Present and future Antiproton Facilities at CERN

2nd International Workshop on Antimatter and Gravity

C. Carli on behalf of the AD & ELENA Teams

14th November 2013

- Introduction
  - Low energy antiproton rings at CERN: LEAR and AD
  - Motivation to add ELENA to the AD
- ELENA
  - Layout
  - Some of the most salient features
  - Magnetic Cycle
  - Lattice
  - Electron cooling
- Limitations (some)
  - Transverse direct space charge defocusing
  - Intra Beam Scattering (IBS)
- Planning
- Tentative Parameter List
- Conclusions, Status and Outlook

Introduction

Low energy Antiprotons rings at CERN - LEAR

ELENA

Low Energy Antiproton Ring LEAR

- p-bar availbale from accumulator AA constructed for $Sp\bar{p}S$ project
- Additional facility making use of the p-bars and
- Ultra-slow (and fast) ejection to experiments in south hall and internal targets
- Commissioning in 1982 with stochastic cooling
- First machine with electron cooler used for operation
- First observations of antihydrogen …

- First proposal to construct ELENA to decelerate to even lower energies (7.85 m circumference to reach 200 keV !!)

HH/fn
20/11/81

CERN/PSCC/82-3
PSCC/P52 Add.1
28 January, 1982

A Small Deceleration Ring for Extra Low Energy Antiprotons (ELENA)

H. Herr

INTRODUCTION

On completion of LEAR, experiments with low energy antiprotons may be carried out for the first time using well defined antiproton beams in the energy range from 1270 MeV down to 5 MeV. As some experiments demand antiprotons even below 5 MeV, several devices for deceleration have been

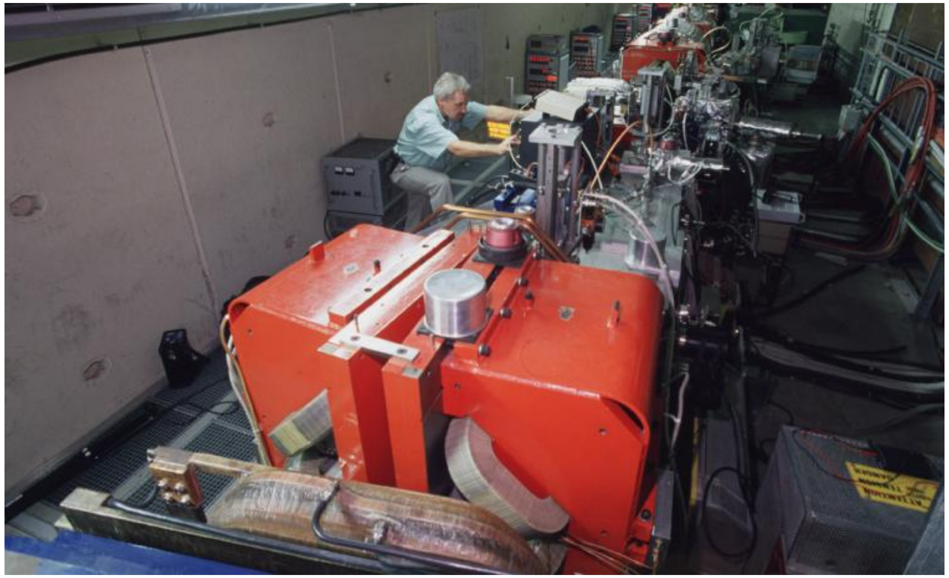
Introduction
Low energy Antiprotons rings at CERN – AD

Antiproton Decelerator AD

- Around 1995:
  - No antiprotons needed for SPS since 1990
  - AC & AA running only for LEAR
  - Decision to discontinue p-bar physics with LEIR by the end of 1996 …
    … to free resources for LHC

- Conversion of AC to AD proposed as simplified scheme for low energy p-bar physics
  - Only one p-bar machine
  - PS used only for p-bar production

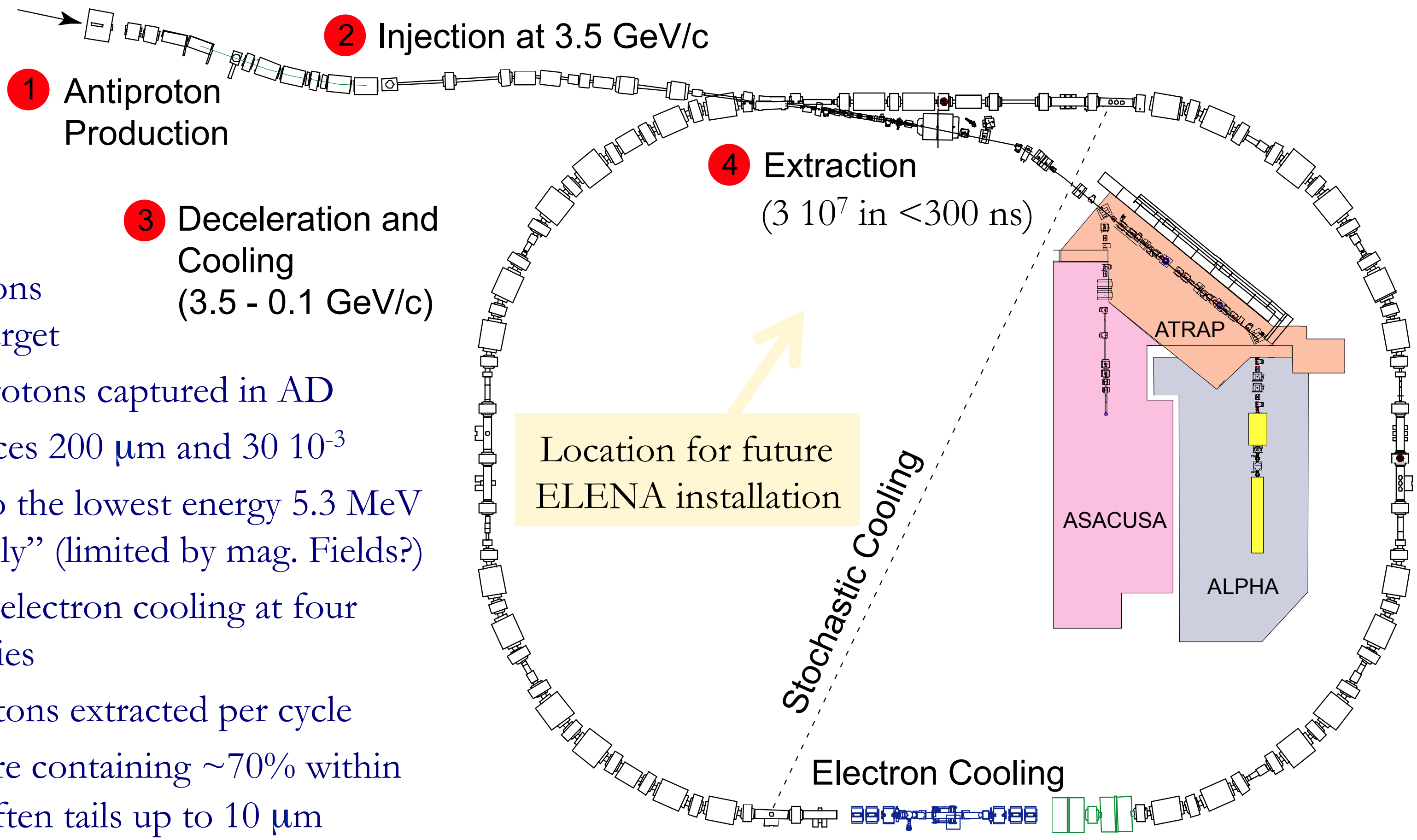
- Start of AD Commissioning in Autumn 1998
- First physics run in summer 2000
- Successful program with an increasing number of experiments



