Low emittance lattice for the CLIC damping ring

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LER 2010, CERN, January 12-14, 2010

Outline

- Reasons for the CLIC DR lattice update
- CLIC DR lattice v06.7
- Ring sections design and optimization
- Parameters without/with IBS
- Chromatic correction and dynamic aperture
- Preliminary magnets design
- Conclusion

Original lattice: main goals and parameters

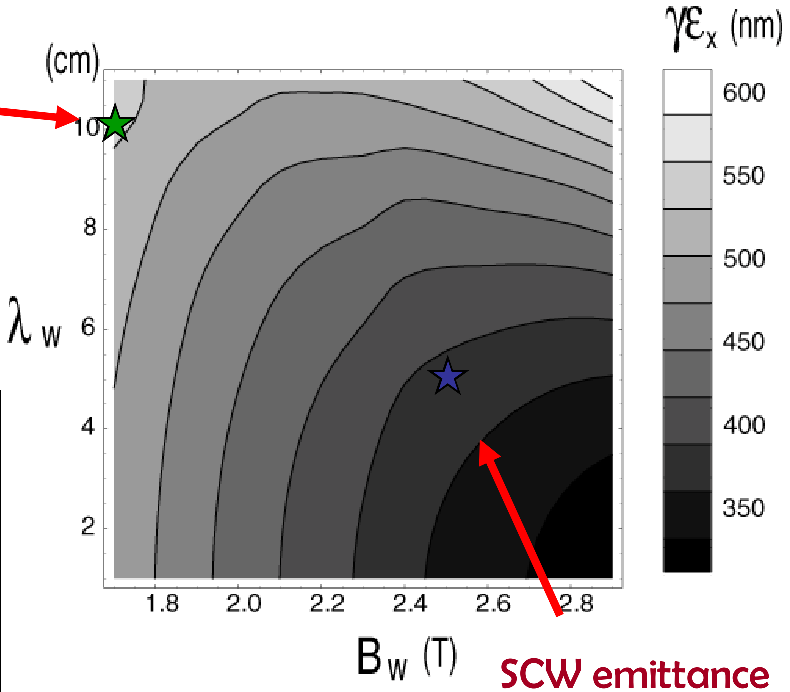
M.Korostelev, F.Zimmerman. Optimization of CLIC damping ring design parameters, Proc. of EPAC 2002, Paris, France, pp.536-538

M.Korostelev, PhD Thesis, CERN, 2006

- E = 2.424 GeV (far from depolarizing resonances)
- I = 150 mA (bunch population is 4 x 10^9)
- C = 360 m (very compact!)
- Two arcs with 48 highly optimized TME cells in each (extremely strong quads and sexts!)
- Two long straight sections with 38 damping wigglers in each. Total wiggler length is 2 sections x 38 w x 2 m = 152 m (lot of SR power radiated!)
- Normalized horizontal emittance with IBS (very strong!) - 400 nm-rad

Damping wiggler parameters

M.Korostelev: horizontal emittance with IBS as a function of wiggler field and period length



PMW emittance

SCW emittance

Damping wigglers:		PM	SC (NbTi)
Period length	cm	10	5
Aperture (beam)	mm	12	12
Peak field	T	1.7	2.5
W. length	m	2	2
Temperature	K	Room	4.2 K

Only SC wigglers with low period length and high field amplitude can satisfy the CLIC DR requirements

Disadvantages of the original lattice

- Very compact lattice but no space between main magnets for correctors, BPMs, vacuum pumps and other equipments

- Strongly radiated damping wigglers but no room for SR absorbers

- Extremely strong quadrupoles and sextupoles can not be developed in the frame of today technology even for SC approach

- Poor separation of the vertical and horizontal betas in the arc TME cell provides problems with chromaticity correction and reduces the ring DA

- Very low vertical emittance induces strong space charge effects (the vertical tune shift >0.1), which, together with external nonlinearities, degrade the beam distribution during damping

A modification of the lattice with relaxed and realistic parameters but still satisfying the CLIC performance was needed!

Lattice versions compare

Lattice	Original	V06	V06.7
Energy [GeV]	2.424	2.424	2.86
Circumference [m]	365.21	493.02	493.2
Length of the TME arc cell [m]	1.73	2.3	2.36
Betatron coupling [%]	0.6	0.6	0.6
Norm.horizontal emittance (SR) hor/ver, [nm-rad]	86/0.5	148/0.9	231/1.4
Energy spread (SR)	1.12×10^{-3}	1.12×10^{-3}	1.09×10^{-3}
Norm.horizontal emittance (IBS) hor/ver, [nm-rad]	465/2.8	436/2.6	487/2.9
Energy spread (IBS)	1.57×10^{-3}	1.56×10^{-3}	1.28×10^{-3}
Bunch length [mm]	1.3	1.32	1.09
Longitudinal emittance [eV×m]	5000	5000	4000
RF voltage [MV]	4.61	4.68	6.49
Energy acceptance	0.015	0.016	0.016
Natural chromaticity hor/ver	-103 / -136	-149 / -79	-172 / -64
Radiation damping time hor/ver [ms]	1.53 / 0.76	1.99 / 1.01	1.62 / 0.82
Bending field [T]	0.93	1.27	1.4
Dipole focusing strength, G [T/m]	0	-8.9	-10.5
Maximal quadrupole strength,G [T/m]	220 / -131	60.3 / -34.5	73.4 / -42.4
Sextupole gradient $[\mathrm{T/m^2}]\times10^{-3}$	62 / -80	6.3 / -6.6	5.0 / -5.0

CLIC DR requirements update

Energy of 2.86 GeV (the energy increase reduces the space charge effects and IBS)

Beam intensity: 312 bunches x $4.1 \cdot 10^9$ positrons (125 mA current)

Circumference less than 500 m (to accommodate all necessary equipment)

50 Hz repetition rate

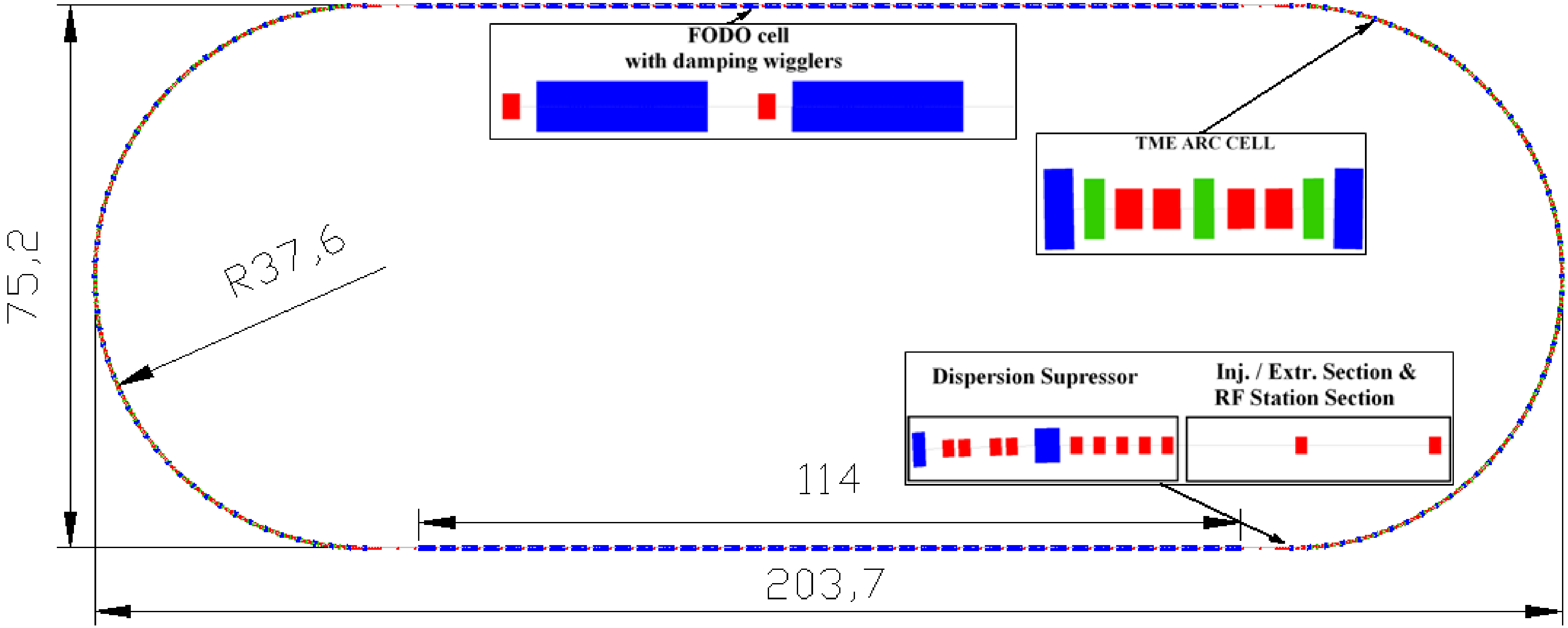
Normal conducting magnets with realizable parameters

