Introduction of the superconducting magnets for HIAF project

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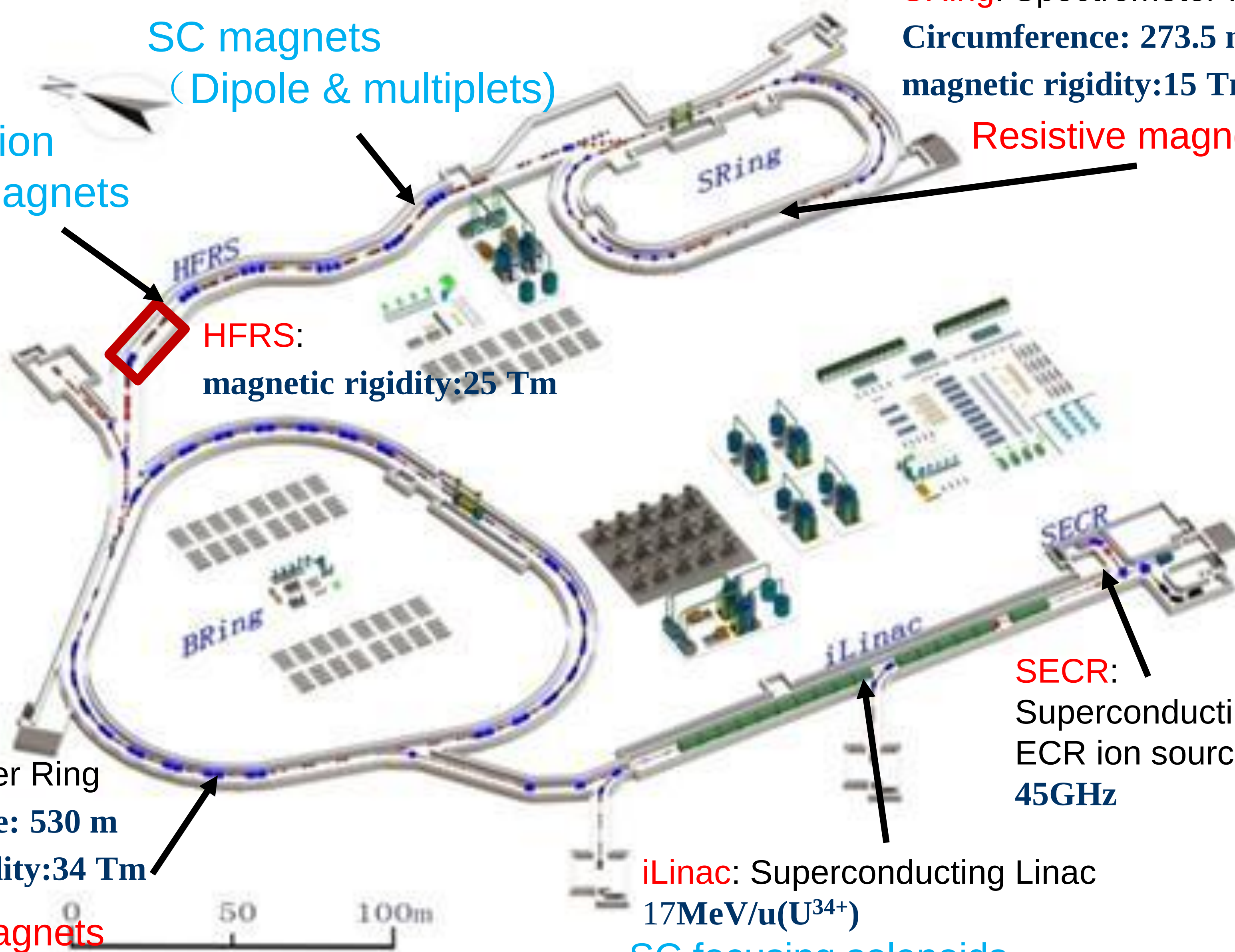
Outline

- ❖ Overview of the SC magnets in HIAF project
- ❖ Superconducting solenoids for iLinac
- ❖ Superconducting multiplets for HFRS
- ❖ Superconducting dipoles for HFRS
- ❖ Design study for BRing RCS superconducting dipole

SC magnets in HIAF project



SC magnets
（Dipole & multiplets)

HTS radiation resistant magnets

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

Resistive magnets

HFRS:
magnetic rigidity:25 Tm

SECR:
Superconducting ECR ion source
45GHz

BRing: Booster Ring
Circumference: 530 m
magnetic rigidity:34 Tm

Resistive magnets

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

SC focusing solenoids

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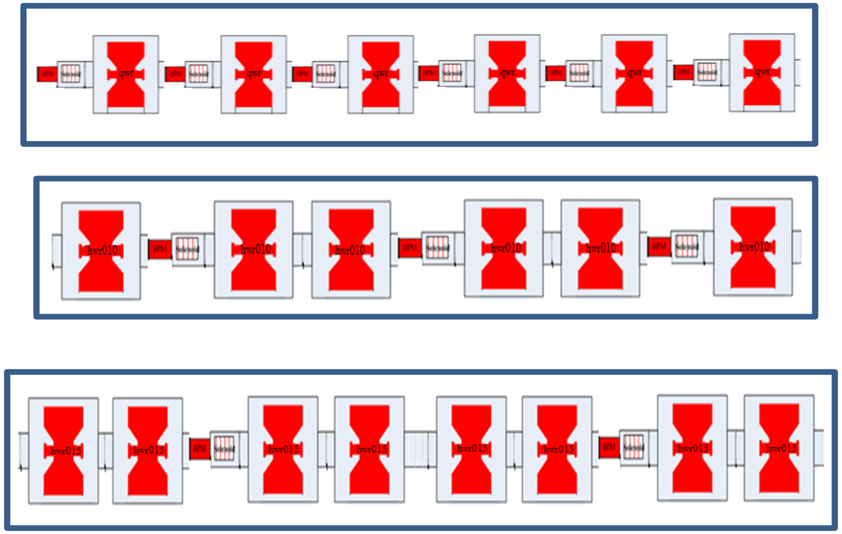
iLinac SC solenoid - Specifications



Specifications of L200 solenoid

Item	Unit	Value
Operation temperature	K	2/4.5
Cold bore	mm	40
Length	mm	340
Stray field（z ≥ 260mm）	T	≤ 0.02
$\int B_z^2 dz$	T^2m	9.8
$\int B_z^2 dz$ **homogeneity（Φ30 mm）**	%	5%
Deviation of field center from mechanical center at magnet ends	mm	< 0.3

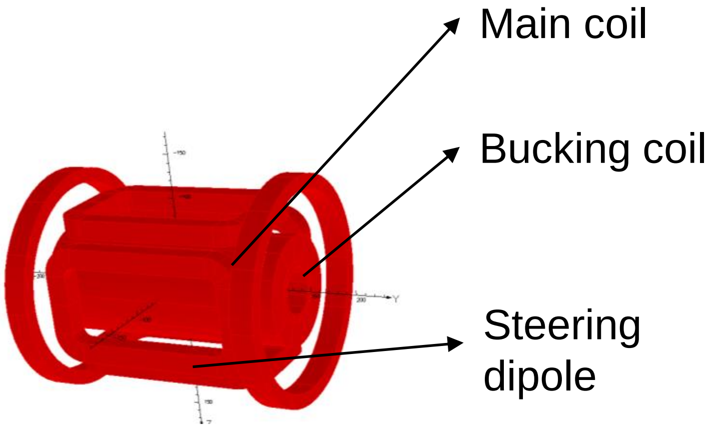
Specifications of L400 solenoid

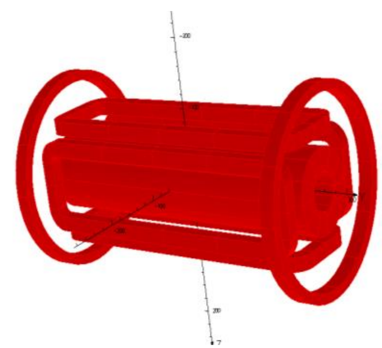
Item	Unit	Value
Operation temperature	K	2/4.5
Cold bore	mm	40
Length	mm	470
Stray field（z ≥ 260mm）	T	≤ 0.02
$\int B_z^2 dz$	T^2m	16.9
$\int B_z^2 dz$ **homogeneity（Φ30 mm）**	%	5%
Deviation of field center from mechanical center at magnet ends	mm	< 0.3

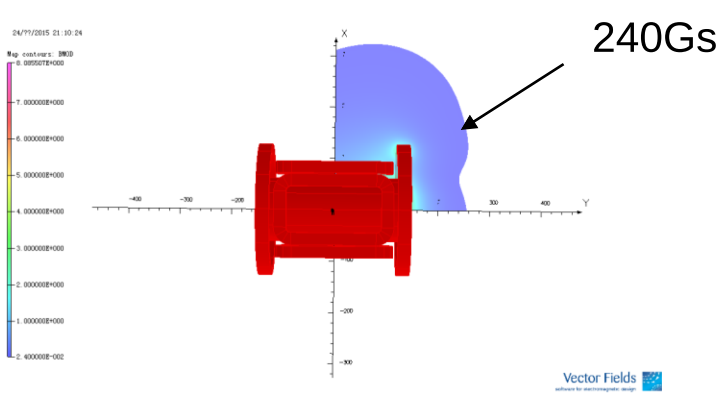
iLinac SC solenoid – Conceptual design

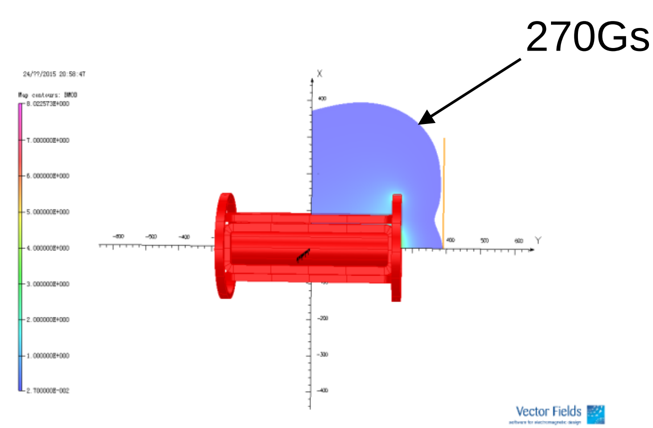
Leff = 250 mm

Leff = 400 mm



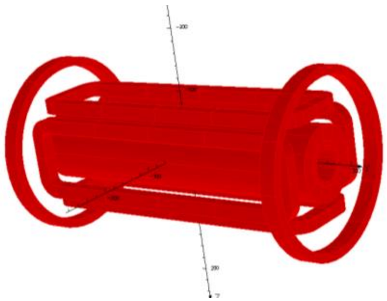


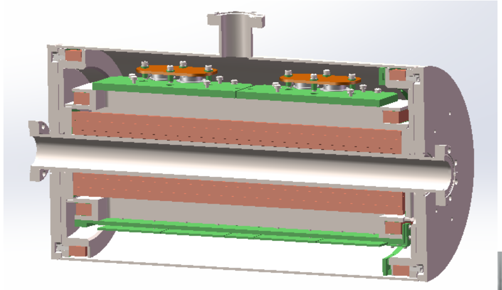




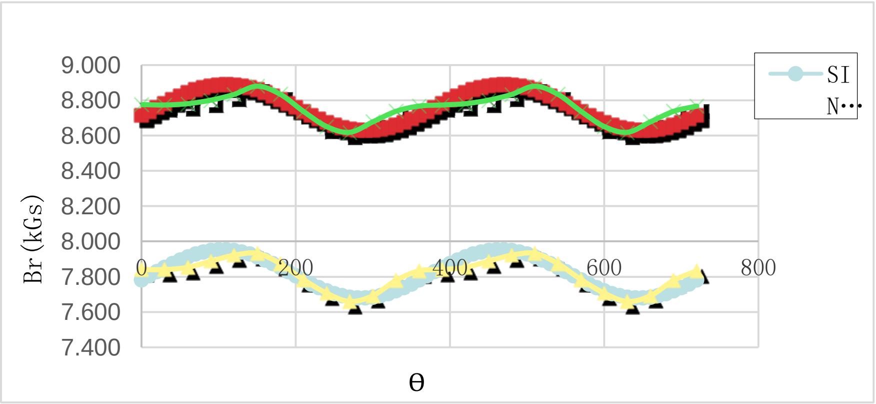
iLinac SC solenoid – experiences

- 26 SC solenoids for ADS injector II;
- Design and measurement of solenoids for FRIB；





