Multipole Magnets for the HIAF Fragment Separator Using the Canted-Cosine-Theta (CCT) Geometry

Wei Wu, Yu Liang, Luncai Zhou, Enming Mei, Dongsheng Ni, Yuquan Chen

Magnet & Mechanical Group

IMP(Institute of Modern Physics)
CAS(Chinese Academy of Sciences)

Oct. 22 , 2018
Lanzhou, China

wuwei@impcas.ac.cn

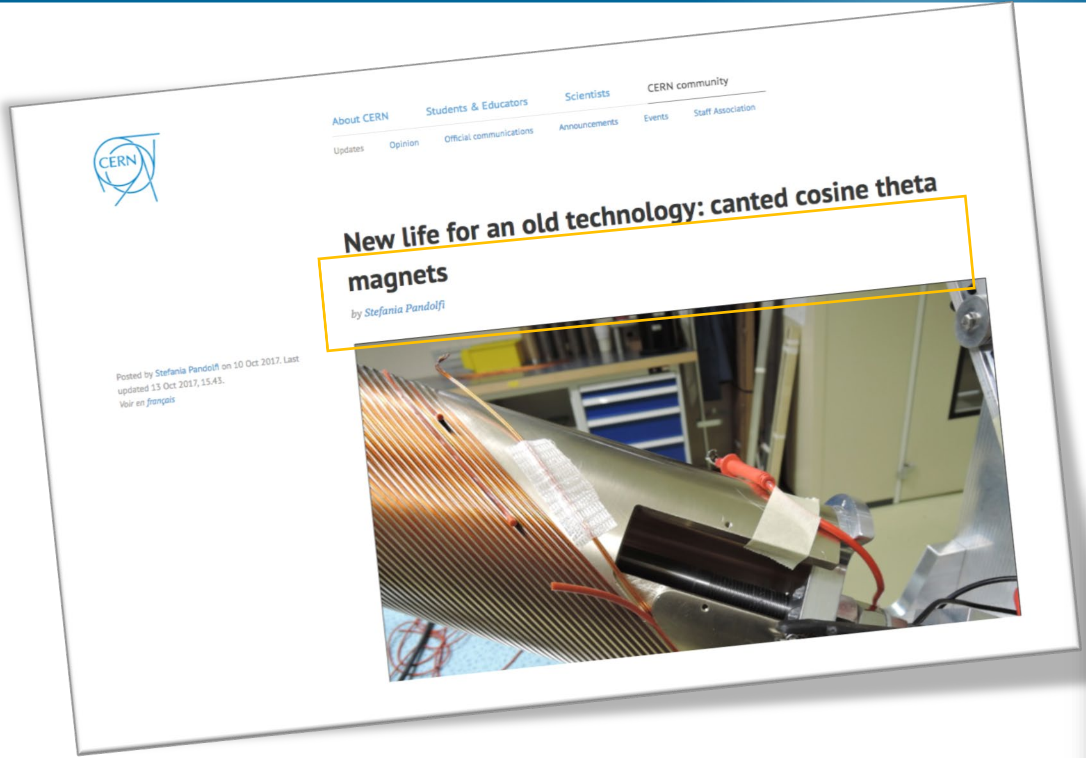
Vintage Style

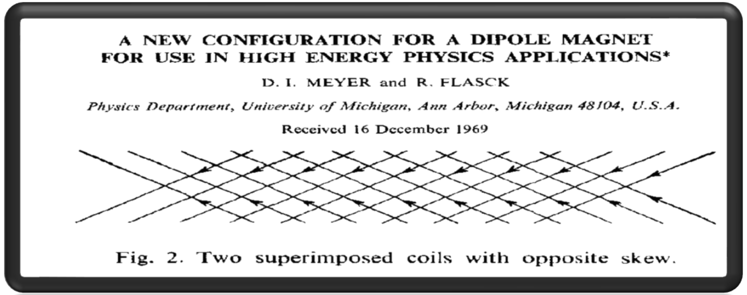
Two weeks ago when we visit CERN,
we saw a car...

Then in down town Geneva...

FUTURE STYLE

Reincarnation(Cycle) between past and future in *Fashion field*!




A NEW CONFIGURATION FOR A DIPOLE MAGNET FOR USE IN HIGH ENERGY PHYSICS APPLICATIONS*

D. I. MEYER and R. FLASCK

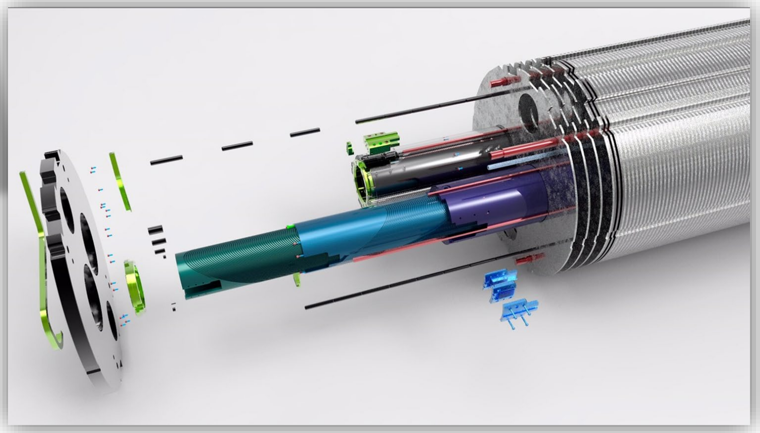
Physics Department, University of Michigan, Ann Arbor, Michigan 48104, U.S.A.

Received 16 December 1969

Fig. 2. Two superimposed coils with opposite skew.

Vintage Style

FUTURE



It also happens in

Magnet field!

Outline

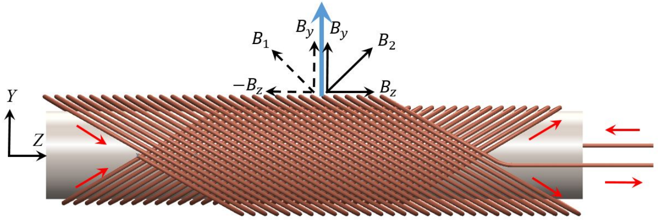
- ❖ CANTED–COSINE–THETA MAGNET
- ❖ INTRODUCTION OF HIAF & HFRS
- ❖ MAGNET DESIGN
- ❖ SUBSCALE MODEL COIL
- ❖ SUMMARY & FUTURE WORKS

CCT (Canted-Cosine-Theta)

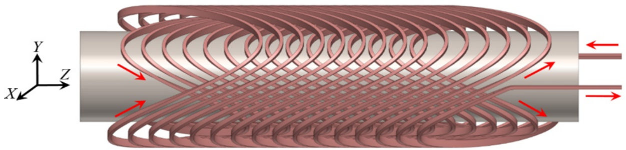
- First suggested by D.I. Meyer and R. Flasck in **1969**
- AML, LBNL & CERN renewed interest in it from 2003
- Compared with conventional cosine-theta coil, it is an almost perfect approximation of a cosine-theta magnet, thus yields very **good field distribution**(especially for **integral field**)
- The **combined function** coil can be easily achieved
- Avoid tight bends for the ends of the coils
- **Less sensitive** to positional (but need **more conductor**)

$$x(\theta) = R\cdot\cos(\theta)$$
$$y(\theta) = R\cdot\sin(\theta)$$
$$z(\theta) = \frac{h\theta}{2\pi} + \sum_n A_n\cdot\sin(n\theta+\varphi_n)$$

