Experience of magnetic simulations with MERMAID 3D at Duke FEL Lab

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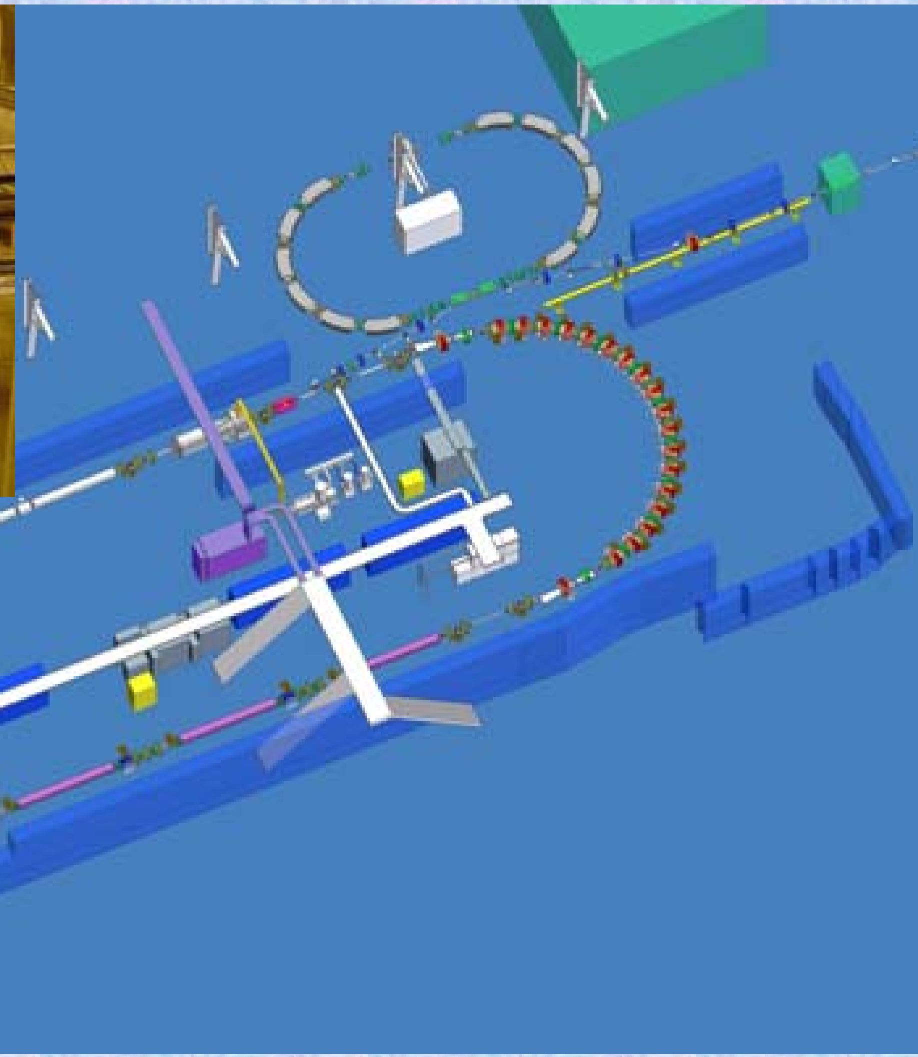
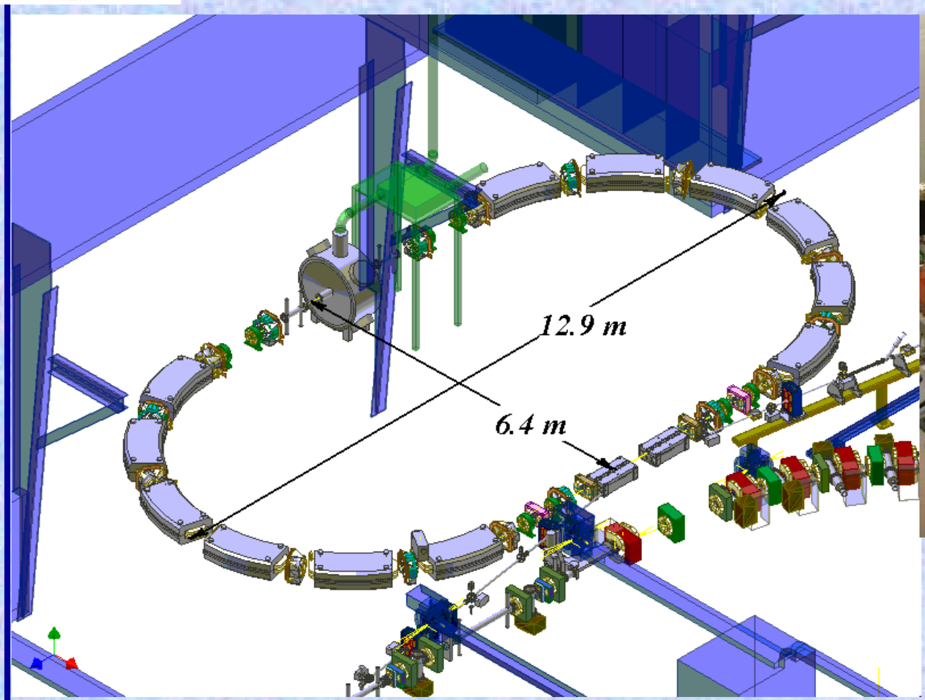
Duke 1.2 GeV storage ring and booster

