Status of the Antiproton Decelerator and of the ELENA Project

P.Belochitskii

CERN, Geneva, Switzerland

AD physics goals

- ATHENA and ATRAP experiments aimed on production and study of antihydrogen atoms.
- ASACUSA experiment is aimed to atomic spectroscopy and collisions studies with antiprotons. The study of antihydrogen atom spectroscopy is planned as well.
- AD-4 experiment is aimed on studies of potential of antiprotons for radiation therapy

AD Ring and Hall

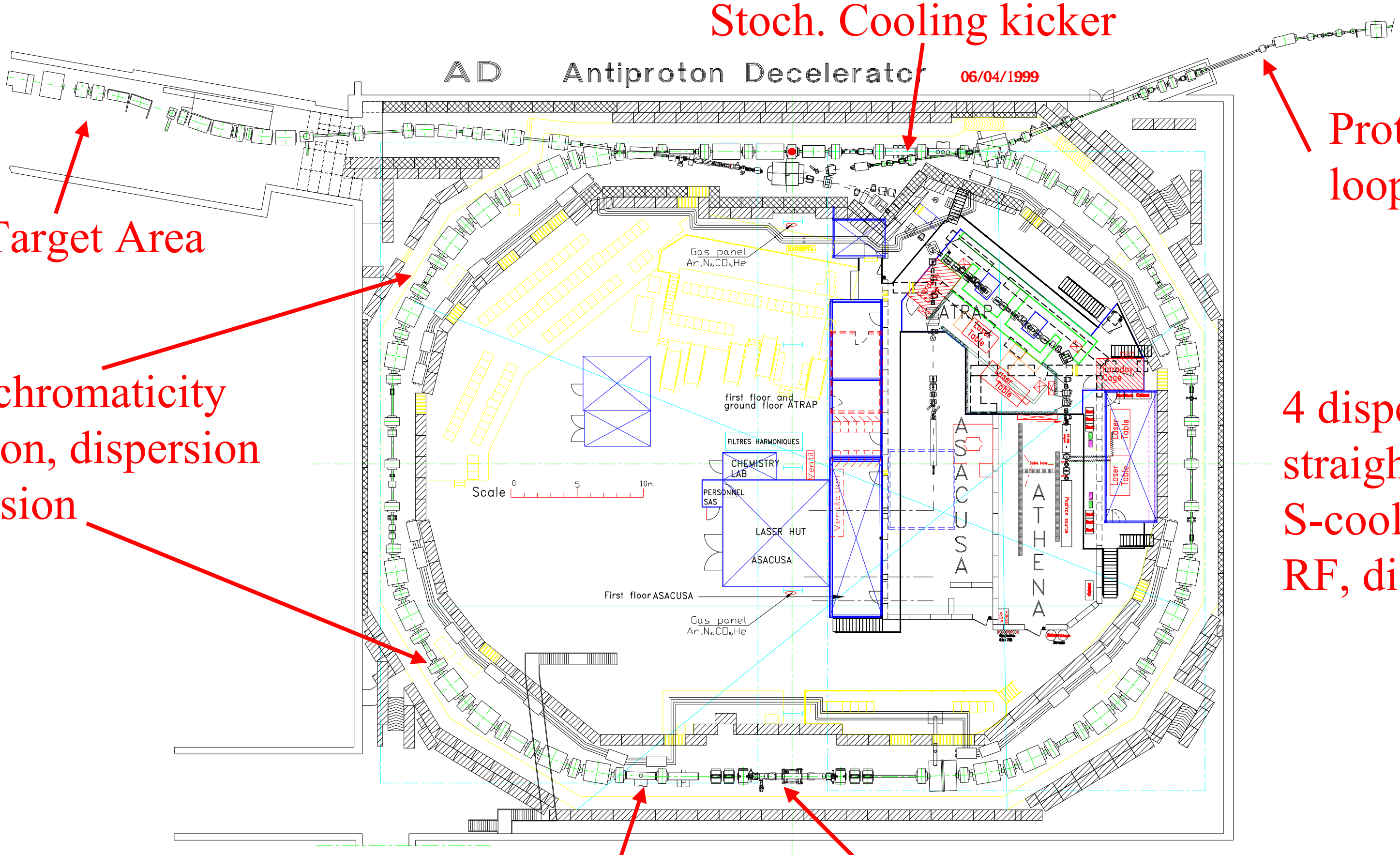
Stoch. Cooling kicker

Protons via loop (TTL2)

