Interviewing

Presented by
Zhan Zhang

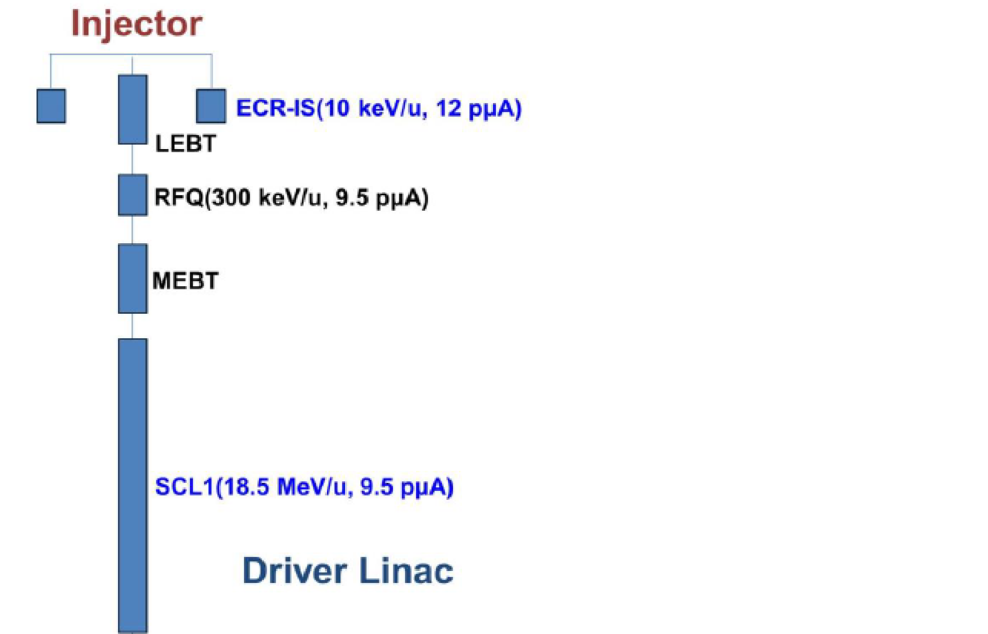
Self-introduction

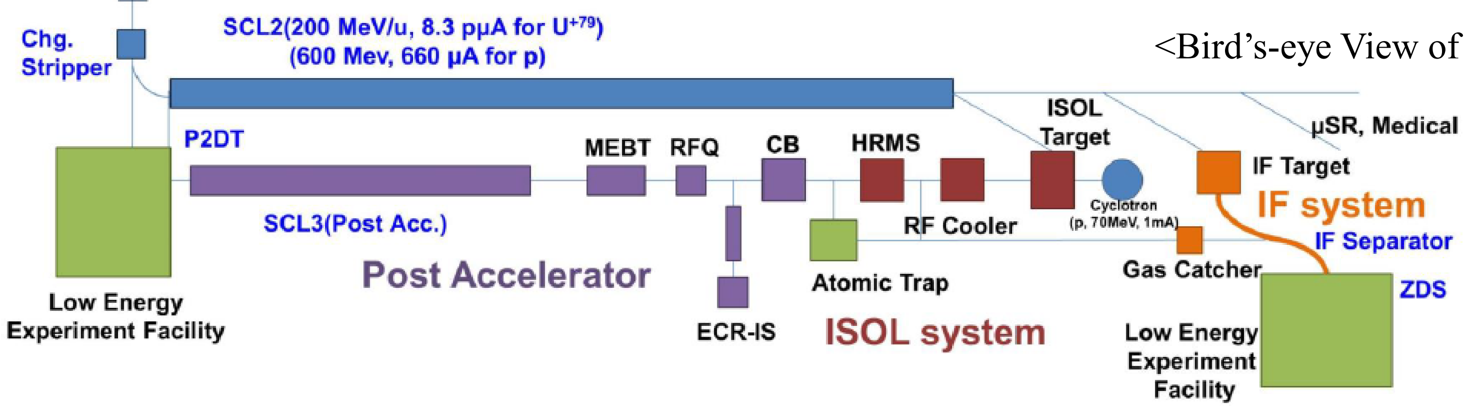
- Name: Zhan Zhang
- Work experience:
  - ✓ 2012.10-2017.07 Research assistant at Department of Energy and Electrical Engineering of Uiduk University in South Korea
- PhD education:
  - ✓ 2013.03-2017.06 Uiduk University in South Korea, Mentor: Sangjin Lee(이상진)
  - ✓ Research Field: accelerator magnet design, harmonic analysis, beam analysis
- Postdoc:
  - ✓ 2017.12-Present Accelerator center of IHEP, Mentor: Qing Qin(秦庆)
  - ✓ Topic: Design of a 12-T Twin-Aperture Dipole Magnet with 1e-4 Field Uniformity

PhD study

Design and Beam Analysis of HTS Multi-Pole Magnet for Accelerators

RAON Heavy Ion Accelerator



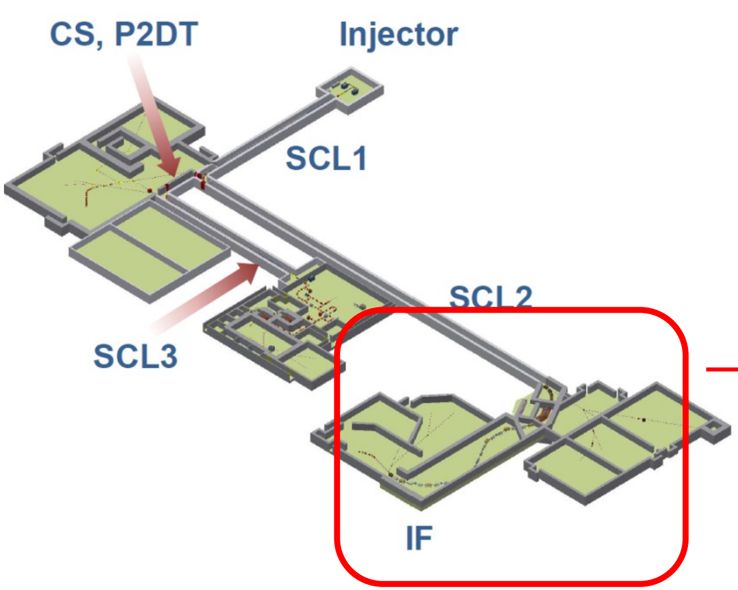


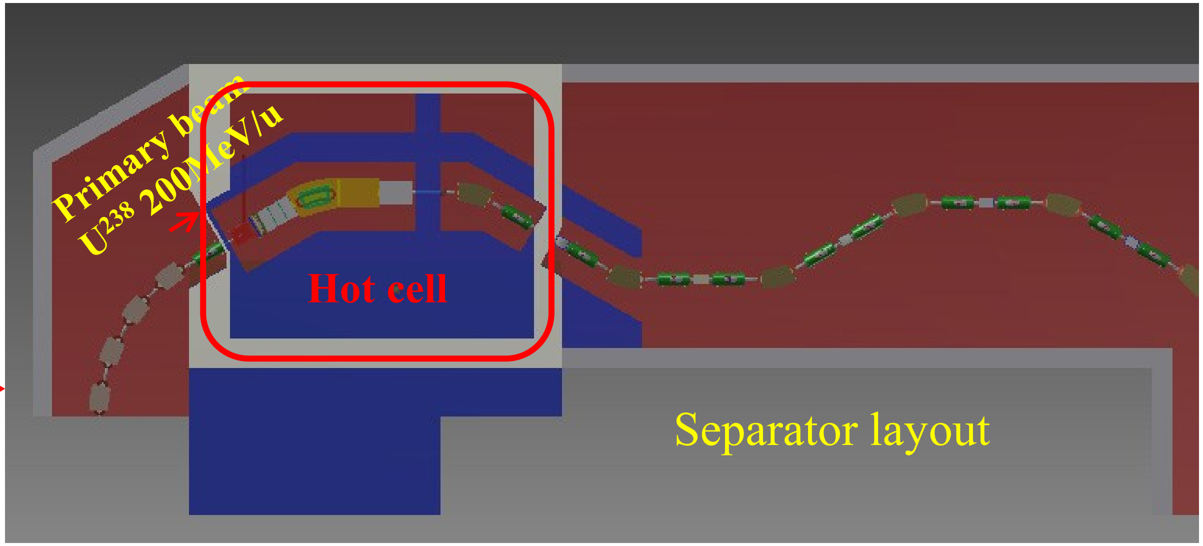
<Bird's-eye View of the RAON >

< Conceptual Design of the RAON >

Motivation

- In heavy ion accelerators, the beam can have ***radiation*** and ***heat loads*** after being accelerated. There can be a high radiation region, called hot cell, at the beginning of the beam transmission system[*].



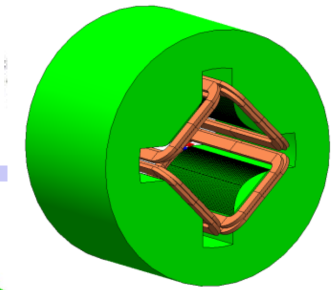


<Separator layout of RAON heavy ion accelerator>

- The HTS multi-pole magnets are suitable for application in such an environment[**].

[*] Dong-O Jeon and Hyung Jin Kim,"Status of the RAON Heavy Ion Accelerator Project", Proceedings of the 27th International Linear Accelerator Conference, 2014.
[**] J. P. Cozzolino et al., "Engineering Design of HTS Quadrupole for FRIB" Accelerator Technology，TUP162，Proceedings of Particle Accelerator Conference, New York, USA, 2011.

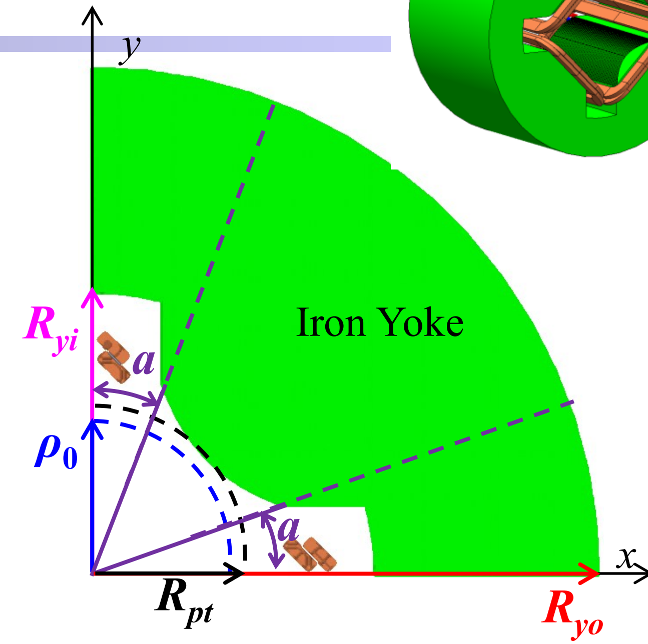
Iron Yoke of Quadrupole Magnet

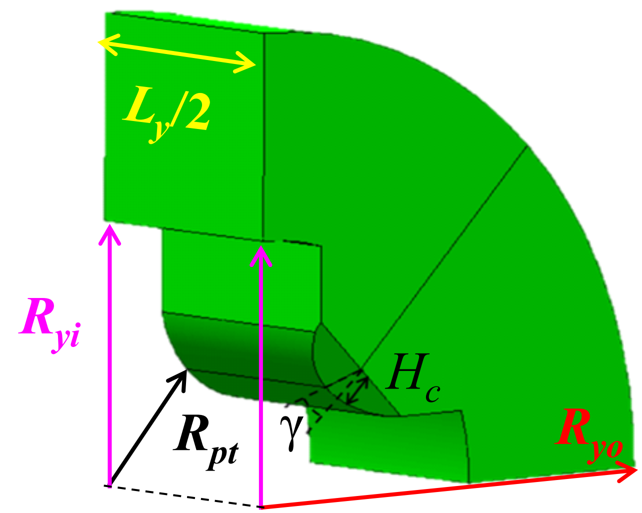


- Yoke: hyperbolic pole.
- Coil: there are four coils in total model, each coils have two windings.

