Report on Operation of Antiproton Decelerator

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- What for AD is?
- How AD works
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- Down to lower energies (ELENA ring)
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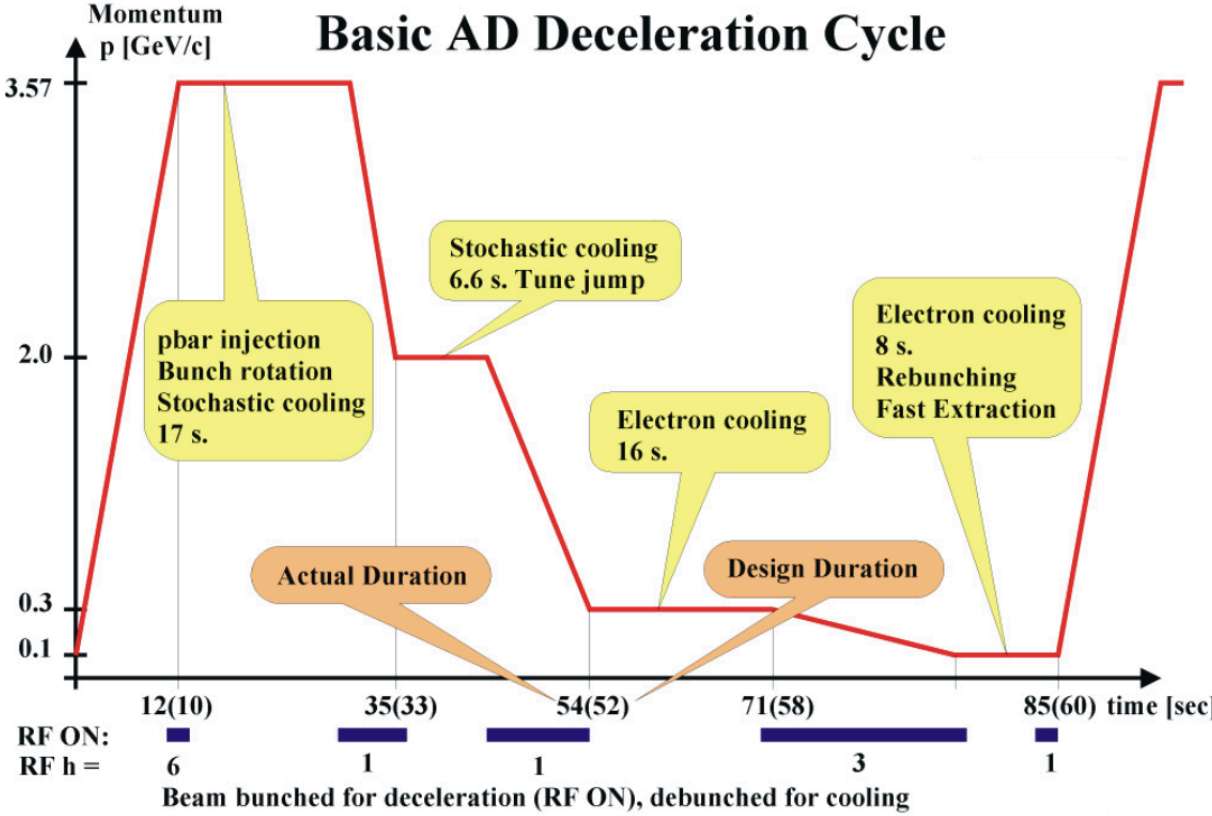
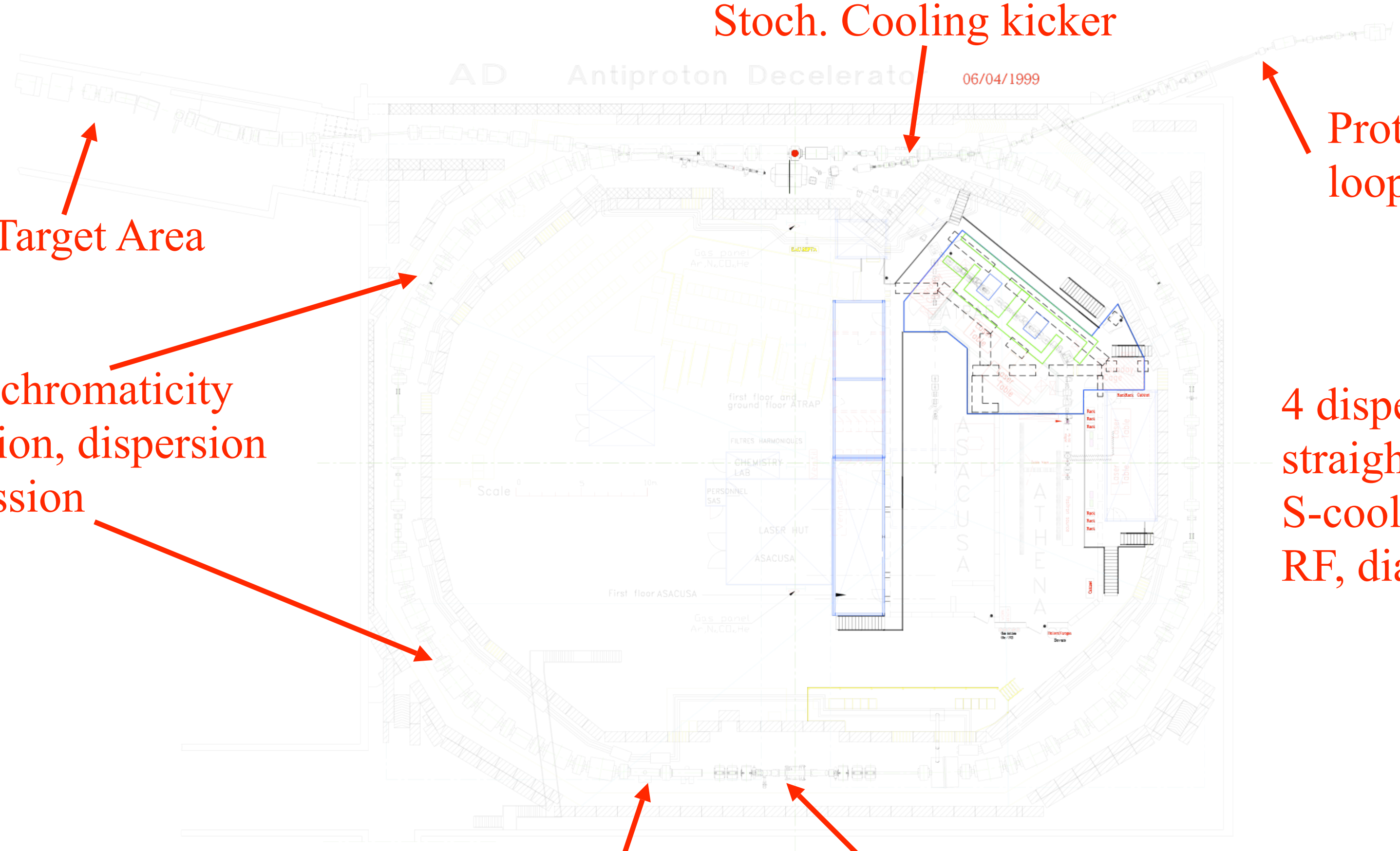
What for AD is?

