APS Upgrade: Magnets

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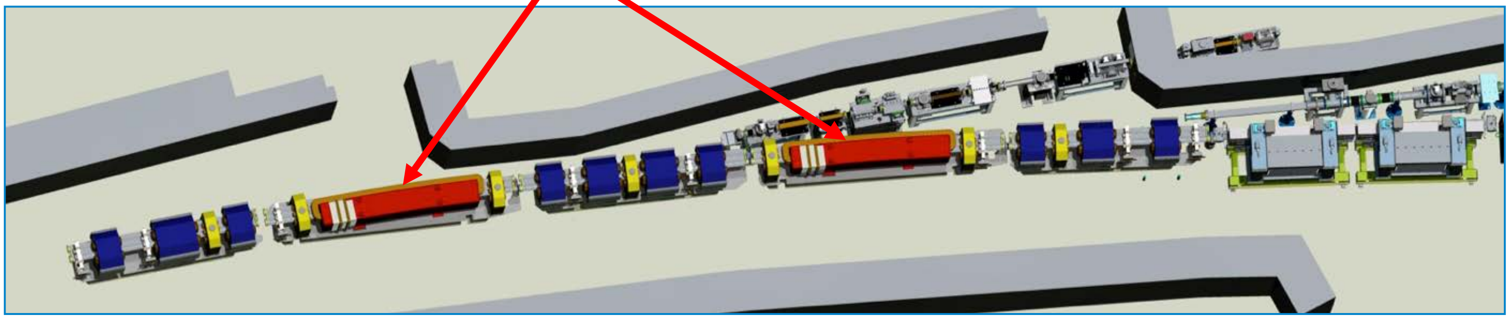
ASD Seminar
April 12, 2017

Outline

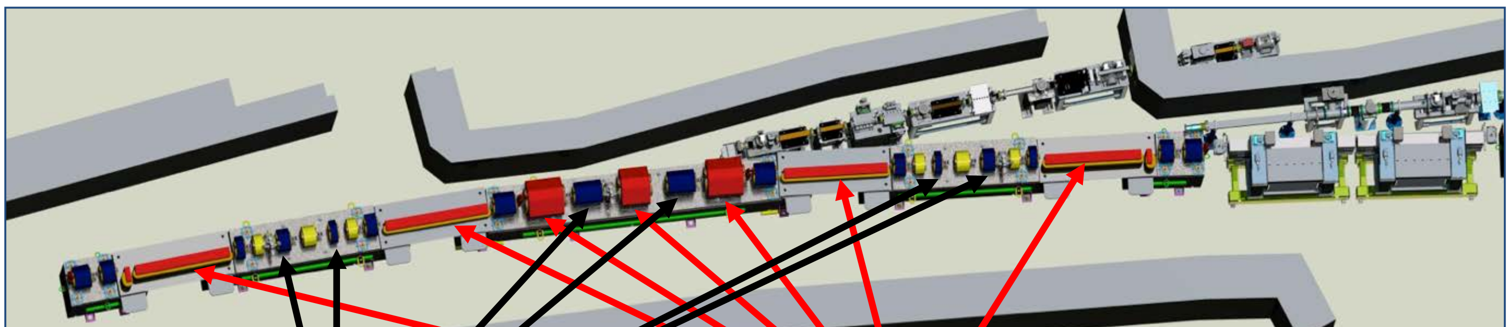
- Before and After
- Scope
- Design maturity
- 8-piece-quadrupole
- Review of the remaining magnets
- Future plans
- Summary
- Staff/org chart

Before and After one sector

two dipole magnets – double-bend-achromat



Before



After

Six Reverse bend quadrupole magnets

Seven dipole magnets

Four (4) longitudinal gradient dipole magnets
Three (3) transverse gradient dipole magnets
Six (6) reverse bend quadrupole magnets

} 13 bends

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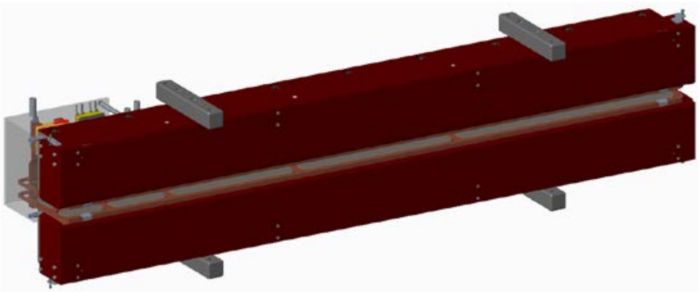
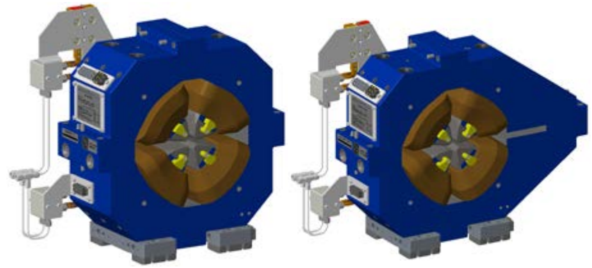
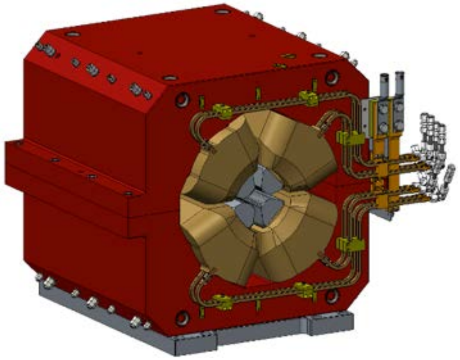
APSU Magnets Scope



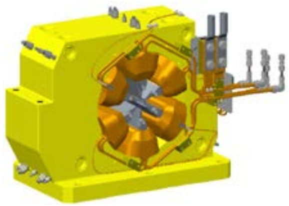
L-Bend Magnets (M1, M2)



Q1, Q2, Q3, Q6 and Q7 Quadrupole Magnets

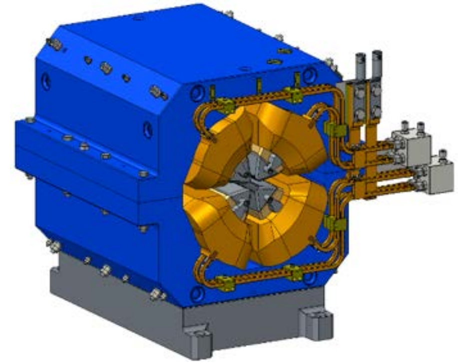


Q-Bend Magnets
M3,M4

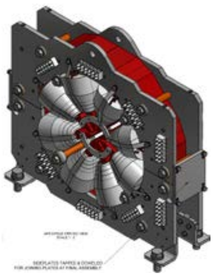


Sextupole Magnets
S1- S3

Item	ID	Types of Magnets	Pole tip material	Total Quantity
1	M1	Longitudinal dipoles	steel	80
2	M2	Longitudinal dipoles	steel	80
3	M3	Transverse-Gradient dipoles	VP	80
4	M4	Transverse-Gradient dipoles	VP	40
5	Q1	Quadrupole	VP	80
6	Q2	Quadrupole	steel	80
7	Q3 and Q6	Quadrupole (**similar to Q2**)	**steel**	160
8	Q4	**Reverse bend Quadrupole**	VP	80
9	Q5	**Reverse bend Quadrupole**	**steel**	80
10	Q7	Quadrupole	VP	80
11	Q8	**Reverse bend Quadrupole**	VP	80
12	S1 and S3	Sextupole	steel	160
13	S2	Sextupole	VP	80
14	FC1 and FC2	Fast Corrector	lamination	160
VP = vanadium permedur			Total Magnets 1320	



Reverse bend Quadrupole
Magnets
Q4, Q5, and Q8



8-Pole Corrector
(FC1 and FC2)

Items in red are what changed from 67pm to 41pm.
Magnet lengths also changed from 67pm to 41pm.

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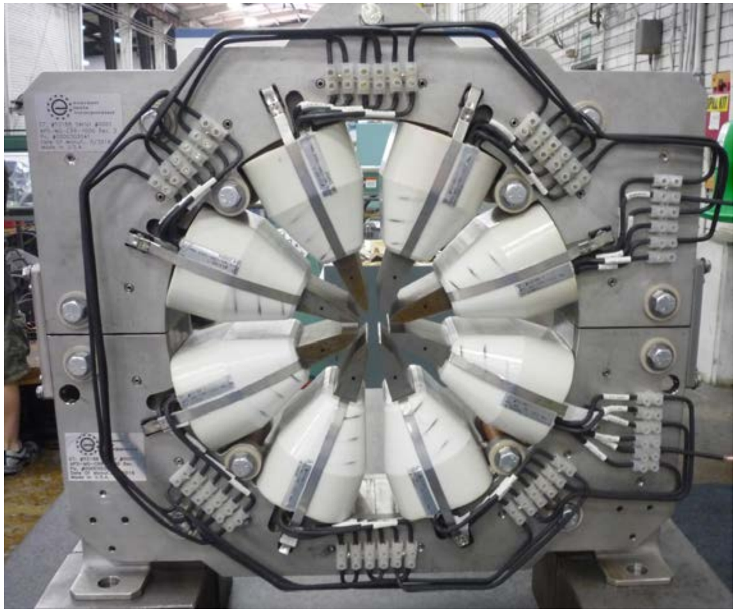
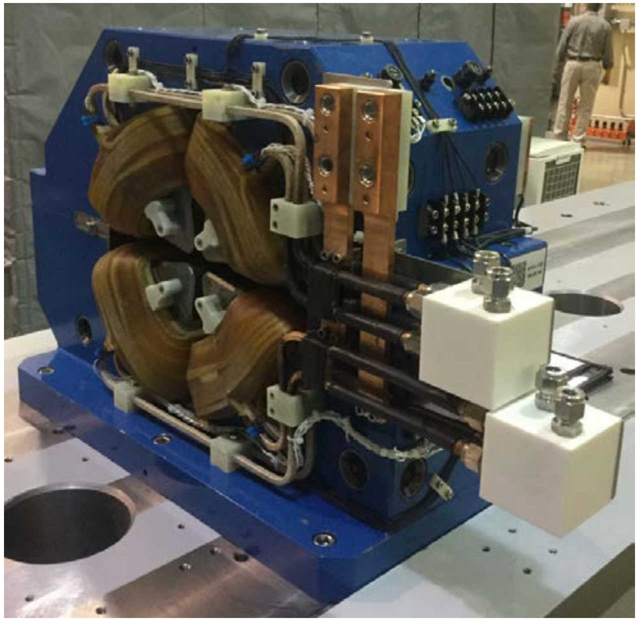
APSU Magnet Design & Design Maturity



Corrector Magnet (laminated)

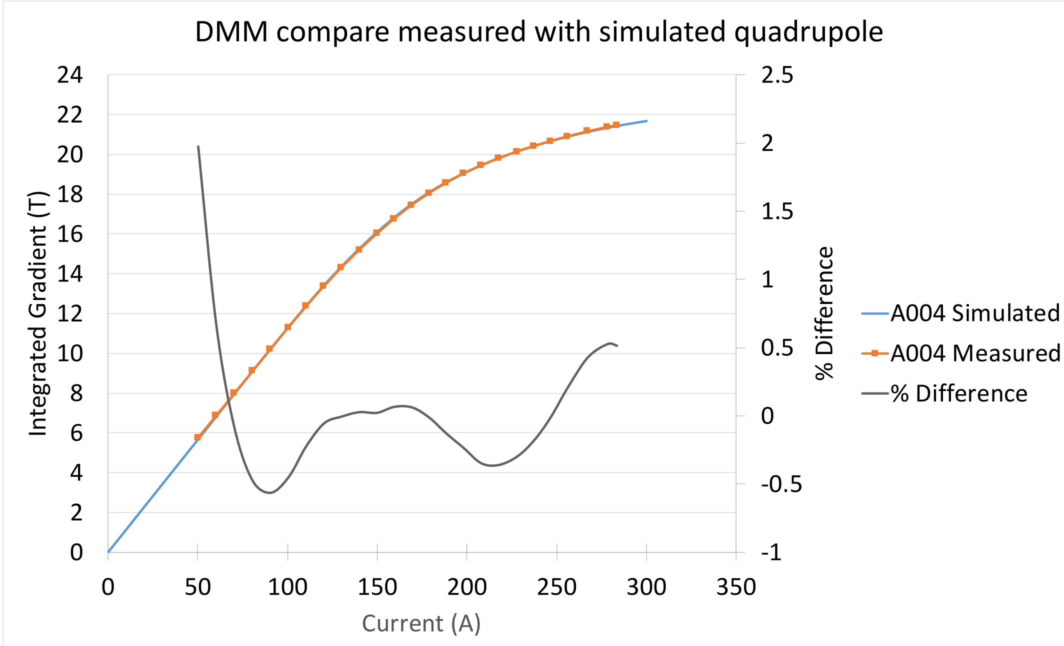
Designed by Brookhaven National Laboratory measurements agree with simulations. Vacuum chamber positioning is critical.



Demonstration Modular Multiplet (DMM) Quadrupole Magnet

Simulations agree with magnet measurements.

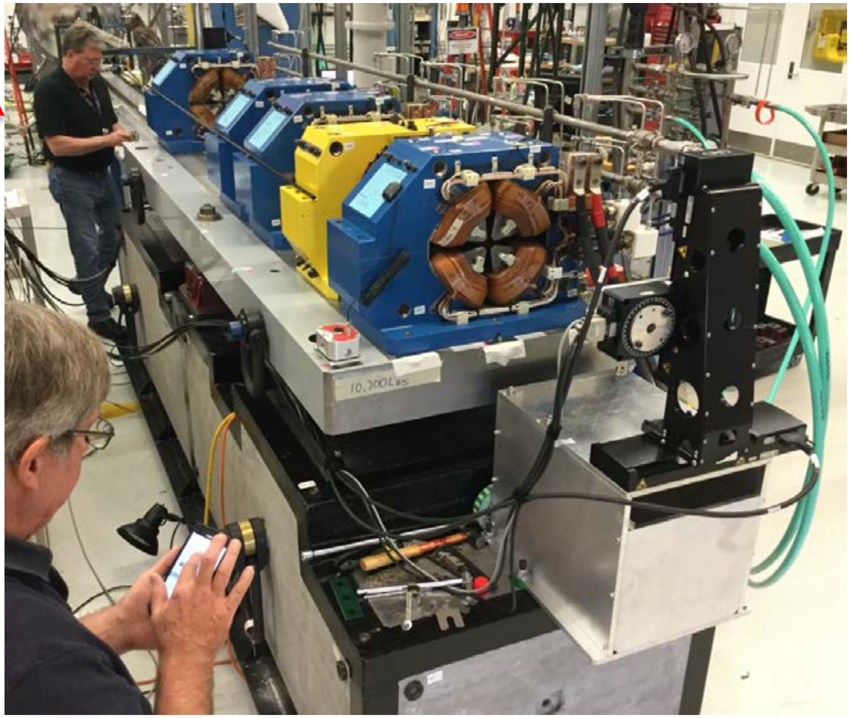
Prototypes Agree with Simulation



- The DMM R&D quadrupole magnet strength measurements agreed with simulated models within a few percent.
- The magnet quality measurements were very good.
- The predicted temperature rise matched the measured temperature rise at the maximum current.
- The long-lead procurement quads Q1 and Q2 lengths are of comparable size to the DMM quadrupole magnets. The DMM magnets are 269 mm long while the Q1 and Q2 magnets are 250 and 225 mm long respectively.
- We expect that Q1 and Q2 will perform in agreement with simulations as demonstrated with the DMM magnets.
- **We are confident** our calculations will match production magnet measurements.

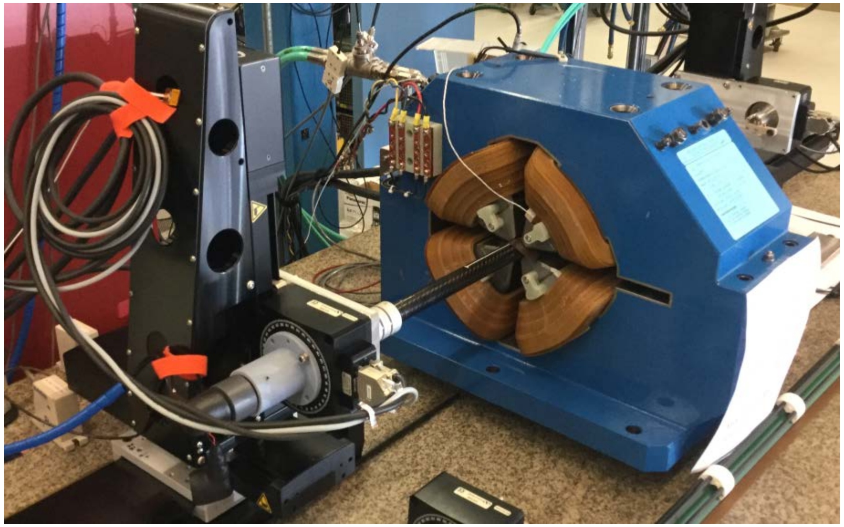
APSU Magnet Requirements & Design Maturity

- Magnet requirements are consistent with the 41pm lattice.
- The most challenging aspects of these magnets are addressed with prototype designs and testing.
  - DMM Assembly
  - 3 magnet FODO
  - M1 L-bend
  - Corrector magnet
    - Designed by Brookhaven National Laboratory

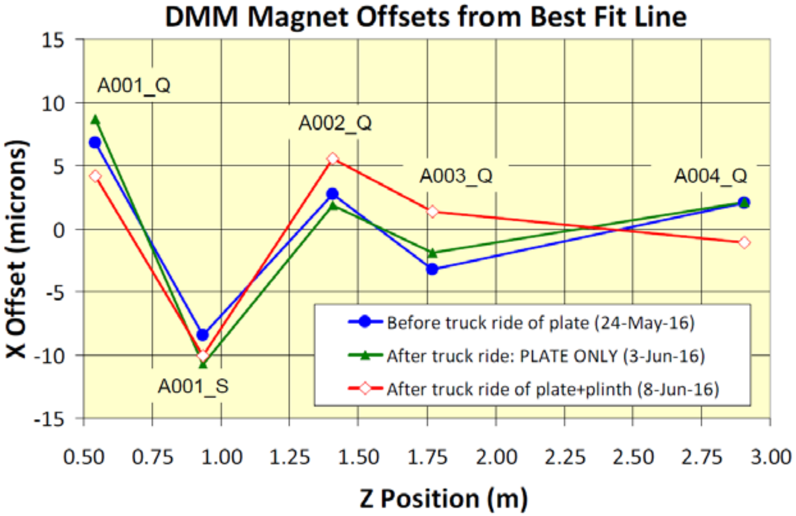


APSU Magnet Design & Design Maturity

Take the DMM assembly for a ride



Magnetically measure a DMM quadrupole magnet



DMM Transportation Tests

Positioning repeated within 5 microns per magnet. The target is all magnets inline within 30 microns rms. Final align is 5.5 microns rms x offset.

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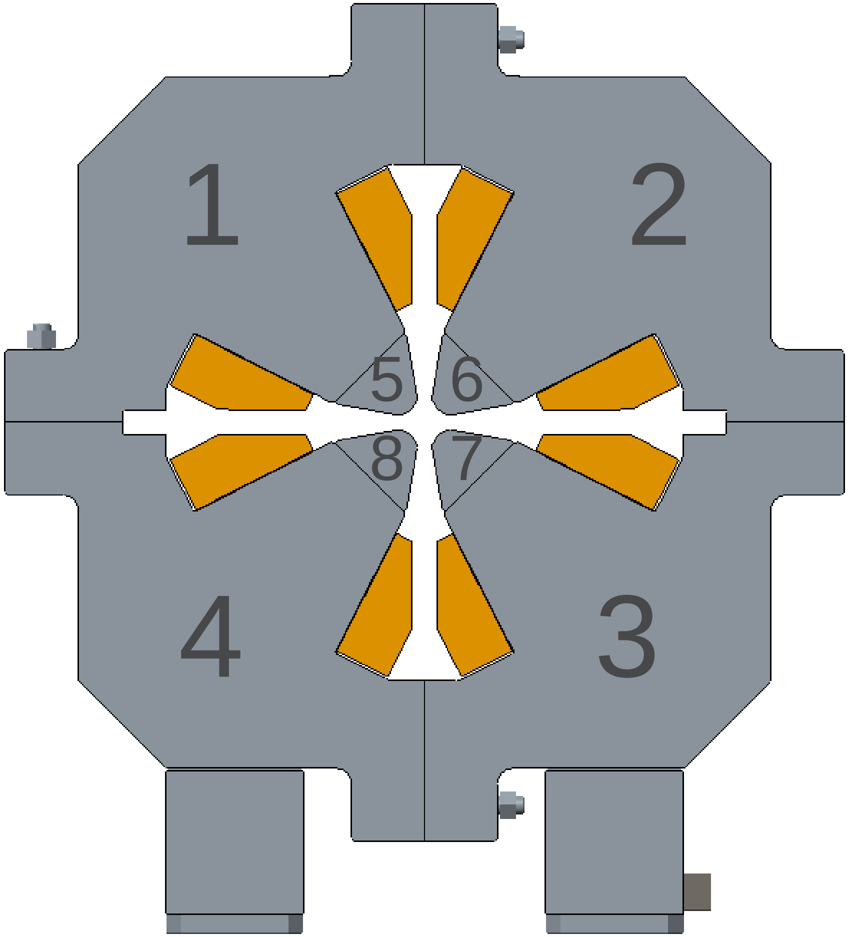
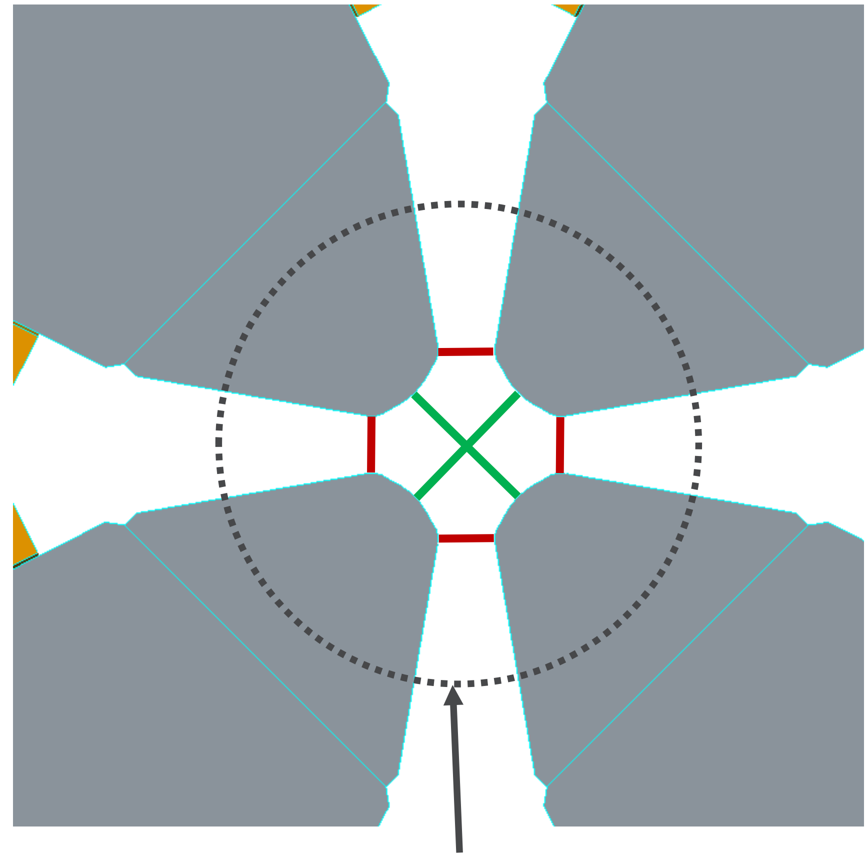
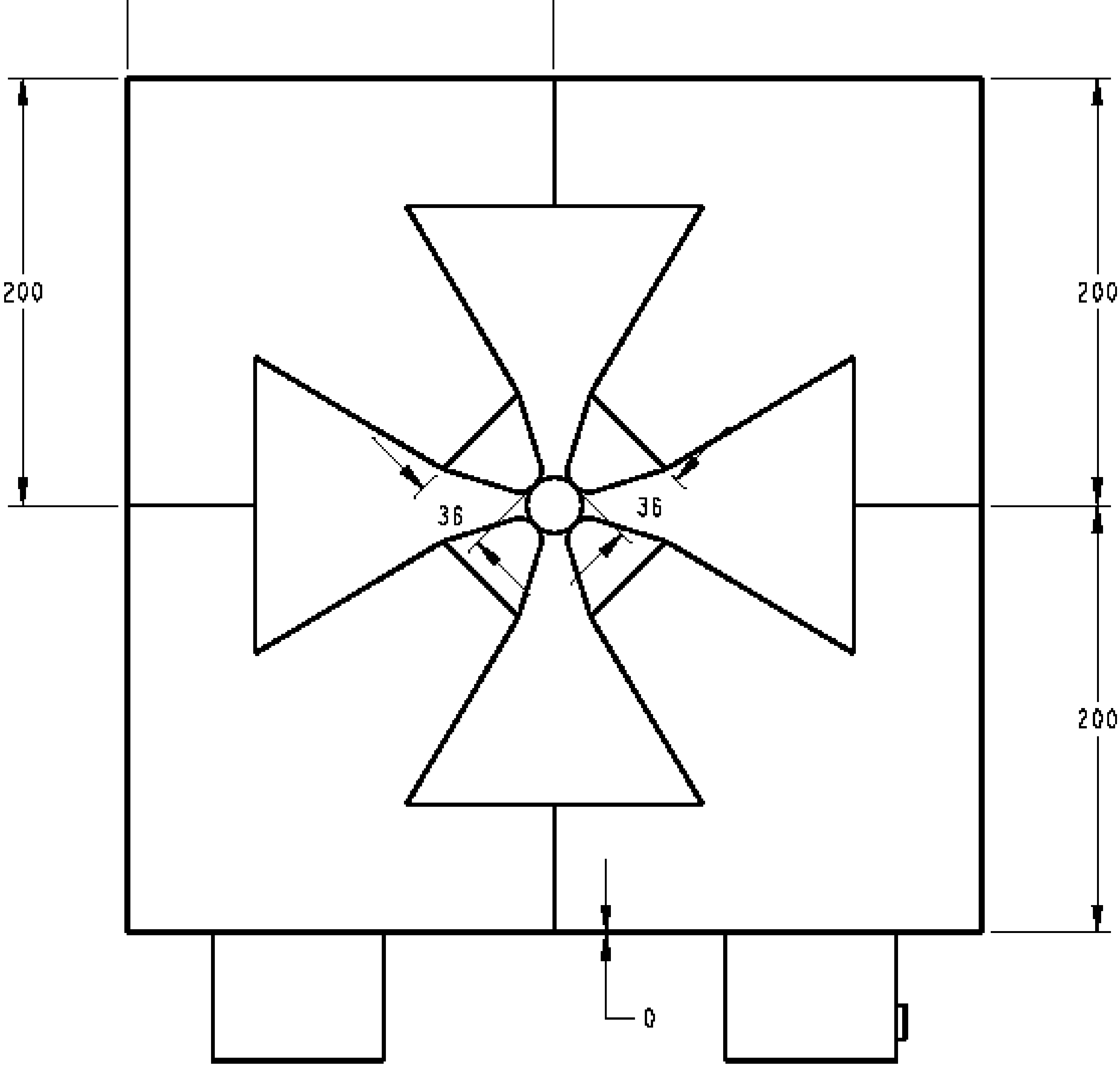
8 Piece Quadrupole

