中國科學院物理研究所
Institute of Physics, Chinese Academy of Sciences

超导基础理论和实验技术讲座
National Lab for Superconductivity Lecture Series

【第91期】

粒子加速器中的高场超导磁体技术

徐庆金

中国科学院高能物理研究所

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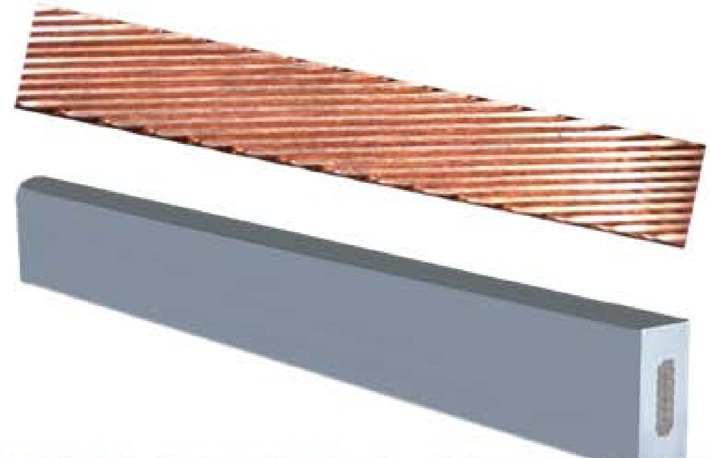

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粒子加速器中的高场超导磁体技术

徐庆金，中科院高能物理研究所研究员，高场超导磁体技术团队负责人，HL-LHC(大型强子对撞机高亮度升级) CCT国际合作项目负责人。2008-2014年于日本高能加速器研究机构(KEK)及欧洲核子研究中心(CERN)开展先进超导磁体技术研究，2014年入选中科院“引进国外杰出人才”。带领团队研制出中国第一个10T级高场超导二极磁体；与国内相关团队合作，国际上首次完成基于铁基超导材料的超导线圈研制及高场下性能验证；带领中国团队承担HL-LHC国际合作项目中新型CCT超导磁体的研制。

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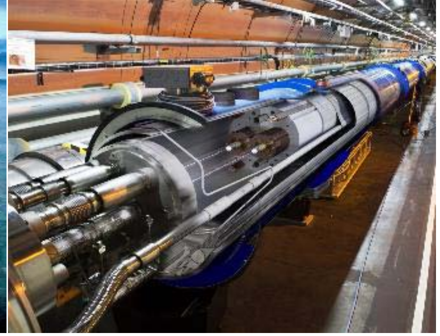
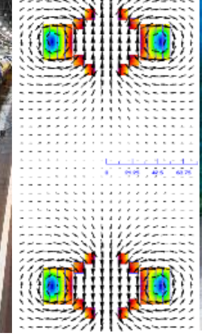

粒子加速器中的高场超导磁体技术
High Field Superconducting Magnets for Particle Accelerators

徐庆金
中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences
(IHEP, CAS)

超导基础理论和实验技术系列讲座第91讲，中科院物理研究所，2020年8月14日，北京

Outline

- **Fundamental Principles of the Superconducting Accelerator Magnets**
- PRINCIPLES of Particle Accelerators
- CHARACTERISTICS and MAIN CHALLENGES of the Superconducting Accelerator Magnets

- **Case Study**
- Progress of the High Field Magnet R&D at IHEP
- Progress of the HL-LHC CCT Magnets

Outline

- **Fundamental Principles of the Superconducting Accelerator Magnets**
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- Progress of the HL-LHC CCT Magnets

Acknowledgement

The materials of this section are based on the following references

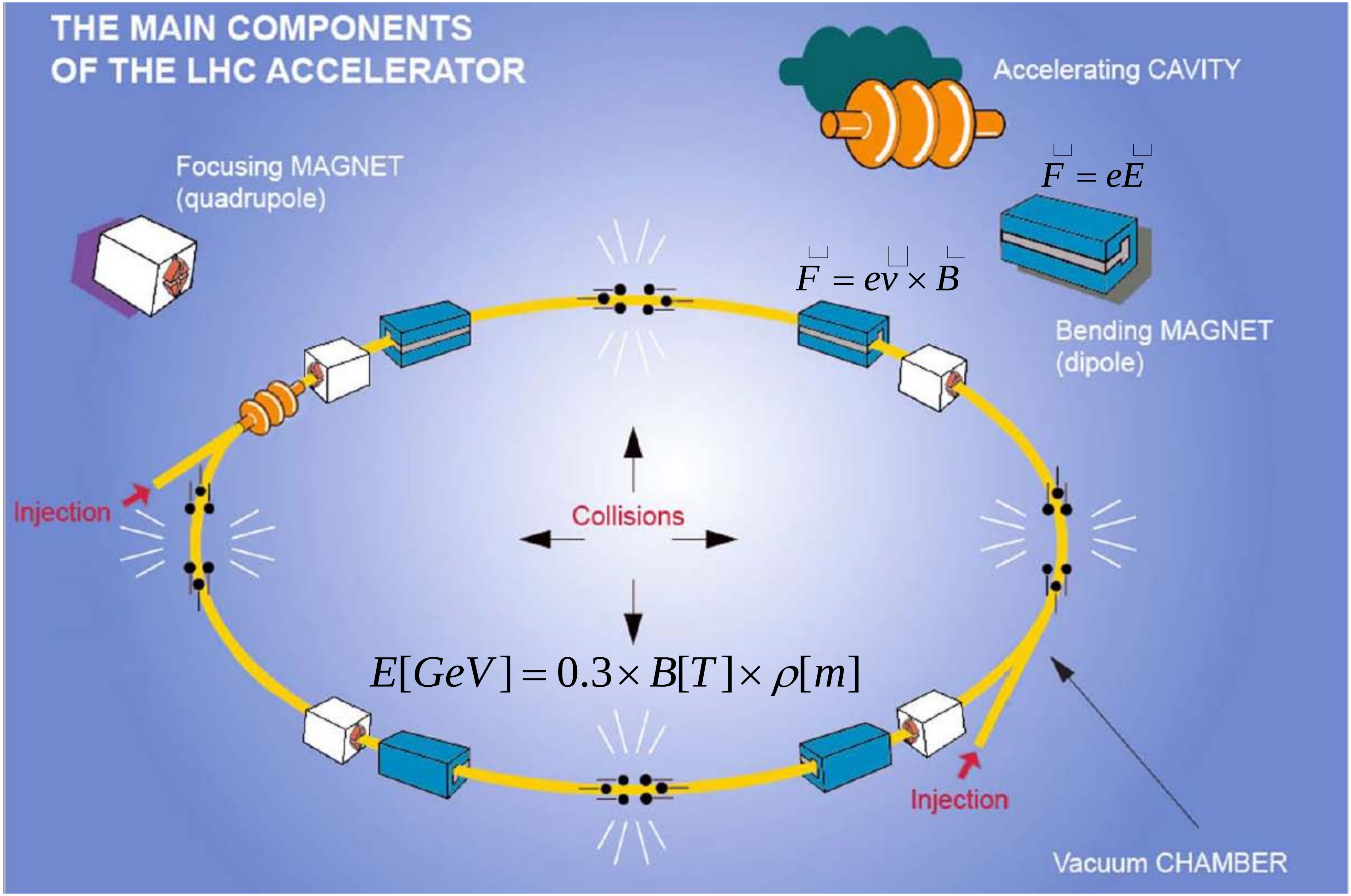
- "Superconducting Accelerator Magnets" by **Steve Gourlay and Soren Prestemon (LBNL),** June 2018
- "Superconducting Accelerator Magnets" by **Soren Prestemon (LBNL), Paolo Ferracin and Ezio Todesco (CERN),** June 2015
- "Applied Electromagnetism: Magnet and RF-Cavity Design" by **Mau Lopes** and Jeremiah Holzbauer (FNAL), January 2016

USPAS website: http://uspas.fnal.gov/materials/materials-table.shtml

And talks from Lucio Rossi, Steve Gourlay et al, and the **textbooks**:

- **Martin N. Wilson**, "Superconducting Magnets", 1983.
- **K.-H. Mess, P. Schmuser, S. Wolff**, "Superconducting accelerator magnets", Singapore: World Scientific, 1996.
- **Fred M. Asner**, "High Field Superconducting Magnets", 1999.

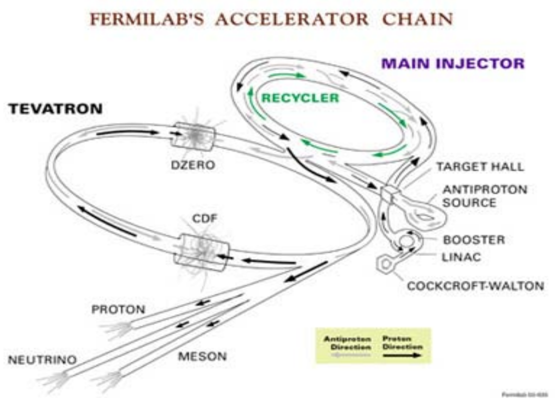
PRINCIPLES of a Circular Collider



The 1st Superconducting Accelerator in the World

Tevatron accelerator at Fermilab. Construction completed in 1980s.

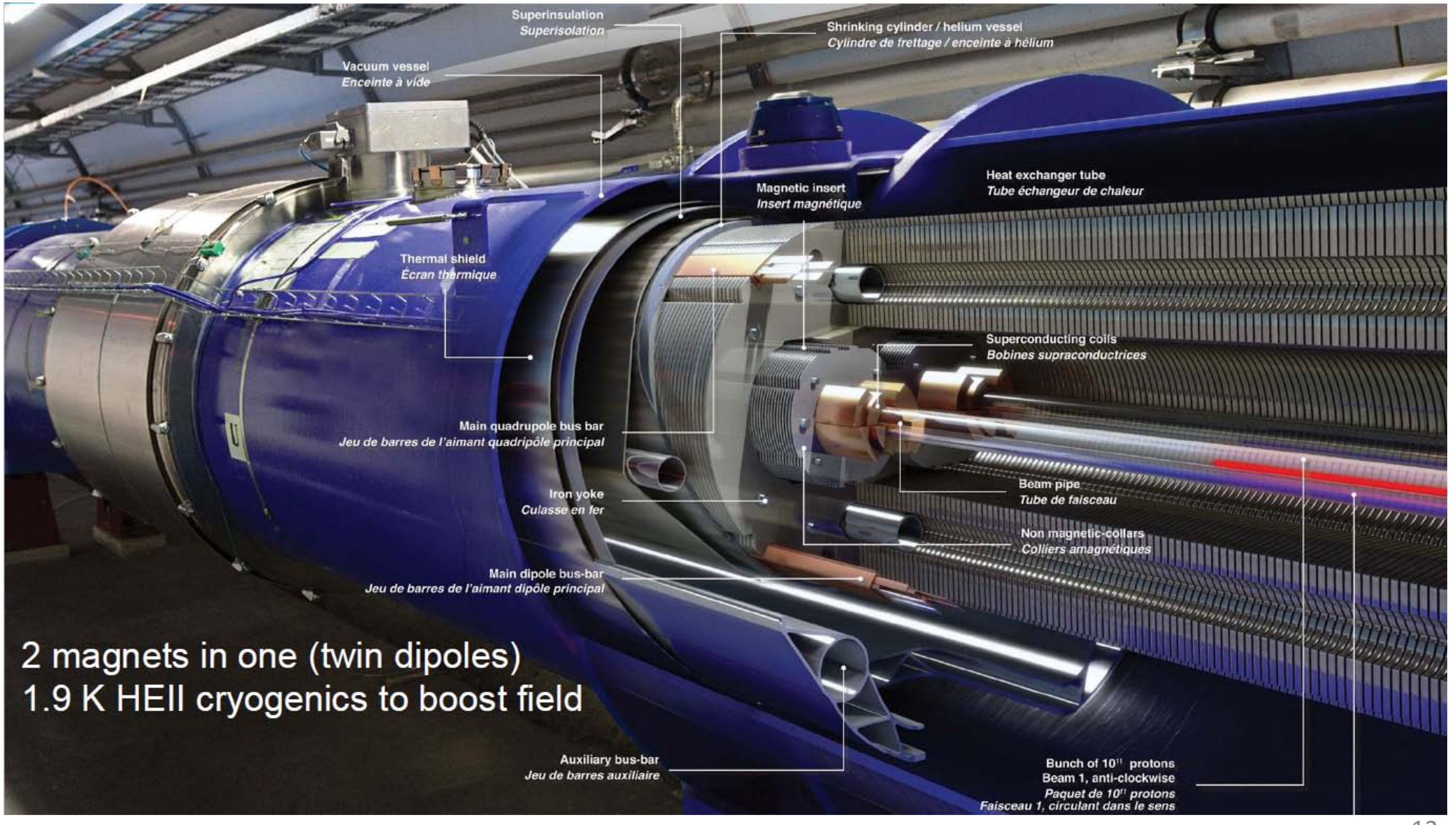
774 superconducting NbTi dipole magnets + 240 NbTi quadrupole magnets



IEEE Milestone Award:** The first large-scale use of superconducting magnets enabled the construction of the Tevatron. Established the superconducting wire manufacturing infrastructure that **made applications such as Magnetic Resonance Imaging (MRI) viable.

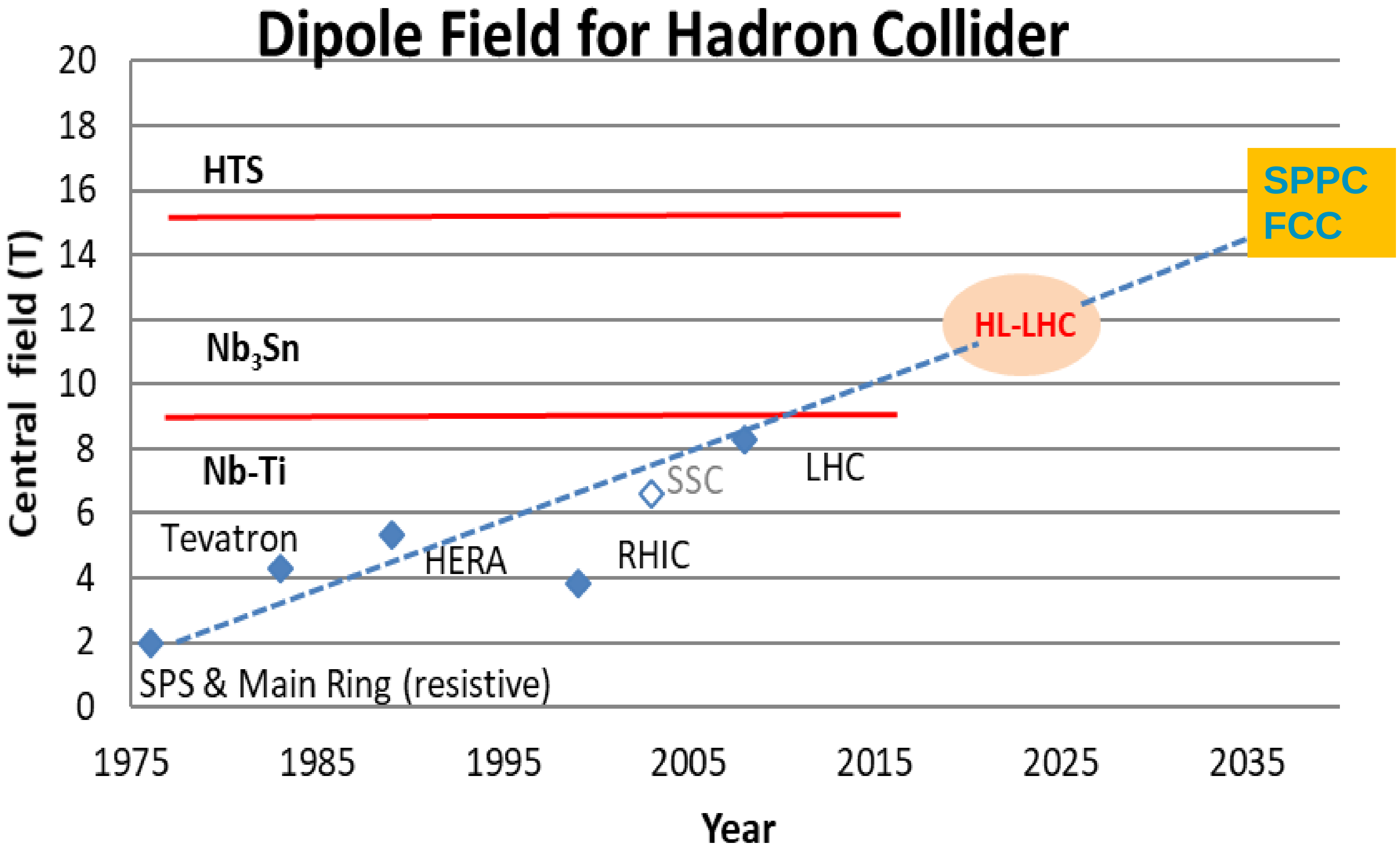
The Largest Application of Superconductivity so far: LHC

1232 SC dipoles–15 m –8.33 T. 500 SC Quadrupoles. 8000 Corrector Magnets. 16 SC Cavities. 40 pairs large Current Leads in HTS