$J_z \sim \cos n\theta$

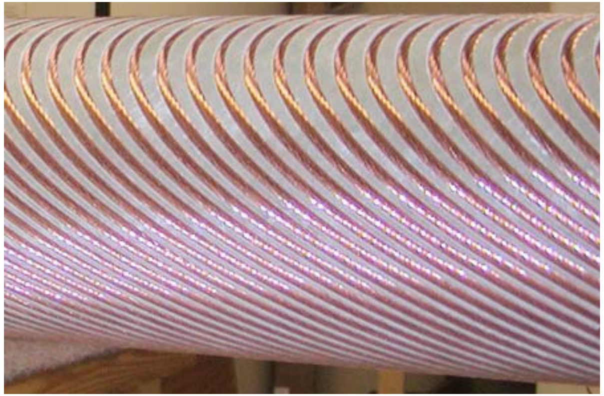


n = 1 Dipole

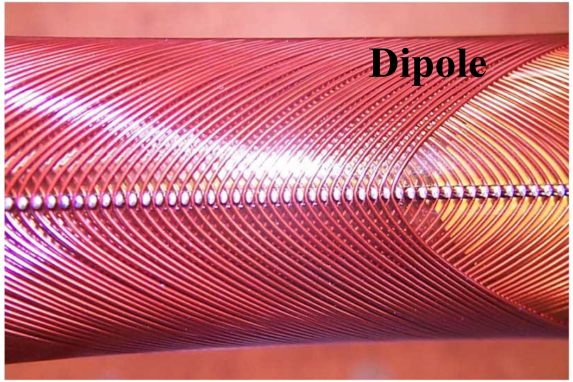


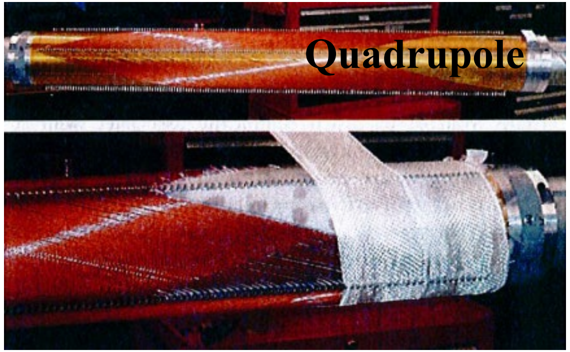
n = 2 Qudrupole

Brief overview

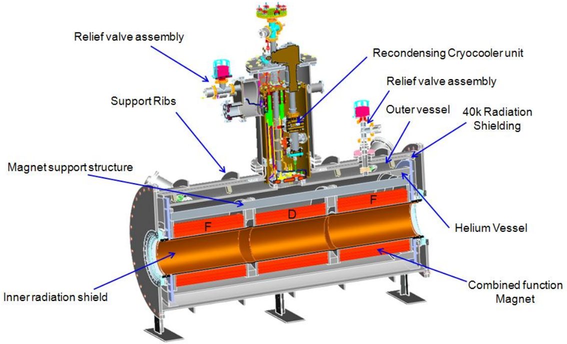


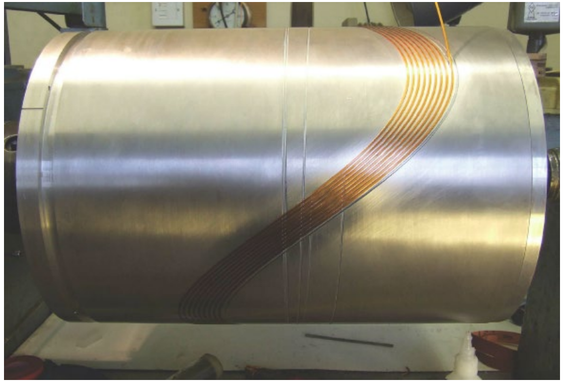
2003□ □ AML Prototype





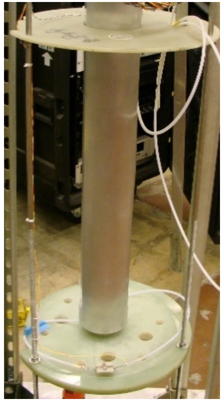
2005~2008□ Two prototype in LBNL





2012□ PAMELA FFAG testing coil

Brief overview



CCT1
B0=2.5T
NbTi Cable
50mm clear bore

CCT2
B0=4.7T
NbTi Cable
90mm clear bore

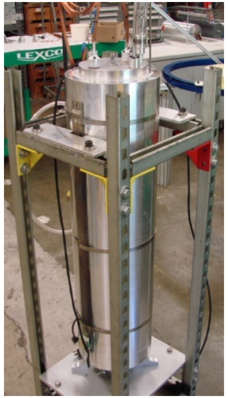
CCT1

CCT2

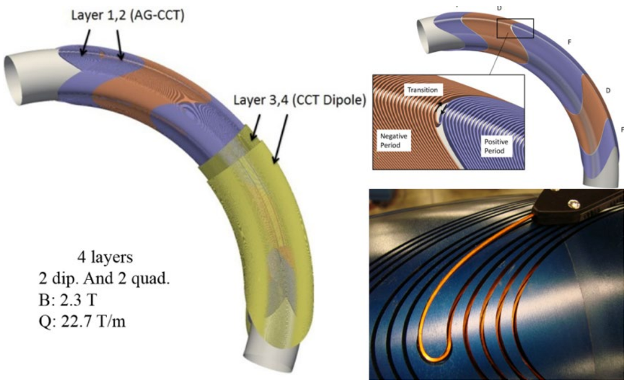
CCT3

CCT3
B0=7.4T
Nb_3Sn Cable
90mm clear bore

CCT4
B0=9.14T
Nb_3Sn Cable
90mm clear bore

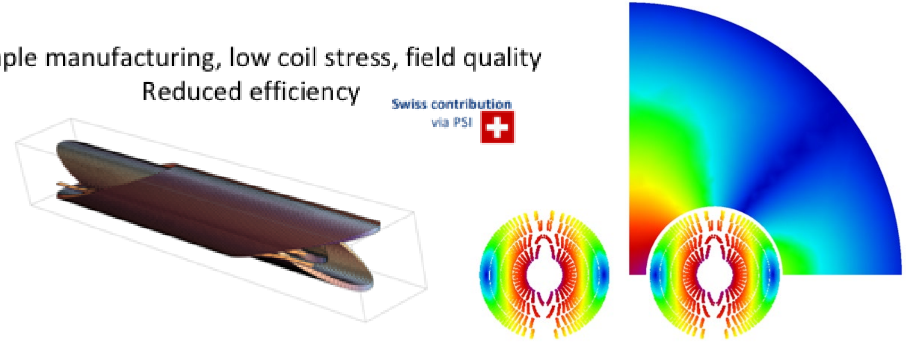


CCT4



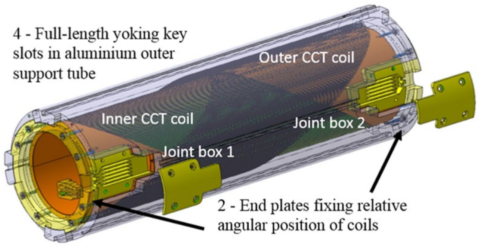
CCT SC magnet for Gantry(LBNL)

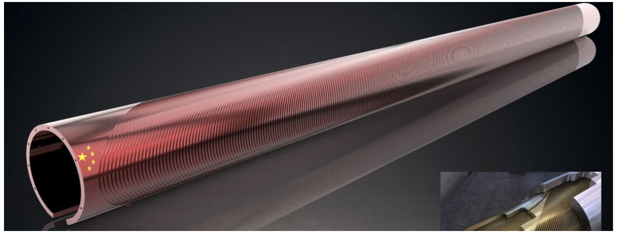
Simple manufacturing, low coil stress, field quality
Reduced efficiency



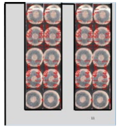
Canted Cosine Theta option for the 16-T FCC-hh main dipole (PSI)

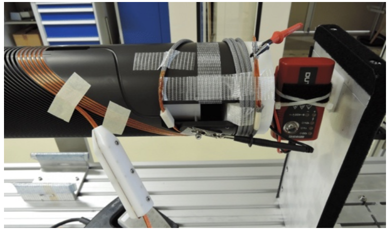
Brief overview

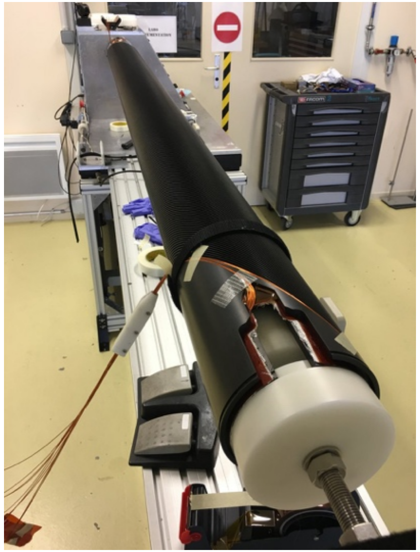


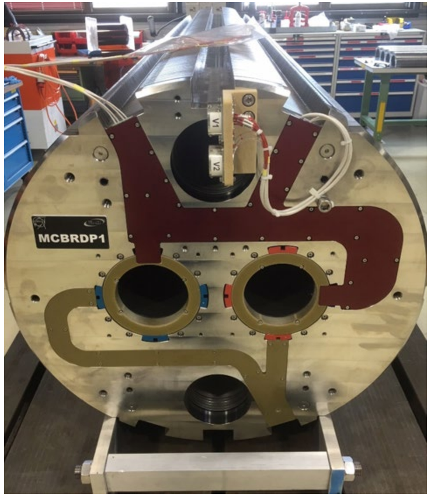


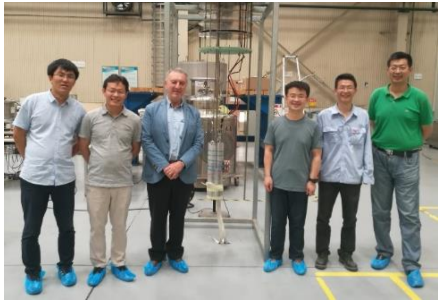
HiLumi HL-LHC PROJECT











- CERN has finished the prototype;
- China (IHEP, IMP & WST) will provide 12 units of CCT magnets for HL-LHC;