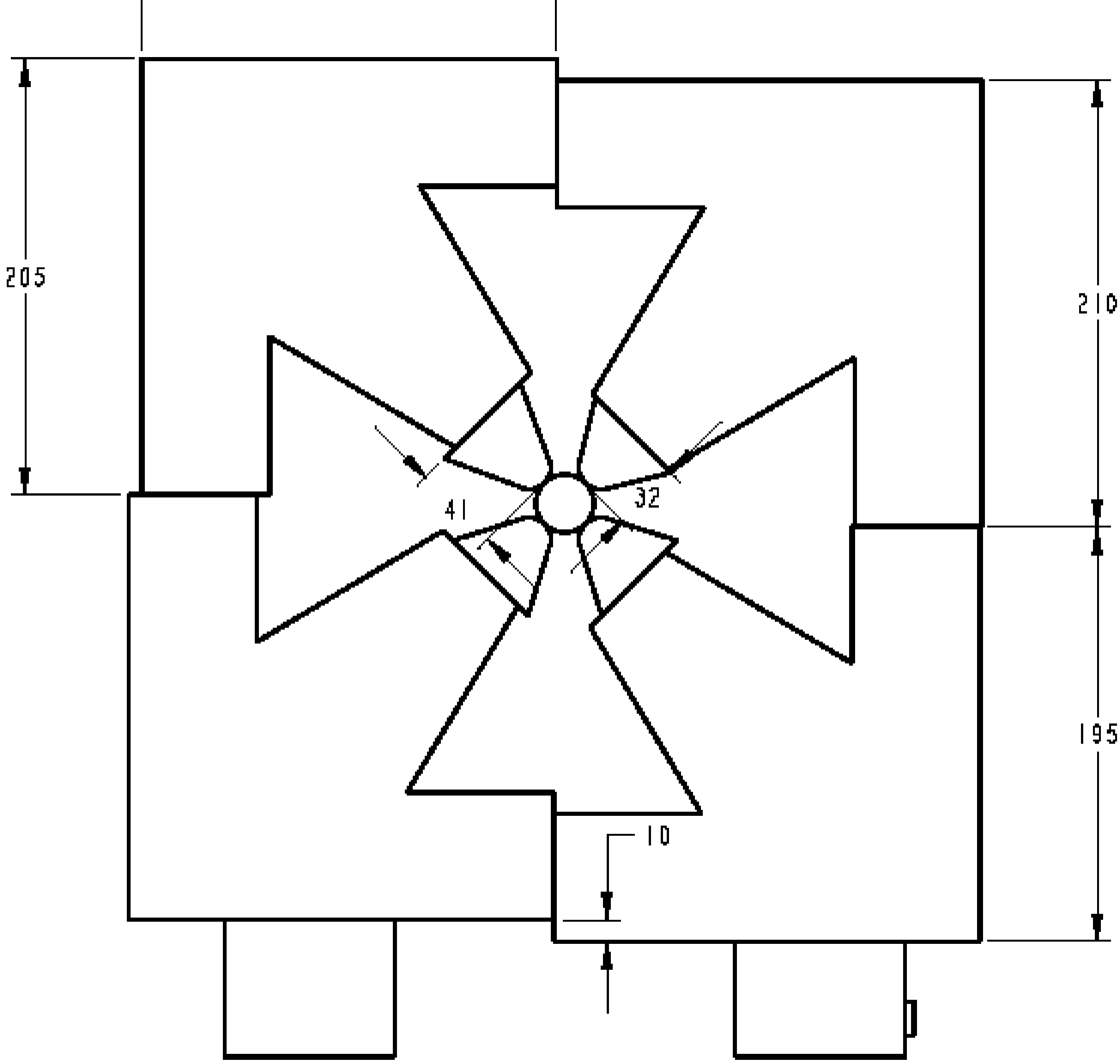


If the spaces and the spaces can be kept equal (symmetrical) then the multipole errors will be small.



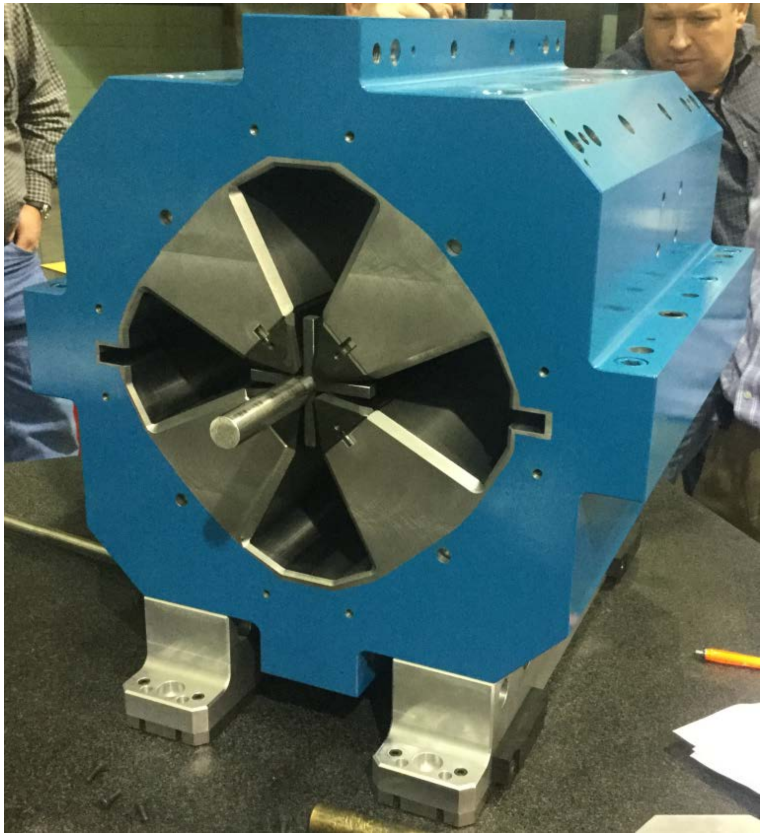
Area of precision.
Inside needs to be precisely positioned. Outside position is not as critical. The further away from the center the less precision is needed.


200
200
200
36
36
0

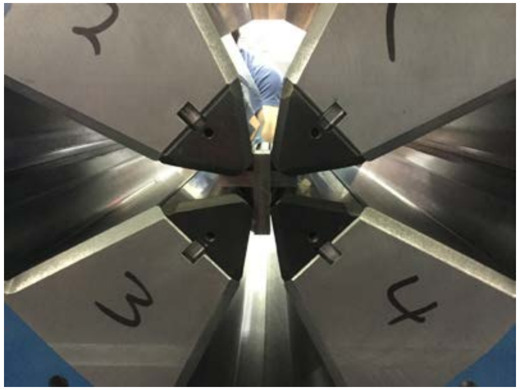

205
210
41
32
195
10

8 Piece Quadrupole

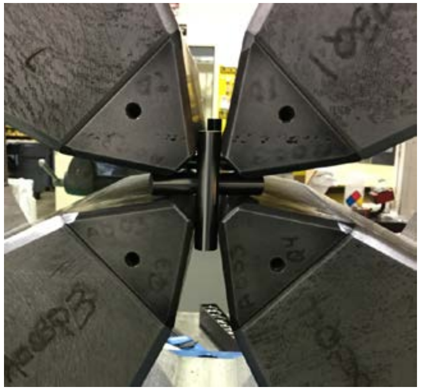
Allows very accurate positioning of the pole tips which essentially promises good field quality



Q8 prototype
(Machined cross, shown, does not work well)



Q8 prototype with crisscross gauge blocks



DMM prototype with crisscross dowel pins (gauge blocks work better)

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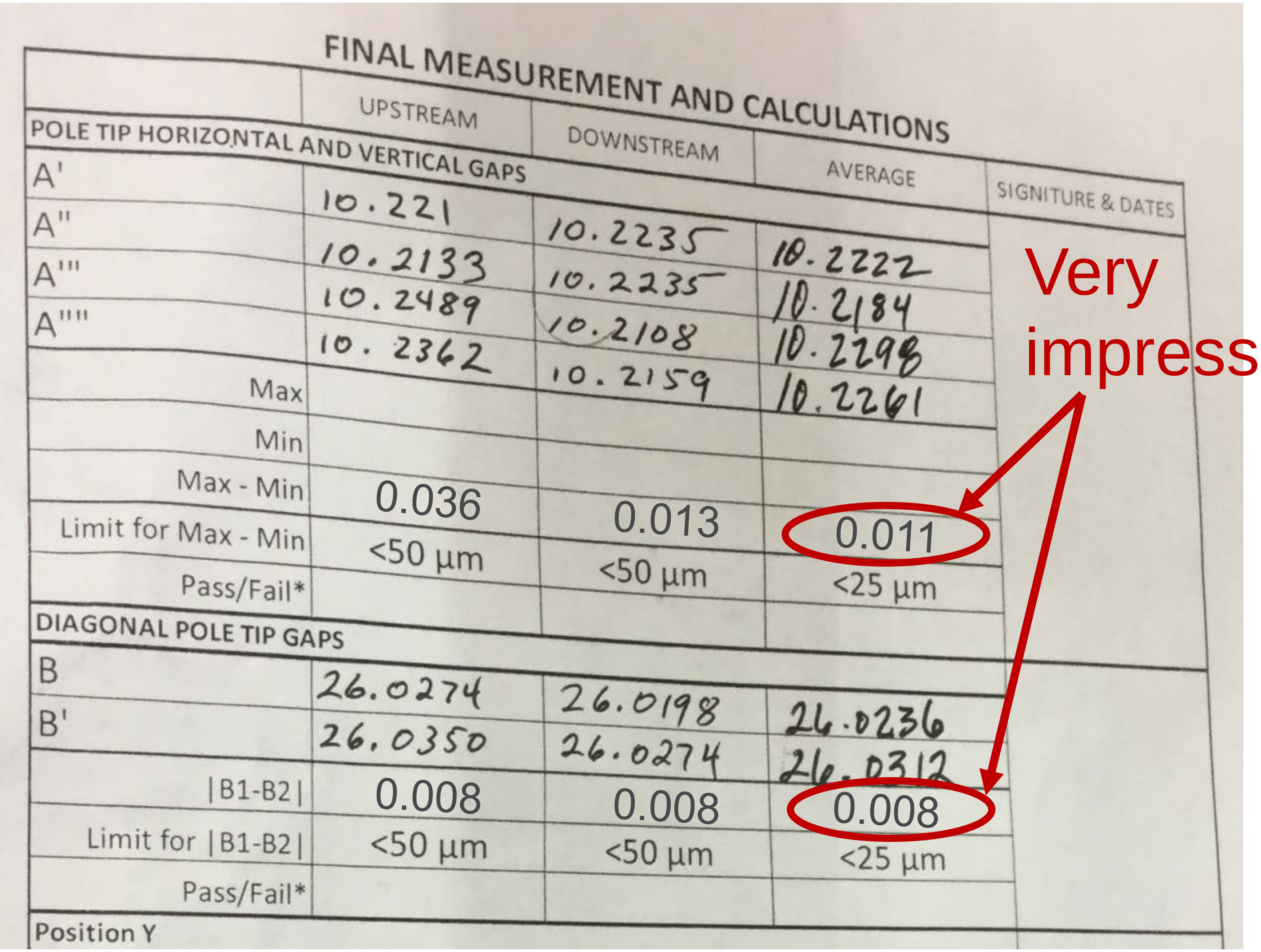
Q8 core measurements after assemble



FINAL MEASUREMENT AND CALCULATIONS

<table>
<tr><th></th><th>UPSTREAM</th><th>DOWNSTREAM</th><th>AVERAGE</th><th>SIGNITURE & DATES</th></tr>
<tr><td>POLE TIP HORIZONTAL AND VERTICAL GAPS</td><td></td><td></td><td></td><td></td></tr>
<tr><td>A'</td><td>10.221</td><td>10.2235</td><td>10.2222</td><td></td></tr>
<tr><td>A''</td><td>10.2133</td><td>10.2235</td><td>10.2184</td><td></td></tr>
<tr><td>A'''</td><td>10.2489</td><td>10.2108</td><td>10.2298</td><td></td></tr>
<tr><td>A''''</td><td>10.2362</td><td>10.2159</td><td>10.2261</td><td></td></tr>
<tr><td>Max</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Min</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Max - Min</td><td>0.036</td><td>0.013</td><td>0.011</td><td></td></tr>
<tr><td>Limit for Max - Min</td><td><50 µm</td><td><50 µm</td><td><25 µm</td><td></td></tr>
<tr><td>Pass/Fail*</td><td></td><td></td><td></td><td></td></tr>
<tr><td>DIAGONAL POLE TIP GAPS</td><td></td><td></td><td></td><td></td></tr>
<tr><td>B</td><td>26.0274</td><td>26.0198</td><td>26.0236</td><td></td></tr>
<tr><td>B'</td><td>26.0350</td><td>26.0274</td><td>26.0312</td><td></td></tr>
<tr><td>|B1-B2|</td><td>0.008</td><td>0.008</td><td>0.008</td><td></td></tr>
<tr><td>Limit for |B1-B2|</td><td><50 µm</td><td><50 µm</td><td><25 µm</td><td></td></tr>
<tr><td>Pass/Fail*</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Position Y</td><td></td><td></td><td></td><td></td></tr>
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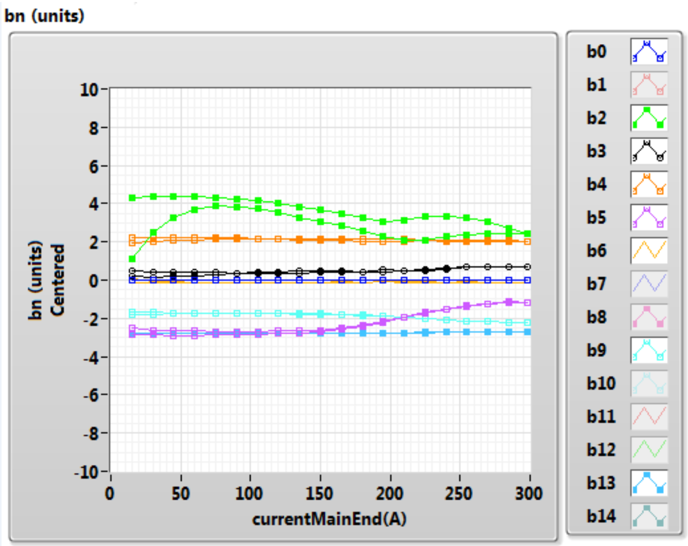
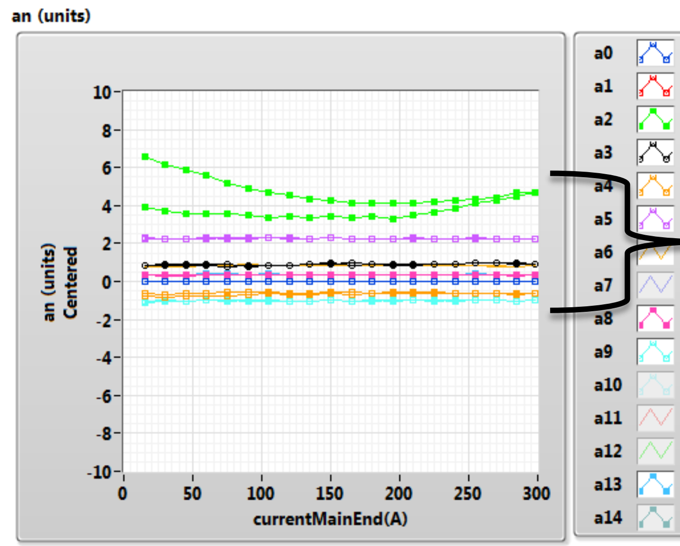
Very impressive

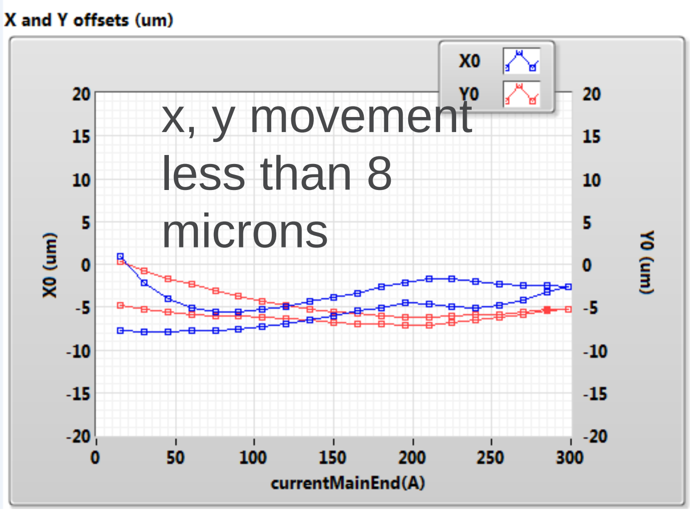
Q8 prototype

Q8 prototype measurements

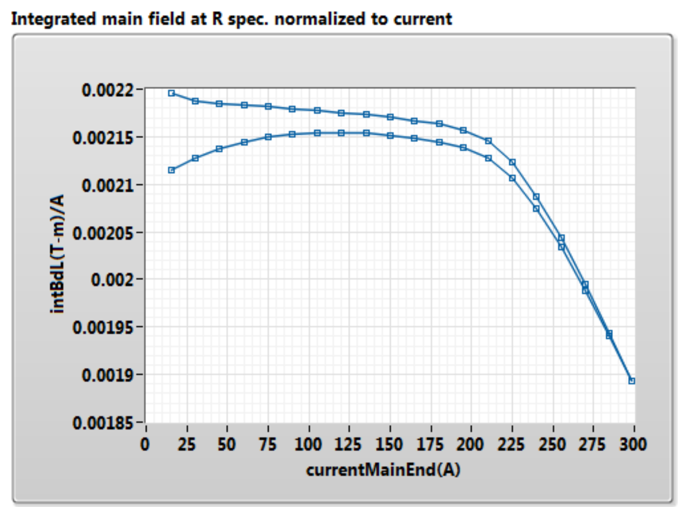
Measurements and data supplied by Chuck Doose.







x, y movement less than 8 microns



All multipole less than 5 units with exception of the sextupole at almost 7 units.

Multipoles required to be less than 10 units using a reference radius of 10 mm.

A unit is 1E-4 of the main field.

