Intra-beam Scattering Effects in the Extra Low ENergy Antiproton ring (ELENA)

Javier Resta-Lopez,
James Hunt, Carsten Welsch,
Cockcroft Institute, The University of Liverpool

IPAC 2015
Richmond, Virginia, USA

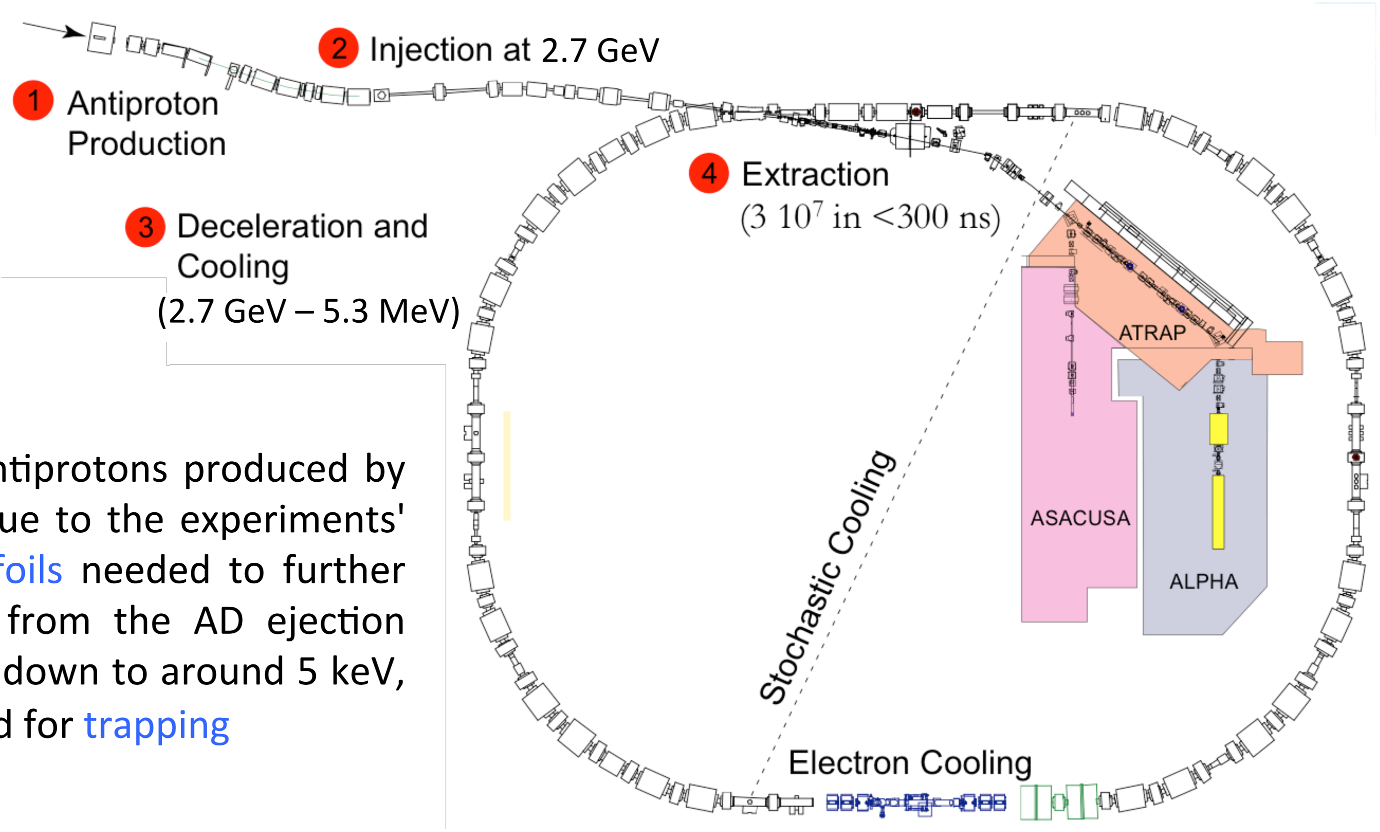
Outline

- Context
- ELENA overview
- Emittance dilution and lifetime limiting processes
  - Rest gas
  - IBS
- Beam evolution
- Summary and Future plans

Context

Antiproton Decelerator (AD) at CERN

The AD provides low-energy antiprotons (5.3 MeV kinetic energy) for different experiments dedicated to the production of antihydrogen and measurement of its properties



① Antiproton Production

② Injection at 2.7 GeV

③ Deceleration and Cooling (2.7 GeV – 5.3 MeV)

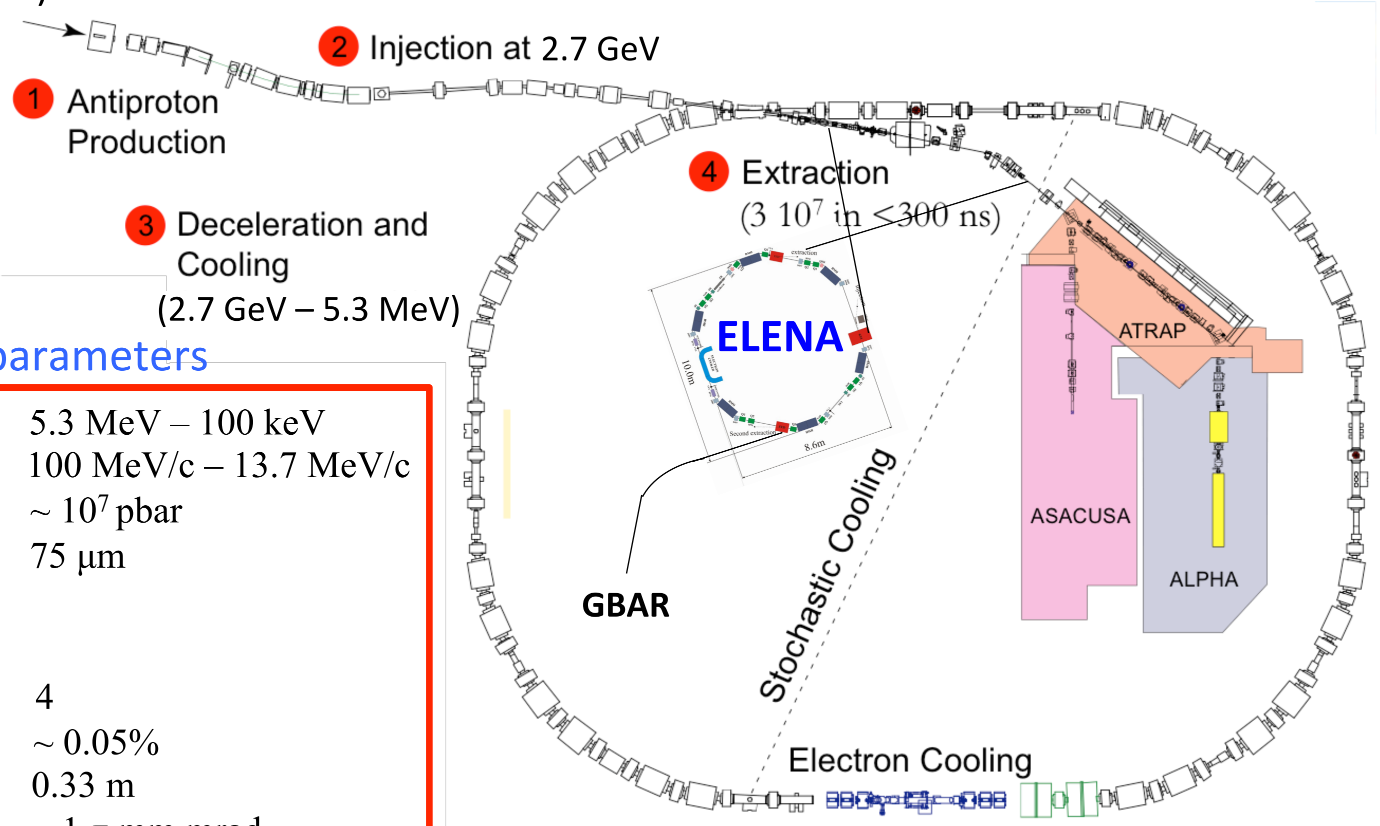
④ Extraction (3 10^{7} in $<$300 ns)

≈ 99.9% of the antiprotons produced by the AD are lost due to the experiments' use of degrader foils needed to further decelerate them from the AD ejection energy (5.3 MeV) down to around 5 keV, the energy needed for trapping

Context

Antiproton Decelerator (AD) and ELENA at CERN

ELENA will bring a 10 to 100-fold increase in the experiments' efficiency, as well as the possibility to accommodate an extra experimental area to investigate gravitation with antihydrogen (GBAR)

