Optics for ELENA: status at the beginning of project

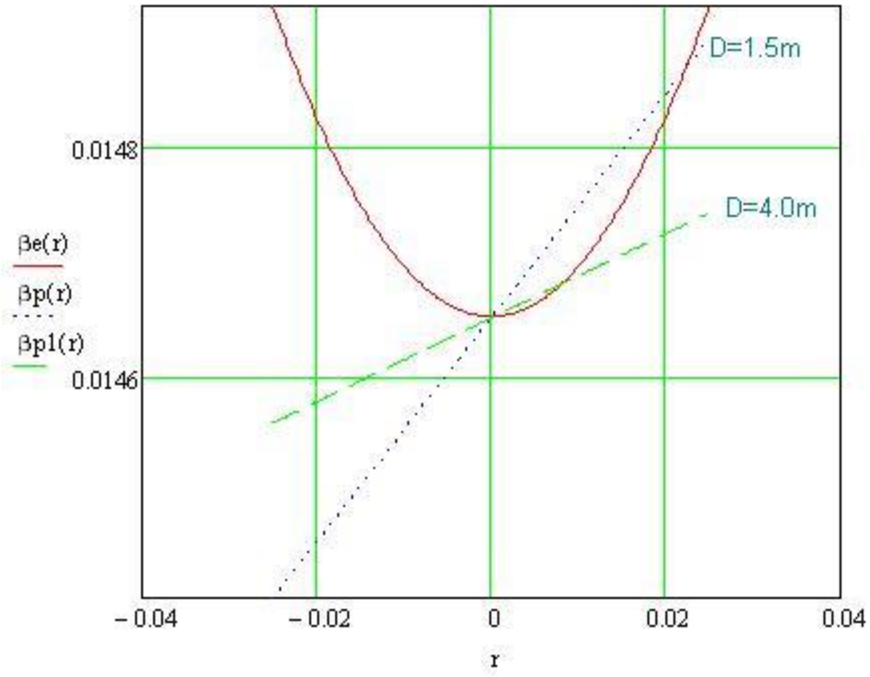
Main requirements to ELENA optics: space constraints

- To prepare adequate space for electron cooler -> long straight section required
- To provide space for beam injection and extraction
- To provide space for all required equipment as well as for one more extraction to the extra experimental area
- 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 at the end of AD to ELENA transfer line is hardly possible, with smaller Δp emittance blow up due to dispersion mismatch will be smaller.

Main requirements to ELENA optics: beam physics constraints

- Tunes must provide decent space in tune diagram to relax intensity limitation set by space charge at extraction energy
- beta function values in cooling section should be suitable for fast cooling of antiproton beam, antiproton beam alignment w.r.t. electron beam should be foreseen. Dispersion in electron cooler should not be large, otherwise beam losses occurs
- Optimal compromise for magnetic field value in a bending magnets at low energy should be defined: the strong field is easy for operation, but short magnets possess stronger focusing properties and produce more stray fields
- The vertical beta function in bending magnet should be small to limit stray fields for the case of short magnet
- Average beta function values must be low to minimize beam emittance blow up due to multiple gas scattering
- Very small beta function values should be avoided to minimize beam emittance blow up due to IBS

Antiproton and electron velocity distribution versus radius in electron cooler drift space



I=1mA. Courtesy of G.Tranquille

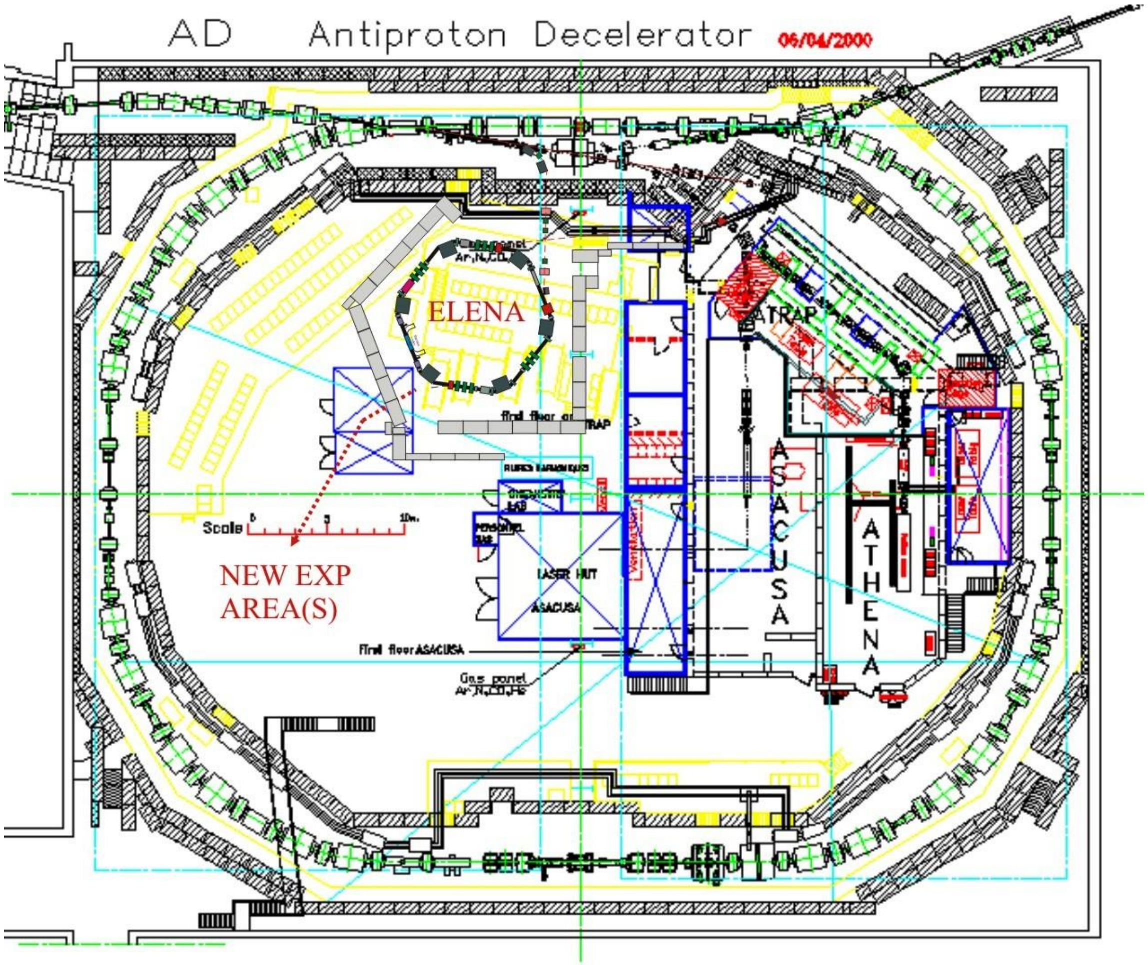
Main requirements to ELENA optics: other constraints

- Lattice should be optimized to simplify magnet system design
- Lattice should be optimized to reduce magnet system cost

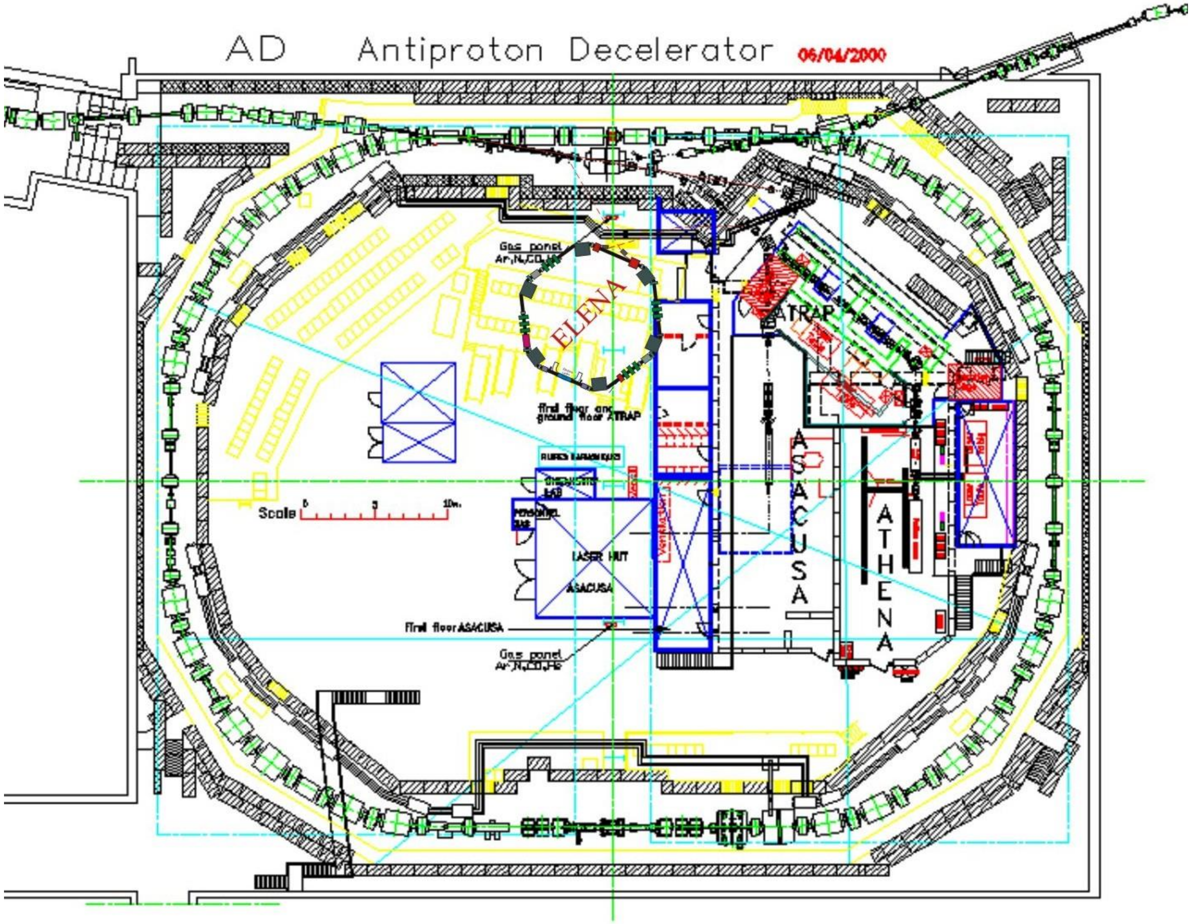
Topics for today’s discussion

- Linear optics
- Injection (layout only related issues)
- Extraction (various options)

ELENA layout in AD Hall



ELENA layout in AD Hall for injection and ejection in the same section



Layout #2: positive and negative features

Advantages:

- Injection and ejection at the same section
- Slightly shorter transfer line from ELENA to experiments

Drawbacks:

- More difficult installation due to not available crane for big part of ELENA equipment
- Short AD to ELENA transfer line, difficult (hardly possible?) matching
- Access to DEO zone??