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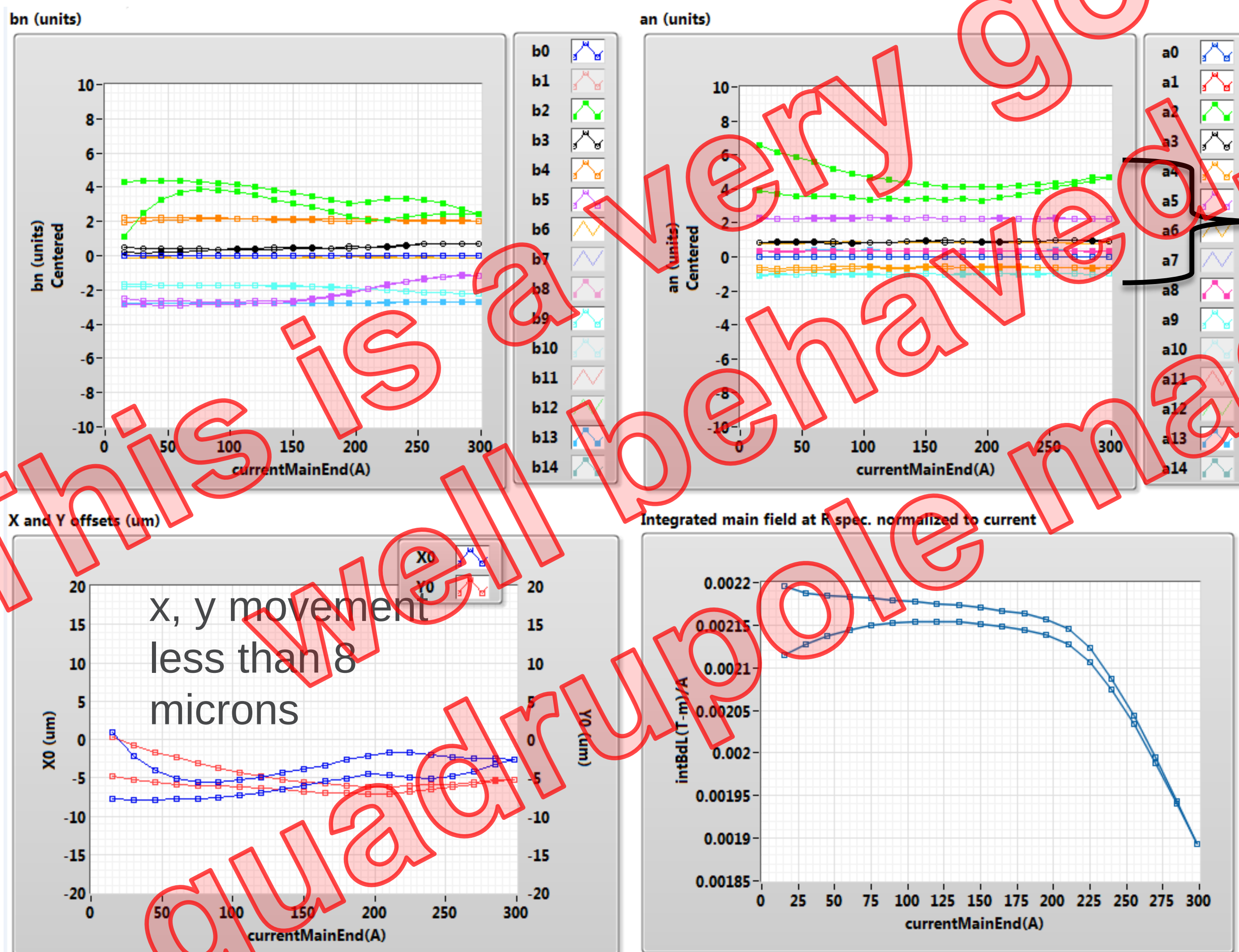
Q8 prototype measurements

Measurements and data supplied by Chuck Doose.



All multipole less than 5 units with exception of the sextupole at almost 7 units.

Multipoles required to be less than 10 units using a reference radius of 10 mm.

A unit is 1E-4 of the main field.

This is a very good, well behaved quadrupole magnet

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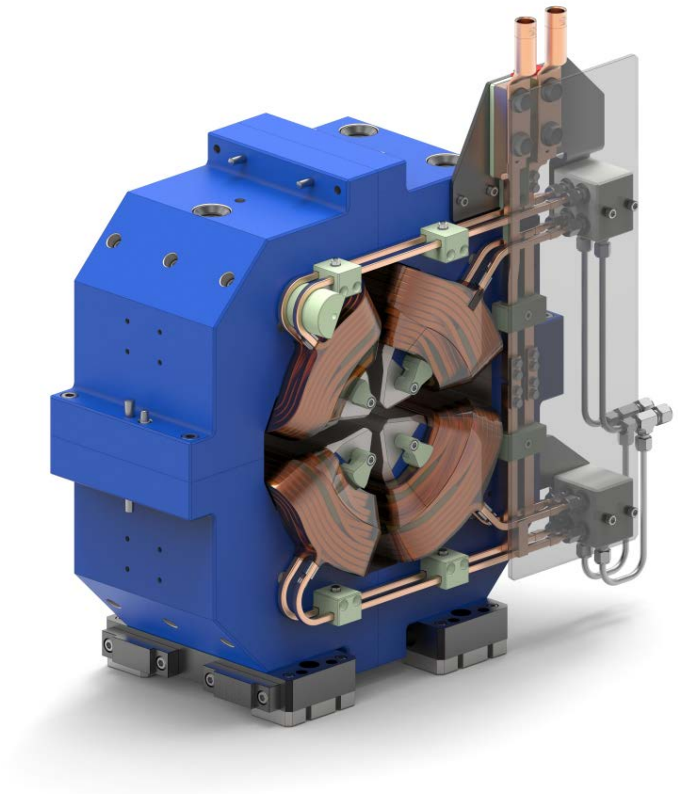
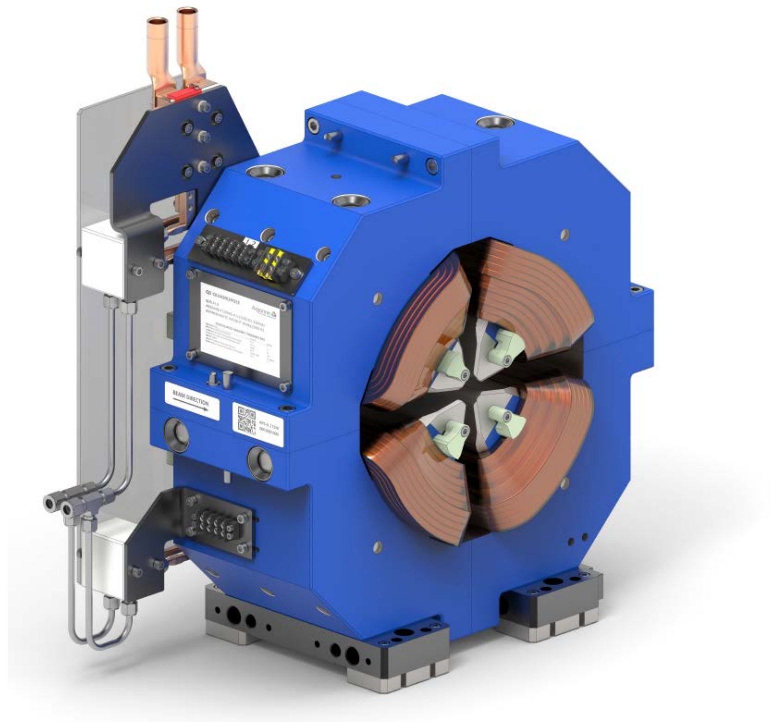
Q1 Magnet for early procurement





Q2 Quadrupole magnet is similar but uses steel pole tips
Q1 is 250 mm long
Q2 is 225 mm long
Bids are in waiting for funding

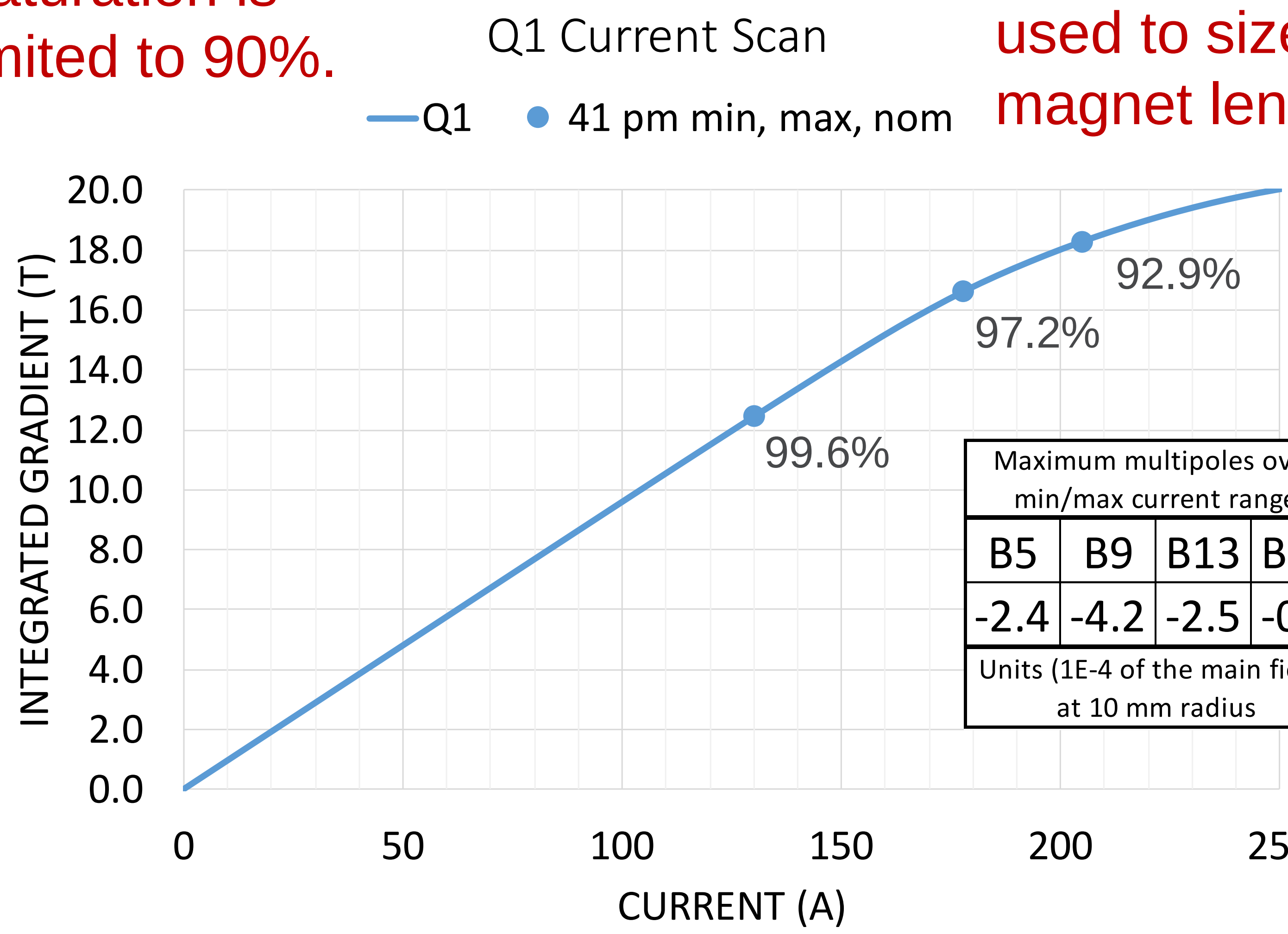
APSU Q1 magnet design

- The aperture is 26 mm, coil gap is 16 mm minimum, and pole tip gap is 10 mm minimum.
- The Q1 quadrupole magnet has vanadium permendur pole tips.
- The core is made of 1006 steel.
- Coils are cooled in parallel.
  - Supply is on the inside of the coils.
- Cooling water supply is 26°C at 0.62 MPa (90 psi) pressure differential.
- Storage ring air temperature is 24.4°C.
- Non magnetic feet are required to separate the Q1 magnet from the iron support plate to minimize top/bottom iron asymmetry which can cause a vertical offset for the magnetic center. Analysis has shown that only a few mm of non-magnetic gap between the support plate and core is enough to have negligible effect on the vertical offset.
- The magnet temperature rise target is 10°C.
- No photon beam tubes go through this magnet except the injected beam tube in sector 39.
- This magnet is expected to be used at sector 39 doublet-B.
- Multipoles, as fraction of the main field at 10 mm ref rad, must be less than 10 units. A unit is 10E-4.

APSU Q1 current scan with magnet efficiencies

Saturation is limited to 90%.

90% efficiency is used to size the magnet lengths.



Maximum multipoles over min/max current range			
B5	B9	B13	B17
-2.4	-4.2	-2.5	-0.1
Units (1E-4 of the main field) at 10 mm radius			

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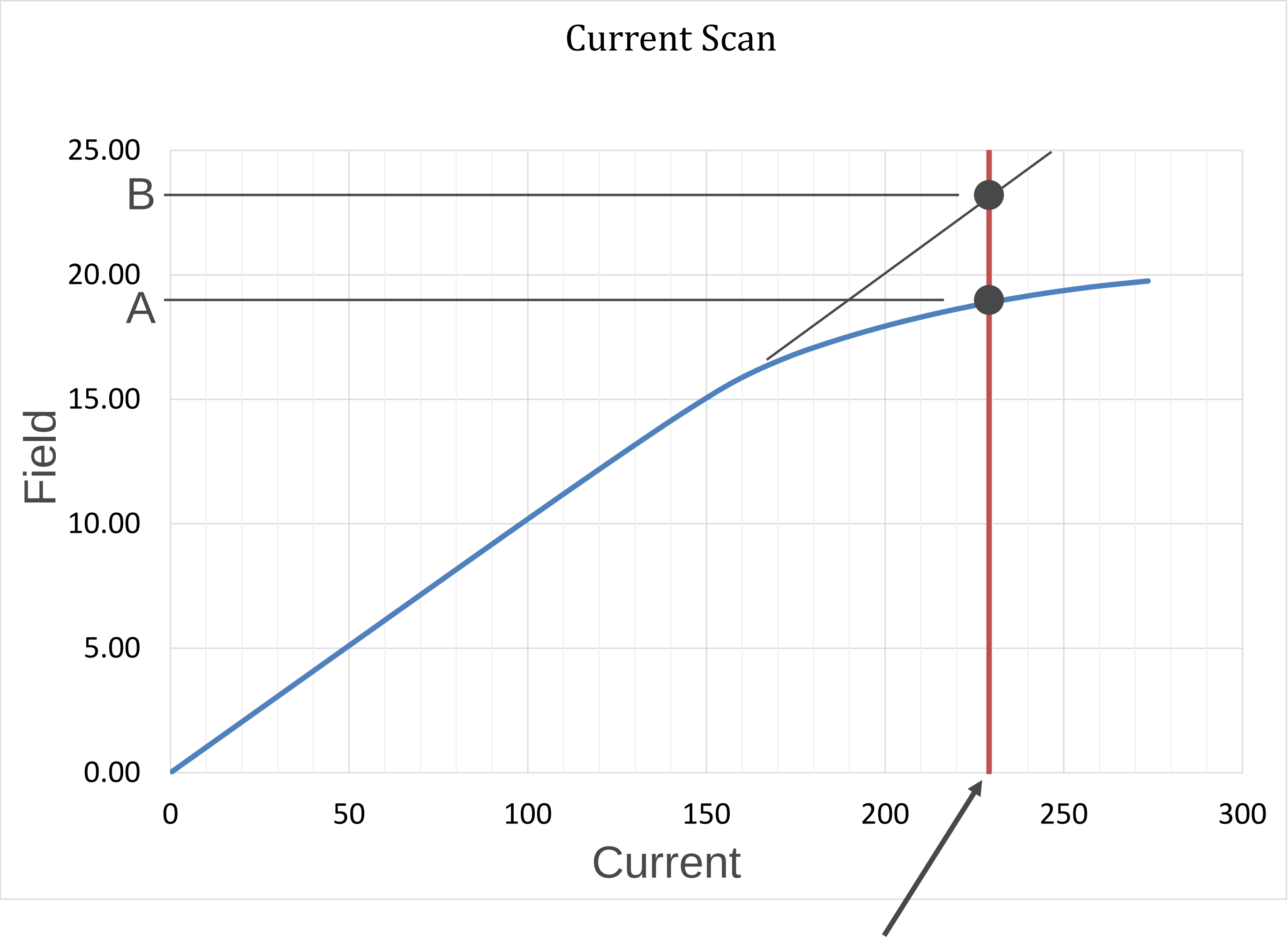
Magnet Saturation Curve example

Magnet efficiency percentage defined

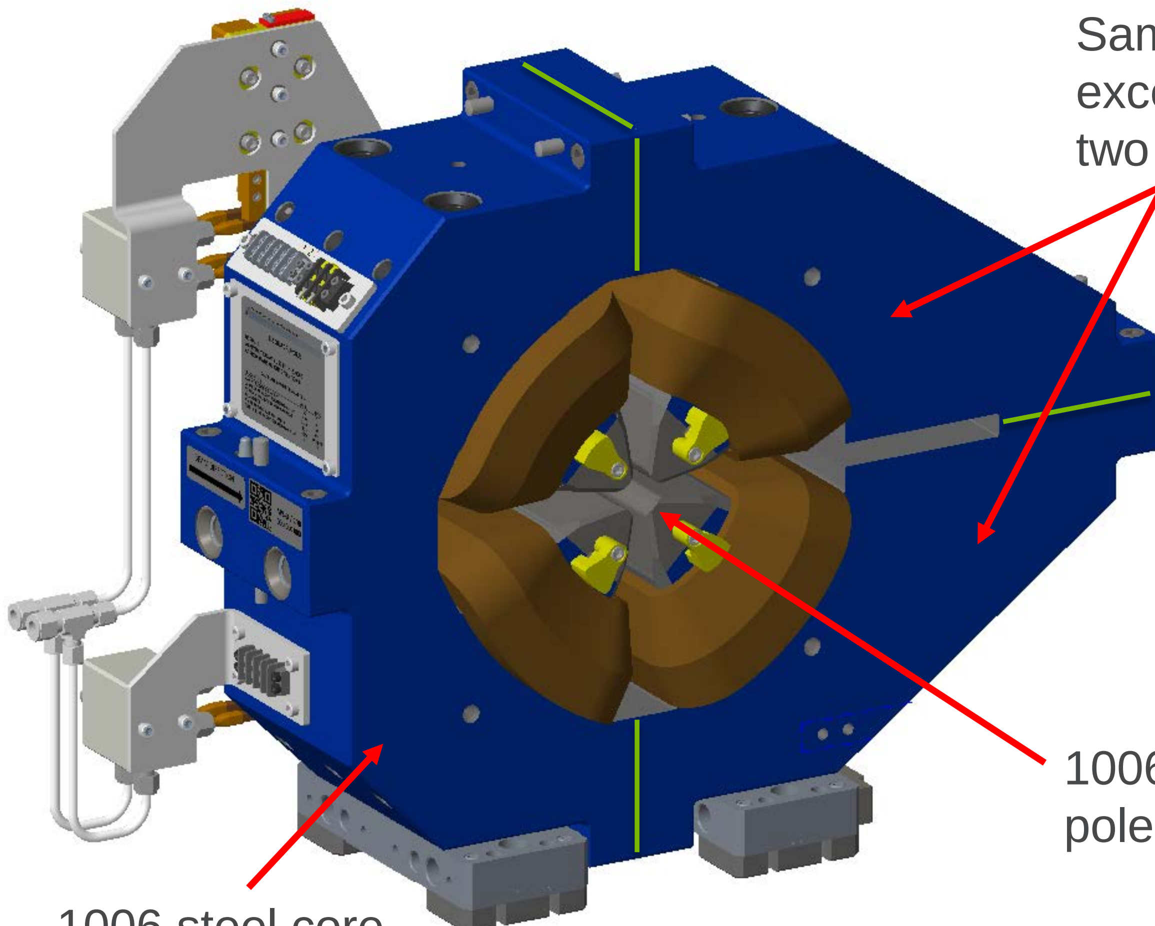


Efficiency = A/B*100%

80.7% magnet efficiency

APSU 41pmV4 Q3 and Q6 magnet model

Same as Q2 except for these two pieces

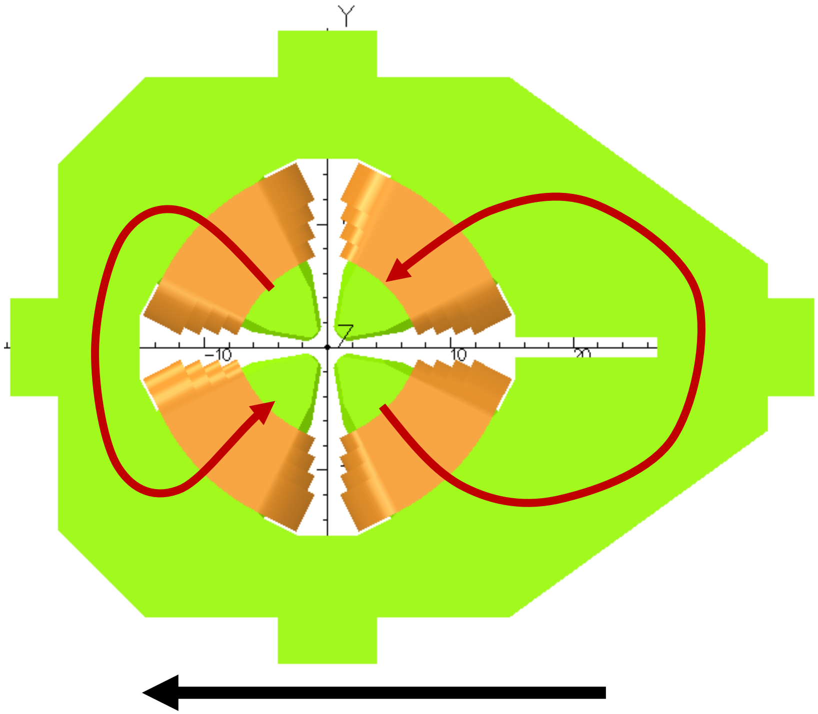


1006 steel pole tips

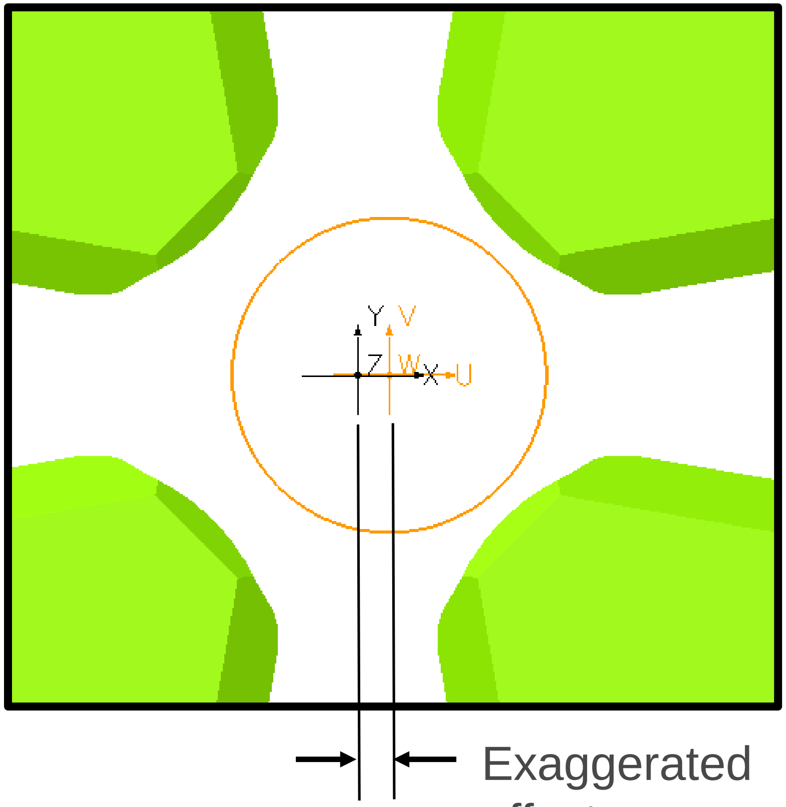
1006 steel core

The same length as the Q2 (225 mm long). Same pole tips and coils as Q2.

APSU Q3 and Q6 magnet center movement due to asymmetry in the y-z plane



Move the whole magnet this way to bring back to center.



Exaggerated offset

This offset was not noticed in the DMM magnet measurements. The offsets are small compared to the 30 micron positioning tolerance. We will ignore this center offset for the production magnets.

