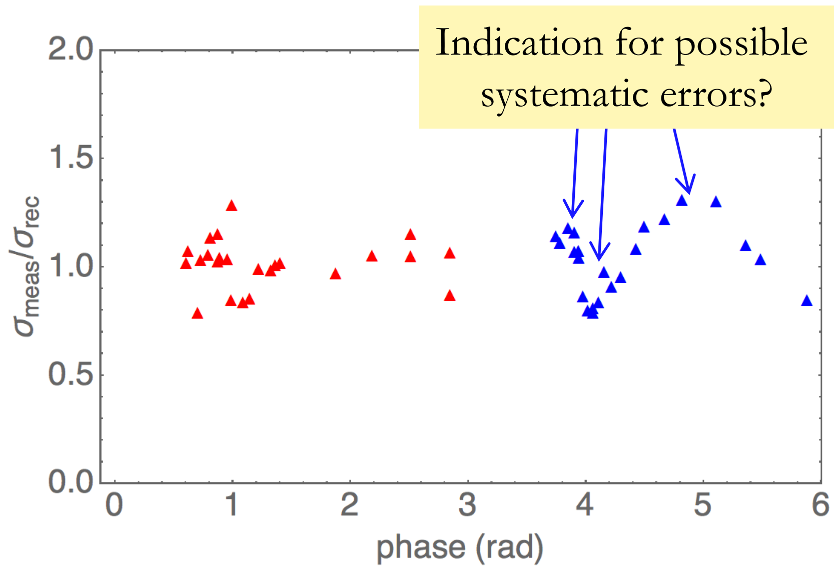
Thanks a lot to all teams contributing!

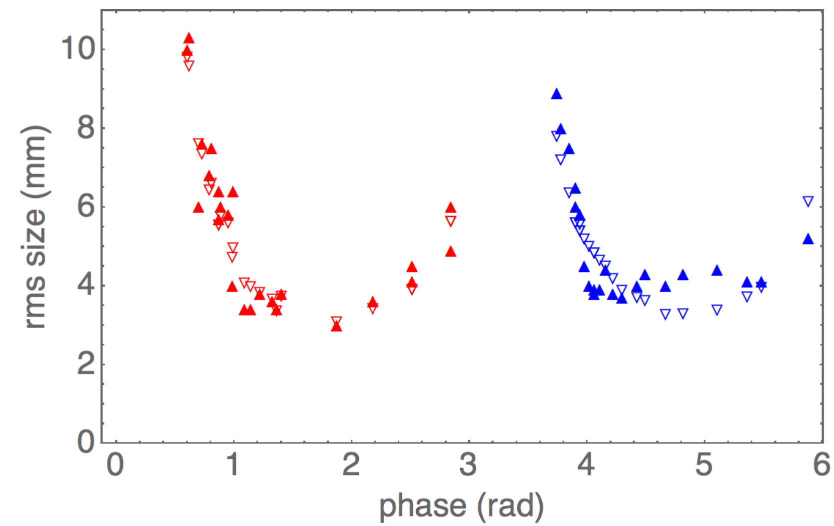
ELENA Commissioning – Ion Source and Line from Source to Ring

- LNS quads $U_{LNSQF20}$ = 1855 V and $U_{LNSQD21}$ = 1220 V
- Reconstructed characteristics at the reference
  - 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



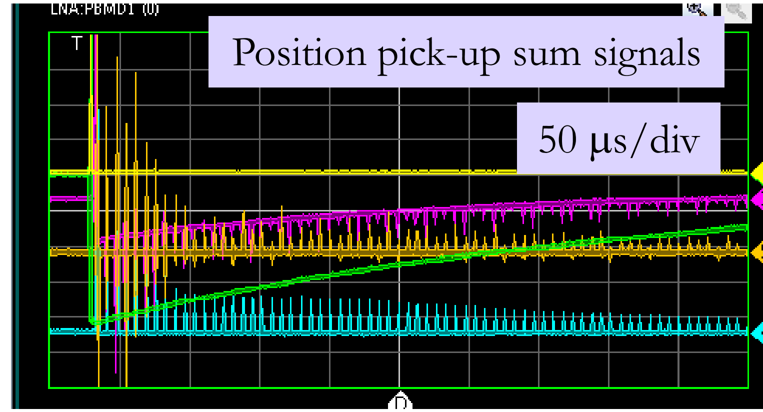
- Comparison of measured beam sizes and reconstructed ones
  - Vertical phase space in red, horizontal in blue
  - Right image: Filled (empty) triangles for measured (reconstructed beam sizes)sizes

