Extra Low Energy Antiproton Ring (ELENA) for antiproton deceleration after the AD: status at the beginning of project

Motivation to build ELENA

Most of AD experiments need antiprotons of 3 keV to 5 keV kinetic energy, AD produces them at 5.3 MeV.

How antiprotons are decelerated further down today by experiments:

- 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 of beam emittances and due to scattering in degraders, less than 0.1 % of AD beam used. Similar efficiency is expected for AEGIS.

Motivation to build ELENA (continued)

How antiprotons are decelerated further down today by ASACUSA experiment:

- RFQD is used for antiproton deceleration down to around 100 keV kinetic energy
- deceleration in RFQD is accompanied by adiabatic blow up (factor 7 in each plane) which causes significant reduction in trapping efficiency
- RFQD is very sensitive to trajectory and optics mismatch errors, difficult and time consuming tuning of transfer line from AD to RFQD needed
- About 70% beam is lost after passing through RFQD, transverse beam size is very big (more than100 mm), only short beam transport is possible after it (few meters)
- about 3-5% of antiprotons are captured after passing through degrader

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

- Deceleration of the antiproton beam in a small ring down to 100 keV and its cooling by electron beam to high density
- Emittances of beam passing through a degrader will be much smaller than now due to electron cooling and due to use of much thinner degrader (100 keV beam instead of 5.3 MeV) => two orders of magnitude gain in intensity is expected for ALPHA, ATRAP and AEGIS.
- 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
- Extra gain for experiments: due to extraction in 4 bunches number of hours/day with available beam increases significantly

Energy range of ELENA

ELENA injection energy is 5.3 keV (100 MeV/c) = AD ejection energy

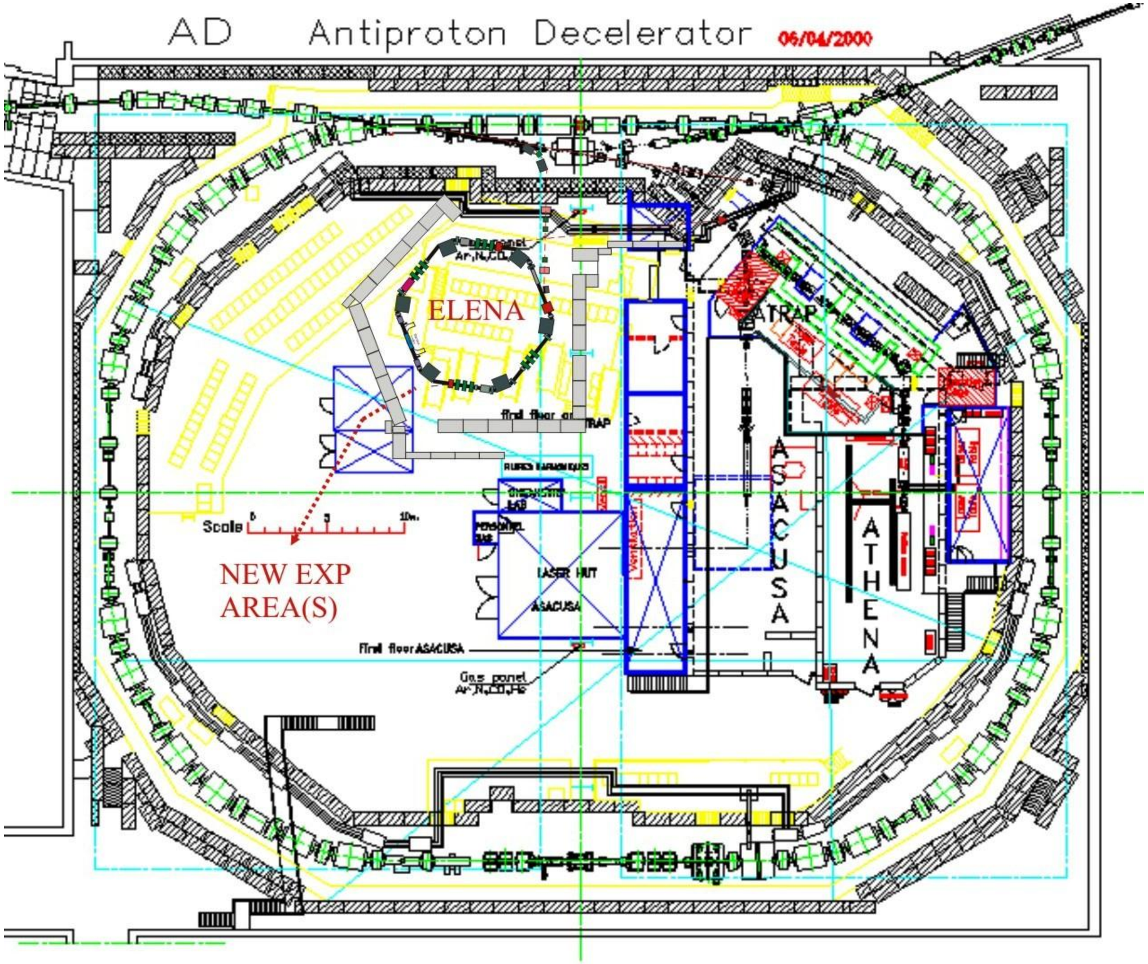
ELENA extraction energy 100 keV (13.7 MeV/c) defined by:

- space charge limit for antiproton beam
- good quality of electron beam for cooling (limited by space charge of electron beam)
- beam lifetime: residual gas scattering and IBS at extraction energy
- strong requirements to high vacuum in machine $3 \cdot 10^{-12}$ Torr
- foil thickness for separation of transfer line and trap vacuum

ELENA must be placed in AD Hall!