Lucio Rossi

Hadron Colliders in the Past and Future



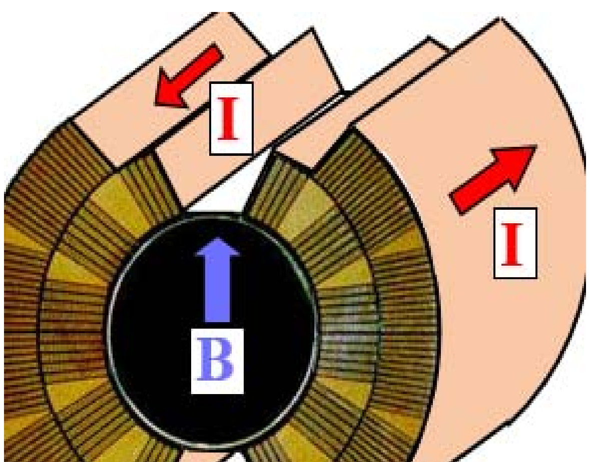
Dipole vs. Solenoid

Dipole

$$B = \mu_o J_e \frac{t}{2}$$

J_e – Current density

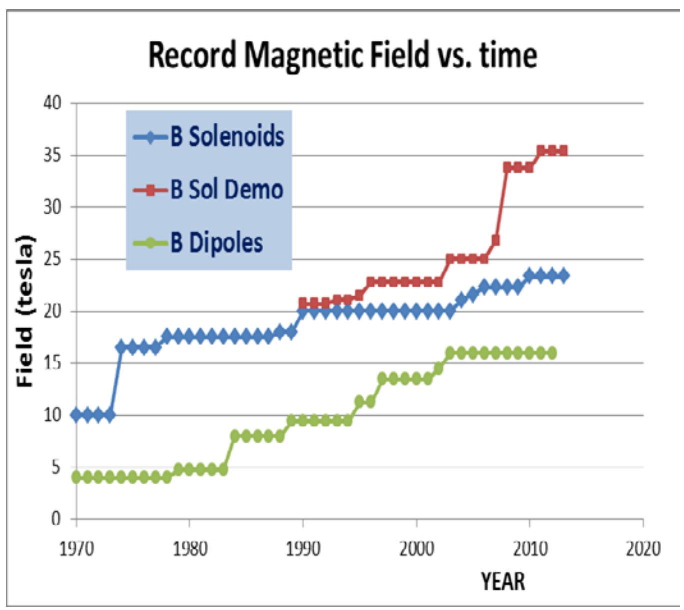
t – Coil thickness



LHC dipole

- *Different coil configurations*

  $B_{dipole} = \frac{1}{2} B_{solenoid}$
- *Limited coil width for dipole*
- *Magnetic shielding*
- *Cost*



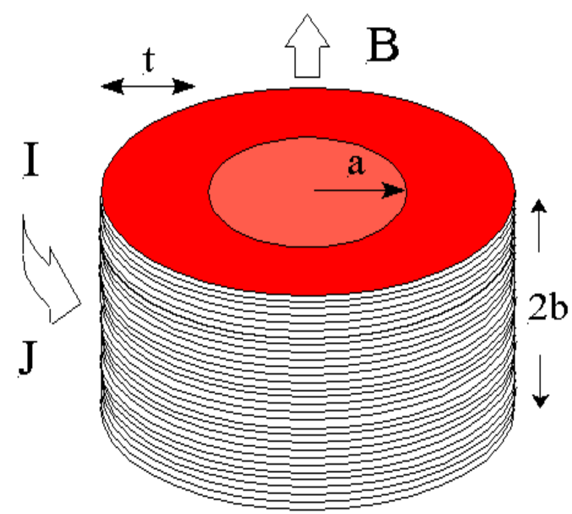
Lucio Rossi

Solenoid

$$B = \mu_o J_e t$$

J_e – Current density

t – Coil thickness



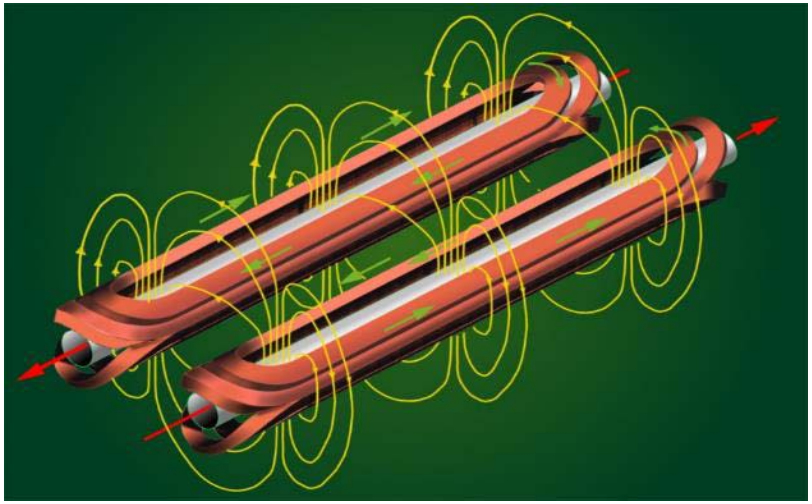
Martin Wilson

Coil Configurations for Dipole Magnets

Efficiency, field quality, stress management, quench protection…

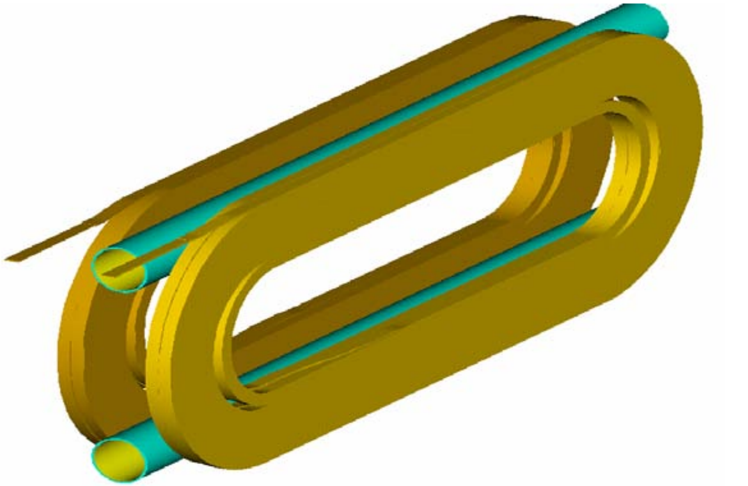
Cos-**th**eta dipole

Highest efficiency, complicated ends with hard-way bending



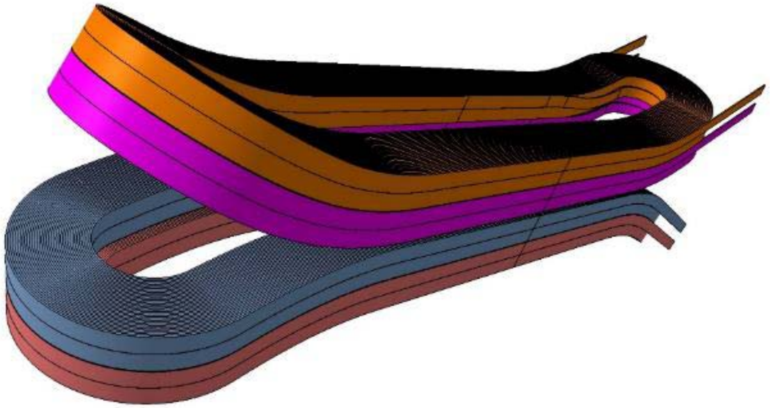
Common coil dipole

Simplest structure with large bending radius, lower efficiency



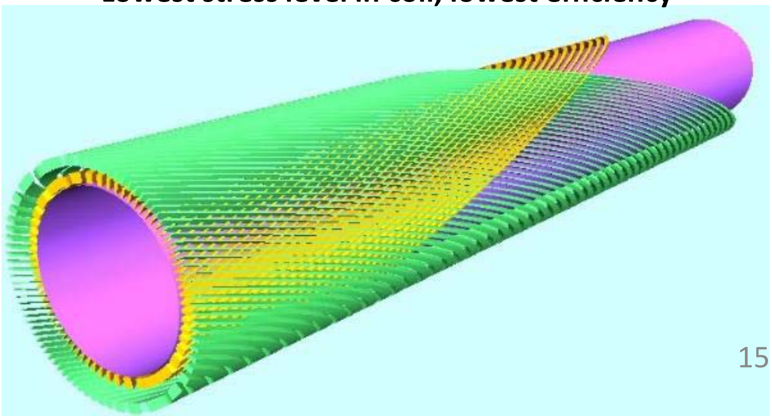
Block type dipole

Simpler structure with hard-way bending, lower efficiency



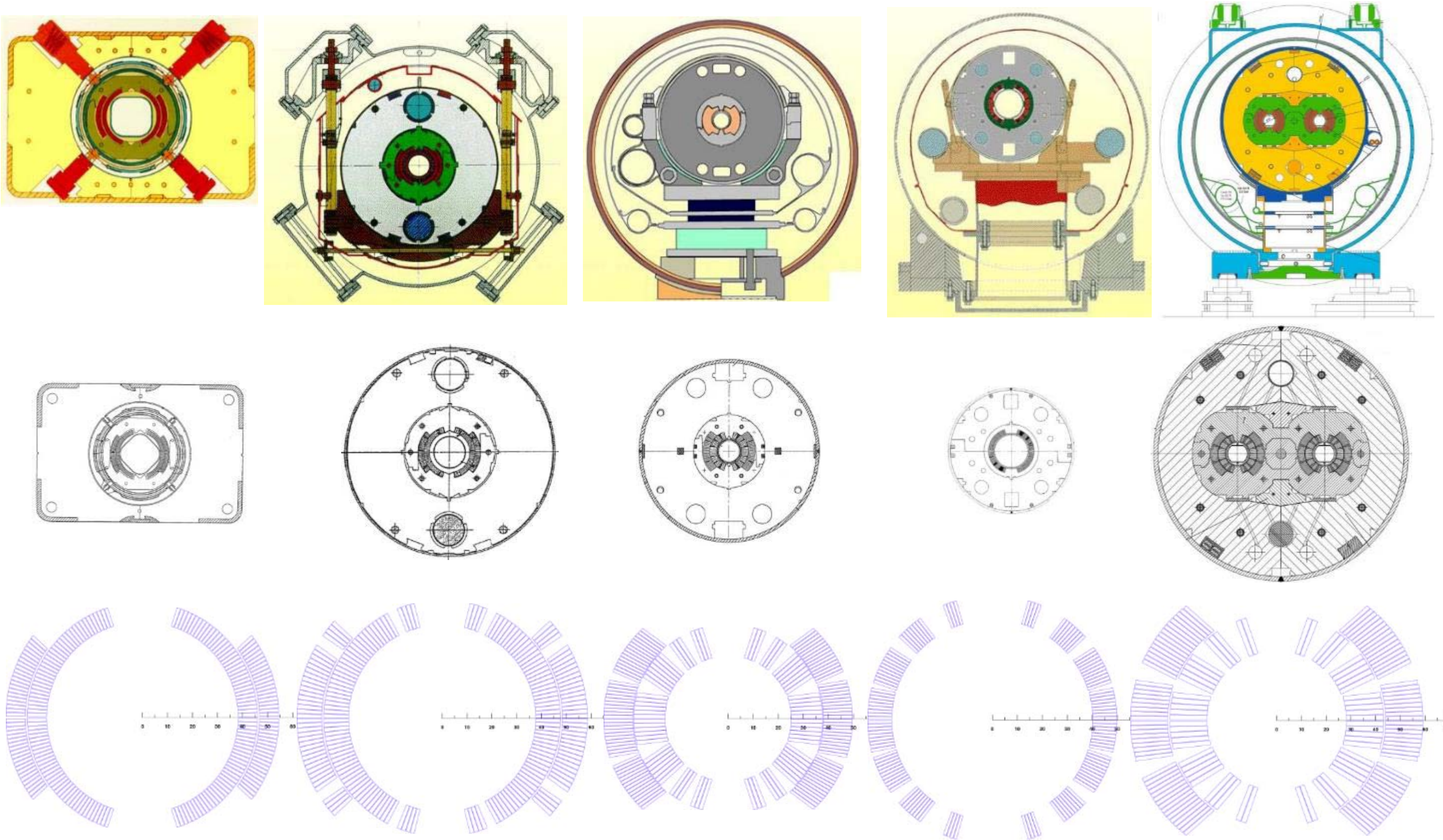
Canted cos-theta dipole

Lowest stress level in coil, lowest efficiency

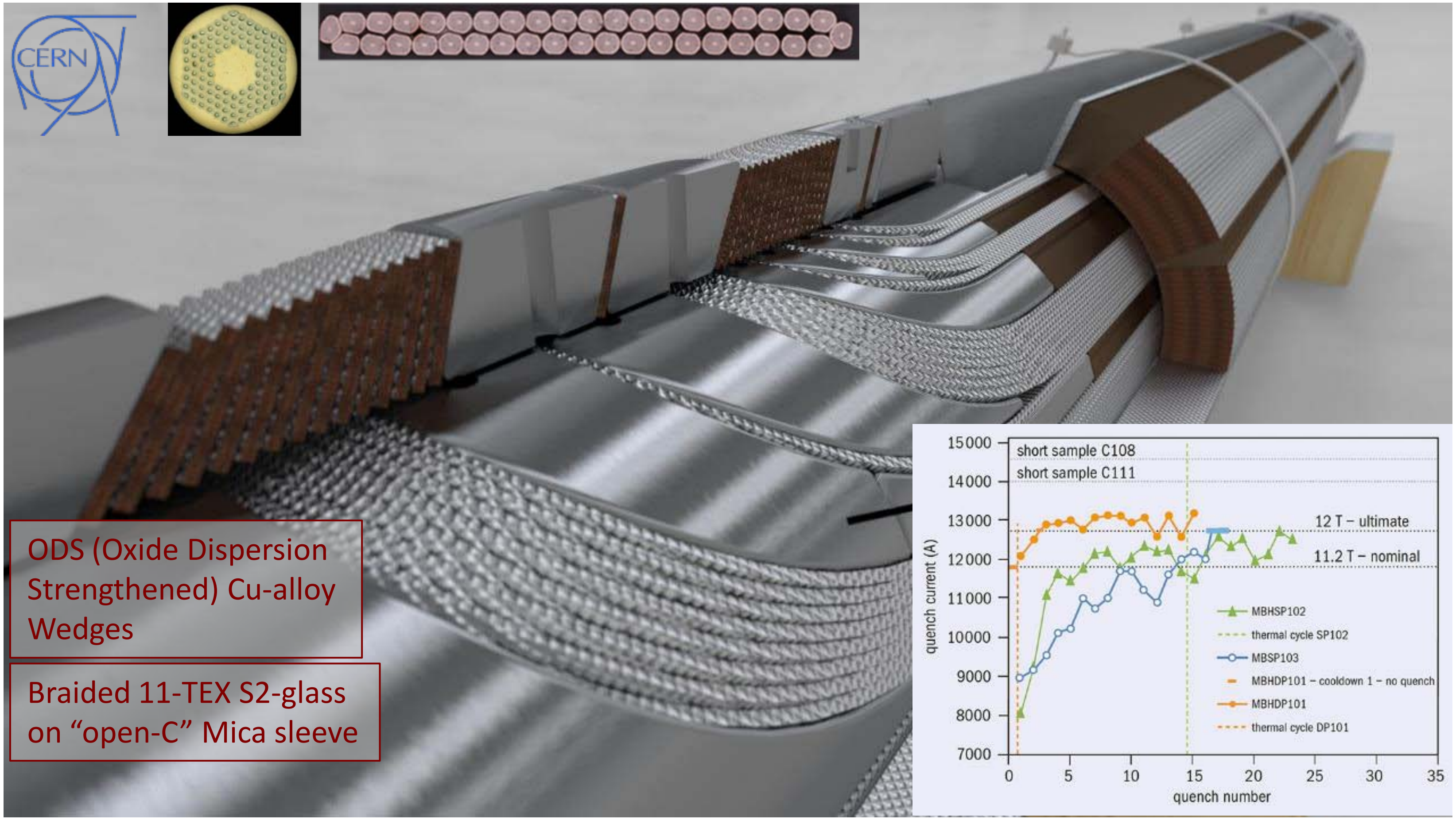


The Dipole Magnets in Past Years

Tevatron HERA SSC RHIC LHC



Ongoing: HL-LHC 11 T Dipole Magnet



New Record： 14.5T Dipole by Fermilab

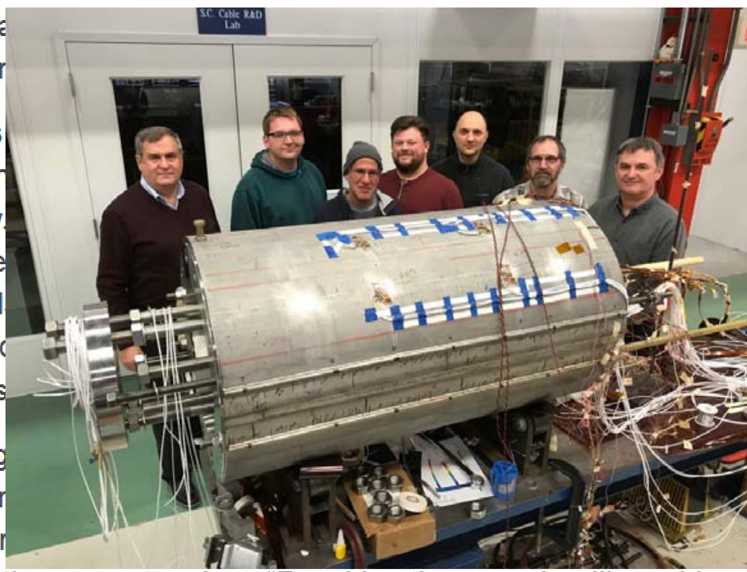
Fermilab achieves 14.5-tesla field for accelerator magnet, setting new world record

July 13, 2020 | Leah Hesla

Share Tweet Email

The Fermilab magnet team has done it again. After setting a world record for an accelerator magnet in 2019, they have broken it a year later.

In a June 2020 test, a demonstrator magnet designed and built by the magnet team
at the Depa ... strength for an
accelerator ... of 14.1 T.



This test is ... gnet
requiremen ... icle physics
community ... most eight
times more ... Collider at the
European ... T. Current
future-colli ... net — the
magnet res ... be up to 16 T.

"Our next g ... um field in
accelerator ... mprove magnet
quench per ... xander Zlobin,
who leads the magnet project. "Reaching these goals will provide strong foundation for future high-energy colliders."

Read more about the Fermilab-built future-collider steering magnet.

