Superconducting Magnet System for HIAF

Wei Wu

Institute of Modern Physics, CAS

November 15-19,2021, Fukuoka

Outline

01 Overview of HIAF SC Magnet system

02 45 GHz ECR ion source magnet (Nb_3Sn)

03 Strong focusing solenoids for SC Linac

04 Dipoles and Multiplets for HFRS

01

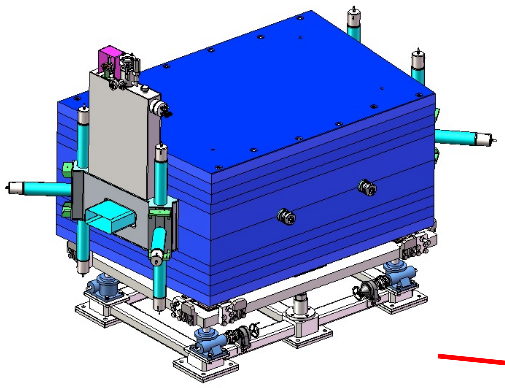
Overview of HIAF SC Magnet system

ABOUT HIAF

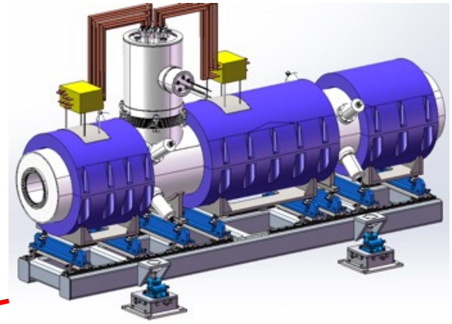
- HIAF - The High Intensity Heavy-ion Accelerator Facility
- Funded jointly by the National Development and Reform Commission of China, Guangdong Province, and Huizhou City
- 2.5 billion (1.5 billion from central government and 1.0 billion from local governments)

- Explore the territories in nuclear chart
- To open new domains of physics researches in experiments
- To develop new ideas and heavy-ion applications beneficial to society

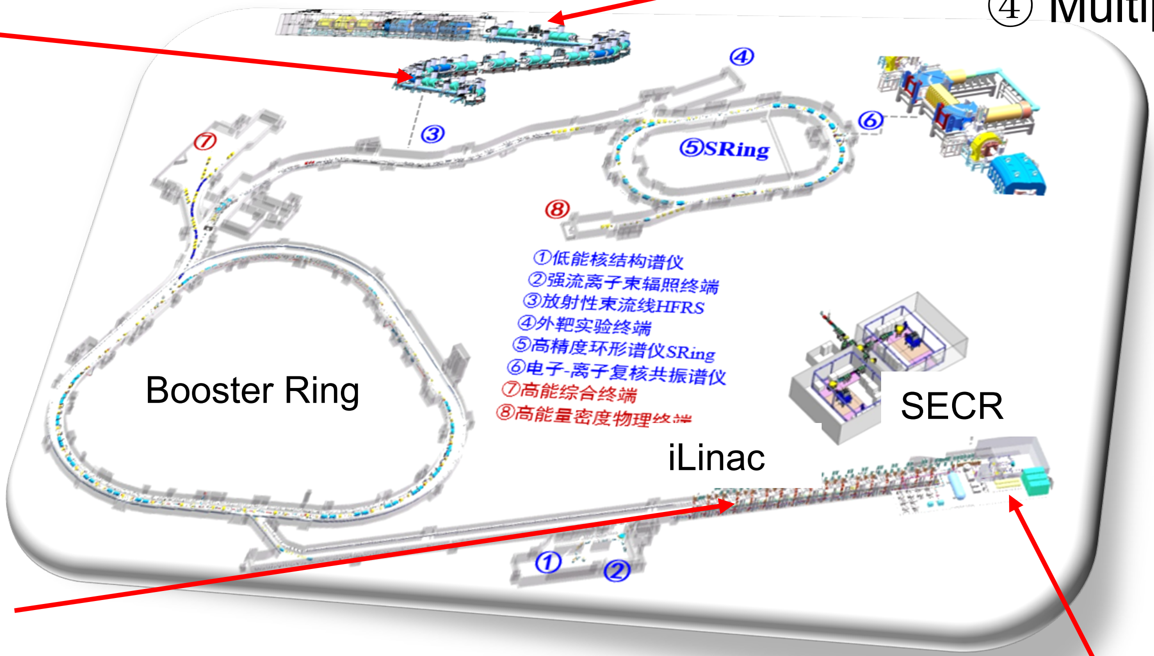
Overview of HIAF SC Magnet system

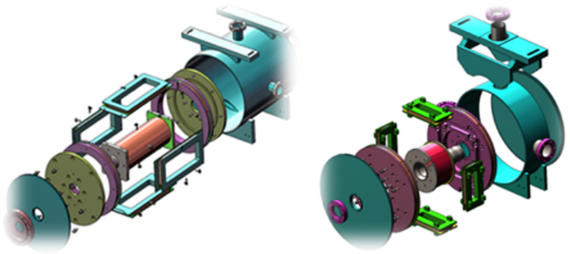


③ HFRS Dipole

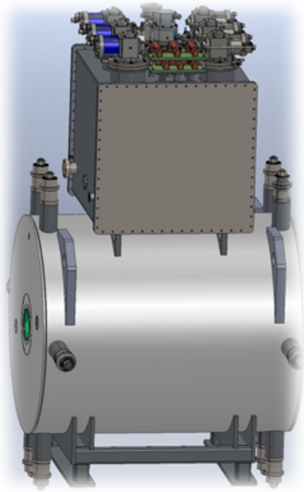


④ Multiplets for HFRS





② Strong focusing solenoids for iLinac



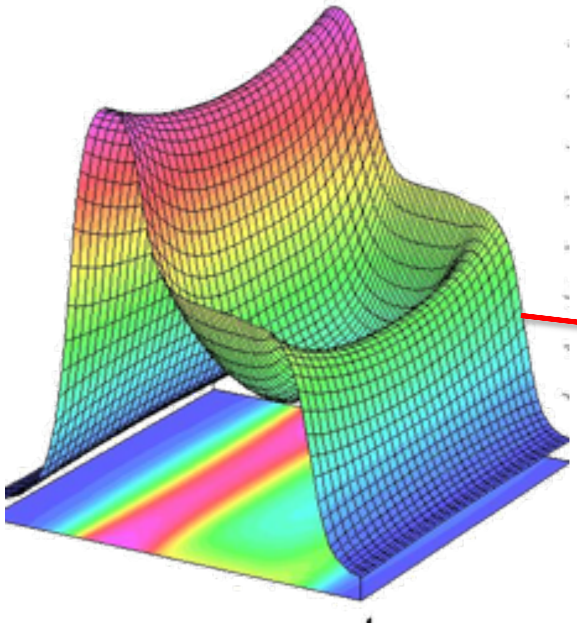
① 4th Generation 45 GHz ECR ion source

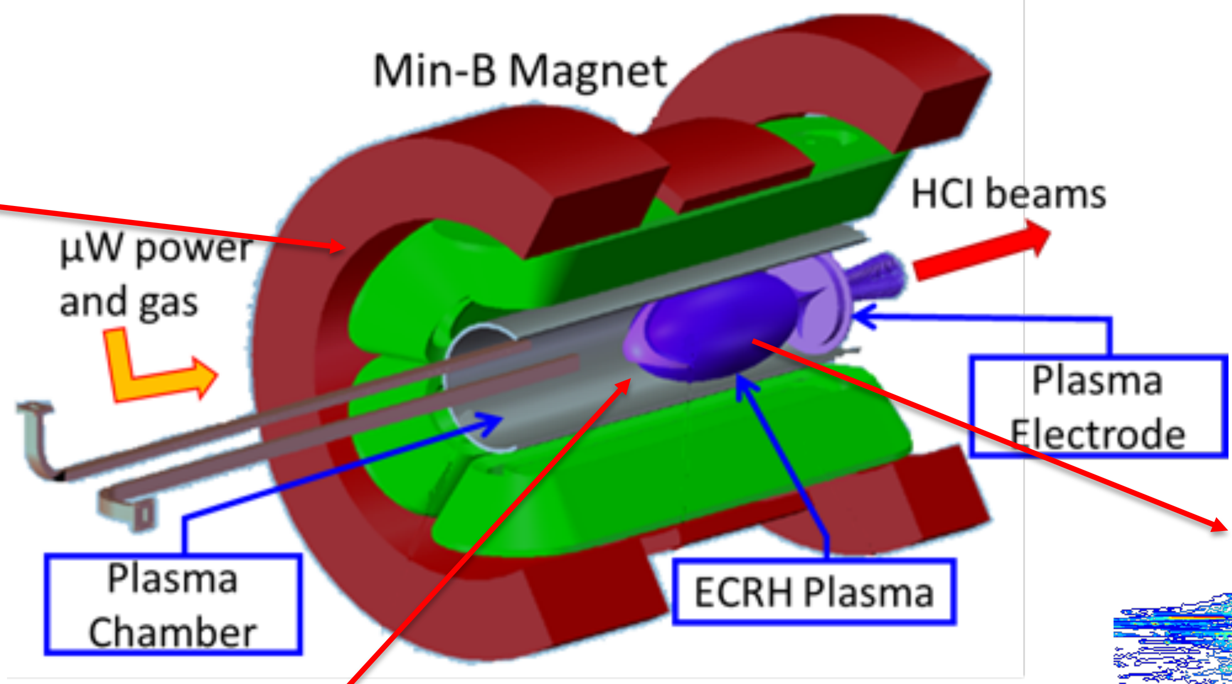
02

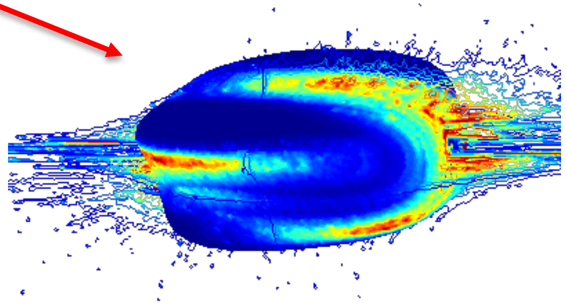
45 GHz ECR ion source magnet (Nb_3Sn)

What is ECR ion source?

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





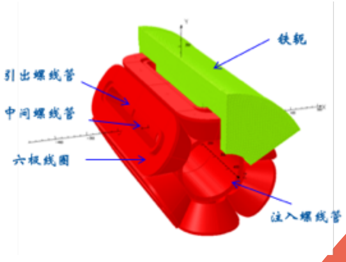


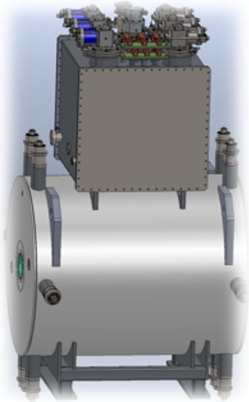
Stochastic heating of electrons through ECRH

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

Dense hot plasma and HCIs production

History & Future of SC ECR ion source





?

