Introduction of the superconducting magnets for HIAF project

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Summary

HIAF

- ❖ Overview of the SC magnets in HIAF project
- ❖ 45GHz ECR ion source
- ❖ Superconducting solenoids for iLinac
- ❖ Superconducting magnets for HFRS

Summary

❖ Overview of the SC magnets in HIAF project

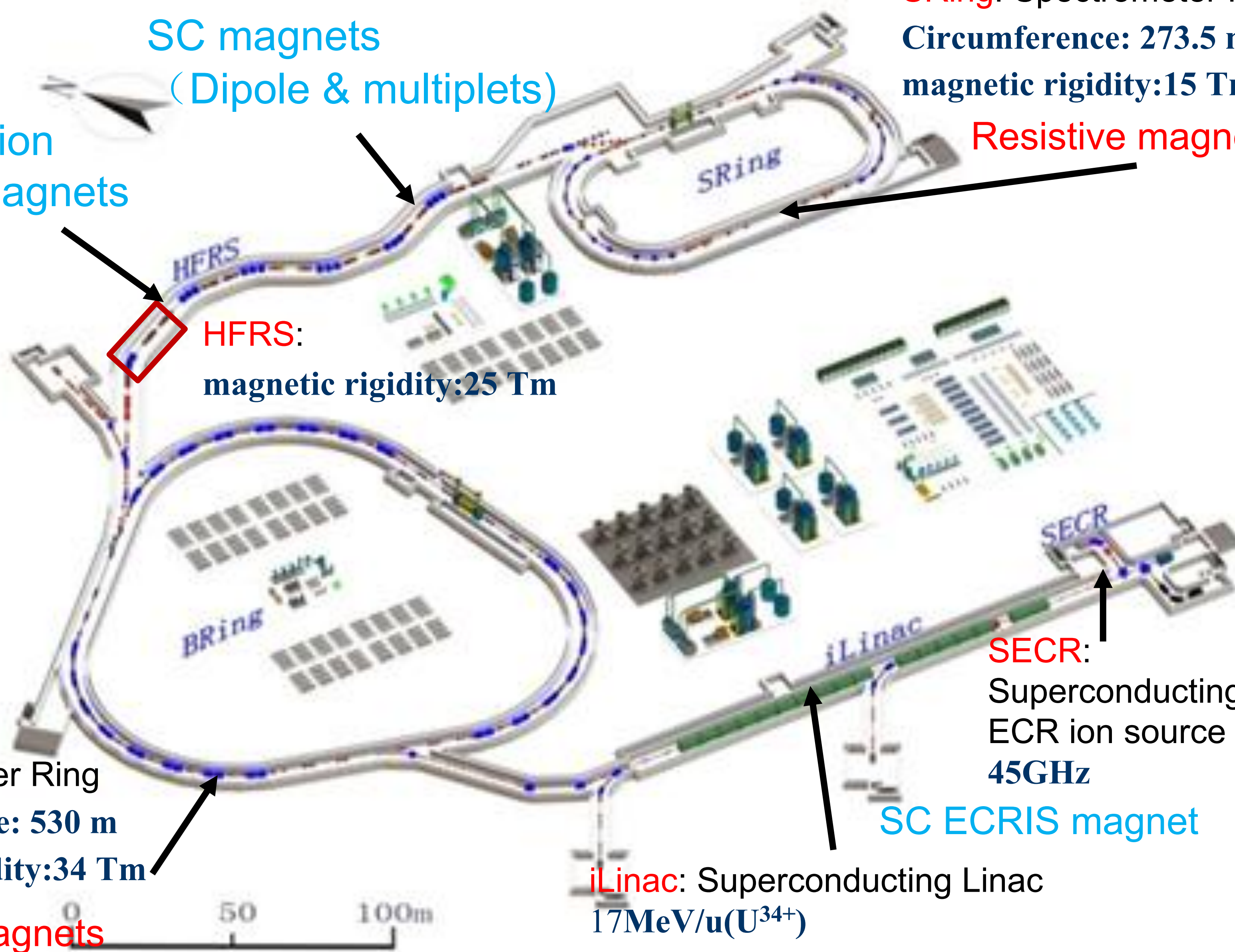
❖ 45GHz ECR ion source

❖ Superconducting solenoids for iLinac

❖ Superconducting magnets for HFRS

Existing accelerators in Lanzhou

High-Intensity Heavy Ion Accelerator Facility HIAF



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

SC ECRIS magnet

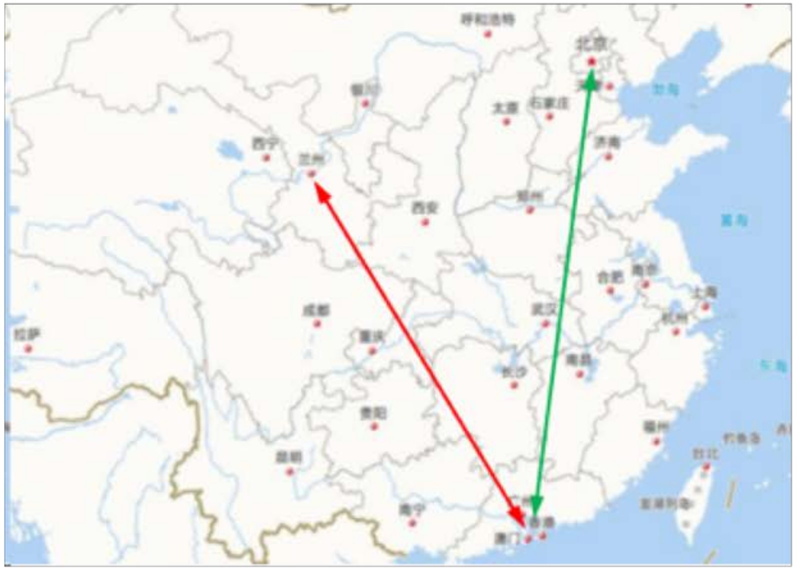
BRing: Booster Ring
Circumference: 530 m
magnetic rigidity:34 Tm

Resistive magnets

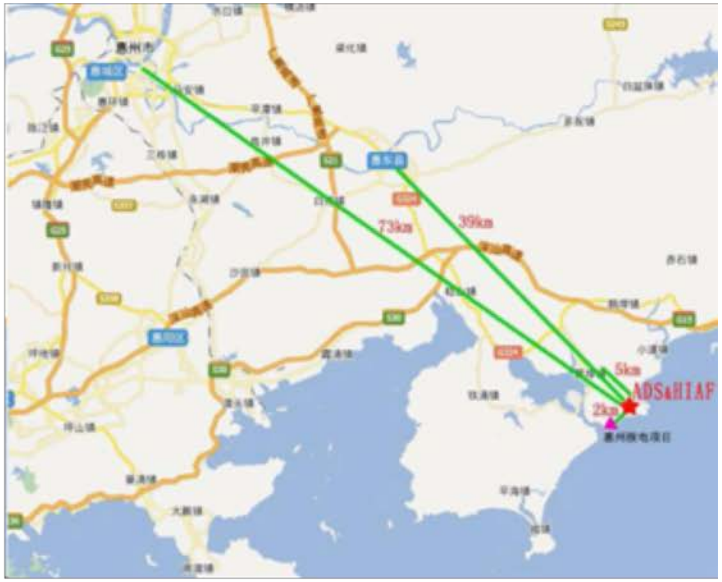
iLinac: Superconducting Linac
17MeV/u(U^{34+})

SC focusing solenoids

Location



Huizhou, Guangdong



~70 km from downtown

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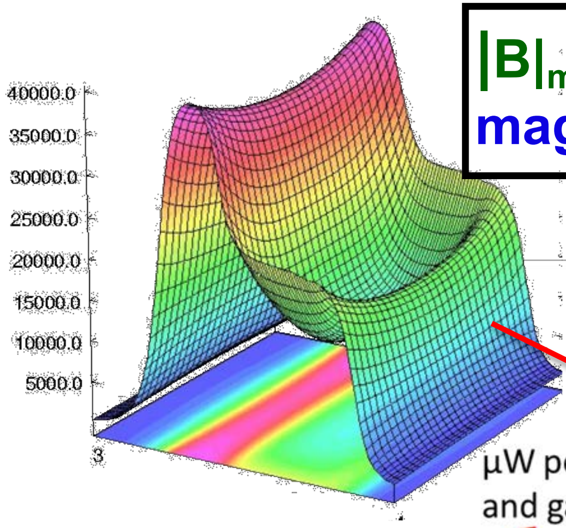
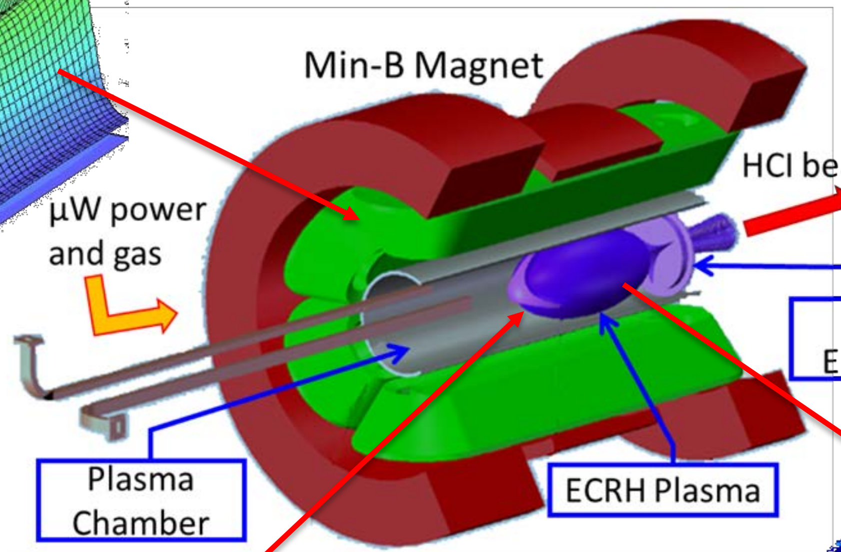
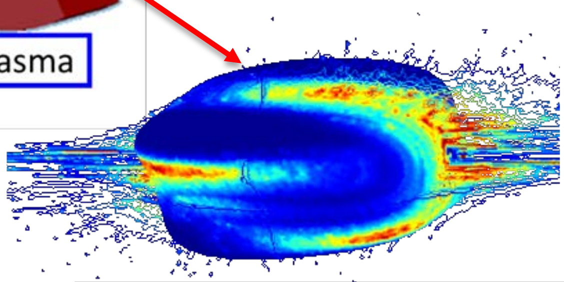
$|B|_{min}$ configuration magnetic confinement