Field Harmonics

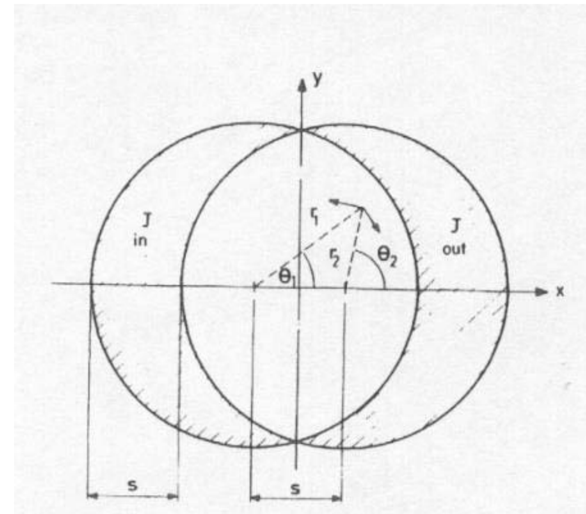
Perfect Dipole

Biot-Savart law

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \int_C \frac{I d\mathbf{l} \times \mathbf{r}'}{|\mathbf{r}'|^3}$$

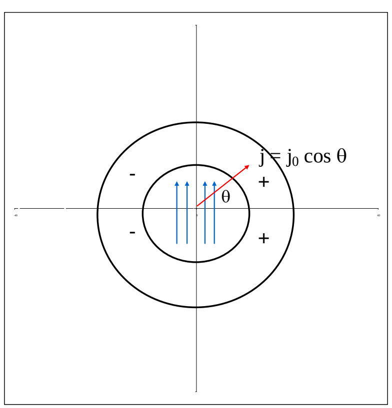
$$B_x = \frac{\mu_0 j_0 r}{2} \{ - r_1 \sin\theta_1 + r_2 \sin\theta_2 \} = 0$$

$$B_y = \frac{\mu_0 j_0 r}{2} \{ - r_1 \cos\theta_1 + r_2 \cos\theta_2 \} = -\frac{\mu_0 j_0}{2} s$$

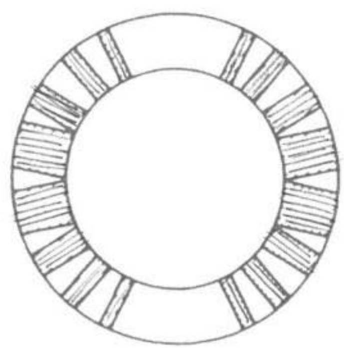


From M. N. Wilson, pg. 28

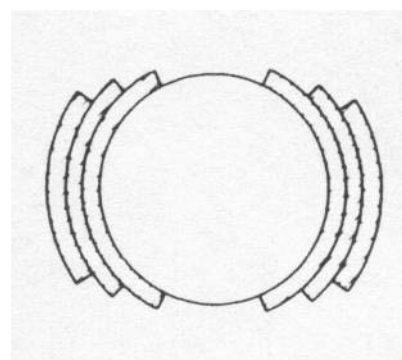
Cosθ: a current density proportional to cosθ in an annulus - it can be approximated by sectors with uniform current density



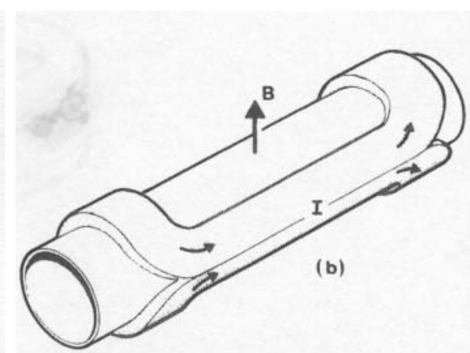
An ideal cosθ



A practical winding with one layer and wedges
[from M. N. Wilson, pg. 33]



A practical winding with three layers and no wedges
[from M. N. Wilson, pg. 33]



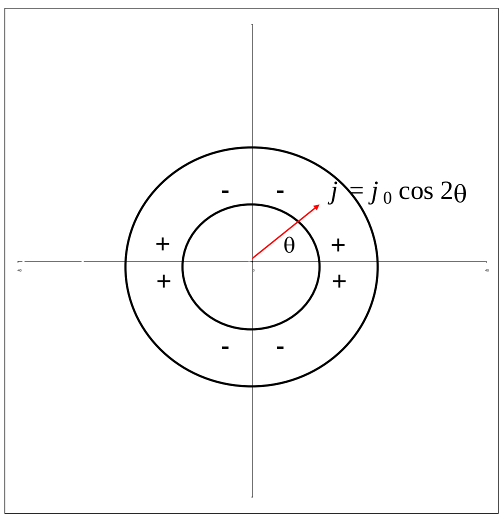
Artist view of a cosθ magnet
[from Schmuser]

Field Harmonics

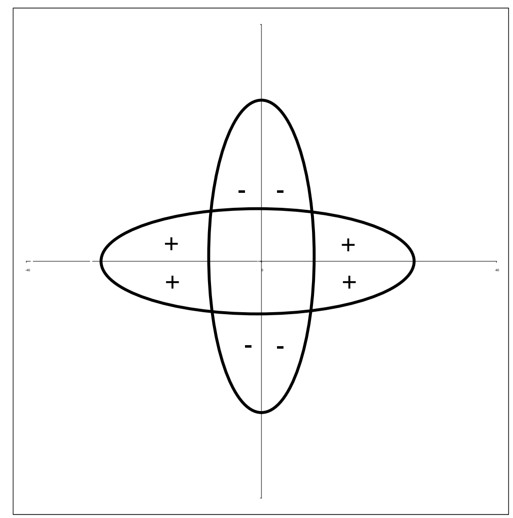
Perfect quadrupole

Cos2θ, a current density proportional to cos2θ in an annulus-approximated by sectors with uniform current density and wedges

(Two) intersecting ellipses



Quadrupole as an ideal cos2θ



Quadrupole as two intersecting ellipses

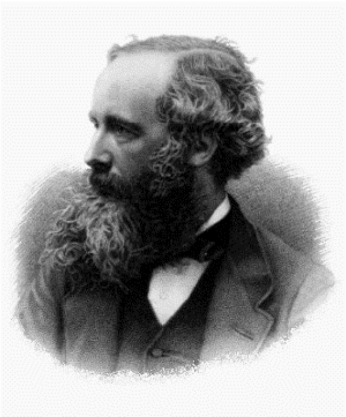
- Perfect sextupoles: cos3θ or three intersecting ellipses
- Perfect $2n$-poles: cos$n\theta$ or n intersecting ellipses

Field Harmonics

- Maxwell equations for magnetic field

$$\nabla \cdot B = \frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} + \frac{\partial B_z}{\partial z} = 0 \qquad \nabla \times B = \mu_0 J + \mu_0 \varepsilon_0 \frac{\partial E}{\partial t}$$

Gauss's law for magnetism — Ampère's circuital law

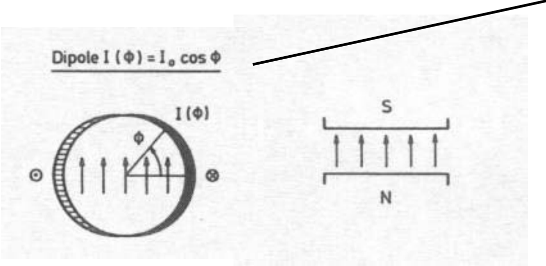


James Clerk Maxwell, Scottish (13 June 1831 – 5 November 1879)

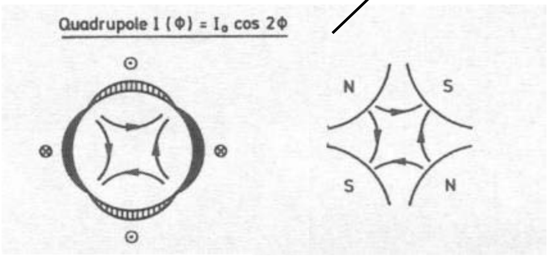
- In absence of charge and magnetized material

and for 2D constant longitudinal field,

$$B_y(x,y) + iB_x(x,y) = \sum_{n=1}^{\infty} C_n (x+iy)^{n-1} = C_0 + C_1(x+iy) + \ldots \qquad (x,y) \in D$$

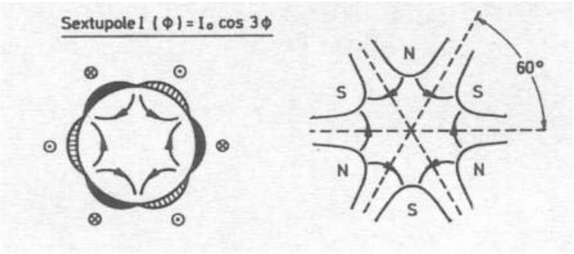


A dipole



A quadrupole

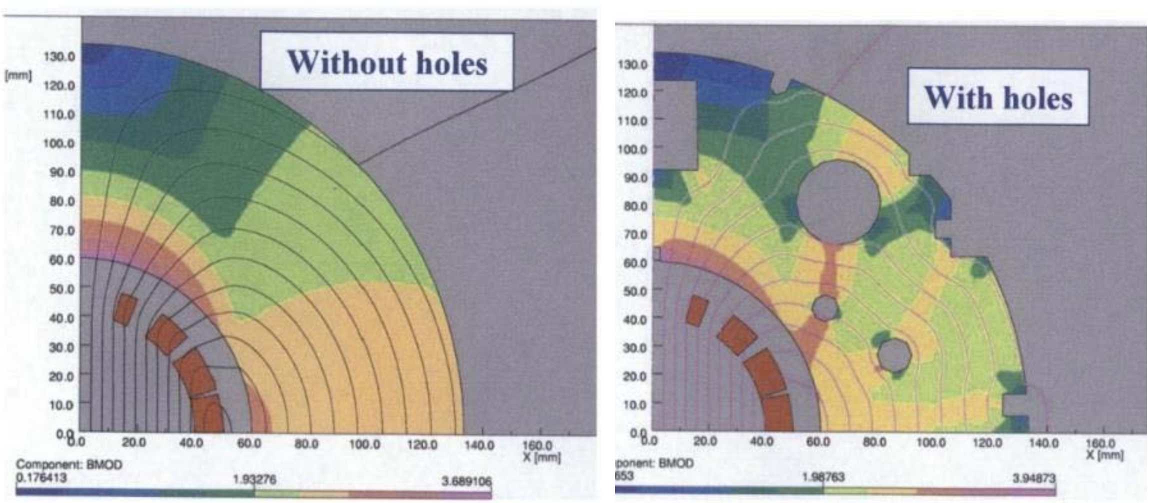
[from P. Schmuser et al, pg. 50]



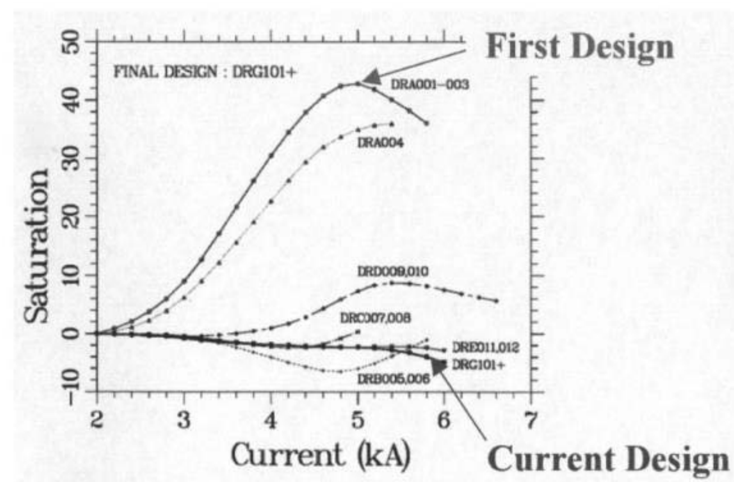
A sextupole

Field Harmonics

- **Iron saturation effect**: shaping the iron – the RHIC dipole
  - The field in the yoke is larger on the pole
  - Drilling holes in the right places, one can reduce saturation of b_3 from 40 units to less than 5 units (one order of magnitude), and to correct also b_5



Field map in the iron for the RHIC dipole, with and without holes
From R. Gupta, USPAS Houston 2006, Lecture V, slide 12



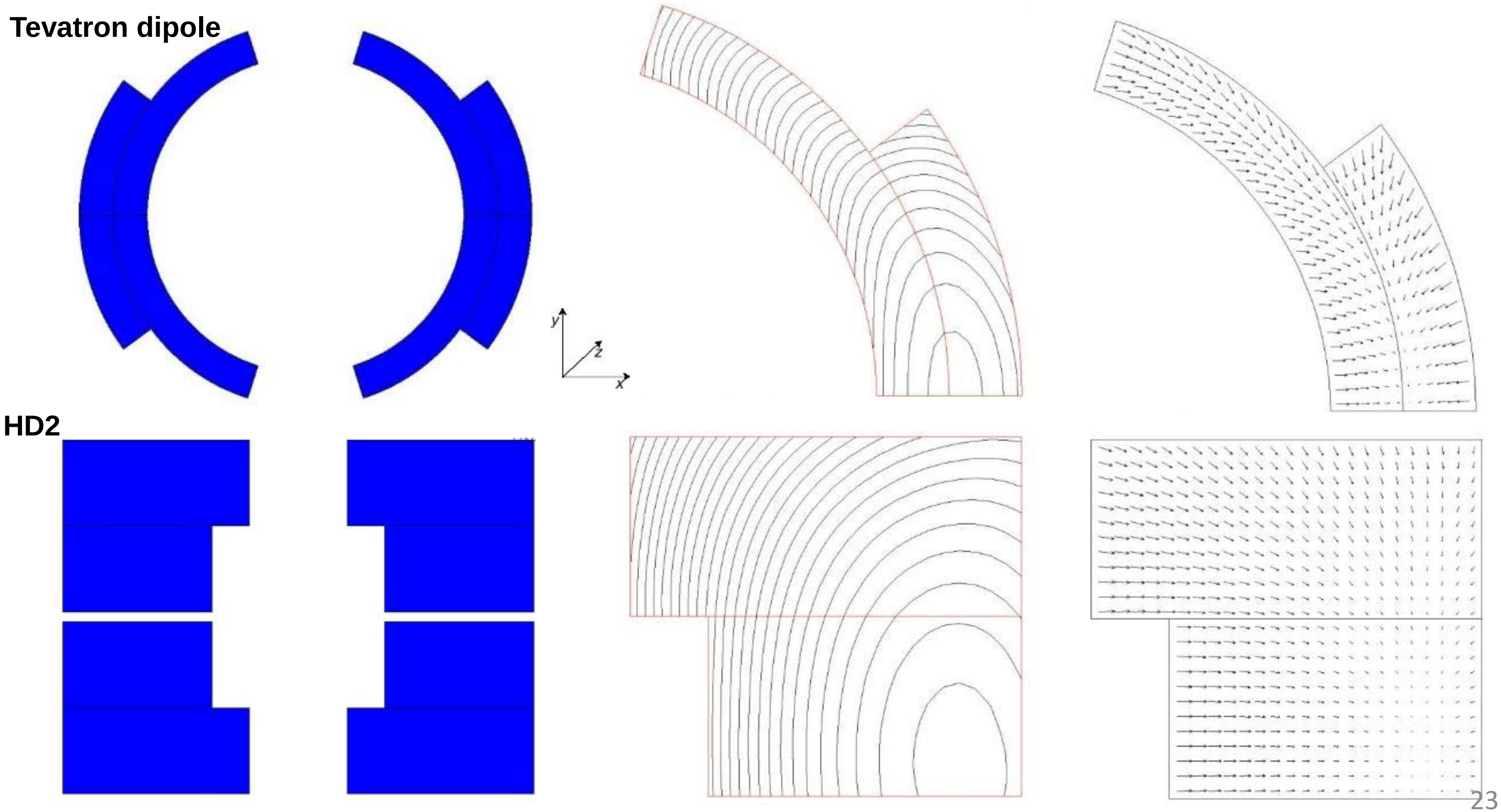
Correction of b3 variation due to saturation for the RHIC dipoles, R. Gupta, ibidem

Electro-magnetic Force

The e.m. forces in a **dipole magnet** tend to push the coil

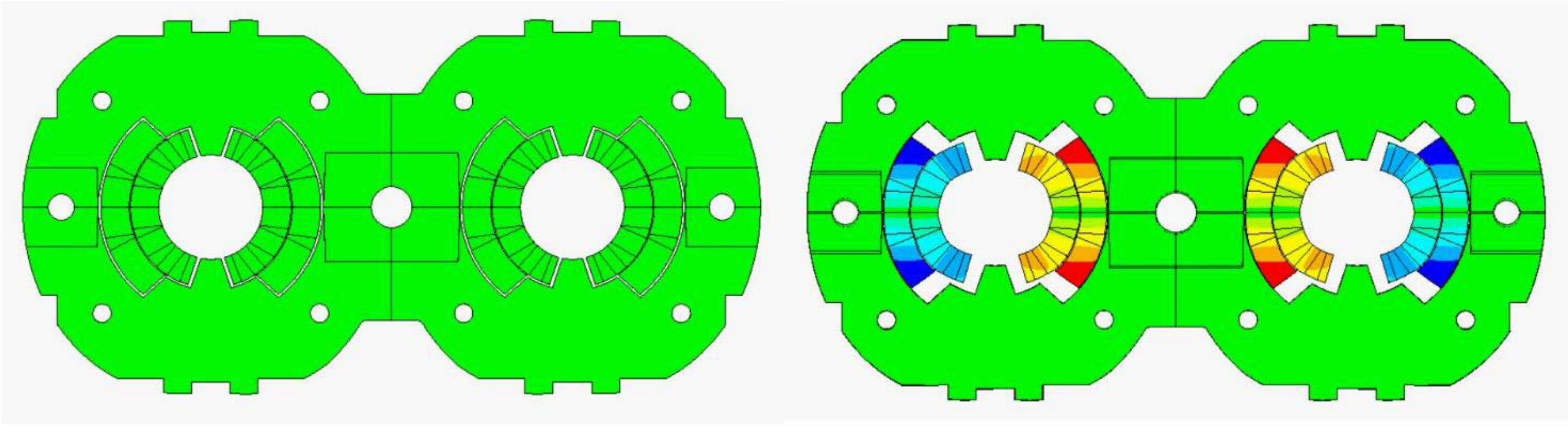
- **Towards the mid-plane** in the vertical-azimuthal direction (F_y, $F_\theta < 0$)

