Superconducting quadrupole for final focus

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Outline

Super Tau Charm factory

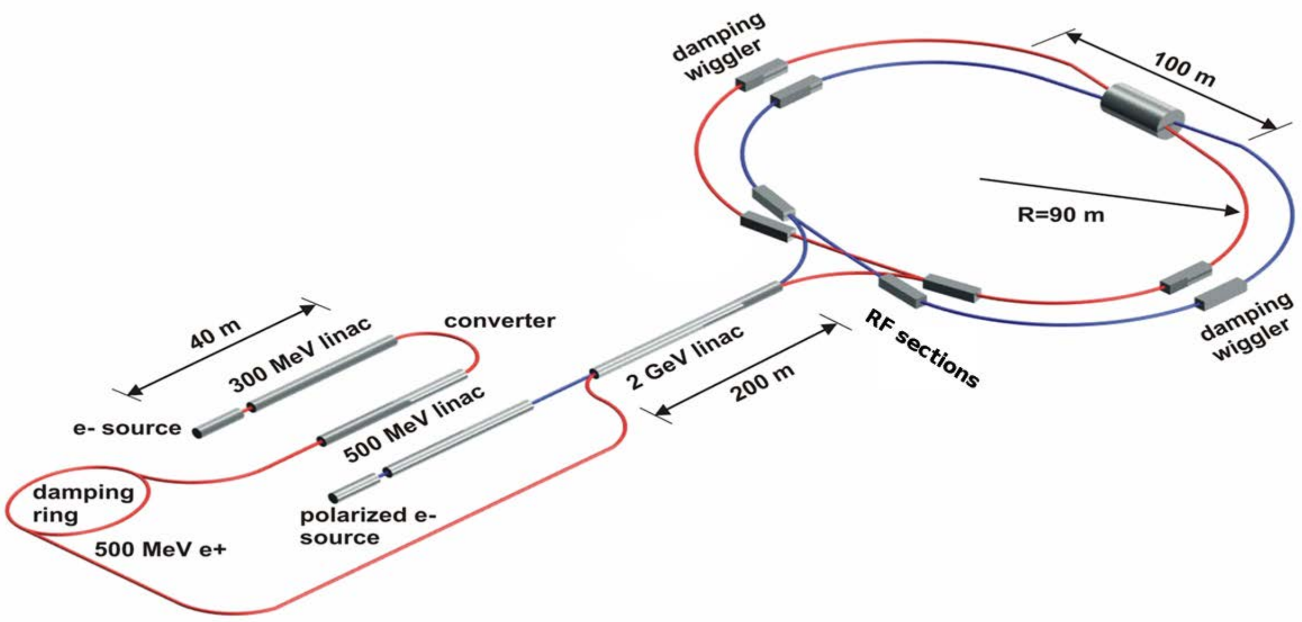
- IR quadrupole configurations
- FF quadrupole design

FCC-ee IR quadrupole design

- IR quadrupole configurations
- Factors influencing the FF quadrupole features
- FF quadrupole design

Summary

Super Tau Charm factory



Accelerator requirements

- Energy 1.0 - 2.5 GeV
- Luminosity 10^{35} for 2 GeV
- Longitudinal polarization of electrons in the IP
- Monochromatisation not required
- Energy Calibration - Inverse Compton scattering method
- Double ring
- Crab waist collision
- Sub-millimeter beta function in the IP
- Saving beam emittance and damping time of the energy
- High currents (using the OS)
- 5 Siberian snakes
- The source of positrons
- The source of polarized electrons
- 2.5 GeV linac
- 50 Hz injection

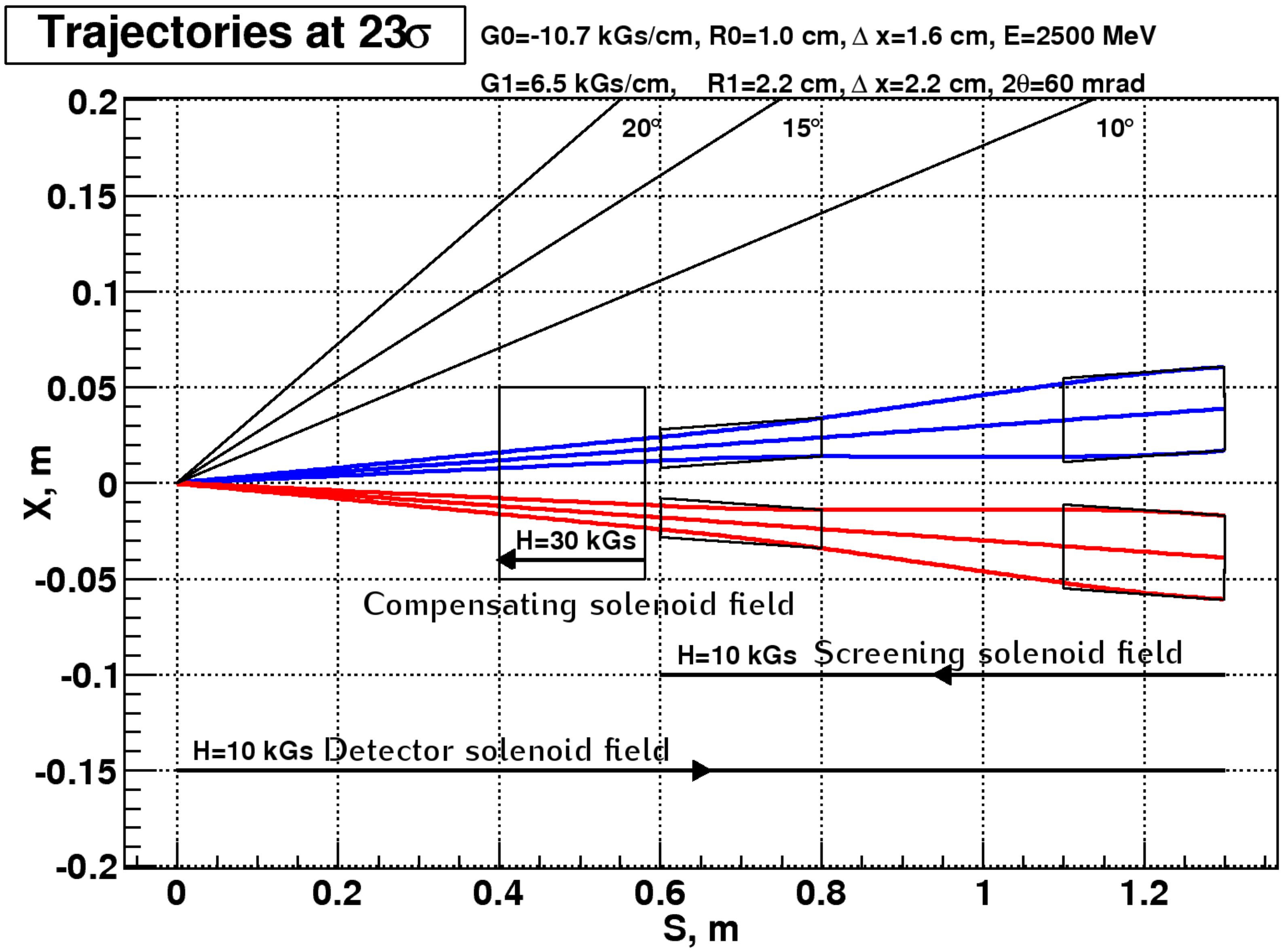
IR requirements

- Small beta function at IP.
- Local chromaticity correction.
- Small geometric aberrations.
- The integral of the longitudinal field compensated befor FF quadrupoles.
- CRAB sextupole closer to the IP as posible, in a place with small chromatic optical functions.
- Minimisation of synchrotron radiation inside the detector vacuum chamber.

Super C-Tau factory main parameters

Energy, GeV	2
Particles in the bunch / bunches	$7 \cdot 10^{10}$ / 354
Beam current, A	1.63
β_x / β_y / σ_s, mm	40 / 0.8 / 9
ε_x, nm·rad	8
The coupling coefficient ε_y / ε_x,%	0.5
meetings Angle, mrad	60
The frequency shift, ξ_y	0.13
The luminosity of the geometric / Hour-Glass, $cm^{-1}sec^{-1}$	$1.17 \cdot 10^{35}$ / $1.06 \cdot 10^{35}$
Pivinsky angle ϕ, mrad	15

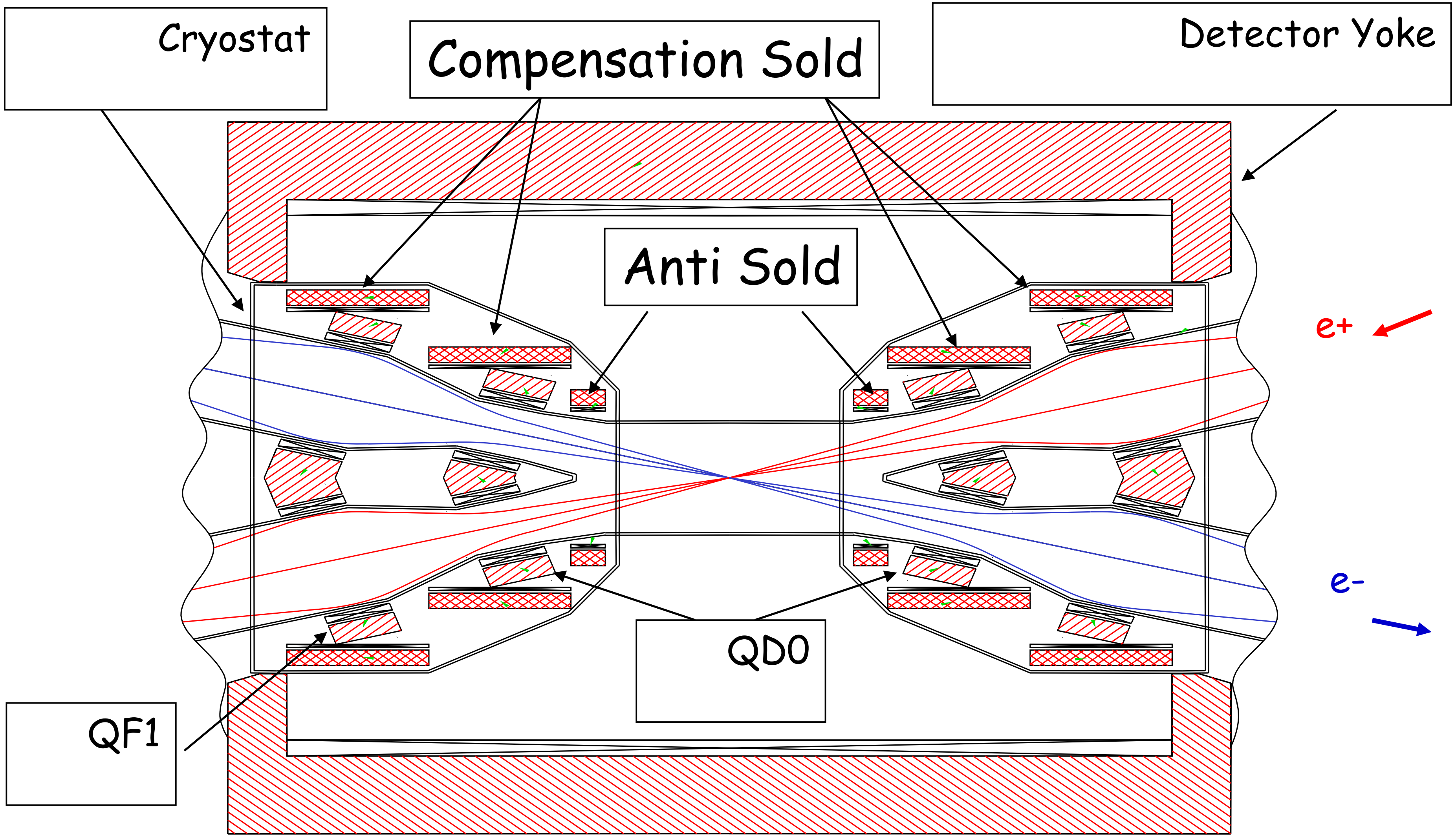
Super C-Tau factory final focus doublet



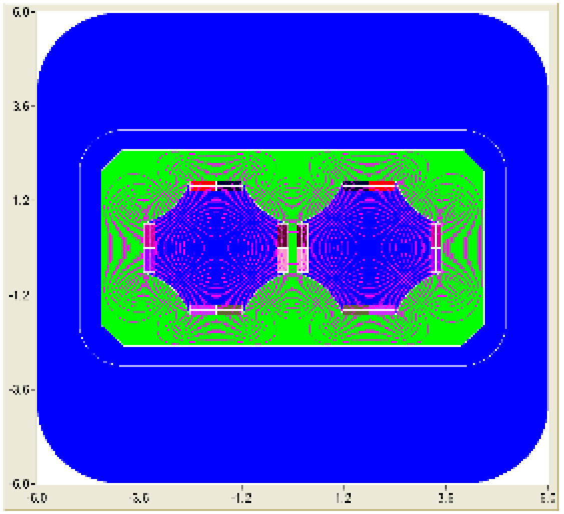
Super C-Tau factory IR parameters

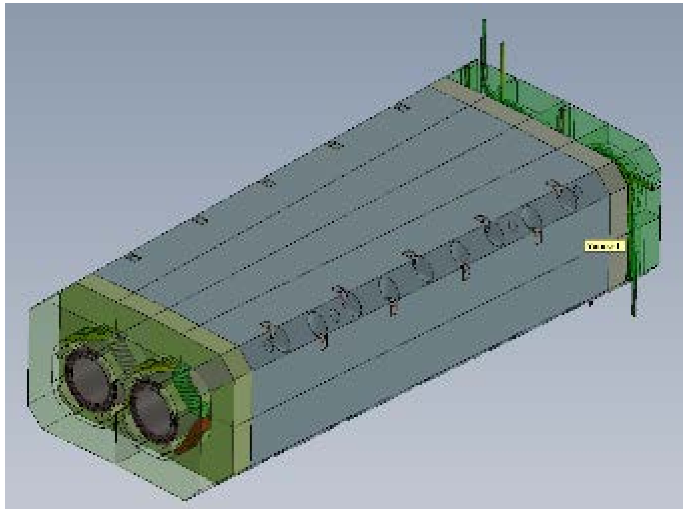
	Effective length, mm	**Position from IP, cm**	**Longitudinal field (kGs), or Gradient (kGs/cm)**	**Aperture radius, mm**	**$\Delta B/B$ or $\Delta G/G$**	**Type**
Interaction point	0.600 mm	0 cm	10 kGs	R = 40 mm	**<ins><1%</ins>**	Interaction point
SC0	100 mm	45 cm	-30 kGs	R = 45 mm	**<ins><1%</ins>**	Superconducting solenoid
SSH1	600 mm	55 cm	-10 kGs	-	<1%	Superconducting solenoid
SEQ0 (NEQ0)	**200 mm**	**60 cm**	**<ins>-10.7 kGs/cm</ins>**	**<ins>R = 10 mm</ins>**	***<ins>1 - 5·10^{-4}</ins>***	**Superconducting double aperture quadrupole lens**
SSH2	900 mm	85 cm	-10 kGs	-	<1%	Superconducting double aperture quadrupole lens
SEQ1 (NEQ1)	**200 mm**	**110 cm**	**<ins>6.5 kGs/cm</ins>**	**<ins>R = 22 mm</ins>**	***<ins>1 - 5·10^{-4}</ins>***	**Superconducting double aperture quadrupole lens**

Final Focus System



Double-aperture quadrupole lens





QD0 calculations in MERMAID

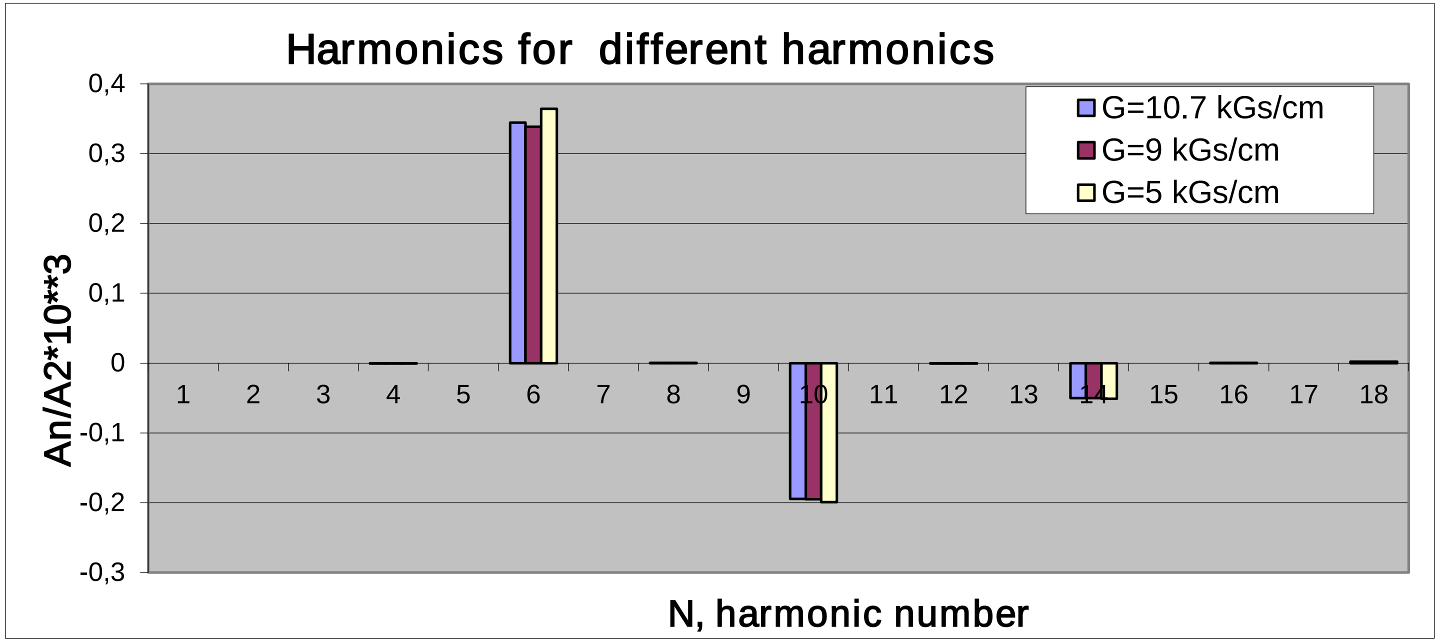
Modified Panofsky type quadrupole was proposed originally by Pavel Vobly.

