ELENA parameters

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Which parameters of ELENA ring we consider as the most essential?

Main ring parameters from the point of view of design:

- Circumference, affects cost and layout
- Momentum range, upper value is fixed by AD extraction, low value is a subject for careful choice
- Cycle length, affects total number of particles received by experiment (for ELENA it is shorter than for AD)
- Tunes, provide stable operation without losses

Which of them might be a subject to concern by physics community:

- Extraction momentum (energy)
- Cycle length (in our case of long AD cycle really not effecting on performance of complex)

Which parameters of ELENA beam we consider as the most important?

Main beam parameters (important for experiments):

- Intensity, or number of particles at extraction
- Transverse beam emittances and momentum spread at extraction, they will be conserved during beam transport in line to experiment
- At the end of transfer line, with optical functions at focal point the beam size is be defined by

$$\tau_{x,y} = \sqrt{\varepsilon_{x,y}\beta_{x,y} + \left(D_{x,y}\frac{\Delta p}{p}\right)^2}$$

- Bunch length of extracted beam is adjusted with RF system and is limited by physical effects, mainly by space charge of beam and intra beam scattering (IBS)
- Momentum (or energy) spread at extraction is defined by equilibrium between cooling force of electron beam of cooler and IBS

Choice of extraction energy

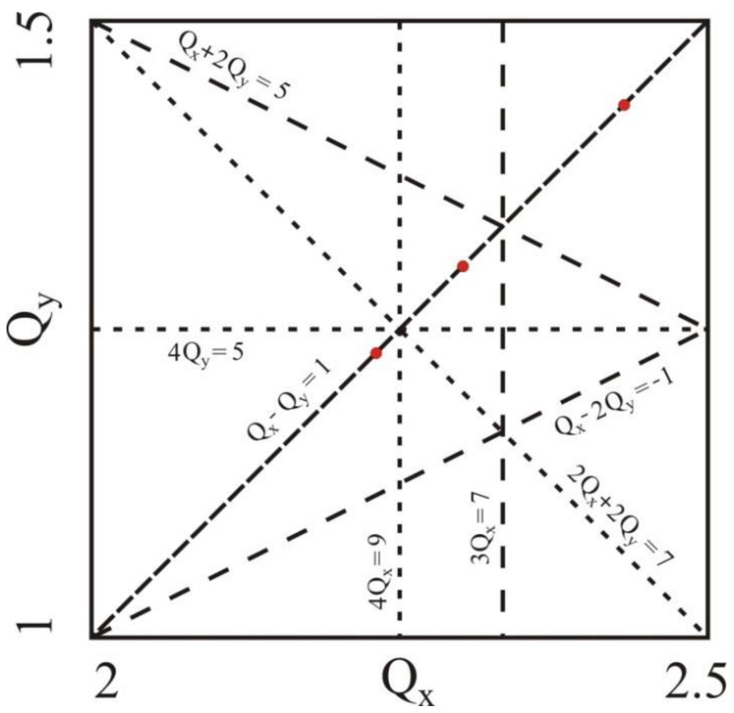
- Extraction energy E_{kin}=100 keV allows to increase significantly an amount of captured antiprotons (~30%)
- If go to lower energy, one meets strong limitations imposed by:
  - IBS (Intra Beam Scattering), growth rate $1/\tau \sim 1/\beta^3$
  - transverse space charge limitations (intensity in one bunch $N_b \sim \beta^2$)
  - very high vacuum required $P \approx 3 \cdot 10^{-12}$ Torr
  - difficult to manufacture foil thinner than 1μm
- If go to higher energy:
  - smaller number of antiprotons due to thicker degrader foil
  - difficult to equip extraction lines with electrostatic elements (high voltage)

Tunes

- The betatron tune is a number of transverse (betatron) oscillations over ring circumference
- Tunes (Q_x and Q_y) must be carefully chosen, the resonance condition

  $$kQ_x \pm lQ_y = m, \quad m,l,k - integer$$

  must be avoided for small *k* and *l*.
- Three pairs of (Q_x,Q_y) values= three working points, (2.23,1.23), (2.30,1.30) and (2.46,1.46) are candidates for operation
- By dashed lines resonances up to 4th order are shown, which are excited in a perfect machine with sextupoles and by space charge