Target Area

4 arcs: chromaticity correction, dispersion suppression

4 dispersion free straight sections: S-cool, E-cool, RF, diagnostics

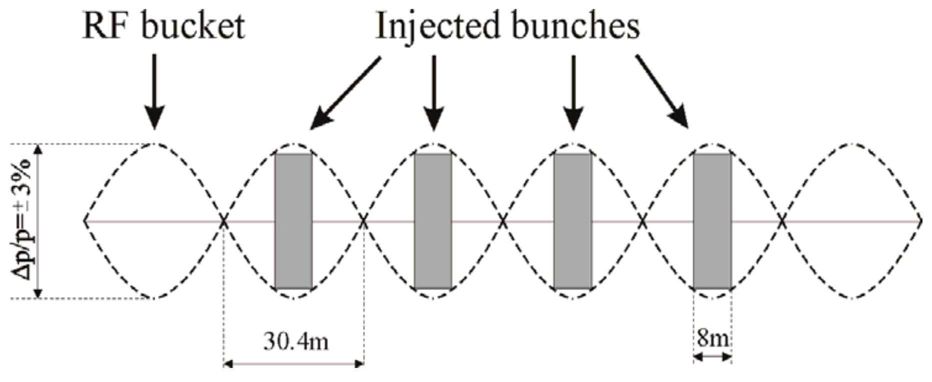


Stoch. Cooling pick-up

Electron Cooling

How AD works

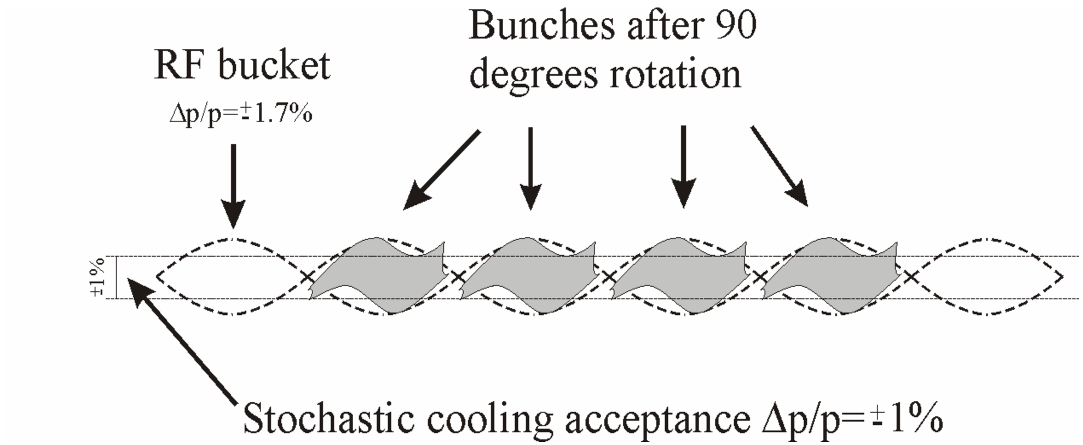
- 26 GeV/c protons from CERN PS delivered to the target in 4 bunches
- Antiprotons collected (magnetic horn), transferred and injected to AD at 3.57 GeV/c. Optics with Q_x=5.385 and Q_y=5.37 provides maximum acceptance for injected beam



- Two 10 MHz RF cavities used (about 0.9 MV totally)

How AD works (continued)

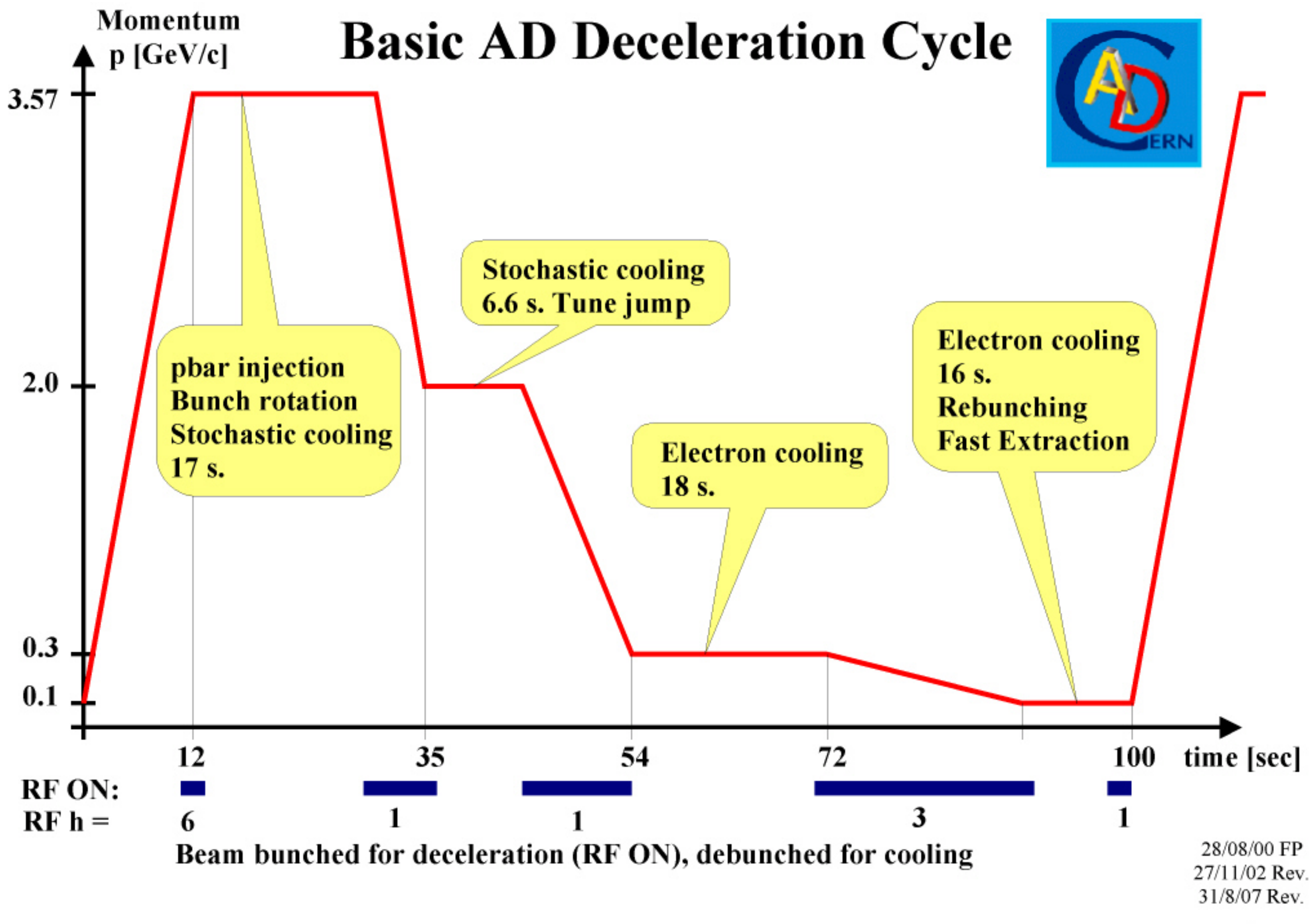
- Short bunches (25ns to 30ns of 100ns bucket length) of antiprotons with large momentum spread $\Delta p/p \approx \pm 3.5\%$ before bunch rotation
- After bunch rotation $\Delta p/p \approx \pm 1.2\%$
- Stochastic cooling system acceptance of $\Delta p/p \approx \pm 1\%$