Solenoids for FRIB



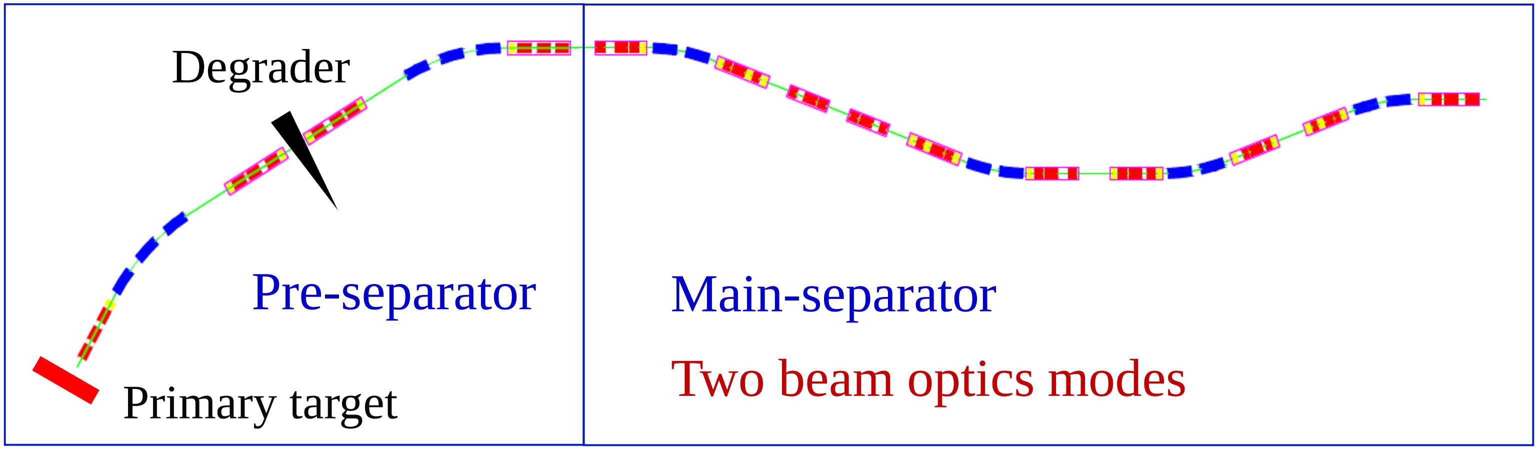
Solenoids for ADS

Measurement of magnetic center

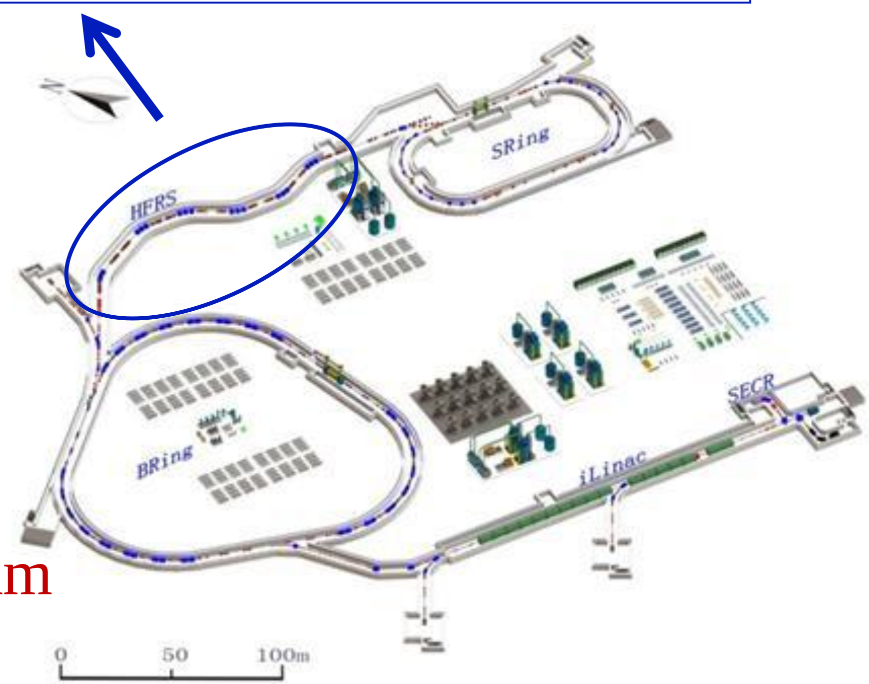
Outline

- ❖ Overview of the SC magnets in HIAF project
- ❖ Superconducting solenoids for ILinac
- ❖ **Superconducting multiplets for HFRS**
- ❖ Superconducting dipoles for HFRS
- ❖ Design study for BRing RCS superconducting dipole

Introduction of HFRS



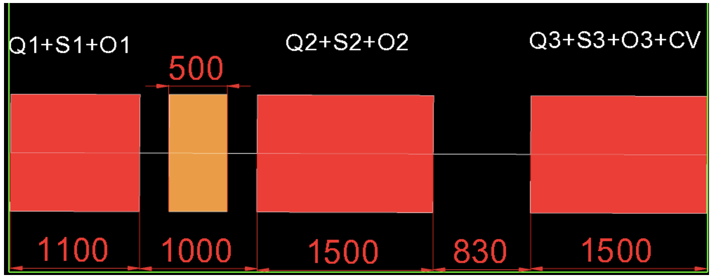
- Production, separation and identification of exotic nuclei
- Primary and secondary beams
- High magnetic rigidity: 25 Tm
- Big beam acceptance: ±160 mm



Layout of HIAF-HFRS

Magnet requirements for the HFRS

- Large bore;
- Pole-tip fields: 2.4T;
- Low current: < 600 A;
- Liquid Helium bath cooling;



A typical triplets

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 **sextupoles**

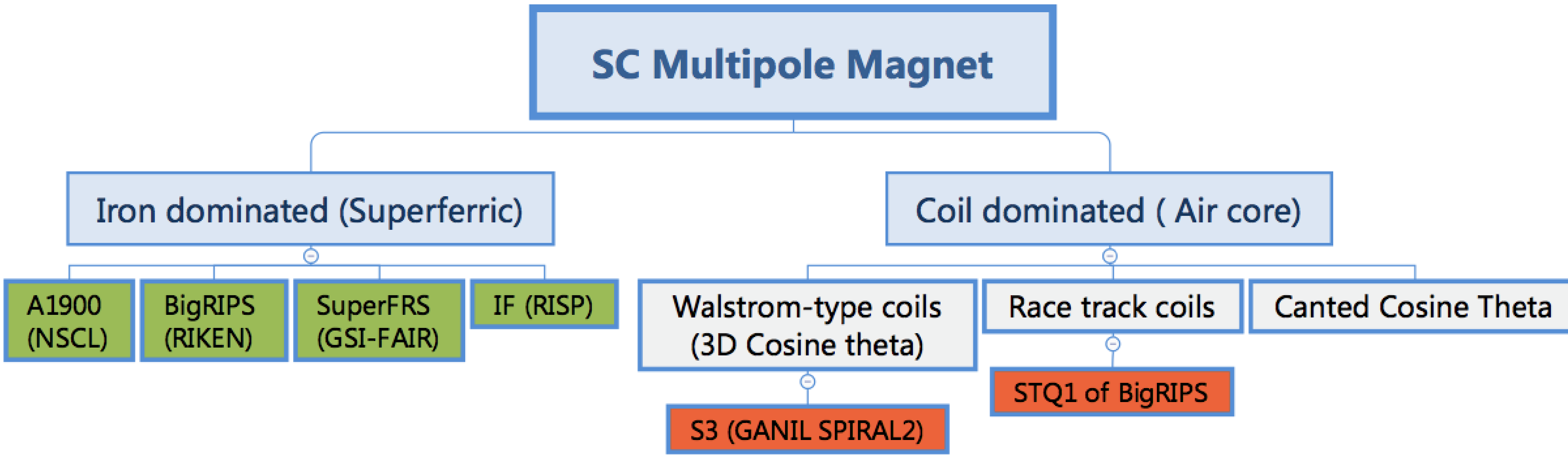
Gradient	T/m^2	30
Effective length	m	0.8(S1), 1.1(S2), 1.5(S3)
Horizontal aperture	mm	±160 mm
Vertical gap	mm	±85 mm
Field Quality		$\pm 5\times 10^{-3}$

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		$\pm 5\times 10^{-3}$

Options for Multipole Magnet Design

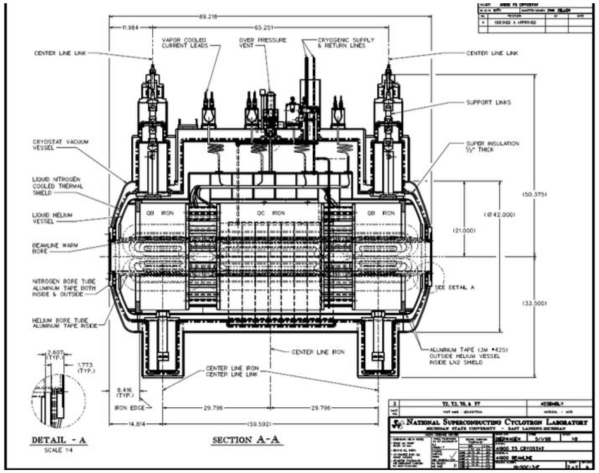
Application status

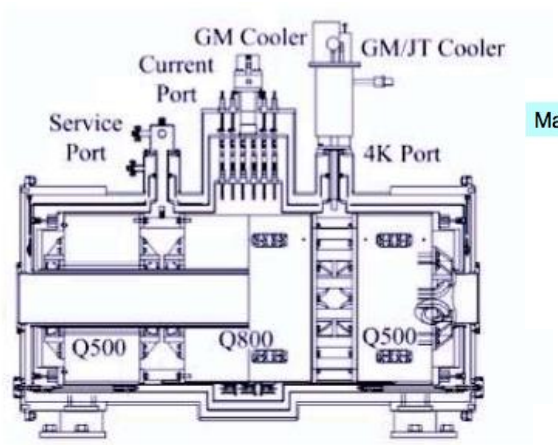


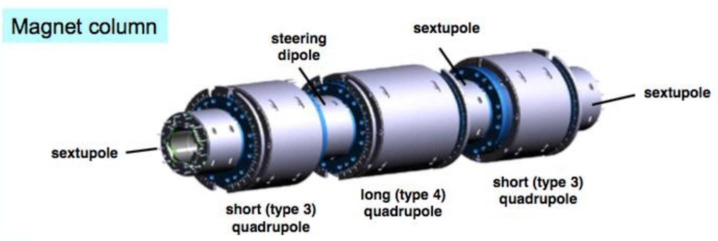
- The **iron dominated magnets** with superconducting coils have been widely used:
  - Easier to fabricate and wind;
  - low request for coils installation precision;
  - Easier to do quench protection.
- **Coil dominated magnet** was some times requested:
  - Small cold mass (speed up cool down or minimize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

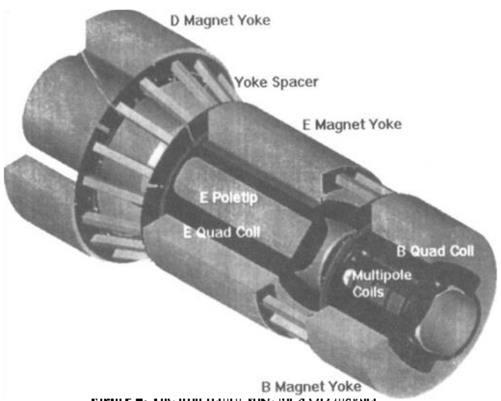
Options for Multipole Magnet Design

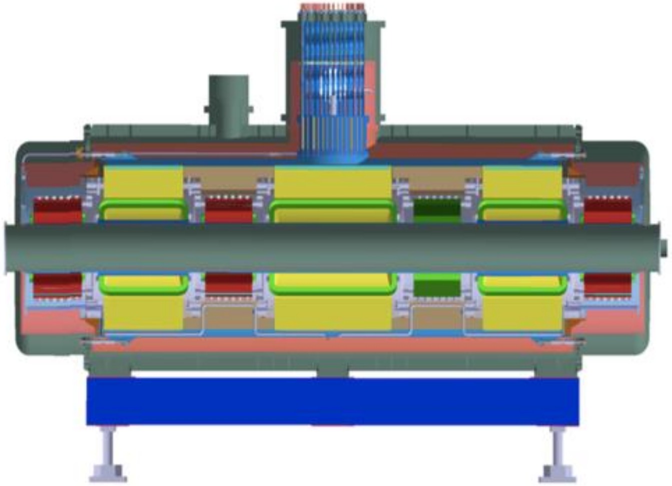
Iron-dominated option











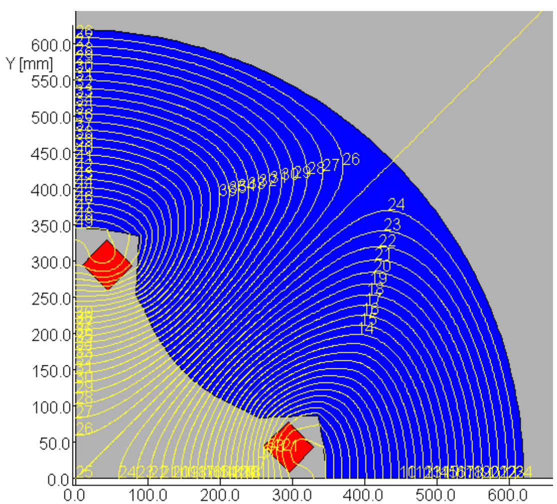
MSU/NSCL A1900 Triplet RIKEN Big-RIPS Triplet GSI/FAIR Super-FRS Multiplet

- Cold iron design is the most popular choice from A1900(1990s)

A. F. Zeller, Advances in Cryogenic Engineering(1998) H.Muller, Proceedings of IPAC2013

K. Kusaka, IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, 2004

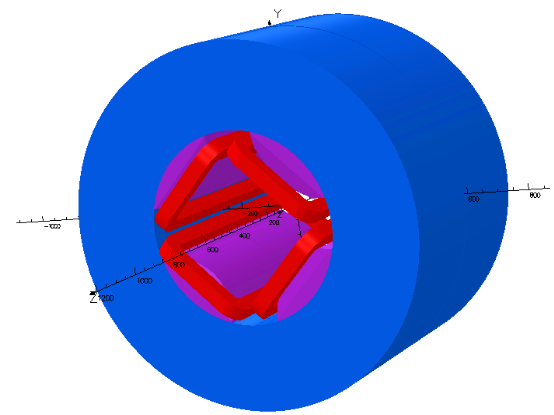
Iron-dominated design for HFRS Quadrupole (1 meter)