- All 2D and 3D calculations were made by MERMAID
- There is no yoke saturation at 11 kGs/cm (vanadium permendure)
- 3D calculations give $\Delta G/G \pm 10^{-3}$
- Maximum current 700 A

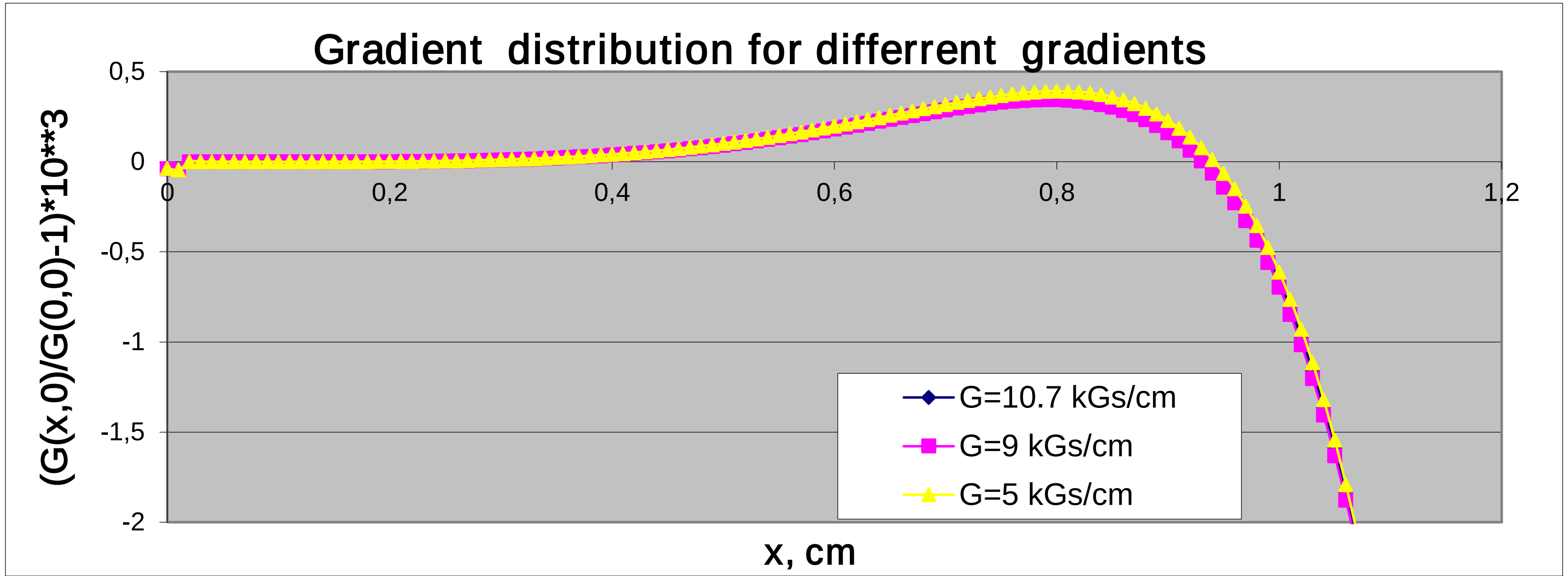
Harmonics of QD0 for different gradients at R = 1 cm

N	an	an	an
2	-10.97	-9.08	-5.32
6	-0.0038	-0.0031	-0.0019
10	0.0021	0.0018	0.0011
14	0.0006	0.00046	0.00027
18	-2.2E-05	-1.8E-05	-1.1E-05

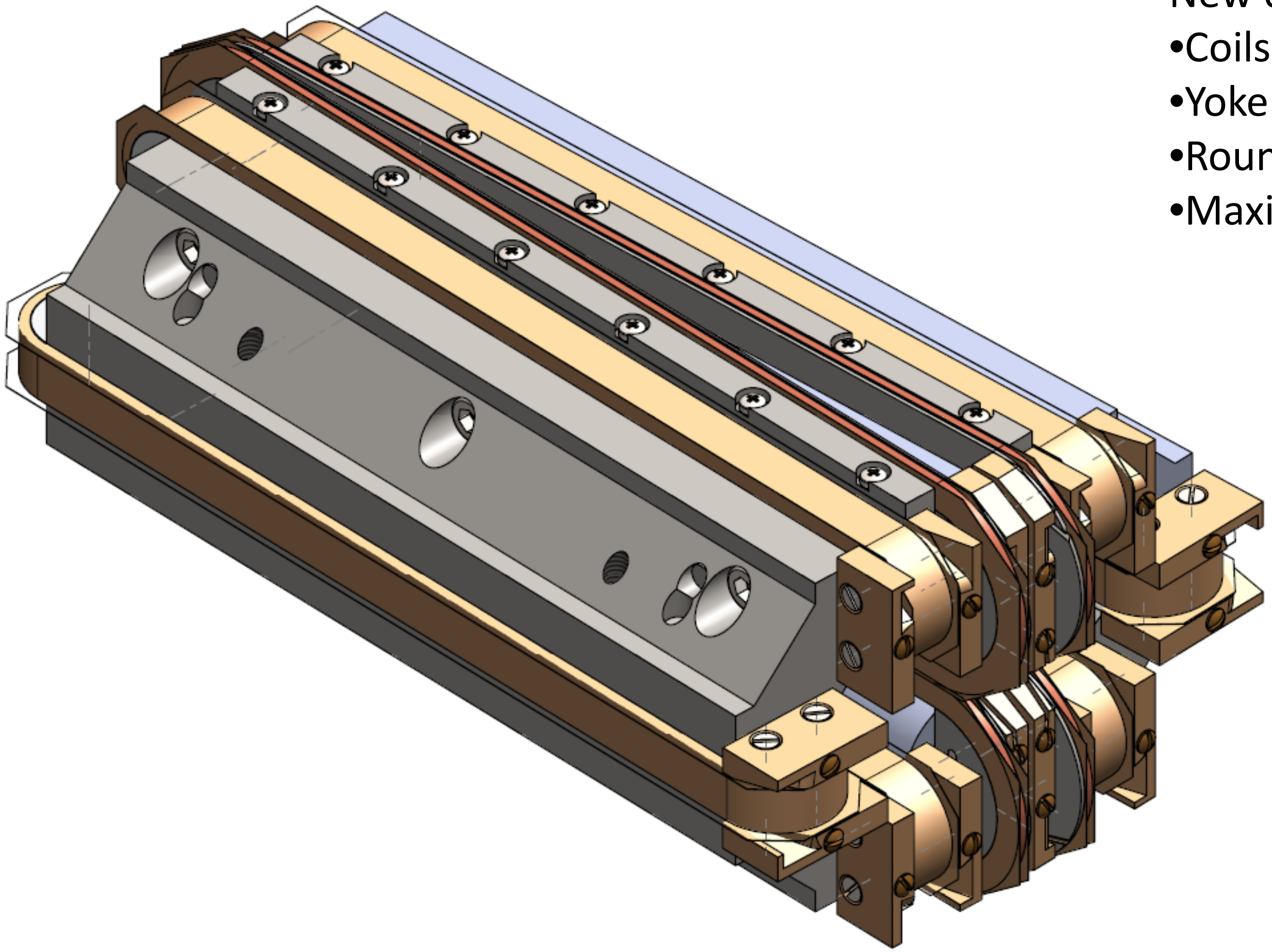
QD0 gradient



QD0 harmonics for different energy

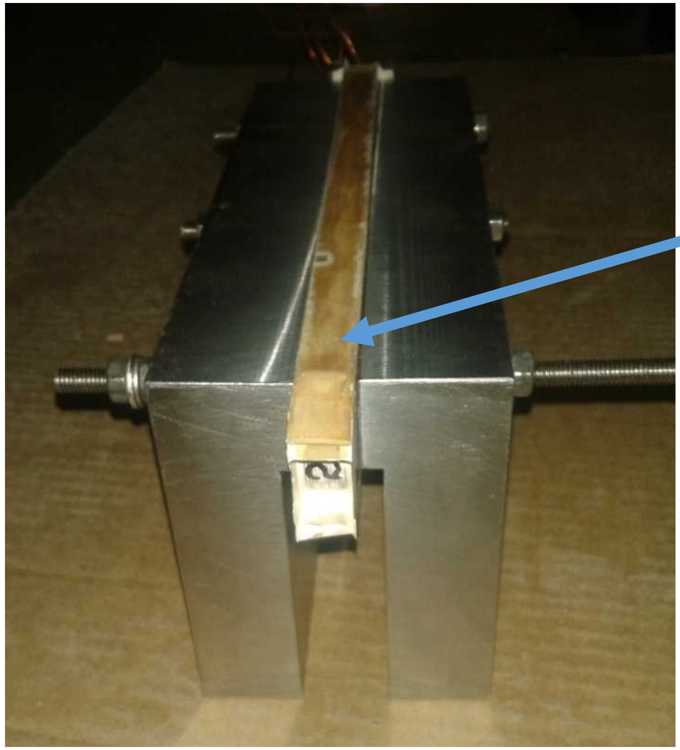


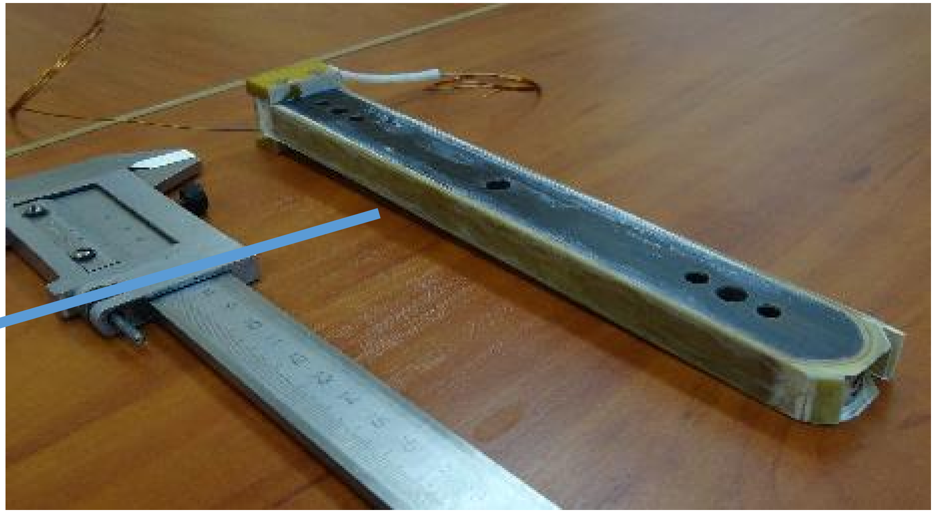
QD0 design (general view)



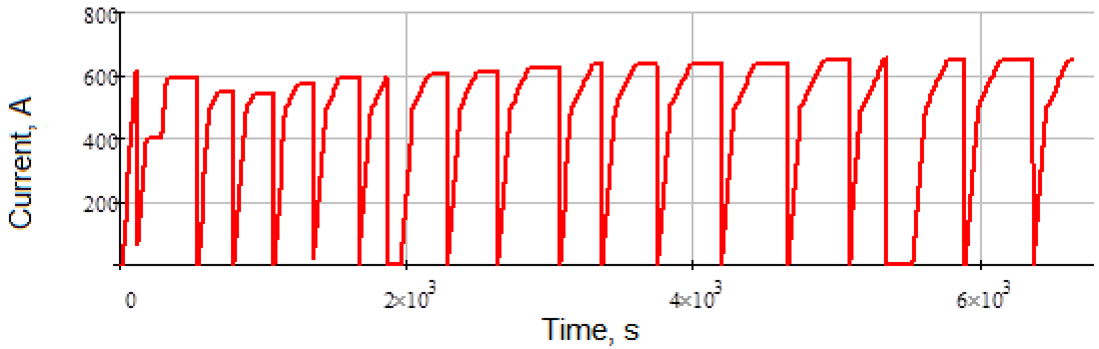
New design:
- Coils more easy in manufacture
- Yoke and poles have same shape
- Round superconducting wire of Ø 0.75 mm
- Maximum current of 400 A

QD0 design



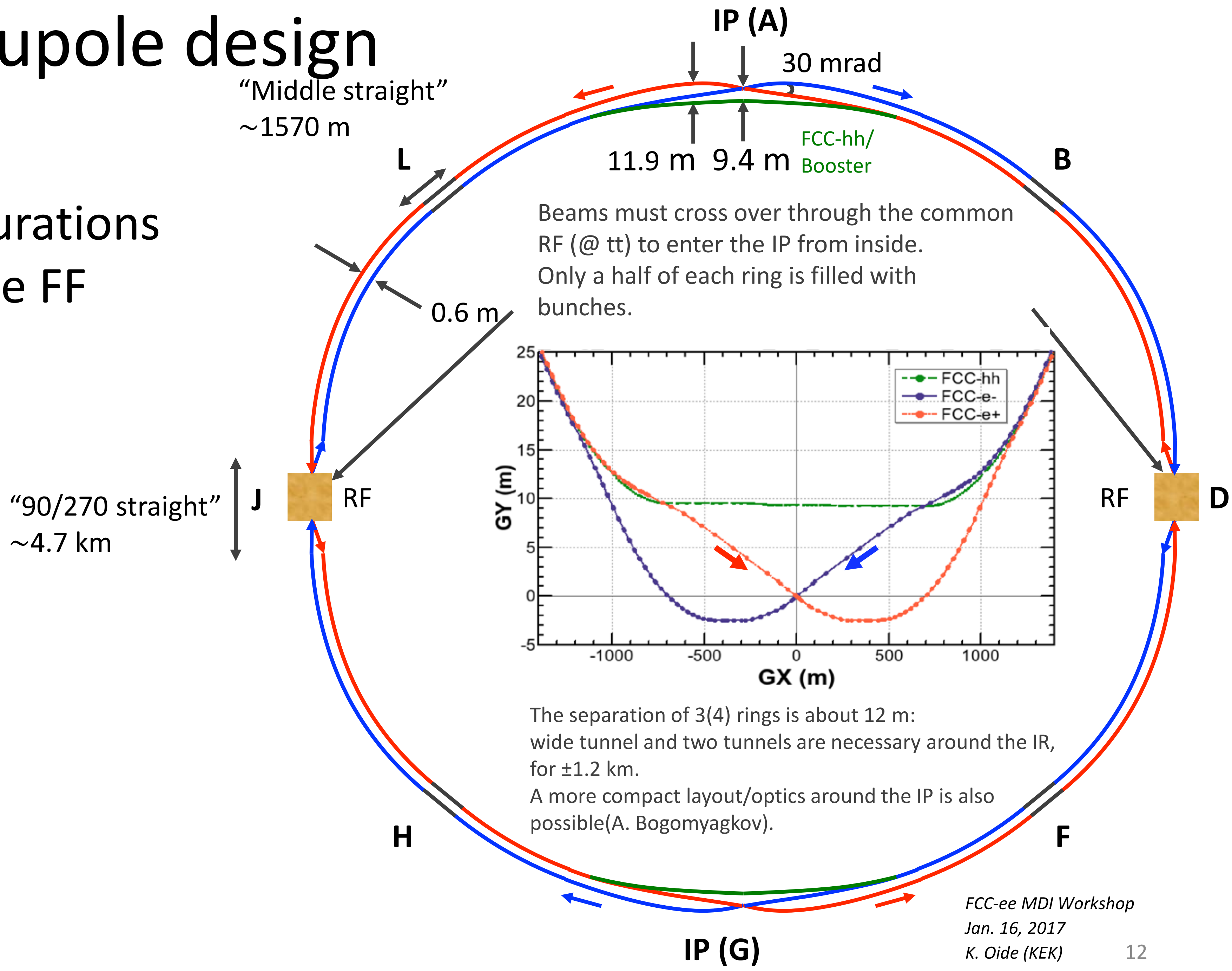


Maximum current in the coil is 720 A provides gradient ~16 kG / cm



FCC-ee IR quadrupole design

- IR quadrupole configurations
- Factors influencing the FF quadrupole features
- FF quadrupole design



2016 Parameters

parameter	FCC-ee			
energy/beam [GeV]	**45**		**120**	**175**
bunches/beam	91500	30180	770	78
beam current [mA]	1450		30	6.6
energy loss/turn [GeV]	0.03		1.67	7.55
synchrotron power [MW]	100			
RF voltage [GV]	0.2	0.4	3.0	10
rms bunch length (SR,+BS) [mm]	1.6, 3.8	1.2, 6.7	2.0, 2.4	2.1, 2.5
rms emittance $\varepsilon_{x,y}$ [nm, pm]	0.1, 1	0.2, 1	0.6, 1	1.3, 2.5
$\beta^*_{x,y}$ [m, mm]	1, 2	0.5, 1	1, 2	1, 2
long. damping time [turns]	1320		72	23
crossing angle [mrad]	30			
beam lifetime [min]	185	94	67	57
luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	**70**	**207**	**5.1**	**1.3**

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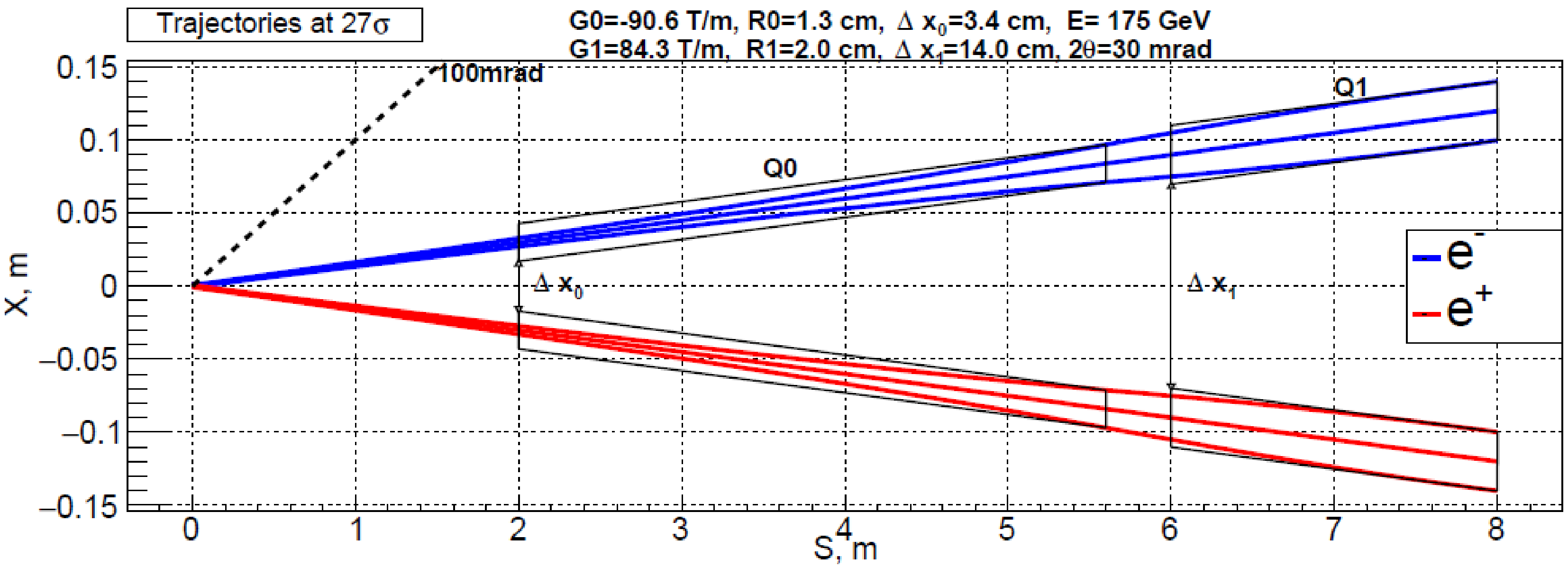
IR configurations (AB FCC 1)

