Multi-Bend-Achromat (MBA) Magnets

Mark Jaski
Mechanical Engineer
Accelerator Systems Division/Magnetic Devices Group

Outline

- Multi-Bend-Achromat (MBA)
- Functional Requirements Document
  - Sector Layout
  - Types of Magnets
  - Magnet requirements
  - Design Parameters
- Magnet Designs
- Coil Designs
- Assembly concepts

The APS Upgrade: The world's leading high-brightness hard x-ray storage ring

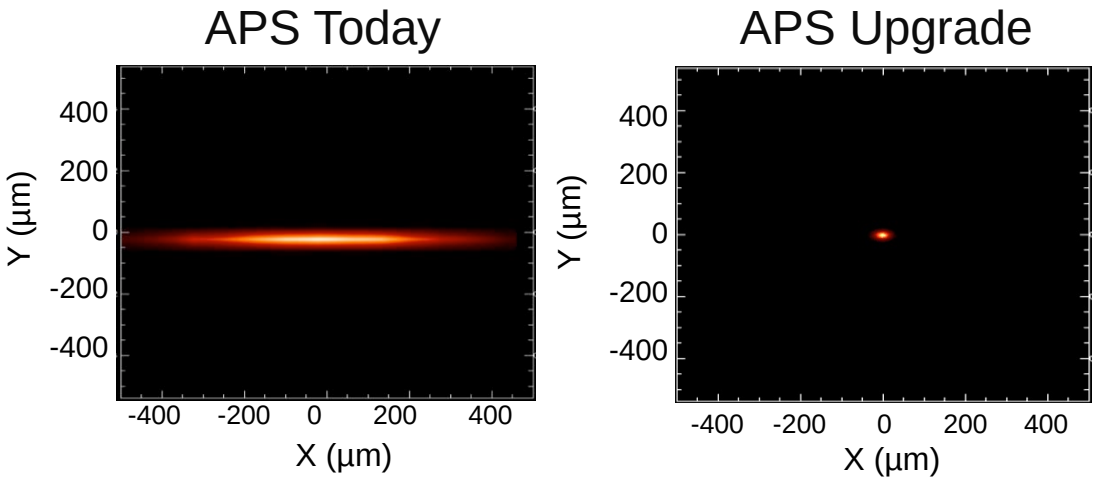
The APS Upgrade will produce the world's leading high-brightness hard x-ray storage ring

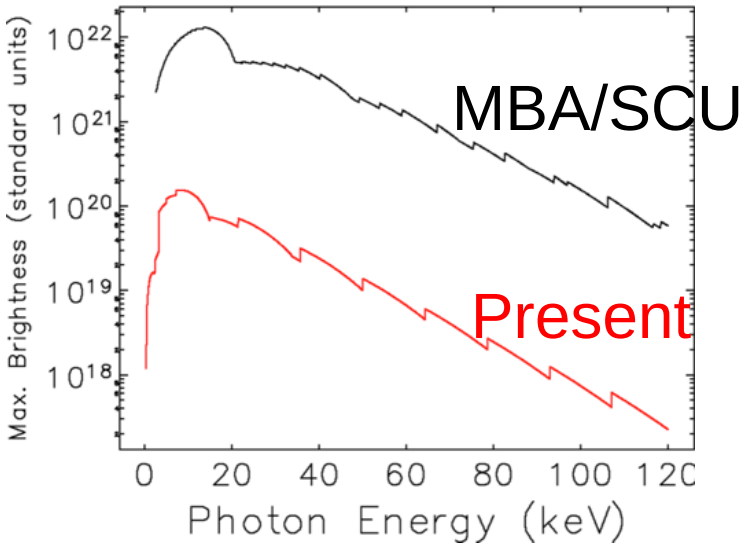
2-3 order-of-magnitude increase in:

- Brightness
- Coherent flux
- Nano-focused flux

Operation with round beams

APS-U ushers in a generational leap in storage ring performance





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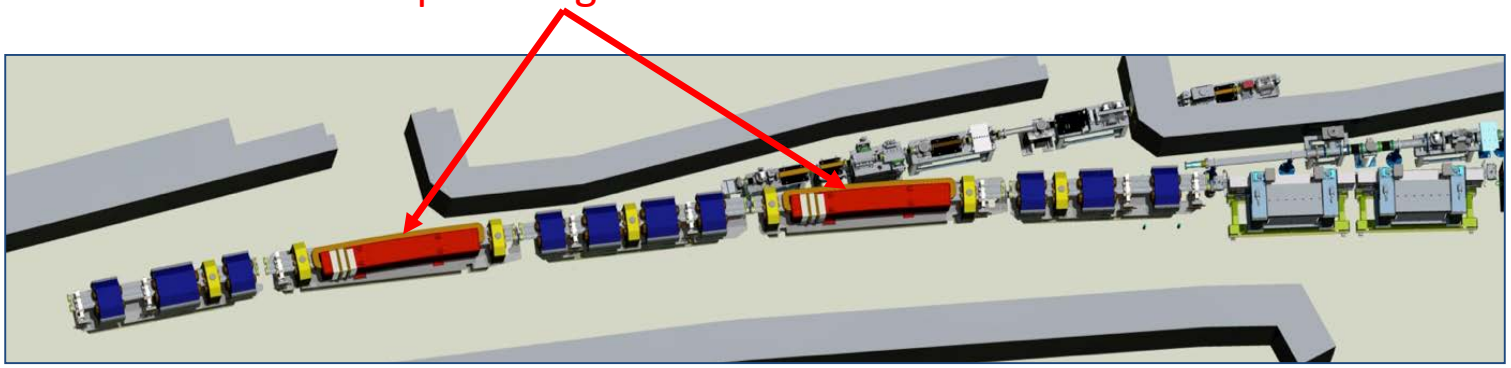
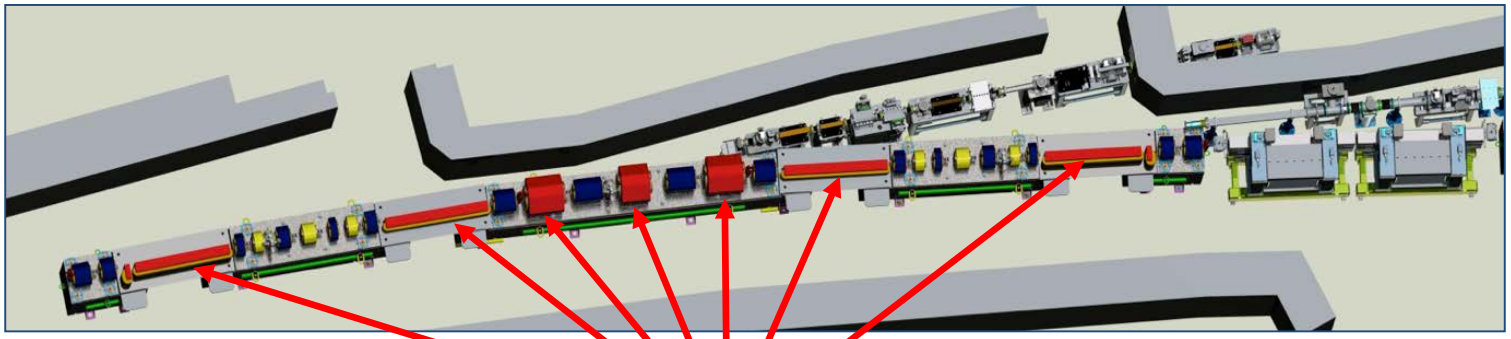
Multi-Bend-Achromat (MBA)

two dipole magnets – double-bend-achromat





Seven dipole magnets – multi-bend-achromat (MBA)

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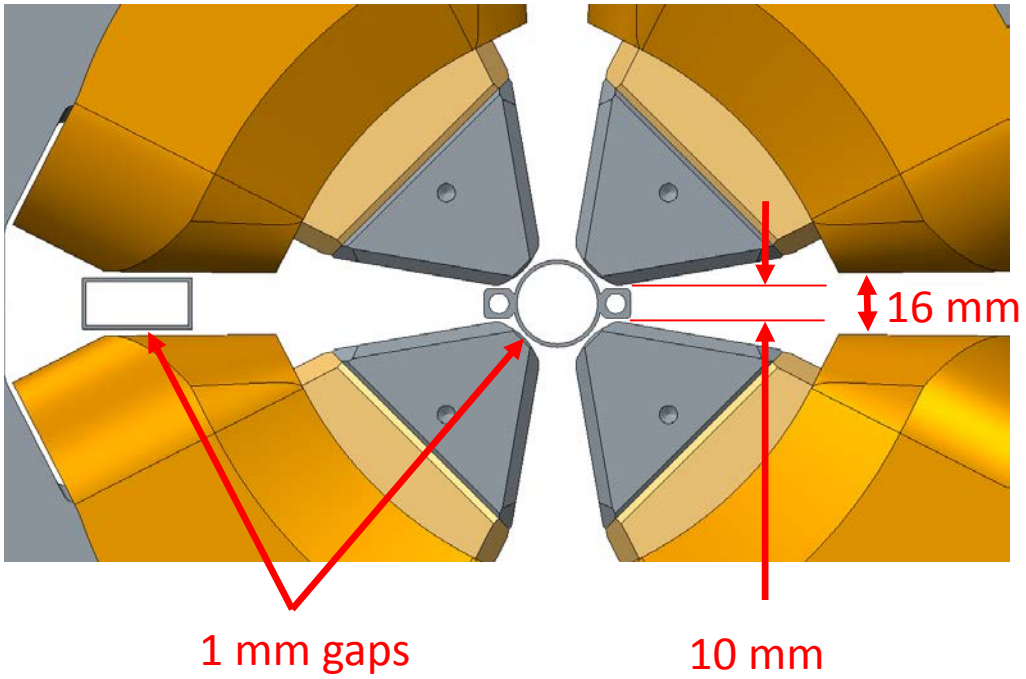
Multi-Bend-Achromat (MBA)

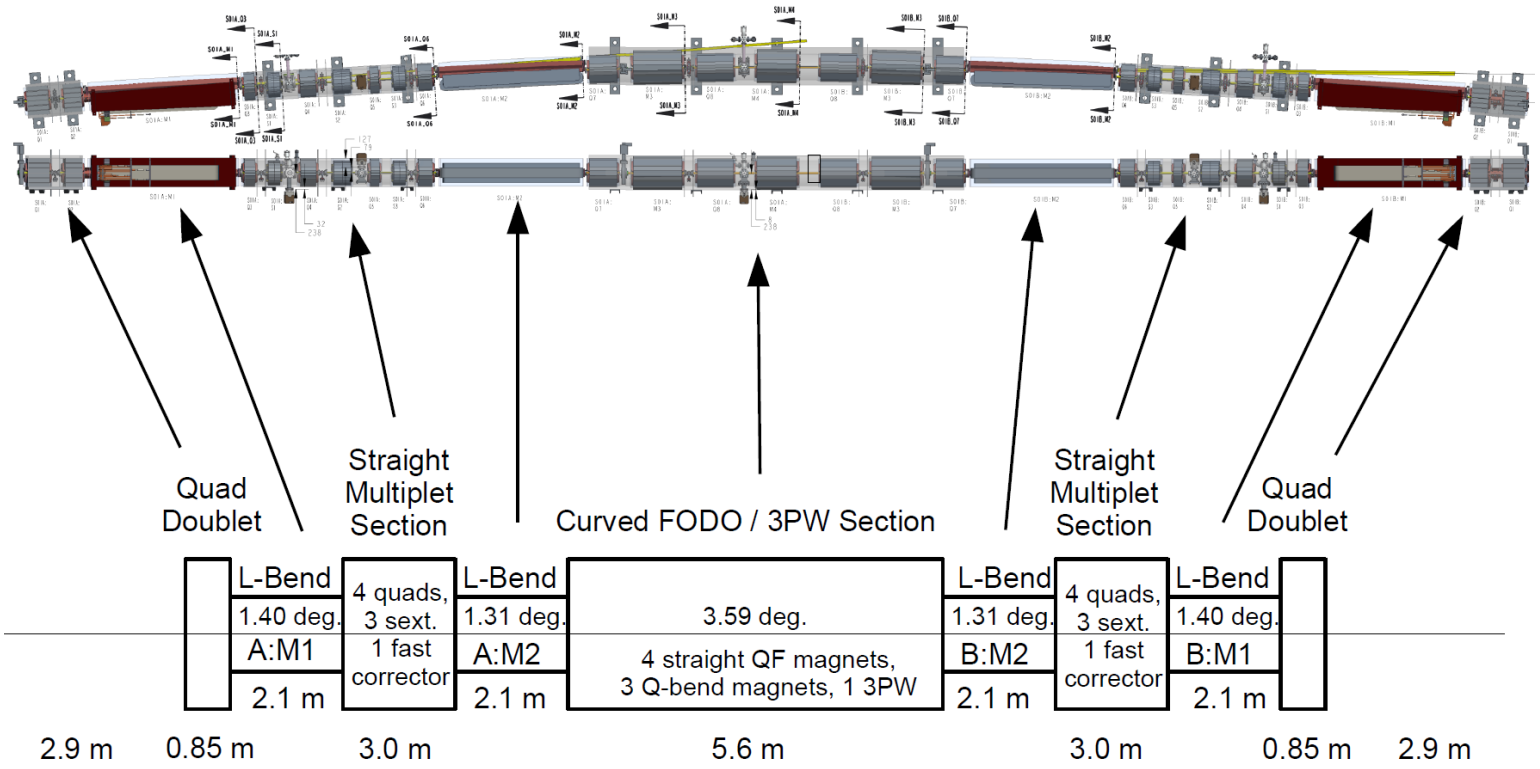
- To go to lower emmitance.
- Requires stronger magnets
- Smaller magnet gaps.
- Tighter tolerances.
- Small gaps between vacuum chamber and magnet poles and magnet coils.



		APS	MBA
		mm	
Dipole	gap	57.20	26.00
Quadrupole	pole tip radius	39.96	13.00
Sextupole	pole tip radius	49.00	14.00

Functional Requirements Document
Sector Layout

with block diagram showing major components



Functional Requirements Document
9 Magnet Types
1320 Total Storage Ring Magnets

Table 1.1: Types of magnets

	Magnet type	Quantity	Core type
L-Bend magnets	M1 Longitudinal dipoles	80	Solid
	M2 Longitudinal dipoles	80	Solid
Q-Bend magnets	M3 Transverse-Gradient dipoles	80	Solid
	M4 Transverse-Gradient dipoles	40	Solid
	Quadrupole 0.592 m	80	Solid
	Quadrupole 0.438 m	80	Solid
	Quadrupole 0.238 m	480	Solid
	Sextupole 0.256 m	240	Solid
Not Presented Here →	Fast Corrector	160	Laminated

Functional Requirements Document
Dipole magnet requirements

Name	Length* m	Angle deg	B_0 T	B' T/m	E_c keV	$P_{\mathrm{d,integ}}$ W/mrad	P_d $W/mrad^2$	Count
M1 (x80)								
M1.1	0.153	0.279	-0.636	-0.000	15.2	116.0	893.7	80
M1.2	0.203	0.238	-0.410	-0.000	9.8	74.7	575.9	80
M1.3	0.612	0.423	-0.241	-0.000	5.8	44.0	339.2	80
M1.4	0.744	0.314	-0.147	-0.000	3.5	26.9	207.1	80
M1.5	0.388	0.141	-0.127	-0.000	3.0	23.2	178.7	80
M2 (x80)								
M2.1	0.386	0.127	-0.115	-0.000	2.8	21.0	161.6	80
M2.2	0.345	0.133	-0.134	-0.000	3.2	24.5	188.5	80
M2.3	0.557	0.343	-0.215	-0.000	5.1	39.2	302.0	80
M2.4	0.321	0.243	-0.264	-0.000	6.3	48.2	371.2	80
M2.5	0.508	0.462	-0.318	-0.000	7.6	58.0	446.6	80
M3 (x80)								
M3.1	0.390	0.617	-0.553	45.372	13.2	100.8	777.0	80
M3.2	0.390	0.617	-0.553	45.372	13.2	100.8	777.0	80
M4 (x40)								
M4.1	0.325	0.562	-0.605	47.215	14.5	110.2	849.4	40
M4.2	0.325	0.562	-0.605	47.215	14.5	110.2	849.4	40

M1

M2

M3

M4

Provided by M. Borland

Functional Requirements Document
Quadrupole magnet requirements

Element Name	Length* m	K_1 $1/m^2$	B' T/m	B'L T	Count
Q1	0.238	3.601	-72.1	-17.16	80
Q2	0.238	-2.787	55.8	13.28	80
Q3	0.238	-2.256	45.1	10.75	80
Q4	0.238	3.203	-64.1	-15.26	80
Q5	0.238	1.693	-33.9	-8.07	80
Q6	0.238	-2.444	48.9	11.64	80
Q7	0.438	3.562	-71.3	-31.22	80
Q8	0.592	4.086	-81.8	-48.41	80

Provided by M. Borland

Functional Requirements Document
Sextupole magnet requirements

Element Name	Length* m	K_2 $1/m^3$	B'' T/m^2	B''L T/m	Count
S01A:S1	0.256	-165.1	3305.2	847.0	20
S01A:S2	0.256	227.1	-4545.4	-1164.8	20
S01A:S3	0.256	-151.3	3028.4	776.0	20
S01B:S3	0.256	-155.9	3121.1	799.8	20
S01B:S2	0.256	230.7	-4616.7	-1183.0	20
S01B:S1	0.256	-153.0	3061.5	784.5	20
S02A:S1	0.256	-157.5	3151.3	807.5	20
S02A:S2	0.256	227.5	-4553.2	-1166.8	20
S02A:S3	0.256	-155.9	3120.5	799.6	20
S02B:S3	0.256	-152.3	3048.2	781.1	20
S02B:S2	0.256	233.1	-4665.7	-1195.6	20
S02B:S1	0.256	-157.0	3142.4	805.2	20

The strengths of the sextupole magnets repeats every other sector.