2D model

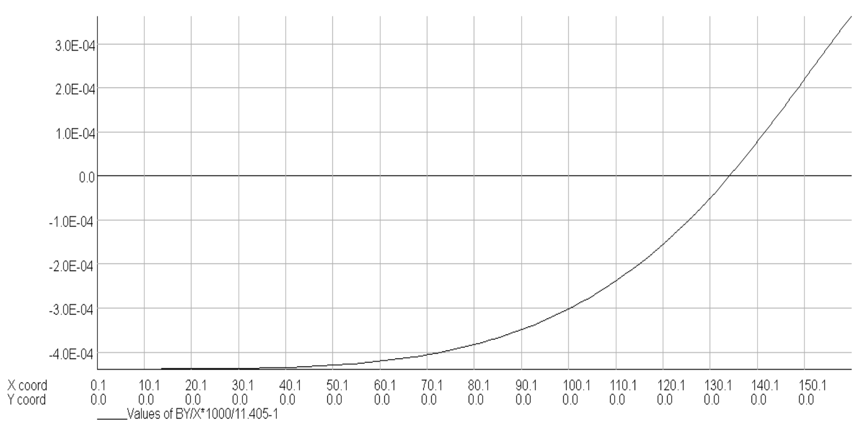
Field Harmonics components

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



3D model

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

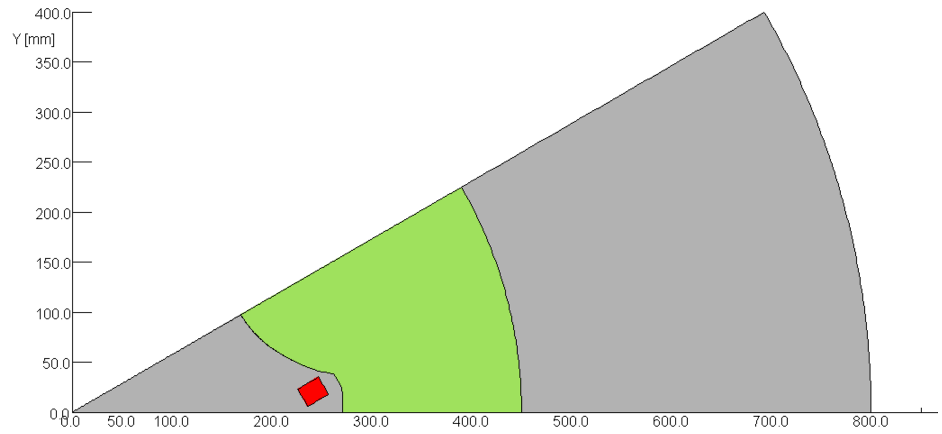


Field gradient homogeneity~0.03%

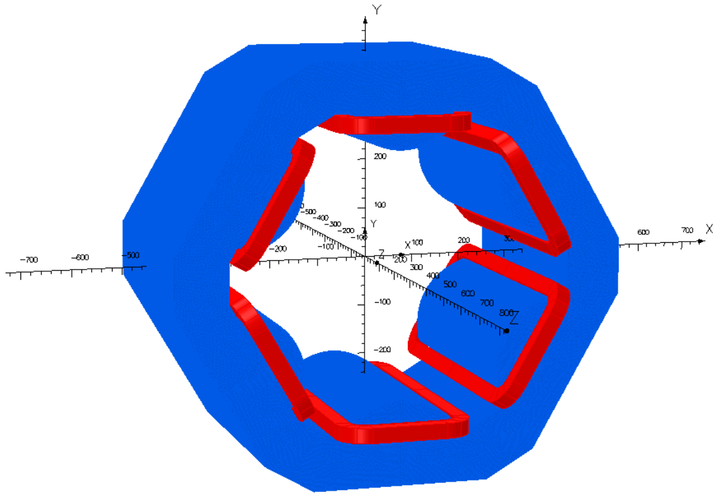
- Hard to achieve good field quality at both low and high field；
- End chamfer needs to be further optimized

Options for Multipole Magnet Design

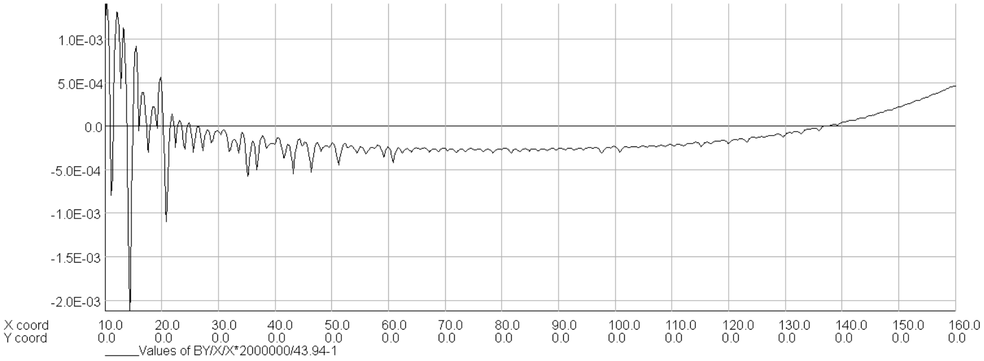
Iron-dominated design for HFRS Sextupole



2D model



3D model

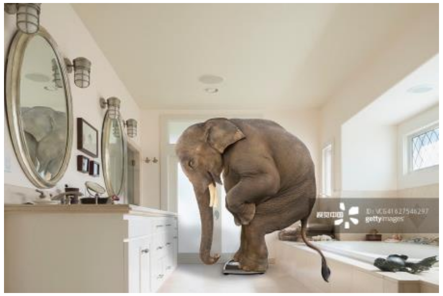


- Easy to reach the field quality;
- Weight of the cold iron is 2.14 ton.

Options for Multipole Magnet Design

Problems in the iron-dominated design for HFRS

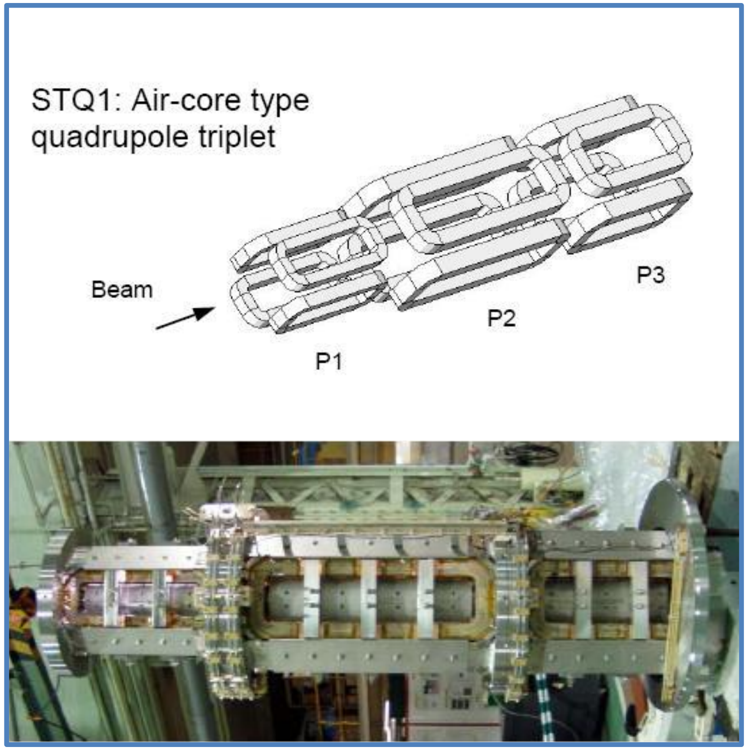
- Large cold mass. Heaviest cold mass of one module is about 40 tons. It will need long time to cool down and warm up;

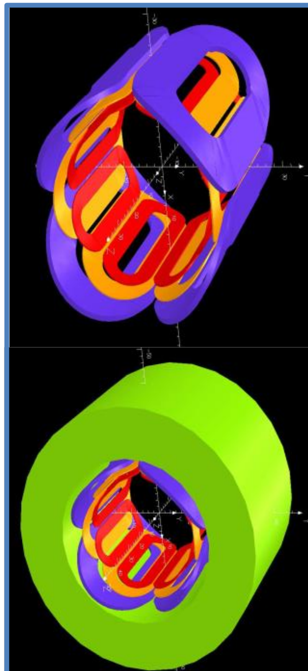


- Triplets, sextupole and steering dipole **integrated** into modular cryostats. The longest magnet column is about **7 m**. Difficult for cold mass support and alignment.

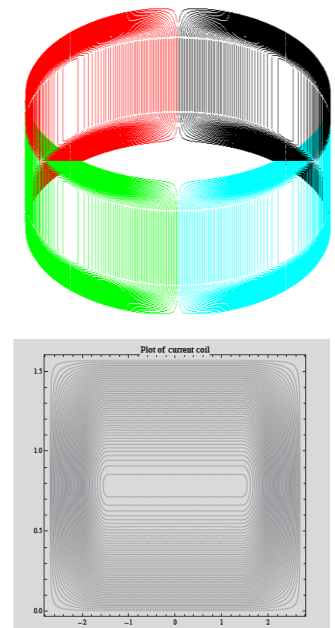
- Large helium containment will cause big pressure rise after a quench;

Coil-dominated option

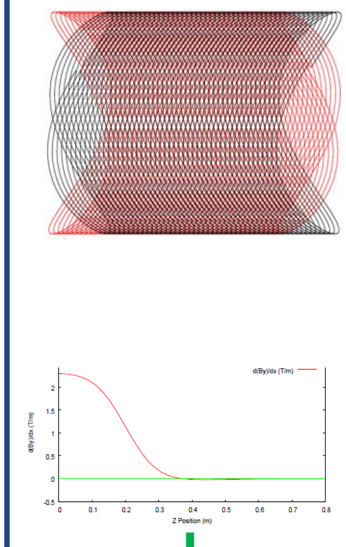




Saddle coils



Walstrom type



double helix (CCT)

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

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.

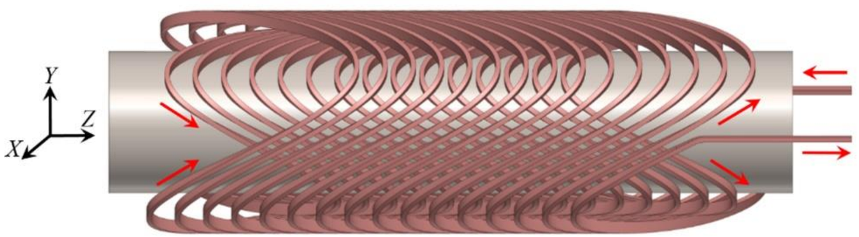
Why CCT (Canted-Cosine-Theta)?

- First suggested by D.I. Meyer and R. Flasck in **1970**
- AML, LBNL & CERN have started the R&D
- 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**)

$$X(\theta) = \frac{h}{2\pi}\theta + \sum_n A_n \sin(n\theta + \varphi_n)$$

$$Y(\theta) = R * \cos(\theta)$$

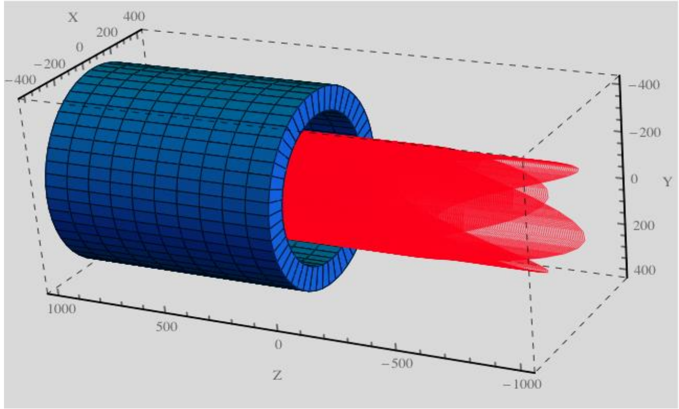
$$Z(\theta) = R * \sin(\theta)$$



HFRS Multipoles based on nested CCT

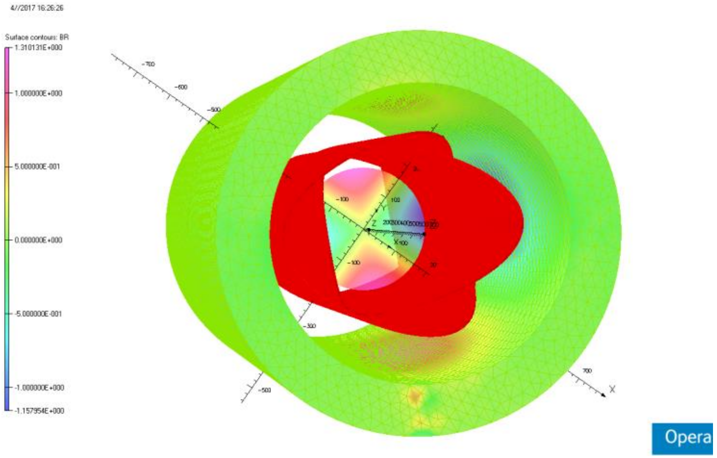
Coil design (quadrupole)

	Q1(L=0.8 m)	Q2(L=1.1 m)	Q3(1.5m)
Gradient Field (T/m)	11.43	11.43	11.43
Current(A)	500	500	500
Layers	5+5	5+5	5+5
CCT angle	36	36	36
Turns per layer	110	150	204
Pitch(mm)	7.4	7.4	7.4
Aperture(mm)	320×170	320 ×170	320 ×170
Wire Diameter (mm)	0.85 0.99±0.01	0.85 0.99±0.01	0.85 0.99±0.01
Bpeak(T)	2.9	2.9	2.9
Current margin	38%	38%	38%
Conductor length(km)	6.3	8.6	11.7
OD of mandrel(m)	420 mm	420 mm	420 mm
Coil groove size	2 mm x 5 mm	2 mm x 5 mm	2 mm x 5 mm