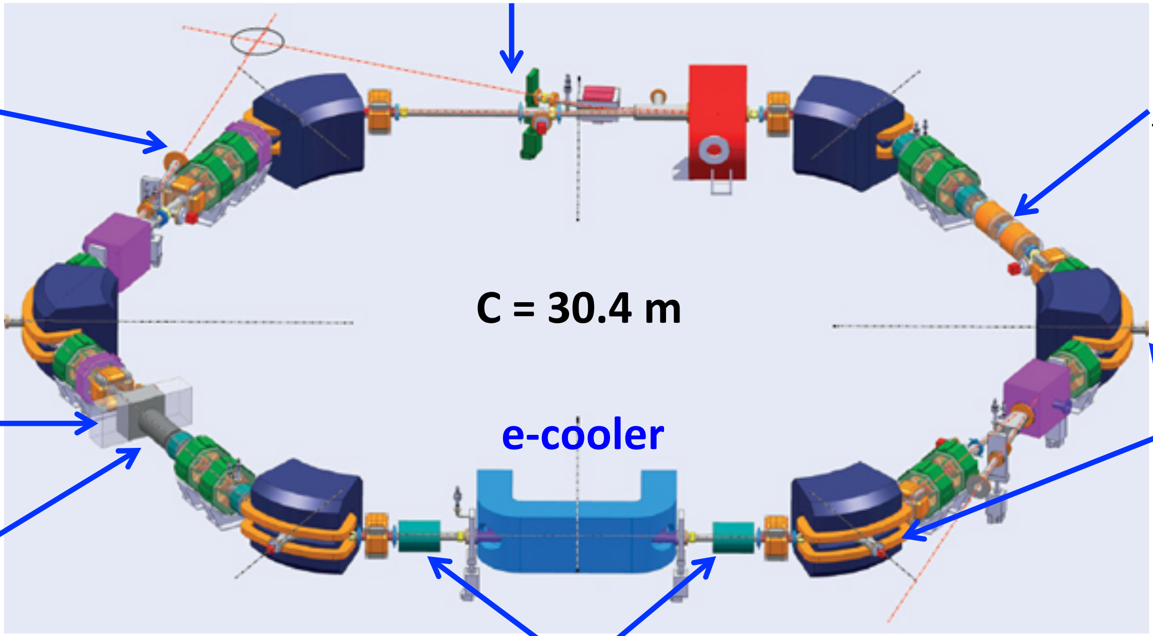


Basic ELENA beam parameters

Energy range	5.3 MeV – 100 keV
Momentum range	100 MeV/c – 13.7 MeV/c
Intensity	~ 10^7 pbar
Transverse acceptance	75 μm
Parameters at ejection:	
Number of bunches	4
$\Delta p/p$ (rms)	~ 0.05%
Bunch length (rms)	0.33 m
ε_x, ε_y (rms)	~ 1 π mm mrad

ELENA overview

Schematic layout



Injection with magnetic septum (≈300 mrad) and kicker (84 mrad)

Extraction towards existing experiments

High sensitivity magnetic pick-up for Schottky diagnostic (for intensity) and LLRF

C = 30.4 m

e-cooler

Wideband RF cavities

Bending magnets ($\pi/3$ kick angle)

Scraper for destructive emittance measurements

Compensation solenoids

Extraction towards new experimental area

The e-cooler must be able to produce a cold and relatively intense electron beam:

$$k_B T_\perp < 0.1\ \mathrm{eV}, \quad k_B T_\parallel < 0.001\ \mathrm{eV} \qquad n_e \approx 1.5 \times 10^{12}\ \mathrm{m}^{-3}$$

Details in ELENA TDR, CERN-2014-002 (April 2014)

ELENA overview

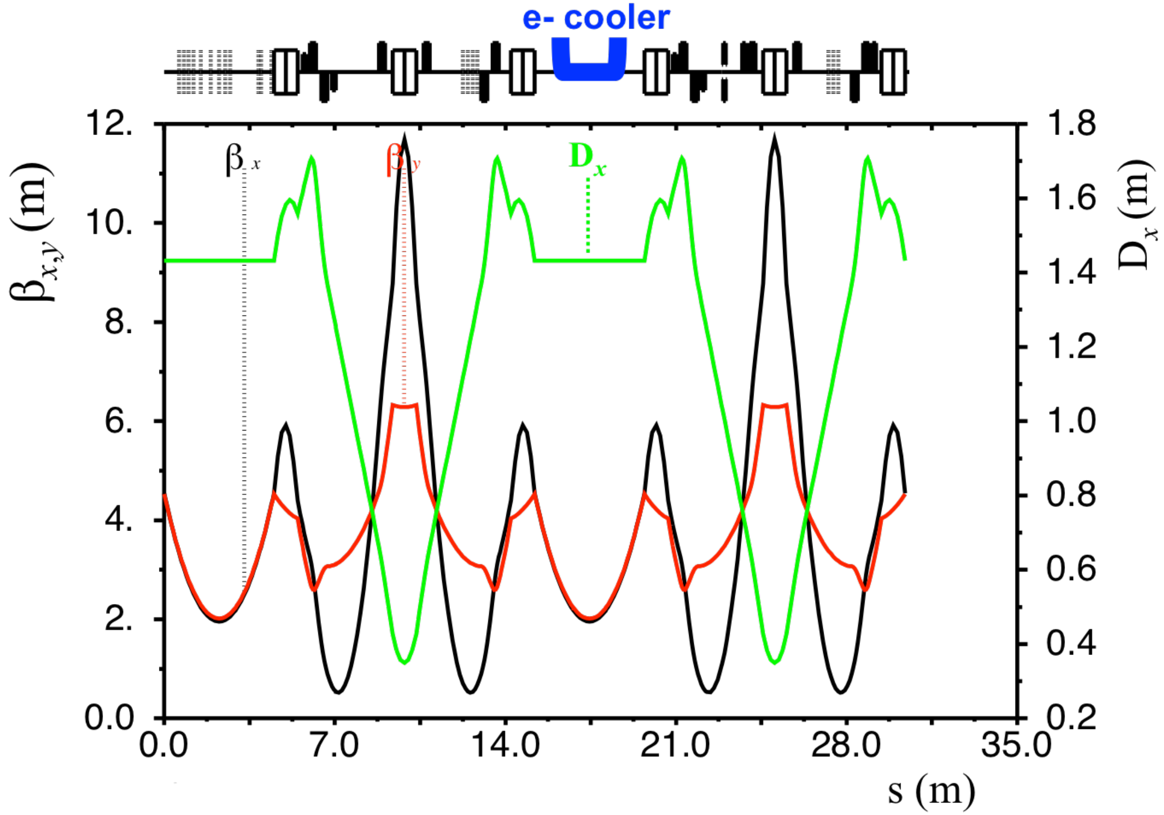
Optics

Good tunability in the range $2 < Q_x < 2.5$ and $1 < Q_y < 1.5$

$Q_x \approx 2.3$, $Q_y \approx 1.3$

max $\beta_x \approx 12$ m
max $\beta_y \approx 6$ m
max $D_x \approx 1.7$ m
$\langle\beta_{x,y}\rangle \approx 3$ m
$\langle D_x\rangle \approx 1.2$ m

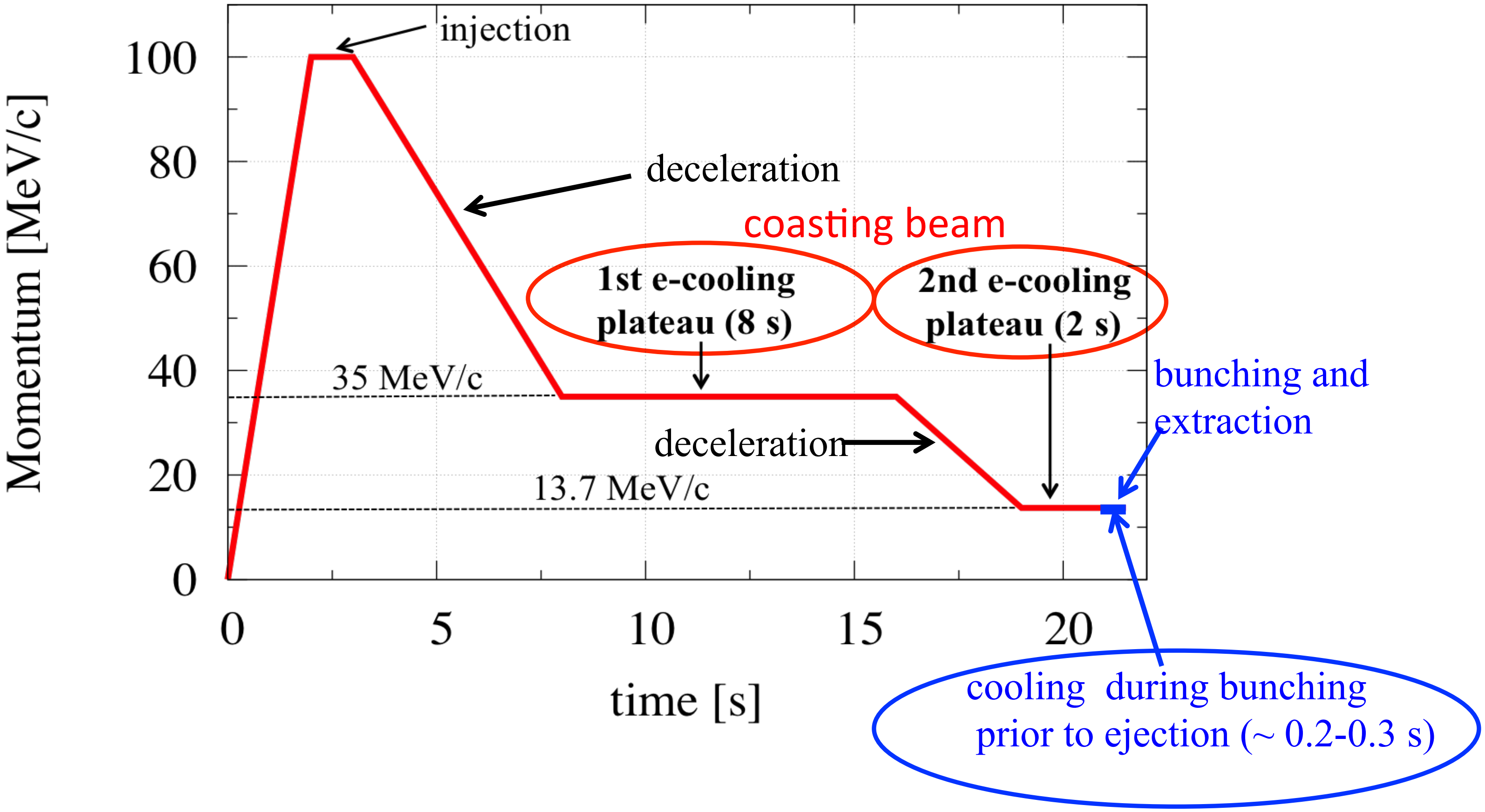
At e-cooler position:
$\beta_x \approx 2$ m
$\beta_y \approx 2$ m
$D_x \approx 1.5$ m



