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High-field superconductors and superconducting magnets for ECRIS and frontier nuclear physics

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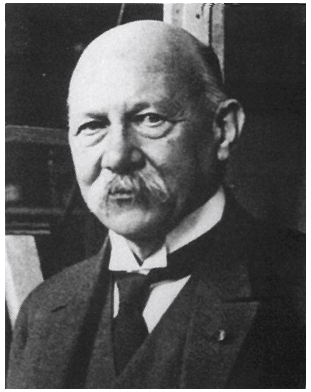
Talk given at the Accelerator Physics/Engineering Seminars, Facility For Rare Isotope Beams, Michigan State University

2024/04/19

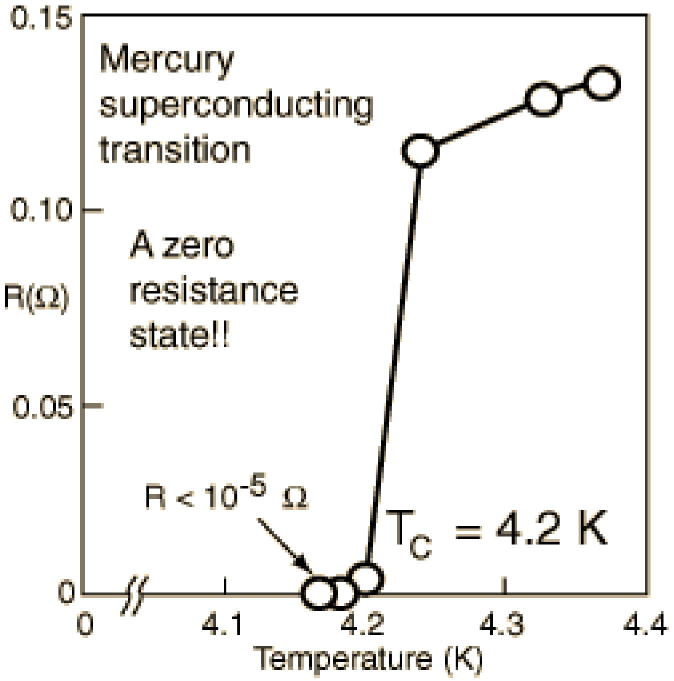
Outline

- **High field superconductors**
- **Superconducting magnets for DOE complex**
- **ECRIS superconducting magnets – Nb-Ti and Nb_3Sn.**
- **HTS (high-temperature superconducting) conductors and applications (if we have time)**

100 years of superconductivity, 60 years of superconducting magnets



Heike Kamerlingh Onnes



Discovery and understanding mechanisms and **magnetic properties** of superconductors

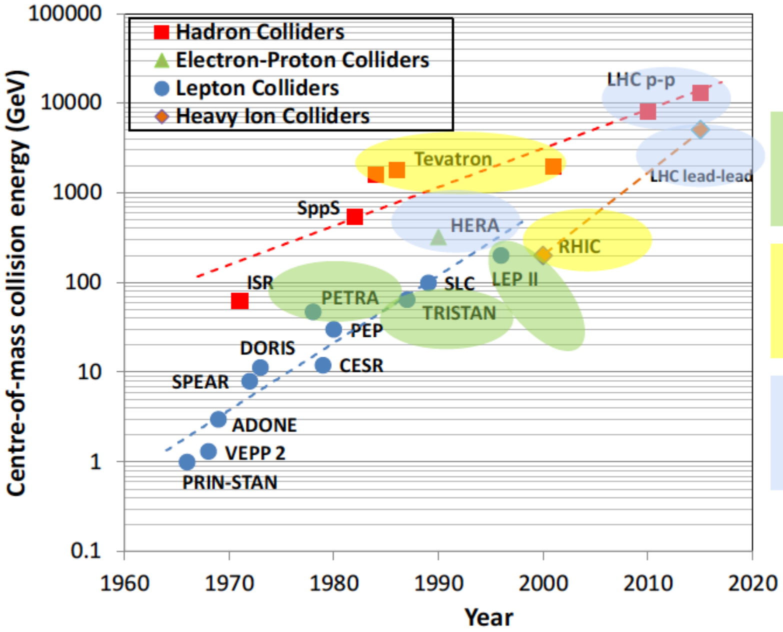
- 1911 – Discovery of superconductivity
- 1957 – Type II superconductors and Abrikosov vortex
- 1957 – BCS theory

- 1961 – High-field superconductivity in Nb_3Sn
- 1962 – Josephson effect
- 1983 – Tevatron – the first large application of superconductivity
- 1980s - MRI
- 1986 – High temperature superconductivity in cuprates
- 2008 – LHC
- 2027 – ITER – first plasma?

Engineering and practical applications

- 2001 – MgB_2
- 2008 – iron-based superconductors

Superconductivity and particle accelerators: The good companions

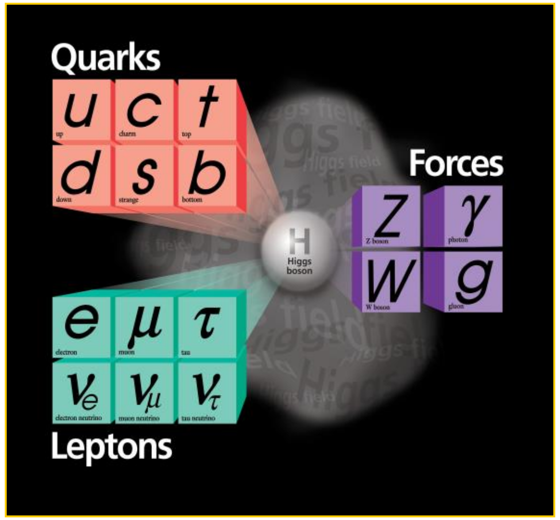


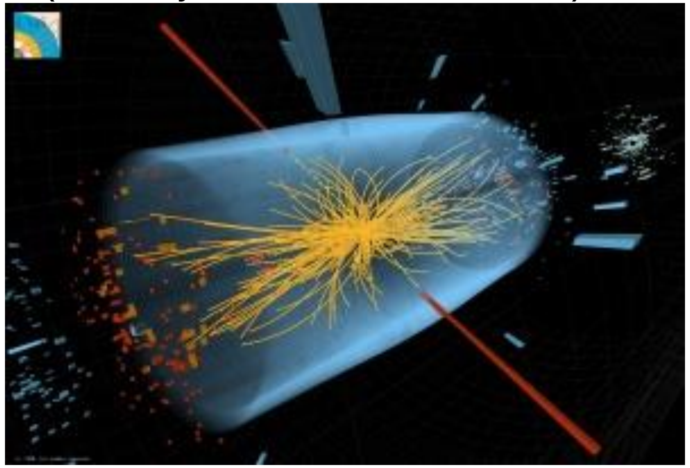
(courtesy of CERN, M. Benedikt)

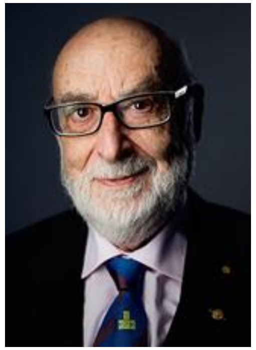
Colliders with superconducting RF system

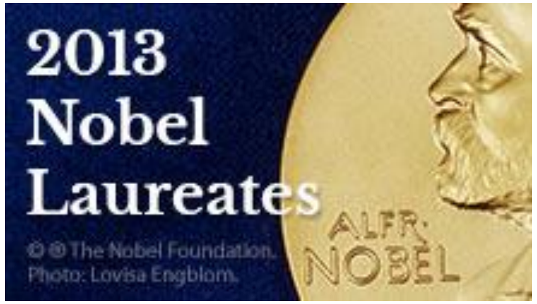
Colliders with superconducting arc magnet system

Colliders with superconducting magnet & RF









Magnetic steering and lens: Superconducting bending dipoles and focusing quadrupoles

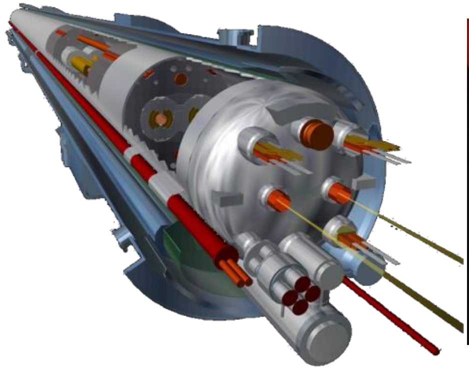
Magnets drive the energy reach.

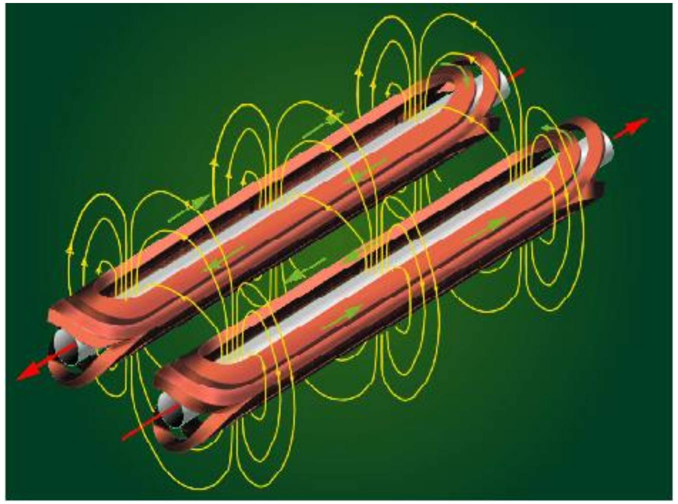
Beam energy, Bending radius

$$E[GeV] = 0.3 \times B[T] \times \rho[m]$$

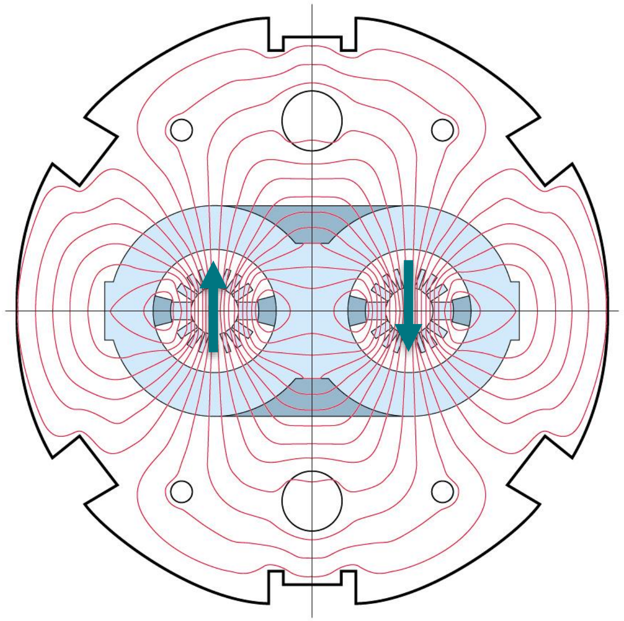
Dipole field

1232 x 15 m, 8.3 T dipole





LHC dipole

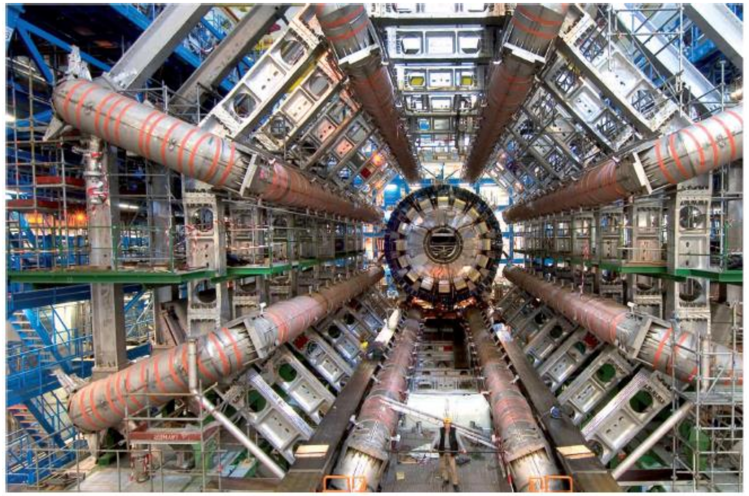


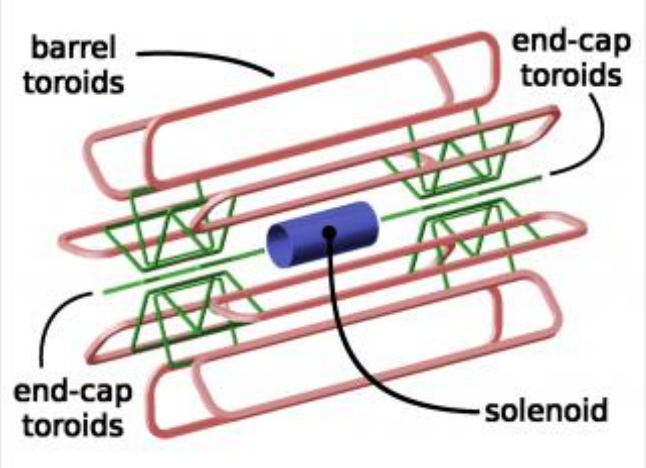
Computed magnetic flux map at B_0=10 Tesla

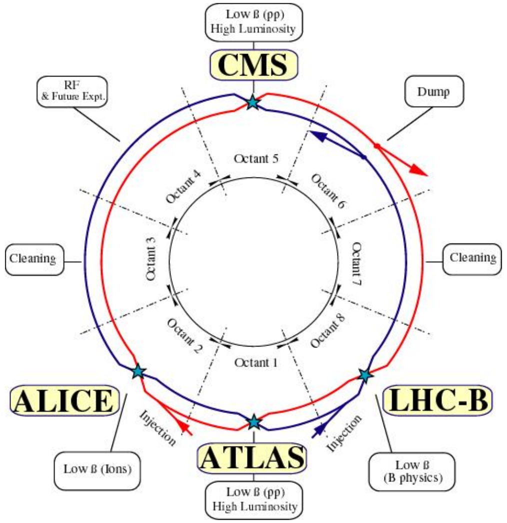
(courtesy of CERN, L. Rossi, M. Benedikt)

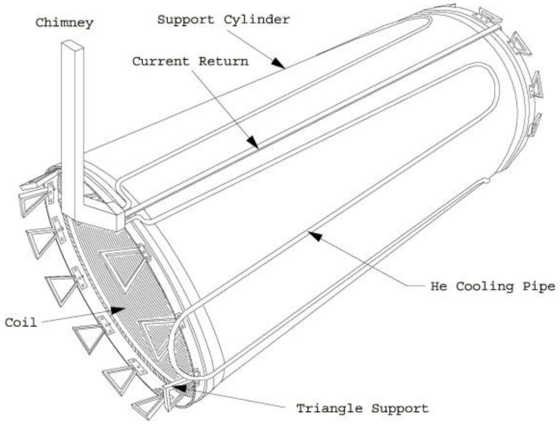
Powerful superconducting detectors – ATLAS and CMS – eyes of LHC

ATLAS









- Solenoids

Resolution, Momentum

$$\frac{\Delta p}{p} \propto \frac{p}{B\ R^2}$$

Coil radius; Solenoid field

- Toroids

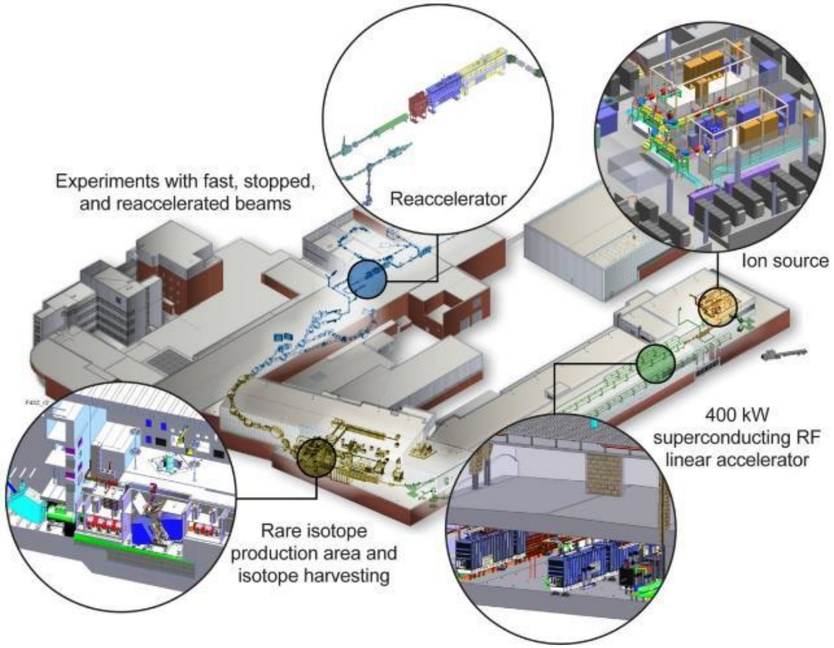
Resolution, Momentum, Forward angle

$$\frac{\Delta p}{p} \propto \frac{p \sin(\theta)}{B_{in}\ R_{in}\ \ln(R_{out}/R_{in})}$$

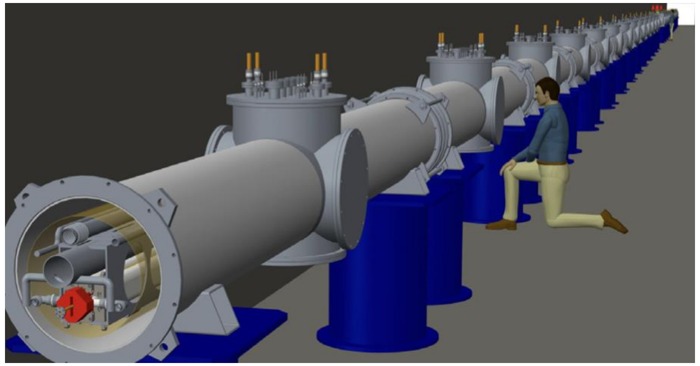
Toroidal peak field; Outer toroid radius; Inner toroid radius

Advanced superconducting magnets impact DOE-SC more broadly

- **Critical to Nuclear Physics:**
  - FRIB – high power ECR sources and high rigidity spectrometer
  - EIC – complex interaction region magnets
  - JLAB – central to 12GeV Upgrade
- **Critical to Basic Energy Sciences**
  - Novel end station magnets
  - Superconducting undulators
- **Central to Fusion Tokamaks and Stellarators**
  - Particularly for compact Tokamaks

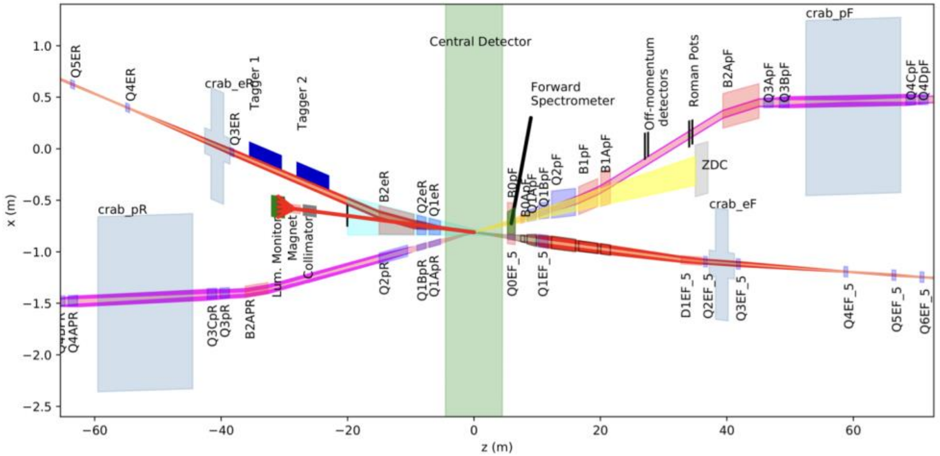


J. Wei et al.



P. Emma et al., Proceedings of FEL2014

Zhang & Calvi, Supercond. Sci. Technol. 35 (2022)



H. Witte et al., IPAC 2021, doi:10.18429

Slide courtesy of Soren Prestemon

Superconducting MRI market – large and growing

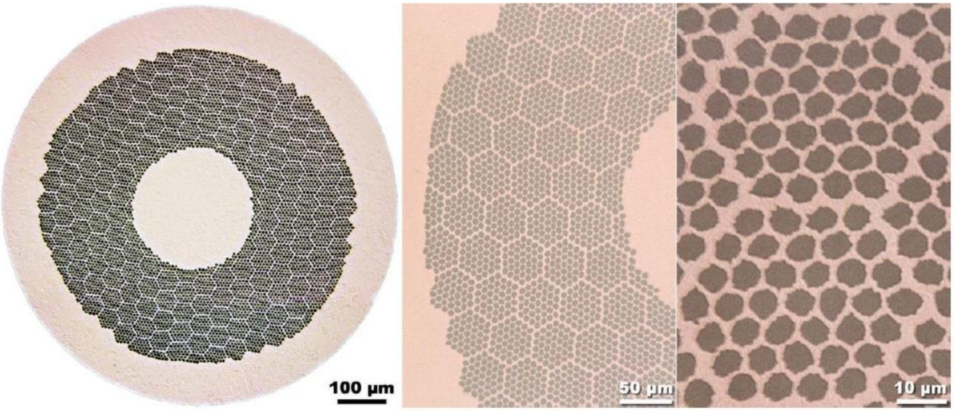
- 40,000 units installed, with 4000 scanners added annually (90% superconducting)

- Conductor is single most expensive MRI component.
  - … but still less than 25% cost of a commerical scanner.
- Nb-Ti price: about $1-2/kAmp-m at 4.2 K and 4 T.

Superconducting magnets are more than just providing a high magnetic field.

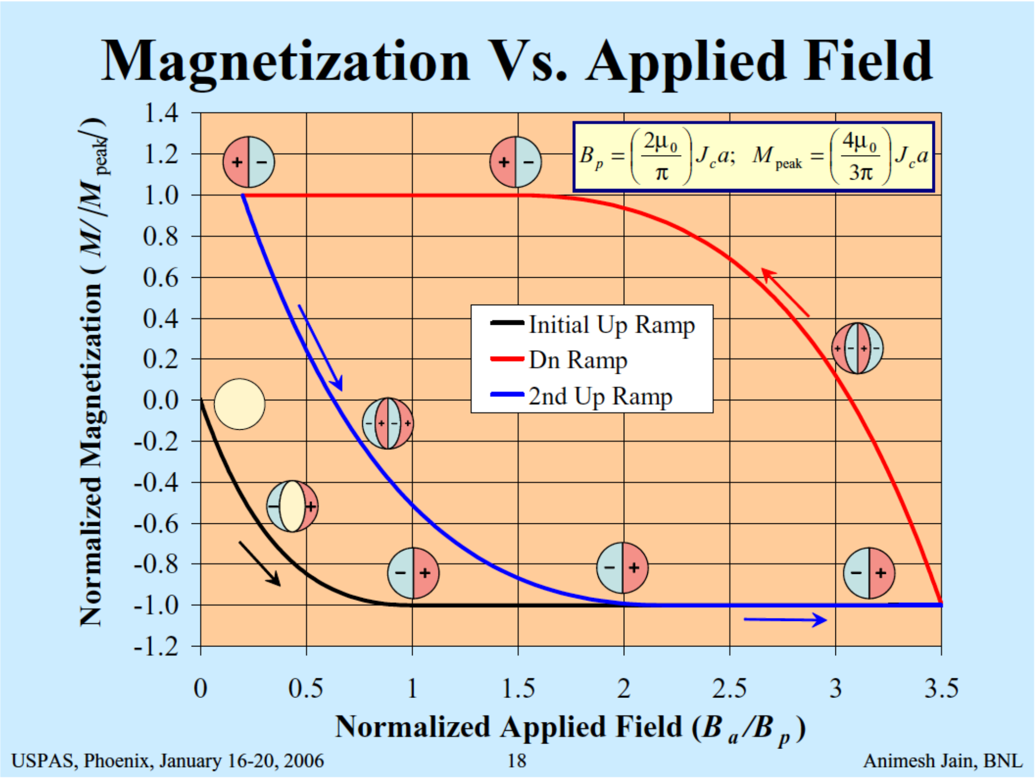
- **Field quality matters for MRI (ppm), NMR (ppb), HEP (10^{-4}) and NP colliders.**
    - **Both temporal and spatial**
- **MRI and NMR magnets enabled by <u>persistent current operations</u> with field decaying at $\tau = L/R$ with $R < 10^{-12}$ ohm provided by superconducting joints.**

Practical superconducting wires and (unfortunately) they are a nonlinear magnetic material



Rossi, L. (2010). Superconductivity: its role, its success and its setbacks in the Large Hadron Collider of CERN *Superconductor Science and Technology*, *23*, 034001

- As described by the **Bean Model**.