Gradient	Horizontal offset
T	microns
12.5	-5.5
11.4	-6.6
8.6	-7.6

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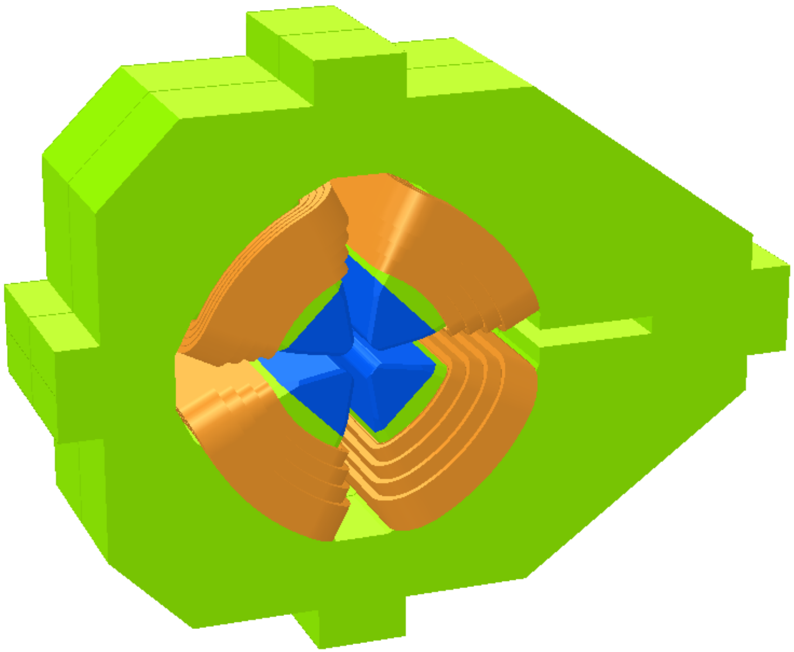
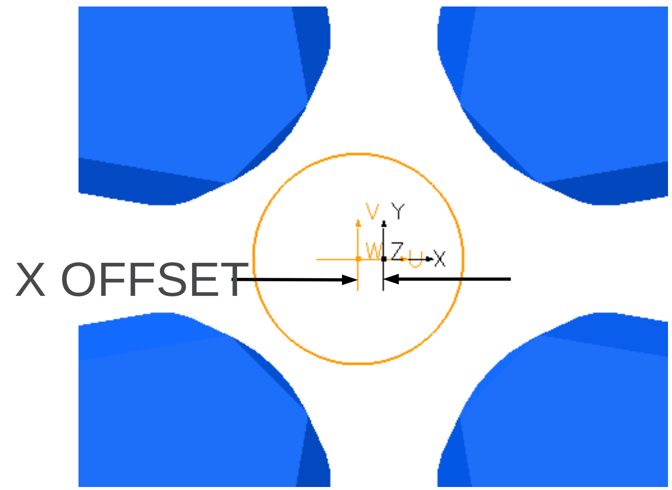
Q4 reverse bend magnet, x_offset of 2.466 mm





Exaggerated offset

Q4 41pmV4			At magnet center		Along the beam path					
current_Q	current_VD	bend_angle	B0_central	B1_central	B0_int	B1_int	B2_int	b0	b1	b2
A	A	degrees	T	T/m	T-m	T	T/m	Units		
207.275	-2.003	-0.109	0.0081	-73.8	0.0381	-14.84	5.7	-2566	10000	-39
225.070	0.052	-0.109	-0.0007	-77.9	0.0381	-15.62	-0.5	-2437	10000	3
246.852	2.734	-0.109	-0.0098	-82.2	0.0381	-16.40	-6.7	-2322	10000	41

This magnet requires vertical dipole coils to allow adjustment of the quadrupole field by +/- 5%.

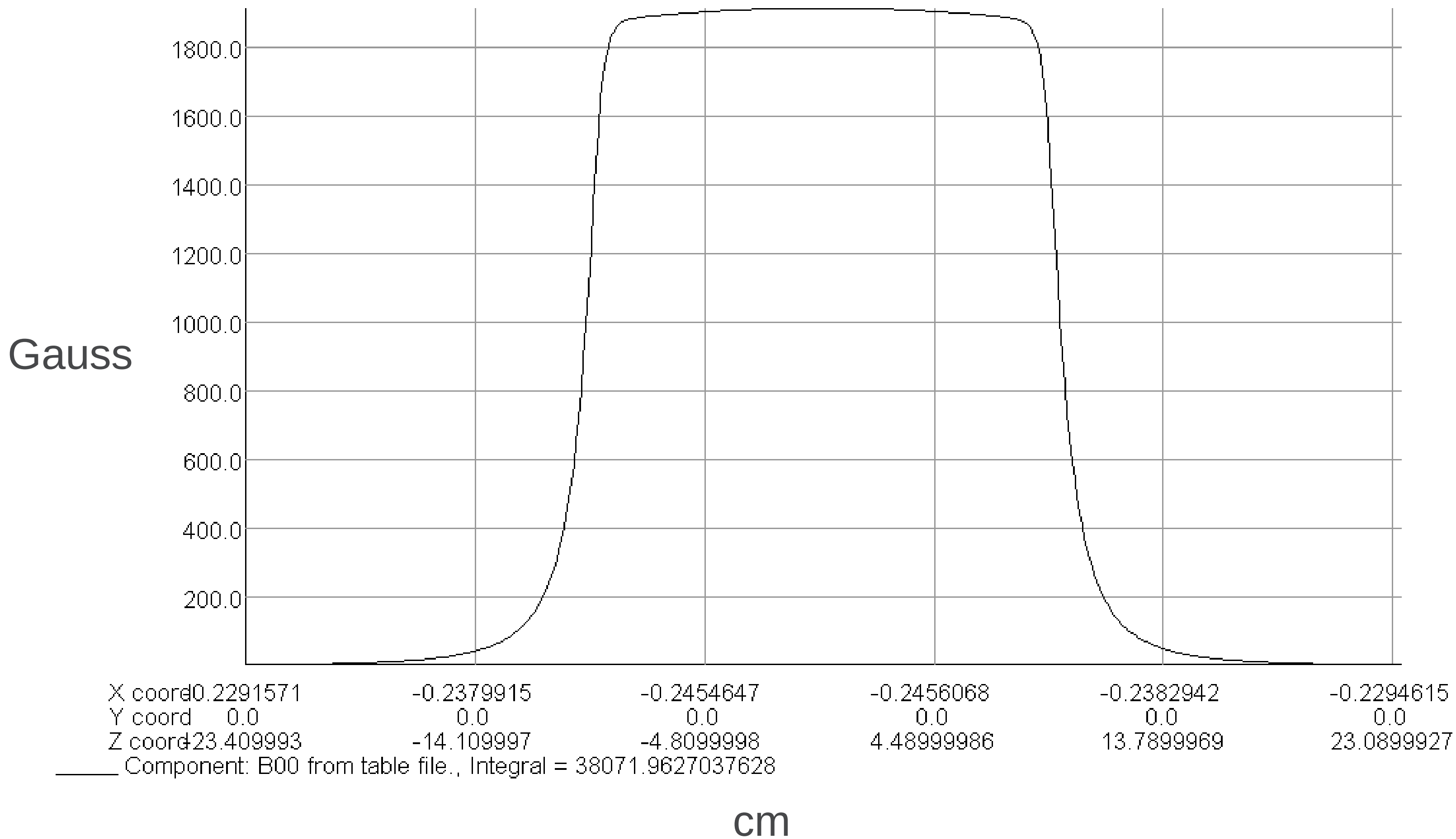
Q4 Reverse bend calculated values

	Maximum	Nominal	Minimum	
current_Q	246.85	225.07	207.28	A
current_VD	2.73	0.05	-2.00	A
B1_integral	-16.40	-15.62	-14.84	T
B0_integral	0.04	0.04	0.04	T-m
B1_central	-82.17	-77.94	-73.82	T/m
B0_central	-0.0098	-0.0007	0.0081	T
Q_power	4797	3988	3382	W
#VD_power	18.21	0.01	9.78	W
x_offset	-2.47	-2.47	-2.47	mm
sagitta	0.051	0.051	0.051	mm
bend_angle	-0.109	-0.109	-0.109	degrees
vertex	-2.514	-2.514	-2.515	mm

All multipoles are less than 10 units, at 10 mm reference radius, except for the sextupole error at max and min quadrupole fields. This is due to the dipole field needed maintain a constant integrated dipole at different quadrupole settings. A unit is 1E-4 of the main field.

	Maximum	Nominal	Minimum	
B0_int	-2321.9	-2437.4	-2565.7	Units R_{ref} = 10mm
B1_int	10000.0	10000.0	10000.0	
B2_int	41.0	3.5	-38.6	
B3_int	-4.0	-2.2	-0.3	
B4_int	5.8	4.6	3.2	
B5_int	-2.9	-4.1	-5.6	
B6_int	0.6	1.5	2.4	
B7_int	-3.1	-3.1	-3.1	
B8_int	3.7	3.7	3.7	
B9_int	-3.1	-3.0	-3.0	
B10_int	2.6	2.6	2.7	
B11_int	-2.8	-2.9	-3.0	
B12_int	2.1	2.2	2.2	
B13_int	-1.0	-1.1	-1.1	
B14_int	0.5	0.5	0.5	
B15_int	-0.4	-0.3	-0.3	
B16_int	0.1	0.0	0.0	
B17_int	0.1	0.2	0.2	

Q4 Dipole Field as a function of trajectory



The Sagitta is 51 microns. This will be a straight magnet.

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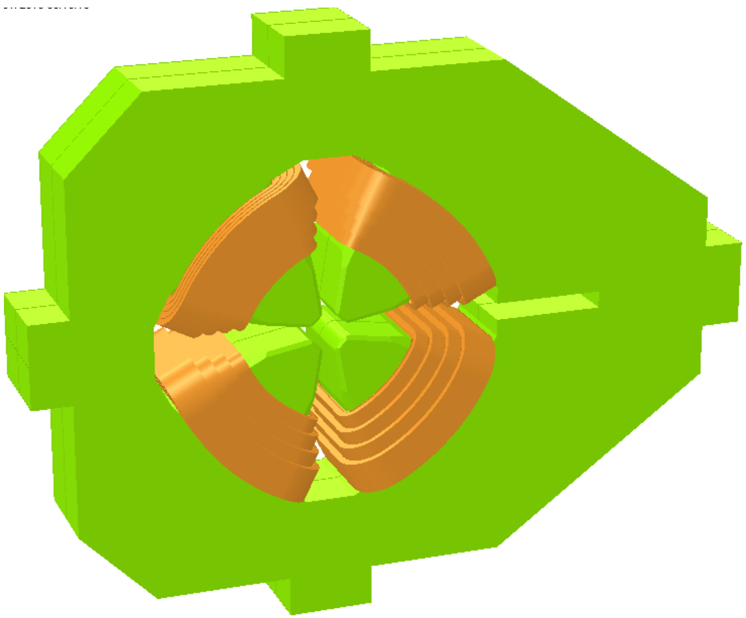
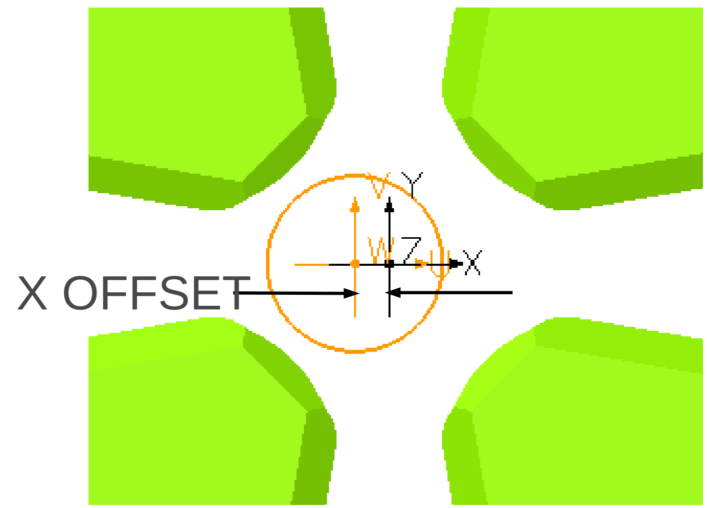
Q5 reverse bend magnet, x_offset of 3.898 mm





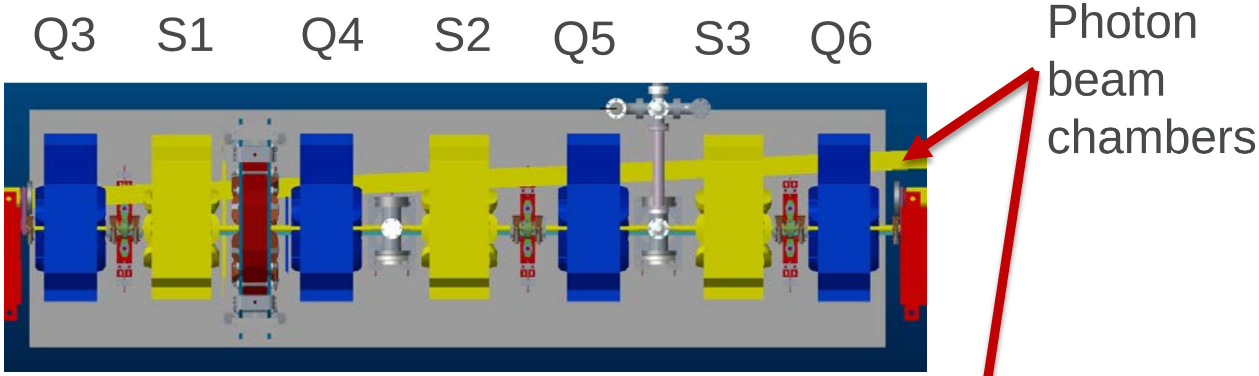
Offset

The photon slot size is not final

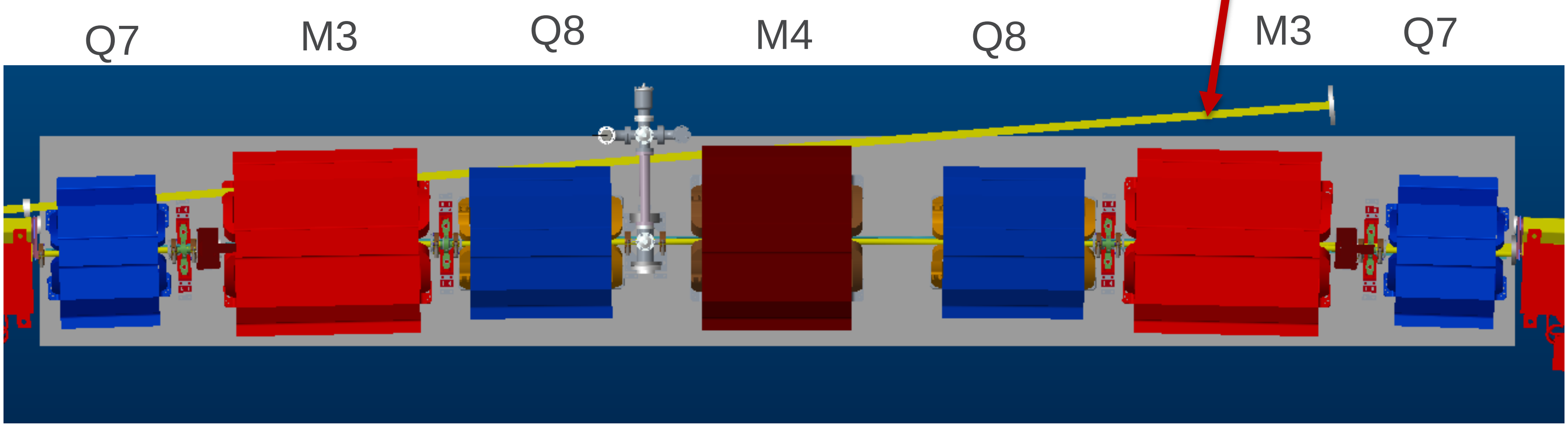
current_Q	current_VD	bend_angle	B0_central	B1_central	B0_int	B1_int	B2_int	b0	b1	b2
A	A	degrees	T	T/m	T-m	T	T/m	Units		
174.571	-2.501	-0.073	0.0105	-55.9	0.0255	-6.21	3.5	-4105	10000	-57
189.394	-0.146	-0.073	0.0005	-59.2	0.0255	-6.54	0.0	-3900	10000	-1
208.928	3.246	-0.073	-0.0095	-62.4	0.0255	-6.86	-3.3	-3714	10000	49

This magnet requires vertical dipole coils to allow adjustment of the quadrupole field by +/- 5%.

Photon beam chamber



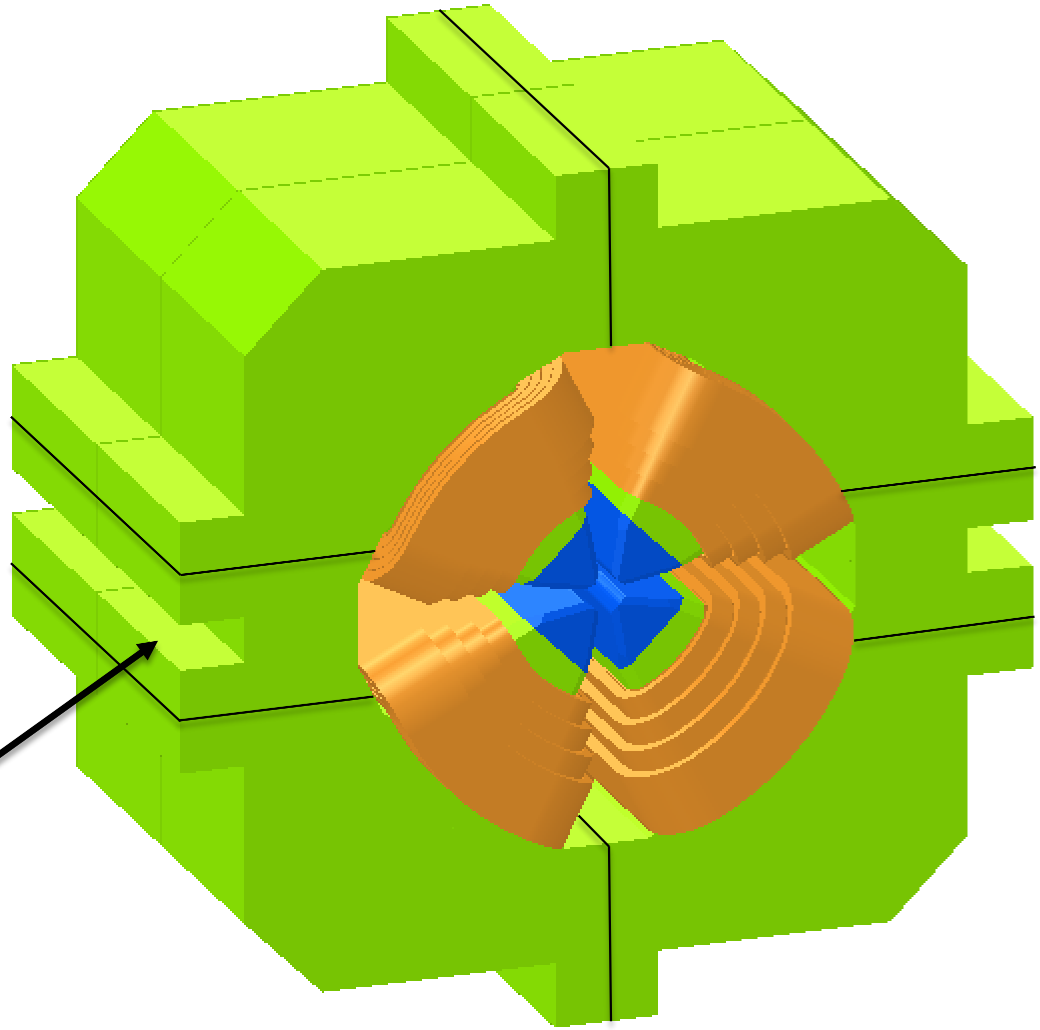
Multiplet section



FODO section

Q8 magnet

Most likely a 10 piece quadrupole magnet to allow for photon beam chamber. This will still have a similar assembly technique as the 8 piece quadrupole magnet.

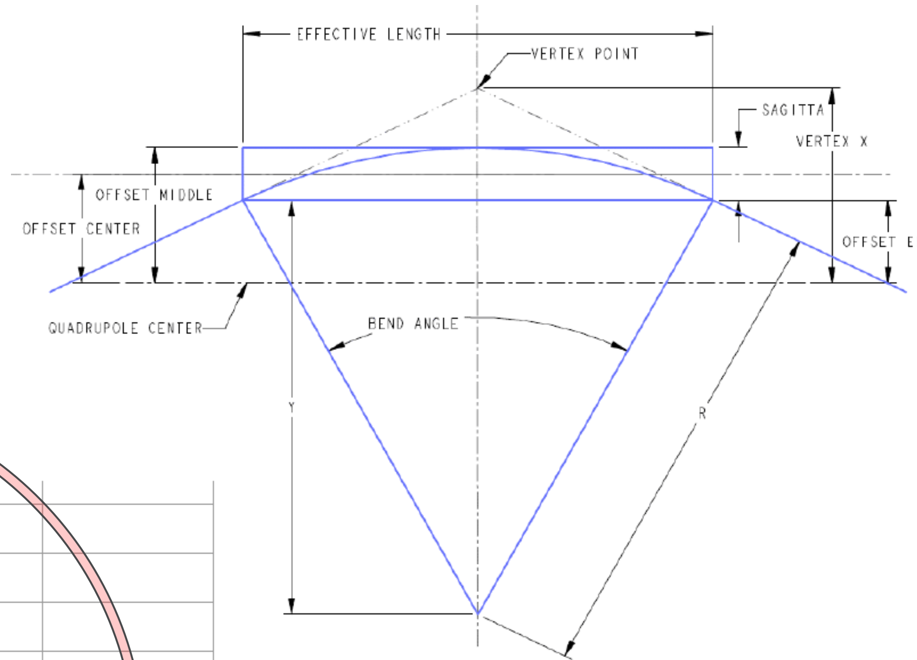


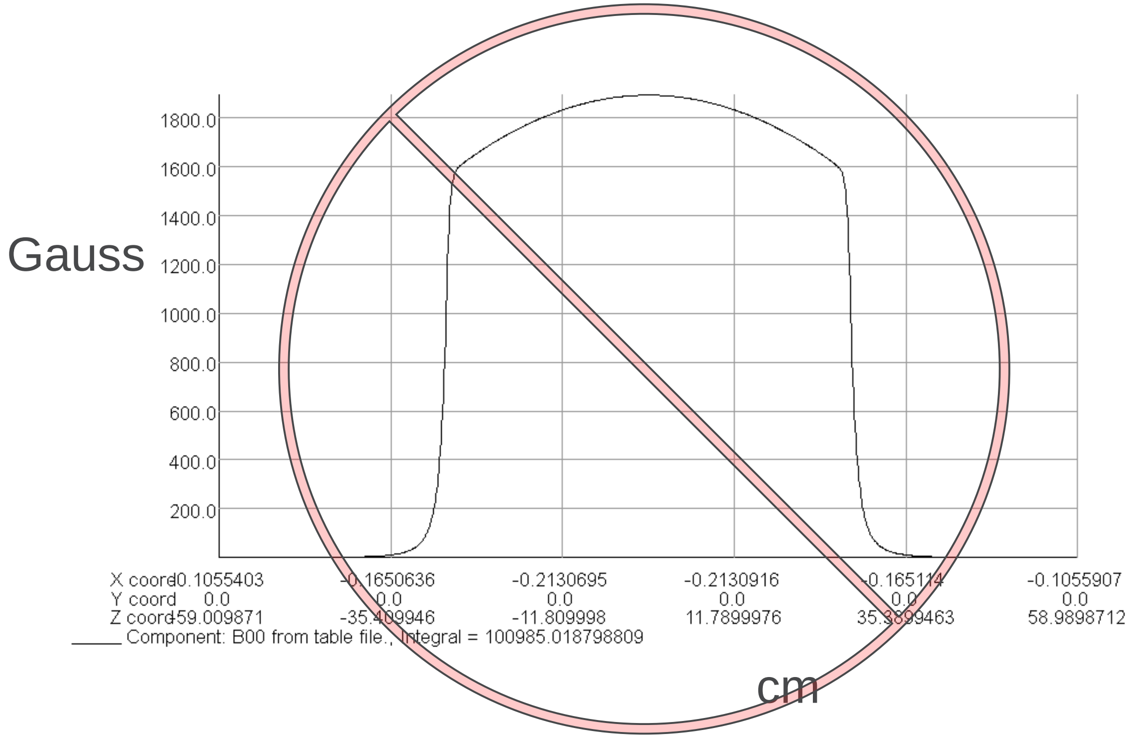
Opening for photon beam chamber.