Symmetric FF L*=2 m ∅Q0 = 2.6 cm ∅Q1 = 4 cm

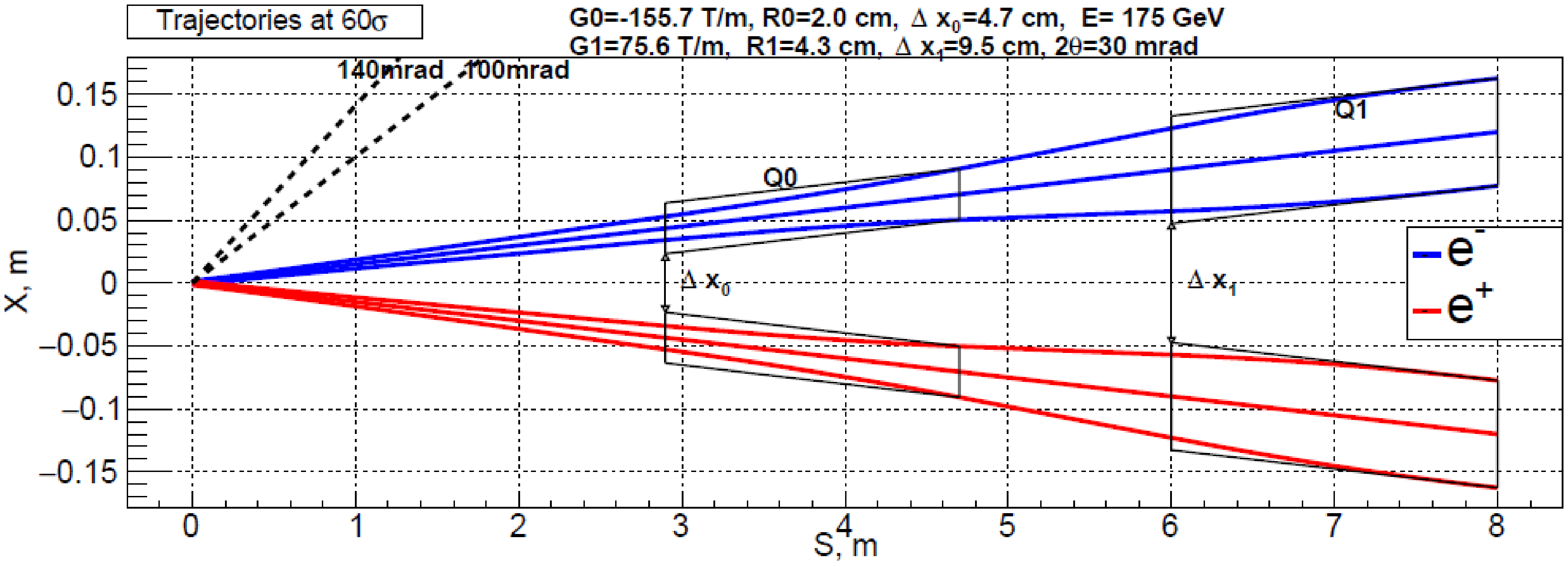


	L [m]
Q0	3.6
Q1	2

R	G [T/m]
Q0	90.6
Q1	84.3

IR configurations (AB FCC 2)

Symmetric FF L* = 2.9 m ∅Q0 = 4 cm ∅Q1 = 8.6 cm



	L [m]
Q0	1.8
Q1	2

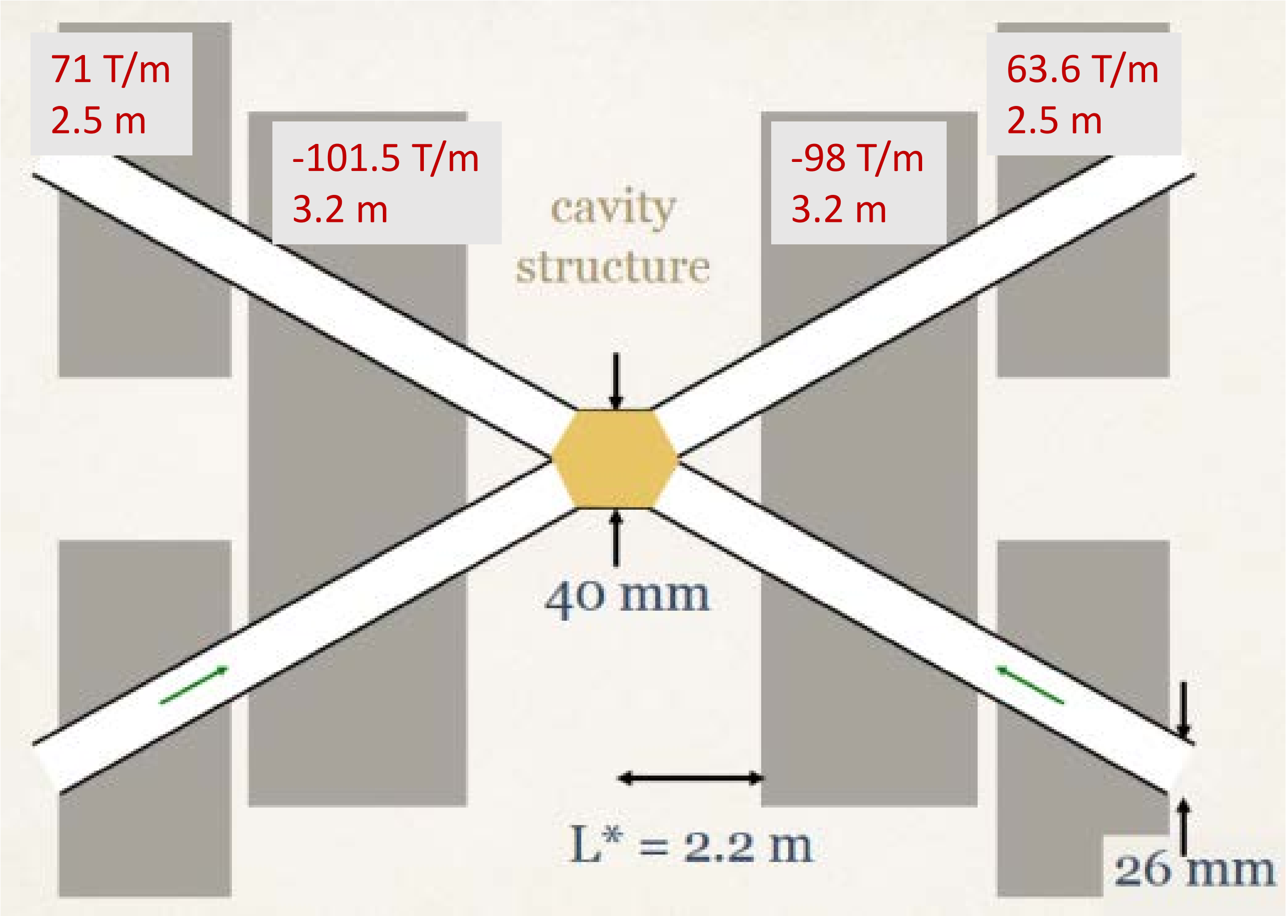
	G [T/m]
Q0	156
Q1	76

Factors defining IR quadrupole choice

- Crossing angle (30 mrad fixed)
- L*, maximum beta, IR chromaticity, fringe fields
- L*, luminometer location and anti-solenoid parameters
- Q radiation and DA reduction
- Q radiation and SR background
- Technology (maximum gradient vs aperture)

IR config.(KO FCCee_t_82_by2_1a_nosol_DS)

Symmetric FF L* = 2.2 m, 30 mrad



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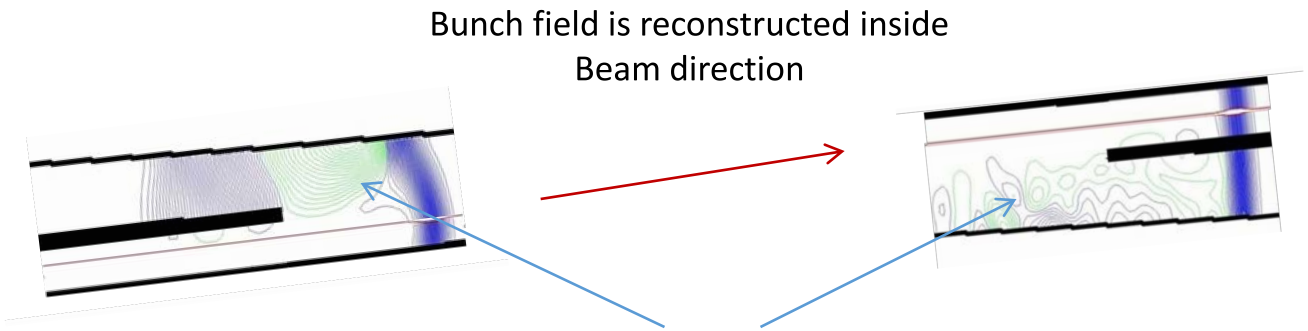
What is not good with HOMs and wake fields in the IR beam pipe?

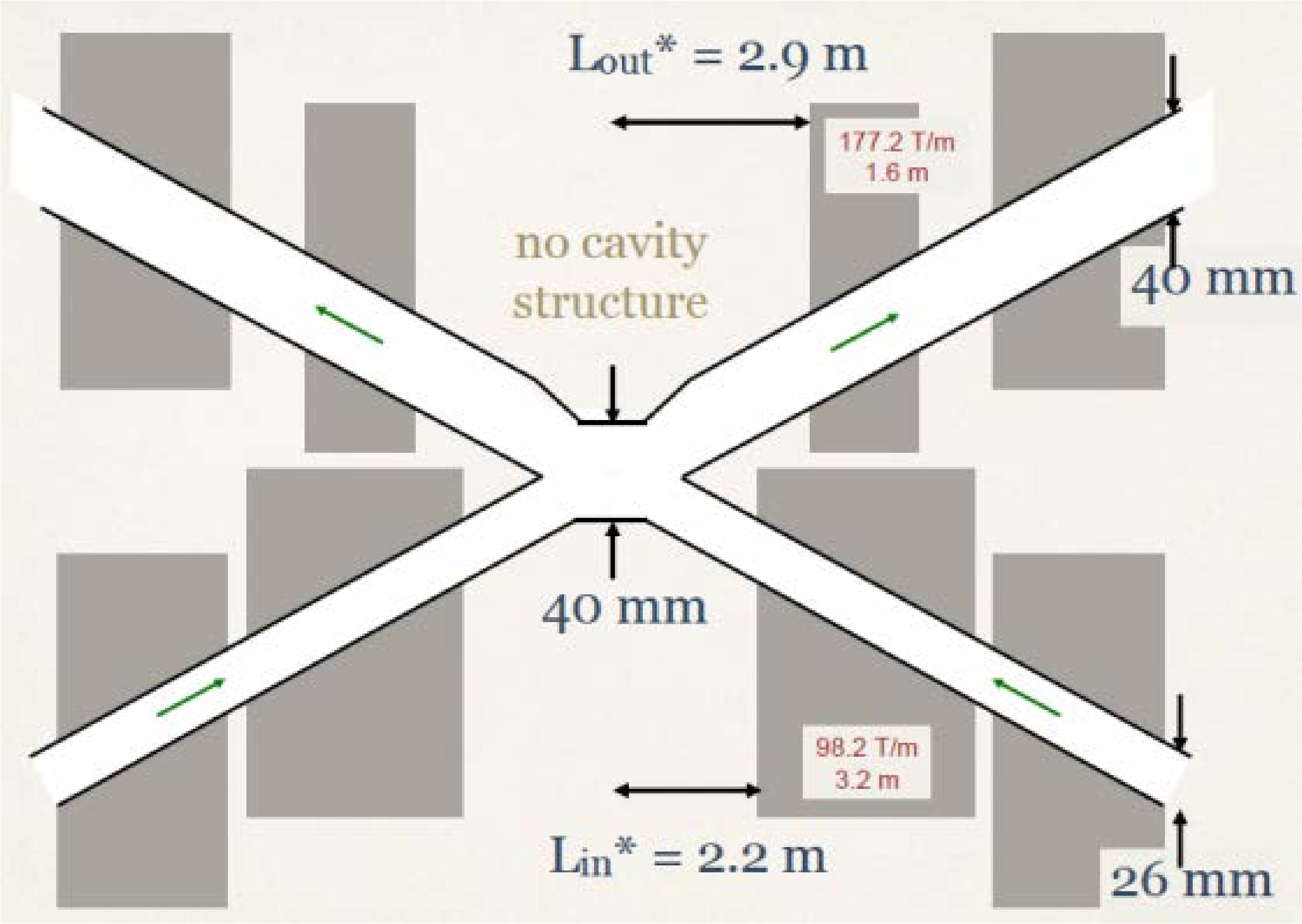
- Heating of the IR chamber elements when these fields are dissipating in the chamber wall.
  - **High temperature raise will destroy good vacuum that may lead to addition background in IR or even vacuum instability**
- Everything starts with excitation of the so called wake fields mainly in the place where two incoming or out coming tubes are connected.



Forward and backward excited fields will propagate to other crotches and can be reflected back.
Under a resonant condition they can make a Higher Order Mode.

IR config.(KO for HOM escape)

Asymmetric FF L* = 2.2÷2.9 m, 30 mrad



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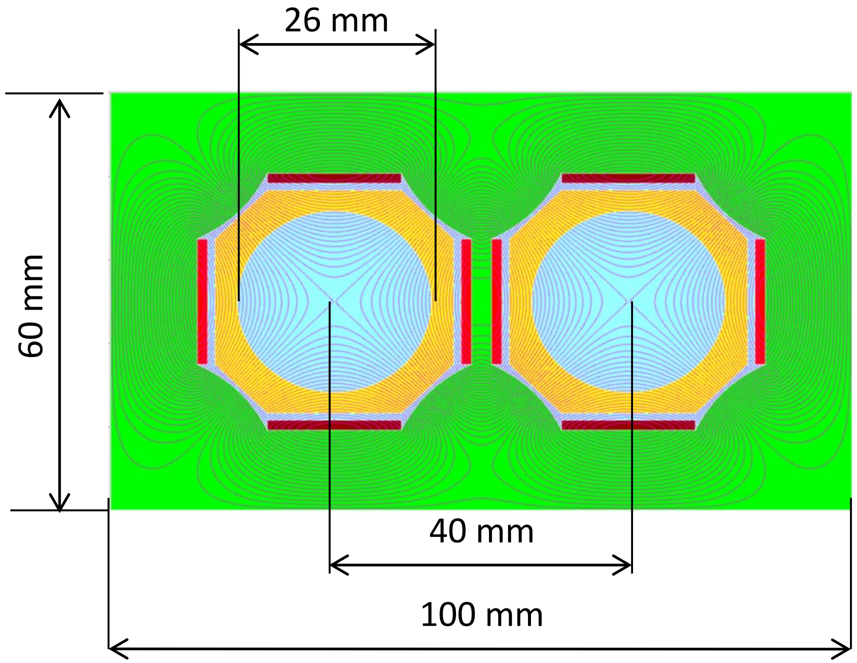
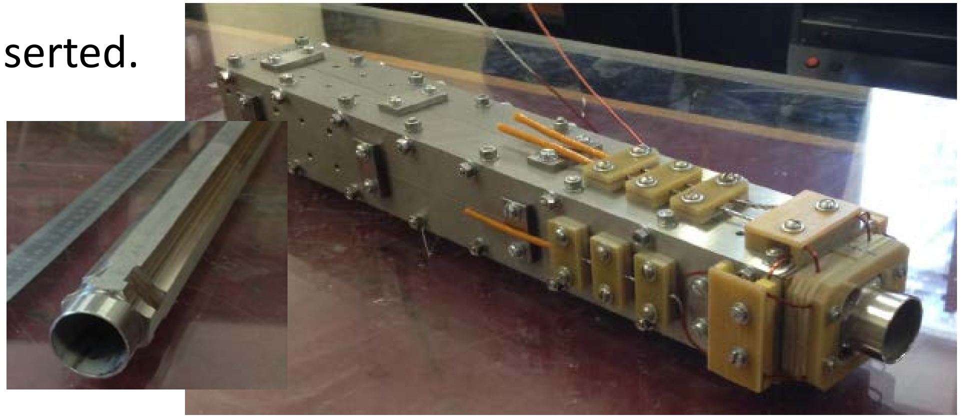
Iron yoke twin-aperture quadrupole

Modified Panofsky type quadrupole was proposed originally by Pavel Vobly for the Super Charm Tau project in Novosibirsk.

Advantage – transversely very compact and can be placed close to the IP to intercept the beta growth; no influence to the adjacent quad; 100 T/m can be achieved in ∅26 mm; the field quality at R = 1 cm is ~10^{-4}.
Disadvantage – no correction coils can be inserted.





A 40-cm-prototype (+vacuum chamber) was built and cryo-tested at BINP. 1060 A was reached after 3 quenches.

Main parameters:

Max.gradient 100 T/m	Max.current 1100 A
Length 40 cm	Aperture 2.6 cm
NbTi 1.8 x 1.4 mm^2	Saddle-type coils

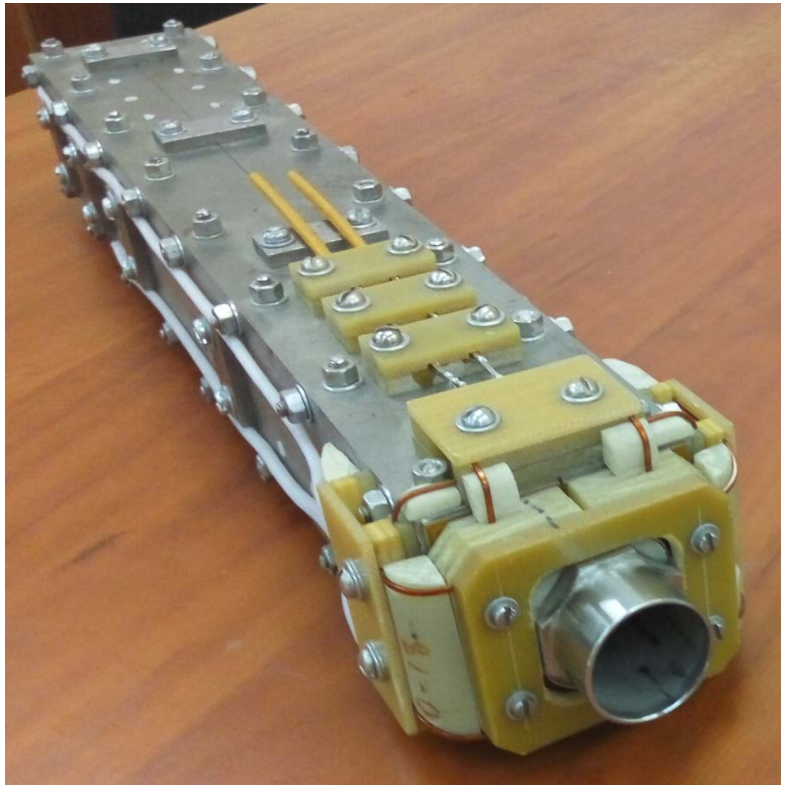
Parameters and materials

- The height of this lens is 6 cm, and the width at the inlet of the lens is 6 cm (one part).
- The inner diameter of the aluminum vacuum chamber is 2.6 cm.
- Current 1000 amperes provides gradient 9.5 kG / cm.
- Superconducting wire is a rectangular tavern size of 0.8 × 1.4 mm.
- Stored energy 400 joules. Winding temperature superconductivity at failure increased only a few degrees.