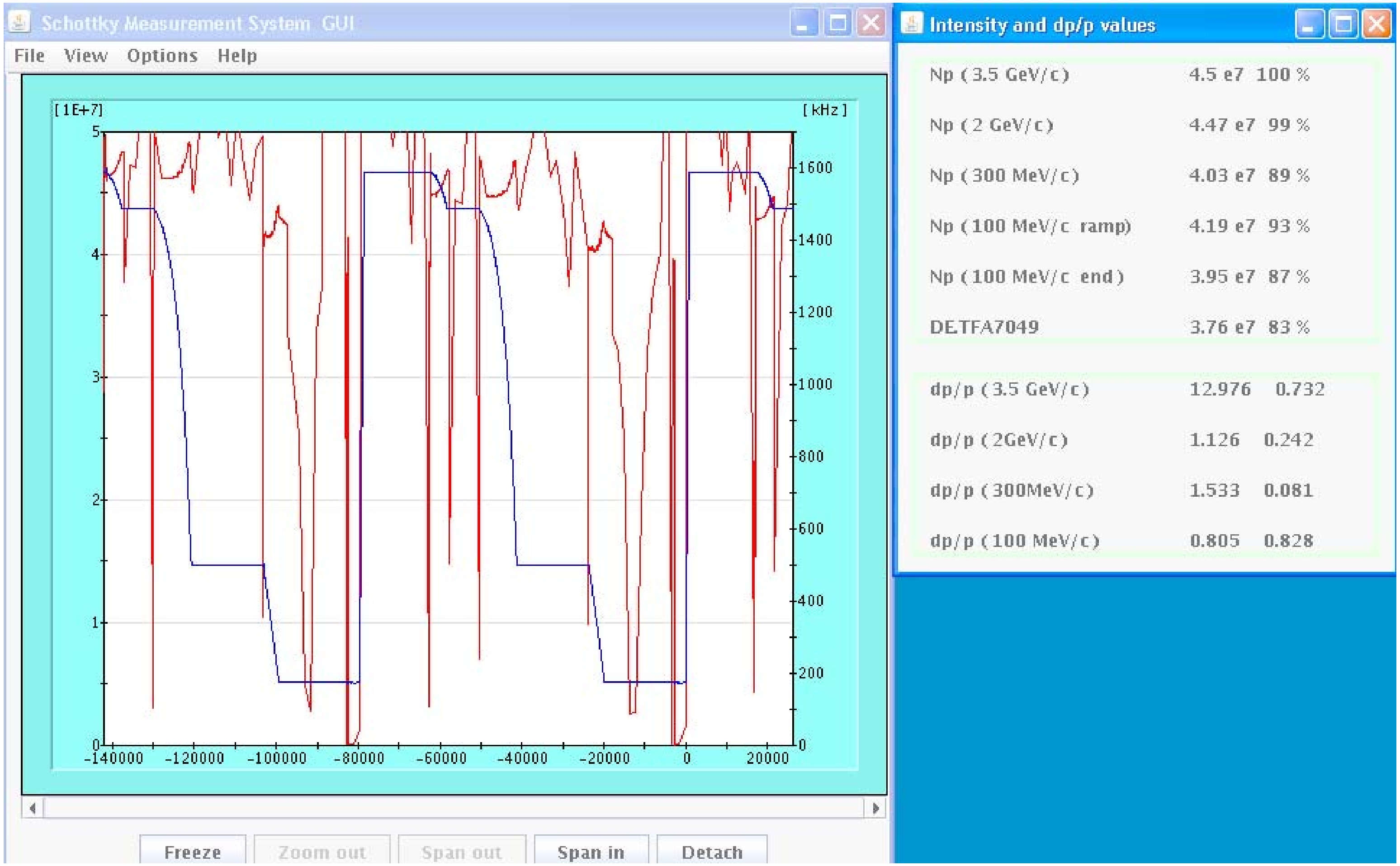
How AD works (continued)

Deceleration with several stops for cooling at:

- 3.57 GeV/c (stochastic cooling)
- 2 GeV/c (stochastic cooling, change of working point)
- 300 MeV/c (electron cooling, change of RF harmonics from 1 to 3)
- 100 MeV/c (electron cooling)
- Bunching on h=1,3,6 (optional), bunch rotation (optional), ejection
- Ejection at 300 MeV/c and 500 MeV/c is possible as well (AD-4)


Basic AD Deceleration Cycle
Momentum p [GeV/c]
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
18 s.
Electron cooling
16 s.
Rebunching
Fast Extraction
12
35
54
72
100
time [sec]
RF ON:
RF h =
6
1
1
3
1
Beam bunched for deceleration (RF ON), debunched for cooling
28/08/00 FP
27/11/02 Rev.
31/8/07 Rev.

Schottky based beam intensity monitoring



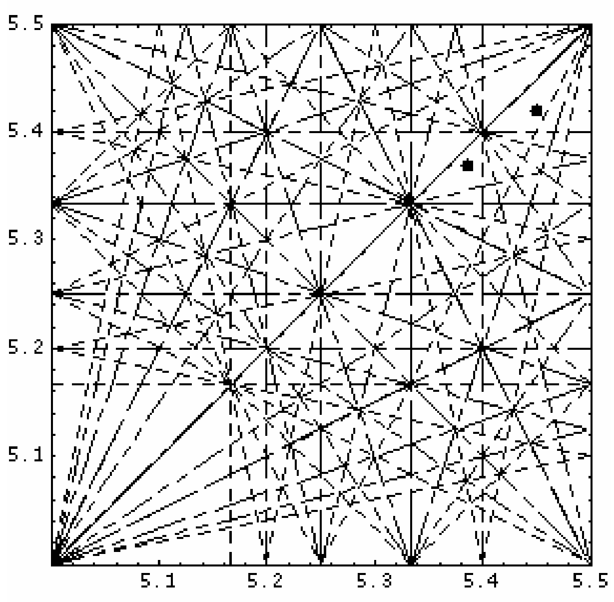
Stochastic cooling system

- Only band I (1 - 1.65 GHz) from AC (AD predecessor) used (H&V pickup tanks and H&V kicker tanks), bands II and III (1.65 GHz to 2.40 GHz and 2.40 GHz to 3.0 GHz) dismantled due to lack of space
- Momentum cooling: notch filters, sum signal from both PUs send to both kickers
- Programmable PUs and kickers movement (only PUs movement used now)
- Programmable delays to optimize phases