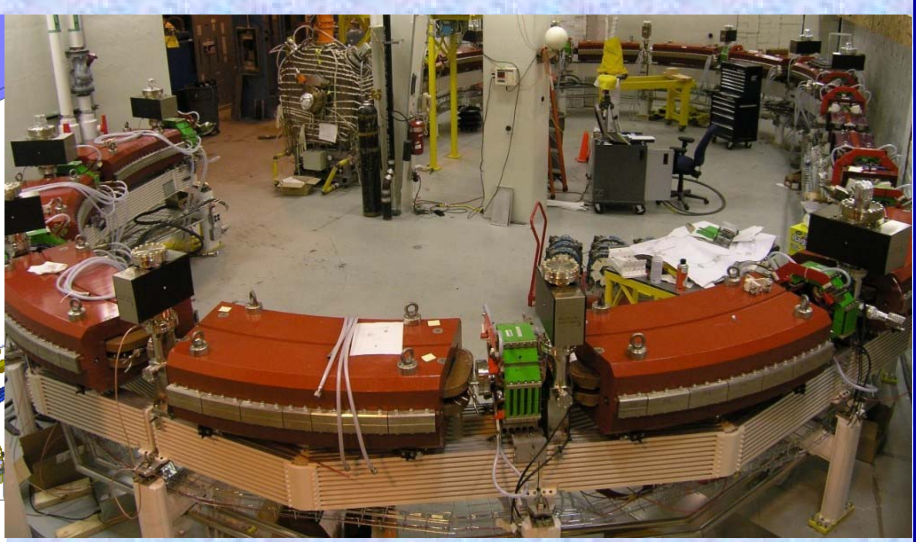


Parameters of the Duke FEL ring

Maximum beam energy E_{max} [GeV]	1.2
Injection energy E_{inj} [GeV]	0.27
Stored beam current [mA]	
- in single bunch	15-20
- In multibunch	300
Circumference [m]	107.46
Bending radius [m]	2.1
RF frequency [MHz]	178.55
Harmonic number	64
@ E_{max} = 1.0 GeV:	
Beam emittance ε_x	18
Betatron tunes Q_x/ Q_y	9.11 / 4.18
Momentum compaction factor	0.0086
Natural chromaticities C_x/ C_y	-10.0 / -9.8
Damping times $\tau_{x,y}$/ τ_s [ms]	18.3 / 17.0
Energy loss per turn [KeV]	42
Energy spread	$5.8 \cdot 10^{-4}$