NbTi rectangular superconductor

Cu/Sc Ratio (nom)	Bare Size (mm)	Ins. Size (mm)	RRR	Ic Amps (min)	Length (m)	Spool ID
1.35:1	1.20x0.75	1.28x0.83	>70	510@7T	2,730	917

Parameters and materials



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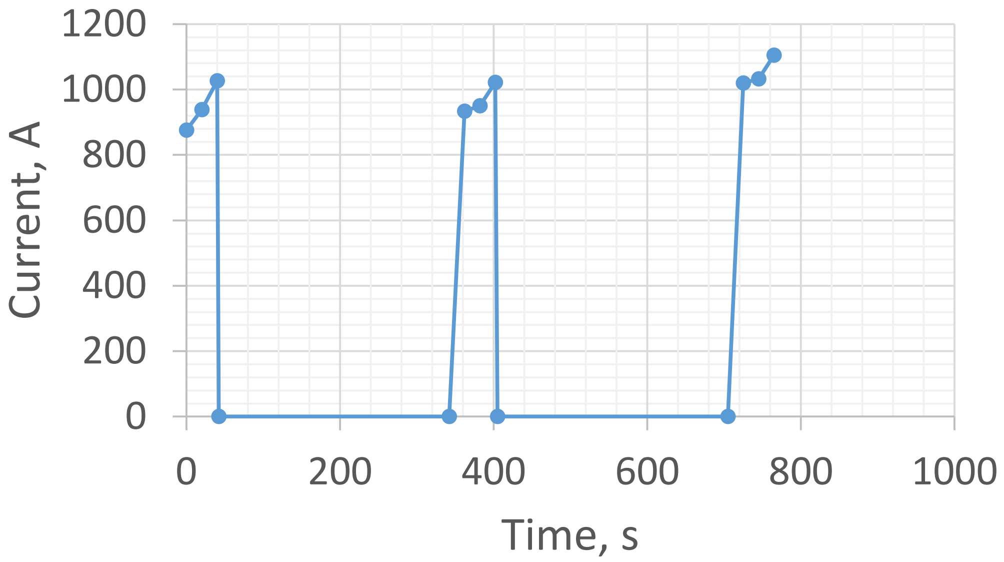
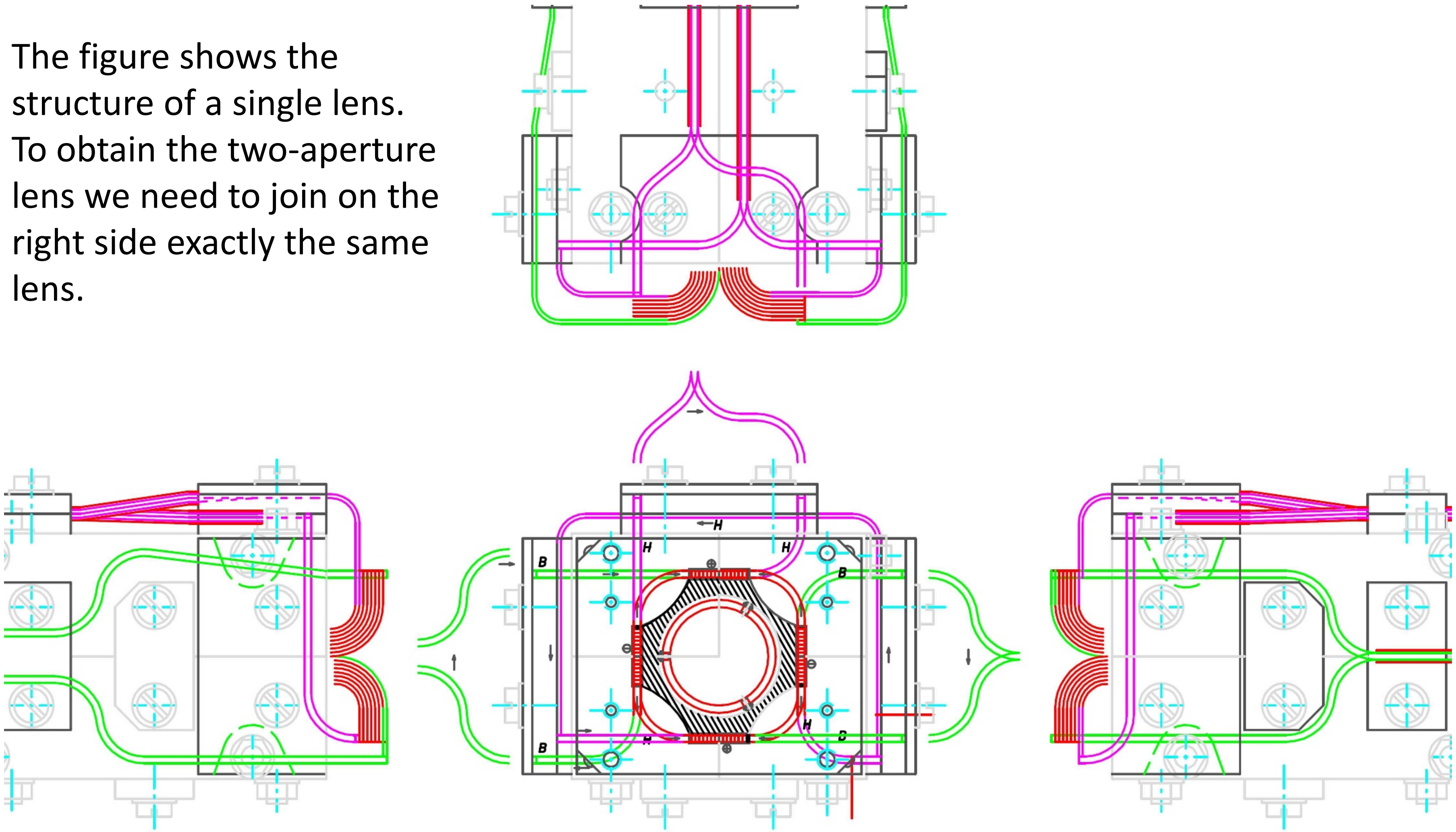
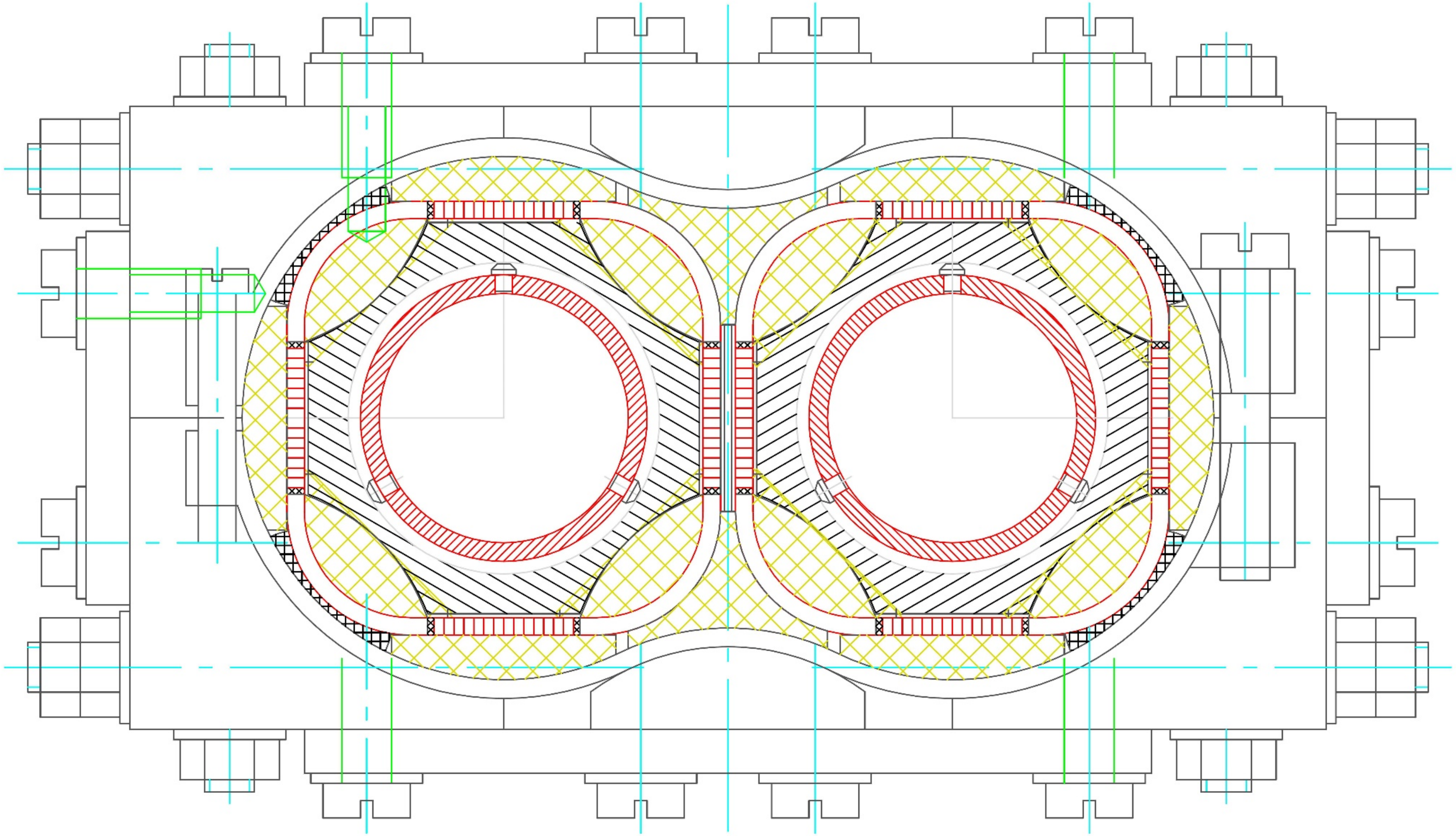


QD0 design

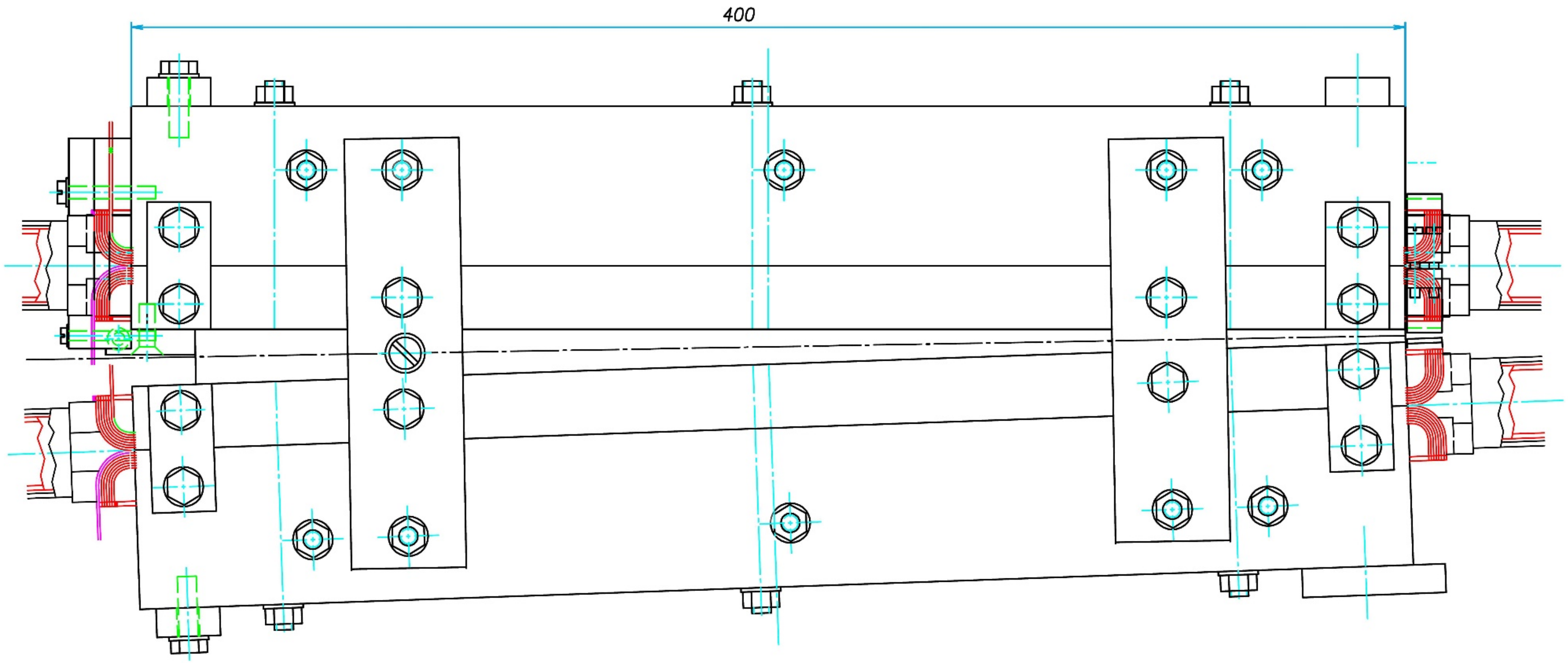
The figure shows the structure of a single lens. To obtain the two-aperture lens we need to join on the right side exactly the same lens.



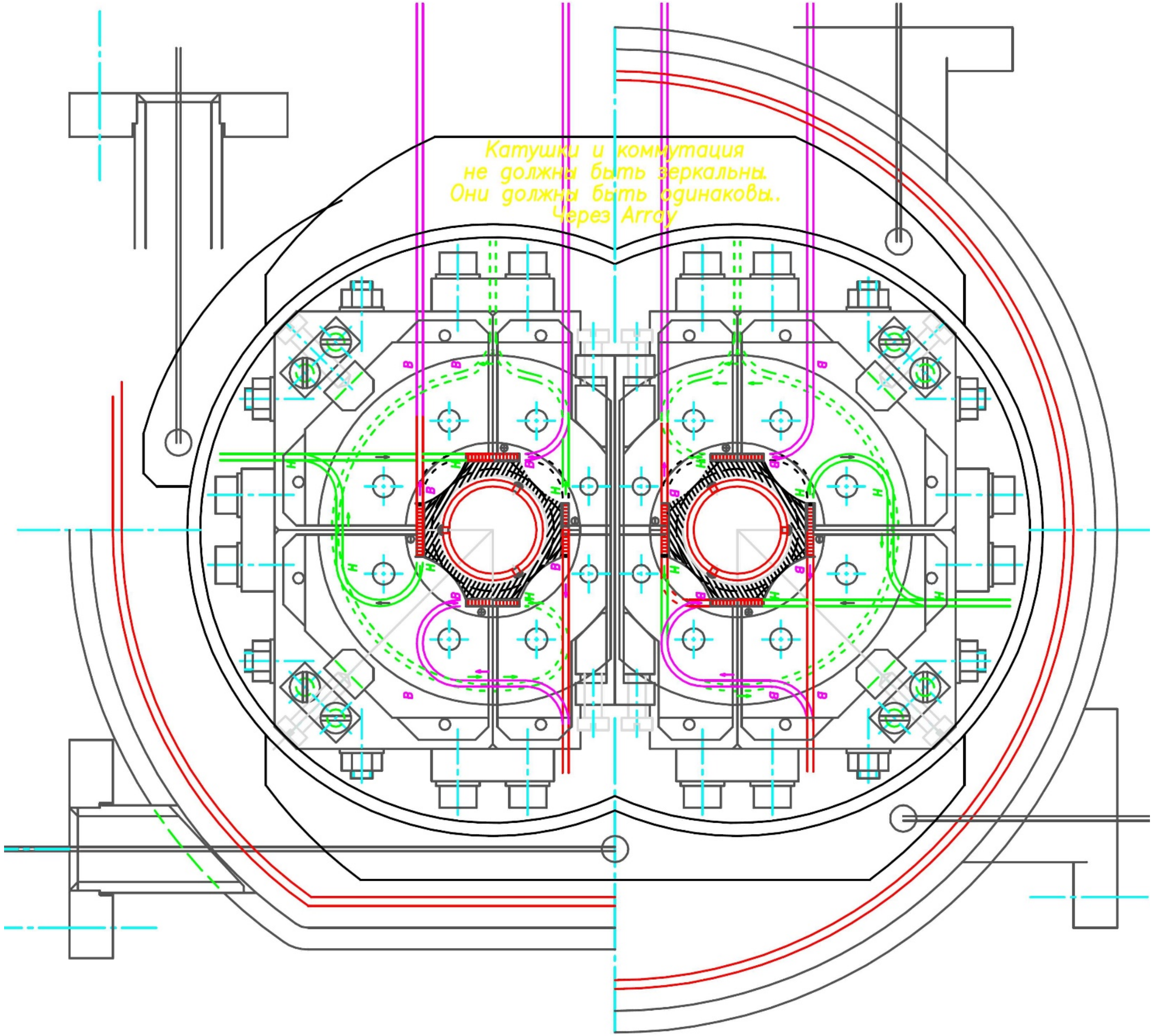
QD0 design



QD0 design

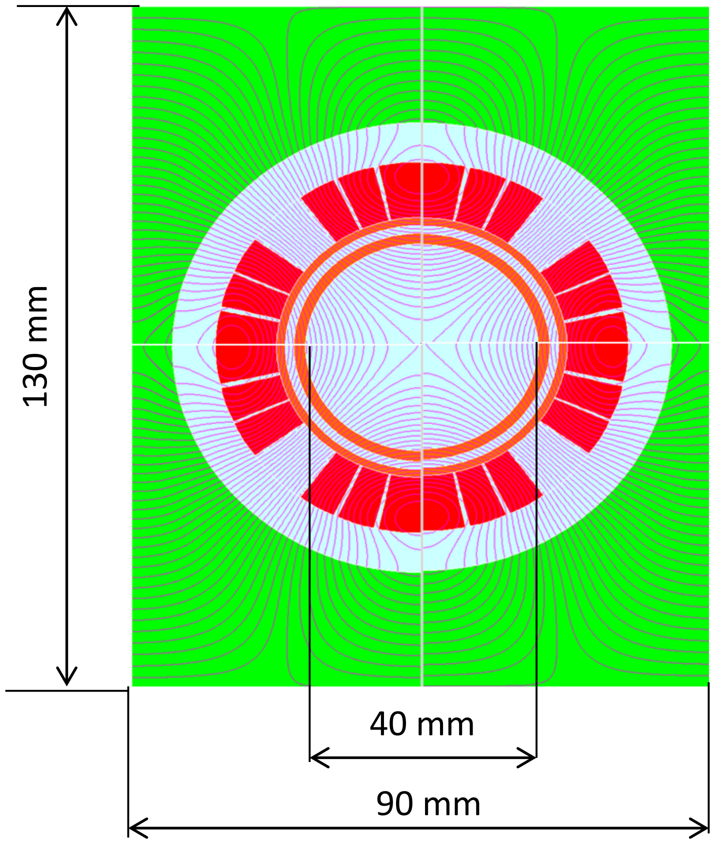


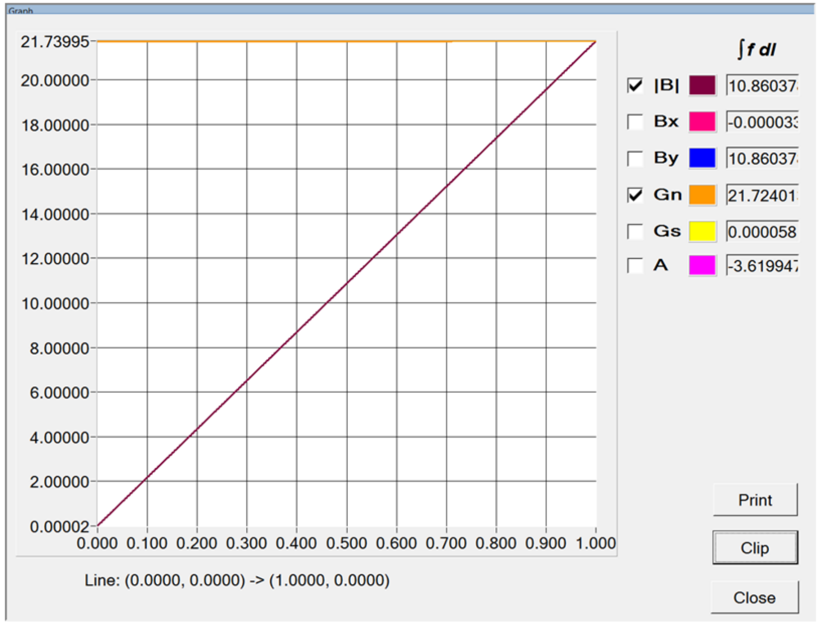
QD0 cryostat design



Cosine theta quadrupole

A single aperture quadrupole with 40 mm beam-stay-clear and maximum gradient 210 T/m was done for FCC-ee. The lens is surrounded by non-saturated iron box shielding the field. The field quality is ~3×10^{-4} inside R = 1 cm. Further optimization is possible.