Comparison of fabrication methods

(I) Direct placement with adhesive

BNL direct winding technology

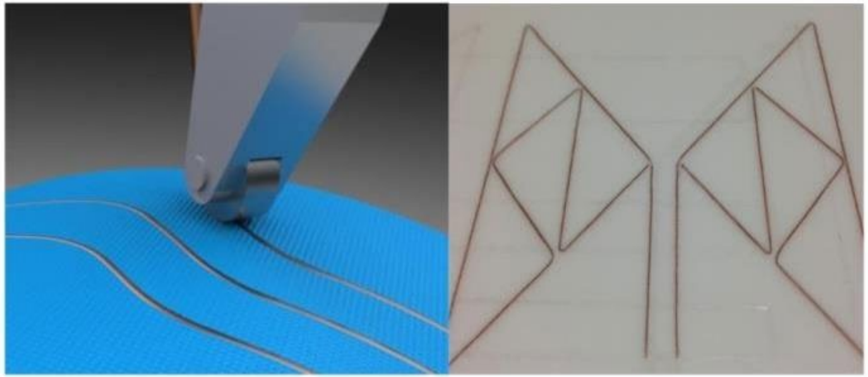


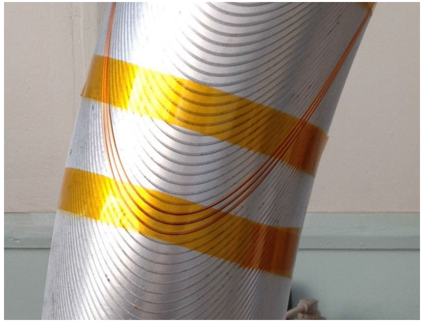
Figure 2 – Thermally embedded wire (a) conceptual depiction of embedding process and (b) in actual example in a 3D printed substrate (fractal antenna)

Thermally embedded wire process
(3D printing coil)

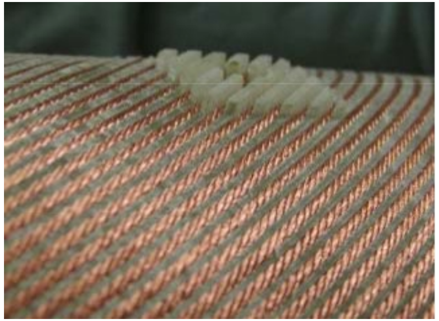
- For complicate coil, special winding machine and techniques are needed, such as BNL's direct winding technology；
- Too long R&D cycle and high cost of the **winding machine**.

Comparison of fabrication methods

(II) Conductor/Cable placement in grooves

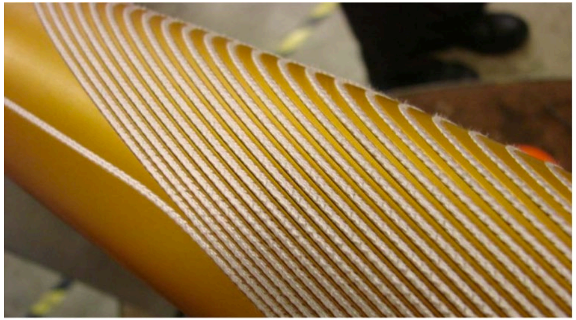


Conductor in grooves (Metal)



Round mini cable in grooves (Composite)

R.B.Meinke, MAGNETICS 2010



Rutherford cable in grooves (Metal)

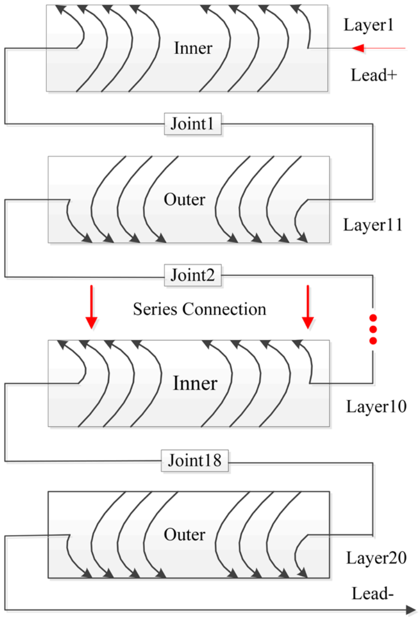
S. Caspi, IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 25, NO. 3, JUNE 2015

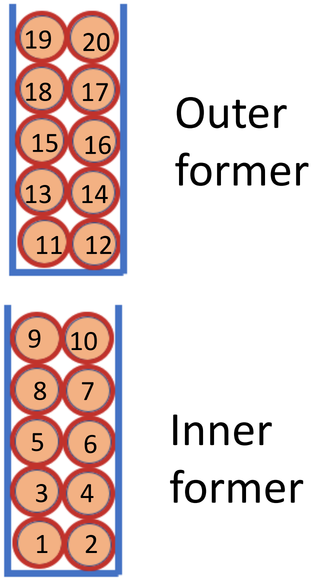
- Cable:
  - **High current**
  - **less** layers and **mandrels**
  - Easy to fabricate mandrels, wind and assembly
- Conductor:
  - **Low current**
  - **more** layers and **mandrels**
  - Difficult to fabricate mandrels, wind and assembly

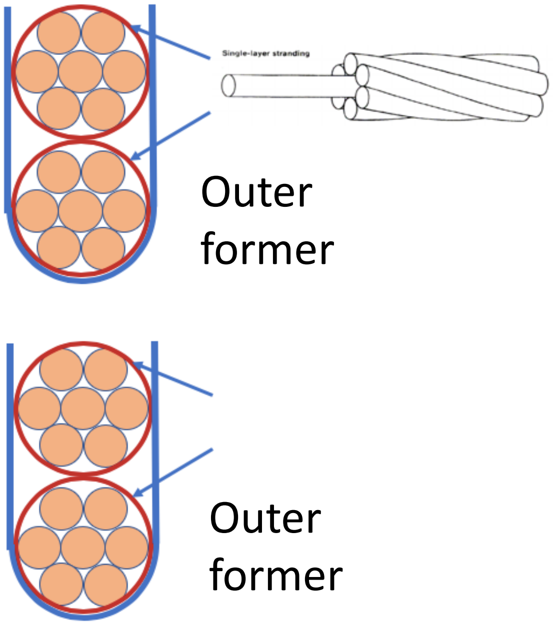
We want **low current & low cost!**

Have the best of both worlds

(III) Coil placement in grooves







Several turns of **insulated conductor** into one grooves (CERN's method):

- Remain low operation current while reduce the number of mandrels;
- Need more splices between coils of two mandrels.

Insulated mini round cables into one grooves (Our variant):

- More flexibility of insulation design ;
- Easier to wind;
- Lower coupling loss between strands.