- Must be compact to fit in available space inside of AD Hall
- One long straight section for electron cooler needed
- Must be placed in AD Hall in an optimal way for transfer antiprotons from AD and deliver them to existing now and possible in future experimental areas
- Placed in AD Hall in a way to minimize reshuffle of existing equipment in the area

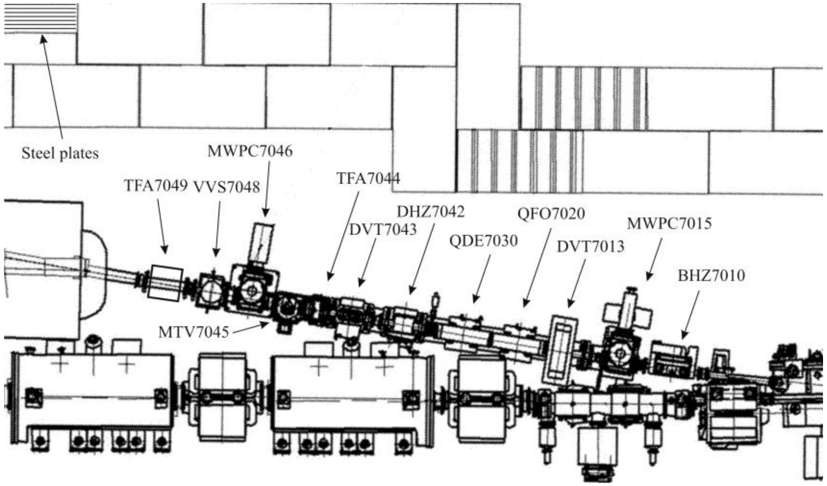
ELENA layout in AD Hall



Why ELENA is placed exactly there?

- Placing the ring inside of AD Hall allows to use existing experimental areas (great saving!)
- The initial part of existing AD injection line should be used, which put strong constraint on position and orientation of ELENA ring
- The extraction section of ELENA ring should be placed in a way to minimize the distance to experimental areas
- To make easy ELENA installation the crane should be available to transport heavy units -> “dead zone” should be avoided
- The hole in AD ring shielding for beam pipe to ELENA should be done in concrete, avoid passing through the steel plates
- The space in AD Hall for new (extra) experimental area has to be foreseen

Beam transfer from AD to ELENA

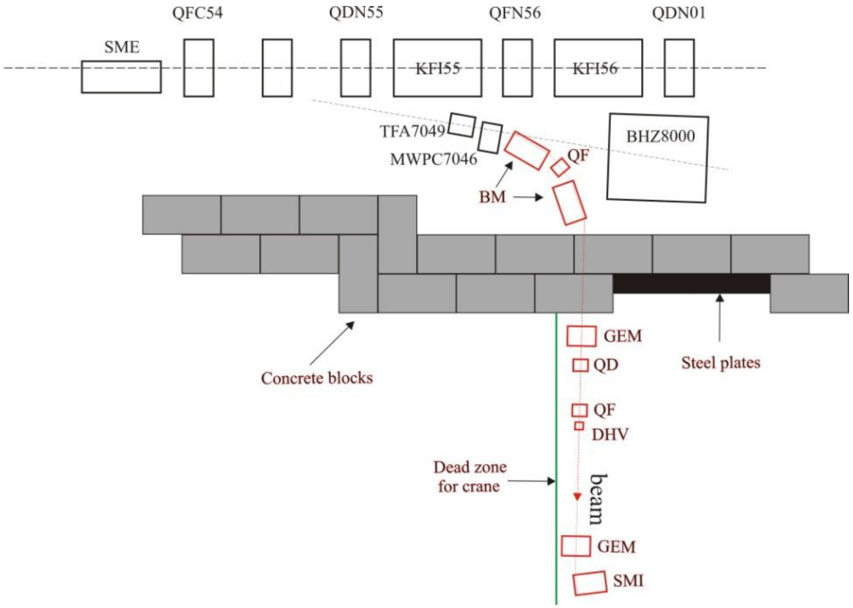


What should we modify in AD ejection line (7000 line):