<Parameters of yoke of an HTS quadrupole magnet>

Item	Symbol	Value
Inner radius of yoke (mm)	R_{yi}	290
Outer radius of yoke (mm)	R_{yo}	520
Yoke length (mm)	L_y	480
Pole tip radius (mm)	R_{pt}	168
Reference radius of good field region (mm)	ρ_0	150
Angle of cutting pole (°)	α	24
Height of chamfer (mm)	H_c	0
Angle of chamfer (°)	γ	45

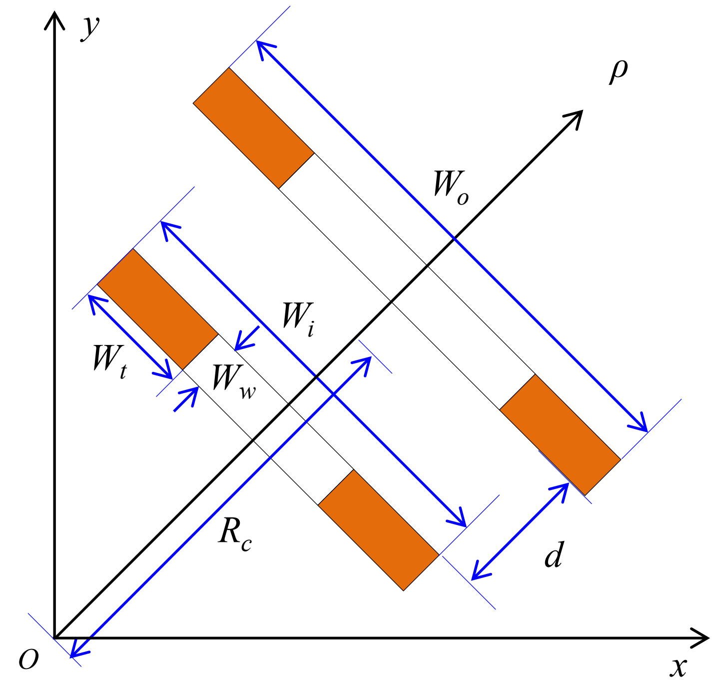


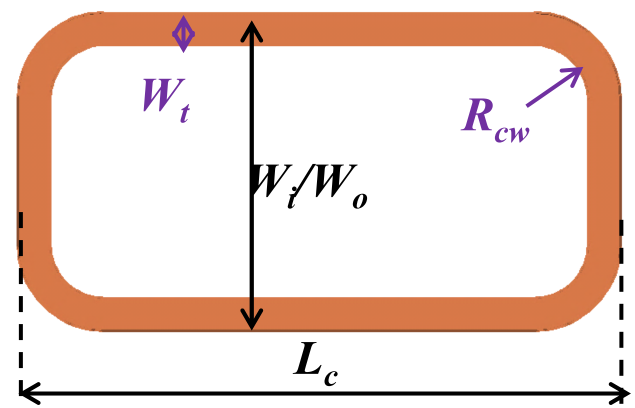


HTS Coil of Quadrupole Magnet

<Parameters of HTS coil of an HTS quadrupole magnet>

Item	Symbol	Value
Number of turns	N	164
Winding thickness (mm)	W_t	36.08
Winding width (mm)	W_w	12
Radius of corner of windings (mm)	R_{cw}	60
Gap of windings (mm)	d	2
Length of coil (mm)	L_c	680.16
Radius of coil (mm)	R_c	173.83
Width of inner winding (mm)	W_i	306.16
Width of outer winding (mm)	W_o	334.16



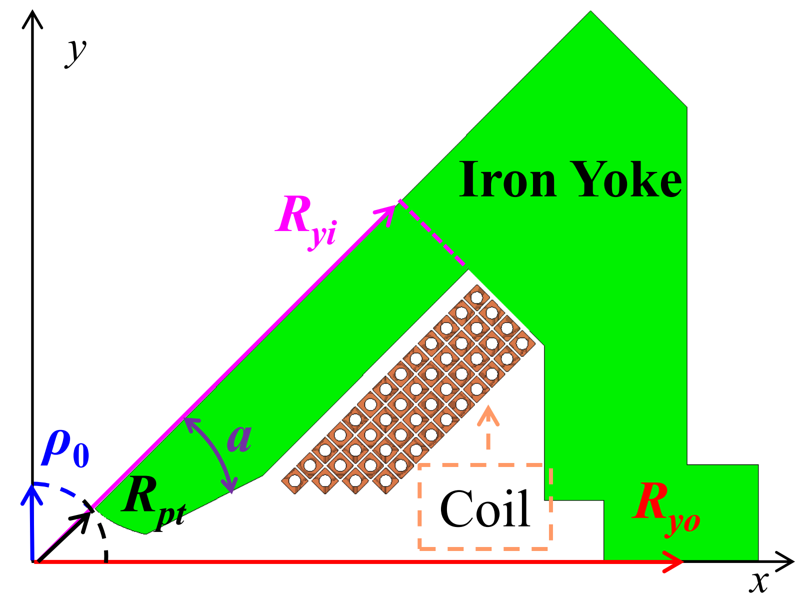


Normal Conducting(NC) Quadrupole Magnet[*]

- In this section, we establish an NC quadrupole magnet model comparing with the HTS quadrupole magnet model.

<Parameters of yoke of NC quadrupole magnet>

Item	Symbol	Value
Inner radius of yoke (mm)	R_{yi}	212
Outer radius of yoke (mm)	R_{yo}	300
Yoke length (mm)	L_y	200
Pole tip radius (mm)	R_{pt}	30.5
Reference radius of good field region (mm)	ρ_0	30.5
Angle of pole (°)	α	18.365



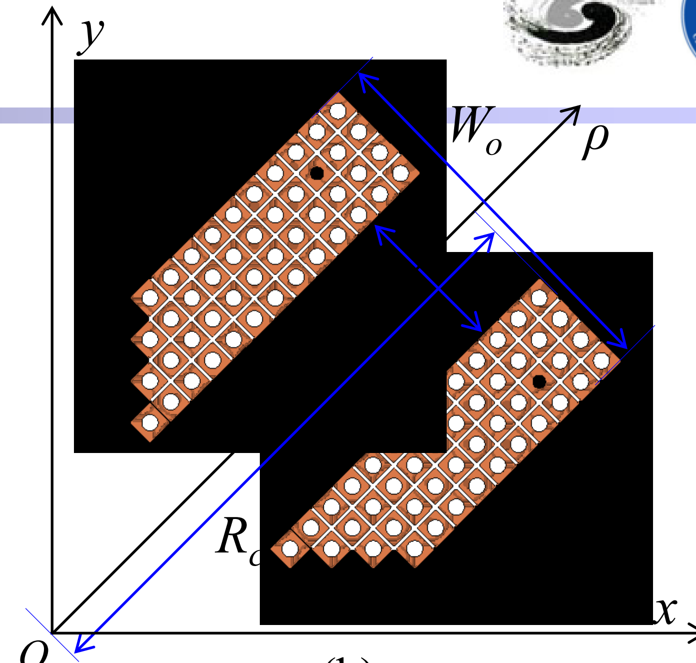
<Parameters of yoke of NC quadrupole magnet>

[*] D. Einfeld, "Specifications, quality control, manufacturing, and testing of accelerator magnets", CELLS-ALBA, Barcelona, Spain, 2016.

NC Quadrupole Magnet[*]

<Parameters of coil of NC quadrupole magnet>

Item	Symbol	Value
Number of turns	N	46
Radius of coil (mm)	R_c	212
Radius of corner of windings (mm)	R_{cw}	26
Width of inner winding (mm)	W_i	90
Width of outer winding (mm)	W_o	168
Inside length of coil (mm)	L_{ci}	220
Length of coil (mm)	L_c	298



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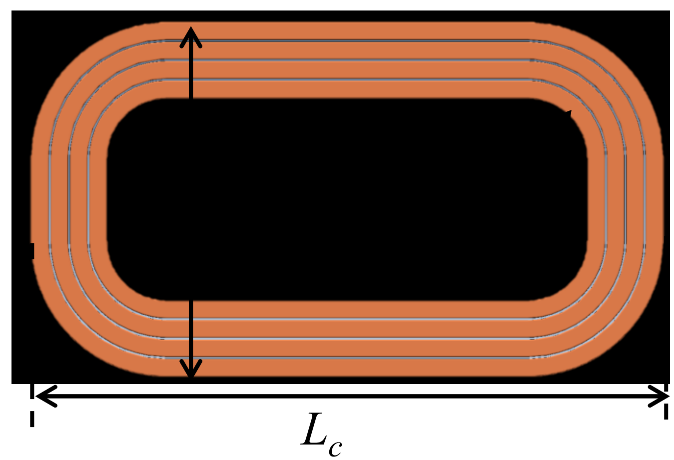


(c)

<parameters of coil of NC quadrupole magnet: (a) section view of the conductor, (b) section view of the NC coil, and (c) size of coil>

[*] D. Einfeld, "Specifications, quality control, manufacturing, and testing of accelerator magnets", CELLS-ALBA, Barcelona, Spain, 2016.

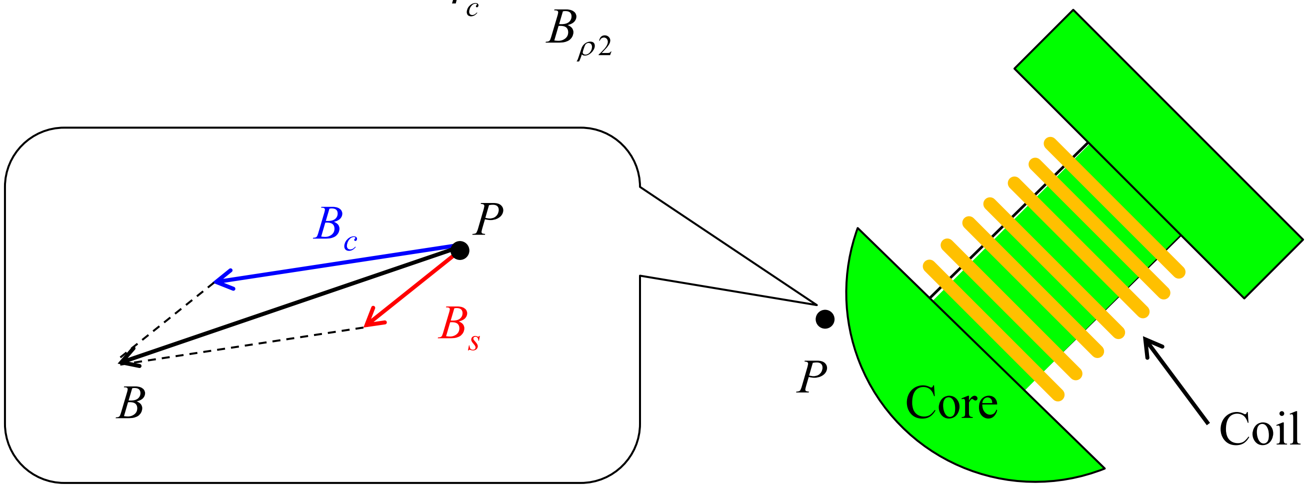
Separated Fields

- In our previous study, the total magnetic field B of the magnets was separated into the coil-induced magnetic field, B_s and the iron-induced magnetic field, B_c for magnetic field analysis[*] as the following

$$B = B_s + B_c$$

- The ratio of iron-induced field, B_c by the total field B is defined using the main field components

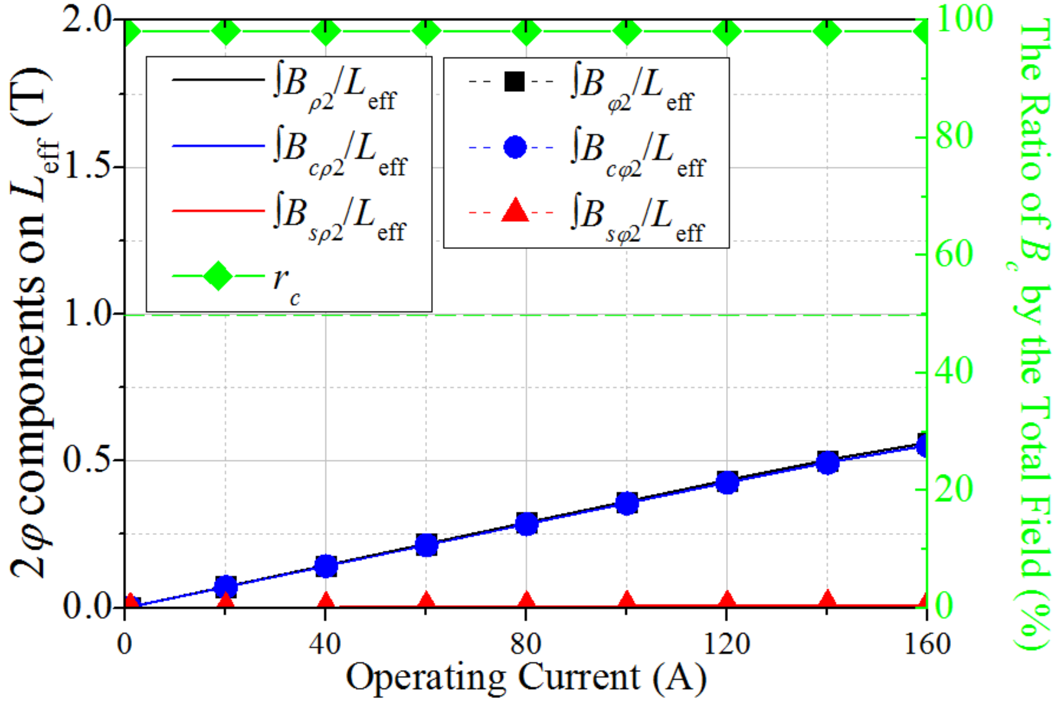
$$r_c = \frac{B_{c\rho 2}}{B_{\rho 2}}$$



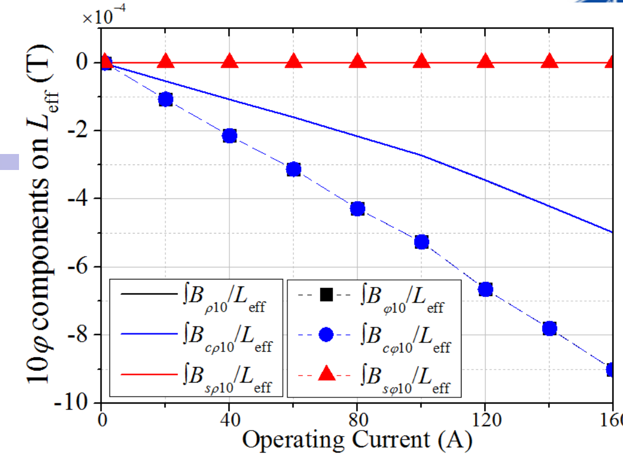
<Separated fields for a quadrupole magnet>

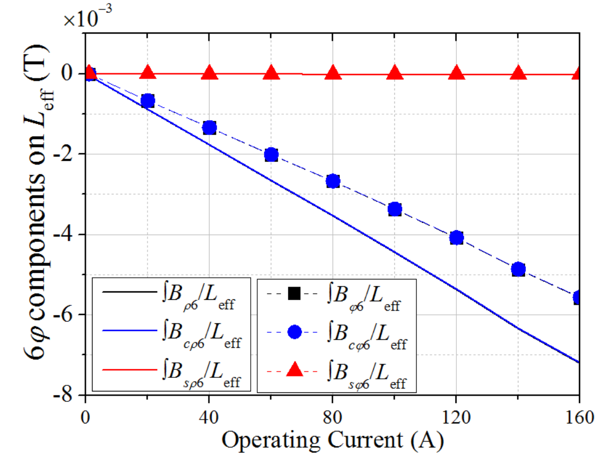
[*] Zhan Zhang, Sangjin Lee, and et al., "Magnetic Field characteristics from HTS Quadrupole Magnet of In-Flight Separator for a Heavy Ion Accelerator", Superconductivity and Cryogenics, Vol.17, No.3, pp. 23–27, 2015.