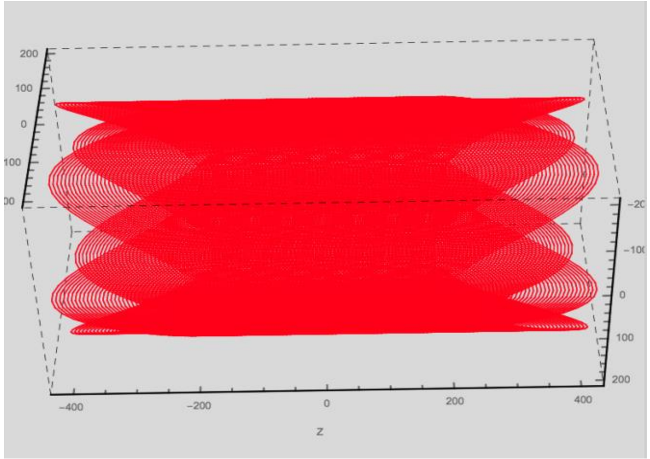


HFRS Multipoles based on nested CCT

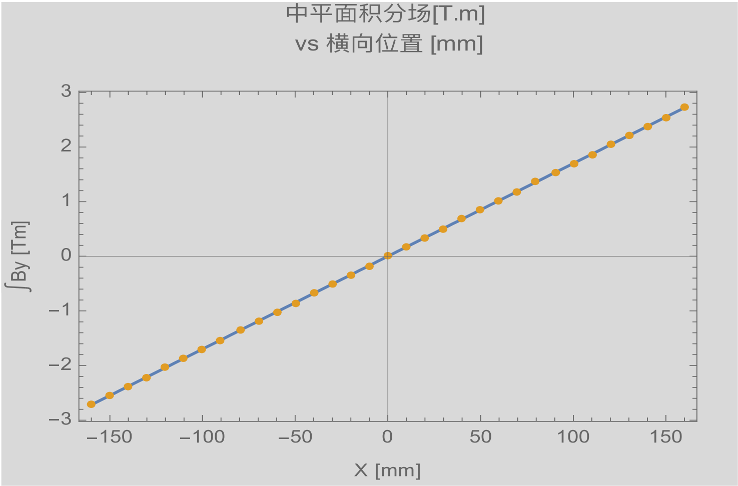
Coil design



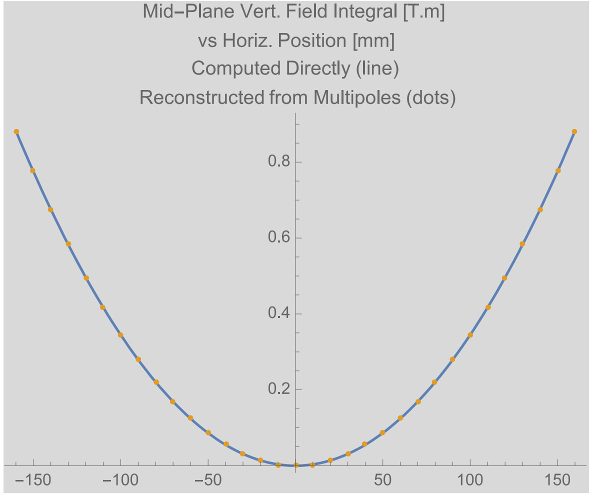
CCT quadrupole EM model



CCT sextupole EM model

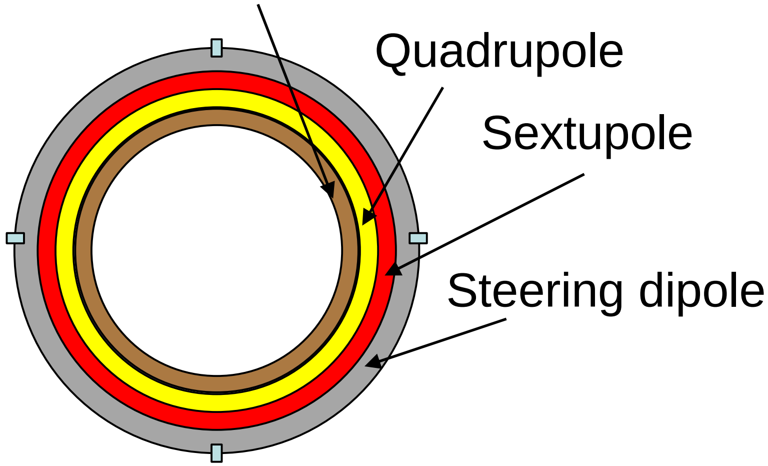


Integral field distribution of the quadrupole



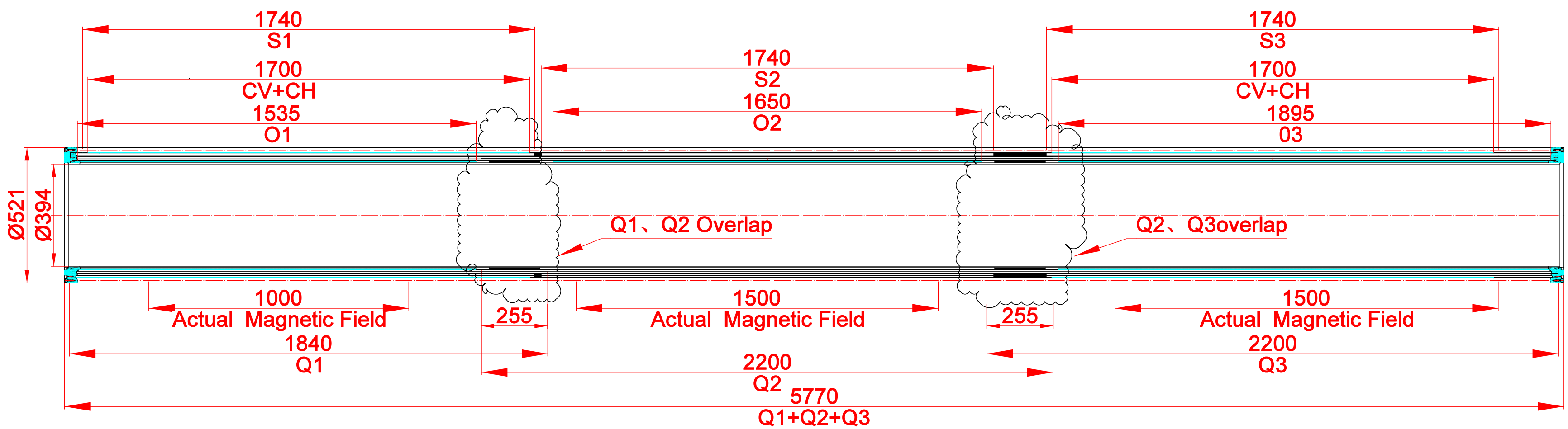
Integral field distribution of the sextupole

HFRS Multipoles based on nested CCT



Coil configuration of singlet

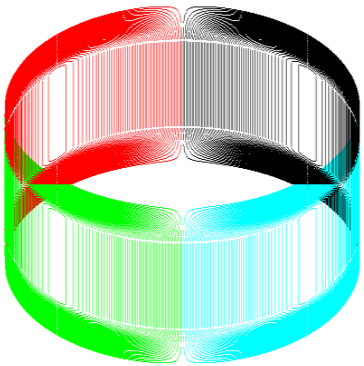
- **Quadrupole** and **sextupole** based on Canted Cosine-Theta (CCT) coil;
- Sextupole, octupole and steering dipole **nested** to reduce the length;
- Weight of cold mass greatly decreased (**40 ton → 4 ton**)



A typical configuration of HFRS triplets

(I) Direct placement with adhesive

BNL direct winding technology



Walstrom type coil

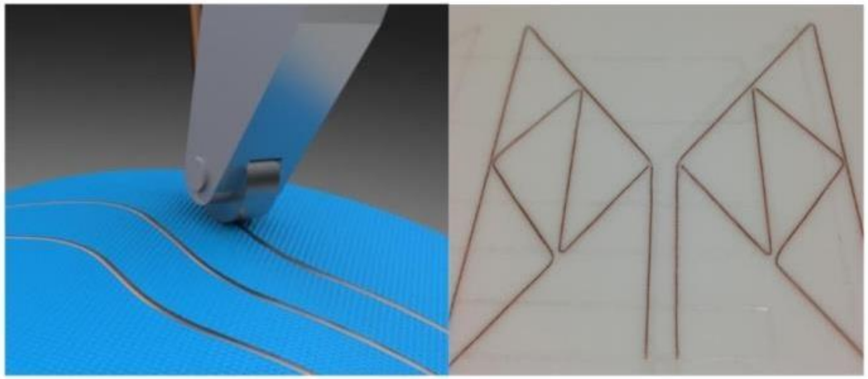
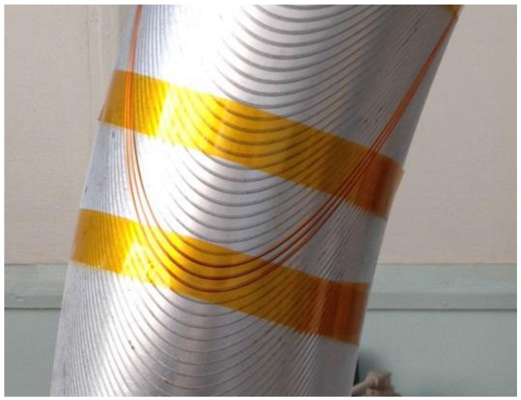


Figure 2 – Thermally embedded wire (a) conceptual depiction of embedding process and (b) in actual example in a 3D printed substrate (fractal antenna)

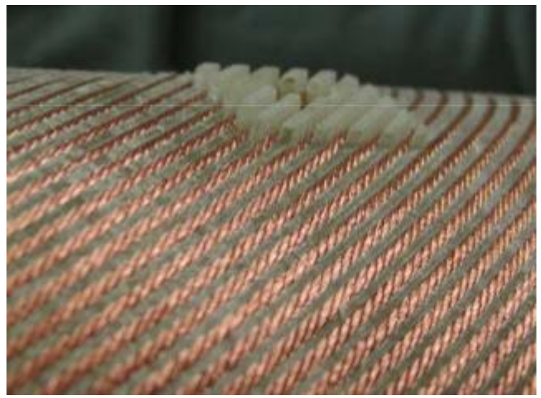
Thermally embedded wire process (3D printing coil)

- For complicate Walstrom type coil, special winding machine and techniques are needed, such as BNL's direct winding technology;
- Complex winding machine.

(II) Conductor/Cable placement in grooves

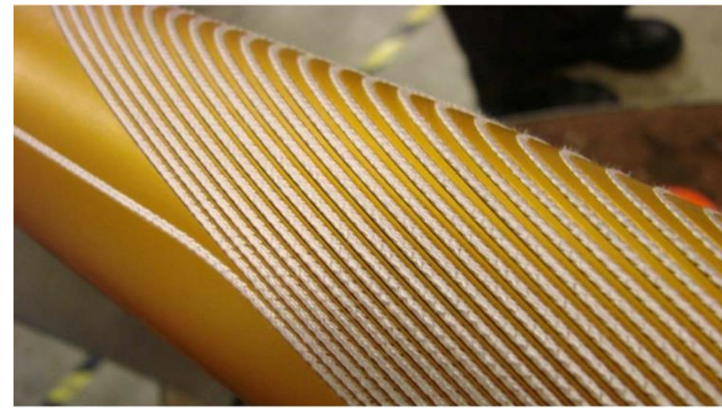


Conductor in grooves
(Metal)



Round mini cable in grooves
(Composite)

R.B.Meinke, MAGNETICS 2010

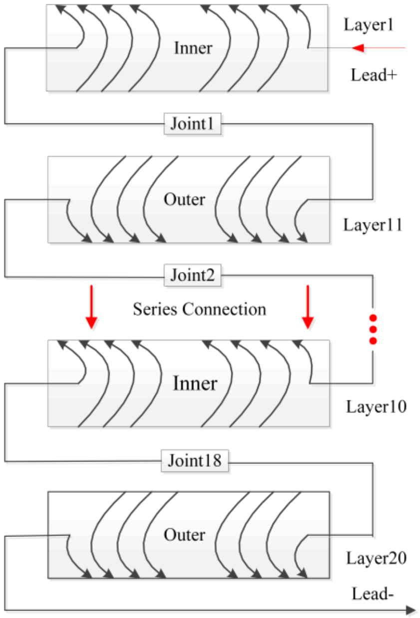


Rutherford cable in grooves
(Metal)

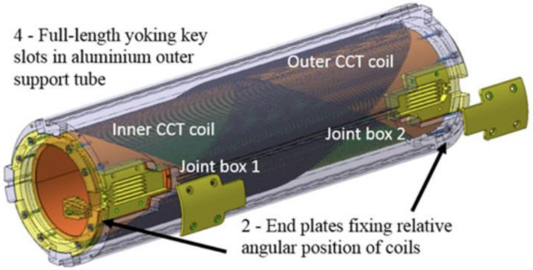
S. Caspi, IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 25, NO. 3, JUNE 2015

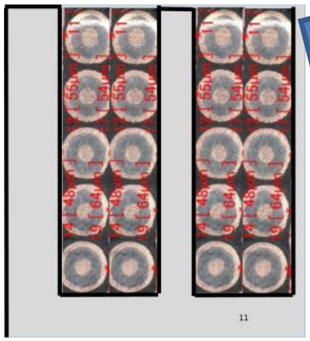
- Cable:
  - High current
  - less layers and mandrels
  - Easy to fabricate mandrels, wind and assembly
- Conductor:
  - Low current
  - more layers and mandrels
  - Difficult to fabricate mandrels, wind and assembly