- **Outwards** in the radial-horizontal direction (F_x, $F_r > 0$)



Electro-magnetic Force

LHC dipole at 0 T　　　　LHC dipole at 9 T



Displacement scaling = 50

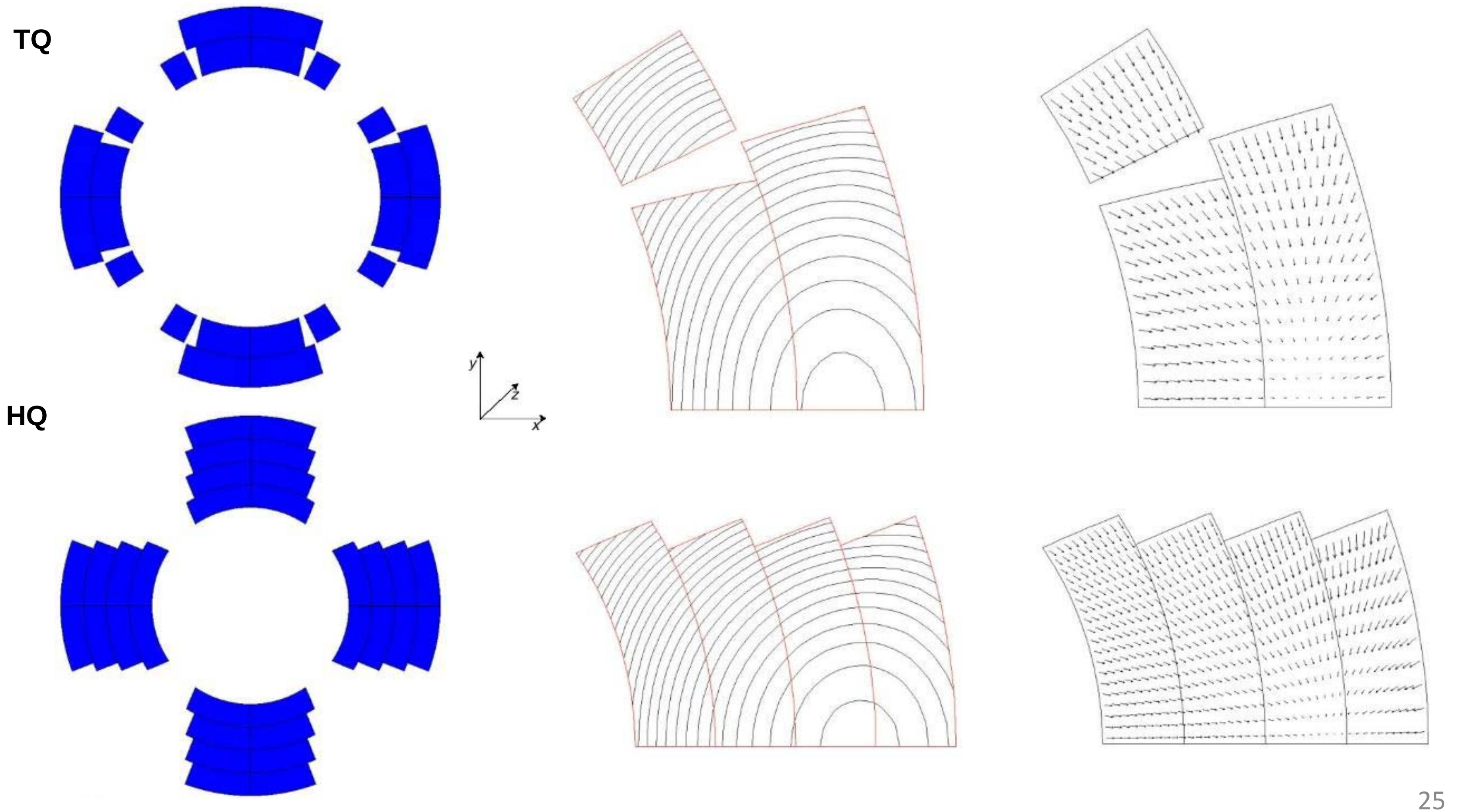
Usually, in a dipole or quadrupole magnet, the **highest stresses** are reached at the mid-plane, where all the azimuthal e.m. forces accumulate (over a small area).

Electro-magnetic Force

The e.m. forces in a **quadrupole magnet** tend to push the coil

Towards the mid-plane in the vertical-azimuthal direction (F_y, $F_\theta < 0$)

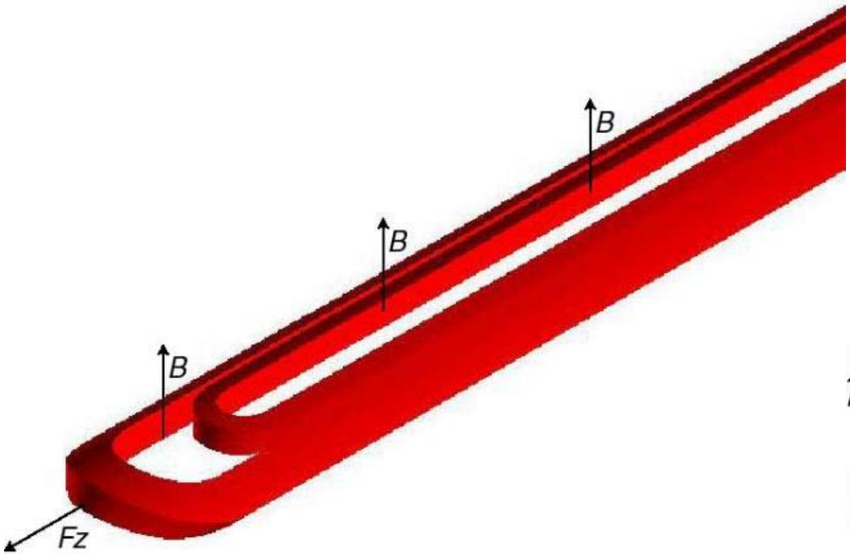
Outwards in the radial-horizontal direction (F_x, $F_r > 0$)

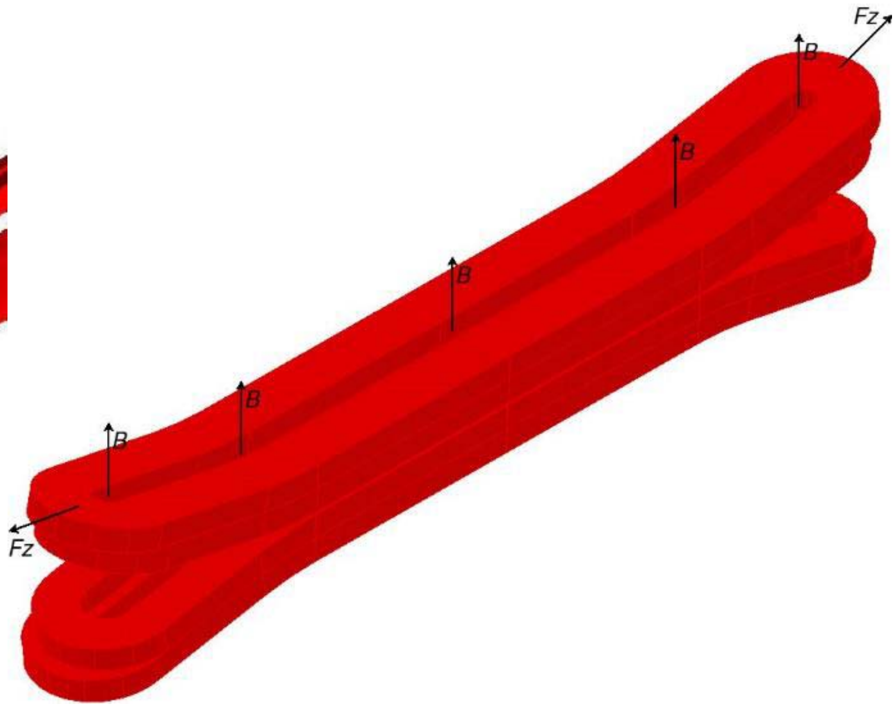


Electro-magnetic Force

In the **coil ends** the Lorentz forces tend to push the coil **Outwards** in the longitudinal direction ($F_z > 0$)

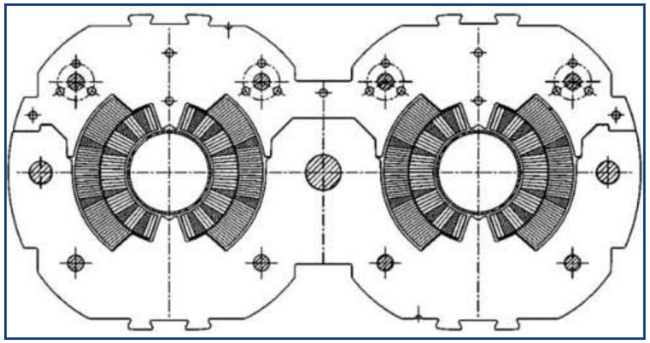
Similarly as for the solenoid, the axial force produces an **axial tension** in the coil straight section.



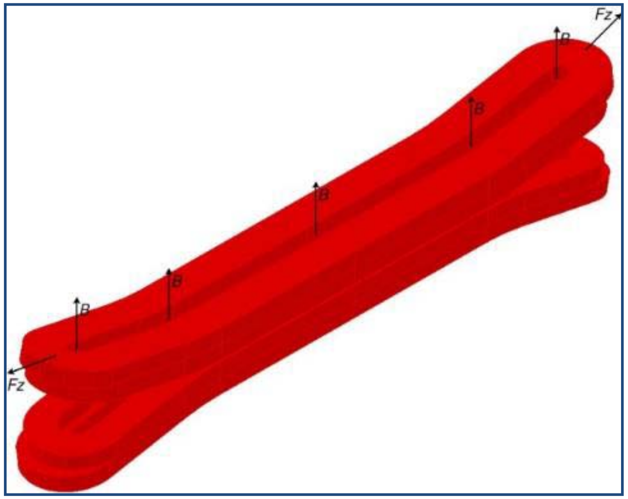


Electro-magnetic Force

- **Nb-Ti LHC** MB (values per aperture)
  - F_x = **340 t** per meter
    - ~300 compact cars
    - Precision of coil positioning: 20-50 µm
  - F_z = **27 t**
    - ~weight of the cold mass

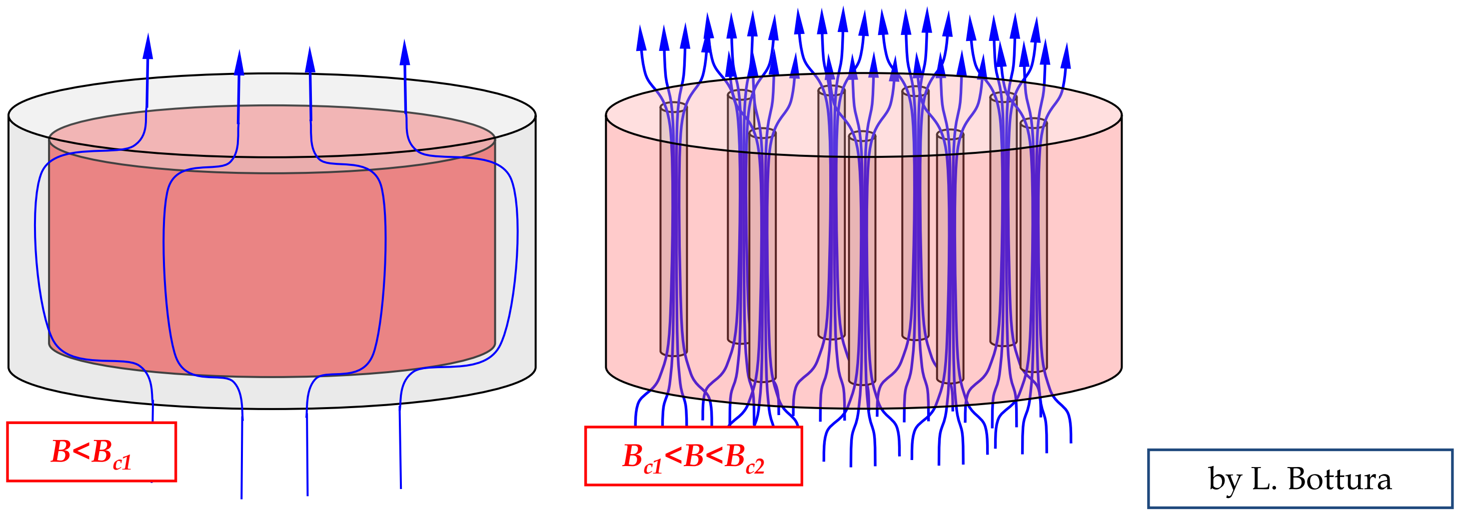


- **Nb_3Sn dipole** (HD2)
  - F_x = **500 t** per meter
  - F_z = **85 t**
  - These forces are applied to an object with a cross-section of 150x100 mm !!!
    - and the material is brittle!



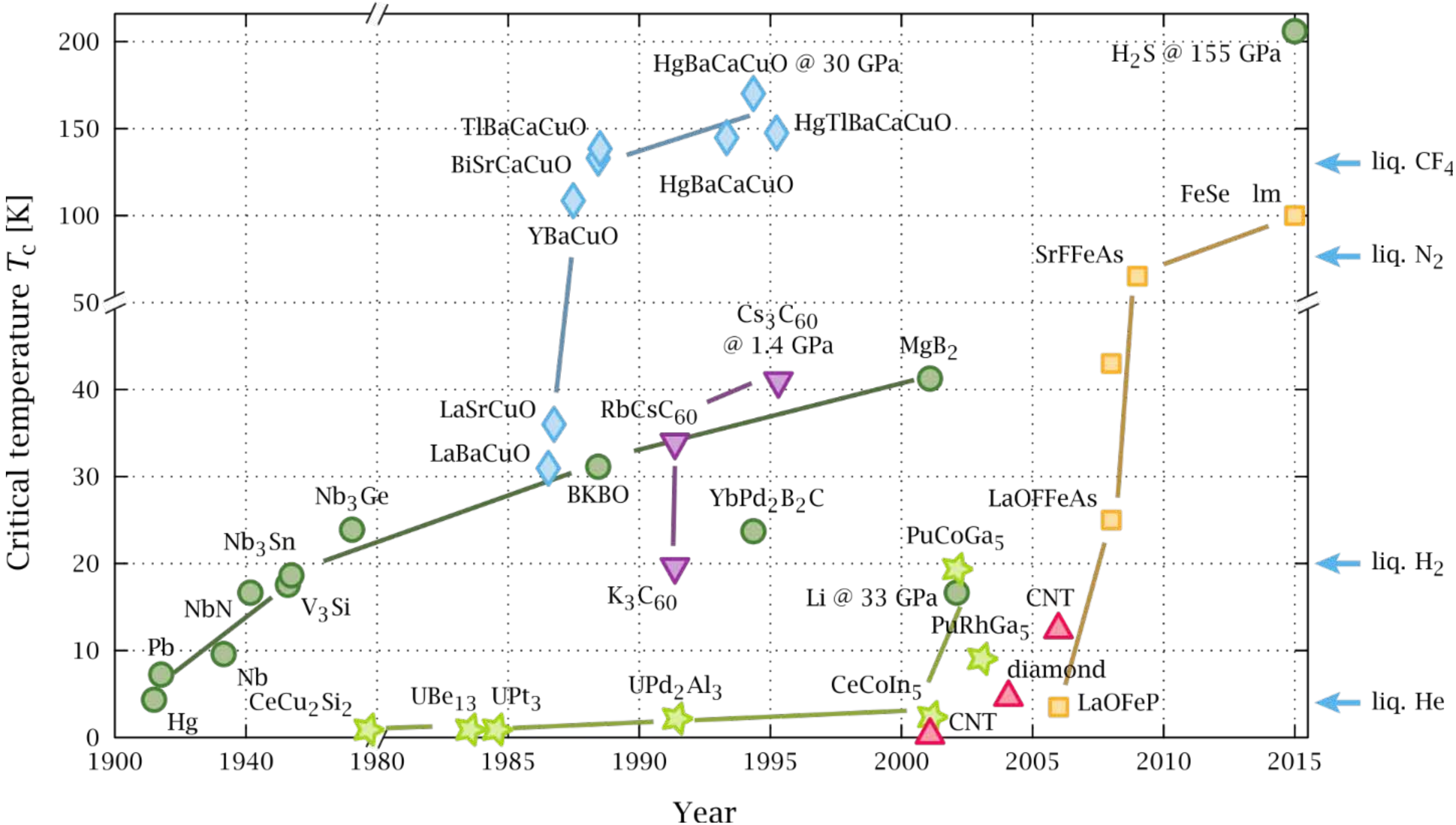
Superconducting Materials

- Discovered in 1911 by Kammerling-Onnes, observed that the resistance of a mercury wire disappeared at 4.2 K.
- Nb_3Sn and Nb-Ti, discovered in 1954 and 1961, are the most commonly used type II superconductors, suitable for practical application .
- The critical temperature T_c is 9 K for NbTi and 18 K for Nb_3Sn at 0 T, they are defined as low temperature superconductors (LTS).
- Discovered from 1986, High temperature superconductors (HTS) have a T_c of up to 40-120 K.