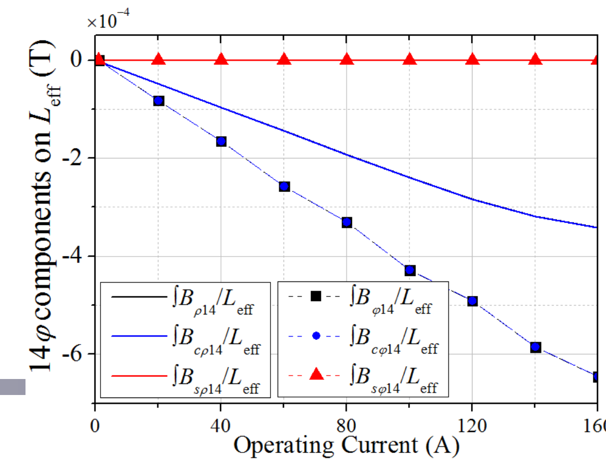
Analysis for NC Magnet



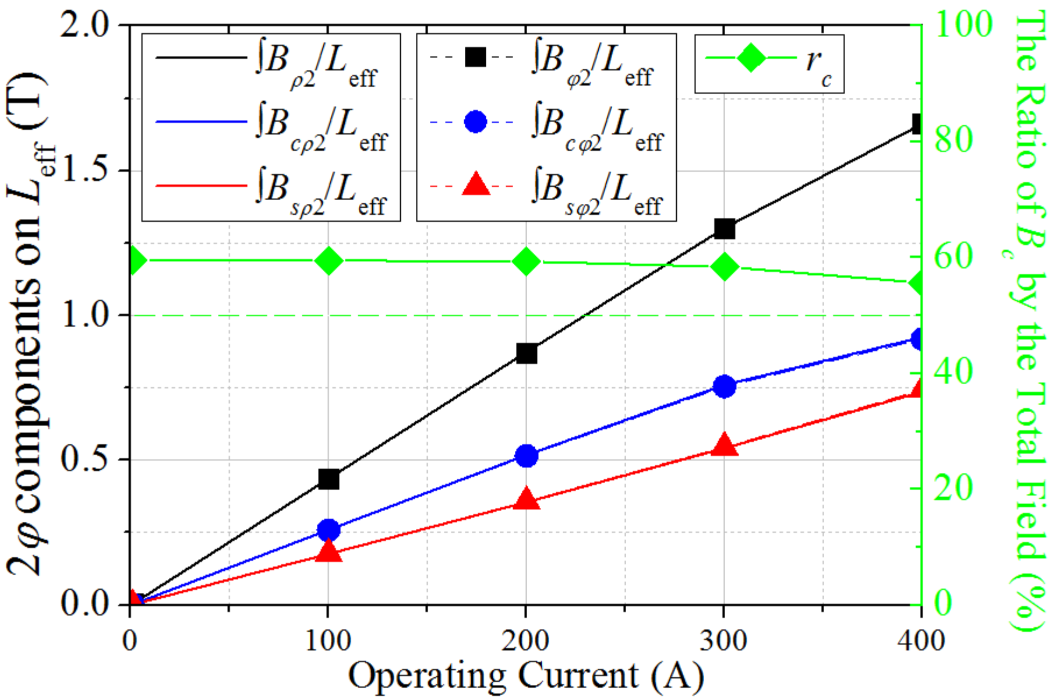
<Harmonic components w.r.t. current for NC Magnet>



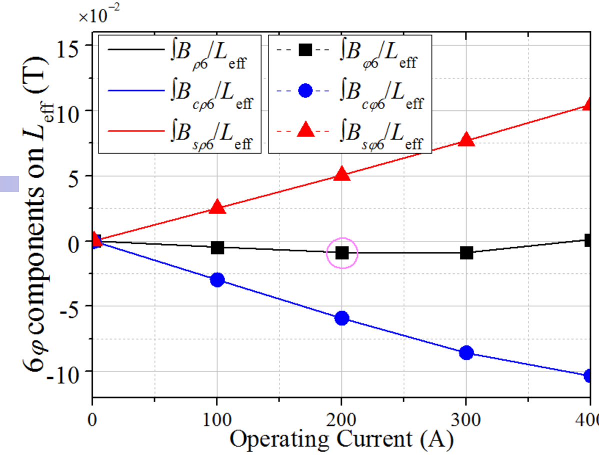


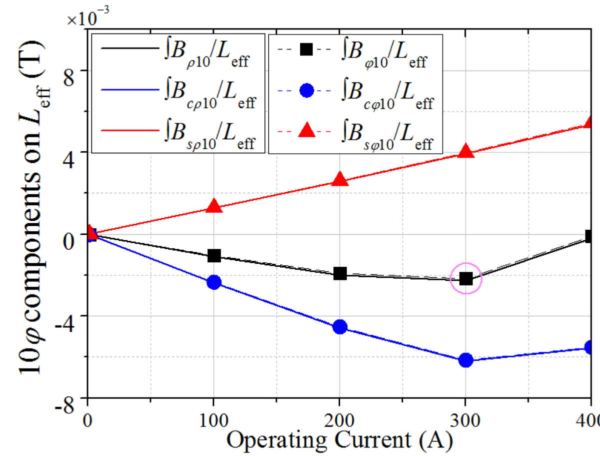


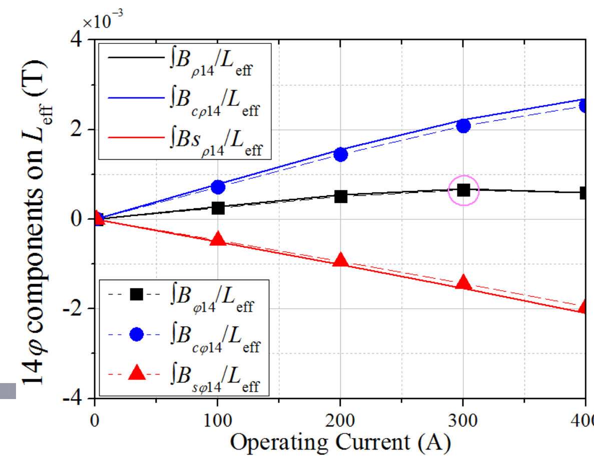
Analysis of HTS Magnet



<Harmonic components w.r.t. current for HTS Magnet>

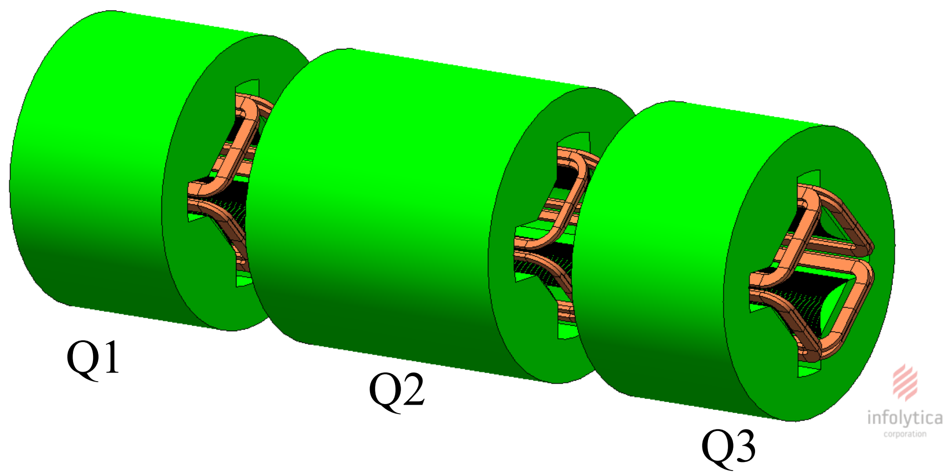






Iron Core Triplet Design

- A triplet system is designed in this section. The triplet is considered for only uranium $^{+79}U^{238}$. Generally, the properties of a quadrupole doublet are better than that of matched a quadrupole triplet to requirements, but a quadrupole triplet will preserve more of the axial symmetry in an initially symmetric beam than will a doublet[*][**].
- The triplet system composes of three quadrupole magnets - Q1, Q2, and Q3, where Q1 and Q3 are totally same.

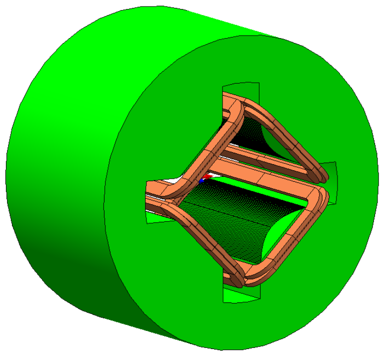


<An iron yoke triplet system>

[*] Ragnar Hellborg, Electrostatic Accelerators Fundamentals and Applications, Sweden, 2005.
[**] Y. S. Choi, H. M. Chang, and et al., " Design of cryostat for superconducting quadrupole magnets in In-Flight fragmentation separator", Progress in Superconductivity and Cryogenics, Vol.17, No.3, pp.62-66, 2015.

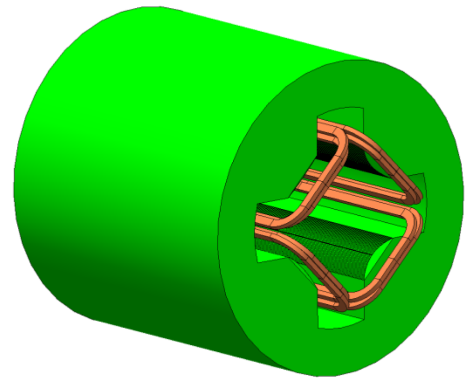
Designed Results

- Harmonic matching (HM) Method can be used for iron core HTS quadrupole magnet design.



Field quality of Designed Q1/Q3

Item	Value
G	12.1 T/m
OF	0.0338 %
$b_{\rho 6}$	-1.238E-2 %
$b_{\rho 10}$	-1.878E-2 %
$b_{\rho 14}$	-0.267E-2 %
I_{op}	329.328 A
L_{eff}	558.528 mm



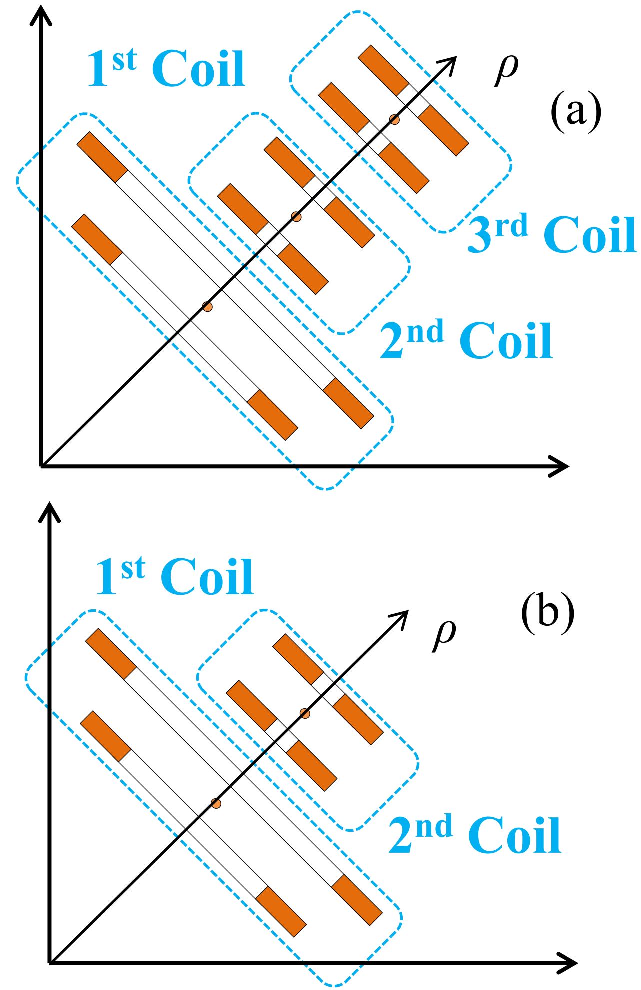
Field quality of Designed Q2

Item	Value
G	7.37 T/m
OF	0.0289 %
$b_{\rho 6}$	0.527E-2 %
$b_{\rho 10}$	1.991E-2 %
$b_{\rho 14}$	0.377E-2 %
I_{op}	376.520 A
L_{eff}	898.784 mm

Initial Model for Q1/Q3

- The larger width coils created the ***positive*** 6th component.
- The smaller width coils created the ***negative*** 6th component.
- Therefore, the HM Method can be used for air core HTS quadrupole design.

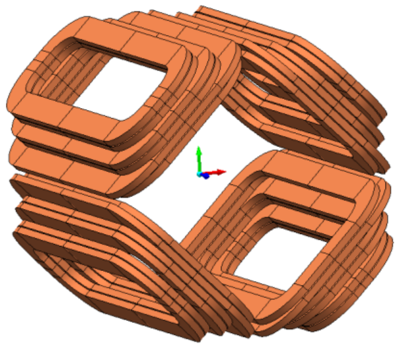
- Q1/Q3:
  - ✓ Three coils should be employed for target field gradient.
- Q2:
  - ✓ Two coils should be employed for target field gradient.