Provided by M. Borland

Functional Requirements Document
Field Quality

- Magnet Field Quality

$$b_n = \frac{B_n R^n / n!}{B_m R^m / m!}$$

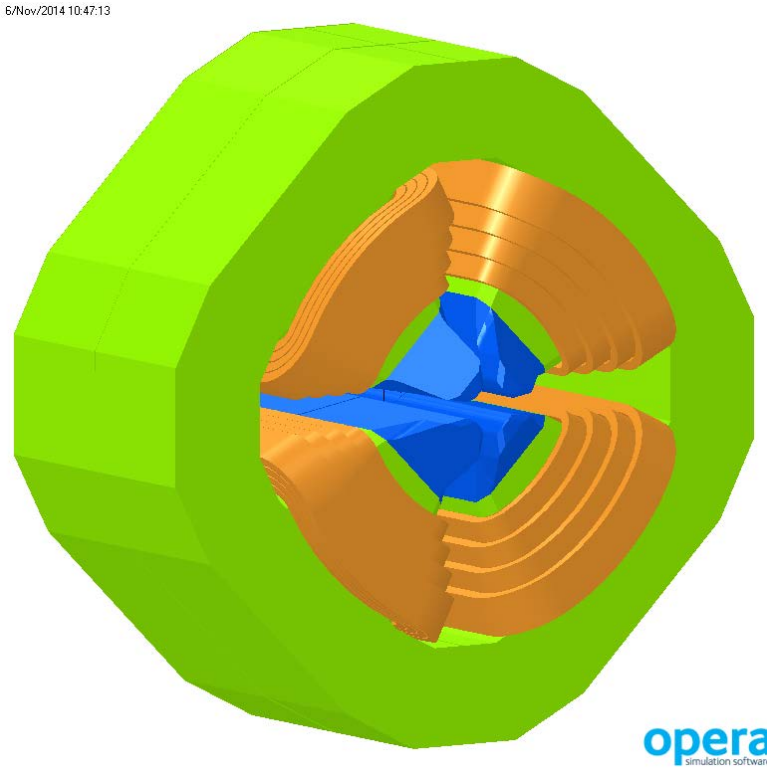
B_0 is the dipole

Table 2.17: Magnet field quality tolerances

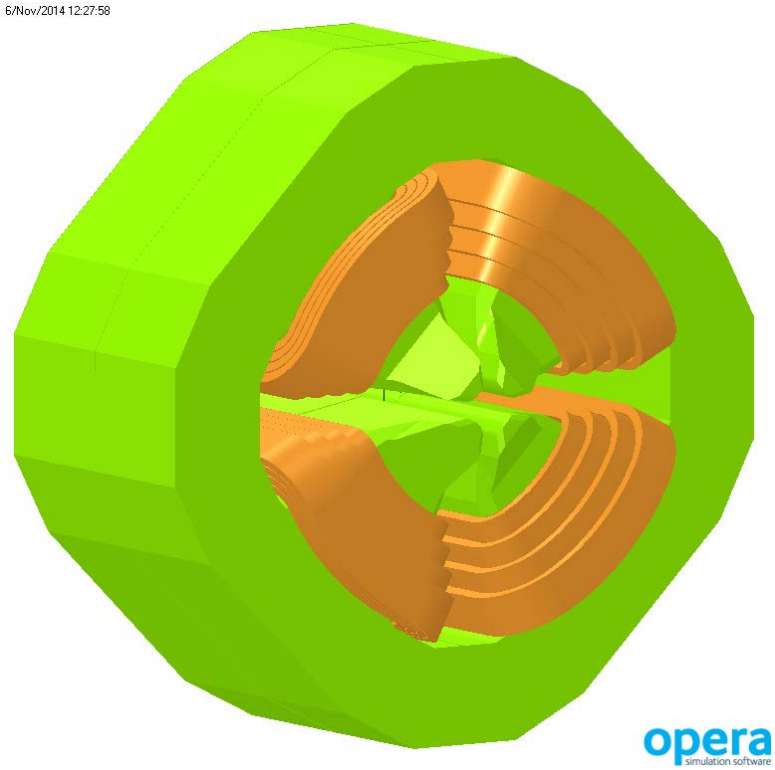
Main field type	m	n	Normal % error at $R = 1$ cm	Skew % error at $R = 1$ cm
dipole	0	2-8	0.1 each	TBD
quadrupole	1	5, 9, 13, 17	0.1 each	TBD
sextupole	2	8, 14, 20	0.1 each	TBD

MBA V6 Quadrupole Magnets

238 mm long



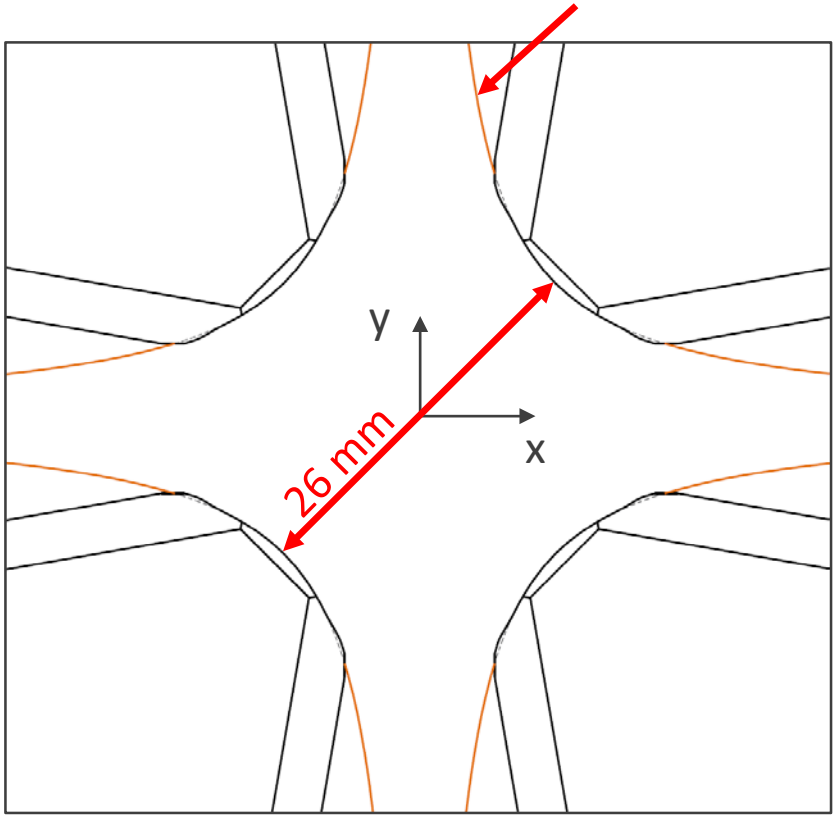
Q1 Quadrupole Magnet
Vanadium permendur pole tips

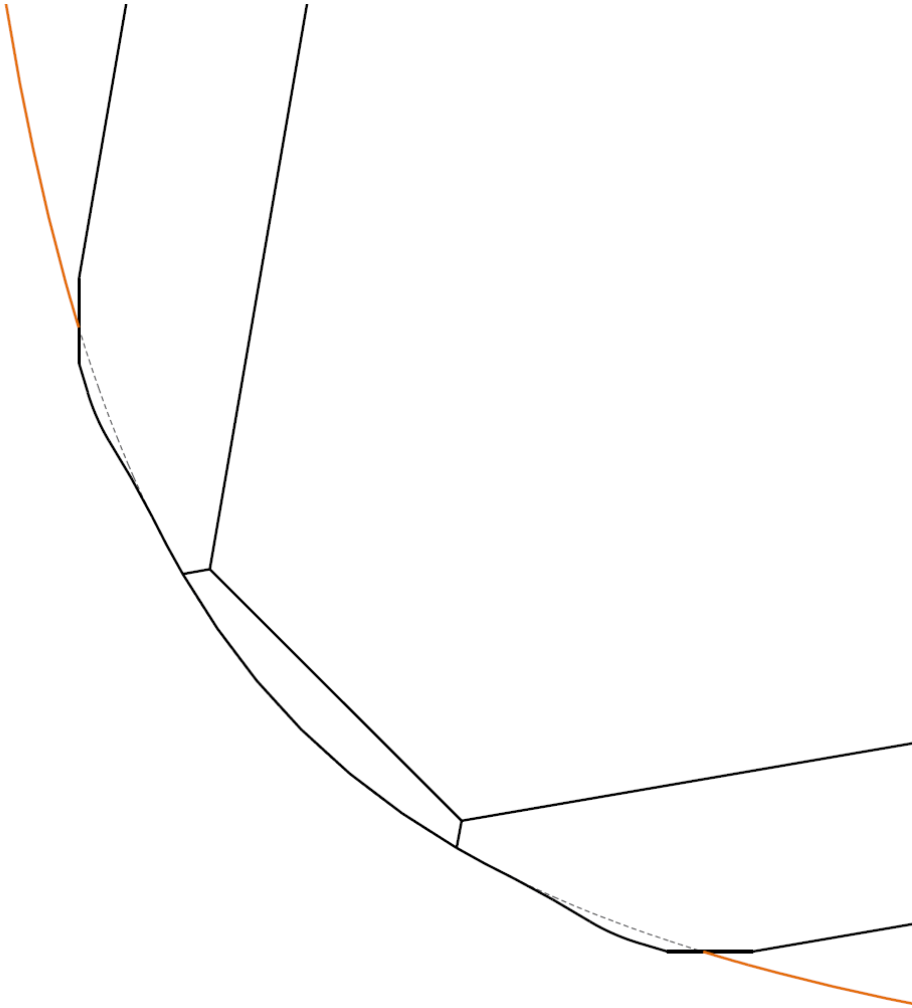


Q2 through Q6 Quadrupole Magnets
Steel pole tips

Field Quality in a Quadrupole Magnet

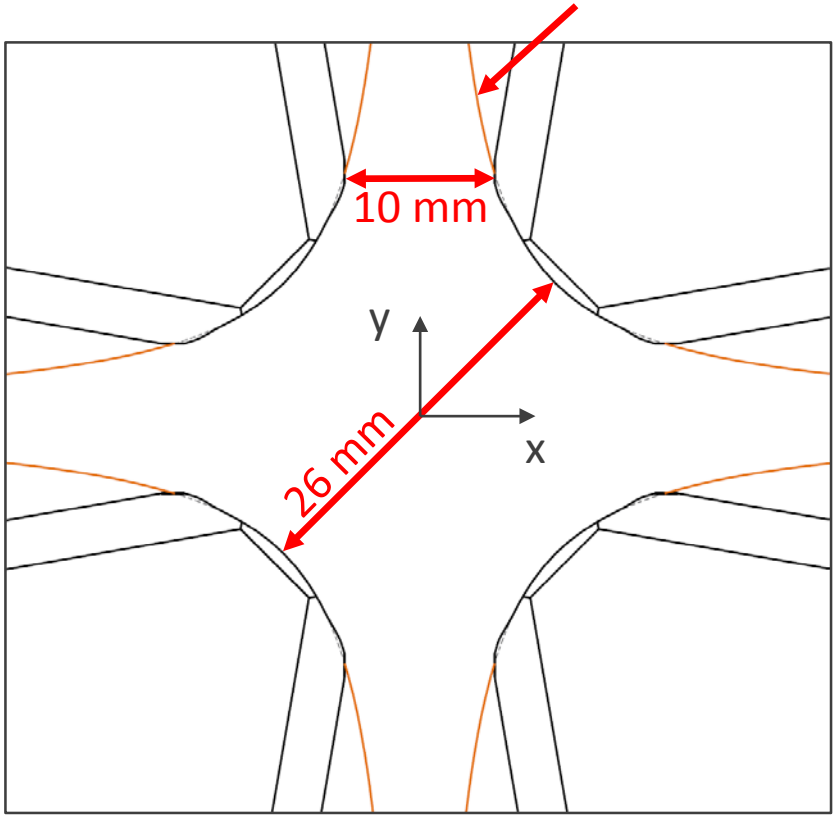
Hyperbolic curve $y=r^2/(2x)$ for an ideal quadrupole magnet