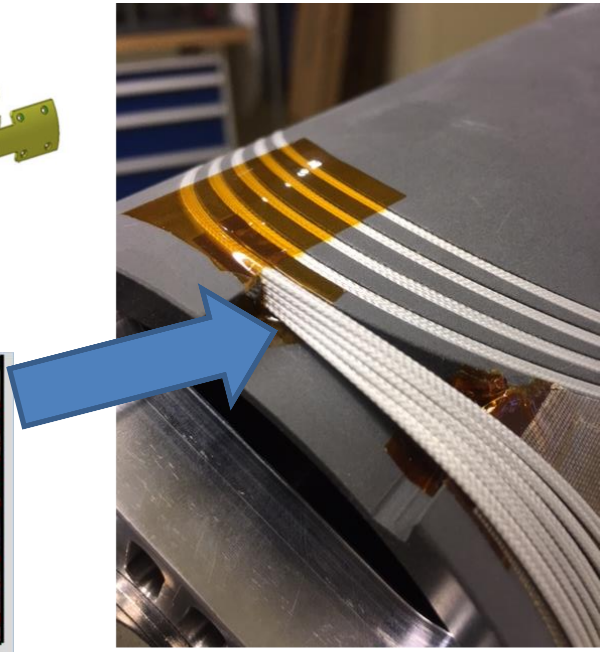
(III) Coil placement in grooves



Wiring diagram





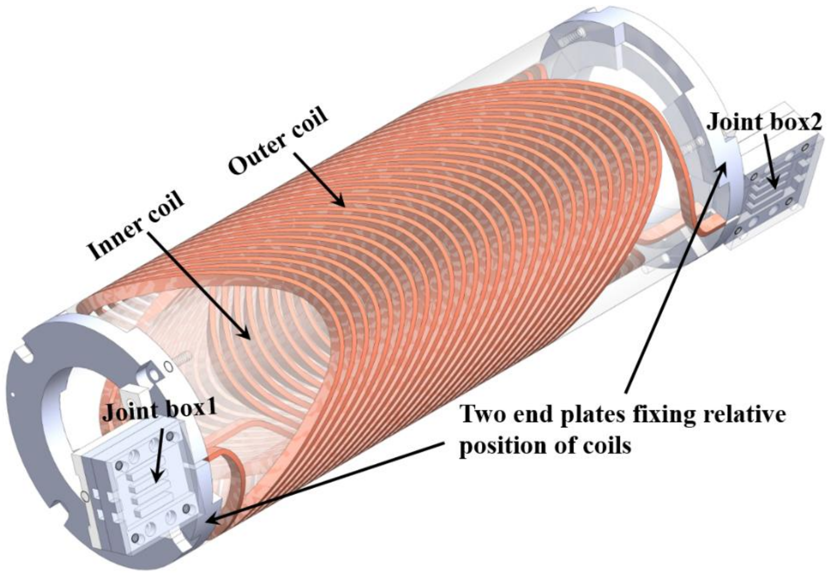


D2 CCT Corrector for High Luminosity LHC

- Wind several turns of conductor into one big grooves;
- Remain low operation current while reduce the number of mandrels;
- Need more splices between coils of two mandrels.

G. A. Kirby et al., "Hi-Lumi LHC Twin-Aperture Orbit Correctors Magnet System Optimisation," in IEEE Transactions on Applied Superconductivity, vol. 27, no. 4, pp. 1-5, June 2017.

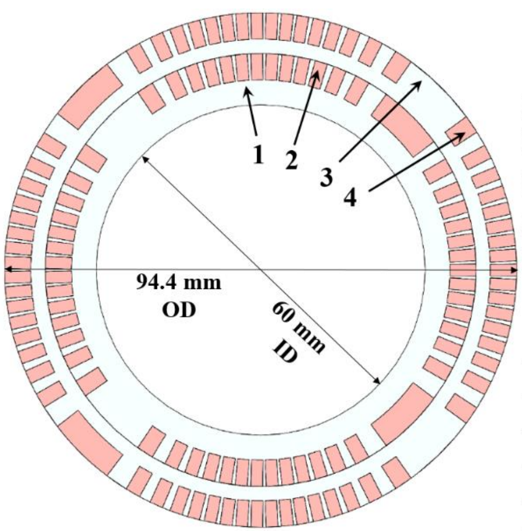
Subscale prototype - design

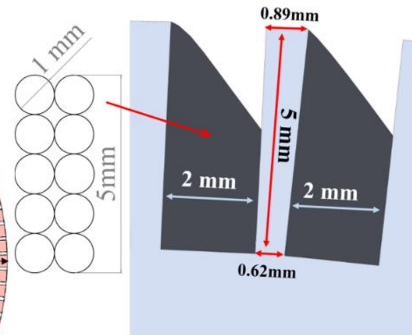


The CCT quadrupole magnet assembly

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	





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

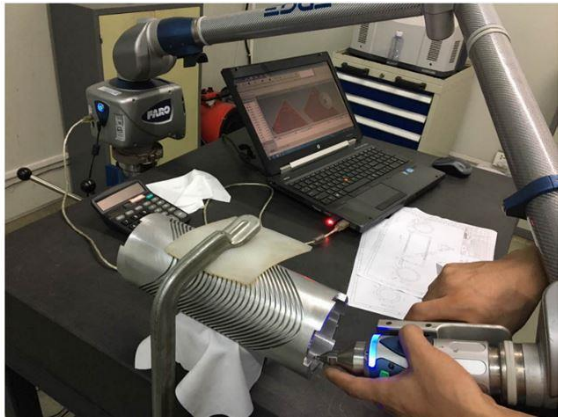
Cross section of the CCT quadrupole coil

Parameters of the NbTi/Cu strand

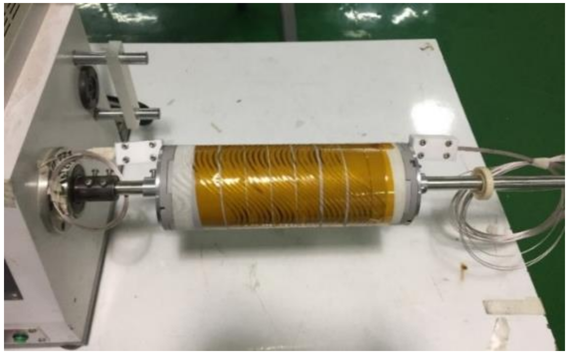
Wire type	**Monolith**
Insulation	Formvar
Bare size	0.72 mm
Insulated size	0.77 mm
Outer Insulated with Nylon braid	0.9±0.005 mm
Cu/SC	1.3:1
RRR (293 K/10 K)	＞100
Ic (6 T,4.2 K)	442.7 A