MADX model based on the specifications of the ELENA TDR

ELENA overview

ELENA cycle



We have mainly focused on beam dynamics studies during the **1st and 2nd e-cooling plateaus**

Emittance dilution and lifetime limiting processes

Heating processes:

- Interaction with the **rest gas**:
  - Nuclear scattering
  - Single Coulomb scattering

  } → particle loss if high scattering angle
  - Multiple Coulomb Scattering (MCS)

  - The ELENA vacuum pipe will be coated with Non-evaporable Getter (NEG) films

  - Expected residual gas composition: **95% H_2, 2% CO, 2% CO_2, 1% CH_4**

  - Nominal vacuum pressure for ELENA: **P=$3\text{x}10^{-12}$ Torr**

  - **This pressure is a very safe limit in terms of both low MCS effect and very low rate of large angle scattering**

- **Intra-Beam Scattering (IBS):** Multiple small-angle Coulomb scatterings of charged particles within the accelerator beam itself. Exchange of energy between the transverse and longitudinal degrees of freedom

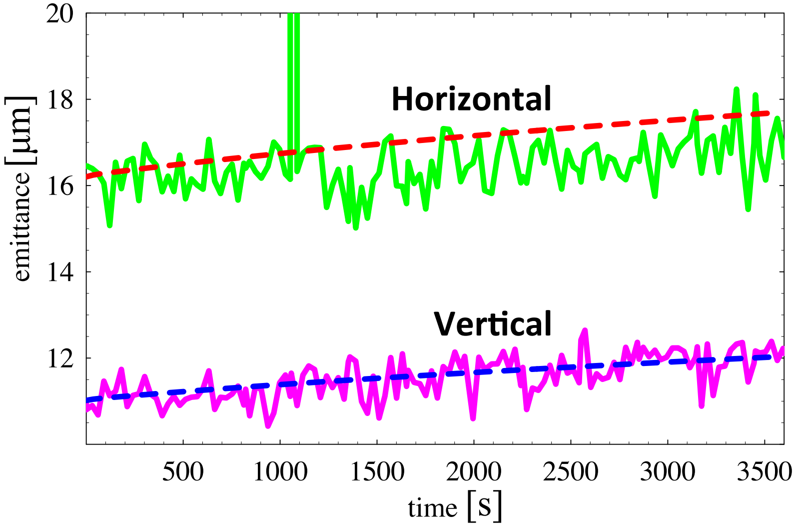
BETACOOL simulations

BETACOOL: [A. Sidorin et al., NIM A 558 (2006), 325]

- Calculation of the evolution of beam distributions under the action of cooling forces (in this case electron cooling) + different scattering effects

- Benchmarked against experimental data in different rings, e.g.

Experimental studies of IBS in RHIC and comparison with BETACOOL simulations



[A. V. Fedotov et al., Proc. of HB2006, WEBY03, Tsukuba, Japan, 2006]

BETACOOL simulations

Simulation conditions:

- Multiparticle simulations based on a Monte-Carlo method (model beam algorithm)
- 1000 modelled particles
- Coasting antiproton beam (at cooling plateaus) and bunched beam (before extraction)
- Electron cooling considering a cylindrical uniform electron beam distribution
- Cooling process + Rest gas + IBS (Martini model)
- Cooling friction force computed using the Parkhomchuk’s model (magnetised electron distributions)

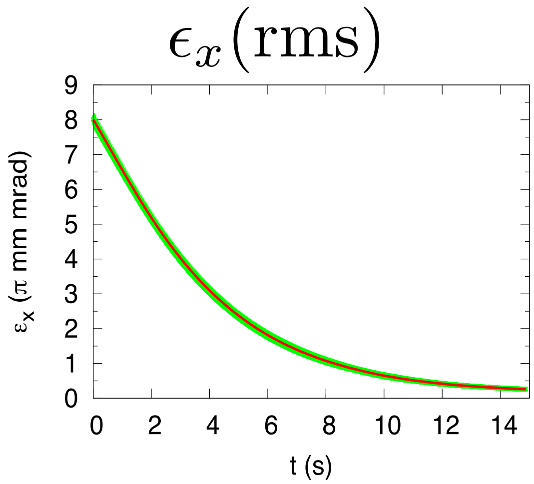
Beam evolution

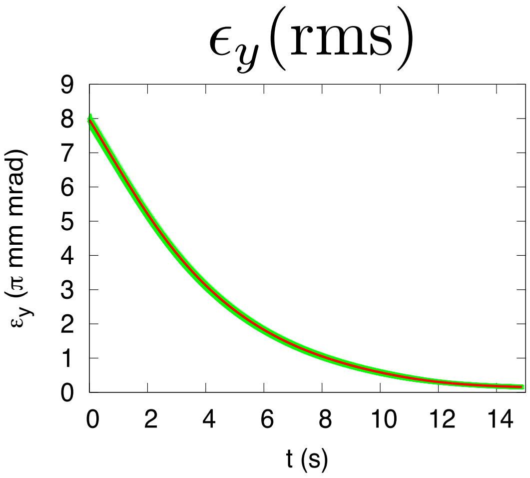
1^{st} cooling plateau, p=35 MeV/c, coasting beam

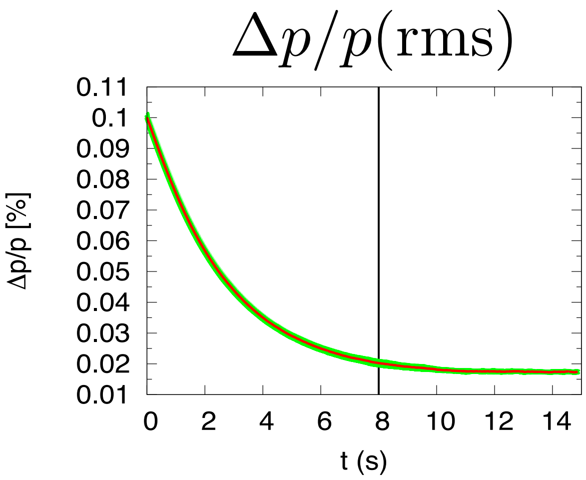
- **Electron cooling process in presence of rest gas and IBS**

  Parameter evolution:

  Simulated 10 random seeds for the evolution of a distribution of 1000 modelled particles


$\epsilon_x(\mathrm{rms})$


$\epsilon_y(\mathrm{rms})$


$\Delta p/p(\mathrm{rms})$

Step in cycle	ϵ_x, ϵ_y [π mm mrad] (rms)	Δp/p [%] (rms)
Start 1^{st} cooling (35 MeV/c)	8.0, 8.0	0.1
After 8 s cooling (35 MeV/c)	**1.1, 1.1**	**0.02**