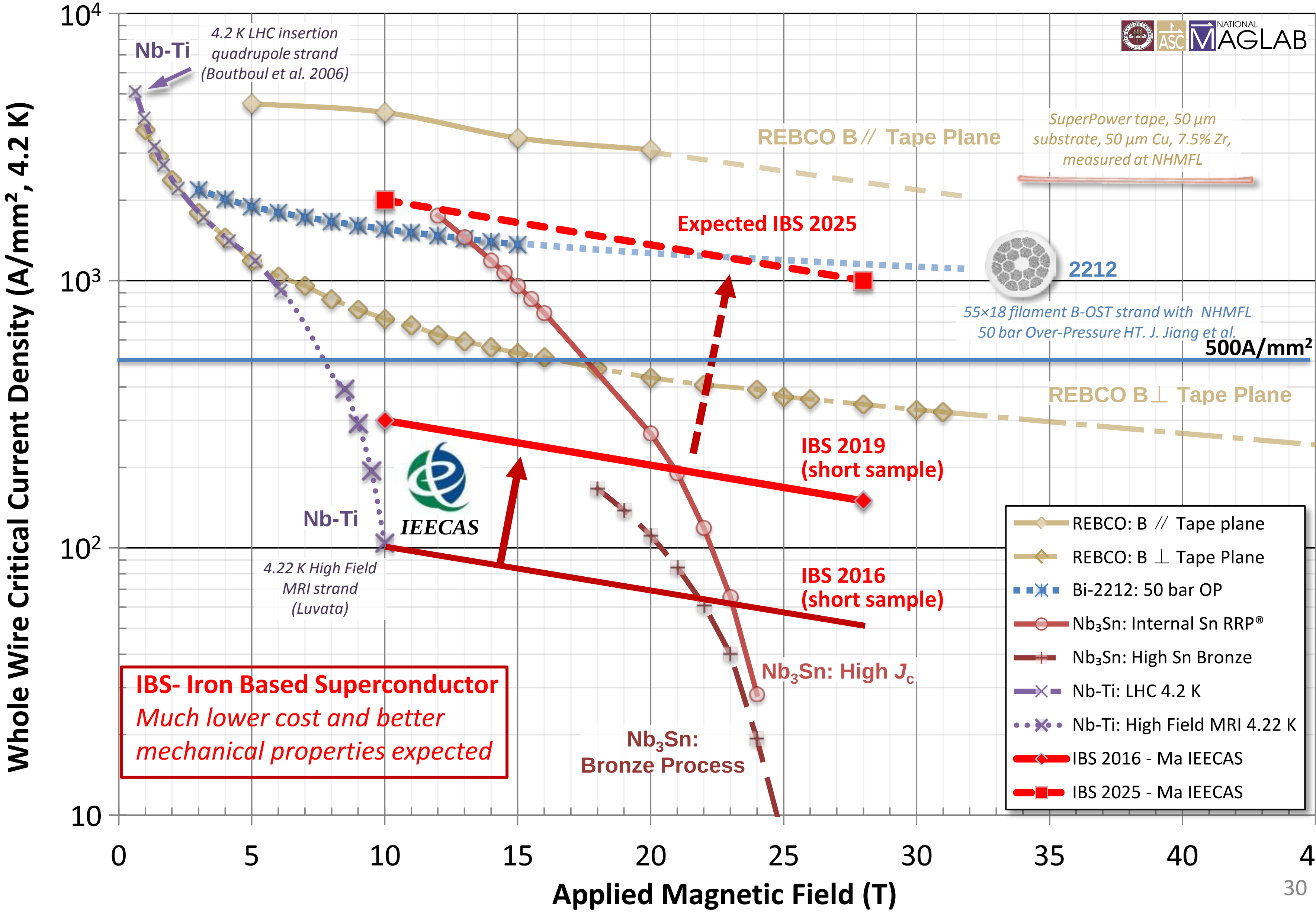


Type II superconductors

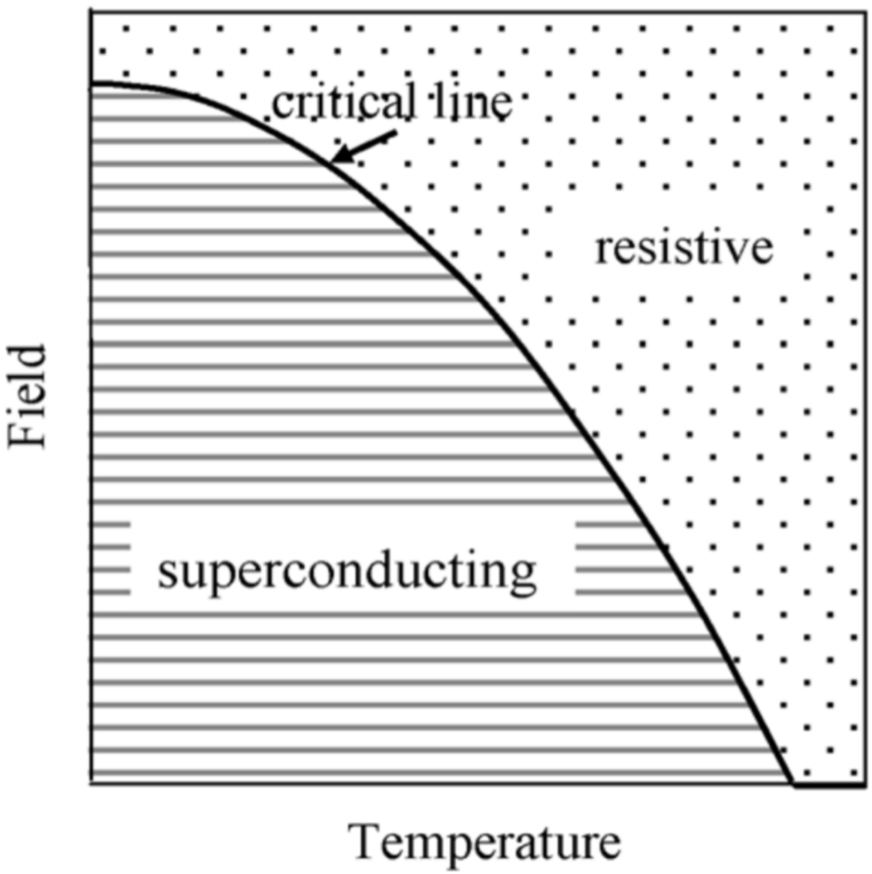
Timeline of Superconducting Materials

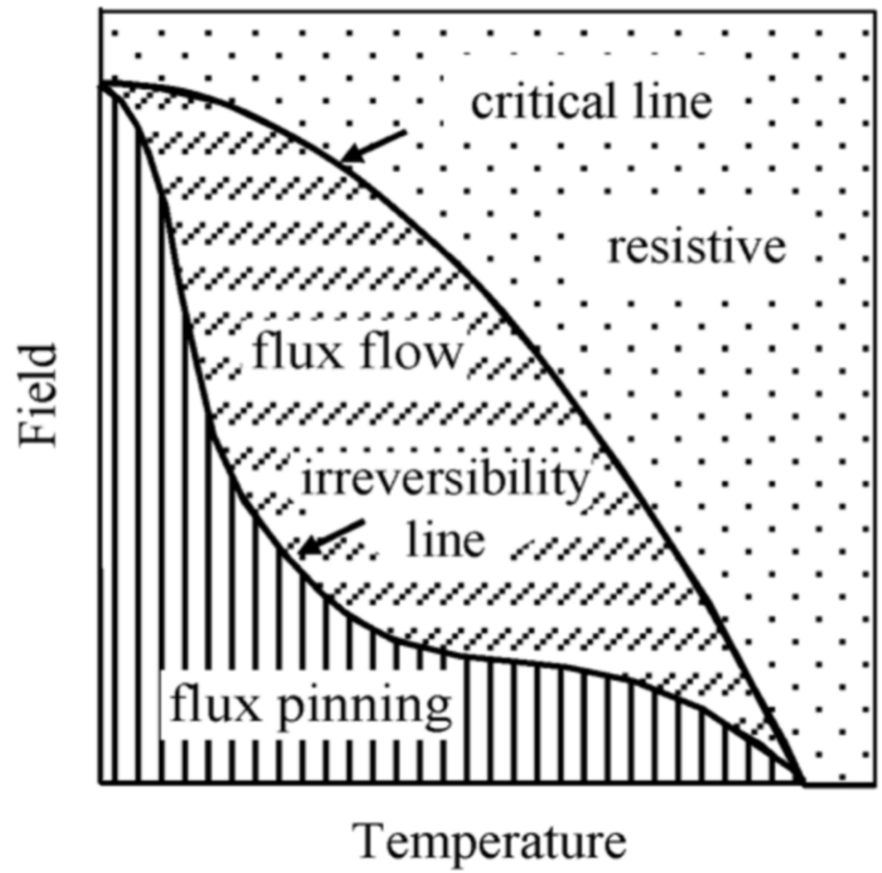


Practical Superconductors Presently

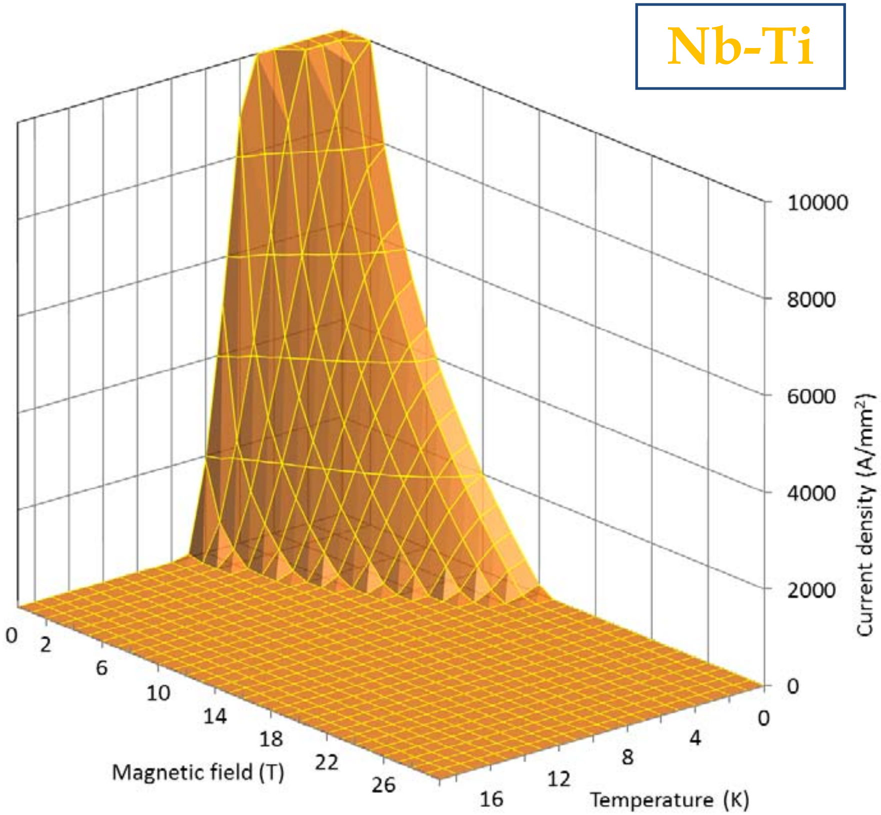


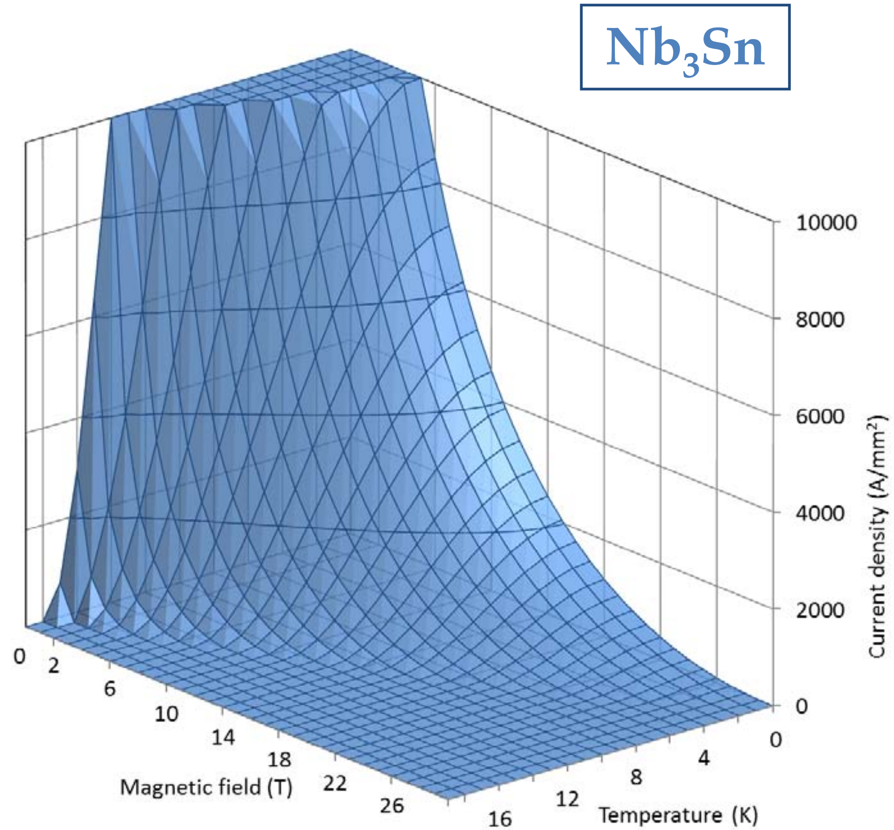
LTS vs HTS


critical line
resistive
superconducting
Field
Temperature


critical line
resistive
flux flow
irreversibility
line
flux pinning
Field
Temperature

Nb-Ti vs Nb_3Sn



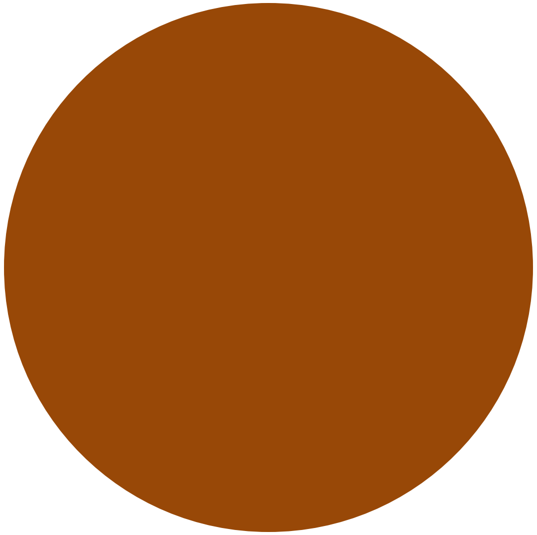


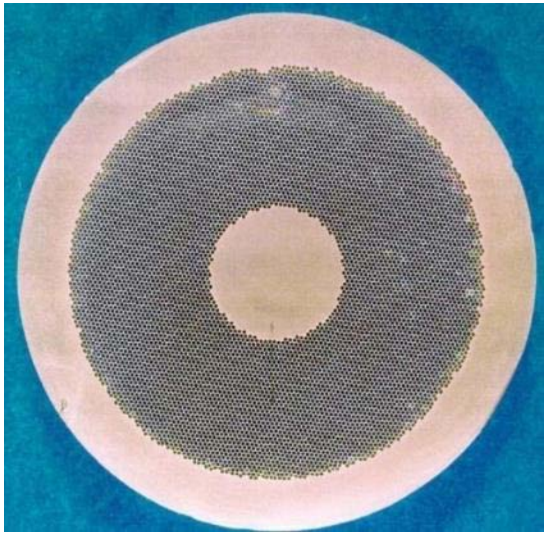
critical surface : B (T), J (A/mm^2), T (K)

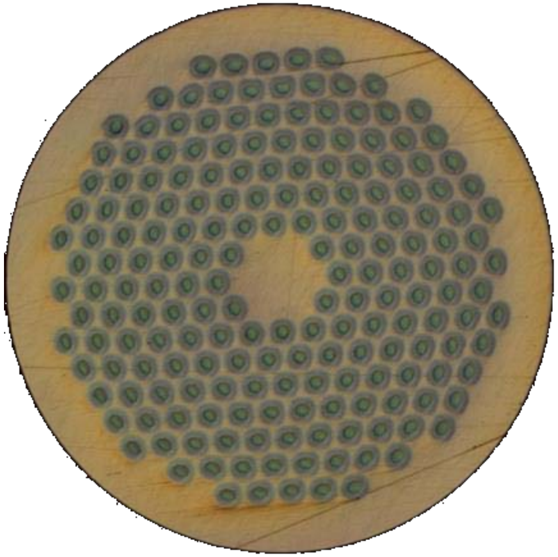
Copper vs Superconductors

Cu	Nb-Ti	Nb_3Sn

Typical operational conditions (0.85 mm diameter strand)



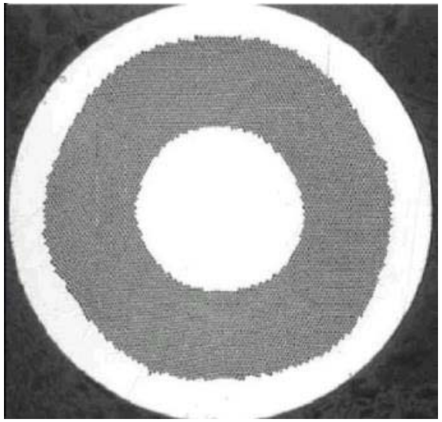


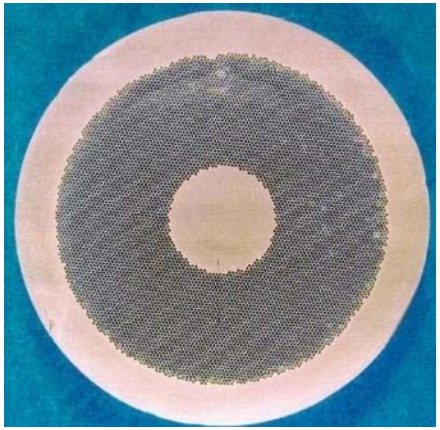


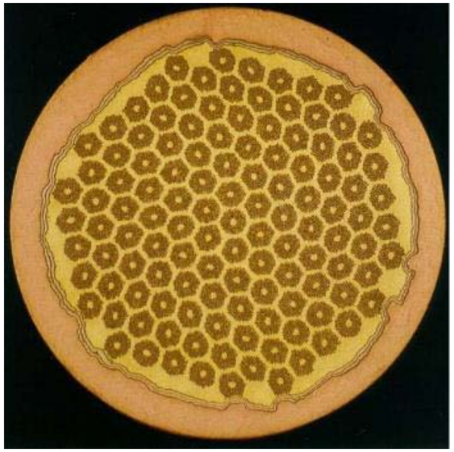
Cu	Nb-Ti	Nb_3Sn
$J_e \sim 5$ A/mm^2	$J_e \sim 600\text{-}700$ A/mm^2	$J_e \sim 600\text{-}700$ A/mm^2
$I \sim 3$ A	$I \sim 300\text{-}400$ A	$I \sim 300\text{-}400$ A
$B = 2$ T	$B = 8\text{-}9$ T	$B = 12\text{-}13$ T