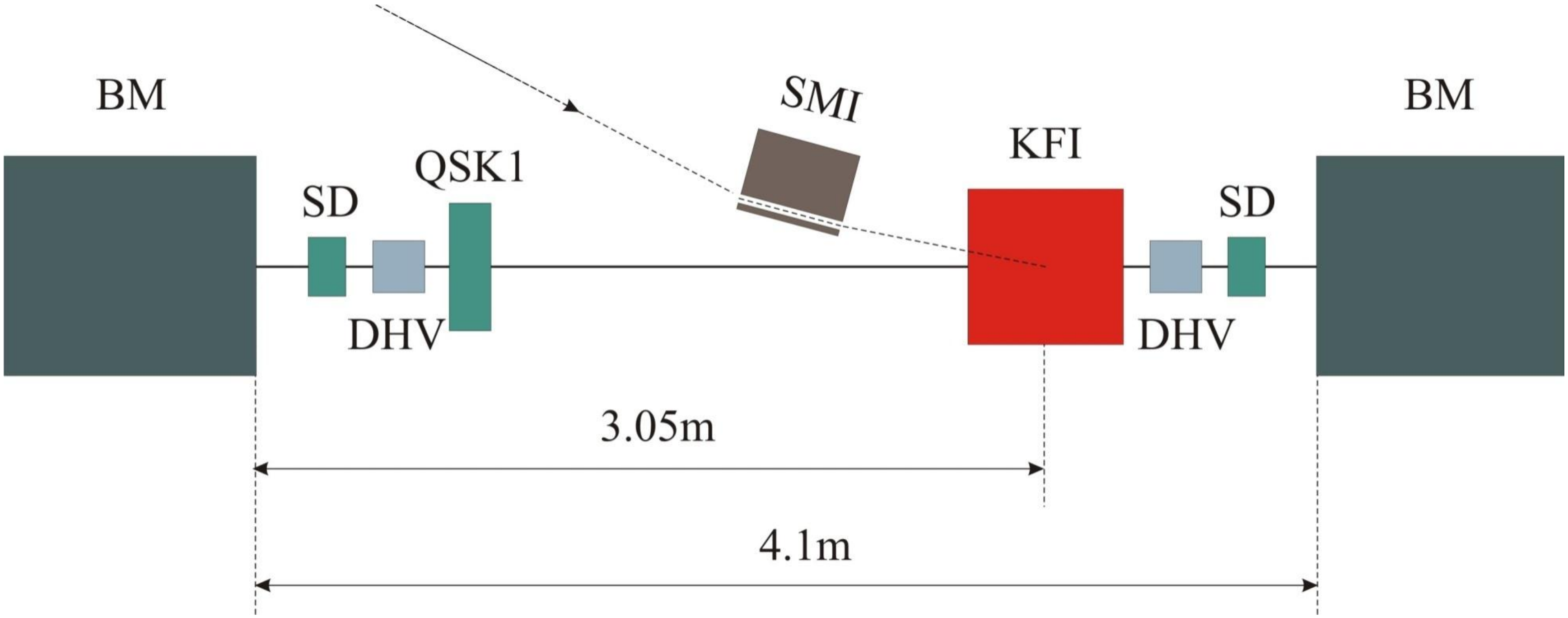
- place sector valve VVS32 between MWPC7015 and DVT7013
- move dipole correctors 7042 and 7043 upstream
- remove proton transformer TFA7044 and MTV7045
- To place current transformer TFA7049 before MWPC7046
- To make small modification in vacuum equipment in this area

AD to ELENA transfer line

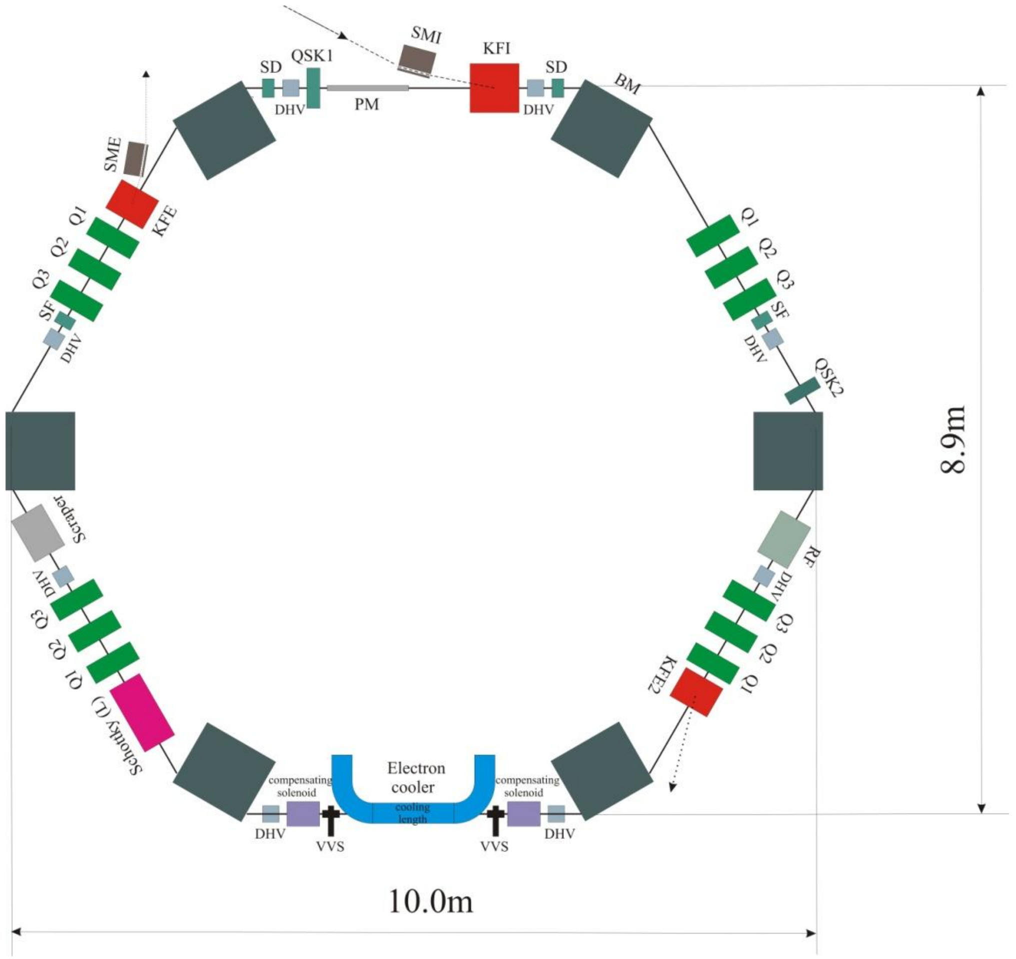
- To make 82° bend, two magnets will be placed upstream to the shielding of AD Hall
- 5 or 6 quads used for matching of the Twiss functions. Matching of dispersion is not possible, a small mismatch and the horizontal emittance blow up expected
- The line layout and length are fixed by layout (unfortunately!)
- Special care should be given to a crossing of injection and extraction lines