- Physics and biology studies with low energy antiprotons
- ATHENA and ATRAP experiments aimed on production and study of antihydrogen atoms
- ASACUSA experiment is aimed to atomic spectroscopy studies with antiprotons
- AD-4 experiment is aimed on studies of potential of antiprotons for radiation therapy


Momentum
p [GeV/c]
Basic AD Deceleration Cycle
3.57
2.0
0.3
0.1
pbar injection
Bunch rotation
Stochastic cooling
17 s.
Stochastic cooling
6.6 s. Tune jump
Electron cooling
16 s.
Electron cooling
8 s.
Rebunching
Fast Extraction
Actual Duration
Design Duration
12(10)
35(33)
54(52)
71(58)
85(60) time [sec]
RF ON:
RF h =
6
1
1
3
1
Beam bunched for deceleration (RF ON), debunched for cooling

AD Ring and Hall



Operational statistics

Run time (h)	2000	2001	2002	2003	2004
Total	3600	3050	2800	2800	3400
Physics	1550	2250	2100	2300	3090
MD	2050	800	700	500	310
Uptime	86%	89%	90%	90%	71%

Faults in 2004

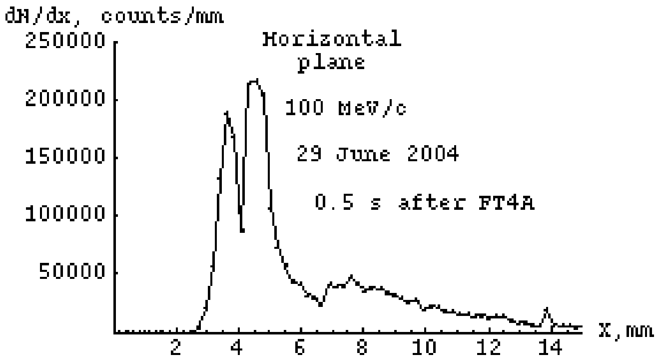
- PS ejection septum
  - Water leak May – 1 week stop to replace with spare unit.
  - Spare unit develops same failure in July – 3 weeks stop to repair spare and install.
- AD electron cooler vacuum
  - 2 weeks stop in June, excessive outgassing in collector region believed to have caused de-activation of NEG:s. Disassembly, inspection, replacement of all suspect equipment, bakeout.
  - Replacement of all NEG's will be done in 2005.

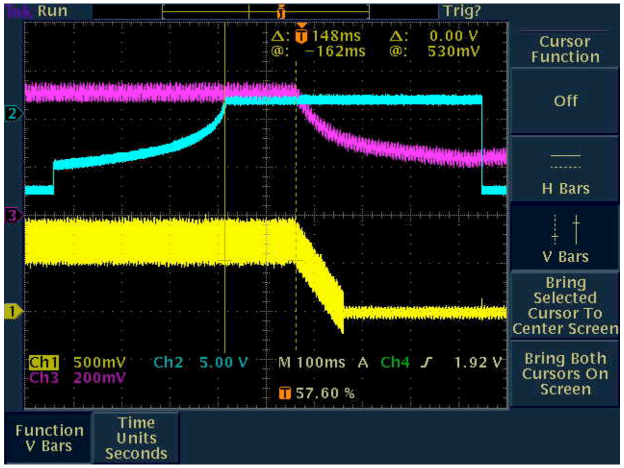
Progress in beam intensity

Np (3.5 GeV/c)	5.15 e7	100 %
Np (2 GeV/c)	5.0 e7	97 %
Np (300 MeV/c)	4.21 e7	81 %
Np (100 MeV/c ramp)	4.27 e7	82 %
Np (100 MeV/c end)	4.26 e7	82 %
DETFA7049	4.22 e7	81 %
dp/p (3.5 GeV/c)	26.975	0.857
dp/p (2GeV/c)	1.656	0.265
dp/p (300MeV/c)	1.37	0.136
dp/p (100 MeV/c)	0.54	0.32

Improving of ejected beam emittances

- Filamented transverse structure of the beam “core”
- Extended tails
- Cross-talk between RF and e-cooling during beam bunching: longitudinal emittances improved resulting in shorter bunch length of 90 ns
- Extra cross-talk during debunching before electron cooling

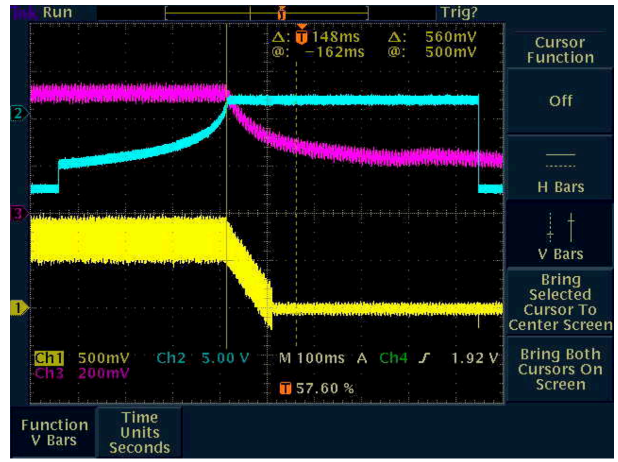


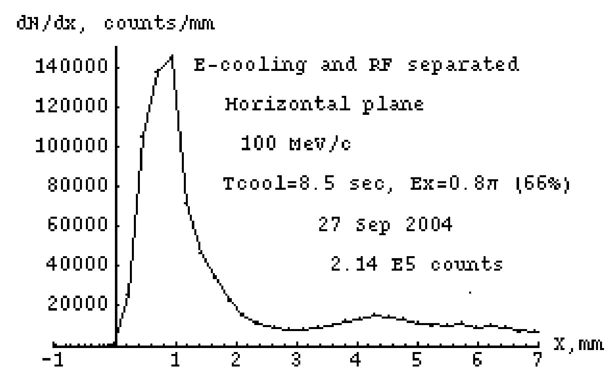


Improving of ejected beam emittances (cont.)