Stochastic heating of electrons through ECRH

$$\omega_{ecr} = \frac{eB_{ecr}}{m_e}$$

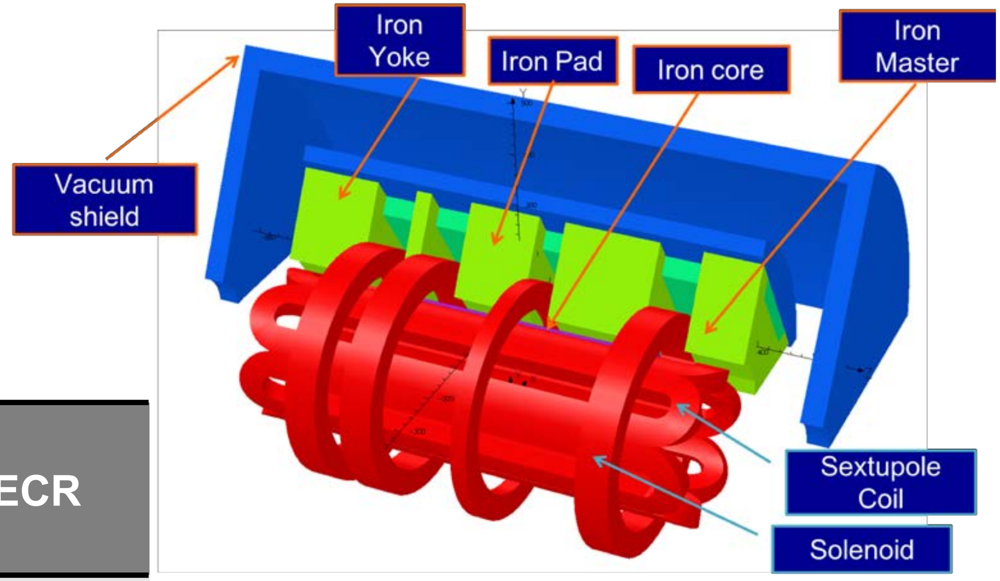
Dense hot plasma and HCIs production

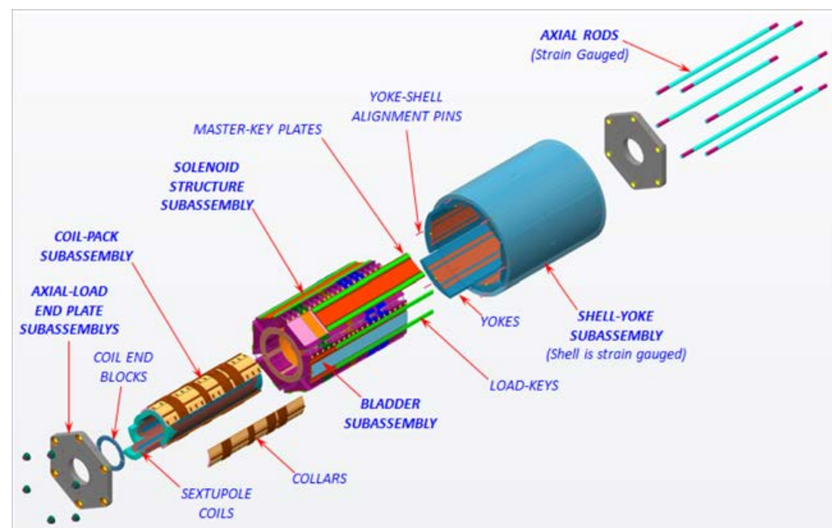
45GHz ECR ion source

- 4th Generation 45GHz ECRIS；
- Sextupole + solenoids；
- Peak field 12 Tesla
- Nb_3Sn conductor

Wire: OST M-Grade Nb3Sn Ø1.3 mm with 0.13 mm S-glass

Specs.	Unit	State of the art ECRIS	FECR
frequency	GHz	24-28	45
B_{ECR}	T	0.86~1.0	1.6
B_{rad}	T	1.8~2.2	≥3.2
B_{inj}	T	3.4~4.0	≥6.4
B_{min}	T	0.5~0.7	0.5~1.1
B_{ext}	T	1.8~2.2	≥3.4
Warmbore ID	mm	120~170	≥160
Mirror Length	mm	420~500	~500
Cooling Capacity@4.2 K	W	0~6.0	≥10.0

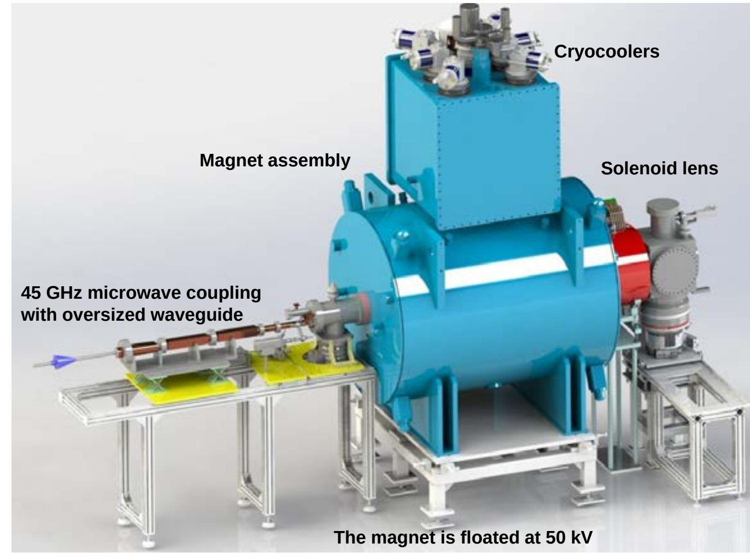




Engineer design by LBNL

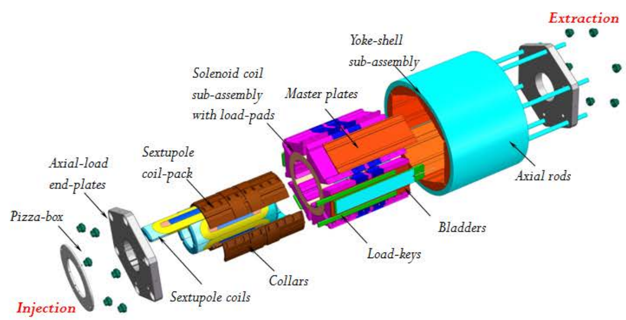
45GHz ECR ion source

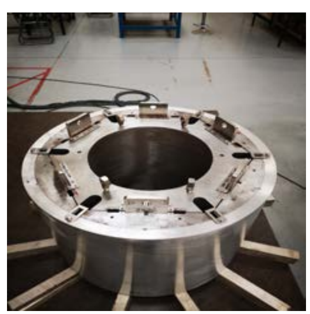
- **Nb$_3$Sn coils with single strand**;
- Wind & React tech of sextupole coils;
- Bladder & Key assembly;
- **Challenging quench protection.**



Sextupole Coil Prototyping

Solenoid Prototyping





Half length prototype

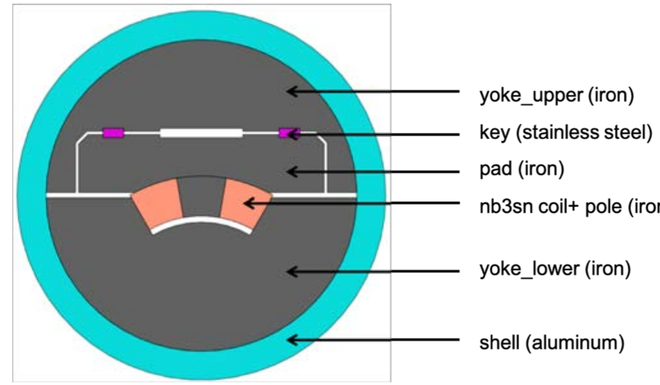
Glass fibre
insulation broken:
- Winding tension
- Final formation by compress

#0 sextupole coil

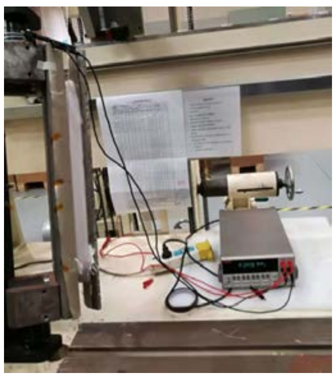
45GHz ECR ion source

1 Half length sextupole coil fabrication and mirror test

Thicker insulation:
0.13 mm S-glass -> 0.26 mm S-glass
Lower filling factor:
70% -> 58.8%

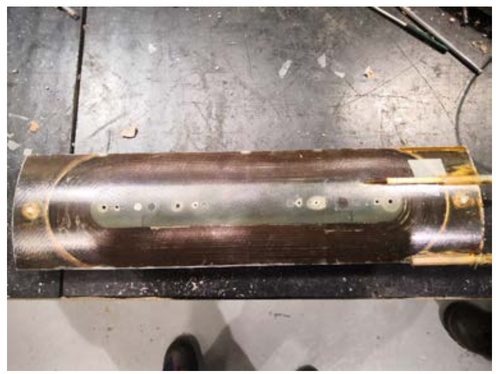


Mirror structure

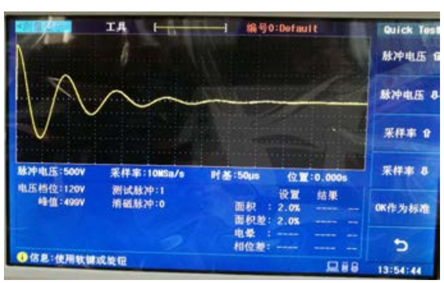


Winding

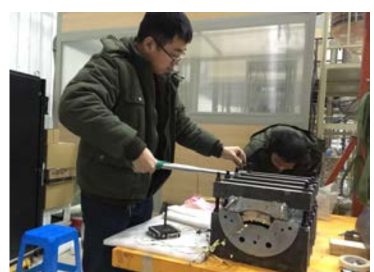
Reaction



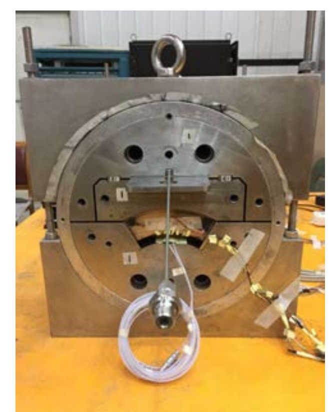
Impregnation



Discharge test



shimming



Bladder & Key preload

Plan

02 / 2019: #1 coil test

03 / 2019: #2 coil fabrication

04 / 2019: #3 & #4 coil fabrication

05 / 2019: #5 & #6 coil fabrication, start to wind full scale sextupole coil

06 / 2019: Assembly of half length prototype

07 / 2019 ~ 08 / 2019: Testing of half length prototype

10 / 2019 ~ 11 / 2019: Assembly of full scale magnet

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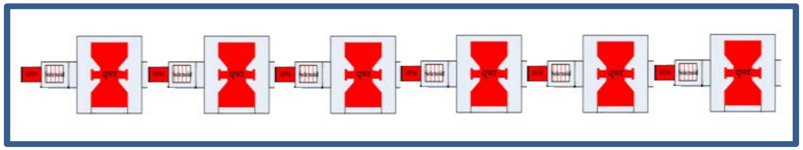
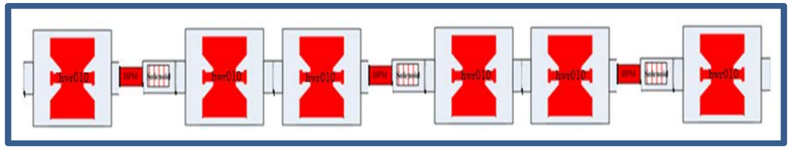
iLinac SC solenoid - Specifications