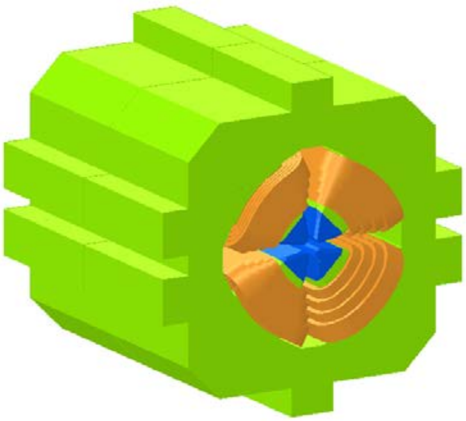
This magnet also has vertical and horizontal dipole coils for beam steering

Q8 reverse bend dipole field as a function of trajectory for a **straight magnet**

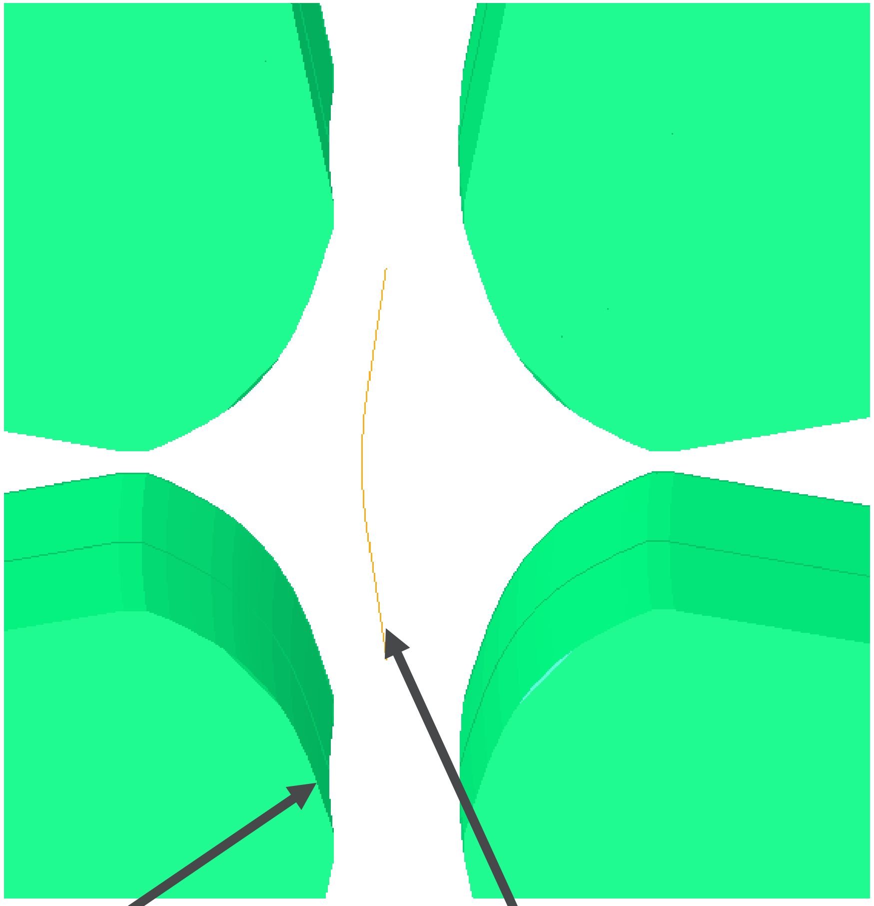
A domed dipole field is not desirable so a curved tip magnet shall be investigated.







Q8 reverse bend **curved magnet**



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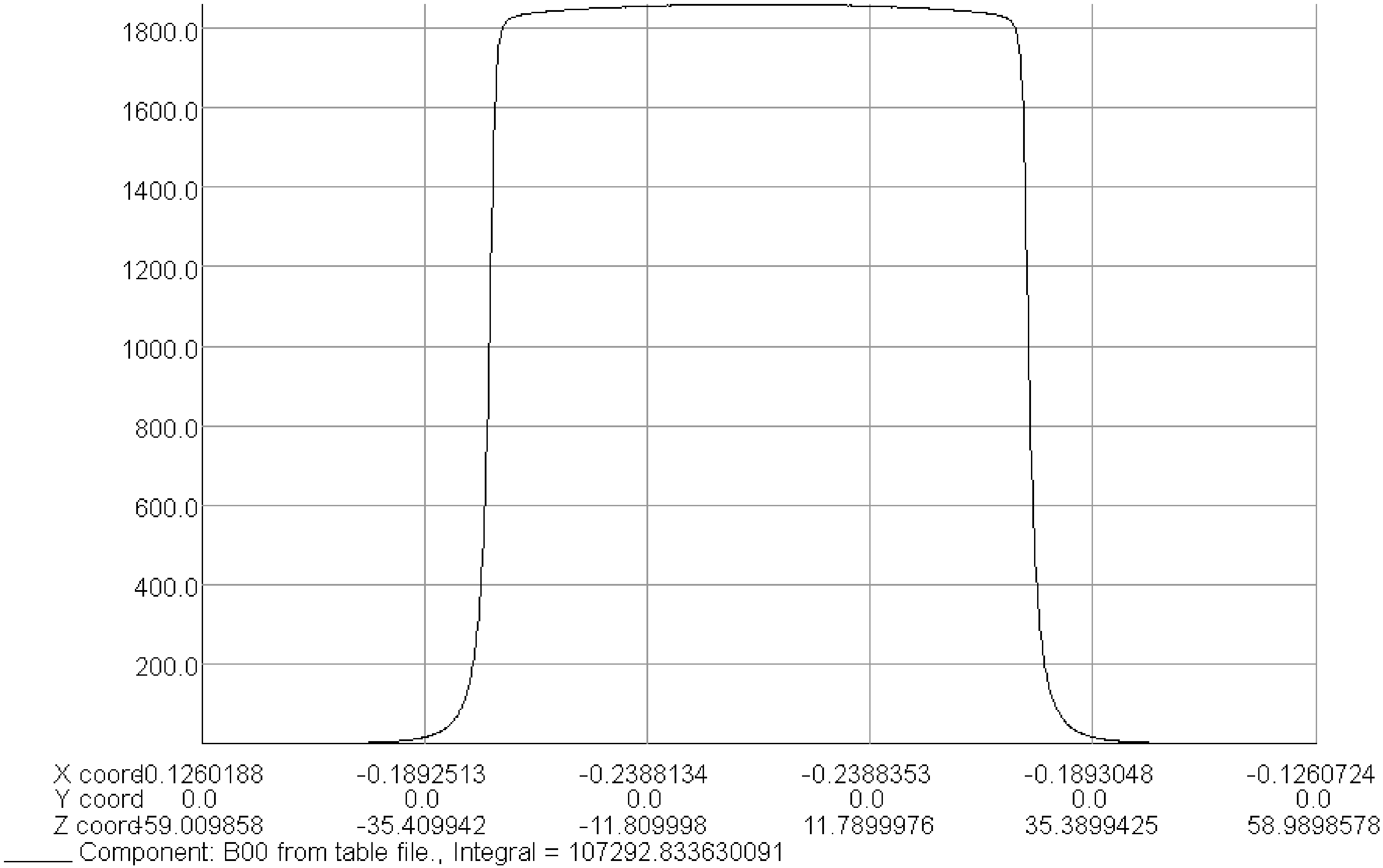
Q8 reverse bend curved magnet dipole profile

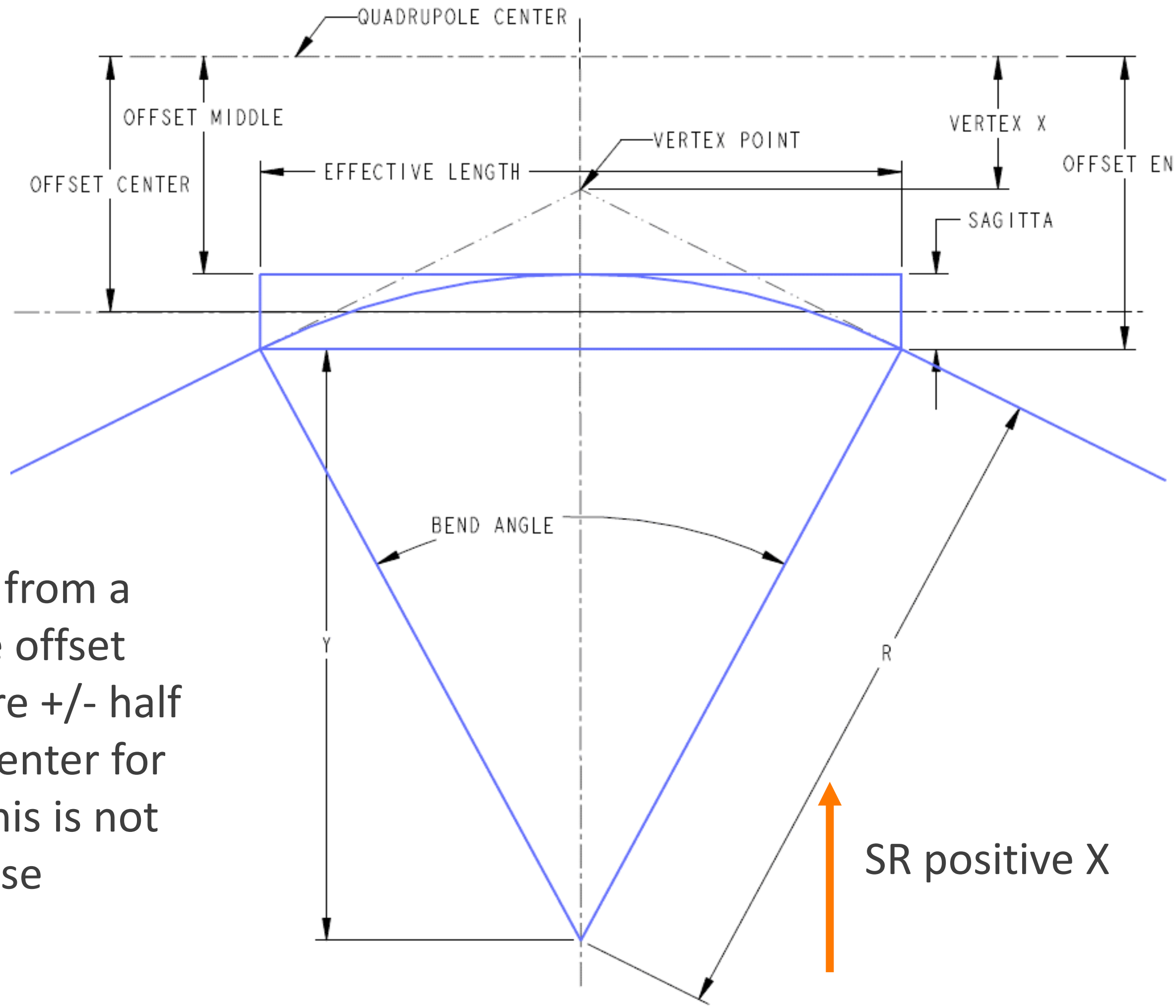


A much flatter dipole profile

M4 requirements

- 41pmV4
- Nominal 31.20 T
- Max 32.76 T
- Min 29.64 T
- 41.4 mm aperture
- 700 mm long
- 1.142 degrees bend angle

M4 Q-bend layout
For hard edge calculations



The Sagitta is calculated from a perfect radius bend. The offset middle and offset end are +/- half Sagitta from the offset center for this hard edge model. This is not exact but considered close enough.

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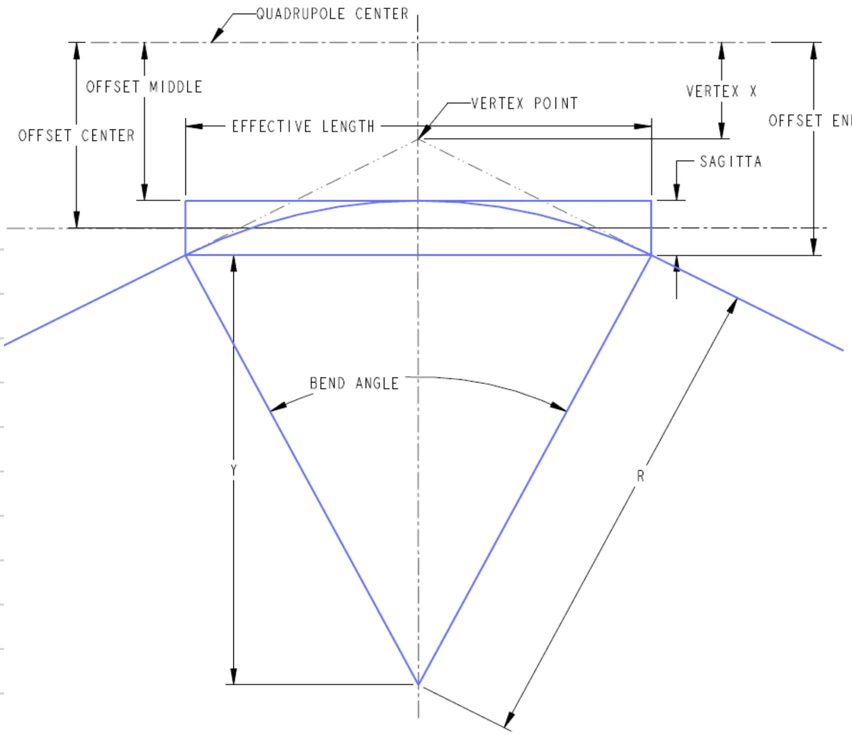
M4 41.4 mm aperture
24 mm OD vacuum chamber
700 mm long
Hard edge calculations

integrated dipole	0.393	T-m	negative dipole
integrated gradient	31.20	T	positive Quad
length	0.700	m	
bend angle	1.124	degrees	
bore diameter	0.0414	m	
coil thickness	0.041	m	
calculated values			
core length	0.618	m	length-2x(coil thickness)
effective length	0.659	m	core length + bore dia
offset center	12.606	mm	(integrated dipole)/(integrated gradient)
sagitta	1.617	mm	
offset middle	11.797	mm	
offset end	13.414	mm	
R	33.613	m	
Y	31.996	m	
Vertex X	10.180	mm	



M4

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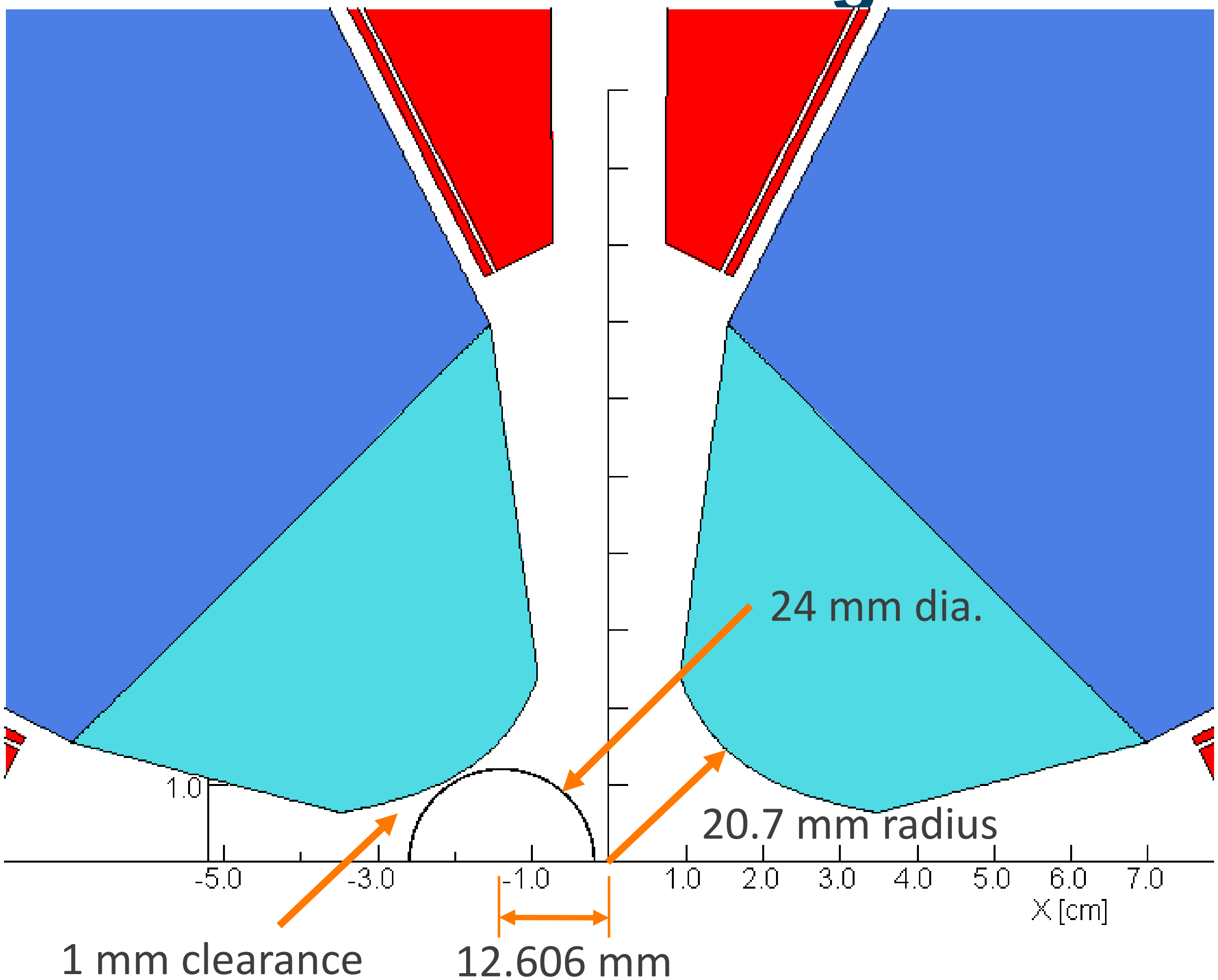
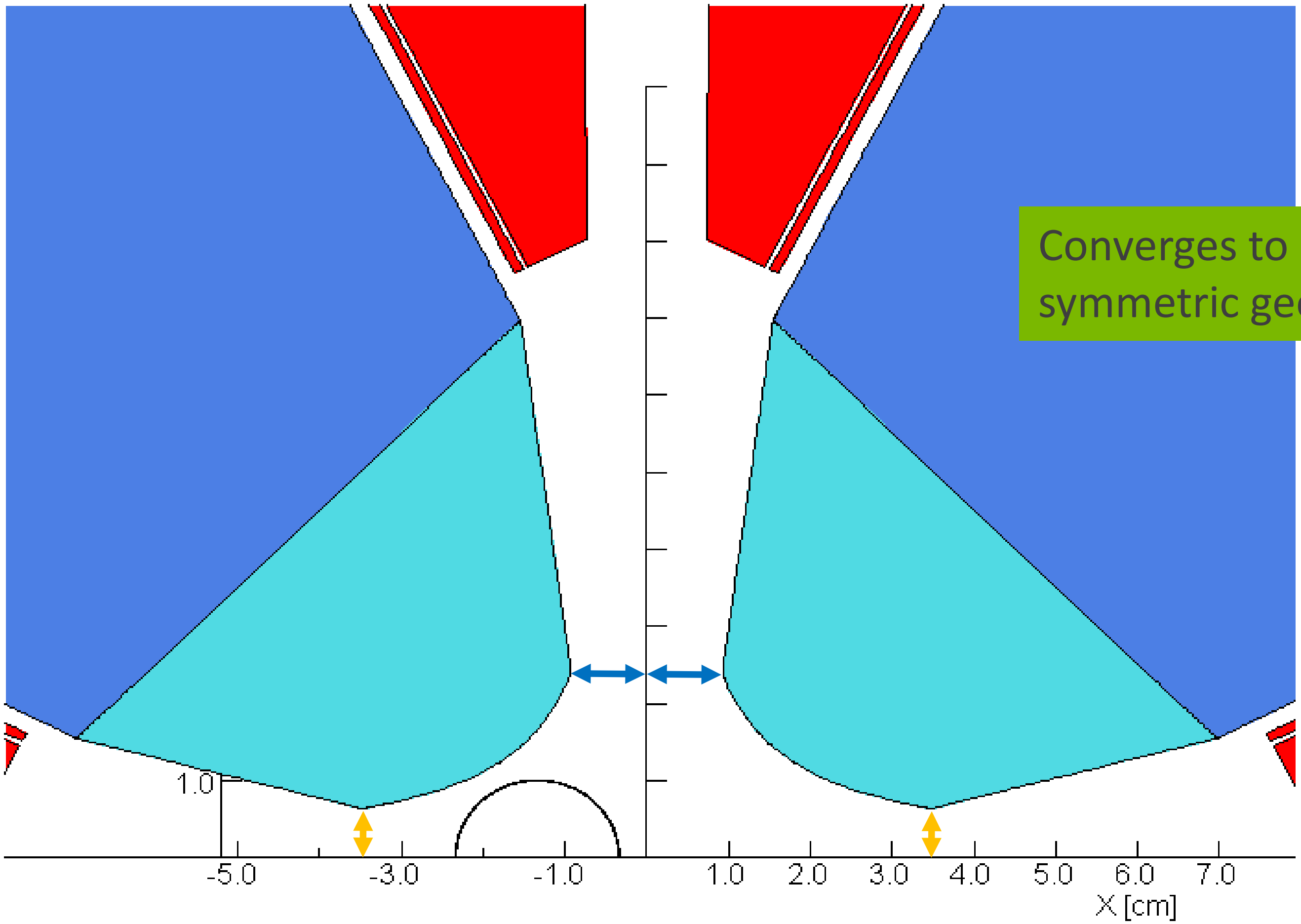
M4 41.4 mm aperture
24 mm OD vacuum chamber
700 mm long