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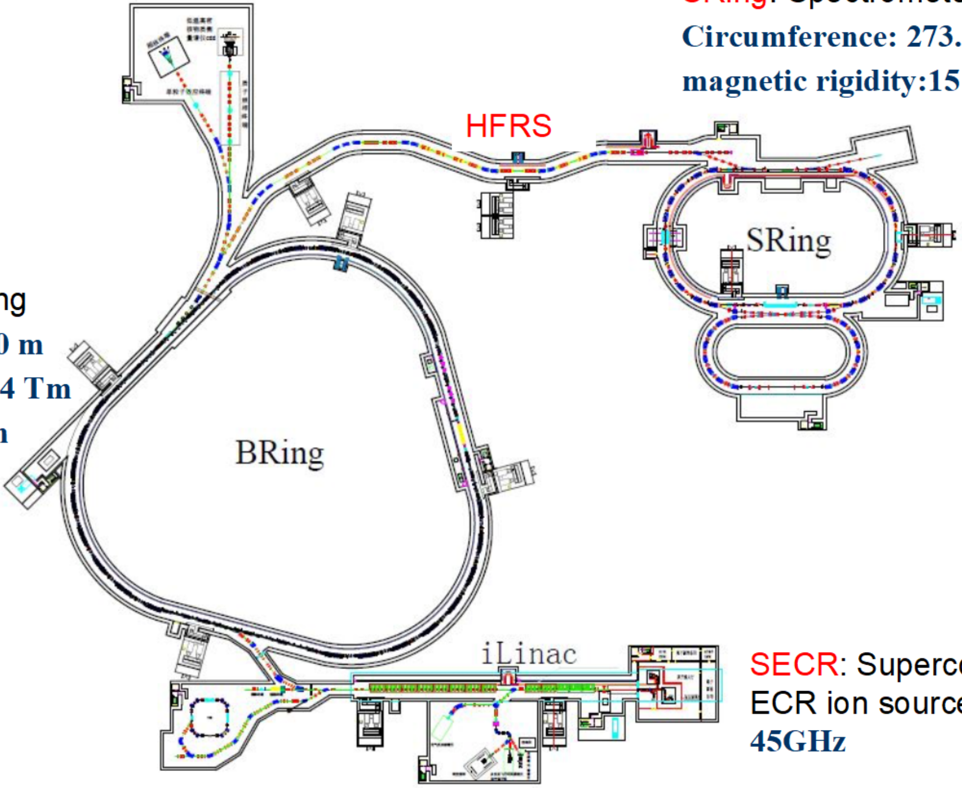
Overview of the HIAF project



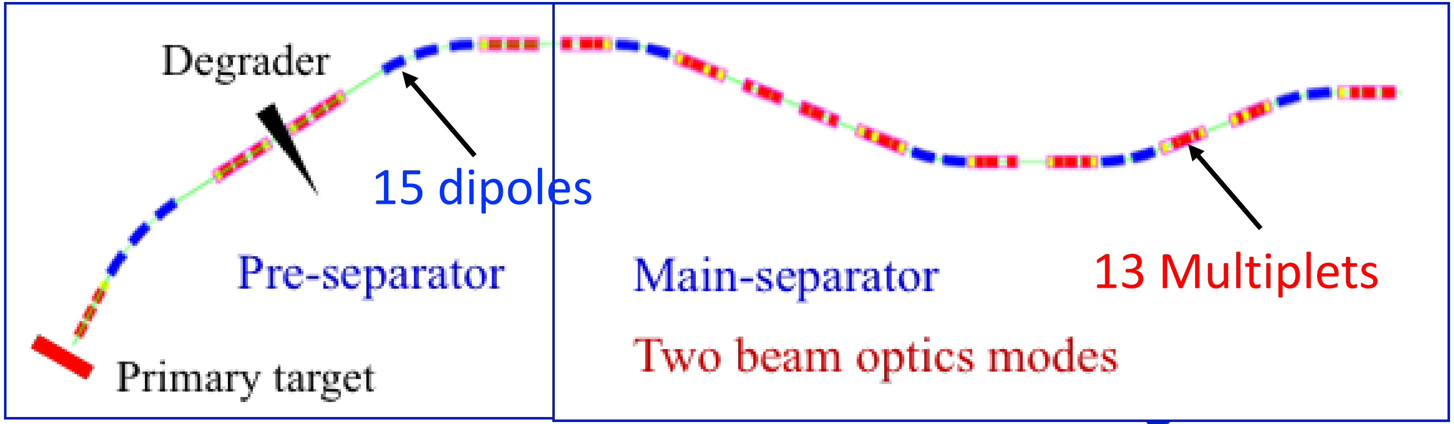
SRing: Spectrometer Ring
Circumference: 273.5 m
magnetic rigidity:15 Tm

BRing: Booster Ring
Circumference: 530 m
magnetic rigidity:34 Tm
Beam accumulation
Beam cooling
Beam acceleration

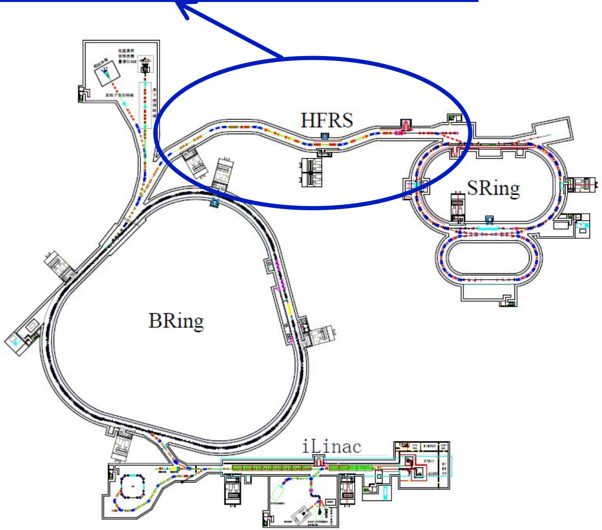
SECR: Superconducting ECR ion source
45GHz

iLinac: Superconducting Linac
17MeV/u(U^{34+})

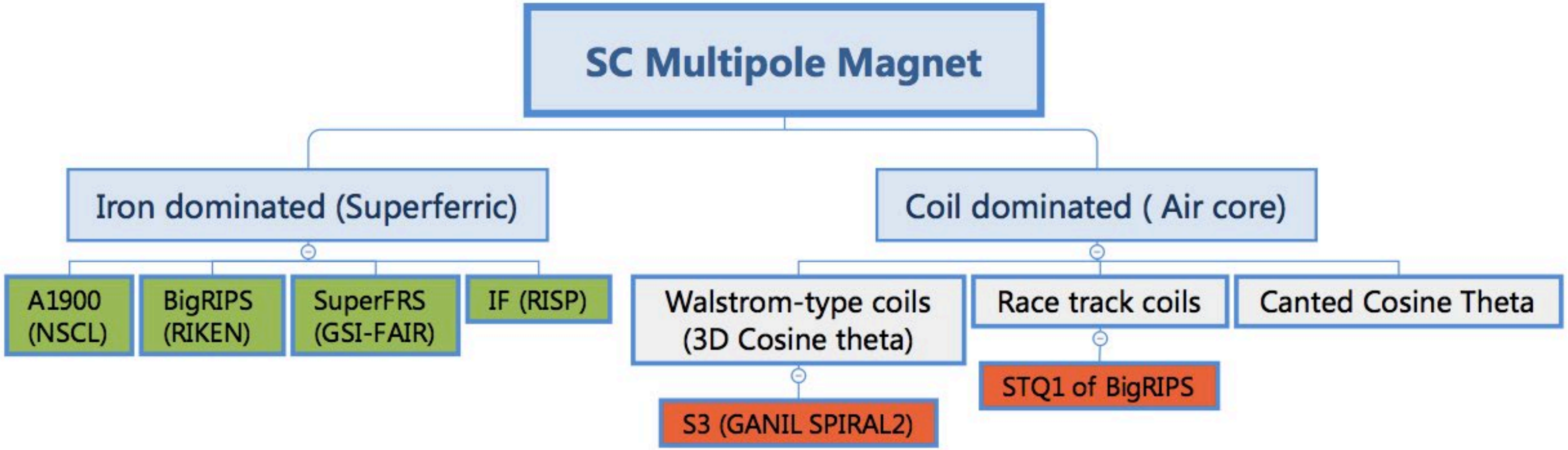
HFRS spectrometer



- Production, separation and identification of exotic nuclei
- Primary and secondary beams
- High magnetic rigidity: 25 T·m
- Big beam acceptance: ± 160 mm