Injection into ELENA



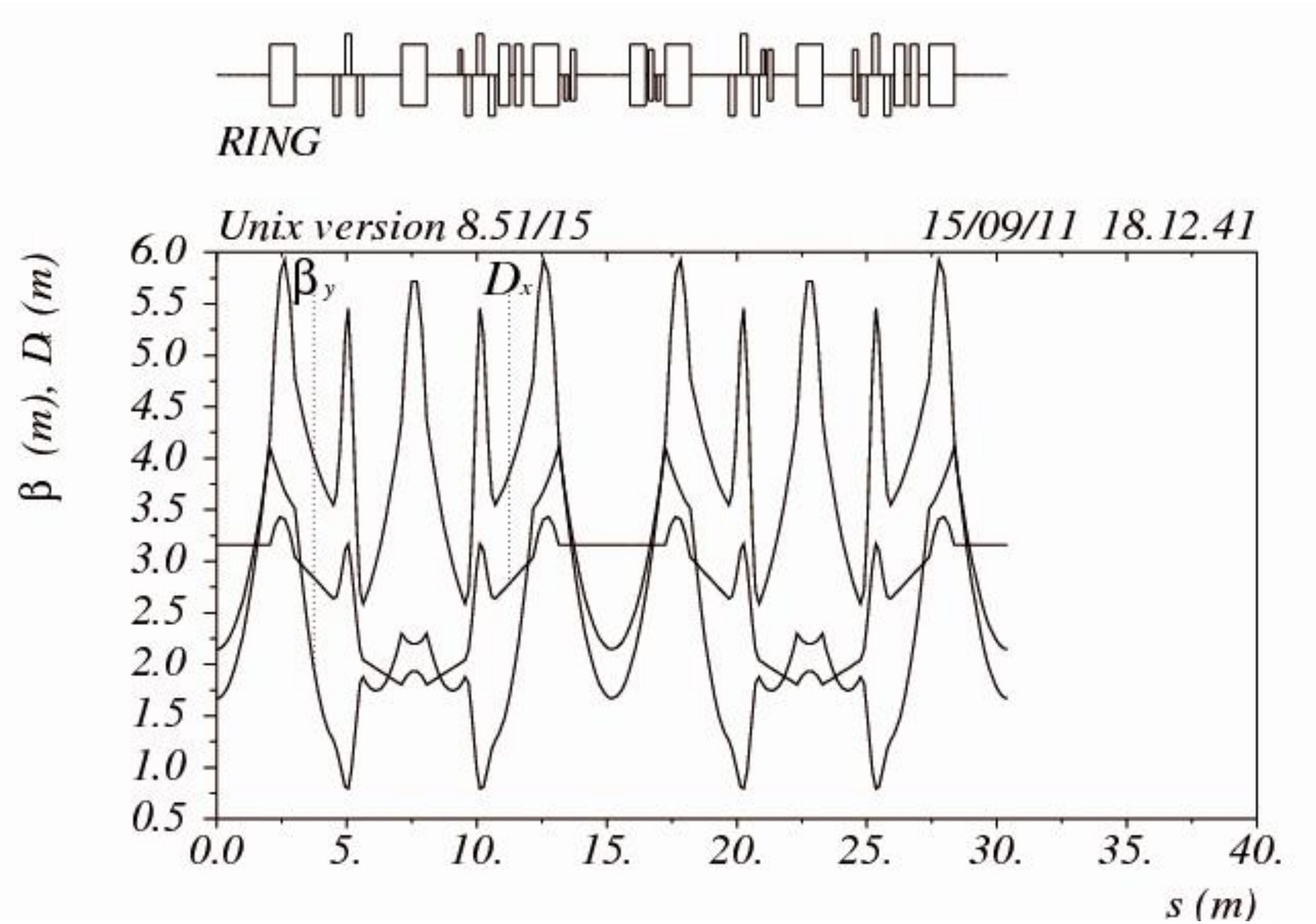
ELENA ring (fast extraction only)