Stochastic cooling performance

- Injection energy: transverse emittances from 200π mm mrad down to $3.5\ \pi$ mm mrad, momentum spread $\Delta p/p$ from 1% down to $1 \cdot 10^{-3}$, cooling time 17 seconds
- Limitations of cooling system at 2 Gev/c (β=0.905): factor 2 lost in pickup sensitivity as pickup combiner boards are fixed and optimised for $\beta = 0.967$, mixing is about 7 times slower
- Beam emittances at 2 GeV/c about 3π mm mrad in both planes, momentum spread $\Delta p/p = 2 \cdot 10^{-4}$, cooling time 6 sec

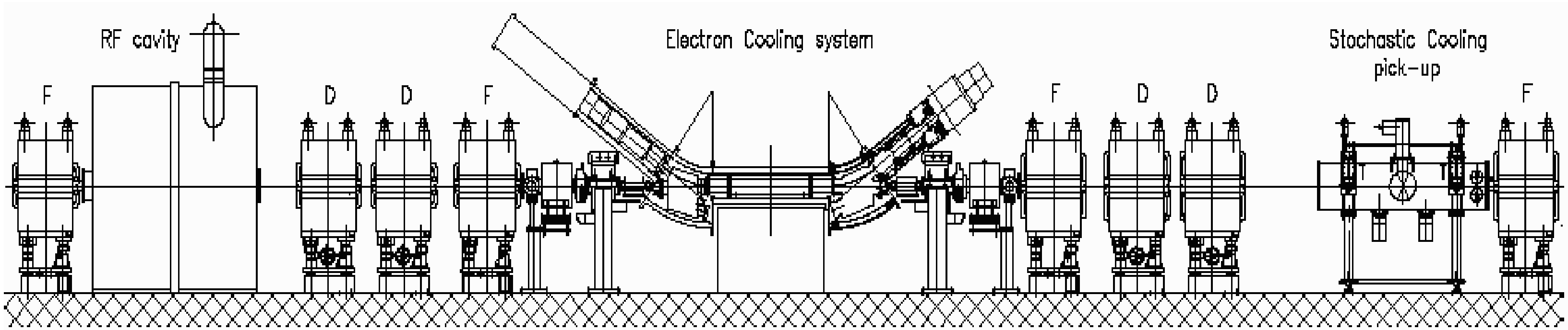
AD working points, jump at 2 GeV/c



- Maximum acceptance at injection energy
- Proper phase advances between stochastic cooling PUs and kickers at injection and at 2 GeV/c
- Sufficient room in tune diafram at low energy

Electron cooling performance

- The electron cooler (ex-ICE, ex-LEAR) is still in operation!
- Gun, collector, and corrector coils upgraded during the LEAR era, but some parts still original ICE components.
- Minimum upgrade after removal from LEAR: mechanical support, change from S-configuration to U-configuration, orbit correction.



Electron cooling at 300 MeV/c

- Transverse cooling from $\varepsilon_{x,y}$ = 20-25 π mm mrad down to 1.6 π mm mrad in the horizontal plane and 2.5 π mm mrad in the vertical plane. Faster horizontal cooling due to specially prepared dispersion in cooler.
- Longitudinal cooling from $\Delta p/p \approx 10^{-3}$ down to $\Delta p/p < 10^{-4}$
- Cooling duration is fairly long but (together with cooling duration at 100 MeV/c) chosen in a way to fit AD cycle length to fit minimal multiple number of PS supercycles
- Emittance measurements with scrapers: slow, but reliable at small beam intensities

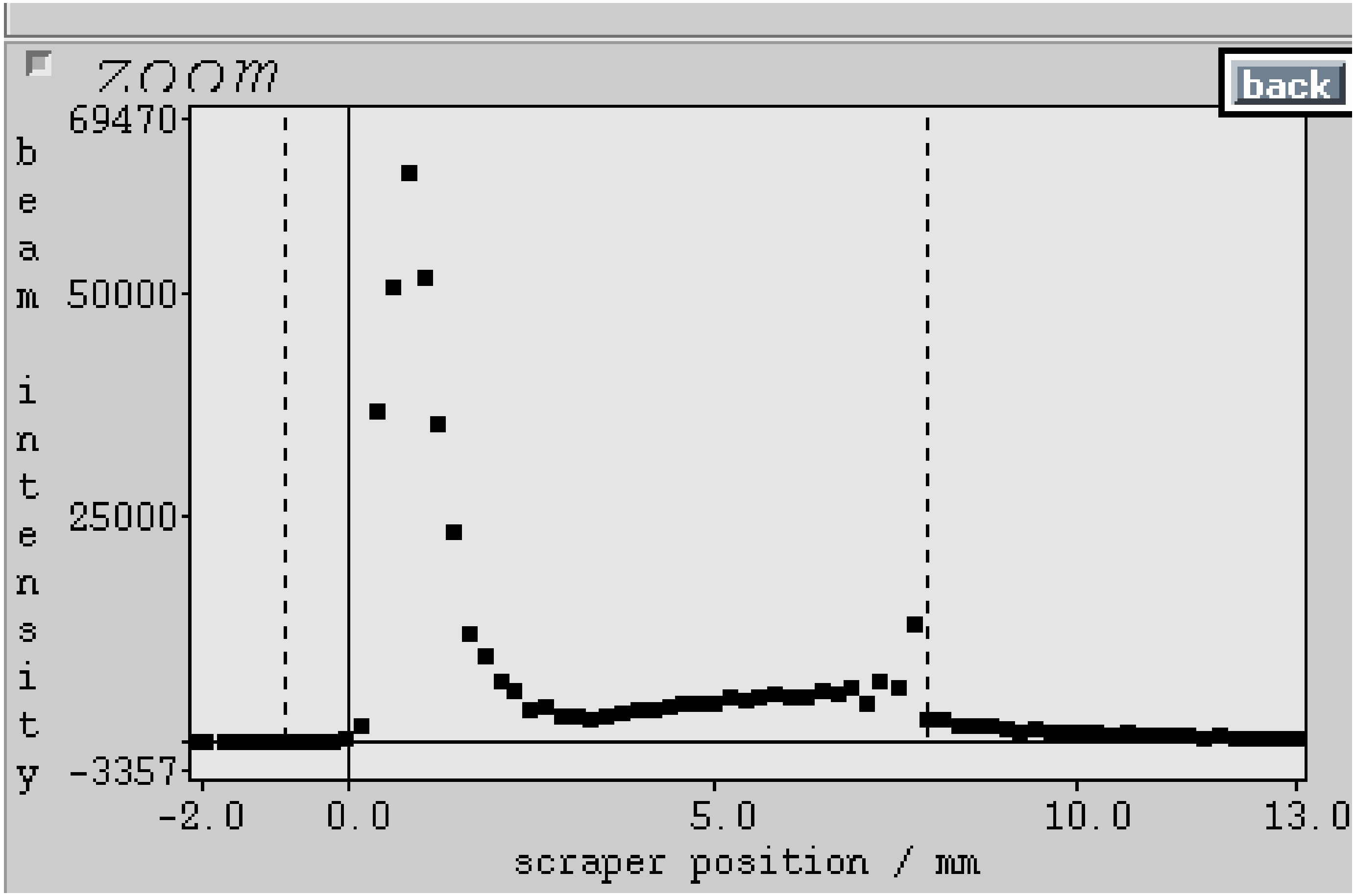
Machine and cooler "cross talk"