Introduction

Antiproton Decelerator AD

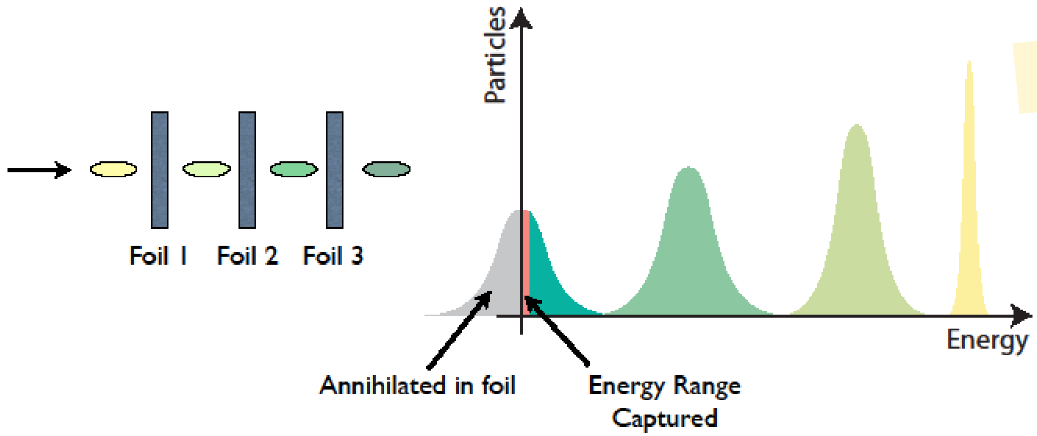
- ~1.5 10^{13} protons (26 GeV) on target
- ~3.5 10^{7} antiprotons captured in AD
  - Acceptances 200 μm and 30 10^{-3}
- Deceleration to the lowest energy 5.3 MeV reachable "safely" (limited by mag. Fields?)
- Stochastic and electron cooling at four different energies
- ~3 10^{7} antiprotons extracted 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



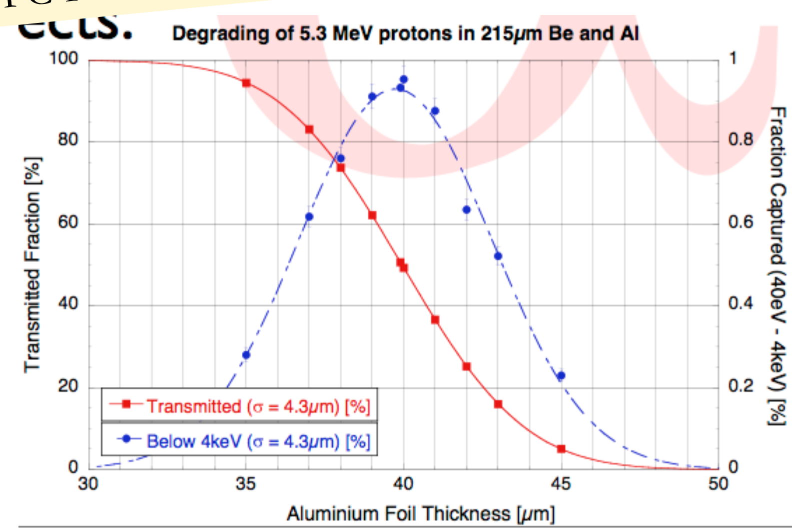
Sketch of the present AD – circumference 182 m
- In addition experiment AEGIS installed
- Experiment BASE being installed
- Gbar approved to receive beam from ELENA