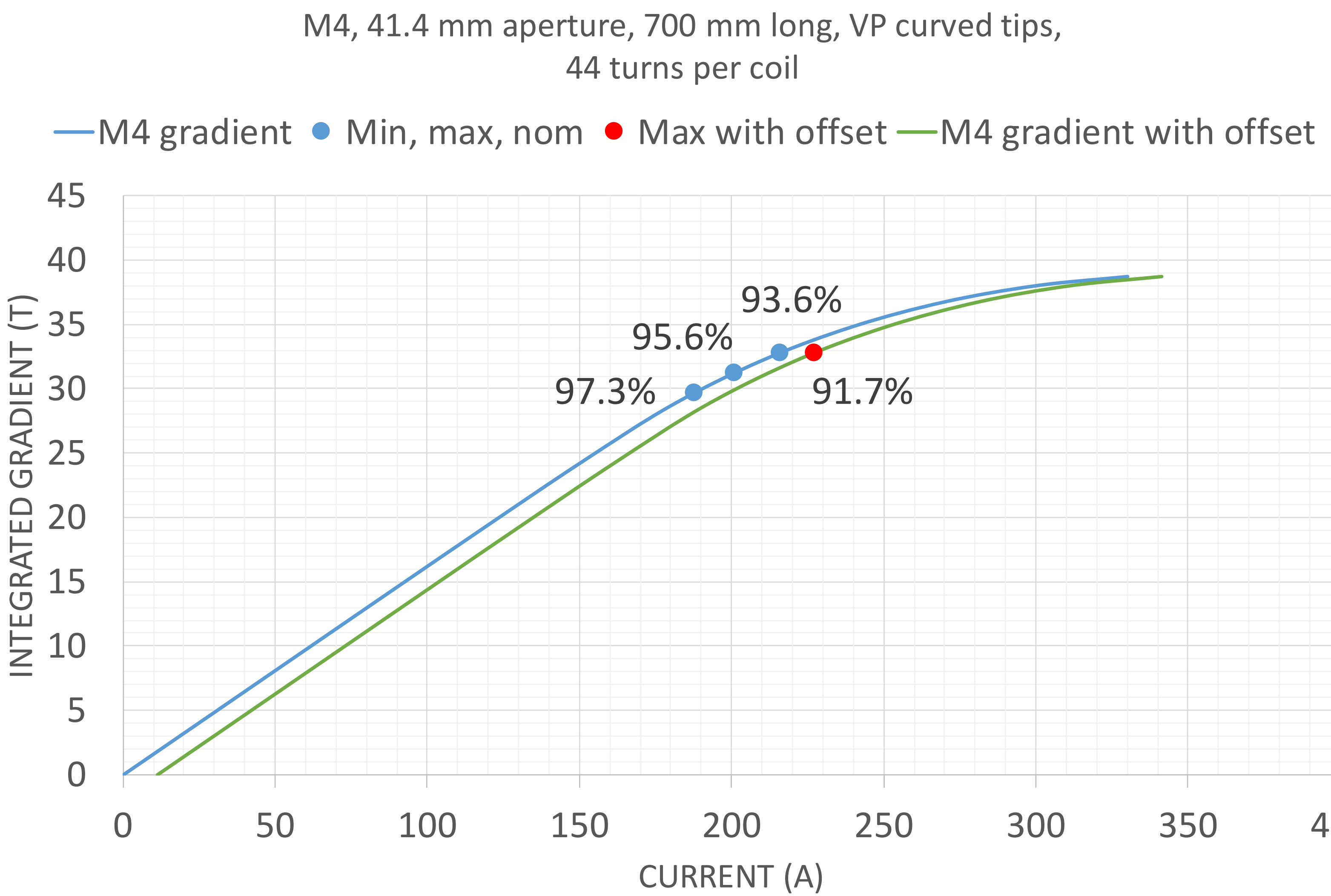


M4 2D optimization convergence criteria: minimize the maximum multipole magnitude while maximizing the gradient

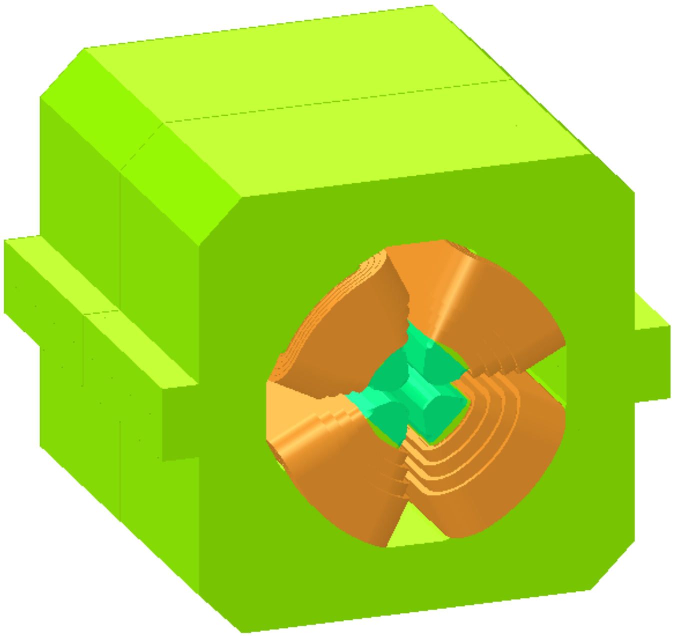


Converges to symmetric geometry

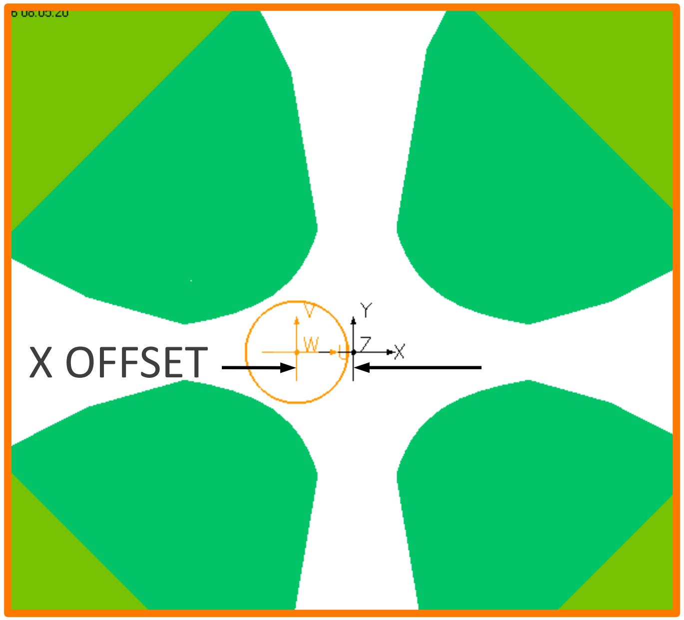
M4 41pmV4 current scan



M4 41pmV4
x_offset 11.663 mm



The photon beam tube not considered yet



Offset

current_Q	current_VD	bend_angle	B0_central	B1_central	B0_int	B1_int	B2_int	b0	b1	b2
A	A	degrees	T	T/m	T-m	T	T/m	Units		
177.008	13.726	1.124	-0.6102	46.4	-0.3927	29.67	-54.8	10000	-7556	140
200.367	1.299	1.124	-0.6123	49.0	-0.3927	31.35	-0.1	10000	-7981	1
230.703	-15.333	1.124	-0.6143	51.5	-0.3928	32.95	51.9	10000	-8387	-132

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M4 Q-bend Calculated values

	Maximum	Nominal	Minimum	
current_Q	230.70	200.37	177.01	A
current_VD	-17.33	-0.36	11.71	A
B1_integral	32.78	31.20	29.48	T
B0_integral	-0.3881	-0.3883	-0.3868	T-m
B1_central	51.25	48.75	46.06	T/m
B0_central	-0.6074	-0.6059	-0.6016	T
Q_power	8776	6620	5167	W
#VD_power	489.09	0.21	223.38	W
x_offset	-11.663	-11.663	-11.663	mm
sagitta	1.617	1.617	1.617	mm
bend_angle	1.111	1.111	1.107	degrees
vertex	-10.107	-10.100	-10.099	mm

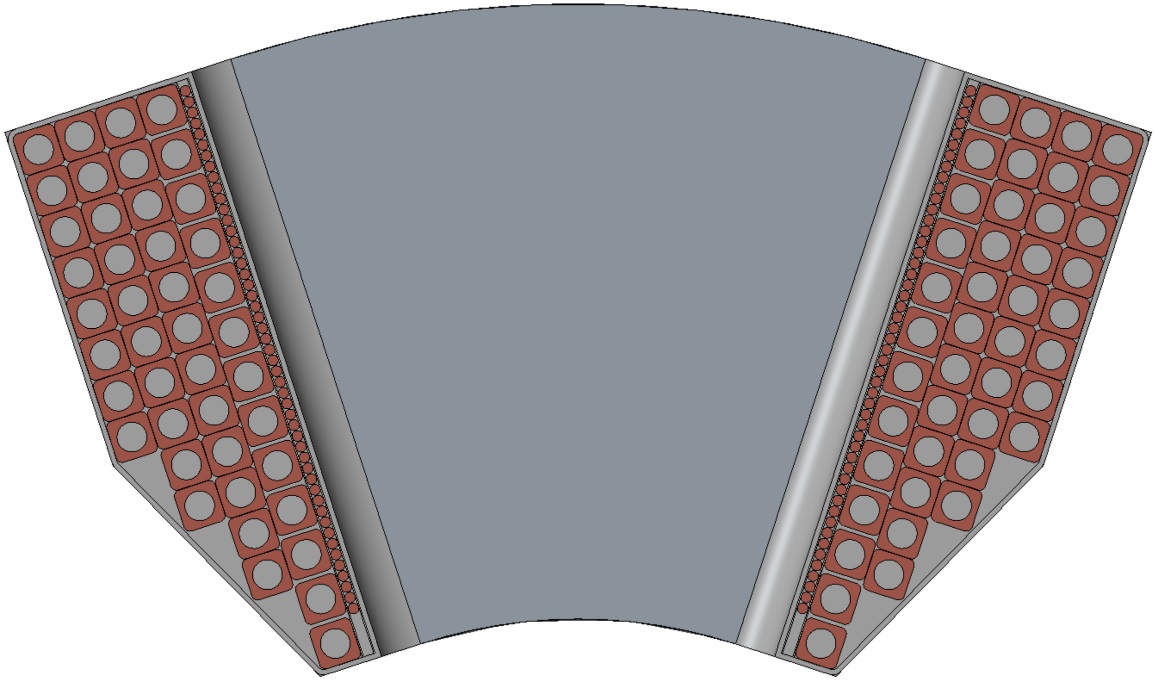
Temp rise **12 C** 8 C 7 C

	Maximum	Nominal	Minimum	
B0_int	10000.0	10000.0	10000.0	Units R_{ref} = 10mm
B1_int	-8445.1	-8034.6	-7622.5	
B2_int	-149.3	-15.3	119.8	
B3_int	6.3	11.4	16.6	
B4_int	5.1	-4.6	-14.1	
B5_int	6.9	9.5	12.2	
B6_int	-10.5	-9.2	-8.3	
B7_int	1.9	1.1	0.5	
B8_int	2.0	2.1	2.4	
B9_int	-0.9	-0.8	-0.9	
B10_int	0.8	0.5	0.2	
B11_int	-1.6	-1.3	-0.9	
B12_int	1.1	1.1	1.0	
B13_int	0.2	0.0	-0.2	
B14_int	-0.4	-0.4	-0.2	
B15_int	-0.7	-0.7	-0.6	
B16_int	1.8	1.7	1.6	
B17_int	-1.4	-1.4	-1.4	

M4 Q-bend Calculated values

44 turns per coil (actually 43)
8 mm x 8 mm conductor
6 mm diameter hole
75.3 m (247 ft) per coil

Water flow data
At 0.62 MPa (90 psi)
0.189 l/s (2.99 gpm) per magnet
1.67 m/s (5.4 ft/s)



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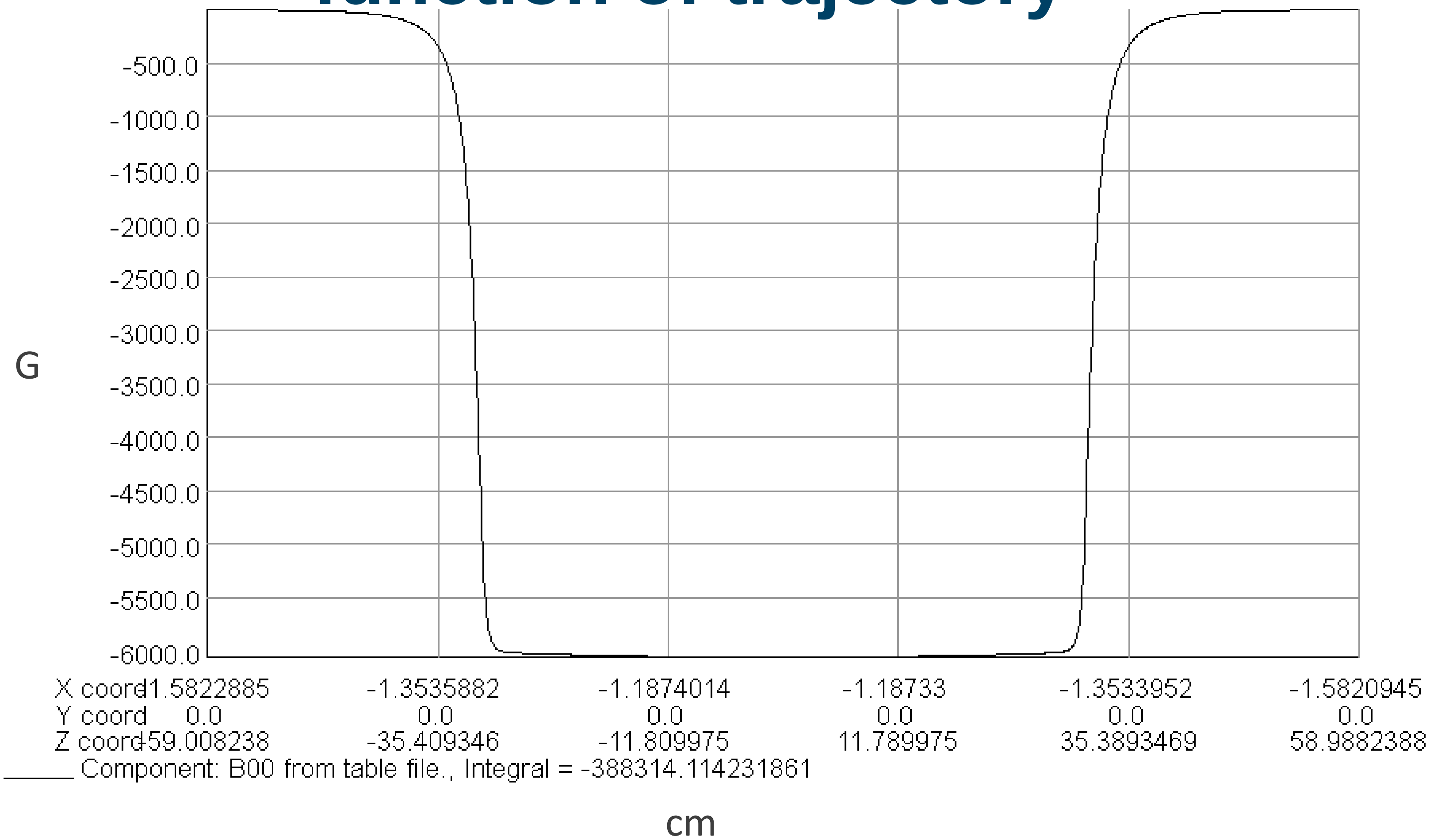
M4 Dipole Field (at nom quad) as a function of trajectory



The Sagitta is 1.617 mm. This is a curved magnet?

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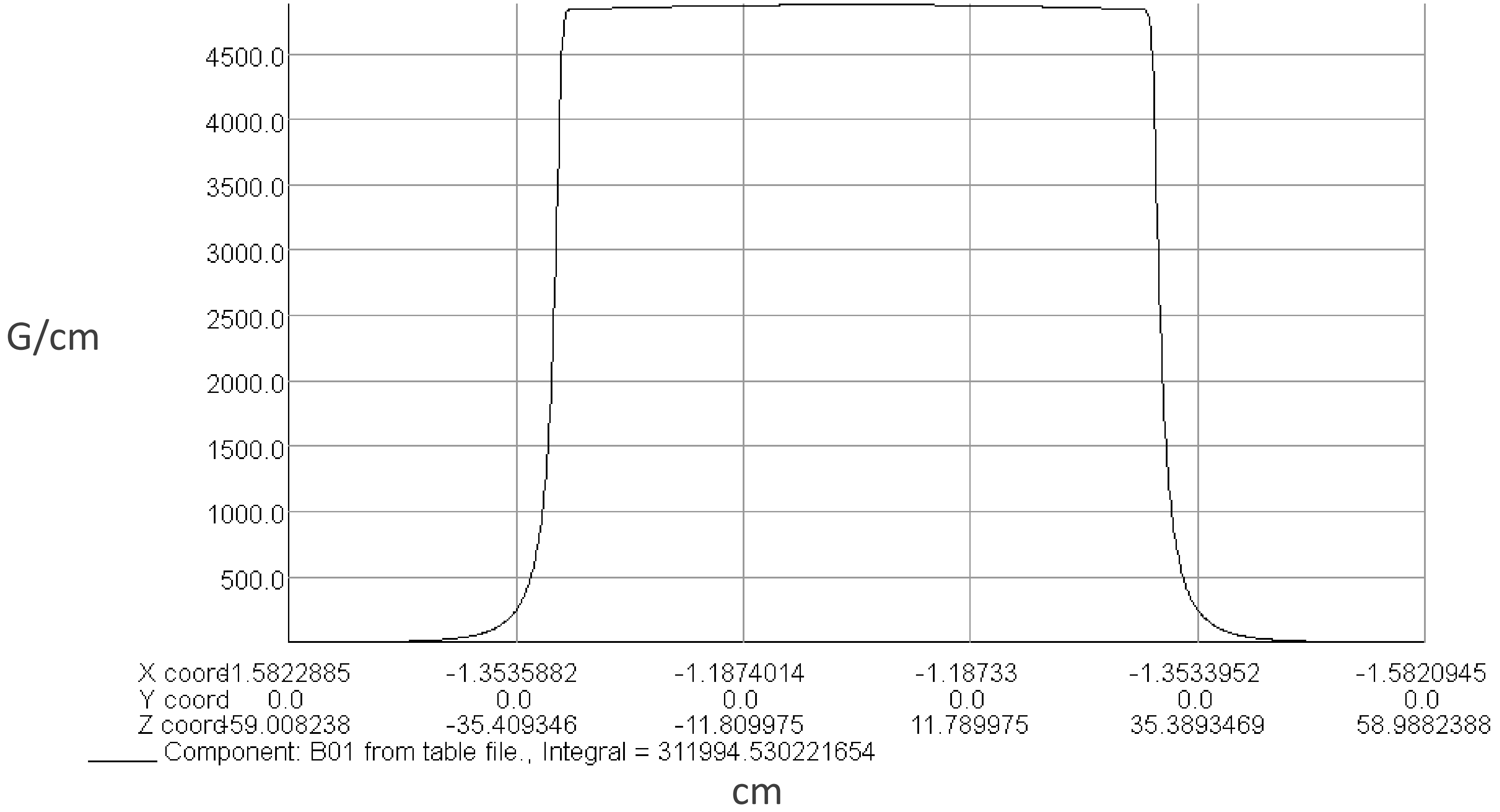
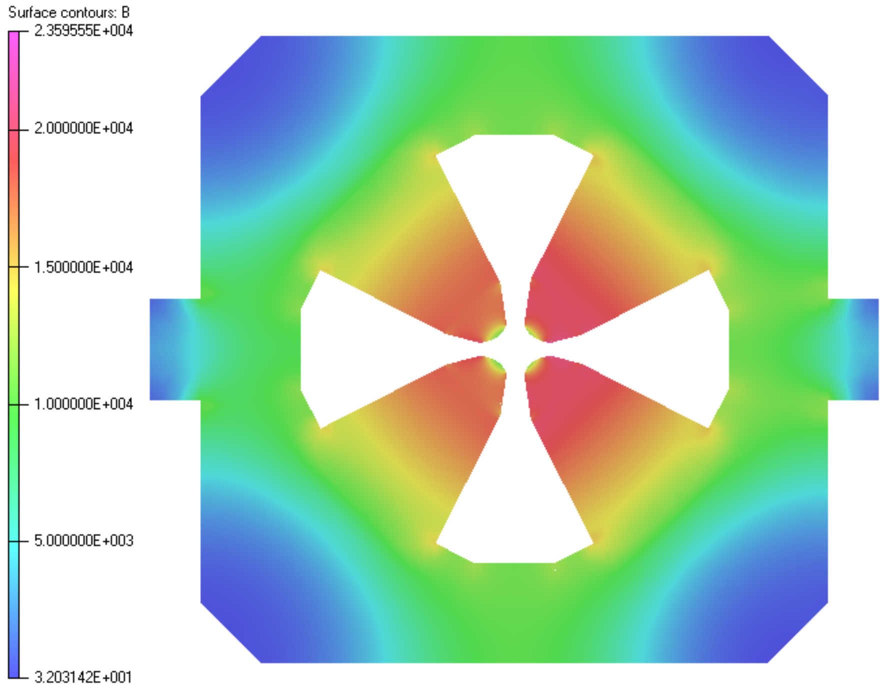
M4 Quadrupole Field (at nom quad) as a function of trajectory

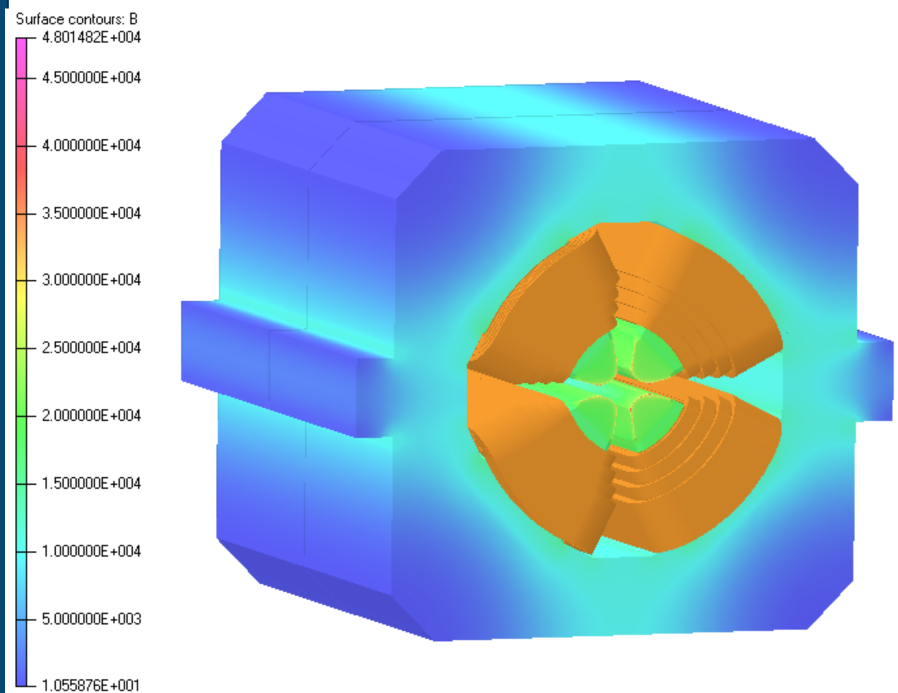


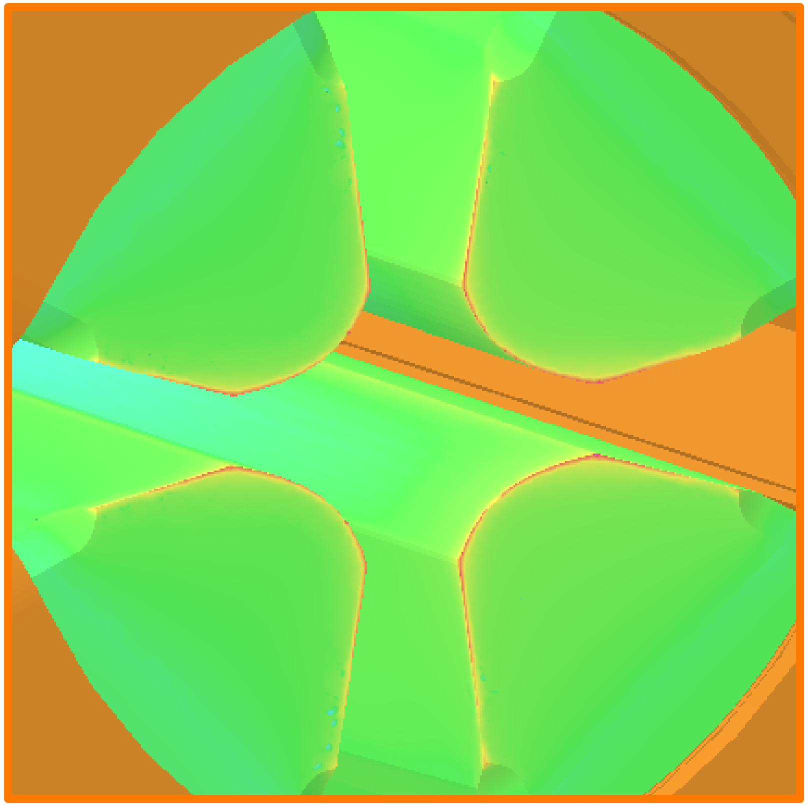
M4 Flux through magnet center at max field