Normalized emittance: <500 nm (hor), <5 nm (vert), <5 keV-m (long)

Wiggler sections sufficient for accommodation of SR power absorption system

Large dynamic aperture

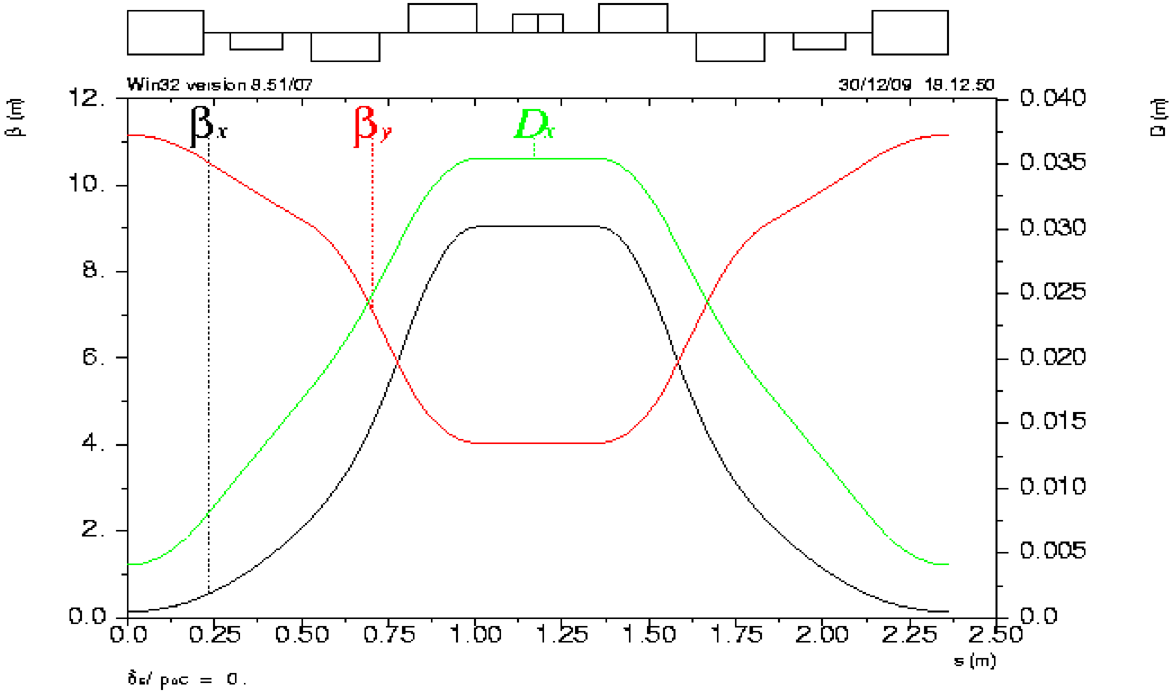
V06.7 general layout



- Circumference	493.2 m
- Radius of arcs	37.6 m
- Length of straight section	114 m
- Number of TME cells	96 + 4
- Number of SC wigglers	76

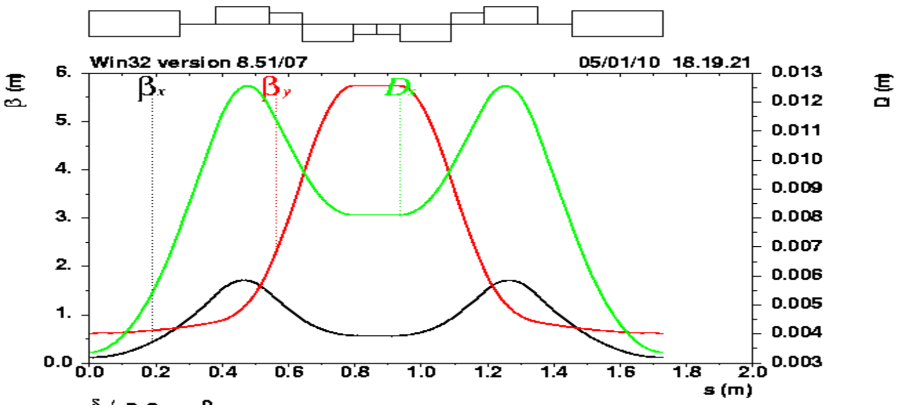
Arc cell design

The arc cell is a TME design providing good separation of betas at chromatic sextupoles. For efficient chromaticity correction and sextupole strength reduction, the central quadrupole is split and the sextupole is placed in the hor. beta maximum.



There is enough space between the magnets for BPMs, vacuum valves, flanges, pumps, etc.

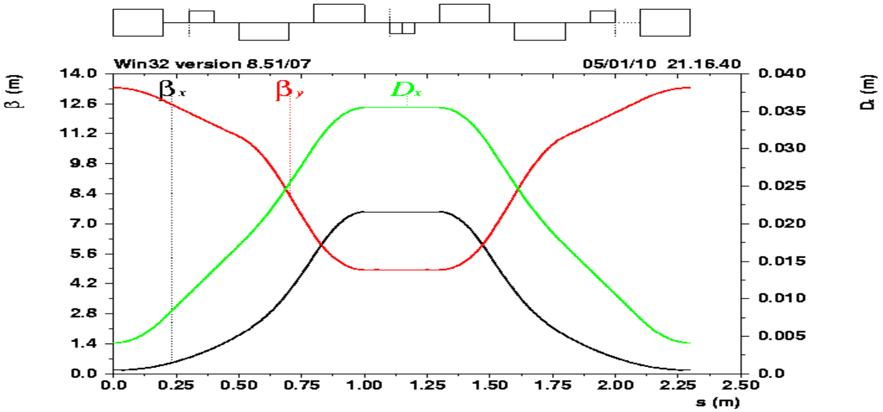
Arc cell evolution



Original lattice:

- Cell length, [m] 1.729
- Phase advance, x/y 0.581 / 0.247
- Natural chromaticity, x / y -0.85 / -1.17

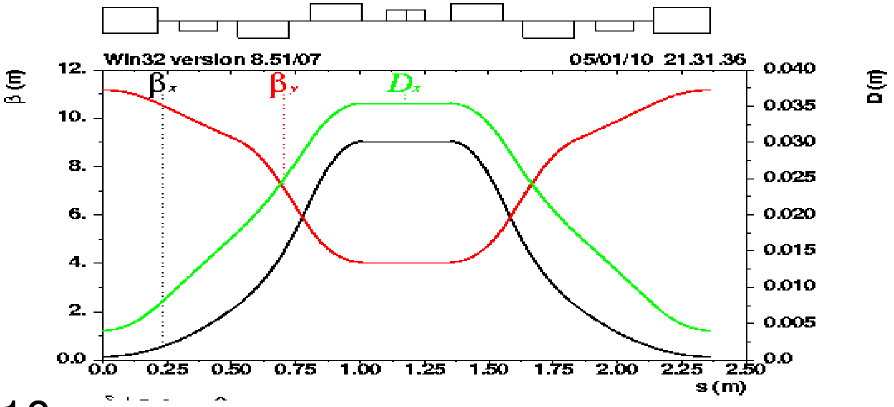
	Length, m	Maximal Strength
Dipole	0.54	0.93 T
Quadrupole	0.16	220 T/m
Sextupole	0.07 / 0.1	80 kT/m^2