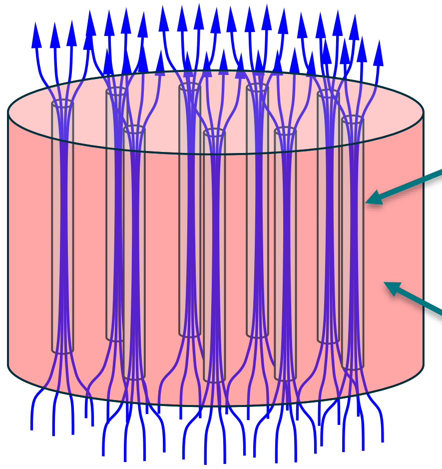
- $\Delta M \propto J_c \cdot D_{eff}$
- **LHC Nb-Ti dipole wire, D_{eff}=6-7 μm.**
- **High-Lumi LHC Nb_3Sn wire, D_{eff}~50 μm.**

- **Practical superconducting wires are multifilamentary, twisted, and embedded in metal (Cu).**

Abriskosov vortex penetrates into Type-II superconductors

Vortex pinning is the foundation of the high J_c superconductors

Type II superconductors ($\kappa > 1/\sqrt{2}$)



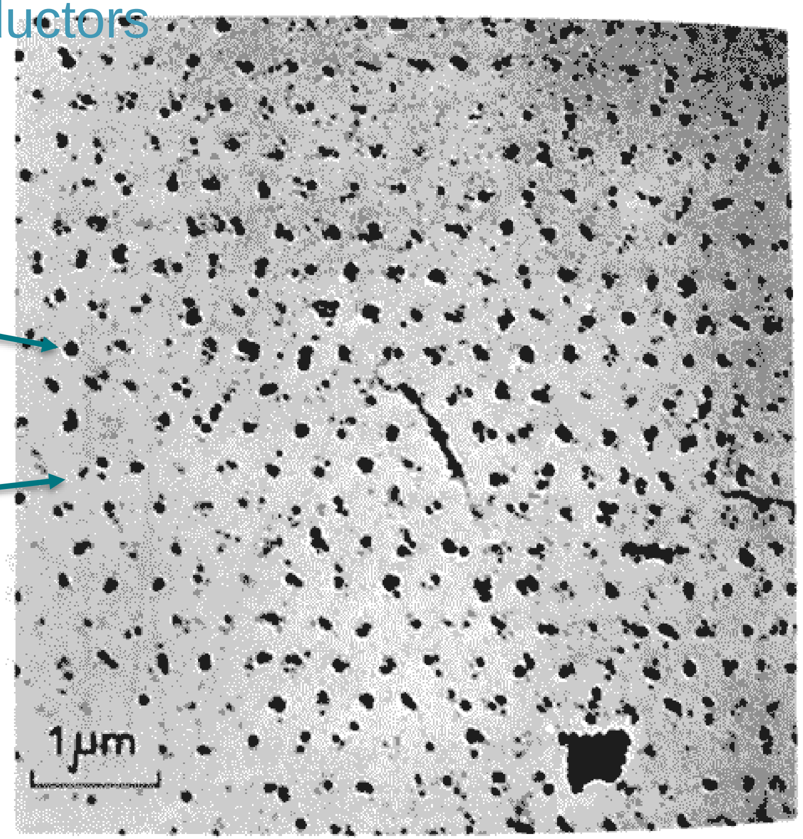
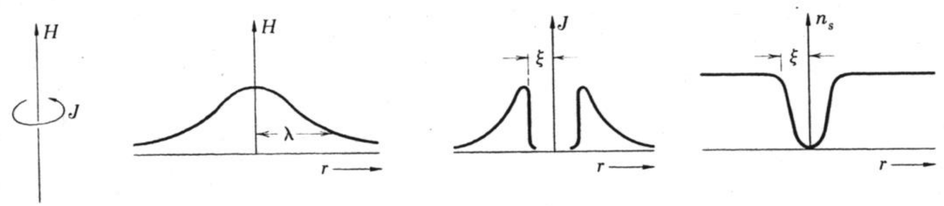


Fig. 1. "Perfect" triangular lattice of flux lines on the surface of a lead-4at% indium rod at 1.1°K. The black dots consist of small cobalt particles which have been stripped from the surface with a carbon replica.

Ginzburg, Landau, Abrikosov, Gor'kov, 1950-1957



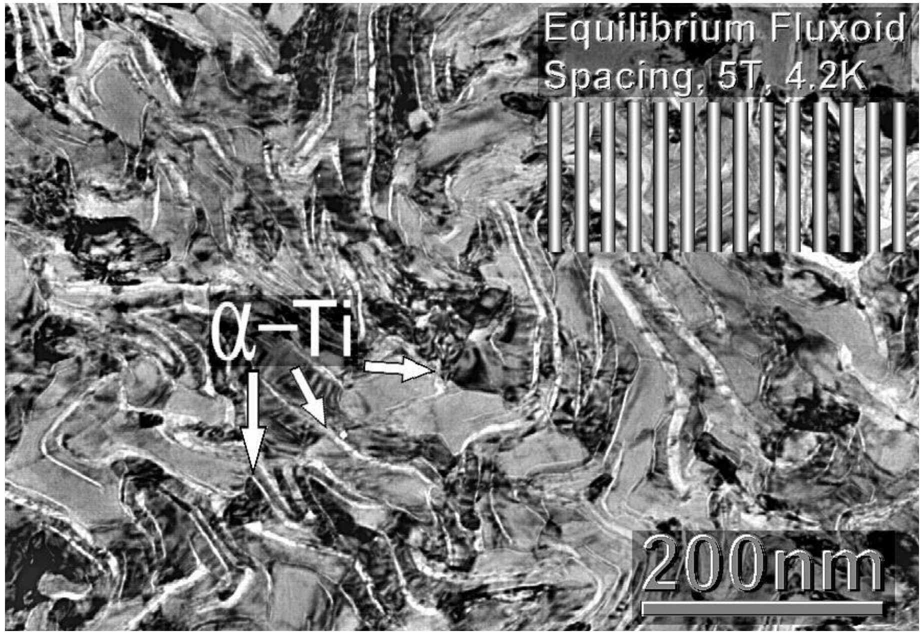
Flux flow under Lorentz force creates Joule heating.

d*B*/d*t* induces heat – AC loss – in superconductors.

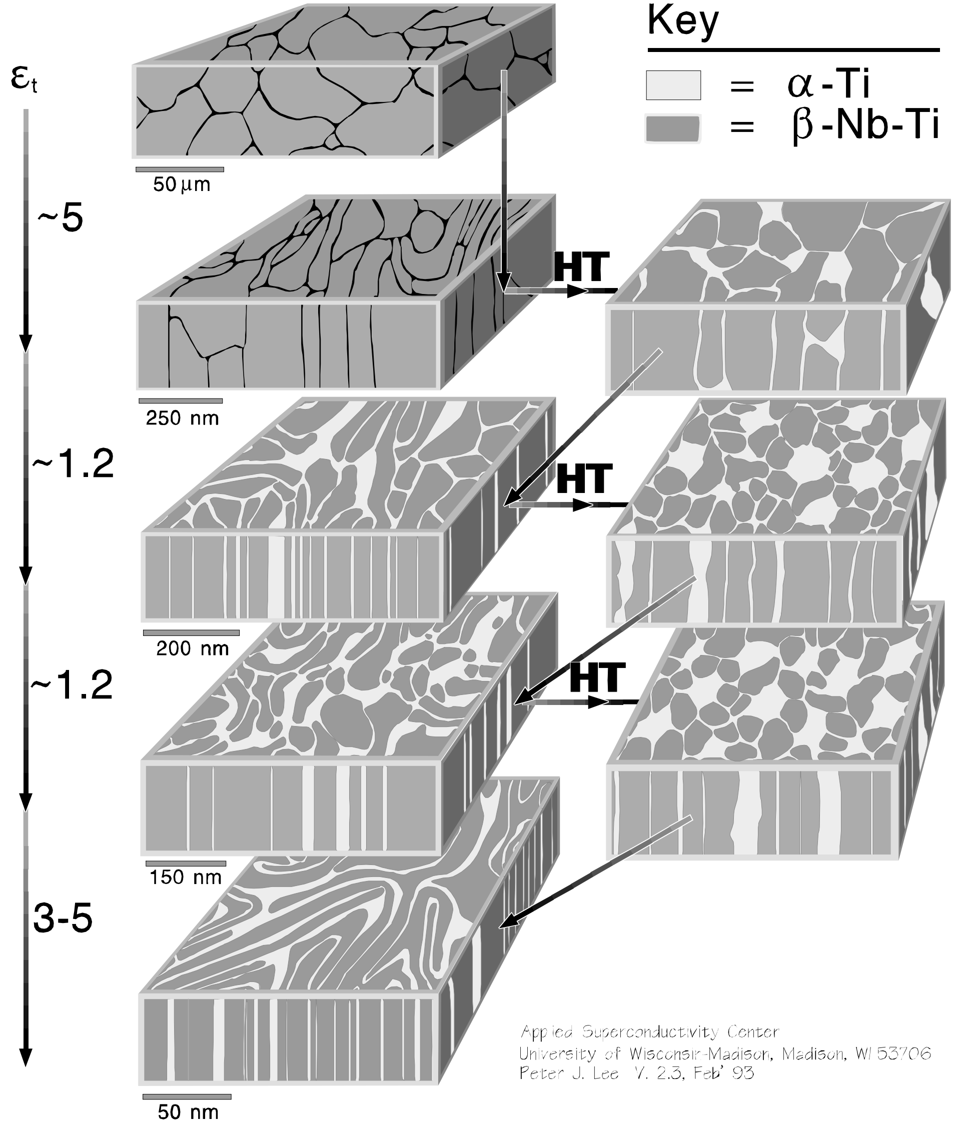
Unfriendly for power applications.

Superconductors are engineered at microscopic scale to maximize flux pinning and J_c

via heat treating, alloying and cold work



Microstructure of Nb-Ti

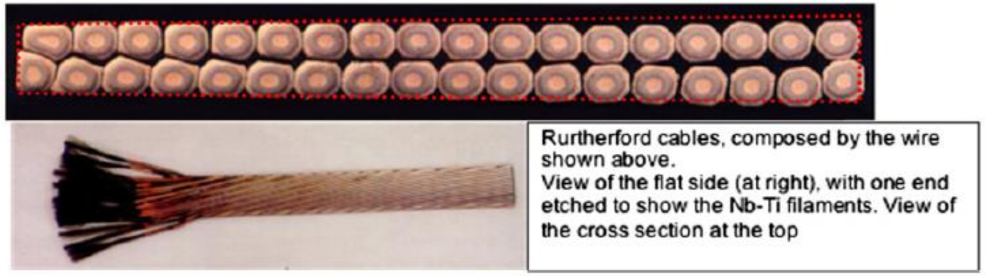


D. Larbalestier, and P. Lee, NHMFL

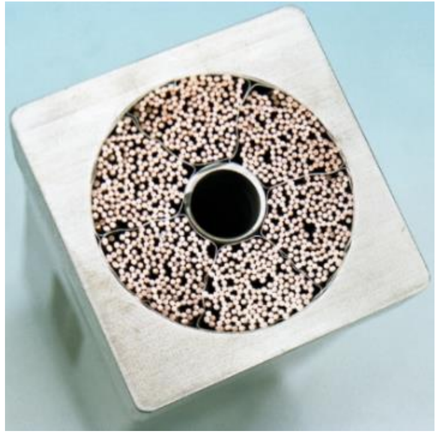
The real magnet conductors are much more than monolithic wires

- Magnet sizes (physical and stored energy).
- Field strength and real-estate available to create magnetic field.
- Whether magnet is DC or pulsed.
  - DC: NMR solenoids.
  - Pulsed: HEP main ring dipoles and fusion tokamak CS and TF coils
  - High-current cables used for pulsed magnets.
- Field quality requirements.
- The need to minimize quenches.
- Cooling method/facility.

Rutherford cable for HEP magnets

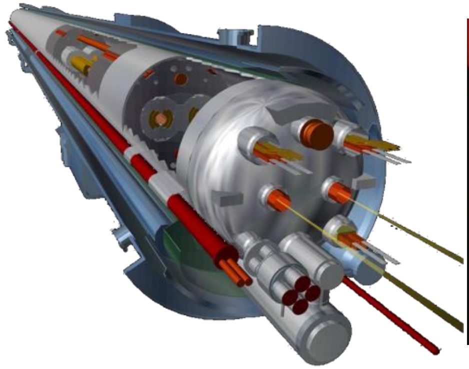


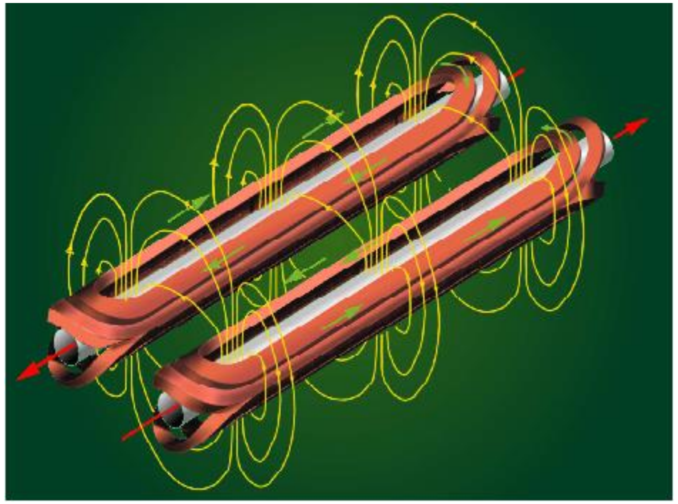
Cable in conduit cable (CICC) for fusion



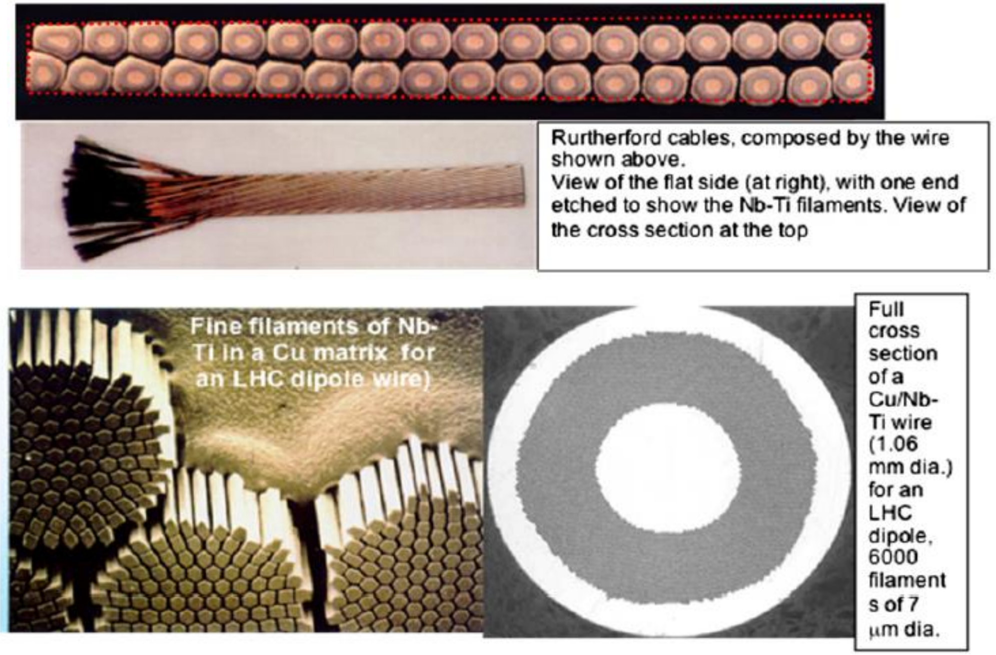
LHC uses >1000 superconducting bending dipoles and focusing quadrupoles, based on 5-20 kA Rutherford cables

1232 x 15 m, 8.3 T LHC Nb-Ti dipole, 1.8 K helium II cooling





Rutherford cable

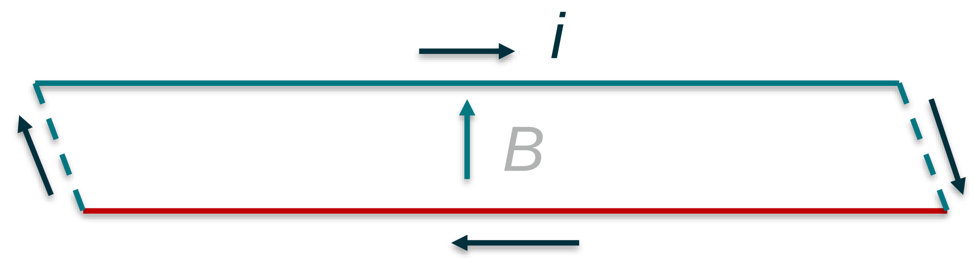


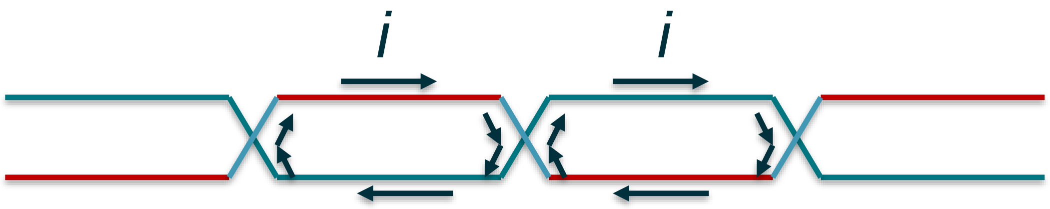
Rossi, L. (2010). Superconductivity: its role, its success and its setbacks in the Large Hadron Collider of CERN *Superconductor Science and Technology*, *23*, 034001

(courtesy of L. Rossi and M. Benedikt, CERN)

The ingenious engineering of Rutherford cable – making strands carry equal currents

- **HEP accelerator magnets are pulsed.**
- **Two parallel conductors joined at ends will have a large loop current flow.**



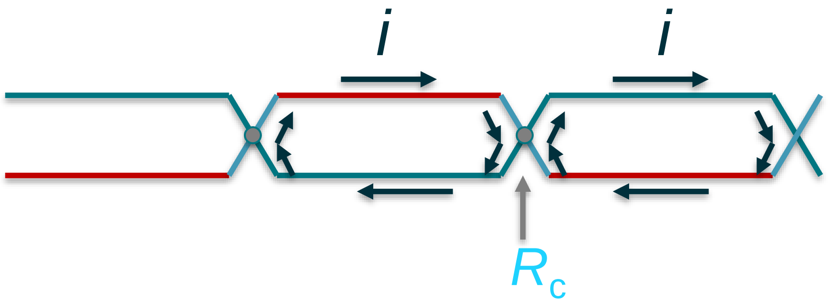


- **Fix – Rutherford cable**
  - **Inside a strand: Filaments are twisted.**
  - **Inside a cable: Strands are twisted and transposed.**

Easy fabrication – strands carrying equal currents – high packing factor

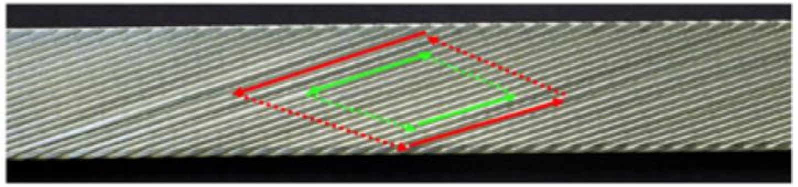
The ingenious engineering of Rutherford cable and Tevatron/LHC dipole magnets: Having the right contact resistance

- **HEP accelerator magnets need the field accuracy in the order of 10^{-4}.**



Each loop has a dipole field.
Field decreases with a time constant of $L/2R_c$

Inter-strand resistance control.



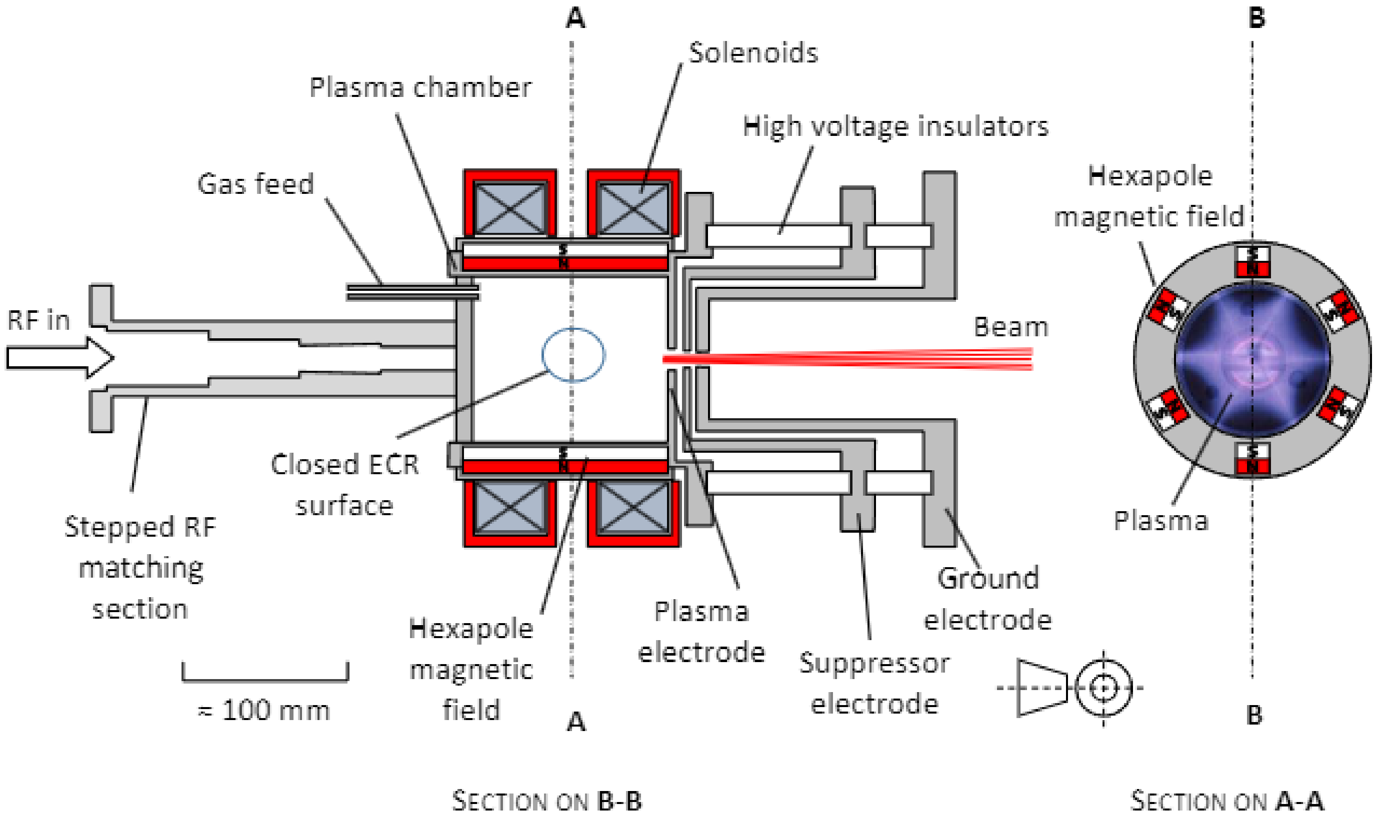
Contact resistance R_c: >10 micro-ohm, <100 micro-ohm.

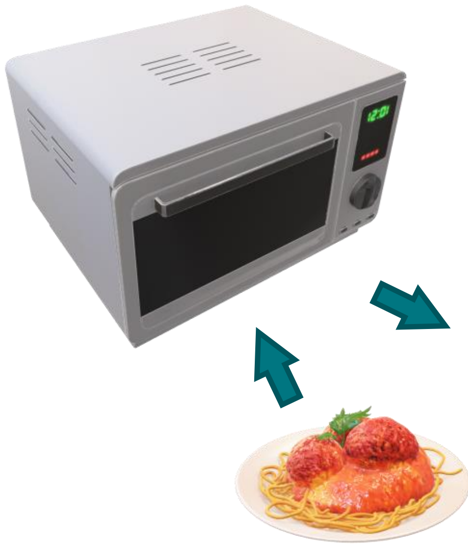
- **Value too low gives field errors**
- **Too high may give instability**

CERN has developed the controlled oxidation method after precise coating with staybrite (Sn-4%Ag)

Rossi, L. (2010). Superconductivity: its role, its success and its setbacks in the Large Hadron Collider of CERN *Superconductor Science and Technology*, *23*, 034001

How to make an ECR ion source?