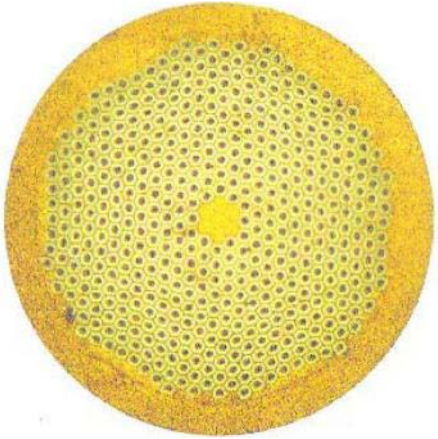
Superconductors for Accelerator Magnets

- The superconductors for accelerator magnets should
  - subdivided in **filaments** of small diameters
    - to reduce **flux jumps**
    - to minimize field distortions due to **magnetization**
  - **twisted** together
    - to reduce inter-filament coupling and **AC losses**
  - embedded in a **copper matrix**
    - to protect the superconductor after a quench
    - to reduce flux jumps


NbTi LHC wire (A. Devred)

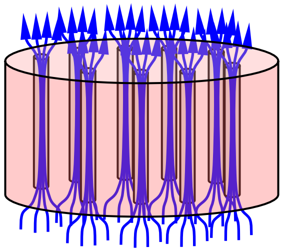

NbTi SSC wire (A. Devred)


Nb_3Sn bronze-process wire (A. Devred)


Nb_3Sn PIT process wire (A. Devred)

Flux Jumps

- An external magnetic field penetrates in a type-II superconductor in the mixed state through **fluxoids**.
- If the superconductor is subjected to a **thermal disturbance**, the local change in J_c produces a motion or **"jump"** of fluxoids, which is accompanied by power dissipation.
- The **stability criteria** for a slab in the adiabatic condition

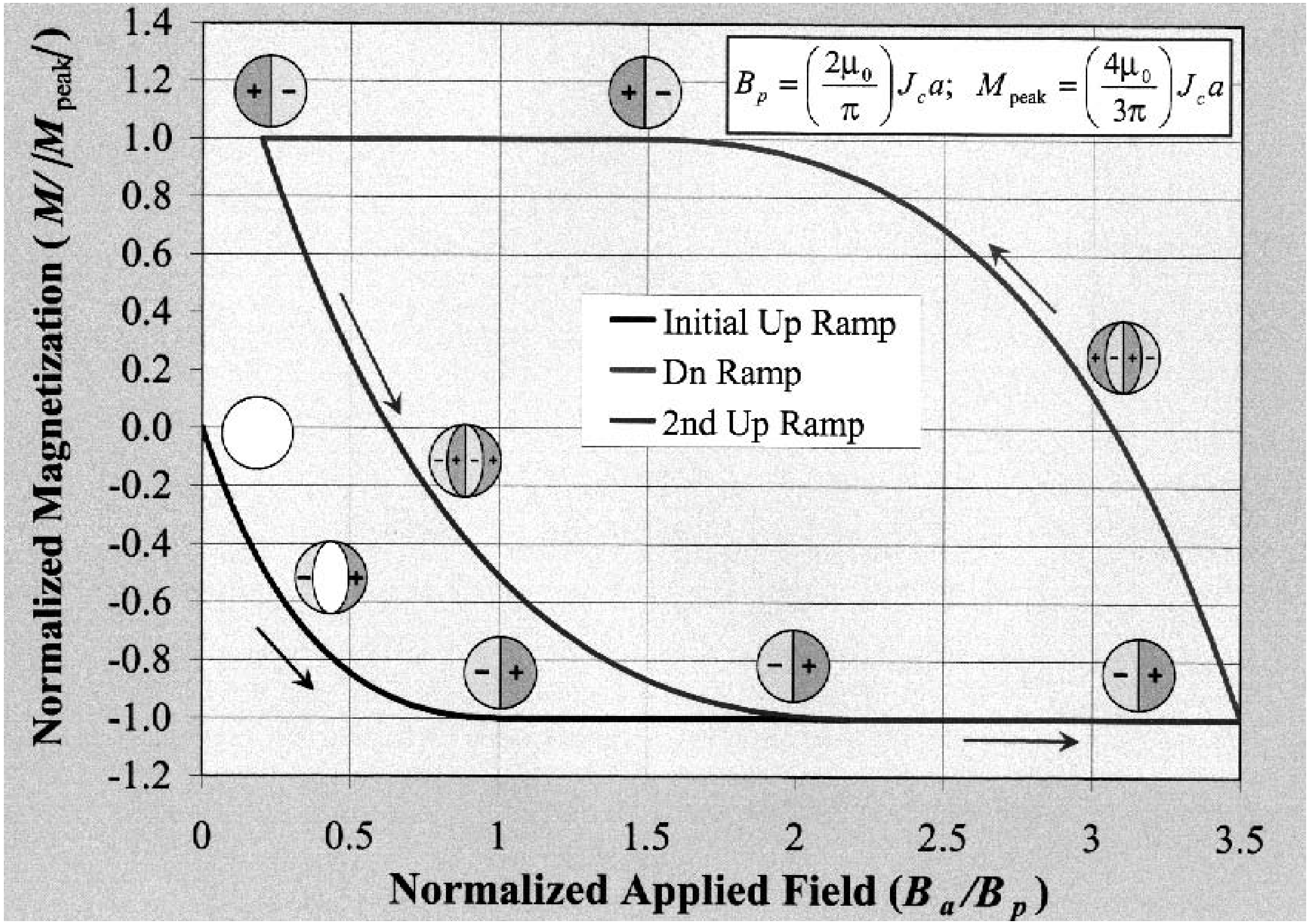


$$a \leq \sqrt{\frac{3\gamma C(\theta_c - \theta_0)}{\mu_0 j_c^2}}$$

where a is the half-thickness of the slab, j_c is the critical current density [A m^{-2}], γ is the density [kg m^{-3}], C is the specific heat [J kg^{-1}], and θ_c is the critical temperature.

- Nb-Ti filament diameters are usually less than 50 µm.
- High conductivity copper reduces instability.

Hysteresis of the Magnetization



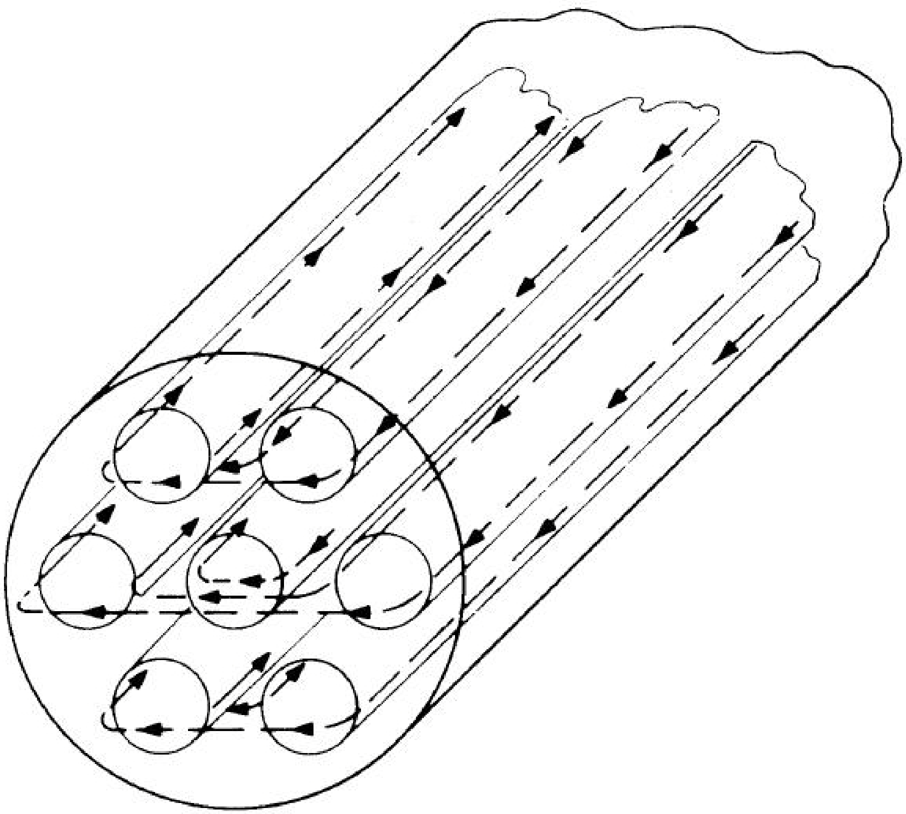
From A. Jain, USPAS 2007, Dynamic effects in superconducting magnets, pg. 18

Field distortions are proportional to r_f. LHC filament diameter 6-7 μm; HERA filament diameter 14 μm.

Interfilament Coupling

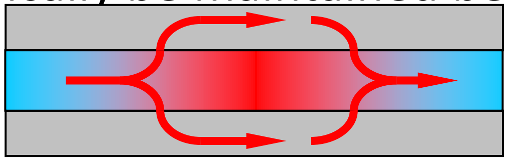
- When a multi-filamentary wire is subjected to a time varying magnetic field, **current loops** are generated between filaments.
- If filaments are straight, large loops are generated, with **large currents**
  - Big losses
- If the strands are magnetically coupled the effective filament size is larger
  - **Flux jumps**
- To reduce these effects, filaments are twisted with a **twist pitch** of the order of 20-30 times of the wire diameter.

M.N. Wilson



Quench Protection and Stabilization

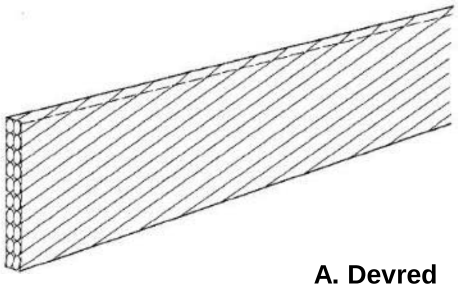
- Superconductors have a very high normal state resistivity. A filament of Nb-Ti, if quenched in free space, could reach **very high temperatures** in few ms.
- If the filament is embedded in a copper matrix, when quench occurs, the **current redistributes** in the low-resistivity matrix and the peak temperature can typically be maintained below 300 K.



- The copper matrix facilitates quench protection: it allows the quench to **propagate** and it provides time to act on the power circuit.
- In the case of a small volume of superconductor heated beyond the critical temperature (for instance because of a flux jump), the current can flow in the copper for a short moment, allowing the filament to **cool-down and recover** superconductivity.
  - The matrix also helps stabilizing the conductor **against flux jumps** (dynamic stability).

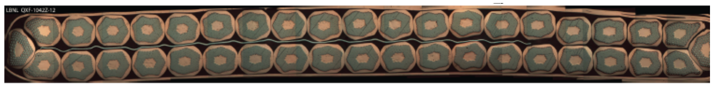
Superconducting Cables

- Most of the superconducting coils for particle accelerators are wound from a **multi-strand cable**.
- The advantages of a multi-strand cable are:
  - reduction of the strand piece length;
  - reduction of number of turns
    - easy winding;
    - smaller coil inductance
      - less voltage required for power supply during ramp-up;
      - after a quench, faster current discharge and less coil voltage.
  - current redistribution in case of a defect or a quench in one strand.



A. Devred

- The strands are **twisted** to
  - reduce inter-strand coupling currents
    - Losses and field distortions
  - provide more mechanical stability



- The most commonly used multi-strand cables are the **Rutherford cable and the cable-in-conduit**.

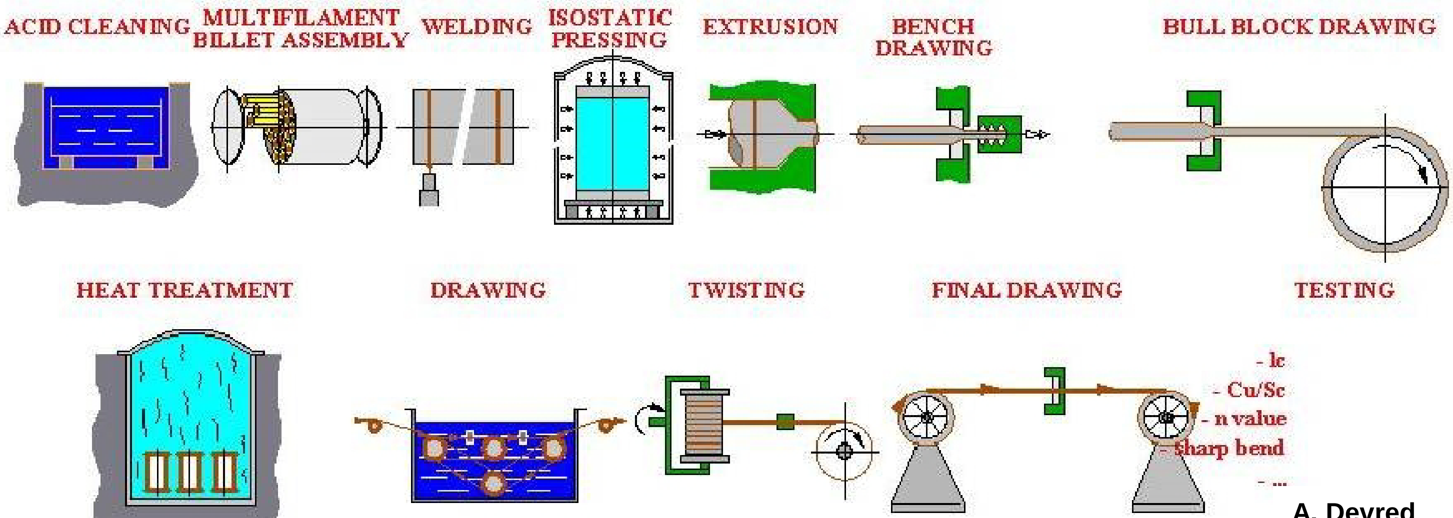
AC losses

- **Hysteresis**: Reduce $_{\text{deff}}$
- **Coupling**: Reduce twist pitch; Modify inter-filament resistance
- **Eddy currents**: laminations

Conductor hysteresis	$P_{hys} \propto M\frac{dB}{dt} \sim J_c\frac{dB}{dt}d_{eff}$
Conductor filament coupling	$P_{coup} \propto \frac{2\tau}{\mu_0}\left(\frac{dB}{dt}\right)^2$
Cable strand coupling	$P_{cable} \propto \left(\frac{dB}{dt}\right)^2 \frac{p}{R_a}\frac{w}{t}$

Fabrication of NbTi wires

- The copper to superconductor ratio is specified for quench protection.
- The filament diameter is chosen to minimize flux jumps and field errors due to persistent currents.
- The inter-filament spacing is kept small for drawing operation, and large enough to prevent filament couplings.
- A copper core and sheath is added to reduce cable degradation.

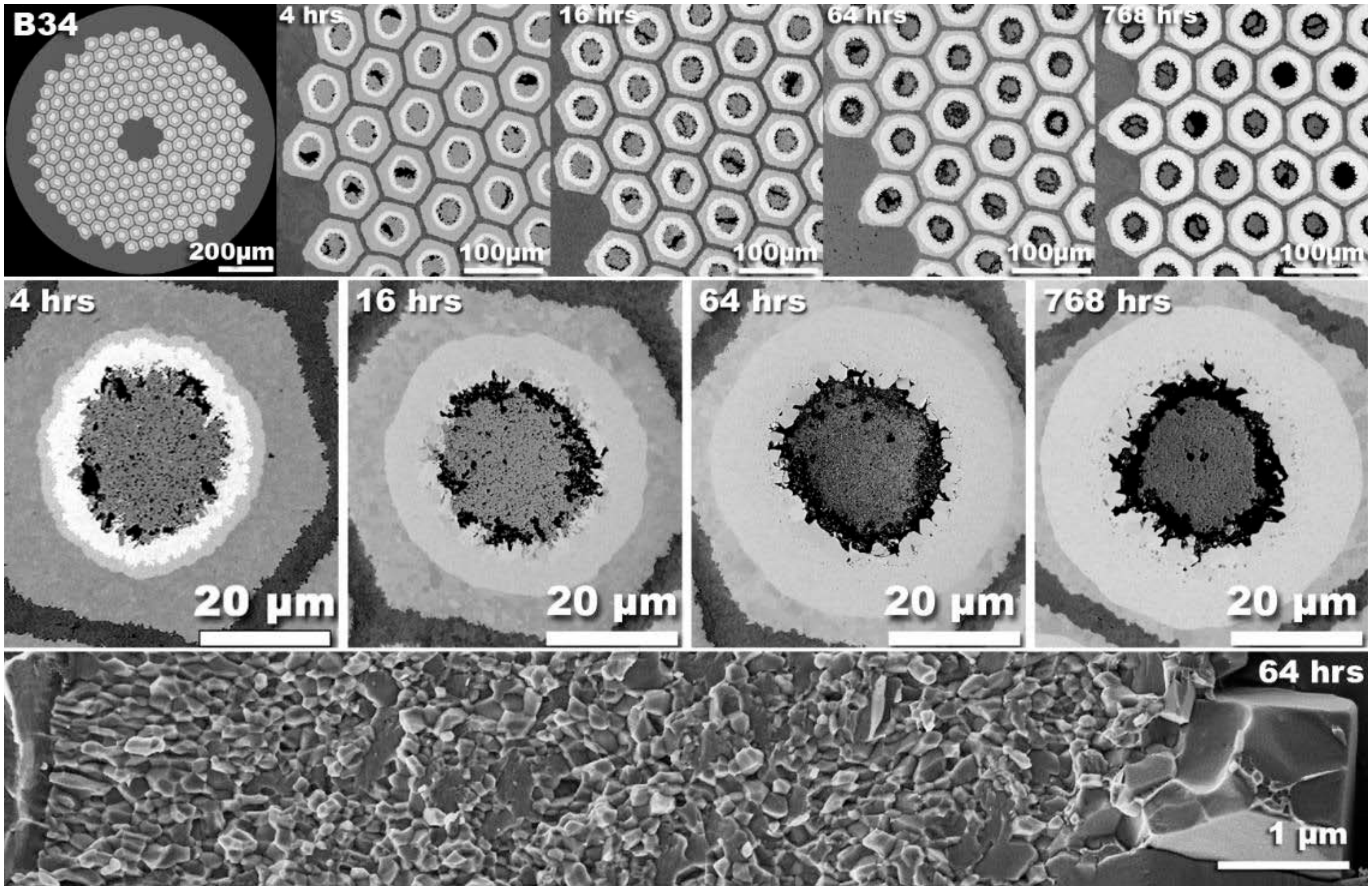


A. Devred

Fabrication of Nb_3Sn wires

Reaction of a PIT wire

A. Godeke

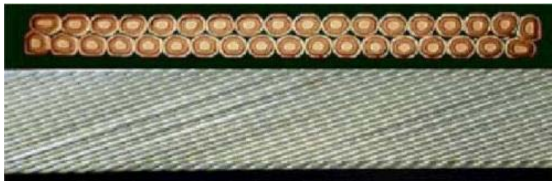


Fabrication of Rutherford cable

- The final shape of a Rutherford cable can be **rectangular or trapezoidal.**

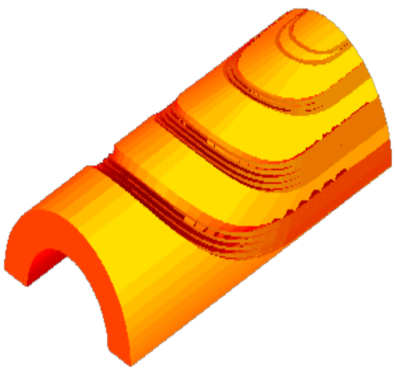
- The cable design parameters are:
  - Number of wires N_{wire}
  - Wire diameter d_{wire}
  - Cable mid-thickness t_{cable}
  - Cable width w_{cable}
  - Pitch length p_{cable}
  - Pitch angle ψ_{cable} ($\tan\psi_{cable} = 2\, w_{cable} / p_{cable}$)
  - **Cable compaction** (or packing factor) k_{cable}