28 GHz （Bmax ~ 8T） NbTi

45 GHz (Bmax ~ 12T) Nb3Sn

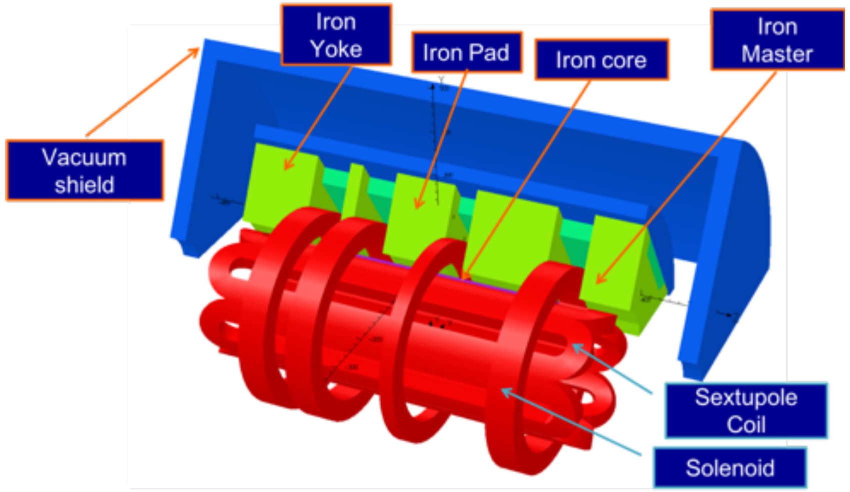
56 GHz (Bmax ~ 15T) Nb_3Sn or HTS

Magnet design of FECR (Fourth generation ECR)

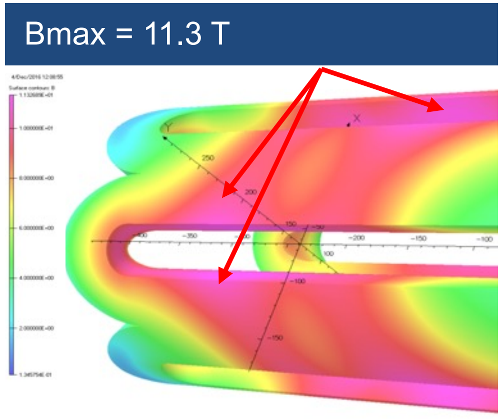
- Sextupole in solenoids
- Peak field 12 Tesla
- Nb_3Sn conductor
- Low operation current with single wire

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

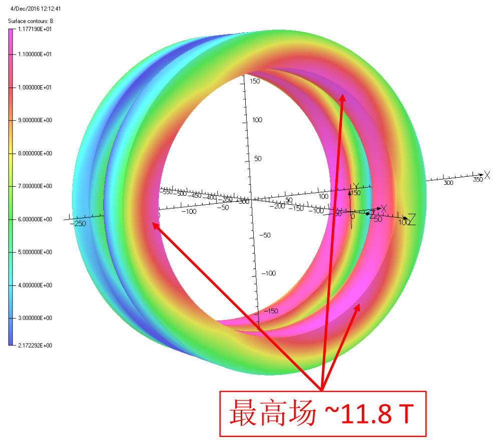
Specs.	Unit	State of the art ECRIS	FECR
frequency	GHz	24-28	45
B_{ECR}	T	0.86~1.0	1.6
B_{rad}	T	1.8~2.2	≥3.2
B_{inj}	T	3.4~4.0	≥6.4
B_{min}	T	0.5~0.7	0.5~1.1
B_{ext}	T	1.8~2.2	≥3.4
Warmbore ID	mm	120~170	≥160
Mirror Length	mm	420~500	~500
Cooling Capacity@4.2 K	W	0~6.0	≥10.0



EM design of FECR



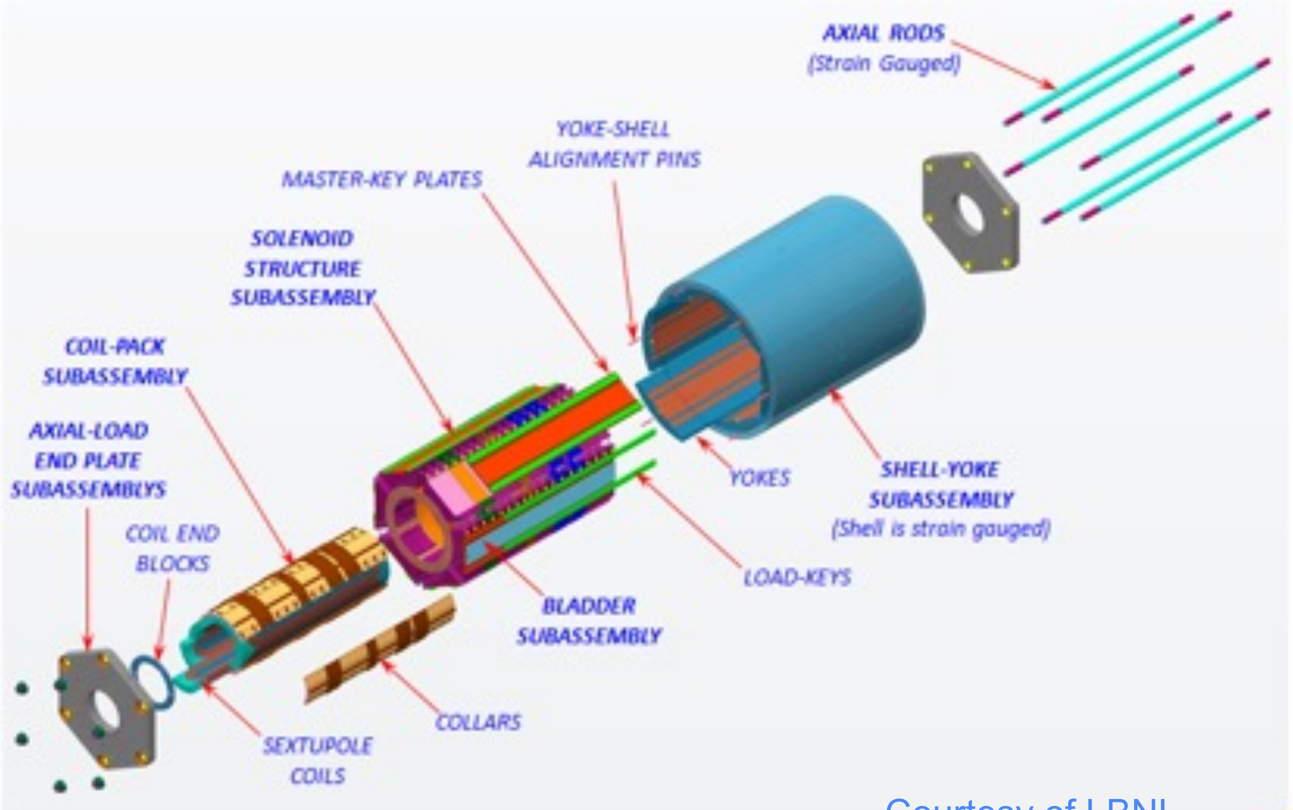
Magnetic field of Sextupole coil



Magnetic field of solenoid

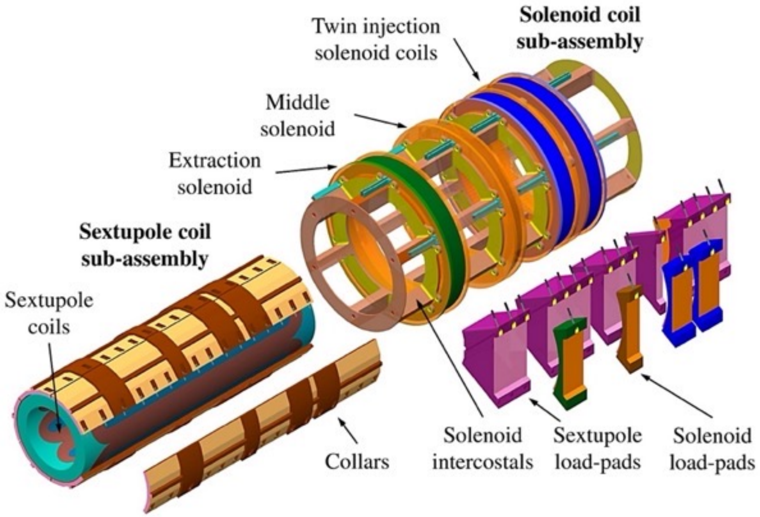
Mechanical Design of FECR

- Al alloy shell-based structure
- Bladder & key prestress assembly
- Maximum stress < 160 MPa

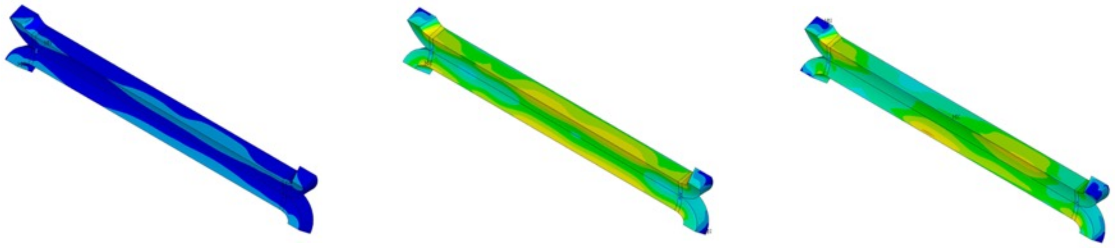


Courtesy of LBNL

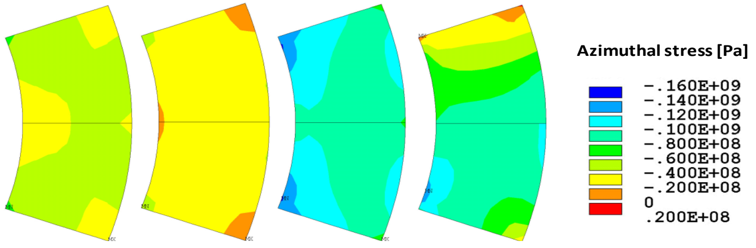
FECR magnet assembly



Strong interaction between Sextupole coil and solenoids



RT Assembly | Cool down (4K) | Energized (4K)



Bladder | 300K | 4K | Energized

Juchno, Mariusz, et al. "Mechanical Design of a Nb3Sn Superconducting Magnet System for a 45 GHz ECR Ion Source." *IEEE Transactions on Applied Superconductivity* 28, no. 3

R&D Road Map of FECR

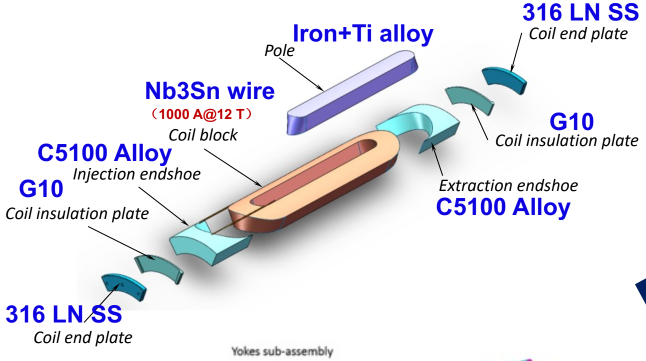
2020 2021 2022

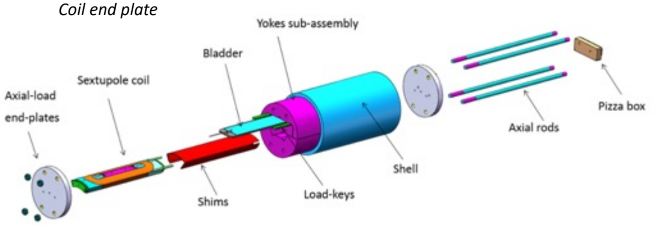
2018 2019 2020

2015 2016 2017 2018

Phase1

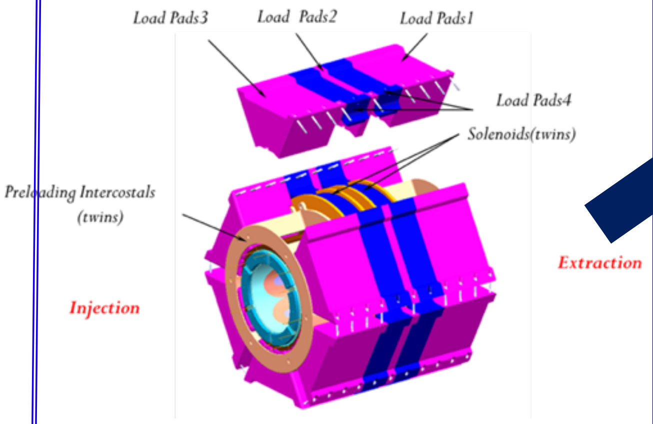
- Magnet design and optimization
- R&D of Nb3Sn Sextupole coil
- Bladder & key based mirror structure