Space charge limit in ELENA

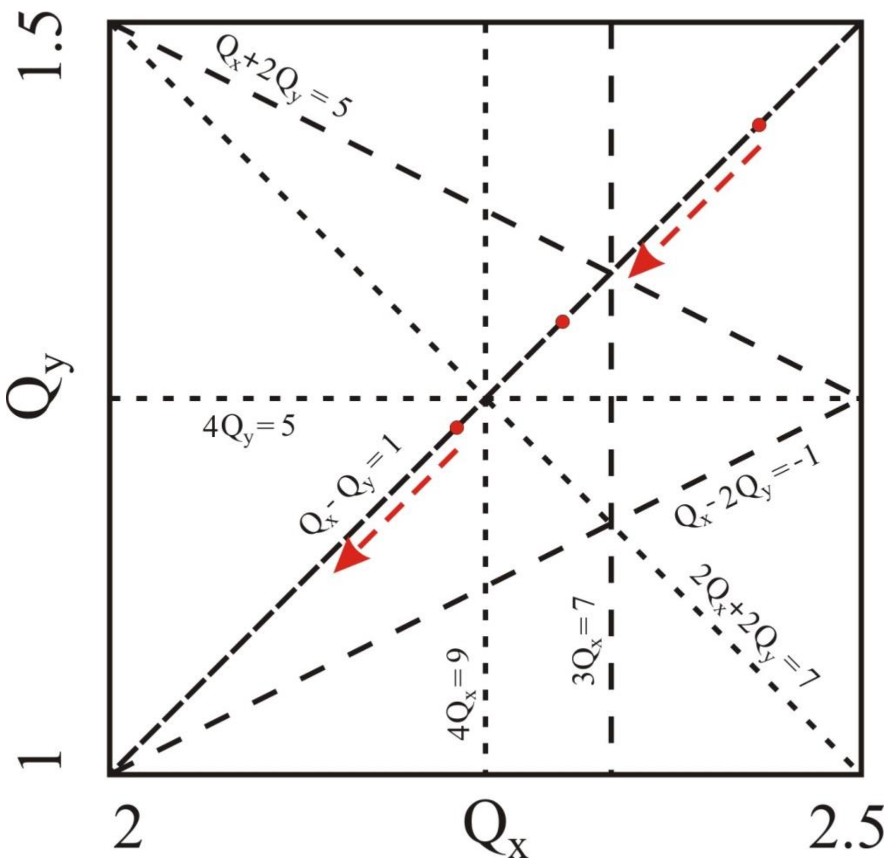
- The extracted bunch parameters are limited by tune shift due to space charge forces

$$\Delta Q = -\frac{G_T r_p N}{2\pi\varepsilon\beta^2\gamma^3}\frac{G_l C}{l_b}$$

Here r_p=1.55 ·10^{-18} m. The coefficient G_T=1 for the uniform beam distribution and G_T=2 for the Gaussian beam distribution, the beam emittance for the first case corresponds to 100% of beam, and for the second case to 95% of beam. The coefficient G_L is the ratio of peak density in the bunch center to its mean density, and C is the ring circumference. By use of double RF harmonics system one can reduce the G_L factor.

- One deduces: the intensity limit is more severe for the bunched beam with small beam transverse sizes at low energy