V06 lattice:

- Cell length, [m] 2.3
- Phase advance, x/y 0.442 / 0.045
- Natural chromaticity, x / y -1.25 / -0.56

	Length, m	Strenght
Dipole	0.4	1.27 T
Quadrupole	0.2	60 T/m
Sextupole	0.15	6.6 kT/m^2

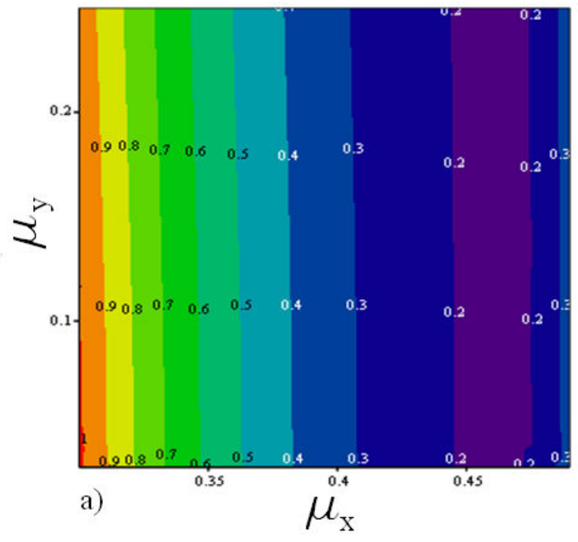


V06.7 lattice:

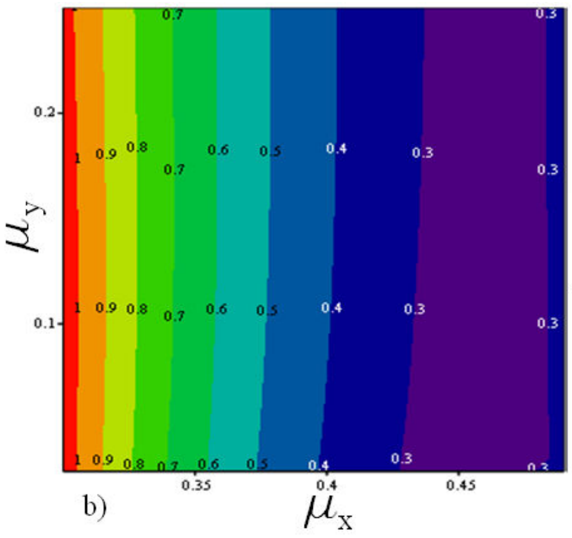
- Cell length, [m] 2.36
- Phase advance, x/y 0.452 / 0.056
- Natural chromaticity, x / y -1.51 / -0.48

	Length, m	Strenght
Dipole	0.43	1.4 T
Quadrupole	0.2	73.4 T/m
Sextupole	0.15	5 kT/m^2

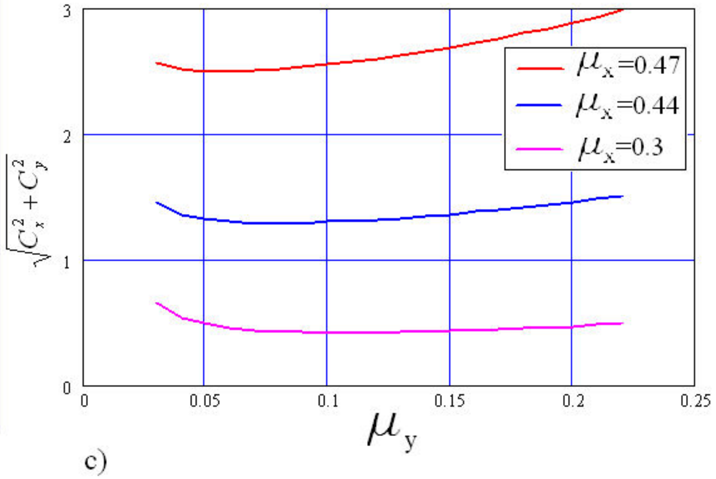
Arc cell optimization



Emittance w/o IBS



Emittance with IBS



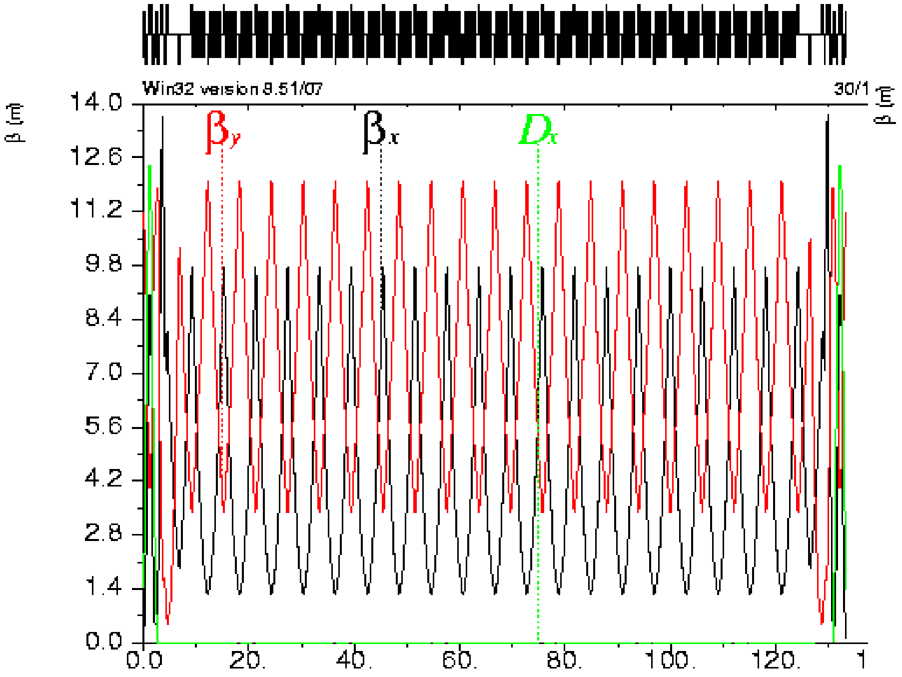
Chromaticity vs. phase advance

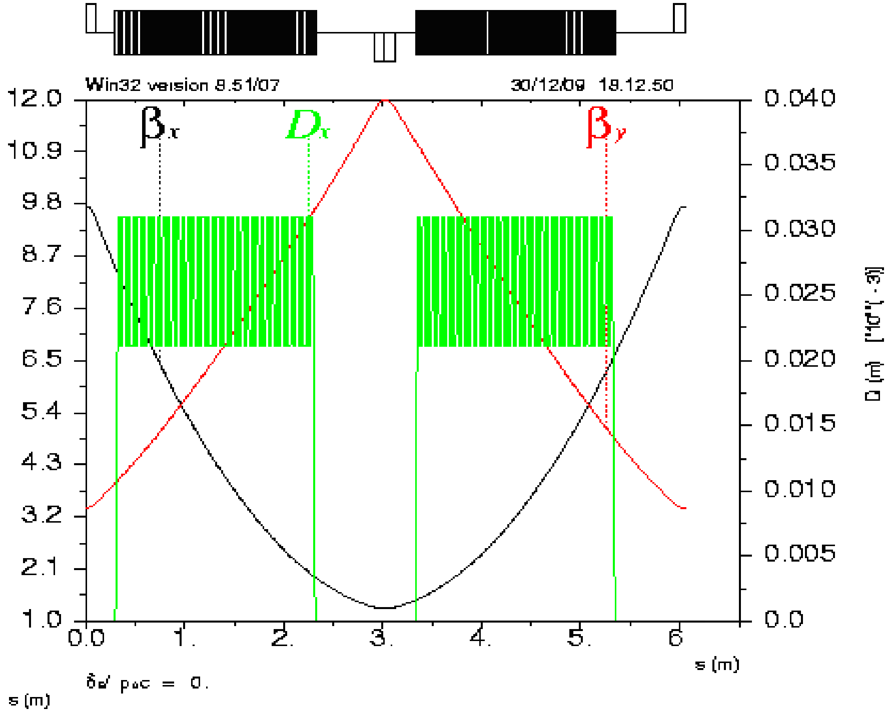
Minimal emittance is: w/o IBS for μx = 0.46 $\mu y \rightarrow 0$
with IBS for μx = 0.47 $\mu y \rightarrow 0$