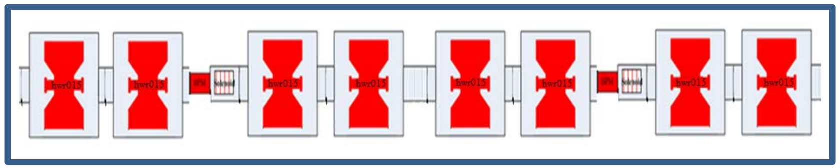
QWR segment



HWR010 segment



HWR015 segment



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

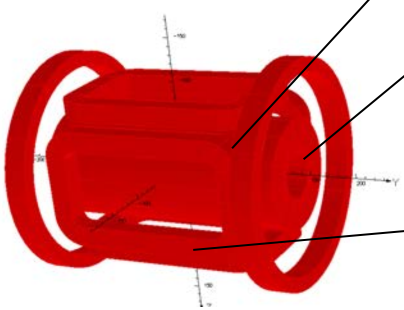
Specifications of L400 solenoid

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

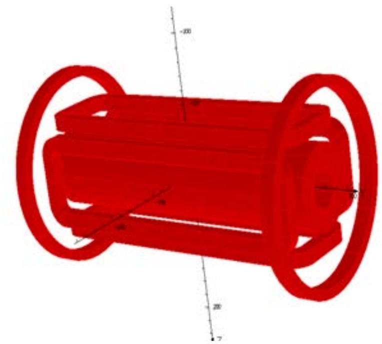
Leff = 400 mm

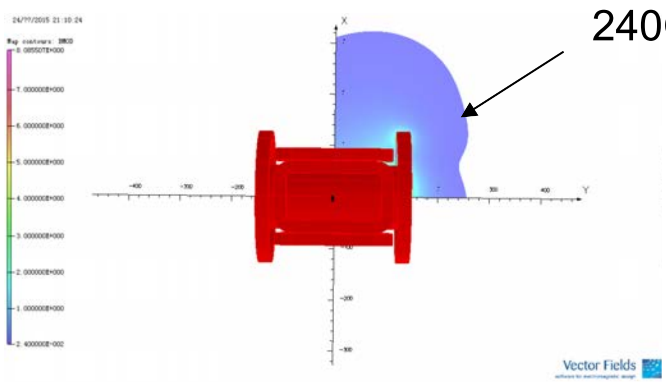


Main coil

Bucking coil

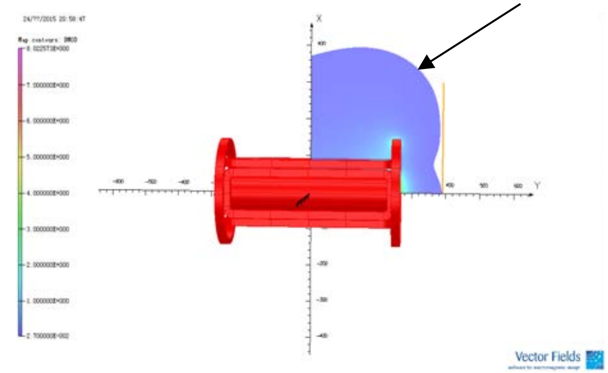
Steering dipole





240Gs

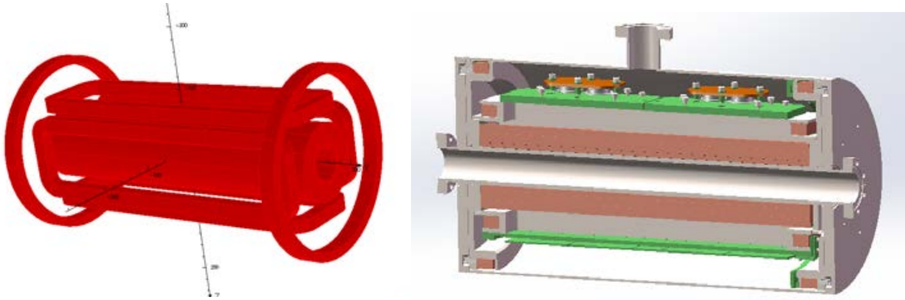
270Gs



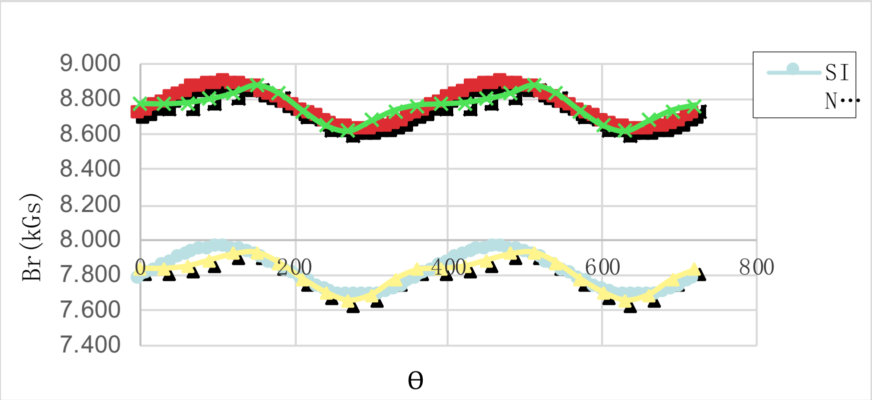
iLinac SC solenoid – experiences

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

Solenoids for ADS



Solenoids for FRIB



Measurement of magnetic center

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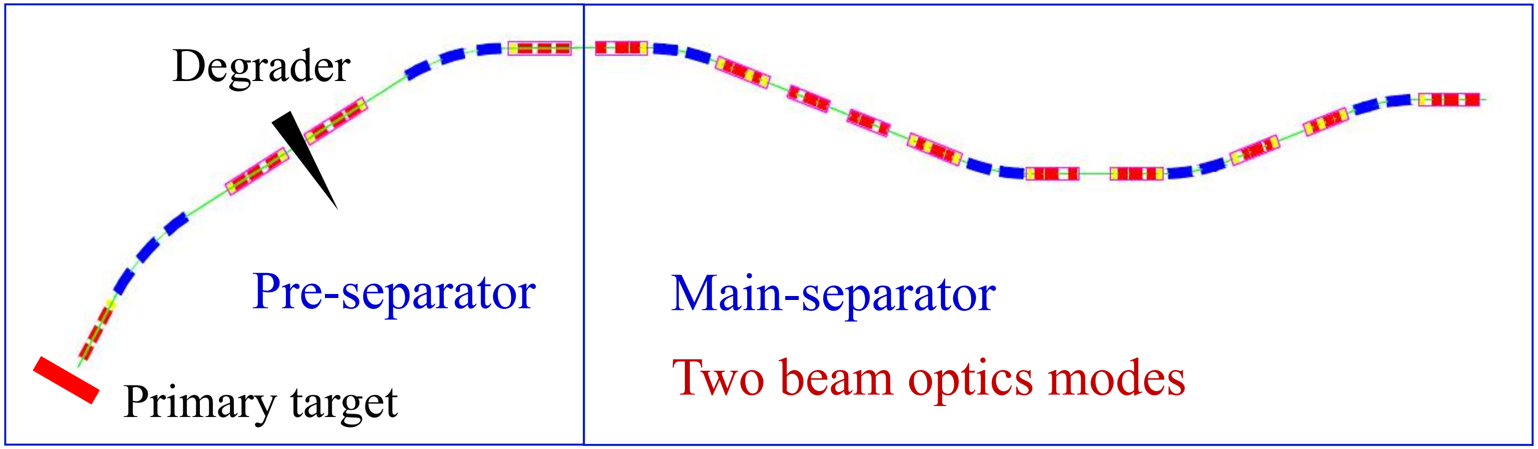
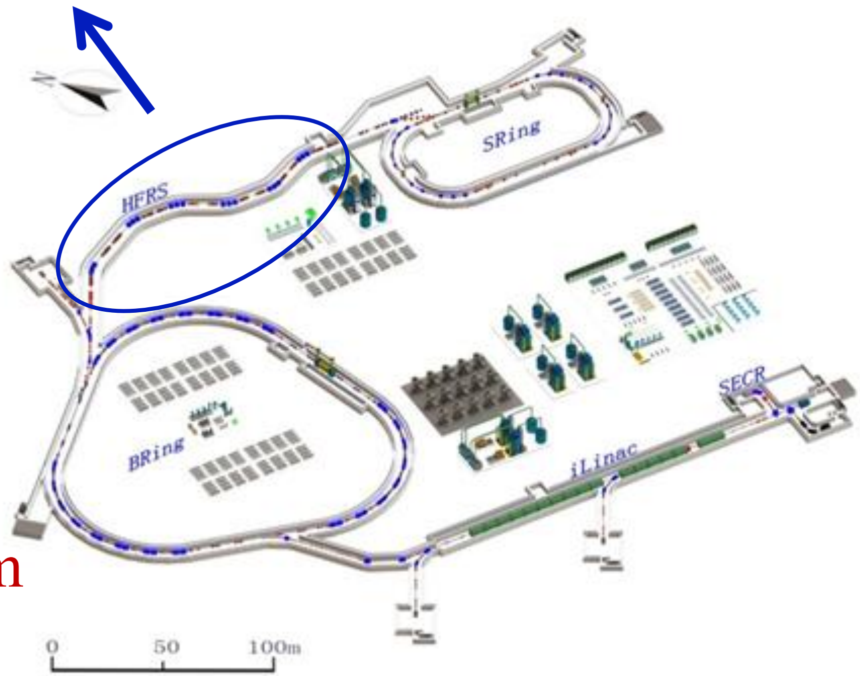
Introduction of HFRS



- 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

- Bρ = 25 Tm
- Large bore；
- Pole-tip fields: 2.4T；
- Low current： < 600 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	±160
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
Vertical gap	mm	±85
Field Quality		$\pm 5\times 10^{-3}$

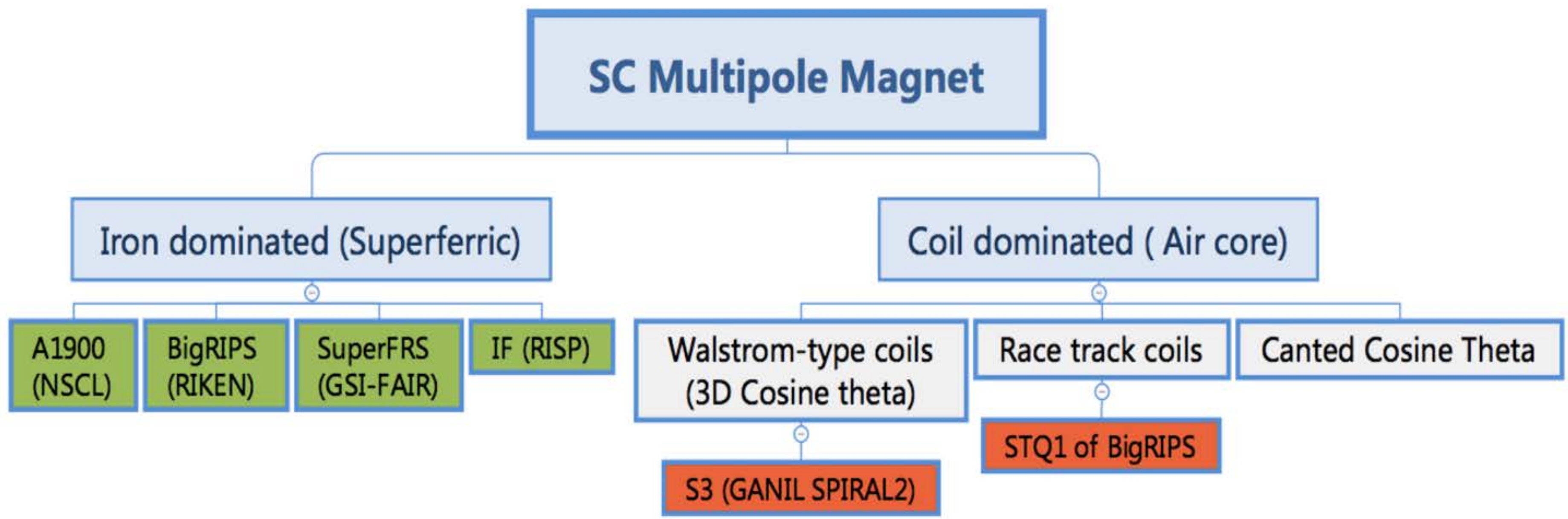
Specifications of **Octupoles**

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

Specifications of **Steering dipoles**

Field	T	0.2
Effective length	m	0.5
Horizontal aperture	mm	±160
Vertical gap	mm	±85
Field Quality		$\pm 5\times 10^{-3}$