Space charge effect on betatron tunes

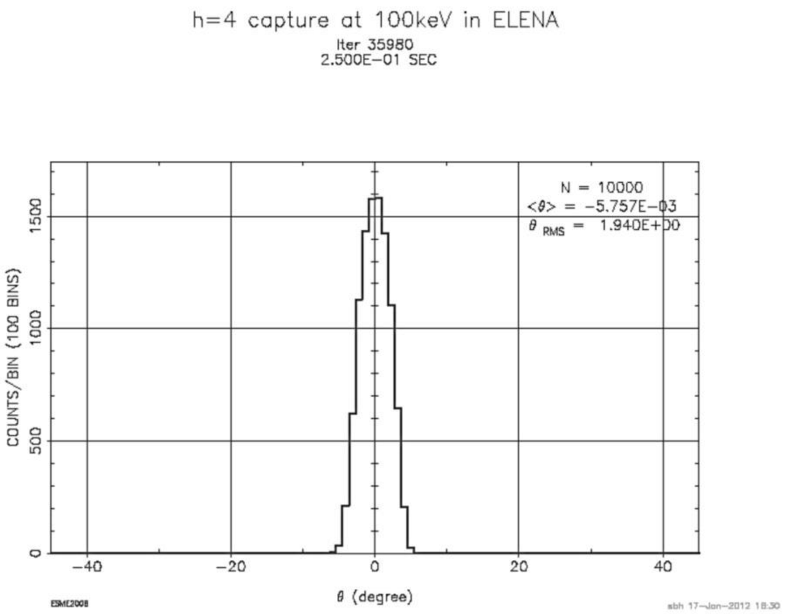


Intensity limitation by charge at extraction

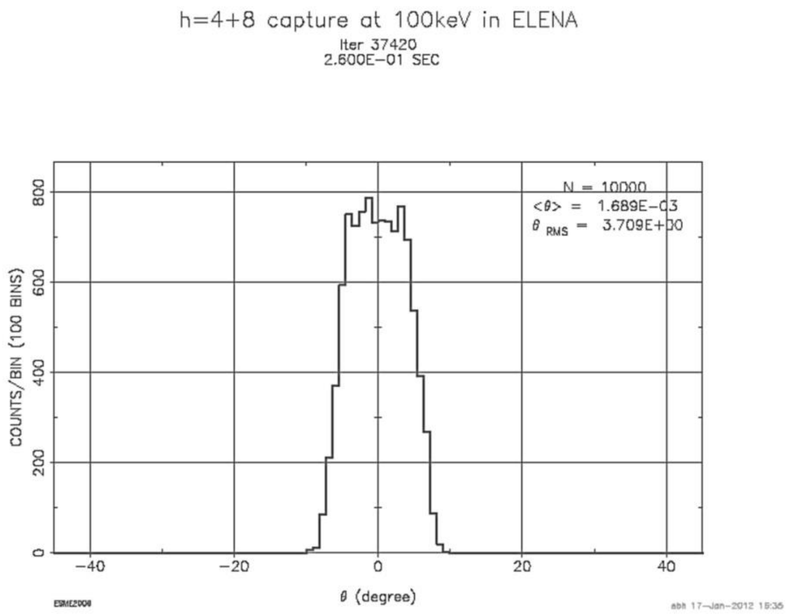
- Assuming intensity of injected beam $N=3\cdot10^7$ and deceleration efficiency 60%, 4 bunches each having $N_b=4.5\cdot10^7$ antiprotons with emittances $\varepsilon_{x,y}=4\pi$ mm mrad and the bunch length $l_b=1.3$ m can be prepared for extraction, and the tune shift value is $\Delta Q=-0.121$, which is on the limit of stability. The coefficients G_T and G_L are equal to 2. By use of RF system with double harmonics (h=4 and h=8) one can flatten the longitudinal beam distribution making tunes shift smaller in about 25% resulting in $\Delta Q=-0.096$.
- One can't extract these amount of antiprotons in 3 bunches, or with smaller emittances, or with shorter bunch length without significant beam losses
- For the high deceleration efficiency 80% and intensity of extracted beam $N=2.4\cdot10^7$ separated in 4 bunches and with use of RF system with double harmonic the tune shift value is $\Delta Q=-0.128$, which is again at the limit of stability.
- One can relax intensity limitation be increasing beam emittance value at extraction. But with imposed constraint of beam size $\sigma_{x,y}=1$ mm at focal point the beta function values must be reduced, which is limited by high voltage in final triplet of electrostatic quadrupoles, and that might be an issue.
- The exact value for intensity limit will be known during commissioning!