For the IBS calculation the following parameters are taken:

- Bunch population 4.1×10^9;
- Bunch length ~1 mm;
- Hor. emittance (w/o IBS) 0.181 nm*rad;

Wiggler cell design



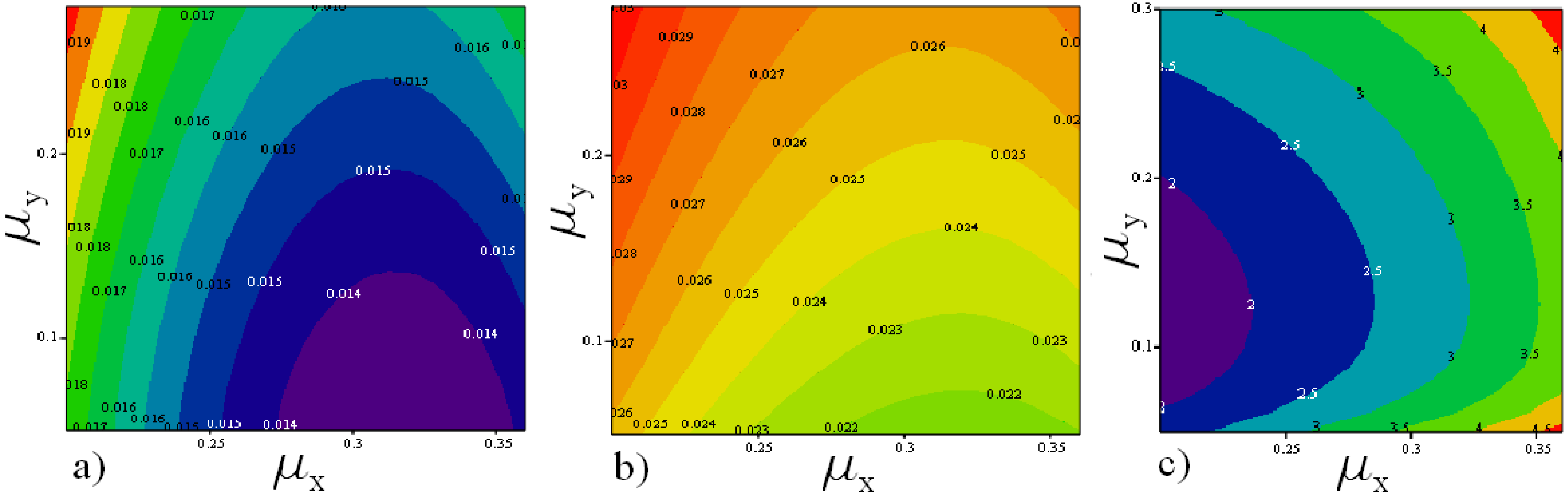


Wiggler cell is a dispersion free FODO with hor. beta optimized to reach the minimum emittance

$$\overline{\beta}_{x\,\min} = \frac{2}{\sqrt{3}} l_w$$

The space between the magnets (~0.6 m) is enough to place SR absorbers, BPM, vacuum system equipment, etc.

Wiggler cell optimization



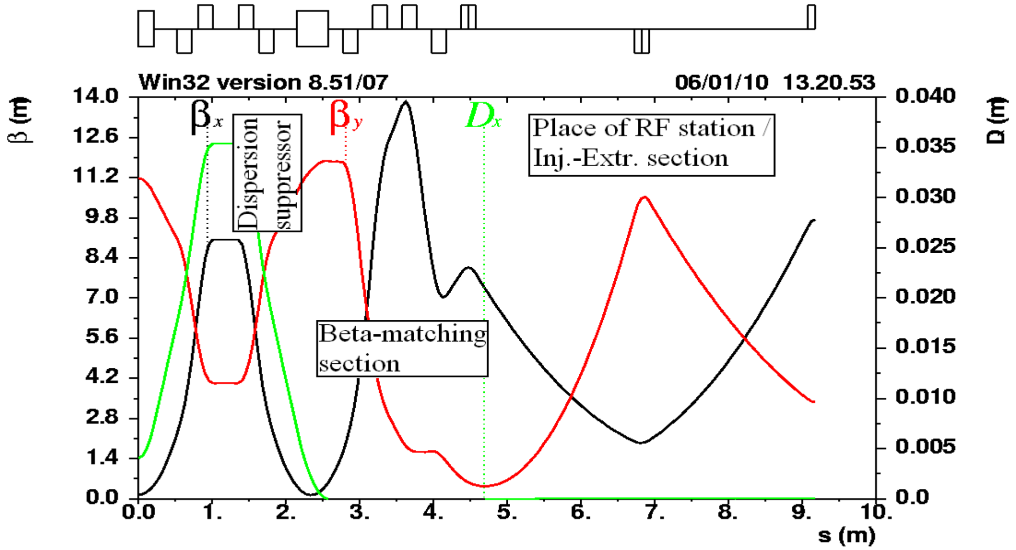
Minimal emittance is: w/o IBS for $\mu x = 0.32$ $\mu y \rightarrow 0$

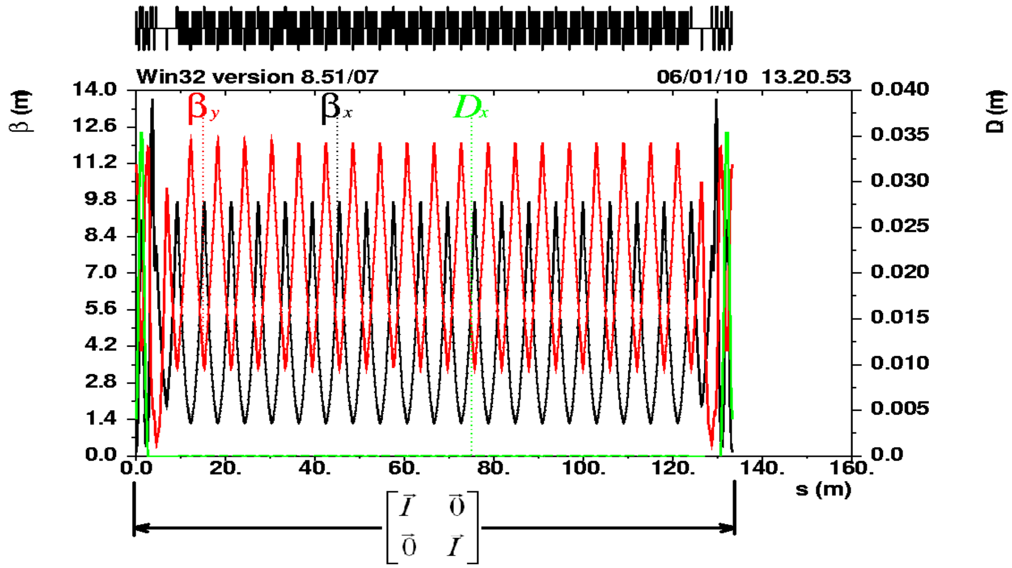
with IBS for $\mu x = 0.34$ $\mu y \rightarrow 0$

At IBS simulation it is taken into account parameters:

Number of particles of bunch	$4.1\text{x}10^9$
Longitudinal beam size	1.0 mm
Minimal hor. emittance (w/o IBS)	0.027 nm*rad