Introduction

Motivation to add ELENA to the AD



BPPC Presentation by N.Madsen, from ALPHA

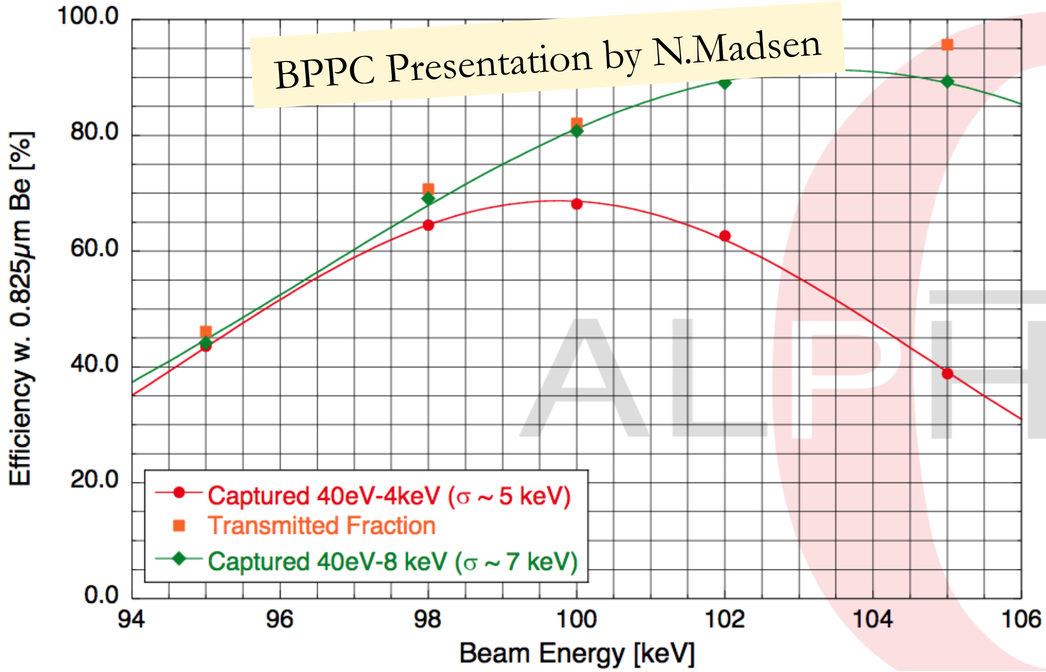


- Most experiments further slow down antiprotons coming from AD now at 5.3 MeV down by "foils" to a few keV and then capture them in traps
- Energy straggling increases energy spread such that only few antiprotons can be captured; even with optimized foil thickness
  - Almost half of the incoming pbars stopped in foil, where they annihilate
  - Almost half of the incoming pbars to energetic to be trapped
- (Note: there are AD experiments as e.g. ASACUSA decelerating antiprotons with an RFQ followed by a thin degrader – they achieve about one order of magnitude higher trapping efficiencies)
- Transverse: beam size on foil small enough for pbars to be cooled in trap

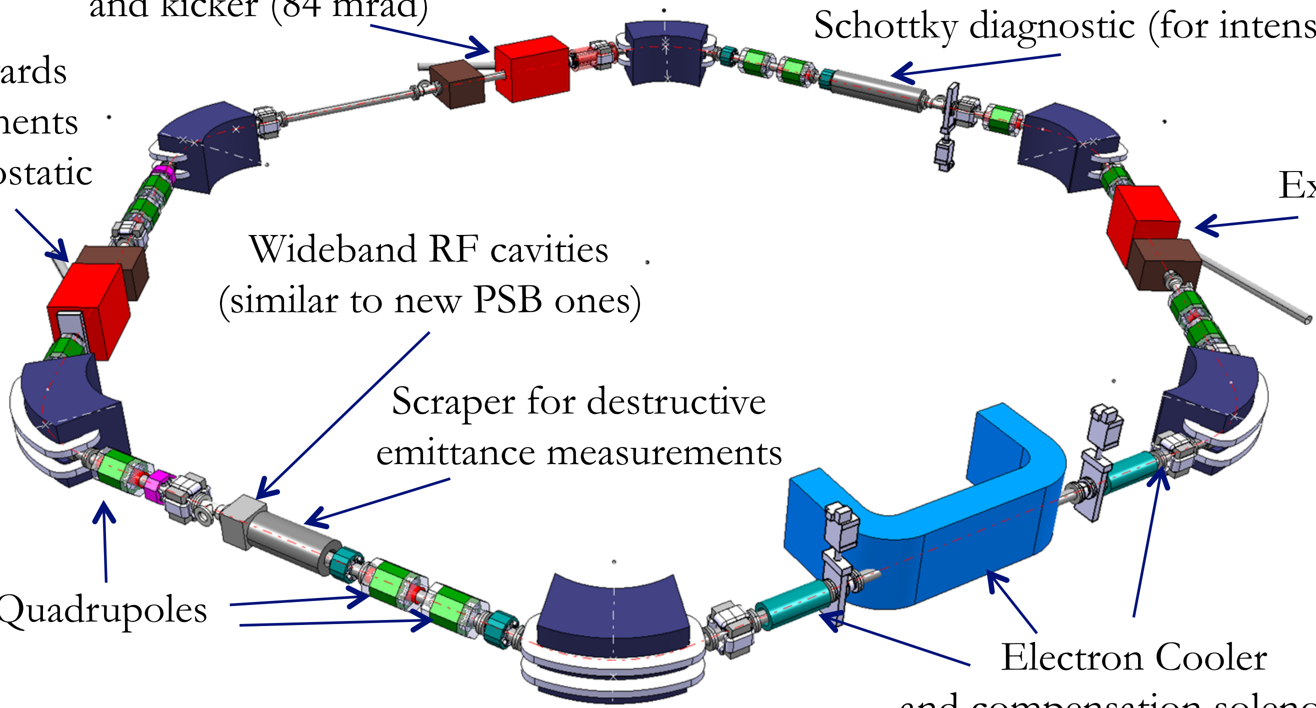
Introduction

Motivation to add ELENA to the AD

- ELENA with further decelerate antiprotons to 100 keV
  - Still too high energy to be used directly by experiments
  - Different schemes for further deceleration
  - Thinner foil used by (most) existing experiments
    - Reduced energy straggling and increase of capture efficiency by about one to two orders of magnitude
    - Energy spread of extracted beam not critical
  - New types of experiments (gravitation of antihydrogen) become possible
    - Deceleration with polarized tube (Gbar, ASACUSA2?)
- Electron cooling at intermediate and final energy to reduce emittances
- Available intensity per shot distribute in several (baseline: four) bunches for several experiments; longer running periods for experiments
- Other requirements from experiments: Beam size (rms <1 mm) Full bunch length less than 300 ns