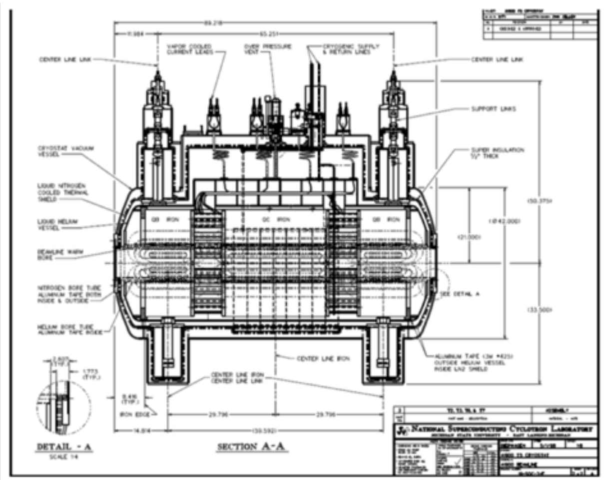
Comparison of similar projects

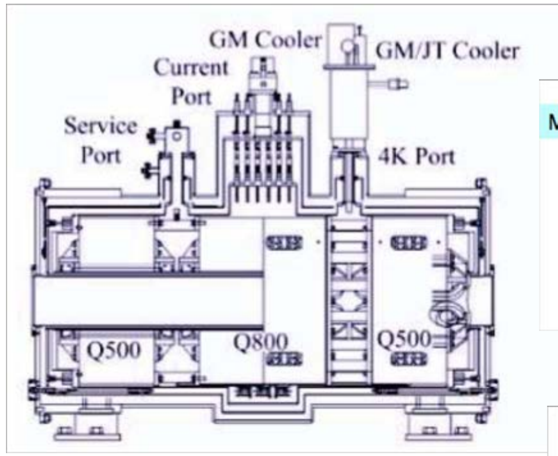


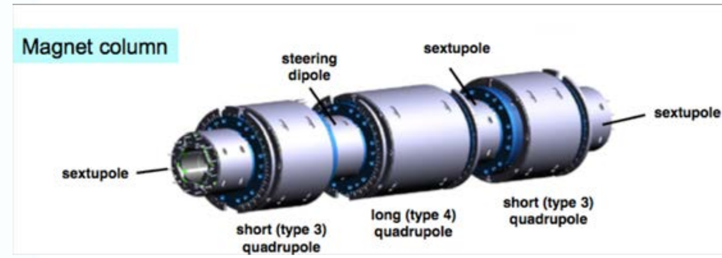
	A1900 (NSCL)	BigRIPS (RIKEN)	SuperFRS (GSI-FAIR)	IF (RISP)	S3 (GANIL SPIRAL2)
Bρ	6.2 T·m	9 T·m	20 T·m	10 T·m	1.8 T·m
Length	22 m	77 m	129 m		38 m
Horizontal aperture	±100 mm	±120 mm	±190 mm	±130 mm	±150 mm
Magnet type	Superferric	Superferric	Superferric	Superferric	3D Cosine theta coil

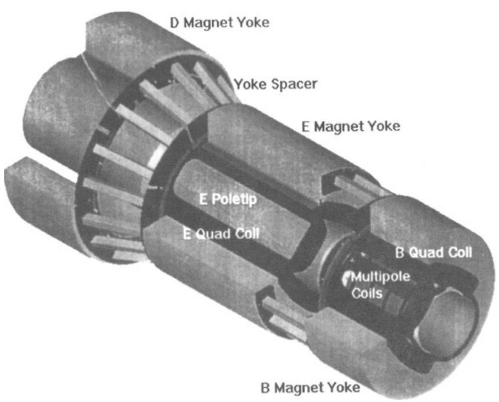
Options for Multipole Magnet Design

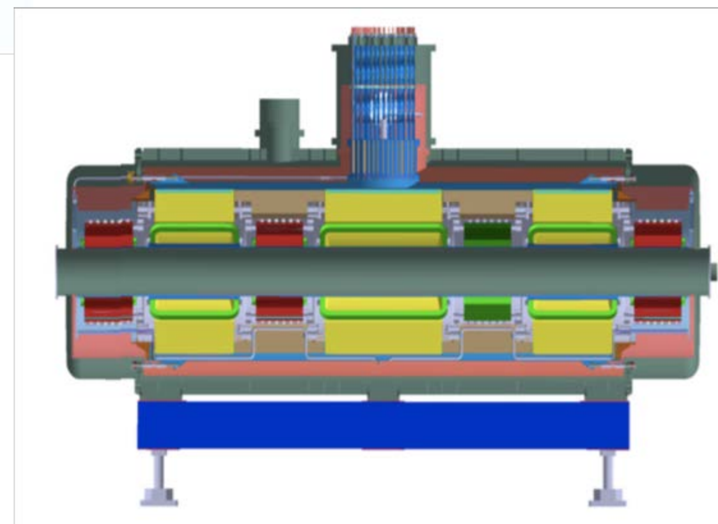
Iron-dominate











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

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;

Problems of large helium containment

Design pressures of the dipoles and the multiplets

Review of FAIR cryogenics, 27-28 February 2012

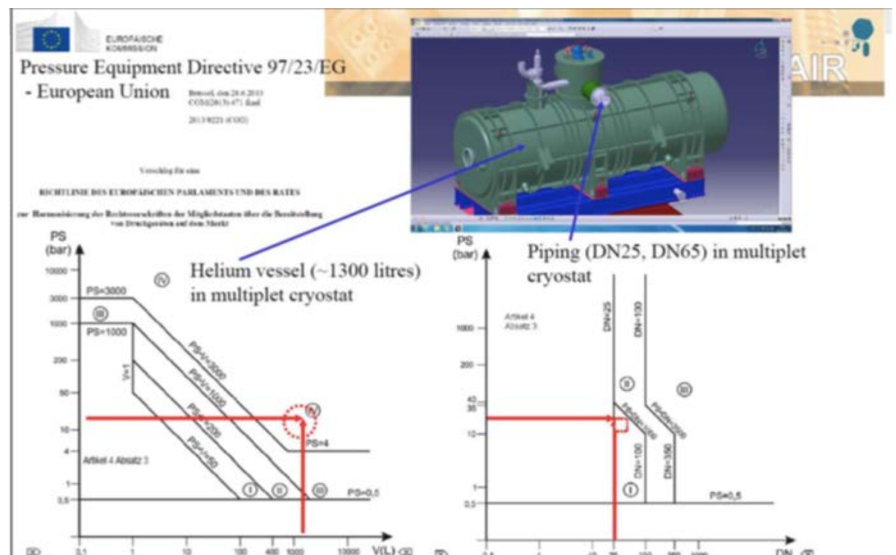
"The design pressures of the dipoles (prototype: 0.3 ~ 0.5 Mpa) and multiplets (Toshiba design: 0.3 Mpa) are rather low and different from each other, with no justification given for their values. The low design pressure makes it more difficult to control the large helium inventory in case of operational problems, which could result in large helium loss."

What if...

- What if I could turn back time (to year 2005) with keeping the knowledge of today:
- I would check: is alignment at high radiation area really necessary?
- Take enough money and time for prototypes of unkown techniques.
- Avoid interfaces if possible (technical interfaces and interfaces between companies, institutes...)
- I would look for a multiplet design with less helium containment.
- Radiation resistant HTS-quadupole of Brookhaven National Laboratory looks promising. Better performance of first quadrupoles after the target possible?

H. Leibrock / Super-FRS Magnets 1/6/2017 51

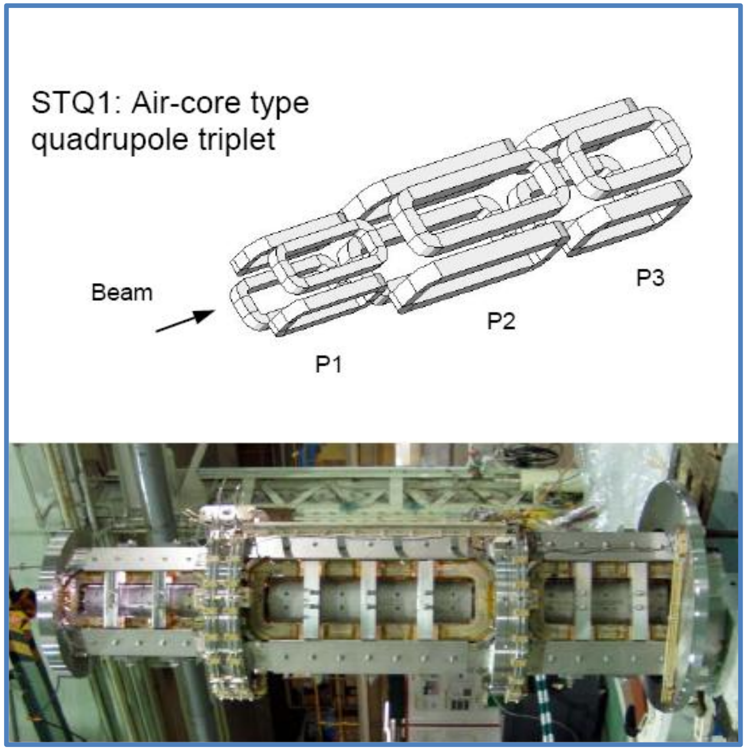
- Large helium inventory result in higher design pressure up to 20 bar；
- High design pressure cost more；
- Large helium inventory led to higher construction and operation cost of cryogenic system.

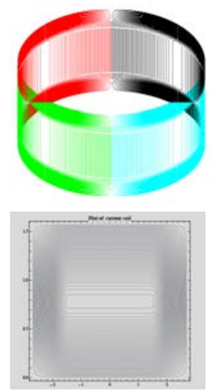


Vessel and pipings for liquid and its vapor whose pressure is 0.5 bar more than atmosphere (1.013 bar) at its maximum allowed temperature.

Options for Multipole Magnet Design

Coil-dominate





Walstrom type

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

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.

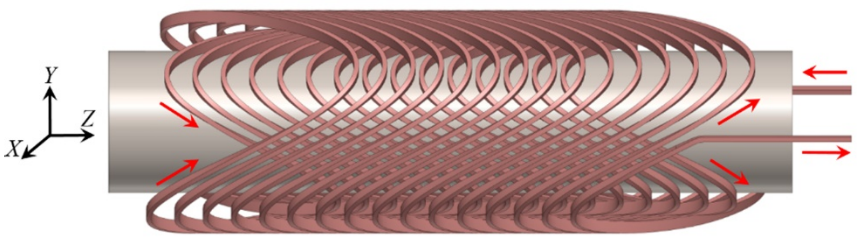
Why CCT (Canted-Cosine-Theta)?