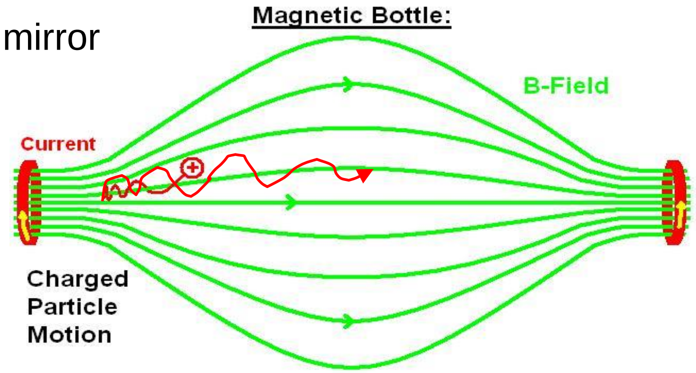


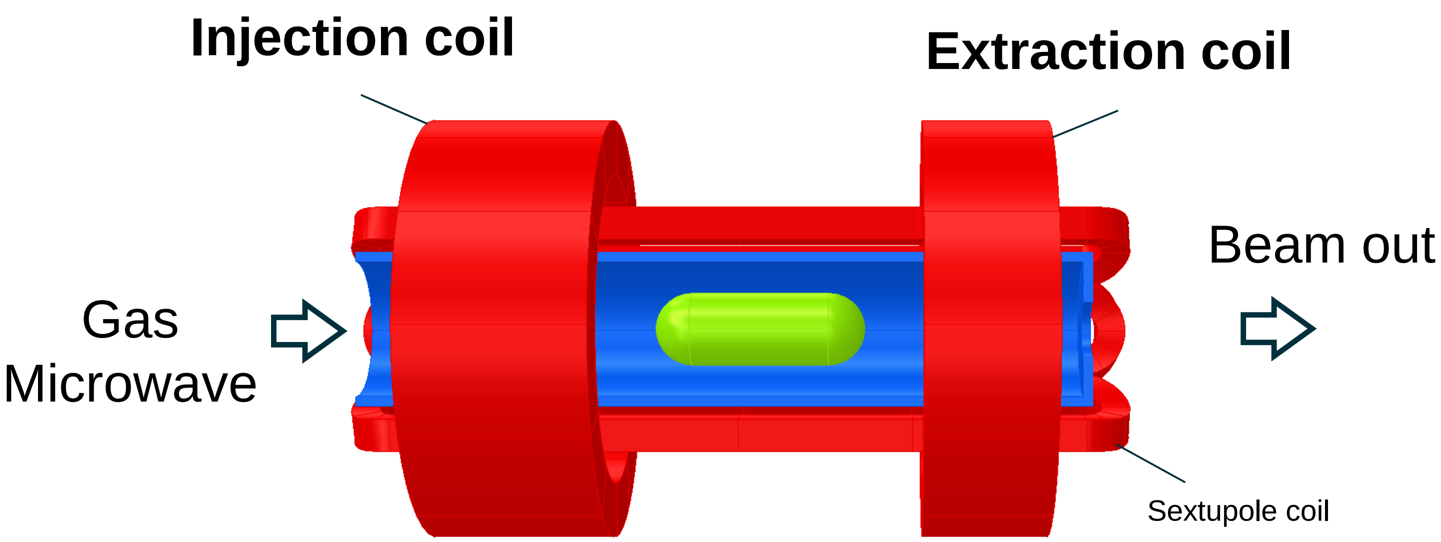


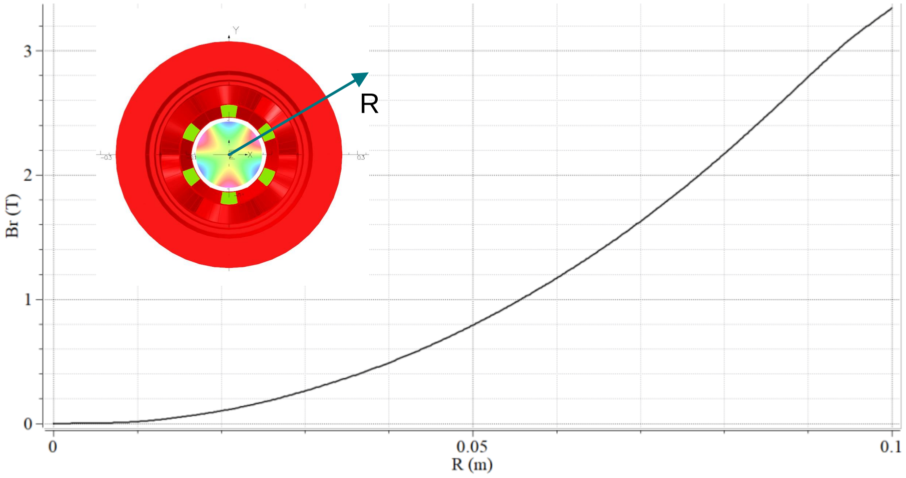
- **Input the gas**
- **Close the gas with the magnetic mirror**
- **Heat the gas with the microwave**
- **Extract the beam with the high voltage**

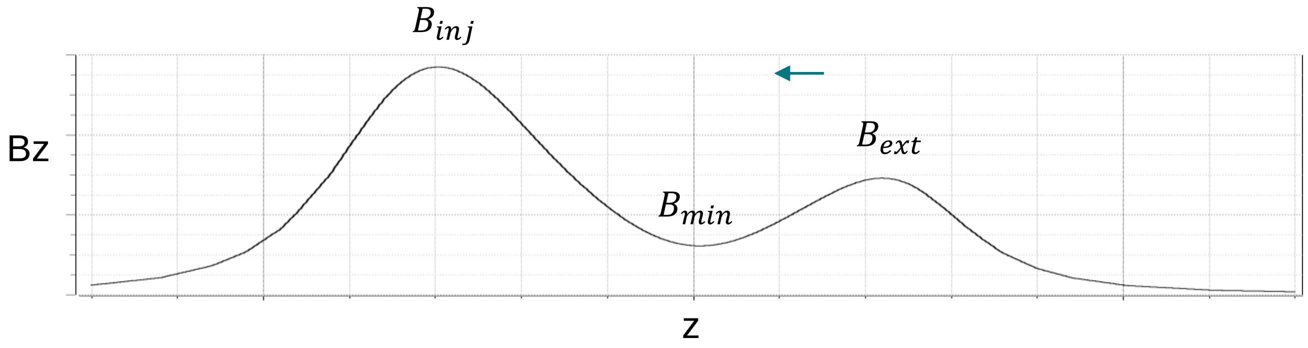
ECRIS magnets as a plasma bottle

Magnetic mirror









- High charged beam, high beam intensity ∝ RF frequency ∝ magnetic field

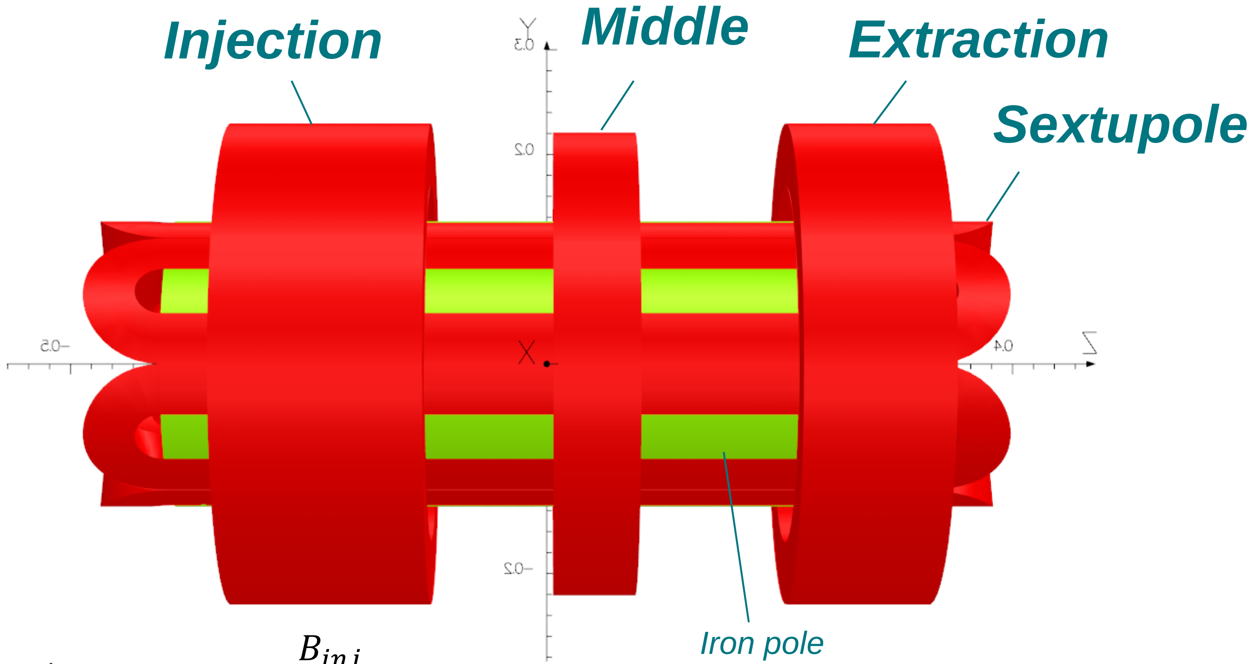
$$B_{ecr} = \frac{\gamma m_e}{e}\omega_{RF} = \frac{f_{RF}}{28\ [\mathrm{GHz}]}$$

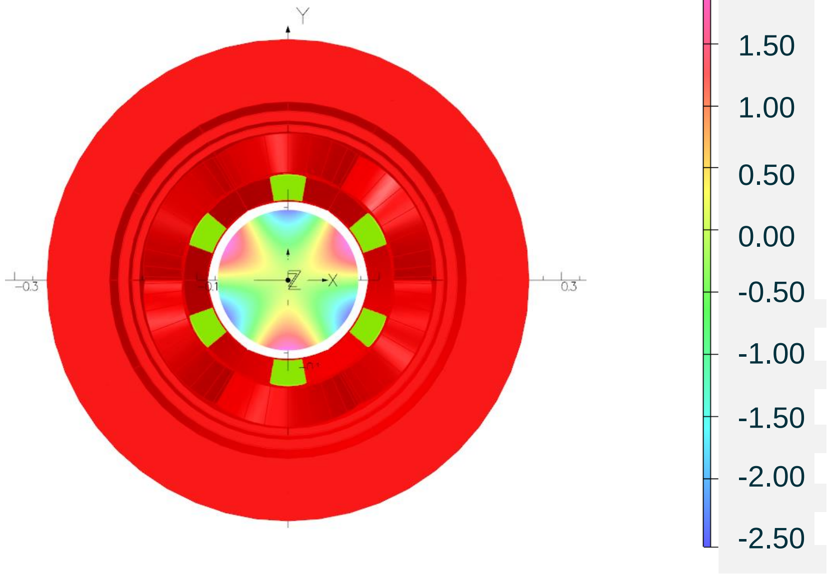
- Field requirements:

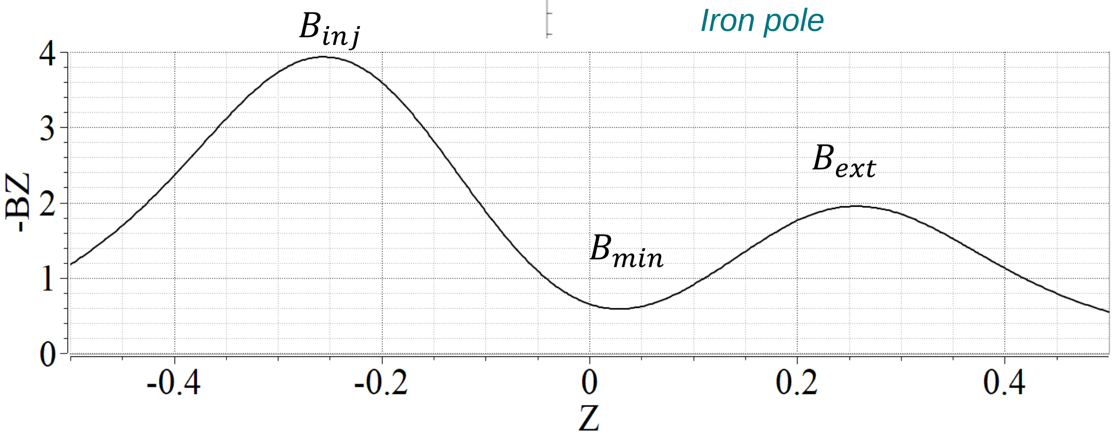
$$B_{inj} \approx 4B_{ecr}$$
$$B_r \approx 2B_{ecr}$$
$$B_{ext} \approx 0.9B_r$$
$$B_{min} \approx 0.4B_r$$

O. Tarvainen et al, Electron cyclotron resonance ion source – physics technology and future challenges, EPJ Web of Conference, 149, 01003, 2017
M. Juchno et al, Novel ECR magnets in development and under construction at LBNL, ICIS 2023 International Conference on Ion Sources, 2023
https://en.wikipedia.org/wiki/Magnetic_mirror

EIRIS superconducting magnet designed for the FRIB



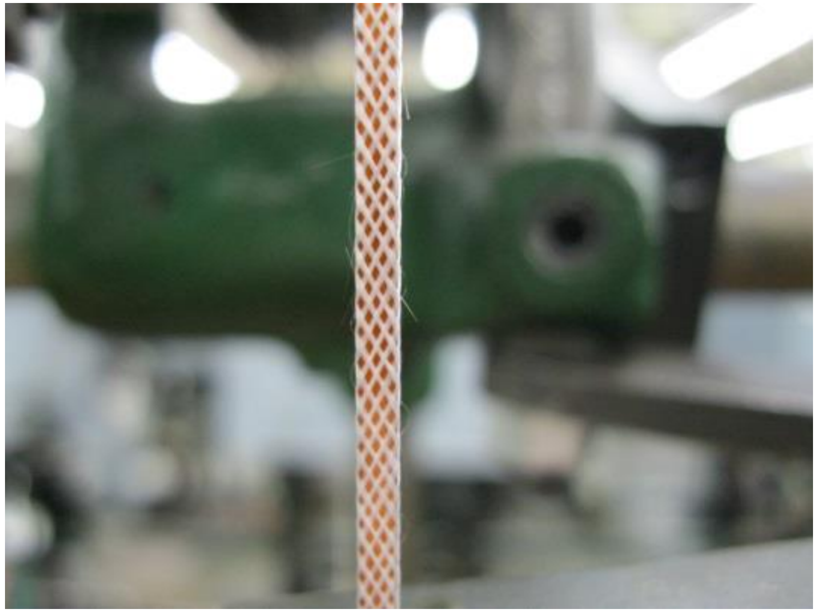


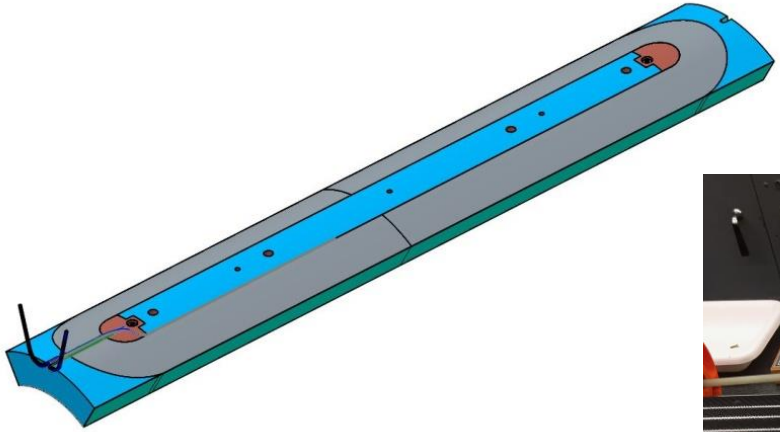


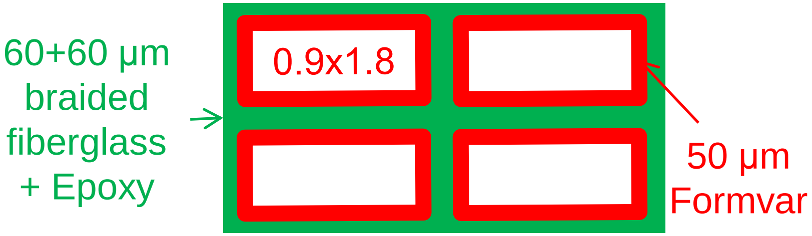
- 9 coils (6 single sextupole + 3 solenoids)
- Iron pole is employed to enhance the field

- Binj / Bmin / Bext: 3.93T / 0.59T / 1.95T
- Br at plasma chamber: 1.96 T
- Maximum field at winding:
  - 6.5T at sextupole
  - 6.1T at solenoids

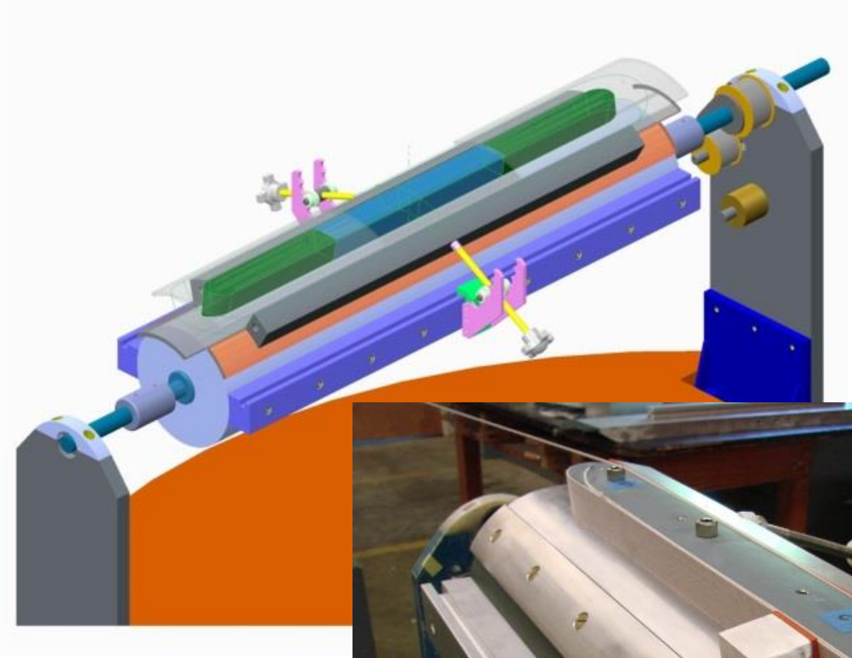
Sextupole coil conductor (Nb-Ti), insulation, and winding

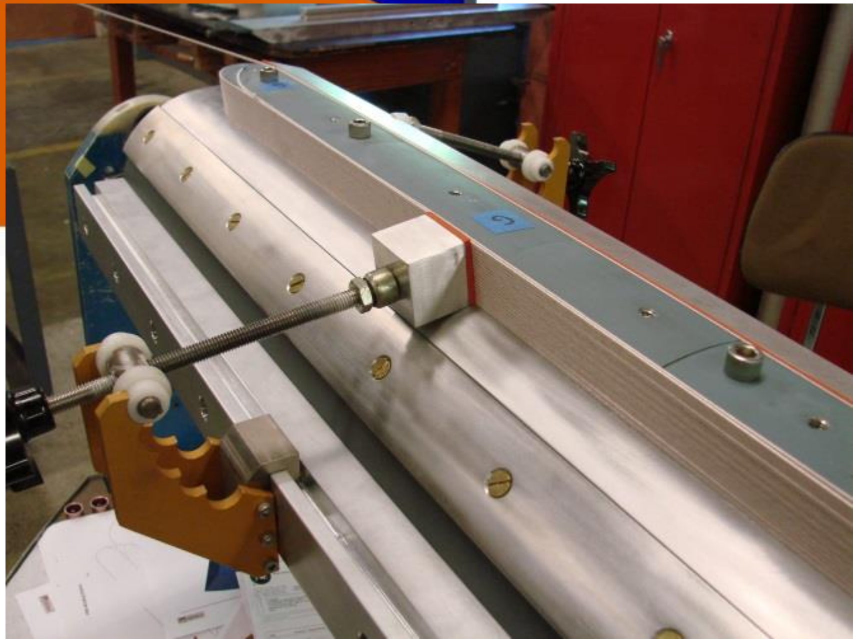


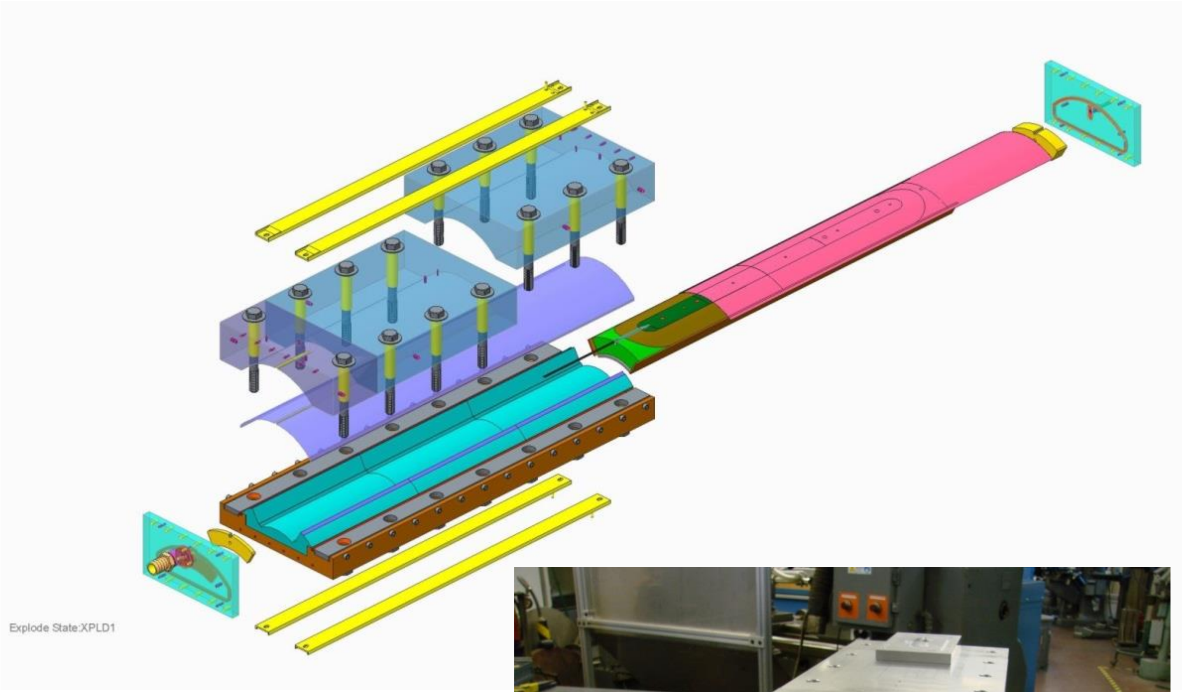


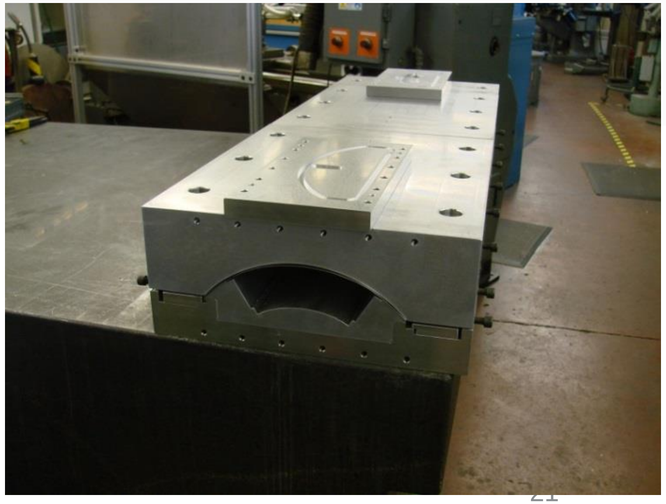


Sextupole coil fabrication



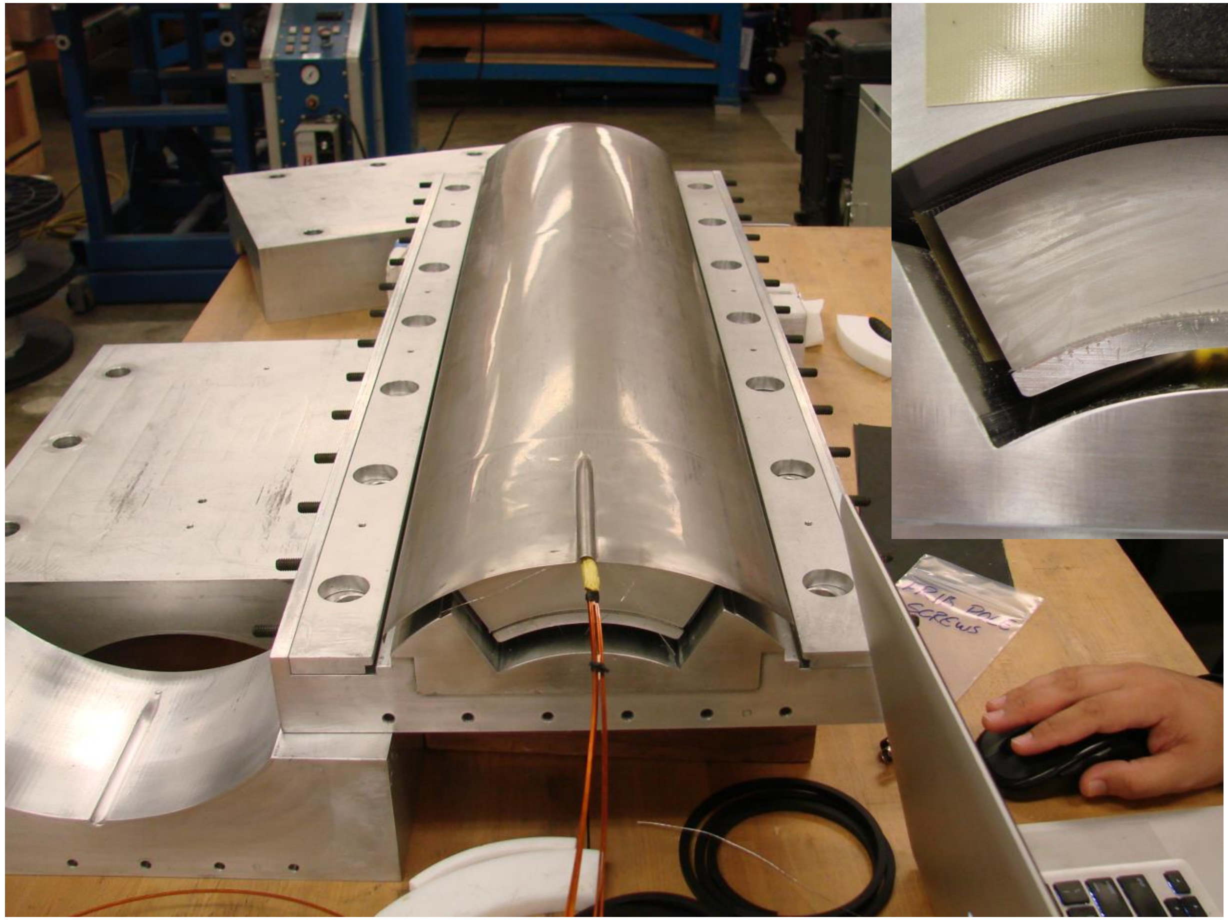


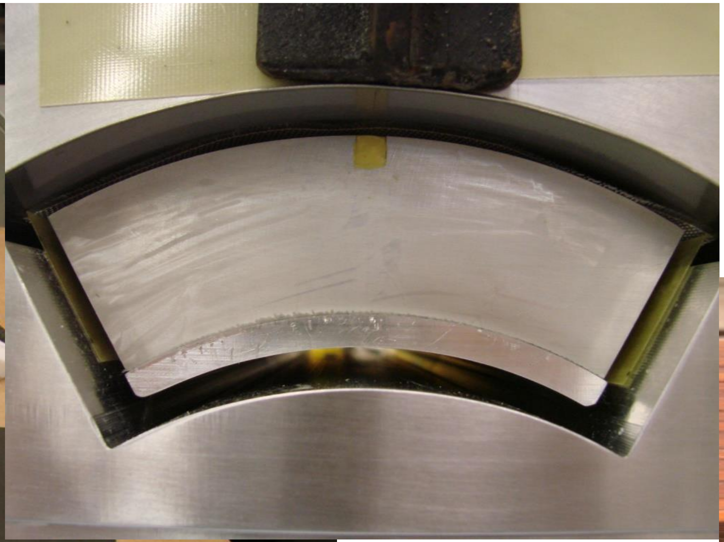


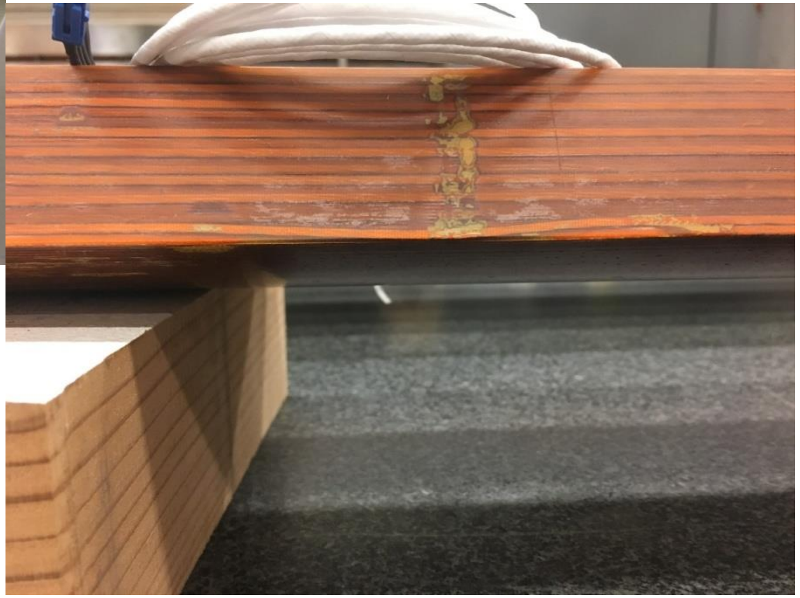


Sextupole coil fabrication – lesson learned

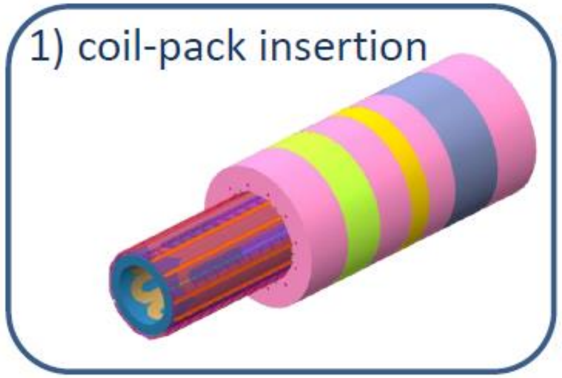
- **Insulation breakdown and strand cross-over**