Matching section

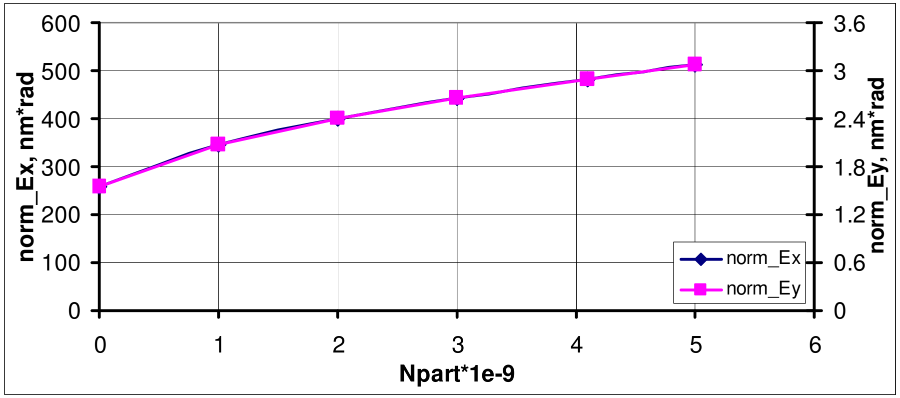


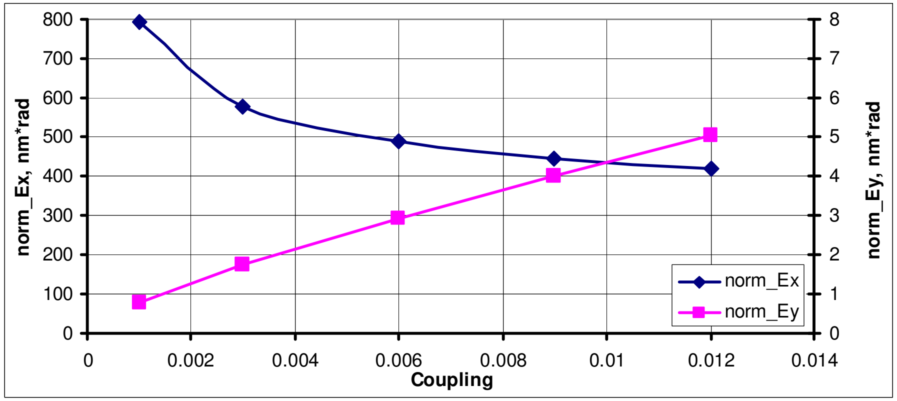


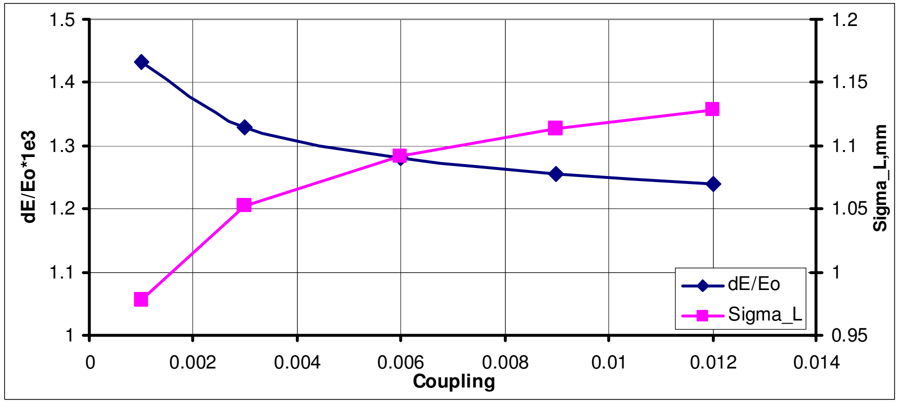
$$\begin{bmatrix} \vec{I} & \vec{0} \\ \vec{0} & \vec{I} \end{bmatrix}$$

- Matching section consists of dispersion suppressor, beta-matching and free straight sections for the RF, injection section and extraction section.
- To increase dynamic aperture the unit matrix cell is created by 2 matching sections and straight section of regular FODO cells.

IBS effect







Bunch current [mA]	0.399
Bunch population	4.10E+09
Betatron coupling	0.006
Without IBS	
Normalized hor. emittance, $\gamma\varepsilon_x$ [nm-rad]	231
Normalized ver. emittance, $\gamma\varepsilon_y$ [nm-rad]	1.39
Energy spread, σ_E/E	1.089
Bunch length [mm]	0.93
Longitudinal emittance [eV·m]	2890
With IBS	
Normalized emittance [nm-rad]	487
Normalized ver. emittance, $\gamma\varepsilon_y$ [nm-rad]	2.9
Energy spread, $\cdot 10^{-3}$	1.281
Bunch length [mm]	1.09
Longitudinal emittance [eV·m]	4002
Ratio Em_ibs/Em_w/o_ibs	2.10

Betatron coupling tuning fixes
the longitudinal emittance at 4 keV*m.

Main ring parameters

Parameters	V06.7
Energy, E [GeV]	2.86
Circumference, P [m]	493.16
Bunch population (10^9)	4.1
Coupling, κ [%]	0.6
Energy loss per turn, U_0 [MeV]	5.75
Dumping time $x/y/s$ [ms]	1.62/ 1.64 /0.82
RF voltage, U_{RF} [MV]	6.49
RF frequence, GHz	2
RF harmonic, h	3289
Energy acceptance, $\Delta E/E$	0.016
Natural chromaticity, ξ_x/ξ_z	-172 / -64
Compaction factor, α	6.49E-05
Damping radiation integral, I_2 [1/m]	6.10
Excitation radiation integral, I_5 [1/m]	2.14E-05
Number of arc cells, N_c	100
Number of damping wigglers, N_w	76
Normalized emittance, $\gamma\varepsilon_x$ [nm-rad]	231
Energy spread, σ_E/E	1.089
Bunch length [mm]	0.93
Longitudinal emittance [eV·m]	2890

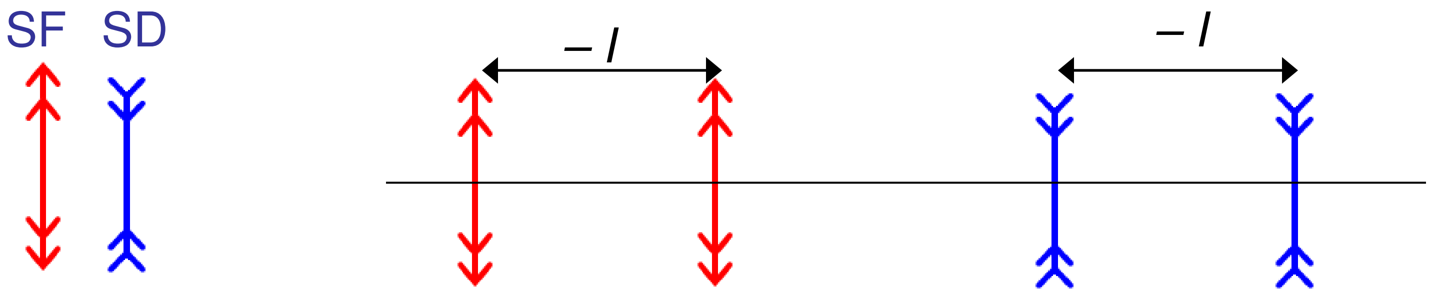
Strategy for DA optimization

Main source of the dynamic aperture limitation is strong chromatic sextupoles in the arcs. The wiggler nonlinearities are small.