New setting provides 20% longer momentum spread (still factor 2 better than with electron cooling off during beam bunching) with much better transverse profile

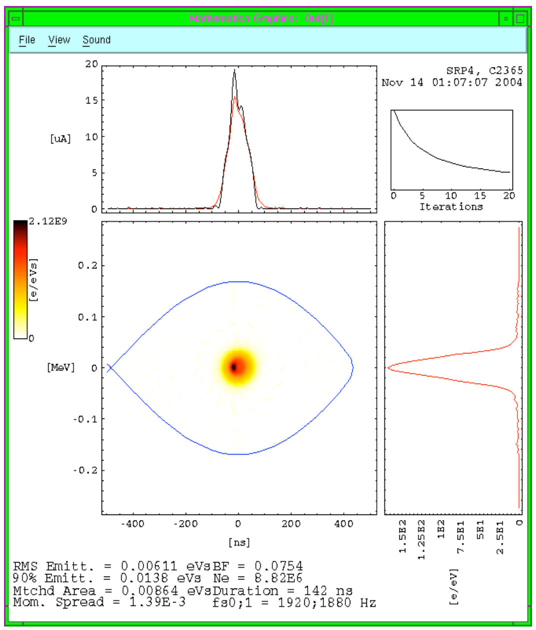
Extra cross-talk during debunching before electron cooling eliminated

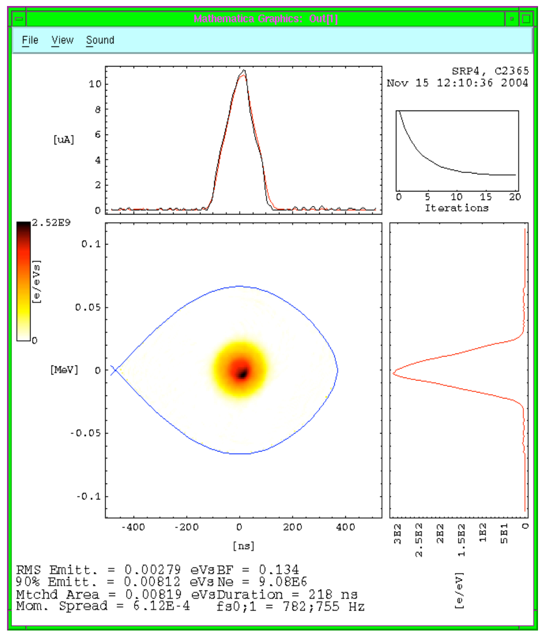




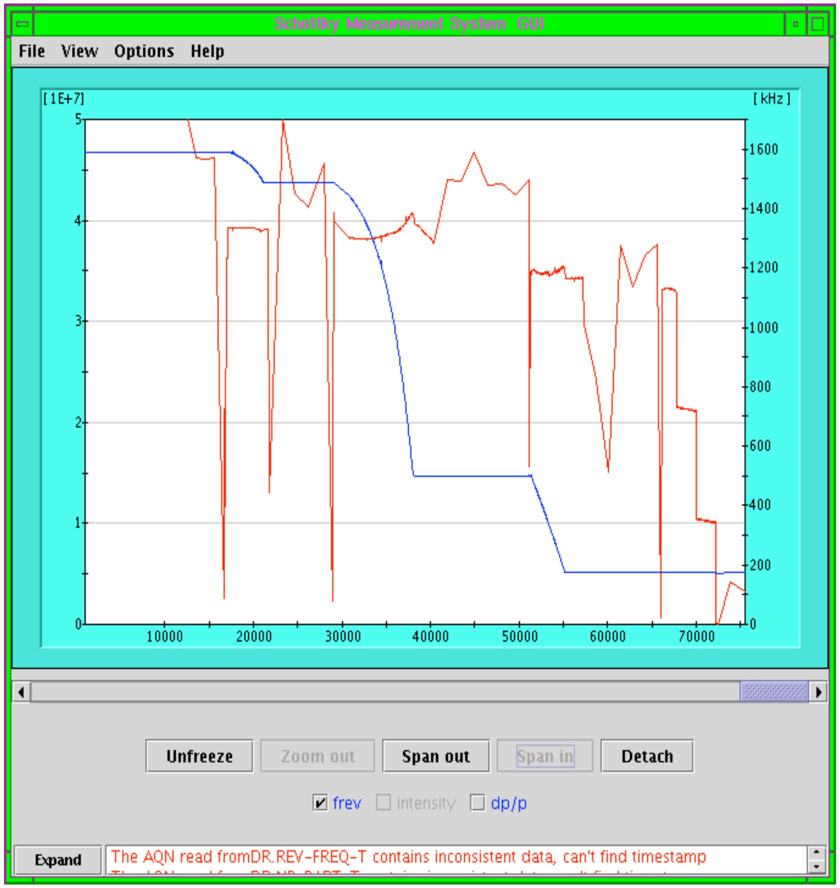
Reduction of Δp/p

- Deceleration 300-100 MeV/c with reduced voltage (3kV –> 500V)
- Smaller bucket->bigger spread of synchrotron frequencies -> stronger damping -> Δp/p halved at 100MeV/c





Multiejection



- Simple scheme introduced at 100 MeV/c using existing RF-HW – minimal modifications.
- Bunching on h=1,3 or 6 is possible with present RF-HW
- 2.4 s. rep.rate imposed by ejection magnets.
- Good efficiencies and beam lifetime obtained. (12 s. longer coast at 100 MeV/c @ h=6)

AD performance: beam intensity limitations

- Production beam: 1.5 10^{13} on the target, only small improvements can be obtained in PS complex, mainly limited by beam space charge in PS Booster
- 25% increase could be gained with 5 bunch production beam (now 4), need 2 injections/cycle into PS and 3.6 (now 2.4) s cycle. Modifications in PS are required
- Stacking in the longitudinal phase space, about 50% pbars/sec gain expected. Modifications in PS and set up in AD required
- Losses during stochastic cooling: bigger voltage in bunch rotation cavities or shorter bunches from PS could help
- Transverse acceptances at injection energy close to optimum
- Losses during cycle optimized vs. cycle length/rep. rate