- 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**) compared with cosine-theta design

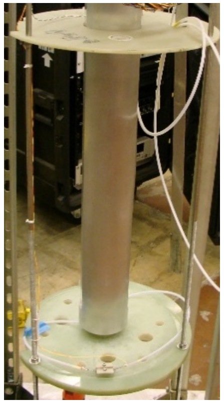
$$X(\theta) = \frac{h}{2\pi}\theta + \sum_n A_n \sin(n\theta + \varphi_n)$$

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

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



R&D activities of LBNL & PSI



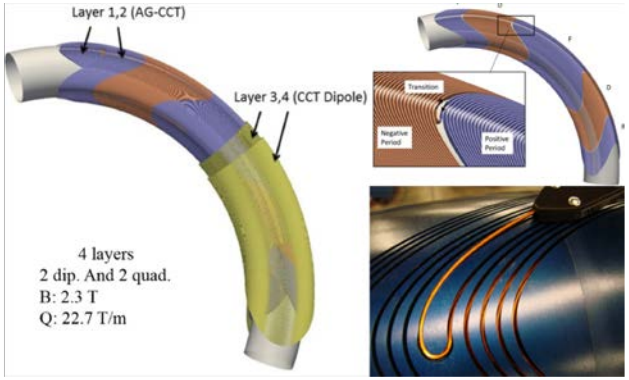
CCT1
B0=2.5T
NbTi Cable
50mm clear bore

CCT2
B0=4.7T
NbTi Cable
90mm clear bore

CCT3
B0=7.4T
Nb_3Sn Cable
90mm clear bore

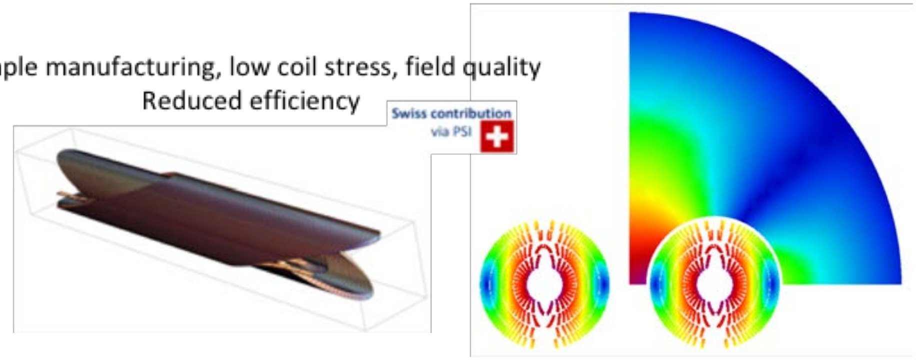
CCT4
B0=9.14T
Nb_3Sn Cable
90mm clear bore

CCT1 CCT2 CCT3 CCT4



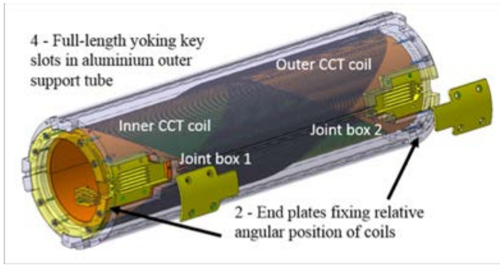
CCT SC magnet for Gantry(LBNL)

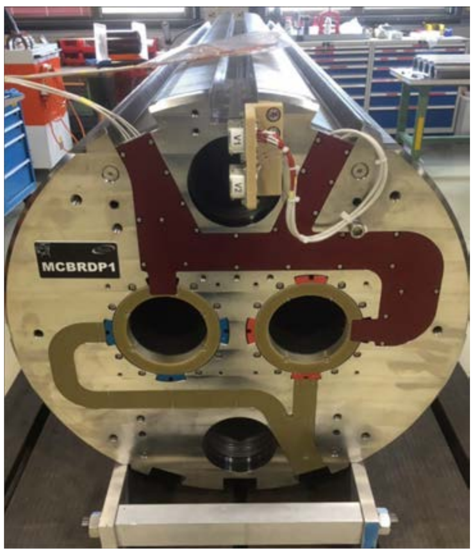
Simple manufacturing, low coil stress, field quality
Reduced efficiency

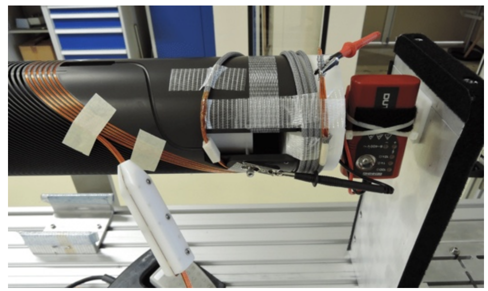


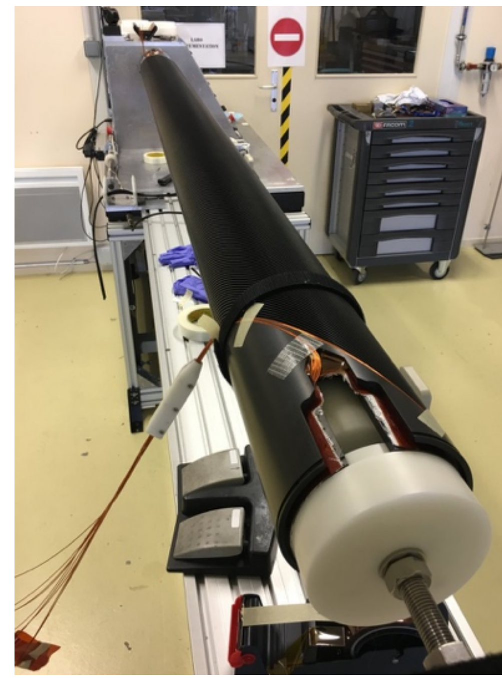
Canted Cosine Theta option for the 16-T FCC-hh main dipole (PSI)

HL-LHC D2 Correctors







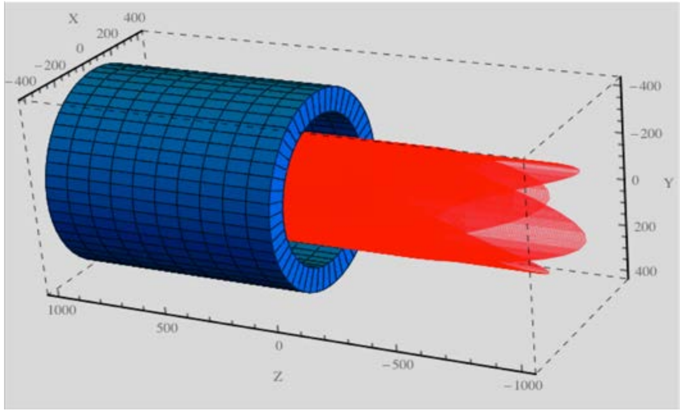


- CERN has finished the prototype;
- China (IHEP, IMP & WST) will provide 12 units of CCT magnets for HL-LHC;

HFRS Multipoles based on nested CCT

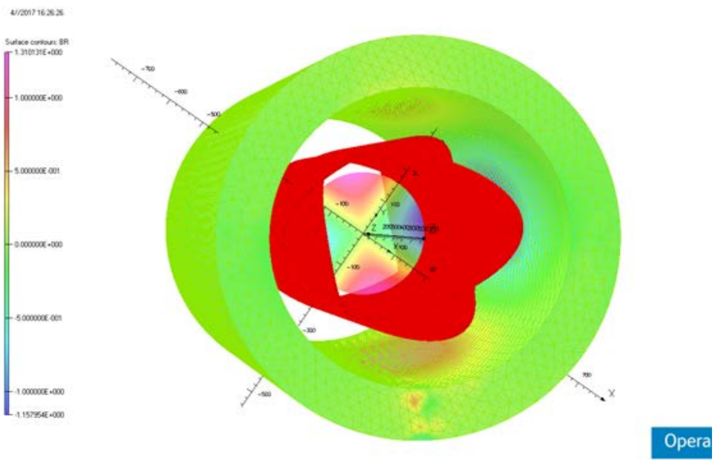
Coil design (quadrupole)

	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

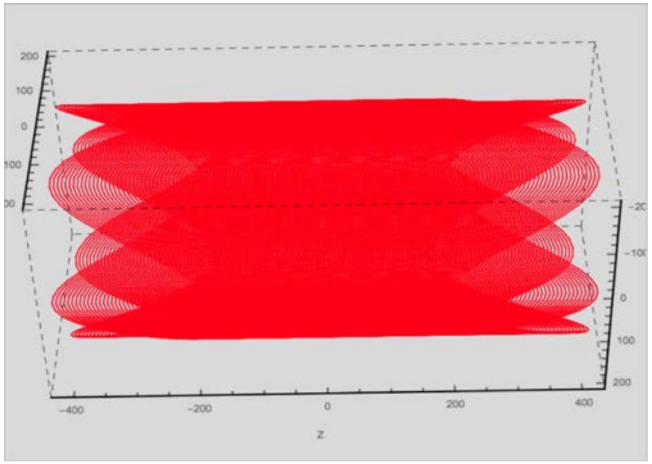


HFRS Multipoles based on nested CCT

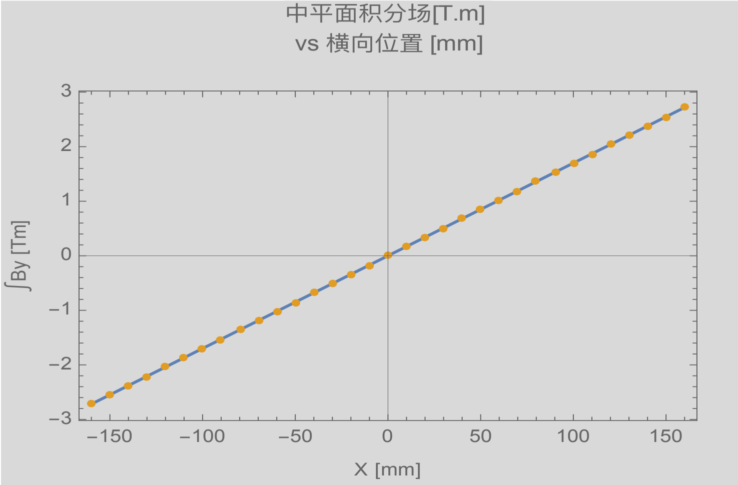
Coil design



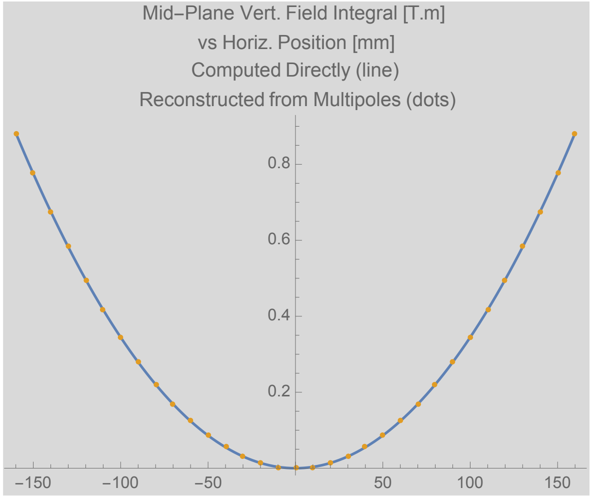
CCT quadrupole EM model



CCT sextupole EM model

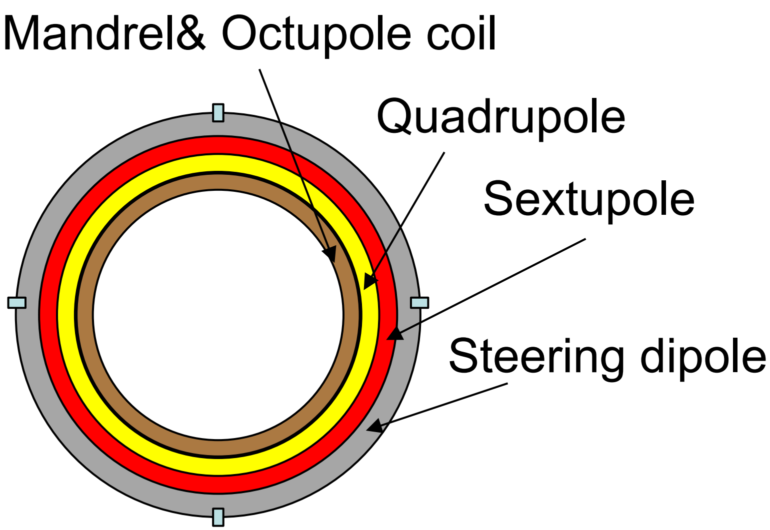


Integral field distribution of the quadrupole



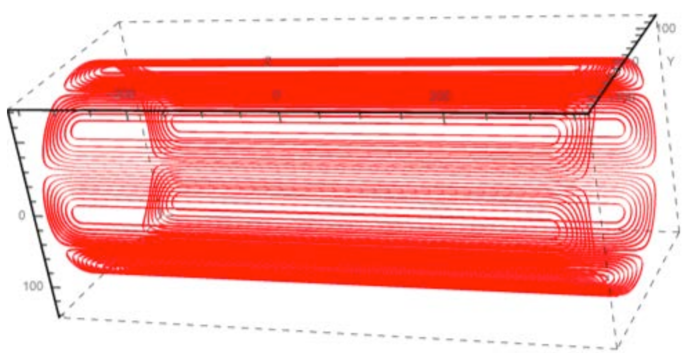
Integral field distribution of the sextupole