2.36 T at max gradient

M4 3D flux
at maximum gradient





4.80 T at max gradient

M4 Summary

- 41.4 mm aperture
- 700 mm long
- Vanadium permendur curved tips
- 91.7% minimum efficiency at maximum gradient
- Sized +/-5% from nominal
- B3, B5 and B6 multipole are larger than 10 units
- Increasing the end chamfer increases the B5 multipole. The end chamfers are very small so the only way to correct the B5 multipoles seems to be to modify the tip profile.
- Still need to
  - Add remaining bolt flanges.
  - Fix the main coil number of turns
  - Fix the corrector coil number of turns
  - Allow for photon beam tube clearance
  - Look at shorter geometry
  - Look at improving field quality

M1_41pmV5rev1 – Preliminary analysis

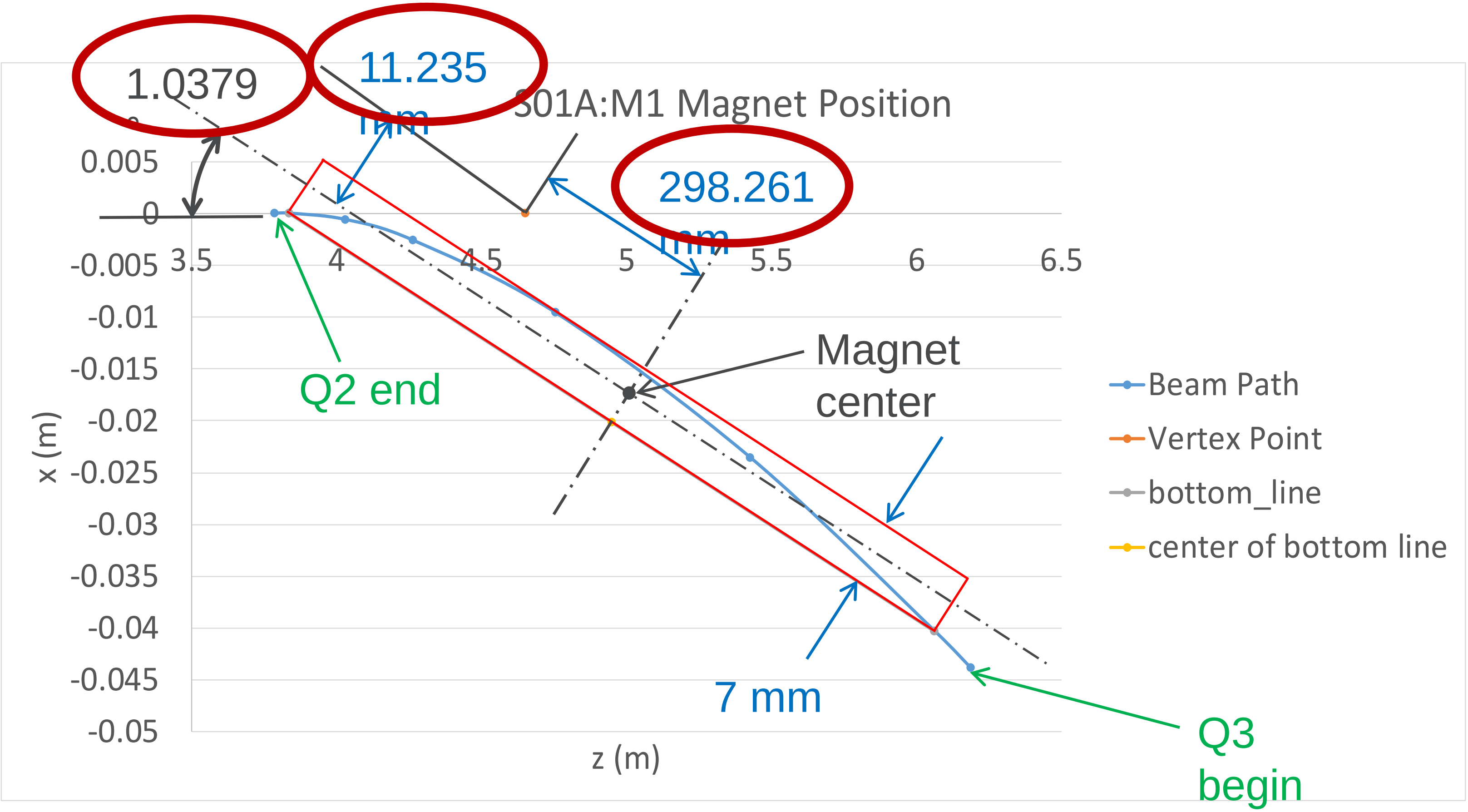
Preliminary design of the M1 41pmV5rev1 L-bend is presented.

1. Find the position and vertex point relative to the magnet center.
2. Find the Sagitta.
3. 2D analysis to flatten the field.
4. Size the coil number-of-turns to match the field under each pole.
5. Size the pole lengths to match the area under the curve (integrated field).
6. Fine tune the pole lengths to achieve the vertex point.
7. Check the field quality.
8. Size the trim coils for the 1st and 2nd integrals.

M1_41pmV5rev1

Required position of M1

Plotted from M. Borland Excel lattice file.



Jeremy Nudell confirmed the data

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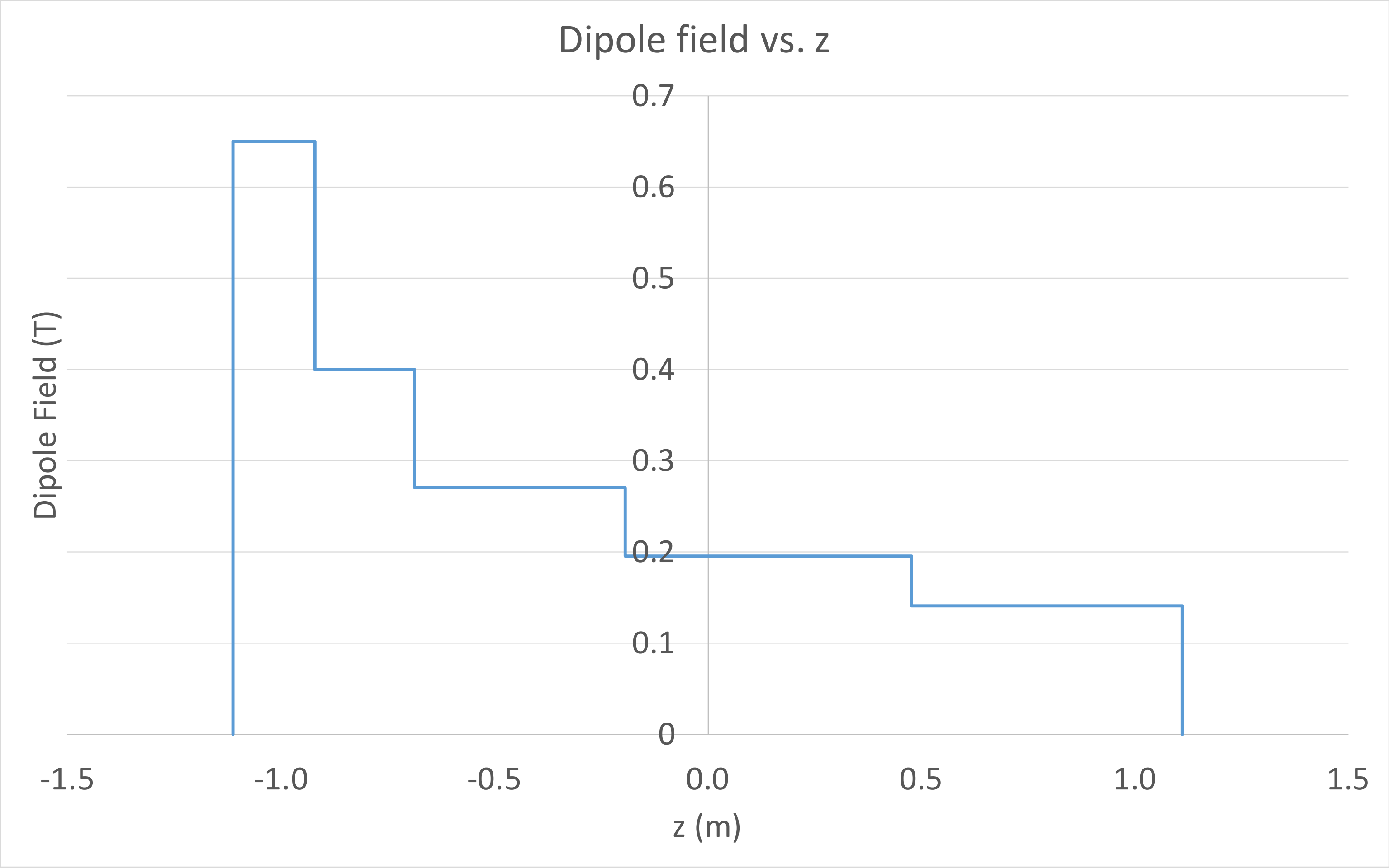
M1_41pmV5rev1 – Required parameters



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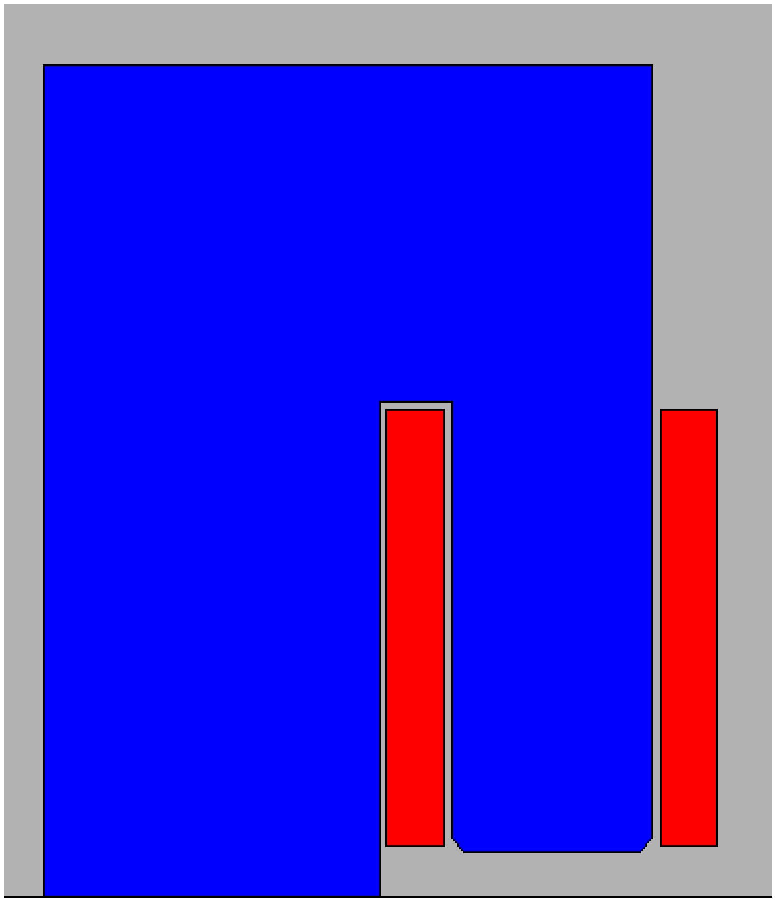
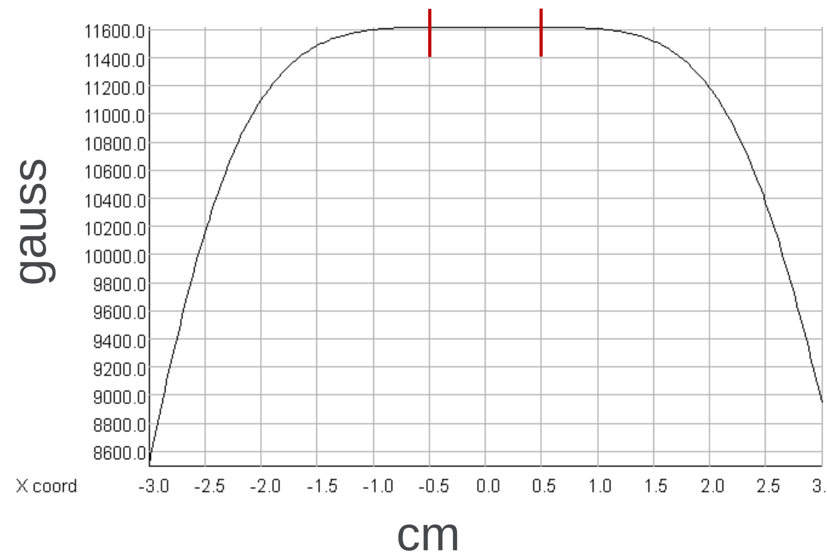
M1_41pmV5rev1 - 2D optimization



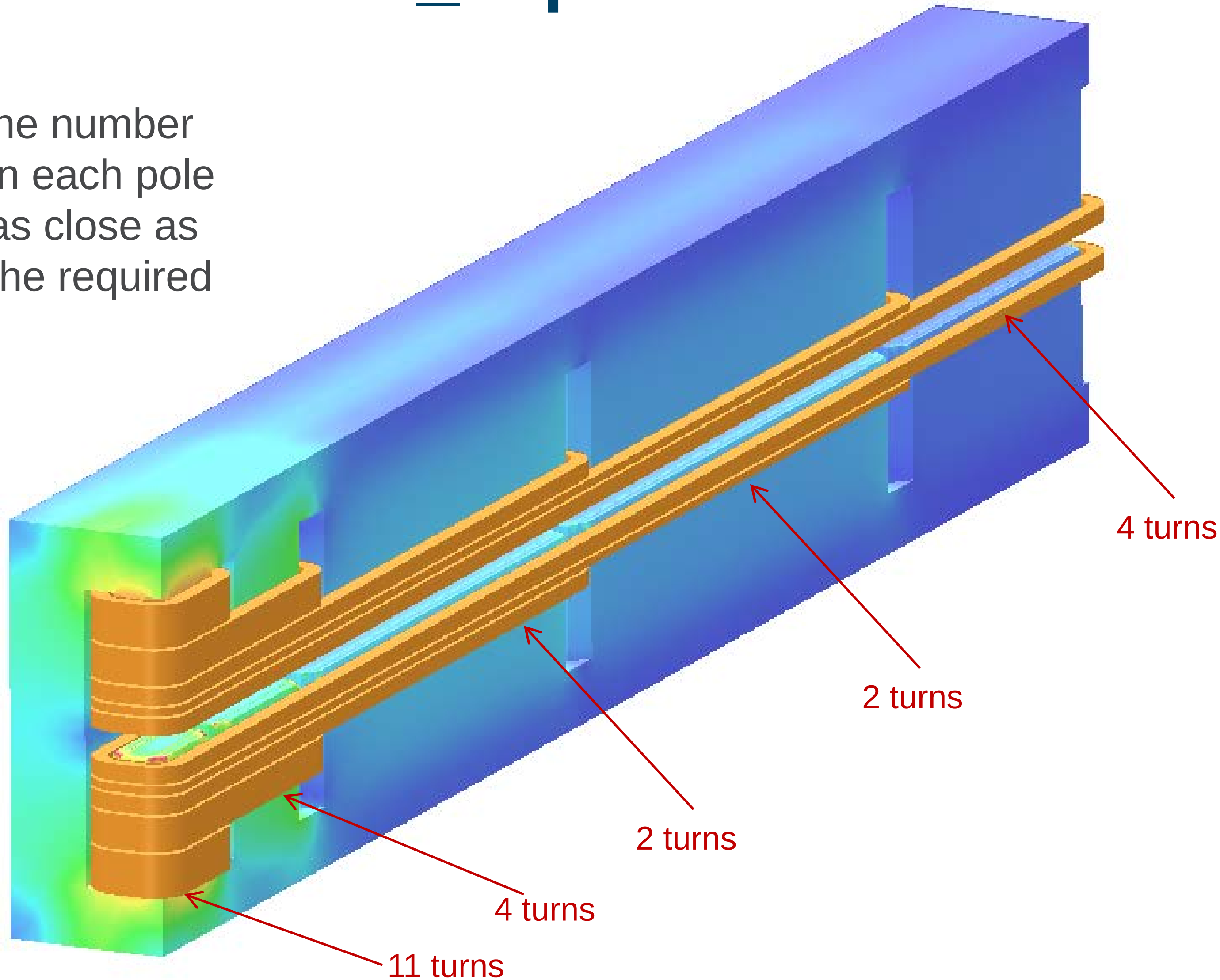


Flatten the field over more than the 7 mm sagitta.

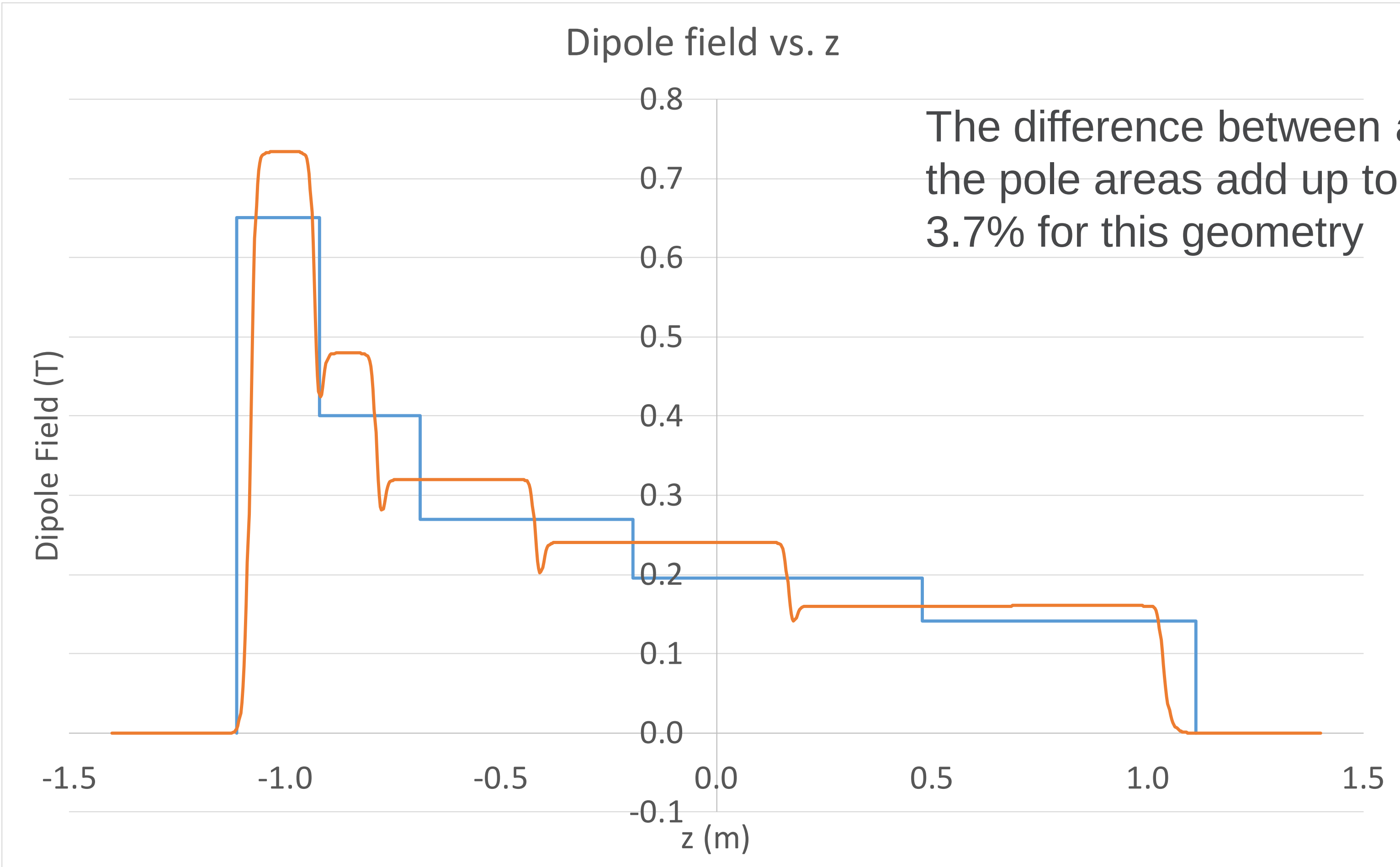
X +/- 5 mm – (max_By-min_By)/min_By = 0.34E-4

M1_41pmV5rev1

Change the number of turns on each pole to target as close as possible the required field.