Subscale prototype - fabrication

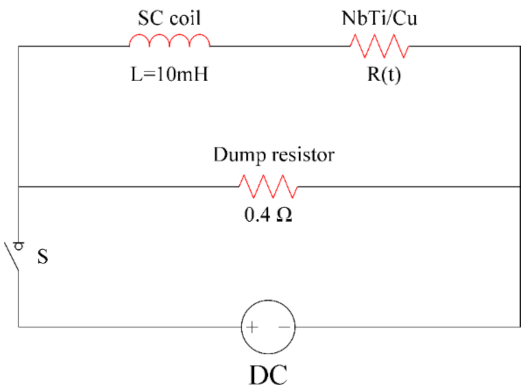
Former Fabrication

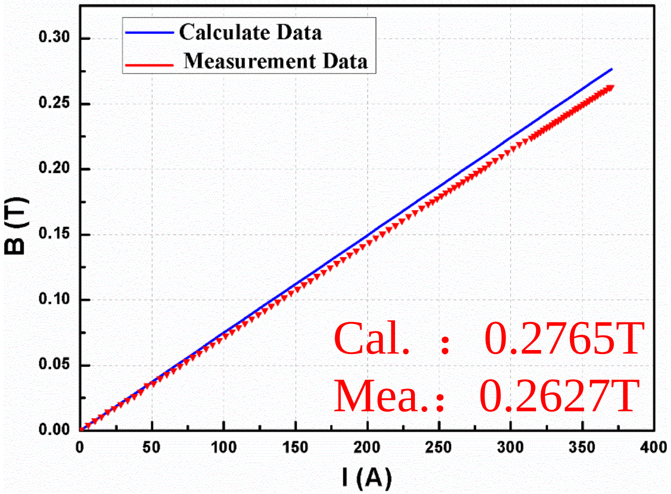
Coil Winding and Impregnation

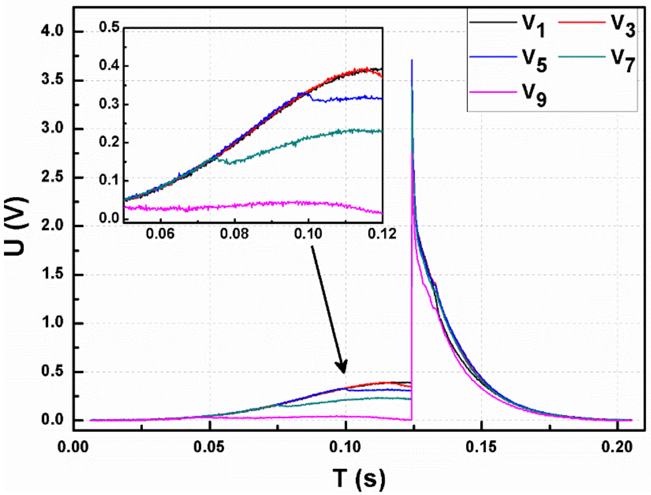

Subscale prototype - cryogenic test



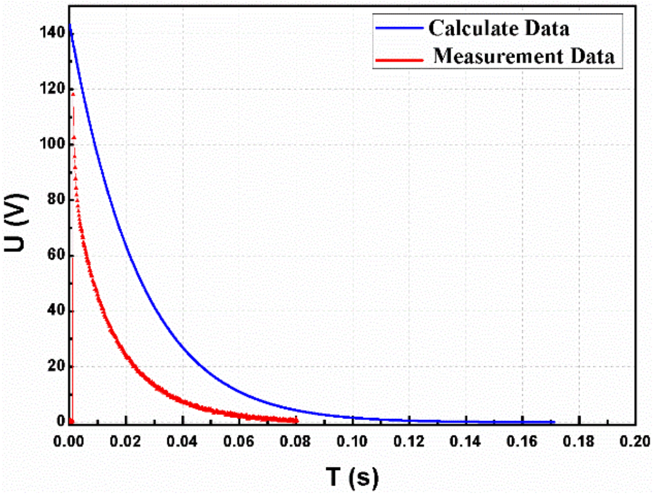
Magnet Test



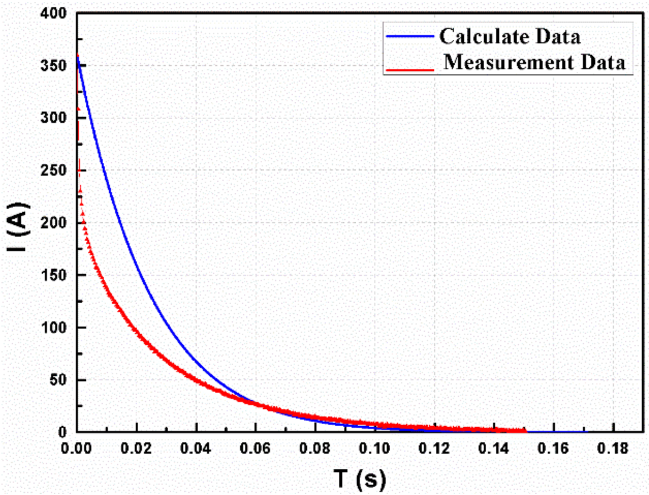
Excitation curve



Coils voltage change

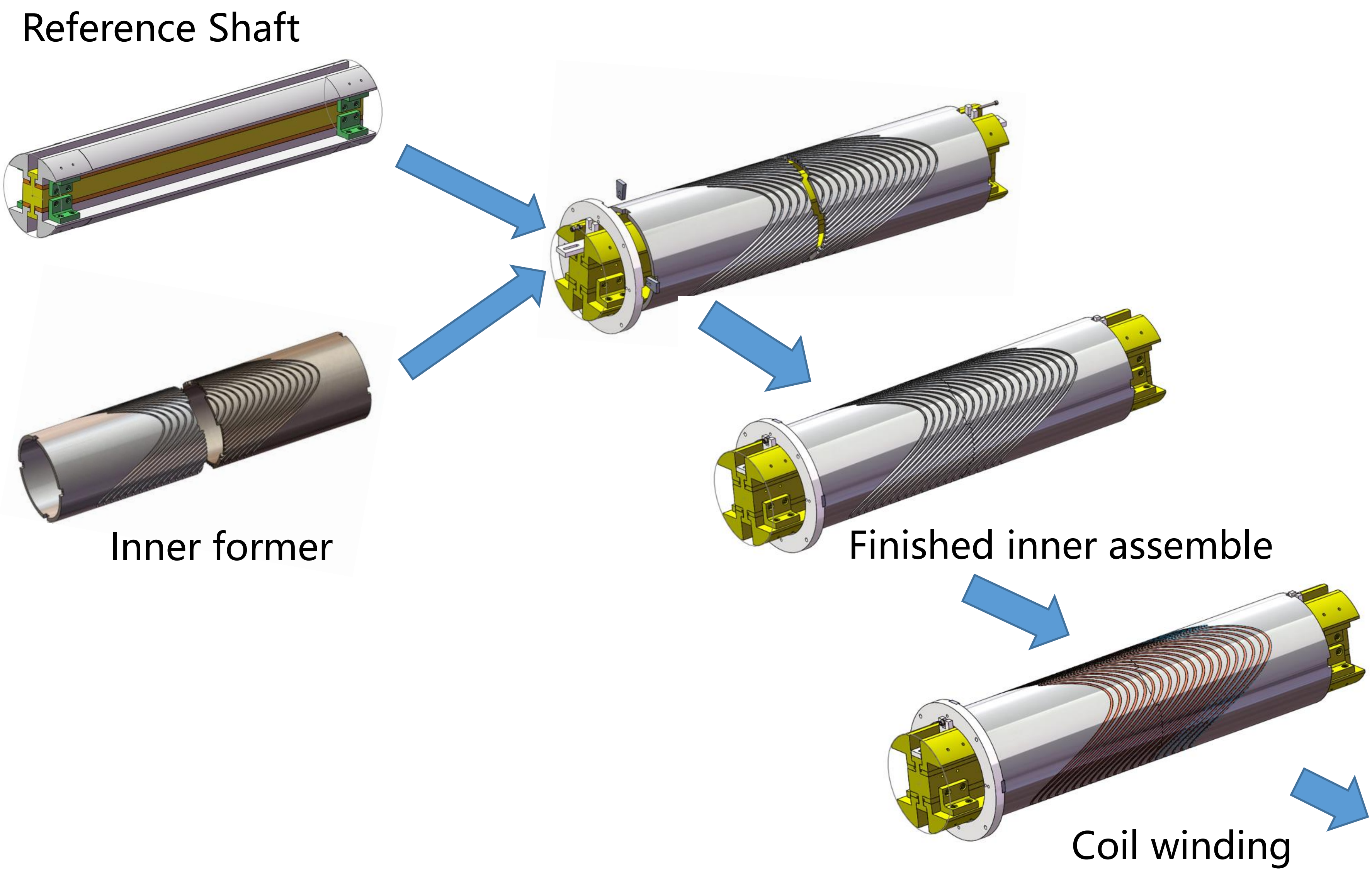


Voltage decay curve

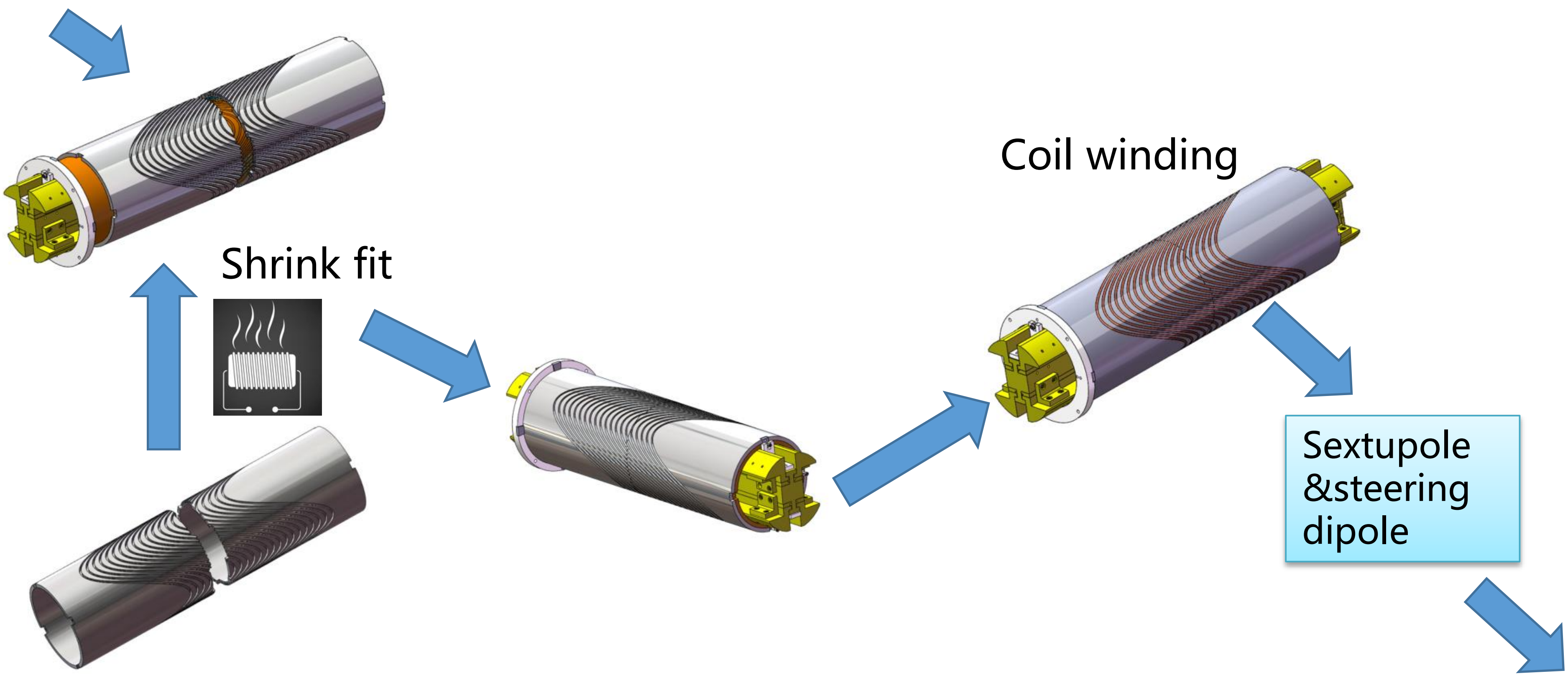


Current decay curve

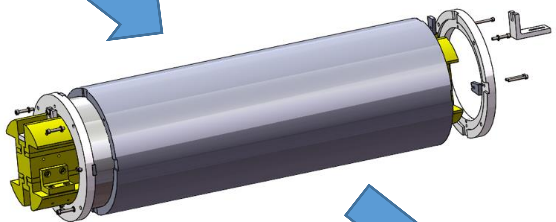
Assembly Sequence of singlet



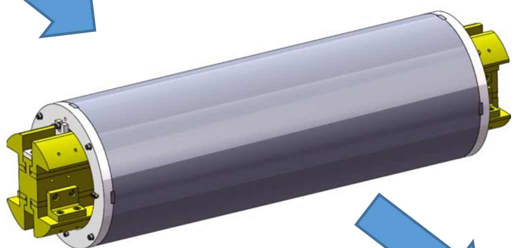
Assembly Sequence of singlet



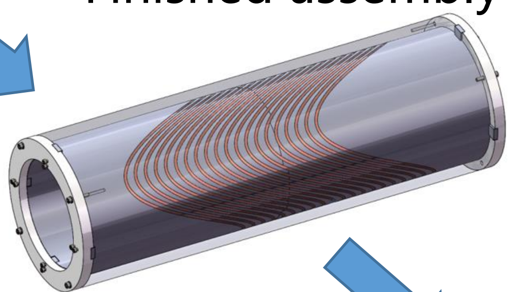
Assembly Sequence of singlet



Shrink fit of aluminum support tube

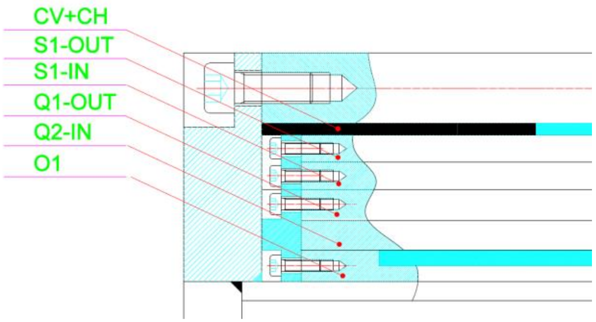


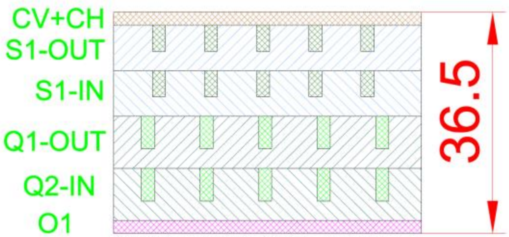
Finished assembly

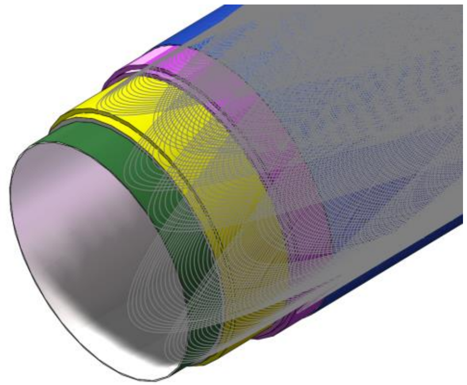


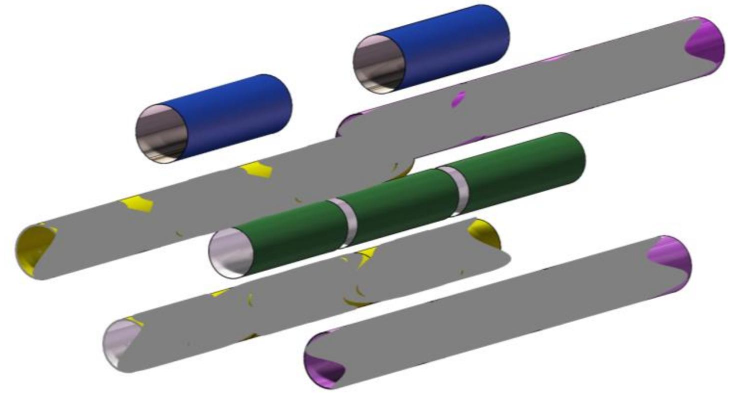
VPI & Instrumentation

Mechanical design of a triplet

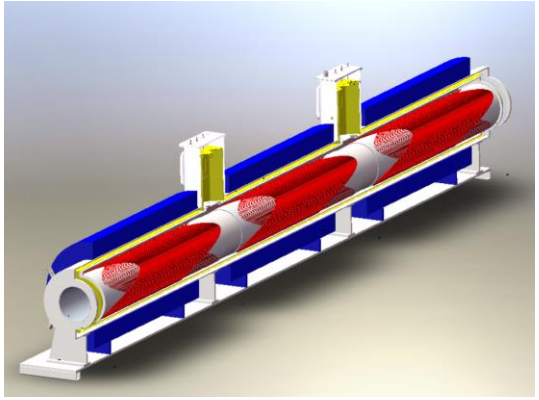


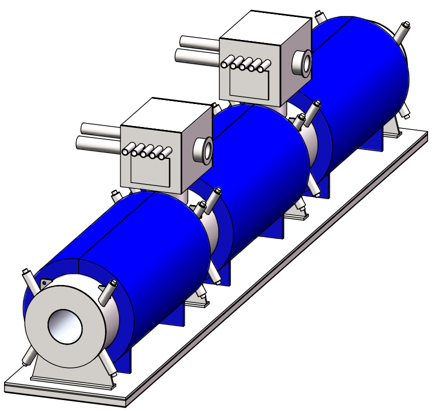






Cross section of the nested multipole coils



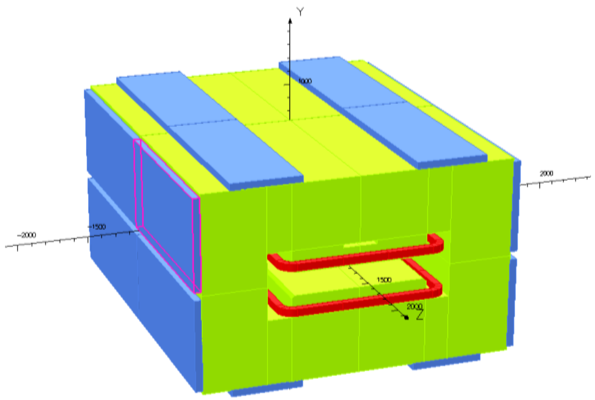


Cryostat design

Outline

- ❖ Overview of the SC magnets in HIAF project
- ❖ Superconducting solenoids for ILinac
- ❖ Superconducting multiplets for HFRS
- ❖ **Superconducting dipoles for HFRS**
- ❖ Design study for BRing RCS superconducting dipole

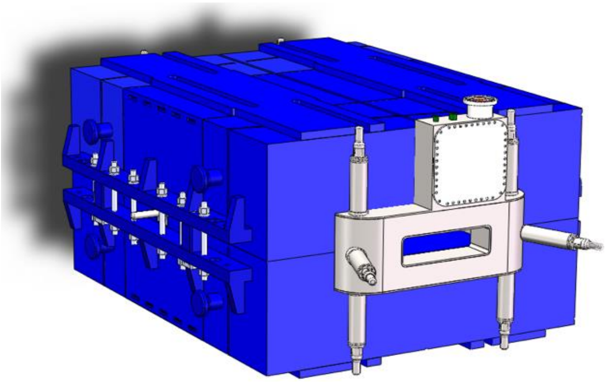
SC dipoles for HFRS – Superferric design



Opera model

Super-FRS dipole prototype

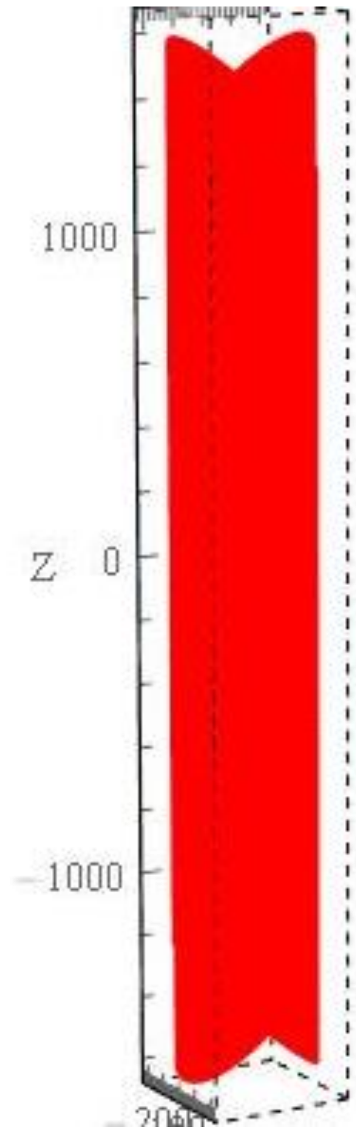
Effective length	2.74 m
Gap	160 mm
Central field	1.6 T
Operation current	300 A
Inductance	15 H
Weight of Iron	**50 t**
Cooling method	LHe bath cooling
Operation temperature	4.2 K