Layout of the booster





Design layout

August 2002

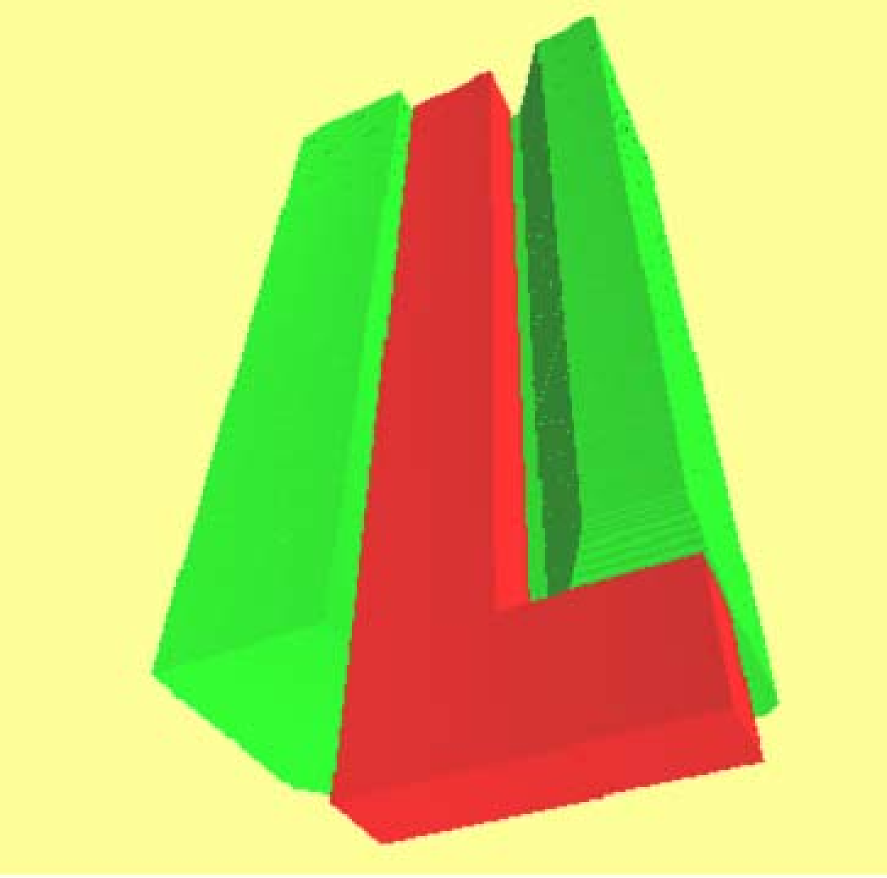
Installation site

May 2005

Parameters of the booster

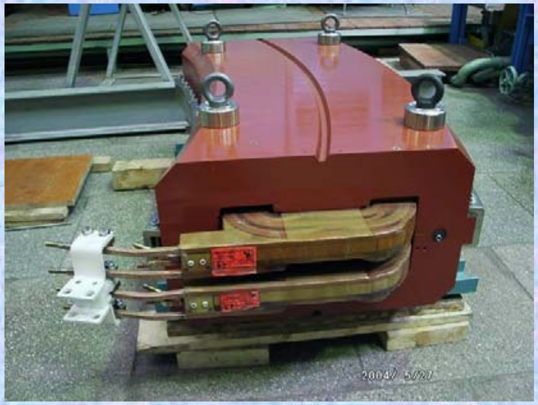
<table>
<tr><th></th><th>Single bunch</th><th>Multibunch</th></tr>
<tr><td>Maximum beam energy E_{max} [GeV]</td><td colspan="2">1.2</td></tr>
<tr><td>Injection energy E_{inj} [GeV]</td><td colspan="2">0.27</td></tr>
<tr><td>Stored beam current [mA]</td><td>1.5 - 2</td><td>100</td></tr>
<tr><td>Circumference [m]</td><td colspan="2">31.902</td></tr>
<tr><td>Bending radius [m]</td><td colspan="2">2.273</td></tr>
<tr><td>RF frequency [MHz]</td><td colspan="2">178.55</td></tr>
<tr><td>Harmonic number</td><td colspan="2">19</td></tr>
<tr><td>Operation cycle [sec]</td><td>1.2</td><td>2.5</td></tr>
<tr><td>Energy rise rate [sec]</td><td colspan="2">0.55</td></tr>
<tr><td colspan="3">@ E_{max} = 1.2 GeV:</td></tr>
<tr><td>Beam emittance ε_x, ε_y</td><td colspan="2">350 / 15</td></tr>
<tr><td>Betatron tunes Q_x / Q_y</td><td colspan="2">2.43 / 0.46</td></tr>
<tr><td>Momentum compaction factor</td><td colspan="2">0.153</td></tr>
<tr><td>Maximum $\beta_x / \beta_y / \eta_x$ [m]</td><td colspan="2">9.4 / 25.4 / 1.4</td></tr>
<tr><td>Natural chromaticities C_x / C_y</td><td colspan="2">-1.7 / -3.7</td></tr>
<tr><td>Damping times $\tau_{x,y} / \tau_s$ [ms]</td><td colspan="2">3.16 / 1.58</td></tr>
<tr><td>Energy loss per turn [KeV]</td><td colspan="2">80.7</td></tr>
<tr><td>Energy spread</td><td colspan="2">$6.8 \cdot 10^{-4}$</td></tr>
</table>