AD performance: cycle length limitations

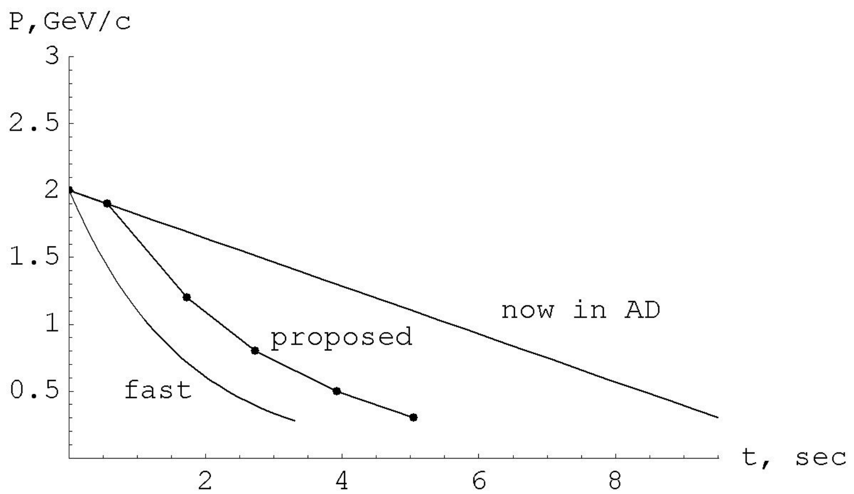
- Ramp lengths: field lag due to eddy currents modifies tunes and orbits on ramps and arrival at plateaus
- Fast eddy currents in vacuum chamber (few msec) can modify tunes as much as 0.01 and provoke orbit excursions up to 40 mm at 300 MeV/c, nothing can be done for this
- Slow eddy currents (magnet end plates, seconds) compensated by special programming of power supplies for B-main only
- Intensity losses are defined by ramp slope (15% on ramp 2 Gev/c -> 300 MeV/c)
- Tunes and orbits cannot (yet) be measured on ramps

Cycle length limitations: ramps

Ramp shape can be further optimized: 1/B dB/dt must be constant

for optimal speed of deceleration, keeping effect of eddy current

the same for different momenta



Cycle length limitations: plateaus

- Stochastic cooling well optimized, no extra shortening possible
- Electron cooling slower than design value, possible explanations:
    - eddy currents in magnet end plates decay slowly, causing orbit drift
    - beams alignment problems at 300 MeV/c due to limited strength of correctors in use
- Simulations with BETACOOL shows that for current vacuum $5\ 10^{-10}$ Torr magnetization is optimal

Cooling performances

Parameters		Design	2004
at 3.57 GeV/c	Number of antiprotons, 10^7 h / v acceptances, π mm mrad Stochastic cooling time, sec h/v emittances (2σ), π mm mrad momentum spread (4σ), 10^{-3}	5 220 / 190 20 5 1	5 200 / 180 17 3 1
at 2 GeV/c	Stochastic cooling time, sec h/v emittances (2σ), π mm mrad momentum spread (4σ), 10^{-3}	15 5 0.3	6.6 3 0.15
at 300 MeV/c	Electron cooling time, sec h/v emittances (2σ), π mm mrad momentum spread (4σ), 10^{-3}	6 2 / 2 1	13.8 2 / 4 0.1
at 100 MeV/c	Electron cooling time, sec h/v emittances (2σ), π mm mrad momentum spread (4σ), 10^{-3}	1 1 0.1	8.4 1 (core) 0.1

AD performance limitations: beam lines

- Experimental area beam line switching:
  - Delays due to inherent AD stability problems at low energy
  - Re-tuning of lines often necessary, slow process due to slow repetition rate and destructive BPMs
  - Non-destructive BPMs would allow on-line measurements and corrections
  - Manpower and financial resources needed…

2006 Run

On the (officially approved) schedule:

- Reduced physics run: June 5 – September 3
- 7d/7, 24h/24 = approximately 2000 h of physics.

Extra Low Energy Antiproton Ring (ELENA) for antiproton deceleration after the AD

- 5.3 MeV antiprotons still too fast for use in experiments, they have to be slow down
- Experiments with antihydrogen program (ATHENA and ATRAP) use degraders to slow 5.3 MeV beam further down: poor efficiency due to adiabatic blow up and due to scattering in degrader
- ASACUSA uses RFQD for antiproton deceleration down to around 100 keV kinetic energy. Due to absence of cooling beam deceleration in RFQD is accompanied by adiabatic blow up (factor 7 in each plane) which causes significant reduction in trapping efficiency.

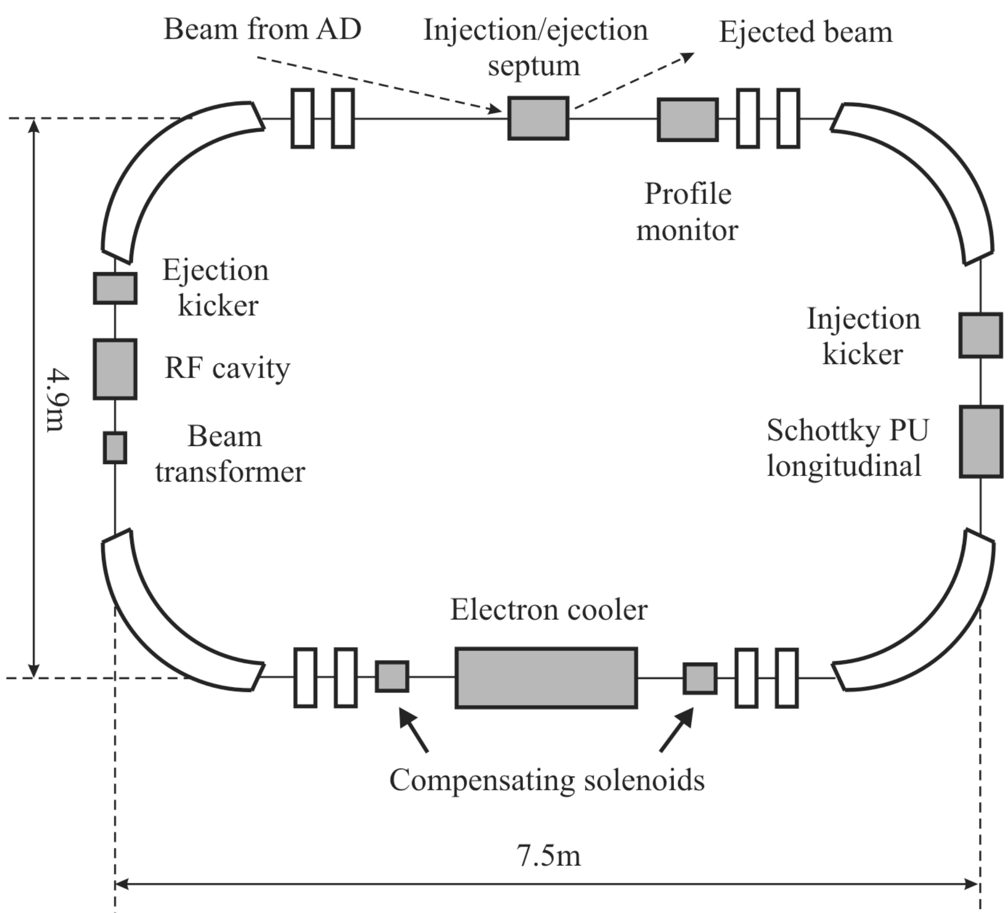
How do we gain in intensity with extra deceleration and cooling ?