Main requirements to ELENA optics

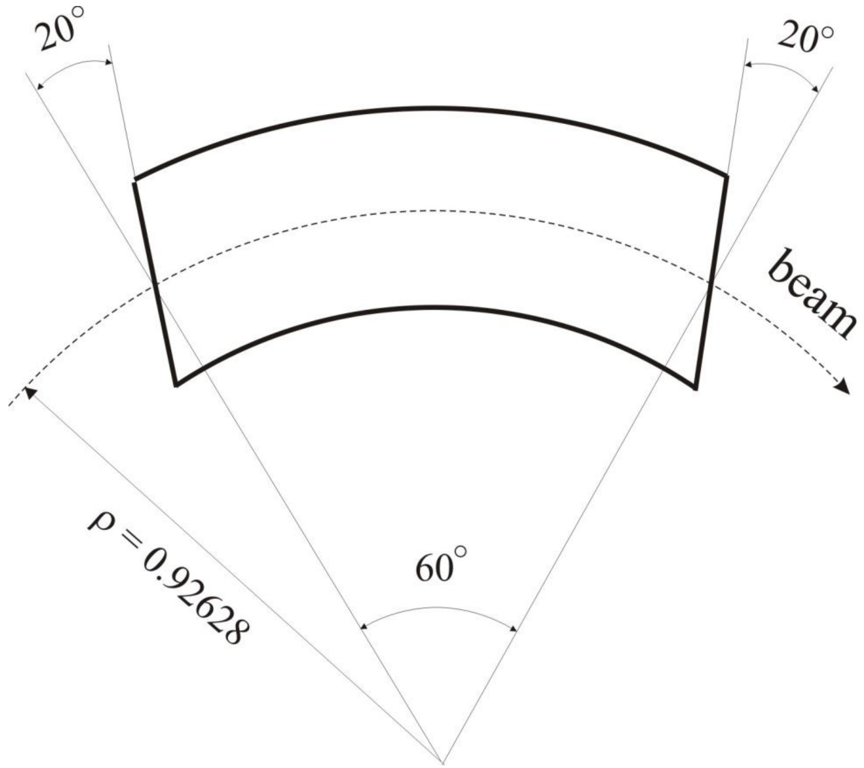
- To facilitate convenient beam injection in and extraction from the ring
- To operate at tunes which provide good margins for intensity limitation set by space charge -> Q_x=1.45 and Q_y=2.45 are chosen
- To provide space as much as possible for all required equipment as well as for one more extraction to the extra experimental area
- To prepare optimal conditions for electron cooler operation (optimal energy range, suitable beta function values in cooling section, antiproton beam alignment w.r.t. electron beam)
- To find the optimal compromise for magnetic field in bending magnets at low energy: the strong field is easy for operation, but short magnets possess stronger focusing properties and produce more stray fields
- To minimize beam emittance blow up due to multiple gas scattering

ELENA optics



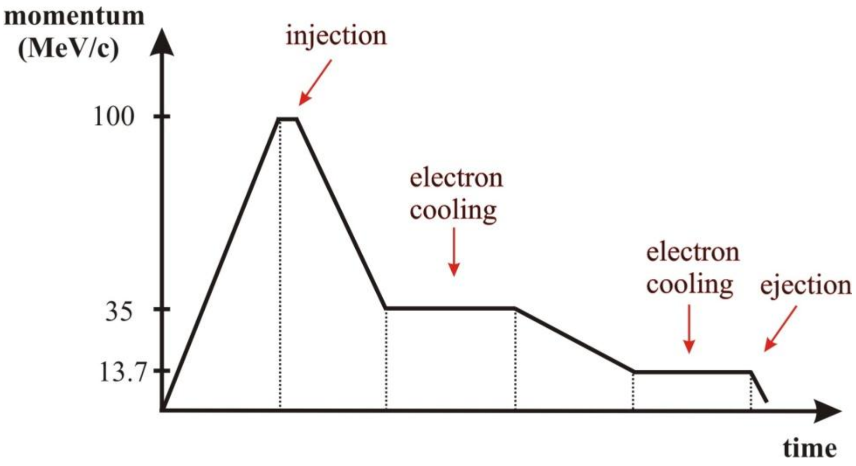
Which bending magnet do we need for ELENA ring

- C-type
- Length 0.97m, gap ≈ 70mm
- 3D model calculations needed to look more deep into effect of fringe fields
- Small change of magnet parameters possible during design study