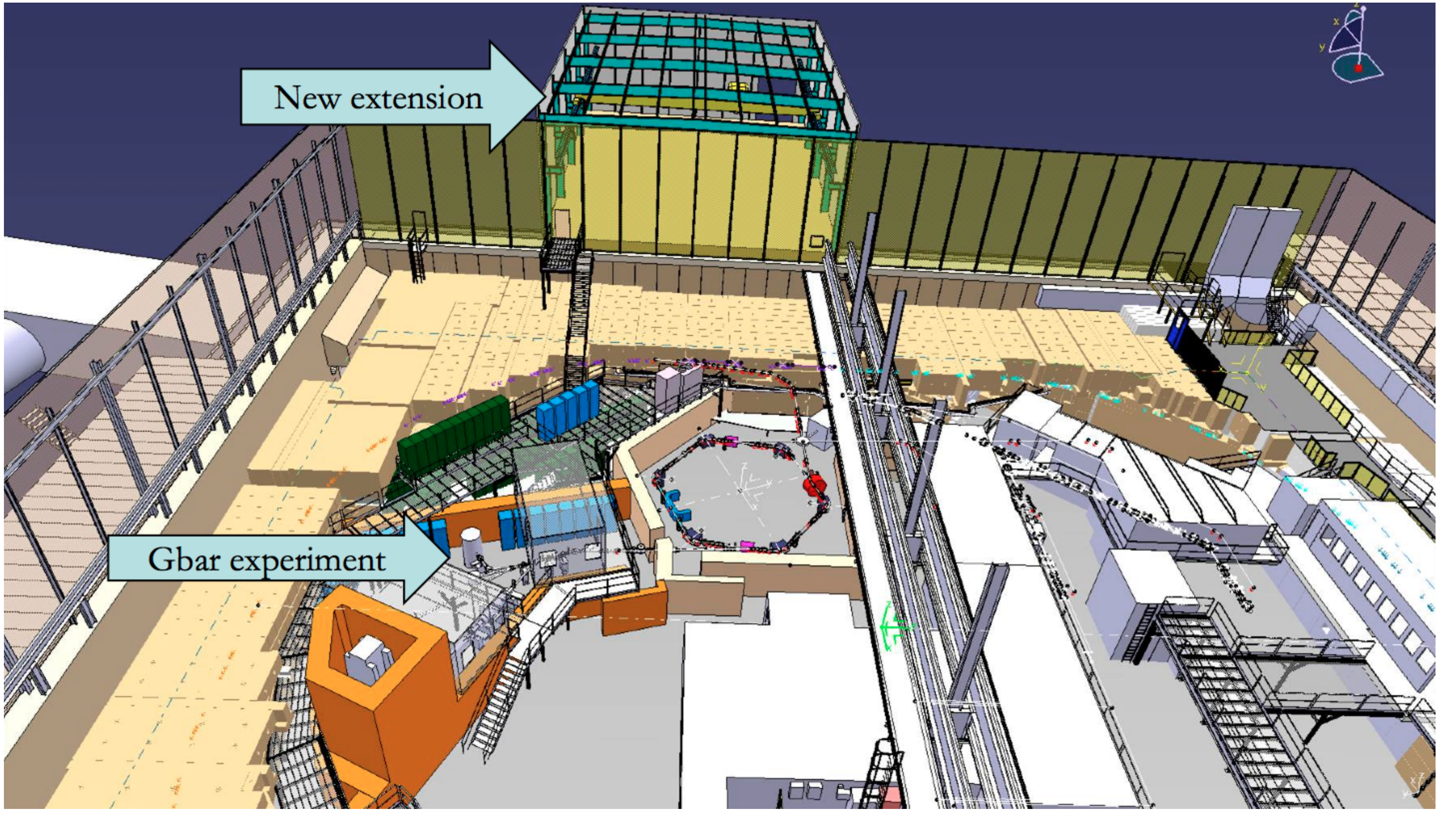


ELENA - Layout



- Improve capture efficiency of experiments (traps) by (i) decelerating antiprotons coming from the AD at 5.3 MeV down to 100 keV and (ii) reducing emittances using an electron cooler
- Circumference 30.4 m or 1/6 the one of the AD (.. 4 times the size of the first proposal in 1982!)
  - Ample space to allocate space for all equipment required or foreseen
  - Fits in the available space inside the AD hall
  - Lowest average field (beam rigidity over average radius) $B\rho/R$ = 94 G smaller than for AD 115 G

ELENA – Layout



- ELENA in AD hall with new experimental area for Gbar and, possibly, another experiment:
  - Cost effective with short transfer line from AD and no relocation of existing experiments
  - New (small) building to house equipment now at location, where ELENA will be installed

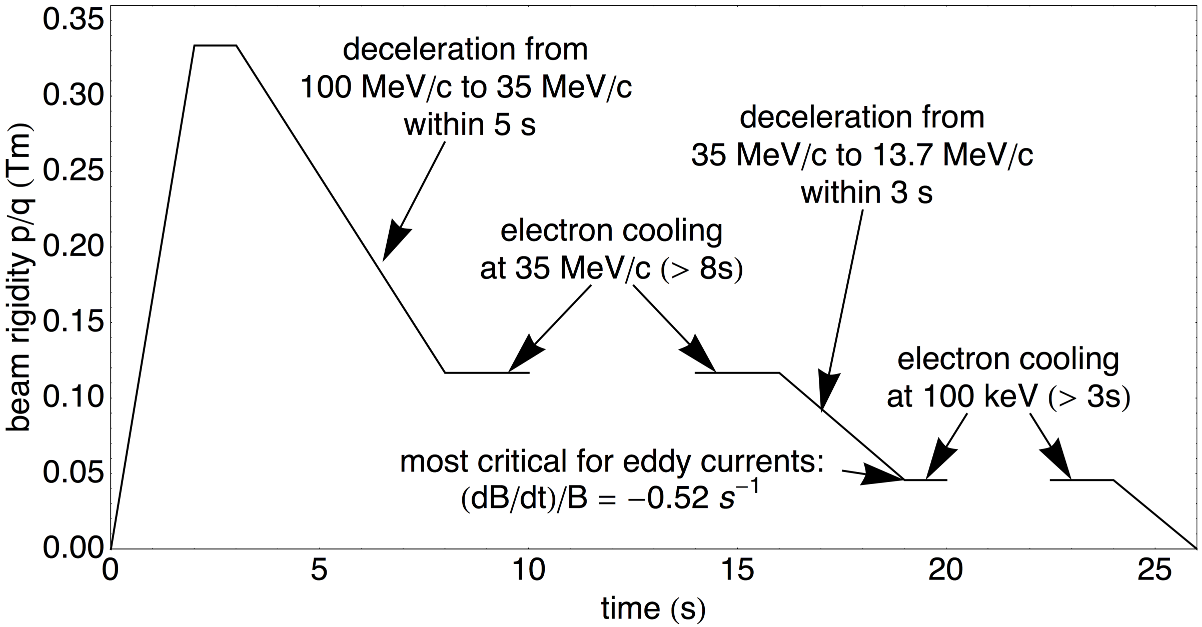
ELENA

Some of the most salient features

- Machine operated at an unusually low energy for a synchrotron (down to 100 keV!)
- Expected main performance limitation: Intra Beam Scattering (IBS, see later)
  - Determines equilibrium emittances together with electron cooling (see below)
- Rest gas interactions: stringent requirements - 3 10^{-12} Torr nominal pressure
- Beam diagnostics with very low intensities and energy
  - Beam currents down to well below 1 μA (far beyond reach standard slow BCTs)
  - Intensity of coasting beam measured with Schottky diagnostics
- Electron cooling (see later) at very low energies
  - Bunched beam cooling to obtain acceptable momentum spread of short extracted bunches
- Magnets with very low fields
  - "Thinning" (mixing of stainless steel and magnetic laminations) for bending magnets and probably for other small magnets
    - Mitigate remanence effects and impact on field quality for quadrupoles, sextupoles … ?
    - Careful magnetic measurement with pre-series magnets ("thinning" as well for other magnets?)
- Electrostatic transfer lines to experiments
  - Cost effective at very low energies, easier for shielding against magnetic stray fields
- RF system with modest voltages, but very large dynamic range
- Commissioning with external H^- and proton source (and electrostatic acceleration to 100 keV)