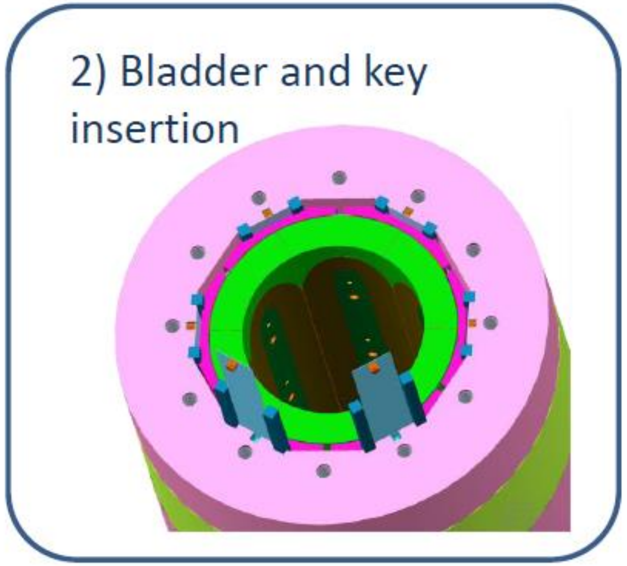


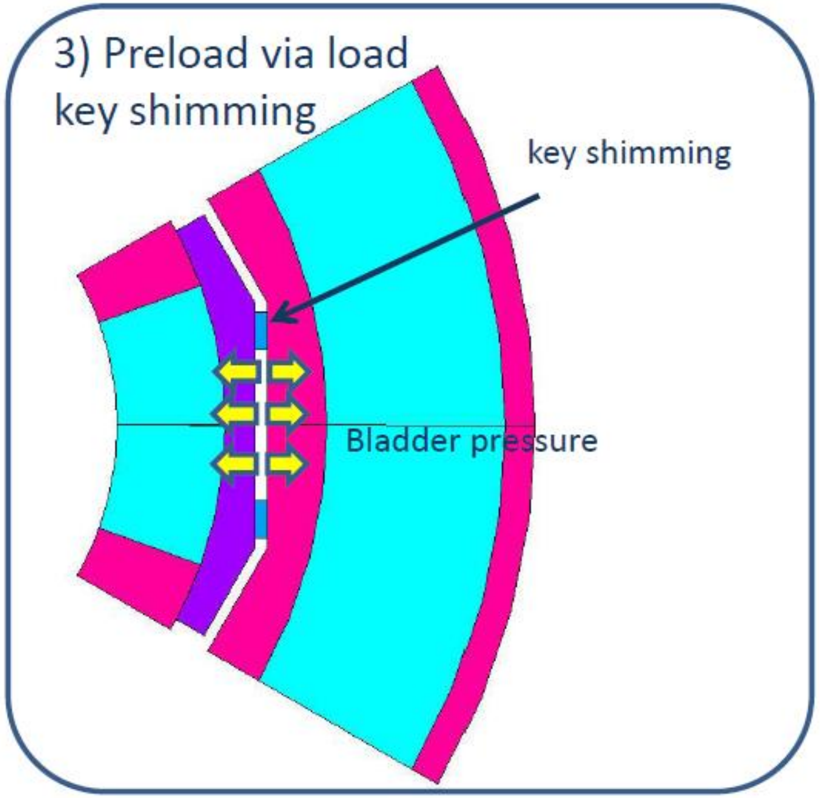




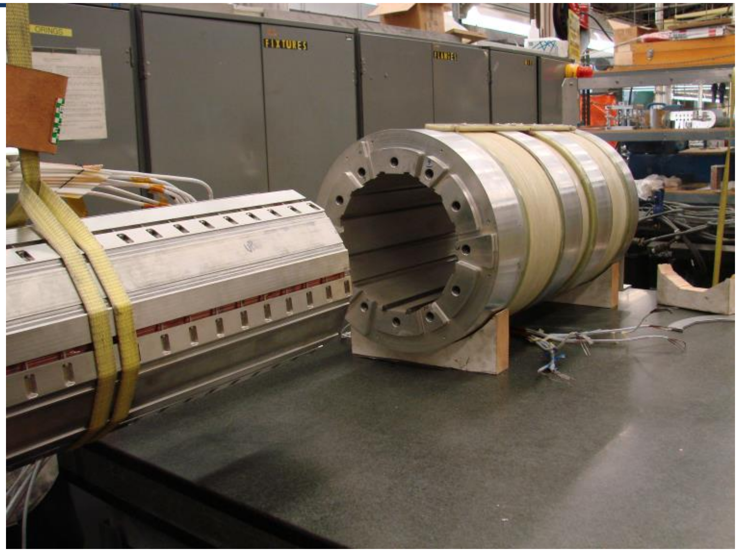
Magnet assembly

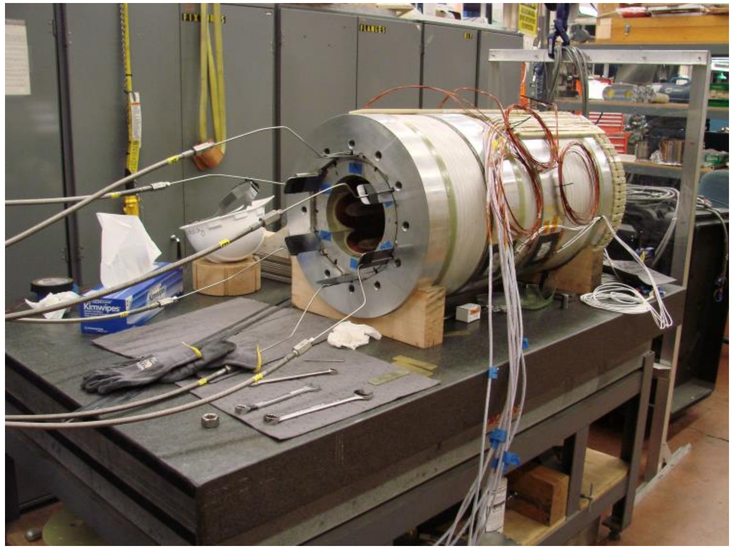






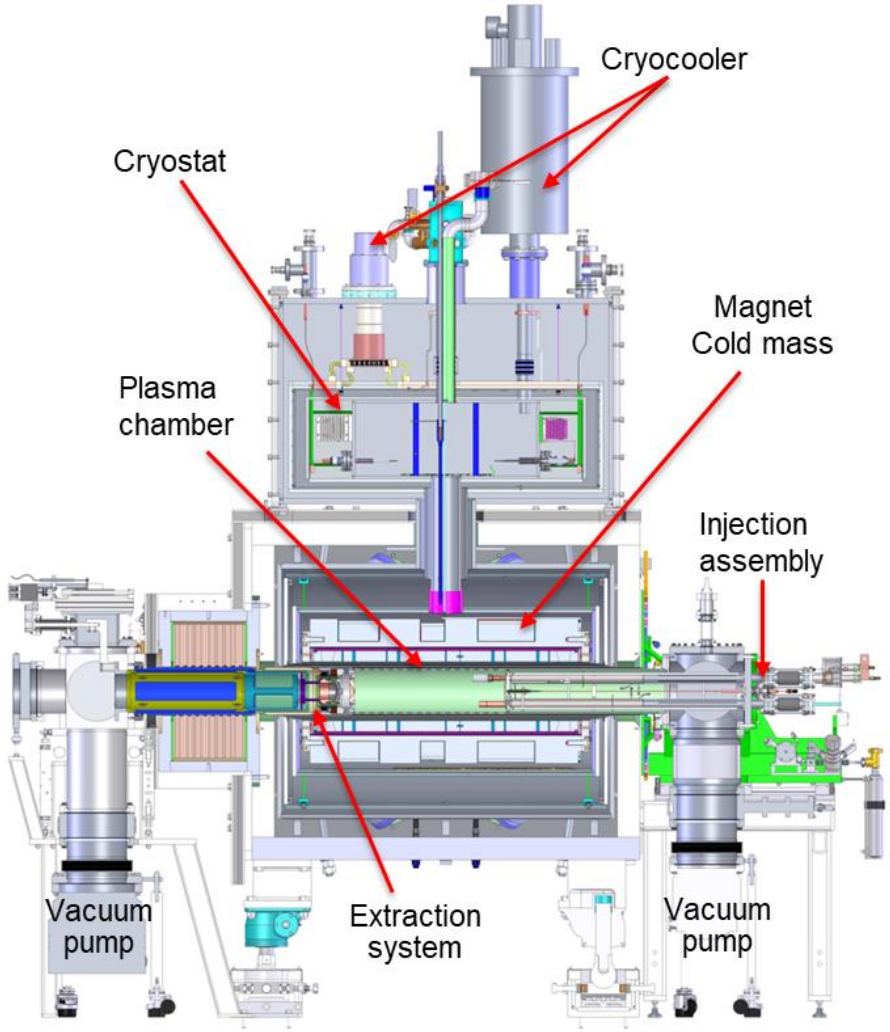
- Bladder and key technique.
- Shell structure



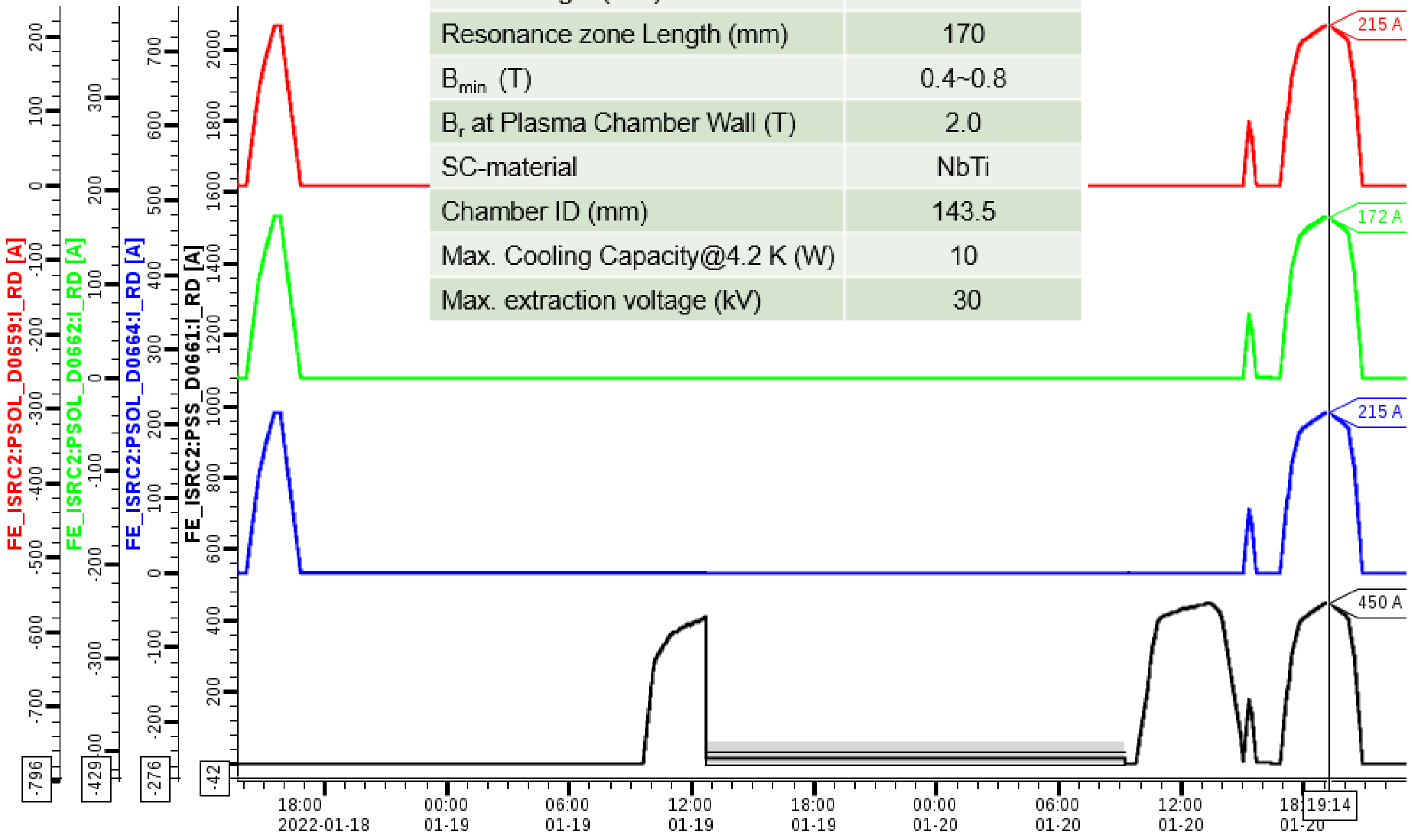


Testing and installation into FRIB have been successful

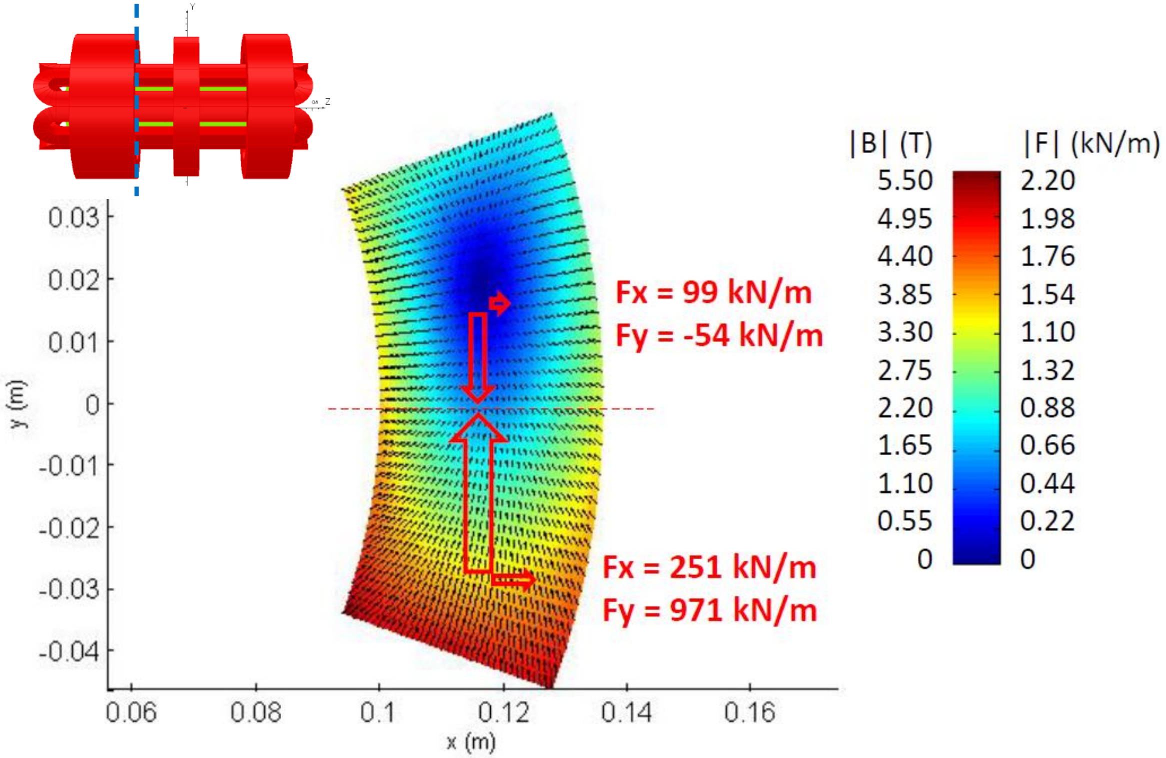
Junwei Guo, Guillaume Machicoane et al.

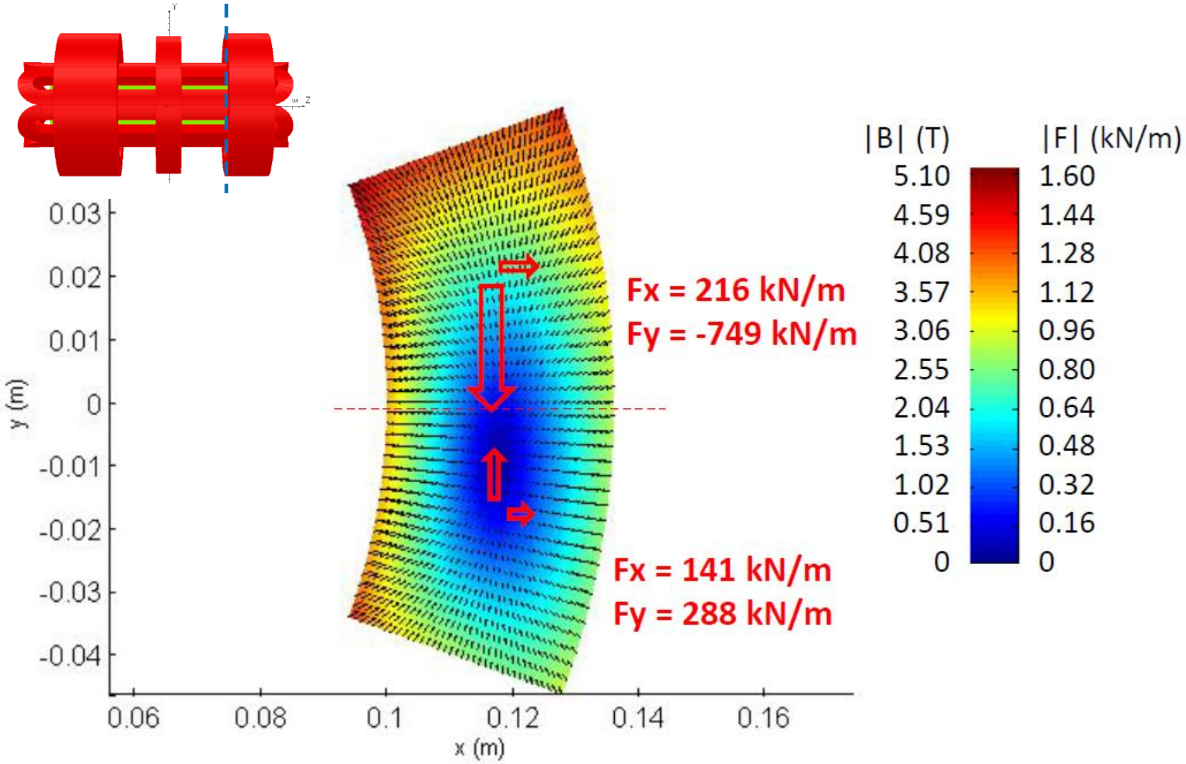


Parameters	HP ECR
RF Frequency (GHz)	28 + 18
RF Frequency (kW)	10 + 2
Axial Field Peaks (T)	4.0 (Inj.), 3.0 (Ext.)
Mirror Length (mm)	500
Resonance zone Length (mm)	170
B_{min} (T)	0.4~0.8
B_r at Plasma Chamber Wall (T)	2.0
SC-material	NbTi
Chamber ID (mm)	143.5
Max. Cooling Capacity@4.2 K (W)	10
Max. extraction voltage (kV)	30

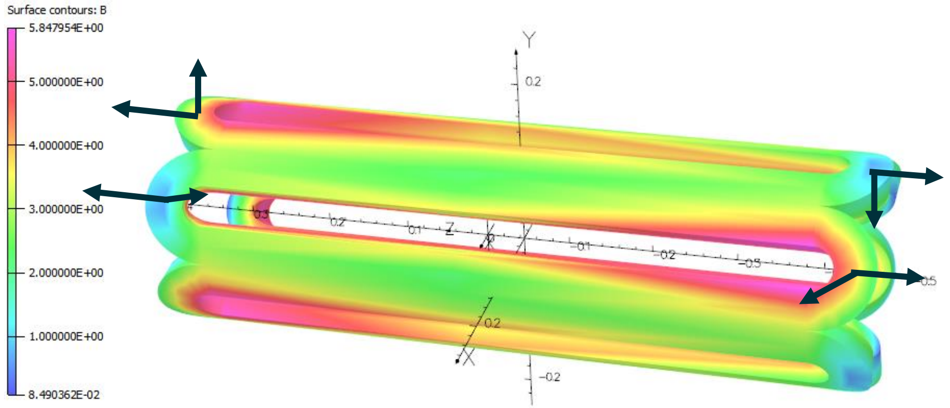


Magnetic force in sextupole coil – superconductors dealing with high forces





- **Inhomogeneous force due to the solenoid field**
- **Radial force at the coil end has different force direction to the adjacent coil.**

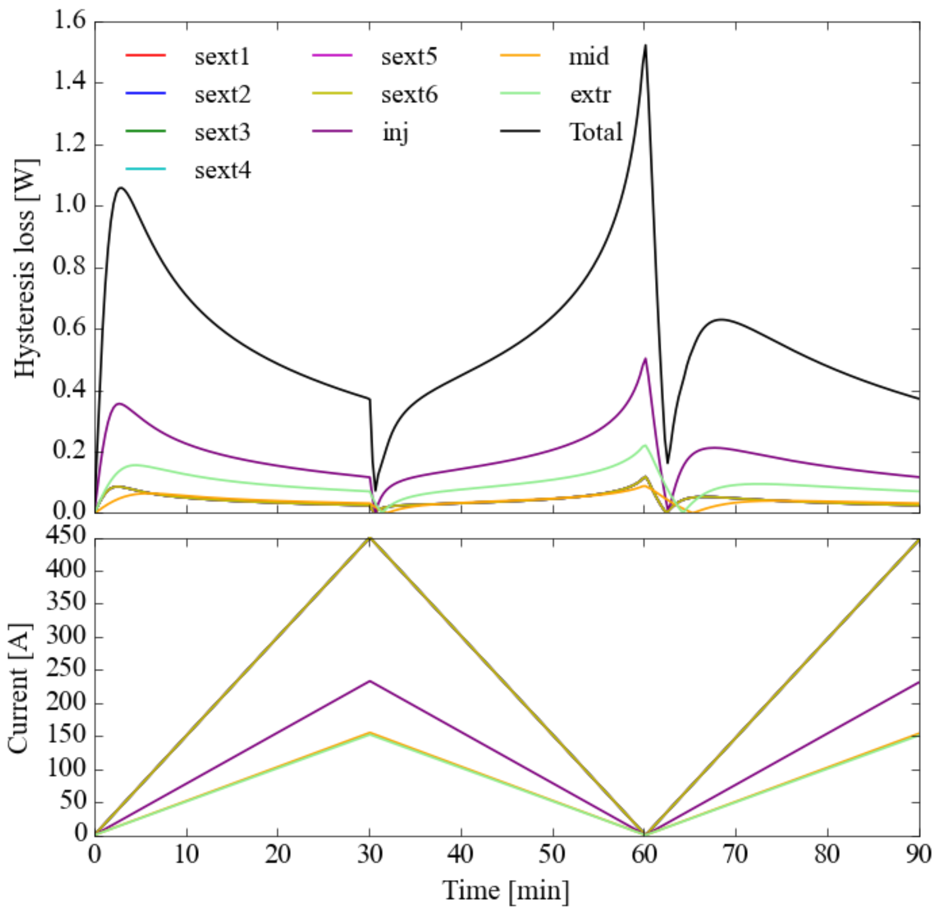


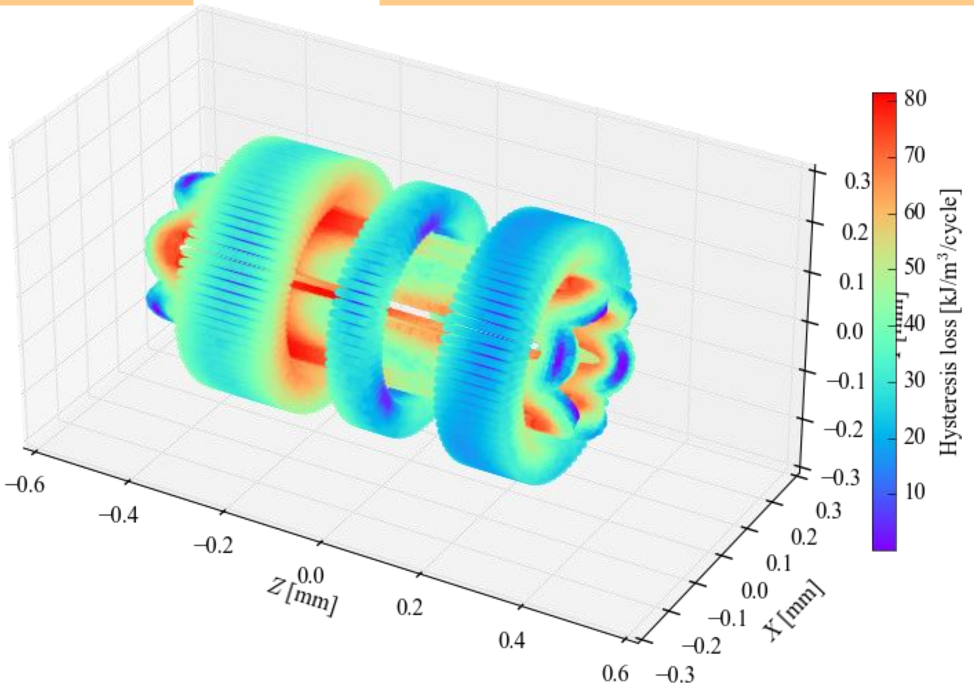
AC Loss (due to magnetization of superconductors) presents a limitation on ramp rates and stability