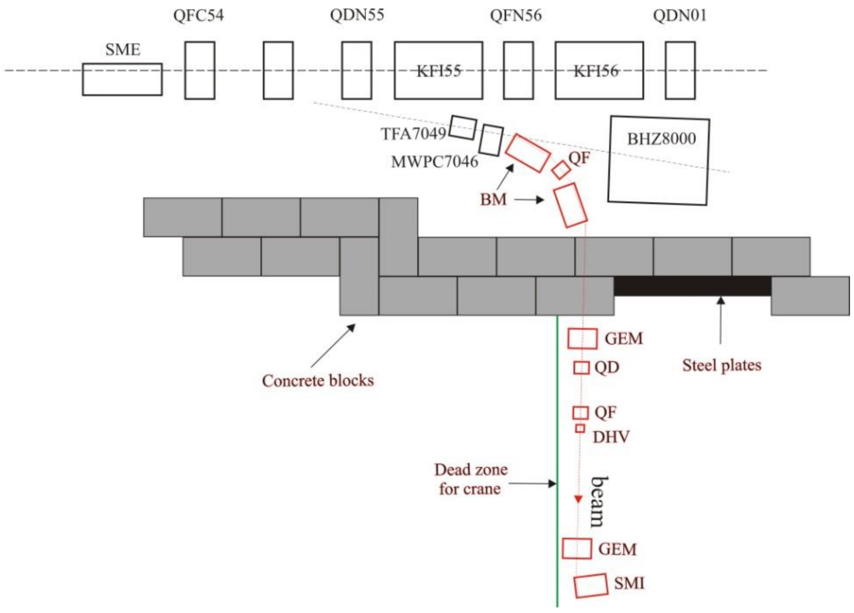
Only layout #1 was studied-> injection and extraction done in different sections

Constraints on optics coming from layout of ELENA in AD Hall

- Crane dead zone -> AD to ELENA transfer line layout is fixed -> the layout of injection straight section is fixed
- The extraction can be done in other (upstream) section only
- The precise position of injection straight section inside of AD Hall is defined by length of AD to ELENA transfer line (matching for longer line is easier, yet position of the Laser Hut set limit on the length)
- The angle of injection transfer line w.r.t. crane dead zone line is defined by optimal conditions for injection into ELENA (kicker and septum strengths and positions)

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



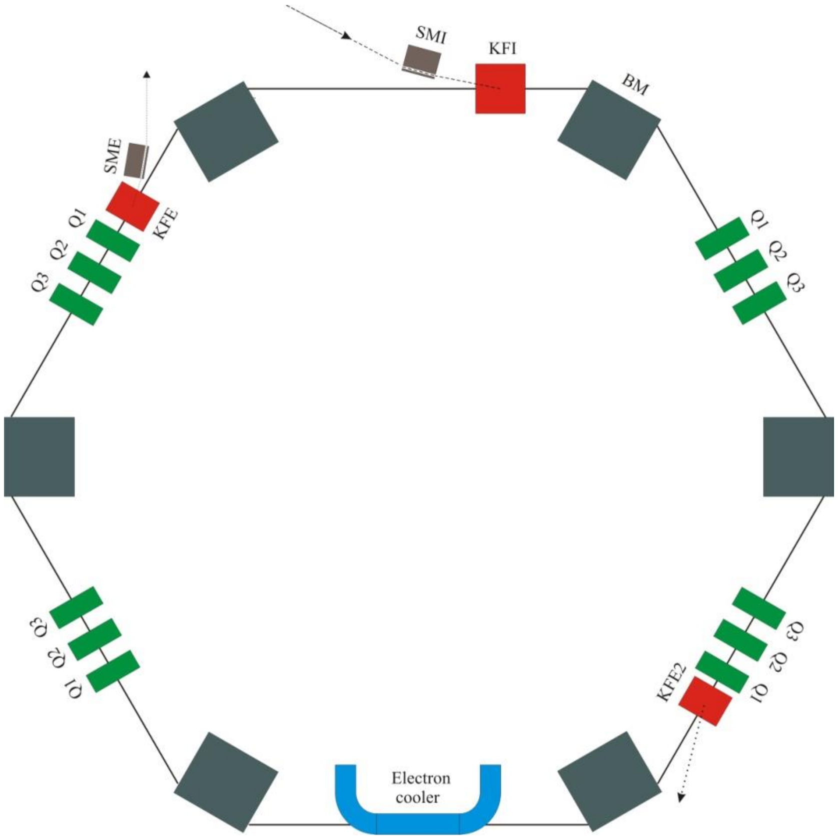
Why did we choose
6 fold ring configuration?

Advantages of the 6 fold ring:

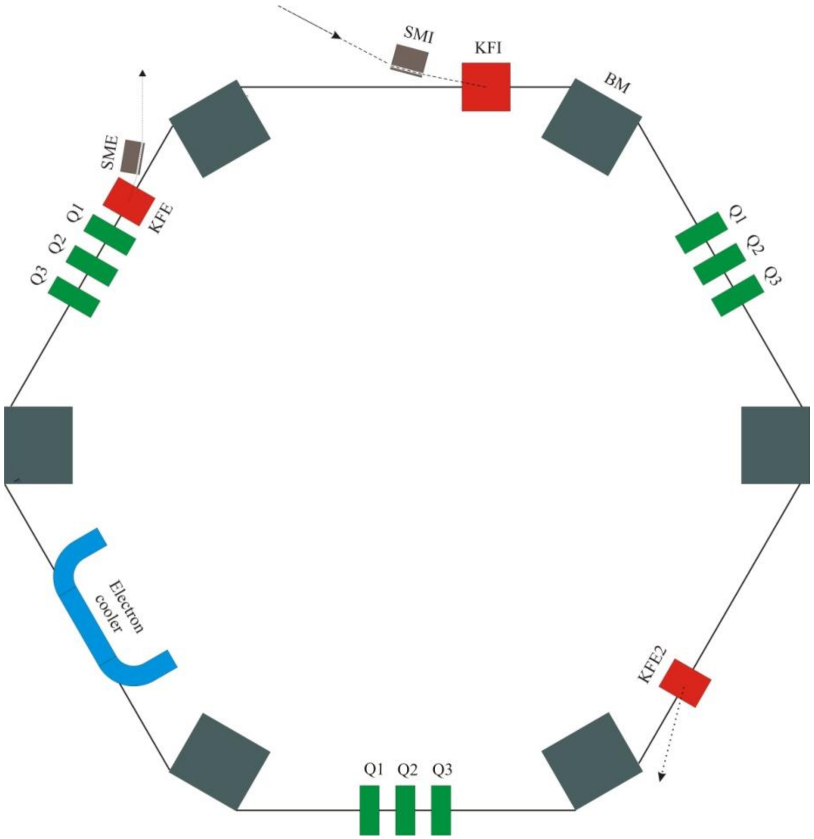
- More flexibility for injection and extraction with the new layout
- The total length of bending magnets is shorter for hexagonal lattice compared with rectangular lattice -> more space for other equipment
- Minimal magnetic field in bending magnets (at 100 keV) increased from 399 Gs to 493 Gs – essential!
- Smaller beta function values -> smaller aperture required by beam, relaxed requirement for vacuum