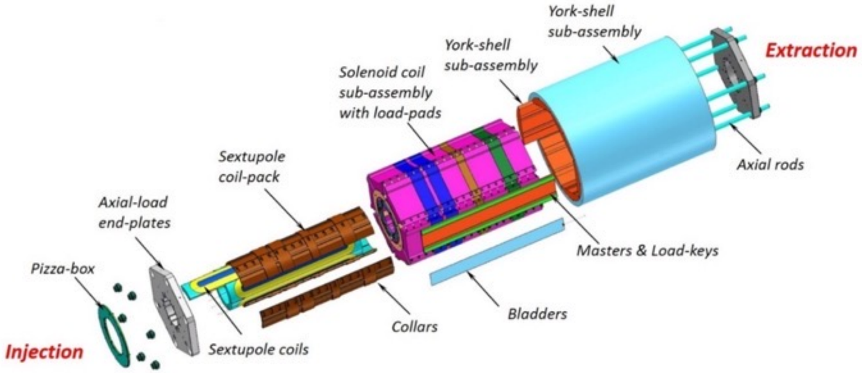


Phase2

- Design of half-length prototype

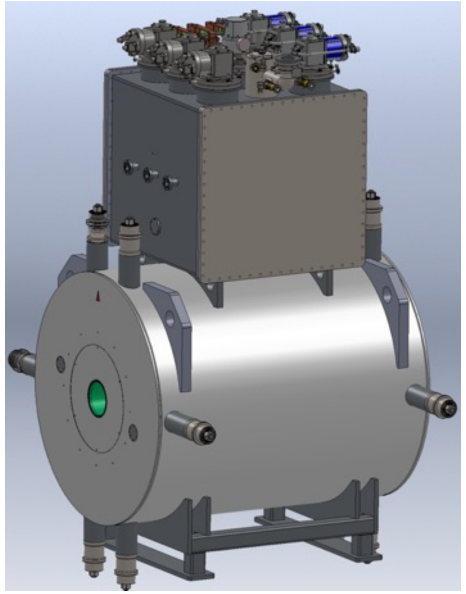


- Quench detection and protection
- Assembly technology based on Bladder & key



Phase3

- Fabrication of full-scale magnet
- Assembly of full-scale magnet
- Cryostat fabrication and magnet integration

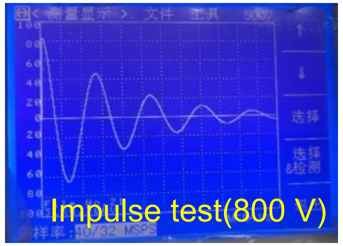


Wind & React technology of Sextupole Coils

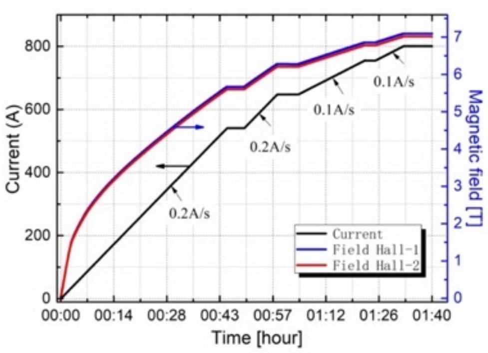
Refer to the details in POSTER:WED-PO2-716-05

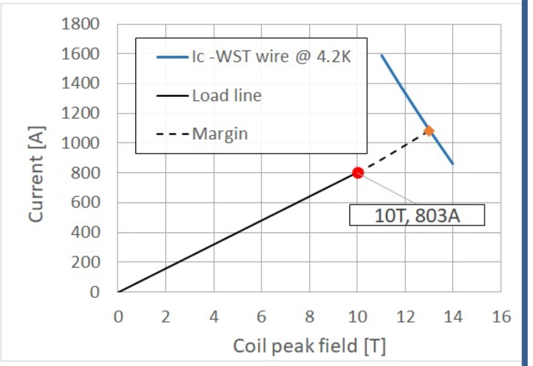
Half length sextupole coil prototyping

Full size coil



Insulation Q&A

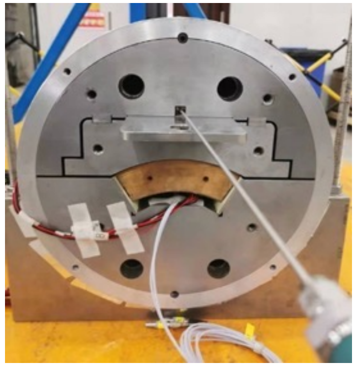




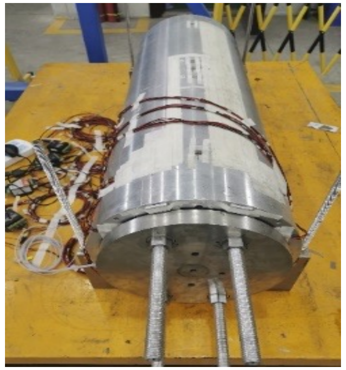
Half length sextuple coil has been energized to 800A without a quench

Full size sextupole coil

Shimming

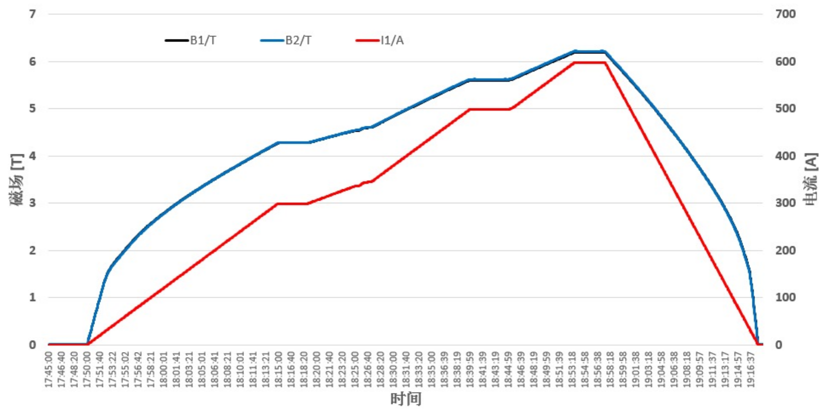


Radial preload



Axial preload

Cool down

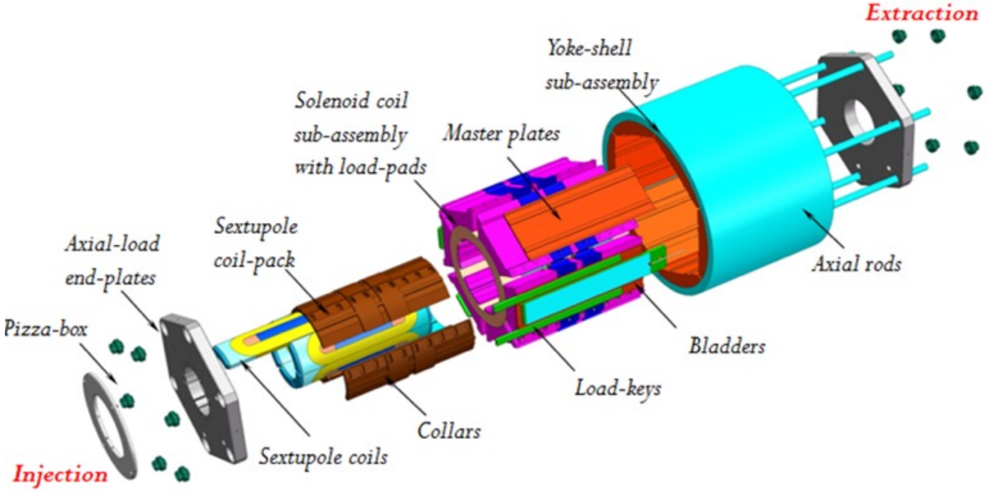


Full size sextuple coil has been energized to 600A without a quench

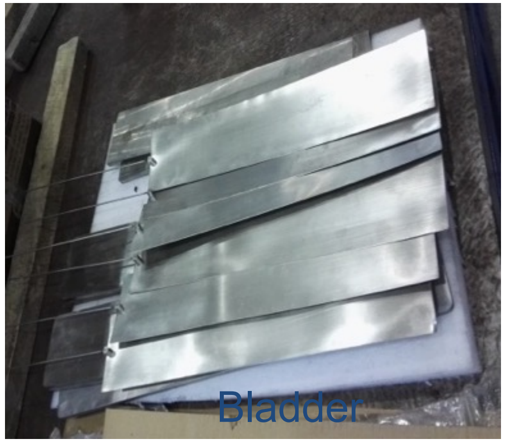
Assemble of Half-length Prototype

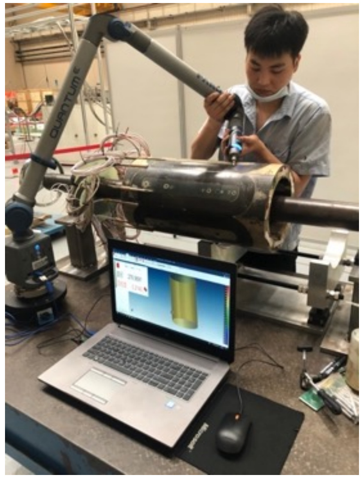
Refer to the details in POSTER: WED-PO2-716-06

- ½ prototype consists of two solenoids and one set of sextupole
- Assemble using Bladder & Key technology origin from LBNL
- Strain monitored with strain gauge and Rayleigh-backscattering interrogated optical fibers

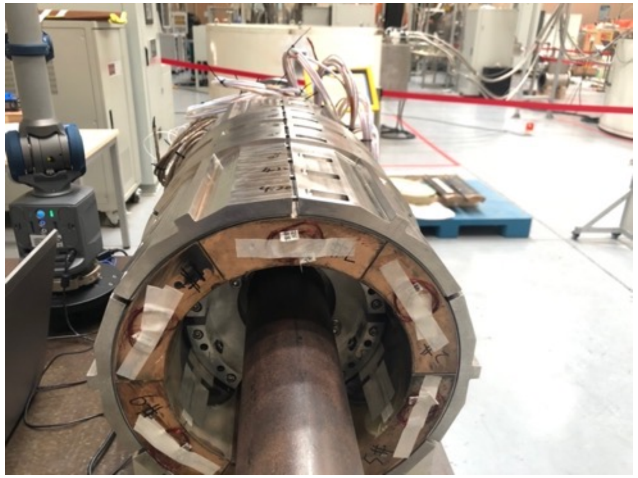


Half-length prototype



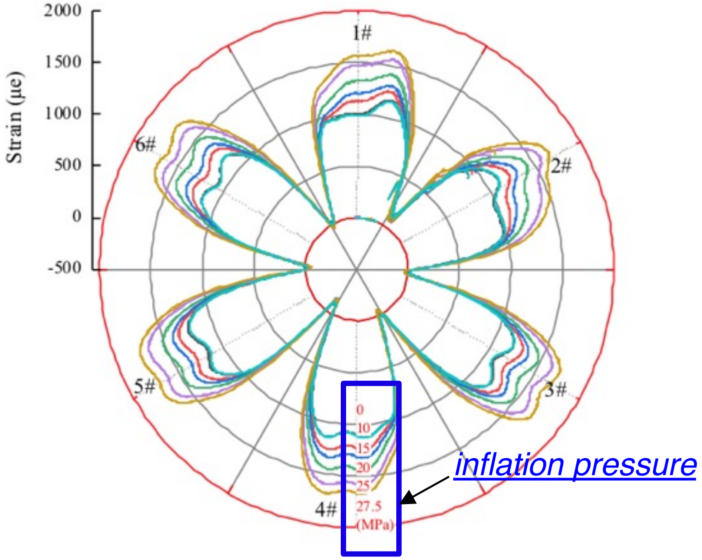


Sextupole coil assembly & shimming



Sextupole coil assembly

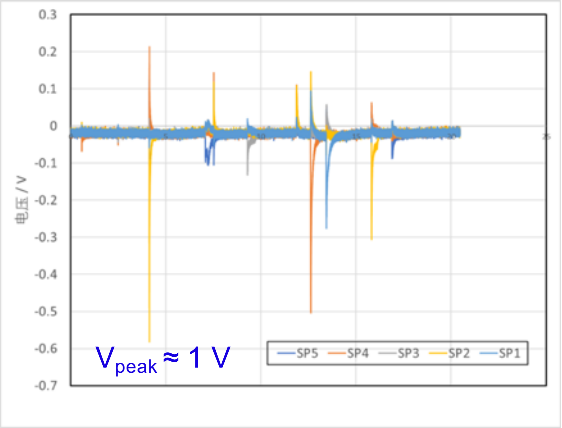
Bladder & key assembly



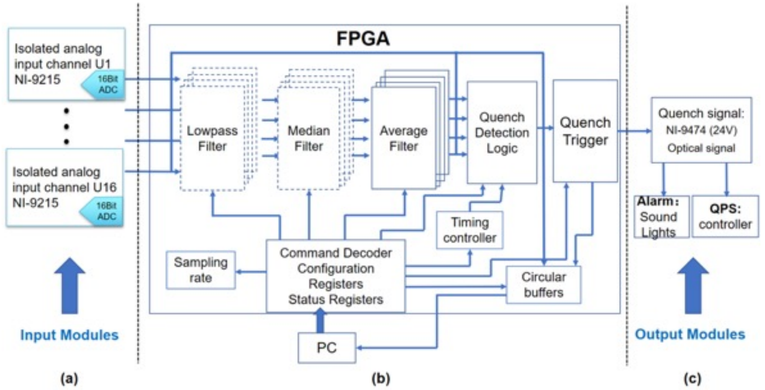
Strain distribution along the circumference of Al shell during bladder inflating