- Sensitivity of cooling performance to machine orbit – it must be stable!
- Slow decay of eddy currents in end plates of AD bending magnets -> orbit drifts on plateau -> cooling disturbed-> Field lag compensation implemented
- Problems with one of the dipole correctors on side of cooler -> permanent monitoring and readjustment now, will be replaced during shutdown
- Overlap of cooling and RF system operation when beam arrives at 300 MeV/c needed to reduce beam losses

Electron cooling at 100 MeV/c

- A bit longer than expected: about 15 sec, “core” and “tails” beam profile structure
- Strong sensitivity to antiproton orbit and to electron beam trajectory
- Morning and evening drift of cooled beam energy-> readjustment of gun voltage required (this year feature)
- High sensitivity of one of the experiments (ASACUSA which uses RFQ for Deceleration) to extracted beam emittances -> fine adjustment needed from time to time

Profile of extracted beam



Could perfomance of electron cooling in AD be improved?

- Priority to cooling at 100 MeV/c (w.r.t. 300 MeV/c) – cooled beam to physics
- Machine parameters which can’t be improved: vacuum, homogeneity of magnetic field in cooler, electron beam parameters
- Solenoidal field (potentially) could be increased, but with strong efforts (new stronger dipoles have to be installed to compensate toroid kicks, which follow step by step machine readjustment -> tunes, coupling compensation, antiproton alignment w.r.t. electron beam
- Stronger dipole correctors around cooler in demand to allow wide range scan

Extracted beam parameters

Momentum, MeV/c	100 to 500	On request
Intensity	$3 \cdot 10^7$	
$\varepsilon_{x,y}$, π mm mrad *	<0.5	Core, 70% to 85% of beam
Bunch length, nsec	170	
Number of bunches	1, 3 or 6	

Could AD performance be improved?

- Machine performance = beam intensity + beam emittances + cycle length
- Cycle length: hard to make significantly shorter
- Beam intensity: can be improved in about 25% by injecting 5 bunches instead of 4 now. Modification of PS RF system required for beam gymnastics
- Stacking in longitudinal phase space: maximum gain of factor 1.5 to 2 feasible, if radiation protection allows (not studied yet). PS modification needed, more protons in request (could be a problem due to lack of them at CERN complex)
- The most efficient way to improve performance is to build Extra Low Energy Antiproton ring (ELENA)!

Motivation to build ELENA

How antiprotons are decelerated further down today:

- Experiments aimed to antihydrogen program (ALPHA and ATRAP) use set of degraders to slow 5.3 MeV beam from AD further down: poor efficiency due to adiabatic blow up and due to scattering in degraders, only 0.1 % of AD beam used.
- 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. About 70% beam is lost after passing through RFQD.

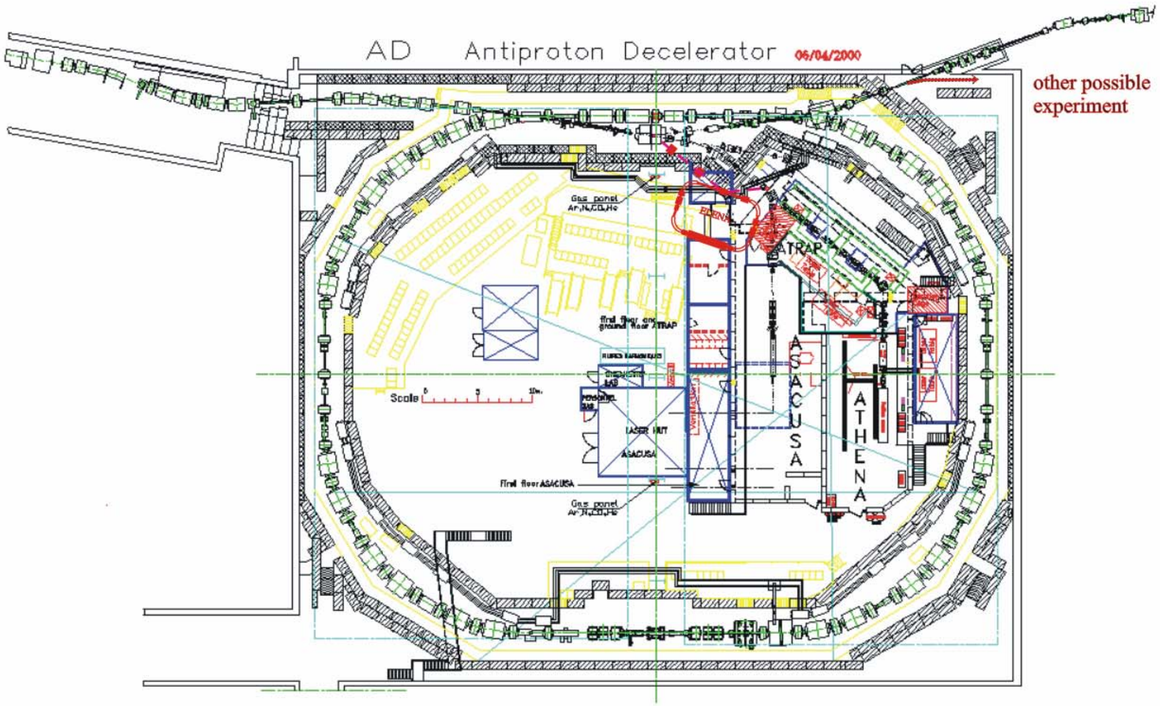
How do we gain in intensity with extra deceleration and cooling ?