3D magnetic simulations of the booster bending magnet

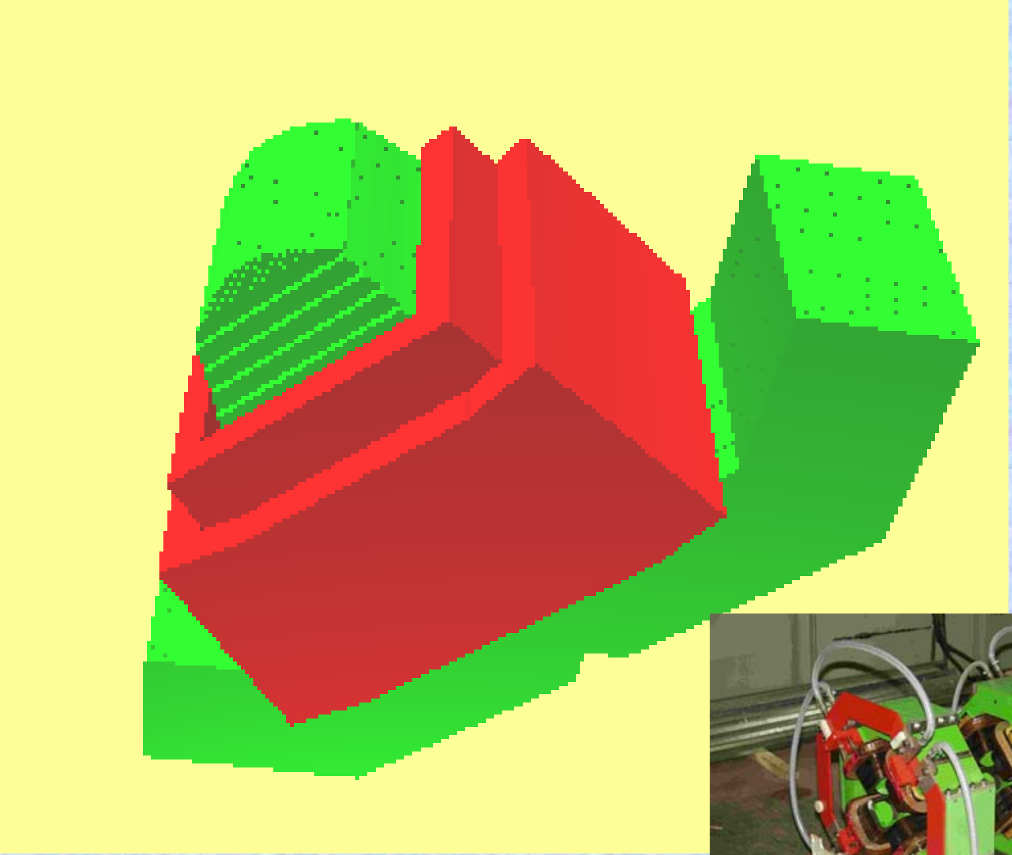


Magnetic simulations by MERMAID 3D

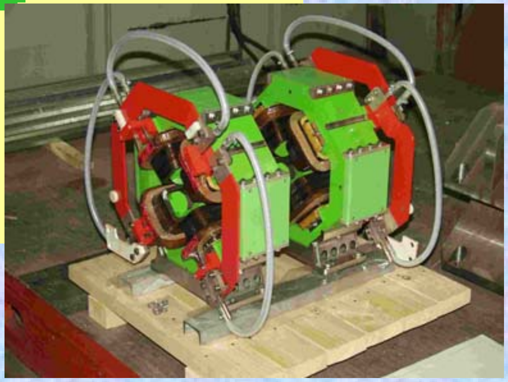
- One quadrant
- 166×151×151 mesh size
- Stacking factor = 0.980
- E [GeV] =
  0.270, 0.385, 0.500,
  0.625, 0.750, 0.850,
  0,950, 1.000, 1.050,
  1.100, 1.150, 1.200



3D magnetic simulations of the booster quadrupole magnets

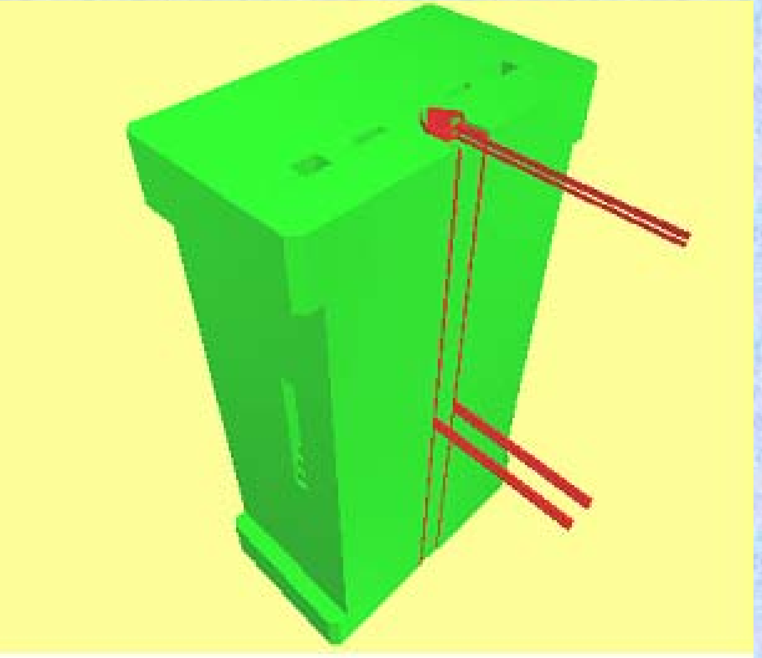


- One quadrant
- 3 types of quadrupole: QF1, QF2 and QD
- 151×201×201 mesh size
- Stacking factor = 0.98
- E [GeV] =
  0.270, 0.385, 0.500, 0.625, 0.750, 0.850, 0,950, 1.000, 1.050, 1.100, 1.150, 1.200

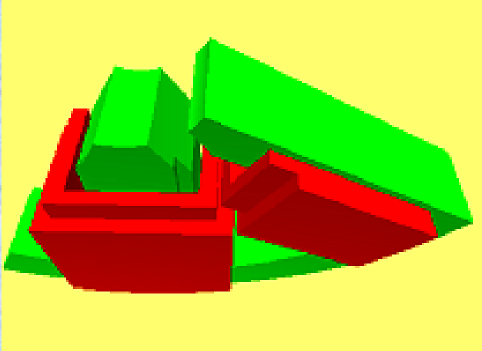


Magnetic simulations by MERMAID 3D

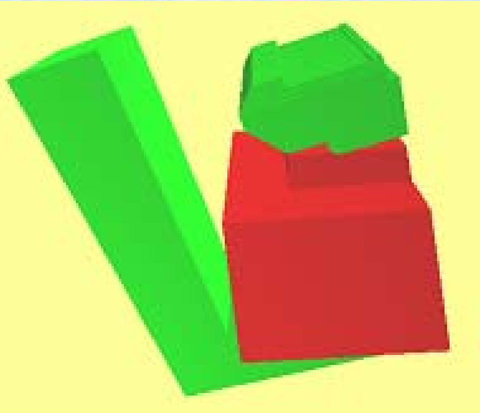
3D magnetic simulations of other elements