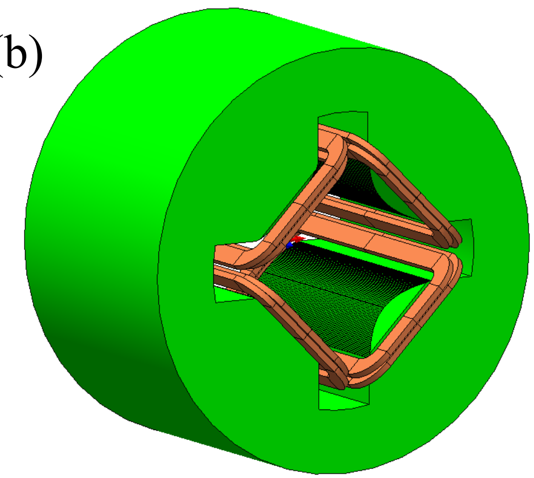
<Schematic view of initial air core models: (a) Q1\Q3, and (b) Q2>

Comparison between Iron Core Magnet & Air Core Magnet

(a)



(b)



<Solid view of quadrupole magnet Q1/Q3: (a) air core, and (b) iron core>

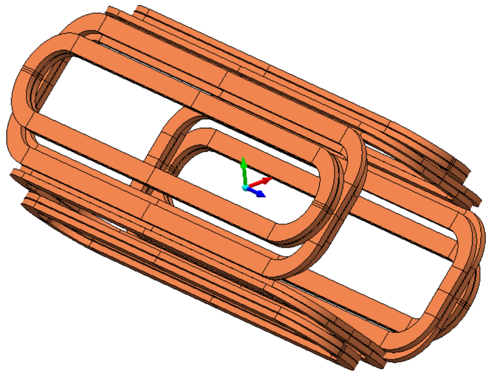
Item	Air Core Model	Iron Core Model
G	12.1 T/m	12.1 T/m
b_6	-1.566E-2 %	-1.238E-2 %
b_{10}	-7.457E-2 %	-1.878E-2 %
b_{14}	-0.190E-2 %	-0.267E-2 %
OF	0.0921%	0.0338 %
I_{op}	381.052 A	329.328 A
Turns per Pole	1200	328
L_{eff}	552.848 mm	558.528 mm
B_{max} on HTS	4.063 T	2.807 T
B_{max_normal} on HTS	2.758 T	2.527 T
Length of magnet	621.00 mm	650.16 mm
Radius of magnet	263.928 mm	400.00 mm
Coil Volume	18.5255 E+6 mm^3	5.744976 E+6 mm^3
Iron Volume	0	0.18623168 E+9 mm^3
Iron Weight	0	1.4664 ton

The density of iron is 7.874 E-9 ton/mm^3.[*]

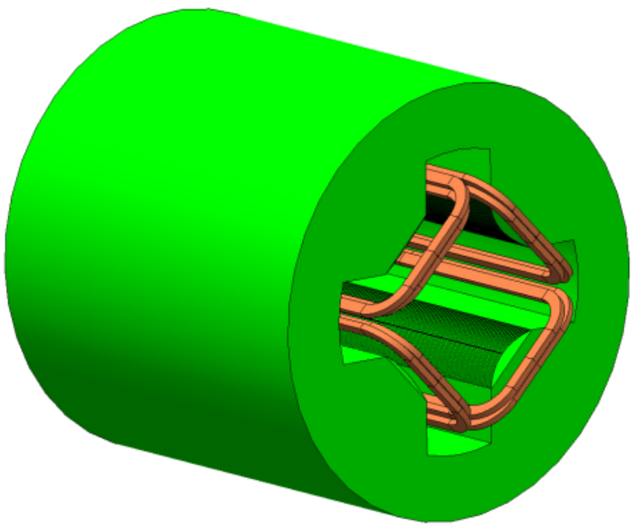
[*] https://en.wikipedia.org/wiki/Iron

Comparison between Iron Core Magnet & Air Core Magnet

(a)



(b)

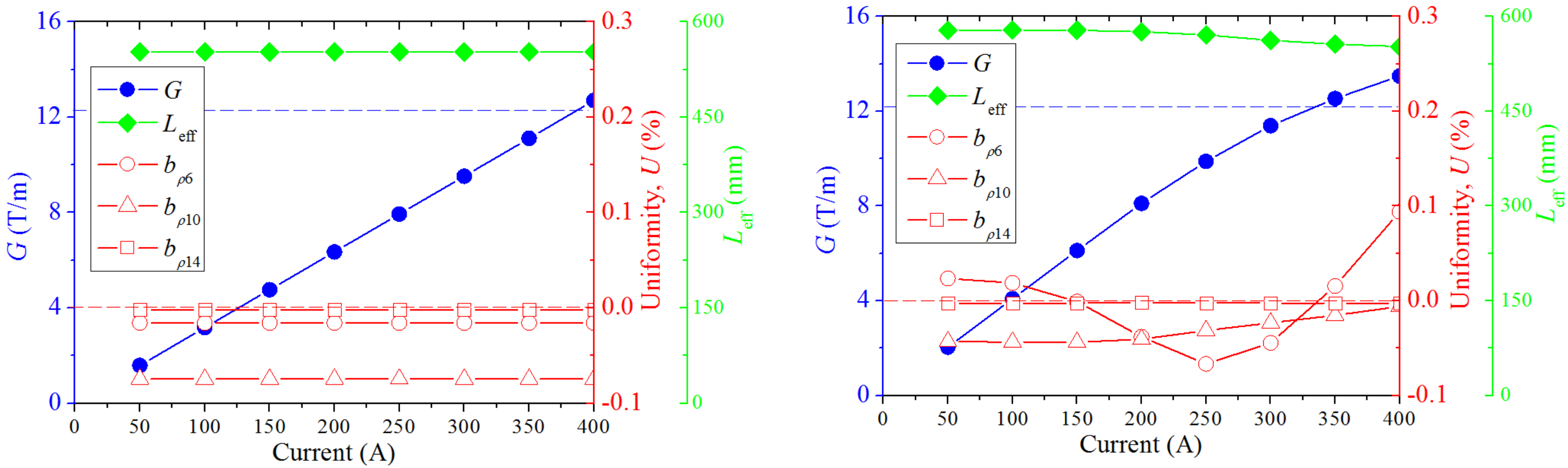


<Solid view of quadrupole magnet Q2: (a) air core, and (b) iron core>

Item	Air Core Model	Iron Core Model
G	7.37 T/m	7.37 T/m
b_6	-0.058E-2 %	0.527E-2 %
b_{10}	-0.545E-2 %	1.991E-2 %
b_{14}	0.030E-2 %	0.377E-2 %
OF	0.0632 %	0.0289 %
I_{op}	392.345 A	376.520 A
Turns per Pole	640	200
L_{eff}	900.386 mm	898.784 mm
B_{max} on HTS	3.004 T	2.121 T
B_{max_normal} on HTS	1.844 T	1.364 T
Length of magnet	951.00 mm	972.00 mm
Radius of magnet	240.1687 mm	400.00 mm
Coil Volume	14.380435 E+6 mm^3	4.8895504 E+6 mm^3
Iron Volume	0	0.27623648 E+9 mm^3
Iron Weight	0	2.1751 ton

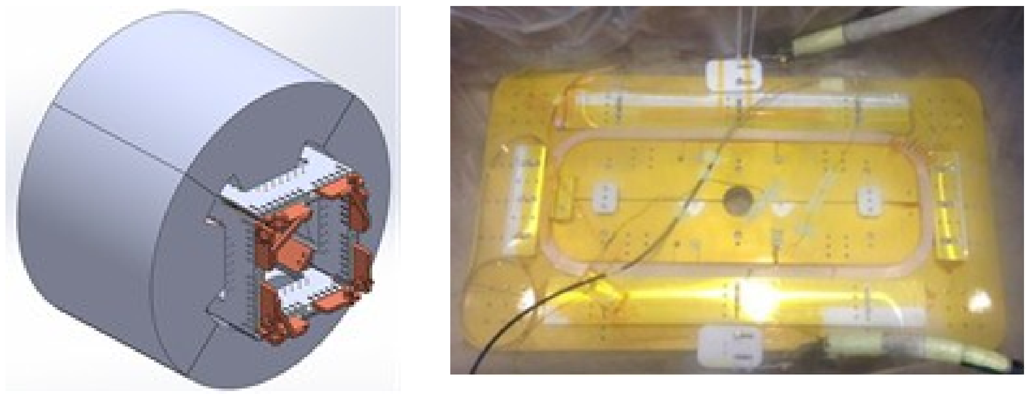
The outer radius of air core model is less than that of iron core model.

Comparison between Iron Core Magnet & Air Core Magnet



(a) (b)

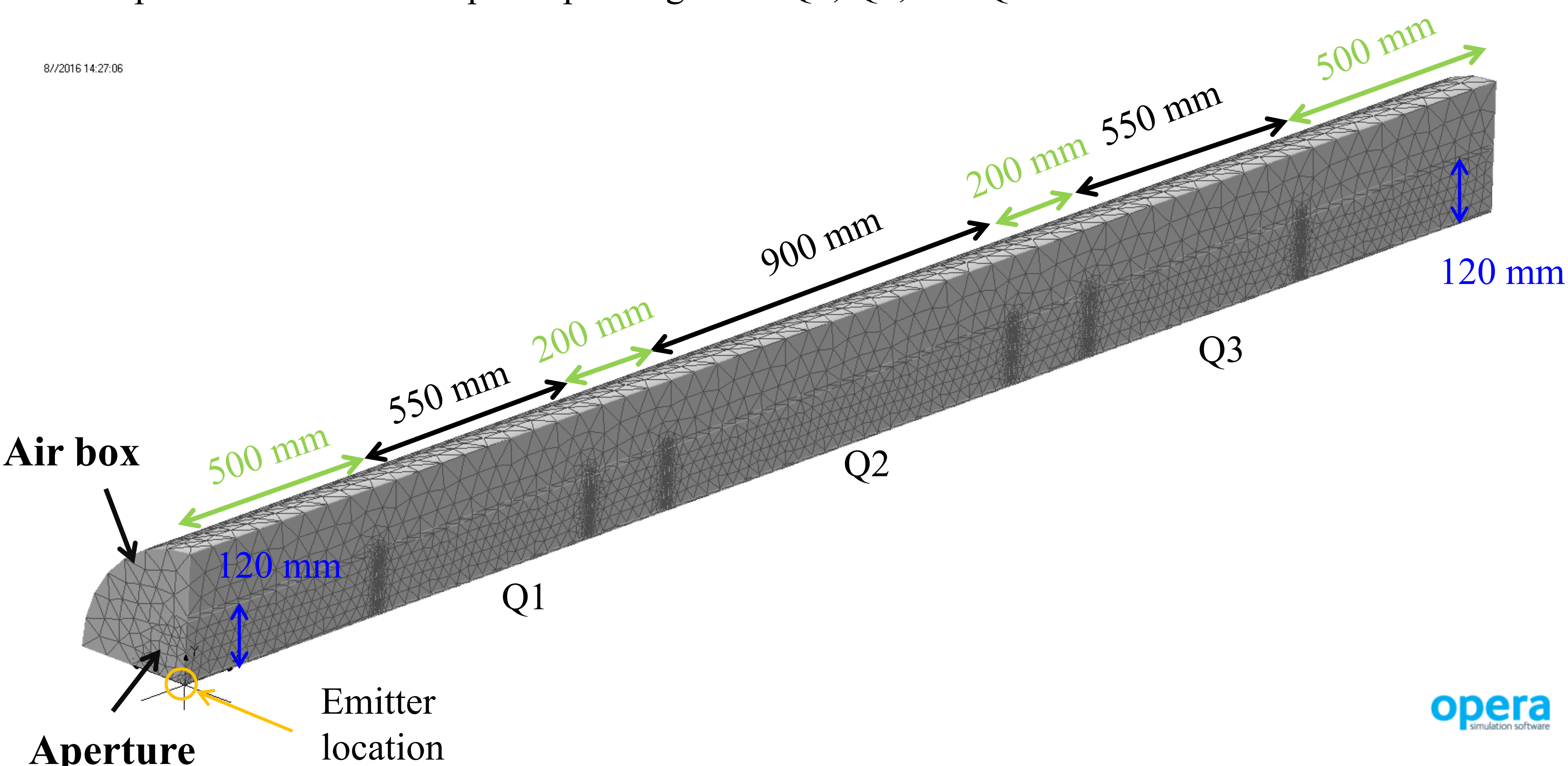
Field quality of designed Q1/Q3:(a) air core, and (b) iron core



<In processing HTS quadrupole of the RAON>

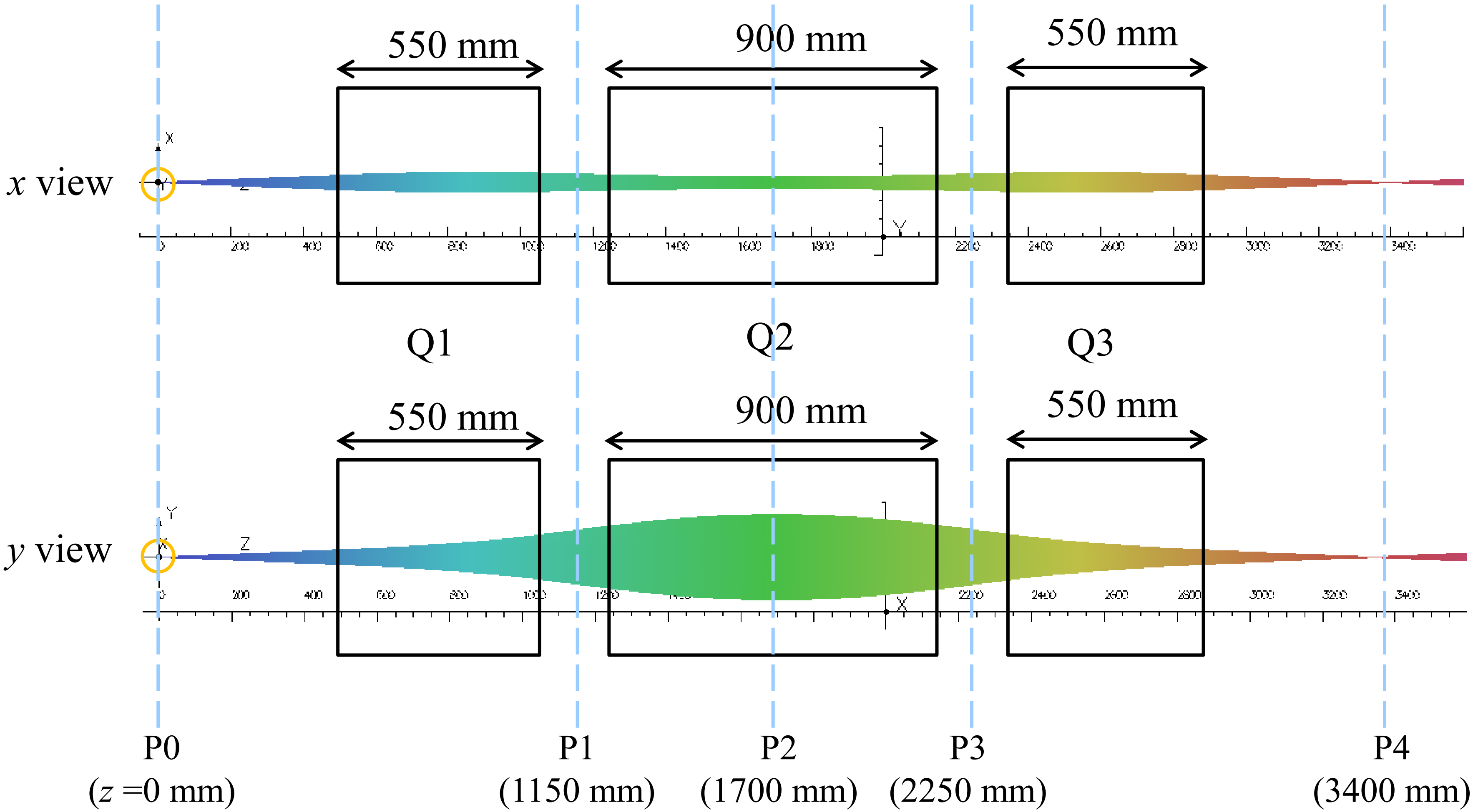
¼ Triplet SCALA Model in Opera™

- Triplet Model has three quadruple magnets – Q1, Q2, and Q3.