- Small ring to decelerate antiproton beam down to 100 keV and to cool it by electron beam to high density will be used
- 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 ALPHA 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.

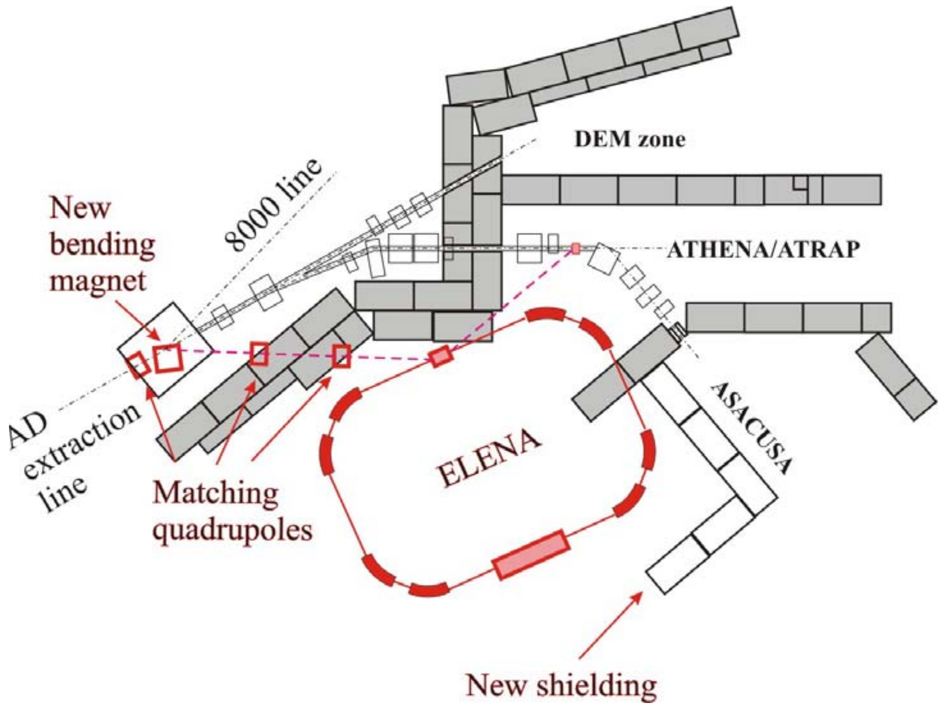
Requirements to ring configuration

- Must be compact to fit in available space inside of AD Hall: solution proposed with circumference 1/7 of AD ring
- Placed in AD Hall in an optimal way for injection from AD and extraction to existing experimental areas
- One long straight section for electron cooler
- One long straight section for beam injection and extraction
- One or two straight sections for other equipment (RF, diagnostics etc.)

AD Hall with ELENA



ELENA layout in AD Hall



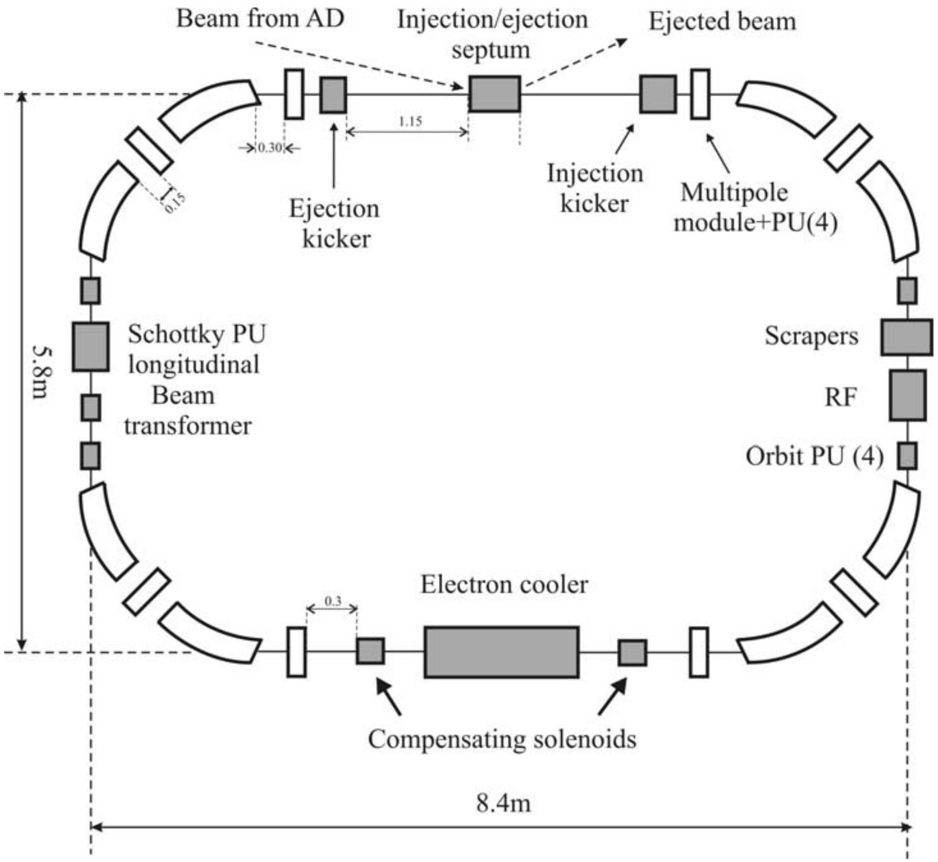
ELENA main parameters

Energy, MeV	5.3 – 0.1
Circumference, m	26.062
Emittances at 100 keV, π mm mrad	5 / 5
Intensity limitation by space charge	$1.1\ 10^{7}$
Maximal incoherent tune shift	0.10
Bunch length at 100 keV, m / ns	1.3 / 300
Expected cooling time at 100 keV, sec	1
Required vacuum* for $\Delta\varepsilon=0.5\pi$ mm mrad/s,Torr	$3\cdot10^{-12}$
IBS blow up times for bunched beam* ($\varepsilon_{x,y}=5\pi$ mm mrad, $\Delta p/p=1\ 10^{-3}$), s	1.1 / -9.1 / 0.85
* No electron cooling is assumed	