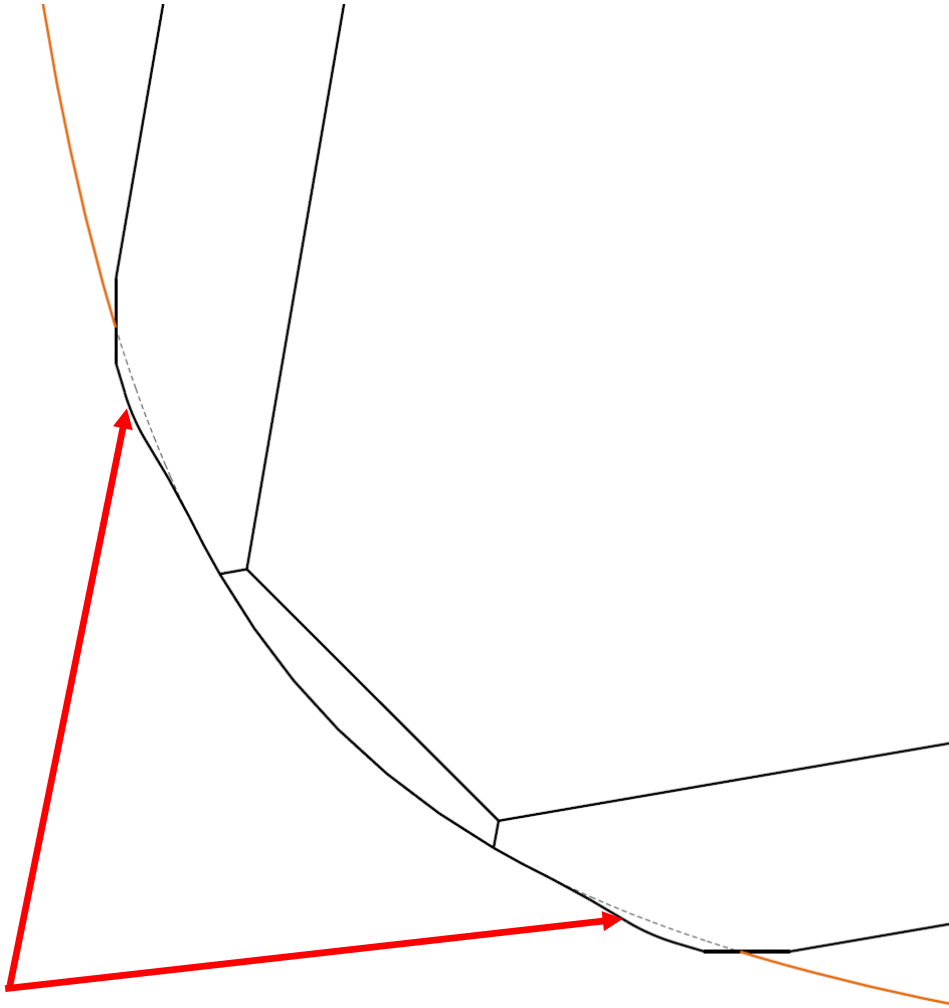




Field Quality in a Quadrupole Magnet

Hyperbolic curve $y=r^2/(2x)$ for an ideal quadrupole magnet

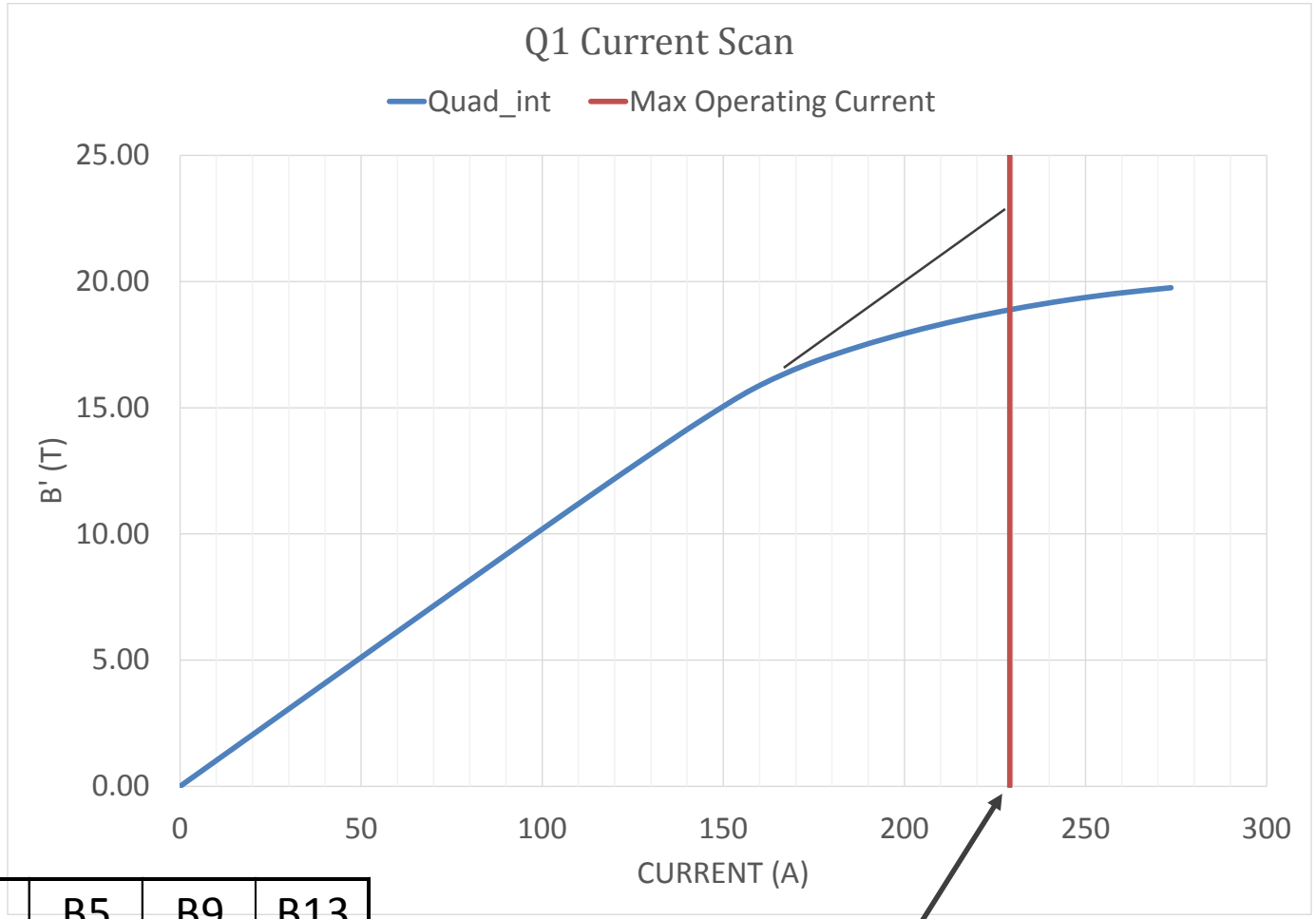




Magnet shims for quadrupole magnet to improve field quality

MBA V6 Quadrupole Magnets

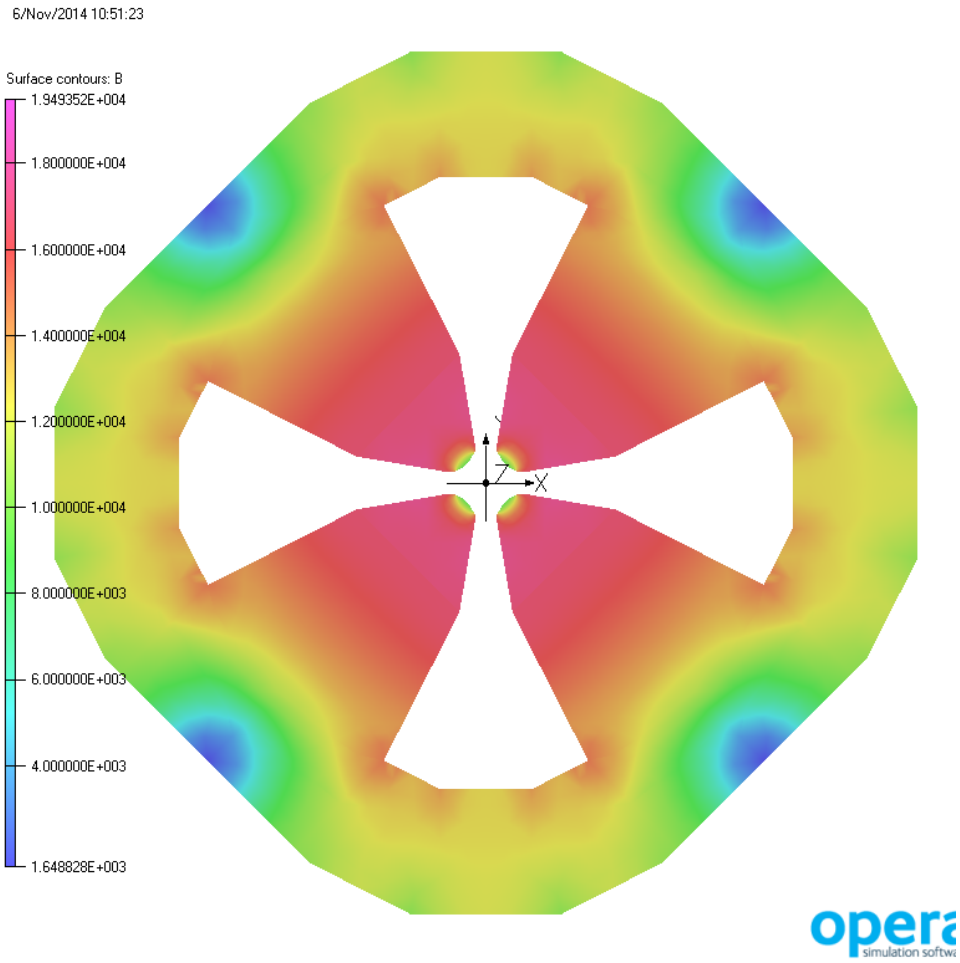
Saturation curve – steel only holds so much field



B1	B5	B9	B13
10000.0	3.2	-4.2	-2.5

80.7% magnet efficiency

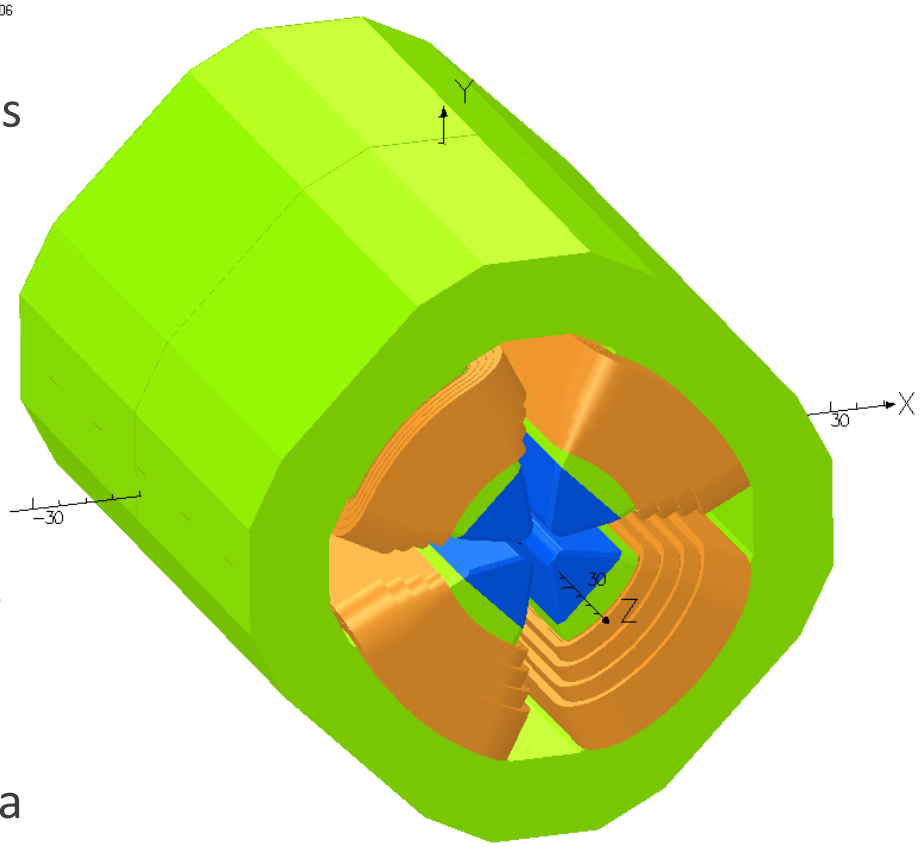
MBA V6 Quadrupole Magnets



Q1 Quadrupole Magnet at maximum current

MBA V6 Quadrupole Magnets

- Q7 and Q8 quadrupole magnets.
- Use vanadium permendur pole tips because of high field (98.9 T/m)
- Do not use long pole tips.
- This is because it is a combined function magnet producing both a vertical and horizontal dipole field as well as a quadrupole field.
- Magnet efficiency must be kept to a maximum.
- The shorter pole tip produces a larger field at high efficiency than a long pole tip at the same efficiency.

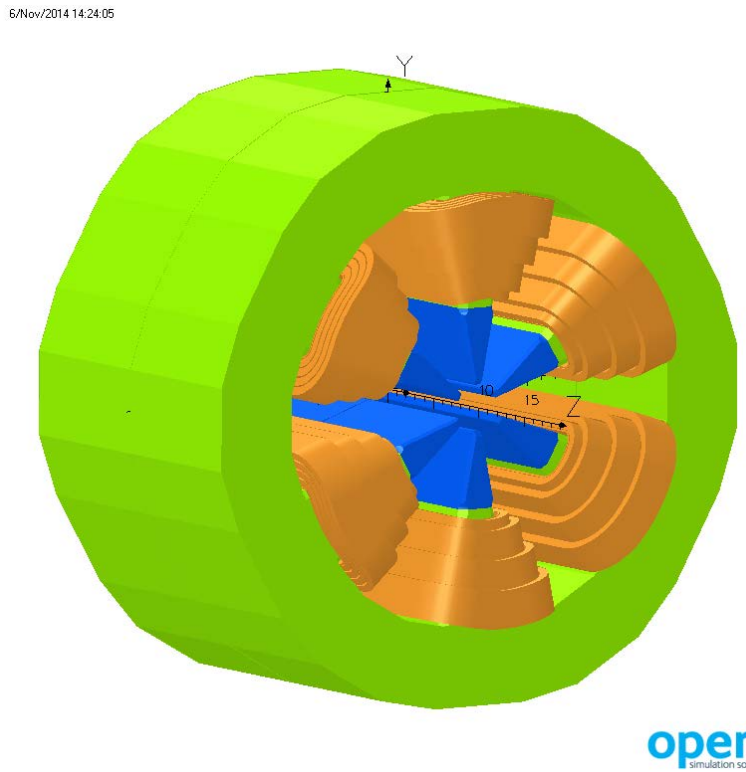


Q8 Quadrupole Magnet

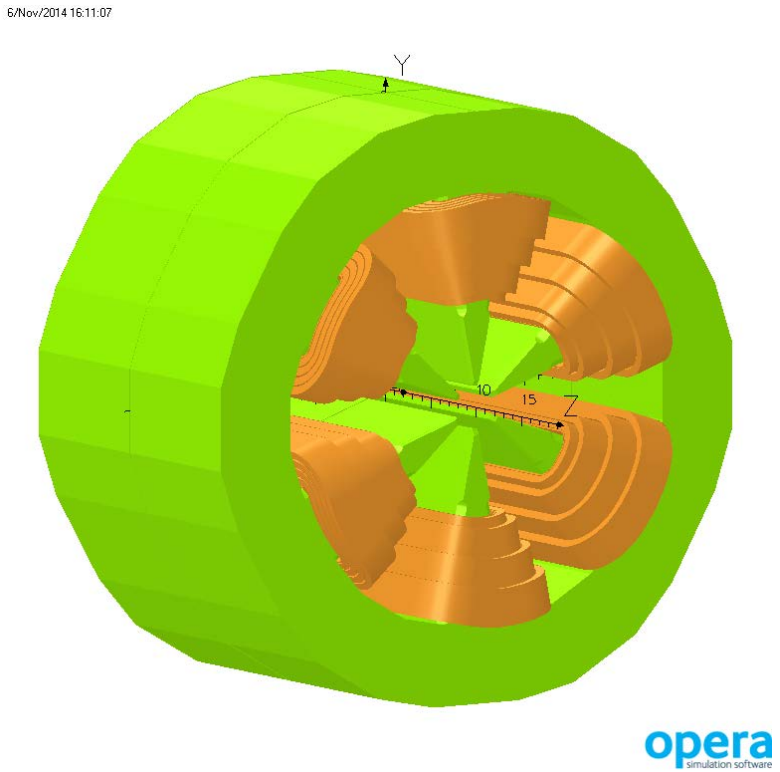
MBA V6 Sextupole Magnets

256 mm long

Has both vertical and horizontal corrector coils

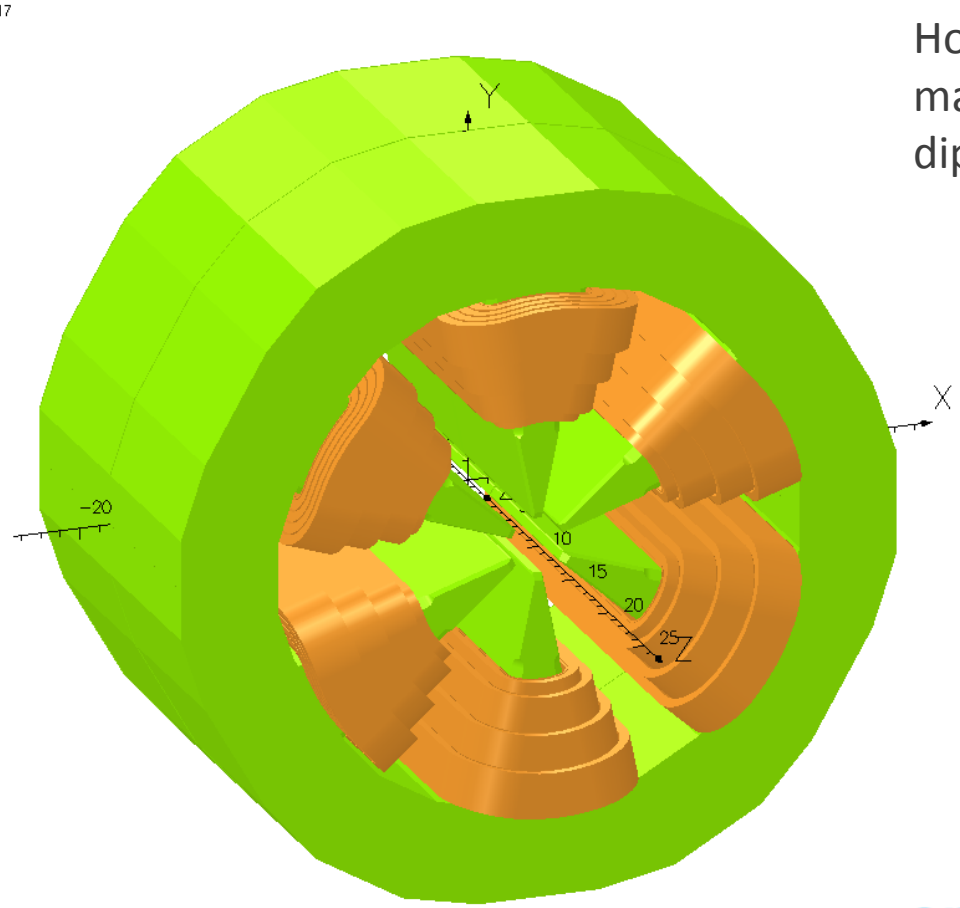


S2 Sextupole Magnet
Vanadium permendur pole tips



S1, S3 Sextupole Magnet
Steel pole tips

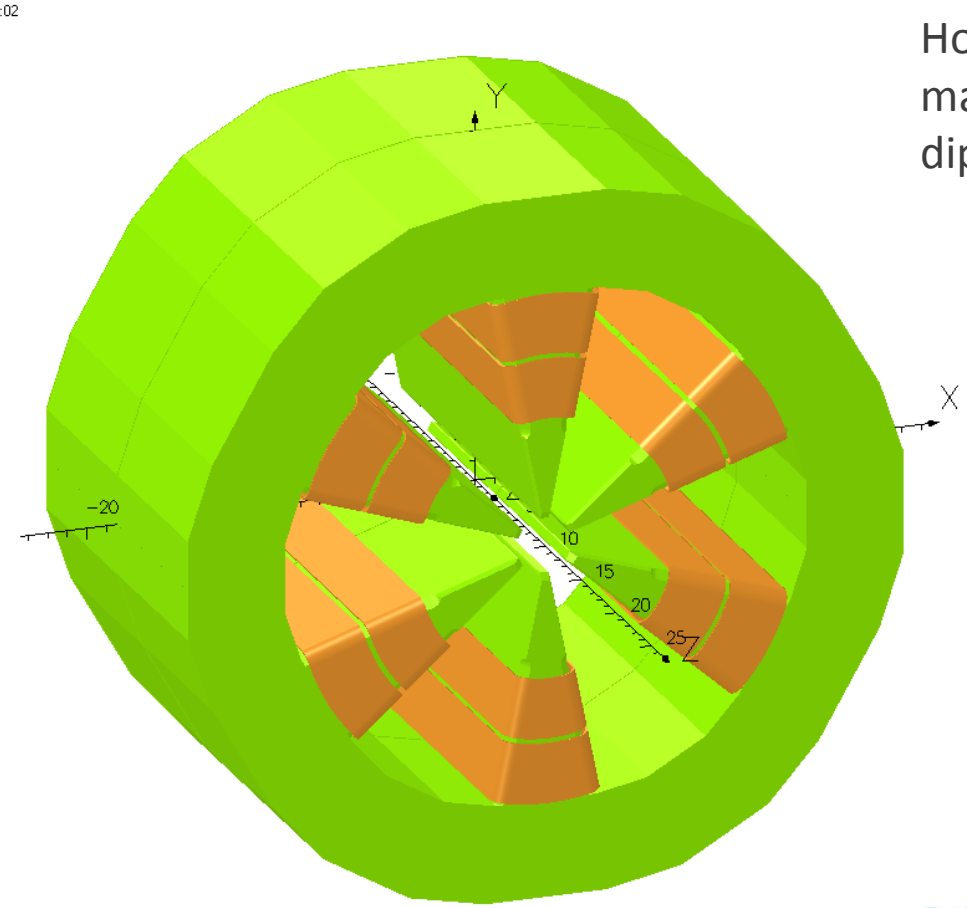
MBA V6 Sextupole Magnets whole coil shown



How does a six pole magnet produce a dipole field?