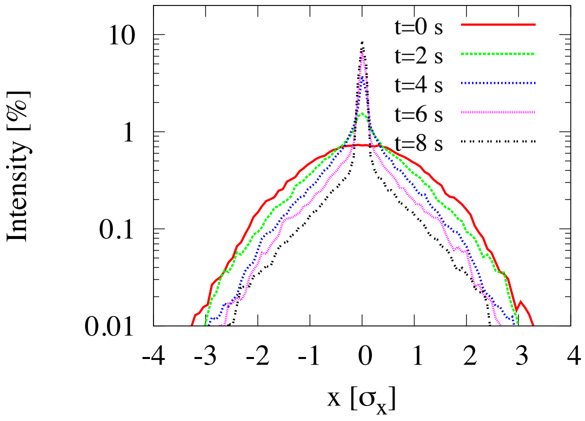
Conservative initial values

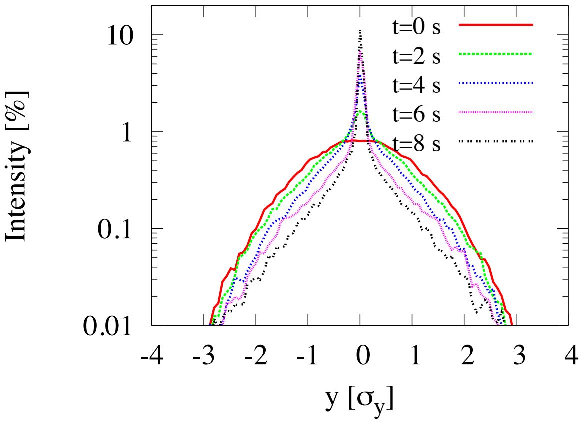
Beam evolution

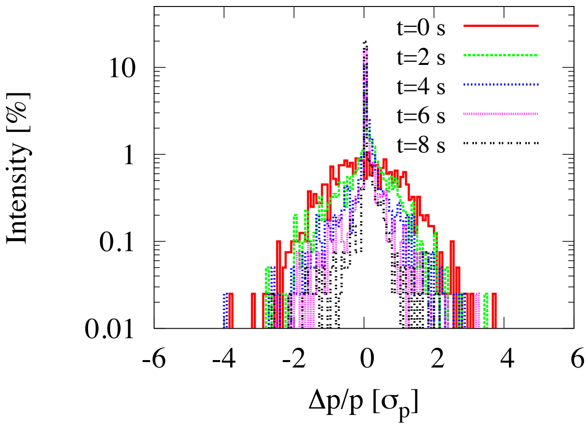
1^{st} cooling plateau, p=35 MeV/c, <u>coasting beam</u>

- **Electron cooling process in presence of rest gas and IBS**

  Beam profile evolution:







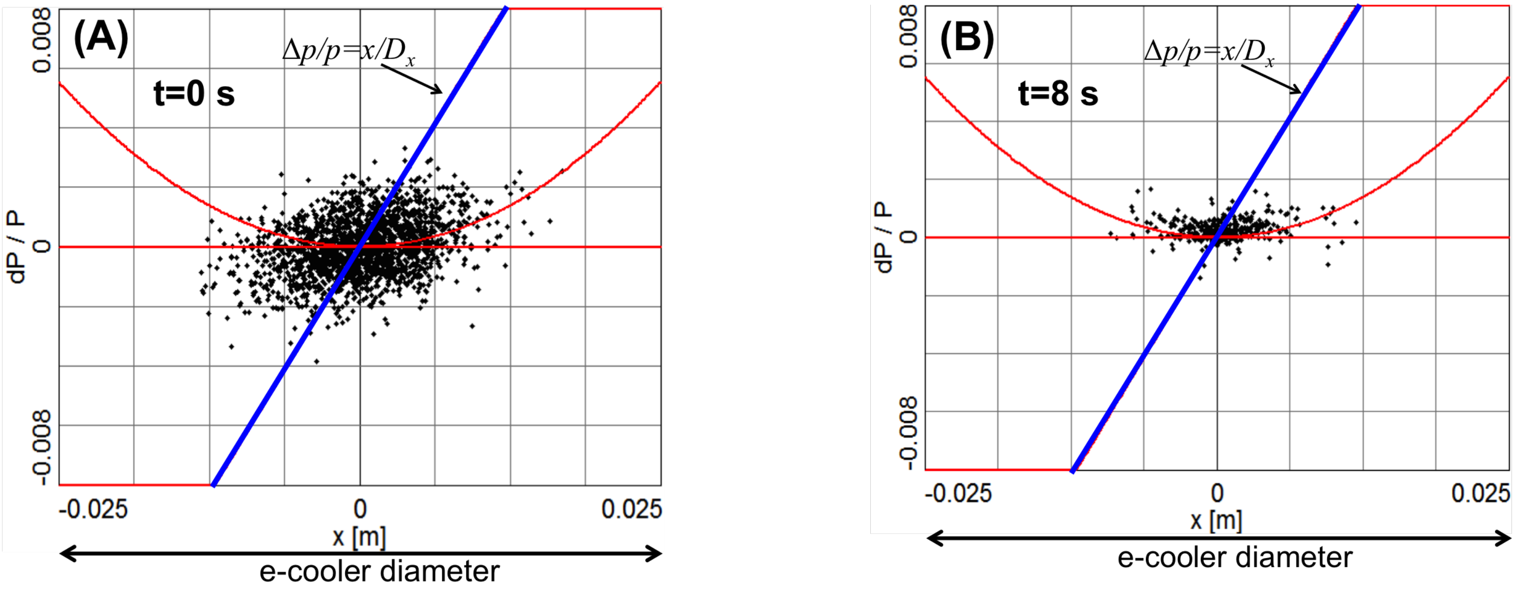
During the cooling process, the beam distribution quickly deviates from a Gaussian profile and a very dense core appears

Core overcooling. Underestimating IBS effect in the core?

Beam evolution

1^{st} cooling plateau, p=35 MeV/c, coasting beam

- **Core-tail development:**



The parabola represents the momentum spread of the electrons due to space charge

For large initial beam size, particles in the tails experience weaker friction forces than in the core → development of core-tail particle distributions

Beam evolution

- **Core-tail development:**

Standard models of IBS, such as the Martini model, are based on the growth of the rms beam parameters of a Gaussian distribution. These models underestimate the IBS effect for non-Gaussian distributions.

Further investigation:

- Apply an IBS "core-tail" model (bi-Gaussian distribution): IBS induced kicks based on diffusion coefficients which are different for particles inside and outside of the core
- Apply a IBS "Local" model: can calculate correctly IBS for arbitrary distributions, but it takes a lot of computation time

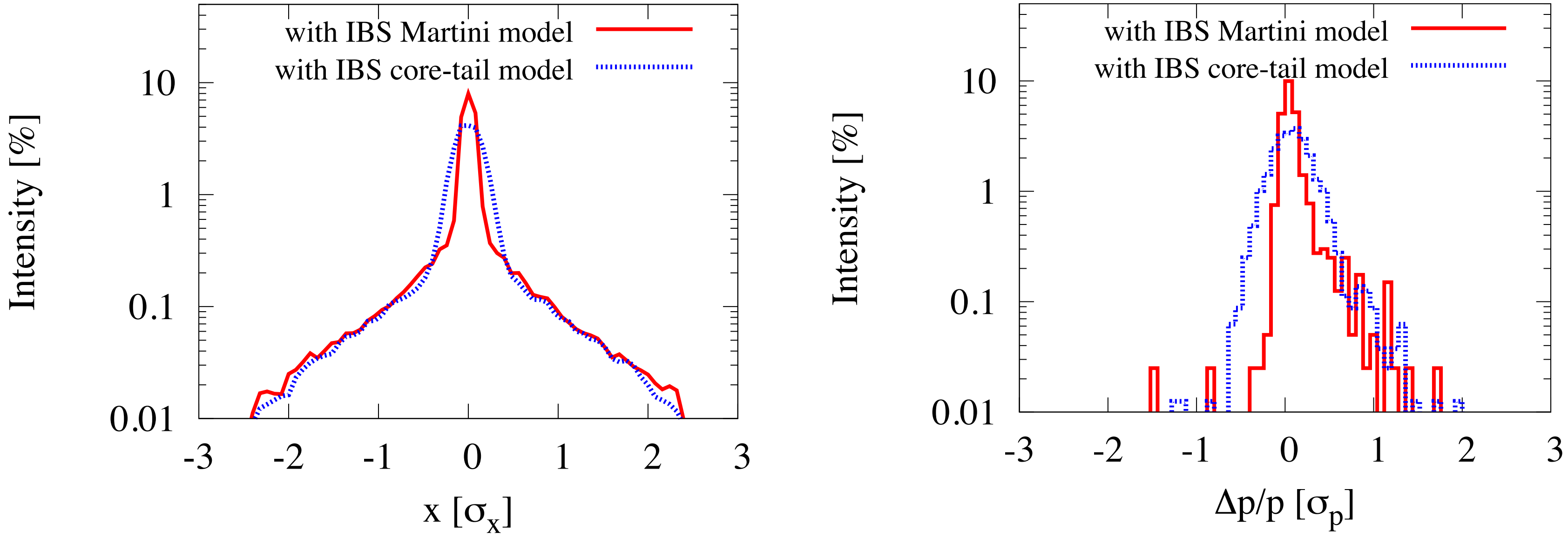
[A. V. Fedotov, "IBS for Ion Distribution Under Electron cooling" Proc. PAC2005]