- Septum magnet



- Sextupole

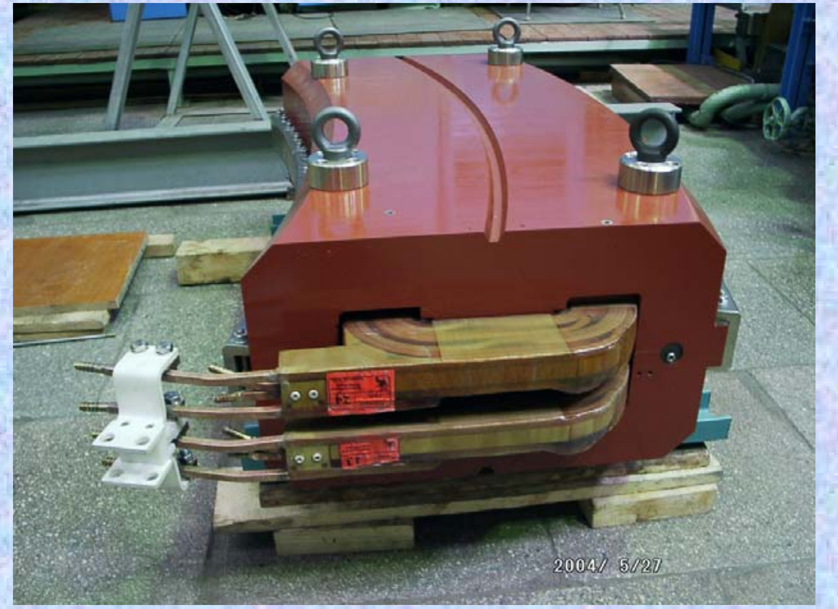


- Y-orbit trim

Magnetic simulations by MERMAID 3D

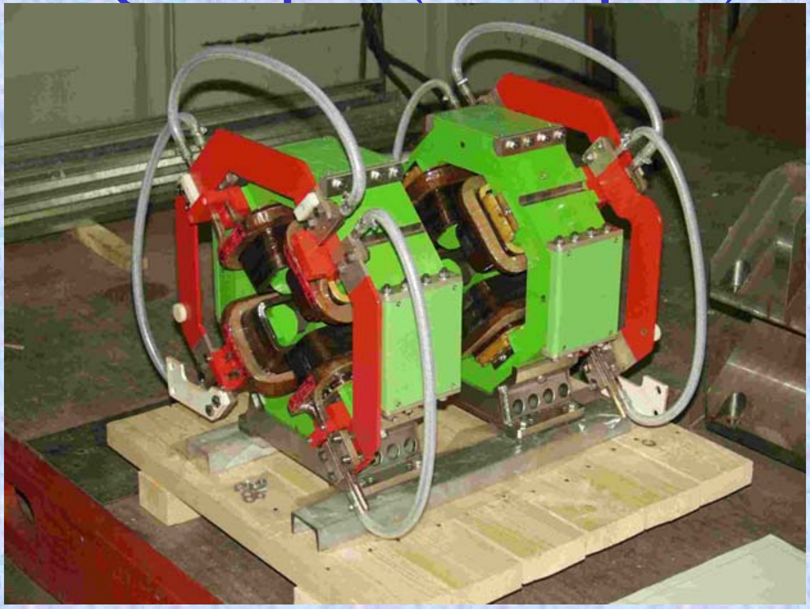
Booster magnetic system

Dipoles (12 + 1 spare)



- Maximum field 1.76 T
- Maximum current [A] 700 A
- Number of turns 2×28
- Gap 2.7 cm
- Radius of curvature 2.273 m
- Effective magnetic length 1.190 m
- 2% dipole trim coil (X-orbit trim):
- Number of turns 2×34
- Maximum current 12 A

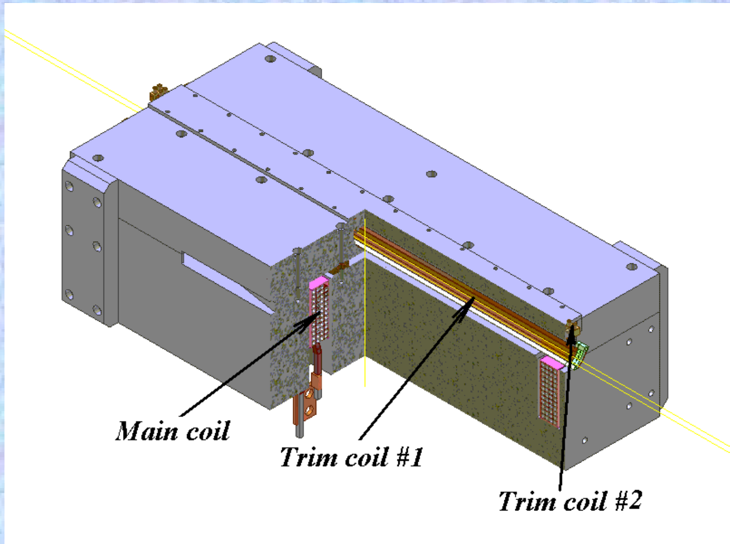
Quadrupoles (16 + 2 spares)