HFRS Multipoles based on nested CCT

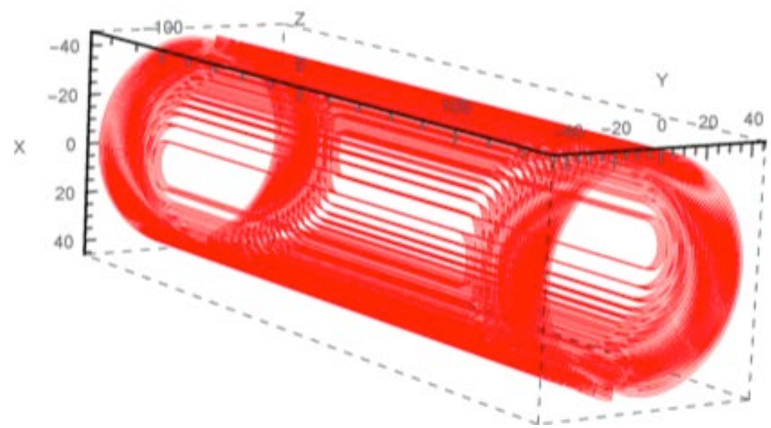


CCT四极线圈

- **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**)



Octupole based on discrete cosine-theta coil



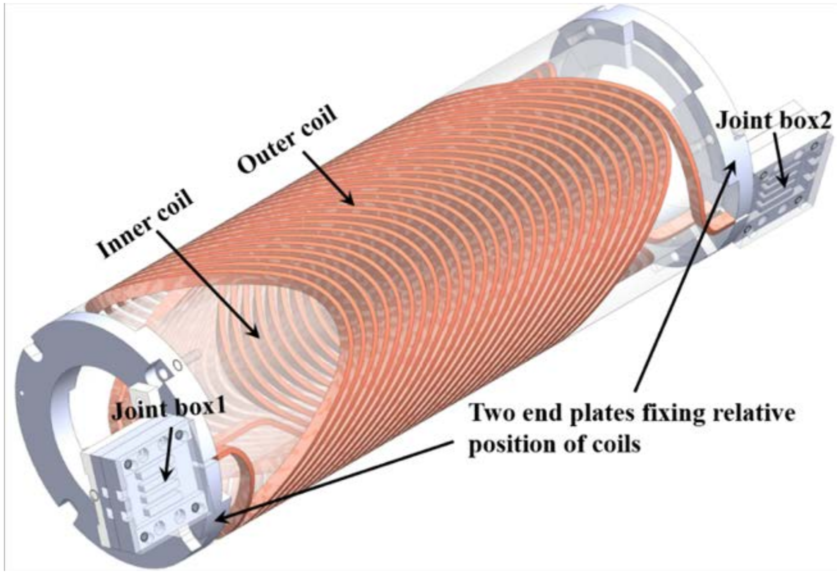
Steering dipole based on discrete cosine-theta coil

	Bρ	Aperture of dipole	Aperture of quadrupole	Length	Weight of cold mass	Helium inventory
HFRS	25Tm	±160×70mm	±160×120mm	~190 meter	~100T	6000-10000L
SuperFRS	20Tm	±190×70mm	±190×120mm	365 meter	~1100T	36000L

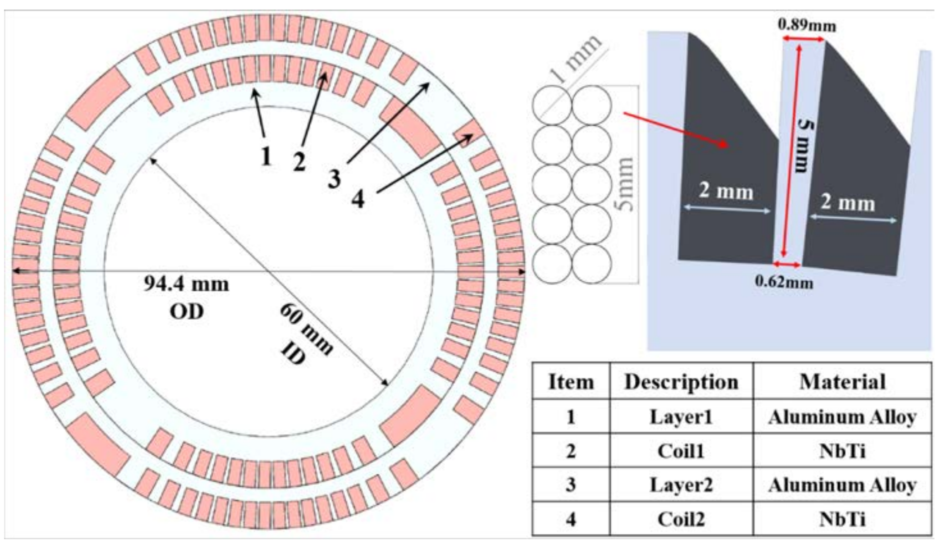
Table 1. Cold mass and liquid helium inventory of SC magnet cryostats in the Super-FRS start version.

SC magnet cryostats	dipoles	long multiplets	short multiplets	GLAD dipole	Total magnet cryostat number
Number	24	22	7	1	54
Average weight of cold mass in individual cryostats [tons]	1.7	42	15	25	Total cold mass weight [tons]
Sum of cold mass weight of all magnets with same type [tons]	40.8	924	105	25	~ 1,095
Liquid helium volume in individual cryostats [liters]	25	1,300	900	525	Total liquid helium volume [liters]
Sum of liquid helium volume in all cryostats of same type [liters]	600	28,600	6,300	525	36,025

Subscale prototype - 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

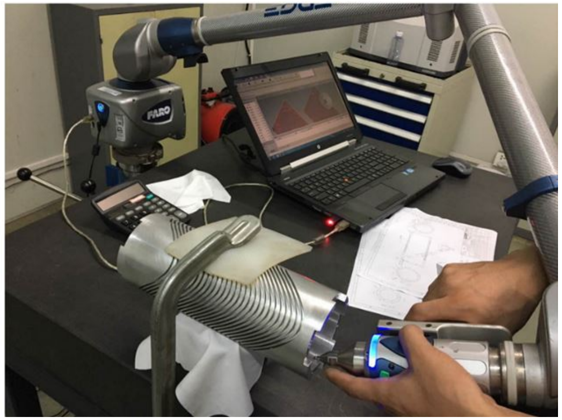
Parameter	Value	Unit
Gradient	40	T/m
Effective length	160	mm
Operation current	400	A
Winding pitch	6	mm
Tilt angle	45	deg
Inductance	10	mH
Aperture	60	mm
Good field	± 20	mm
Uniformity	± 4E-4	

Parameters of the NbTi/Cu strand

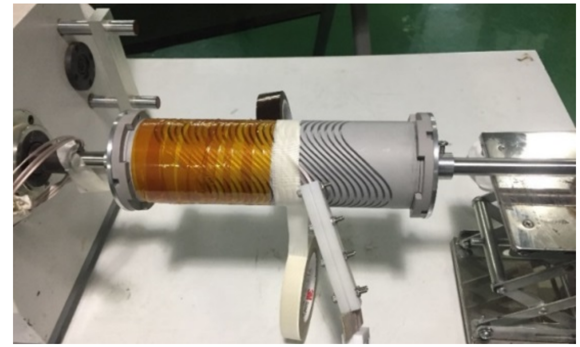
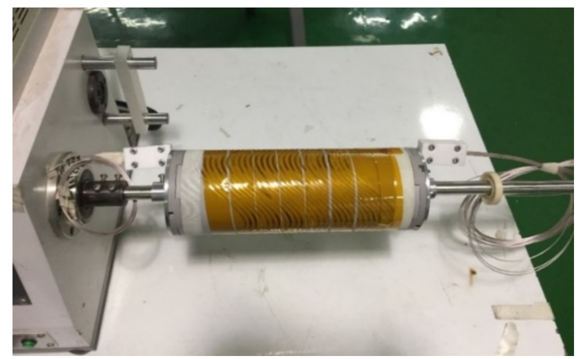
Wire type	Monolith
Insulation	Formvar
Bare size	0.72 mm
Insulated size	0.77 mm
Outer Insulated with Nylon braid	0.9±0.005 mm
Cu/SC	1.3:1
RRR (293 K/10 K)	>100
Ic (6 T,4.2 K)	442.7 A