Field Map
FEA – TOSCA/OPERA

Hysteresis loss calculation with C++

Postprocessing and visualization Python



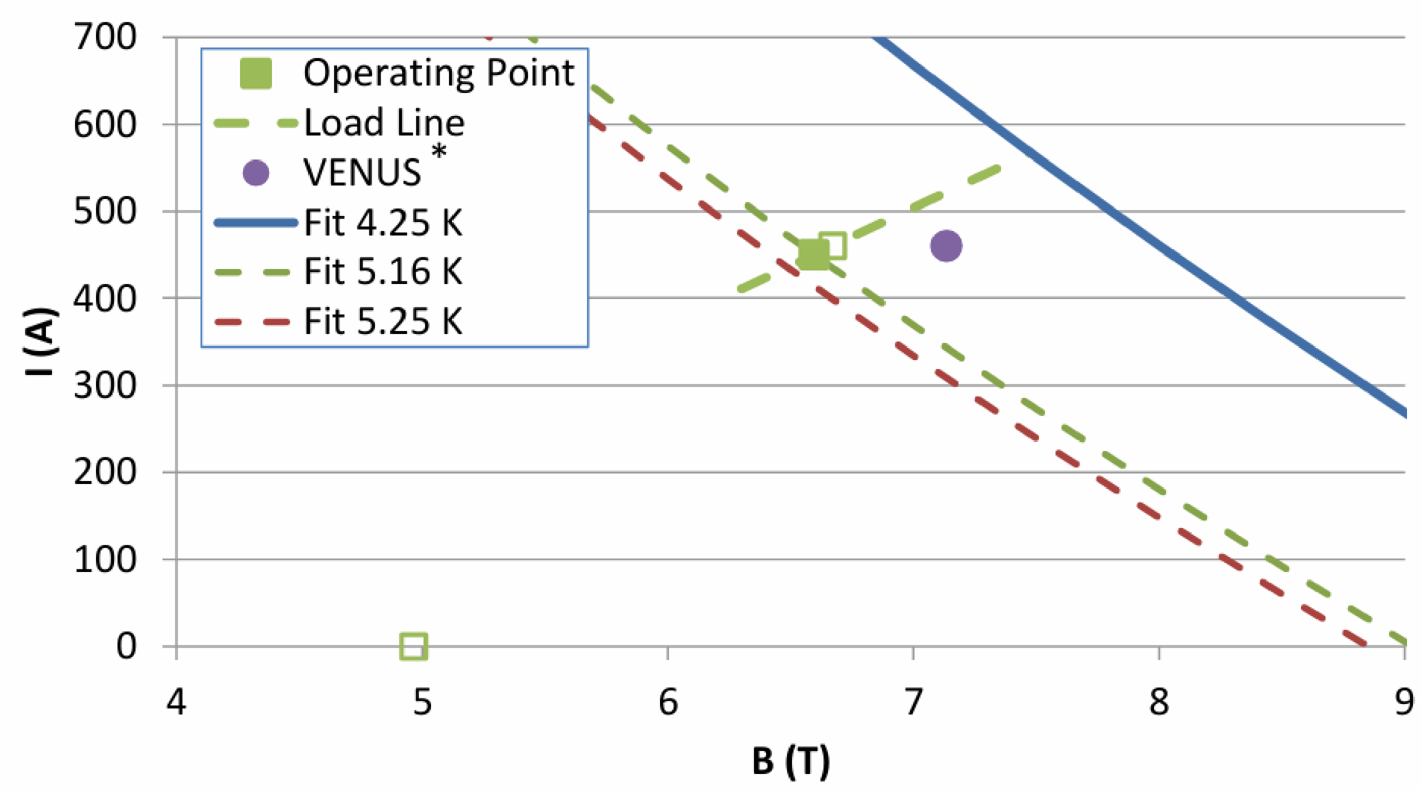


- AC loss generates heat during ramping
- Heat generation in 30 min for the FRIB ECR magnet:
  - 1.7 kJ/cycle
  - 0.5 W

Ye Yang, LBNL

The FRIB ECR Nb-Ti magnet is field limited.

Config. Sext	. Config. Sol.	I (A)	Bsext (T)	Bpeak (T)	% load line	Margin (K)
1 K margin	*Nominal*	*438*	*1.95*	*6.48*	*77*	*1.00*
Nominal	**Nominal**	**450**	**1.99**	**6.60**	**79**	**0.90**
Short sample	*Nominal*	*570*	*2.54*	*7.46*	*100*	*0.00*
Nominal	Max.	450	1.99	6.65	-	0.87



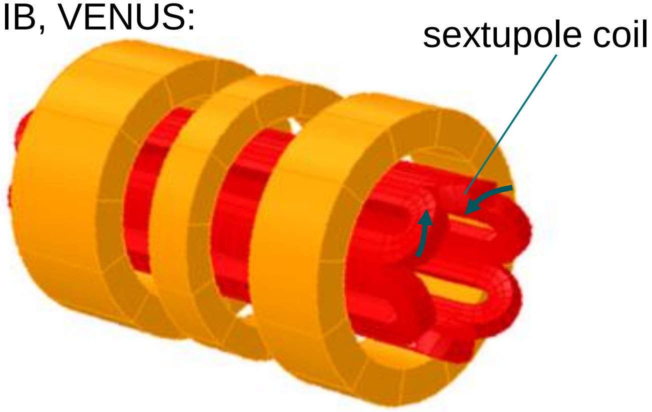
Solenoid	Nominal	Maximum
Injection	1.47	1.48
Middle	3.07	2.99
Extraction	2.76	1.71

*estimation based on the VENUS modeling and measurements at 460 A

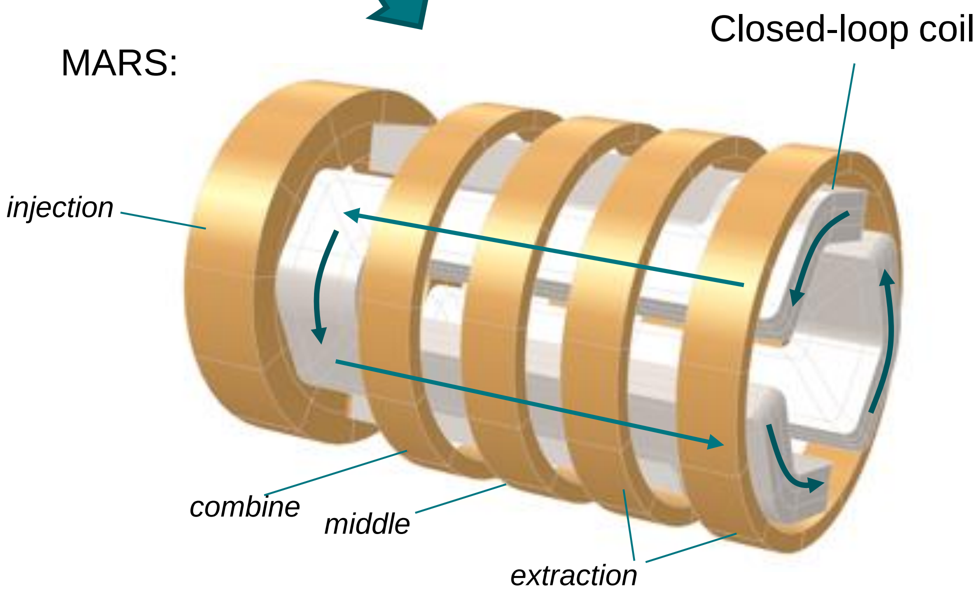
New ECRIS concept being explored at LBNL: MARS

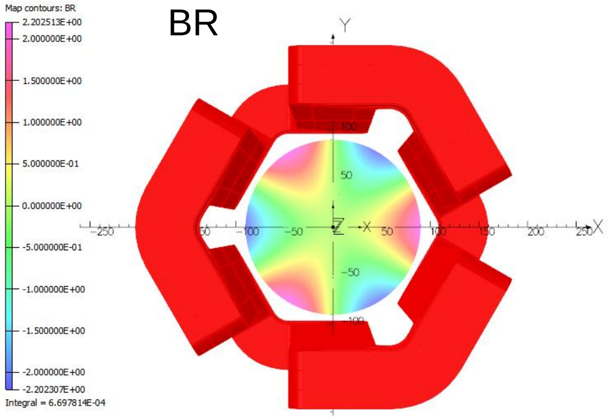
- Potential to reach 45 GHz with Nb-Ti Difficult coil fabrication. Plasma chamber and cryostat are hexagonal.

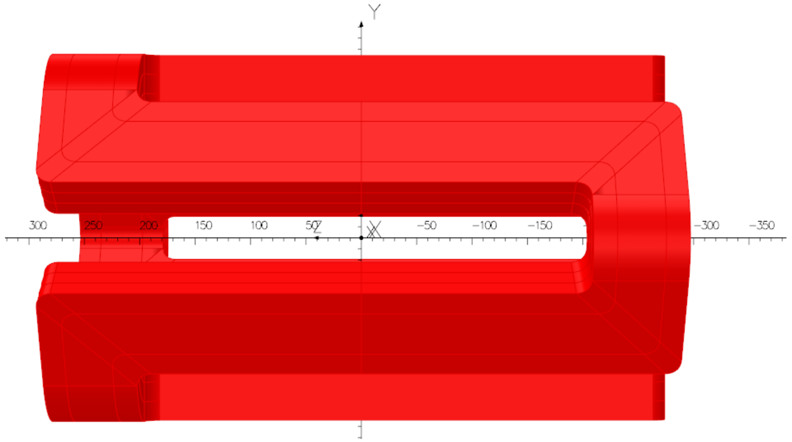
FRIB, VENUS:

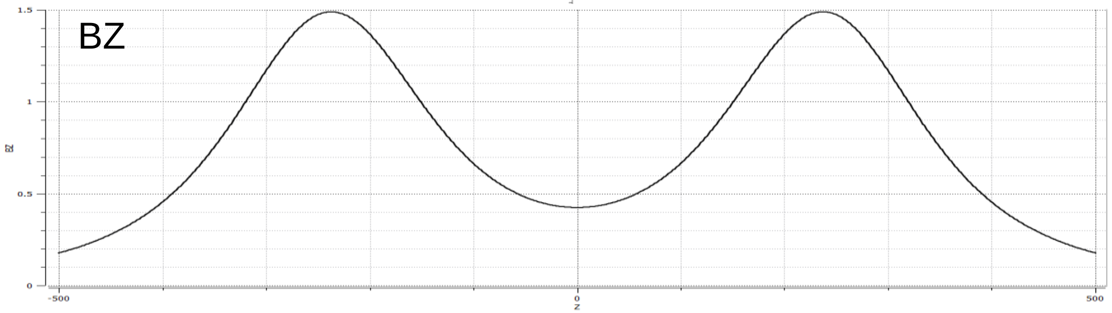


MARS:









- Using the closed-loop coil to generate not only Bz but also Br
- Hexagonal shaped coil to generate Br efficiently

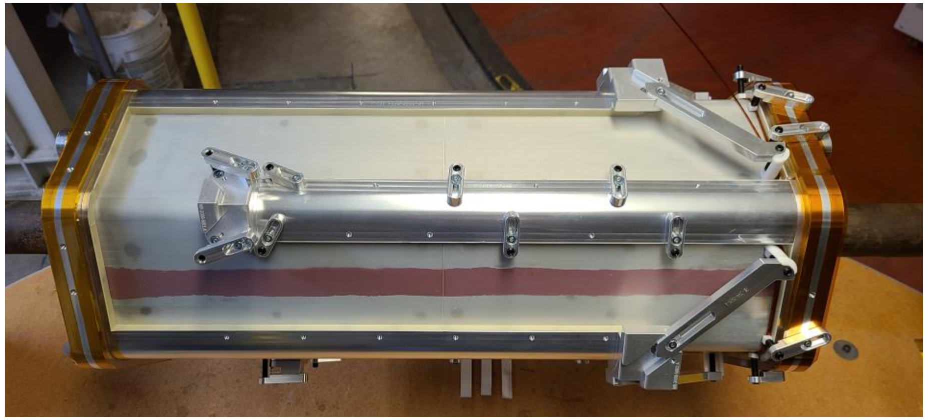
$$B_y + iB_x = \sum_{n=1}^{\infty} (B_n + iA_n) \left(\frac{x}{R_{ref}} \right)^{n-1}$$

- Targeting 45GHz with the NbTi superconducting wire

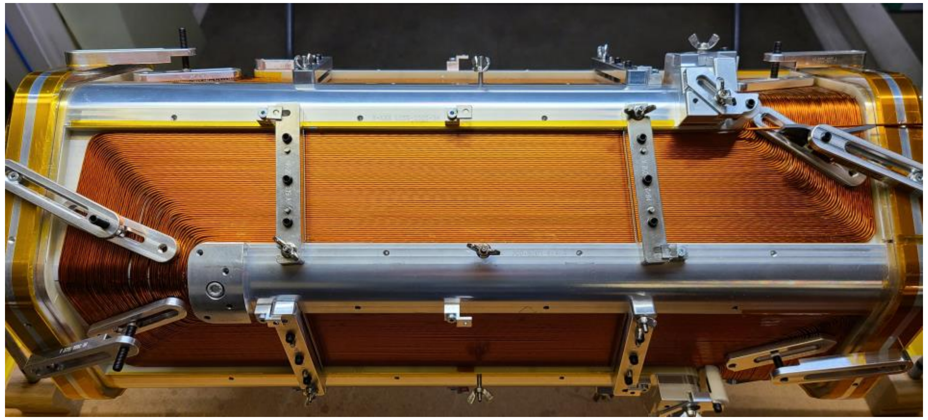
MARS magnet fabrication

Courtesy of L. Xu and MARS magnet team

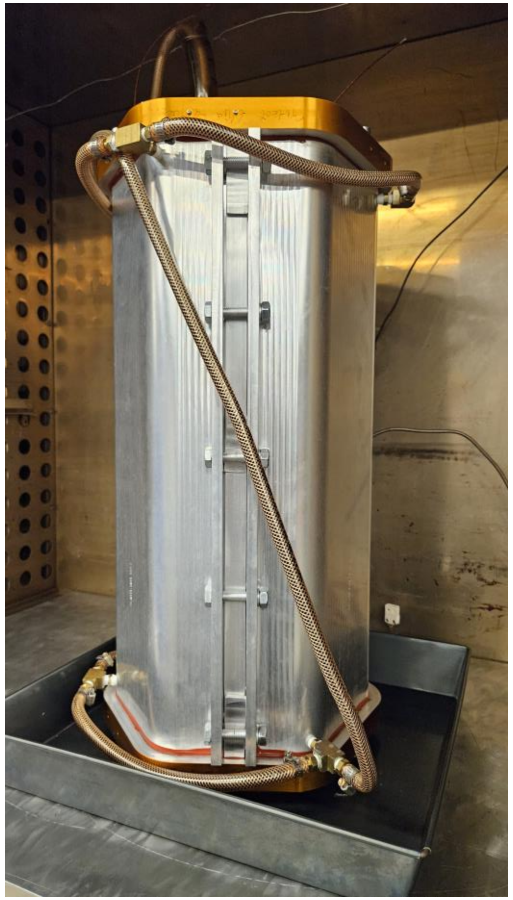
Before winding



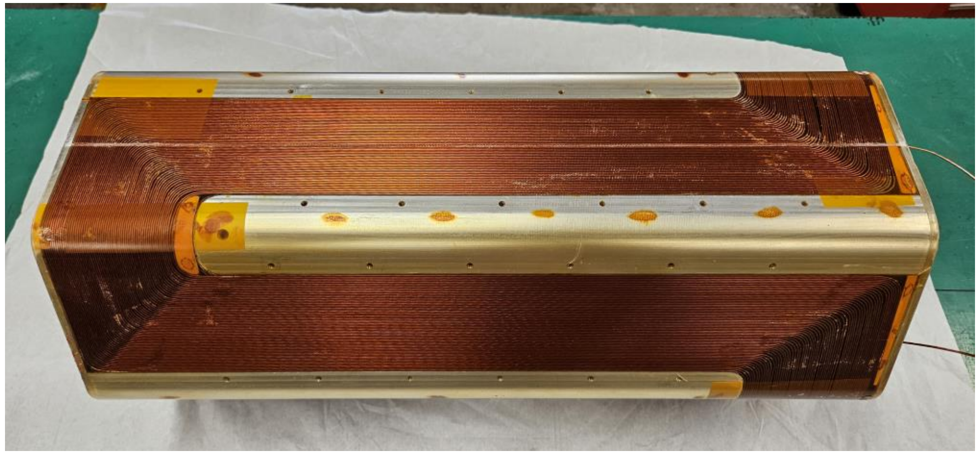
Coil winding



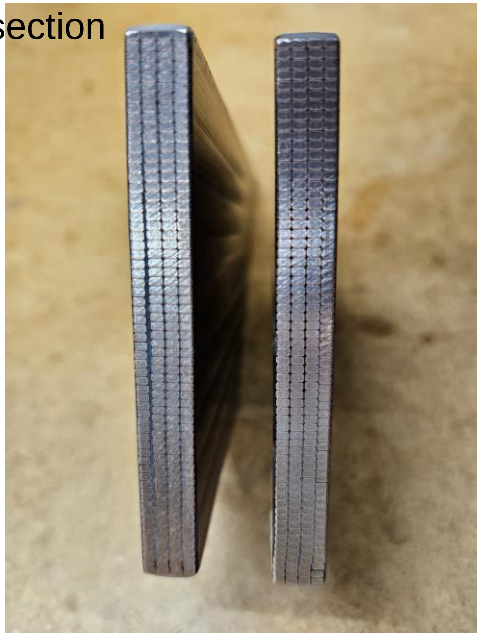
Coil impregnation



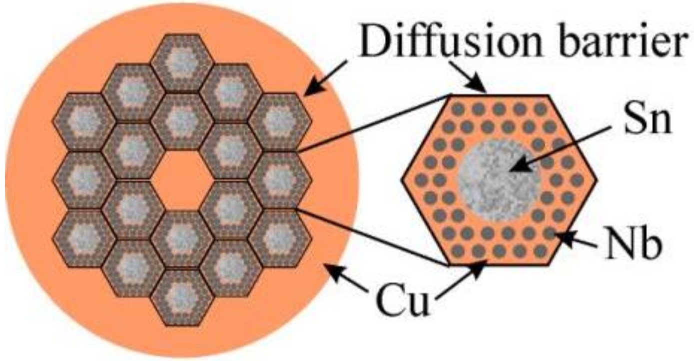
After impregnation



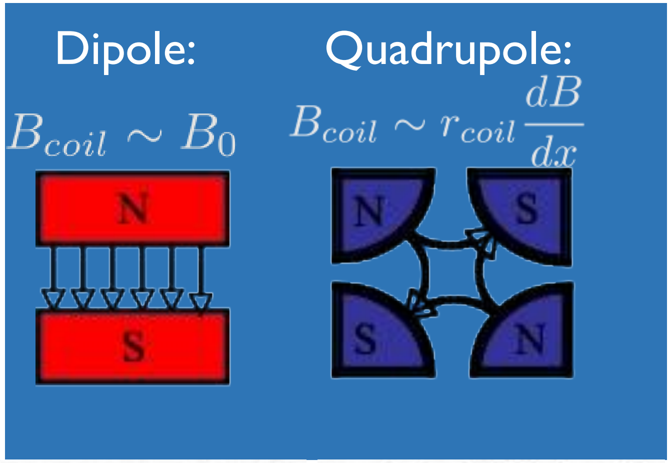
Coil cross section

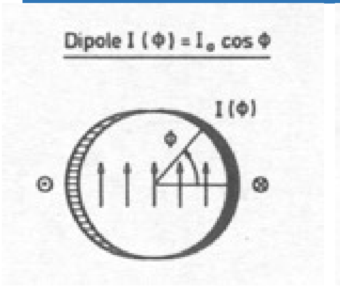


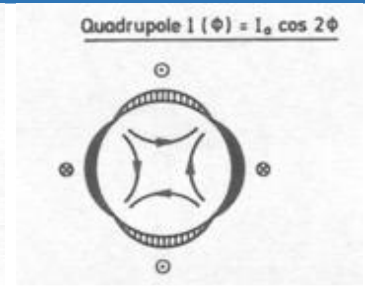
High field Nb_3Sn is enabling high-luminosity LHC

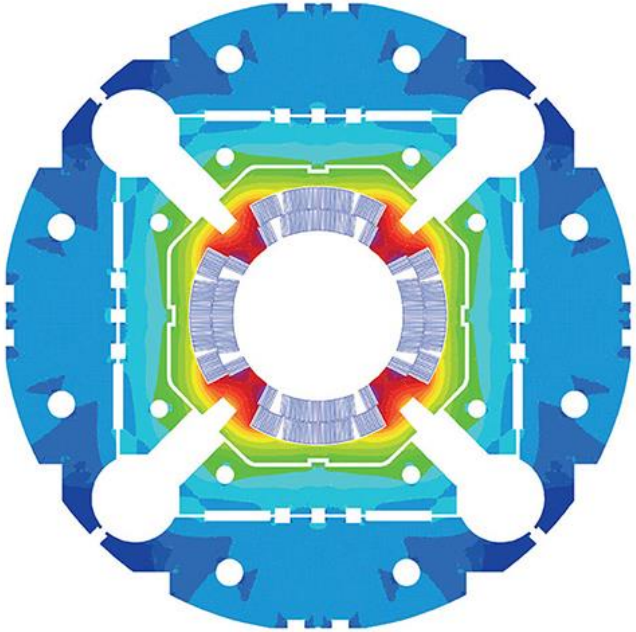


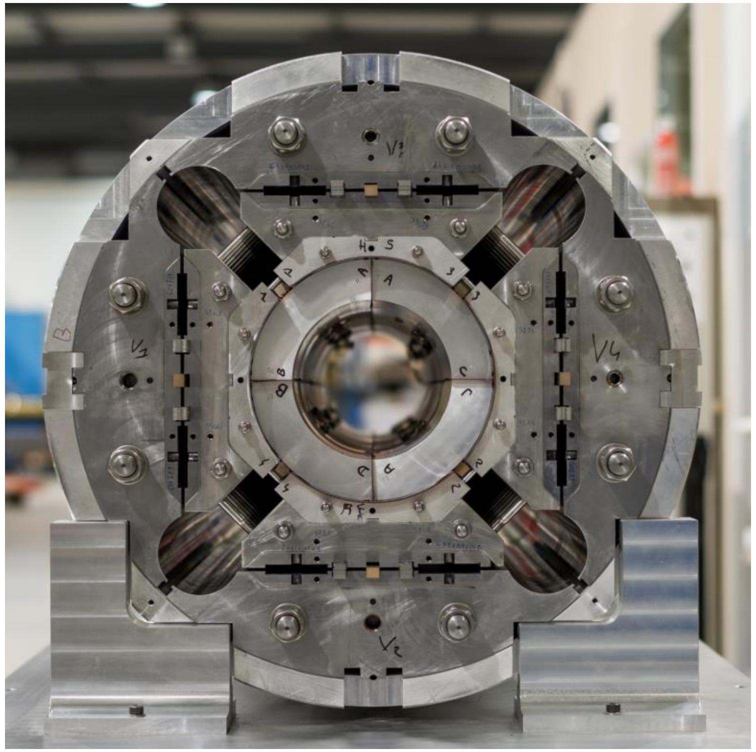
- **150 mm aperture**
- **Peak field – 11.3 T**



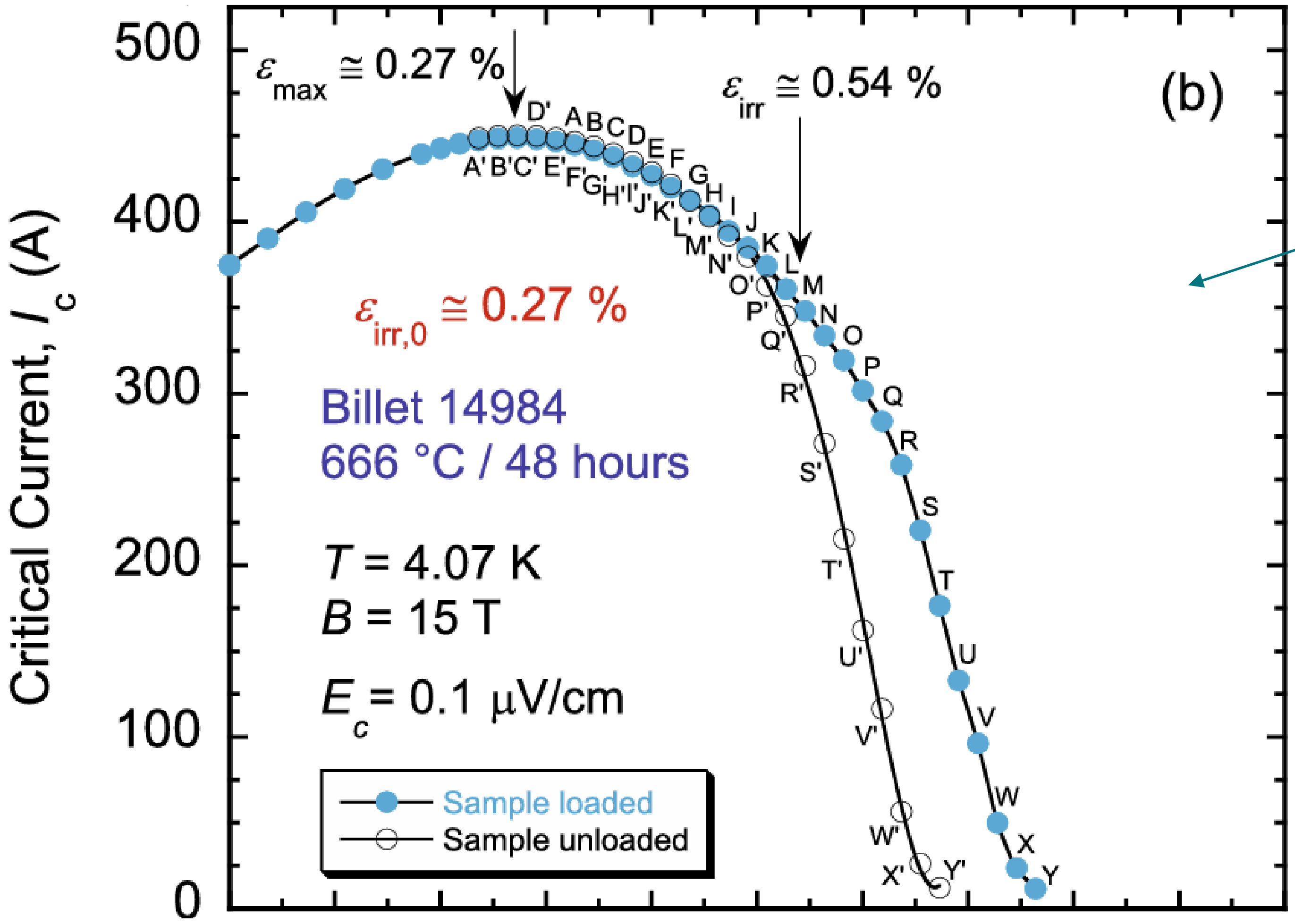


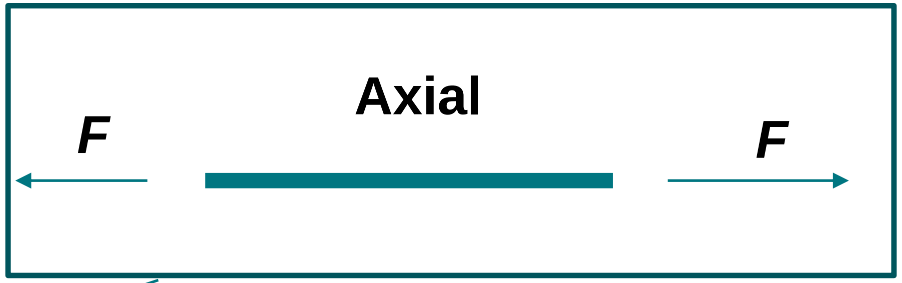




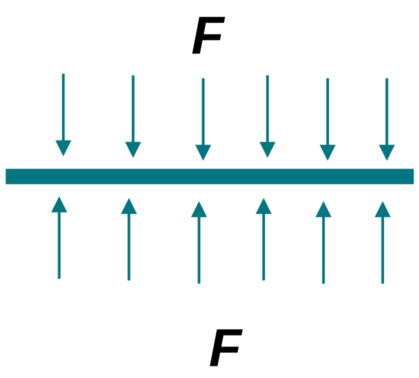


Challenges – Nb_3Sn is brittle.