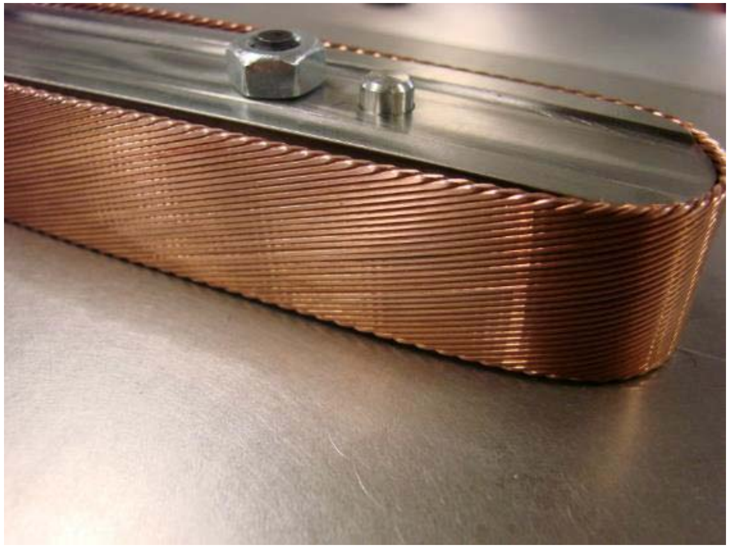
$$k_{cable} = \frac{N_{wire}\pi d_{wire}^2}{4 w_{cable} t_{cable} \cos\psi_{cable}}$$

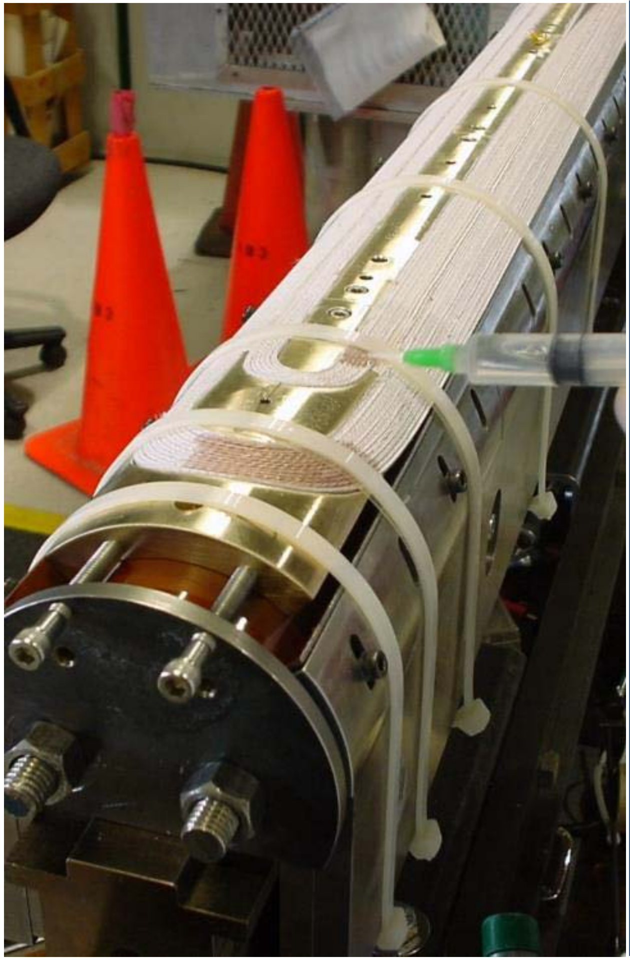


- Typical cable compaction: from 88% (Tevatron) to 92.3% (HERA).

Fabrication of Coils for Accelerator Magnets







Heat Reaction

DIMENSIONAL CHANGES OF Nb_3Sn, Nb_3Al AND $Bi_2Sr_2CaCu_2O_8$ CONDUCTORS DURING HEAT TREATMENT AND THEIR IMPLICATION FOR COIL DESIGN

ICMC '97

D.R. Dietderich, J.R. Litty, and R.M. Scanlan

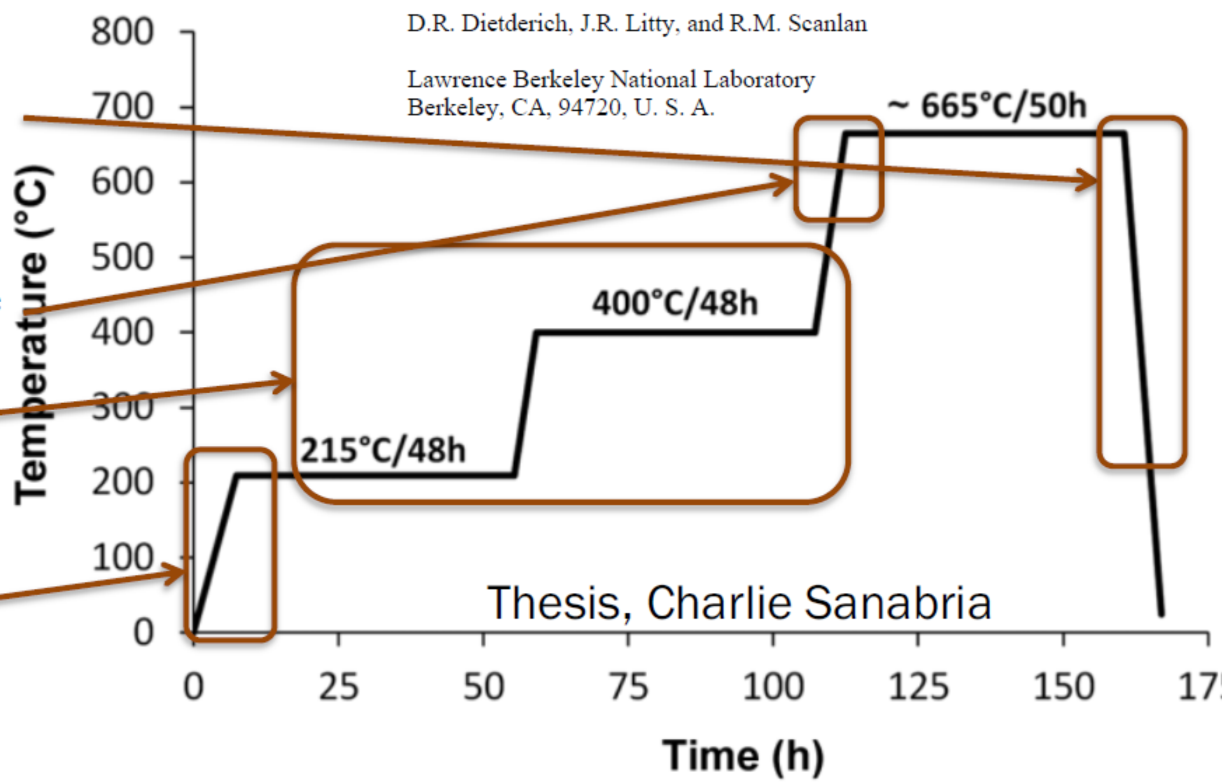
Lawrence Berkeley National Laboratory
Berkeley, CA, 94720, U. S. A.

Change in dL/dT due to different volume fraction after formation of intermetallics

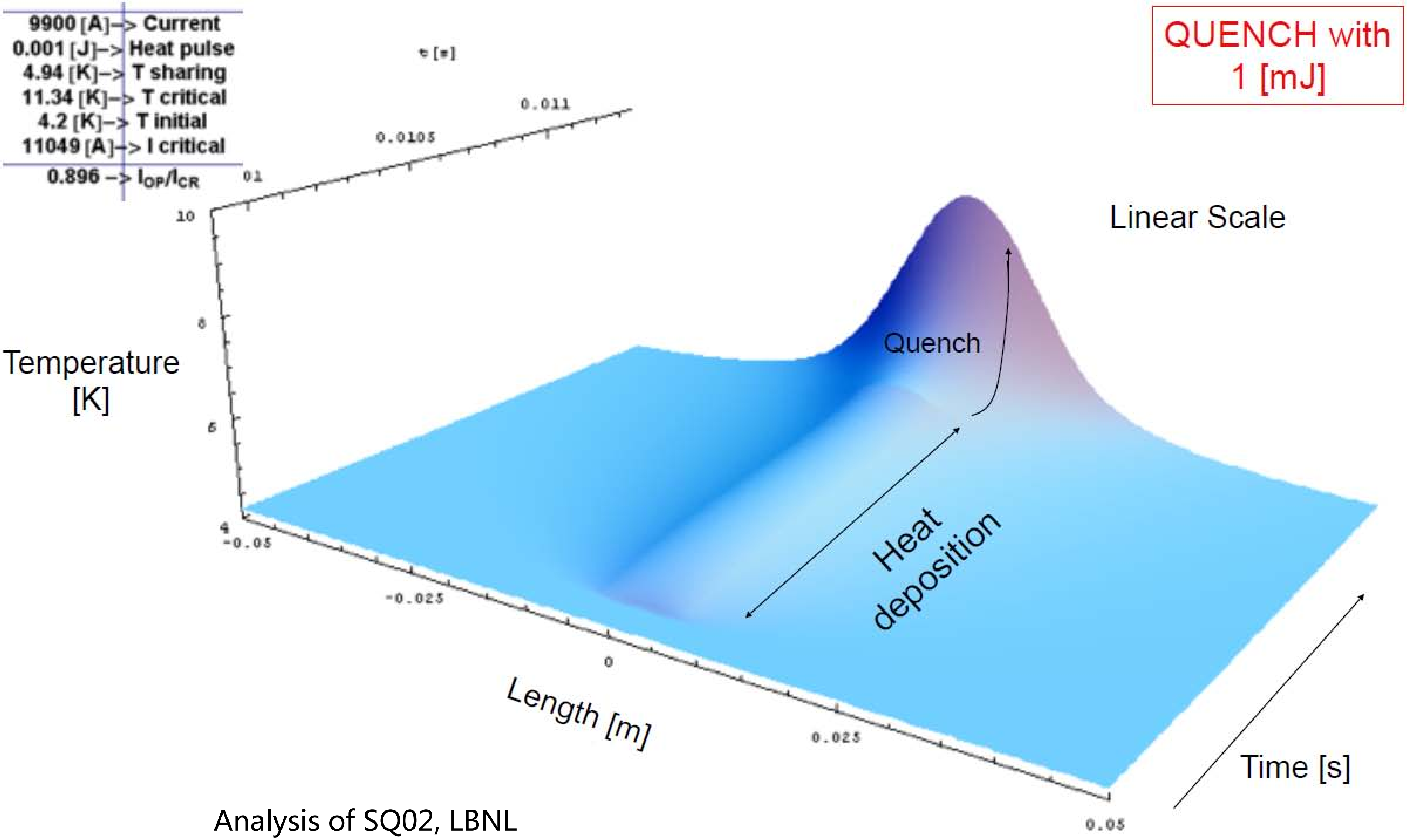
Expansions with composite nature; Nb and Cu mix. Length increases with temperature similar to Cu

Formation of Cu-Sn phases results in density change – no increase in length, or even contraction

Conductor elongates with temperature

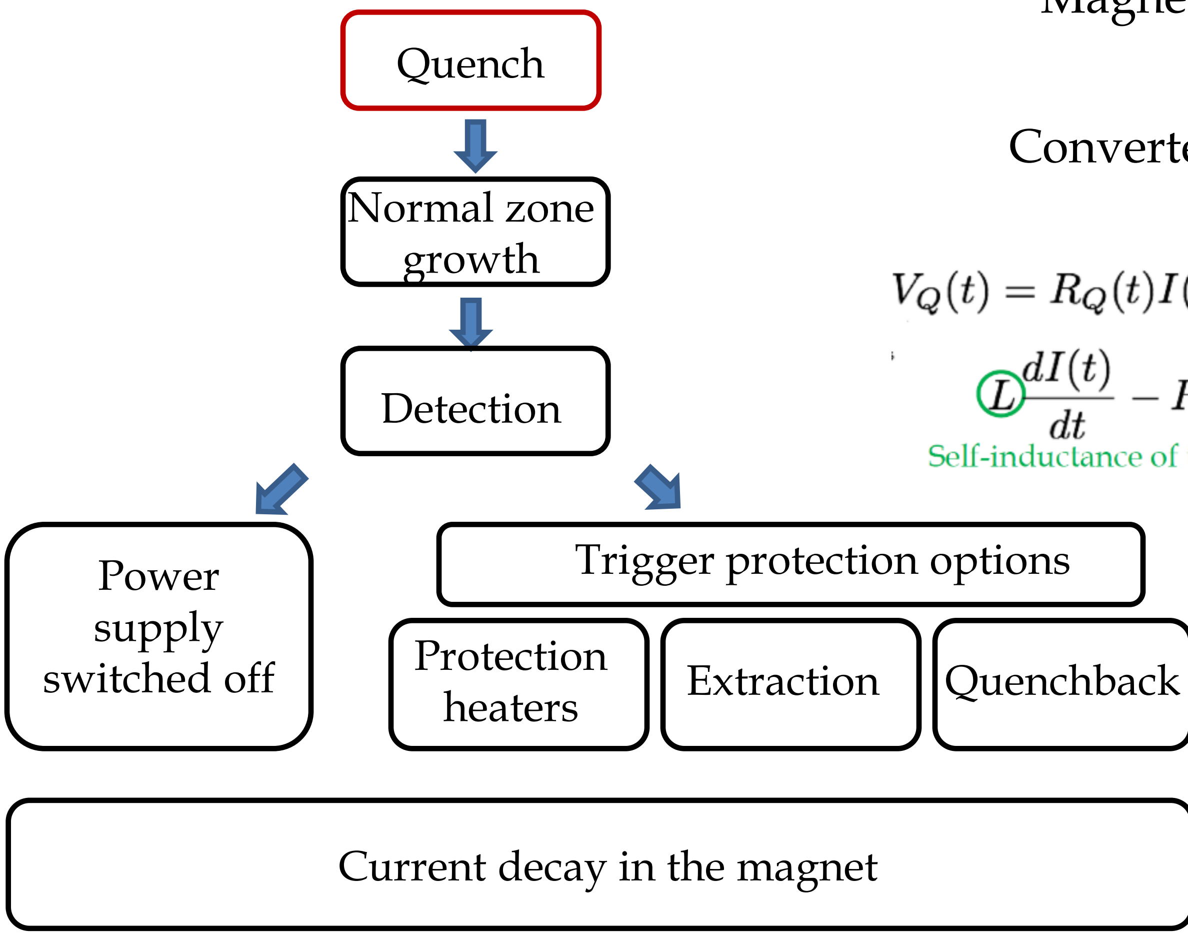


Quench



Analysis of SQ02, LBNL

Quench Protection



Magnetic energy $\frac{1}{2}LI^2$

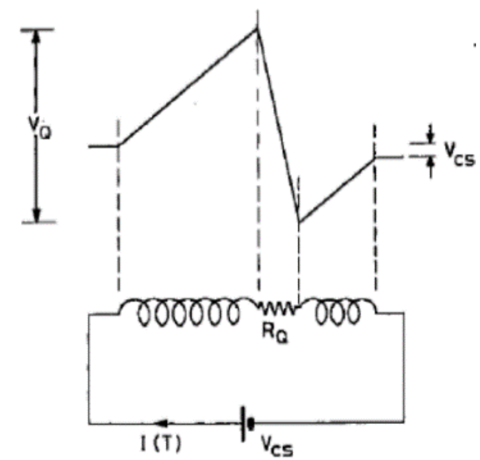
Converted to heat $\int_0^{\tau} R(t)I(t)^2\,dt$

$$V_Q(t) = R_Q(t)I(t) - M\frac{dI(t)}{dt}$$

Mutual inductance between the normal zone and the rest of the coil

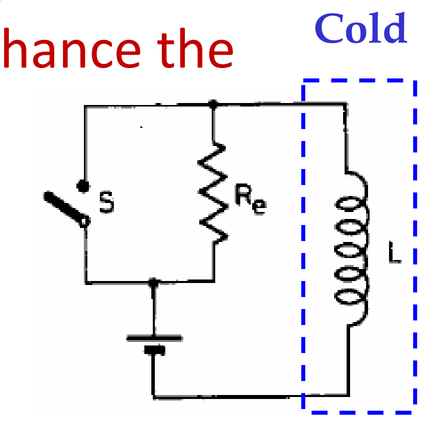
$$L\frac{dI(t)}{dt} - R_Q(t)I(t) = 0$$

Self-inductance of the system



Quench Protection

- In most accelerator magnets, the "natural" resistance growth is insufficient to provide a good protection => Need to enhance the resistance