Test and Quench Protection of ½ Prototype

Refer to the details in POSTER: TUE-PO1-708-07

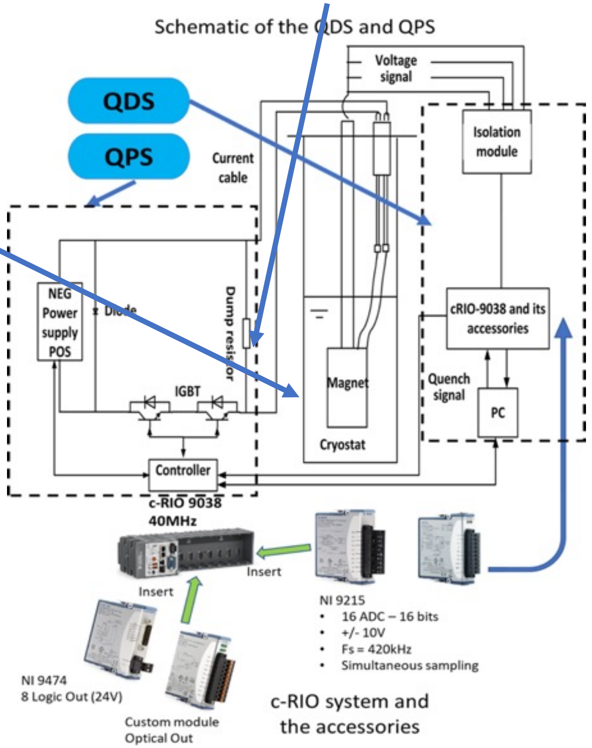


Frequency and large Voltage spikes due to flux jump

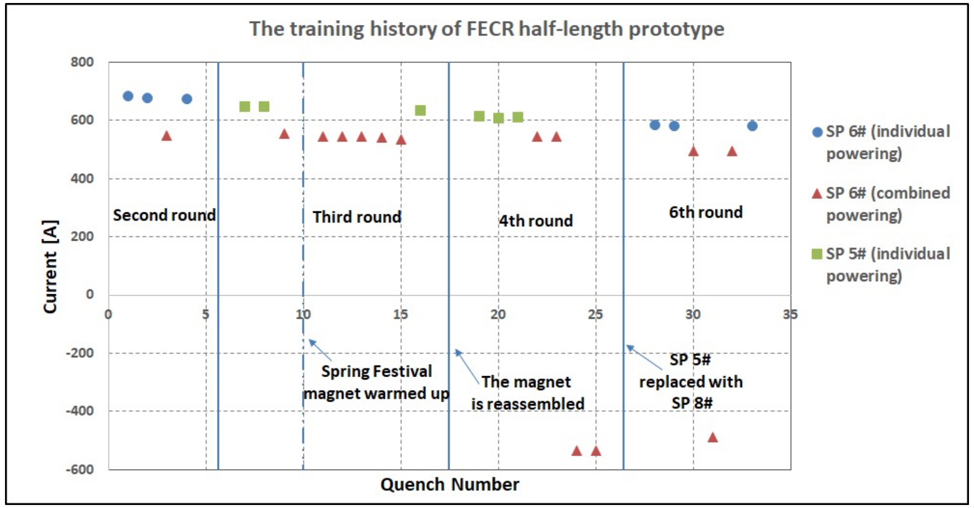


Quench detection system based on c-RIO FPGA

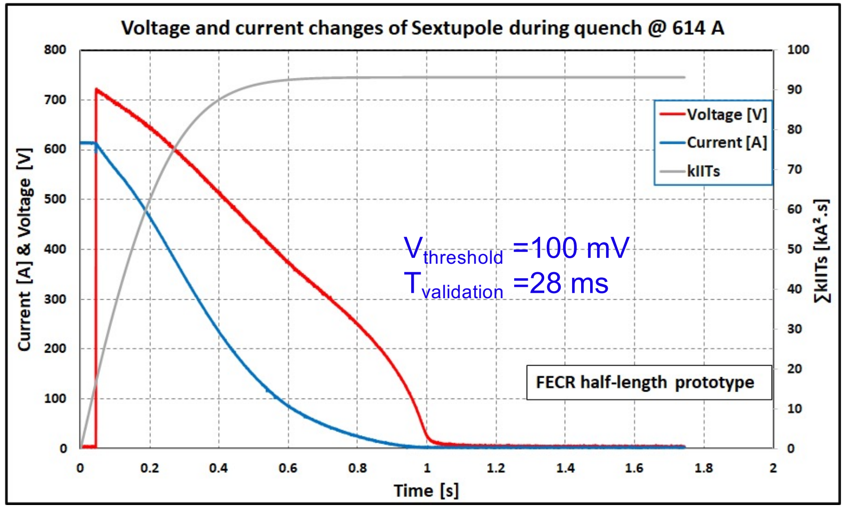
Metrosil Varistor as dump resistor



Quench protection scheme for FECR ½ prototype



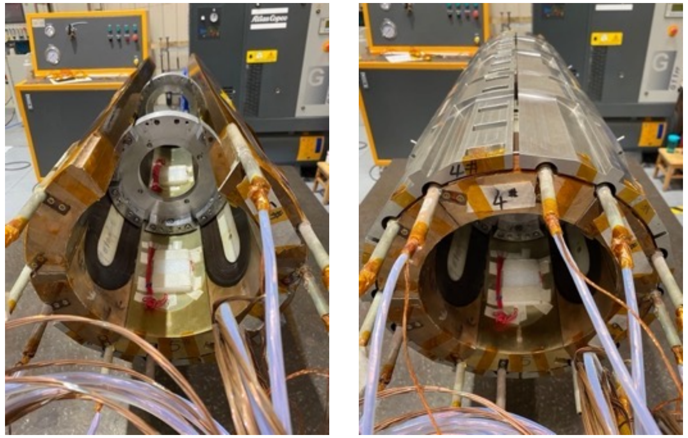
Training of ½ prototype at 4.2 K



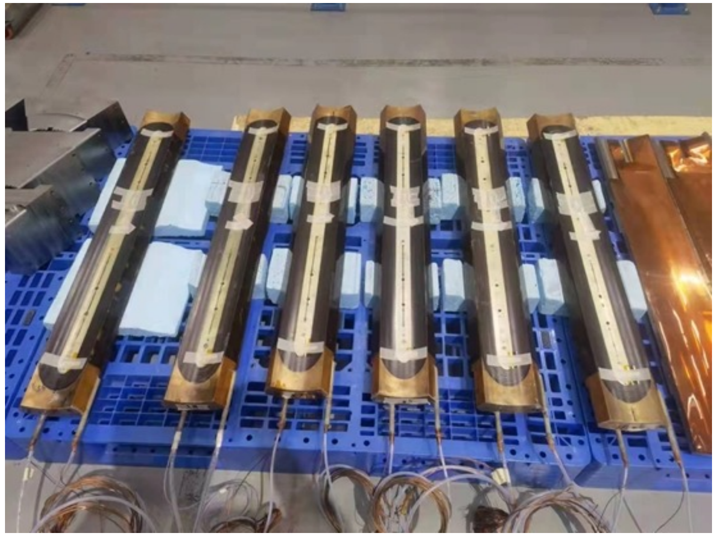
Quench protection discharge of sextupole coil @ 614 A

Status of the Full-scale Magnet

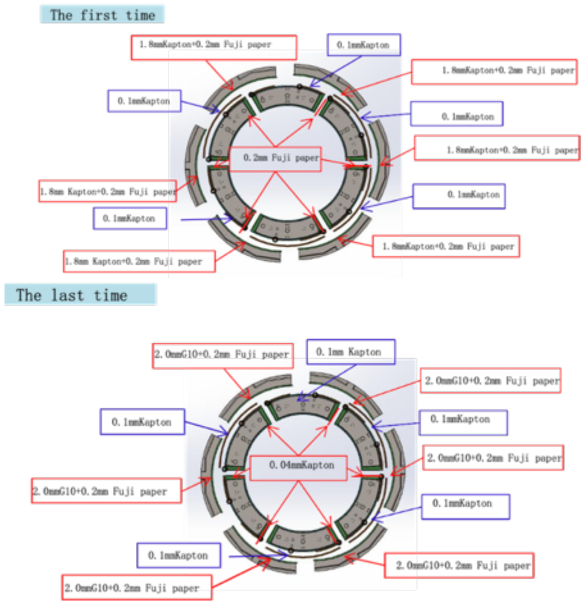
- Nine full-length sextupole coils have been wound, reacted and impregnated. three of them are for backup.
- Four solenoids will be available soon.
- Shimming of the coil-pack sub-assembly have been completed.
- Components are now ready for the final assembly and test.



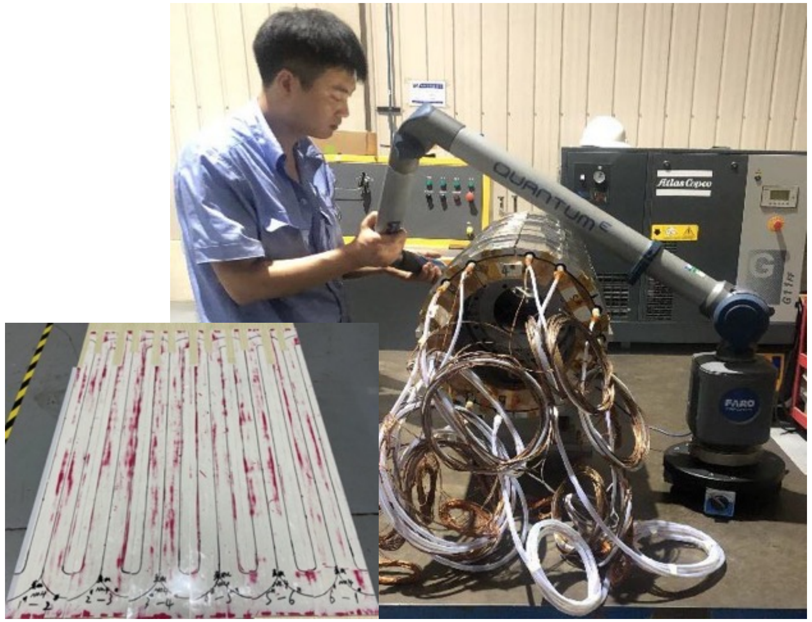
Coil-pack with collar



Sextupole cois



The shimming of sextupole coils
in mid-plane & ID of collars



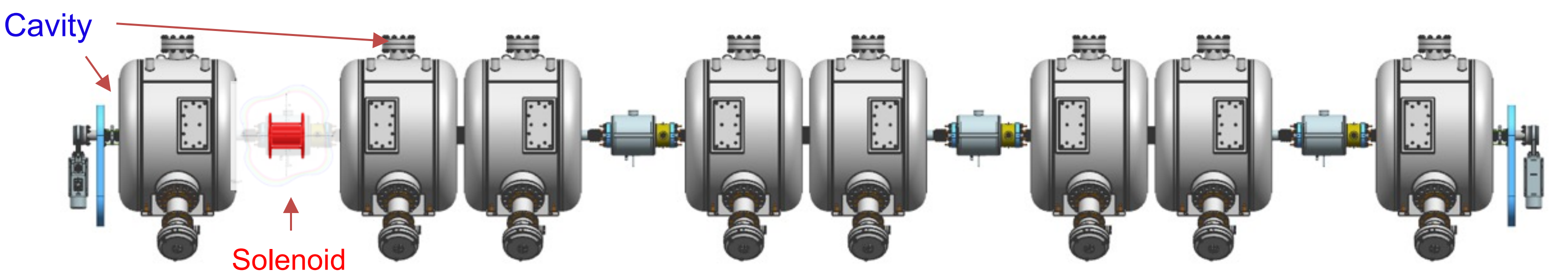
FARO arm and Fuji paper are used to check the assembly effect