Subscale prototype - fabrication

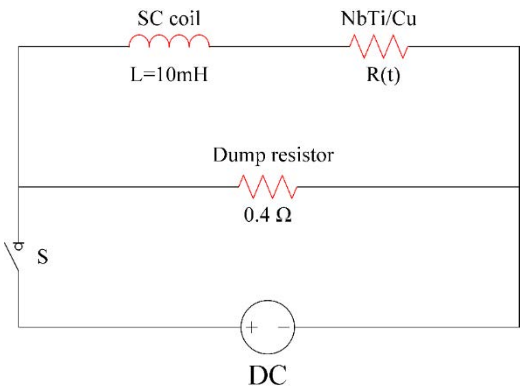
Former Fabrication

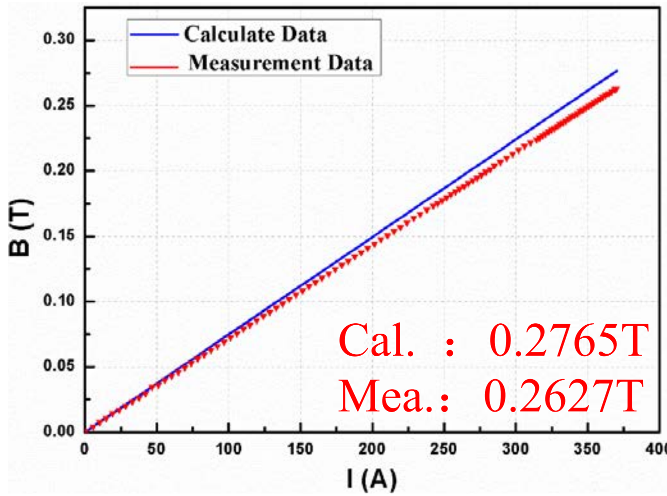
Coil Winding and Impregnation

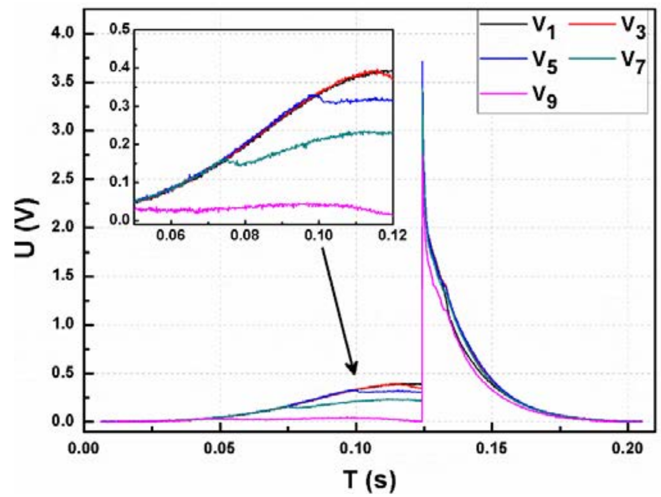

Subscale prototype - cryogenic test



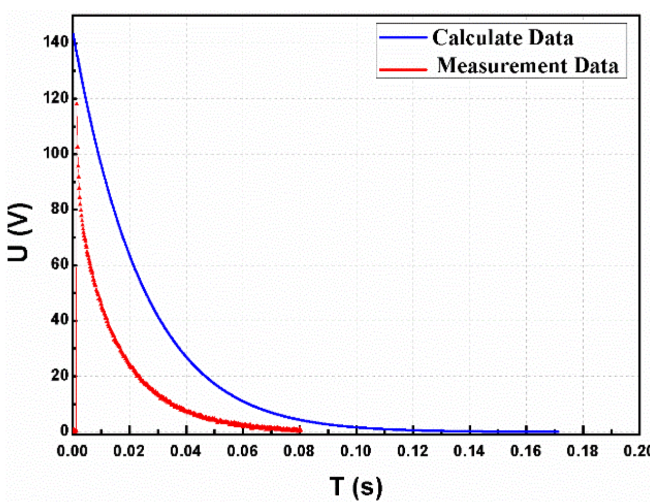
Magnet Test



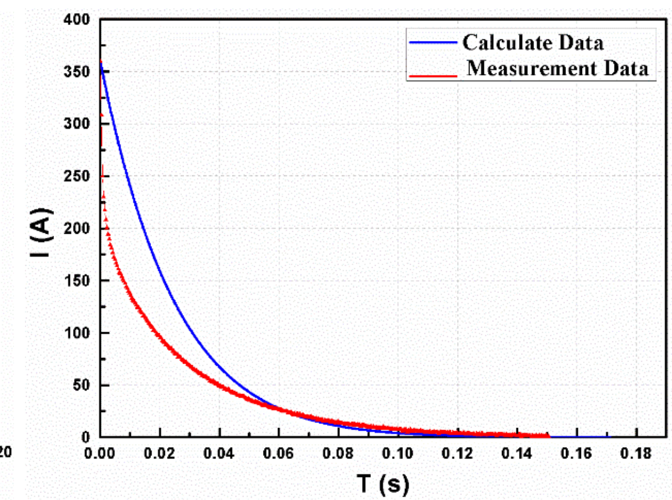
Excitation curve



Coils voltage change

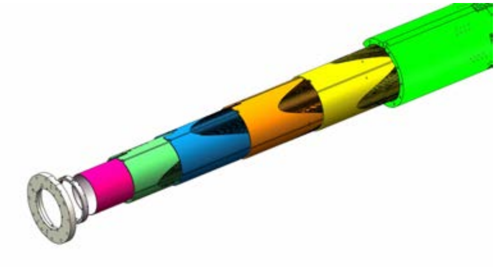


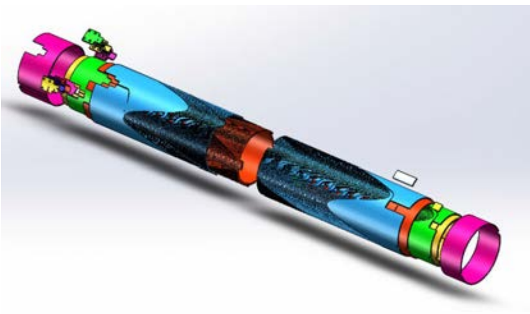
Voltage decay curve

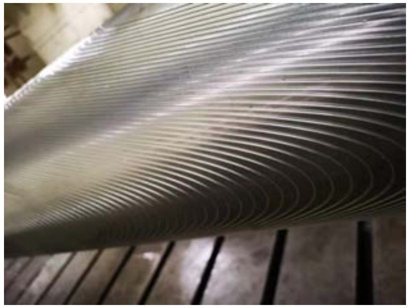


Current decay curve

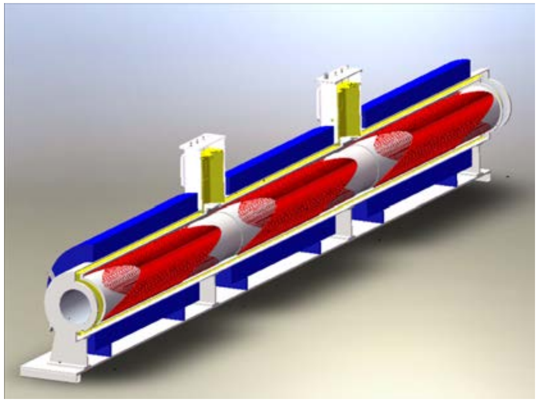
Mechanical design & trial fabrication

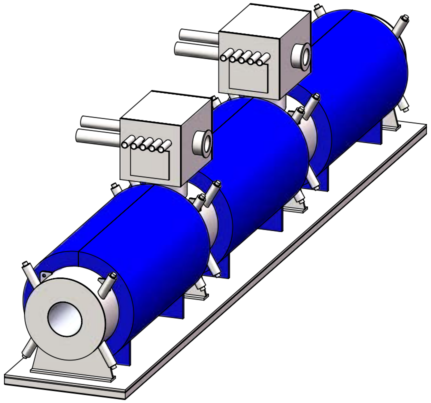






Mechanical design and fabrication of formers

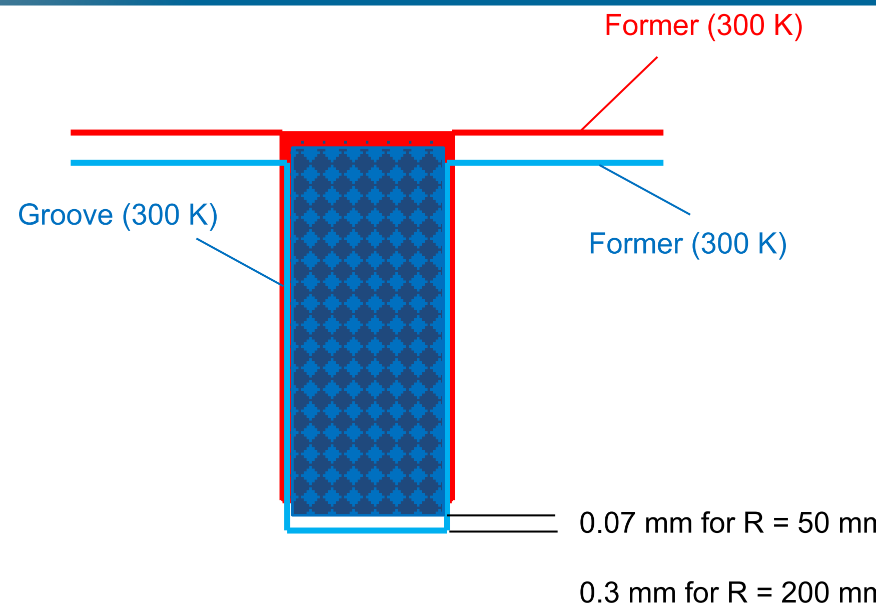




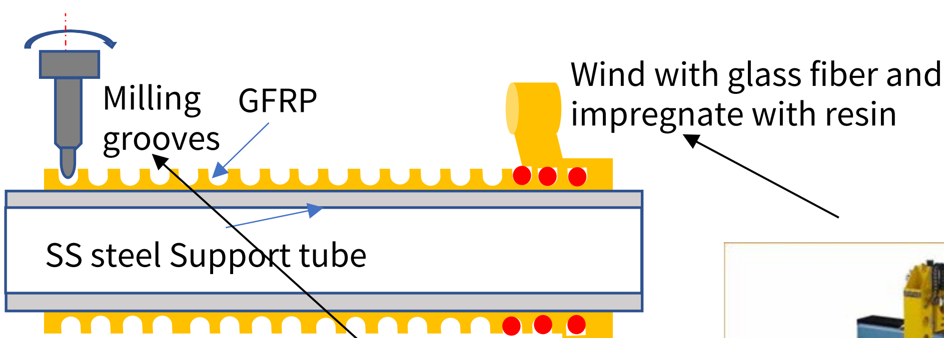
Cryostat design

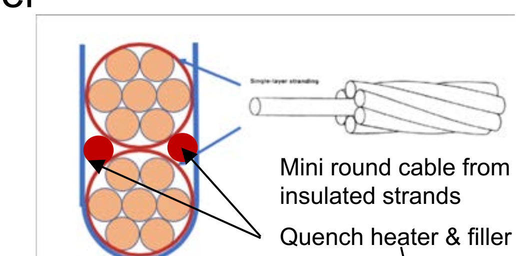
Former material: Al alloy vs. GFRP

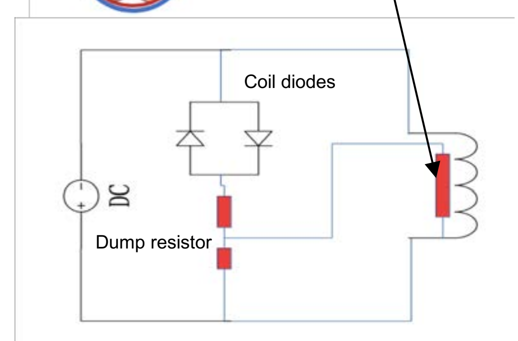
	ΔL / L at 4K (%)
Cu	0.324
Al-6061-T6	0.414
SS 316	0.297
NbTi/Cu	0.265
G10 // glass fibers	**0.241**
G10⊥ glass fibers	0.706



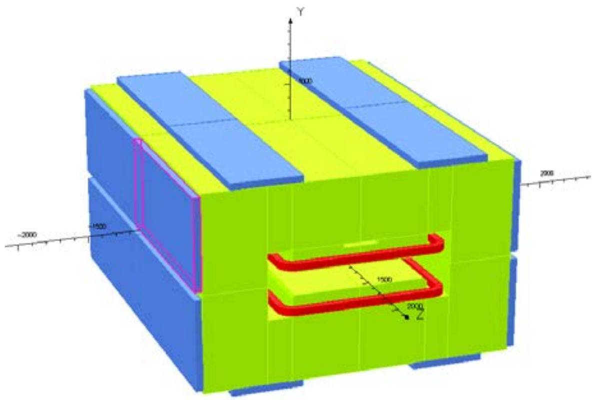
Bigger slip between coil and groove for larger former







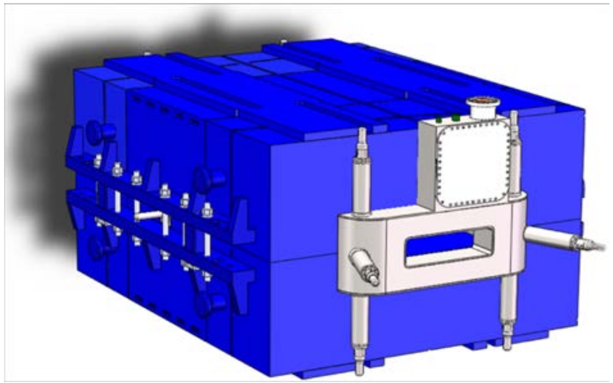
SC dipoles for HFRS – Superferric design