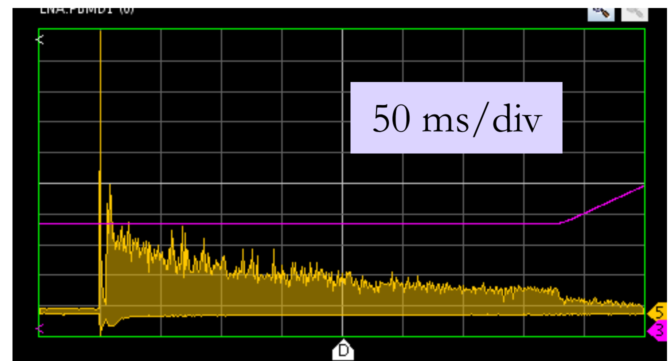


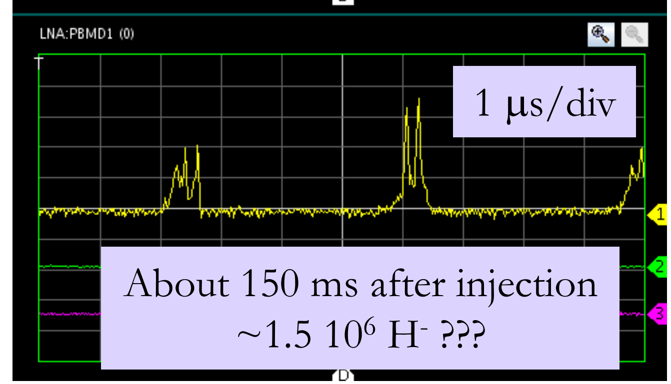


Start of ELENA Commissioning – Ring

- 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

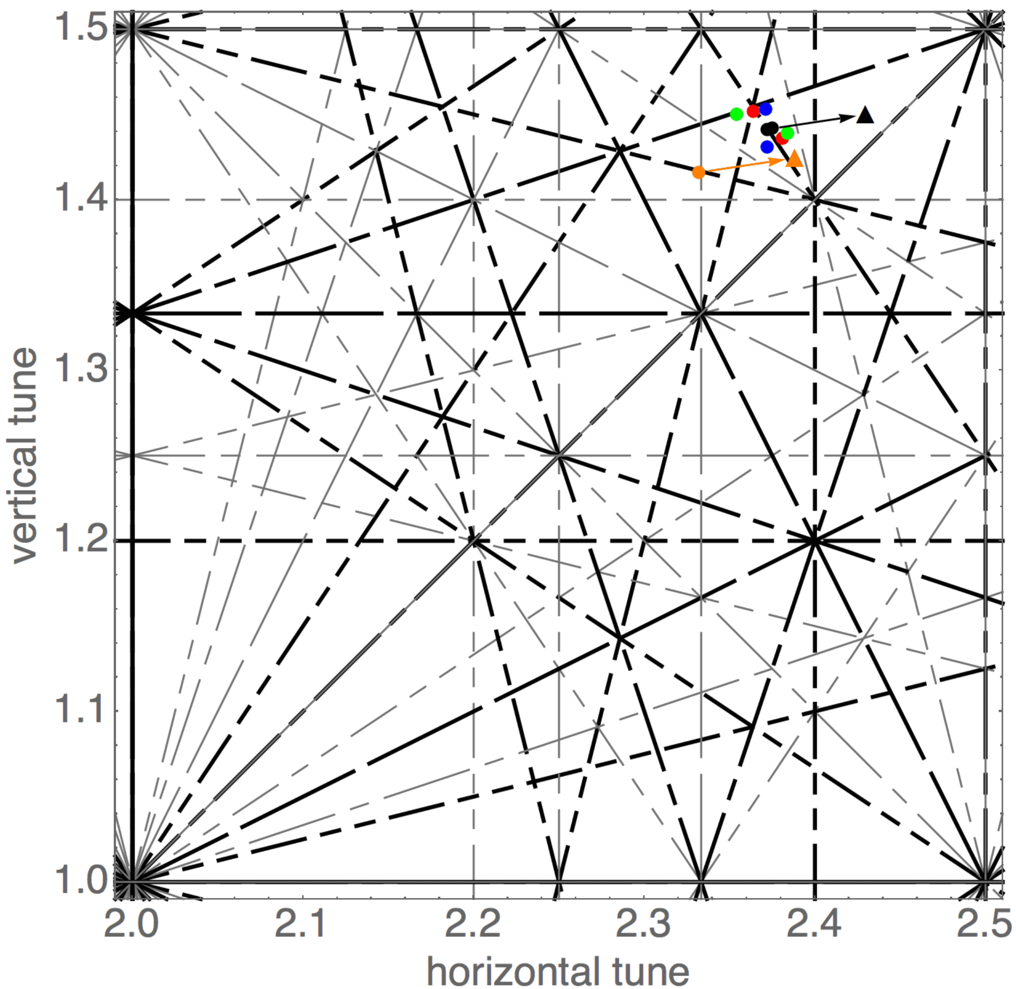






Working points