opera simulation software

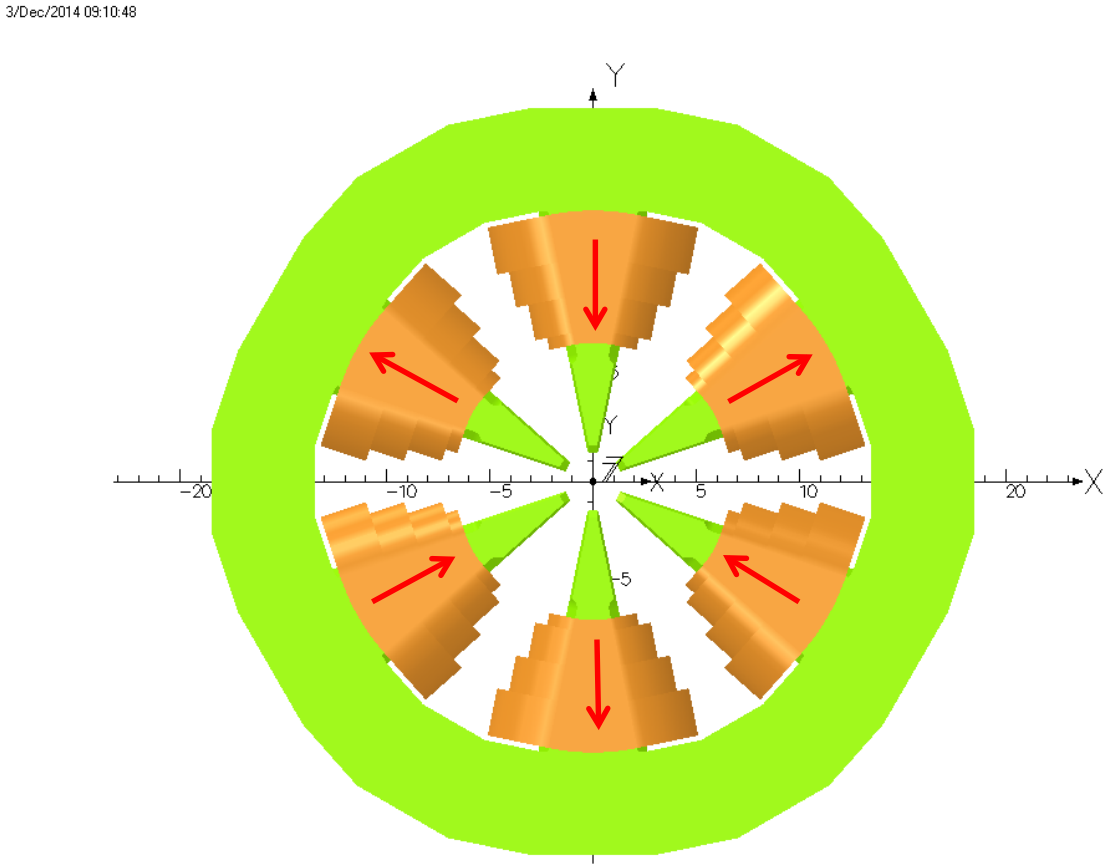
MBA V6 Sextupole Magnets
Sextupole coil removed exposing dipole coils



How does a six pole magnet produce a dipole field?

opera simulation software

MBA V6 Sextupole Magnets
Sextupole Dipole coils



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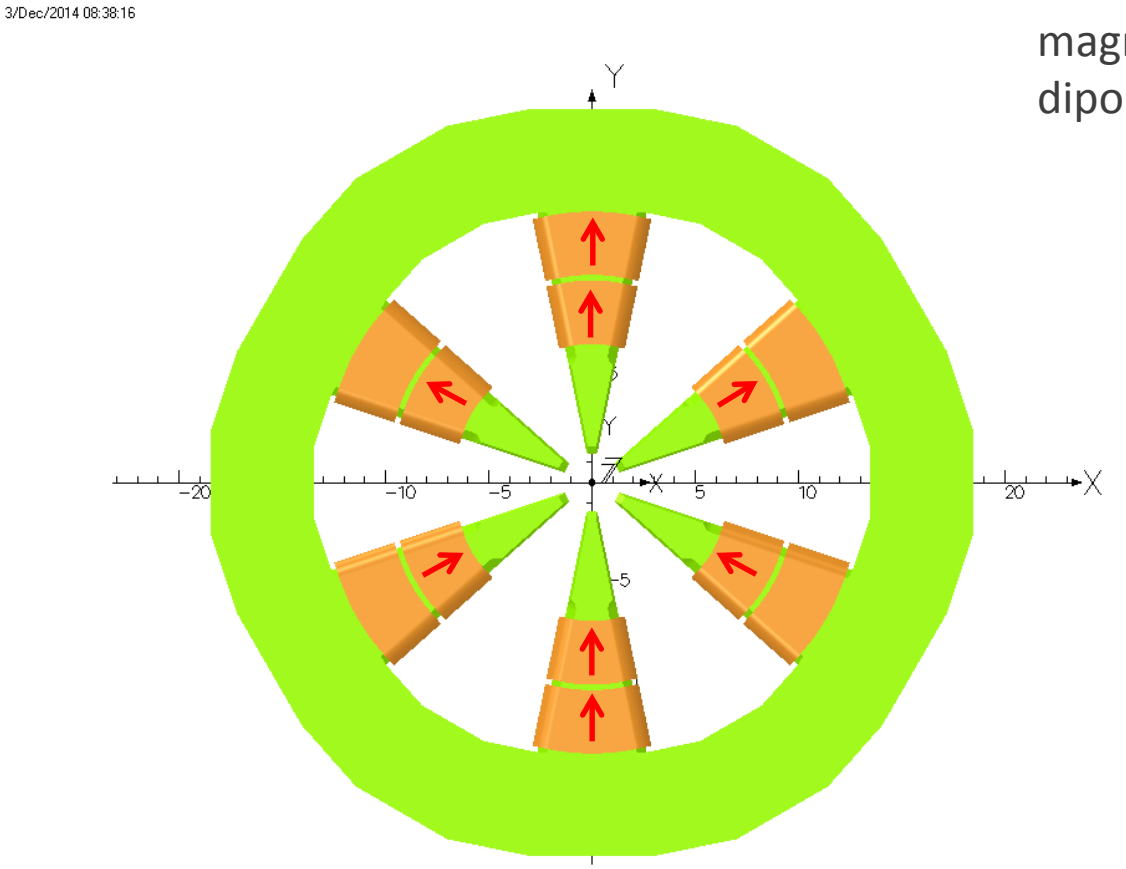
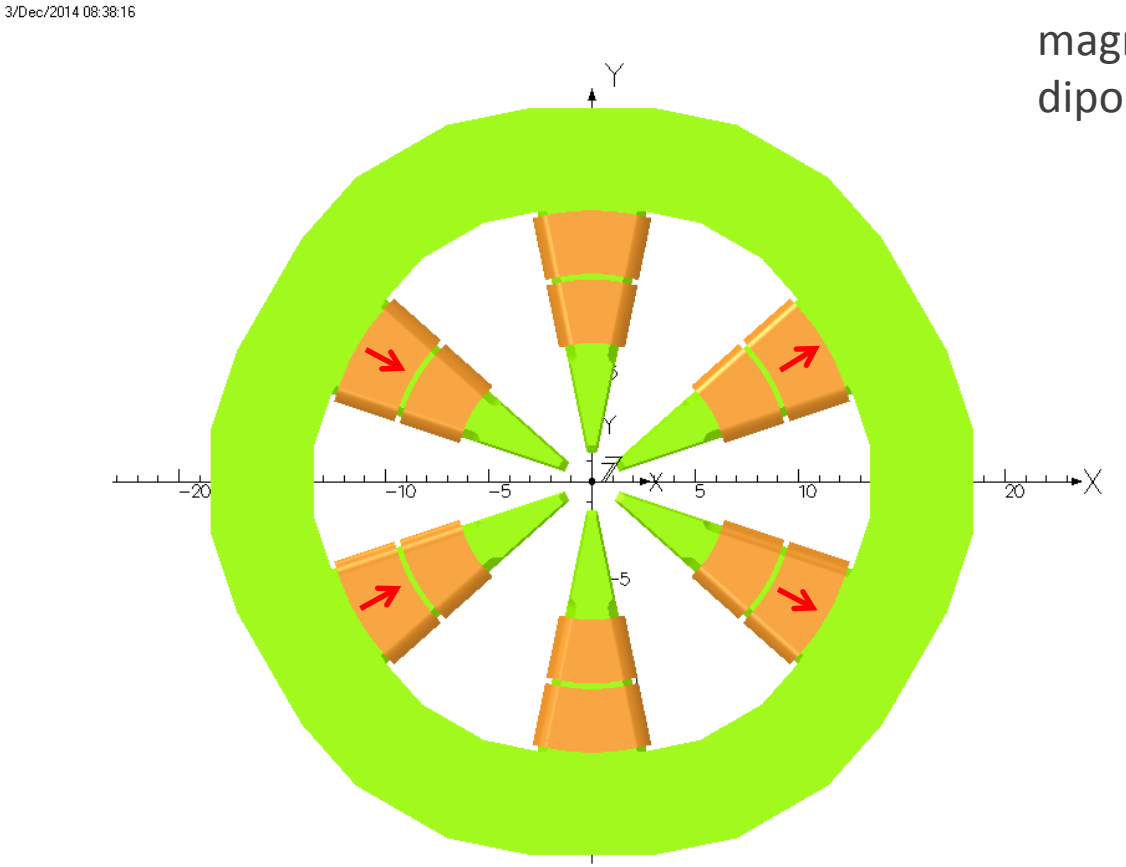
MBA V6 Sextupole Magnets
Sextupole Vertical Dipole coils



How does a six pole magnet produce a dipole field?

opera simulation software

MBA V6 Sextupole Magnets
Sextupole Horizontal Dipole coils

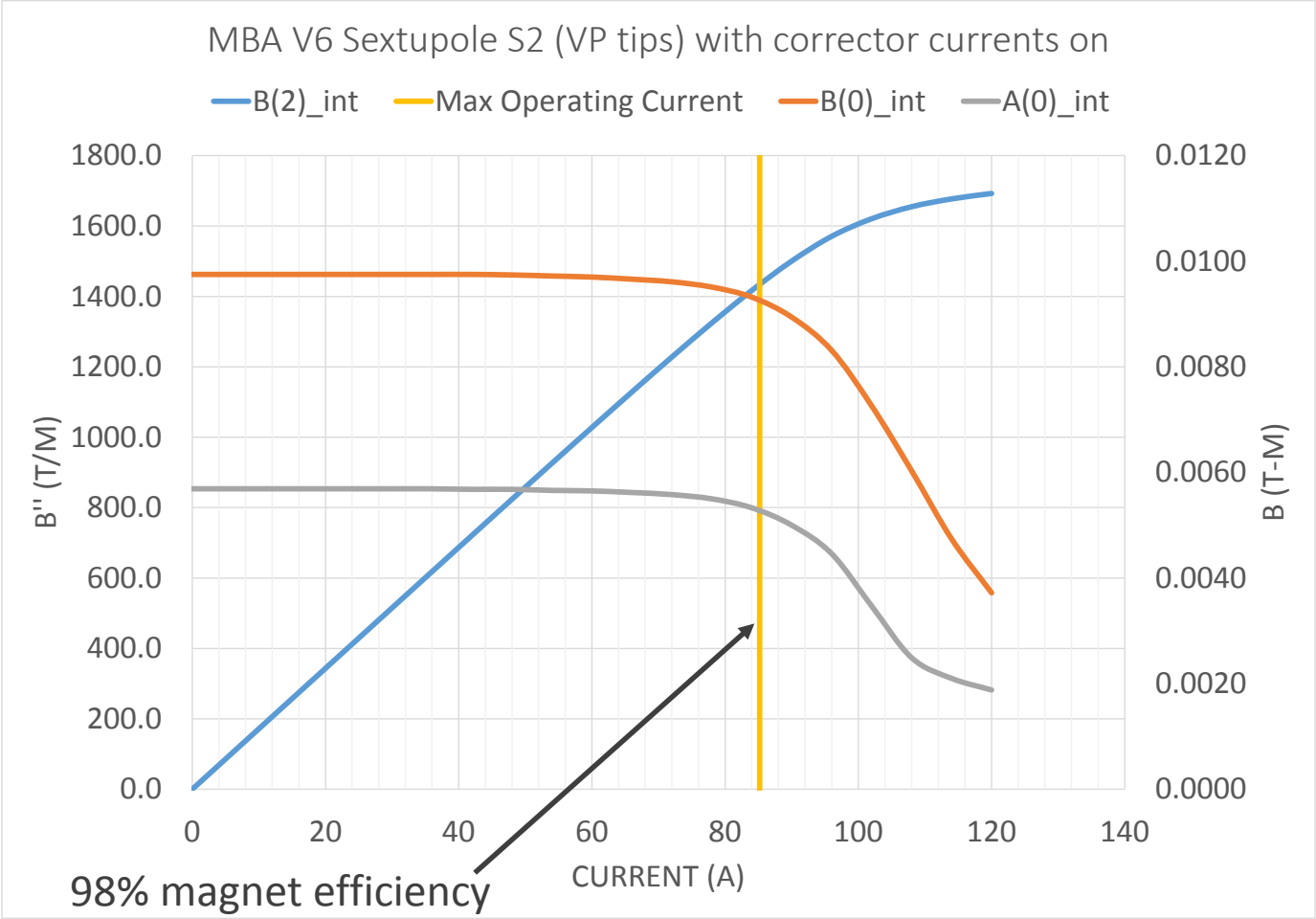


How does a six pole magnet produce a dipole field?