Possible optics configurations for 6 fold ring

4 triplets in 6 sections

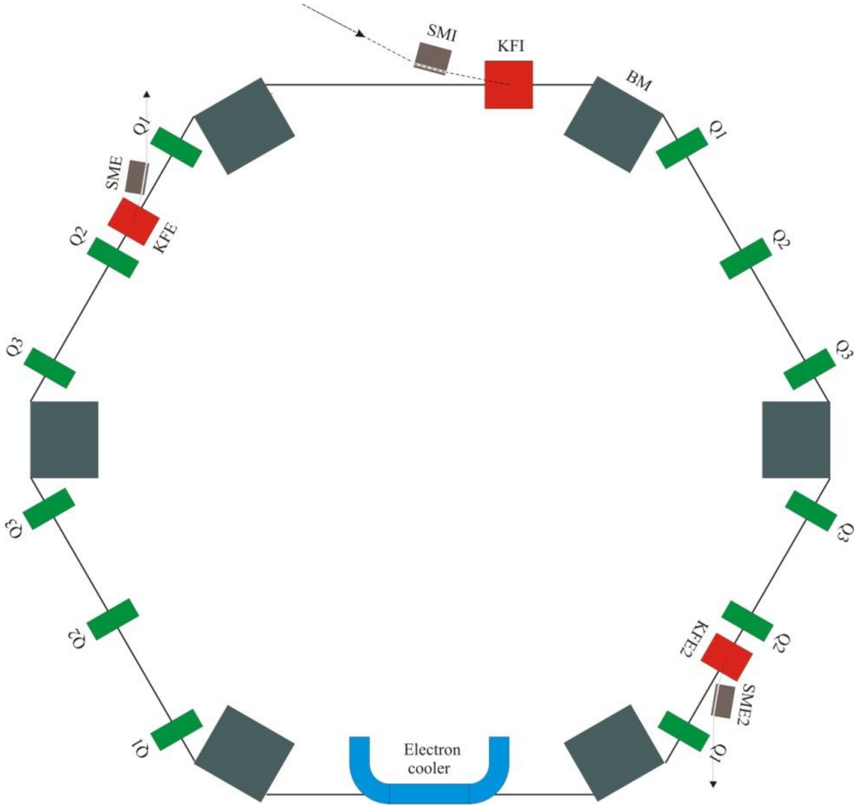


3 triplets in 6 sections

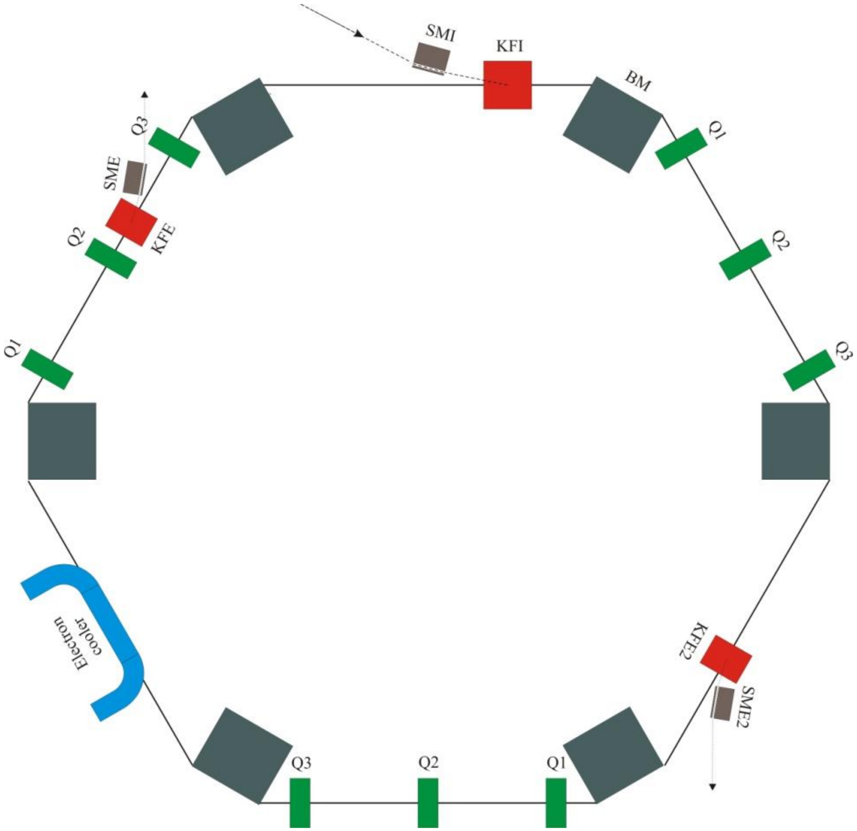


Possible optics configurations for 6 fold ring

3 quads in 4 straight sections



3 quads in 3 straight sections

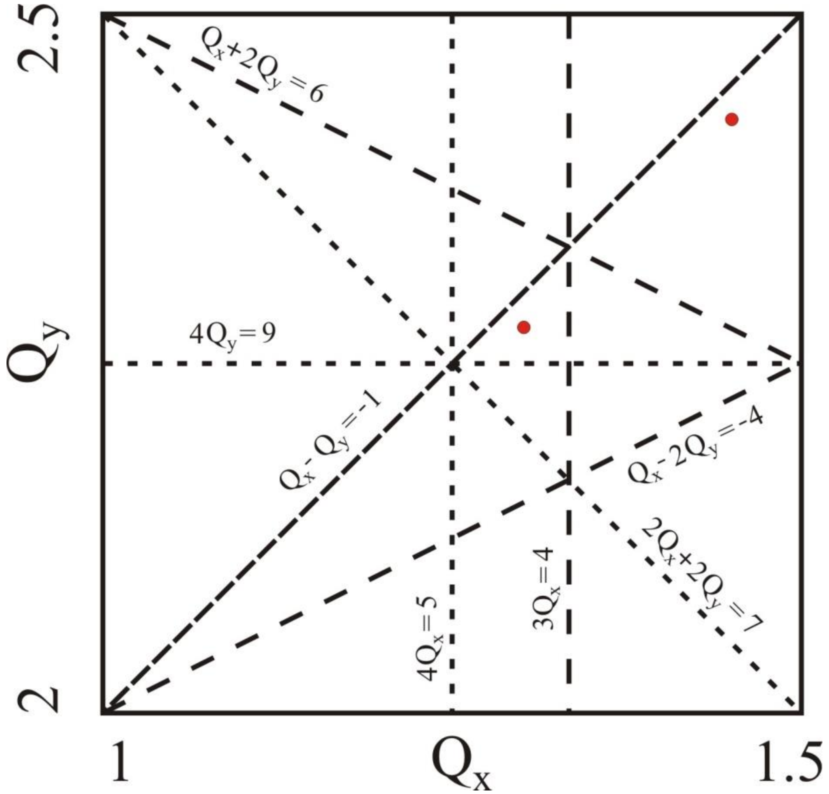


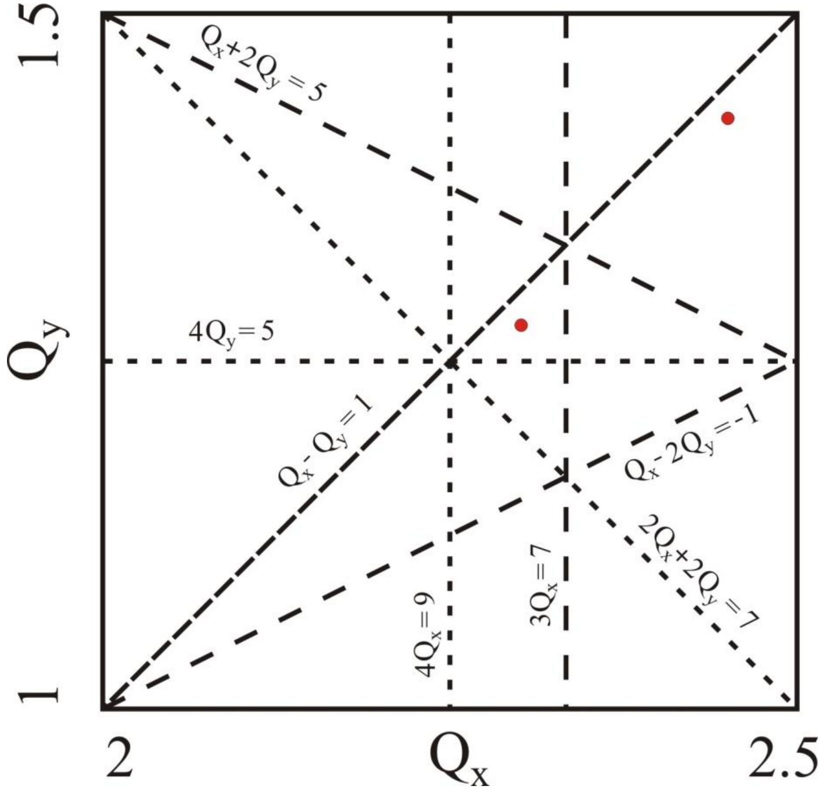
Choice of tunes: possible and impossible options

- $1<Q_x<2$, $1<Q_y<2$ is impossible due to strong focusing effect in bending magnet (small ρ)
- $2<Q_x<3$, $2<Q_y<3$ is impossible due to compact size of machine. Example: CRYring had tunes $Q_x=2.3$, $Q_y=2.27$ with circumference 51.6 m
- Possible choice: $1<Q_x<2$, $2<Q_y<3$ and $2<Q_x<3$, $1<Q_y<2$
- Useful consideration for optics with sector bending magnets having no fringe fields: if solution with $Q_x=Q_1$, $Q_y=Q_2$ and $\beta_x=f(s)$ and $\beta_y=g(s)$ is found, then exist another solution with tunes $Q_x=Q_2$, $Q_y=Q_1$ and $\beta_x=g(s)$ and $\beta_y=g(s)$ for magnet system with rectangular bending magnet and quadrupoles with opposite polarity. The finite effect of fringe field destroys this transformation, yet it works approximately. If for the first solution the sector magnet has edges $E_1=E_2=E_0$, then for the second solution rectangular magnet has the same edge angle.
- This consideration is useful in special cases like minimization of the vertical aperture of bending magnet, optimization of dispersion in electron cooler etc.

Choice of tunes

Main requirement to tunes is to provide the possible biggest area free from the low order resonances to relax intensity limit imposed by space charge





Which parameters can be varied?

- 4 possible configurations of optics, 4 possible tunes for each optics: Q_x=1.3, Q_y=2.3, or Q_x=1.45, Q_y=2.45, or Q_x=2.3, Q_y=1.3, or Q_x=2.45, Q_y=1.45
- Variable parameters: edge angle $E_1=E_2$
- Fixed (for the time being): length of bending magnet l_{bm} =0.97 m (the same as in feasibility study)
- Fixed: gap of bending magnet is 70 mm, FINT=0.5

Tunes comparison

0.3 non-integer part advantages:

- No special care of sum coupling resonance $Q_x+Q_y=4$
- Weakness of the 4th order resonances -> space charge limit is up to ΔQ = 0.2 to 0.25
- Small sensitivity to quadrupole errors due to large distance from the second order resonances

0.45 non-integer part advantages:

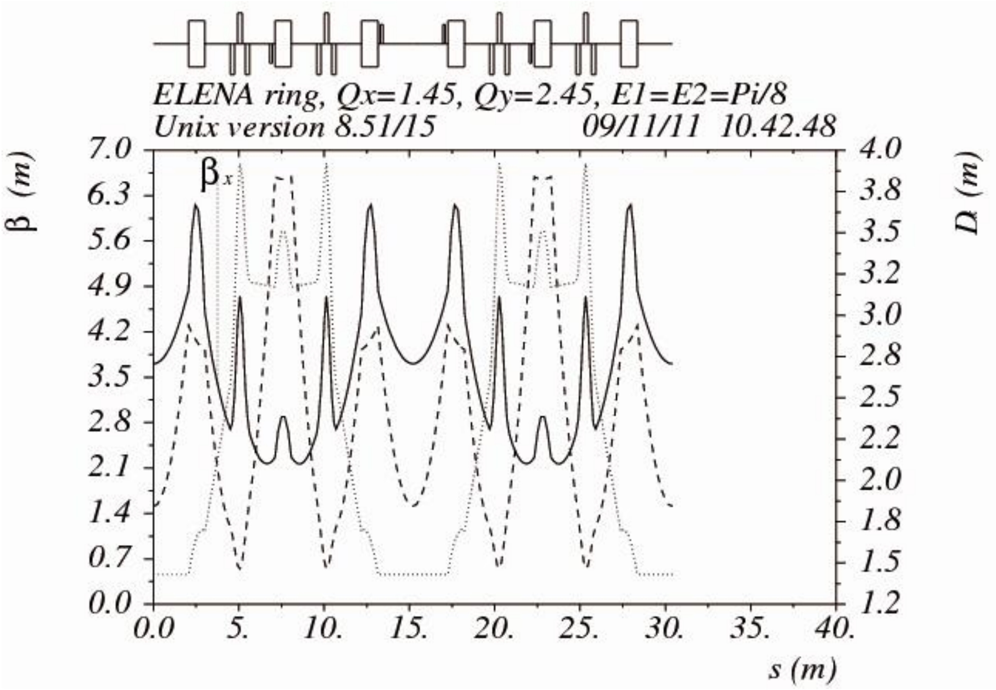
- Potential of having space charge limit up to ΔQ = 0.4

4 triplets, Qx=1.3, Qy=2.3 and Qx=1.45, Qy=2.45

$E_1=E_2$	Q_x/Q_y	β_x/β_y /D_x, m (max)	β_x/β_y /D_x, m (cooler)	K1, m^{-2}	K2, m^{-3}
π/7.5	1.3/2.3	6.6/5.9/4.0	4.1/0.9/2.7	0.19/-0.20/0.50	10/-9
π/7.5	1.45/2.45	6.3/7.0/3.6	3.6/0.9/1.2	-2.3/4.1/-1.5	21/-17
π/8	1.3/2.3	6.4/6.7/4.2	4.0/1.5/3.0	-2.1/2.7/-1.0	4/-3
π/8	**1.45/2.45**	**6.1/6.5/3.9**	**3.7/1.5/1.4**	**-3.7/5.3/-2.4**	**18/-11**
π/9	1.3/2.3	9.7/6.7/4.4	2.6/3.4/4.1	-3.9/4.3/-2.4	2.0/-1.6
π/9	1.45 /2.45	6.0/4.1/3.4	1.7/2.2/3.2	-2.8/5.6/-4.9	19/-9
π/9	1.45 /2.45	6.2/8.4/4.1	4.1/4.3/2.0	-6.5/6.7/-3.2	12/-5
π/10	1.3 /2.3	13.3/4.8/3.3	0.7/3.6/4.0	1.9/-2.1/0.7	?
π/10	1.45 /2.45	8.1/5.0/3.8	1.5/3.6/4.0	-4.0/6.2/-5.3	11/-3

4 triplets, Qx=1.3, Qy=2.3 and Qx=1.45, Qy=2.45 (summary)

- The best choice for edge angle is π/8=22.5° and for tunes Q_x=1.45, Q_y=2.45
- the chromaticity correction is straightforward
- Unfortunately, optics with the same edge angle but with tunes Q_x=1.3, Q_y=2.3 has big dispersion of 3.0m and can’t be used as backup solution