- 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

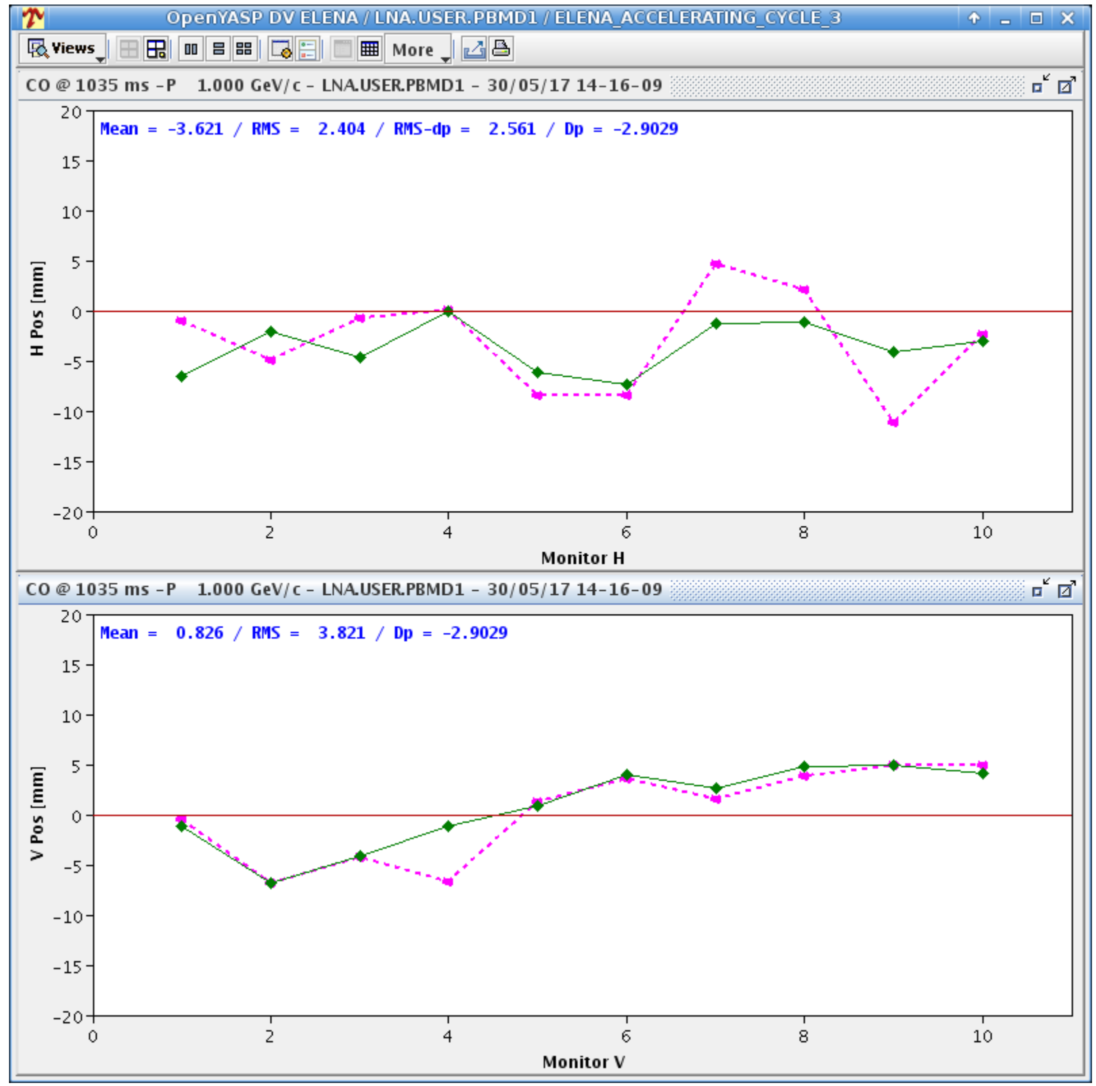


Resonance diagram with working point(s) close to 5th order resonance

First orbit corrections

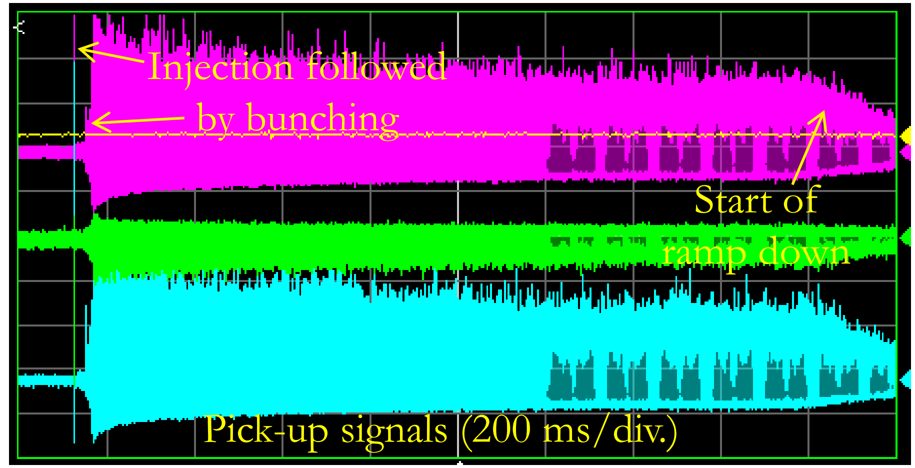
- Orbit is the transverse position of the beam as a function of the longitudinal position
  - Measured at some locations with “pick-ups”
  - Beam not at center of chamber due to perturbations (stray fields magnet mis-alignment ..)
  - Corrector dipoles to improve