Space charge limit: profit by using double harmonic RF system

Bunching on harmonic *h*=4



Bunching on harmonic *h*=4+8



Beam parameters limitations due to intra beam scattering (IBS)

- The beam emittances blow up due to IBS is defined by formula

$$\frac{1}{\tau_x} \propto \frac{N}{\beta^3 \gamma^4 \varepsilon_x \varepsilon_y \sigma_p \sigma_l} \frac{\gamma^2}{\varepsilon_x} Int1,$$

$$\frac{1}{\tau_l} \propto \frac{N}{\beta^3 \gamma^4 \varepsilon_x \varepsilon_y \sigma_p \sigma_l} \frac{\gamma^2}{\sigma_p^2} Int2,$$

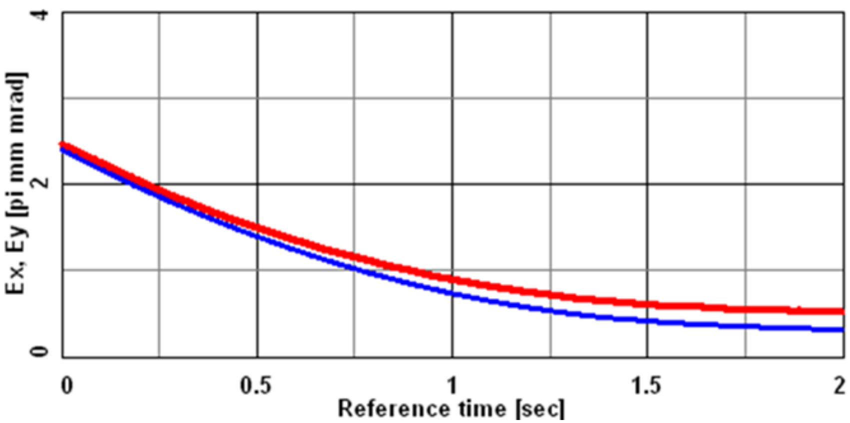
$$\frac{1}{\tau_y} \propto \frac{N}{\beta^3 \gamma^4 \varepsilon_x \varepsilon_y \sigma_p \sigma_l} \frac{\beta_y}{\varepsilon_y} Int3.$$

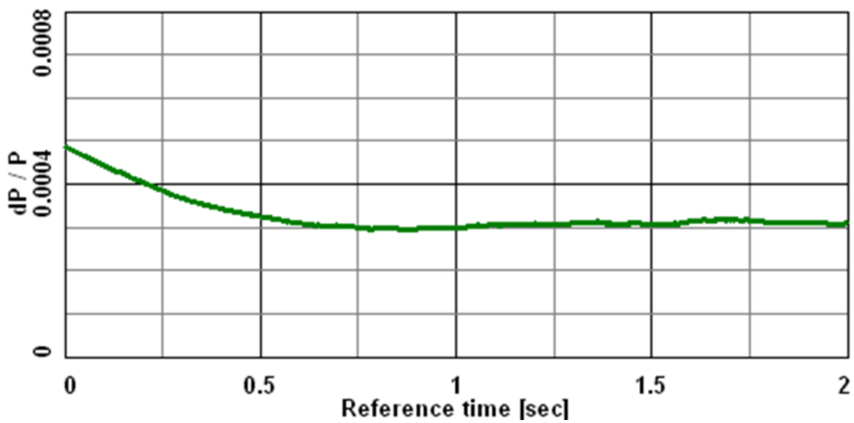
- IBS is the main limiting factor to achieve small emittances and momentum spread during beam cooling at extraction energy

Electron cooling of coasting beam with electron beam current I_e = 1 mA

Emittances calculated with BETACOOL program must be multiplied by 6 for 95% of beam. Equilibrium values $\varepsilon_{x,y}<3$ mm mrad can be achieved. To fit to space charge limitation will be adjusted by a) proper time of injection, b) by putting excitation into beam

Momentum spread calculated with BETACOOL program must be multiplied by 4 for 95% of beam. Equilibrium momentum spread $\Delta p/p \approx 1.2 \cdot 10^{-3}$ can be achieved