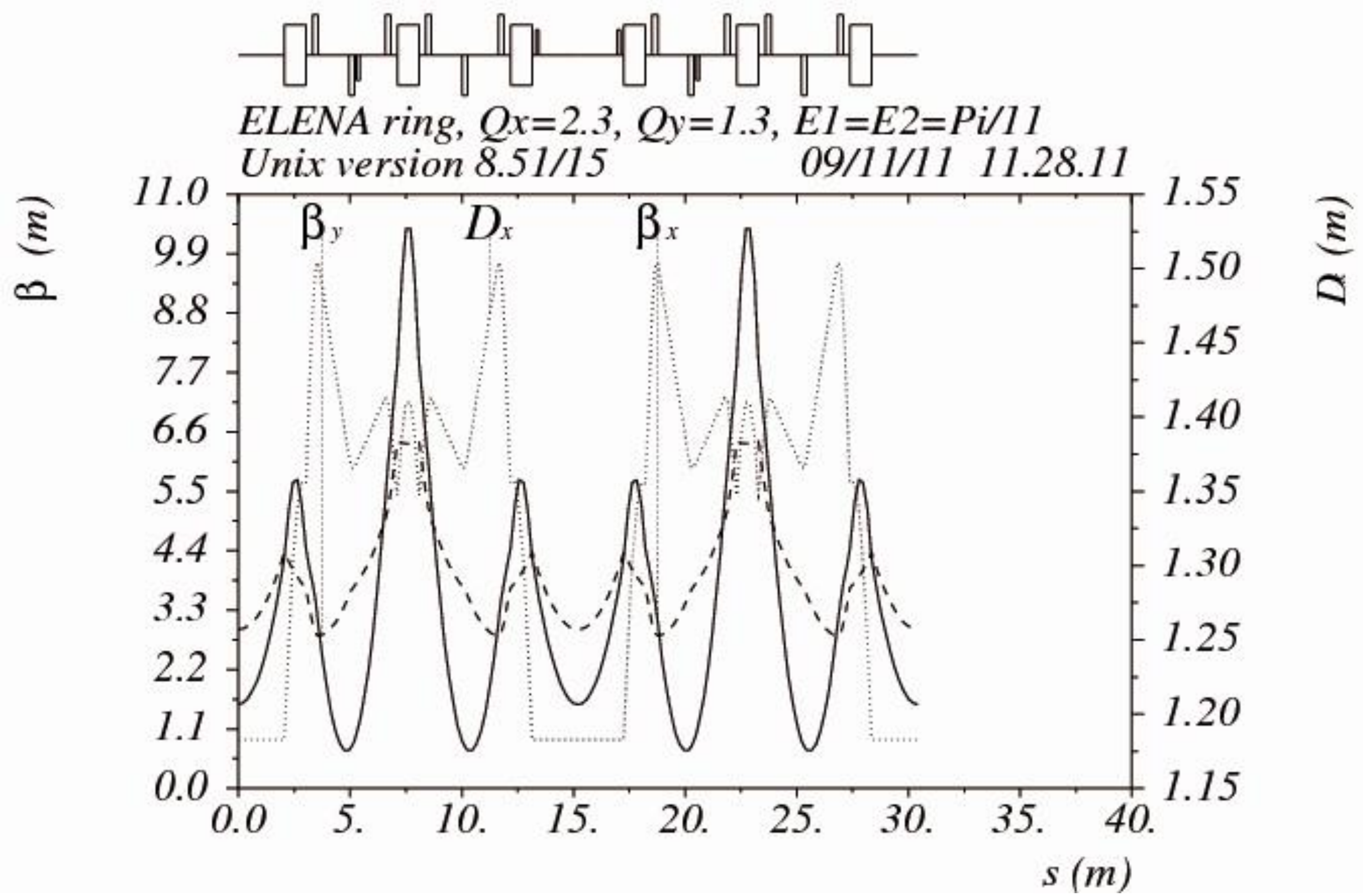


4 triplets, Qx=2.3, Qy=1.3

- The best solution is that having tunes tunes Q_x=2.3 ,Q_y=1.3 and edge angle of π/15. It provides small dispersion in electron cooler and small gap in bending magnet
- On the negative side is strong sensitivity of chromaticity correction to the value of edge angle
- No good solutions with tunes Q_x=2.45 ,Q_y=1.45 found.

E_1=E_2	Q_x/Q_y	β_x/β_y /D_x, m (max)	β_x/β_y /D_x, m (cooler)	K1, m^{-2}	K2, m^{-3}
π/12	2.3 /1.3	5.1/8.6/4.1	1.9/1.0/4.0	0.8/-3.1/4.1	20/-146
π/14	2.3 /1.3	9.0/5.6/1.6	1.9/3.3/1.5	2.7/-3.0/1.4	159/-106
π/15	**2.3 /1.3**	**9.2/4.9/1.5**	**1.5/3.8/1.2**	**1.9/-2.1/0.7**	**27/-43**
π/16	2.3 /1.3	9.0/5.1/2.0	1.2/4.1/2.1	1.0/-0.9/0	14/-25

Lattice functions for optics with Qx=2.3, Qy=1.3



4 sections each with 3 quadrupoles, Qx=1.3, Qy=2.3 and Qx=1.45, Qy=2.45

$E_1=E_2$	Q_x/Q_y	$\beta_x/\beta_y/D_x$, m (max)	$\beta_x/\beta_y/D_x$, m (cooler)	K1, m^{-2}	K2, m^{-3}
π/8	1.3/2.3	6.5/6.9/4.1	4.2/1.1/2.7	-0.4/0.5/-0.1	9.1/-11.0
π/8	1.45/2.45	5.9/8.6/3.4	3.4/0.7/1.4	-0.6/1.5/-0.4	78/-74*
π/9	1.3/2.3	5.7/7.0/3.9	3.4/1.4/3.3	-0.9/0.5/-0.4	3.3/-3.0
π/9	1.45 /2.45	5.7/7.4/3.4	3.2/0.8/1.9	-1.1/1.5/-0.7	47/-51*
π/10	1.3 /2.3	8.0/6.5/4.0	2.5/1.5/3.8	-1.2/0.4/-0.7	3.3/-4.8
π/10	1.45 /2.45	14.1/14.1/3.1	0.5/0.5/3.1	-4.0/6.2/-5.3	42/-4.4*
π/11	1.3 /2.3	10.0/6.8/4.3	2.0/1.7/4.0	-1.5/0.4/-0.8	14/-16*
π/12	1.3 /2.3	10.6/5.7/4.1	1.2/1.3/3.9	-1.4/0.54/-1.3	5.4/-9.1

4 sections each with 3 quadrupoles, Qx=1.3, Qy=2.3 and Qx=1.45, Qy=2.45 (summary)

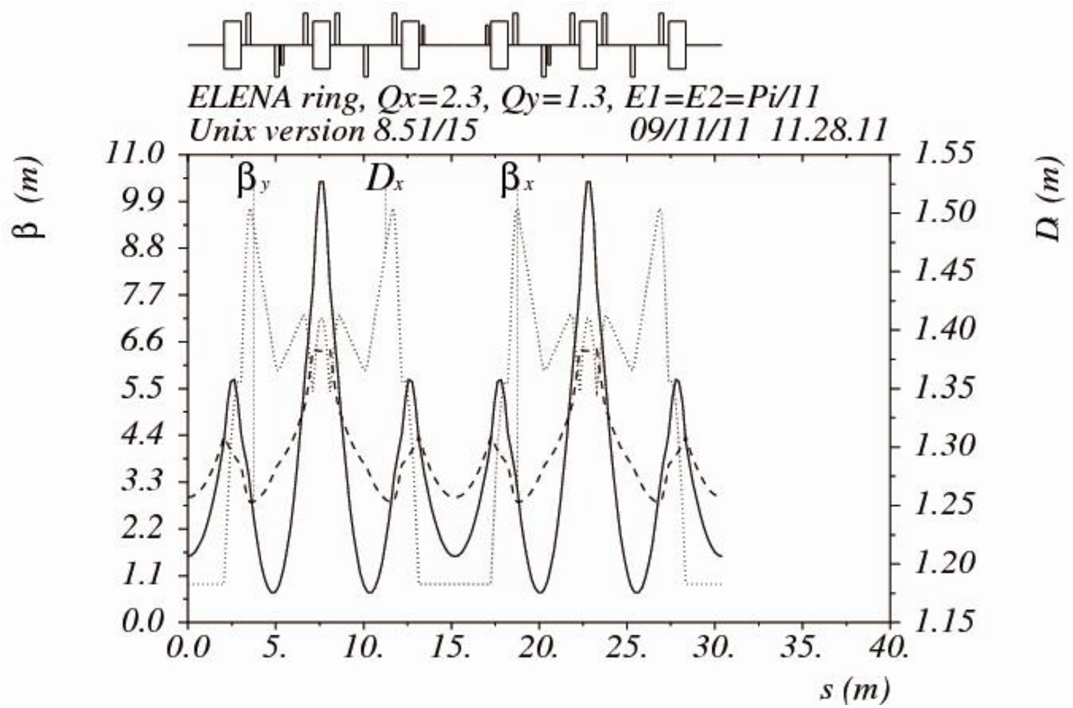
- No good solution was found.
- The better one, with edge angle π/8 and tunes Q_x=1.45, Q_y=2.45 provides small dispersion in electron cooler D_x=1.4m, but the vertical beta function is β_y=0.7m, which is too small.

4 sections each with 3 quadrupoles, Qx=2.3, Qy=1.3 and Qx=2.45, Qy=1.45

$E_1=E_2$	Q_x/Q_y	$\beta_x/\beta_y/D_x$, m (max)	$\beta_x/\beta_y/D_x$, m (cooler)	K1, m^{-2}	K2, m^{-3}
π/9	2.3/1.3	5.7/7.0/3.9	1.0/1.1/2.4	1.5/-0.7/1.5	*
π/9	2.45 /1.45	10.6/7.7/1.7	1.1/2.4/1.3	2.1/-1.2/1.3	*
π/10	**2.3 /1.3**	**10.1/7.8/1.7**	**1.7/2.3/1.4**	**1.5/-0.4/0.8**	*
π/10	2.45 /1.45	10.6/4.3/1.6	1.0/2.9/1.3	1.7/-1.3/1.0	*
π/11	**2.3 /1.3**	**10.4/6.4/1.5**	**1.6/2.9/1.2**	**1.3/-0.38/0.56**	**36/-45**
π/11	2.45 /1.45	10.6/4.4/1.6	0.9/3.2/1.2	1.5/-1.3/0.8	*
π/12	**2.3 /1.3**	**10.5/5.4/1.9**	**1.5/3.5/1.0**	**1.0/-0.4/0.4**	75/-124*

4 sections each with 3 quadrupoles, Qx=2.3, Qy=1.3 and Qx=2.45, Qy=1.45 (summary)

- Tunes choice is Qx=2.3, Qy=1.3
- Edge angle choice can be in the range from π/10 to π/12



3 sections each with 3 quads (2 families), Qx=1.3, Qy=2.3 and Qx=1.45, Qy=2.45

$E_1=E_2$	Q_x/Q_y	$\beta_x/\beta_y/D_x$, m (max)	$\beta_x/\beta_y/D_x$, m (cooler)	K1, m^{-2}
π/7	1.3/2.3	6.3/5.5/3.7	2.0/0.9/3.2	0.05/0.51
π/7	1.45/2.45	31.6/7.2/4.0	0.4/0.6/2.8	0.95/0.12
π/8	1.3/2.3	5.7/5.5/3.7	2.5/1.0/3.2	0.55/-0.29
π/9	1.3/2.3	6.0/5.4/3.8	3.9/1.1/3.5	0.49/-0.78
π/9	1.45/2.45	17.6/7.2/3.7	0.7/0.8/2.7	1.4/-1.1