opera simulation software

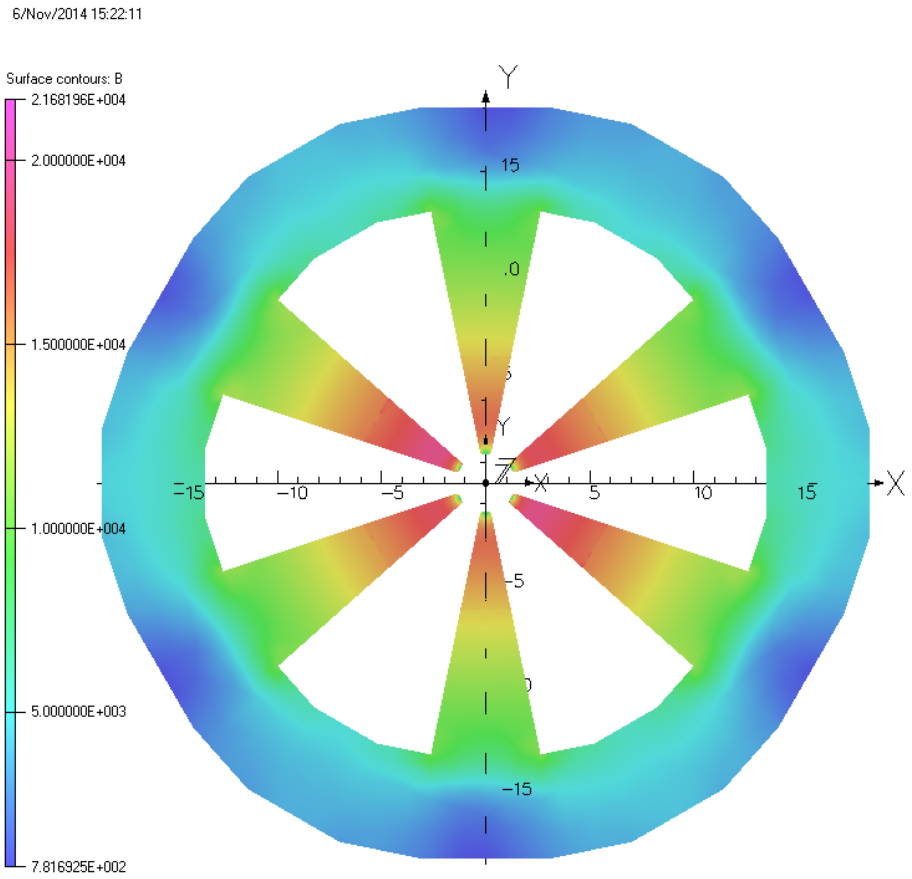
MBA V6 Sextupole Magnets

Corrector coils turned on at 10 ampers



Look-up tables will be required for both vertical and horizontal correctors

MBA V6 Sextupole Magnets



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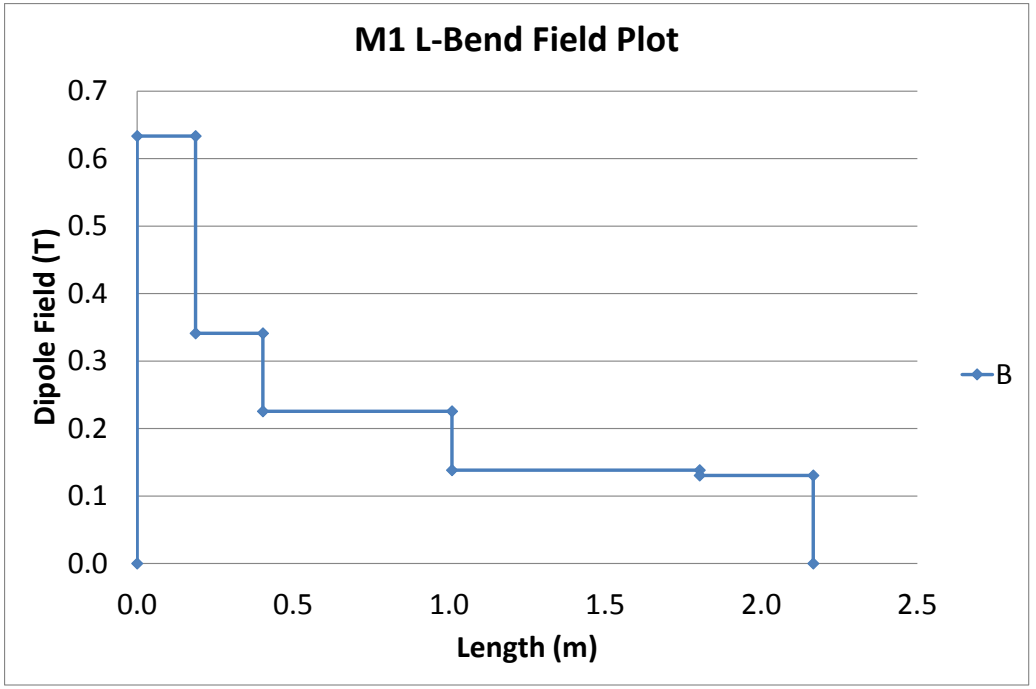
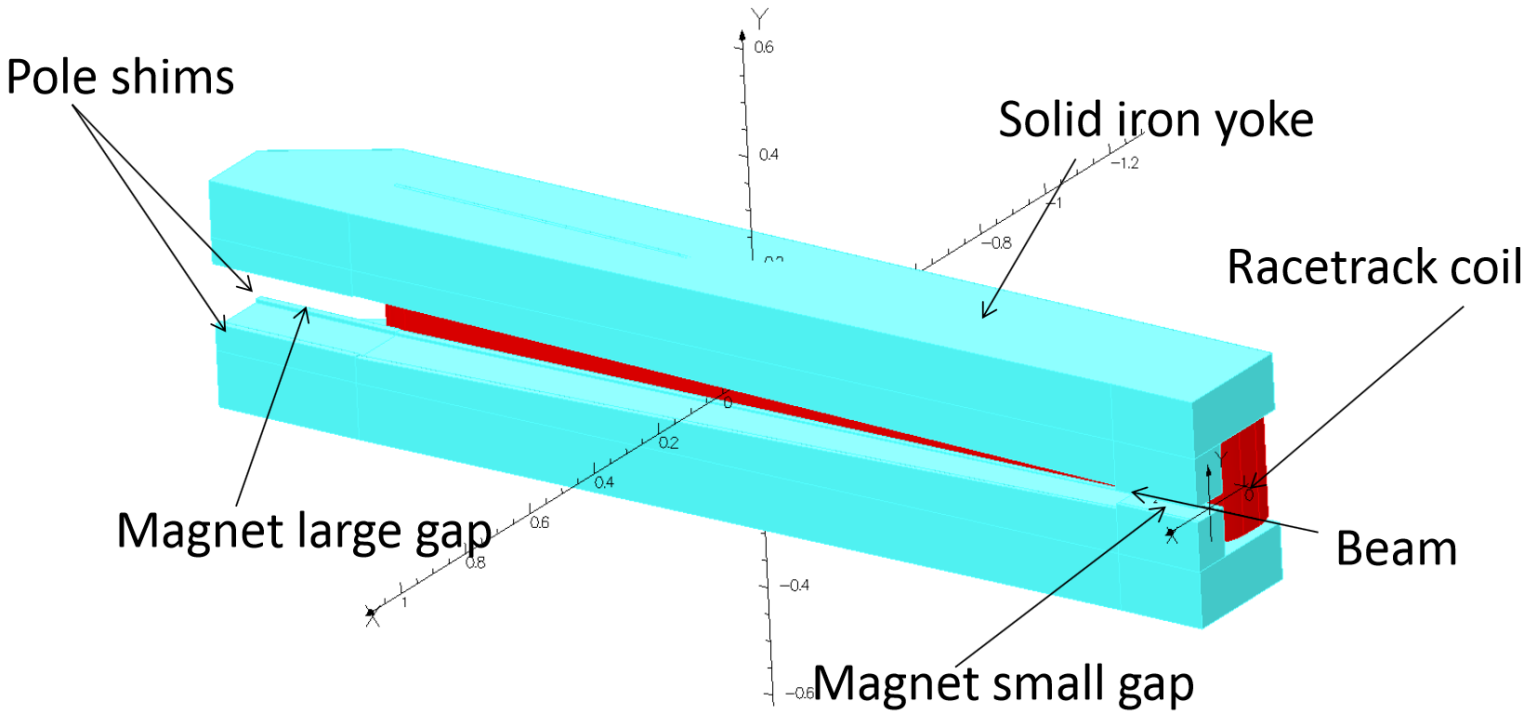
S2 sextupole magnet at maximum current

L-Bend Magnets

- Longitudinal gradient dipole magnets.
- Called L-bend dipole magnets.
- Field varies along the length

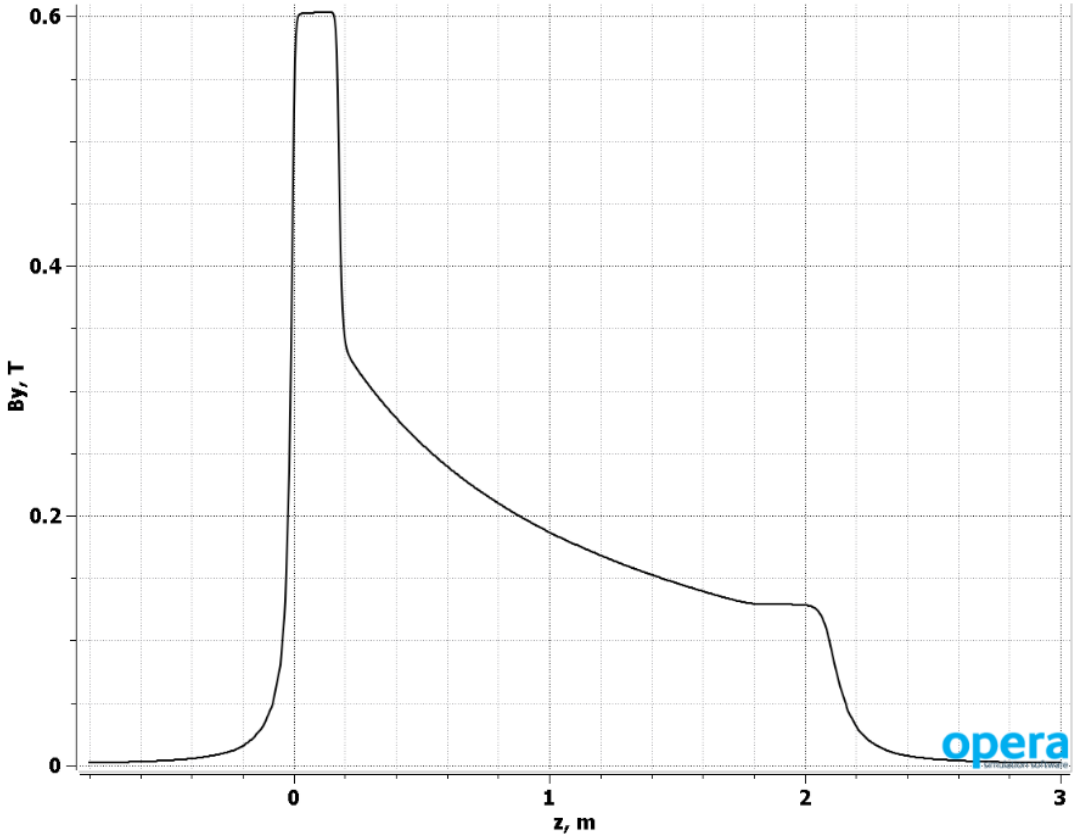


L-Bend Magnets
Tapered Pole Gap - Magnet Model



Courtesy of Vladimir Kashikhin of Fermilab

L-Bend Magnets
Tapered Pole Gap - Field Plot



Courtesy of Vladimir Kashikhin of Fermilab

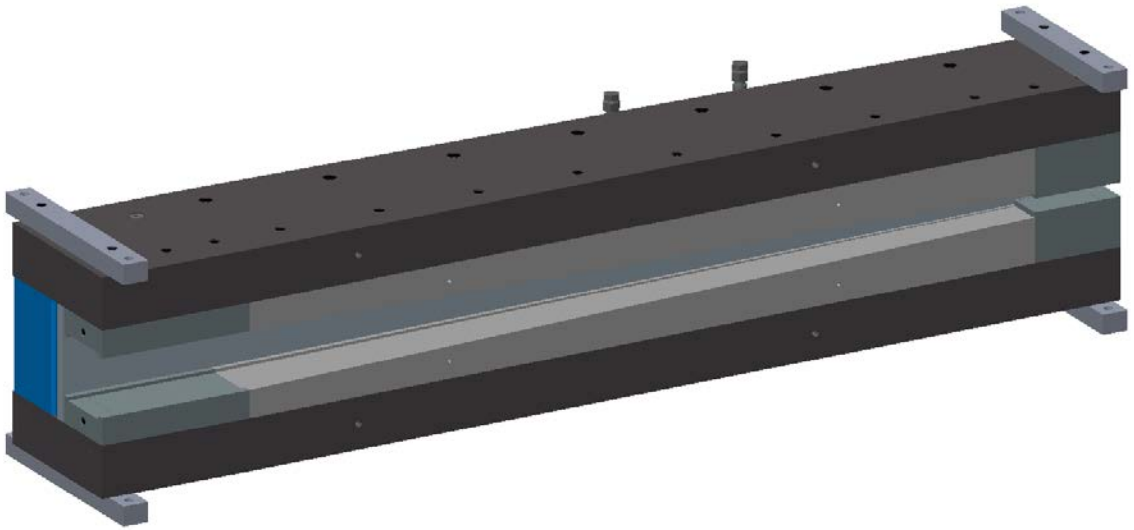
L-Bend Magnets
Tapered Pole Gap - Selected Parameters

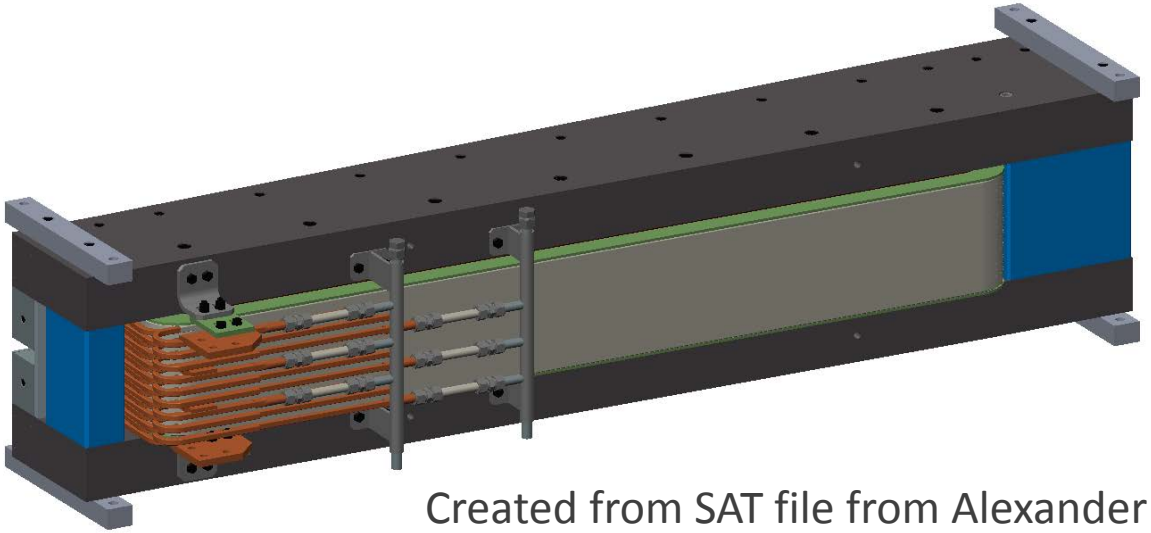
Parameter	Unit	Value
Pole length	m	2.09
Small gap (between shims)	mm	26
Large gap	mm	126
Copper conductor	mm	10.4x10.4 dia. 5.8
Coil number of turns		72
Coil current	A	184
Coil resistance	mΩ	68
Coil voltage drop	V	12.5
Power loss/magnet	kW	2.3
Water pressure drop	MPa	0.56 (80 psi)
Water temperature rise at 1 (3) water cooling circuits	°C	27 (5)

Courtesy of Vladimir Kashikhin of Fermilab

L-Bend Magnets
Tapered Pole Gap - 3D Model

A prototype of this magnet is being built by Fermilab





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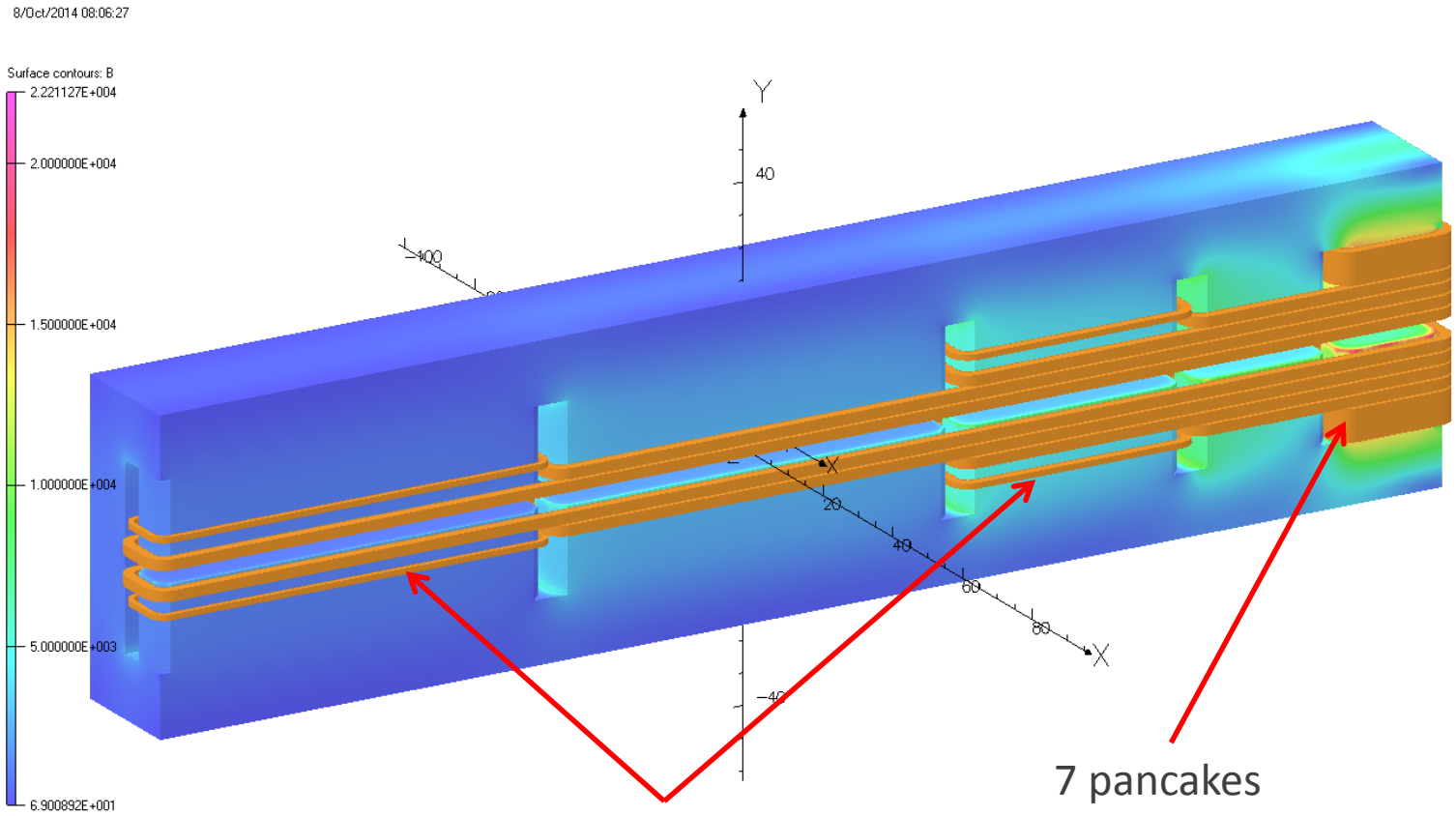
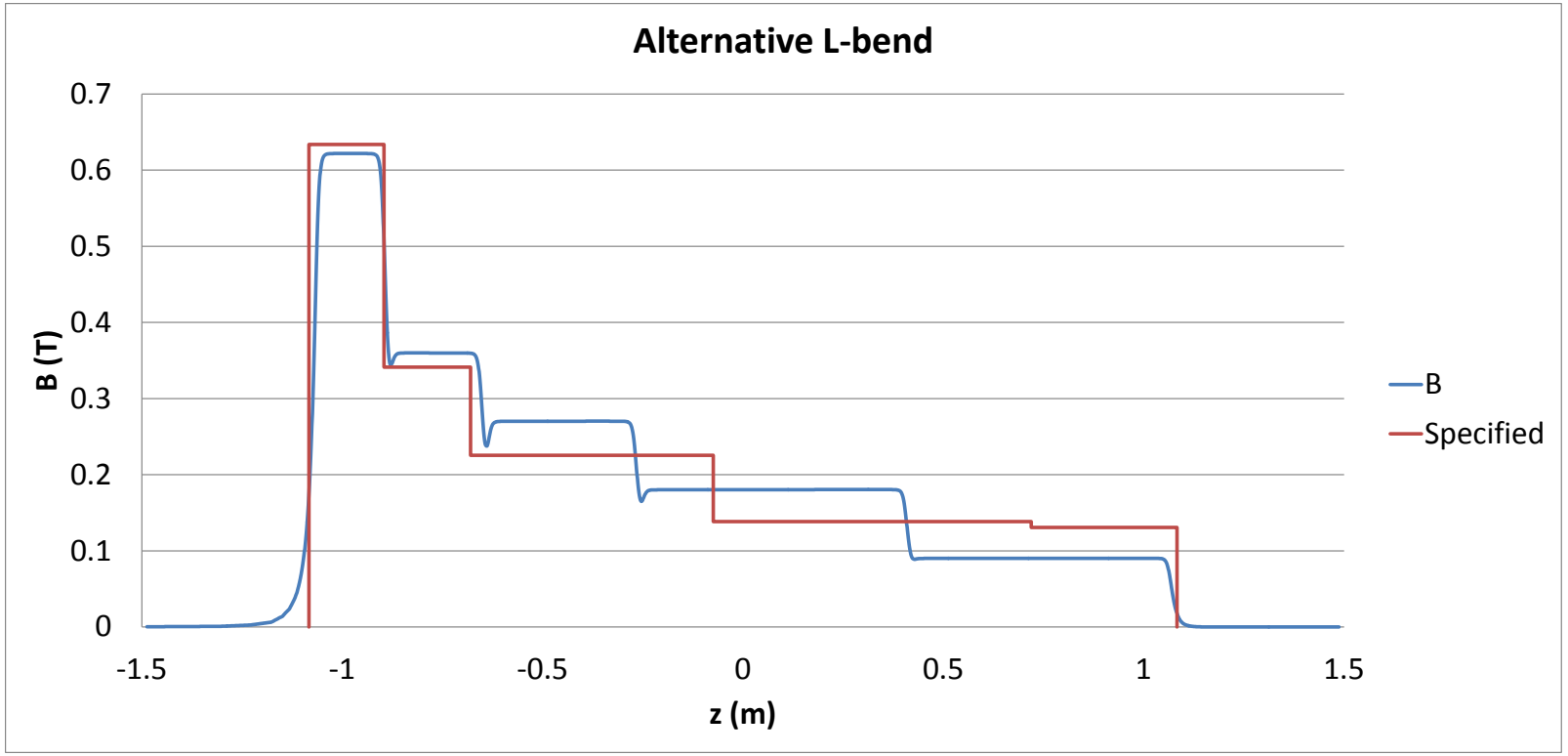
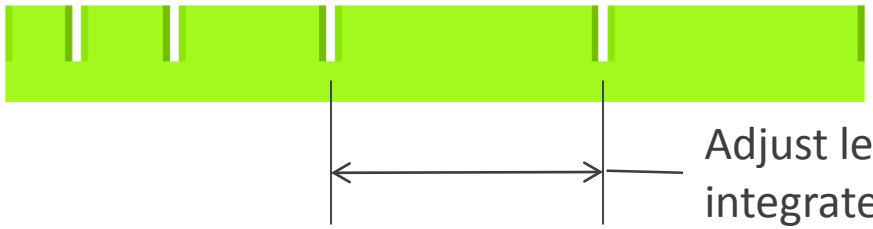
Alternative L-Bend