M1_41pmV5rev1 – The latest model



The difference between all the pole areas add up to 3.7% for this geometry

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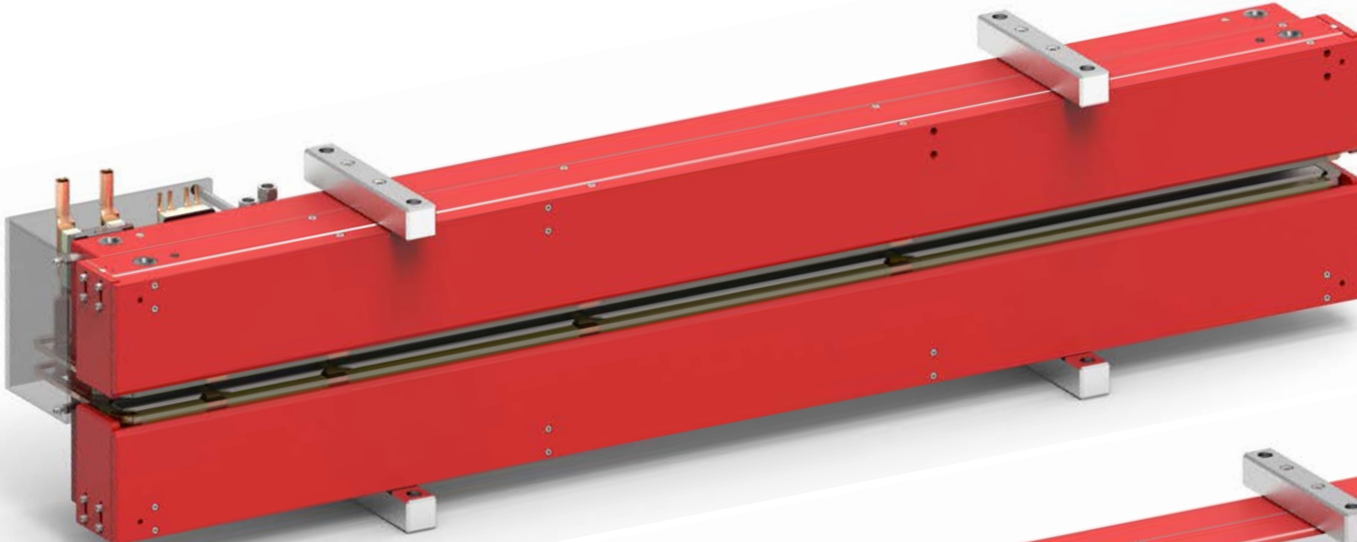
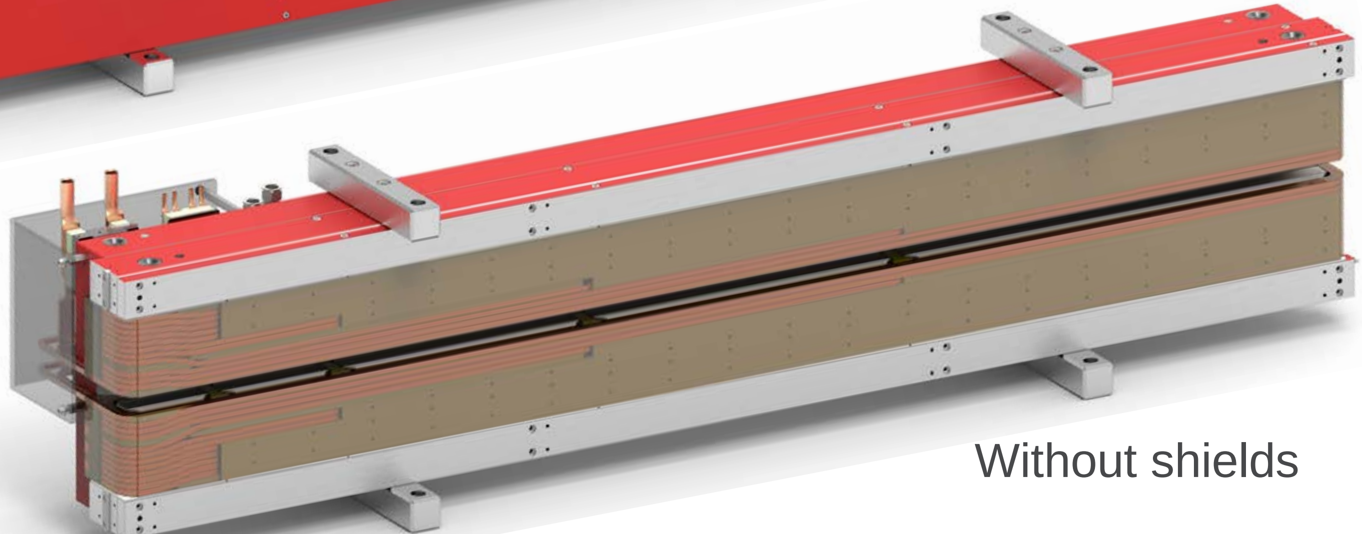
R&D M1 5 Pole R&D Prototype Assembly



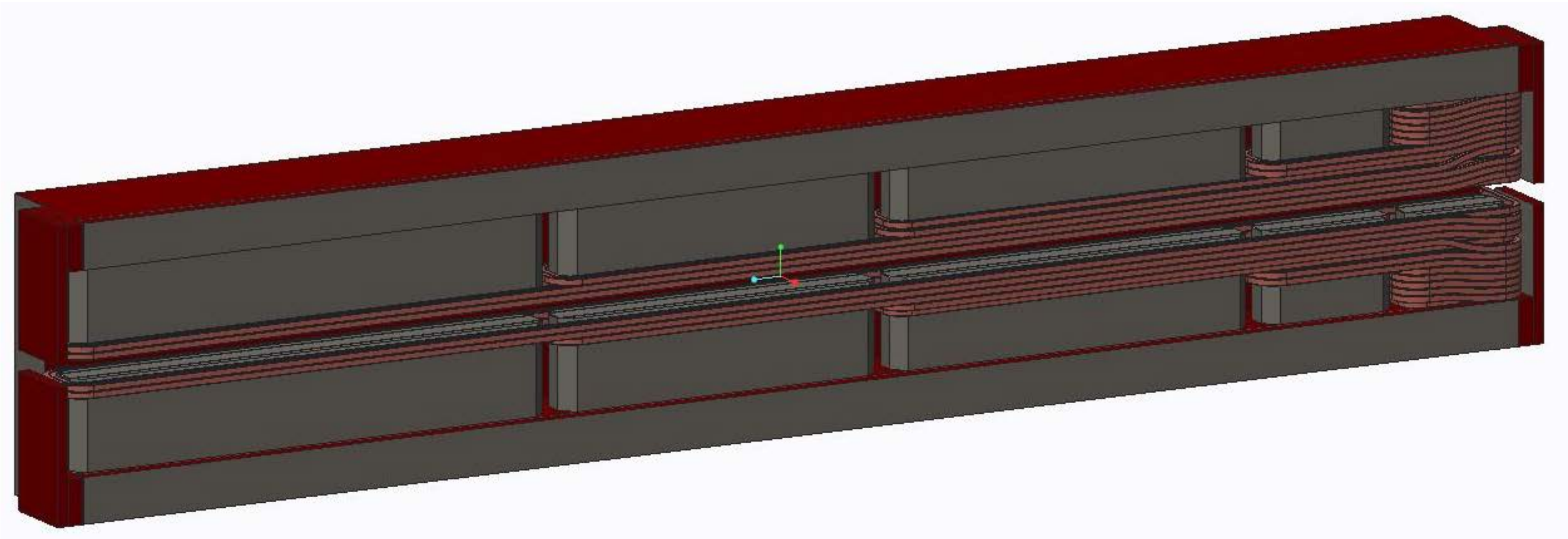
With shields

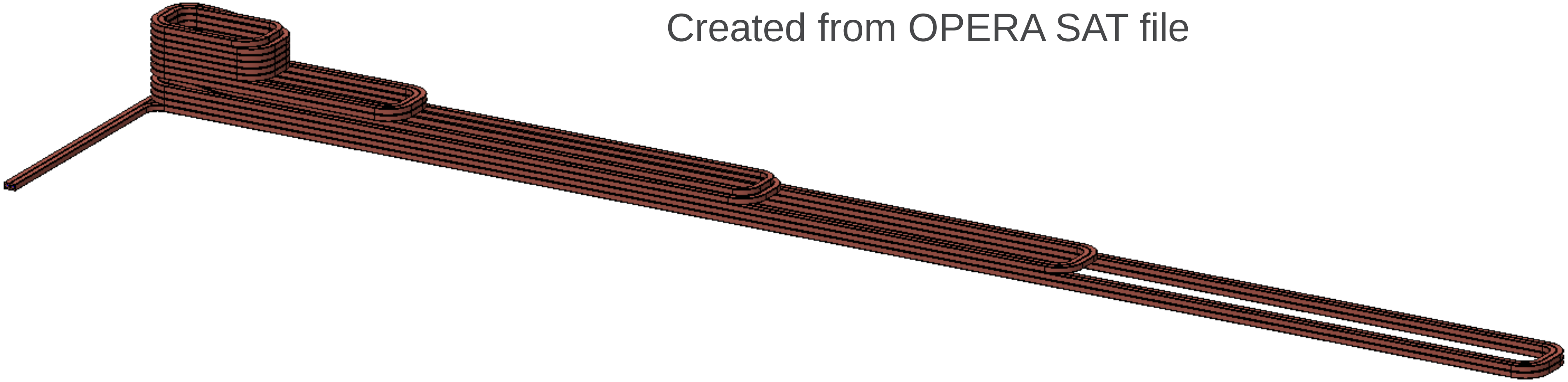


Without shields

Rendering by O. Schmidt

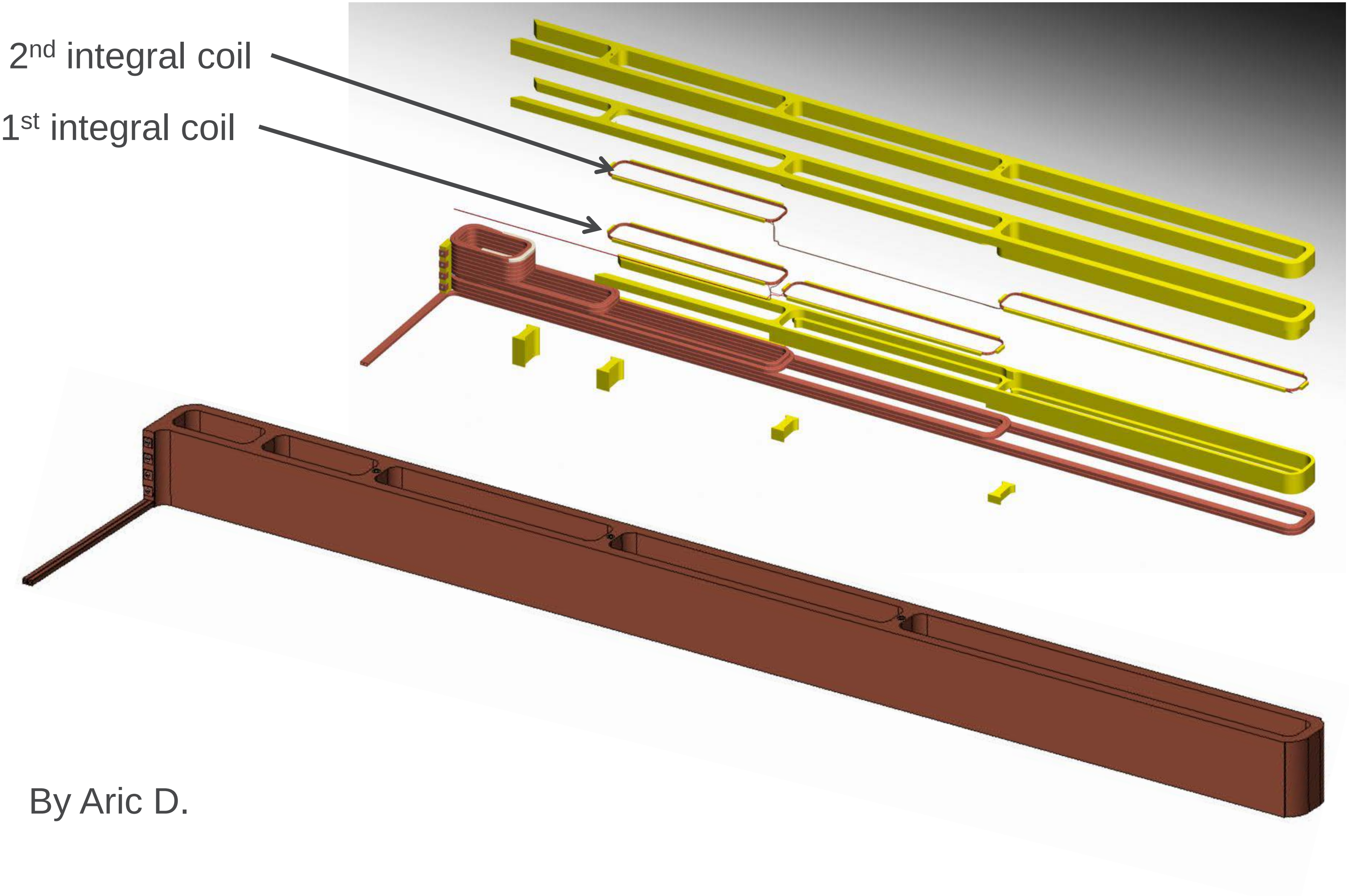
R&D M1





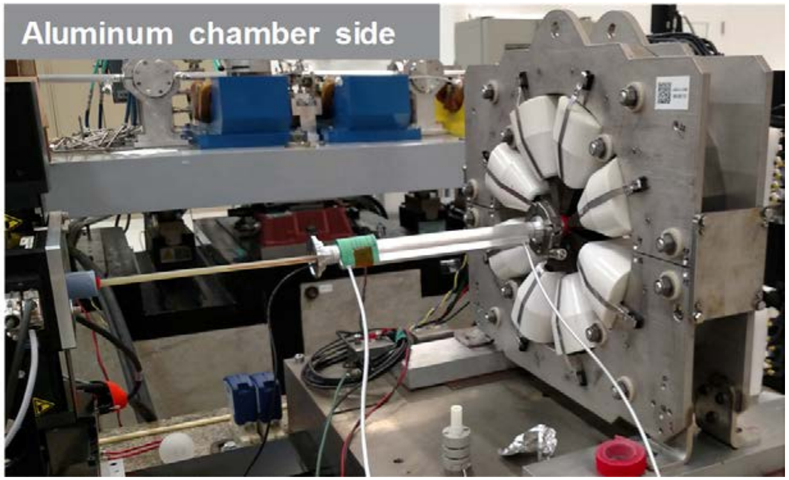
Created from OPERA SAT file

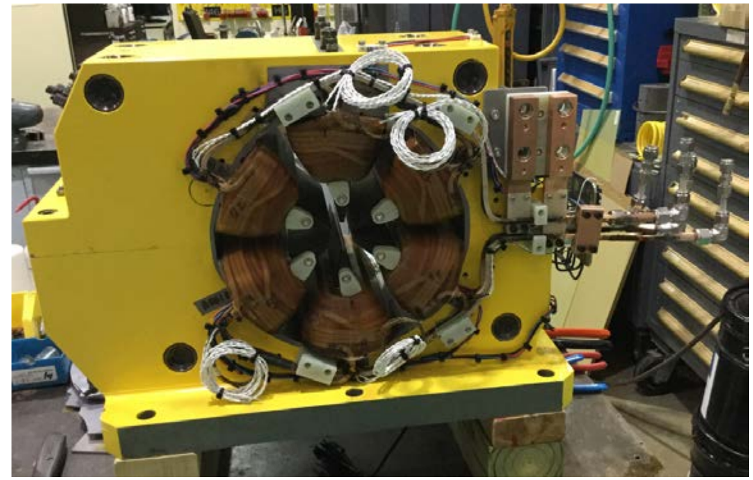
R&D M1 coils assembly



By Aric D.

Corrector and sextupole magnets

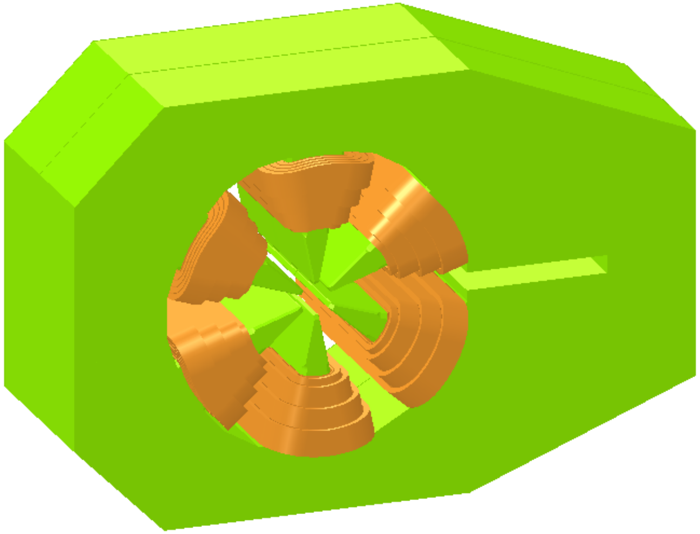




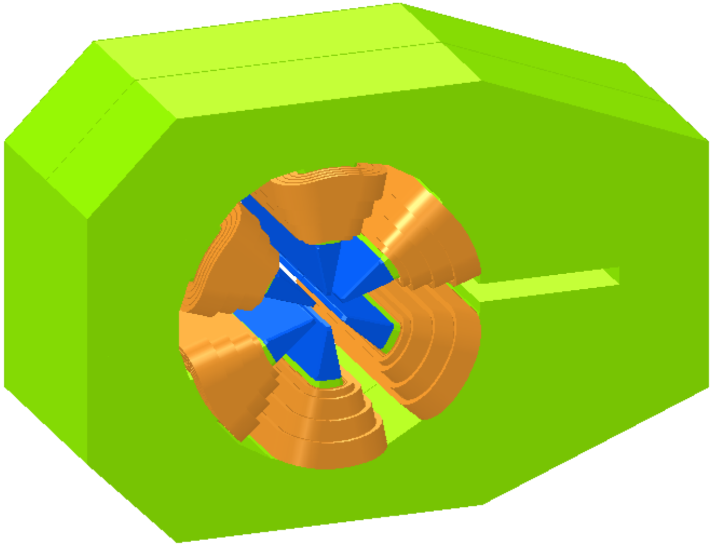
Corrector magnet designed by Brookhaven National Laboratory, built by Everson Tesla, and tested with vacuum chamber installed at the Advanced Photon Source (APS). We now know the minimum distance of the aluminum flange to the core is 40 mm before it causes a disturbance to the field.

DMM sextupole magnet designed, built, and tested at APS.

Sextupole magnets



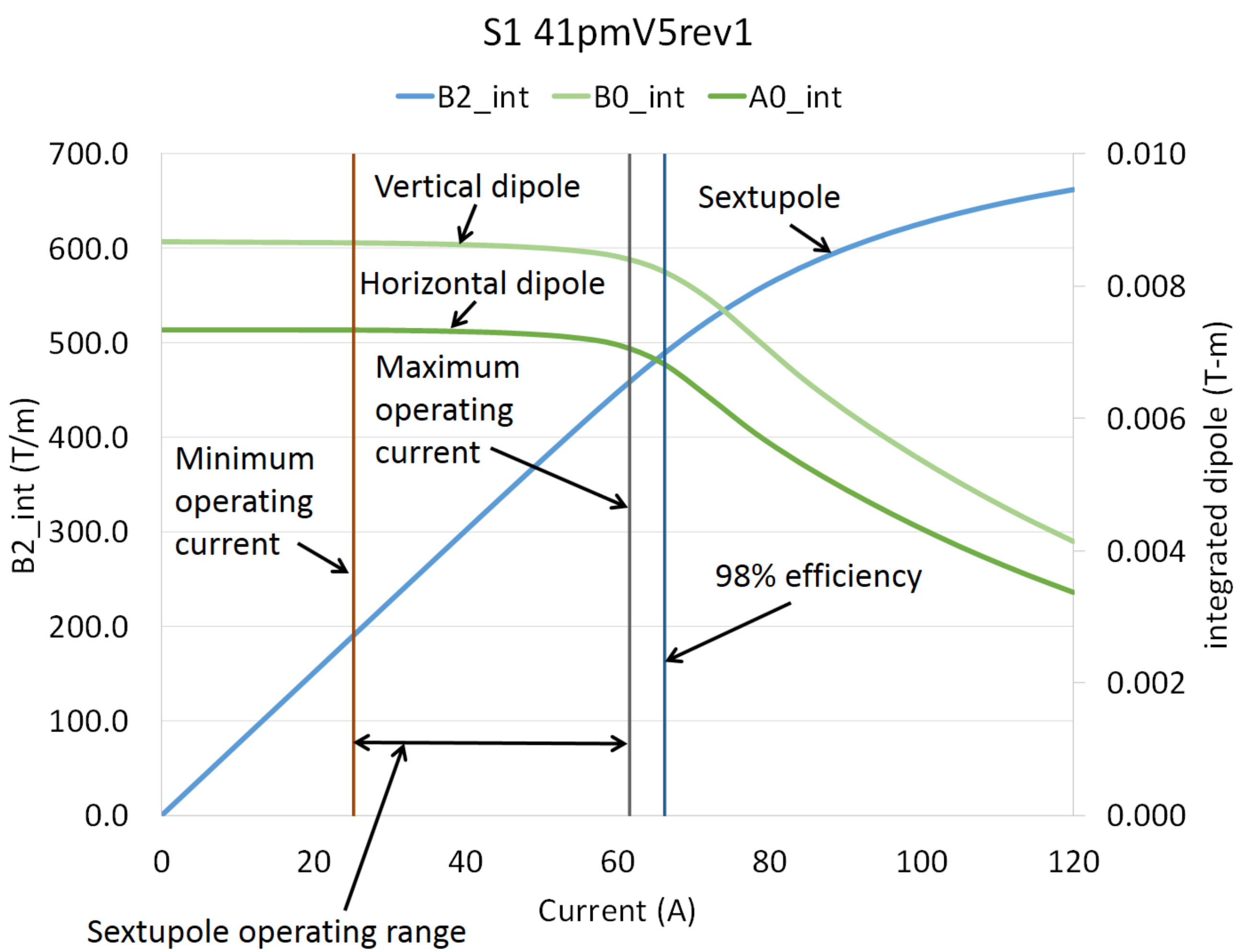
S1/S2
230 mm long
Iron pole tips



S3
260 mm long
VP pole tips

They both have the same cross section.

S1 Sextupole current scan with dipoles turned on



APSU Magnets Plan

- Finish testing the DMM prototype and corrector magnet.
- Complete designing, building and testing of the R&D 3-magnet-FODO, and M1 L-bend.
- Confirm the photon beam tube locations through the magnet cores understanding the differences between doublet and multiplet A and B types.
- Leakage field and magnet cross talk shall be analyzed, measured, and understood. Corrector magnet to Q1 cross talk analysis done by BNL shows negligible effect. Cross talk analysis between the Q2 and M1 by Melike Abliz shows negligible effect.
- Further refine magnet designs using experience and knowledge gained from the R&D program.
- Safe work practices are a matter of practice and we are constantly vigilant about this.

Summary

- There are Fourteen different kinds of magnets
  - Q1, Q2, Q3/Q6, Q4, Q5, Q7, Q8, M3, M4, M1, M2, S1/S3, S2, and corrector
- We have made good progress on our R&D / technical designs.
- The DMM and corrector magnet R&D has shown that simulations agree with magnet measurements.
- Saturation is limited to 90% which defines the length of the magnets.
- An 8-piece-quadrupole magnet design is used to produce very accurate positioning of the pole tips which essentially promises good field quality.
- Changing from 67 to 41 pm lattice changed some of the magnet lengths and configurations but does not change the R&D path. The existing magnet R&D benefits the 41 pm lattice.
- Magnet designs are maturing and we are ready to proceed with CD-2 and CD-3B.

APSU Magnets Org Chart

APSU Magnet Group is in Red.

Analysis
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Jie Liu
Mau Lopes, FNAL
Charlie Spataro, BNL

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Mike Johnson
Glenn Moonier
Leonard Morrison
Ed Theres

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Herman P. Cease
Glenn Decker
Efim Gluskin
Stuart Henderson
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Sushil Sharma, BNL
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Nathaniel Poindexter
Ben Rocke
William Turner

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Mike Oprondek

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Chuck Doose
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Matt Kasa
Isaac Vaaserman

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Sherese Humphrey
Katherine Martin
Elmie Peoples-Evans
Brian Smith

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Bill Jansma
Kristine Mietsner
Keith Knight
Jeromir Penicka

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Jim Lang

Quality
Tom Barkalow
Tom Barsz

Riggers
Josh Abraham

Vacuum
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Michelle Leighton
Cindy Schmitt
Diane Wilkinson

Physics
Michael Borland
Vadim Sajev
Uli Wienands
Aimin Xiao