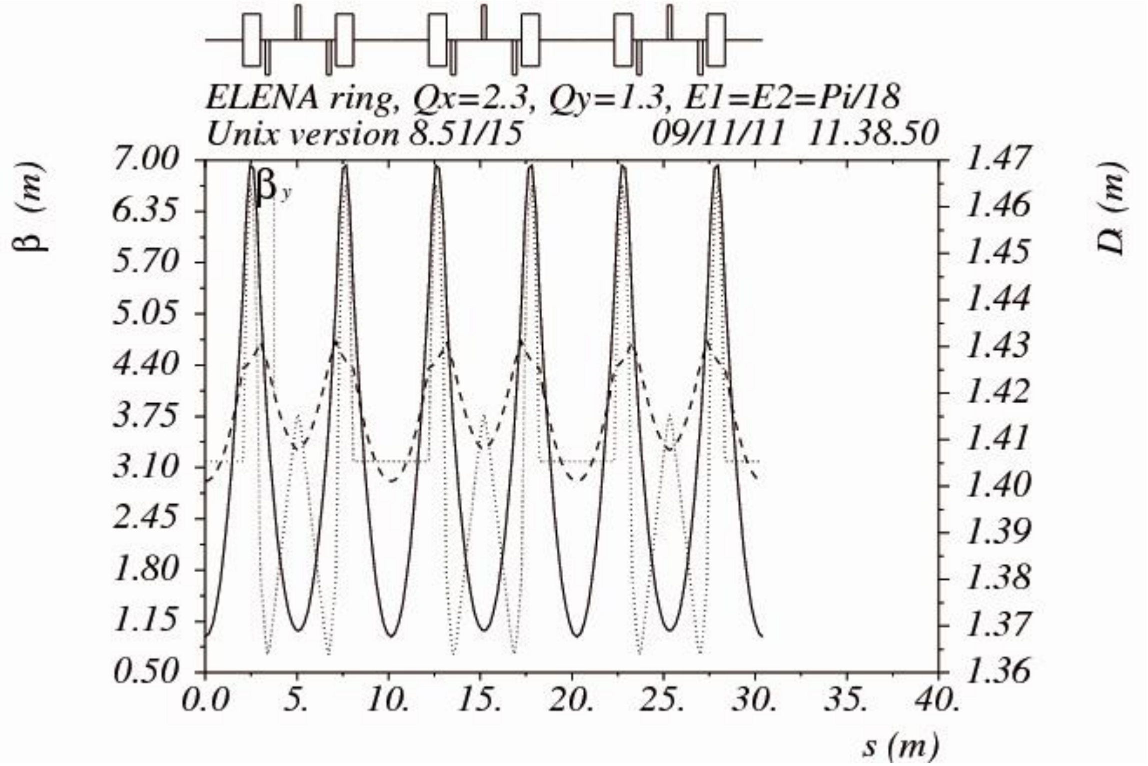
No good solutions found

3 sections each with 3 quads (2 families), Qx=2.3, Qy=1.3 and Qx=2.45, Qy=1.45

$E_1=E_2$	Q_x/Q_y	β_x/β_y /D_x, m (max)	β_x/β_y /D_x, m (cooler)	K1, m^{-2}
π/12	2.3/1.3	6.5/7.6/1.5	1.2/7.0/1.2	0.14/0.80
π/15	2.3/1.3	7.0/4.6/1.5	1.0/3.4/1.4	-0.18/0.23
π/18	**2.3/1.3**	**7.0/4.7/1.5**	**1.0/2.9/1.4**	**0.19/-0.25**
π/18	2.45/1.45	9.2/22.7/1.5	0.7/0.5/1.5	-0.91/0.15
π/20	2.3/1.3	6.7/4.9/1.5	1.0/2.9/1.4	0.57/-0.53

3 sections each with 3 quadrupoles Qx=2.3, Qy=1.3 and Qx=2.45, Qy=1.45

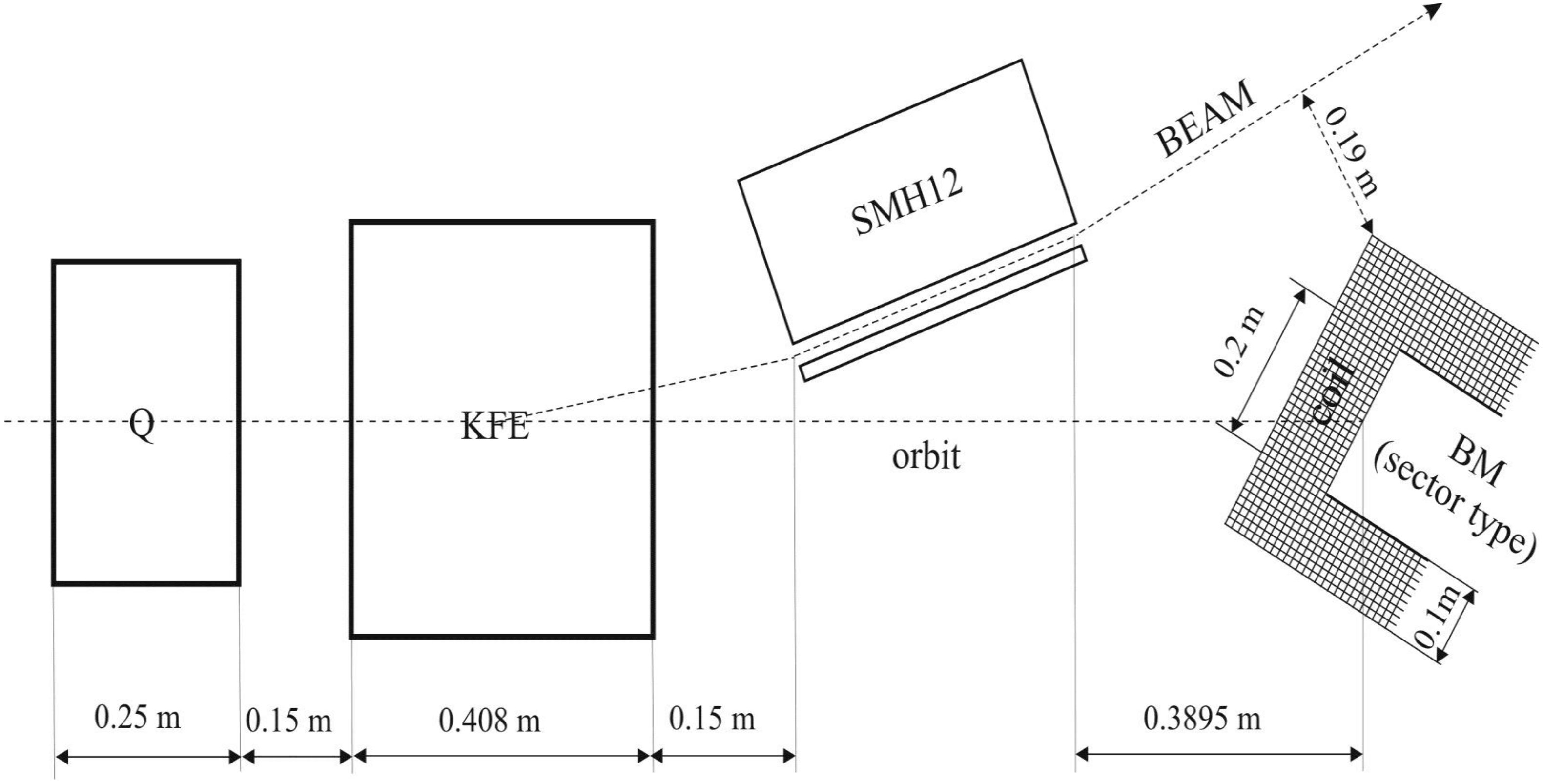
There are plenty of variants with suitable dispersion in electron cooler, unfortunately all of them provide not good beta function values there



Preliminary conclusions on optics studies of 6 fold ring with circumference 30.4m

- It was found that main limitation comes from the requirements to dispersion and Twiss functions (in a less extent) in electron cooler
- Several solutions have been found, they have been mentioned above
- These solutions vary in maximal strengths in quadrupoles and sextupoles, in sensitivity of chromaticity correction to the value of edge angle
- They have different working points, with non integer parts either 0.3 or 0.45
- Due to different beta function values in electron cooler optics distortion due to solenoidal fields will be different
- The IBS lifetime and multiple gas scattering will differ as well
- The comparison of these linear optics will be done later

Extraction from ELENA in a short straight section



Extraction from ELENA in a short straight section: summary

- Suitable for various optics
- Short section (less than 1.5m), big angles in deflecting elements required
- Strong kicker needed (δ_k=190 mrad) , module of former AA injection kicker may be used. The beam deviation inside the kicker is 38.8mm, the beam size is space required for ejected beam is

$$\sigma_x = [\varepsilon_x \beta_x + (\Delta p / p)^2]^{1/2} = [8 \cdot 5 + (3 \cdot 1)^2]^{1/2} = 7\ mm$$

and the space for beam is 38.8+2·(7+3)=58.8 mm (3 mm added for trajectory error), which fits good field region. When optics will be finalized, this value should be revised.

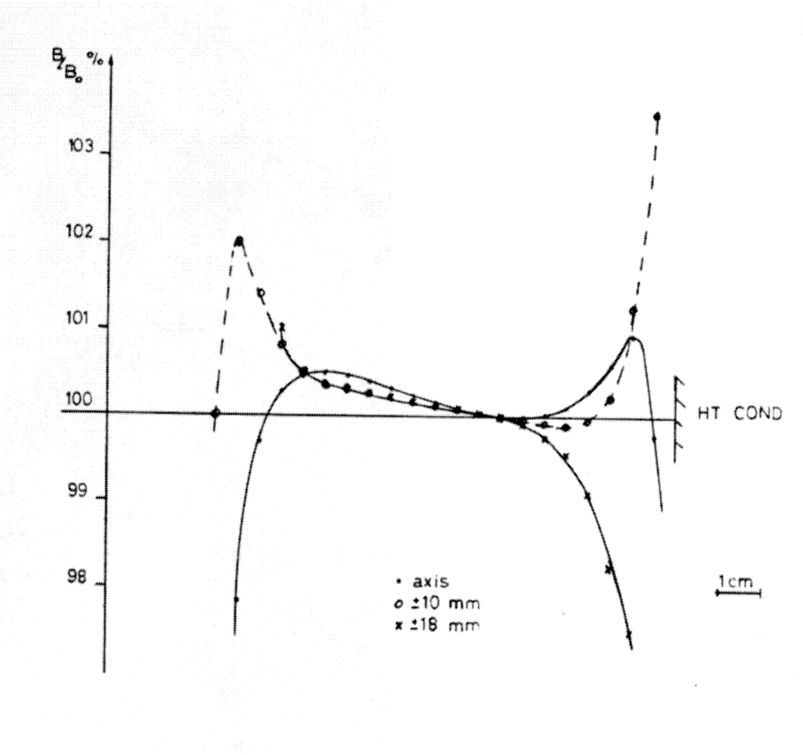
- Magnetic septum SMH12 may be used (HxV=135x74 mm), δ_s=393 mrad -> 80 mm needed for trajectory deviation and 55 mm available for ejected beam

Some parameters of ejection kicker (PS/BT/Note 87-5)

Kicker parameters

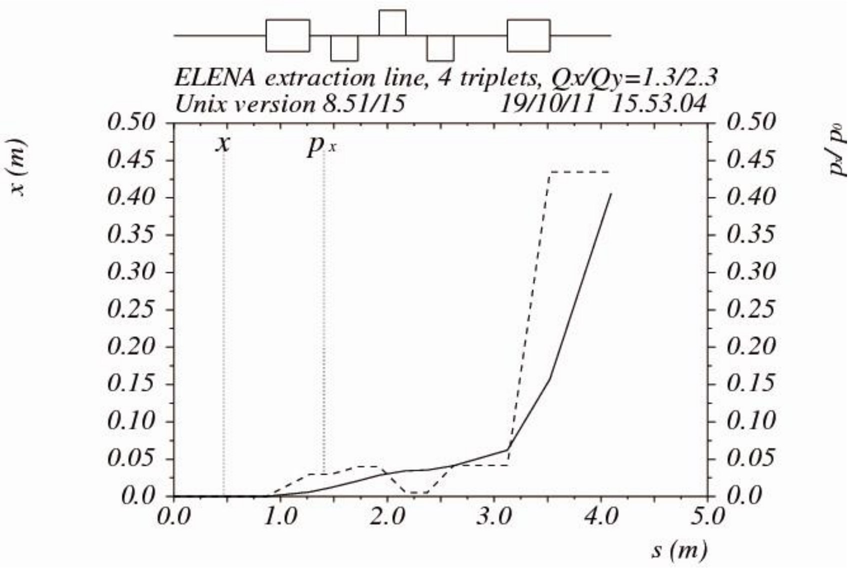
w (w_{eff})	mm	110 (132)
h	mm	45
L (L_{eff})	mm	408 (432)
$\int B dl$	T·m	0.03136
$\int B_{rem} dl$	T·m	$0.75 \cdot 10^{-4}$
Rise time (2-98)%	ns	300
Fall time (98-2)%	ns	300
Flat top length	ns	400