Alternative L-Bend Field Plot





Adjust lengths to control the integrated field in each section

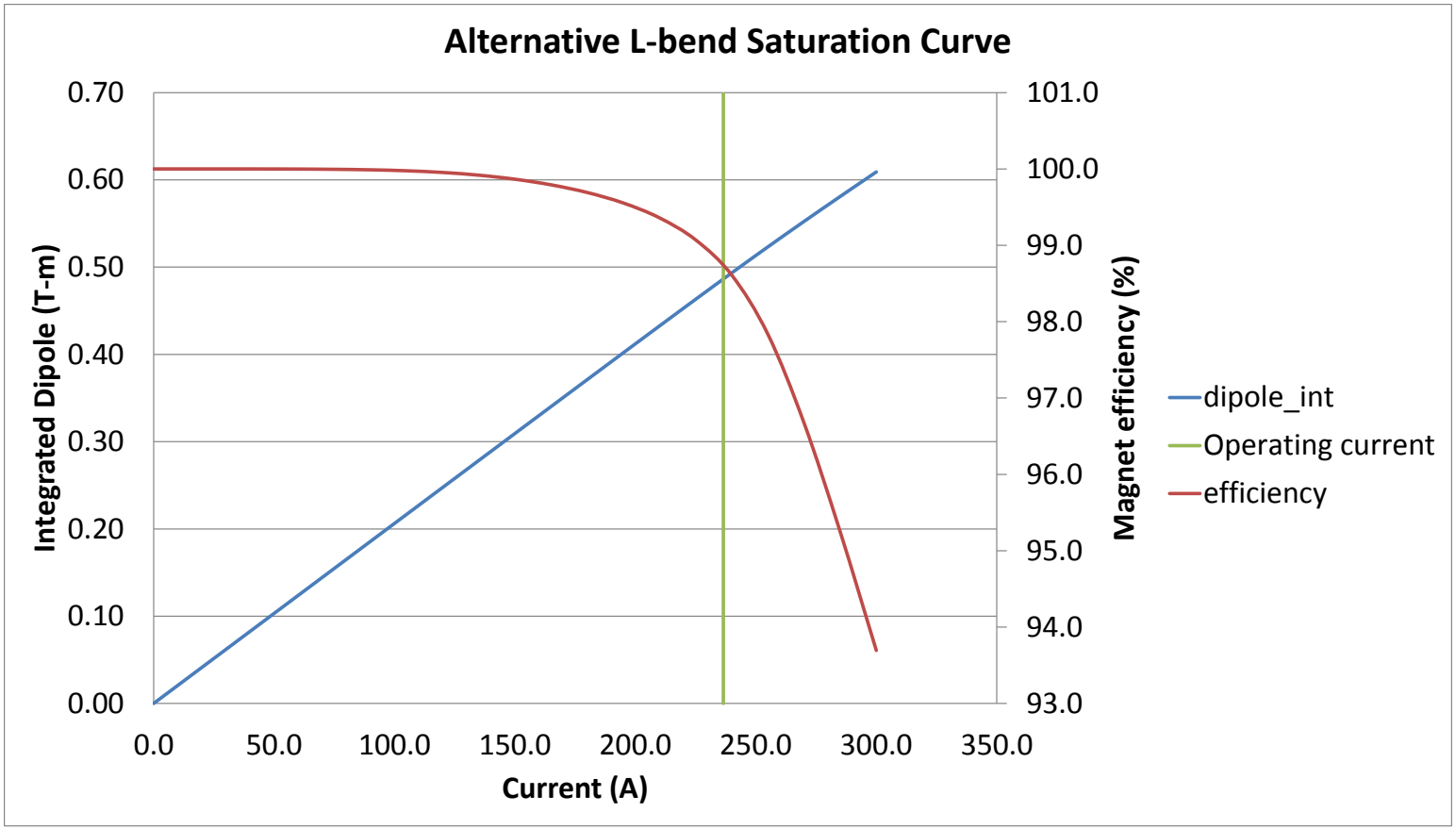
Alternative L-Bend Selected Parameters and field quality

Optimizing the pole tip will reduce the sextupole component

D_current	-236.60	A
B0_int	-486319	Gauss-cm
D_power	1200	W
Conductor square	8.0	mm
Conductor hole	5.0	mm
Flow rate (@ 90 psi)	0.036 (0.58)	l/s (gpm)
Temp. rise	8.0	°C

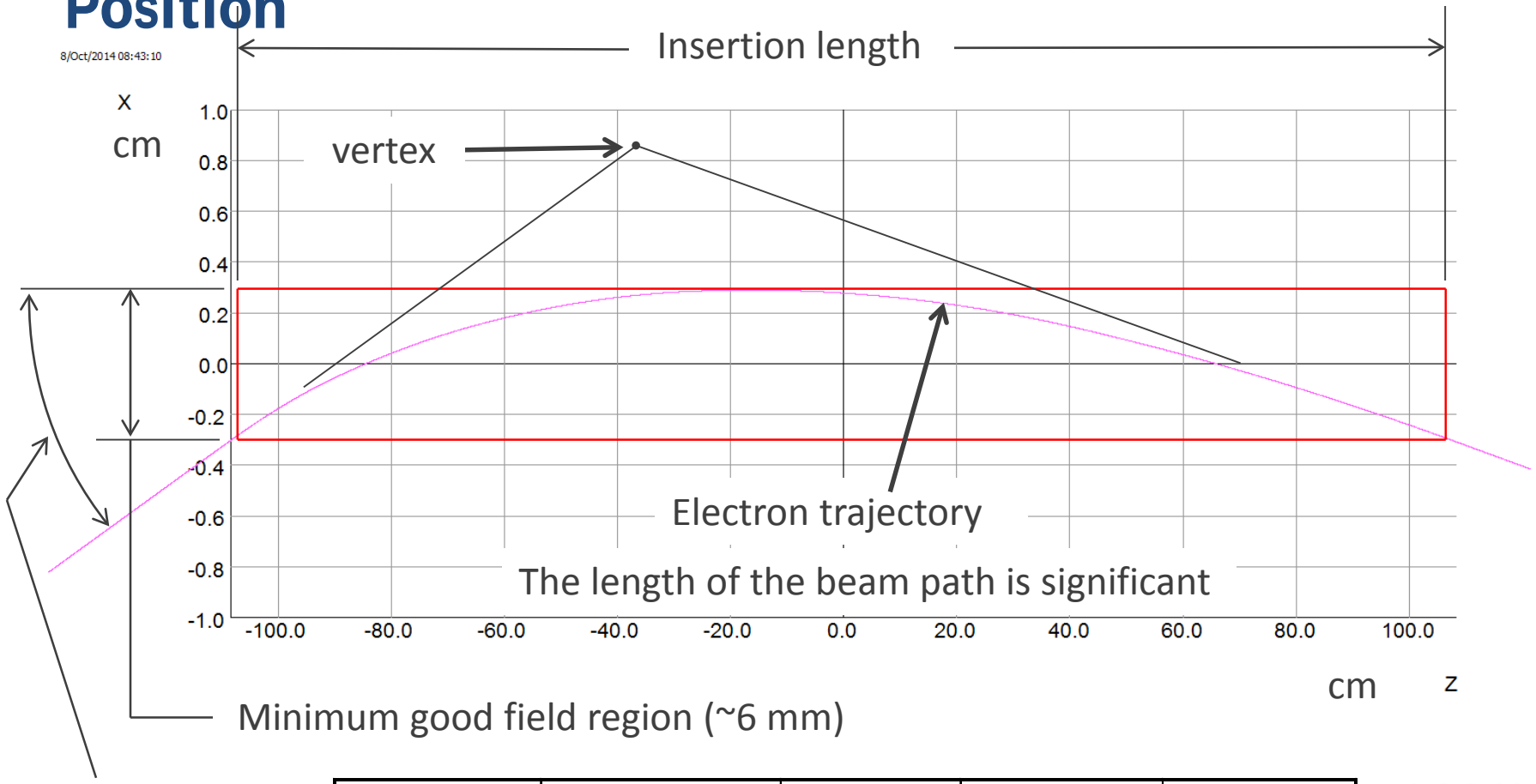
B0_int	10000	Units
B1_int	9	
B2_int	-13	
B3_int	3	
B4_int	-3	
B5_int	1	
B6_int	0	
B7_int	0	
B8_int	0	
B9_int	0	
B10_int	0	
B11_int	0	
B12_int	0	
B13_int	0	
B14_int	0	
B15_int	0	
B16_int	0	
B17_int	0	

Alternative L-Bend Saturation Curve



98.5% Magnet efficiency

Alternative L-Bend Position

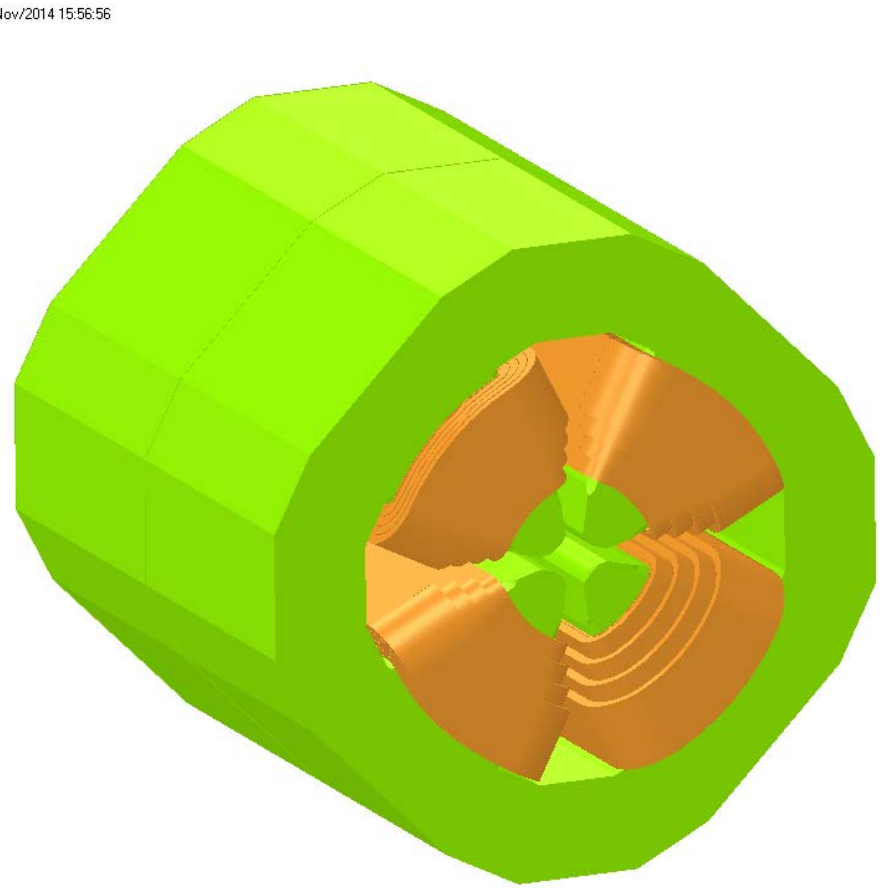


D_current	bend_angle	vertex_x	vertex_z	US_angle
A	°	mm	mm	°
-236.6	1.392	8.68	-359.36	0.925

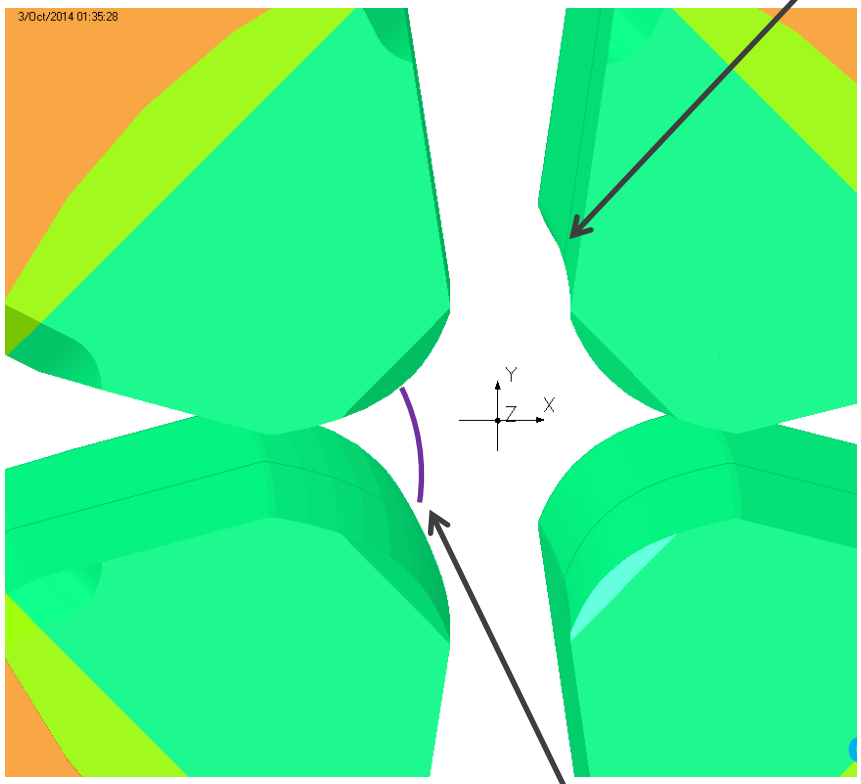
opera simulation software

Q-Bend

- It is a dipole magnet that looks like a quadrupole magnet.
- Produces both dipole and quadrupole fields.
- The beam is offset from center.
- It has curved pole tips.
- Pole tips are made of vanadium permendur.