Beam evolution

1^{st} cooling plateau, p=35 MeV/c, coasting beam

- **Core-tail development: IBS Martini model vs core-tail model:**

Beam distributions after 8 s cooling



The cooling of the core is smoother if an IBS core-tail model (bi-Gaussian) is applied and, probably, it describes more accurately the actual process

Beam evolution

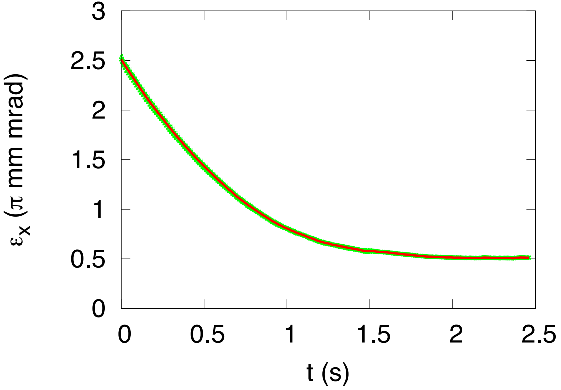
2nd cooling plateau, p=13.7 MeV/c, coasting beam

- **Electron cooling process in presence of rest gas and IBS**

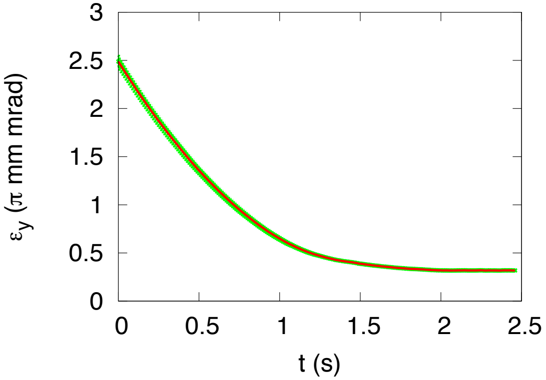
Parameter evolution:

Simulated 10 random seeds for the evolution of a distribution of 1000 modelled particles

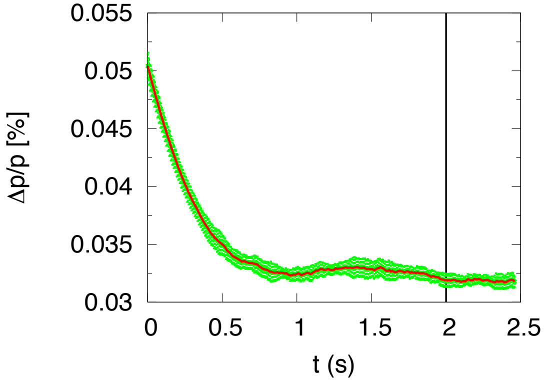
$\epsilon_x(\mathrm{rms})$



$\epsilon_y(\mathrm{rms})$



$\Delta p/p(\mathrm{rms})$



Step in cycle	ε_x, ε_y [π mm mrad] (rms)	Δp/p [%] (rms)
Start 2nd cooling (13.7 MeV/c)[*]	2.8, 2.8	0.05
After 2 s cooling (13.7 MeV/c)	**0.52, 0.33**	**0.033**

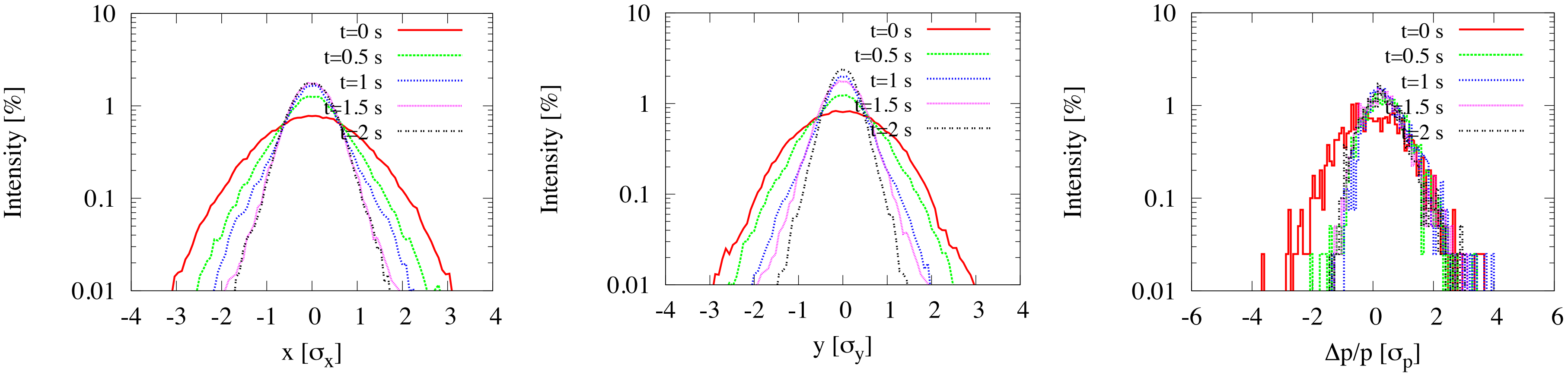
[*] Taking into account the adiabatic emittance increase by a factor ≈ 2.55 because of the deceleration from 35 MeV/c to 13.7 MeV/c

Beam evolution

2^{nd} cooling plateau, p=13.7 MeV/c, coasting beam

- **Electron cooling process in presence of rest gas and IBS**

  Beam profile evolution:



In this case, the cooling is more homogeneous for both core and tails, and after 2 s cooling the beam reaches the equilibrium

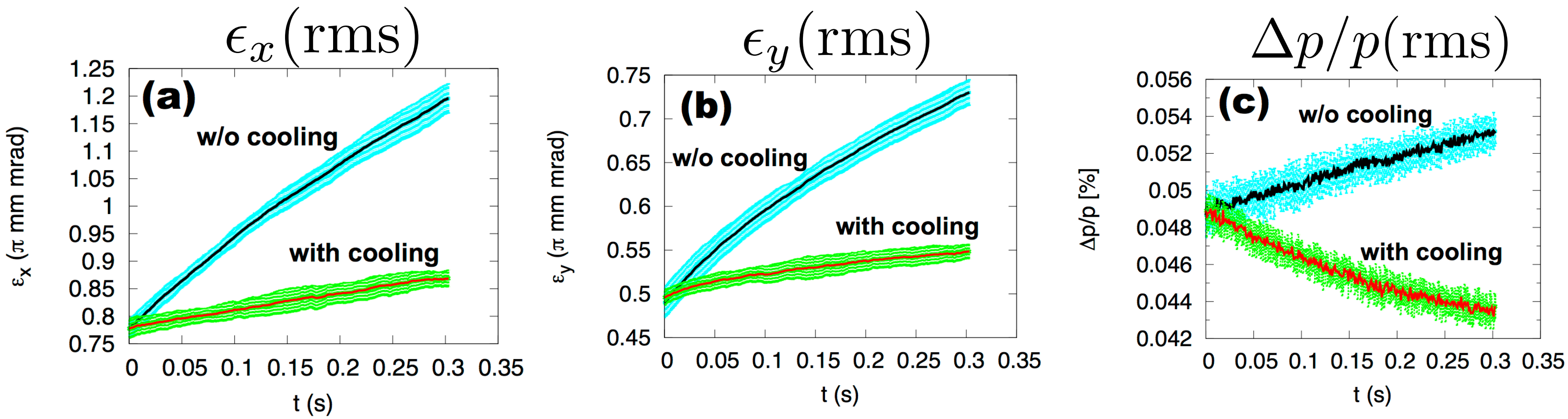
Beam evolution

Before extraction, p=13.7 MeV/c, bunched beam

- **Electron cooling process in presence of rest gas and IBS**

Parameter evolution:

Simulated 10 random seeds for the evolution of a distribution of 1000 modelled particles



With cooling:

Step in cycle	ϵ_x, ϵ_y [π mm mrad] (rms)	Δp/p [%] (rms)
Start cooling (13.7 MeV/c)*	0.78, 0.49	0.049
After 0.3 s cooling (13.7 MeV/c)	**0.9, 0.55**	**0.043**

* Starting values assuming Debunching/bunching with 50% blow-up

Summary and Future plans

- For a better understanding of the long term beam dynamics in the ELENA ring, we have started a detailed investigation into the different cooling and heating processes which determine the beam lifetime and quality of the antiproton beam

- Here we have put special emphasis on the study of the cooling process in presence of IBS

Next steps:

- Comparison of equilibrium parameters using different models of IBS

- Simulations including e-cooler imperfections

- For simplicity we have assumed initial Gaussian beam profiles. However, in practice, the distribution of the beam injected from the AD could have a significant non-Gaussian shape. This characteristic will be taken into account in future studies.