Field uniformity



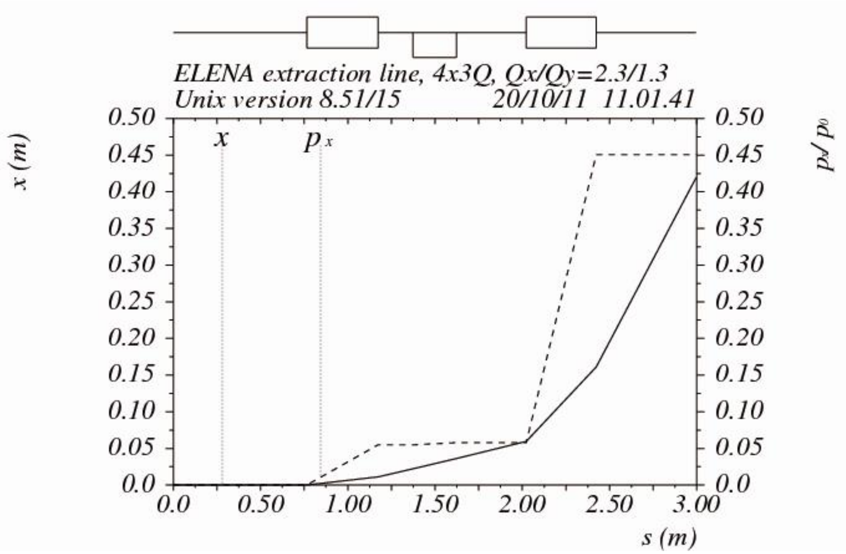
Beam extraction through a triplet

- The best among optics with tunes Q_x=1.3, Q_y=2.3 has been chosen for study, with edge angles of $\pi/9$. For the same edge angle the ejection through triplet is less efficient in case of tunes Q_x=1.45, Q_y=2.45
- Positive: small kicker angle of 30 mrad
- Negative: 32 mm only needed for circulating beam (4σ) with ε_x=50 π mm mrad (ring acceptance), and 2 · (50 to 60) mm needed for ejected beam
- Negative: 1 to 3 quadrupoles of special design needed (wider aperture-> bigger length), extra power supplies, 2 extractions in ELENA foreseen-> double problems

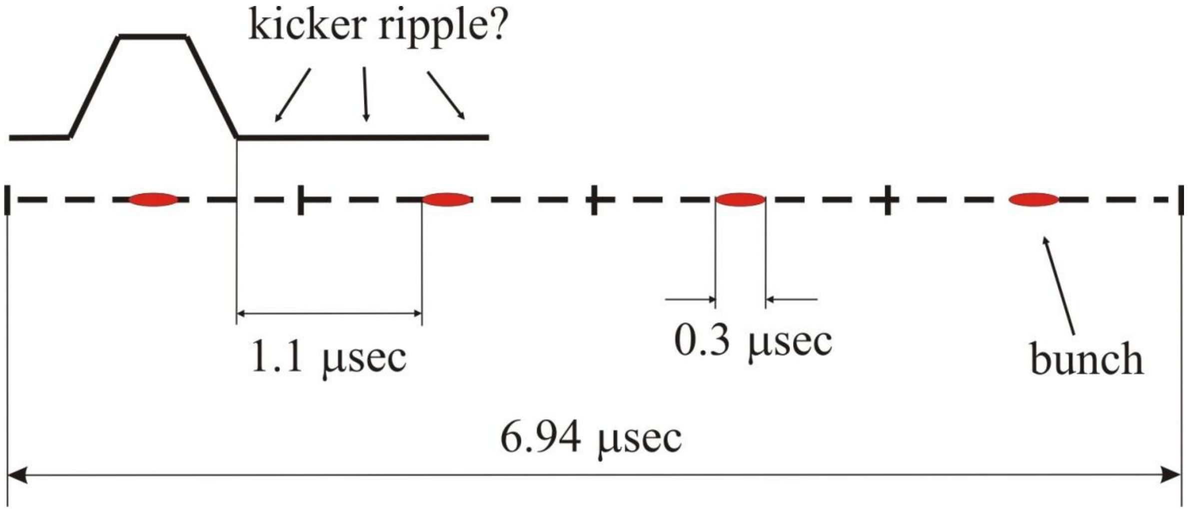


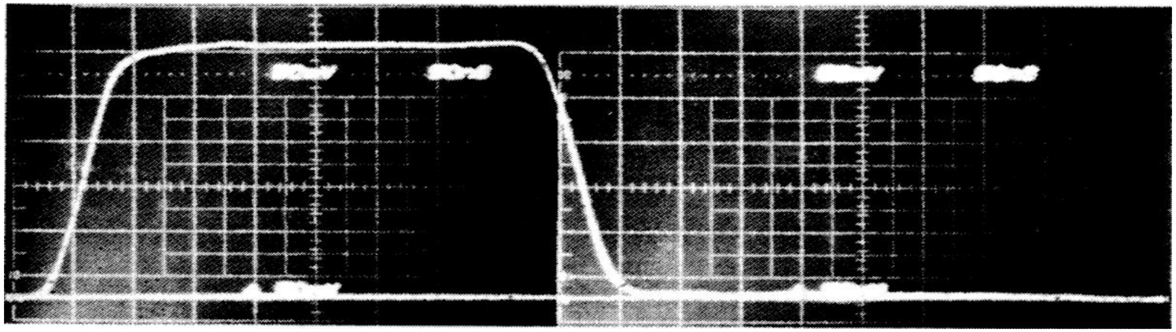
Beam extraction through central defocusing quadrupole

- Optics with 3 quads in each of 4 straight section was chosen. The edge angle is π/11, tunes are Q_x=2.3, Q_y=1.3
- Modest kick of 55 mrad required, and trajectory deviation at the exit of quadrupole is 36 mm
- About 20 mm required for circulating beam (4σ) with ε_x=50 π mm mrad (ring acceptance), and 2 · 45 mm needed for ejected beam
- Negative: one quadrupole of special design with big aperture needed, extra power supply, 2 extractions in ELENA foreseen -> double the problems



Effect of the kicker ripple (4 bunches case)





Effect of the kicker remanent field

- Kick applied to circulated bunches is noticeable and has to be compensated

$$\delta = \frac{\int B_{rem} dl}{B\rho} = \frac{0.75 \cdot 10^{-4}}{13.7 \cdot 10^{-3} \cdot 10/3} = 1.6 \cdot 10^{-3}$$

Extraction from ELENA (summary)

Extraction from ELENA can’t be made in the same long straight section where injection is planned to be due to layout limitations. Three other possible options of beam extraction from ELENA have been studied:

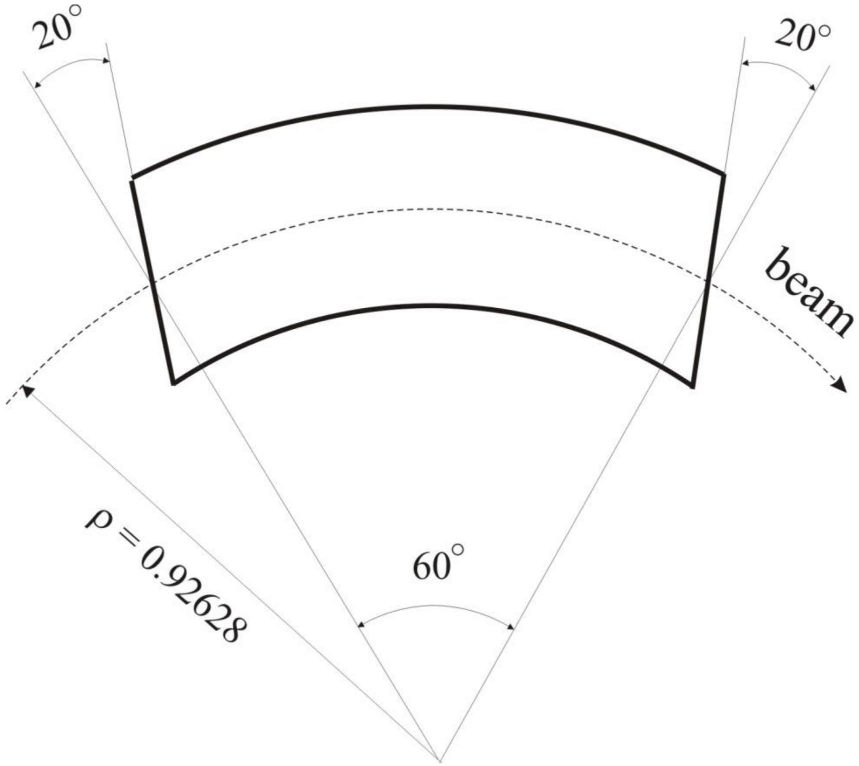
- Kicker and septum in the same straight section one after another
- Kicker is placed upstream to quadrupole triplet, and septum downstream to it in the same section
- Kicker is placed upstream to defocusing quadrupole, septum downstream to it in the same section
- The first option is preferable, in spite of fact that in requires big kick. It has strong advantage of building all quadrupoles with the same design and small aperture. The commissioning will be simplified as well
- Due to short fall time of kicker and much longer time separation between consecutive bunches kicker ripple is not important
- If necessary, beam can be debunched, cooled again, bunched and extracted. Proper control has to be prepared

How we extract from ELENA more than one bunch?

- One can’t extract more than 1 bunch during one turn due to limitation on kicker flat part duration (400 nsec) and speed of switching between experiments
- The limiting factor for the next extraction is recharging of kicker capacitor, it takes up to 100 msec.
- Two scenario to continue extraction process: a) beam is keeping bunched until kicker is ready for the next fire, one needs about 100 msec, 200 msec or 300 msec to extract 2, 3 or 4 bunches (synchronization between RF and kicker takes 20 to 30 msec) or b) beam is debunched, cooled again and rebunched after each extraction
- For the first option a) relatively small beam emittance blow up due to residual gas scattering is expected, b) IBS-caused emittance blow up occurs during beam bunching and keeping on extraction plateau
- Could one make fast emittance measurement right before extraction? This is the only way to estimate danger from IBS
- Both options have to be foreseen from the point of view of control system: long beam stay on extraction plateau and debunching/cooling/bunching procedure

Which bending magnet do we need for ELENA ring

- C-type, with edge angle (to be defined later)
- Length 0.97m, gap ≈ 70 to 75 mm
- 3D model calculations needed to look more deep into effect of fringe fields
- Small change of magnet parameters possible during design study
- Do we need field homogeneity as good as 10^{-4} (to be studied)?