- Small ring could be used to decelerate antiproton beam down to 100 keV and cool by electron beam to high density
- Emittances of beam passing through a degrader will be much smaller than now due to electron cooling and a much thinner degrader (100 keV beam instead of 5.3 MeV) => two orders of magnitude gain in intensity is expected for ATHENA and ATRAP.
- Due to cooling, beam emittances after deceleration in ELENA will be much smaller than after RFQD => one order of magnitude gain in intensity is expected for ASACUSA.
- Kinetic energy 100 keV is close to optimal both from the point of view of beam intensity, momentum spread and separation of transfer line and trap vacuum.

Requirements to ELENA:

- Compact machine located inside of AD Hall with minimum of reshuffle.
- Energy range from 5.3 MeV (AD extraction energy) down to 100 keV.
- Equipped with electron cooler to make beam phase space smaller in about two orders of magnitude with respect what we have today
- Machine assembling and commissioning has to be done without disturbing current AD operation.

ELENA layout

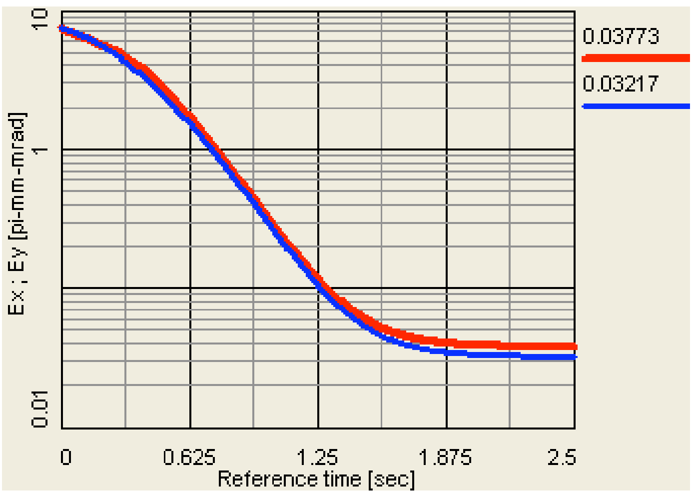


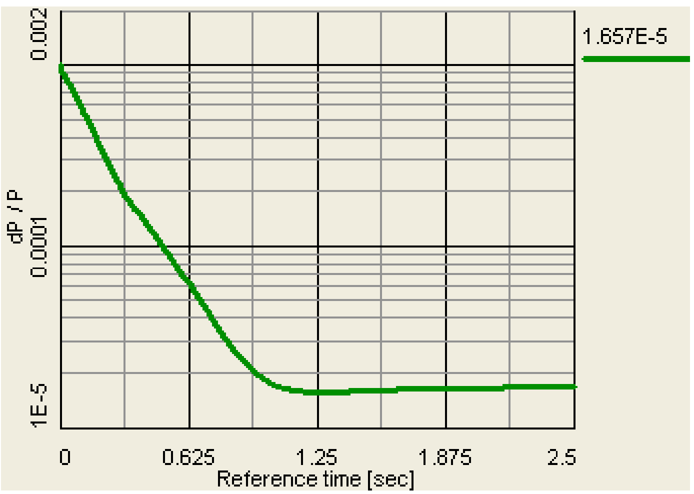
Electron cooler for ELENA

- Fast electron cooling required to maintain small beam emittances and counteract IBS and gas scattering at low energies
- Cooling used twice: at intermediate energy about 900 keV (40 MeV/c) and final energy 100 keV
- 1 m cooling length, with integrated correctors, 90° bent to minimize space, coated with NEG's
- careful cooler design which provides low transverse temperatures of electron beam at very low energies needed for fast cooling

Cooling in ELENA: simulations with BETACOOL

cooling + residual gas with P=1 10^{-11} Torr, electron beam temperatures Te=0.1eV / 0.001 eV, B=100 Gs, I_e=2mA





Parameters of electron cooler for ELENA

Cooling length, m	1
Voltage, V	490 / 54
Electron beam current, mA	55 / 2
Beam temperature, eV (transv / long)	0.1 / 0.001
Beam radius, cm	2.5
Perveance, μP	5
Magnetic field, Gs	150
$\beta_x/\beta_y/D_x$, m (unperturbed machine)	2.3 / 3 / 2.3
Full cooling time at 100 keV, s	2

ELENA optics

- Beam focusing is achieved (mainly) by proper choice of edge angle of the dipoles.
- Quadrupoles required to compensate effects of cooler on lattice (tune shift, coupling), which is stronger at low energies
- Big area in tune diagram should be available for tune excursion caused by space charge. Conservative estimate for coherent tune shift $\Delta Q = 0.10$ was accepted which is based on CERN Booster, PS and AD experience.
- Tunes $Q_x=1.45$, $Q_y=1.43$ (the same non-integer parts as in the AD) fit requirements.
- Choice of tunes together with required straight section lengths defines machine circumference which is about 23m.

ELENA: effects of cooler on machine optics

- Tune shifts due to electron beam

$$\Delta Q_{x,y} = \frac{r_p n_e l_c \langle \beta_{x,y} \rangle}{2\beta_0^2 \gamma^3}$$

where r_p=1.53 10^{-18}m, n_e is electron beam density, l_c is cooling length, $<\beta>$ is average beta function in cooler and β_0 and γ are relativistic factors. For ELENA parameters at 100keV $\Delta Q \approx 0.016$, 4 times bigger than in AD.