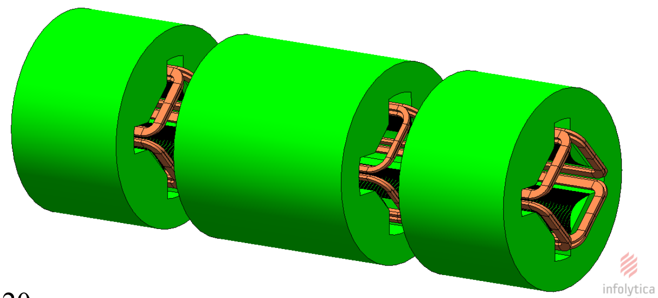
<¼ Triplet SCALA Model in Opera™>

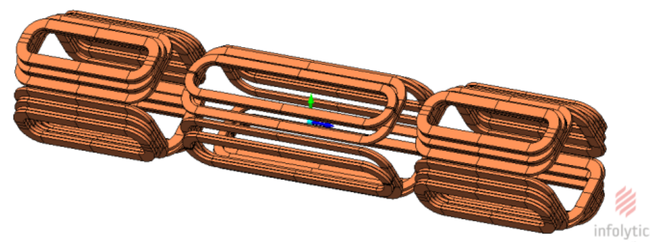
Beam Trajectory in Ideal Triplet

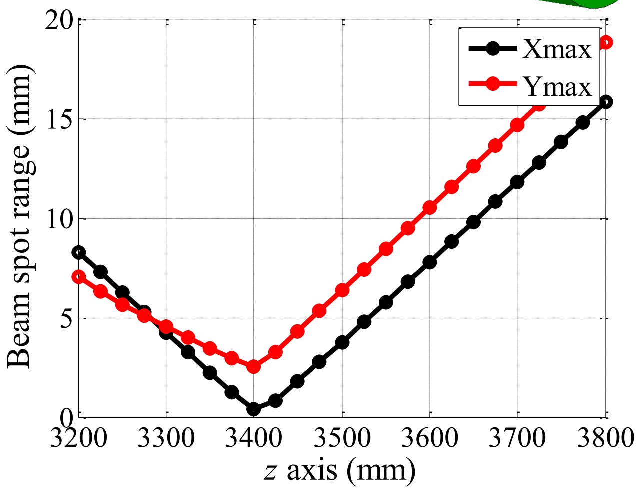


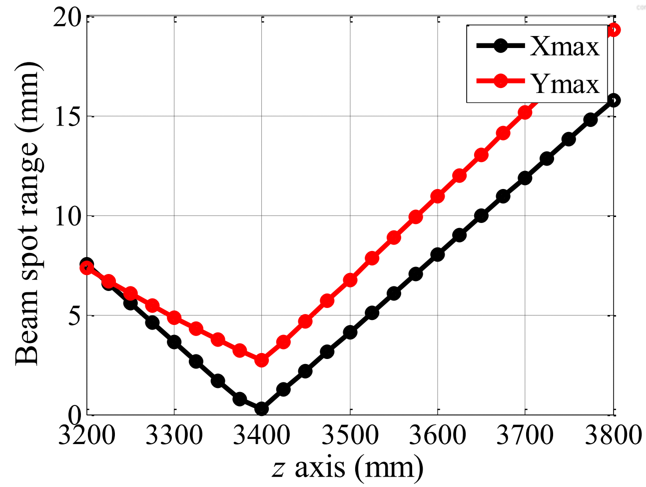
<Beam trajectory in ideal triplet>

Iron & Air Core HTS Quadruple Triplet

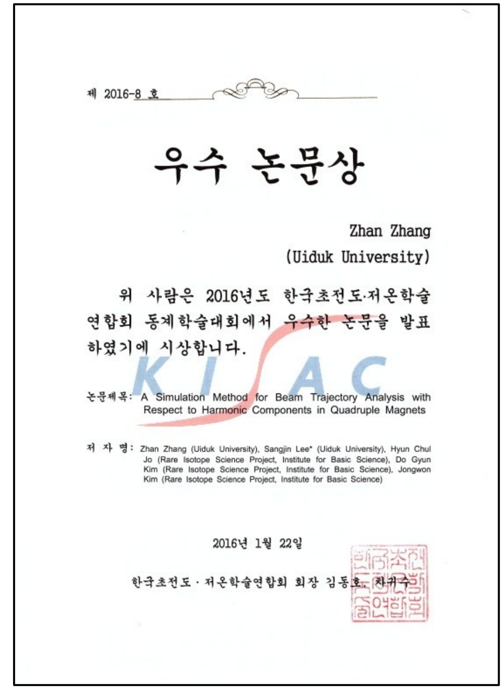








	Iron core triplet	Air core triplet
Coil Volume	10.6345264 E+6 mm^3	51.4826E+6 mm^3
Iron Volume	0.46246816 E+9 mm^3	0 mm^3
Iron Weight	3.6415 ton	0 ton
Xmax	0.3697 mm	0.2822 mm
Ymax	2.5061 mm	2.7366 mm



제 2016-8 호

우수 논문상

Zhan Zhang
(Uiduk University)

위 사람은 2016년도 한국초전도·저온학술 연합회 동계학술대회에서 우수한 논문을 발표 하였기에 시상합니다.

논문제목: A Simulation Method for Beam Trajectory Analysis with Respect to Harmonic Components in Quadruple Magnets

저 자 명: Zhan Zhang (Uiduk University), Sangjin Lee* (Uiduk University), Hyun Chul Jo (Rare Isotope Science Project, Institute for Basic Science), Do Gyun Kim (Rare Isotope Science Project, Institute for Basic Science), Jongwon Kim (Rare Isotope Science Project, Institute for Basic Science)

2016년 1월 22일

한국초전도 · 저온학술연합회 회장 김동호, 차귀수

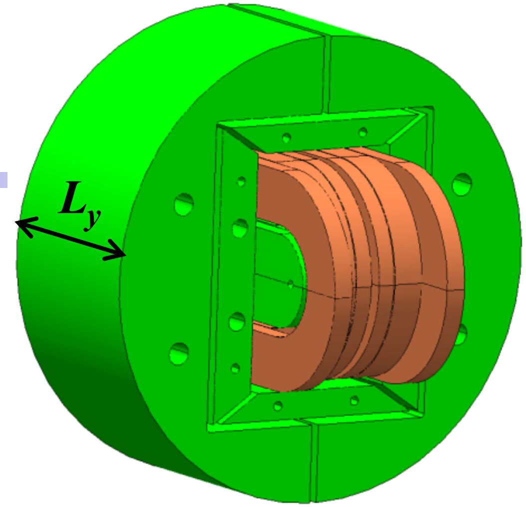
Published List

- [1] Zhan Zhang, Sangjin Lee*,Hyun Chul Jo, Do Gyun Kim, and Jongwon Kim, "A Study on the Optimization of an HTS Quadrupole Magnet System for a Heavy Ion Accelerator Through Evolution Strategy," *IEEE transactions on applied superconductivity*, Vol. 26, No. 4, June 2016.
- [2] Zhan Zhang, Shaoqing Wei, and Sangjin Lee*, Jo, Hyun Chul; Kim, Do Gyun; Kim, Jongwon , "Harmonic analysis and field quality improvement of an HTS quadrupole magnet for a heavy ion accelerator*," Progress in Superconductivity and Cryogenics*, Vol.18, No.2, pp.21-24, 2016.
- [3] Zhan Zhang, Shaoqing Wei, and Sangjin Lee*, "Design of an Air-Core HTS quadruple triplet for a heavy ion accelerator," *Progress in Superconductivity and Cryogenics*, Vol.18, No.4, pp.35-39, 2016.
- [4] Zhan Zhang, Sangjin Lee*, Hyun Chul Jo, Do Gyun Kim, and Jongwon Kim, "Magnetic field characteristics from HTS quadruple magnet of in-flight separator for a heavy ion accelerator*," Progress in Superconductivity and Cryogenics*, Vol.17, No.3, pp.23~27, 2015.
- [5] Shaoqing Wei, Zhan Zhang, Sangjin Lee* , Do Gyun Kim, and Jang Youl Kim, "Control the length of beam trajectory with a quadruple triplet for heavy ion accelerator," *Progress in Superconductivity and Cryogenics*, Vol.18, No.4, pp.40~43, 2016.
- [6] Shaoqing Wei, Zhan Zhang, Sangjin Lee*, and Sukjin Choi, "A study on the design of hexapole in an 18-GHz ECR ion source for heavy ion accelerators," *Progress in Superconductivity and Cryogenics*, Vol.18, No.2, pp.25~29, 2016.
- [7] Shaoqing Wei#, Zhan Zhang, Sangjin Lee*, "A Study on the Sextupole Design with Iron Yoke inside Solenoids for 56 GHz ECR Ion Source," IEEE Transactions on Applied Superconductivity, 2017.11.09, 28(3): 4001905
- [8] Jeyull Lee#, Junseong Kim#, Geonwoo Baek#, Yojong Choi#, Yoon Hyuck Choi#, Yoon Do Chung#, Hyoungku Kang#, Haigun Lee#, Sangjin Lee#, Zhan Zhang#, Tae Kuk Ko#, "Comparative Study of Magnetic Characteristics of Air-Core and Iron-Core High-Temperature Superconducting Quadrupole Magnets", IEEE Transactions on Applied Superconductivity , 2017.12.22, 28(3): 4601005

Postdoc study

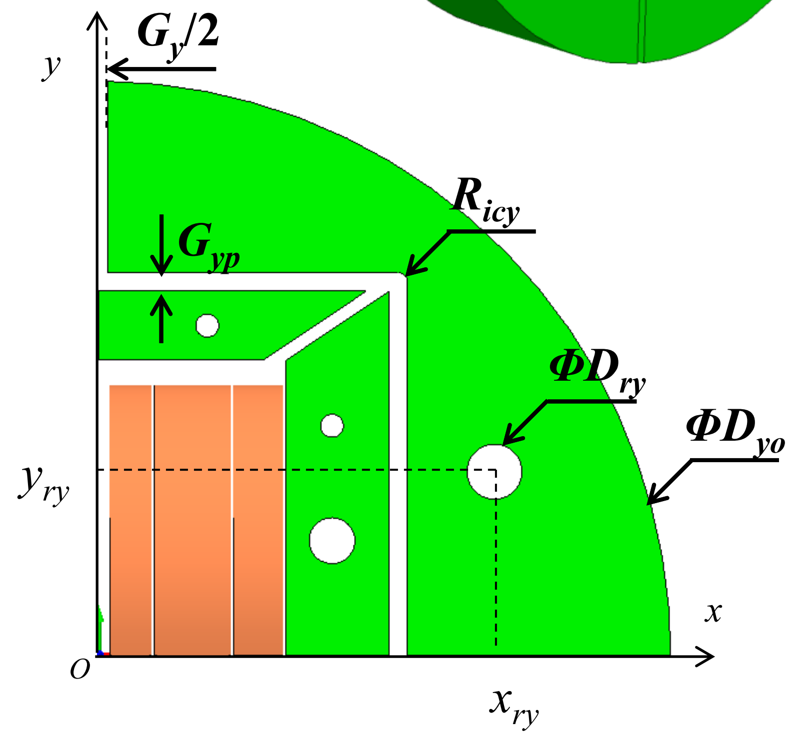
Design of a 12-T Twin-Aperture Dipole Magnet with 1e-4 Field Uniformity

12-T Hybrid Common-Coil Dipole Magnet



<Parameters of yoke of Dipole Magnet>

Item	Symbol	Value
Outer diameter of the magnet (mm)	D_{mo}	620
Length of the magnet (mm)	L_m	630
Outer radius of yoke (mm)	D_{yo}	500
Length of yoke (mm)	L_y	210
Gap of yoke (mm)	G_y	4
Gap between yoke and pads (mm)	G_{yp}	8
Diameter of rod of yoke	D_{ry}	24
x coordinate of rod of yoke	x_{ry}	173
y coordinate of rod of H-pad	y_{ry}	80
Thickness of each piece of yoke	T_y	6
Radius of inner chamfer of yoke	R_{icy}	4