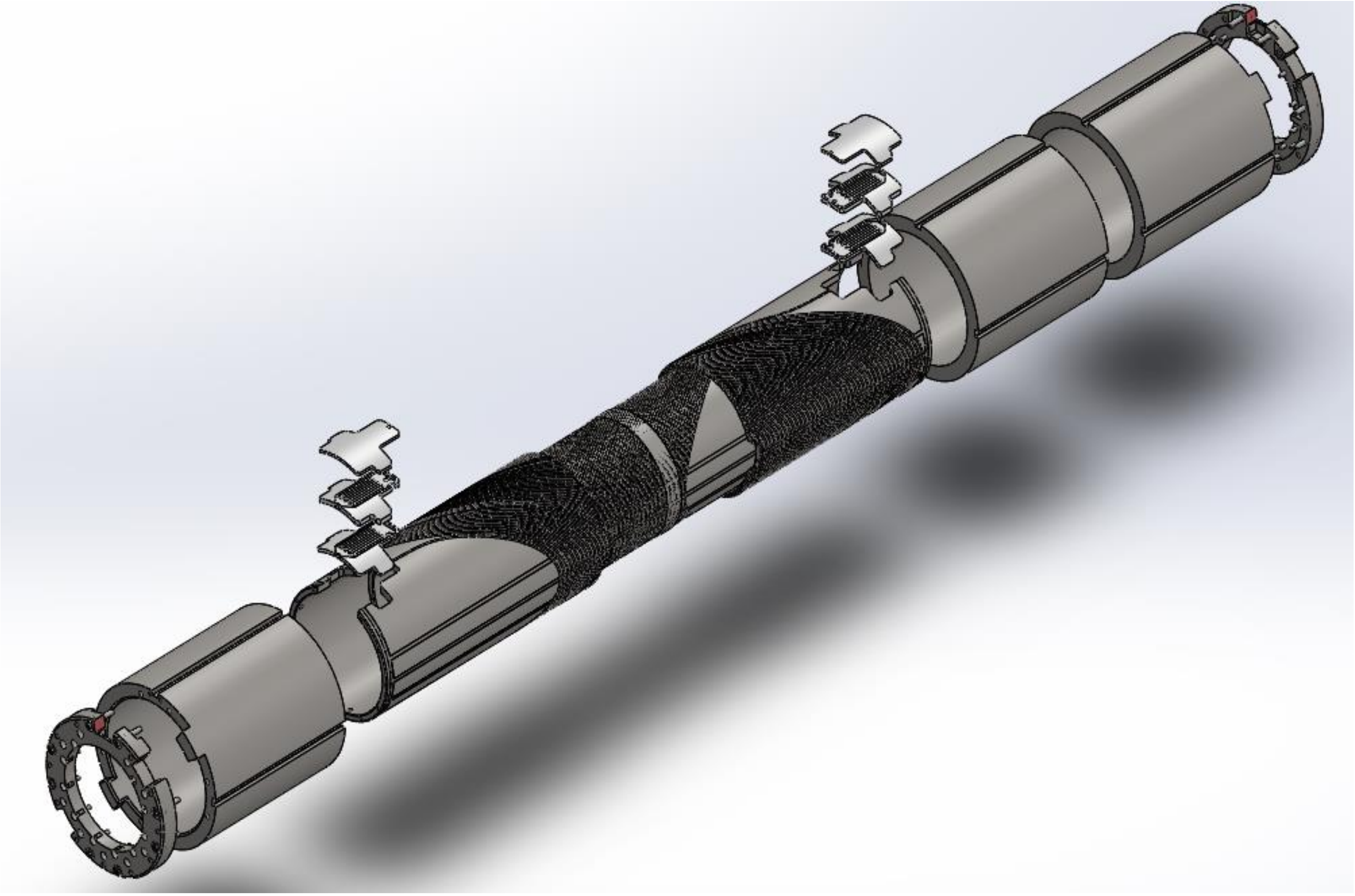
Superferric design of HFRS dipole

SC dipoles for HFRS – CCT design

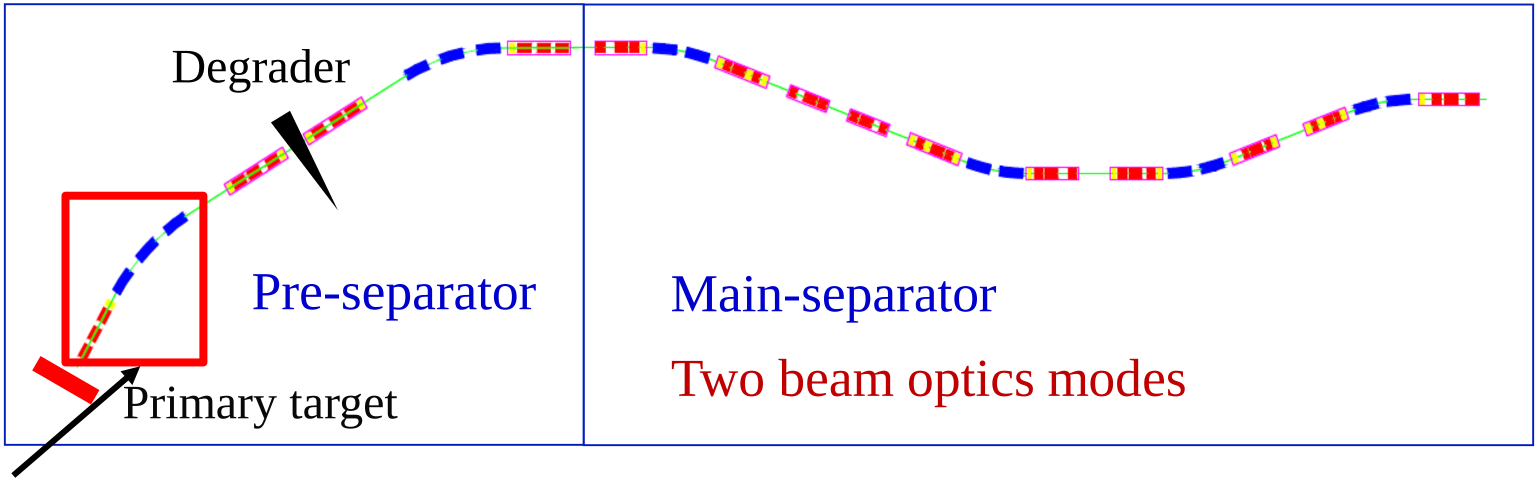
Central Field (T)	1.6
Current(A)	500
Layers	2 (5+5)
CCT angle	36 °
Turns per layer	1030
Pitch(mm)	2.7
Aperture(mm)	320×140
Wire Diameter (mm)	0.85 0.99±0.01
Insulation meterial	Kapton
Cu/SC	2.0
Bpeak(T)	2.5
SSL	64%
Conductor length(km)	23.5
ID of mandrel(mm)	420
Coil groove size	2 mm x 5 mm



Mechanical design of the Cold mass

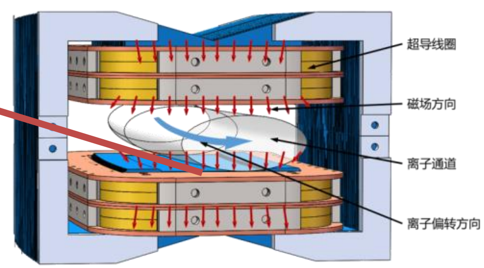


HTS Radiation Resistant Magnets for HFRS

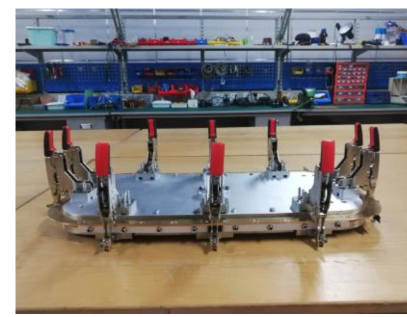


Higher Operation Temperature → **YBCO coil**

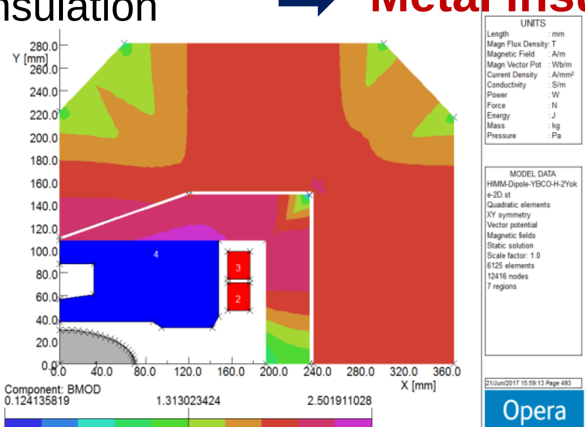
No organic insulation → **Metal insulation!**



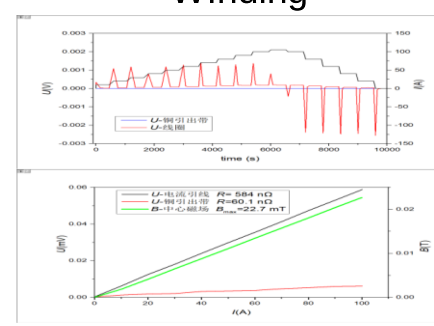
Design (Coil & Cold iron)



WInding



EM Design (20K pole & 60K yoke)



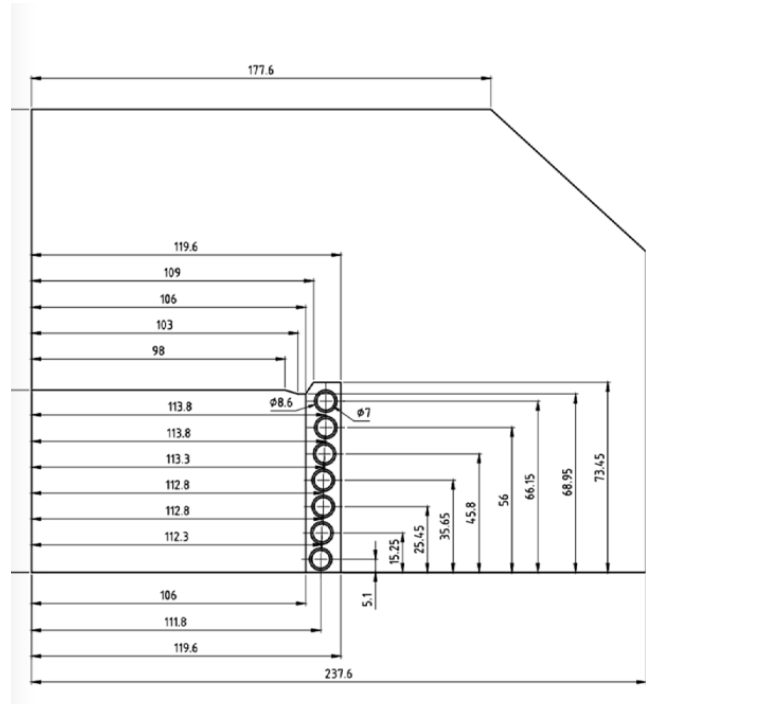
Testing (LN2)

Outline

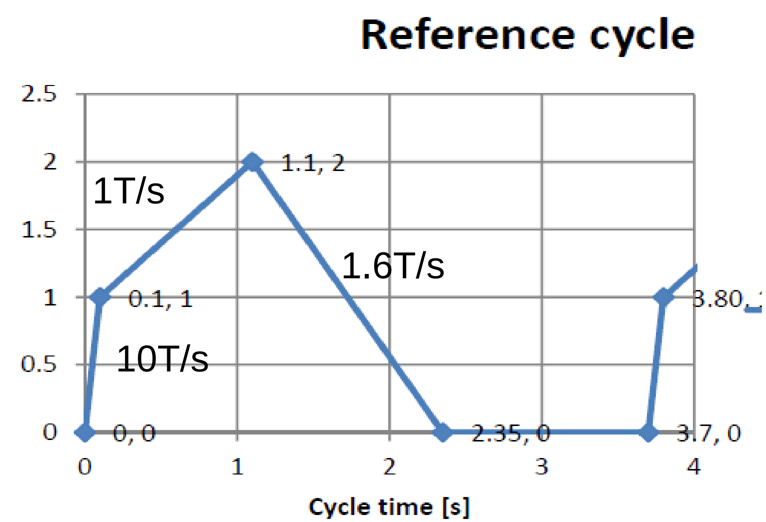
- ❖ Overview of the SC magnets in HIAF project
- ❖ Superconducting solenoids for ILinac
- ❖ Superconducting multiplets for HFRS
- ❖ Superconducting dipoles for HFRS
- ❖ **Design study for BRing RCS superconducting dipole**

SC dipole for BRing

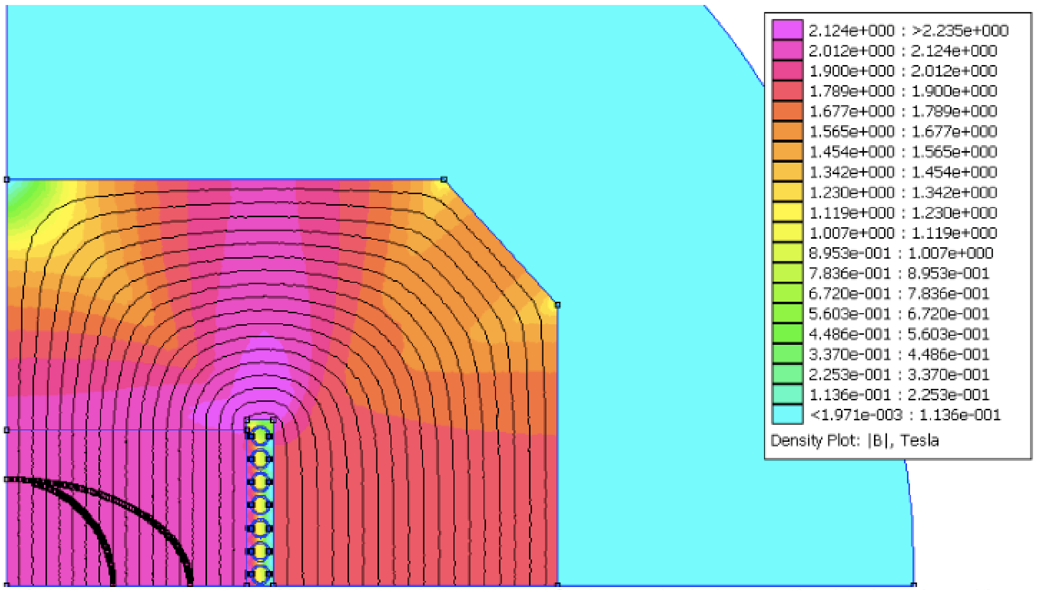
- Baseline: resistive magnets;
- SC magnets: lower energy consumption, large cryogenic pump;
- Nuclotron type cable, helium force flow cooling;
- Superferric, window frame cold iron yoke, single layer to simplify fabrication, coil is supported by GFRP.