Opera model

Super-FRS dipole prototype

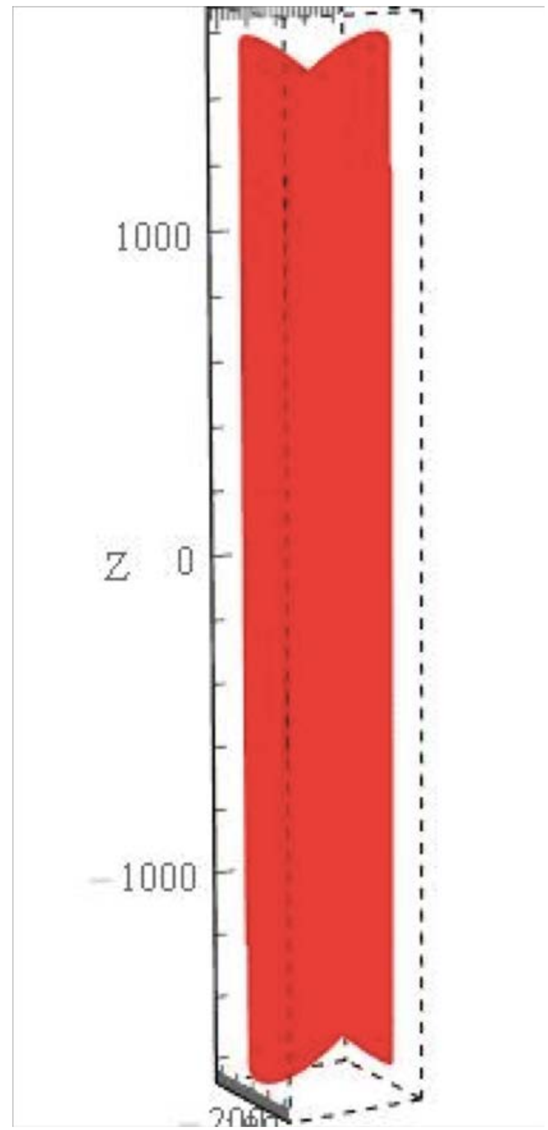
Effective length	2.74 m
Gap	160 mm
Central field	1.6 T
Operation current	300 A
Inductance	15 H
Weight of Iron	**50 t**
Cooling method	LHe bath cooling
Operation temperature	4.2 K



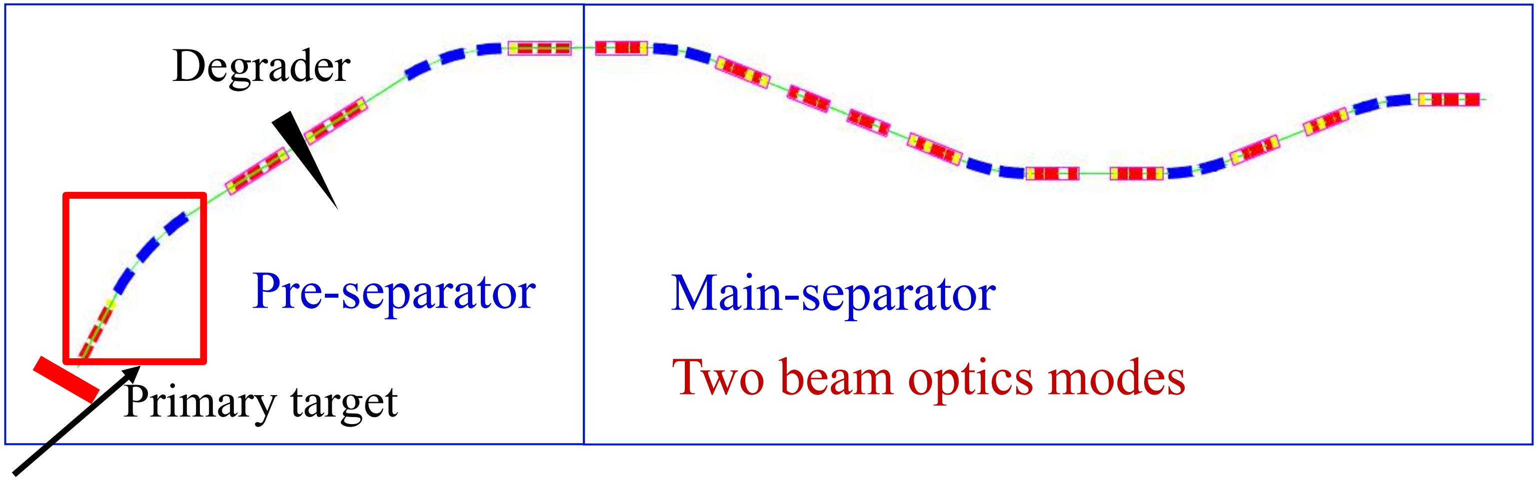
Superferric design of HFRS dipole

SC dipoles for HFRS – CCT design

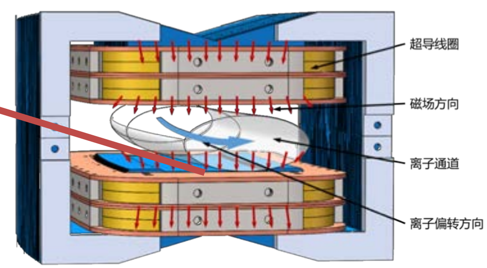
Central Field (T)	1.6
Current(A)	500
Layers	2 (5+5)
CCT angle	36 °
Turns per layer	1030
Pitch(mm)	2.7
Aperture(mm)	320×140
Wire Diameter (mm)	0.85 0.99±0.01
Insulation meterial	Kapton
Cu/SC	2.0
Bpeak(T)	2.5
SSL	64%
Conductor length(km)	23.5
ID of mandrel(mm)	420
Coil groove size	2 mm x 5 mm



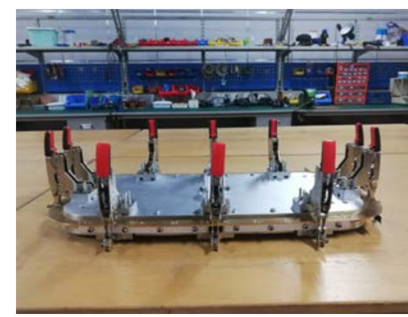
HTS Radiation Resistant Magnets for HFRS



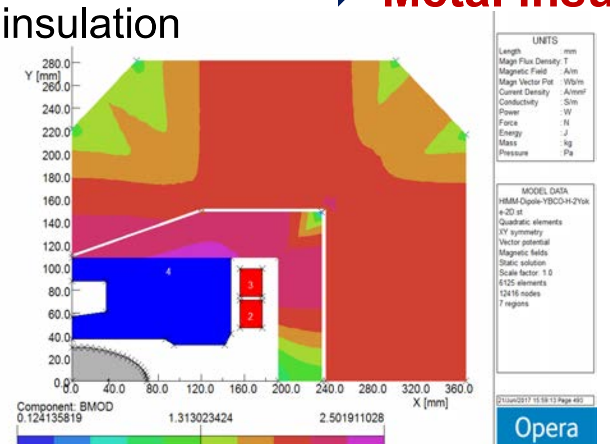
- Higher Operation Temperature ➡ **YBCO coil**
- No organic insulation ➡ **Metal insulation!**



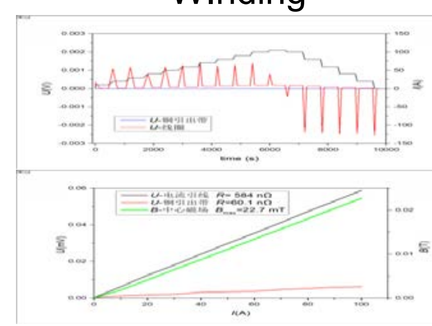
Design (Coil & Cold iron)



WInding

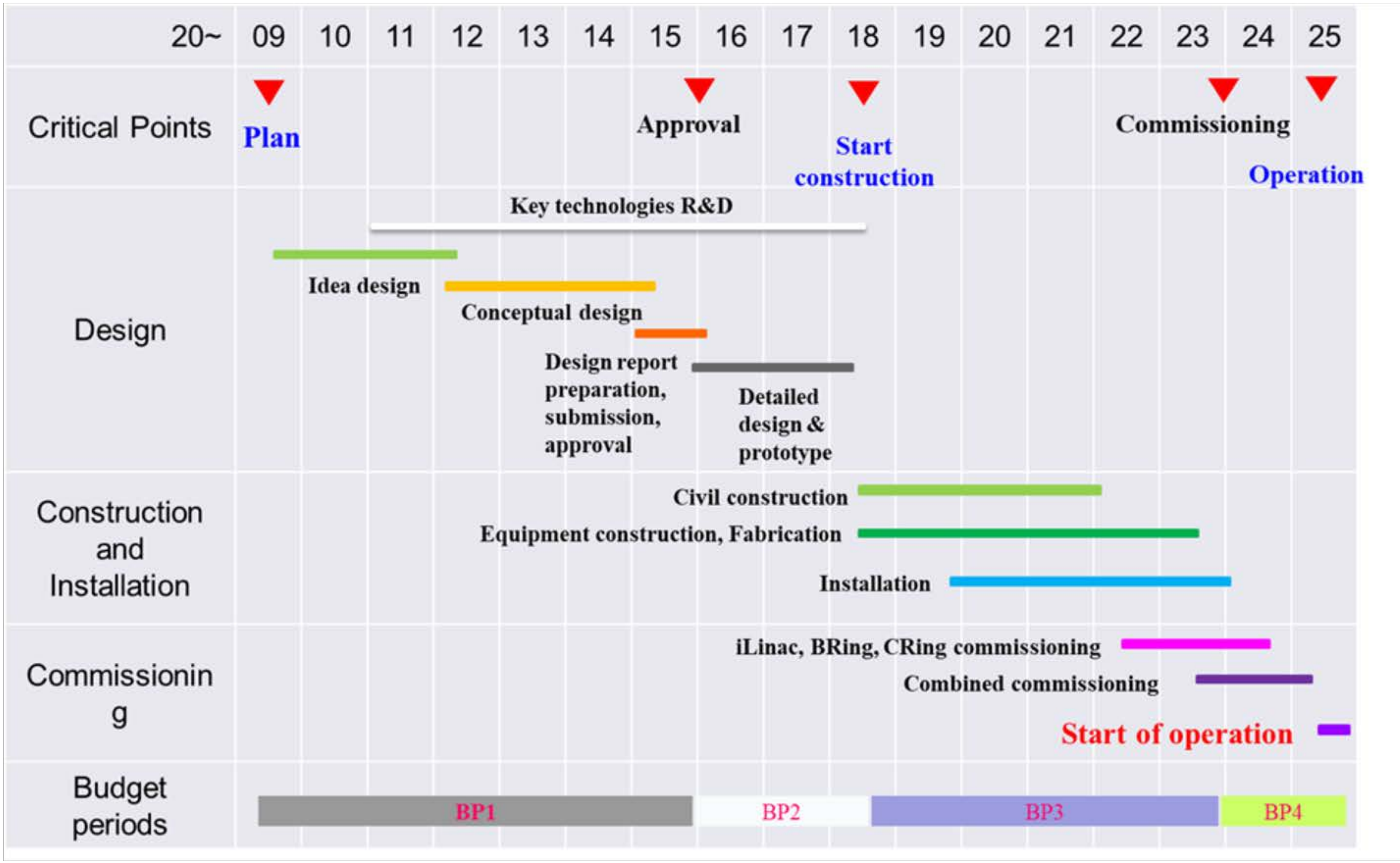


EM Design (20K pole & 60K yoke)



Testing (LN2)

CPM 0 of HIAF



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Critical Points
Plan
Approval
Start construction
Commissioning
Operation
Design
Key technologies R&D
Idea design
Conceptual design
Design report preparation, submission, approval
Detailed design & prototype
Construction and Installation
Civil construction
Equipment construction, Fabrication
Installation
Commissioning
iLinac, BRing, CRing commissioning
Combined commissioning
Start of operation
Budget periods
BP1
BP2
BP3
BP4

Thanks a lot for your attention!