Q-Bend
M4



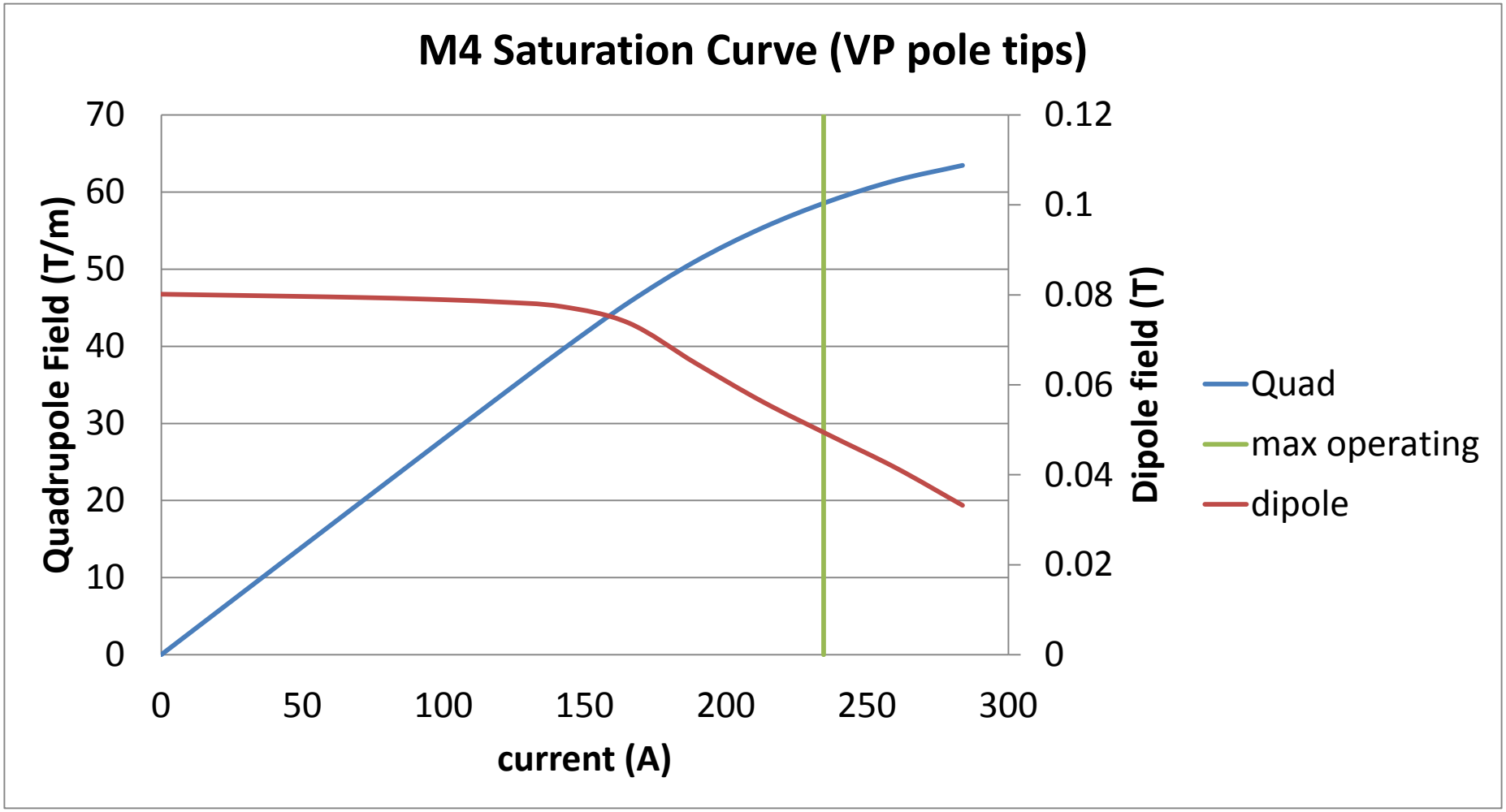
Curved tips

Electron Trajectory

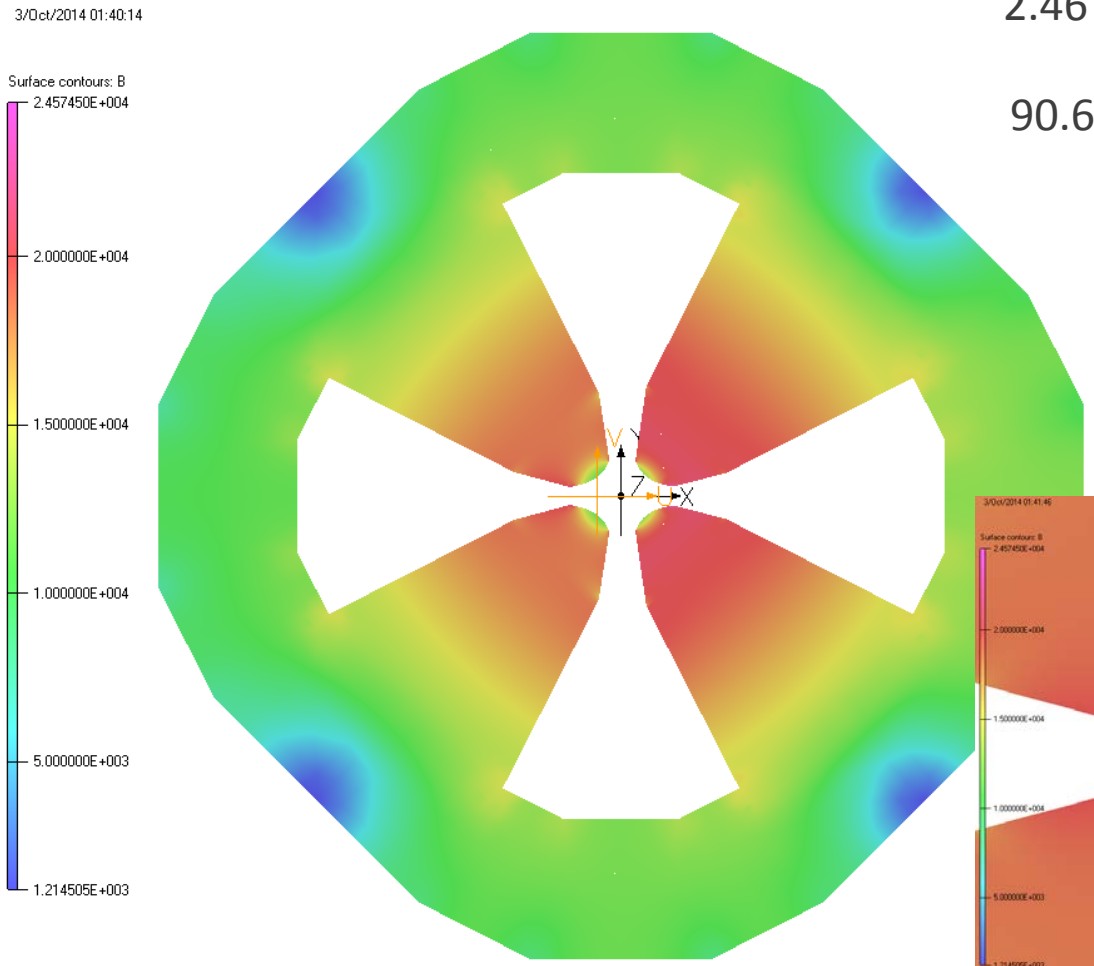
current_Q	236.48	A
current_VD	-18.80	A
B1_central	56.16	T/m
B0_central	-0.6708	T
Q_power	7884	W
#VD_power	660	W
x_offset	-12.53	mm
sagitta	1.412	mm
bend_angle	1.126	degrees
vertex	-1.037	mm

Vanadium Permendur
Pole tips
90.6 % magnet efficiency

Q-Bend
M4

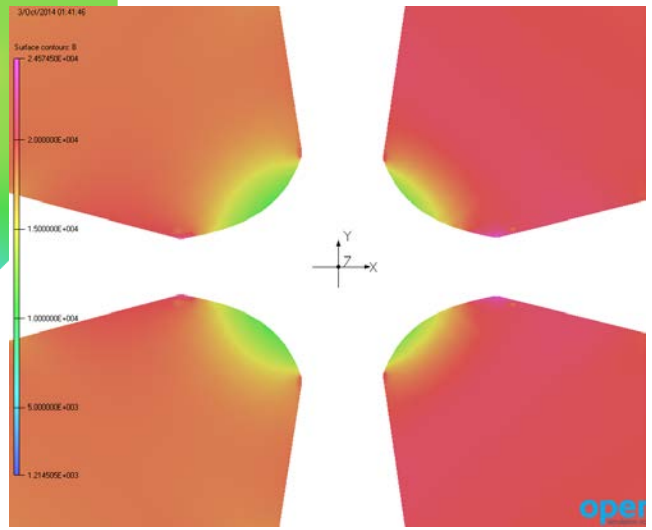

M4 Saturation Curve (VP pole tips)
Quadrupole Field (T/m)
70
60
50
40
30
20
10
0
0
50
100
150
200
250
300
current (A)
0.12
0.1
0.08
0.06
0.04
0.02
0
Dipole field (T)
Quad
max operating
dipole

Q-Bend
M4



2.46 T max

90.6 % magnet efficiency



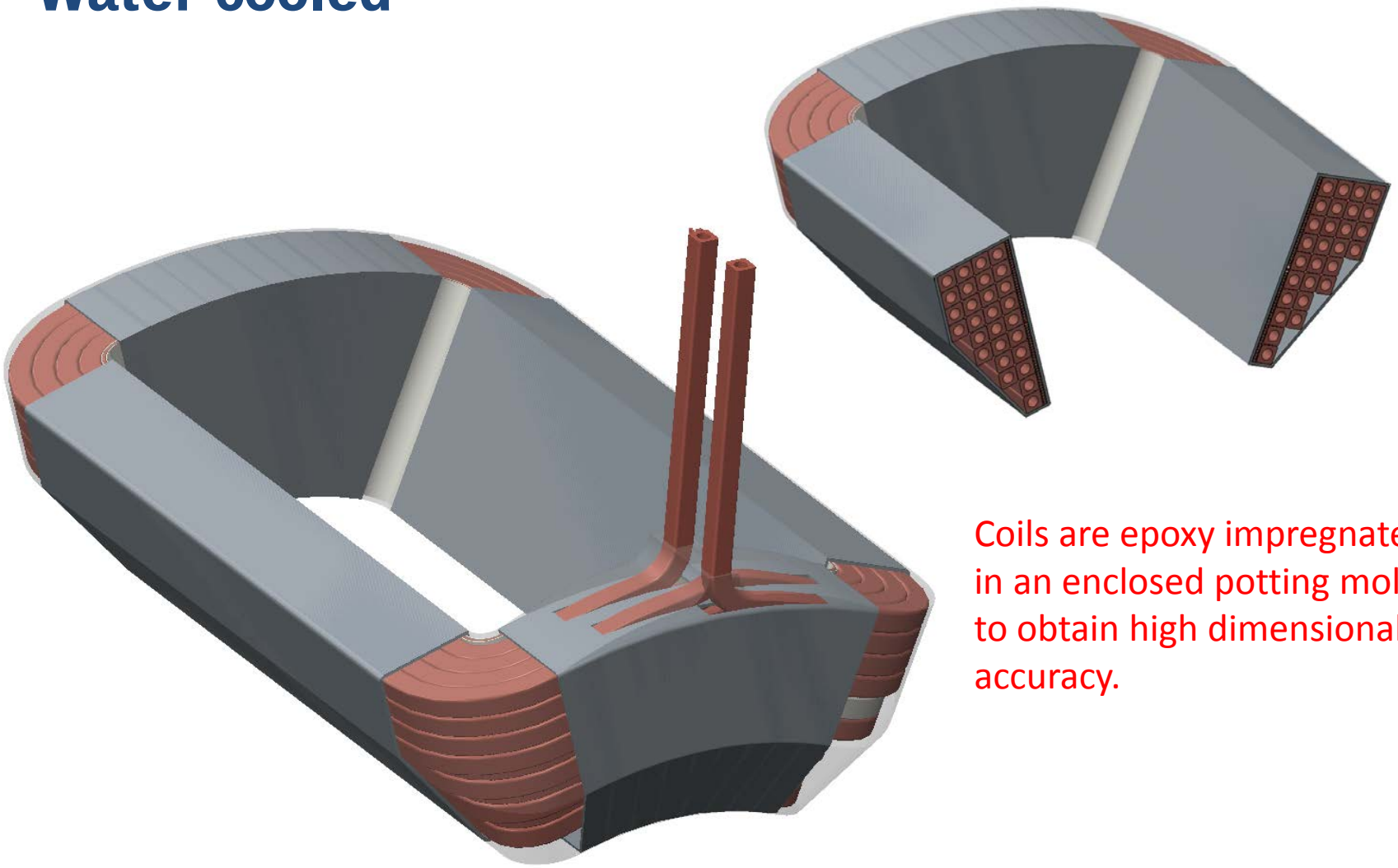
Q-Bend

- M4.
- Field quality.
- At maximum field.

B0_int	10000.0	Units R_{ref} = 10mm
B1_int	-8374.2	
B2_int	-144.7	
B3_int	-7.5	
B4_int	5.4	
B5_int	-0.1	
B6_int	1.1	
B7_int	-0.9	
B8_int	-3.9	
B9_int	0.3	
B10_int	6.6	
B11_int	-1.8	
B12_int	-10.2	
B13_int	12.3	
B14_int	-2.5	
B15_int	-5.1	
B16_int	2.1	
B17_int	4.5	

Vanadium Permendur
90.6 % magnet efficiency

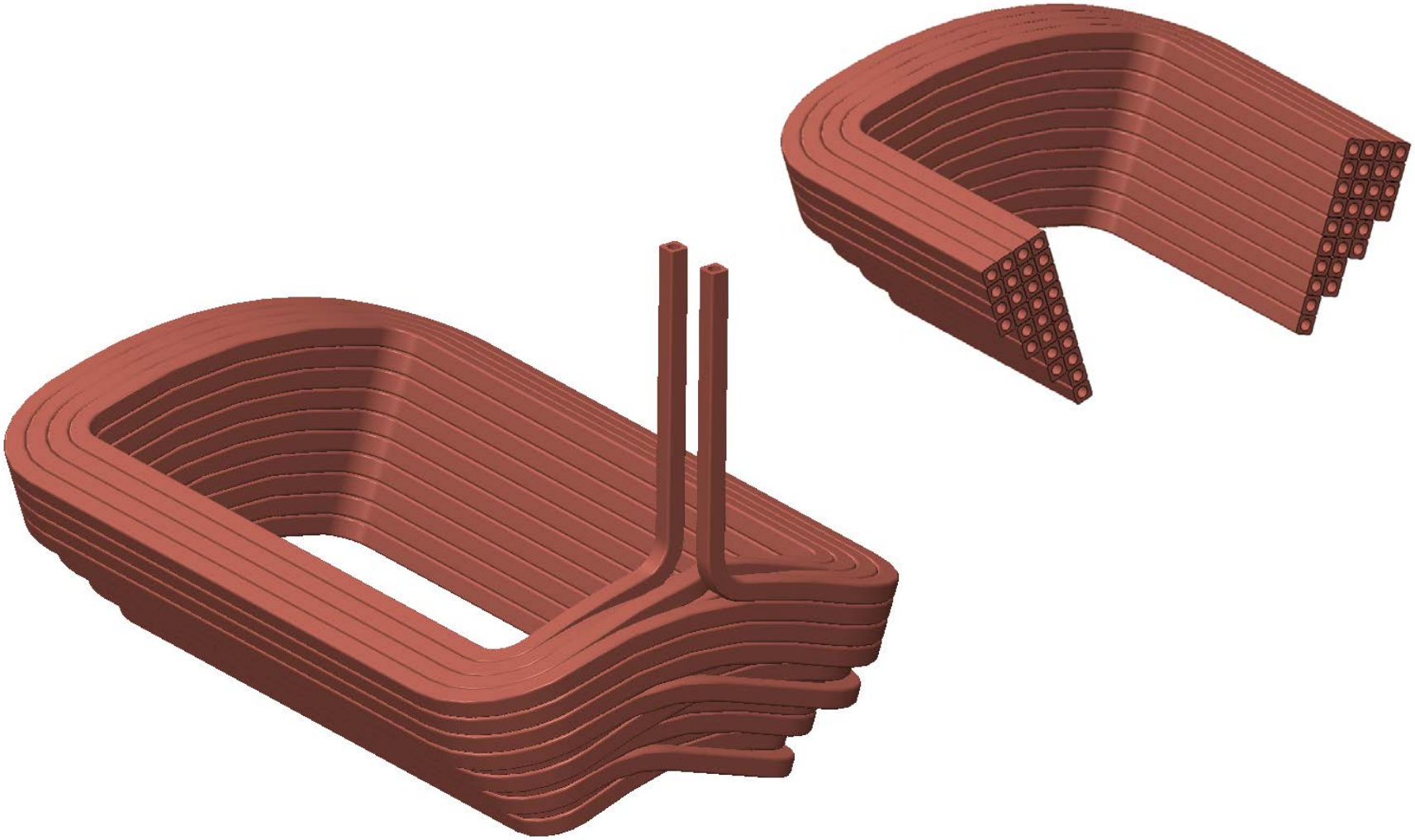
Quadrupole Coil
Water cooled



Coils are epoxy impregnated in an enclosed potting mold to obtain high dimensional accuracy.