ELENA – Magnetic Cycle

- Present Ideas on Magnetic Cycle of Ring
- Ramp up within one up to a few seconds (not critical)
- Total duration not critical if longer than ~100 s AD cycle

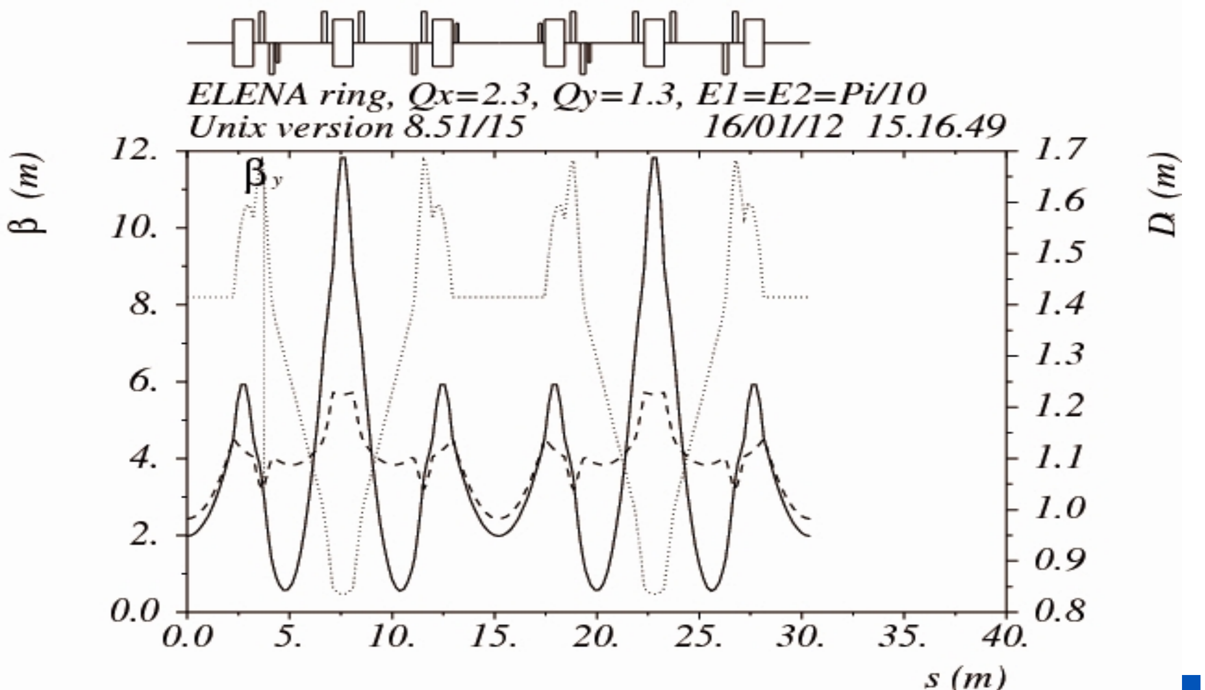


- Duration of ramps with beam compromise between
  - Short enough to keep blow-up due to Intra Beam Scattering (see later) acceptable
  - Long enough too avoid perturbations of optics due to Eddy currents in bending magnet chamber (net current along not isolated chamber in C-magnet created gradient)
- Length of cooling plateaus from simulations with BETACOOL (large "error bar" – longer cooling times than predicted seen for other machines)
- Significant remanence effects to be expected due to low fields for quadrupole, sextupoles…
  - Repeat always the same hysteresis cycles (good understanding of remanence from measurements)

ELENA - Lattice

- Lattice: arrangement of bending focusing (quadrupole) magnets with their strengths
  - Defines basic beam dynamics properties
- Challenges (usual for low small rings) for lattice design and optics
  - Many constraints and few "free parameters" (quadrupole strengths)
    - Suitable tunes (number of transverse "betatron" oscillations per revolution) and sufficient acceptances, …)
    - Long straight section with small dispersion for electron cooling ..
- Many geometries and options: square, hexagonal, triangular, different quadrupole locations
- Baseline lattice
  - Hexagonal shape with two periods and two long straights (for cooler and injection)
  - Tunes: $Q_X \approx 2.3$, $Q_Y \approx 1.3$ (e.g. $Q_X = 2.23$, $Q_Y = 1.23$)
- Acceptances: 75 µm
  - Maximum expected emittances plus some margin for reserve