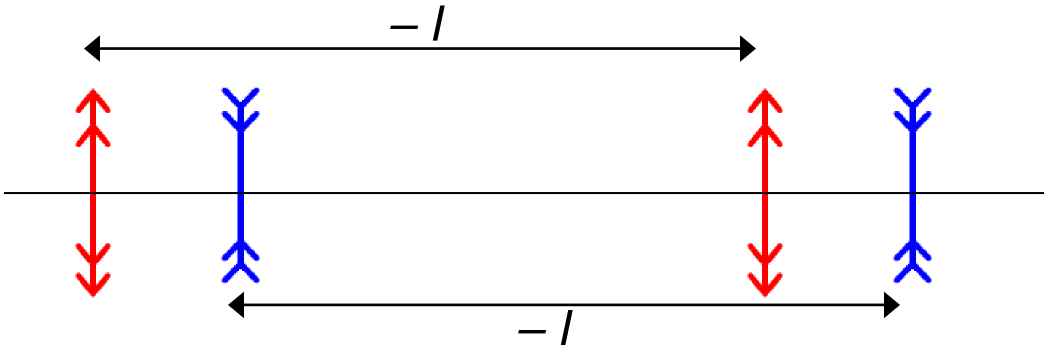
To optimize the DA the following strategy was applied:

- Rejection of the original interleaved sextupole (comment at the next slide)
- Arrangement of simple and effective sextupole families (SF, SD) with well separated betatron functions
- Minimizing of the arc cell chromaticity
- Adjusting of the phase advance for a single cell to achieve required emittance together with the maximum DA
- Constructing of two-arc ring; optimum DA for the single cell will be also optimum for the whole ring
- Adjustment for the wiggler section unit matrix in both transverse directions

Comment of the interleaved sextupoles

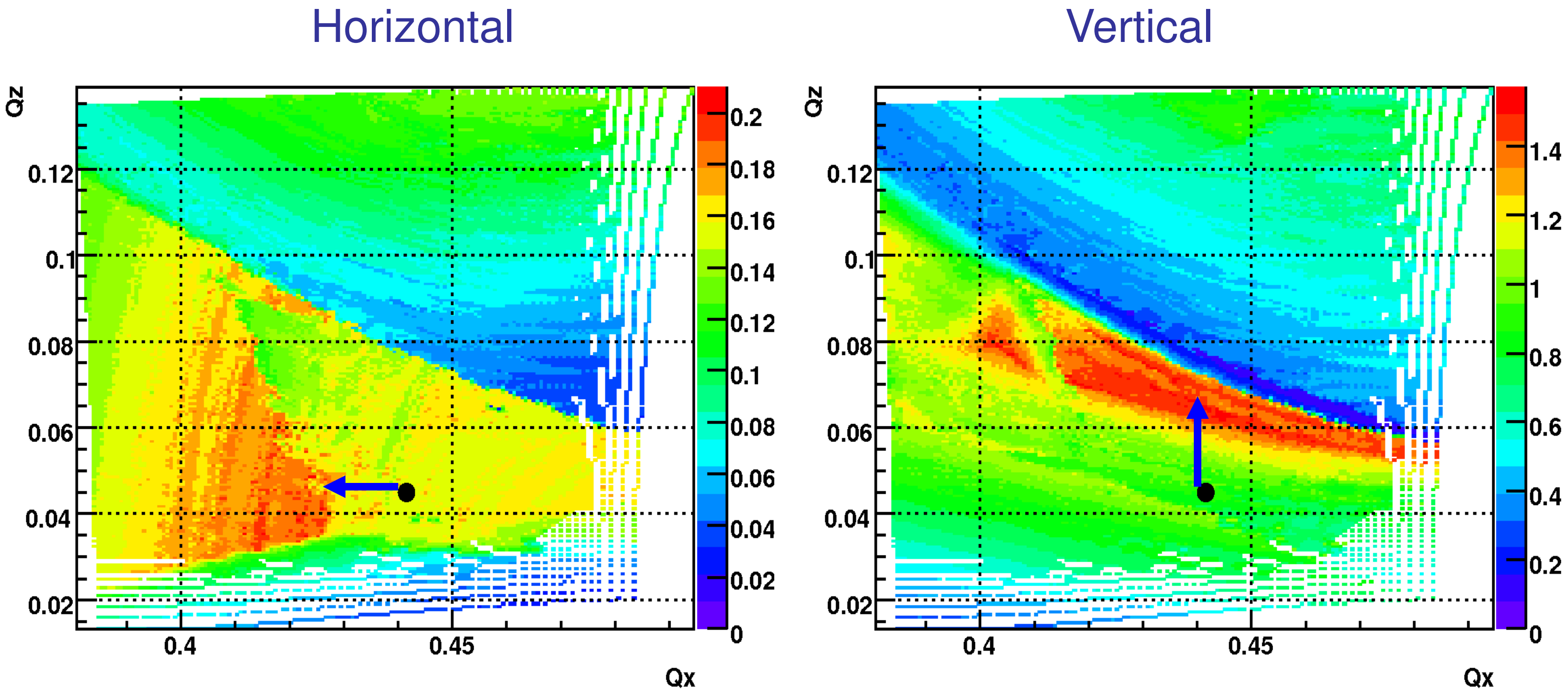


Non-interleaved sextupoles cancel all orders of nonlinear aberrations



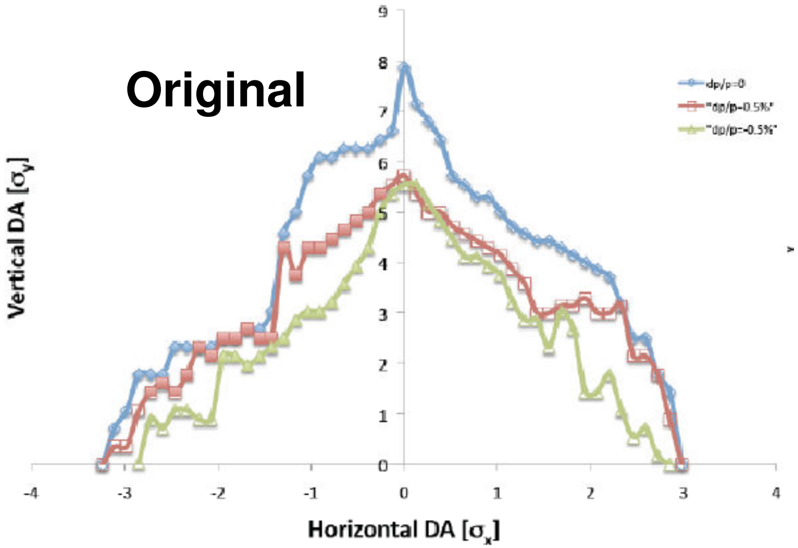
Interleaved sextupoles cancel only second order aberrations but produces higher orders, which can reduce dynamic aperture drastically.