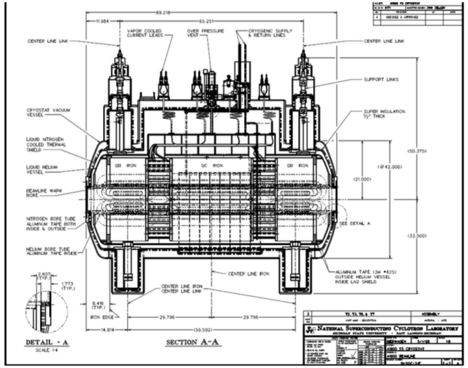


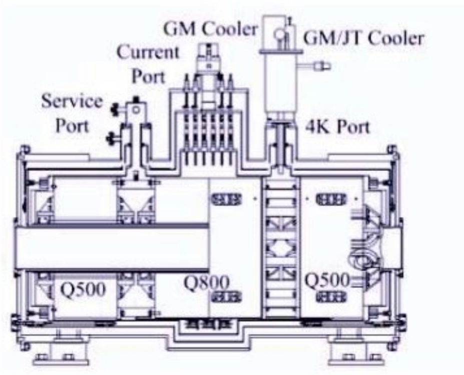
Options for Multipole Magnet Design

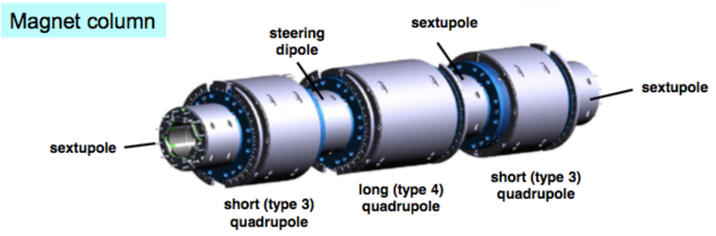


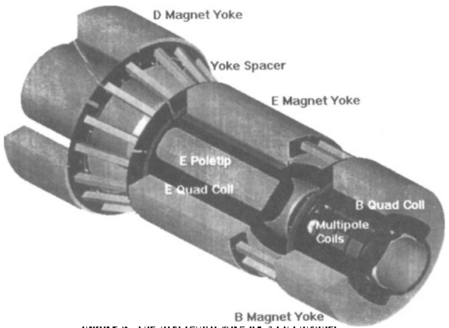
- The **iron dominated magnets** with superconducting coils have been widely used:
  - Easier to fabricate and wind;
  - low request for coils installation precision;
  - Easier to do quench protection.
- **Coil dominated magnet** was some times requested:
  - Small cold mass (speed up cool down or minimize radiation heat load) ;
  - No saturation effect;

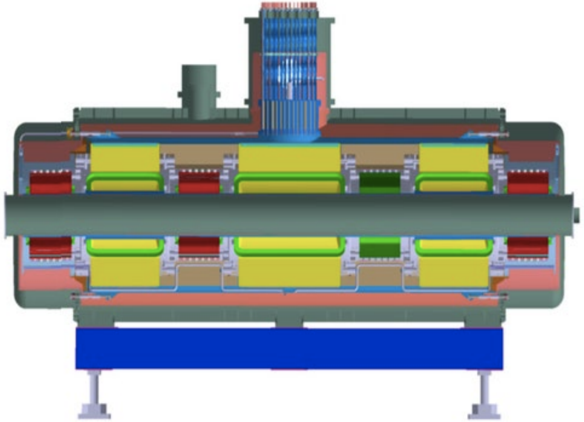
Iron-dominated option





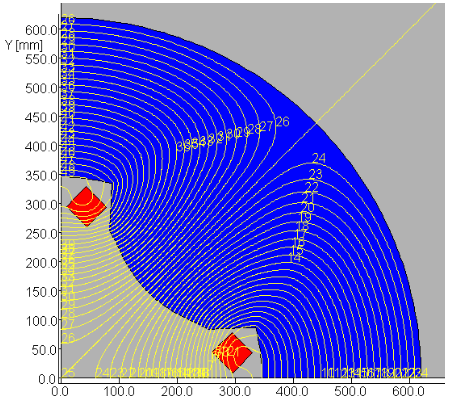




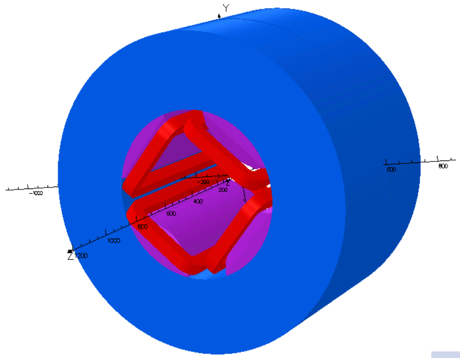


MSU/NSCL A1900 Triplet RIKEN Big-RIPS Triplet GSI/FAIR Super-FRS Multiplet

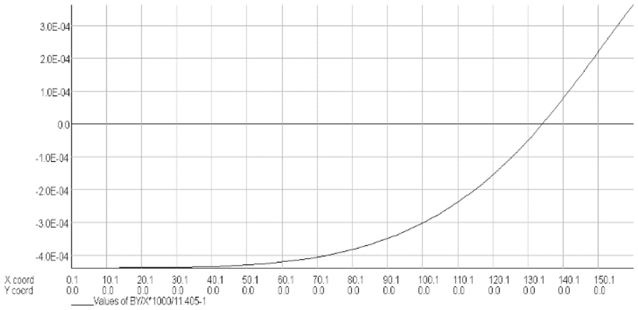
Iron-dominated design



2D model



3D model



Field gradient homogeneity~0.03%

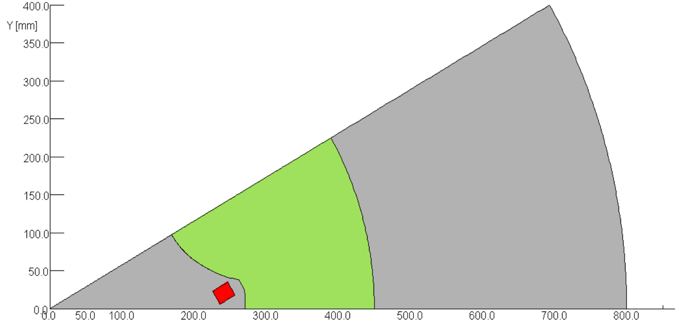
Field Harmonics components

Harmonics	value
n2	1
n6	8.8×10^{-4}
n10	0.7×10^{-4}
n14	1.8×10^{-4}

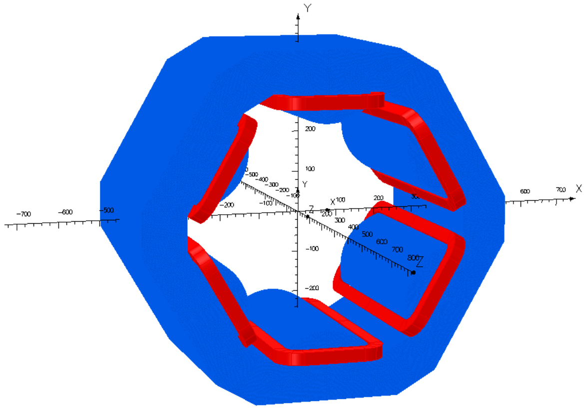
Cross section of coils	50mm×48mm
J_e	106 A/mm
Dia of Iron	1,240 mm
Weight of Iron	7.8 ton

- Hard to achieve good field quality at both low and high field ;
- End chamfer needs to be carefully optimized.

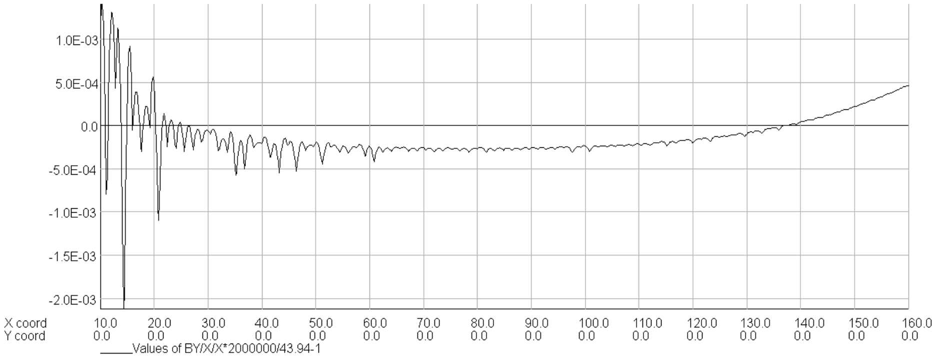
Iron-dominated design



2D model



3D model

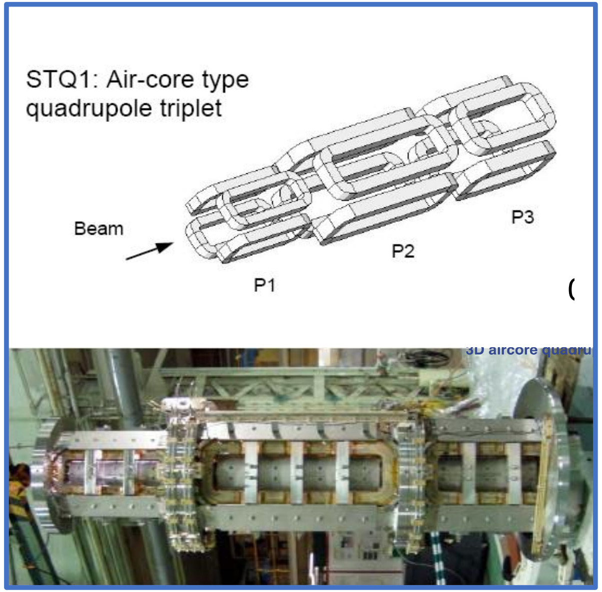


- Easy to reach the field quality;
- Weight of the cold iron is 2.14 ton.