- Identify potential aspects of the machine that could be optimised

- ELENA will be an ideal test-bench to compare experiments and simulations of e-cooling at very low energies

Special thanks to:

Christian Carli, Alexander Smirnov, and all the ELENA team at CERN

Thank you

Intrabeam scattering

IBS theory extensively described in the literature, see e.g.

- A. Piwinski, Proc. of the 9th International Conference on High Energy Accelerators, 1974, p. 405: smooth lattice approximation

- J. Bjorken, S. Mtingwa (B-M), Part. Accel. 13 (1983) 115: using the scattering matrix formalism; valid for strong focusing machines; approximations valid for ultrarelativistic beams only

- M. Martini, CERN PS/84-9 (AA) 1984: (extended Piwinski's model) valid for strong focusing machines.

- M. Conte, M. Martini, Part. Accel. 17 (1985) 1: B-M theory adapted to include non-ultrarelativistic corrections

- and several approximations for practical purposes in some regimes of applicability (Wei, Parzen, Bane, Rao and Katayama, …), as well as refinements of the standard theories above, …

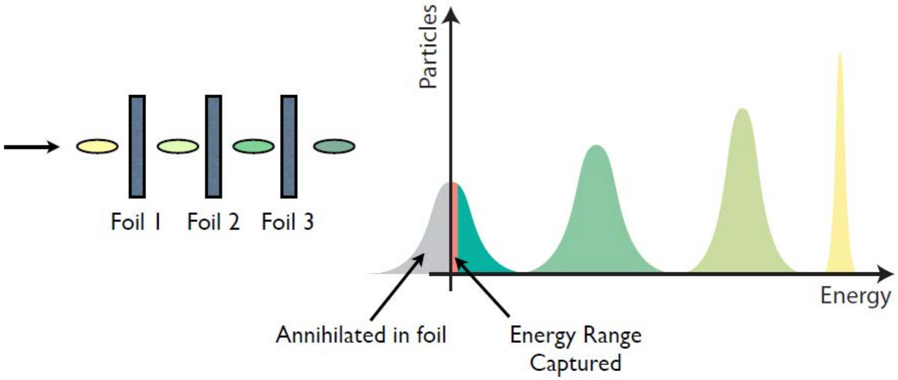
Reservoir

Context

- The **Antiproton Decelerator (AD)** at CERN provides low-energy antiprotons (5.3 MeV kinetic energy) for different experiments dedicated to the production of antihydrogen and measurement of its properties

- In today's set-up, about 99.9% of the antiprotons produced by the AD are lost due to the experiments' use of degrader foils needed to further decelerate them from the AD ejection energy (5.3 MeV) down to around 5 keV, the energy needed for trapping

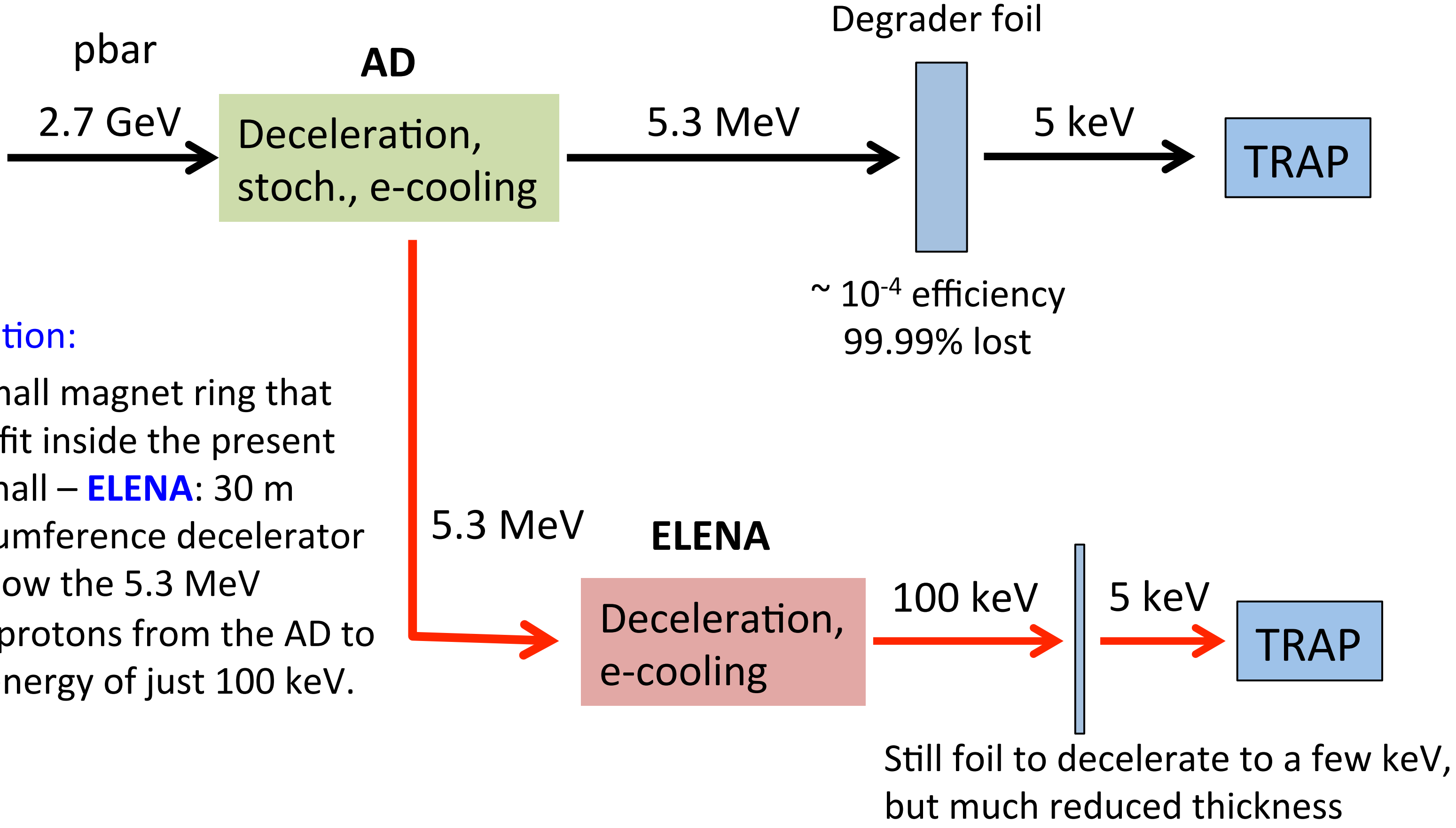
From N. Madsen, Antiproton catching for antihydrogen experiments,
ELENA Beam Physics and Performance Committee (19 July 2012):



Energy straggling increases energy spread such that only few antiprotons can be captured

Context

Current setup:



pbar

2.7 GeV

AD

Deceleration, stoch., e-cooling

5.3 MeV

Degrader foil

5 keV

TRAP

~ 10^{-4} efficiency
99.99% lost

5.3 MeV

ELENA

Deceleration, e-cooling

100 keV

5 keV

TRAP

Still foil to decelerate to a few keV, but much reduced thickness

The solution:

- A small magnet ring that will fit inside the present AD hall – **ELENA**: 30 m circumference decelerator to slow the 5.3 MeV antiprotons from the AD to an energy of just 100 keV.

ELENA will bring a 10 to 100-fold increase in the experiments' efficiency, as well as the possibility to accommodate an extra experimental area to investigate gravitation with antihydrogen (GBAR)

ELENA overview

- **ELENA parameters**

For a coasting beam

Parameter	1st plateau	2nd plateau
Beam momentum	**35 MeV/c**	**13.7 MeV/c**
Initial *Δp/p*	0.1%	0.05%
Initial 1σ emittance	8 π mm mrad	2.8 π mm mrad
Beam intensity	$2.5\text{x}10^7$	$2.5\text{x}10^7$
Average beta function β_T	3 m	3 m
Average dispersion D_x	1.2 m	1.2 m
ELENA acceptance A_T	75 µm	75 µm
Vacuum pressure	$3\text{x}10^{-12}$ Torr	$3\text{x}10^{-12}$ Torr
Gas density *n* (at room *T*)	$9.6\text{x}10^{10}$ m^{-3}	$9.6\text{x}10^{10}$ m^{-3}

Electron cooler

- **ELENA e-cooler system parameters for the simulations**

From ELENA TDR, CERN-2014-002 (2014):