Transverse

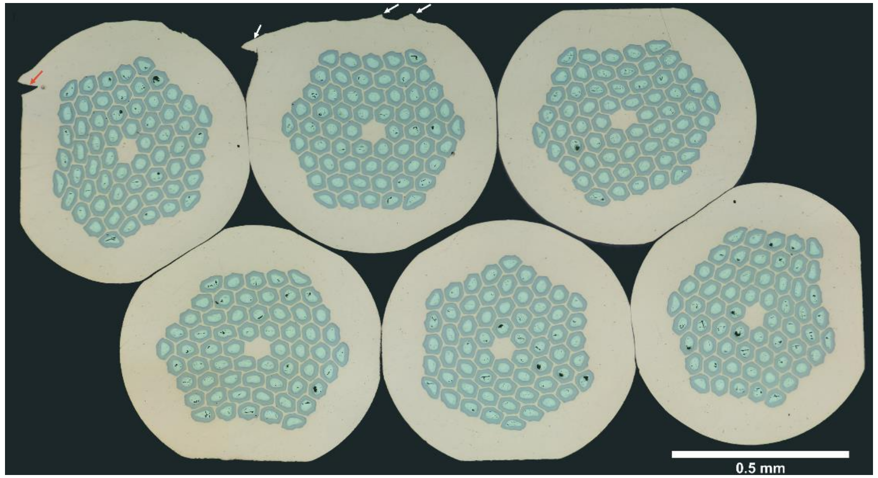


Reduced Sn RRP wires

N. Cheggour, *Scientific Reports* **volume 9**, Article number: 5466 (2019)

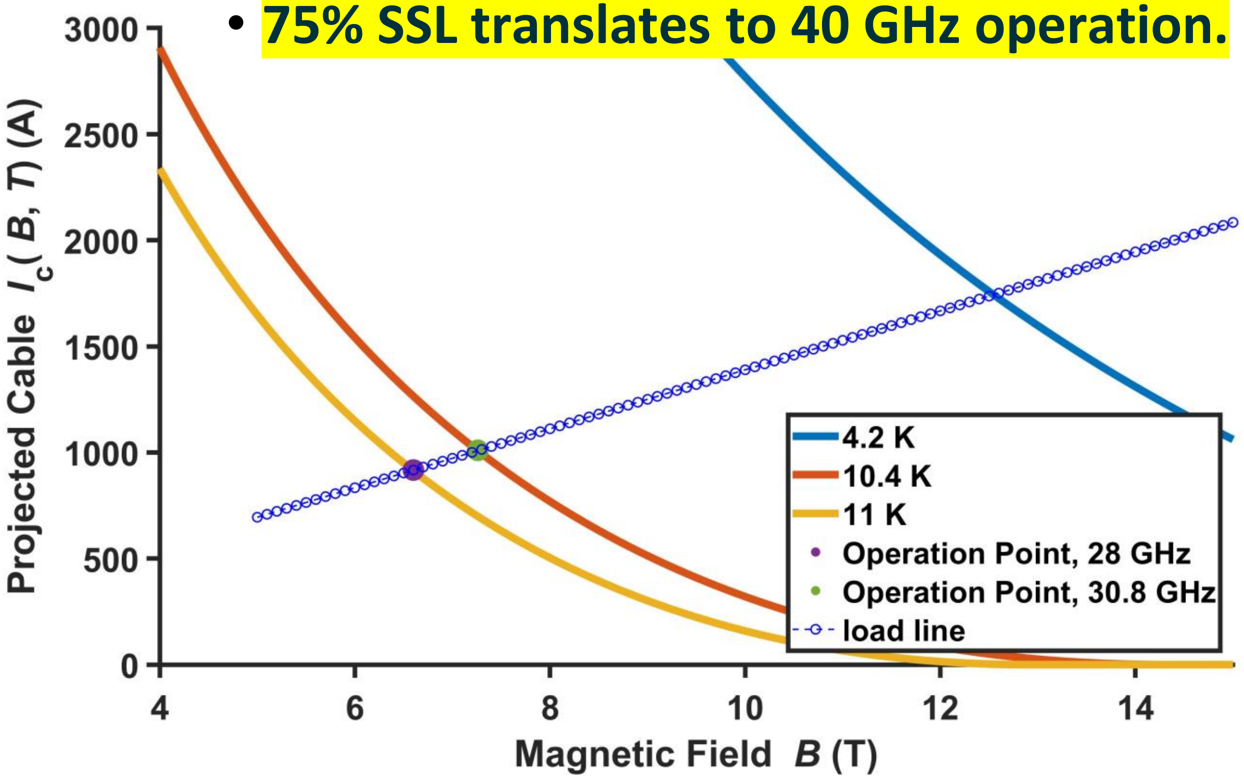
FRIB and LBNL are working together to ultimate high field Nb_3Sn for ECR magnets

RRP Nb_3Sn, 60/91, Cu/non-Cu = 1.6



Item	Unit	Value
Superconducting cable:		
Cable dimension (bare)	mm^2	2.39×1.25
Cable dimension (insulated)	mm^2	2.69×1.55
Insulation	-	S-2 glass, 2-ply, QXF type
Cable pitch angle	degree	22
Number of strands	-	6
Strand:		
Diameter	mm	0.7
Wire design	-	RRP® 60/91 (Nb:Sn = 3.6:1)
Subelement number	-	60
Subelement diameter, d_s	μm	56
Cu:non-Cu	-	1.6
Twist pitch	mm	19
RRR	-	>100
Minimum non-Cu J_c	A/mm^2	2180 (12 T, 4 K)

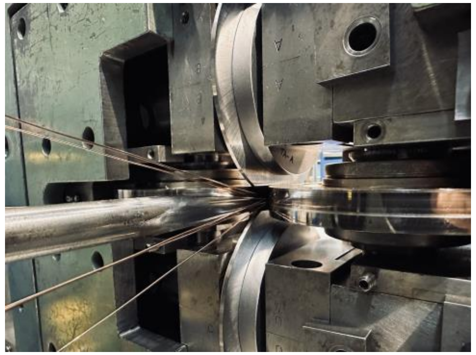
- **75% SSL translates to 40 GHz operation.**

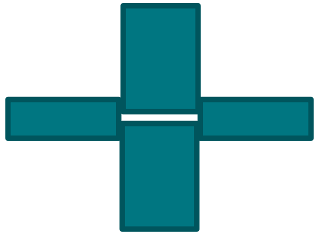


T. Shen *et al, IEEE Transactions on Applied Superconductivity*, vol. 34, no. 5, pp. 1-5, Aug. 2024, Art no. 4301105, doi: 10.1109/TASC.2024.3358767.

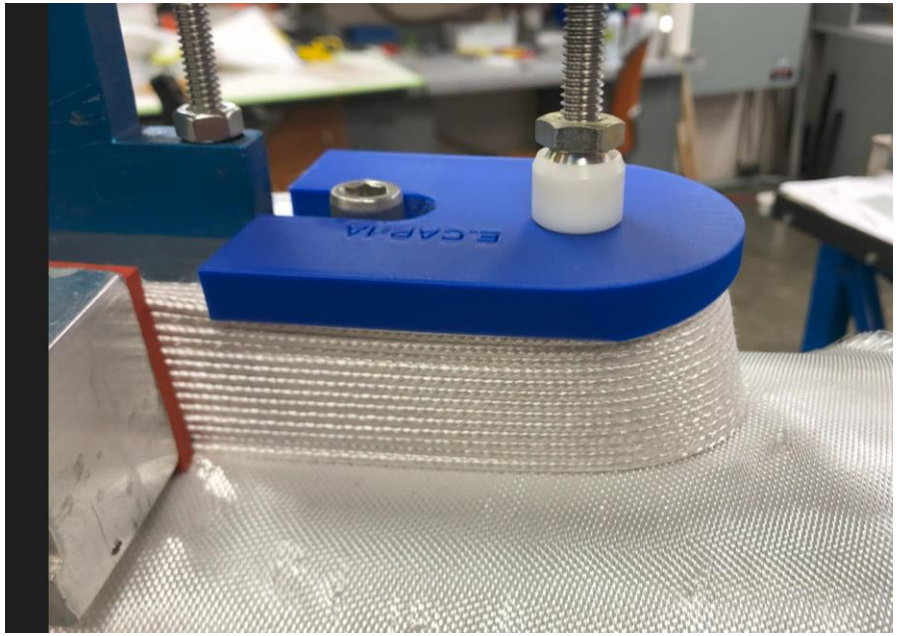
Nb_3Sn able and coil fabrication

~800 m fabricated



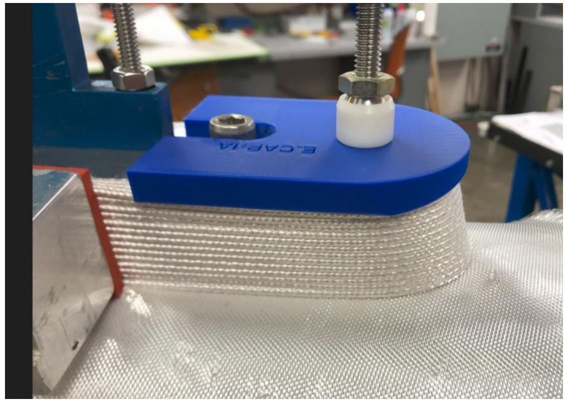


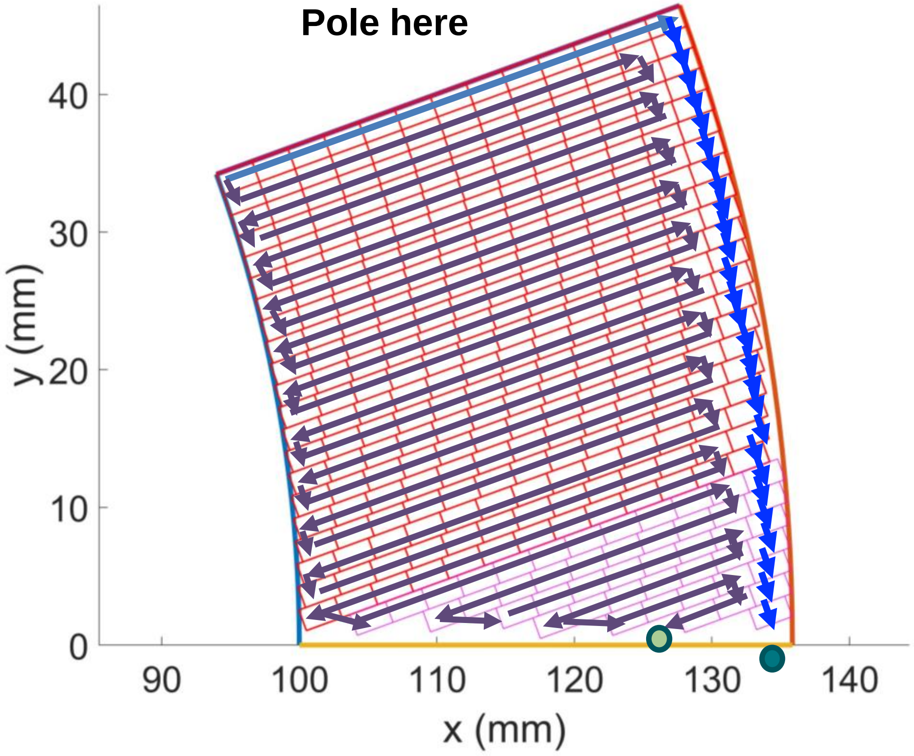
Insulated with braided S-2 glass



Coil fabrication prototyping – process and tooling development

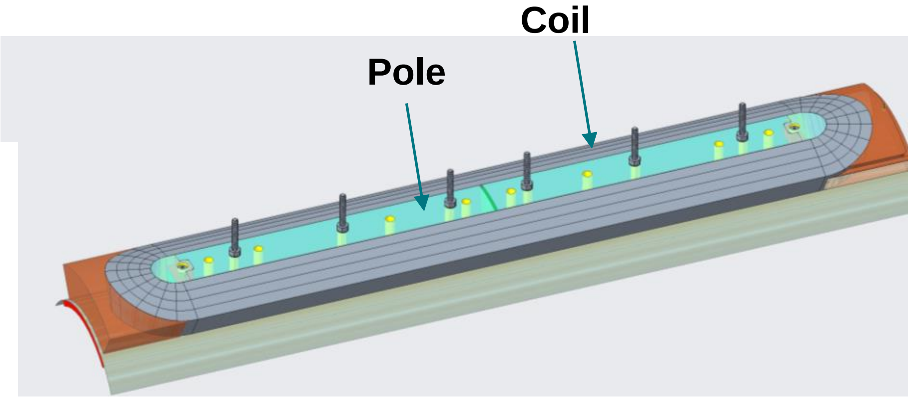
Winding



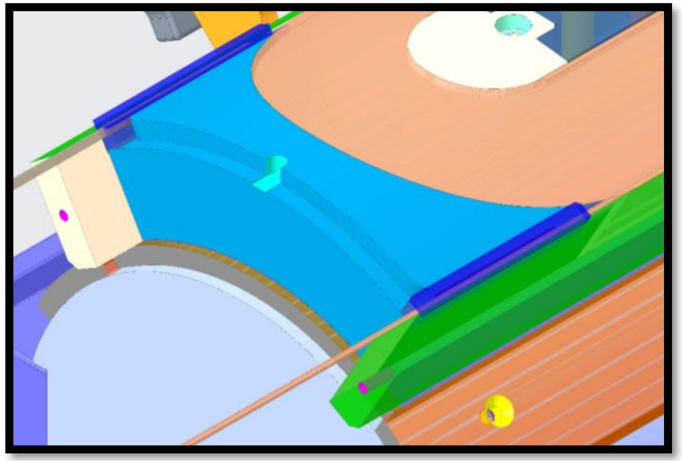


Spool 1 winding path

Spool 2 winding path

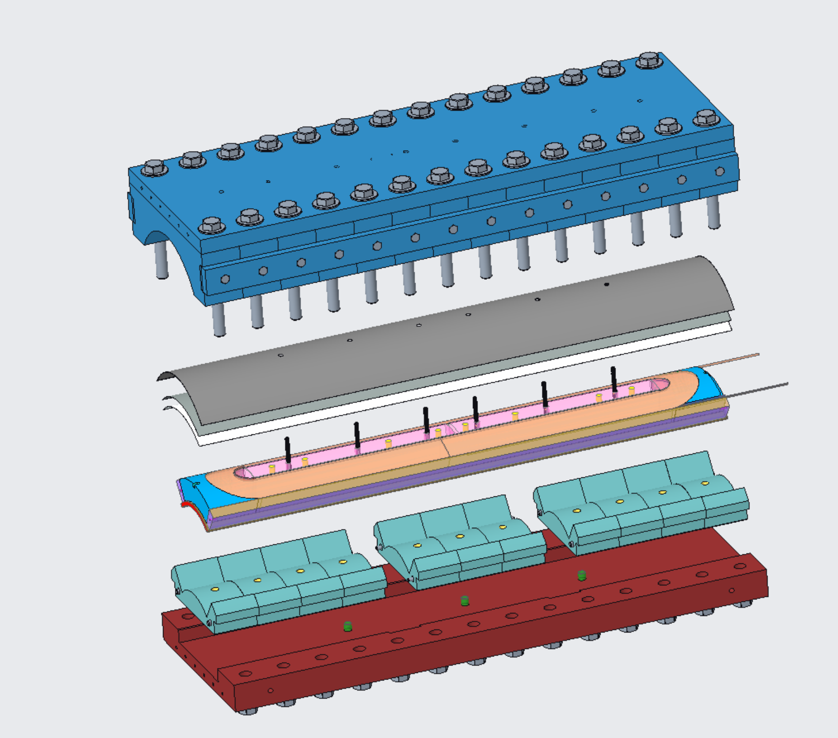


Nb_3Sn leads exist at the mid-plane

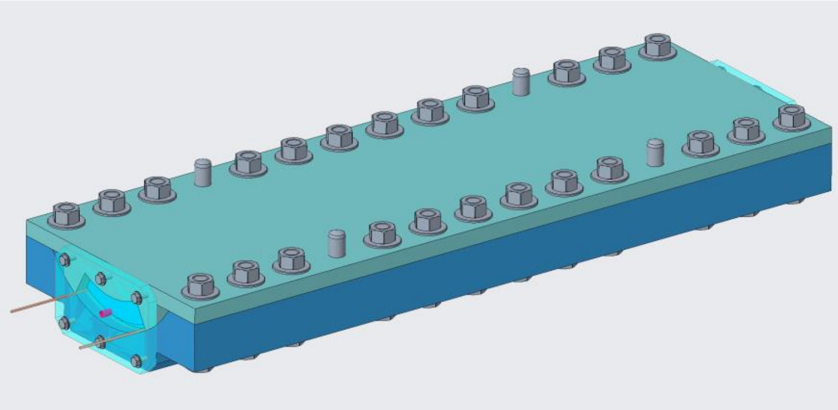


Coil fabrication prototyping – process and tooling development

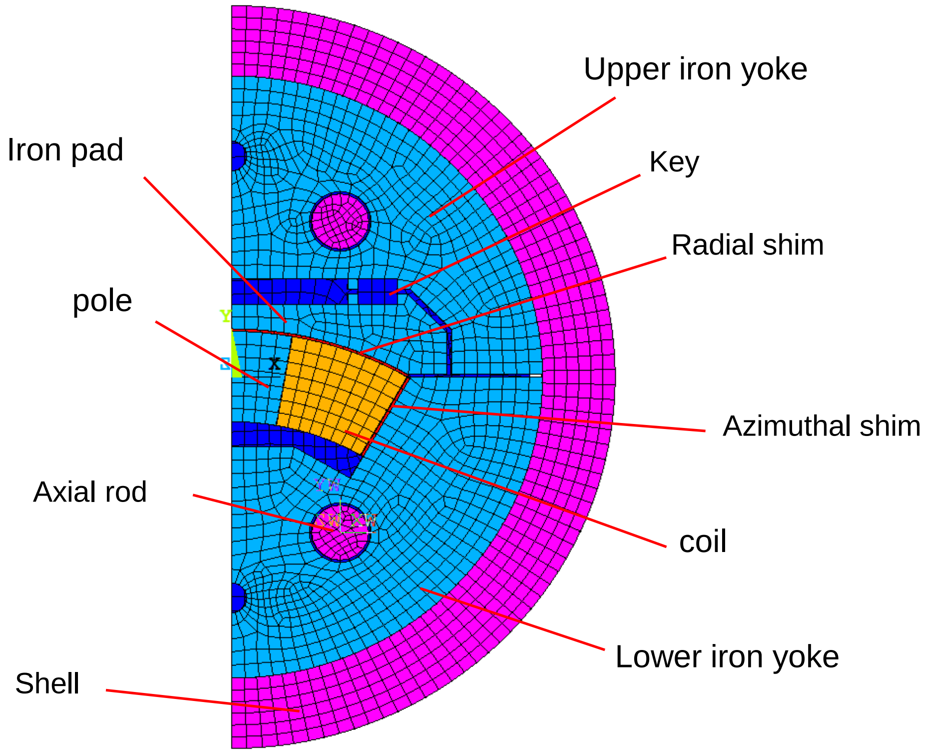
Heat treatment

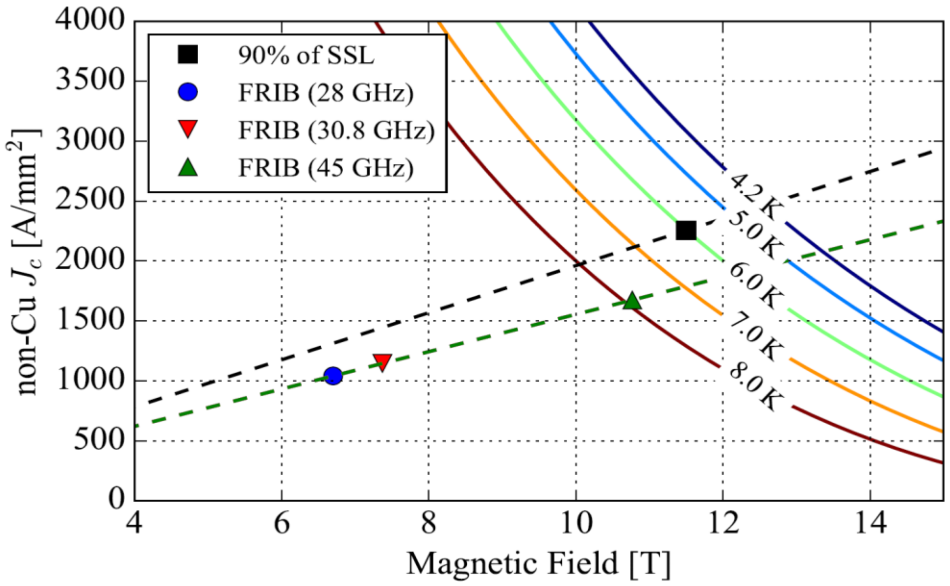


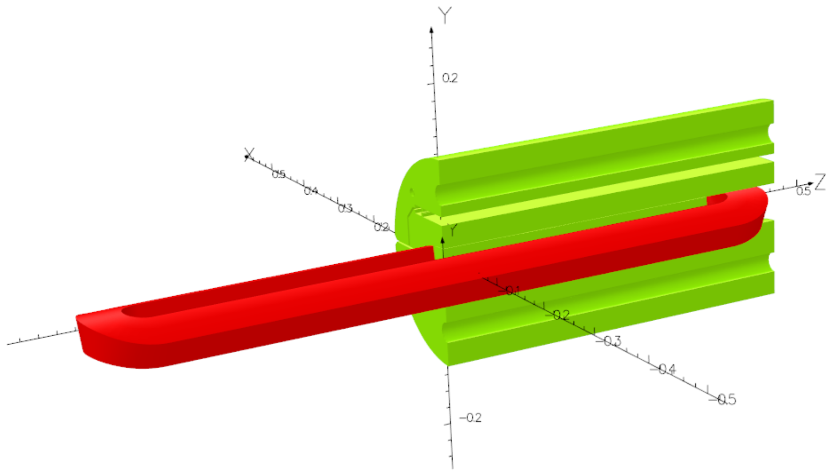
Vacuum impregnation with Epoxy Resin



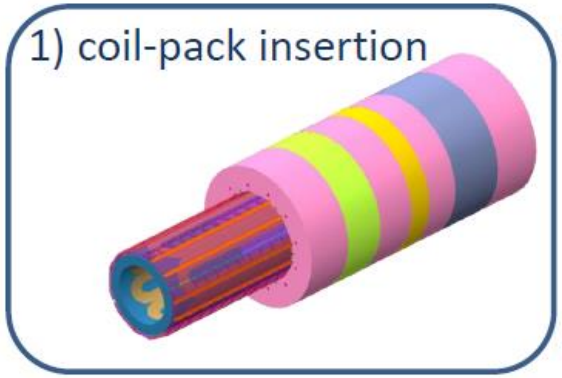
Prototype coil verified by a mirror magnet structure