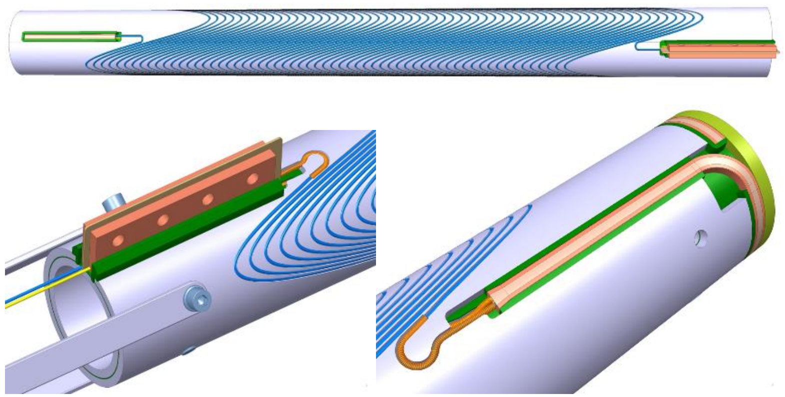




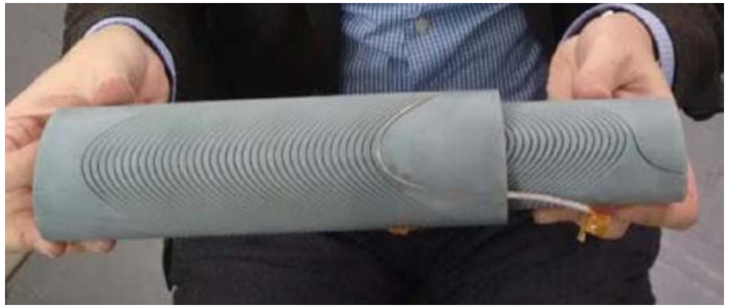
Corrector coils can be incorporated in the quadrupole . The question is how it can increase the size?

Double helix quadrupole

Double helix (canted cosine theta) quadrupole was proposed for SuperB FF by Eugenio Paoloni and studied for FCC-ee by Mike Koratzinos. The double helix magnets achieve pure multipole fields by the sinusoidal modulation of the axial position of the turns of a solenoid wound coil.



E Paoloni's design for Super B



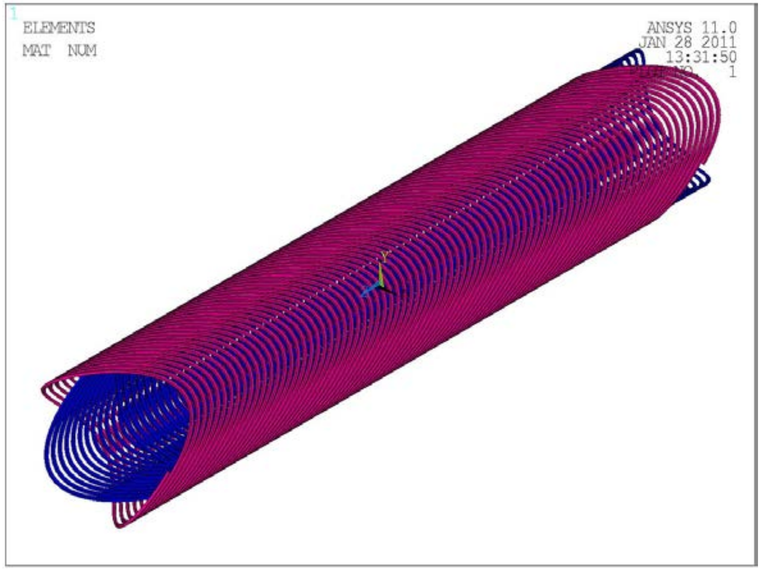
M Koratzinos with the cylindrical composite tubes for placement of the conductor turns

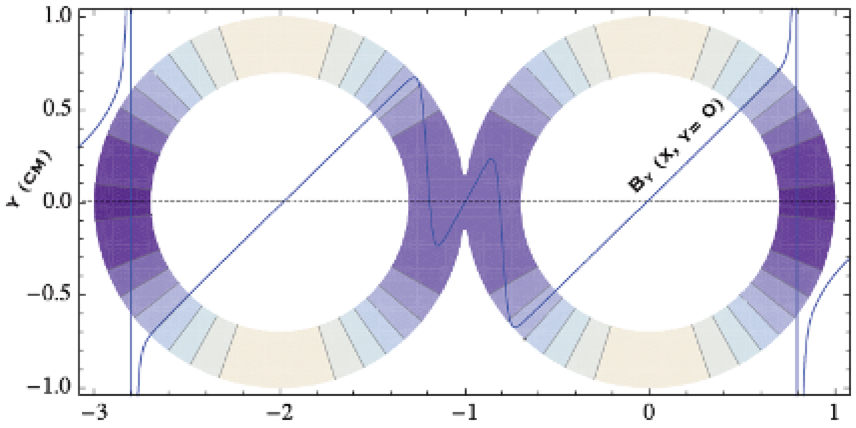
Promising technology, cheap, simple, corrector coils are incorporated easily. The question is if the required for FCC-ee FF gradient can be achieved together with compact transverse magnet dimensions. For SuperB QD0 it was 100 T/m for 35 mm aperture with 2 layer coil and ~2600 A current (I/I_c = 64% at 4.2 K).

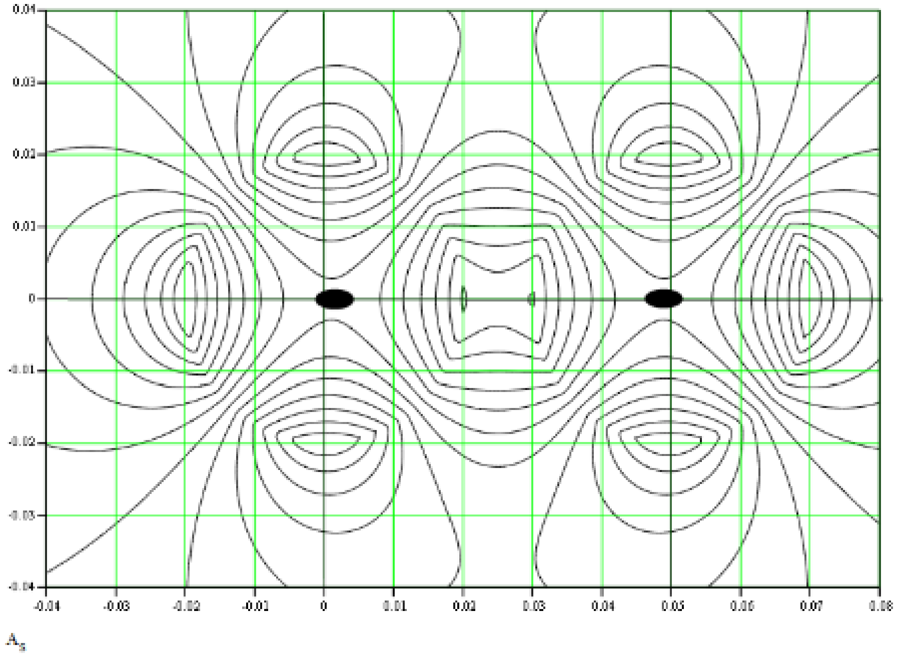
Basic layout: double helix qudrupole

The quadrupoles are done according the double helix principle. This lay-out allows to modulate the winding introducing suitable multipole corrections. The overall structure is compact and the effect of coil ends on field quality is minimal (wrt more conventional designs)

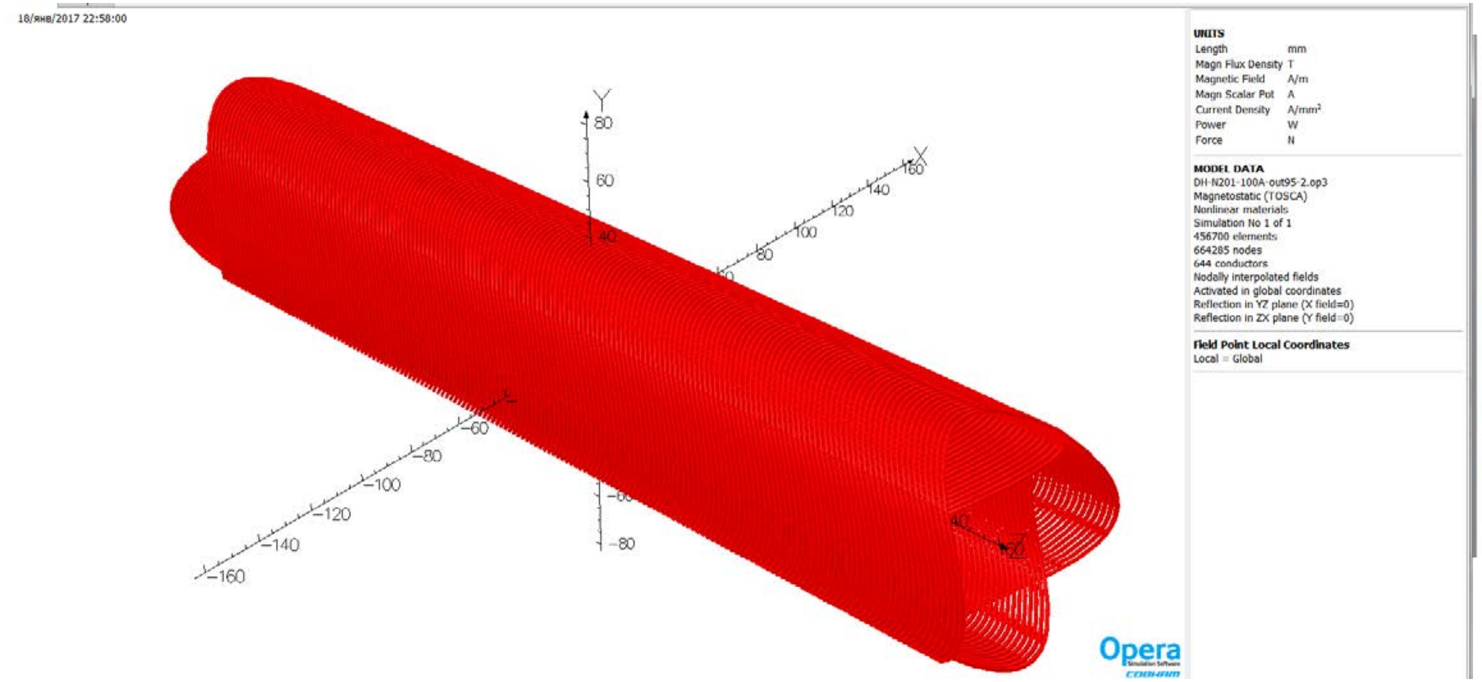
$$z(\theta) = \frac{h\vartheta}{2\pi} + \sum_{n=1}^{N} A_n \sin(n\theta + \varphi_n)$$

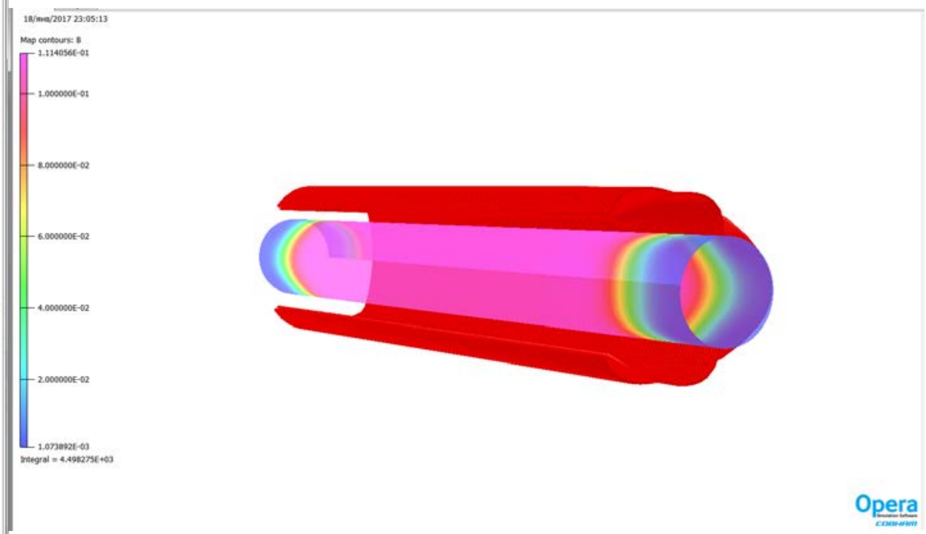


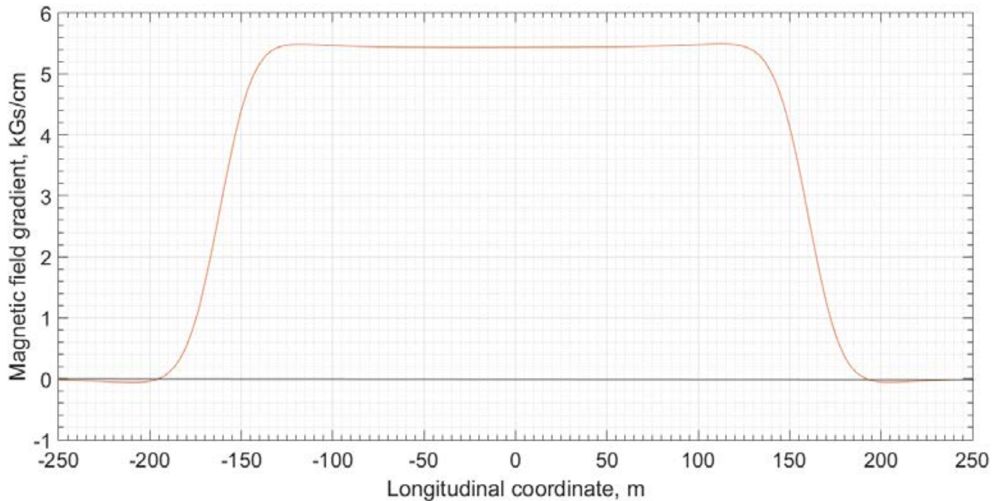


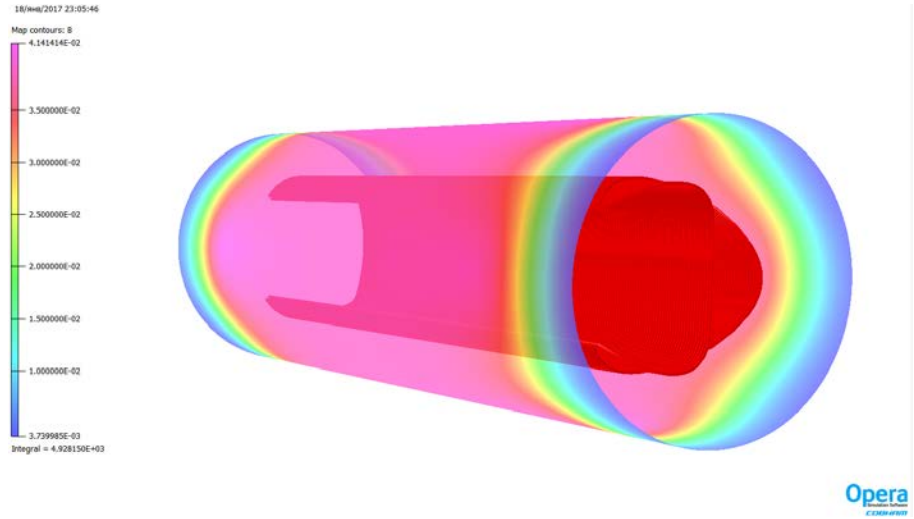


Double helix qudrupole









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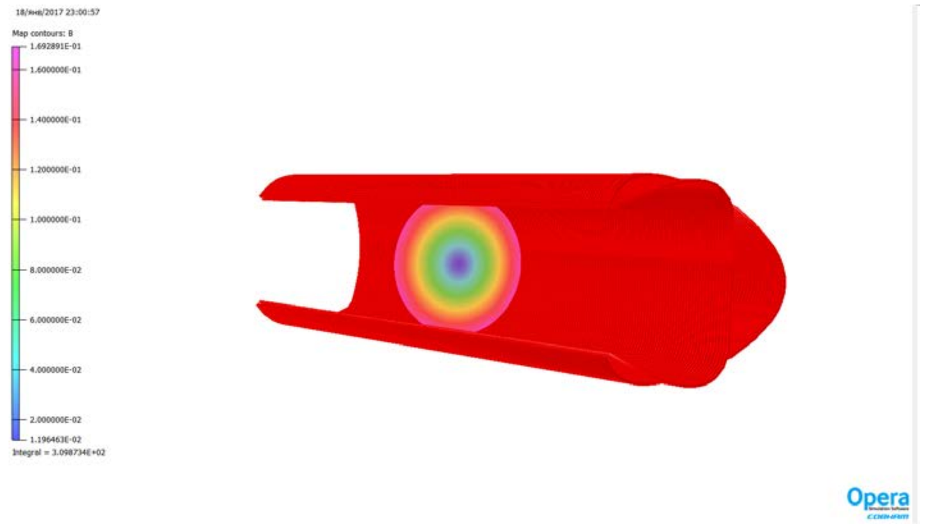
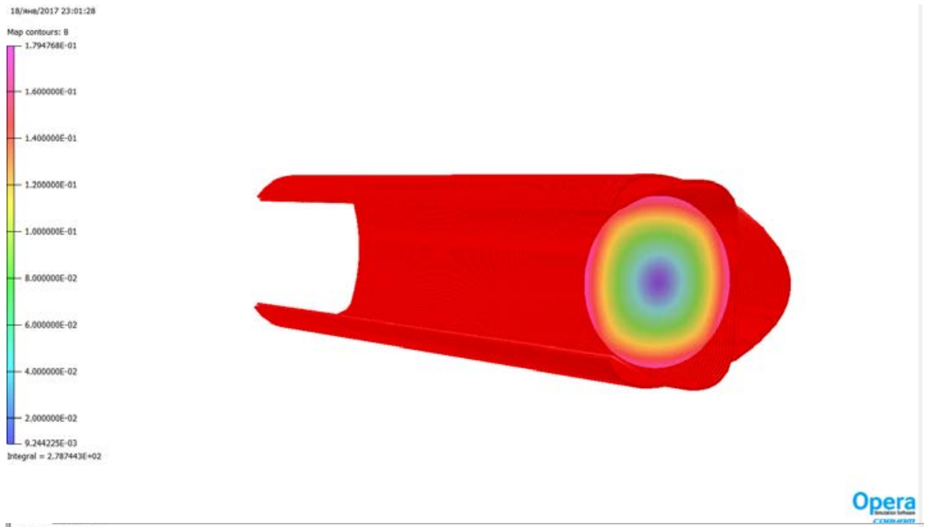
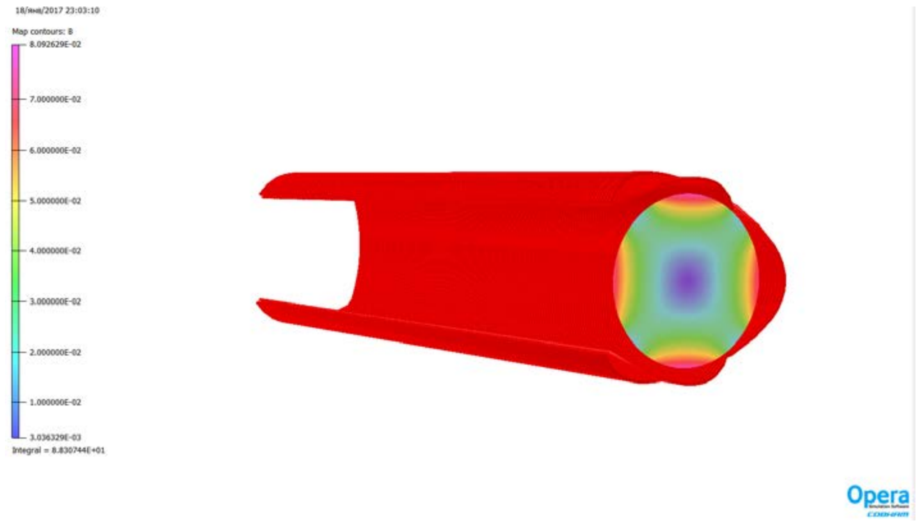
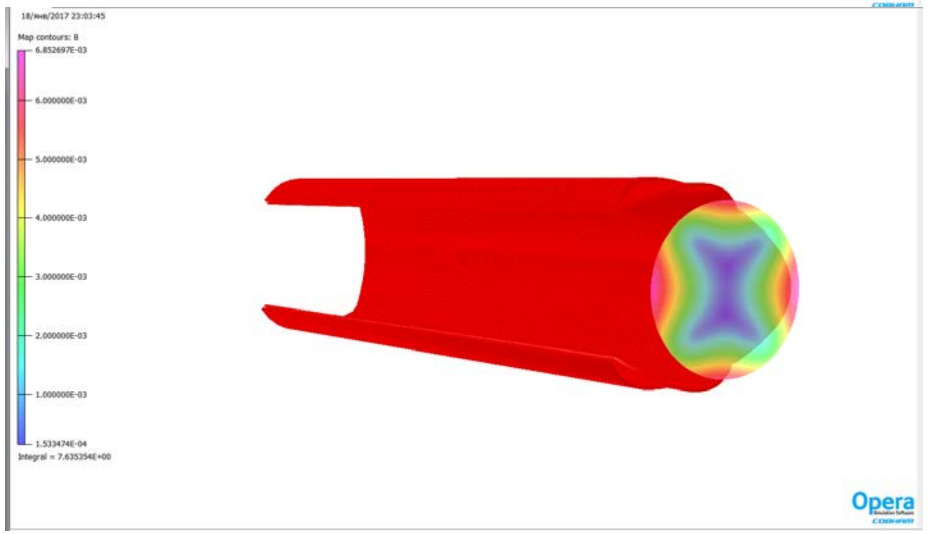
Double helix qudrupole