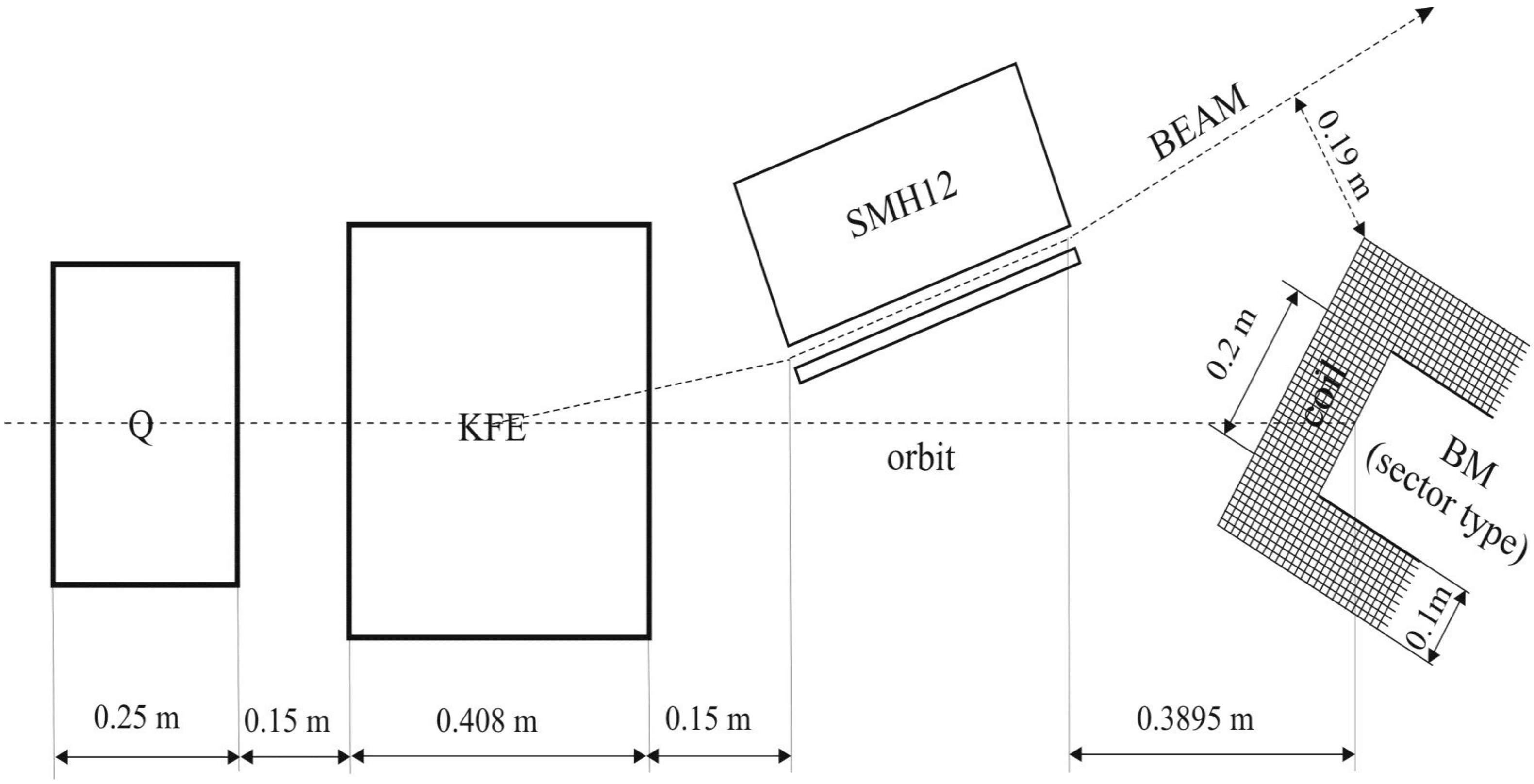


Schematic view of ELENA cycle

- No electron cooling is performed at injection energy: beam is cooled already in AD. After single bunch injection the beam is decelerated immediately.
- One intermediate cooling at 35 MeV/c is needed to avoid beam losses
- The expected cycle duration is in the range of 10 to 15 seconds



Extraction from ELENA



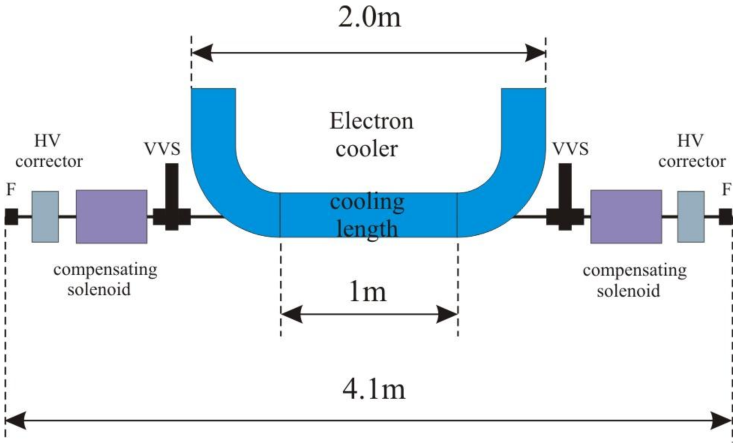
Space charge limit in ELENA

- important for bunched beam only (right before extraction)

$$\Delta Q = -\frac{F r_p N C}{2\pi\varepsilon_x \beta^2 \gamma^3 l_b}$$

- example: ΔQ=0.1, the bunch length l_b=1.3m (300ns) , beam emittance $\varepsilon_{x,y}=4\pi$ mm mrad, $\beta=1.46\cdot10^{-2}$ ring circumference C=30.4m , Gaussian distribution (F=2) -> the bunch intensity is limited at $N=0.625\cdot10^7$.
- Can be increased by factor 2 with flattened longitudinal beam distribution with superimposing RF voltage with harmonics 1 and 2
- With 60% of deceleration efficiency ($3\cdot10^7$ antiprotons injected into ELENA, $1.8\cdot10^7$ antiprotons decelerated down to 100 keV) at least 3 bunches has to be prepared for extraction to avoid space charge problems
- To deliver at the same time beam up to 4 experiment, RF system should be able to operate at harmonics h=1,2,3,4.