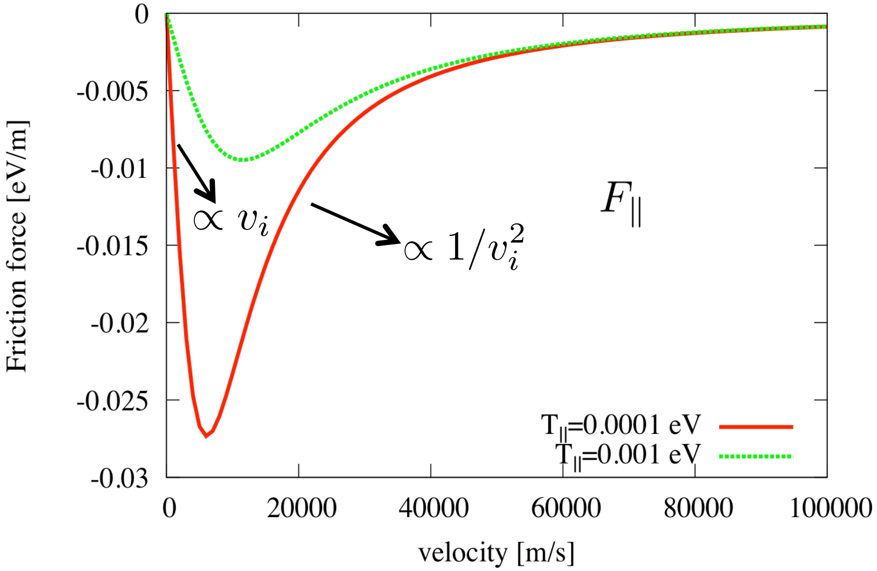
Parameter	Value
Momentum [MeV/c]	35 - 13.7
Velocity factor β=v/c	0.037 – 0.015
Electron beam energy [eV]	355 - 55
Electron current [mA]	5 - 2
Electron beam density [m^{-3}]	1.38×10^{12} – 1.41×10^{12}
B_{gun} [G]	1000
B_{drift} [G]	100
Expansion factor	10
Cathode radius [mm]	8
Electron beam radius [mm]	25
Twiss parameters [m]	β_x=2.103, β_y=2.186, D_x=1.498
Flange-to-flange length [mm]	1930
Drift solenoid length [mm]	1000
Effective length (good field region) [mm]	700
Electron beam transverse, longitudinal temperature [eV]	0.01, 0.001

Electron cooling

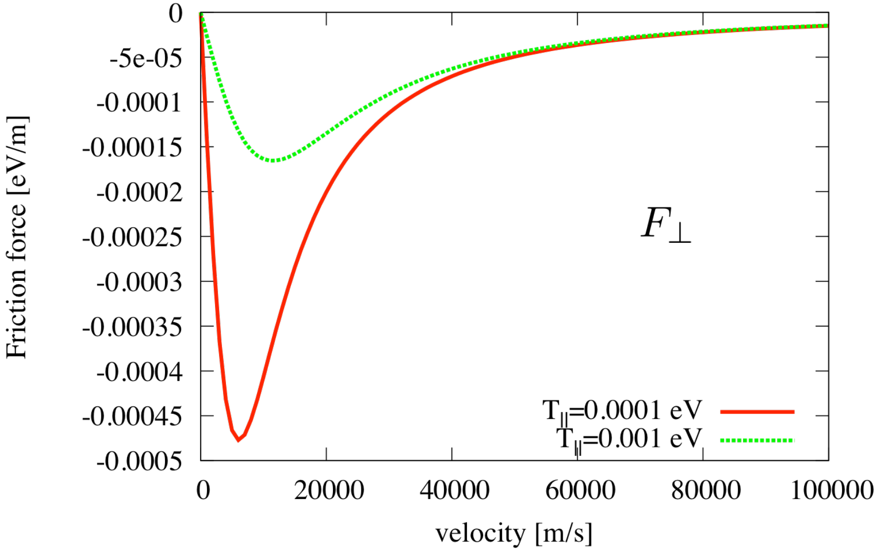
- **Friction force:**

The corresponding **friction force vs ion velocity**:

Longitudinal



Transverse



F peak (for T_{tr}=0.01 eV and T_{long}=0.0001 eV)= -0.027 eV/m, at v_i=6000 m/s
F peak (for T_{tr}=0.01 eV and T_{long}=0.001 eV)=-0.0095 eV/m, at v_i=11000 m/s

F peak (for T_{tr}=0.01 eV and T_{long}=0.0001 eV)= -0.00048 eV/m, at v_i=6000 m/s
F peak (for T_{tr}=0.01 eV and T_{long}=0.001 eV)=-0.00016 eV/m, at v_i=11000 m/s

Intrabeam scattering

IBS heating rates

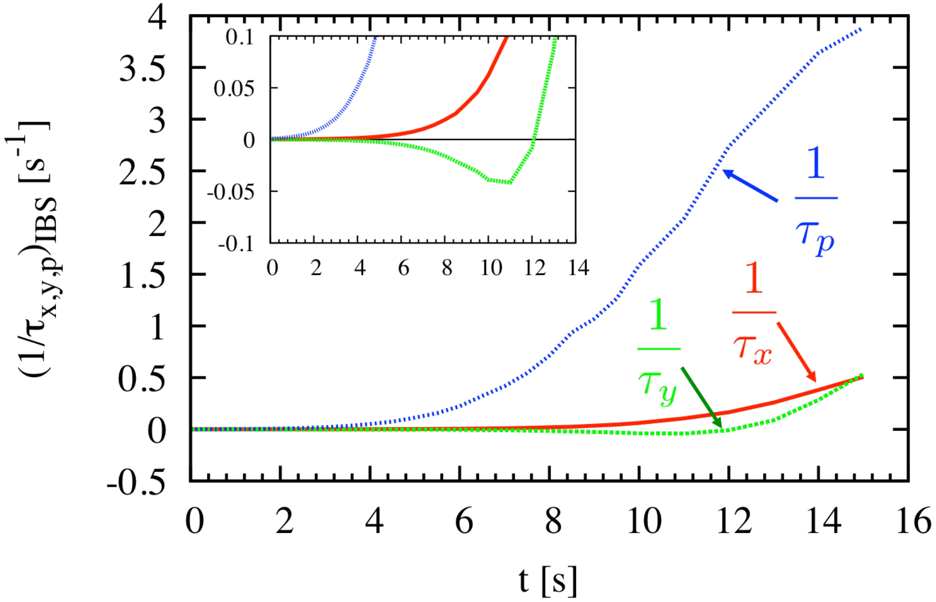
$$\boxed{\frac{1}{\tau_x}, \frac{1}{\tau_y}, \frac{1}{\tau_p} \propto \frac{r_p^2 c}{32\pi\sqrt{\pi}\beta^3\gamma^4\epsilon_x\epsilon_y\sigma_p}\lambda}$$

$$\lambda = \begin{cases} N/C & \text{for coasting beams} \\ N_b/(2\sqrt{\pi}\sigma_s) & \text{for bunched beams} \end{cases}$$

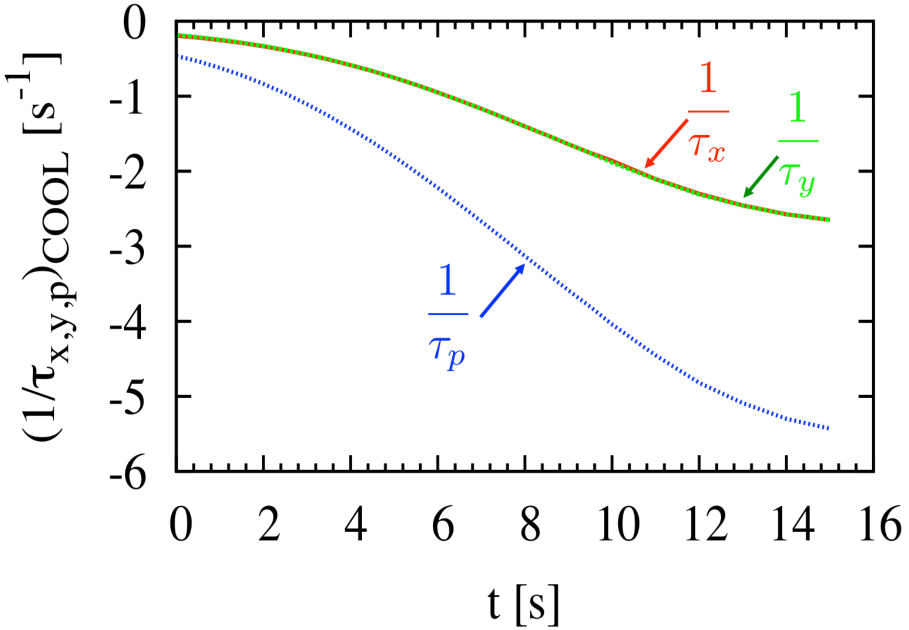
IBS becomes stronger when the phase space volume of the beam is reduced by cooling, thus limiting the achievable final emittances

Beam dynamics

- 1^{st} cooling plateau, p=35 MeV/c, coasting beam
- Electron cooling process in presence of rest gas and IBS