Choice of machine acceptance

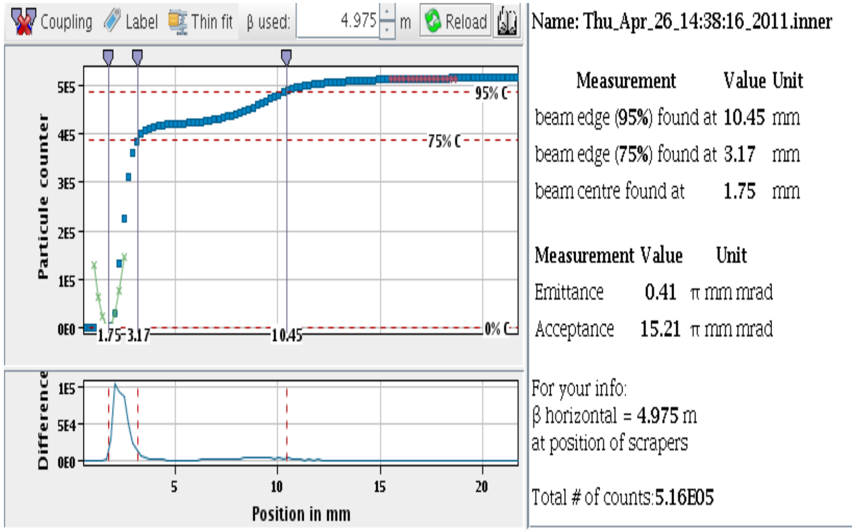
- Transverse profiles of AD beam, core and tails, the origin of tails is not well understood
- The idea is to “misalign” slightly two beams (electrons and antiprotons)

  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 12 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 limited tools to set up optics in transfer line, unavoidable blow up due to dispersion mismatch, drift of AD parameters at extraction energy during operation)
- Beam is blowing up during deceleration from 100 MeV/c down to 35 MeV/c and at the second plateau, where electron cooling will be applied for the first time emittance is at least 45 π mm mrad
- The proposed choice of acceptance is 50 π mm mrad

Typical beam emittances in AD right before extraction

The beam horizontal emittance at
100 MeV/c after electron cooling

The beam vertical emittance at
100 MeV/c after electron cooling



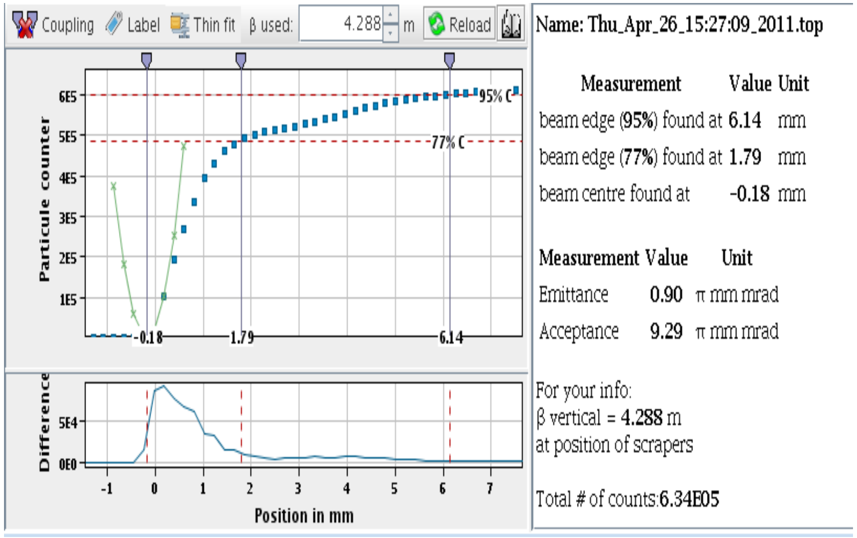
Name: Thu_Apr_26_14:38:16_2011.inner

Measurement	Value	Unit
beam edge (95%) found at	10.45	mm
beam edge (75%) found at	3.17	mm
beam centre found at	1.75	mm

Measurement	Value	Unit
Emittance	0.41	π mm mrad
Acceptance	15.21	π mm mrad

For your info:
β horizontal = 4.975 m
at position of scrapers

Total # of counts:5.16E05



Name: Thu_Apr_26_15:27:09_2011.top

Measurement	Value	Unit
beam edge (95%) found at	6.14	mm
beam edge (77%) found at	1.79	mm
beam centre found at	-0.18	mm

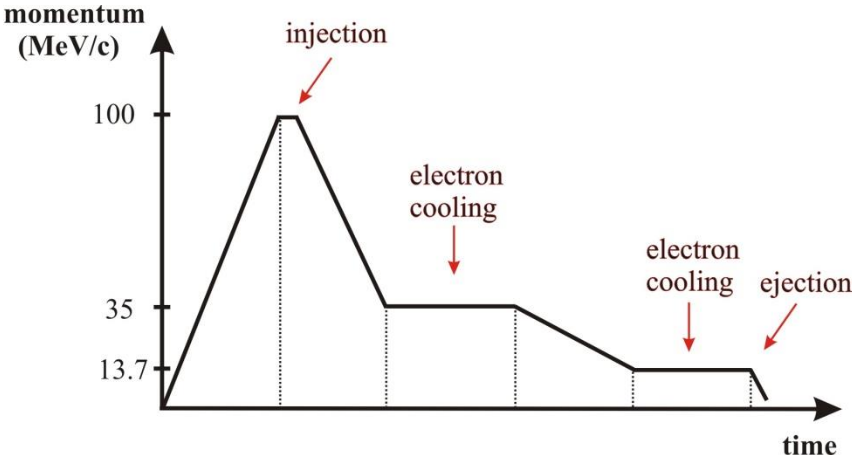
Measurement	Value	Unit
Emittance	0.90	π mm mrad
Acceptance	9.29	π mm mrad

For your info:
β vertical = 4.288 m
at position of scrapers

Total # of counts:6.34E05

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



Could one make ELENA ring with circumference of 26.1 m?

Expected advantages:

- Smaller effect of the earth field on machine orbit and magnet apertures (reduced $\int B_{earth}\, dl$)
- Weaker space charge limit
- Smaller number of quadrupoles (expected)

Expected disadvantages:

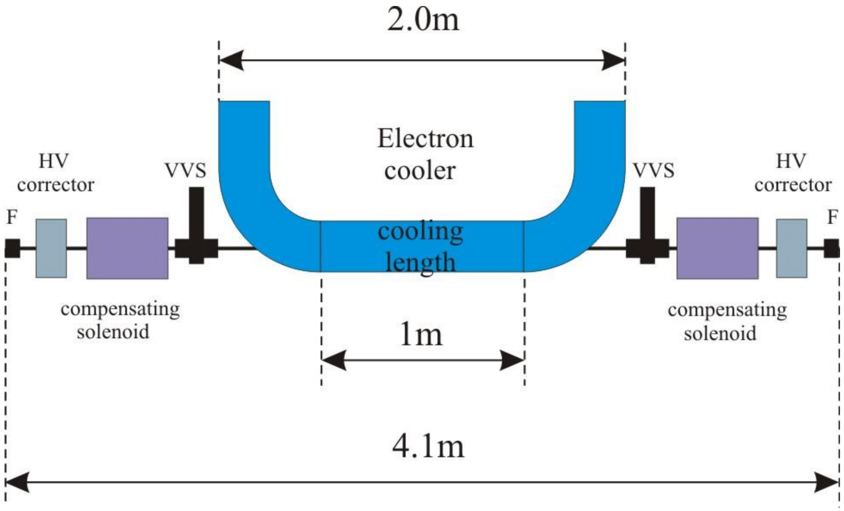
- Less space for equipment
- With the same tunes as for bigger ring, bigger maximal values of beta functions expected, magnet aperture will be bigger
- The “nearest” lower tunes (i.e. Q_x=1.64, Q_y= 1.62) makes space charge limit about 0.1, which is twice smaller compared with lattice of 30.4m long

Could one make ELENA ring with circumference of 26.1m (6 folder ring case)?

- With the same ring configuration as before, which sections could be made shorter to reduce circumference in 4.3 m?
- Section with electron cooler hardly can be shortened (see next slide)
- 4 straight sections with triplets must be shorter each in 1.075m
- Each of sections consists of 2 drift space 1.473m long, and triplet-> each of drift space should be as short as 0.935m-> impossible to place existing kicker module (l_{mec}=0.408m) and existing septum SMH12 (l_{mec}=0.4m, l_{mag}=0.3m) there. New kicker and new septum can't be significantly shorter.
- To make ejection with kicker upstream to central quadrupole of triplet, one has to increase aperture significanly more that discussed above due to shorter drift space after quadrupole
- Another option is to move 2nd quadrupole from the center umstream->bigger beta functions expected

Electron cooler section: could it be shorter?

- Compensating solenoids are as long as 0.4 m each, operating at field 2 times stronger than solenoid -> main optics perturbation comes from compensators
- Orbit correctors used for local bump in cooler, putting them out of section will make orbit alignment lattice dependent and more tricky. In addition, more aperture in adjacent BMs is required

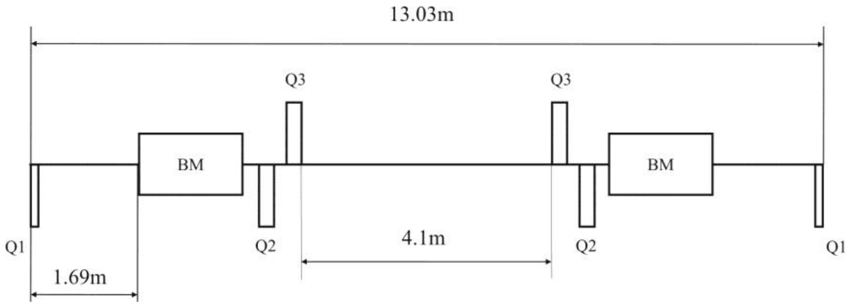


Could one make ELENA ring with circumference of 26.1m (4 folder ring case)?

focusing in bending magnets:

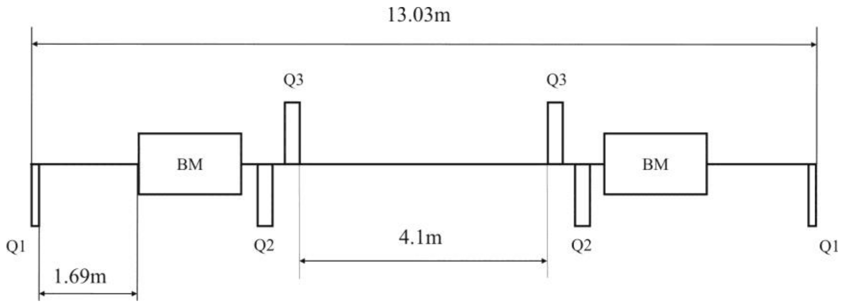
- For the simple rectangular bending magnet case (no edge fields) integrated focusing strength in one bending magnet is given by $K1_{BM} \cdot l_{BM} = l_{BM}/\rho^2 = \varphi^2/l_{BM}$.
- Comparison of focusing strength of two magnets, one is for 4 fold machine with angle π/2 and other with angle of π/3. They have identical integrated focusing strength in case one magnet is $(3/2)^2$=2.25 times longer than the other.
- The total magnet length for 6 fold ring is 0.97m·6=5.82m, the corresponding total length for 4 fold machine is 0.97m·2.25·4=8.73m, which is 2.9m bigger.
- To keep similar focusing properties per 1m, in the ring with reduced circumference one has to scale this value by factor 6/7 -> extra 2.5m may be needed for placing bending magnets
- Extra gain in space with rectangular ring can be obtained in case of smaller number of quadrupoles

ELENA optics possibilities for rectangular ring 26.1 m long with 2×(2×2+1)=10 quads



$E_1=E_2$	Q_x/Q_y	β_x/β_y /D_x, m (max)	β_x/β_y /D_x, m (cooler)	K1, m^{-2}
π/5	1.3/2.3	18.5/5.2/6.8	2.9/2.9/3.6	-1.6/3.1/-4.2
π/5	1.45/2.45	20.9/4.2/7.0	1.2/1.7/4.4	-4.2/3.0/-3.3
π/6	1.3/2.3	17.1/4.1/7.8	2.2/2.3/4.6	-4.1/0.80/-1.8
π/6	1.45/2.45	21.3/4.5/7.3	1.6/1.3/4.0	-4.1/1.7/-2.9
π/7	1.3/2.3	22.4/6.4/7.2	3.4/2.3/3.5	-3.0/0.12/-2.2
π/7	1.45/2.45	22.5/4.8/7.1	1.9/1.2/3.7	-4.2/0.38/-2.2

ELENA optics possibilities for rectangular ring 26.1 m long with 2×(2×2+1)=10 quads



$E_1=E_2$	Q_x/Q_y	β_x/β_y /D_x, m (max)	β_x/β_y /D_x, m (cooler)	K1, m^{-2}
π/8	2.45/1.45	4.8/13.8/4.0	1.3/1.2/4.0	6.2/-1.6/1.7
π/9	2.3/1.3	6.3/12.4/1.5	2.6/2.5/1.5	3.6/-2.3/3.9
π/9	2.45/1.45	4.6/14.1/2.6	1.5/1.4/2.6	4.7-/2.5/3.8
π/10	2.3/1.3	6.2/12.2/1.5	2.7/2.3/1.4	3.5/-2.7/4.0
π/10	2.45/1.45	4.8/14.4/1.9	1.6/1.4/1.9	4.2/-2.9/4.2
π/11	2.3/1.3	6.0/12.1/1.5	2.8/2.0/1.5	3.5/-2.9/4.1
π/11	2.45/1.45	5.1/14.7/1.5	1.7/1.4/1.4	3.9/-3.3/4.5

ELENA optics possibilities for rectangular ring 26.1m long with 2×(2×2+1)=10 quads (summary)

- optics with tunes Q_x=2.3, Q_y=1.3 and edge angle about π/10 is acceptable. It provides decent beta function values and dispersion at electron cooler. Unfortunately, the vertical beta function in bending magnets is on higher side.