Parameter	Value
Number of magnets	48
Maximum field (T)	2
Minimum field (T)	0.04
Bend radius (m)	17
Good field region (mm×mm)	162×94
Field quality	$\pm 1\times 10^{-4}$
Effective magnetic length (m)	2.225
Maximum ramp rate (T/s)	10



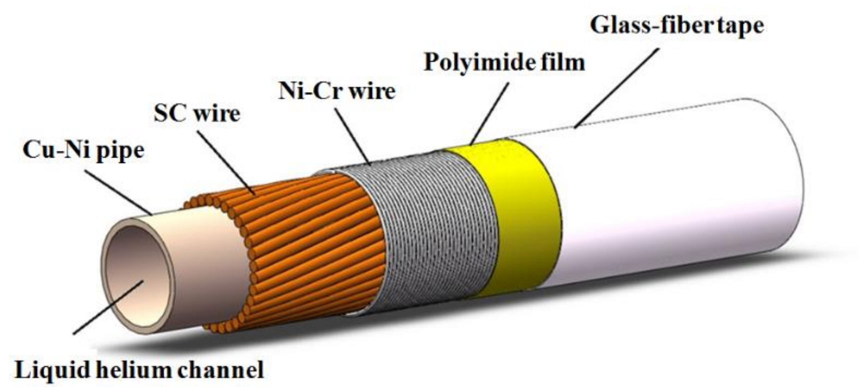
Fast cycling superconducting magnets



237.6 mm

- Cu-Ni pipe: inner dia 6 mm with thickness 0.5 mm
- NbTi superconducting wire: diameter 0.8 mm
- 33 strands in cable
- One layer 14 turns saddle coil
- Operating temperature: 4.7 K
- Loadline margin: 20%

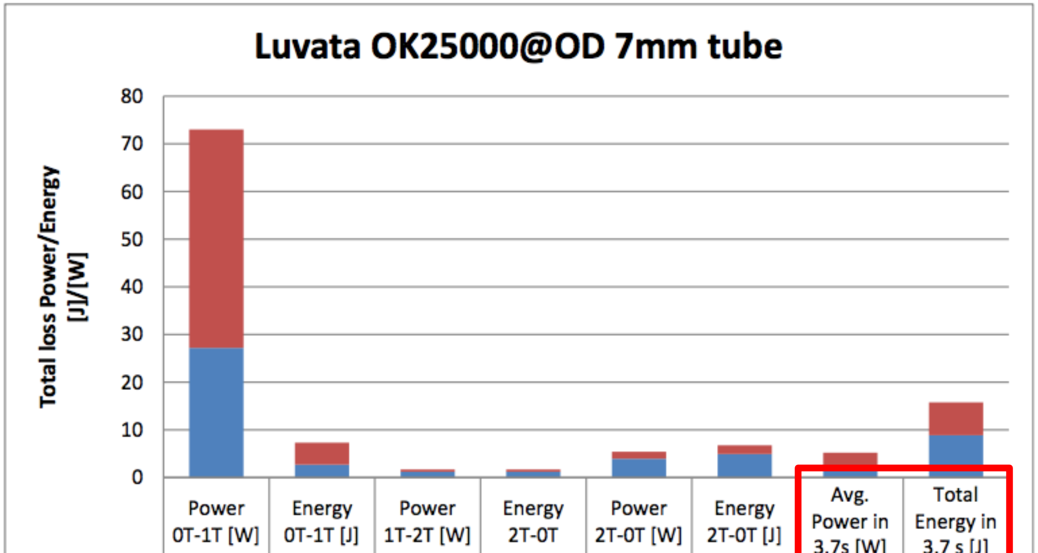
- Emag=101.5 kJ
- Emag of the whole ring ~ 5 MJ (SIS100 ~ 4.5 MJ)
- Iop=17kA
- L = 0.774 mH
- U(@10T/s) = 62 V



Fast cycling superconducting magnets

Length specific coil losses for Luvata OK2500 cable

Luvata OK25000@OD7mm tube								
Ramp	0 to 1 T @ 10 T/s		1 T to 2 T in @ 1T/s		2T to 0 T @ 1.6 T/s		Cycle average over 3.7s	
Per Length	Power [W/m]	Energy [J/m]	Power [W/m]	Energy [J/m]	Power [W/m]	Energy [J/m]	Power [W/m]	Energy [J/m]
Hysteresis	0.405	0.040	0.018	0.018	0.059	0.074	0.036	0.132
Coupling	0.682	0.068	0.007	0.007	0.022	0.027	0.042	0.102
Total	1.086	0.109	0.025	0.025	0.081	0.101	0.077	0.235



	Power 0T-1T [W]	Energy 0T-1T [J]	Power 1T-2T [W]	Energy 2T-0T	Power 2T-0T [W]	Energy 2T-0T [J]	Avg. Power in 3.7s [W]	Total Energy in 3.7 s [J]
Total	73.0	7.3	1.7	1.7	5.4	6.8	5.2	15.8
Coupling	45.8	4.6	0.5	0.5	1.5	1.8	2.8	6.9
Hysteresis	27.2	2.7	1.2	1.2	4.0	4.9	2.4	8.9

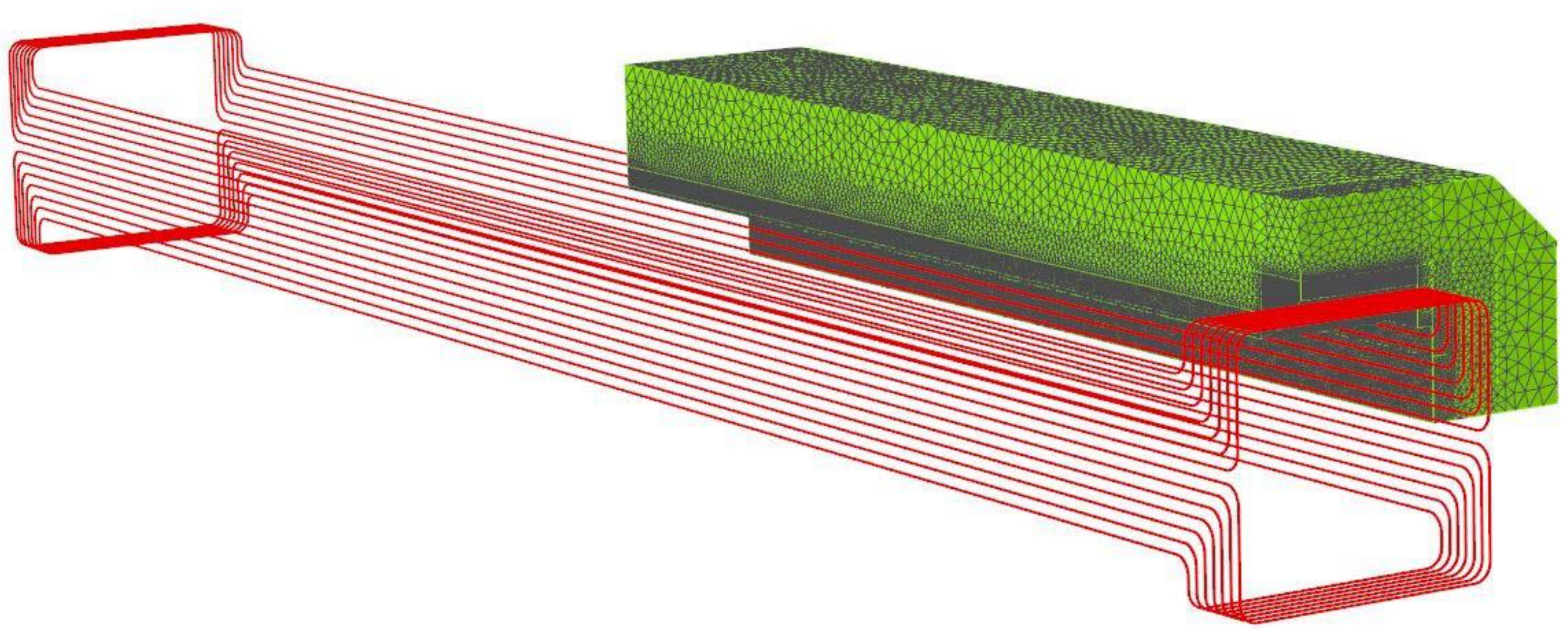
Total losses for 14 turns coil length (without bus bars) of 67.2 m

Fast cycling superconducting magnets

- Channel diameter: 6 mm for an OD 7mm tube
- Channel length: 67 m coil + 40 m bus bar = 107 m
- Critical helium

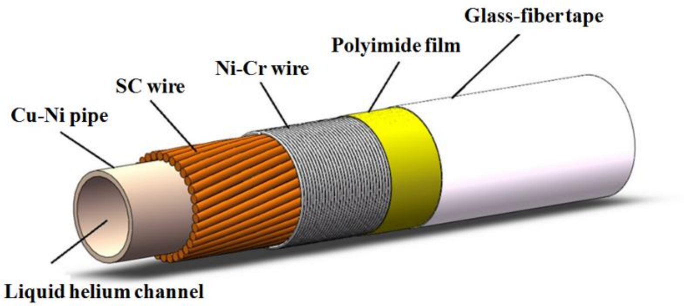
Reference cable	Luvata OK25000 @ OD7mm tube
Average heat load $\boldsymbol{Q}$	15.8 J
Channel diameter ID	6 mm
Inlet pressure $\boldsymbol{p}_0$ [bar]	1.50 bar
Inlet temperature $\boldsymbol{T}_0$	4.68 K
Pressure drop $\Delta \boldsymbol{p}$	0.17 bar
Mass flow d$\boldsymbol{m}$/d$\boldsymbol{t}$	3.5 g/s
Hom. flow velocity in $\boldsymbol{u}_0$	1.1 m/s
Outlet pressure $\boldsymbol{p}_{out}$	1.33 bar
Outlet temperature $\boldsymbol{T}_{out}$	4.53 K
Steam quality outlet $\boldsymbol{x}_{out}$	0.31
Void fraction outlet ε_{out}	0.70
Hom. flow velocity out $\boldsymbol{u}_{out}$	2.4 m/s

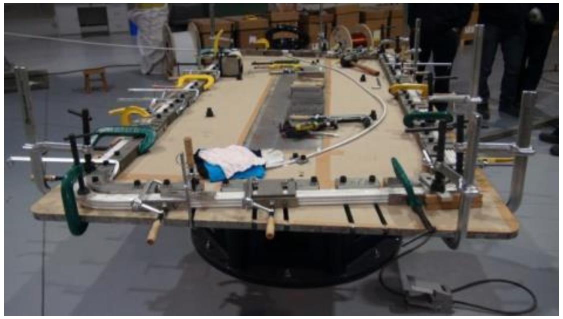
Fast cycling superconducting magnets



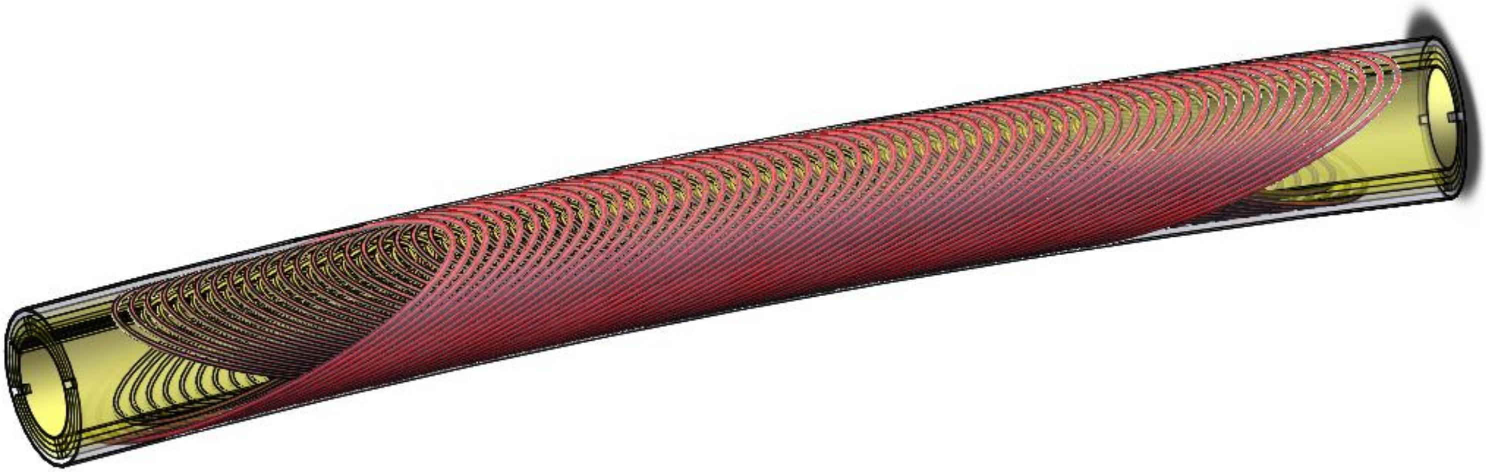
3D EM model of the BRing dipole SC alternative

Fast cycling superconducting magnets





Nuclotron type cable developed in IMP



CCT dipole based on Nuclotron cable

Thanks a lot for your attention!