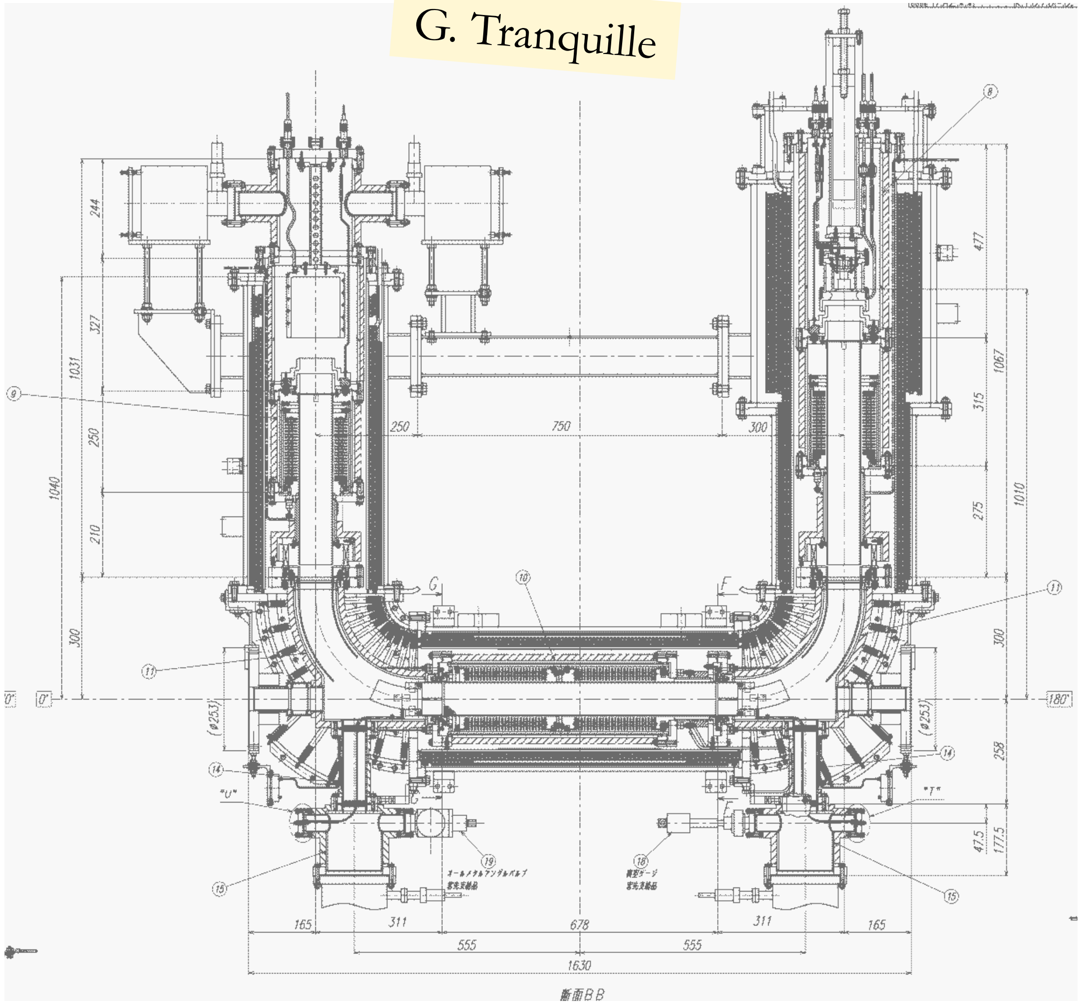
Pavel Beloshitsky



ELENA - Electron Cooling

- Circulating antiproton beam and electron beam travelling together
  - In co-moving coordinate system: now average velocity, but unordered motion corresponds to temperature
  - Mixing with cold electrons (regenerated continuously)
  - Temperature transfer – decrease of transverse antiproton velocities
  - With transverse oscillations, reduction of beam size as well
- Cooling at intermediate and final 100 keV energy
  - Expected cooling times a few seconds

G. Tranquille



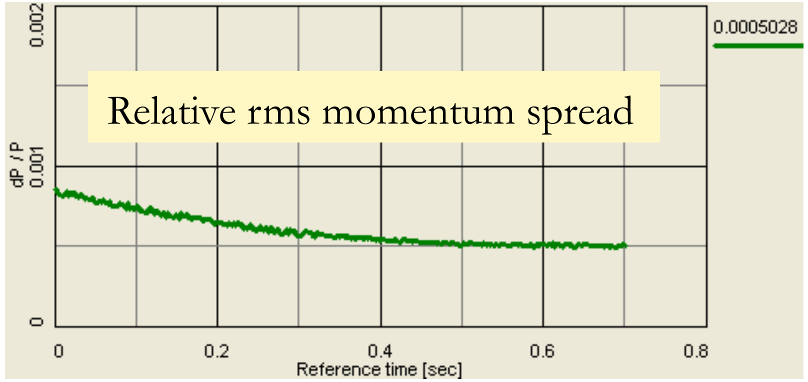
Sketch of the S-LSR Electron Cooler
ELENA Cooler expected to be similar

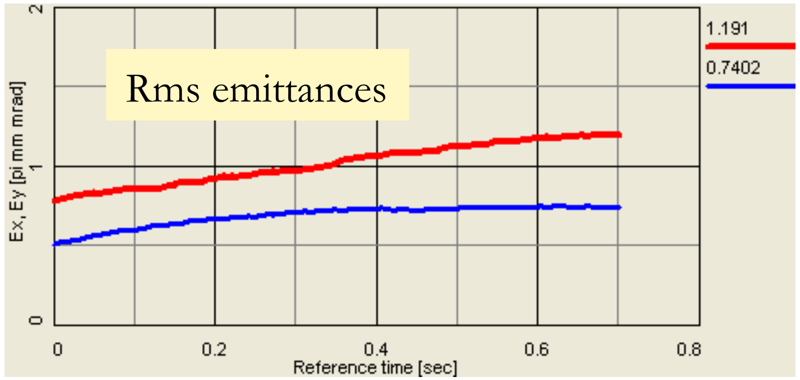
Bunched beam electron cooling at 100 keV

BetaCool simulations to estimate beam properties at ejection

S. Smirnov, P. Belochitski, G. Tranquille …

- Motivation: larger than initially expected equilibrium momentum spread of coasting beams due to IBS
  - Further strong increase during bunching
  - Issue for some experiments (and transfer lines)
- Keep cooler on during bunching process
  - Reduces longitudinal emittances
  - Simulation with RF voltage in three steps
  - Expected beam parameters for baseline ELENA operational scheme (4 bunches per cycle)
    - 0.6 10^7 pbars per bunch (optimistic)
    - Within 300 ns (full length) and $\sigma_p/p = 0.6\ 10^{-3}$
    - Transverse (physical rms) emittances of around 1.0 μm
  - Larger intensities (less bunches) per bunch lead larger momentum spread and emittances

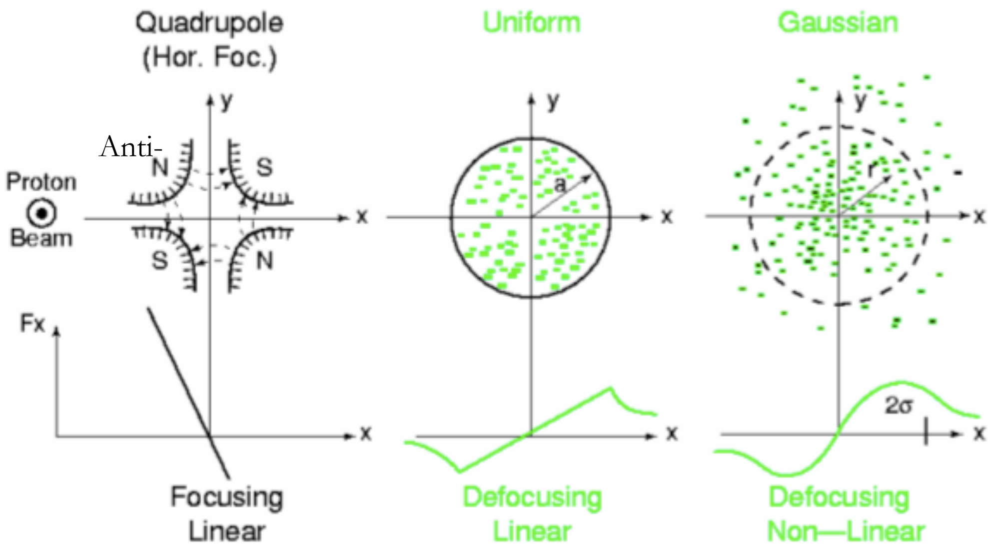




Last cooling step with:

- 0.6 10^7 pbars per bunch (optimistic)
- harmonic h = 4 (number of bunches)

Limitations
Direct Space Charge Effects



Transverse direct space charge defocusing

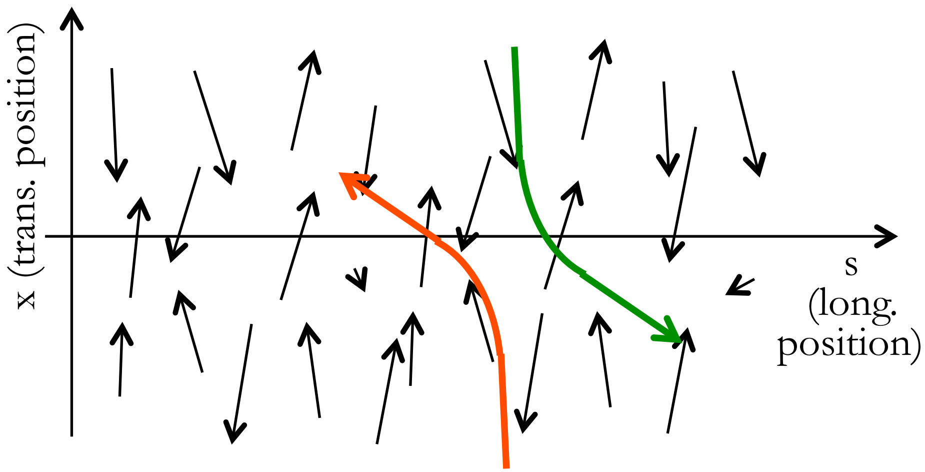
- Transverse direct space charge effects
  - Additional defocusing due to Coulomb repulsion
  - Non-linear, depending on position in bunch
  - Tune shift and spread

$$\Delta Q = -\frac{N\,e^2}{16\pi^2\varepsilon_0\beta^2\gamma^3}\frac{F_T}{\varepsilon_{rms}B_f} = -0.10$$

with
- N Number of $\overline{\mathrm{p}}$ per bunch, with four bunches $N = 0.425\times10^7$
- F_T transverse form factor, for Gaussian beams $F_T = 1$
- ε_{rms} physical rms emittance, for Gaussian beams $\varepsilon_{rms} = (4/6)\varepsilon_{95\%} = (4/6)\mu\text{m}$
- B_f Bunching factor, i.e. ratio average to peak current for parab. bunches $B_f = (2/3)L_b/C = 0.029$

  - With ELENA baseline parameters ΔQ ≈ -0.10, which should be fine, higher with less bunches
  - One of the reasons to split available intensity in several bunches
- Longitudinal direct space charge significant as well

Limitations
Intra Beam Scattering (IBS)



Intra Beam Scattering IBS – co-moving coord. system

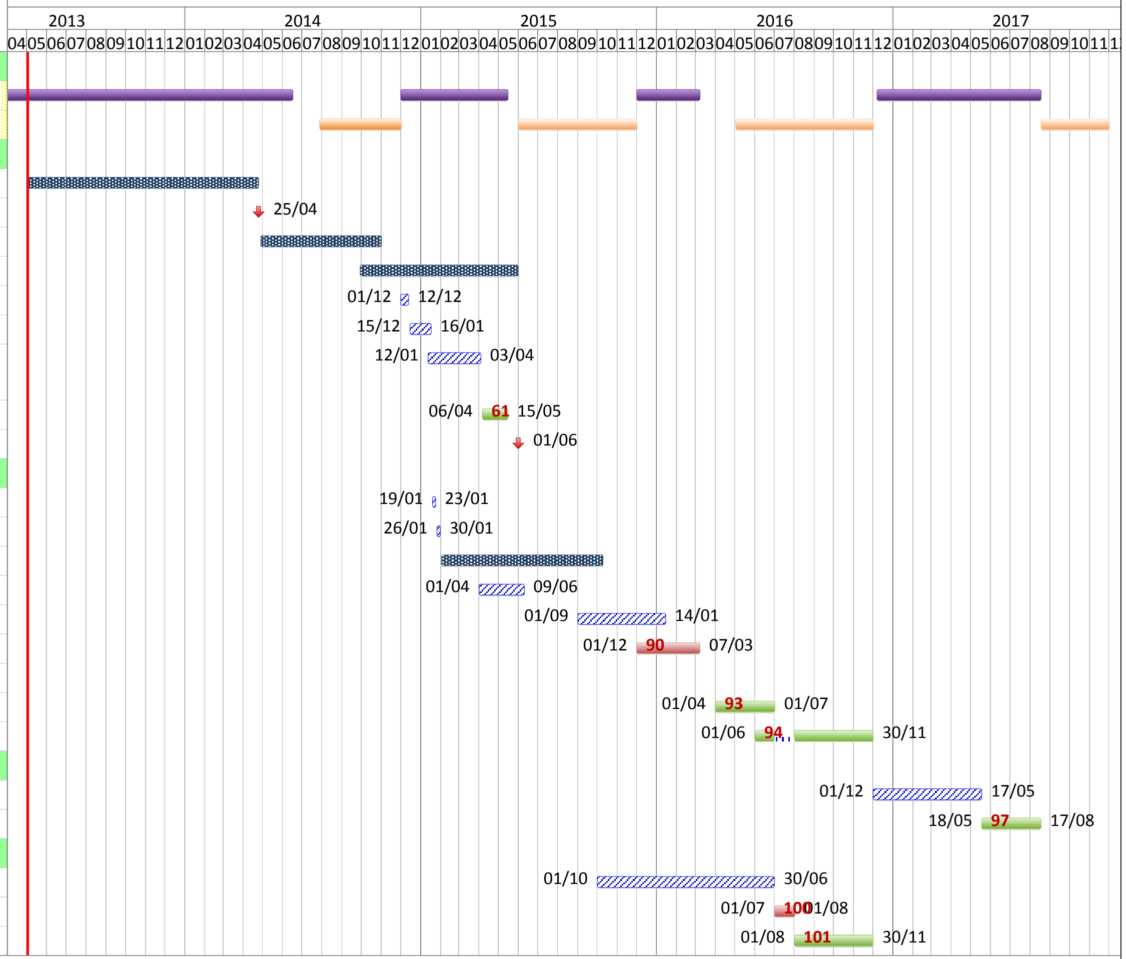
- Intra Beam Scattering IBS
  - In coordinate system moving with (average velocity of) antiproton beam
  - Coulomb scattering between beam particles
    - For example two trajectories (red and green) in sketch transfer energy from transverse into longitudinal plane
  - Transfer of heat between phase spaces (longitudinal & two transverse)
  - Temperatures vary along accelerator (higher where beam size is smaller) with focusing structure (lattice)
  - No solution with constant emittances, but always growth (in at least one phase space)
- Expected to be main source of blow-up in ELENA
  - Determines together with cooling emittances of available beams