- Aperture (inscribed diameter) 5.0 cm
- Maximum current 700 A
- Maximum trim current for Y & Q trims 6 A
- Number of trim turns per quadrant:
- Y-orbit trim 116
- Q trim 40
- Maximum strength of the trims @ E=1.2 GeV :
- Y trim: Y'_{max} 1 mrad
- Q trim: $\Delta G/G$ 3.3 %

Booster magnetic system

Septum magnets (2)

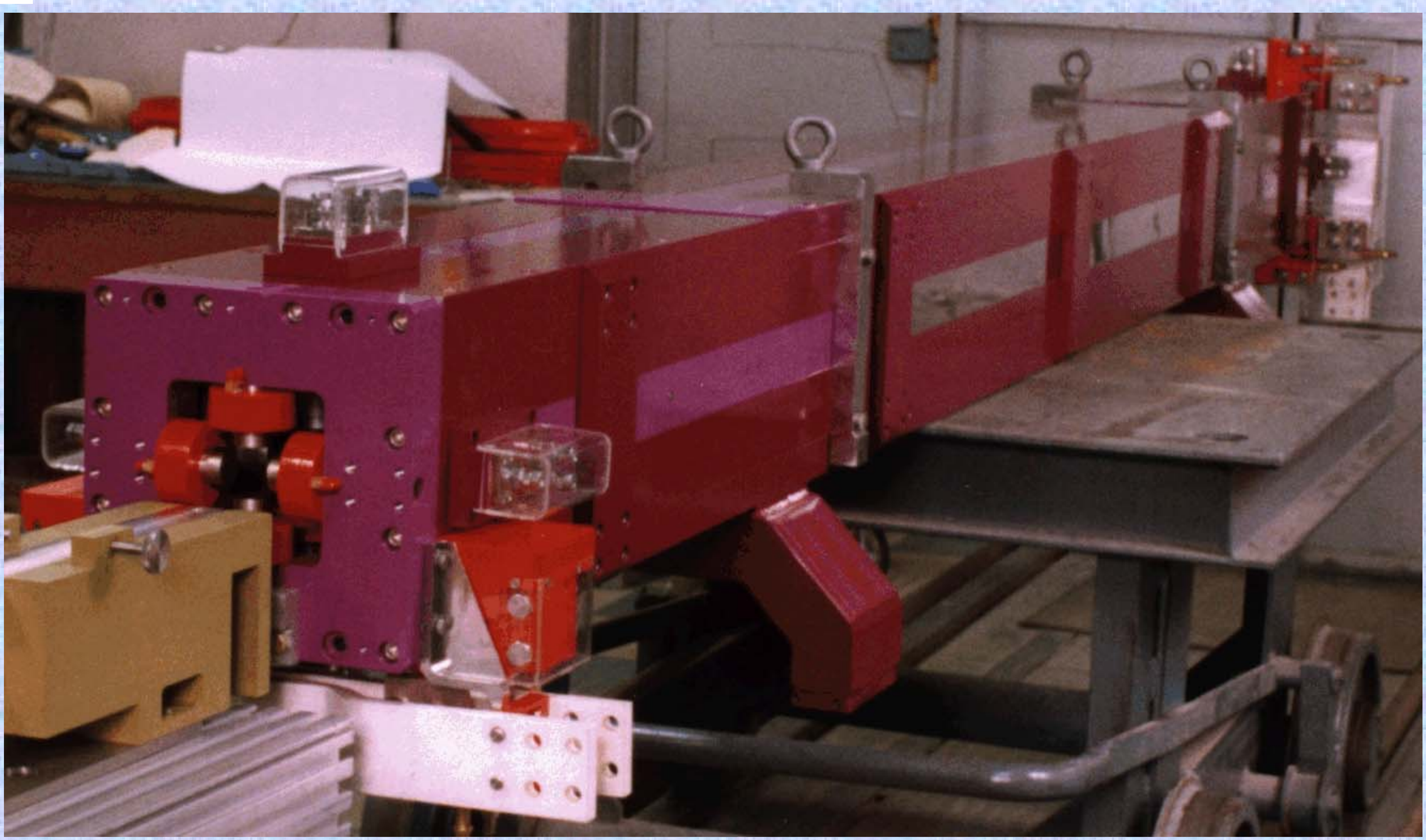


Sextupoles (8)

Maximum bending field	1.00 T
Maximum current	175 A
Number of turns	48
Gap	1.0 cm
Bending angle	9.0°
Effective magnetic length	0.642 m
Width of "knife"	2 mm
Corrected field integral in zero chamber	<50 G*cm
Corrected gradient integral in zero chamber	<40 G

Maximum sextupole strength [B"]	650 T/m^2
Maximum Current	15 A
Aperture (ID)	6.0 cm
Effective Length	0.085 m
# of turns per coil1	40