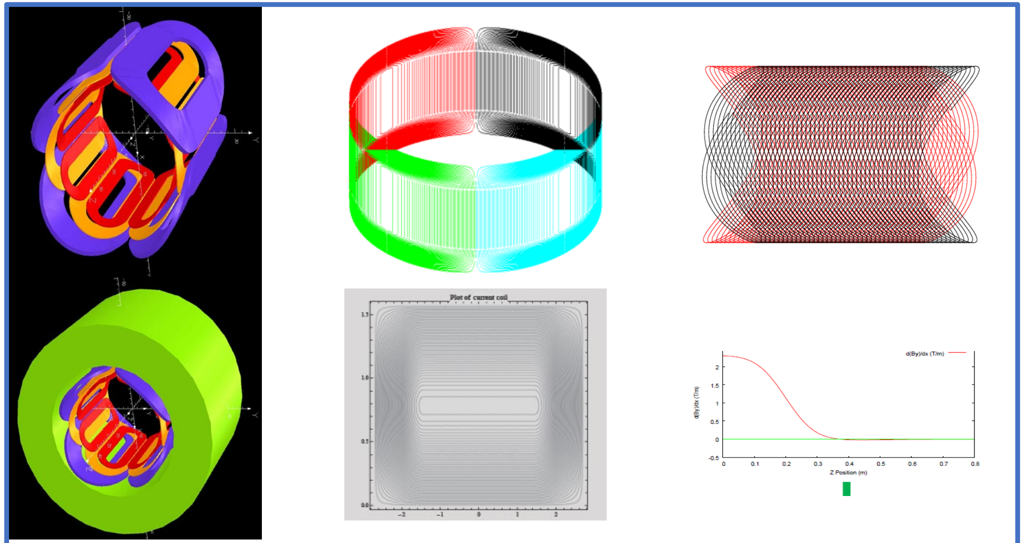
Problems in the iron-dominated design

- **Large cold mass**. Heaviest cold mass of one module is about 40 tons. It will need long time to cool down and warm up;
- Triplets, sextupole and steering dipole **integrated** into modular cryostats. The longest magnet column is about **7 m**. Difficult for cold mass **support and alignment**.
- Large helium containment will cause big pressure rise after a quench;

Coil-dominated option



Air-core type triplet for BigRIPS
(Simple racetrack coil)



Saddle coils Walstrom type double helix (CCT)

Proposals for S^3 of SPIRAL2
(Walstrom type coil was taken, fabricated by AML□
S. Manikonda,17Feb, 2016

- Advantages of **light weight** and **good field linearity**;
- Magnetic field are more **sensitive** to positioning error;
- **Difficult** to fabricate and wind, especially Walstrom type coil.

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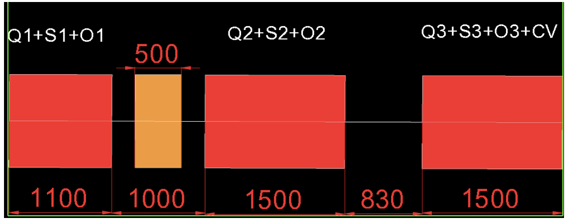
Magnet requirements for the HFRS



A typical triplets

- Large bore□
- Pole-tip fields: ~2.4T□
- Low current□ < 500 A□
- Liquid Helium bath cooling□

Specifications of **quadrupoles**

Gradient	T/m	**11.43**
Effective length	m	0.8(Q1), 1.1(Q2), 1.5(Q3)
Horizontal aperture	mm	**±160mm**
Vertical gap	mm	±85
Field Quality		$\pm 8 \cdot 10^{-4}$

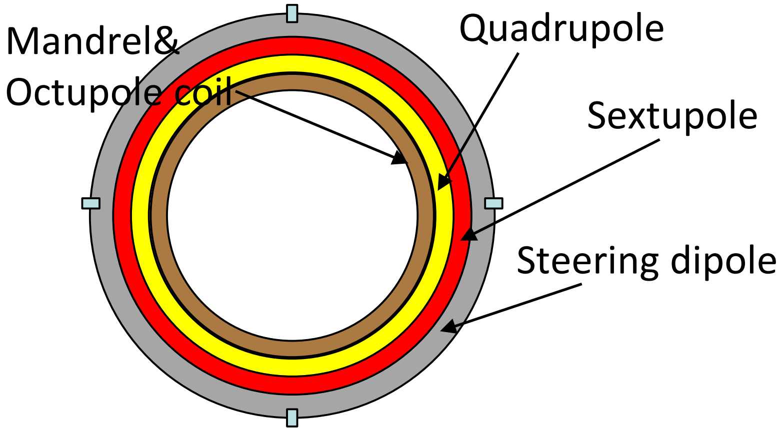
Specifications of **Octupoles**

Gradient	T/m^3	105
Effective length	m	0.8(O1), 1.1(O2), 1.5(Q3)
Horizontal aperture	mm	±160 mm
Vertical gap	mm	±85 mm
Field Quality		$\pm 5 \times 10^{-3}$

Specifications of **sextupoles**

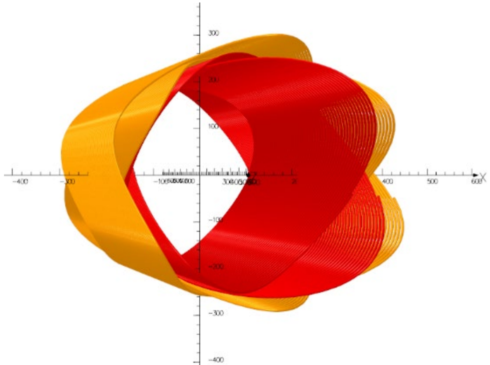
Gradient	T/m^2	**30**
Effective length	m	0.8(S1), 1.1(S2), 1.5(S3)
Horizontal aperture	mm	±160 mm
Vertical gap	mm	±85 mm
Field Quality		$\pm 5 \times 10^{-3}$

HFRS Multipoles based on nested CCT

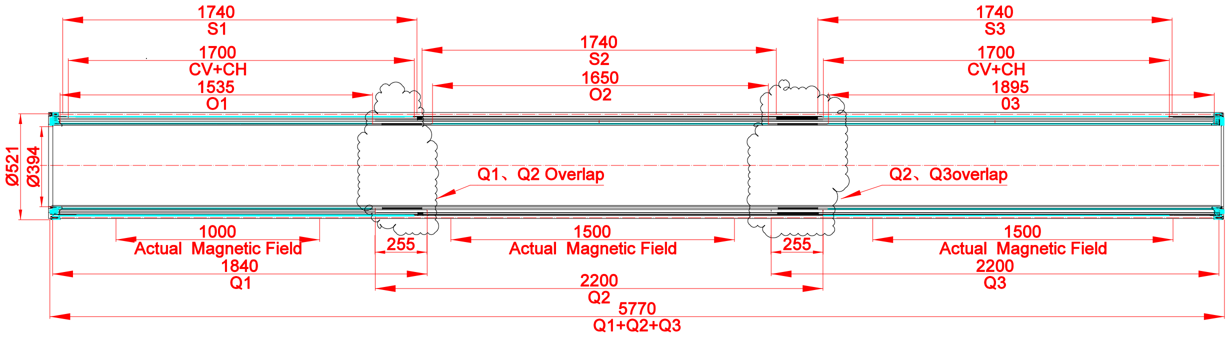


Coil configuration of singlet

- **Quadrupole** and **sextupole** based on Canted Cosine-Theta (CCT) coil;
- Sextupole, octupole and steering dipole **nested** to reduce the length;
- Weight of cold mass greatly decreased (**40 ton → 4 ton**)