Present Planning

(To be updated after review with target date for first physics as now)

ELENA Project - General Reference Planning

ID	Task Name
1	General milestones
7	AD shutdowns
12	Experimental physics
39	Annexed building 393
40	Construction
47	Annexed bldg delivery
48	Installation equipment in annexed bldg
53	Move kicker platform
58	Dismantling kickers platform and accessories
59	Migration kicker equipment to annexed bldg
60	Electrical works (cabinet, racks, cabling, connectors)
61	Kickers commissioning
62	Beam back to AD experimental areas
66	Elena machine installation
67	Survey marking (incl. Gbar and H- source)
68	Install surrounding concrete shielding
70	H- source
78	Magnet installation
89	Vacuum system + ejection towards Gbar
90	Connection AD-ring to ELENA
92	Commissioning ELENA
93	Commissioning ELENA (H-) (100 keV -> 5.3 Mev)
94	Commissioning ELENA (p-) (a few %)
95	Redevelopment TL towards experiments
96	Installation TL
97	Commissioning ELENA - Experiments
98	Installation Gbar
99	Installation Gbar experiment
100	Connection Gbar-Elena
101	Commissioning Gbar



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Basic ELENA Parameters

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		with bunched beam cooling
Number of bunches	4	baseline with four bunches
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

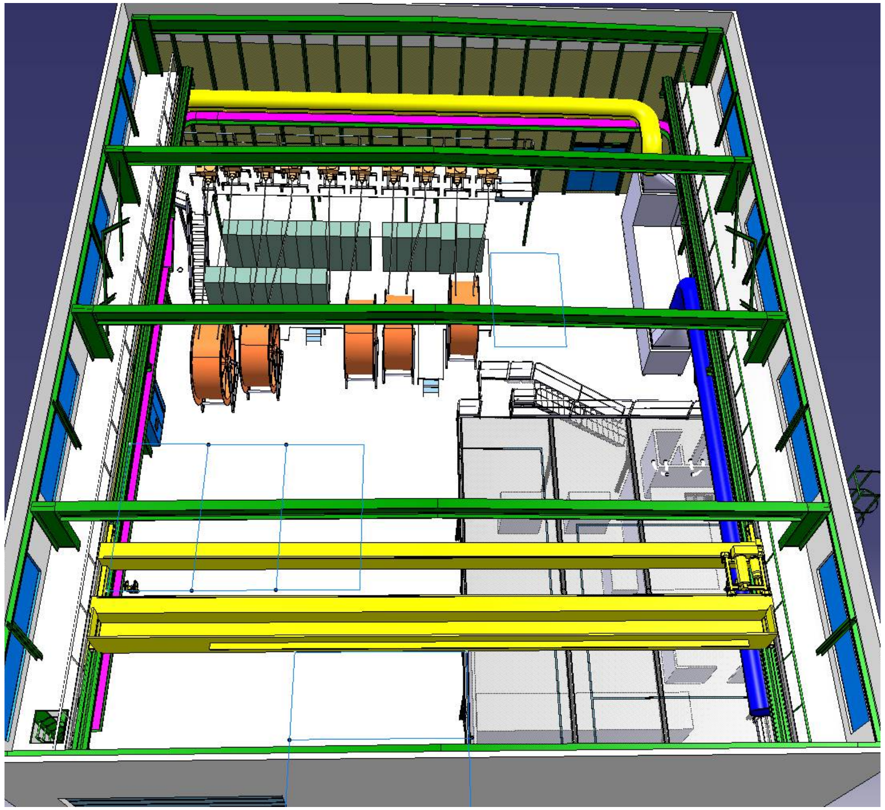
Basic ELENA Parameters

Present best Guess for beam parameters combining different Sources

Step in cycle	ε_L (meVs)	σ_p/p (10^{-3})	σ_E (keV)	σ_T (ns)	$\varepsilon_{H,r.s}$ (μm)	$\varepsilon_{V,r.s}$ (μm)
Injection[+,a)]	6.3	0.38	4	125	0.5	0.3
Start 1st ramp[+,b)]	6.3	0.43	7	72	0.5	0.3
End 1st ramp[c)]	6.1	1.8	2.4	200	1.8	1.1
Start plateau 35 MeV/c[d)]	9.1	0.8	1.05	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)]	3.2	0.46	.092	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

+) difficult to determine due to (i) dense core and long tails, (ii) variations with time
a) AD measurements about a year ago – smaller values obtained in 2012, in particular with bunched cooling
b) Increase of voltage from 16 V at transfer to 100 V on ramp
c) Simulations of IBS on ramp – Slides sent on 14th November
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) BPPC presentation by G.Tranquille
f) From BPPC presentation by P. Beloshitsky on 2nd August 2012 – case for four bunches and 2.4 10^7 pbars

Construction of new annex Building 393



- Needed to free space needed for ELENA in AD hall
  - Construction well advanced
  - Delivery of building around February 2014 to followed by infrastructure installation

Conclusions, Status and Outlook

- ELENA will be a small ring to further decelerate antiprotons from the AD
  - Electron cooler to reduce beam emittances and, thus, sizes and energy spread
  - Extension and further improvement of existing CERN antiproton facilities
  - Improvement for existing experiments and new types of experiments
- ELENA Machine to be built well known now
  - General Project Review on 14th and 15th October
    - Technical design sound and no showstoppers identified
    - Many proposals to improve (Tunability for working point, "thinning" of small magnets ..)
    - Concept of decelerator with electron cooling endorsed again
  - Technical Design Report TDR describing machine well advanced
- Outlook
  - Revision of budgets, "work packages" describing who does what and when, schedule ..
  - Completion of adjacent building 393 beginning 2014, then infrastructure installation
  - ELENA installation in 2nd half of 2015 and beginning 2016 followed by commissioning
  - Transfer line installation followed by commissioning during 1st half 2017
  - Bright future for antiproton physics with first 100 keV beam from ELENA around late summer 2017

Thanks for your attention !