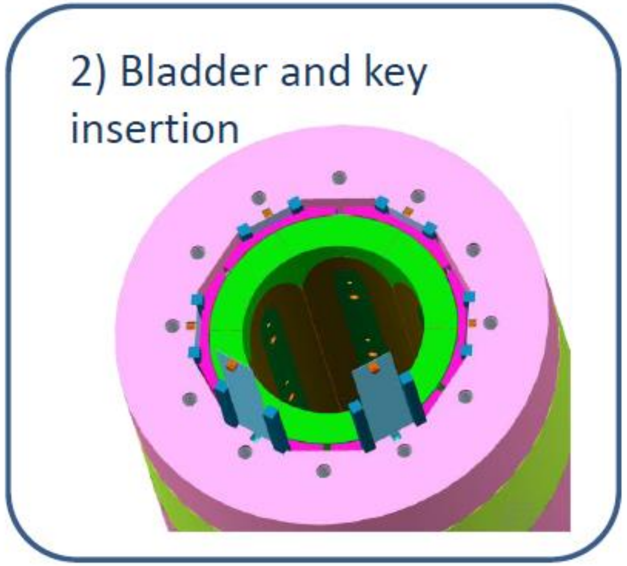


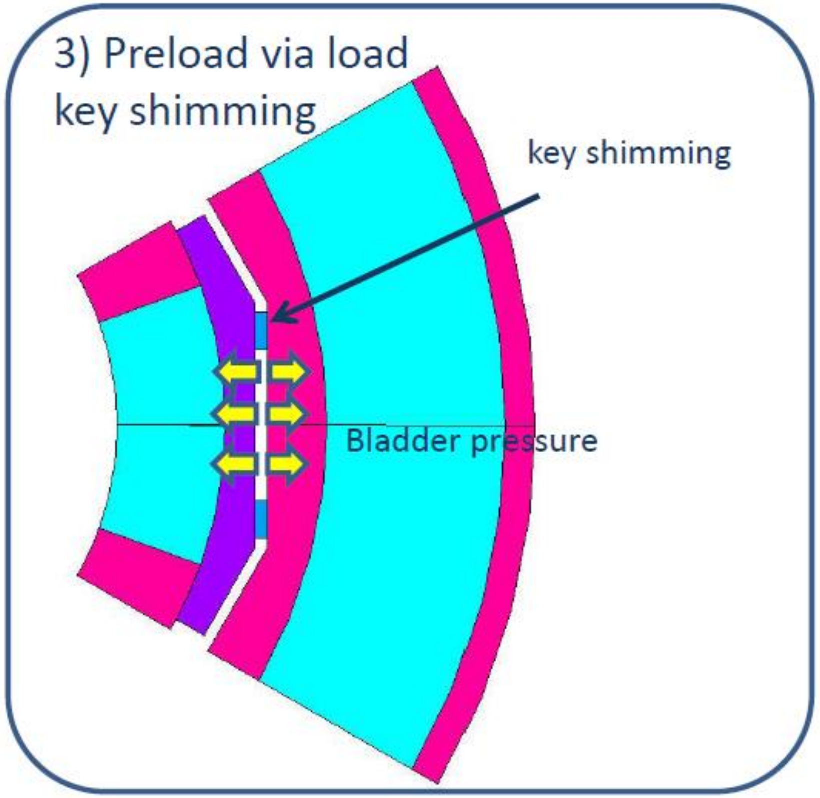


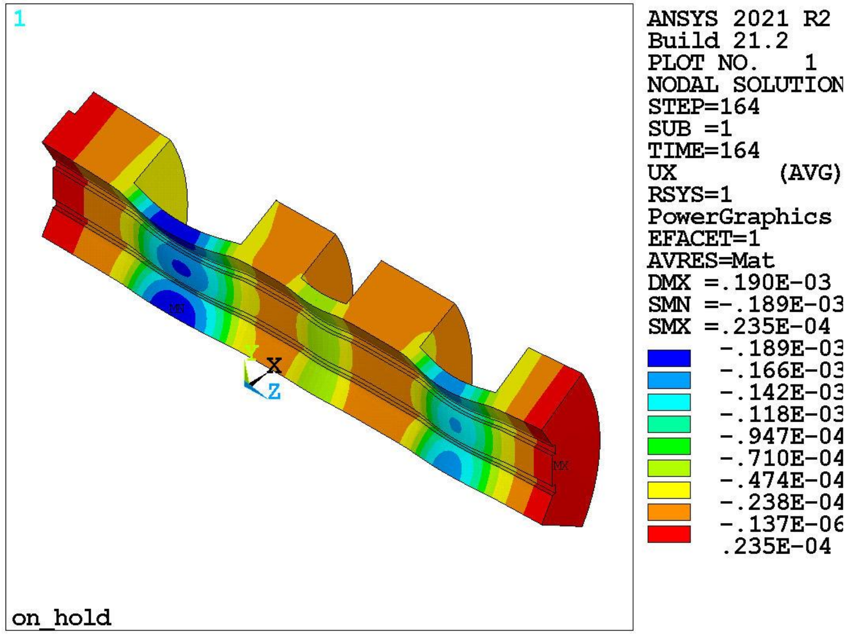


Managing stress for Nb_3Sn coils



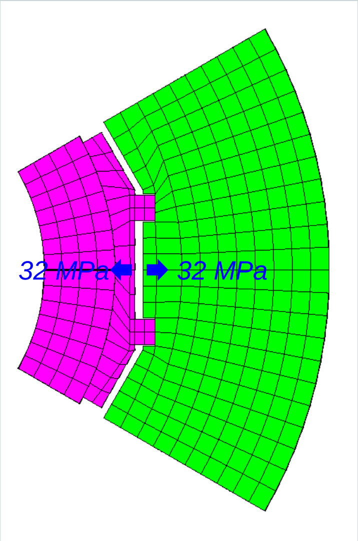
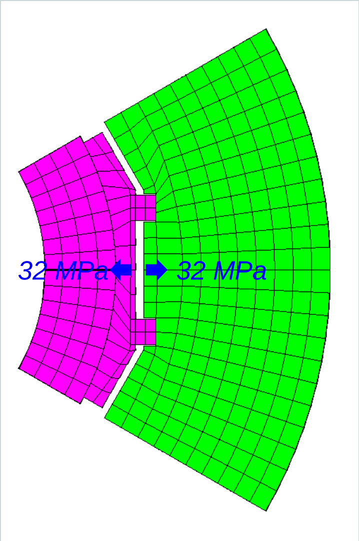
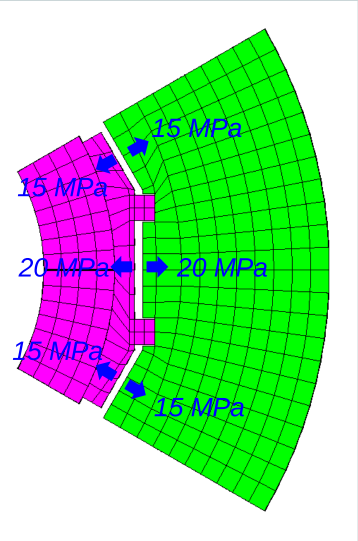
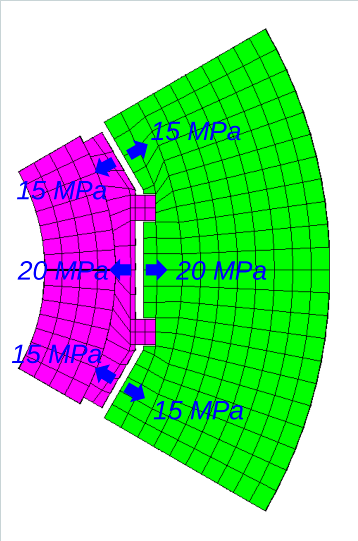






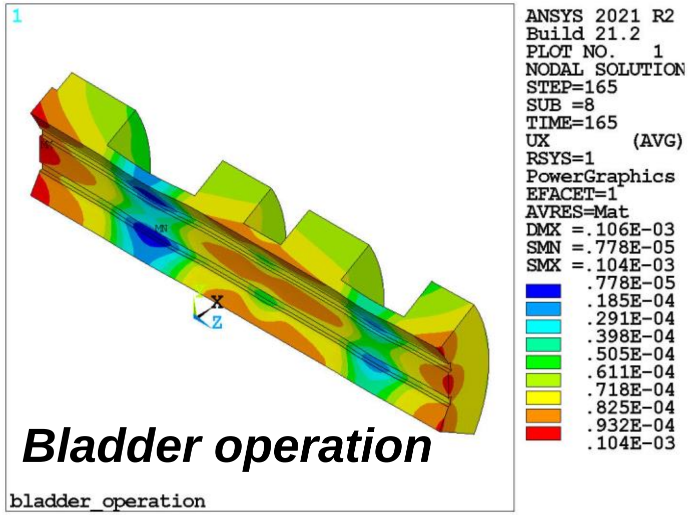
- The waved displacement in the key grooves will impact the sextupole coil insertion and shimming;
- The preload impacts frictional movements on the solenoid/mandrel interfaces.

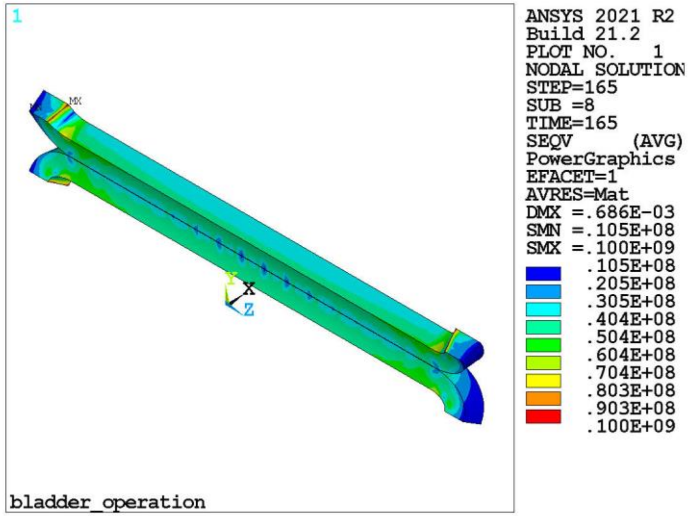
Stress simulations with FEM (ANSYS) during the assembly step

Item	Case 1	Case 2	Case 3	Case 4
Geometry				
Additional mandrel thickness [mm]	0	5	0	0
Number of bladder	6	6	12	12
Bladder pressure [MPa]	32	32	15, 20	15, 20
Additional key grove [mm]	0	0	0	1.0

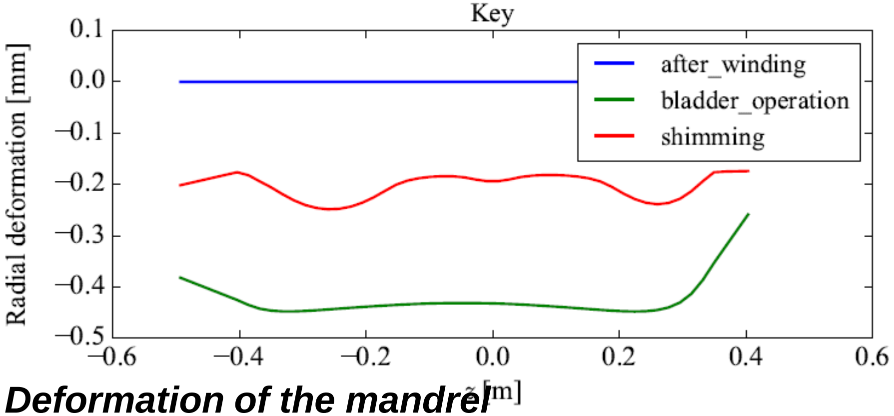
Original design (Case 1) **New design** (Case 4)

FEM simulations to minimize coil stress during assembly

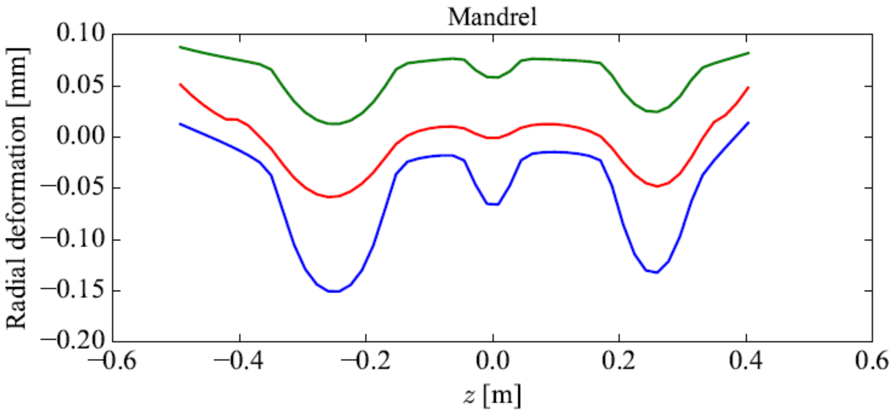




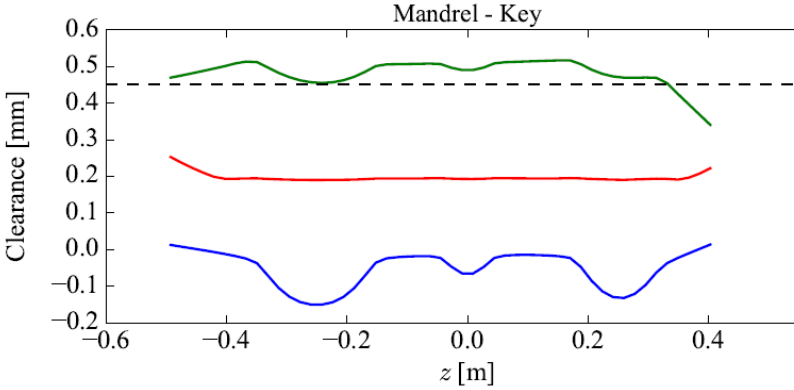
Deformation of the key

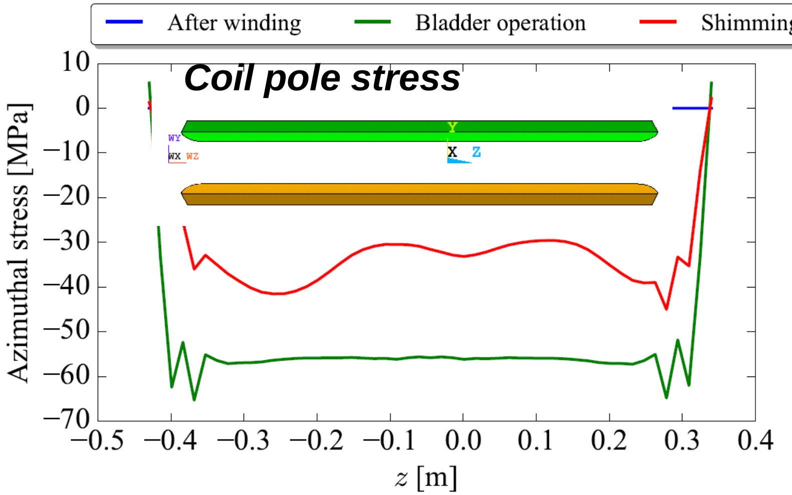


Deformation of the mandrel



Clearance for key insertion





Ye Yang, LBNL

Summary

- **High field superconducting magnets have broad applications and impacts on DOE missions.**

- **High power superconducting ECR magnets are an interesting area, with successes in VENUS and FRIB ECR, new concepts (MARS), and the potential of leveraging the HEP Nb_3Sn conductors and magnets development to get into > 45 Ghz.**

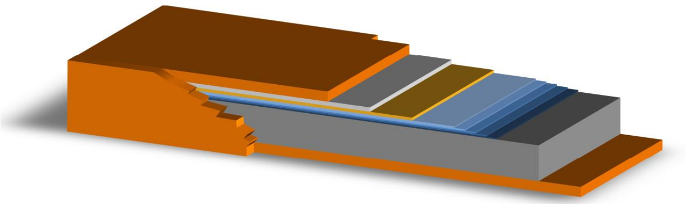
Acknowledgement

- Ting Xu and Peter Ostroumov
- Ting Xu and magnet group's Yoonhyuck Choi, Xiaoji Du, David Greene, Junwei Guo, Guillaume Machicoane, Tomofumi Maruta, Jie Wei, Ting Xu, Danlu Zhang for collaboration and hospitality
- LBNL colleagues especially Soren Prestemon and Ye Yang with preparing this presentation.
- VENUS and FRIB Nb-Ti ECR magnet teams

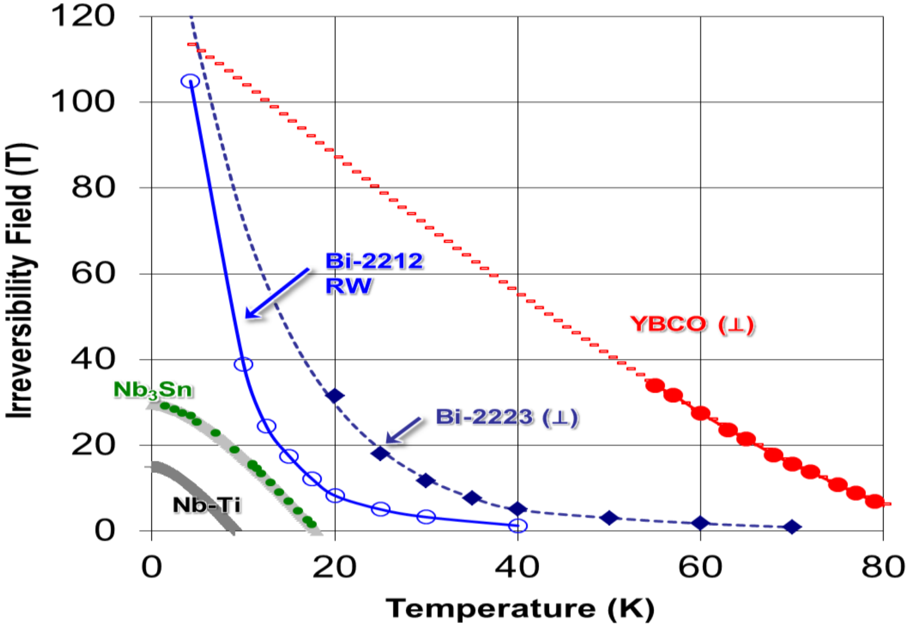
Thank You

HTS (REBCO coated conductor) has remarkable properties

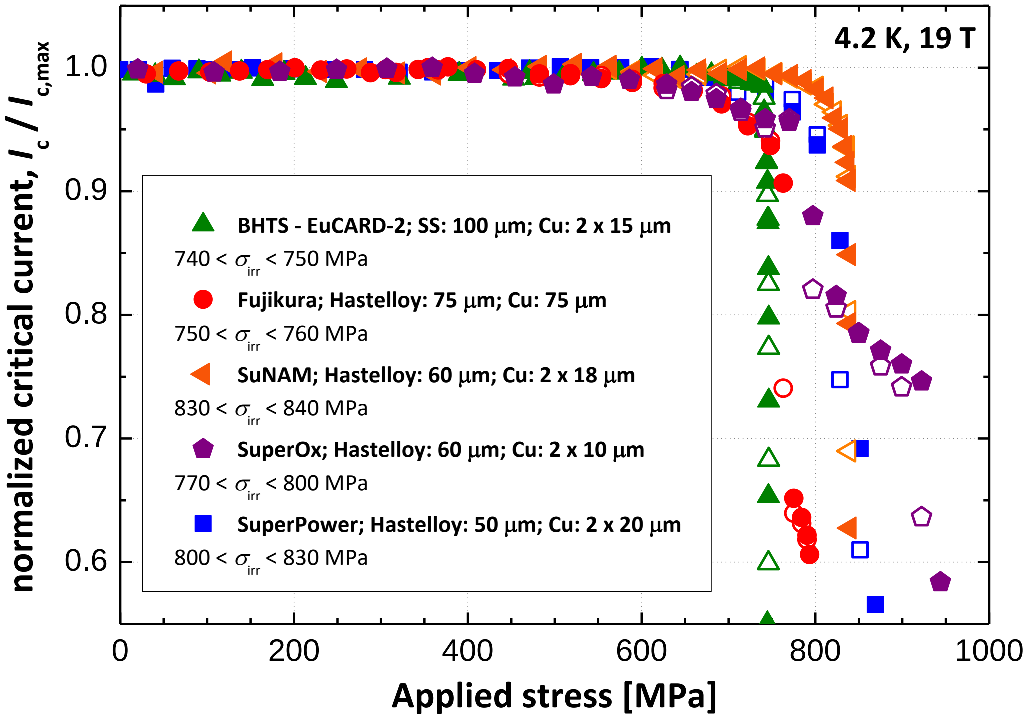
- Nb_3Sn and HTS supplies ~2x and ~10x higher H_{c2} or H_{irr}



(courtesy of D. Larbalestier, NHMFL)



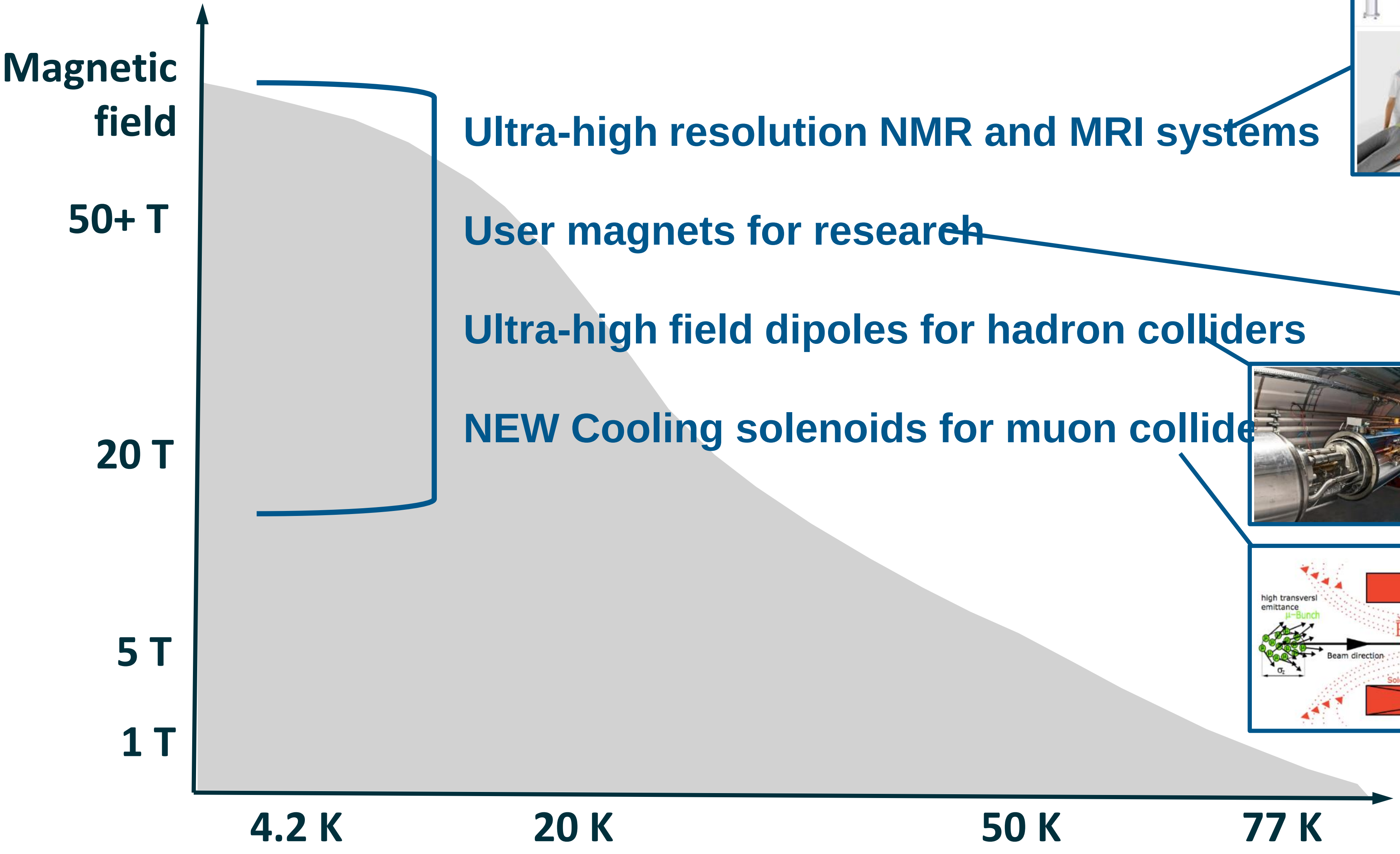
I_c vs. longitudinal stress

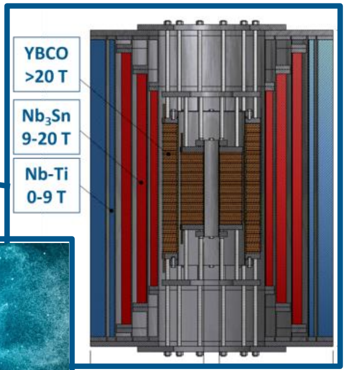


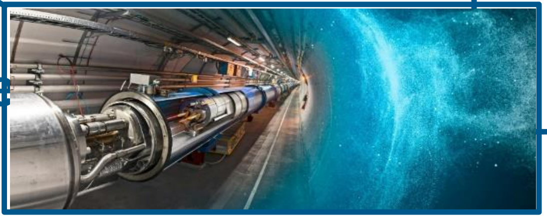
Barth, Mondonico, and Senatore, SUST 28 (2015) 045011
DOI: 10.1088/0953-2048/28/4/045011