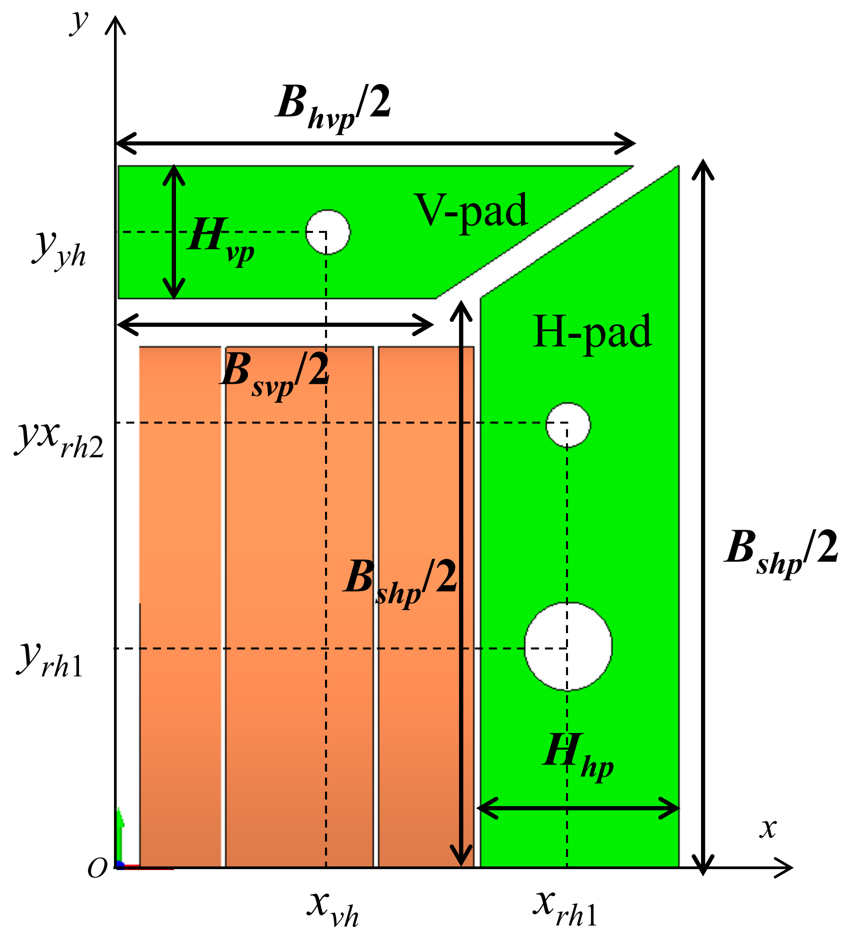


<Section views of a12-T hybrid common-coil dipole magnet>

12-T Hybrid Common-Coil Dipole Magnet

<Parameters of yoke of Pads>

Item	Symbol	Value
Height of H-pad	H_{hp}	45
Shorter base of H-pad	B_{shp}	257.2
longer base of H-pad	B_{hhp}	317.2
Diameter of rod 1 of H-pad	D_{rh1}	20
x coordinate of rod 1 of H-pad	x_{rh1}	102
y coordinate of rod 1 of H-pad	y_{rh1}	50
Diameter of rod 2 of H-pad	D_{rh2}	10
x coordinate of rod 2 of H-pad	x_{rh2}	102
y coordinate of rod 2 of H-pad	y_{rh2}	100
Height of V-pad	H_{vp}	30
Shorter base of V-pad	B_{svp}	144
longer base of V-pad	B_{hvp}	234
Diameter of rod of V-pad	D_{rv}	10
x coordinate of rod of V-pad	x_{vh}	47.5
y coordinate of rod of V-pad	y_{vh}	143.6



<Section views of a12-T hybrid common-coil dipole magnet>

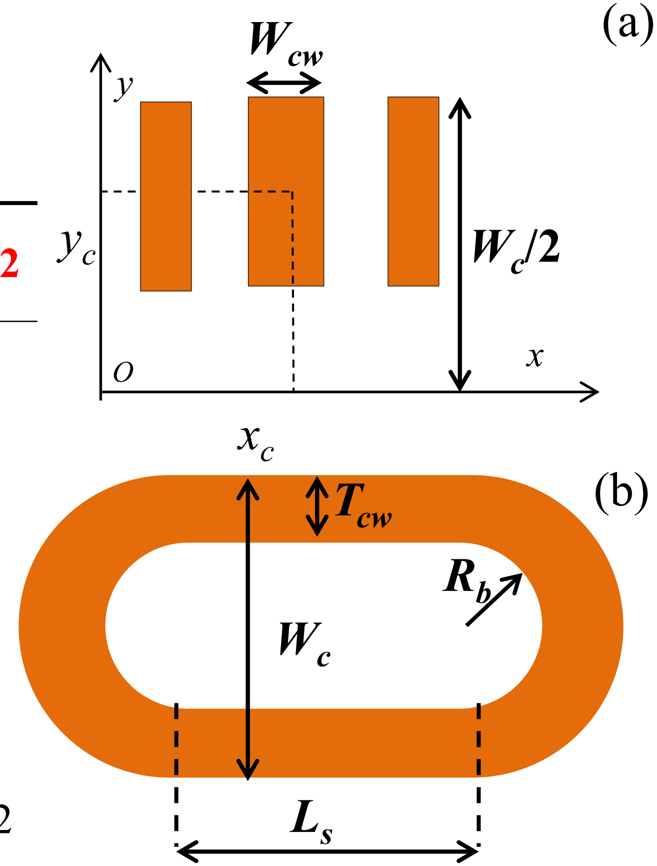
12-T Hybrid Common-Coil Dipole

<Rutherford Cable> [*]

- Double pancake (DPC) coil by Rutherford Cable

<Parameters of coil of Dipole Magnet>

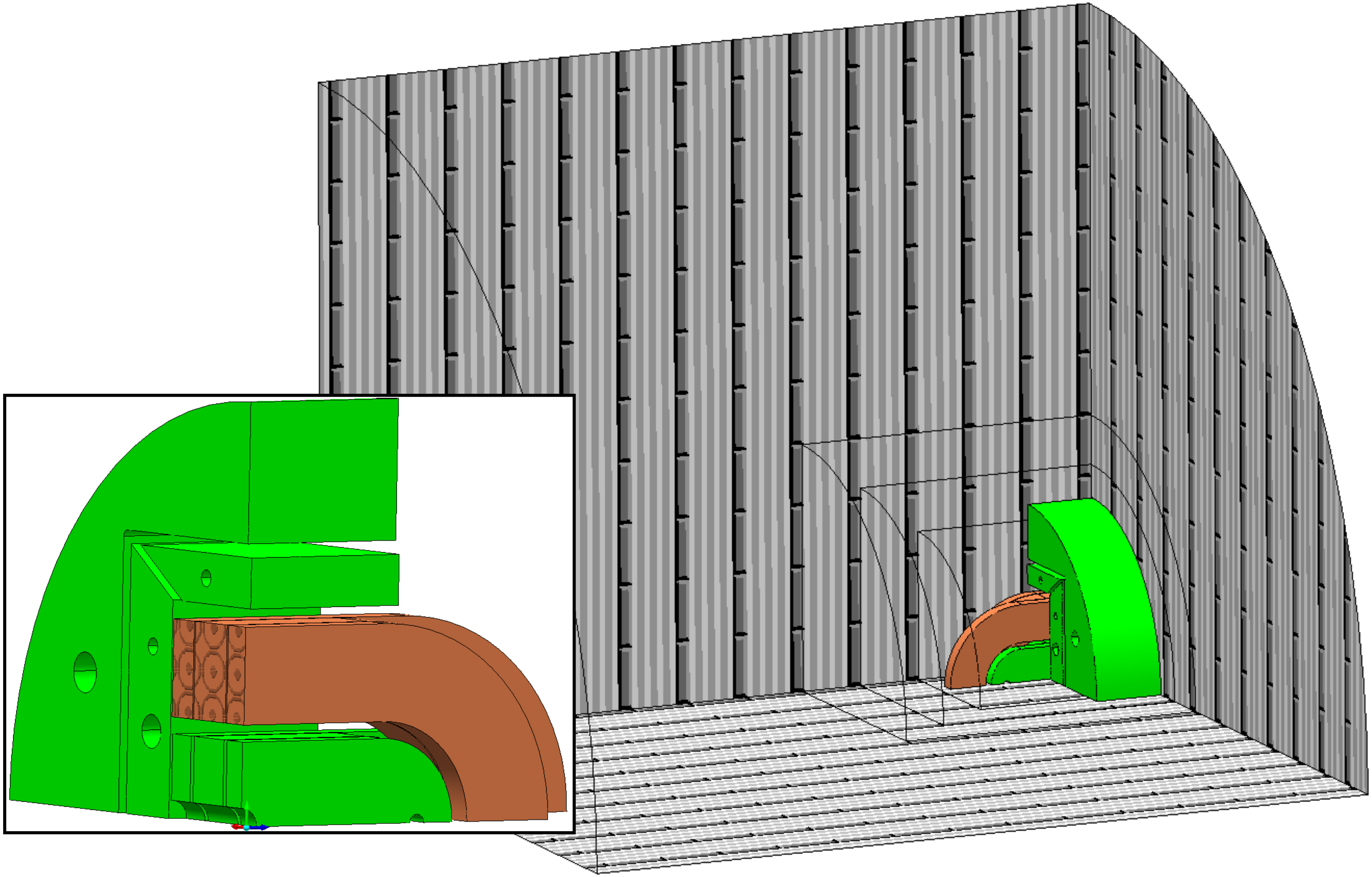
Item	Symbol	IHEP5	IHEPWN1	IHEPWN2
No. of turns of single winding	N	28	32	33
Thickness of coil winding (mm)	T_{cw}	57.6	57.6	57.6
Width of coil winding (mm)	W_{cw}	18.3	33.3	21.5
Length of straight part (mm)	L_s	200	200	300
Width of coil (mm)	W_c	235.2	235.2	235.2
Bending radius (mm)	R_b	60	60	60
x coordinate of coil	x_c	13.975	41.075	69.775
y coordinate of coil	y_c	$W_c/2-T_{cw}/2$	$W_c/2-T_{cw}/2$	$W_c/2-T_{cw}/2$
Operating current (A)	I_{op}	6000	6000	6000
Materials		Nb_3Sn	NbTi	NbTi



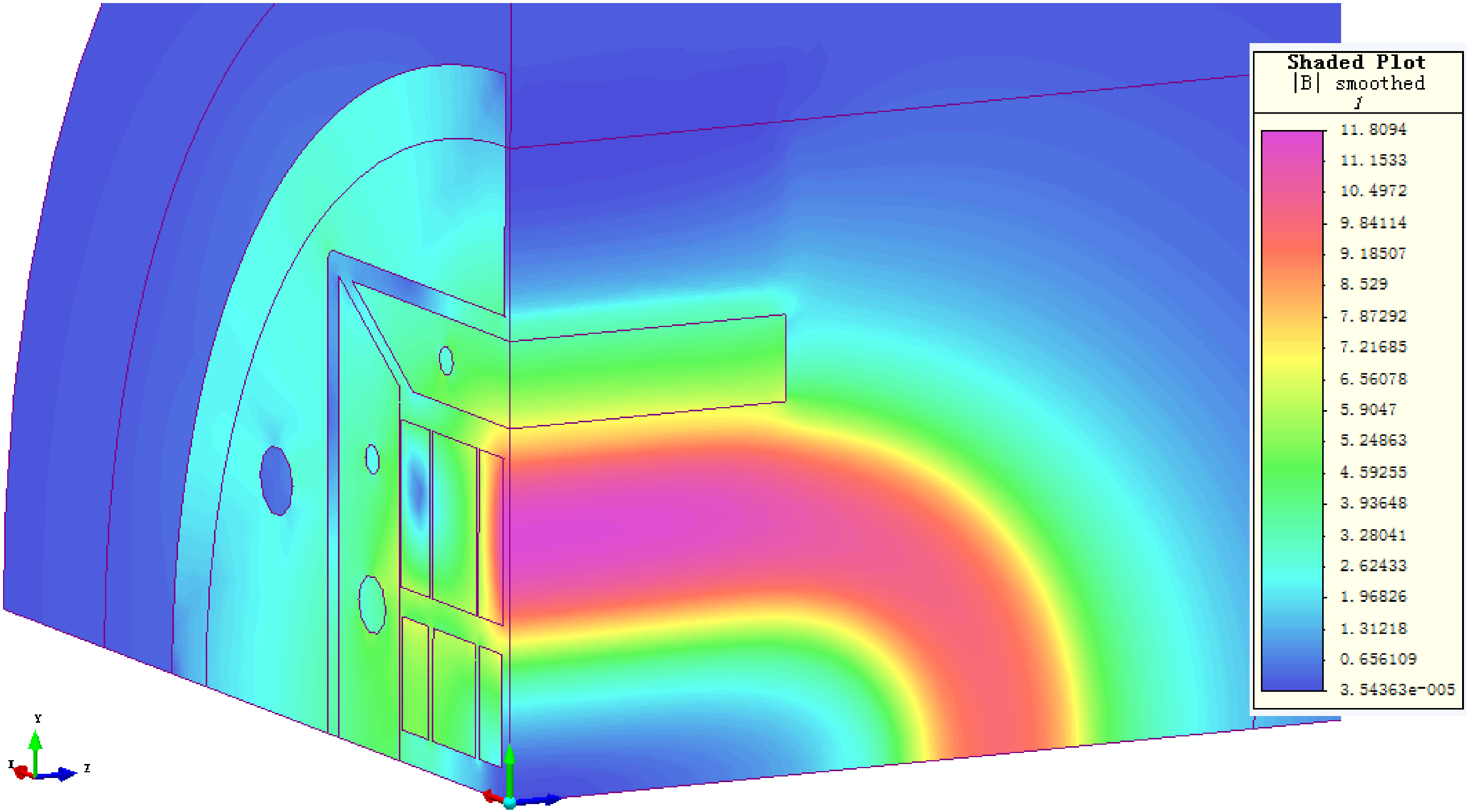
Parameters of coils:
(a) Section view at first quadrant;
(b) Up view.