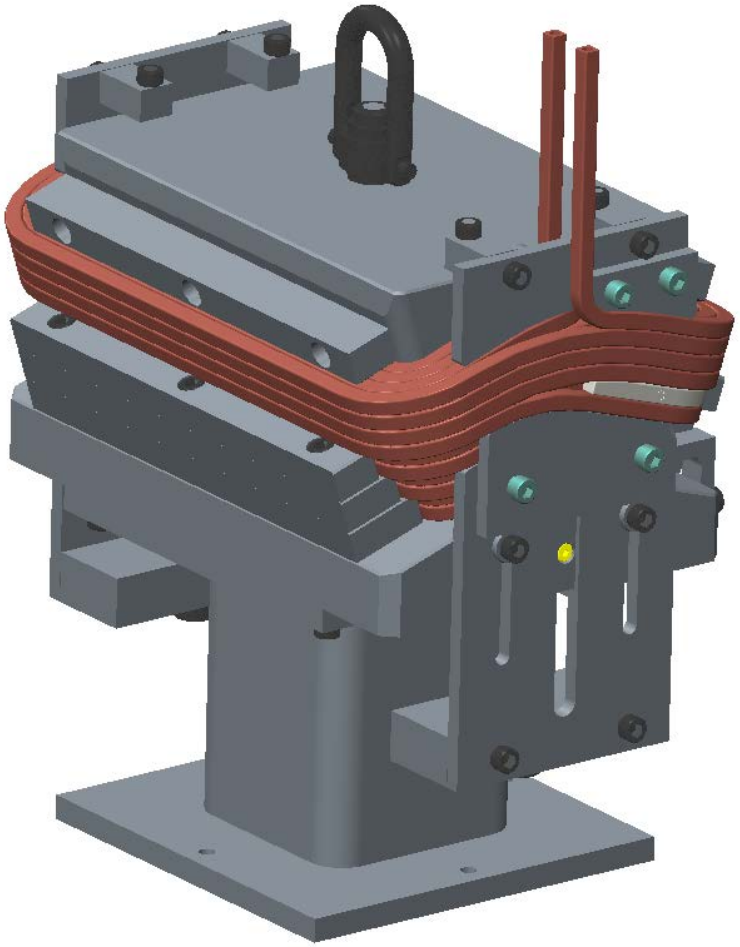
Model created by Aric Donnelly

Quadrupole Coil
Model of copper only

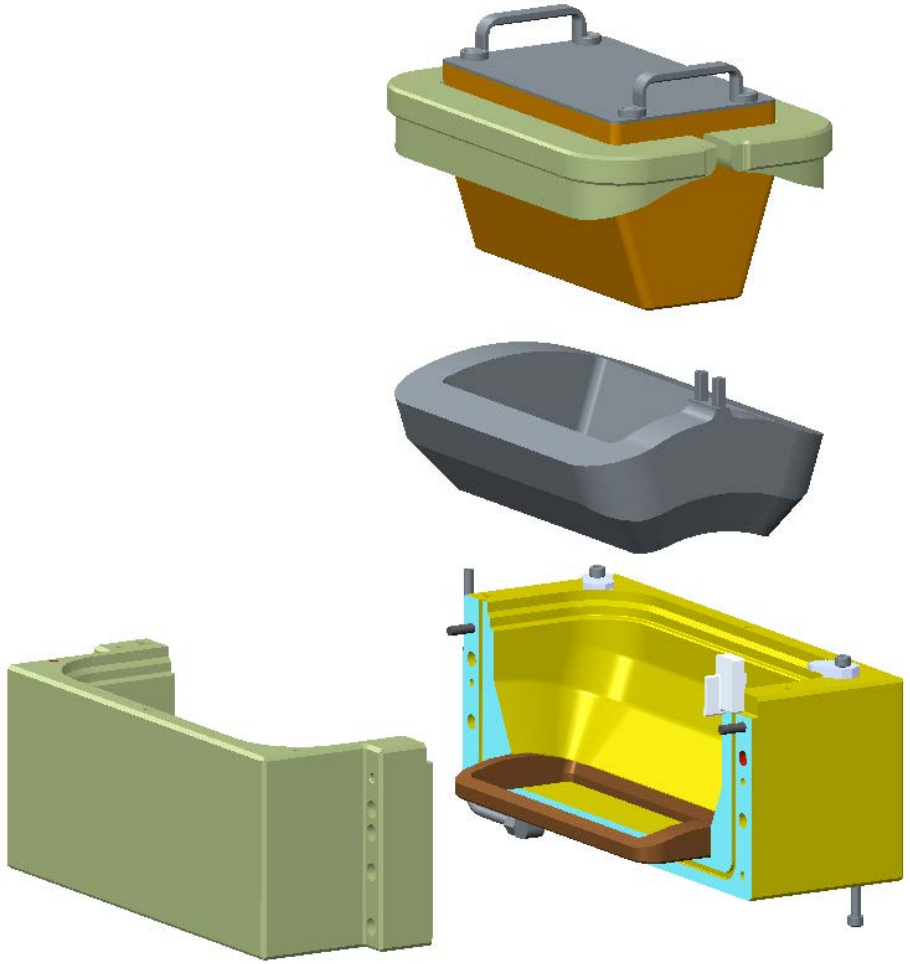


Model created by Aric Donnelly

Quadrupole Coil
Models of winding and potting tooling

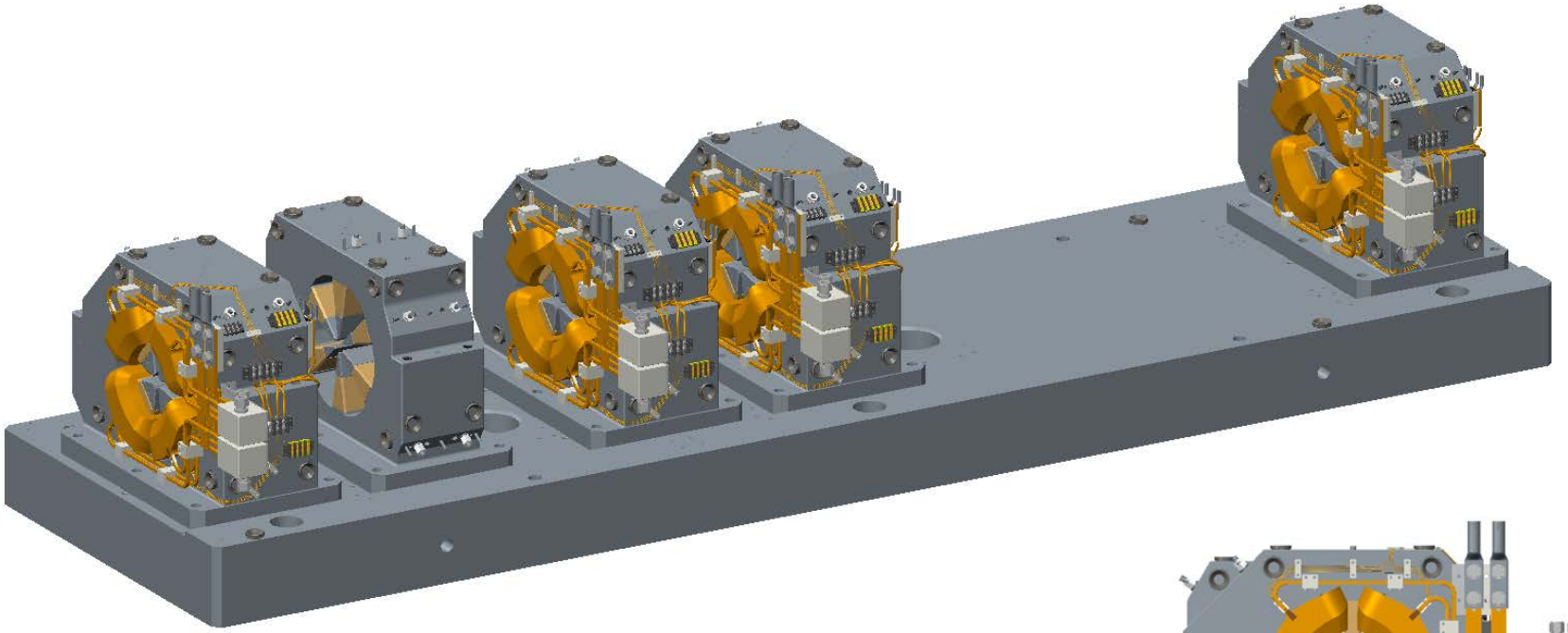


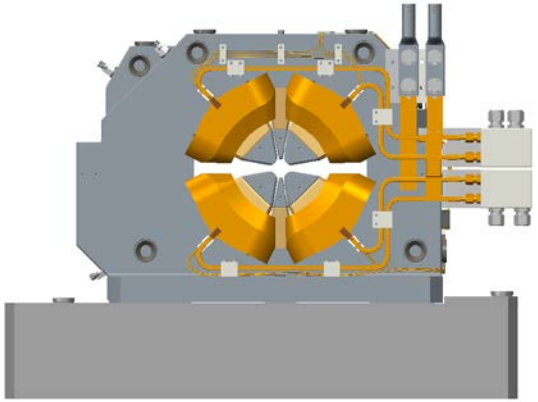
Winding Tooling



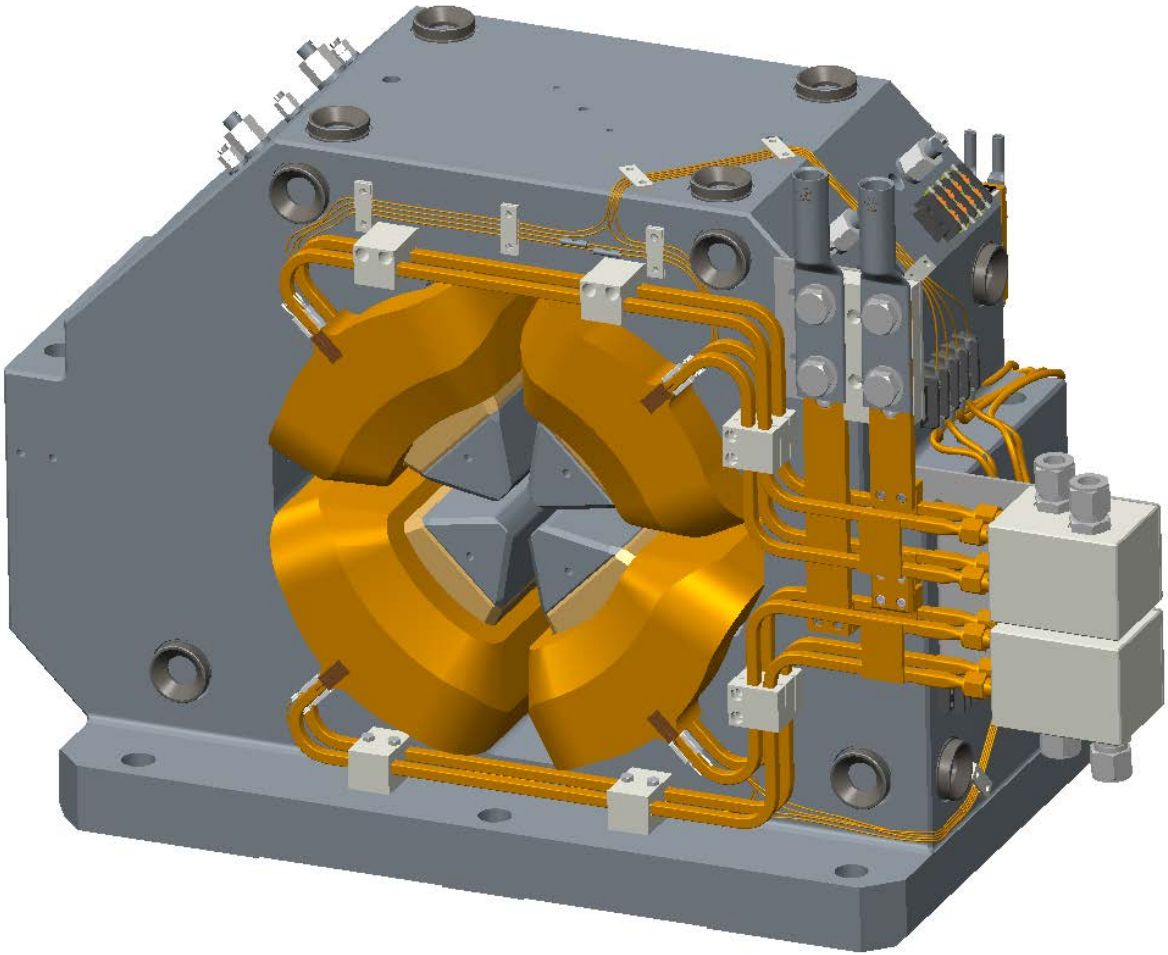
Potting Tooling

Demo-Modular-Multiplet (DMM)



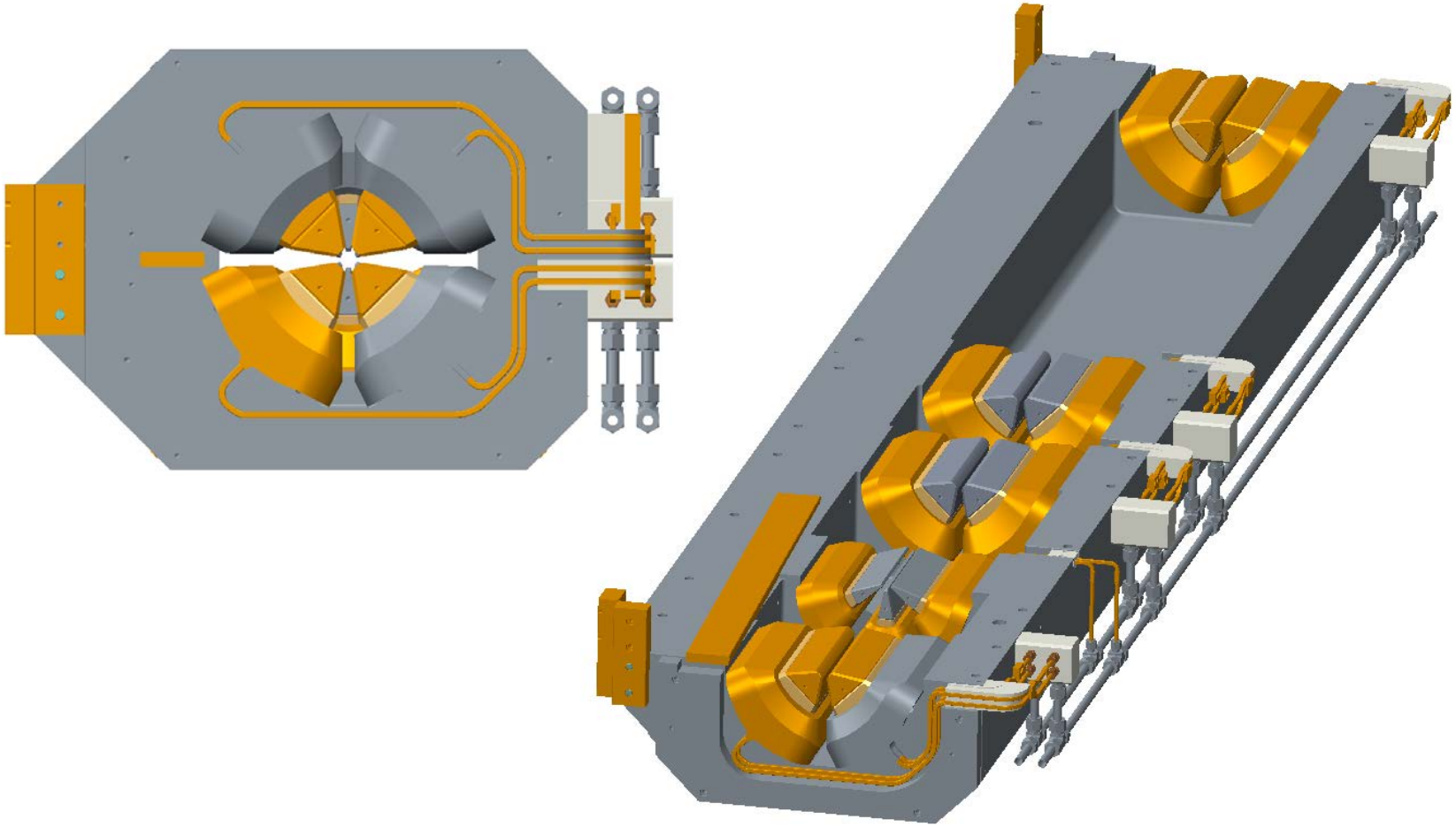


Quadrupole Magnet Assembly for DMM

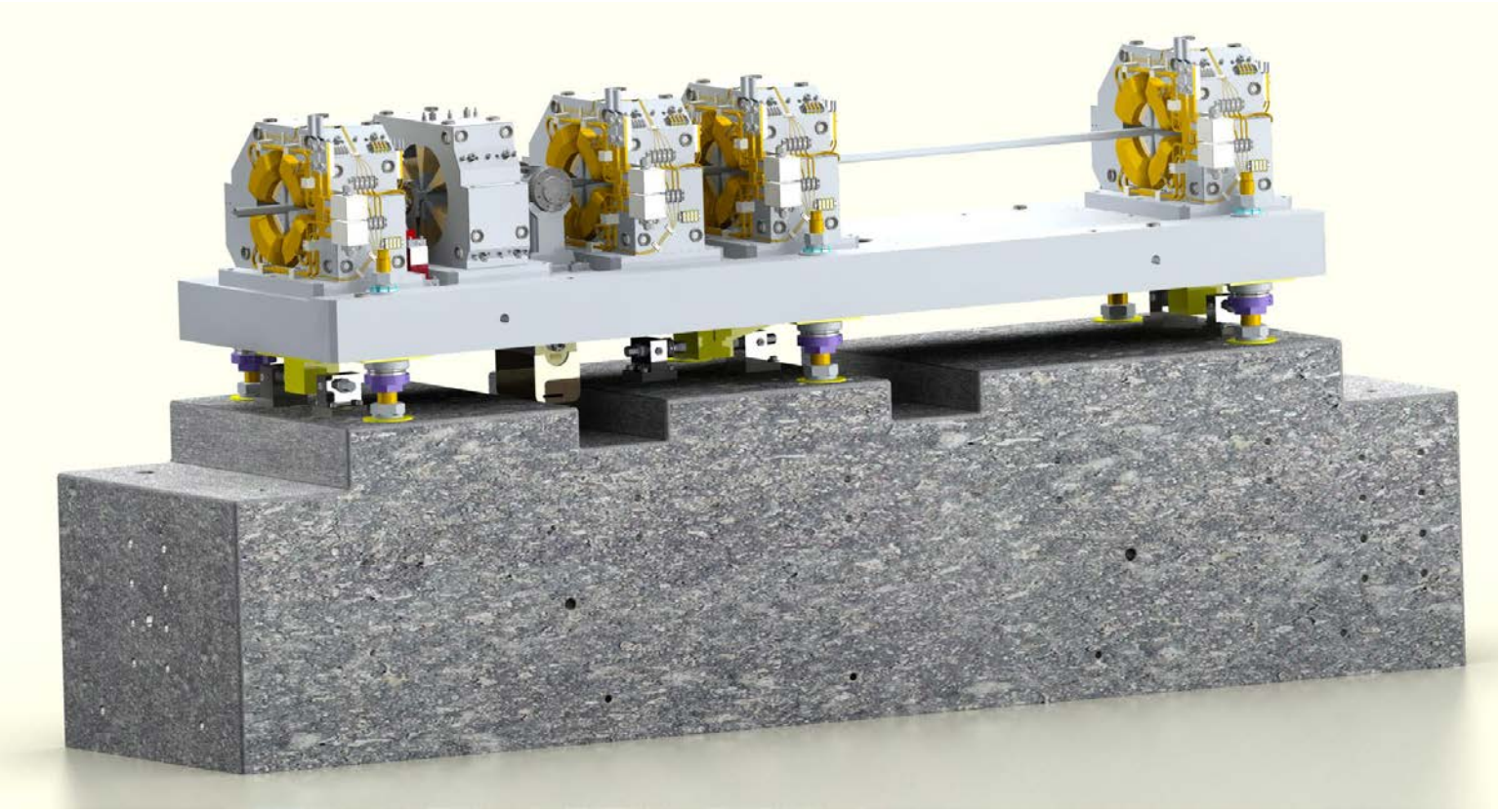


Quadrupole Sextupole Quadrupole (QSQ)

Quadrupole Sextupole Quadrupole (QSQ)



DMM mounted on a granite plinth



Rendering by Bill Turner