Main parts of the FECR magnet

03 Strong focusing solenoids for SC Linac

Specifications of Focusing Solenoid

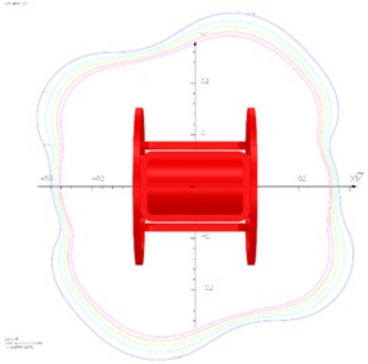
- Maximize $\int B_z^2 dz$ with limited space between cavities
- Active shielding design to minimize fringe field at cavities' region
- XY steering dipoles are integrated



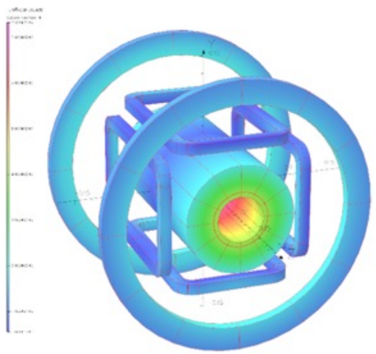
Between RF cavities for beam focusing and steering

	item		QWR007	HWR015
	bore diameter	mm	40	40
	Mechanical length	mm	362	676
	Operation Temperature	K	4.5	4.5
	Stary field (95 mm distance from end flange)	T	0.018	0.0183
Solenoid	integral squared field	T^2m	10	27
	integral squared field error (80% aperture)		1.8%	0.4%
	peak field along axis	T	7.2856	7.5865
	current	A	82.05	77.58
	Loadline margin		15.6%	13.4%
	coil inductance	H	7.427	21.36
	Excitation time	s	120	120
	ramping rate	A /s	0.68	0.65
	induced voltage	V	5.08	13.81
	Power supply voltage	V	±10	±20
	Power supply current	A	±100	±100
DCH/DCV	integral field	Tm	0.02	0.06
	peak field along axis	T	0.1116	0.1212
	current	A	40	45.57
	Loadline margin		71.2%	68.8%
	coil inductance	H	0.166	0.421
	Excitation time	s	5	5
	ramping rate	A /s	8.00	9.11
	induced voltage	V	1.33	3.84
	Power supply voltage	V	±5	±5
	Power supply current	A	±50	±50

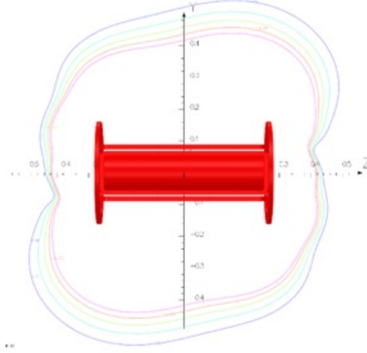
HWR007 (B0=7.3 T)



200 Gs line

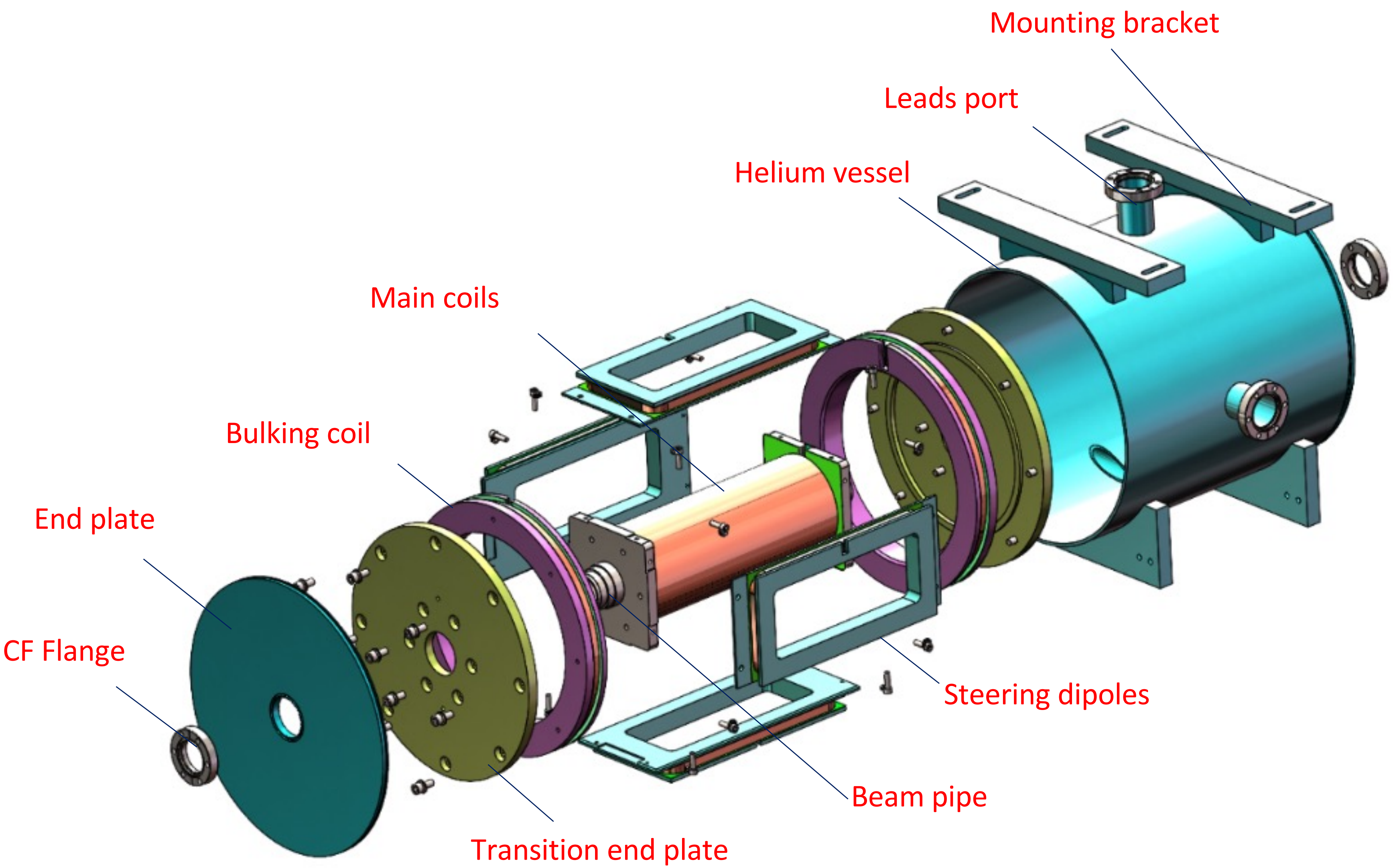


HWR015 (B0=7.6 T)



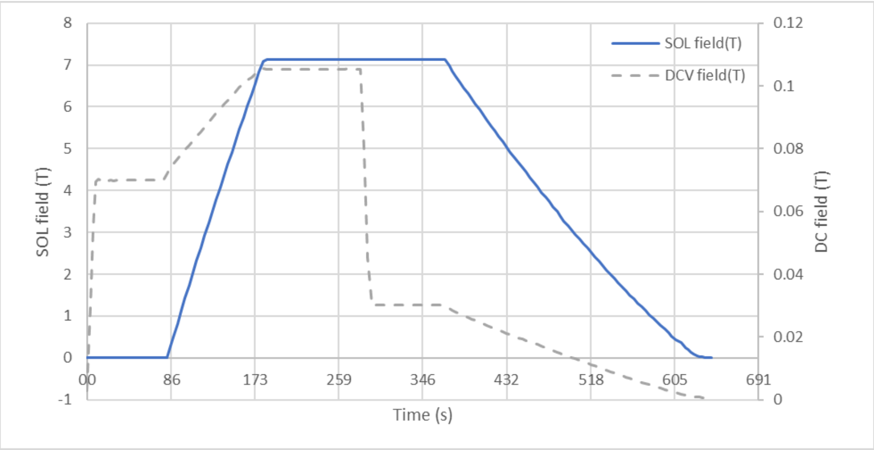
200 Gs line

Mechanical Design of Focusing Solenoid

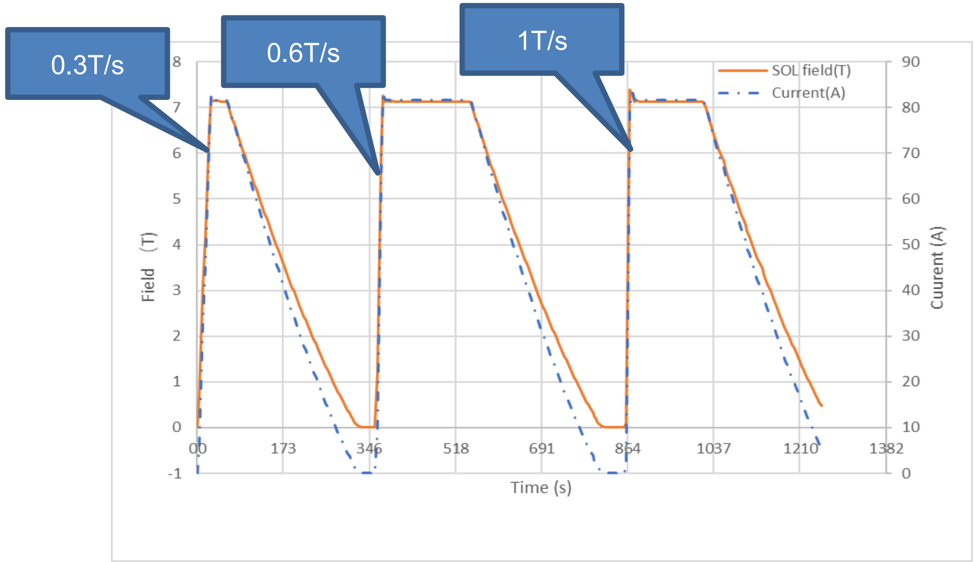


Prototype of Fast Ramping Focusing Solenoid

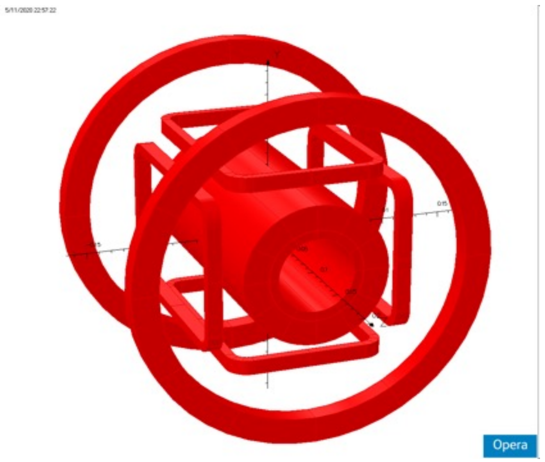
- For more efficient operation and fast lattice recovery in case cavity trip, focusing solenoids capable of fast ramping are required
- Fast ramping prototype with low AC loss NbTi/Cu/CuNi conductor has been developed
- Ramping rate of 1T/s reached