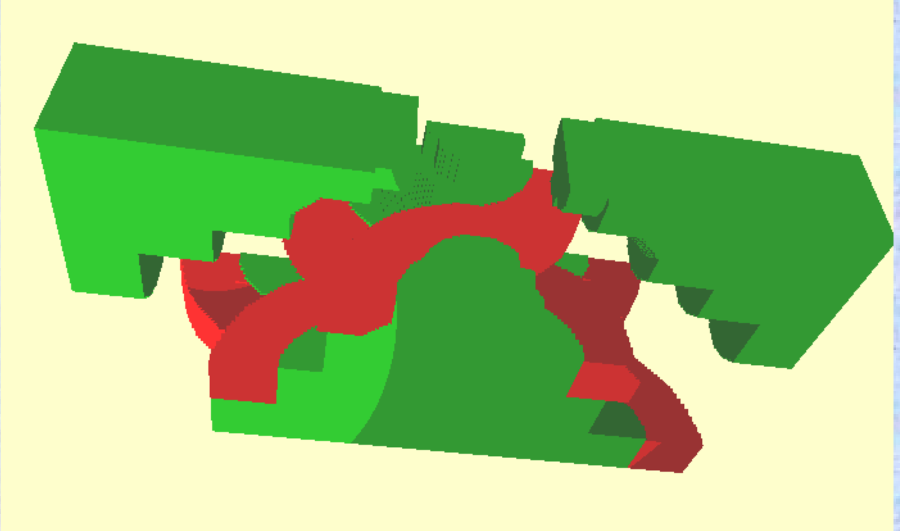
OK-5 FEL wigglers

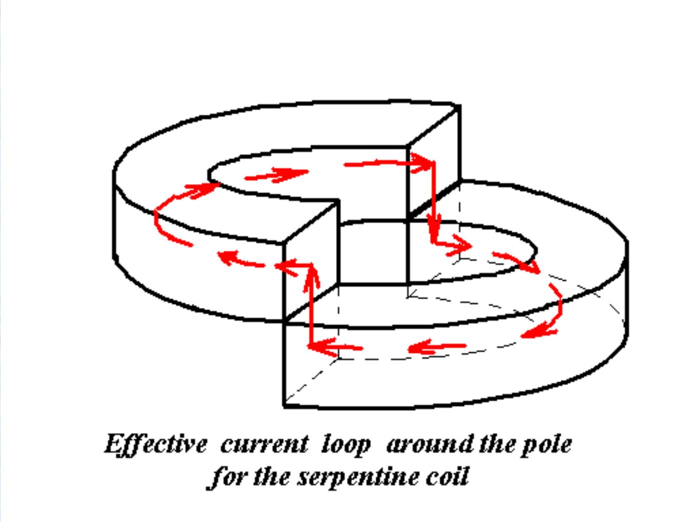


OK-5 FEL wigglers

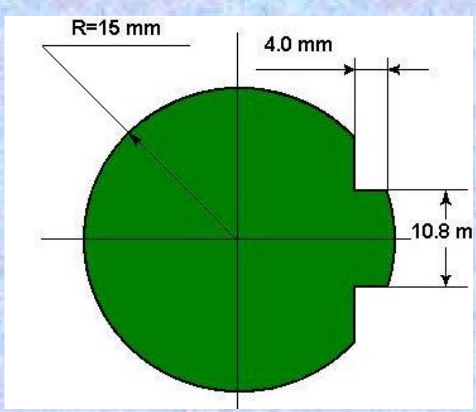
Wiggler period λw, cm	12.0
Wiggler gap (vertical and horizontal), cm	4 × 4
Number of periods (vertical and horizontal)	32
Maximum current [kA]	2 × 3
Maximum field, kG	2.86
Amplitude of fundamental harmonic @ I=2 kA, kG	2.07
Relative value of the 3rd harmonic, %	0.6
Power consumprion [kW]	2×57
Overoll dimensions: -Horizontal (width) [m] -Vertical (height) [m] -longitudinal (length) [m]	0.274 0.324 4.04

OK-5 FEL wigglers





Pole cut compensating intergal gradient and octuppole



Magnetic simulations by MERMAID 3D

OK-5 FEL wigglers

Compensation of asymmetry of the coils

	I=2kA				I=3kA	
	Not cut		With cut		No cut	With cut
	3D calc.	Mag. meas.	3D calc.	Mag. meas.	3D calculations.	
GradientGs/cm	5.64	6.60	-0.21	1.57	8.64	0.22
Octupole G/cm^3	-2.76	-2.70	0.00	-0.32	-4.38	0.03