[*] *"Magnet Capabilities", Fermilab, Technical Division, http://td.fnal.gov/magnet-capabilities/*

1/8 Model of Dipole Magnet

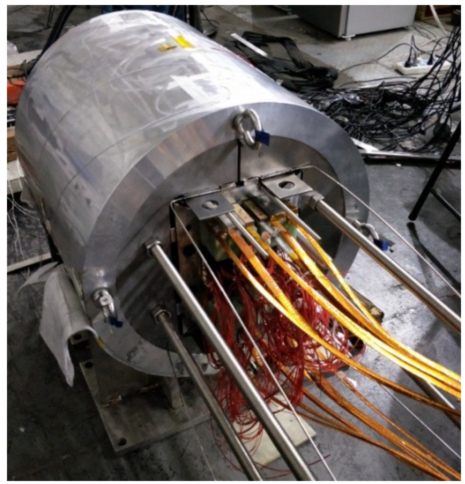


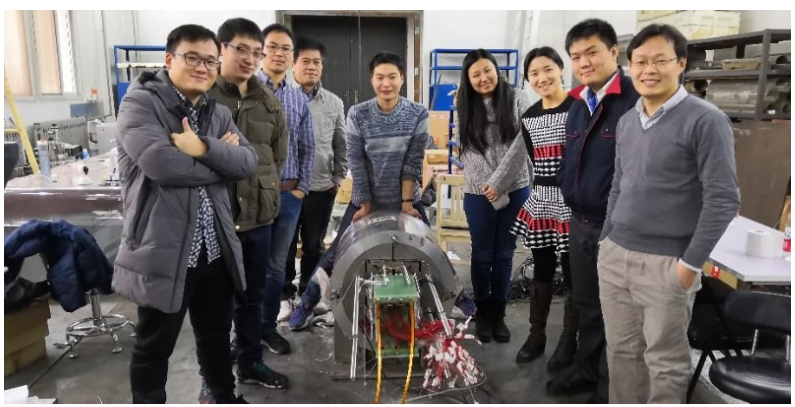
Magnetic Field Distribution

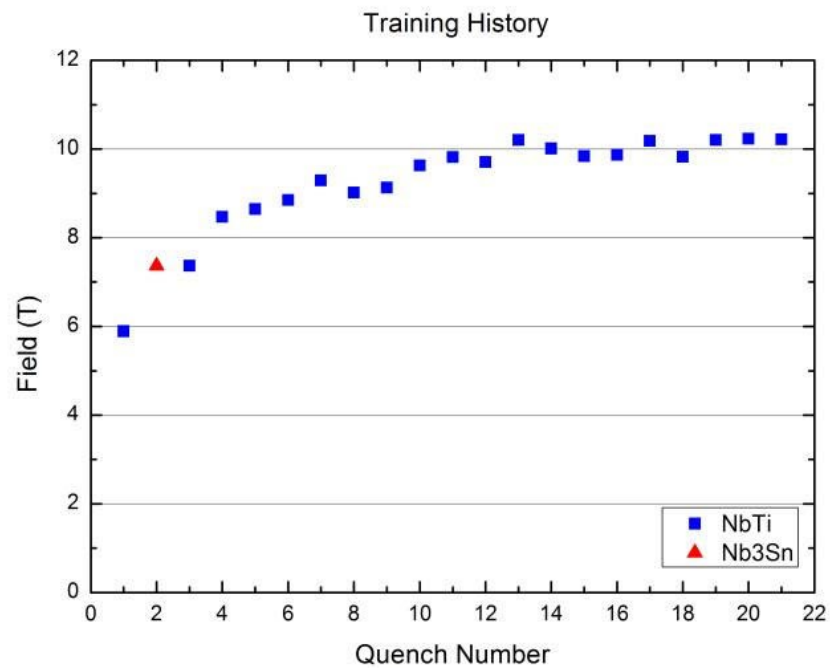


Experiment

- Bladder & Key Technology was used for prestress [*]







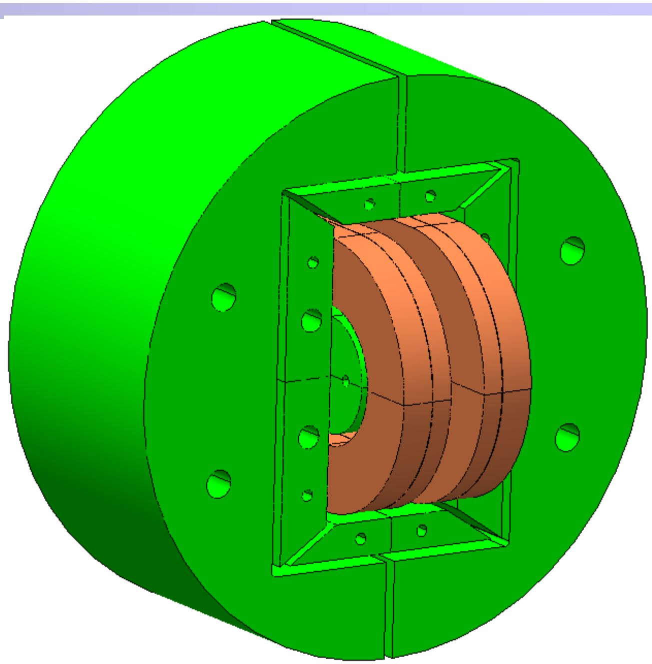
<Experiment of magnet training in Hefer>[*]

[*] *Shlomo Caspi, et al, "The Use of Pressurized Bladders for Stress Control of Superconducting Magnets", IEEE TRAN. ON APPL. SUPE. VOL. 11, NO. 1, 2001.*
[*] *王呈涛2018年2月9日绘制*

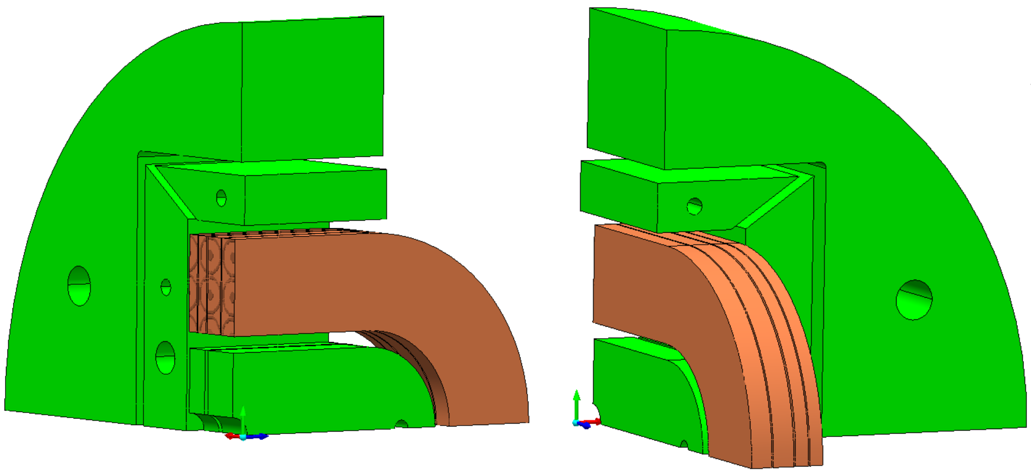
Further Work 1: 12-T All Nb_3Sn Coil Dipole Magnet

- The design targets

Item	Target
$B_{\rho 1}(z=0)$	$\geq$ 12 T
$\int a_{\rho n}$	$< 10^{-4}$
$\int b_{\rho n}$	$< 10^{-4}$
Safety margin of SC wires	$\geq$ 20%



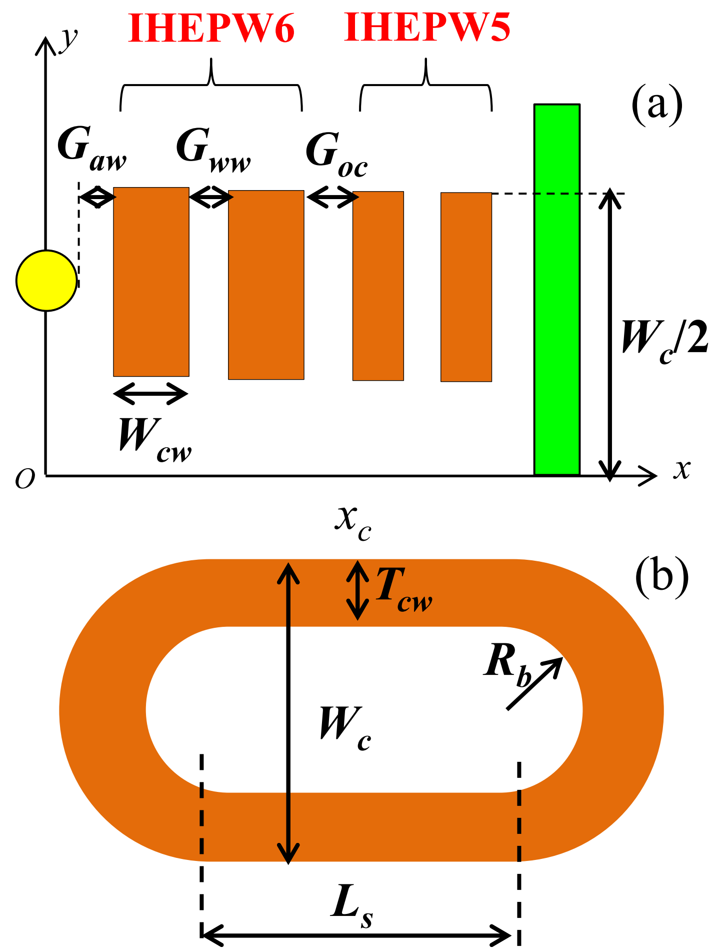
<12-T All Nb_3Sn Coil Dipole Magnet>



12-T All Nb_3Sn Coil Dipole Magnet

<Parameters of coil of Dipole Magnet>

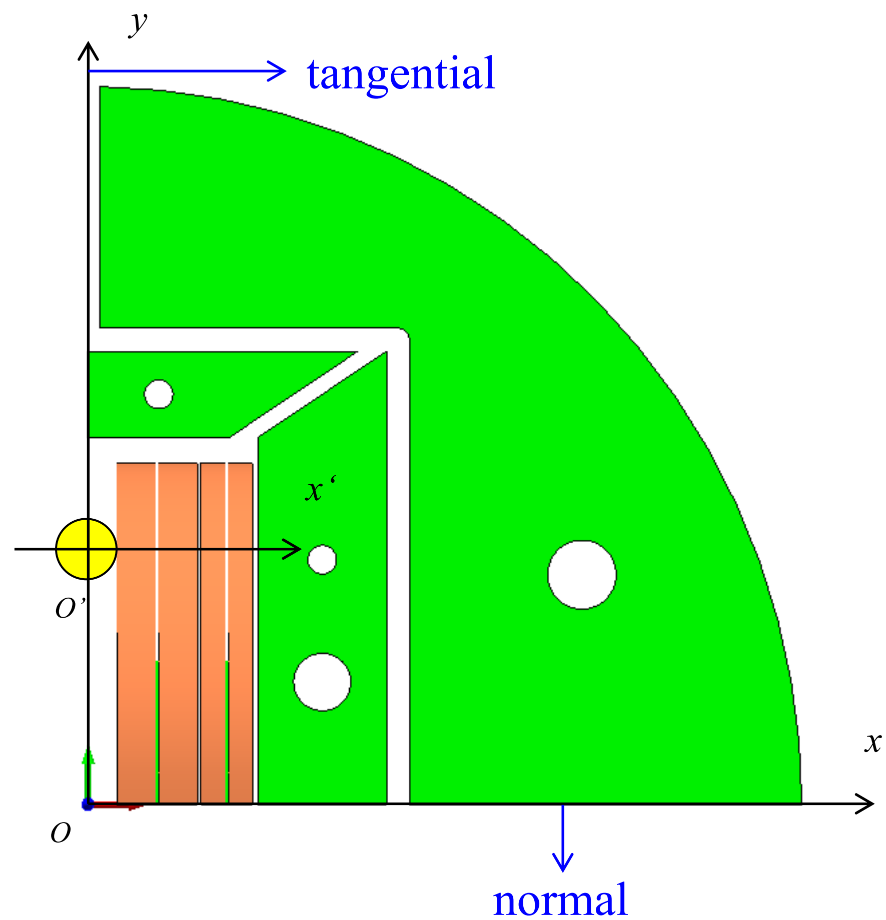
Item	Symbol	IHEPW6	IHEPW5
No. turns of single winding	N	28	28
No. of strands of Rutherford	Ns	34	20
Operating current (A)	I_{op}	10000	10000
Thickness of Nb_3Sn tape	W_{nb}	1.5	
Thickness of insulation in width	T_{iw}	0.2	
Thickness of insulation in width	T_{it}	0.3	
Gap between aperture & windings	G_{aw}	0	
Width of coil winding (mm)	W_{cw}	14.45	8.5
Gap between two windings	G_{ww}	1	1
Gap at outside of coils	G_{oc}	1.3	2(24.5)
Length of straight part of coil (mm)	L_s	200	200
Bending radius (mm)	R_b	60	60
Thickness of coil winding (mm)	T_{cw}	$(W_{nb}+2*T_{iw})*N$	
Width of coil (mm)	W_c	$(R_b+T_{cw})*2$	



Parameters of coils:
(a) Section view at first quadrant;
(b) Up view.