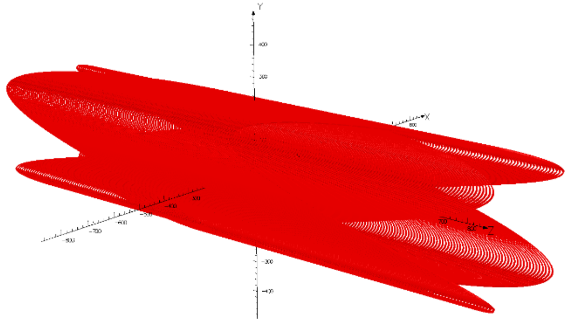


Quadrupole & sextupole

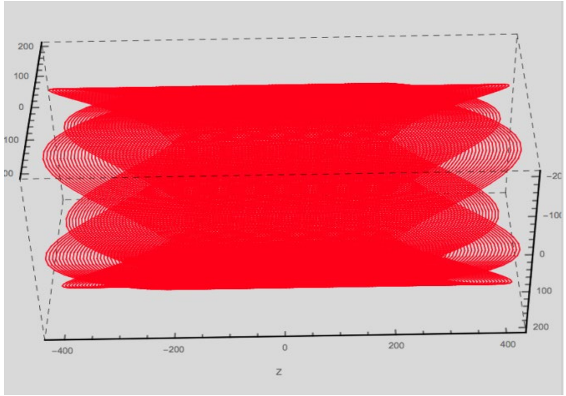


A typical configuration of HFRS triplets

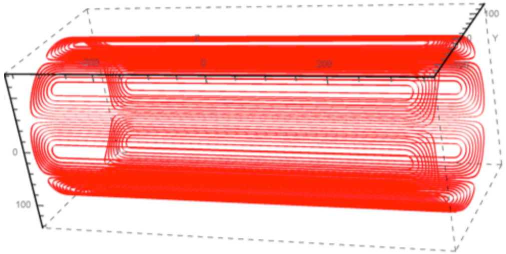
Coil design



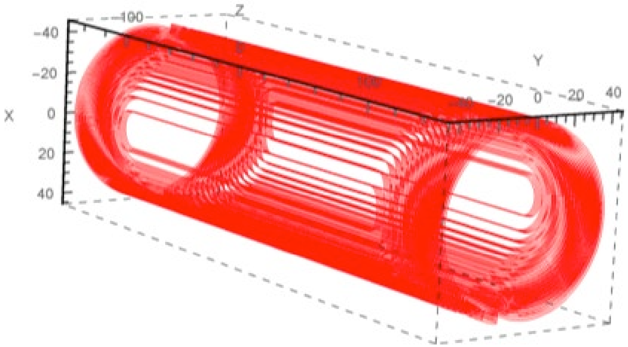
CCT quadrupole coil



CCT sextupole coil



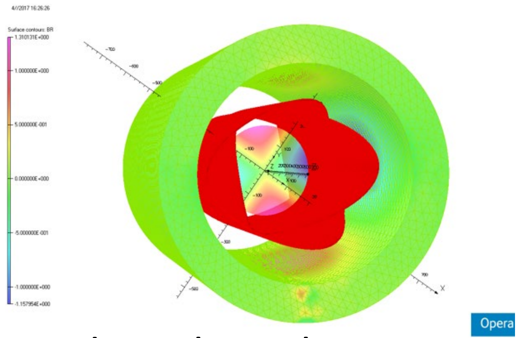
Octupole coil



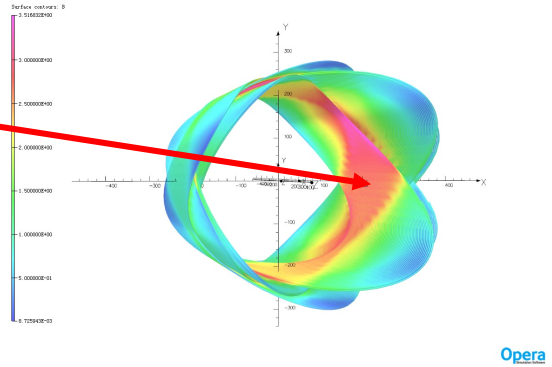
Steering dipole coil

Coil design (quadrupole)

	Q1(L=0.8m)	Q2(L=1.1m)	Q3(1.5m)
Gradient Field (T/m)	10	10	10
Current(A)	440	440	440
Layers	2×(6+1)	2× (6+1)	2× (6+1)
CCT angle	30	30	30
Turns per layer	66	90	124
Pitch(mm)	12.2	12.2	12.2
Aperture(mm)	320×170	320 ×170	320 ×170
Wire Diameter(mm) Cable Diameter(mm)	0.85 2.8±0.01	0.85 2.8±0.01	0.85 2.8±0.01
Bpeak(T)	3.5	3.5	3.5
Loadline	67.7%	67.7%	67.7%
Conductor length(km)	6.4	8.7	11.9
ID of mandrel(m)	420 mm	420 mm	420 mm
Coil groove size	2.8 mm × 5.8 mm	2.8 mm × 5.8 mm	2.8 mm x 5.8 mm

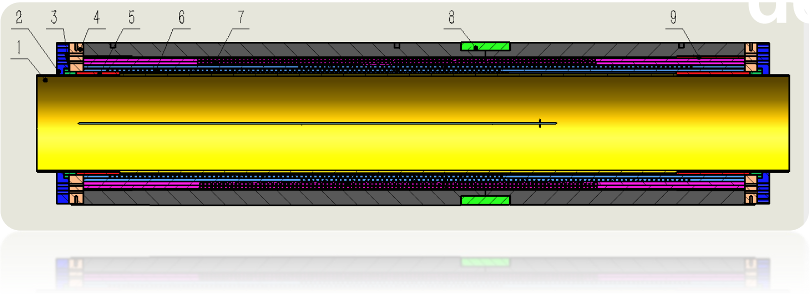


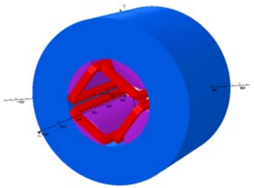
Quadrupole with warm iron yoke (6% enhancement of B)