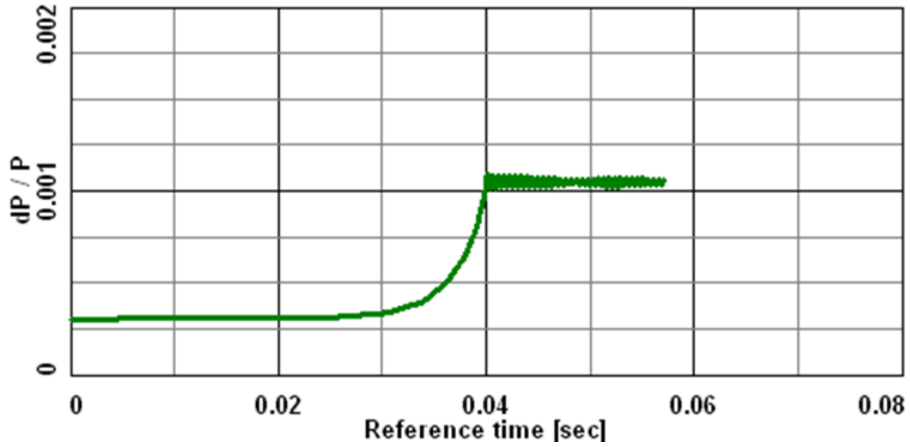


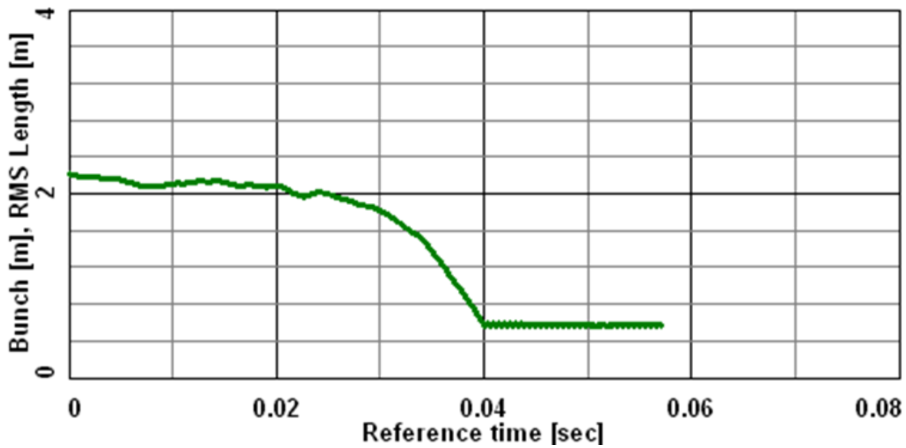


Beam extraction after cooling of coasting beam and its bunching

- After cooling of coasting beam in will be captured and bunched to get required bunch length l_b=1.3 m, then kick out. The RF system will operate at harmonic *h=4* to avoid intensity limit imposed by space charge forces
- Due to short bunching time no significant blow up caused by IBS occurs
- The expected emittances $\varepsilon_{x,y}$=4 mm mrad (defined by space charge limit)
- The momentum spread is about $\Delta p/p \approx 8 \cdot 10^{-3}$ (defined by minimal momentum spread achieved during cooling of coasting beam)
- The drawback: with noticeable dispersion in electrostatic transfer line losses might occur due to limited aperture of electrostatic deflecting elements
- For that experiments needed beam with smaller momentum spread *the bunched beam cooling* has to be applied after beam bunching and before its extraction