IBS growth rates

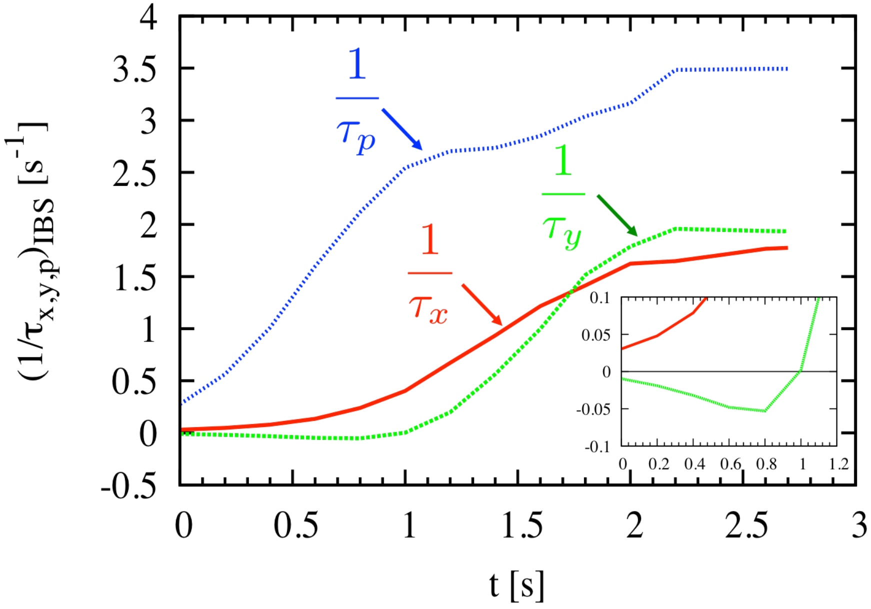


Cooling rates

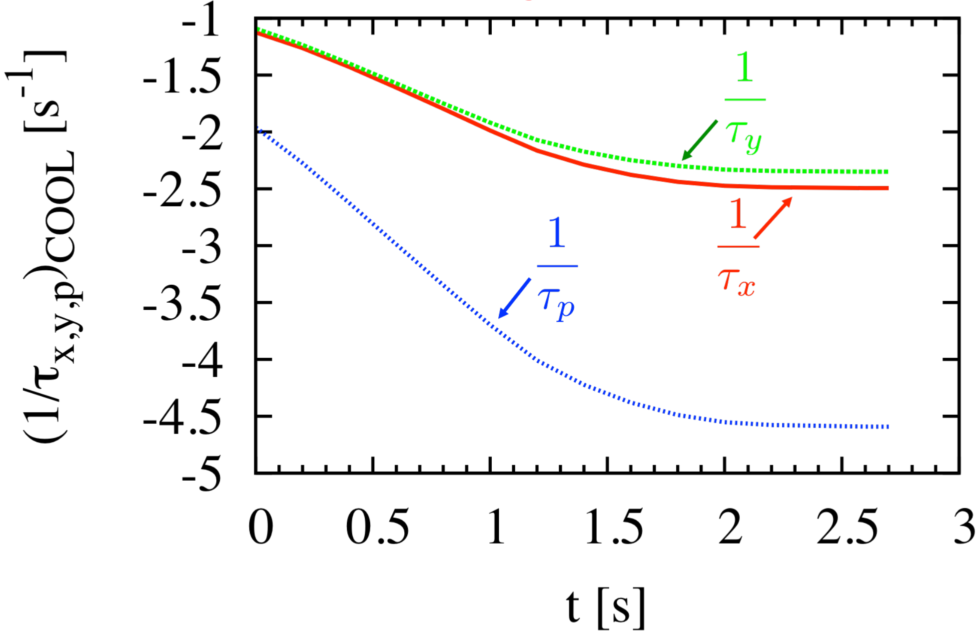
After 8s cooling, equilibrium is not yet reached
$(1/\tau_y)_{IBS}$ changes sign from negative (damping or cooling) to positive (heating) at t ≈13 s

Beam dynamics

- **2nd cooling plateau, p=13.7 MeV/c, coasting beam**
- **Electron cooling process in presence of rest gas and IBS**



IBS growth rates



Cooling rates

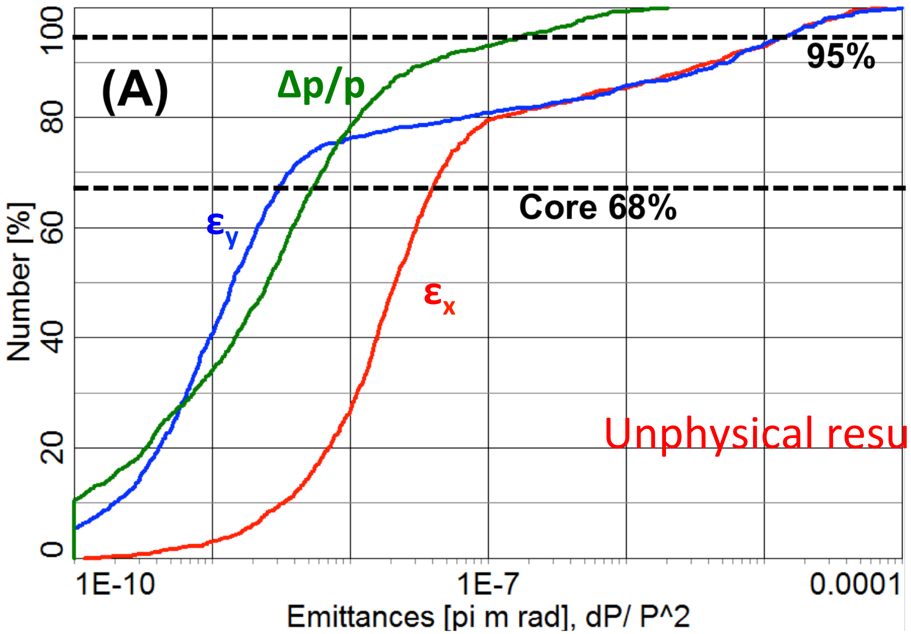
Equilibrium practically reached after 2 s cooling
$(1/\tau_y)_{IBS}$ changes sign from negative (damping or cooling) to positive (heating) at t ≈ 1 s

Beam dynamics

- **Electron cooling process in presence of rest gas and IBS**

  Invariant distributions

1st cooling plateau, p=35 MeV/c



Unphysical result?

Core emittances (68%) ~ 10^{-8} , 10^{-9} π m rad
95% emittances ~ 10^{-5} π m rad

Very dense core
Long tails highly populated

Standard models of IBS, such as the Martini model, are based on the growth of the rms beam parameters of a Gaussian distribution. These models underestimate the IBS effect for beam distributions far from Gaussian.

Further investigation to prevent overcooling:

- Apply "core-tail" models
- Apply a "Local" model: it takes a lot of computation time!

Space charge

- Space charge limit N for a stored antiproton beam with **ΔQ=-0.1**

Incoherent tune shift due to space charge effects:

For a Gaussian distributed round beam:

$$\Delta Q_{sc} \approx -\frac{r_p N}{4\pi\beta^2\gamma^3\epsilon} B_f^{-1}$$

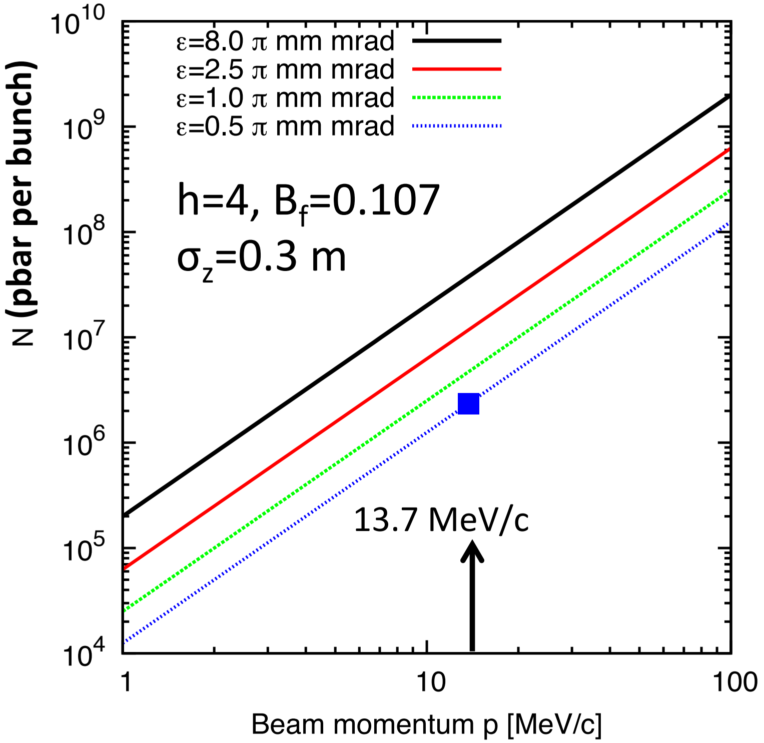
where B_f is a bunching factor:

$$B_f = \frac{\langle I \rangle}{\hat{I}} \begin{cases} 1 & \text{if coasting beam} \\ \frac{\sqrt{2\pi}\sigma_z}{C} h & \text{if bunched beam} \end{cases}$$

Here we have taken the rms emittance ϵ

h is the harmonic number

Bunched beam



4 bunches, assuming $\epsilon_{x,y}$≈0.5 π mm mrad

N_{total} ≈ 1x10^7