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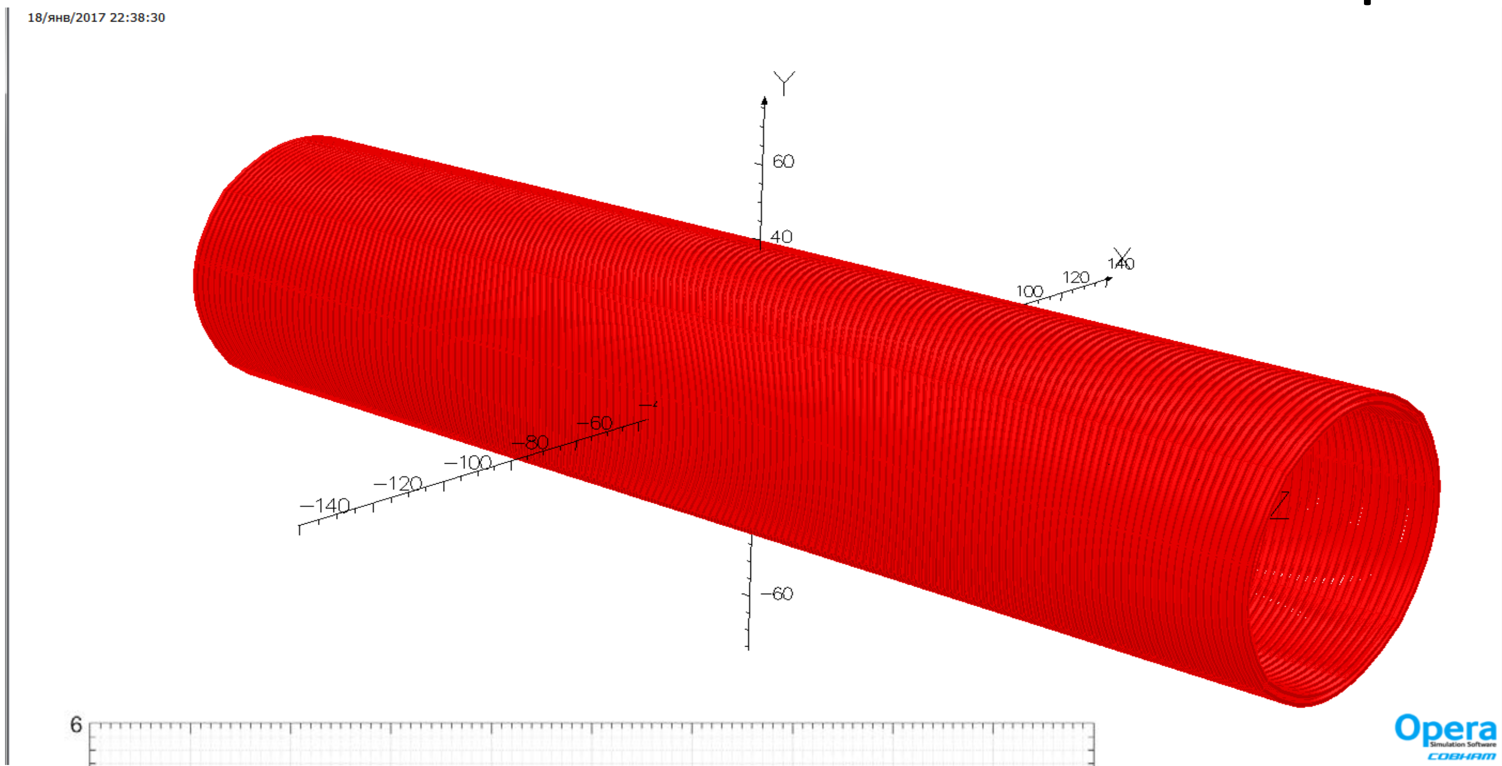
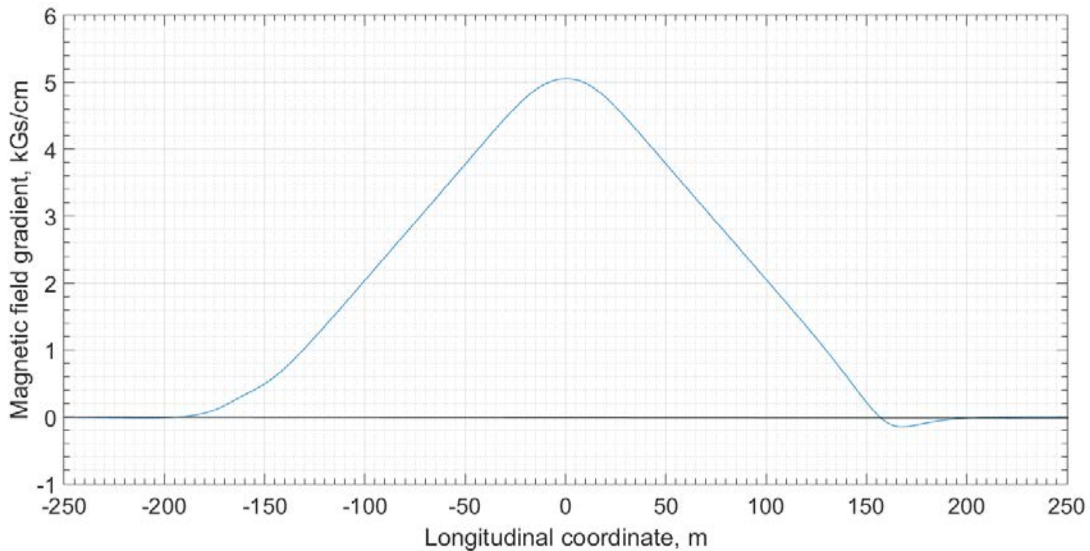
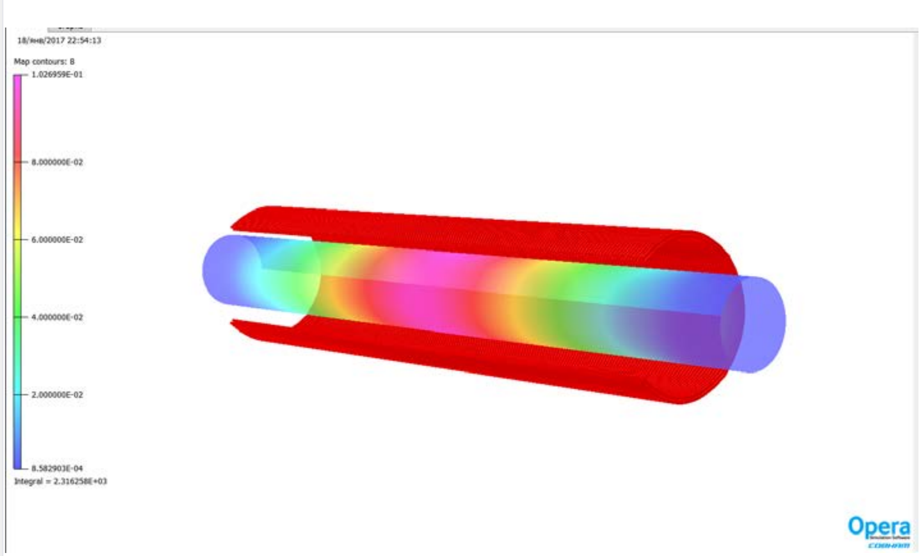
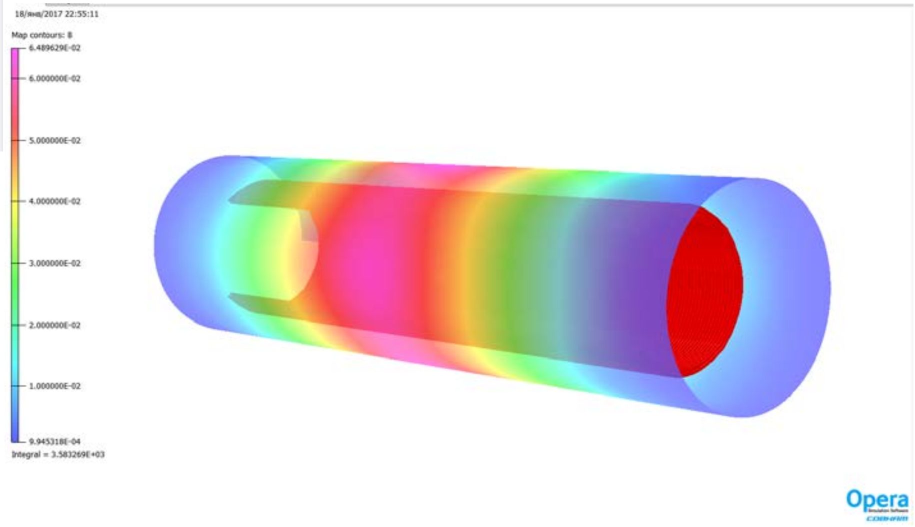
Double helix qudrupole









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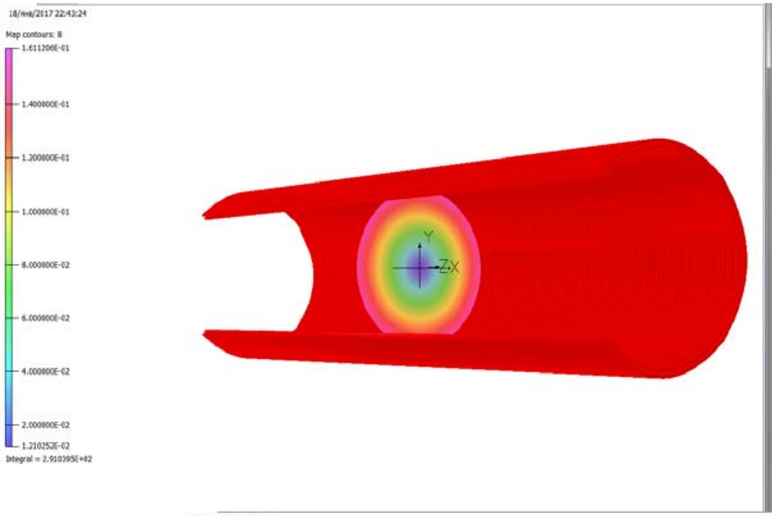
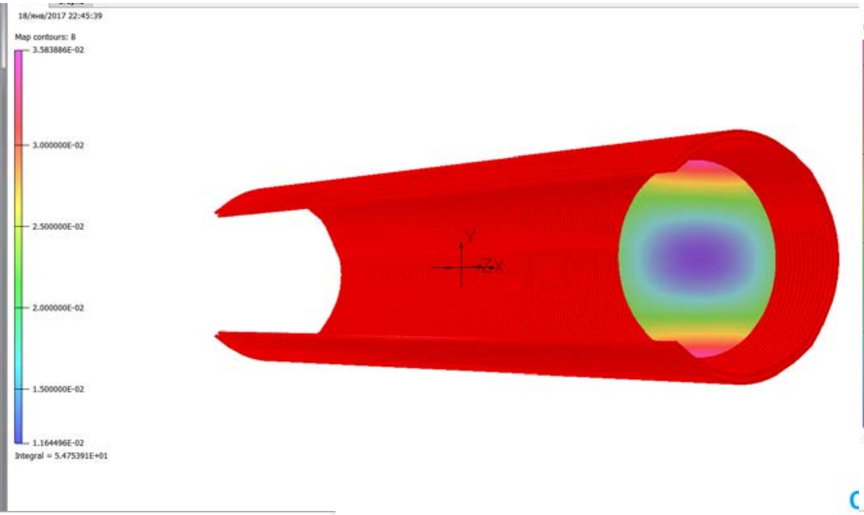
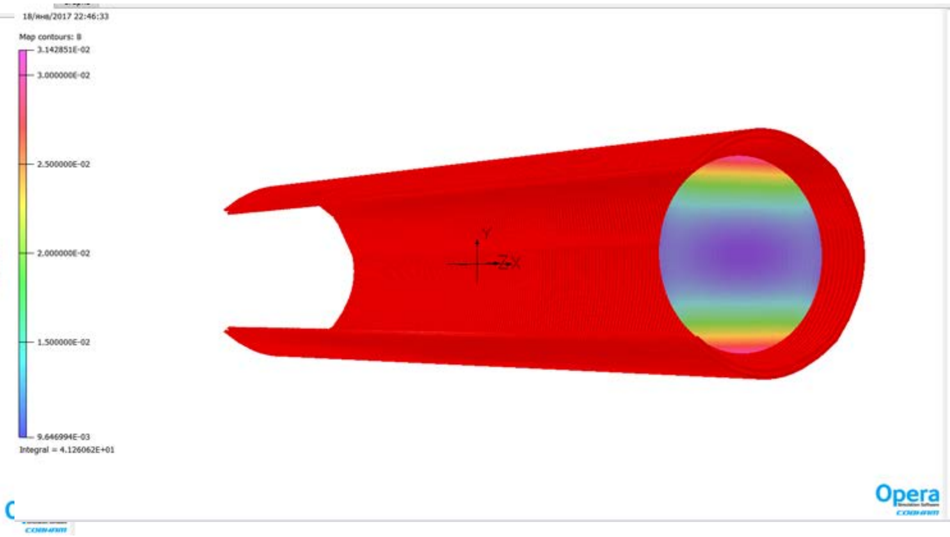
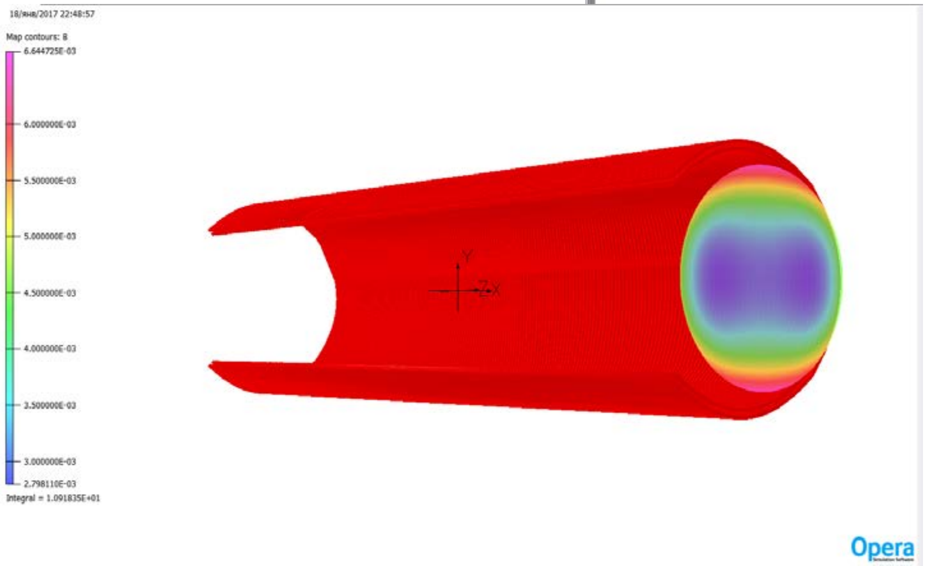
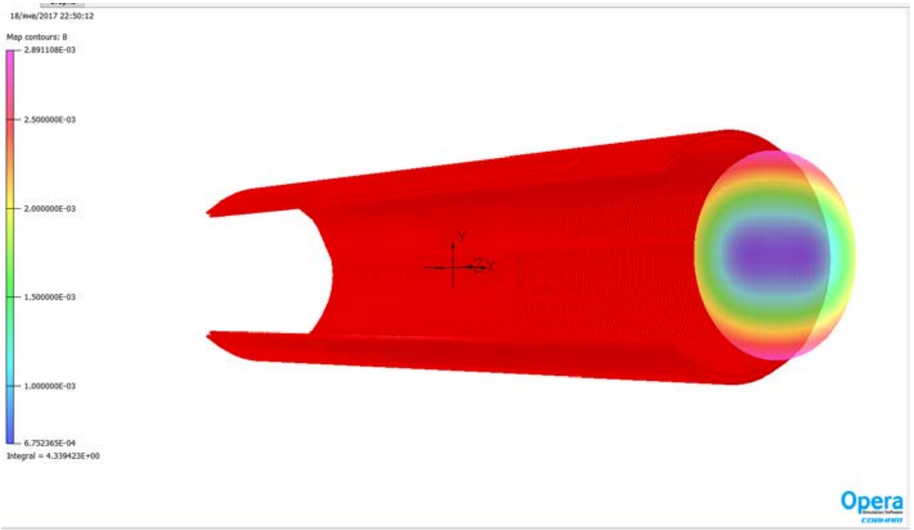
Double helix qudrupole

A. Starostenko, T. Rybitskaya

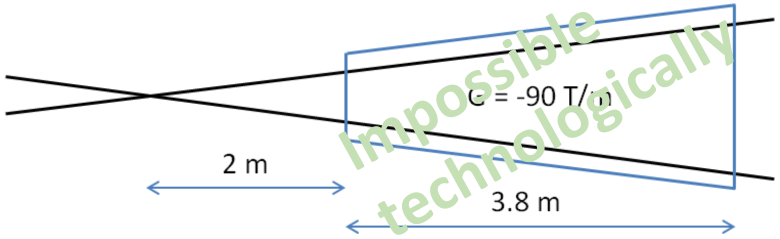
Summary

- The Panovsky quadrupole compact and provides gradient 100 - 150 T/m for 26mm aperture . Gradient limited only by the maximum critical current of the conductor and steel properties.
- Cosine theta quadrupole requires shielding and has a relatively large size. It is possible to add a multipole all components. Gradient limited only by the maximum critical current of the conductor. Gradient 200 T/m is reachable for 40 mm aperture
- Double helix quadrupole compact with compared to cosine theta quadrupole . It may be used as double-aperture quadrupole. Also requires an external shielding. Gradient limited only by the maximum critical current of the conductor. 100 T/m for 35 mm aperture with 2 layer coil and ~2600 A current