ELENA main parameters (comments)

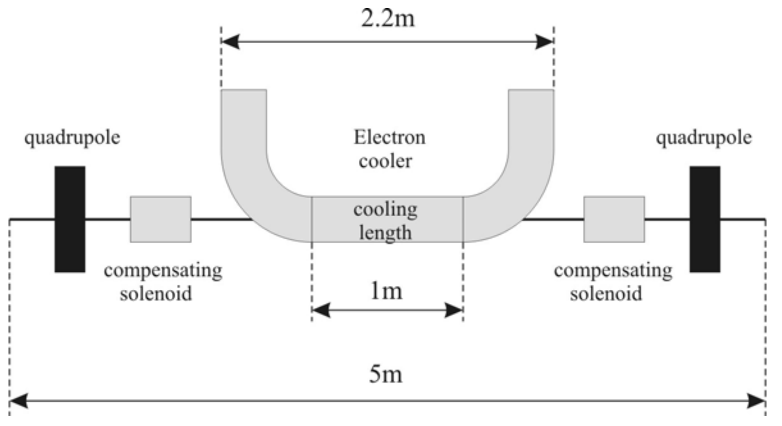
- The extraction energy choice of 100 keV is a compromise between request of ultra low energy beam from physics community and limitations imposed by space charge, vacuum, electron cooler specifications, sensitivity of diagnostics and others
- The low energy choice is limited by 100 keV due to space charge, IBS and gas scattering, reliable operation of electron cooler, complication of machine optics due to solenoidal field of cooler.
- The estimate of intensity limit due to space charge refers to bunched beam before extraction – couple of hundred of ms only!

Ring layout



Beam from AD
Injection/ejection septum
Ejected beam
1.15
0.30
0.15
Ejection kicker
Injection kicker
Multipole module+PU(4)
Schottky PU
longitudinal
Beam
transformer
Scrapers
RF
Orbit PU (4)
5.8m
0.3
Electron cooler
Compensating solenoids
8.4m

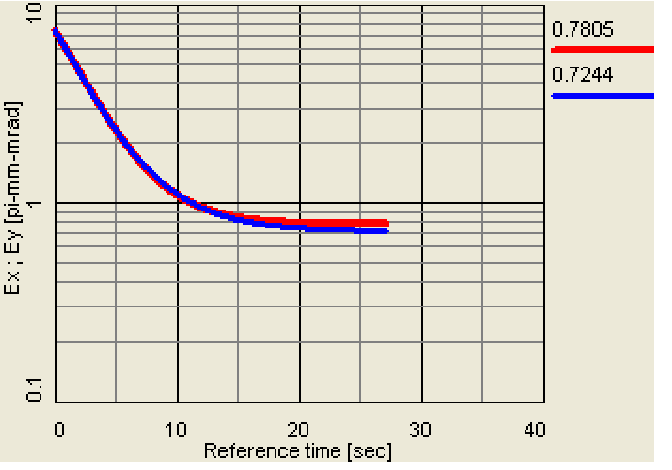
Electron cooler for ELENA

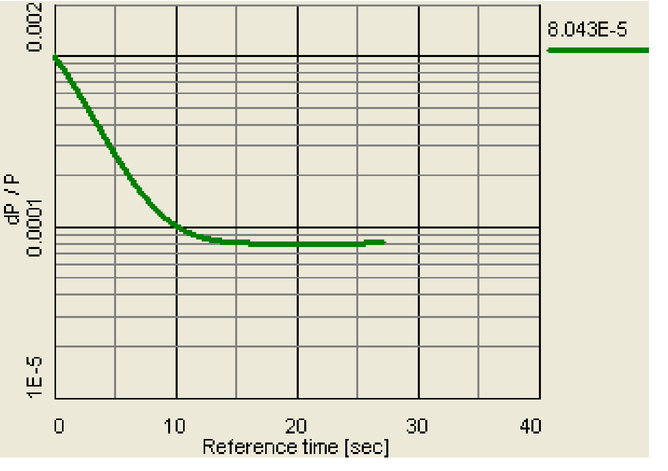


Cooling length l_c, m	1
Beam cooled at momentum, MeV/c	35 & 13.7
Electron beam current I_e, mA	15 & 2
Maximal magnetic field in solenoid B_0, Gs	200
Electron beam radius a, cm	2.5

Electron cooling simulation for ELENA with BETACOOL code

- Helpful to define sensitivity of cooling time to magnetic field in drift solenoid
- Helpful to define other important parameters: allowed errors in magnetic field, vacuum in machine, effect of IBS, electron beam temperatures