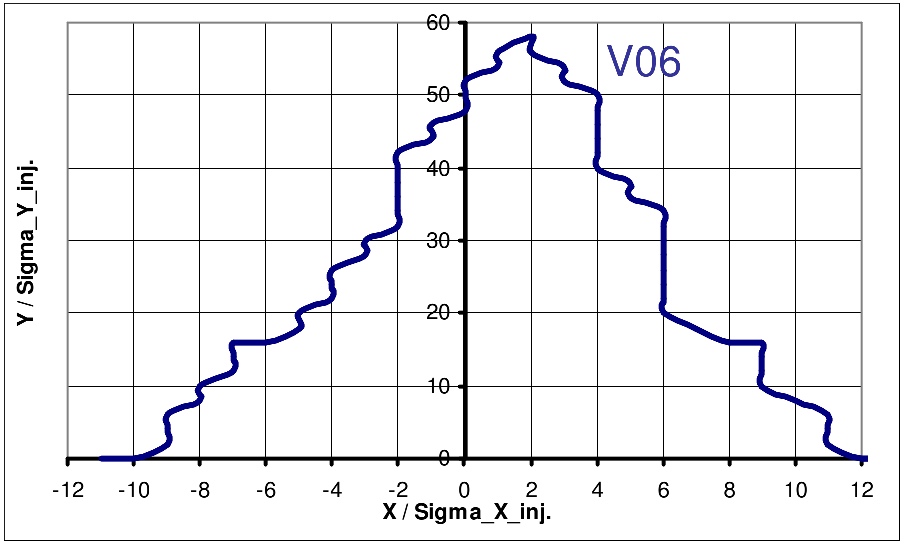
Arc cell aperture optimization

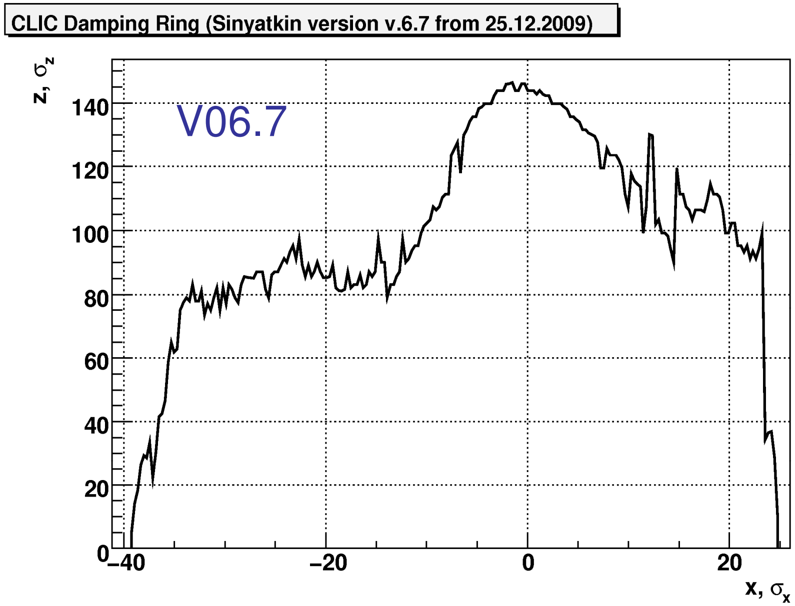


DA vs betatron tune advance for the arc cell. Color indicates the DA size (red is for the large and blue is for the small size). Black point shows the tune before optimization; arrows shows a direction of the tune change to increase the aperture.

DA comparison







4D DA for the whole ring in terms of injection sigmas (hor x ver):

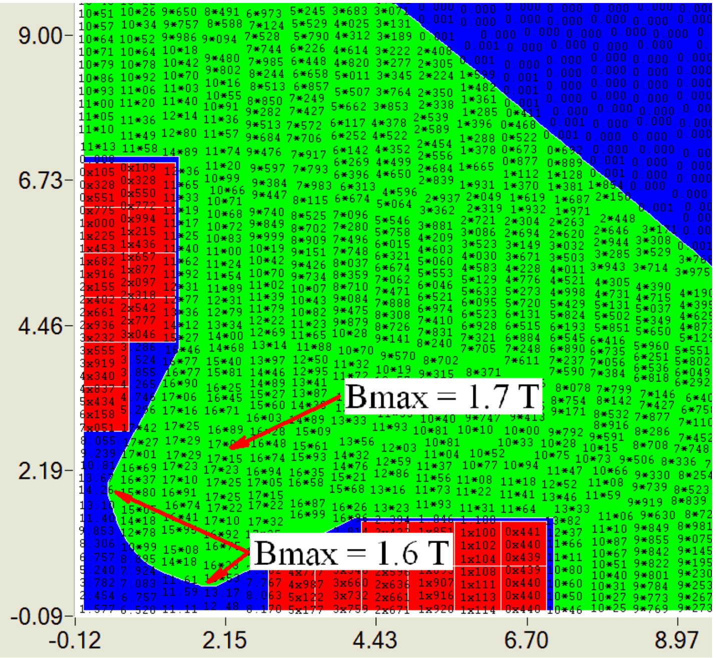
Original: 3 x 8
V06: 10 x 48
V06.7: 23 x 142

Main magnetic elements

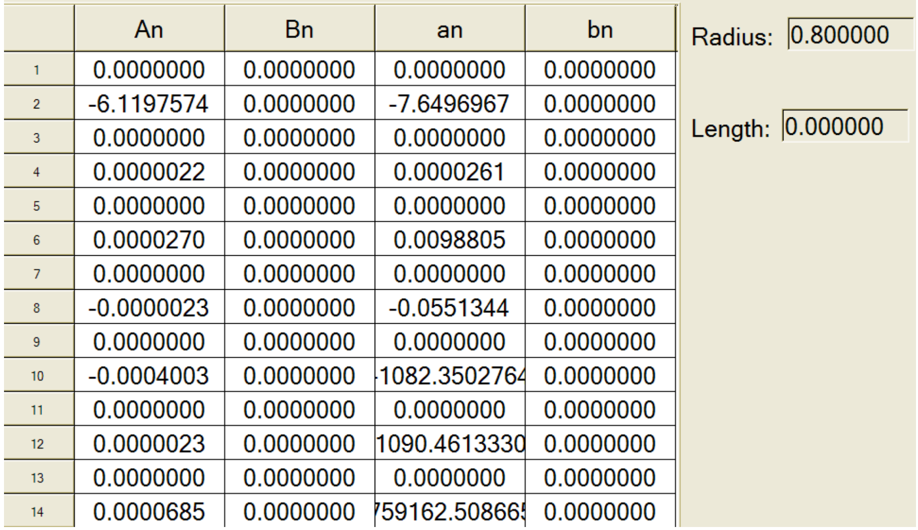
Element	No	Length, m	Max. Strength
Dipole	102	0.43	1.4 T
Quadrupole	492	0.2	73.4 T/m
Sextupole	296	0.15	5 kT/m^2
Wiggler	76	2	2.5 T

All normal conducting magnets are made of laminated iron in usual technology. For the sextupole an alternative design with permanent magnet concentrator and increased sextupole strength is proposed.

Quadrupole preliminary design



Magnetic induction distribution



	An	Bn	an	bn
1	0.0000000	0.0000000	0.0000000	0.0000000
2	-6.1197574	0.0000000	-7.6496967	0.0000000
3	0.0000000	0.0000000	0.0000000	0.0000000
4	0.0000022	0.0000000	0.0000261	0.0000000
5	0.0000000	0.0000000	0.0000000	0.0000000
6	0.0000270	0.0000000	0.0098805	0.0000000
7	0.0000000	0.0000000	0.0000000	0.0000000
8	-0.0000023	0.0000000	-0.0551344	0.0000000
9	0.0000000	0.0000000	0.0000000	0.0000000
10	-0.0004003	0.0000000	1082.3502764	0.0000000
11	0.0000000	0.0000000	0.0000000	0.0000000
12	0.0000023	0.0000000	1090.4613330	0.0000000
13	0.0000000	0.0000000	0.0000000	0.0000000
14	0.0000685	0.0000000	59162.50866	0.0000000