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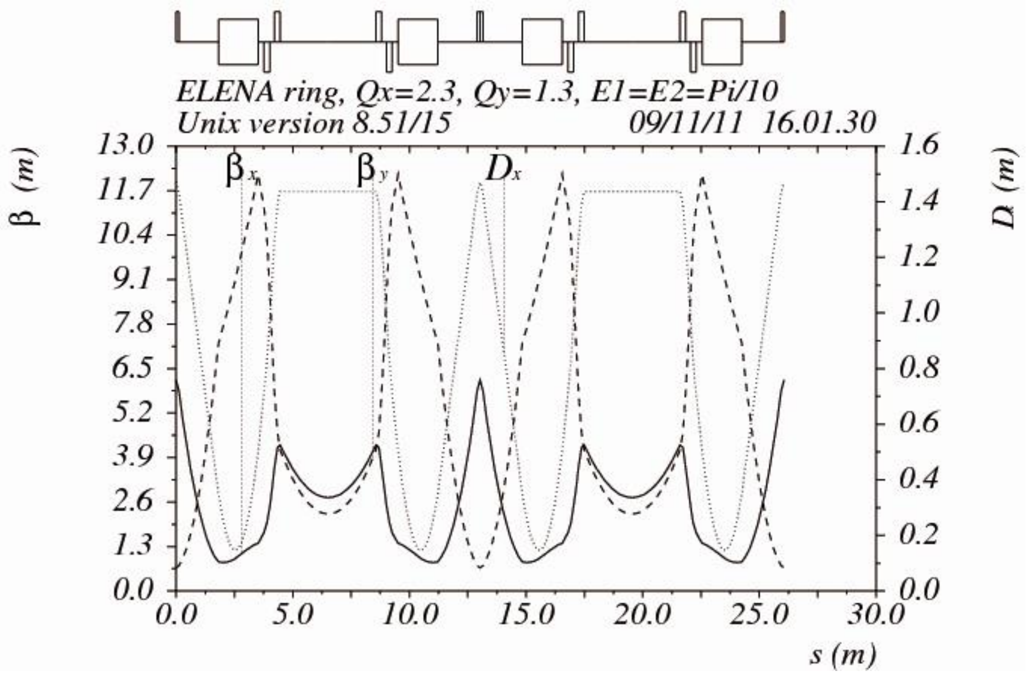
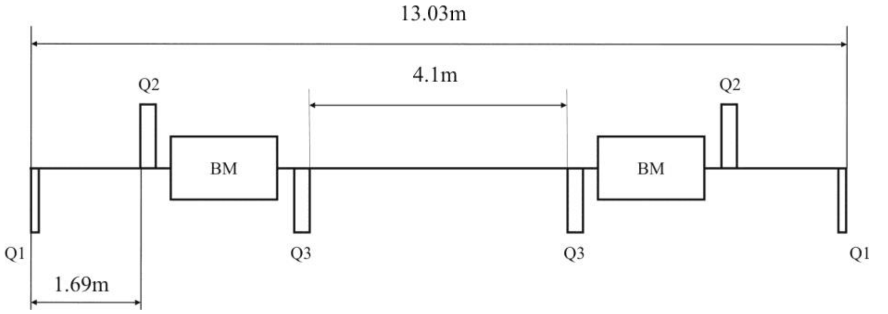
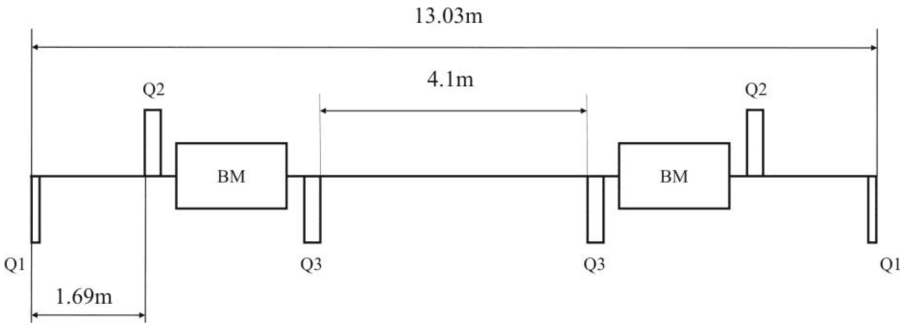


ELENA optics possibilities for rectangular ring 26.1 m long with 2×(2+3)=10 quads



E_1=E_2	Q_x/Q_y	$\beta_x/\beta_y/D_x$, m (max)	$\beta_x/\beta_y/D_x$, m (cooler)	K1, m^{-2}
π/4	1.3/2.3	13.8/12.0/4.6	1.0/3.2/4.2	-3.9/1.8/1.3
π/4	1.45/2.45	12.6/12.0/4.5	1.3/1.8/3.5	-3.9/2.4/0.77
π/5	1.45/2.45	16.1/7.3/5.5	1.2/1.4/3.9	-4.1/1.3/-0.33
π/6	1.3/2.3	16.3/6.7/6.7	1.2/2.3/4.7	-3.7/0.18/-0.84
π/6	1.45/2.45	18.0/6.5/6.1	1.2/1.3/4.0	-4.0/0.60/-1.1
π/6	1.64/2.64	25.6 /8.9/5.5	1.2/1.3/4.0	-4.7/0.90/-1.2
π/7	1.45/2.45	19.0 /6.3/6.5	1.2/1.2/4.1	-3.8/0.11/-1.6
π/8	1.45/2.45	20.0/6.4/6.8	1.2/1.3/4.1	-3.6/-0.25/-1.9

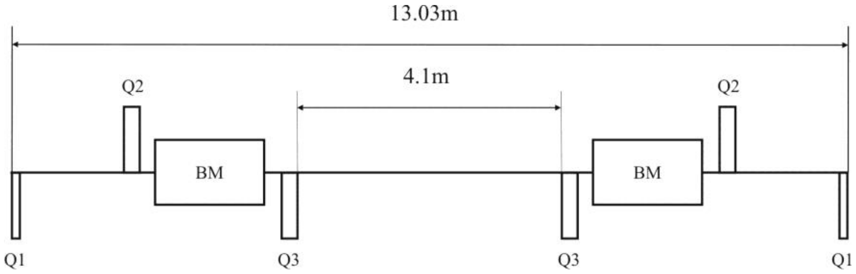
ELENA optics possibilities for rectangular ring 26.1 m long with 2×(2+3)=10 quads (cont.)



E_1=E_2	Q_x/Q_y	β_x/β_y /D_x, m (max)	β_x/β_y /D_x, m (cooler)	K1, m^{-2}
π/5	2.45/1.45	6.7/13.3/4.0	1.3/1.2/4.0	4.3/1.1/2.7
π/6	2.45/1.45	6.0/12.4/4.8	1.3/1.2/4.7	4.8/0.25/1.8
π/7	2.45/1.45	6.5/11.8/5.2	1.2/1.2/5.1	5.0/-0.25/1.3
π/8	2.3/1.3	7.2 /10.4/9.6	2.3/1.2/8.8	4.6/-0.25/0.83
π/8	2.45/1.45	7.0 /11.3/5.5	1.3/1.2/5.4	5.1/-0.57/0.95
π/8	2.64/1.64	11.9/16.4/4.2	0.65/0.84/4.2	5.9/-0.85/1.0
π/9	2.45/1.45	7.2 /10.9/6.7	1.3/1.2/5.6	5.1/-0.79/0.69

ELENA optics possibilities for rectangular ring 26.1m long with 2×(2+3)=10 quads (conclusions)

No one good optics was found in this configuration, the dispersion inside of electron cooler is too big.



ELENA optics for rectangular ring 26.1 m long (summary)

- One solution with tunes Q_x=2.3, Q_y=1.3 and edge angles E_1=E_2=π/10 was found. It has approximately twice bigger vertical beta function in the bending magnets compared with best rings of 30.4 m long
- Four short straight sections of 1.69 m long foreseen, two of them can be used for extraction. Small space downstream to septum (about 0.2m) is available for other equipment
- One long straight section will be dedicated completely to electron cooler
- Another long section is partly dedicated to injection (1.7m needed), and 2.4 m is available for other equipment
- Total available space is 2·1.69 + 2·0.2 + 2.4=6.2m

How much space do we need for equipment installation (cooler, injection, ejection are already counted)?

- Longitudinal Schottky PU needs at least 1.2 m (M.-A. Angoletta)
- RF module 0.6m? (not defined yet)
- Scrapers 0.8m? (not defined yet)
- IPMs: two modules each about 0.5m long, the horizontal module can be placed inside of bending magnet (under discussion)
- 8+8 BPMs will be placed inside of quadrupoles, some small space needed for feedthroughs
- 4 sextupoles (2 SF+2 SD) minimum, each approximately 0.15 m long, totally 0.6 m
- 2 sqew quadrupoles minimum required for correction of residual coupling (coupling difference resonance Q_x-Q_y=±1), totally 0.3m long
- 8 combined orbit correctors each 0.2 m long, totally 1.6 m
- Valves 5·0.25m=1.25m
- Damper for controlled emittance blow up at 100 keV and for tune measurements (not defined yet)
- Some space is needed for vacuum equipment (ports, flanges, bellows)
- Totally minimum 6.9 m required to place all equipment mention above, except BPMs, damper and vacuum equipment and assuming the horizontal PM is placed inside of bending magnet

Summary on linear optics studies for ELENA ring

- Optics with 6 fold configuration has been studied for ELENA. It fits well to layout requirements in AD hall.
- Main parameters for control have been defined. They are tunes and Twiss functions and dispersion in electron cooler.
- Tune choice have to provide maximal space for tune shit due to space charge. Non integer parts of tune 0.3 and 0.45 have been accepted.
- AD to ELENA transfer line is defined strongly by layout. Injection into ELENA is straightforward
- Extraction from ELENA is made with septum placed downstream to kicker at the same short straight section
- Several solutions for linear optics is proposed, they will be studied in more details.
- The ring with circumference of 30.4m provides enough space for equipment installation (6·1.47+2.4=11.2 m), while the ring of 26m looks too short (to be confirmed)

Topics for further studies

- Sensitivity to quadrupole errors (calibration, misalignment, power supply)
- Sensitivity to gap value and to edge angle value
- Proper chromaticity correction
- Correction of residual coupling
- Orbit correction (including earth magnetic field based on magnetic measurements to be done in AD Hall)
- What is the value of $|C^-|$ (distance between normal modes)?
- How strong is effect of the third order resonance for $Q_x=1.3$ and $\varepsilon_x=50\ \pi$ mm mrad?
- Effect of electron beam on optics
- IBS for different lattices

Thanks for your attention!