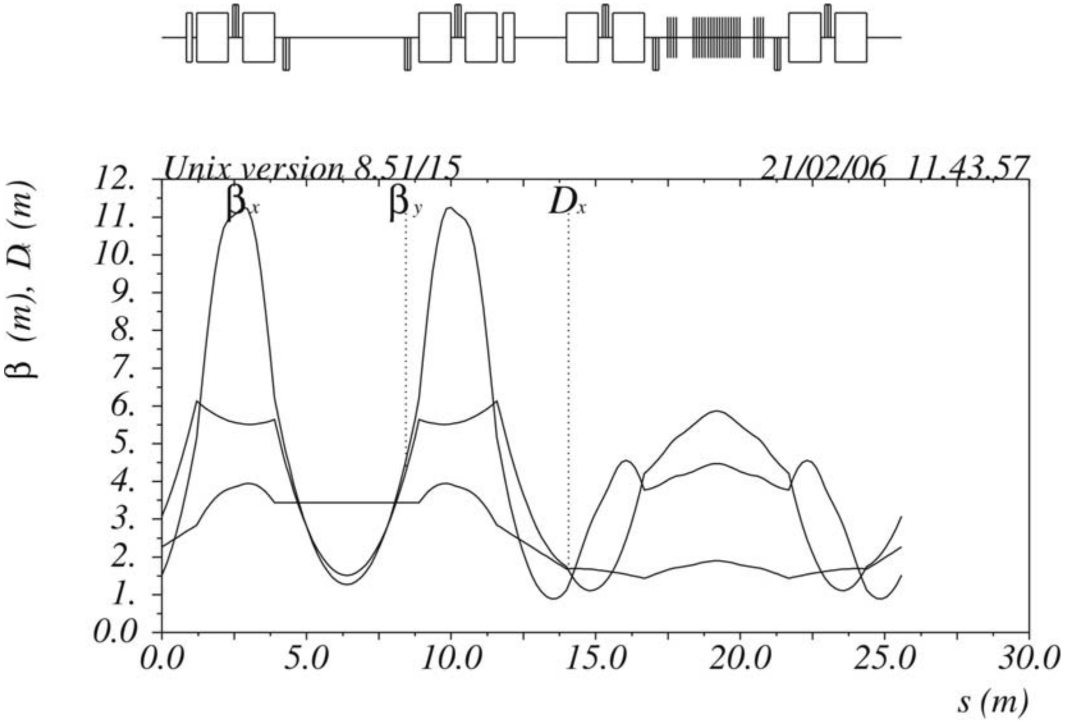




ELENA optics study

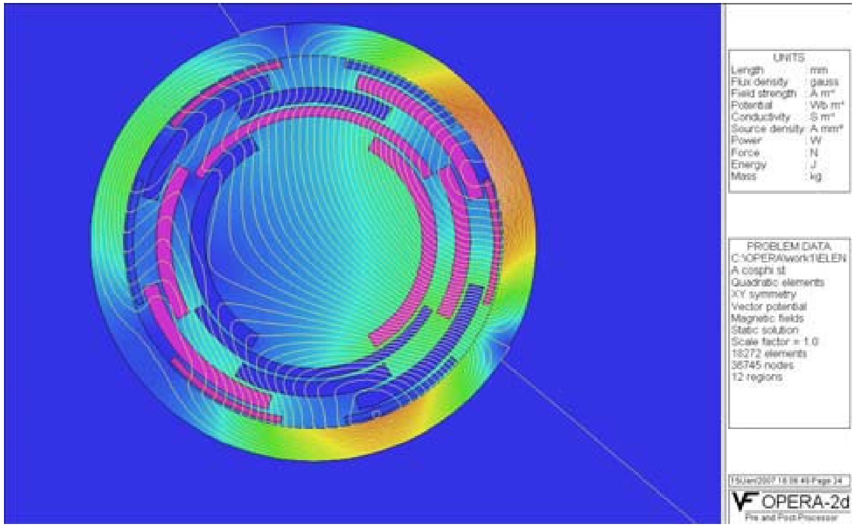
- Choice of tunes: Qx/Qy =1.45/1.42, tune shift (i.e. due to SC) of 0.1 is allowed
- Beam focussing is done mainly in bending magnets, weak quadrupoles used as “knobs” for machine tuning
- Huge effect of cooler drift solenoid (B_{sol}=200 Gs) on optics at low momenta
- Noticeable tune shift due to electron beam $\Delta Q \approx 0.016$
- Multipole cell used for saving space: horizontal/vertical dipole, normal quadrupole, skew quadrupole, sextupole

Effect of drift solenoid on cooler optics at extraction energy (compensators on, no tune correction)



Multipole corrector magnet for ELENA

- module include: horizontal and vertical dipoles, normal and skew quadrupoles, sextupoles
- low field->normal conducting iron-less magnet
- all 8 modules identical to reduce cost, but some of magnets may not be used -> not provided with power supplies



Chromaticity and coupling correction

- Straightforward coupling compensation with 2 compensating solenoids, 2 weak skew quadrupoles used for fine adjustment
- No way to compensate tune shift introduced by solenoids even with extra quadrupole families
- Weak natural chromaticity, straightforward compensation

Beam diagnostics

- 2 H/V PUs in each of straight sections (totally 8 in each plane). Performance similar to AD expected (reliable orbit measurement with $5 \div 10 \cdot 10^6$ antiprotons)
- Longitudinal Schottky PU for intensity measurement and cooling control
- IPM (for commissioning and MDs)
- Scrapers for beam profile/emittance measurements
- Transverse BTF DSP system+dedicated kicker for tune measurements

ELENA cost estimate

Item	Material (kCHF)	Manpower FSU (kCHF)	Manpower FTE (MY)
Magnets (ring+inj. line)	885	160	3.2
Power converters	857		1.5
Injection/ejection septa	220		2.9
Injection/ejection kickers	830		4.8
Electron cooler	1350		6.5
Vacuum	1139	27	5.0
RF + Schottky diagnostics	253		2.6
Diagnostics	620	85	2.4
Controls	682		0.7
H^- source	400		
Experimental area	2245		3.0
Mech. Design/Drawings			17.0
Other	290		6.5
Total (MCHF/MY)	9.771	0.272	56.1
Grand Total (MCHF/MY)	10.043		56.1

From Director General presentation to CERN staff in June 2007

- Theme 1 to 3: LHC, LHC upgrade, LHC Injector chain upgrade
- The Fourth Theme includes activities that are of high scientific interest, but which rely only partially on CERN contributions and will require an agreement with outside partners for an amount that is currently unknown.
- The fourth Theme includes activities which cannot be decided upon without reaching agreement within collaborations that will have to be established. Estimates of contributions from CERN are given but are far from being certain (41 MCHF + ~ 145 FTEs)
- The management proposes to earmark some funds from 2010 onwards on this fourth theme at the level of 10 MCHF per annum.

ELENA status now

- Included in White paper activity (beyond of LHC program)
- Low level priority
- Conditioned to physics community contribution
- Physics community is looking for money

Conclusion

- AD operate for physics since 2000
- Delivered beam emittances less than 1π mm mrad, bunch length about 170 nsec
- The best way to deliver more (much more!) antiprotons is to build extra low energy ring with electron cooling
- Approximate cost estimate for ELENA is 10 MCHF
- Contribution of physics community about 50% is required
- Could be build approximately in 3 years
- AD operation is disturbed only slightly

Thank you for attention!