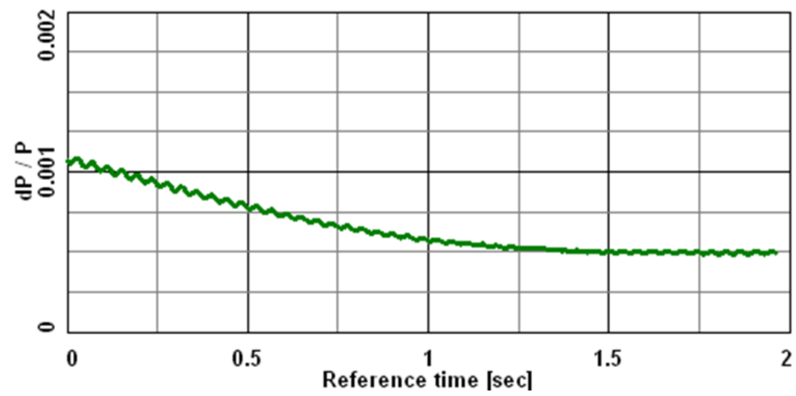
Capture and bunching with V_{RF}=20 V

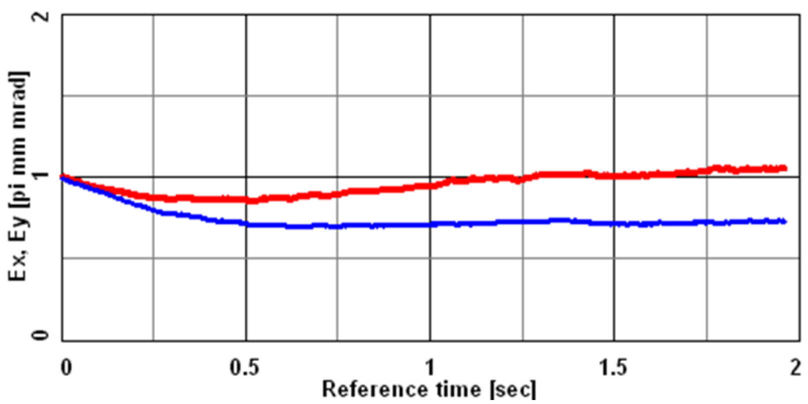


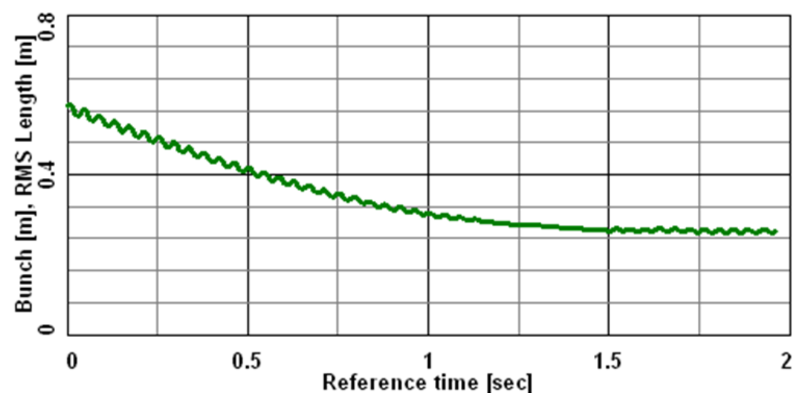


Electron cooling of bunched beam with I_e=1 mA

If the main goal is to reduce momentum spread in extracted beam, the best way is to start bunched beam cooling after the end of bunch compression. In this case the longitudinal blow up due to IBS will be smallest, and momentum cooling will be the most effective.







Beam parameters during cooling and bunching processes with V_{RF} = 20 V and I_e = 1 mA

	ε_x, ε_y π mm mrad	$\Delta p/p_{rms}$, 10^{-3}	σ_{rms}, m	ε_{long}, mm	t, sec
initial coasting beam	15 / 15	2	-	-	0
cooling of coasting beam	5.4 / 4.2	1.2	-	-	0,8
capture and bunching	5.6 / 4.2	4.2	2.2	9.2	0,84
cooling of bunched beam	6.3 / 4.5	2	1.04	2.1	2,3

- About four times smaller momentum spread can be achieved
- Slightly higher transverse emittances compared with standard fast extraction, is the price for smaller momentum spread, can be readjusted

ELENA main parameters

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 (basic scenario)	4
$\varepsilon_{x,y}$ of extracted beam, $\pi\cdot$mm$\cdot$mrad, [95%], standard	4 / 4
$\varepsilon_{x,y}$ of extracted beam, $\pi\cdot$mm$\cdot$mrad, [95%], with bbc*	6 / 4
$\Delta p/p$of extracted beam, [95%], standard	$8\cdot10^{-3}$
$\Delta p/p$ of extracted beam, [95%], with bbc*	$2\cdot10^{-3}$
Bunch length at 100 keV, m / ns	1.3 / 300

bbc* -> bunched beam cooling

Thanks for your attention