- Compensation is straightforward, 2 quadrupole families required

ELENA: effects of cooler on machine optics (continued)

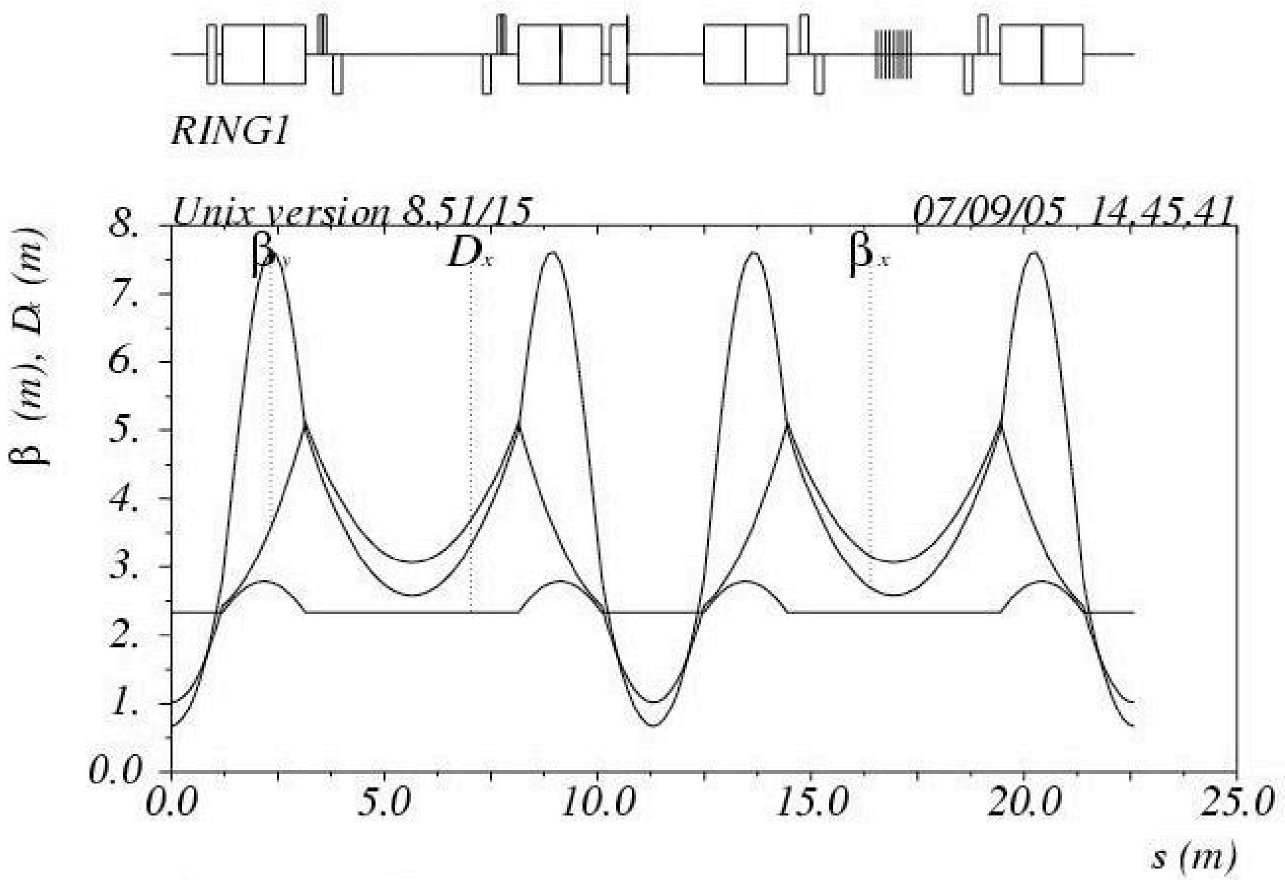
Tune shift due to solenoidal field B_s in cooler and compensators

$$\Delta Q = \frac{R}{32\pi (B\rho)^2} \int_0^{2\pi} \beta_y B_s^2 d\theta$$

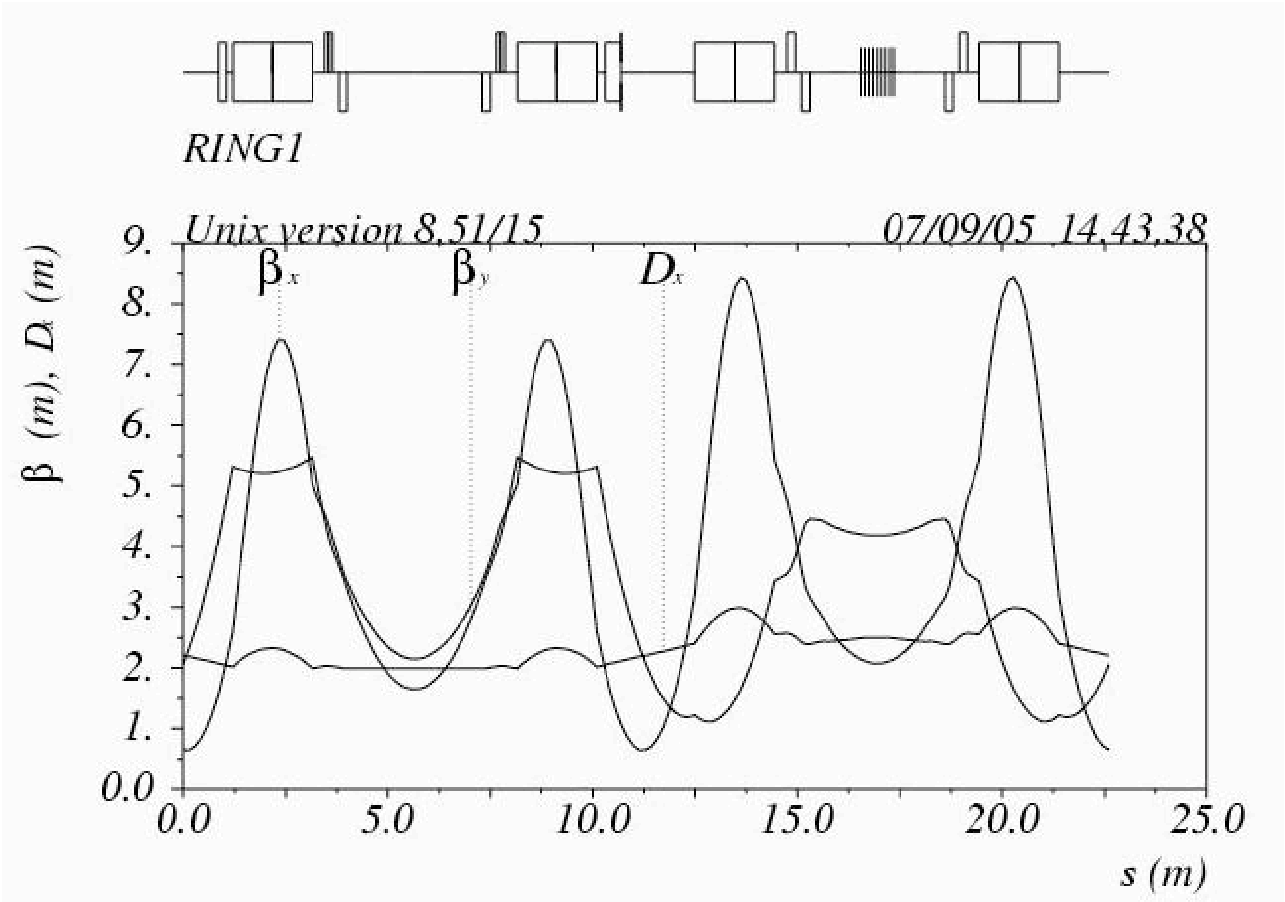
is as large as 0.275. To handle with this, one has to:

- prepare machine with focusing properties of bending magnets which provides smaller tunes, say 1.38 / 1.36
- use 4 quadrupole families to keep tunes constant during ramp and maintain “reasonable” optics at low energies
- make careful beam-based optics set up on ramps, and have diagnostics for this

ELENA: optics with cooler off



ELENA: optics with cooler on



ELENA: intensity limitation due to space charge

The incoherent tune shift for beam with N_b particles is

$$\Delta Q_y = \frac{r_p N_b}{\pi \varepsilon_y (1 + \sqrt{\varepsilon_x / \varepsilon_y}) \beta_0^2 \gamma^3 B_b} \quad ,$$

where B_b is bunching factor (ratio of bunch length and machine circumference) and 2D Gaussian distribution assumed.

The limitation is more severe:

- At low energies
- For bunched beam

ELENA: intensity limitation due to space charge (continued)

Examples:

- AD beam before extraction, 3 10^7 antiprotons, 100 ns long, $\varepsilon_{x,y}$=1 π mm mrad => ΔQx,y=-0.074.
- ELENA, 1.5 10^7 antiprotons at the end of deceleration (50% deceleration efficiency assumed), bunched beam occupies 1/3 of ring circumference, $\varepsilon_{x,y}$=10 π mm mrad => ΔQx,y=-0.01 => no problems during deceleration.
- ELENA, 1.3 10^7 antiprotons in bunched beam before extraction, 300 ns long, $\varepsilon_{x,y}$=5 π mm mrad => ΔQx,y= -0.10
- Accepting conservative estimate for allowed tune shift 0.1, one comes to limitations on beam intensity and emittances mentioned above

ELENA: Could we relax intensity limitation due to space charge?

- AD cycle is much longer than ELENA cycle expected duration
- Ejection from ELENA could be done in few shots (as now in AD for one experiment)
- Time separation between ejections defined by experiments (10 to 20 sec expected)
- Beam stays at 100 keV with cooling on
- RF system has to to fit requirements

Lifetime considerations:

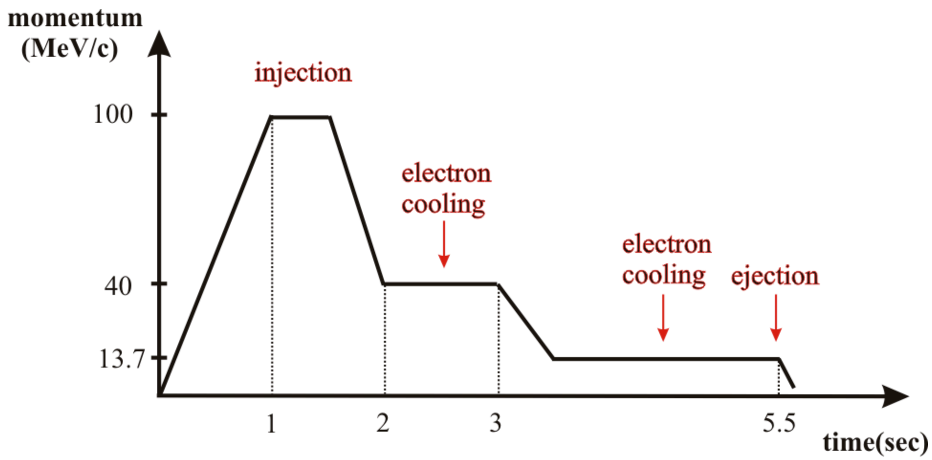
- Residual gas scattering produces beam blow up 0.5π mm mrad/s at energy 100 keV and pressure $3\ 10^{-12}$ Torr.
- Electron cooling at 100 keV is strong enough to fight successfully residual gas scattering.
- Intrabeam scattering (IBS) is important at very low energies in a short bunch with small emittances. With beam parameters at 100 keV after cooling ($N_b=1.5\ 10^7$, $\varepsilon_{x,y}=1\pi$ mm mrad and $\Delta p/p=10^{-4}$) emittances go as high as $\varepsilon_{x,y}=2.4\ /\ 0.96\ \pi$ mm mrad and $\Delta p/p=6.4\ 10^{-4}$ during 0.5 sec for bunch length 1.3m
- Beam extraction must be prepared as fast as possible, and RF voltage has to have significant margins keeping in mind beam blow up during the bunching