Thank you for your attention

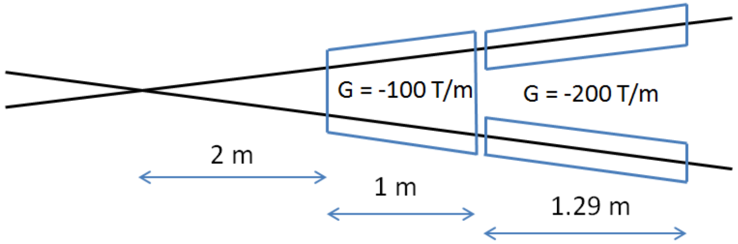
L*, maximum beta and IR chromaticity

$\beta_{ymax} \approx 10$ km



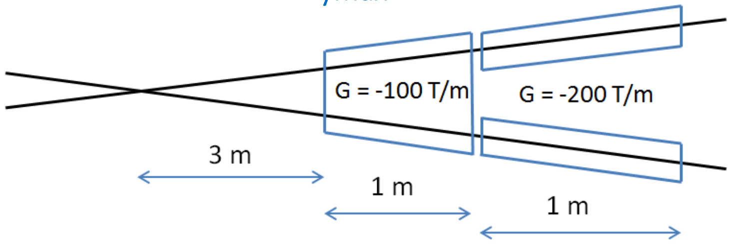
FF chromaticity: ξ_x=-5 ξ_y=-280

$\beta_{ymax} \approx 8$ km



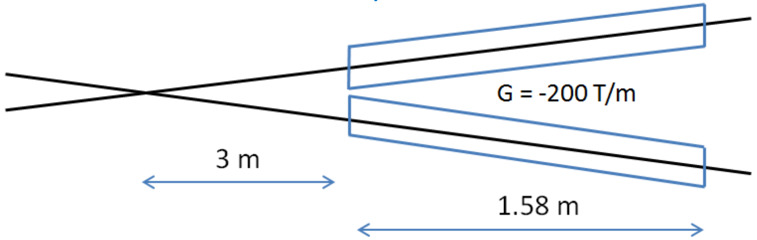
FF chromaticity: ξ_x=-4 ξ_y=-270

$\beta_{ymax} \approx 14$ km



FF chromaticity: ξ_x=-4 ξ_y=-370

$\beta_{ymax} \approx 12$ km

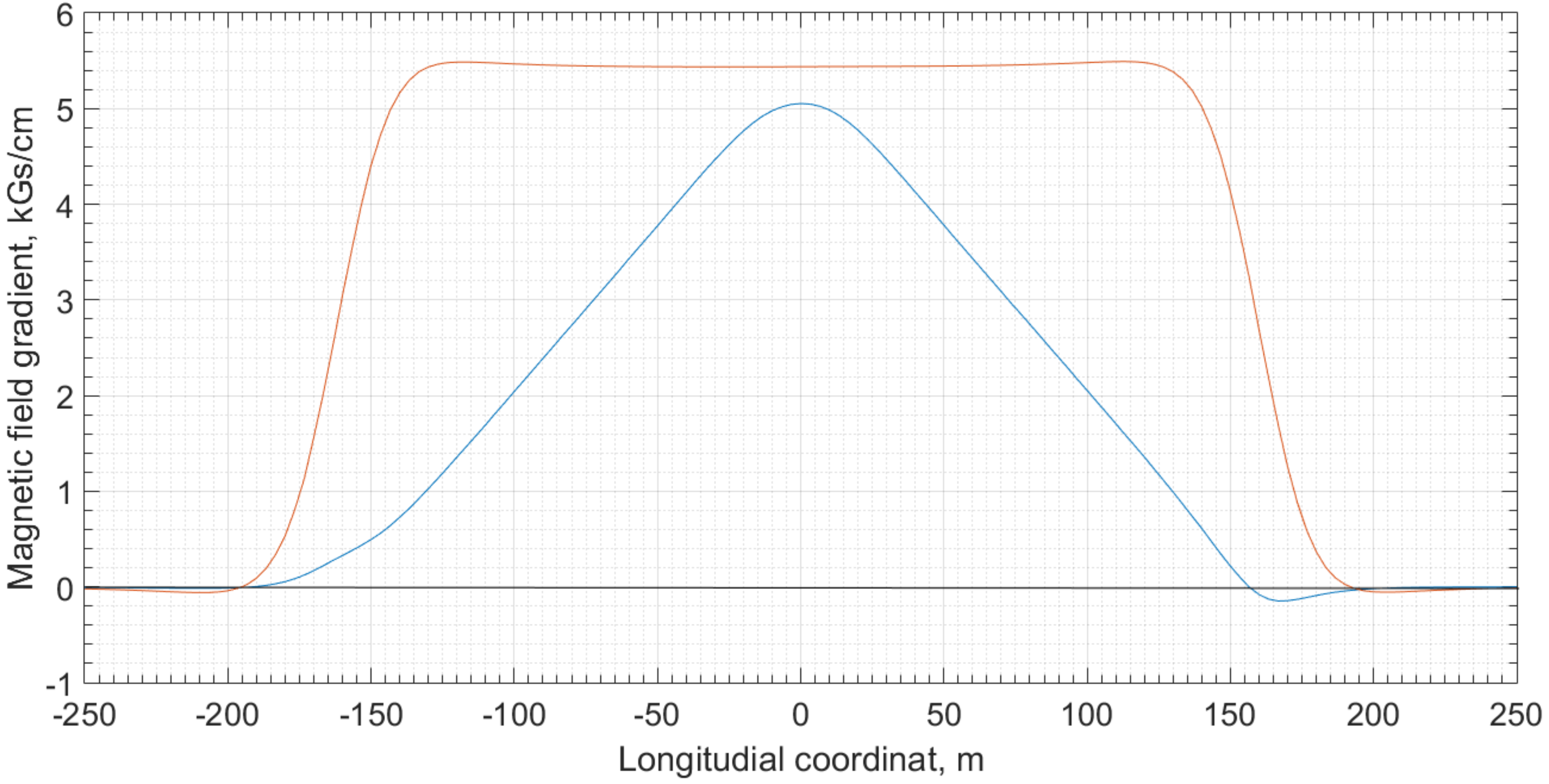


FF chromaticity: ξ_x=-4 ξ_y=-340

Levichev, Sinyatkin,
FCCee review, CERN, March 2016

Difference between [L* = 2 m, QD0 G=100 T/m, ∅26 mm] and [L* = 3 m, QD0 G=200 T/m, ∅40 mm] is not critical for beam dynamics.

Double helix qudrupole, gradient destribution

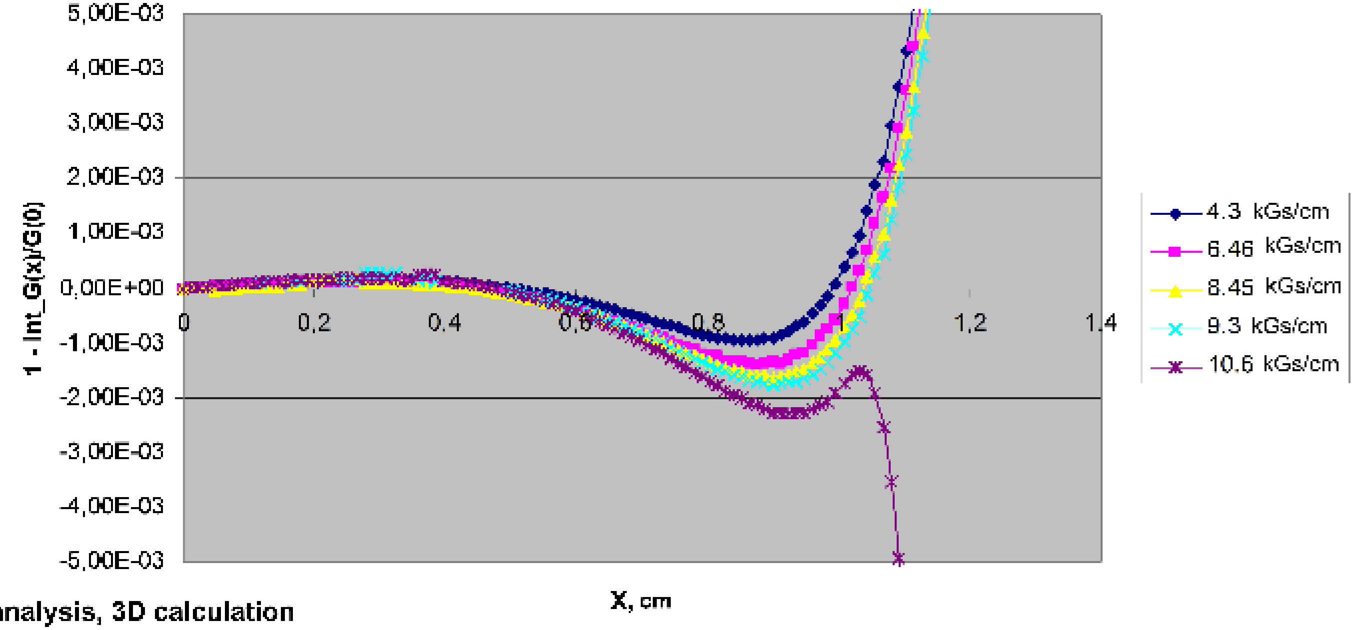


A. Starostenko, T. Rybitskaya

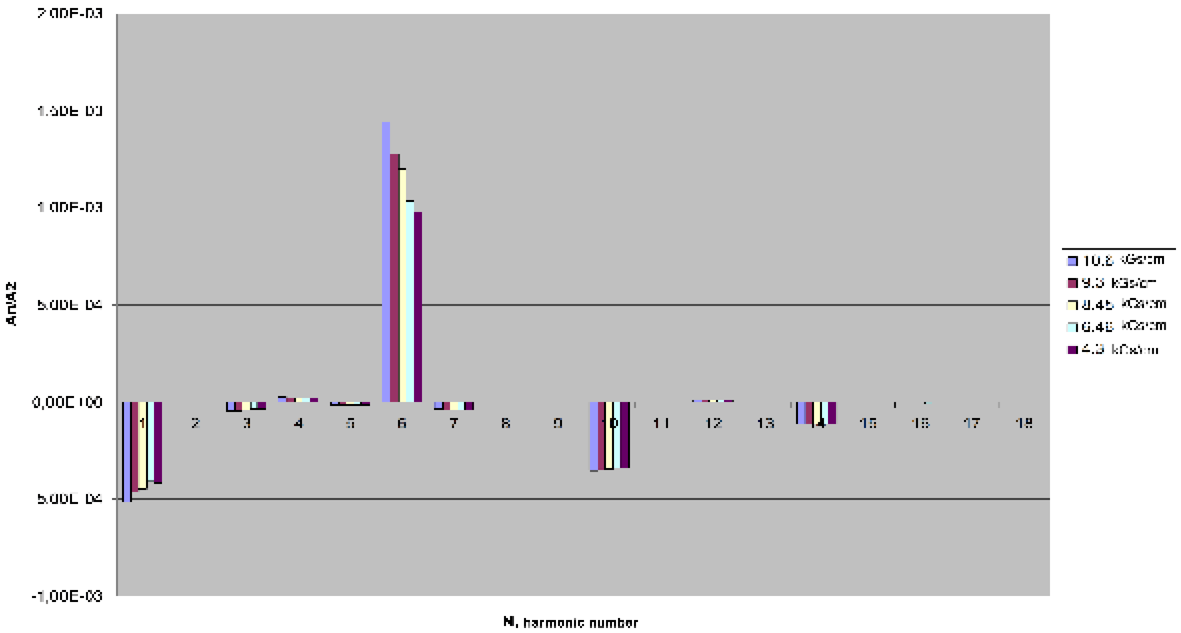
Super C-Tau factory main parameters

Energy	1.0 GeV	1.5 GeV	2.0 GeV	2.5 GeV
Circumference	780 m			
Emittance hor/ver	8 nm/0.04 nm @ 0.5% coupling			
Damping time hor/ver/long	30/30/15 ms			
Bunch length	16 mm	11 mm	10 mm	10 mm
Energy spread	$10.1\cdot10^{-4}$	$9.96\cdot10^{-4}$	$8.44\cdot10^{-4}$	$7.38\cdot10^{-4}$
Momentum compaction	$1.00\cdot10^{-3}$	$1.06\cdot10^{-3}$	$1.06\cdot10^{-3}$	$1.06\cdot10^{-3}$
Synchrotron tune	0.007	0.010	0.009	0.008
RF frequency	508 MHz			
Harmonic number	1300			
Particles in bunch	$7\cdot10^{10}$			
Number of bunches	390 (10% gap)			
Bunch current	4.4 mA			
Total beam current	1.7 A			
Beam-beam parameter	0.15	0.15	0.12	0.095
Luminosity	$0.63\cdot10^{35}$	$0.95\cdot10^{35}$	$1.00\cdot10^{35}$	$1.00\cdot10^{35}$

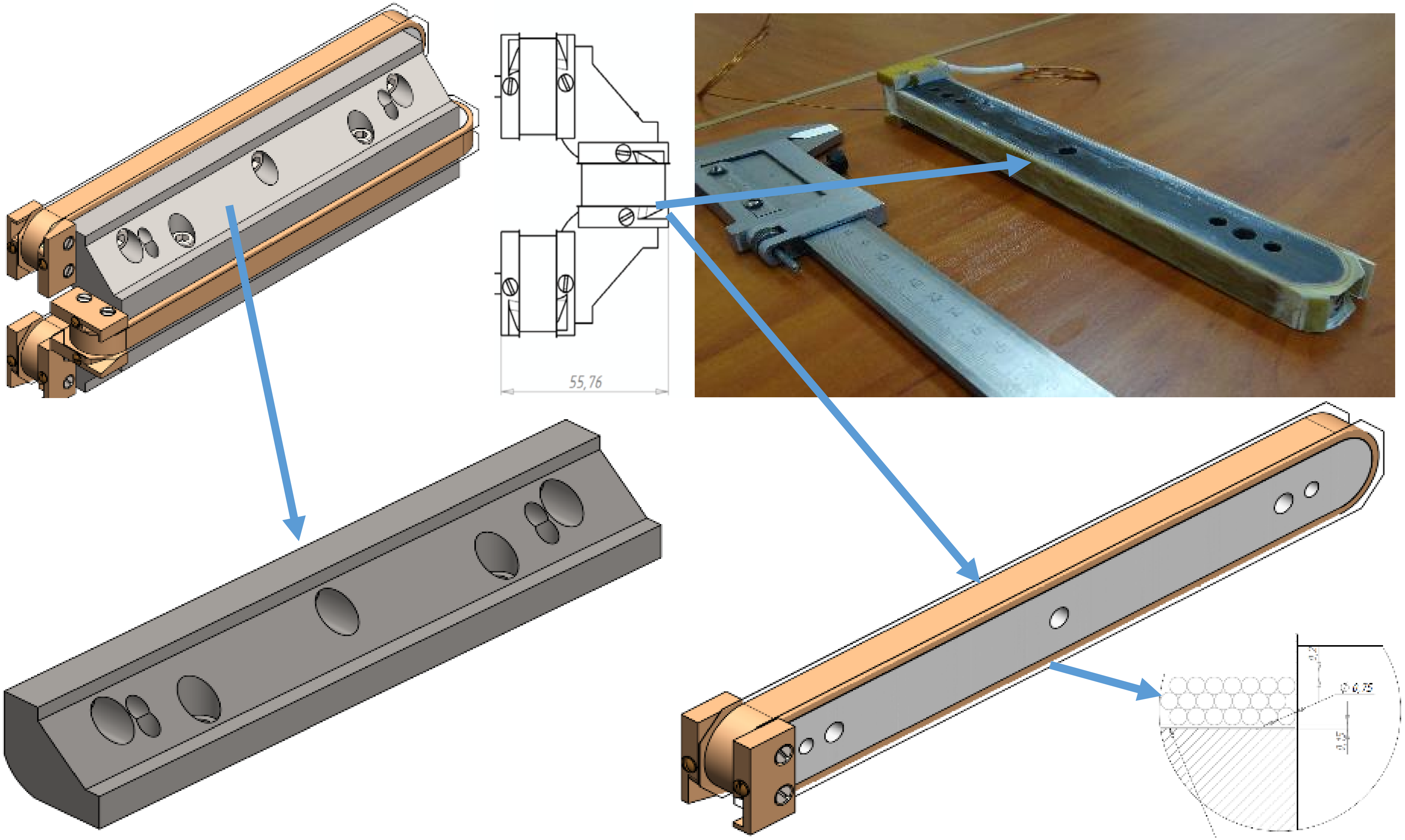
Magnetic gradient integral distribution



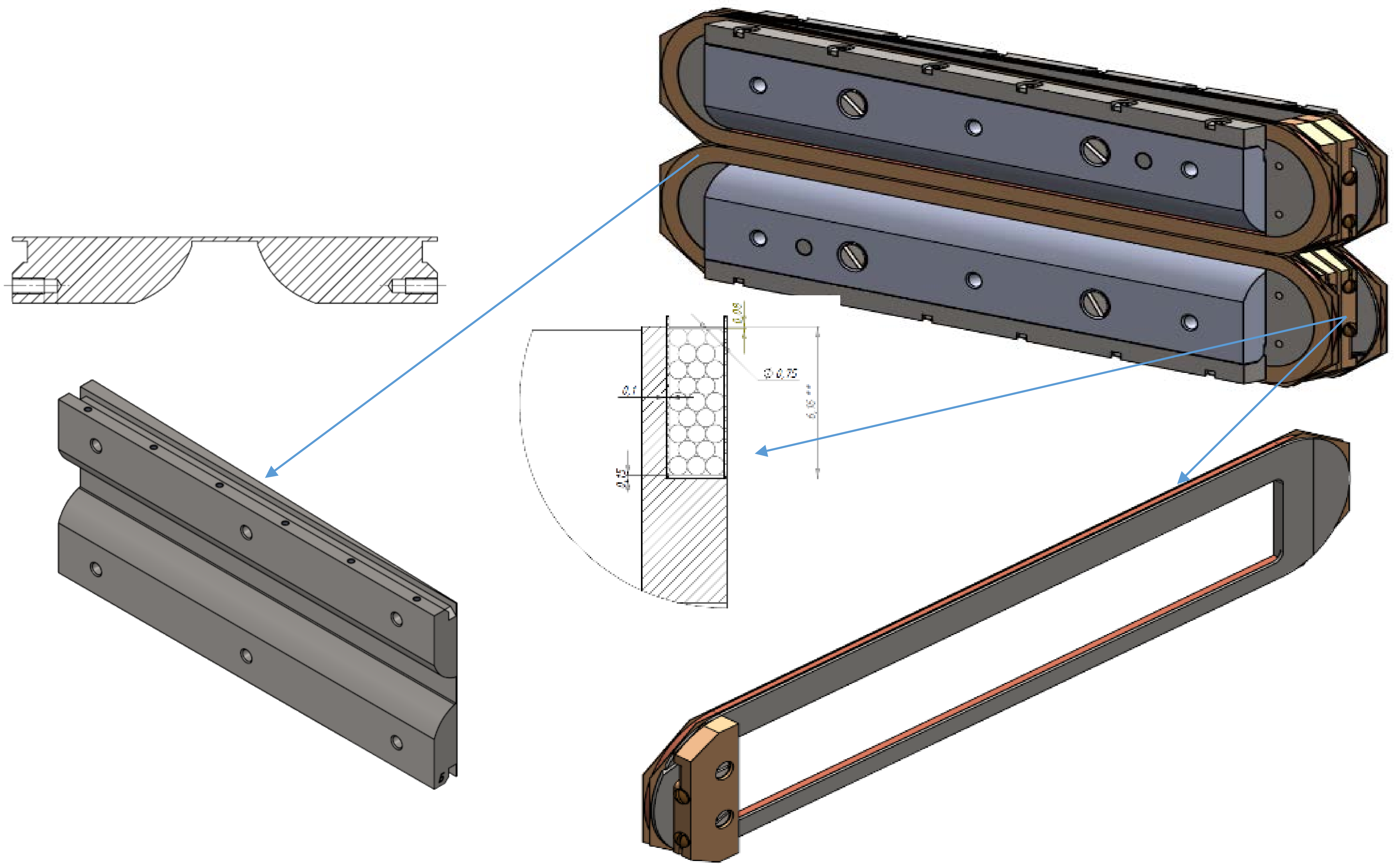
Harmonic analysis, 3D calculation



QD0 design



QD0 design type 2(second coil)



L*, fringe fields, kinematics, etc.