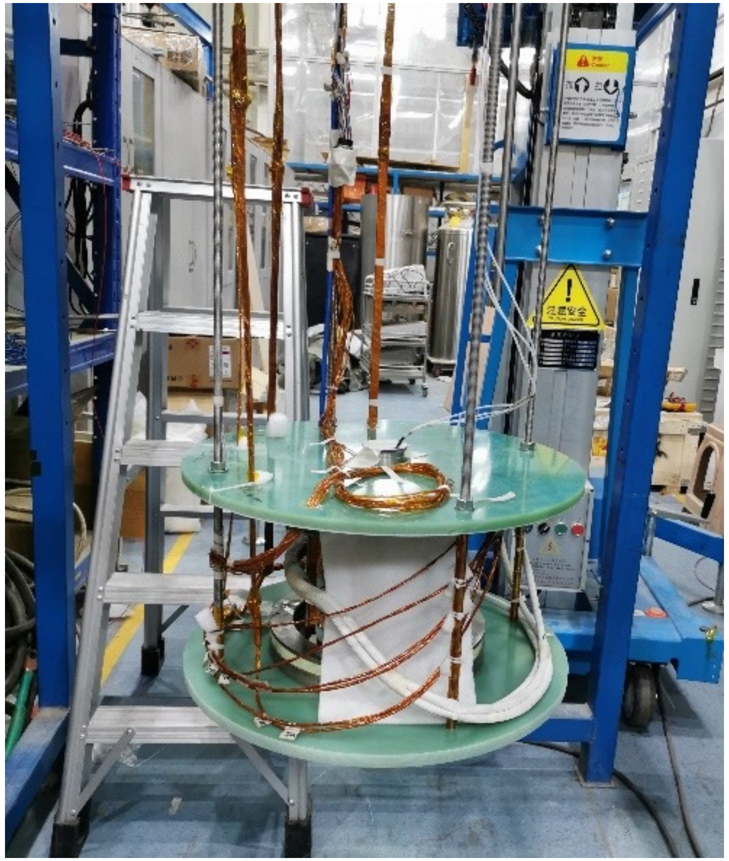


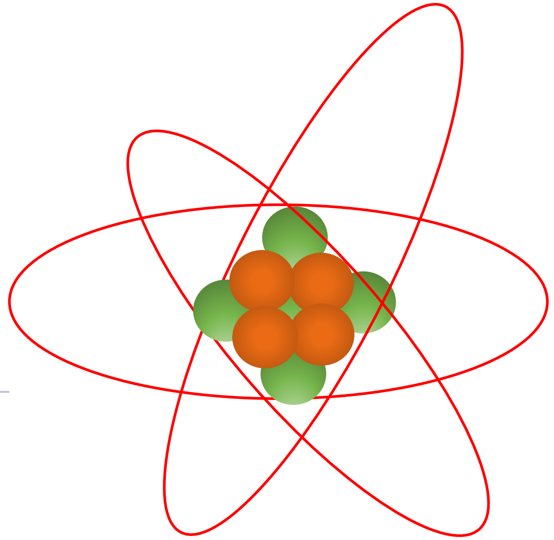
Fast ramping of solenoid and steering coils



Ramping test with different rates



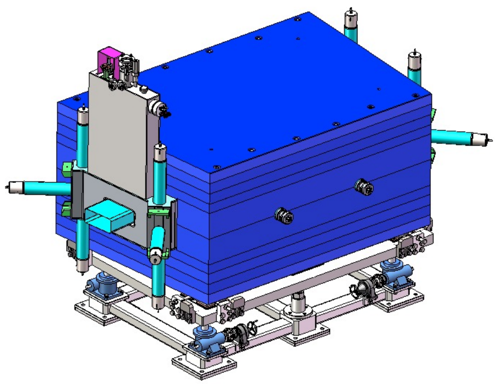




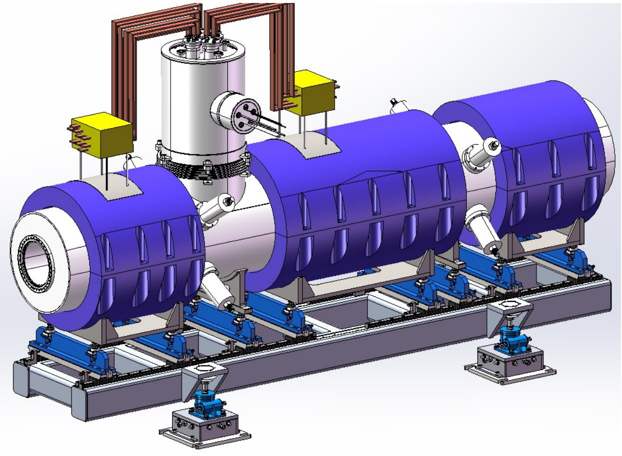
04 Dipoles and Multiplets for HFRS

Overview of HFRS Magnet System

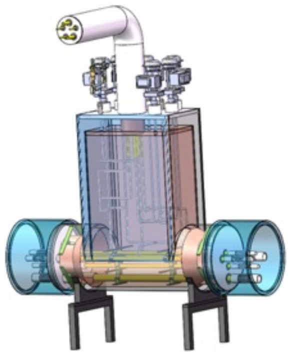
- First full superconducting beam line system in China
- Magnetic Rigidity: 25 T·m
- 180 m long, 24 sets of cryostat
- 600 W @ 4.5K, 6800 W @ 50K



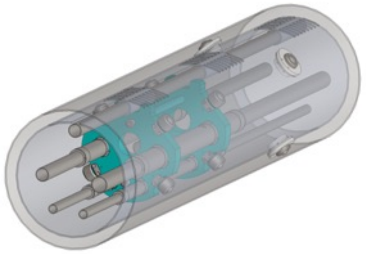
11 SC dipoles

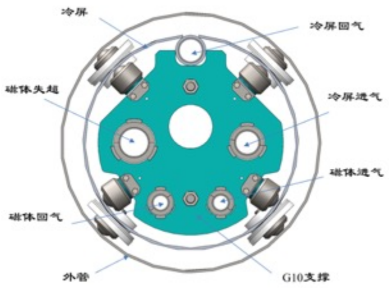


13 SC Multiplets

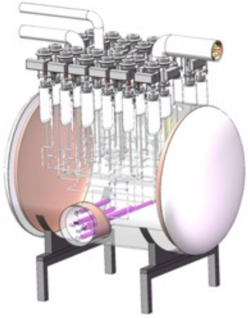


24 feed in boxes





Cryogenic transfer line

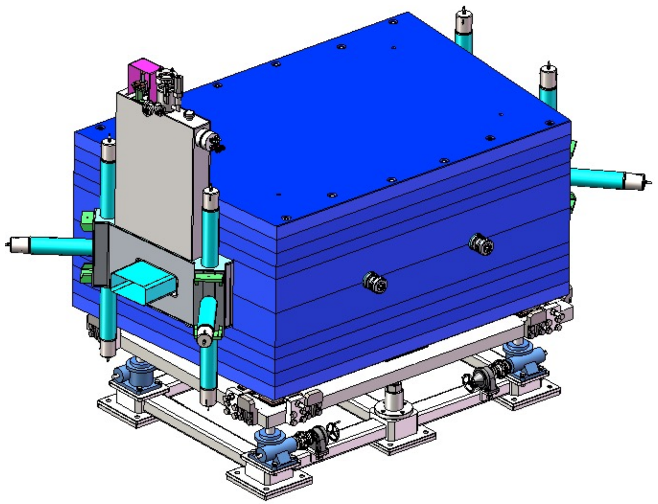


Distribution valve box

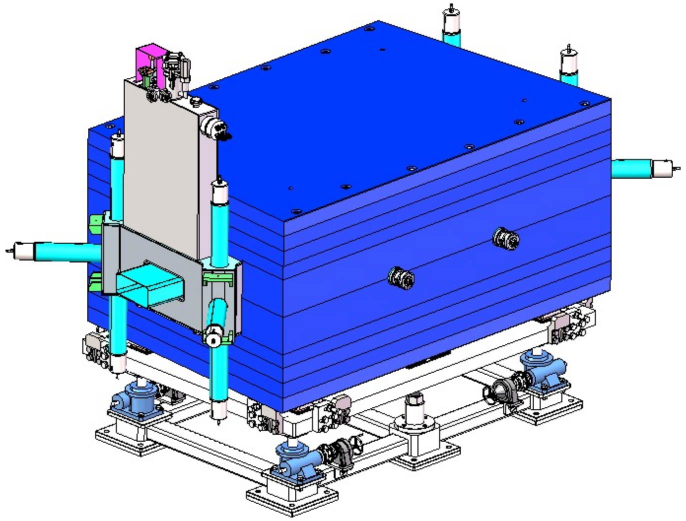
HFRS Superferric dipole

- Large good field region ($\pm 160 \times \pm 60$ mm^2)
- Superconducting coil & warm iron yoke

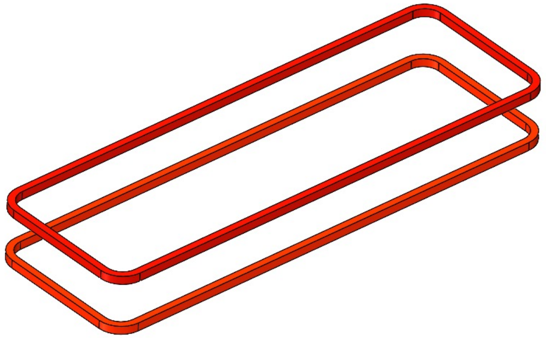
Effective length	2.74 m
Gap	160 mm
Central field	1.6 T
Operation current	210 A
Inductance	20 H
Weight of Iron	**40 t**
Cooling method	LHe bath cooling
Operation temperature	4.2 K



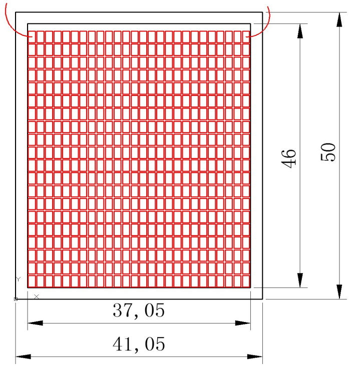
Type A: 7 sets



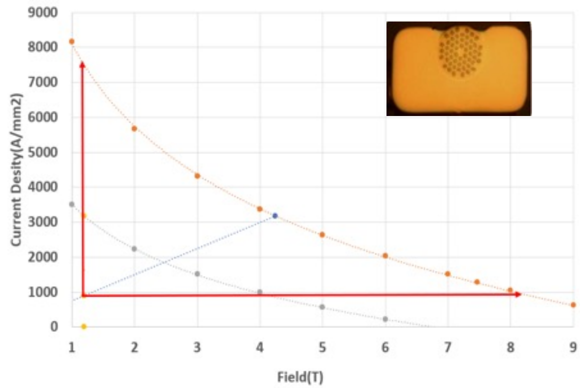
Type B: 4 sets



SC coil



Cross section of SC coil



Load line & working point （28.2%@1.6T)

Prototype coil

Status of Large bore SC Multiplets

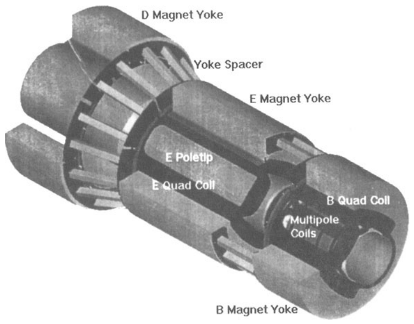
- Cold iron design is the most popular choice from A1900(1990s)

Cos. of cold iron superferric 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;
- Difficult for cold mass support and alignment. Triplets, sextupole and steering dipole **integrated** into modular cryostats. The longest magnet column is about **7 m**.
- Large helium containment will cause big pressure rise after a quench;

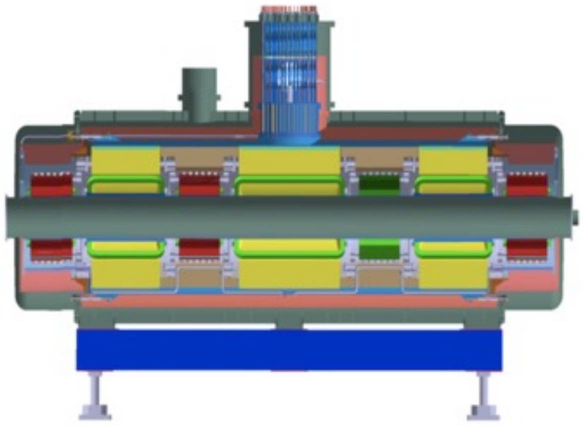
Comparison of existing and ongoing Fragment Separator Projects