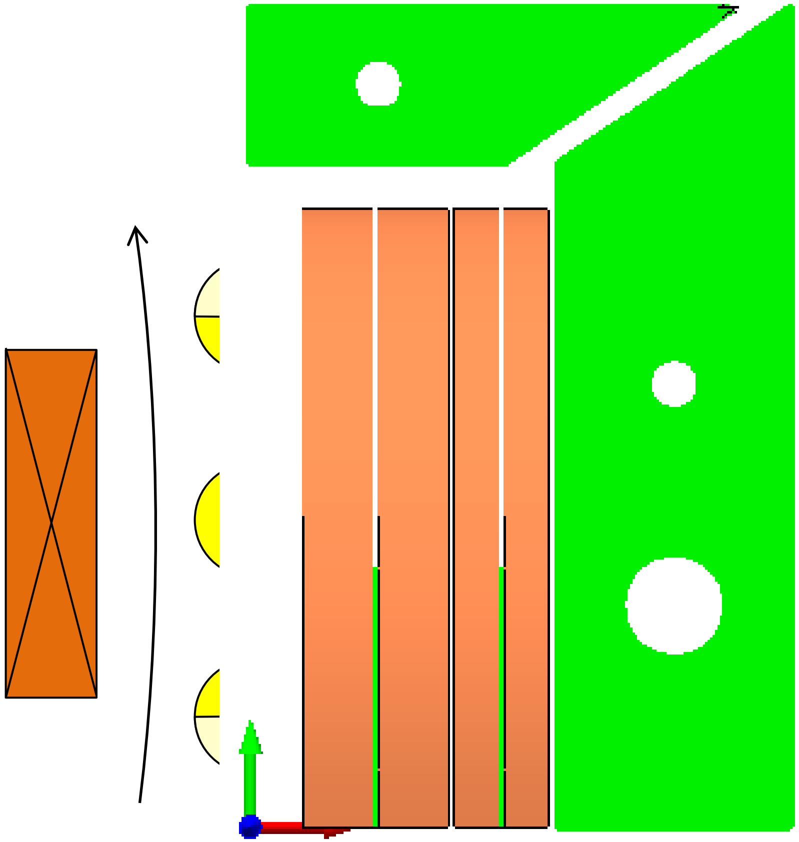
Further Work 2: Optimization

- In this study, the designed dipole only has tangential symmetry. Therefore, the allowed harmonics are
  - ✓ ***normal*** terms when n = 1,3,5,7…
  - ✓ ***skew*** terms when n = 0,2,4,6…



Skew Harmonics Matching Method

- The analysis shows that
  - ✓ The good field regain location could have a great effect on ***skew*** harmonics.
  - ✓ The signs of ***skew*** harmonics can be changed along the transverse direction.
- Therefore, the integral value of ***skew*** harmonics along transverse direction could be controlled by adjusting the good field regain location and the magnetic flux density induced by nonlinear material in/out of the Common-Coil. The method can be called ***skew*** harmonics matching (SHM) method.

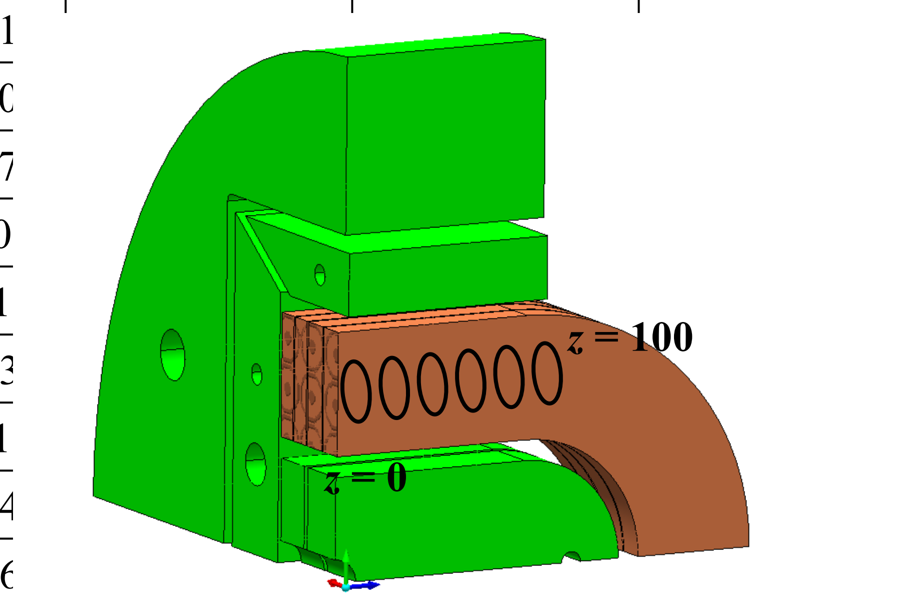


Skew Harmonics in Unit of Tesla @ y = 93

$>10^{-3}$T
$>10^{-2}$T

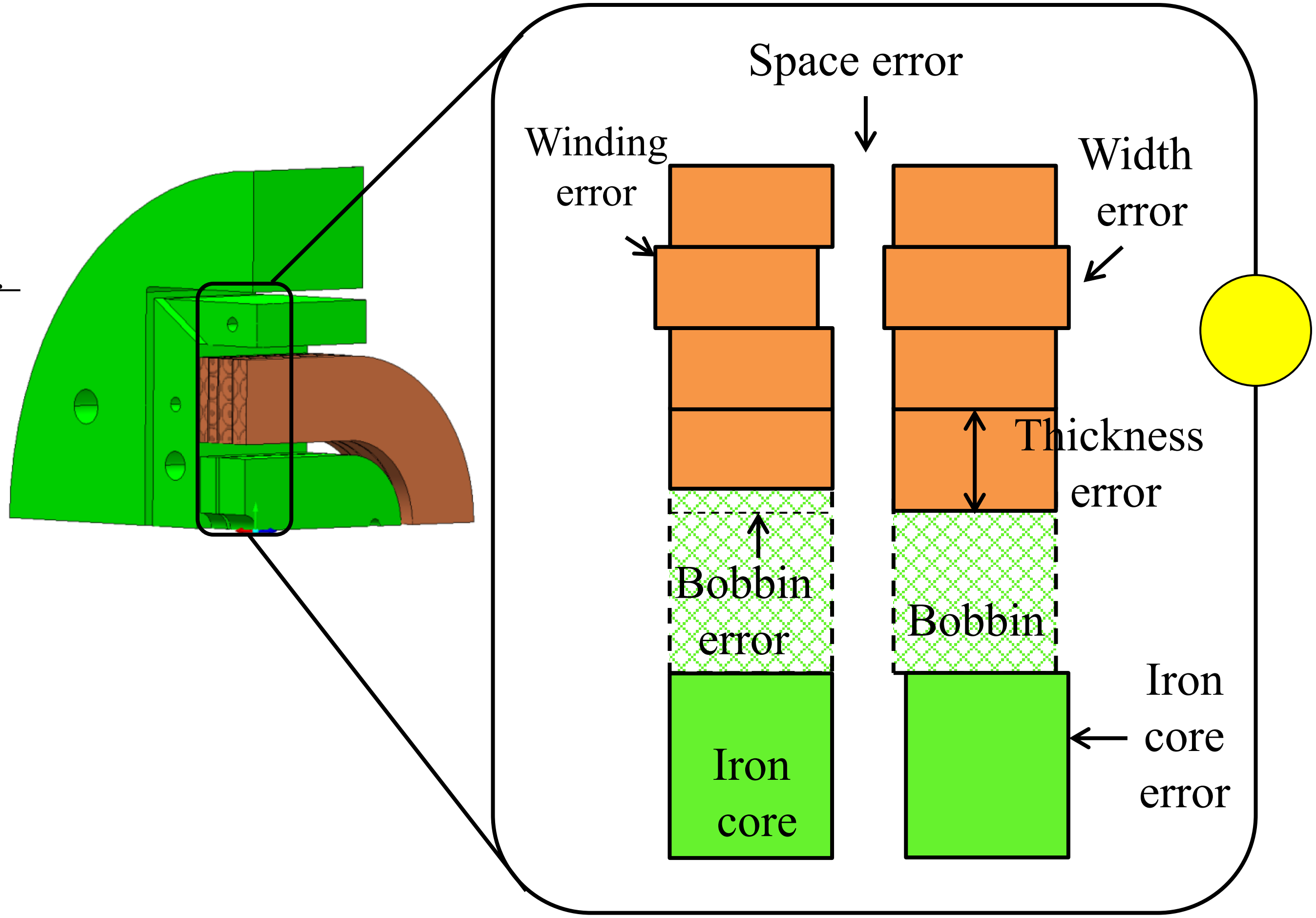
ρ_0=10

n	z = 0	z = 20	z = 40	z = 60	z = 80	z = 100
0	-0.048569268	-0.054369367	-0.075638762	-0.130487121	-0.261538343	-0.500245891
1	-1.15463E-15	-1.15463E-15	-1.43885E-15	-1.63425E-15	-1.26121E-15	-9.41469E-16
2	0.062963659	0.058681116	0.045265982	0.01924794	-0.014409938	-0.008490276
3	-5.06127E-16	-4.18492E-16	-2.94235E-16	-2.86689E-16	-3.70097E-16	-5.45251E-16
4	-0.005264417	-0.005674455	-0.006279606	-0.00732525	-0.008555778	-0.008717459
5	1.34119E-16	2.39805E-16	-2.51639E-1			
6	-0.000148576	6.56494E-05	-8.40885E-0			
7	1.50862E-16	1.2845E-16	-2.757E-17			
8	-2.92534E-05	-6.48165E-05	4.42078E-0			
9	7.2383E-16	-3.6823E-17	3.39205E-1			
10	0.000125501	-0.000224377	-0.00042143			
11	3.89713E-16	-3.6823E-17	5.08782E-1			
12	-0.000218334	-0.0002716	-0.00020944			
13	-0.048569268	-0.054369367	-0.07563876			



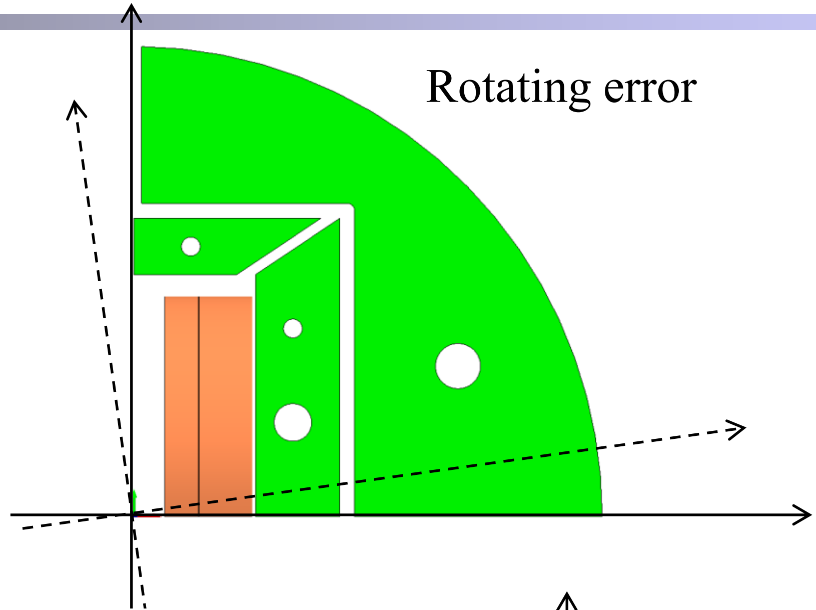
Further Work 3: Manufacturing Error Effects

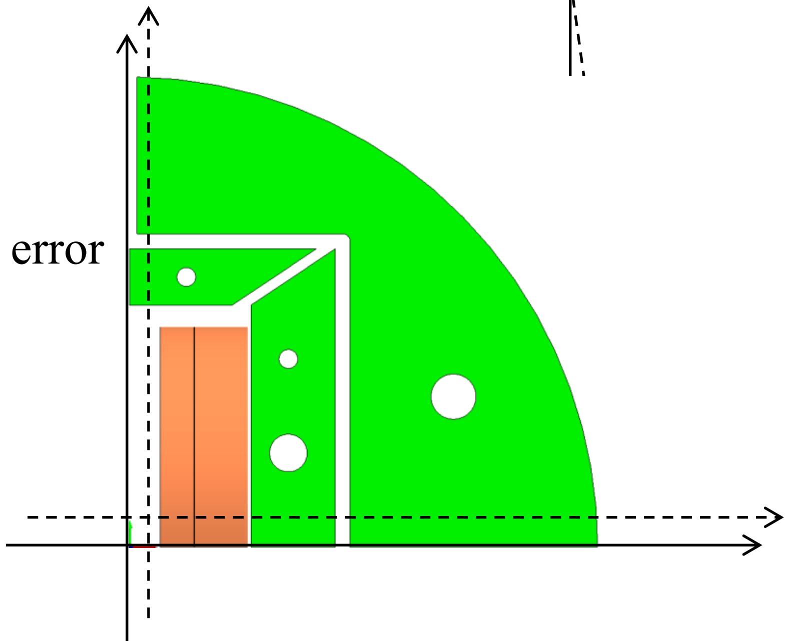
- Manufacturing Error:
  - ✓ Winding error
  - ✓ Coil width error
  - ✓ ~~Coil thickness error~~
  - ✓ ~~Bobbin error~~
  - ✓ Space error
  - ✓ Iron core error
  - ✓ Axis error

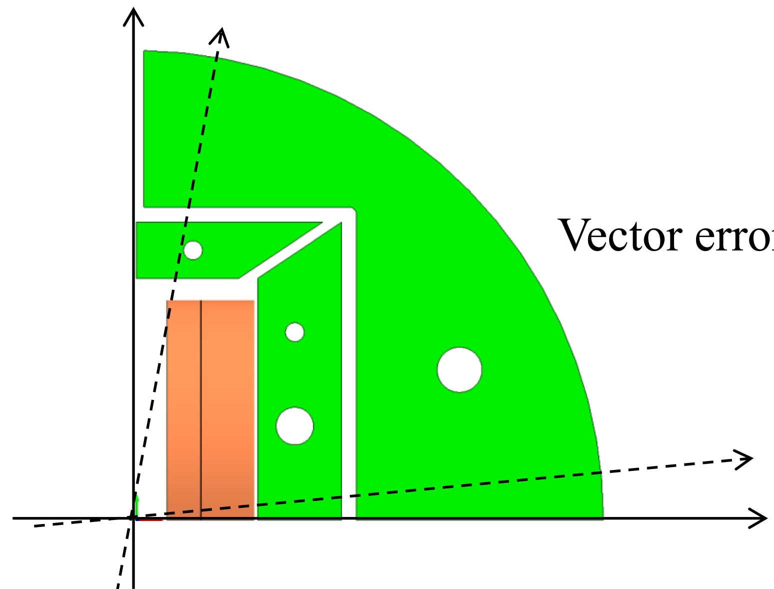


Further Work 3: Manufacturing Error Effects

- Axis error
  - Rotating error
  - ~~*x*, *y* error~~
  - Vector error







Thanks for your attention!