Levichev, Bogomyagkov,
March 2014

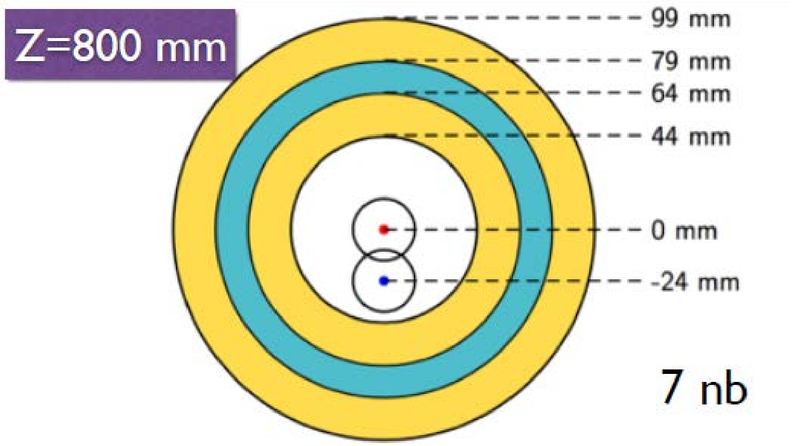
$\beta^* = 1$ mm, $K_1 = 0.16$ m^{-1}, Ls = 0.5 m, $\eta_s = 5$ cm

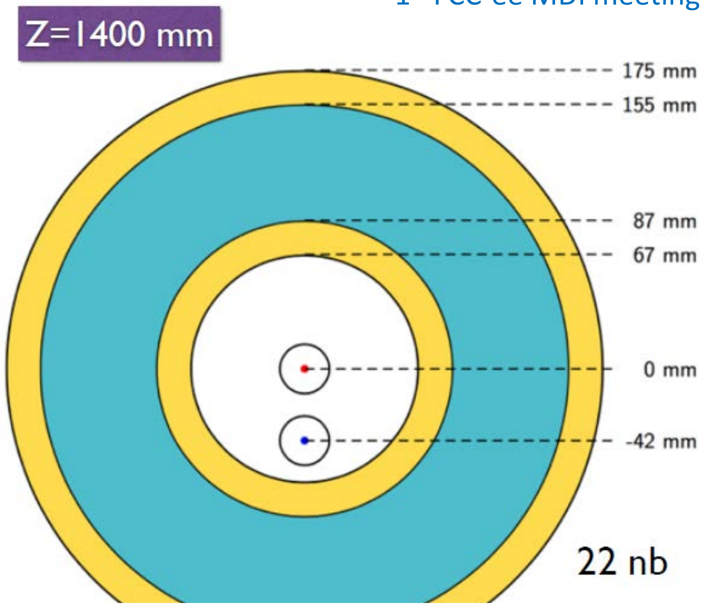
L*(m)	0.7	1	2	3	
$-\xi^*$	1400	2000	4000	6000	
$10^{-6}\,\alpha^k$ (m^{-1})	0.08	0.12	0.24	0.36	$\sim L^*$
$10^{-6}\,\alpha^e$ (m^{-1})	0.004	0.013	0.1	0.34	$\sim L^{*3}$
$10^{-6}\,\alpha^s$ (m^{-1})	-2	-4	-16	-36	$\sim L^{*2}$

Nonlinearity of the FF quadrupoles fringe field increases fast with L*. Up to L* = 3 m it is still not a problem because the chromatic sextupoles prevail, but further increase of L* can be dangerous.

L* and luminometer

Mogens Dam, Feb 29 2016
1st FCC-ee MDI meeting

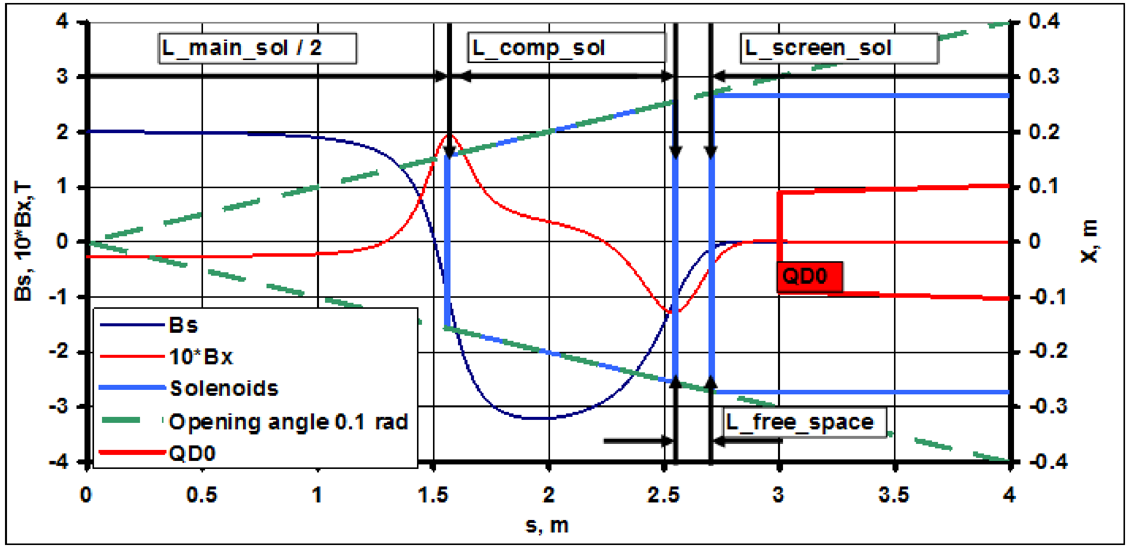


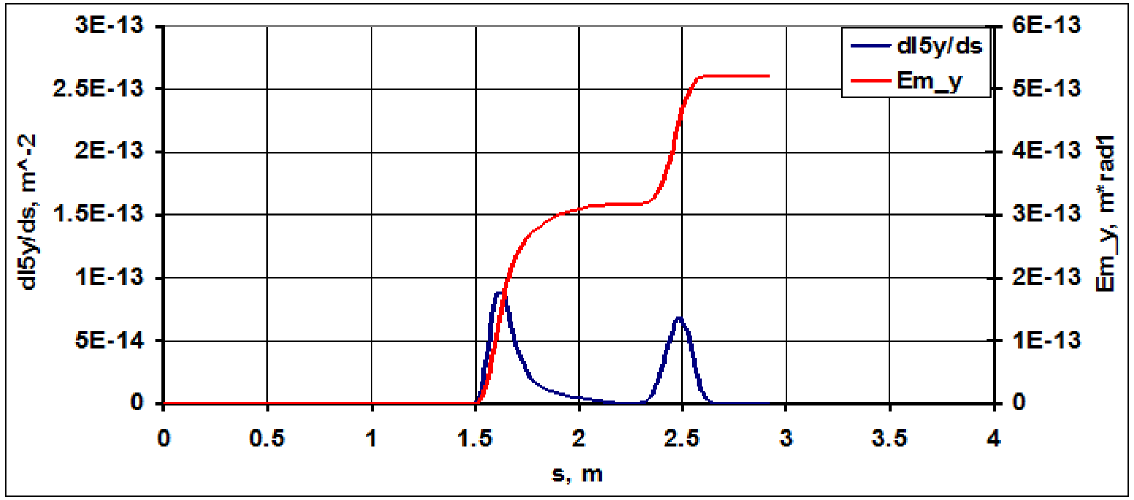


Xing angle	θ_{max}^{global}	Beam-to-tight	Z	r_{min}	r_{max}	cross section	Δr_{min} for $+10^{-4}$	Δz for $+10^{-4}$
mrad	mrad	mm	mm	mm	mm	nb	μm	μm
30	140	45	800	69	80	4.3	-0.9	40
30	140	45	1000	75	105	10.9	-1.8	50
30	140	45	1400	87	155	22.2	-3.0	70
30	140	45	2000	105	230	35.9	-4.2	100

- Clear advantage to have more space
- For baseline, interesting cross sections require z ≥ 1400 mm
  - Lower crossing angle from 30 to 26 mrad: 20 nb reachable at z = 1200 mm

L* and anti-solenoid - I





E = 45 GeV

Main solenoid:

B_s = 2 T

L_{eff_geom}=2*1.56 m

Compensating solenoid:

$|B|_{s\_max\_eff}$ = 3.2 T

L_{geom}= 1 m

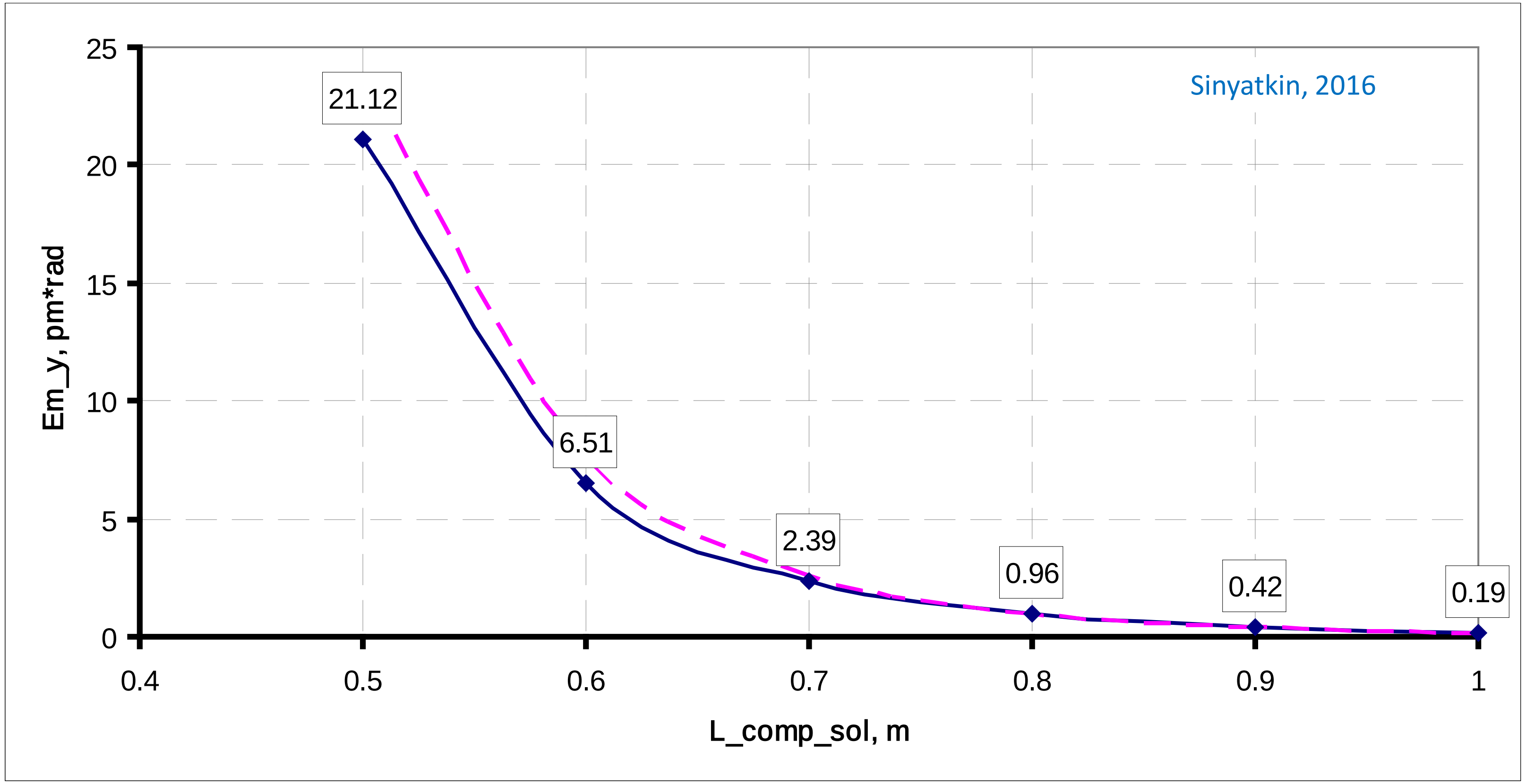
e_y = 0.5 pm*rad

Sinyatkin, 2015

Dam's requirement for z ≥ 1400 mm is satisfied with L* ≥ 3 m. The corresponding anti-solenoid increases the vertical emittance by $\Delta\varepsilon_y$ = 0.5 pm.

L* and anti-solenoid - II

L* reduction and keeping the same z for the luminometer shortens the anti-solenoid length and increases its field which, in turn, increases greatly the vertical emittance because $\Delta\varepsilon_y \sim B^5$



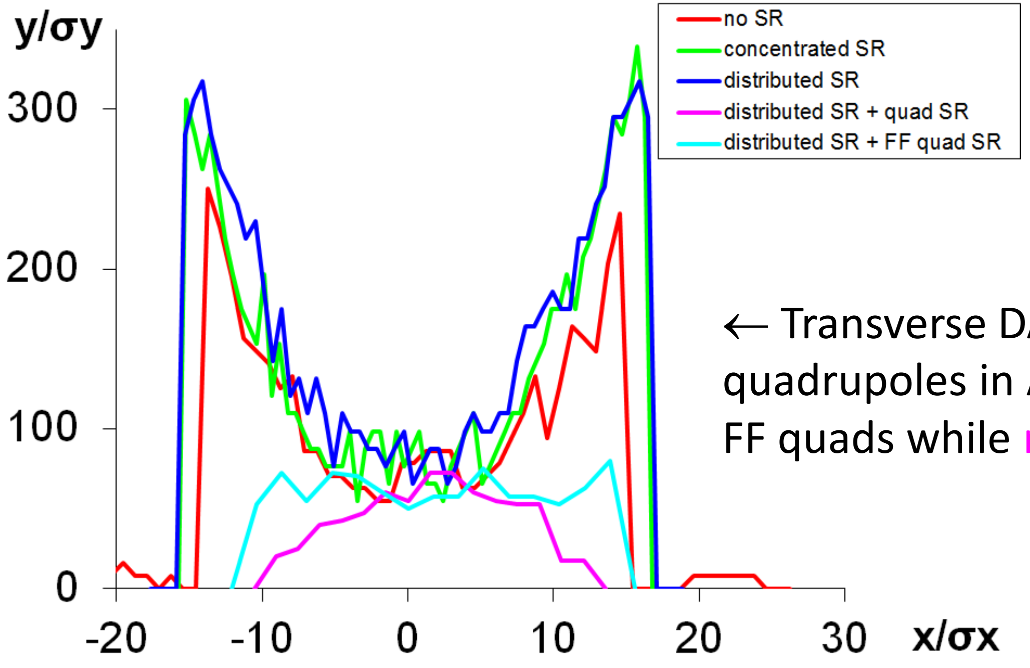
SR from FF quadrupoles and DA reduction

SR power loss estimation from quadrupole (Oide, Bogomyagkov)

$$P_Q \propto \frac{(K_1 L_Q)^2 y^2}{L_Q}$$ For QD0 $$y^2 = n^2 \sigma_y^2 \approx n^2 \varepsilon_y \frac{\left(L^* + L_Q/2\right)^2}{\beta_{0y}}$$ $$K_1 L_Q \approx -\frac{2}{L^* + L_Q/2}$$

$$\boxed{P_Q \propto \frac{4n^2 \varepsilon_y}{\beta_{0y} L_Q}}$$

– independent from L* but increases with quadrupole length decrease (for the same integrated gradient)



Particles with large betatron amplitudes make extra energy loss in quadrupoles so their "stable phase angles" change. This effect is important in determining the **transverse** dynamic aperture at LEP2 energies.

John M. Jowett ~1983

← Transverse DA reduction due to the SR from quadrupoles in AB FCC-1. Light blue is for the FF quads while magenta is for all the quads.

S. Glukhov

SR from FF quadrupoles and background

KO symmetrical FF layout:

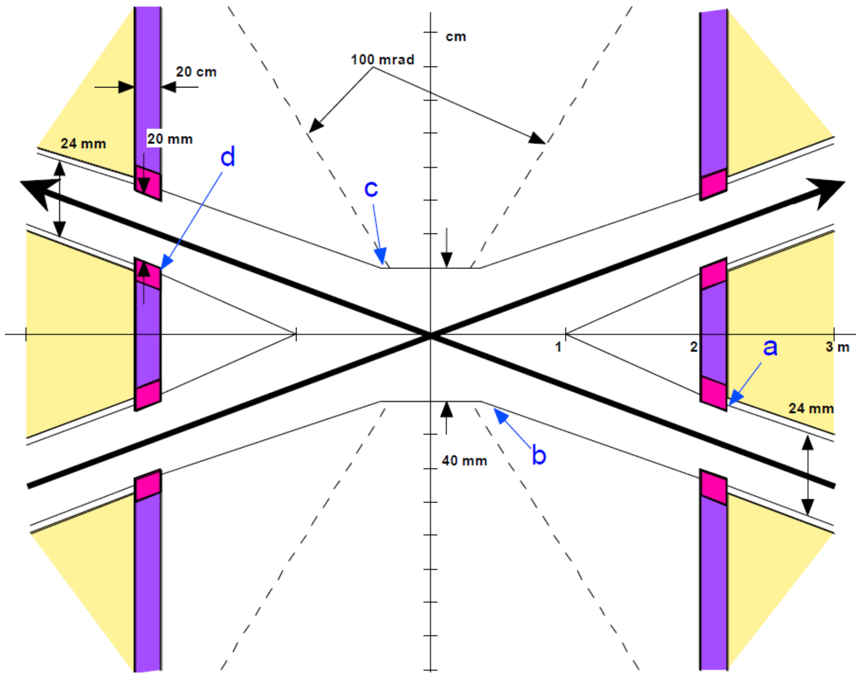
Magnet	L (m)	Z face (m)	G (T/m)
Q1C1	1.6	2.2	97
Q1C2	1.6	3.8	97
Q2C1	1.25	5.7	61.5
Q2C2	1.25	6.95	61.5

- Beam pipe aperture 24 mm dia.
- SR masks 20 mm dia.

Mike's recommendation from simulation of multi-MeV photons hitting the detector vacuum chamber (points b and c) from FF quads and first dipoles:

Sullivan, FCC-ee optical meeting, March 2016

Close up of IP Area



- Size of IP beam pipe is 20 mm radius
  - 15 mm is just OK. There is no margin and no orbit distortions

→ At least one of the quadrupole beam pipes also should have 20 mm radius for the HOM escaping (KO asymmetrical layout).

QD0 design, second edition

obtain the two-aperture lens we need to join on the right side exactly the same lens.