Electron cooler for ELENA

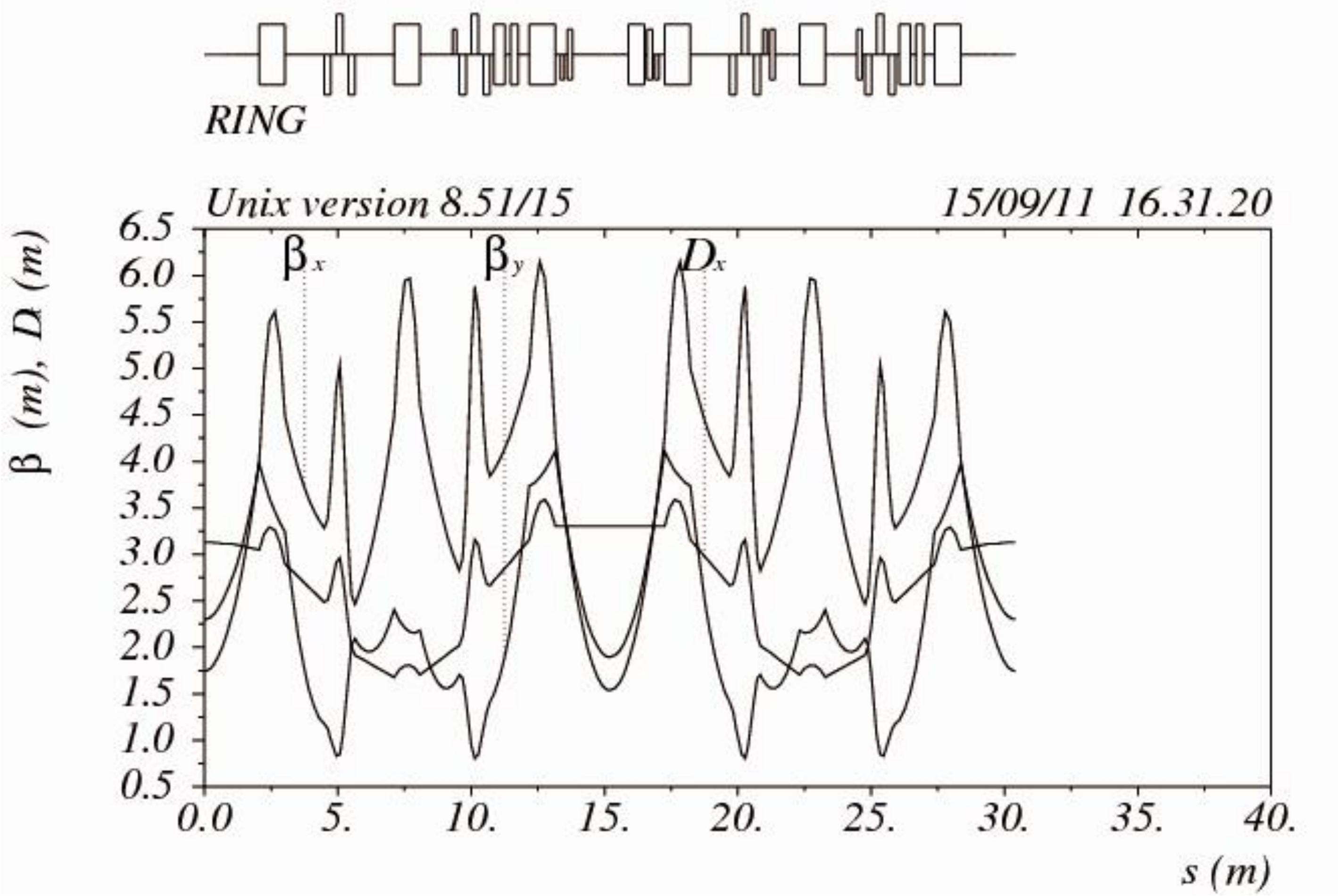


Cooling length l_c, m	1
Beam cooled at momentum, MeV/c	35 & 13.7
Electron beam current I_e, mA	15 & 2
Cathode voltage at 100 keV, V	55
Maximal magnetic field in solenoid B_0, G	100
Electron beam radius a, cm	2.5

Effects of cooler solenoid and compensators on machine optics

- Tune shift due to solenoidal fields, maximal at low energy due to constant magnetic field in electron cooler solenoid and compensators
- Coupling in the part of cooling section (effects on antiproton beam alignment). No coupling outside of cooling section due to use of compensating solenoids
- Focusing effect of electron beam on antiproton beam -> tunes shift of ELENA ring
- Trims can be used to compensate partly these effects

ELENA optics at low energy with main solenoid and compensators on



Effect of cooler electron beam on machine optics

Tune shift due to space charge of electron beam

$$\Delta Q_{x,y} = \frac{G r_p I_e}{2\pi e c \beta^3 \gamma^3} \frac{<\beta_{x,y}> l_c}{a^2}$$

- Independent on energy for fixed perveance gun
- Dependant on electron beam distribution (G=1 for uniform beam, G=2 for Gaussian beam)
- Linear with beta function value in cooler
- ELENA case: cooling length l_c=1m, β_z=2m, G=1, electron beam current at 100 kev, I_e=2mA => ΔQ=0.011 at momentum range 35 MeV/c to 13.7 MeV/c, smaller at higher momenta

Beam lifetime and vacuum requirements

The main limiting factor at the low energy is multiple Coulomb scattering -> beam emittance blow up

$$\Delta\varepsilon_{x,k\sigma} \approx 0.14k^2 \frac{q_p^2}{A_p^2} \bar{\beta}_x \frac{Pt}{\beta_p^3 \gamma_p^2} \qquad \left(P\{Torr\], \beta_x[m], t[\sec]\right)$$

For ELENA at extraction energy (pc=13.7 MeV/c, β=0.0146, $P=3\cdot10^{-12}$, averaged β=3.5m, k=2) emittance blow up $\Delta\varepsilon$=0.6 π mm mrad/s.