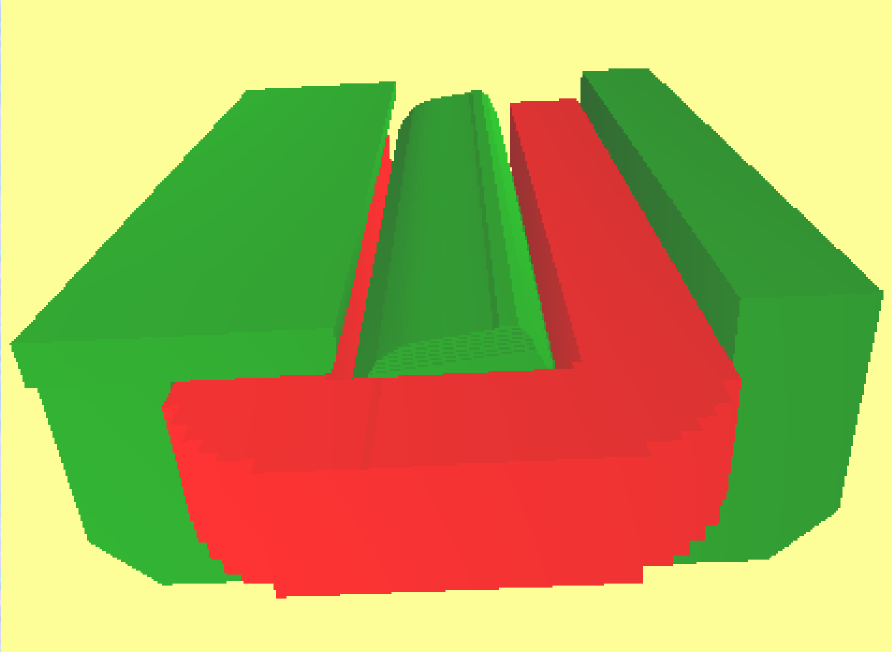
Magnetic simulations by MERMAID 3D

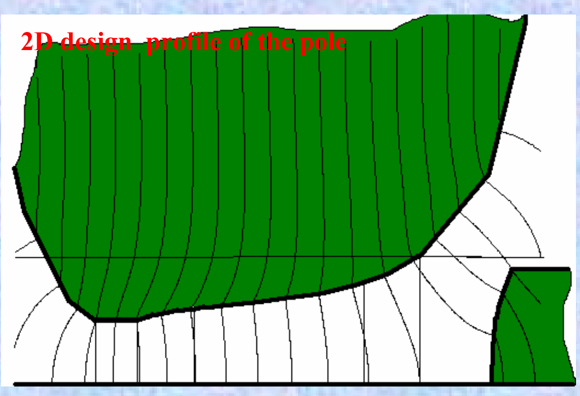
Dipo-Quadro-Sextu-Octupole magnet (DQSO) for low emmitance Duke lattice

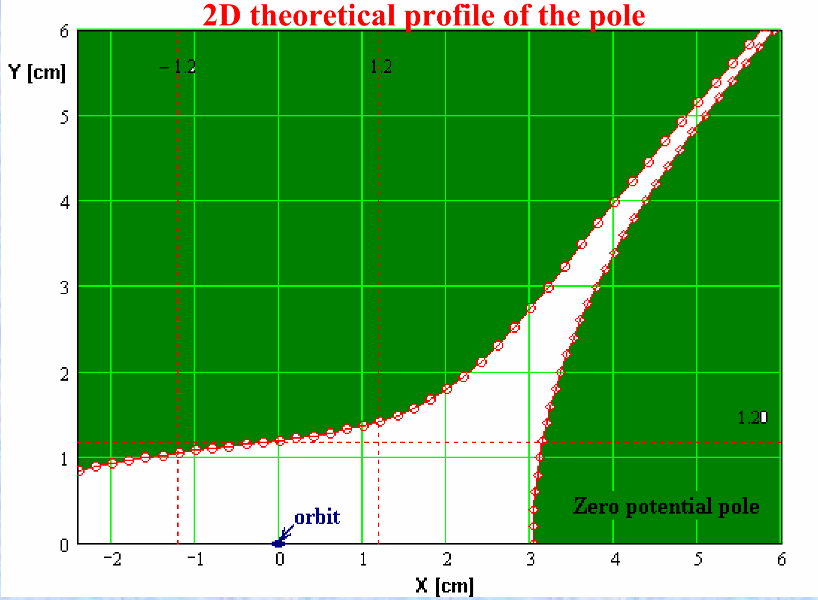
Required harmonics contents of DQSO magnet at nominal energy E=1.0 GeV:

n	Field term	for L_{eff}=68.0 cm		$K_{n-1}L=\int K_{n-1}dz$	$\int \partial^{n-1}B/\partial x^{n-1}dz$
		K_{n-1}	$\partial^{n-1}B/\partial x^{n-1}(0,0)$		
		$1/m^{n}$	kG/cm^{n-1}	$1/m^{n-1}$	kG/cm^{n-2}
1	Dipole	$\pi/(14\cdot L_{eff})$	11.008	$\pi/14$	748.52
2	Quadrupole	-4.2448	-1.416	-2.8865	-96.3
3	Sextupole	-105.88	-0.353	-72.0	-24.0
4	Octupole	-33250	-1.109	-22610	-75.4

Dipo-Quadro-Sextu-Octupole magnet (DQSO) for low emmitance Duke lattice







- One half
- 161×199×199 mesh size

Magnetic simulations by MERMAID 3D

Conclusions:

- MERMAID 3D is a powerful tool for magnetic design ;
- Mesh up to 20×10^6 elements with RAM drive of 2 Gb;
- Fast calculation;
- Well developed library of nonlinear materials of all the types;
- Easy to learn, to master, and to use.