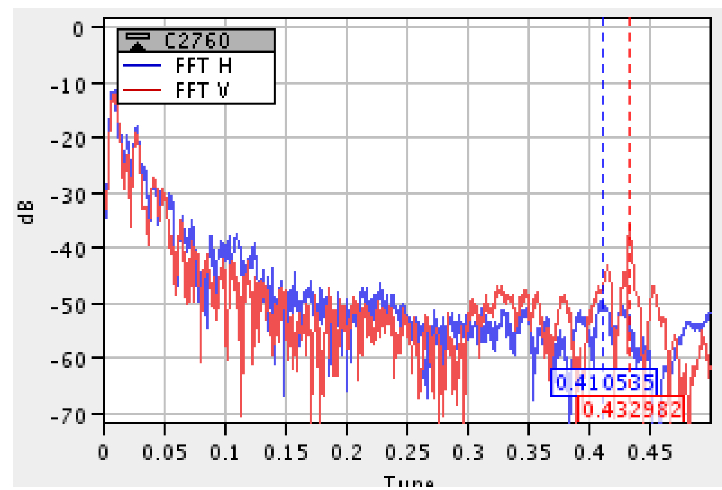
- Confidence in basic machine optics

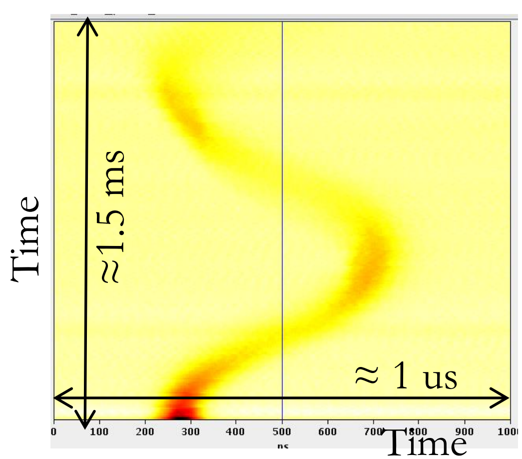


ELENA Commissioning Progress with Antiprotons

- Antiprotons injected followed by bunching
  - 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 oscillations from injection
- Synchrotron oscillation with RF on at injection

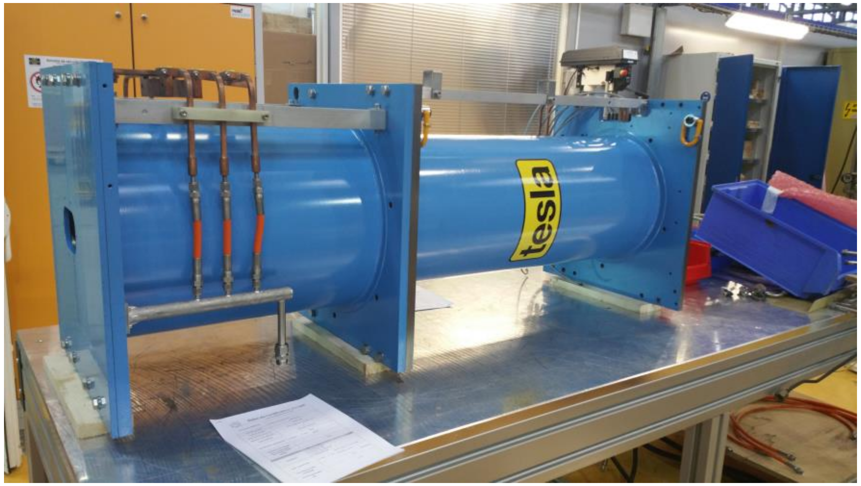


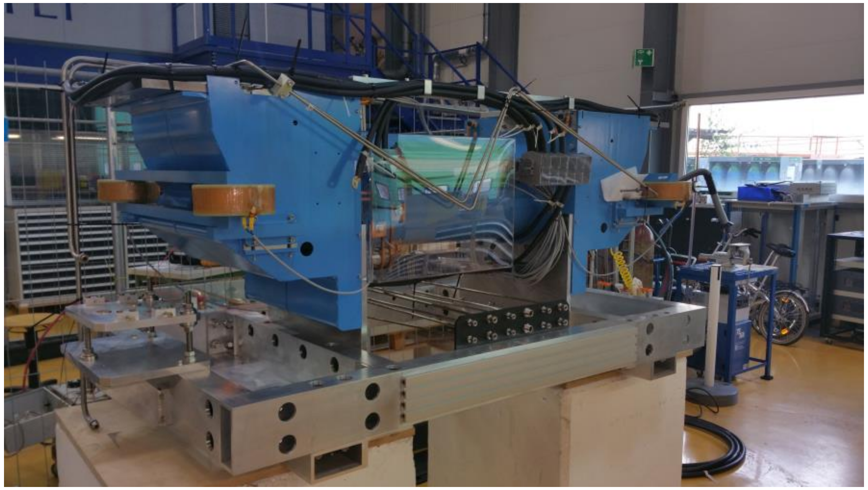




Status of the Electron Cooler

- Magnetic system at CERN since about three weeks





  - Now with Magnet Group for “Certification” (standard tests done with magnets)
  - Some issues with magnetic measurements done by company
    - Compensation scheme combining info. from measurements of single solenoids and full system
    - Try to understand (simulations and/or measurements?) unexpected field and possible impact
- 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