ELENA main parameters

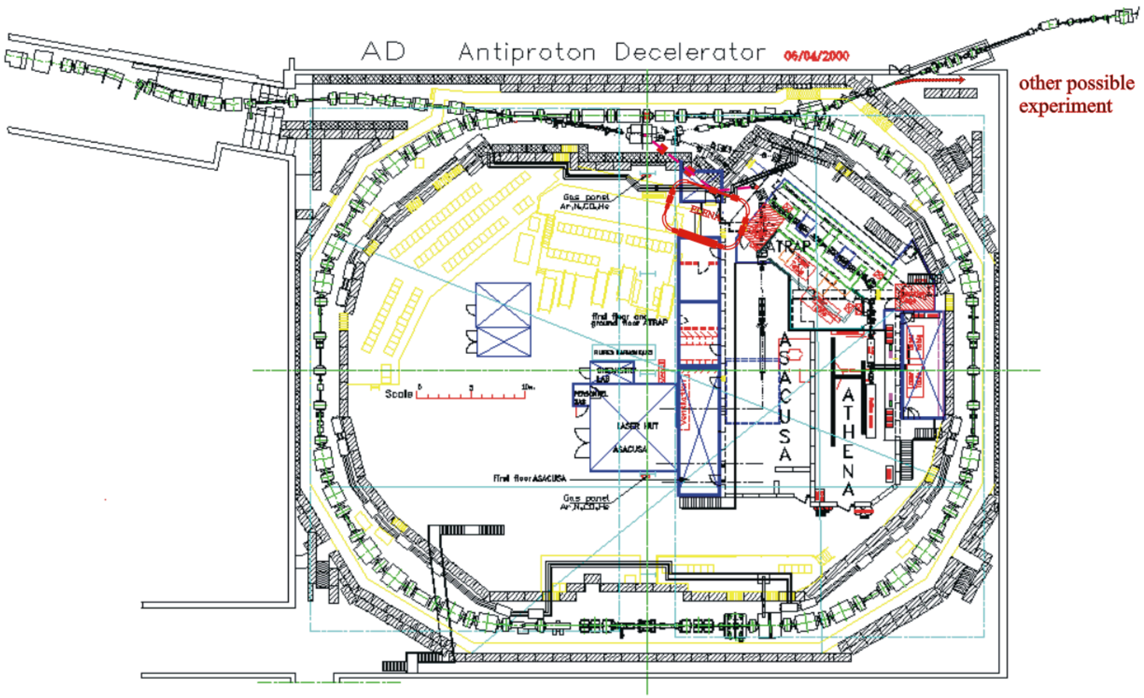
Energy, MeV	5.3 – 0.1
Circumference, m	22.6
Working point	1.45 / 1.43
Emittances at 100 keV, π mm mrad	5 / 5
Intensity limitation by space charge (for 1 bunch)	$1.3\ 10^{7}$
Average antiproton flux, 1/sec	$1.5\ 10^{5}$
Maximal incoherent tune shift	0.10
Bunch length at 100 keV, m / ns	1.3 / 300
Required vacuum for $\Delta\varepsilon=0.5\pi$ mm mrad/s,Torr	$3\ 10^{-12}$
Beam emittances after 0.5s blow up by IBS ($\varepsilon_{x,y}=1\pi$ mm mrad, $\Delta p/p=1\ 10^{-4}$), s	$2.4 / 0.96 / 6.4\ 10^{-4}$

Schematic view of ELENA cycle

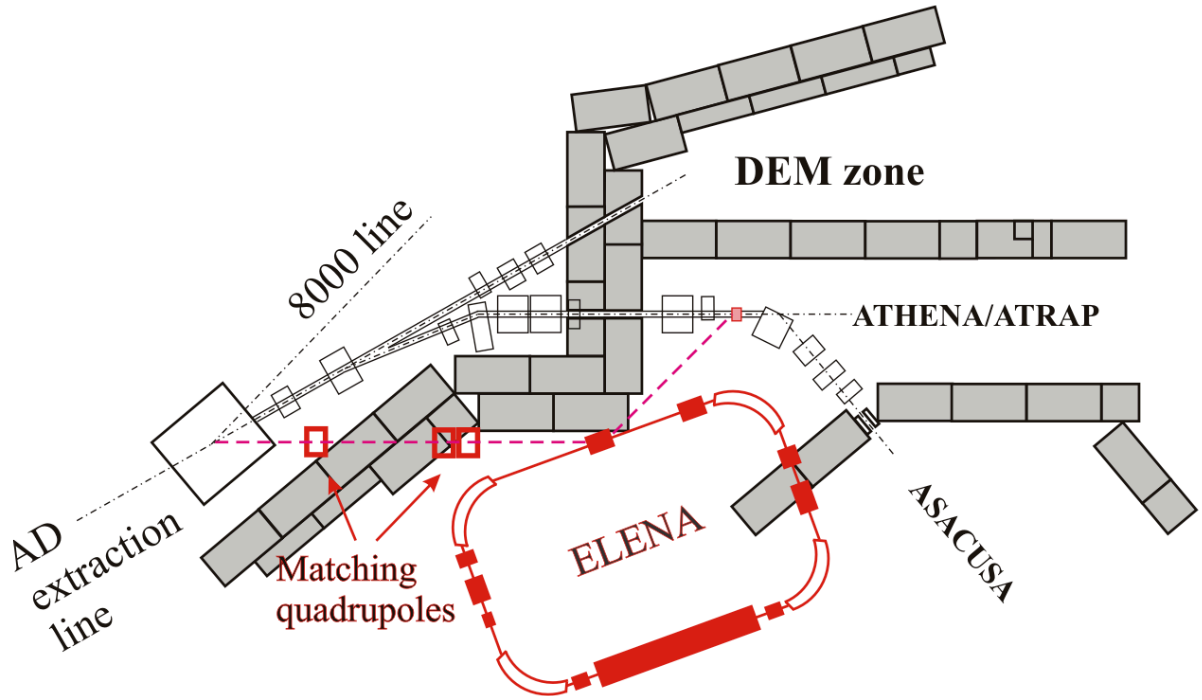
- No electron cooling is performed at injection energy: beam is cooled already in AD. After injection beam is decelerated immediately.
- One intermediate cooling (at 40 MeV/c probably) is needed to avoid beam losses



AD Hall with ELENA



ELENA layout in AD Hall



What has to be done to locate ELENA in AD Hall:

- Shielding rearrangement.
- Water distribution circuits rearrangement.
- One of the barracks on the ground floor has to be moved.
- Small part of ASACUSA experimental area needed (no real problems for physicists are created).
- Part of injection line between BMZ8000 and ELENA must be prepared, including 2 or 3 quadrupoles for matching lattice functions and beam position diagnostics.
- Bending magnet BMZ8000 (may be) needs some clockwise rotation to bend beam from AD ejection line to ELENA injection line.
- Weak bending magnet in ELENA ejection line needed. It brings beam back to existing transfer line.

Conclusions

- A small machine for decelerations and cooling of antiprotons after AD to lower energies around 100 keV is feasible.
- One to two orders of magnitude more antiprotons can be available for physics.
- Main challenges for the low energy decelerator like ultra low vacuum, beam diagnostics and effective electron cooling can be solved, using experience of AD and member-state laboratories where similar low energy ion machines are operational (ASTRID, Aarhus; CRYring, Stockholm).
- The machine can be located inside of the AD Hall with only minor modifications and reshuffling of the present installation.
- Machine assembling and commissioning can be done without disturbing current AD operation.