	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



MSU/NSCL A1900 Triplet

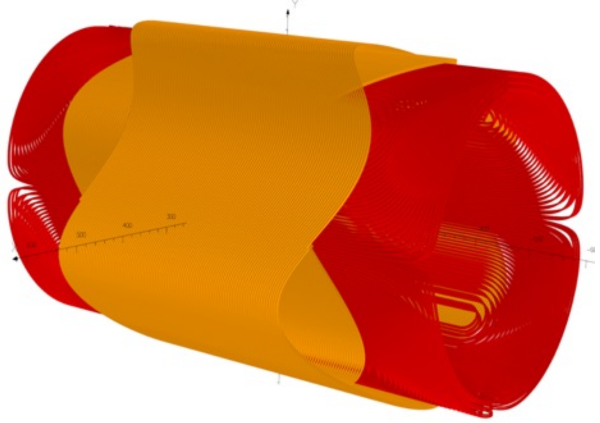
RIKEN Big-RIPS Triplet



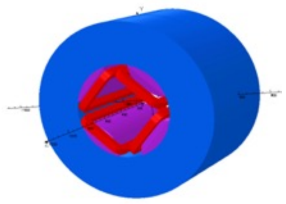
GSI/FAIR Super-FRS Multiplet

Light and Compact Multiplets for HFRS

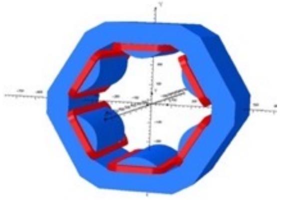
- Innovative nested Discrete Cosine Theta (DCT) & Canted Cosine Theta (CCT) EM design
- DCT quadrupole for shorter ends and higher efficiency
- CCT sextupole for easier fabrication and winding
- Warm iron: field shielding, good field linearity and smaller cold mass
- 1/10 cold mass weight of superferric design
- Nested design reduce the beam line length



SC coils of HFRS multiplets

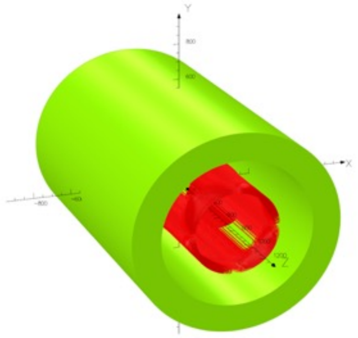


Quadrupole

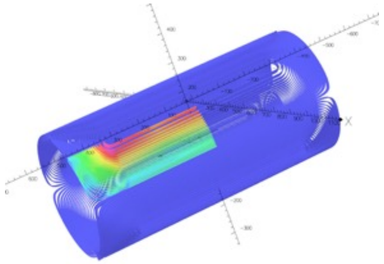


Sextupole

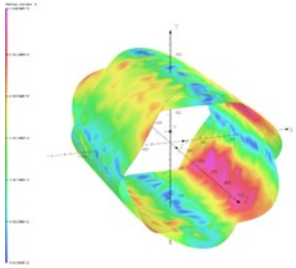
Superferric（40 tons）



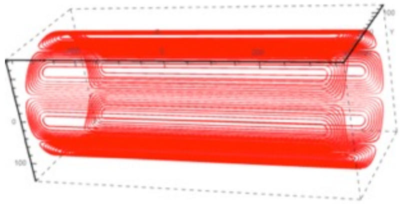
Nested DCT & CCT （4 tons）



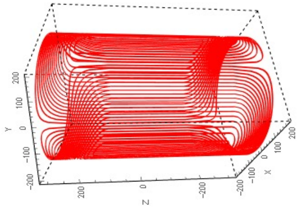
Quadrupole (DCT)



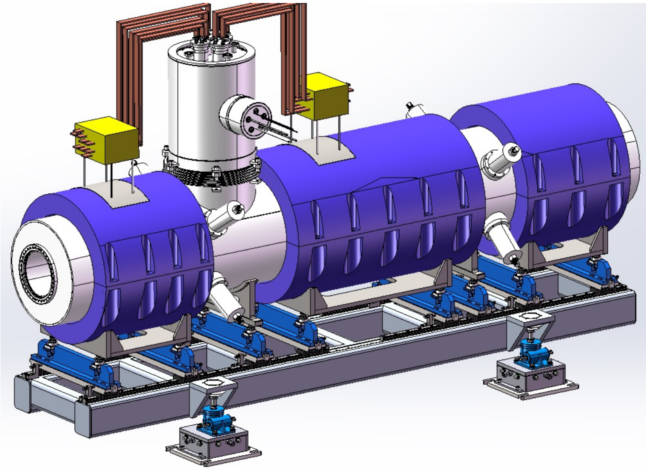
Sexpole (CCT)



Octupole (DCT)



Steering dipole (DCT)

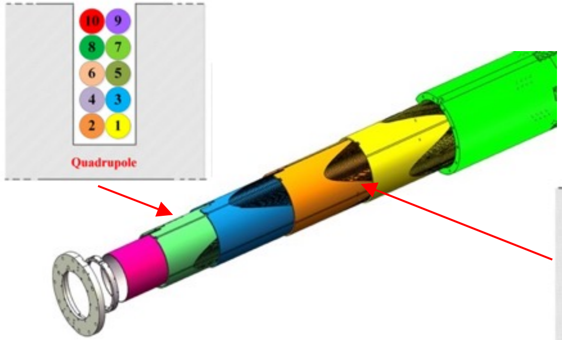


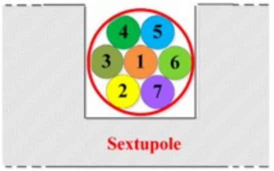
Cryostat for HFRS Triplets

Half Aperture Prototype

Refer to the details in POSTER: THU-PO3-108-02

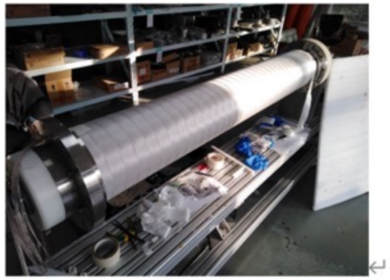
- Φ200 mm prototype fabricated and tested
- After only one quench, reached design current





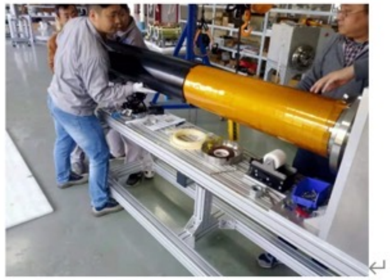
- Two layers of CCT quadrupole
- Two layers of CCT sextupole
- Al alloy mandrel

Winding of CCT quadrupole

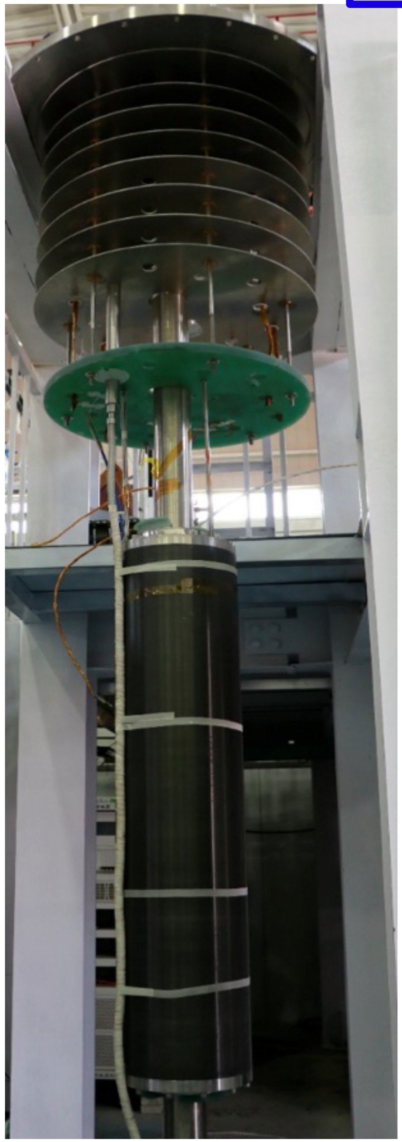


Wrap of fiber glass tape

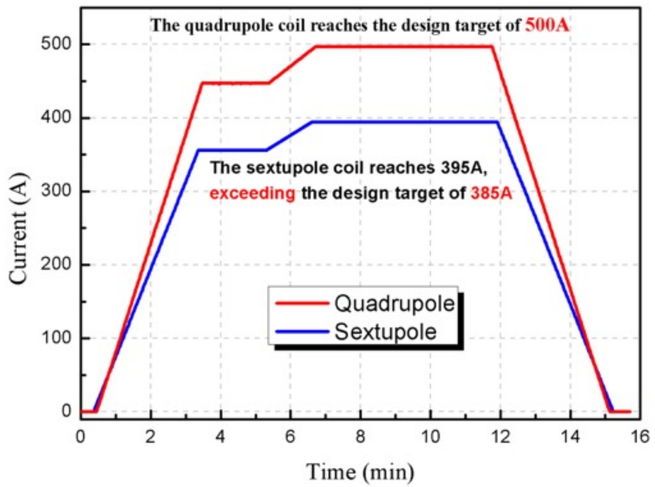
Kapton for inter mandrel insulation



Installation of outter mandrel



Sextupole coil winding



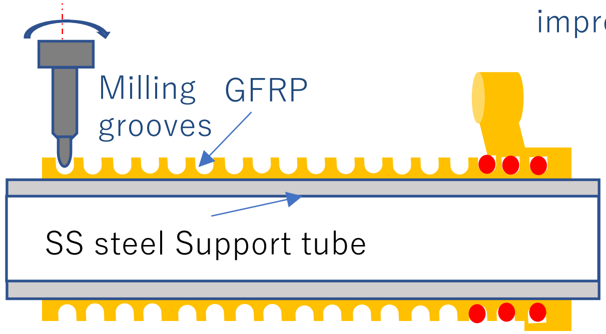
Quadrupole and Sextupole energized to design current simultaneously

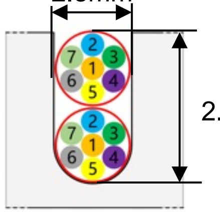
Full-Size Prototype

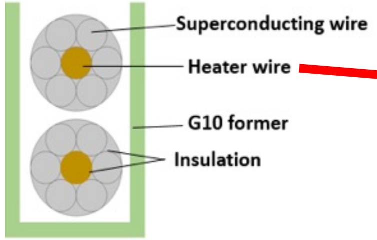
- 6 around 1 insulated cable embedded in grooves
- GFRP coil former, CNC machined grooves
- Dump resistor combined with Quench back effect from center copper heater for quench protection. Overcome the heat conduction problem of GFRP former

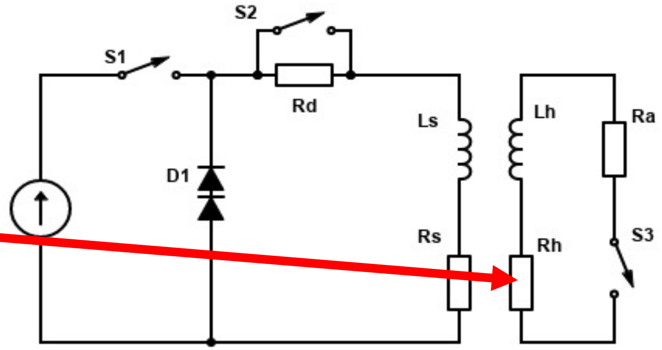
Refer to the details in POSTER: TUE-PO1-705-01