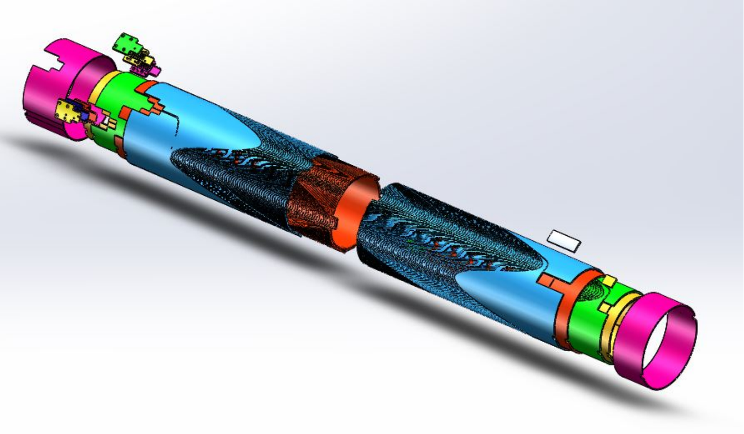
Quadrupole & Sextupole coils

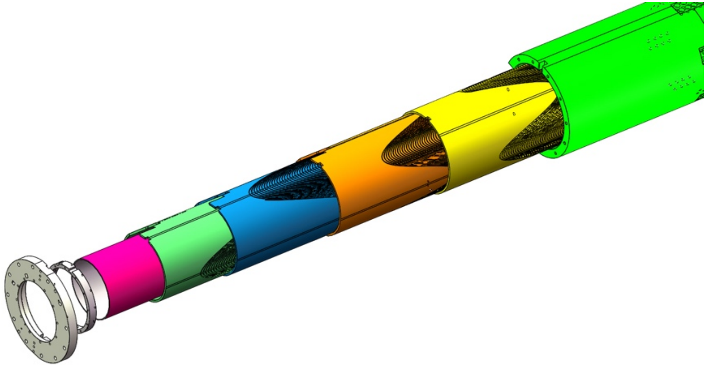
Mechanical



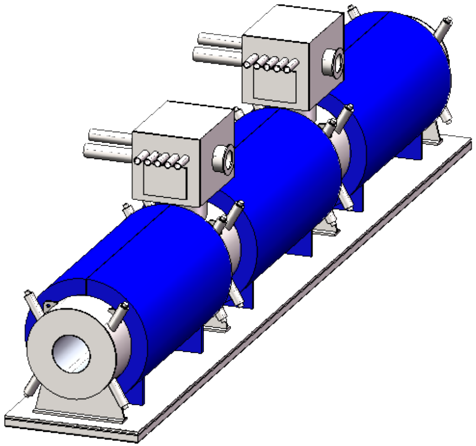


40 tons





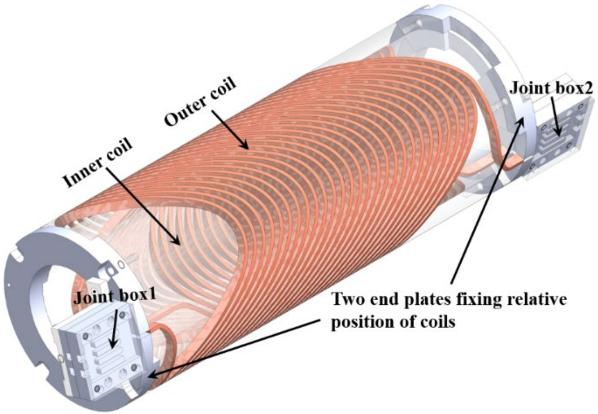
4 tons



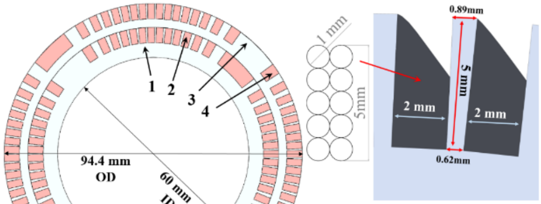
Outline

- ❖ CANTED–COSINE–THETA MAGNET
- ❖ INTRODUCTION OF HIAF & HFRS
- ❖ MAGNET DESIGN
- ❖ SUBSCALE MODEL COIL
- ❖ SUMMARY & FUTURE WORKS

Subscale model coil - design



The CCT quadrupole magnet assembly



Item	Description	Material
1	Layer1	Aluminum Alloy
2	Coil1	NbTi
3	Layer2	Aluminum Alloy
4	Coil2	NbTi

Cross section of the CCT quadrupole coil

Main Design Parameters of Quadrupole Magnet

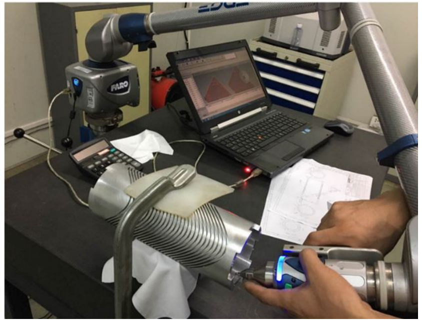
Parameter	Value	Unit
Gradient	40	T/m
Effective length	160	mm
Operation current	400	A
Winding pitch	6	mm
Tilt angle	45	deg
Inductance	10	mH
Aperture	60	mm
Good field	± 20	mm
Uniformity	± 4E-4	

Parameters of the NbTi/Cu strand

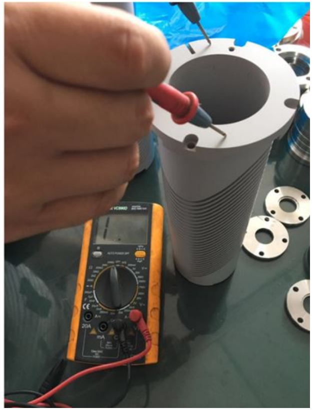
Wire type	Monolith
Insulation	Formvar
Bare size	0.72 mm
Insulated size	0.77 mm
Outer Insulated with Nylon braid	0.9±0.005 mm
Cu/SC	1.3:1
RRR (293 K/10 K)	＞100
Ic (6 T,4.2 K)	442.7 A

Subscale model coil - fabrication

Milling

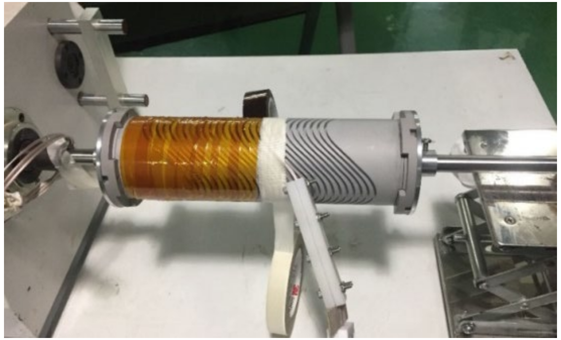


Measurement



Anodized

Former Fabrication



Winding

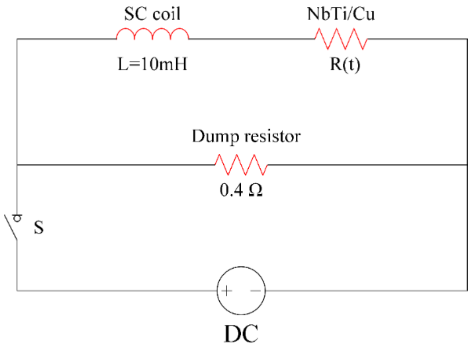
Finished winding

After Vacuum impregnation

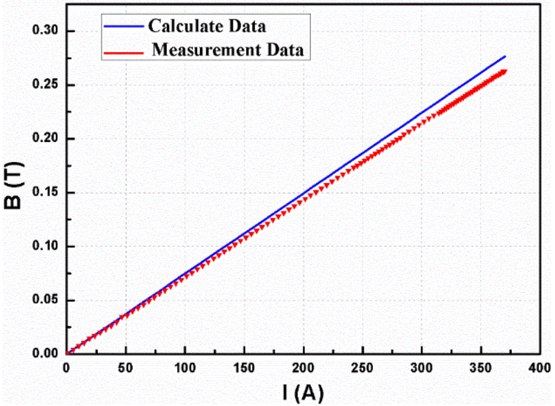
Coil Winding and Impregnation

Subscale model coil - fabrication

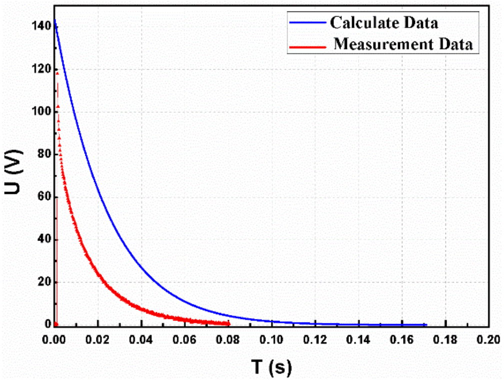
Cold test insert



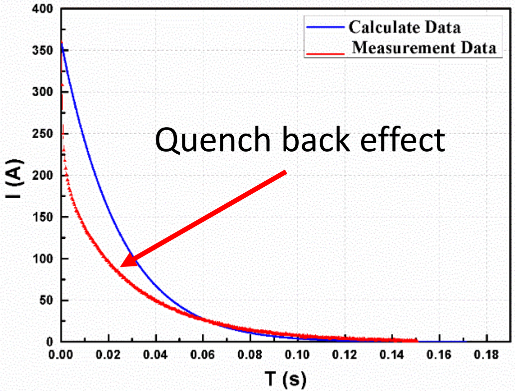
Quench protection circuit



Excitation curve



Voltage decay curve



Current decay curve

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Summary

- Thanks for the modern manufacture technology, CCT magnet (old technology) has a new life (High field, Gantry, FFAG, LHC-HL);
- CCT magnet: **Simple manufacturing, low coil stress, field quality** but **reduced efficiency;**
- CCT magnet will be used in HIAF-HFRS spectrometer: lower field, low current & large aperture;
- Coil in groove with insulated mini-round-cable is proposed and will be used;
- Subscale testing coil has been successfully fabricate and tested.

Future works

- Detailed error analysis of magnetic field ;
- Structural analysis of the magnet;
- Quench simulation and protection design;
- Fabrication of the half-size and full size nested multiplet prototype in next 2 years;
- Serial production of 13 multiplets modules in next 5 years.

Thanks a lot for your attention!

Thanks for Prof. Glyn Kirby, Prof. Lucio Rossi (CERN) and Prof. Shlomo Caspi's(LBNL) suggestions and help!