The required cooling rate for emittance equilibrium is

$$\tau_{cool} = \frac{\varepsilon_{x,eq}}{\Delta\varepsilon_{xq}/\Delta t} = \frac{4}{0.6} = 6.7\sec$$

ELENA main parameters (to be revised by TDR)

Momentum range, MeV/c	100 - 13.7
Energy range, MeV	5.3 - 0.1
Circumference, m	30.4
Intensity of injected beam	3×10^{7}
Intensity of ejected beam	1.8×10^{7}
Number of extracted bunches	1 to 4
Emittances (h/v) at 100 KeV, $\pi\cdot$mm$\cdot$mrad, [95%]	4 / 4
$\Delta p/p$ after cooling, [95%]	10^{-4}
Bunch length at 100 keV, m / ns	1.3 / 300
Required (dynamic) vacuum, Torr	3×10^{-12}

Possible scenarios of beam extraction from ELENA

With $1.8 \cdot 10^7$ antiprotons in the ring (60% of deceleration efficiency):

- Extraction in 4 bunches to 4 experiments with nominal emittances and reduced bunch length 220 nsec. The fast switch between destinations will be provided by electrostatic bending magnet(s). Timing for extraction of each bunch at given turn by kicker can be adjusted to relax (if necessary) requirements to switcher. Extraction to new experimental area can be arranged with proper timing as well.
- Extraction in 3 bunches to 3 experiments with nominal parameters
- Extraction in 2 bunches to 2 experiments with nominal parameters (RF system works with harmonics h=2 and h=4)
- Extraction in 1 bunch to 1 experiment with emittances 2 times bigger than nominal

What do we want to know from physics community?

- The intensity limit in ELENA is defined by emittance and bunch length
- Which maximal bunch length in ELENA ring is acceptable for each experiment? Length of 300 ns was defined in 2004, should it be revised?
- Which maximal emittance in ELENA ring is acceptable for experiments?
- Which parameter is more important to minimize, bunch length or emittance?
- Waiting for your (prompt?) reply…

Which help do we want ask from physics community for design studies?

- Electrostatic beam line studies: 1 MY
- Machine physics studies: ≥ 1 MY

Thanks for your attention!

Injection into ELENA: kicker and septum parameters

<table>
<tr><td colspan="5">Former AC ejection kicker (one module)</td></tr>
<tr><td>L_{magn}/L_{mech}</td><td>Kick</td><td>∫Bdl, G·m</td><td>Gap, mm</td><td>Flat top, ns</td></tr>
<tr><td>0.6/0.576</td><td>100mrad</td><td>300 G·m</td><td>100</td><td>400</td></tr>
<tr><td colspan="5">Former LEAR SMH12 septum</td></tr>
<tr><td>L_{magn}/L_{mech}</td><td>Kick, mrad</td><td>∫Bdl, G·m</td><td>Gap, mm</td><td>Aperture, mm</td></tr>
<tr><td>0.3m/0.4m</td><td>303</td><td>1011</td><td>75</td><td>180</td></tr>
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ELENA ring circumference

- Must be as small as possible due to limited space in AD Hall
- Should be 1/n (integer) of AD ring (bucket to bucket beam transfer to avoid longitudinal blow up of the beam at injection plateau + matching of dispersion and its derivative in the AD to ELENA transfer line is hardly possible, with smaller Δp emittance blow up due to dispersion mismatch will be smaller)

Evolution in time:

- 22.8m, 4-folder ring in 2004 (presented to SPSC in Villar)
- 26.1m , 4-folder ring in 2007 (ELENA cost study…)
- 30.4m, 6-folder ring since 2010

Why did we choose 6-fold ring configuration?

Initial ring circumference was 26.2m (1/7 of AD ring) -> not enough space to place all required equipment, not possible to prepare extra experimental area (SPSC request) -> new circumference is 30.4 (1/6 of AD ring)

Advantages of the new rings:

- More flexibility for injection and extraction with the new layout
- The total length of bending magnets is shorter for hexagonal lattice compared with rectangular lattice -> more space for other equipment
- Minimal magnetic field in bending magnets (at 100 keV) increased form 399 Gs to 493 Gs – essential!
- Optics for 4 fold ring of 30 m long has unfavorable tunes (too much focusing in magnets), wide choice of tunes in 6 fold ring
- Smaller beta function values -> smaller aperture required by beam, relaxed requirement for vacuum

Choice of machine acceptance

- Transverse profiles of AD beam, core and tails, the origin of tails is not well understood
- The idea is to “misalign” slightly two beams (electrons and antiprotons)

  and to create beam with smooth distribution for 95% of particles and emittance of about 5 to 10 π mm mrad
- Successfully done in June 2011, but failed in August 2011
- With emittance of 10 π mm mrad of AD beam at extraction one could expect beam in ELENA at injection plateau with emittance up to 15 π mm mrad (expected blowup due to absence of tools to set up optics in transfer line, and unavoidable blow up due to dispersion mismatch)
- During deceleration down to 35 MeV/c adiabatic blow up make emittance about 45 π mm mrad at the second plateau, where electron cooling is applied for the first time
- Our choice of acceptance is 50 π mm mrad

Extraction from ELENA: kicker parameters

- Limited space available
- Former AA injection kicker can be used
- Kicker can't be used at full strength due to limited good field region
- To operate at bigger strength, kicker has to be displaced in the horizontal plane in about 30 mm

L_{magn}/L_{mech}, m	0.432/0.408
Kick, mrad	210
Good field region, mm	± 30
Gap, mm	45
Flat top, ns	<400

Beam diagnostics

- 8 combined HV BPMs for orbit measurements. 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
- Profile monitors (for commissioning and MDs)
- Scrapers for beam profile/emittance measurements
- Transverse BTF DSP system+dedicated kicker for tune measurements