Wind with glass fiber and impregnate with resin

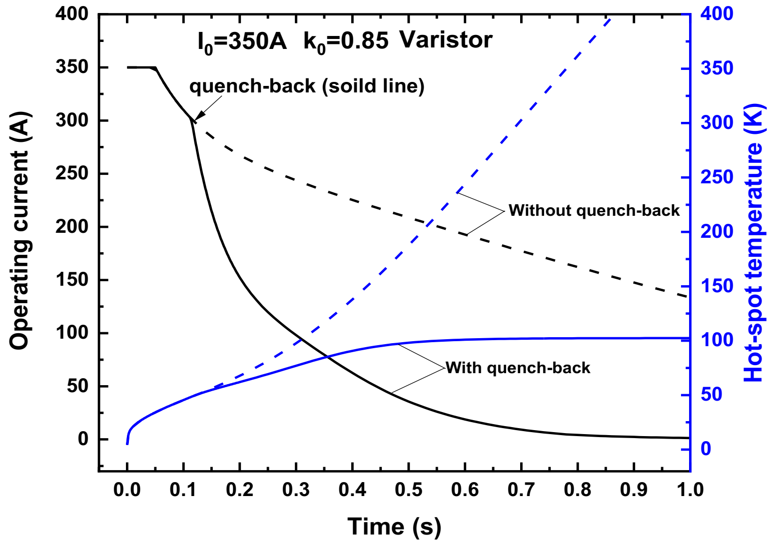


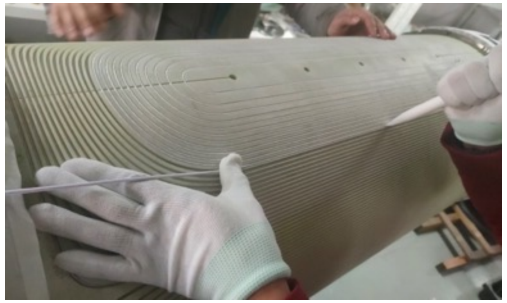




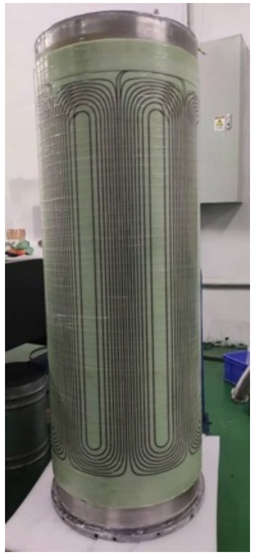


Non-linear quench back protection

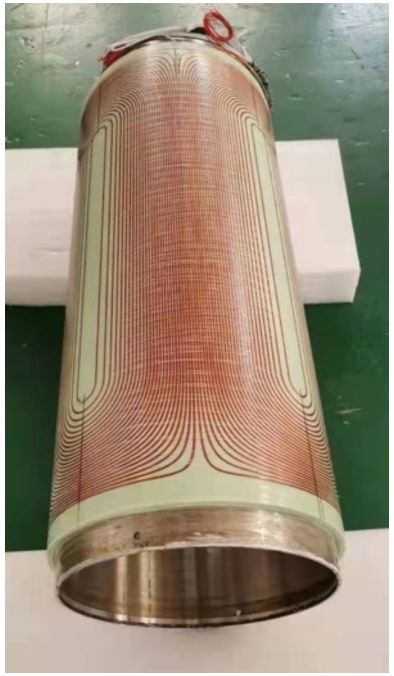




Winding process



Octupole

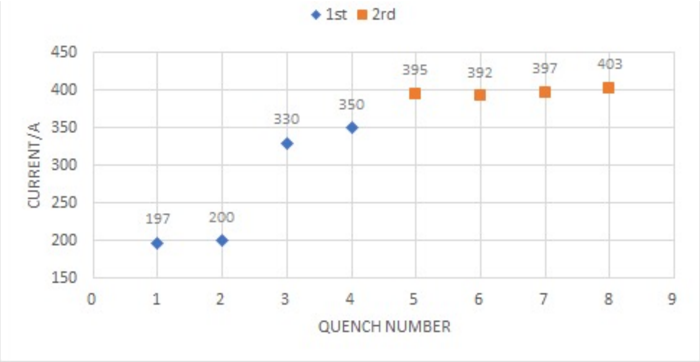


Quadrupole

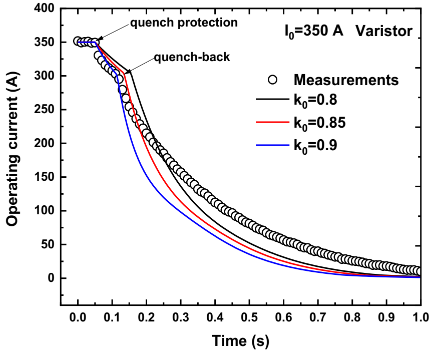
Evolution of current and hot-spot temperature with and without quench back

Cryogenic Test of the Full-Size Prototype

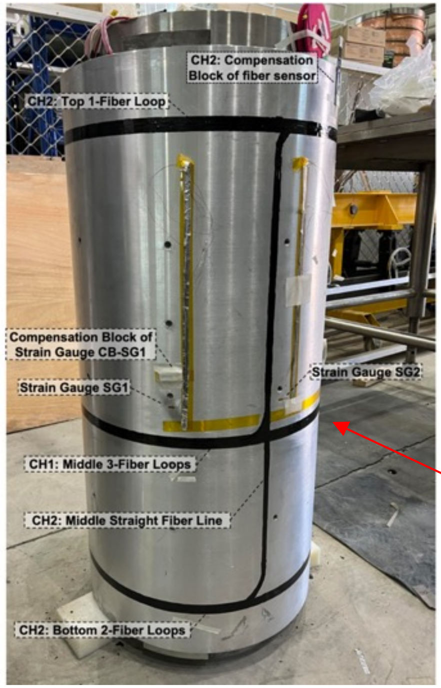
- After 8 quenches, 403 A reached
- Due to helium shortage, training was interrupted
- The quench simulation data agree well with experiments
- Strain measured with resistance strain gauge & optical fibers

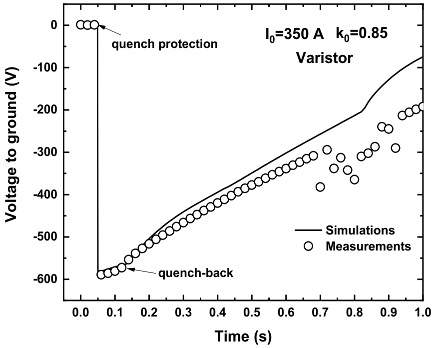


Training history of the full-size prototype

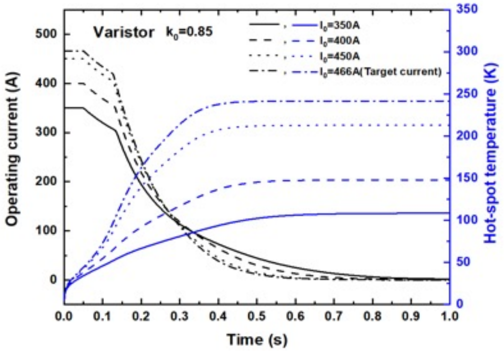


Comparisons of simulated and measured current of a quench at 350A

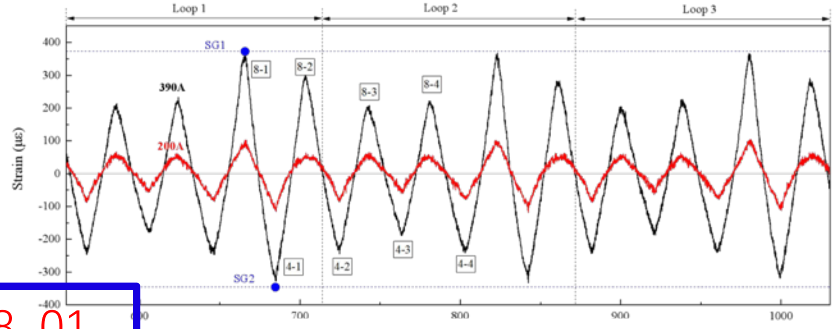




Comparisons of simulated and measured voltage-to-ground of a quenched magnet at 350A

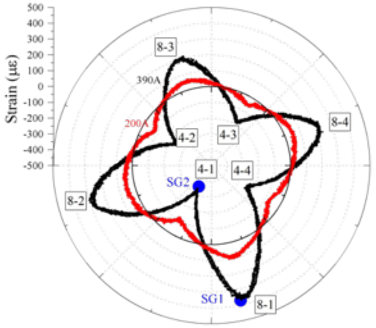


Evolution of current and hotspot temperature of different current



Strain along the optical fibers

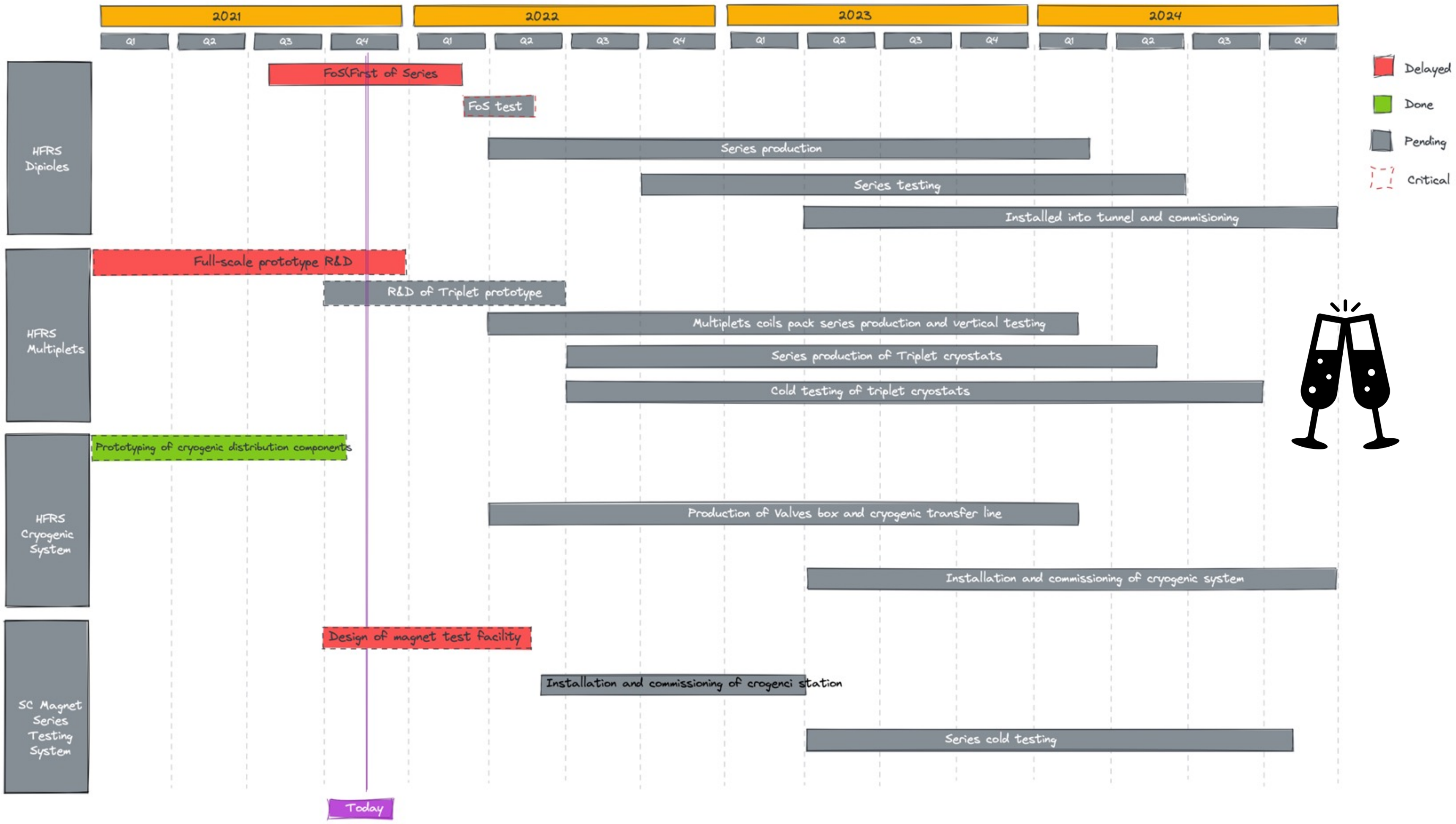
Convert to polar coordinates



Measured strain around the Al shell during charging (200A, 390A)

Refer to the details in POSTER: THU-PO3-108-01

Status and Outlook



Thanks！

Our team would like to thank

Dr. Sabbi GianLuca, LBNL

Dr. Emmanuele Ravaioli and Dr. Mariusz Juchno, CERN

for their pioneering work on the design of FECR

thank

Glyn Kirby, CERN

for his constructive suggestion and help on CCT magnet