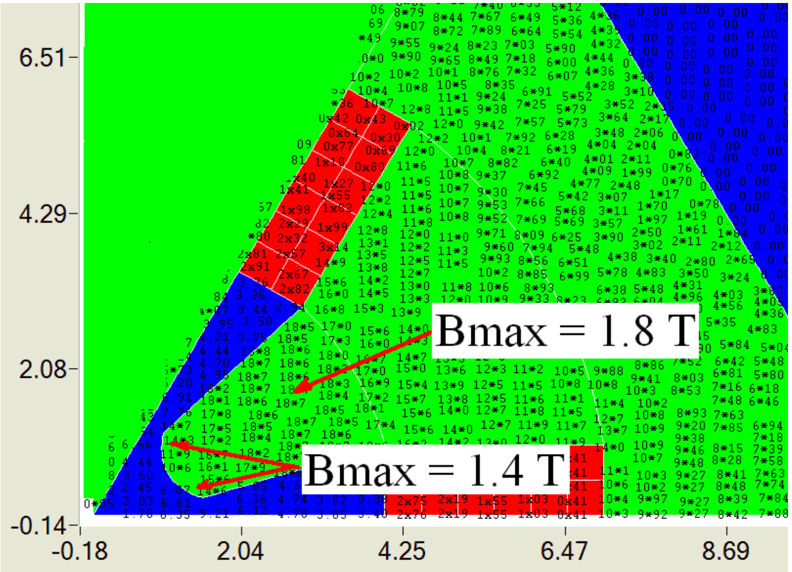
Radius: 0.800000

Length: 0.000000

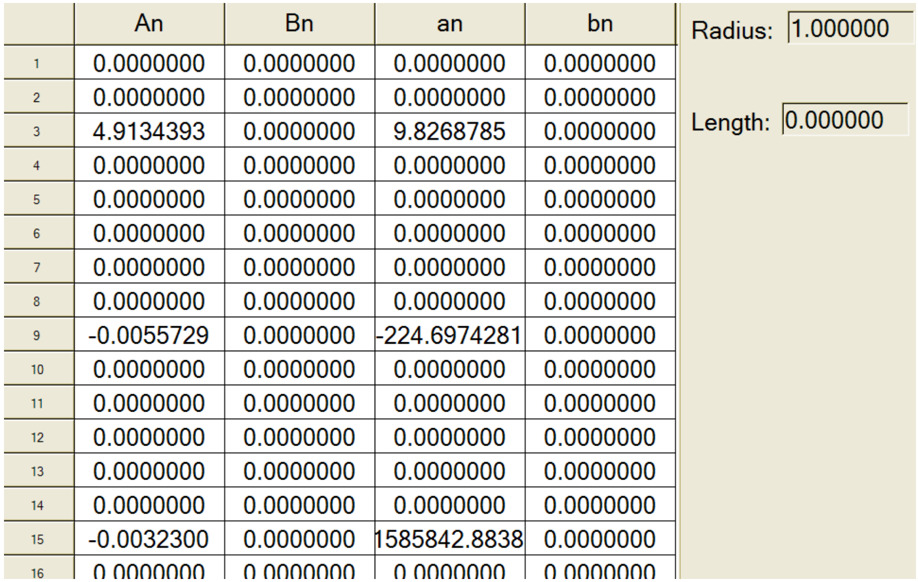
2D Fourier analysis of quadrupole

Ampere turns	2.5 кA×turns
Overall length	23 cm
Inscribed radius	12 mm
Gradient	~ 7.5 kGs/cm

Sextupole preliminary design



Magnetic induction distribution



	An	Bn	an	bn
1	0.0000000	0.0000000	0.0000000	0.0000000
2	0.0000000	0.0000000	0.0000000	0.0000000
3	4.9134393	0.0000000	9.8268785	0.0000000
4	0.0000000	0.0000000	0.0000000	0.0000000
5	0.0000000	0.0000000	0.0000000	0.0000000
6	0.0000000	0.0000000	0.0000000	0.0000000
7	0.0000000	0.0000000	0.0000000	0.0000000
8	0.0000000	0.0000000	0.0000000	0.0000000
9	-0.0055729	0.0000000	-224.6974281	0.0000000
10	0.0000000	0.0000000	0.0000000	0.0000000
11	0.0000000	0.0000000	0.0000000	0.0000000
12	0.0000000	0.0000000	0.0000000	0.0000000
13	0.0000000	0.0000000	0.0000000	0.0000000
14	0.0000000	0.0000000	0.0000000	0.0000000
15	-0.0032300	0.0000000	1585842.8838	0.0000000
16	0.0000000	0.0000000	0.0000000	0.0000000

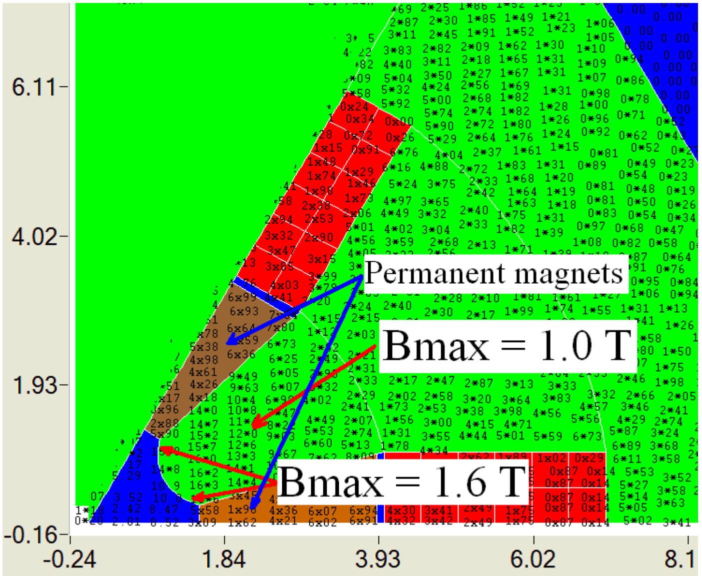
Radius: 1.000000

Length: 0.000000

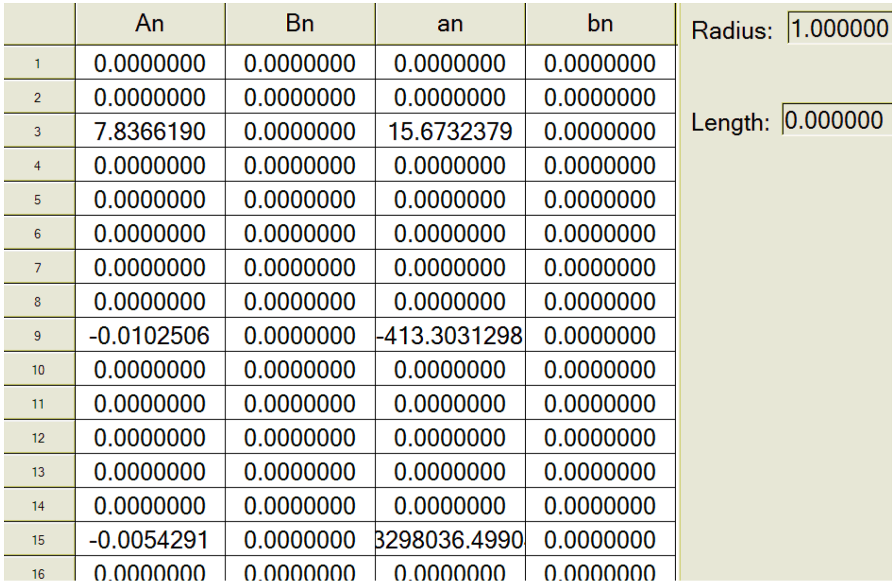
2D Fourier analysis of sextupole

Ampere turns	**2.5 кA×turns**
Overall length	**13 cm**
Inscribed radius	**12 mm**
Sextupole strength	**~ 5 kGs/cm^2**

Sextupole with permanent magnet concentrator



Magnetic induction distribution



	An	Bn	an	bn
1	0.0000000	0.0000000	0.0000000	0.0000000
2	0.0000000	0.0000000	0.0000000	0.0000000
3	7.8366190	0.0000000	15.6732379	0.0000000
4	0.0000000	0.0000000	0.0000000	0.0000000
5	0.0000000	0.0000000	0.0000000	0.0000000
6	0.0000000	0.0000000	0.0000000	0.0000000
7	0.0000000	0.0000000	0.0000000	0.0000000
8	0.0000000	0.0000000	0.0000000	0.0000000
9	-0.0102506	0.0000000	-413.3031298	0.0000000
10	0.0000000	0.0000000	0.0000000	0.0000000
11	0.0000000	0.0000000	0.0000000	0.0000000
12	0.0000000	0.0000000	0.0000000	0.0000000
13	0.0000000	0.0000000	0.0000000	0.0000000
14	0.0000000	0.0000000	0.0000000	0.0000000
15	-0.0054291	0.0000000	3298036.4990	0.0000000
16	0.0000000	0.0000000	0.0000000	0.0000000

Radius: 1.000000

Length: 0.000000

2D Fourier analysis of sextupole

Ampere turns	4.5 κA×turns
Overall length	13 cm
Inscribed radius	12 mm
Sextupole strength	~ 7.5 kGs/cm^2

Conclusion

- The CLIC DR lattice v06.7 with realistic parameters is designed. The lattice performance satisfies the damping ring requirements
- The dynamic aperture of the v06.7 lattice is optimized. The size of the DA seems quite enough for reliable machine operation
- Preliminary design of the normal conducting quadrupole and sextupole magnets is considered
- BINP is ready to participate in the CLIC DR design report preparation