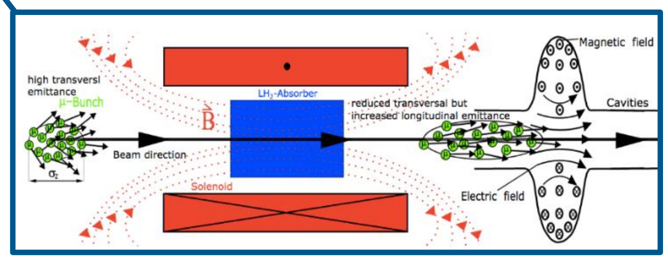
What we can do with HTS

A wide range of applications in various domains





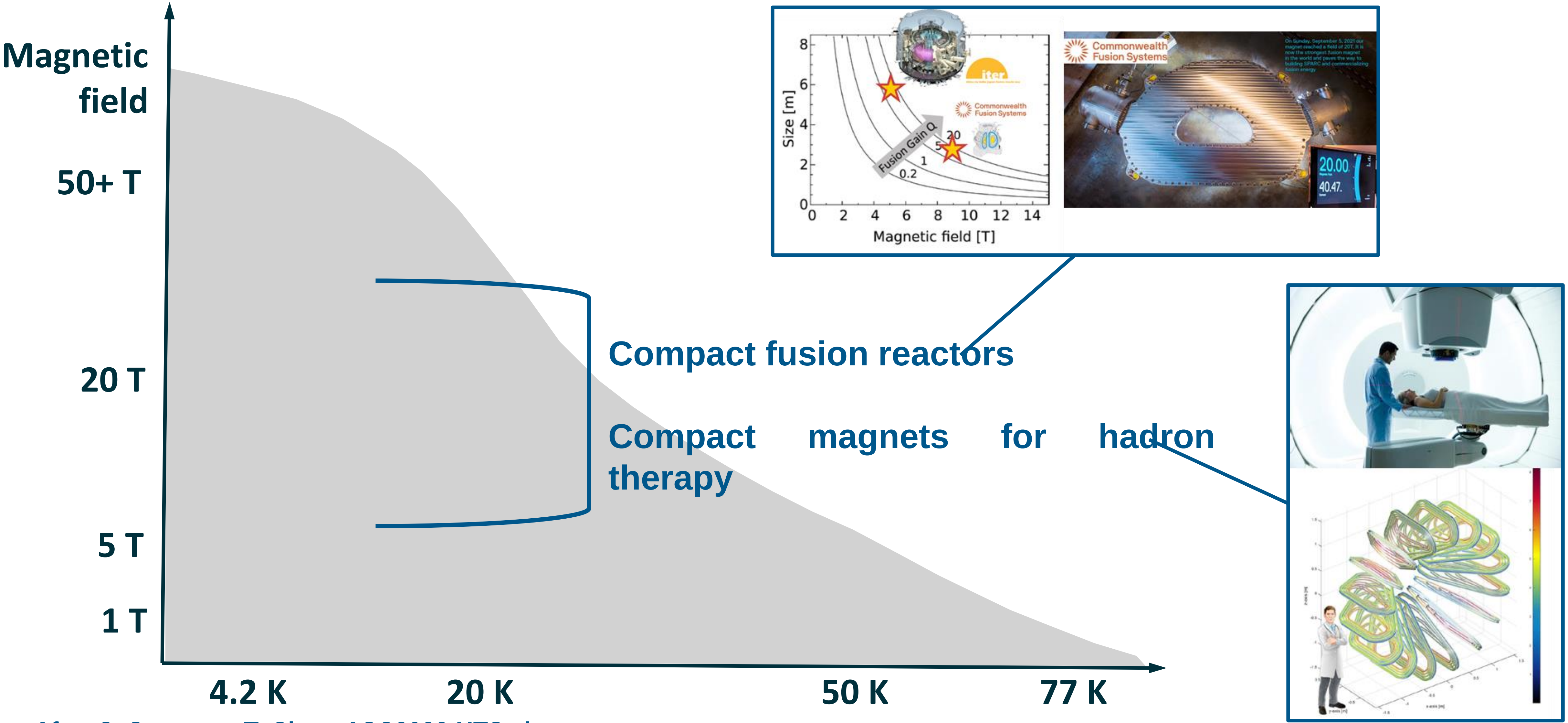




After C. Senatore, T. Shen, ASC2022 HTS short course

What we can do with HTS

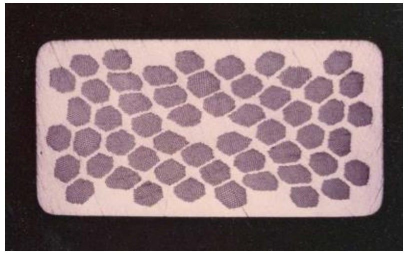
A wide range of applications in various domains



After C. Senatore, T. Shen, ASC2022 HTS short course

High-field, compact, HTS based fusion reactor gains huge momentum

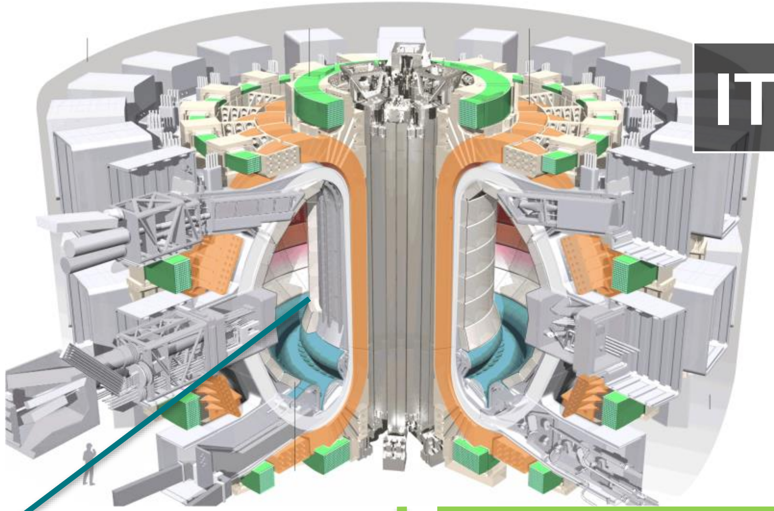
1980s - now:
NbTi superconductors
First SC fusion devices



Tore Supra 1988
B_{coil} = 9 T

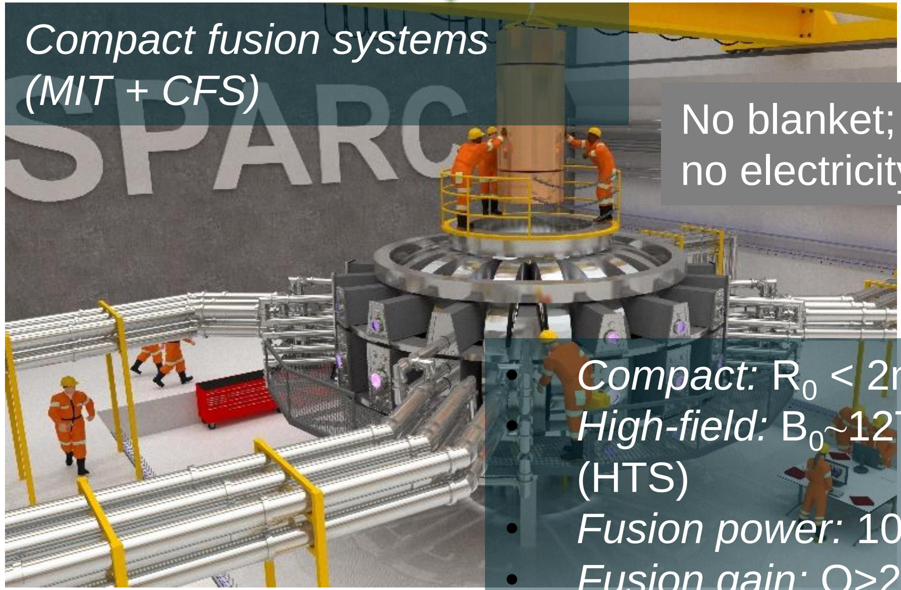
1990s - now
Nb_3Sn for higher field
Reactor-class devices

ITER 2015
B_{coil} = 13 T



ITER

B x2; Plasma density x16;



Compact fusion systems (MIT + CFS)

No blanket;
no electricity generation

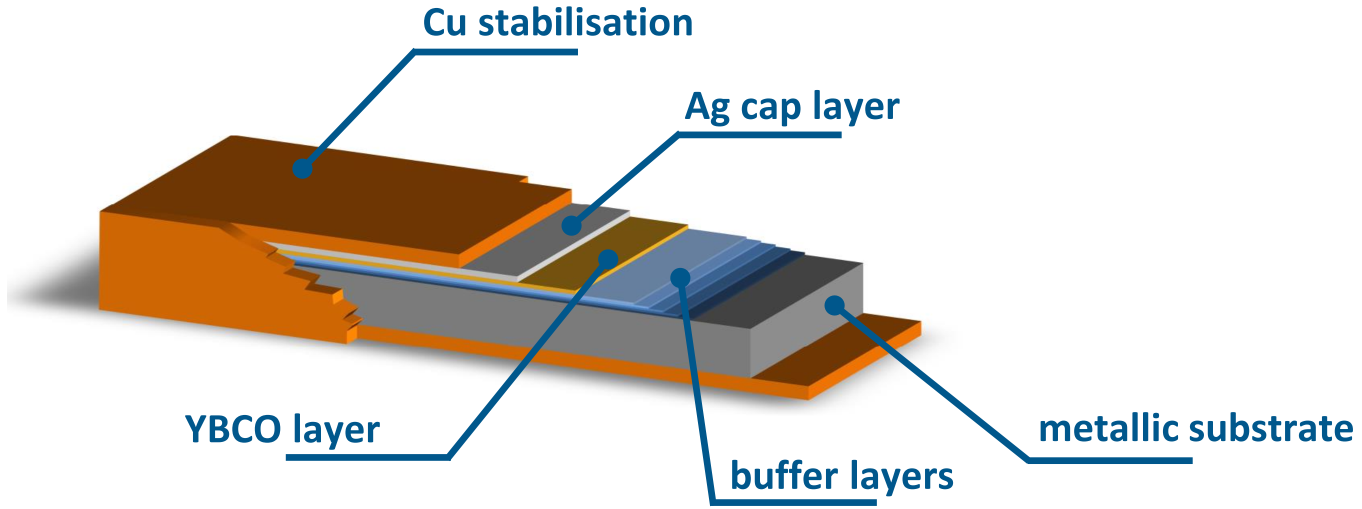
- *Compact:* R_0 < 2m
- *High-field:* B_0~12T, B_{max}~21T (HTS)
- *Fusion power:* 100 MW
- *Fusion gain:* Q>2

After Z. Hartwig (MIT)

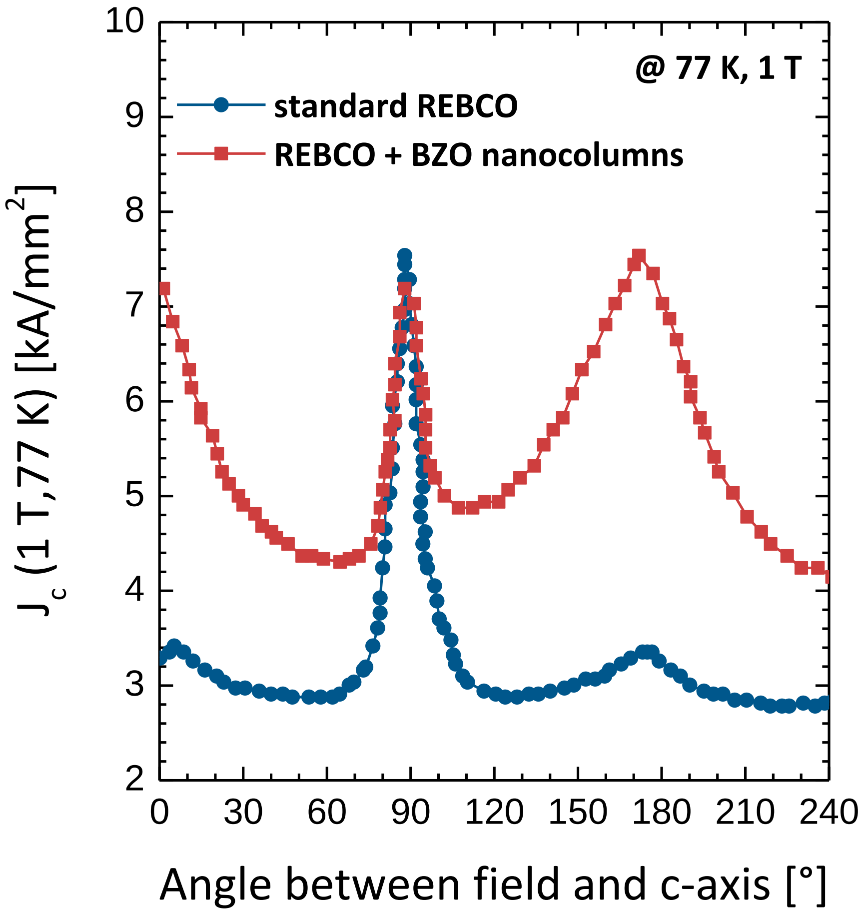
Engineering challenges with using REBCO coated conductors in high field magnets

- **Complex conductor properties and QA/QC.**

~1 µm of YBCO in a ~100 µm thick tape



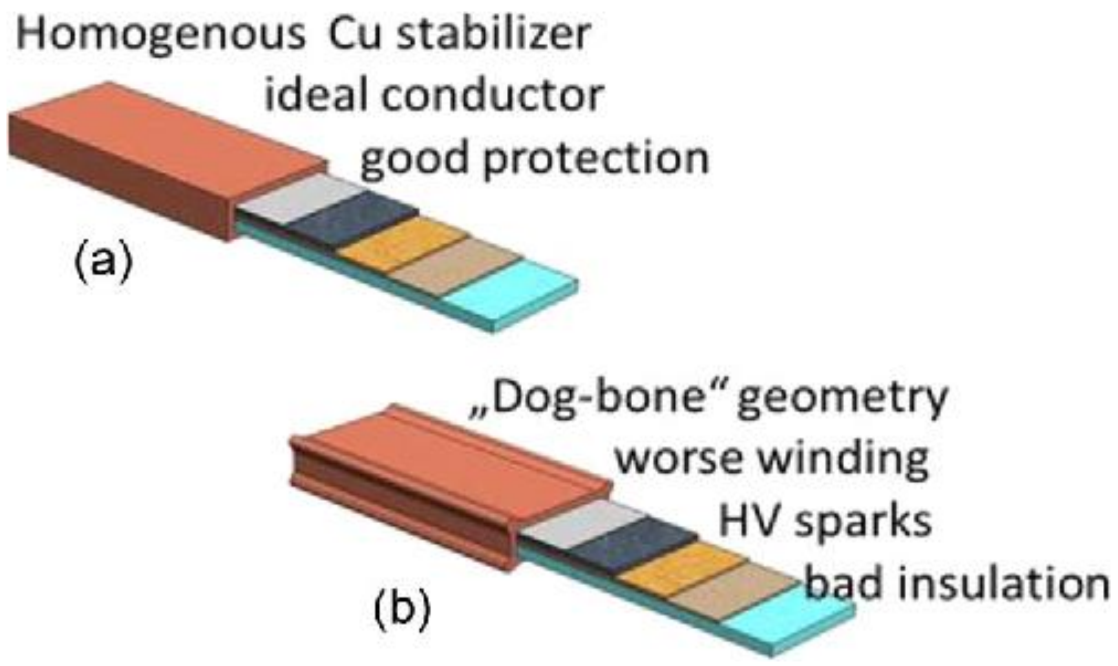
Barth, Mondonico, and Senatore, SUST 28 (2015) 045011
DOI: 10.1088/0953-2048/28/4/045011



Selvamanickam et al., IEEE TAS 21 (2011) 3049 – DOI: 10.1109/TASC.2011.2107310

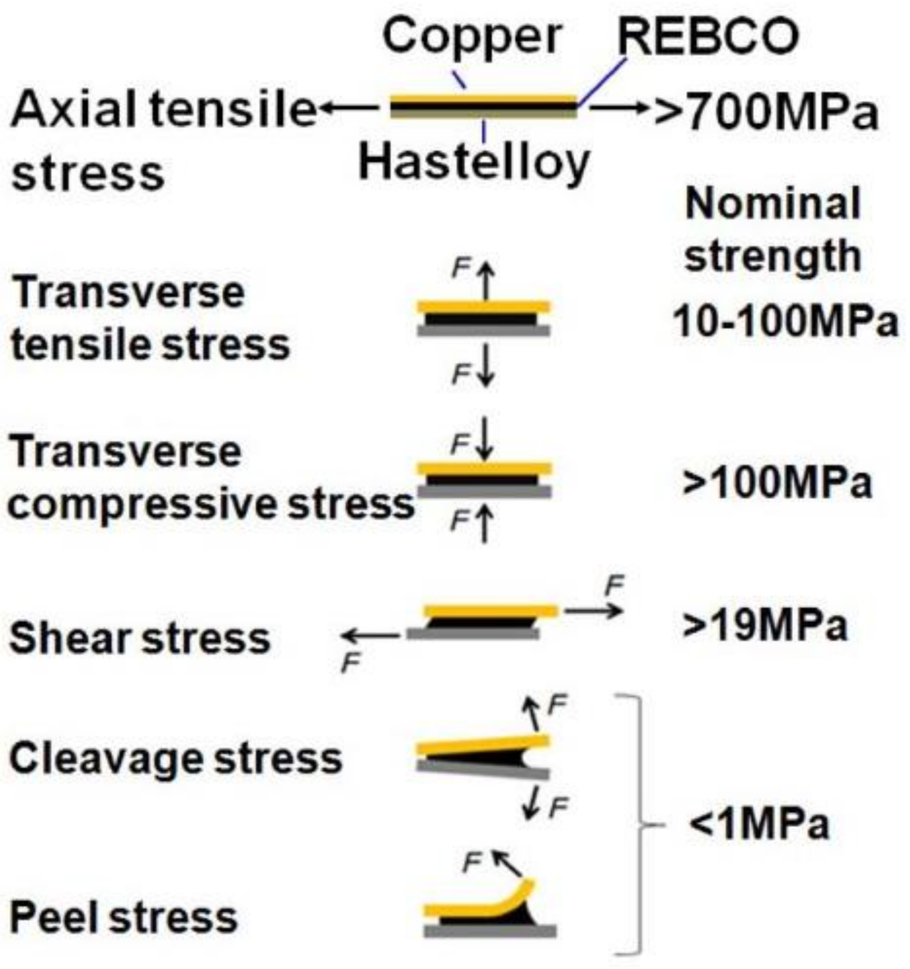
Engineering challenges with using REBCO coated conductors in high field magnets

- **Dimensional/geometrical accuracy.**



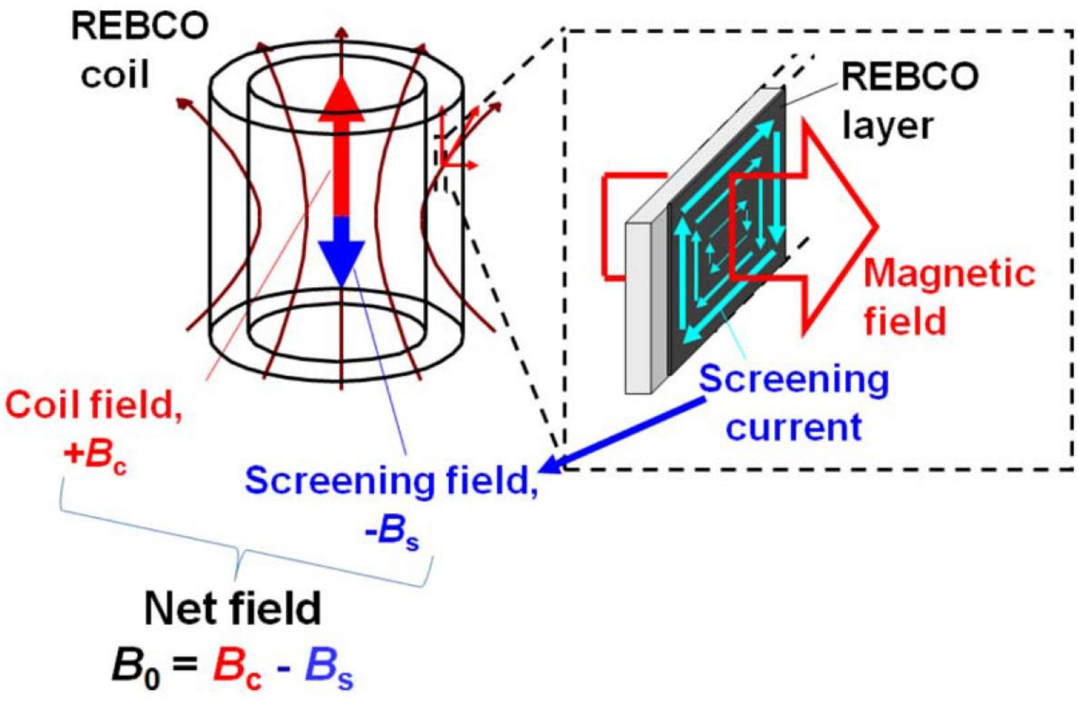
[10.1109/TASC.2016.2549859](https://doi.org/10.1109/TASC.2016.2549859)

- **Delamination and shear stresses.**



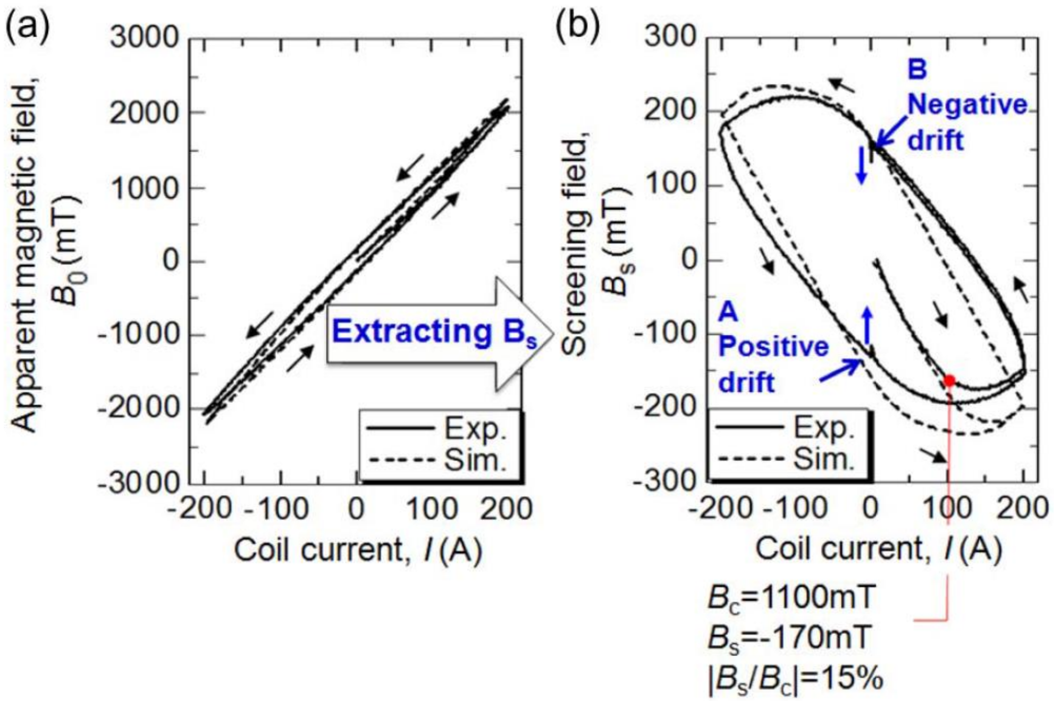
H. Maeda, Y. Yanagisawa, TAS, 24 (2014) 4602412

Persistent current compromises field quality



Important for both MRI/NMR and HEP magnets.

- **Consequence I: Field hysteresis.**

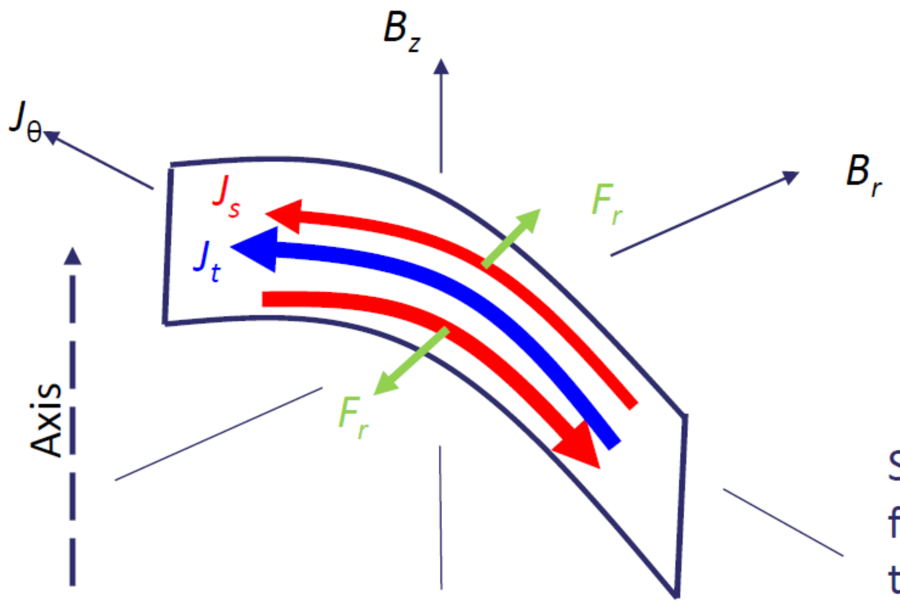


- **Consequence II: Field decays.**

H. Maeda, Y. Yanagisawa, TAS, 24 (2014) 4602412

Mechanical consequence of screening currents

Screening Currents: Tape Conductors



- J_t = transport current in θ direction. It creates B_z. At top of magnet B_r is positive.
- During charging of the magnet, B_r creates screening currents, J_s, in the tape.
- The Screening Current changes the field distribution.

Naoyuki Amemiya & Ken Akachi, *SuST* (2008) 095001.

Screening Currents: Strain

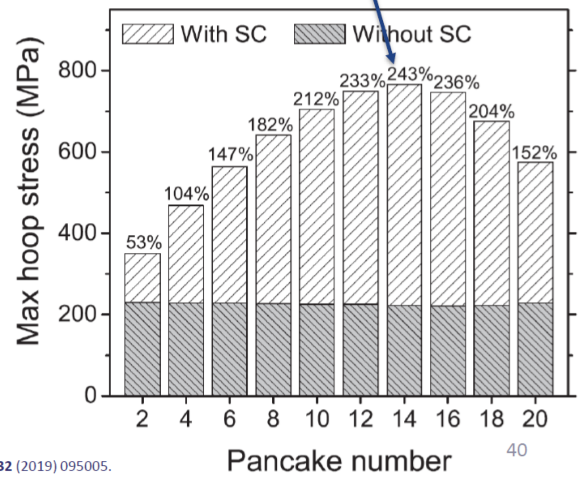
In the 1970s & 1980s, IGC built Nb_3Sn tape magnets.

Rippling of the edge of used tapes was observed.

In 2019 Jing Xia, et al., showed that if a coil was designed for uniform stress due to transport current only, actual stress including screening currents might be 2.4x higher.

Low screening currents at mid-plane due to low radial field.
High radial field at end of coil limits Jc.

Max. Torque and Strain for REBCO.



Jing Xia, Hongyu Bai, Huadong Yong, Hubertus W. Weijers, Thomas A. Painter, & Mark D. Bird, *SuST* **32** (2019) 095005.

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After Mark Bird, MT26 plenary