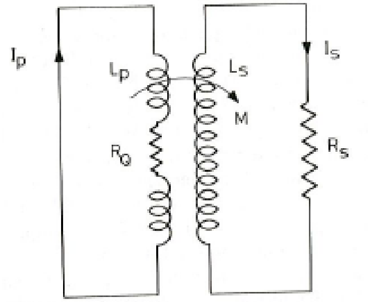


- ***Method 1:***
  - Add an external resistor
- ***Method 2:***
  - Protection heaters mounted on the coils
    - Optimized to minimize thermal diffusion time

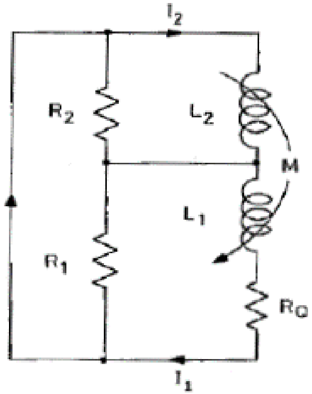
- ***Method 3:***
  - Use of couple secondary circuits
    - Can be external or internal to the coil
    - Quench back

$$L_p \frac{dI_p(t)}{dt} + R_Q(t) I_p(t) + M \frac{dI_s(t)}{dt} = 0$$

$$L_s \frac{dI_s(t)}{dt} + R_s(t) I_s(t) + M \frac{dI_p(t)}{dt} = 0$$

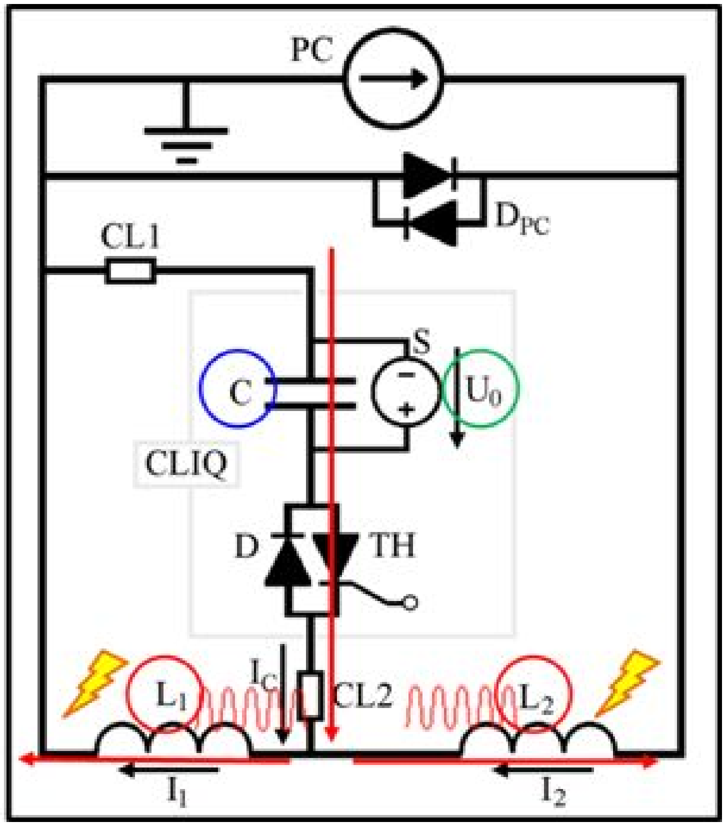


- ***Method 4***:
  - Coil subdivision



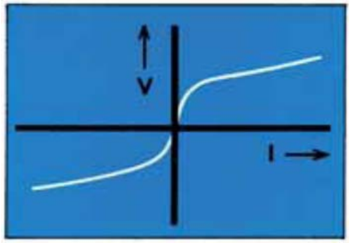
Quench Protection

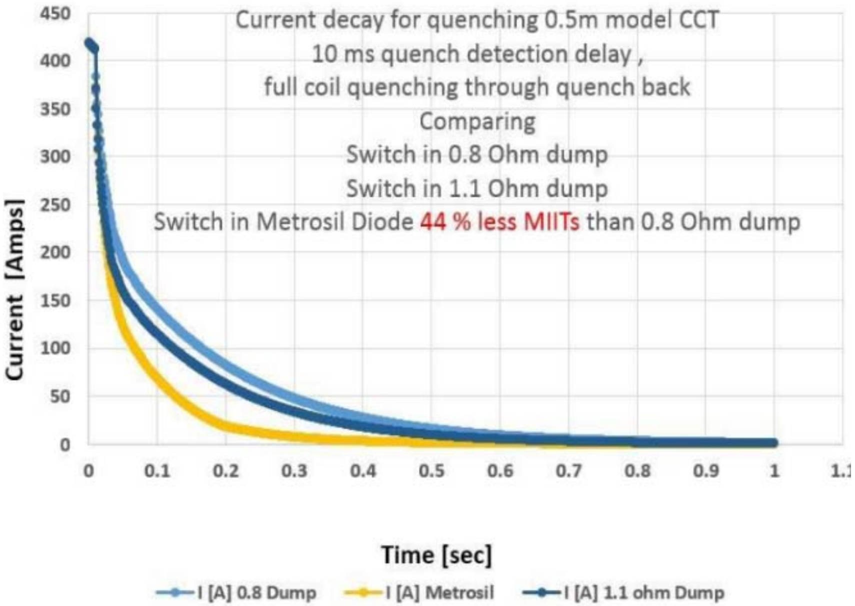
Coupling-Loss Induced Quench Protection CLIQ



E. Ravaioli et al.

METROSIL Quench Protection

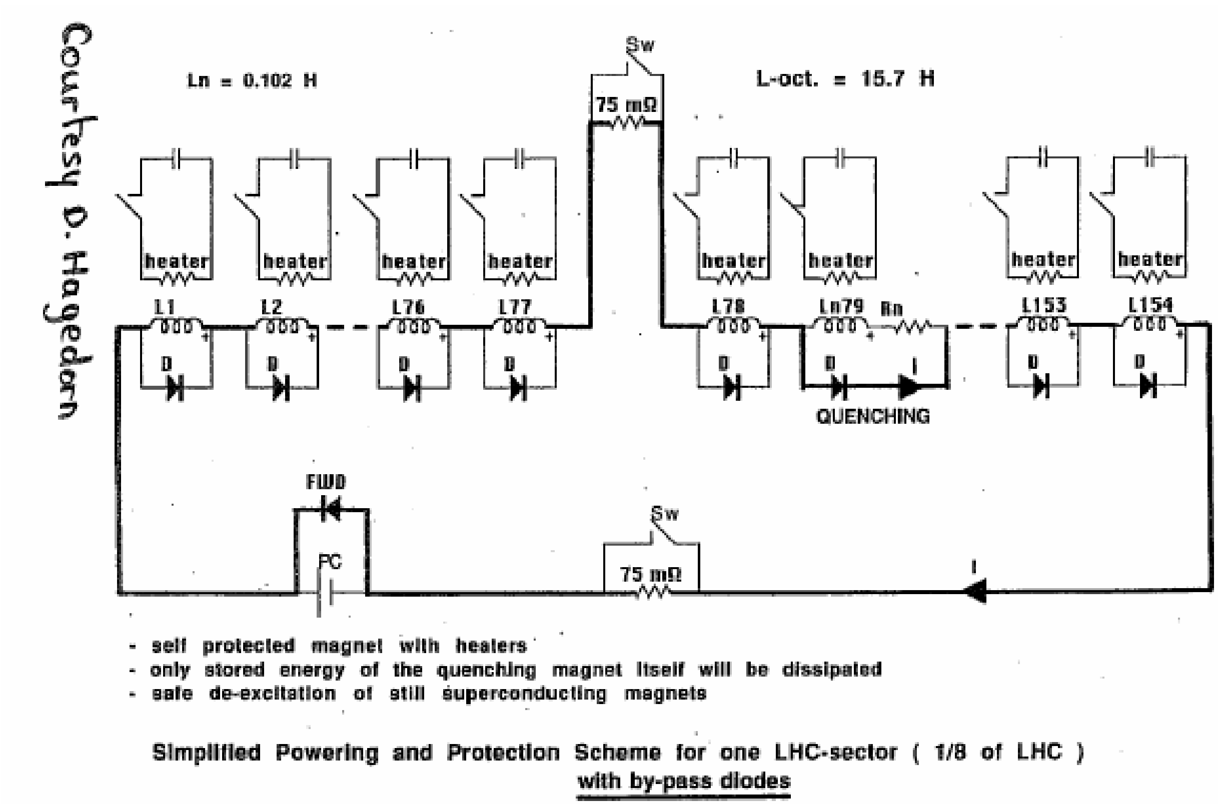




G. Kirby et al.

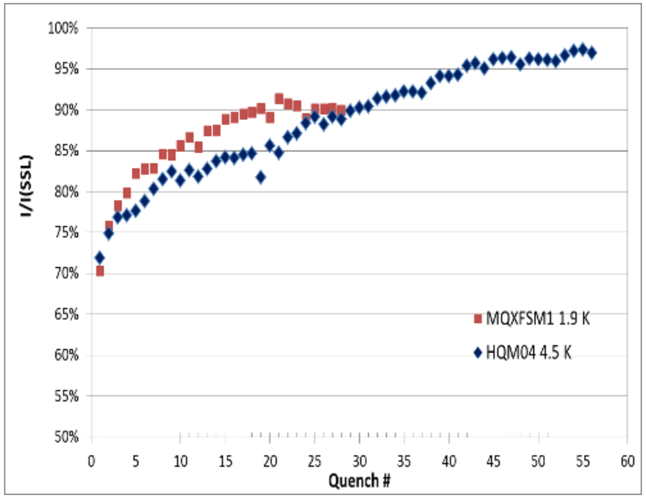
Quench Protection

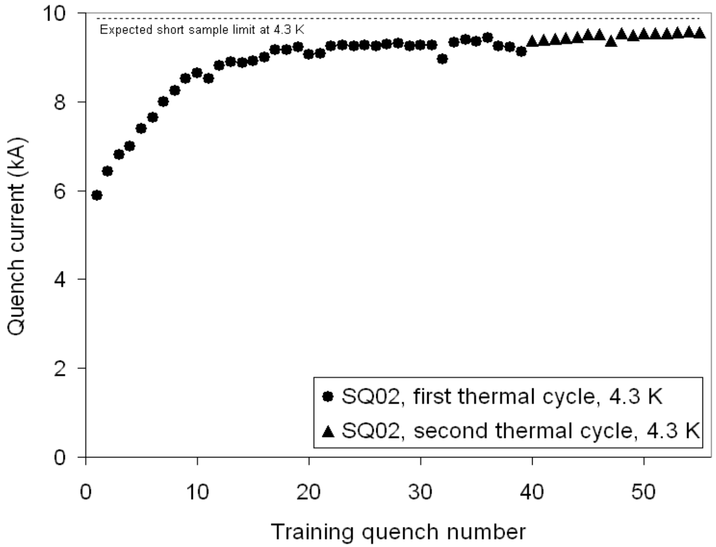
- In the LHC main ring, the dipoles are connected in series. The principle is
  - to “by-pass” the quenching magnet to avoid dumping all the string energy in one magnet
  - To de-excite the rest of the magnets into a dump resistor
- Combination of various methods: heaters, dump resistor, diodes



Training

- Training is characterized by two phenomena
  - The **occurrence of premature quenches**
    - Frictional motion of a superconductor
    - Epoxy failure
    - ……
  - The **progressive increase of quench current**
    - Some irreversible change in the coil's mechanical status.
- In R&D magnets, training may not be an issues.
- For accelerator magnets it can be expensive, both in term of time and cost.

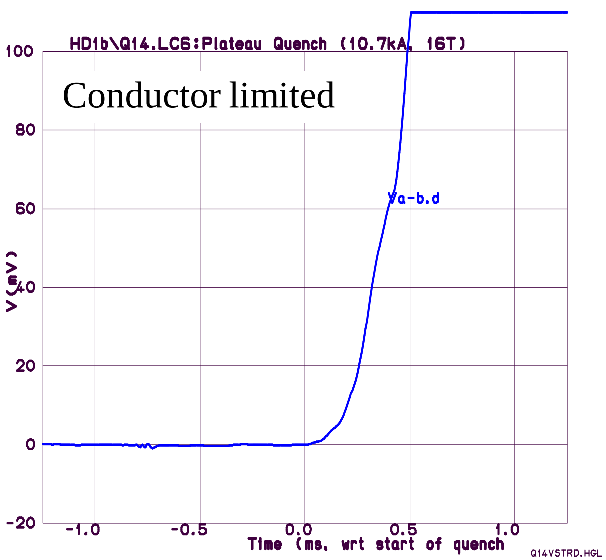


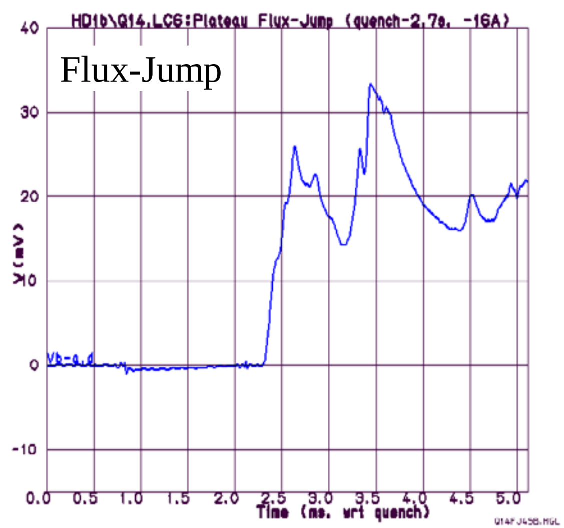


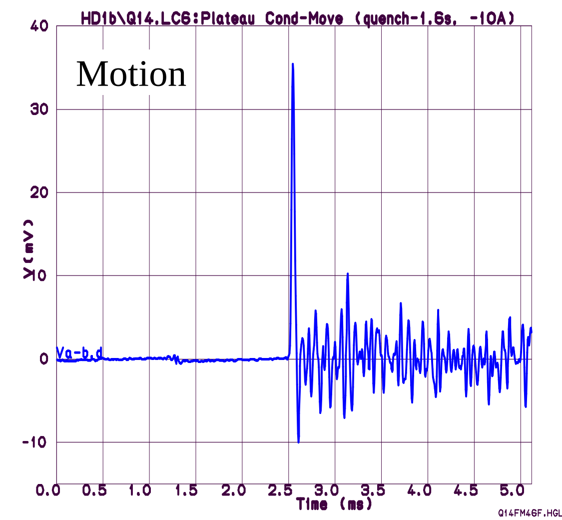
Quench Origins

Depending on the shape of the voltage signal, it is possible to identify

- Conductor limited quenches: slow, gradual resistive growth
- Flux jump induced quenches: low-frequency flux changes
- Motion induced quenches: acceleration-deceleration-ringing

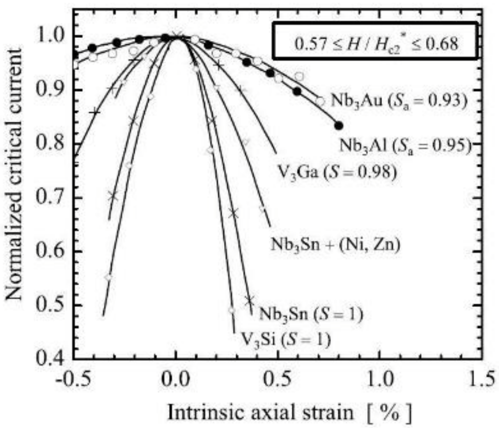


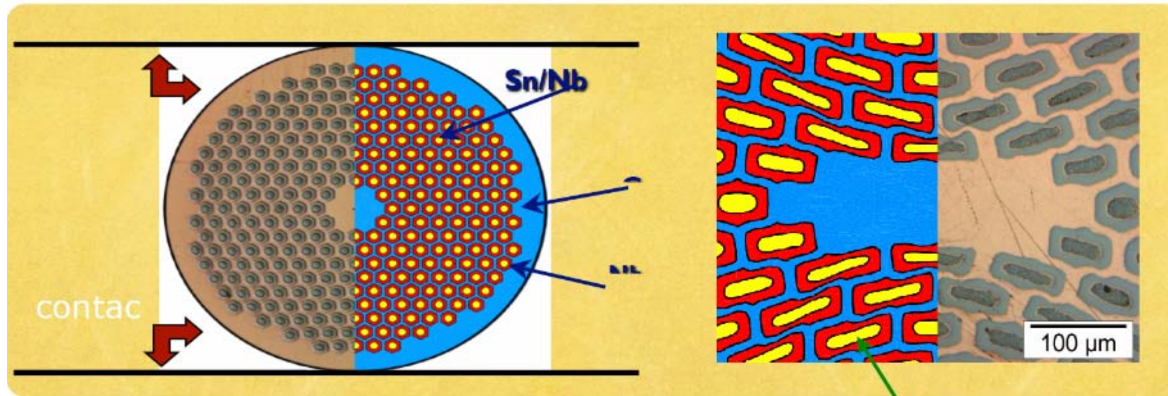




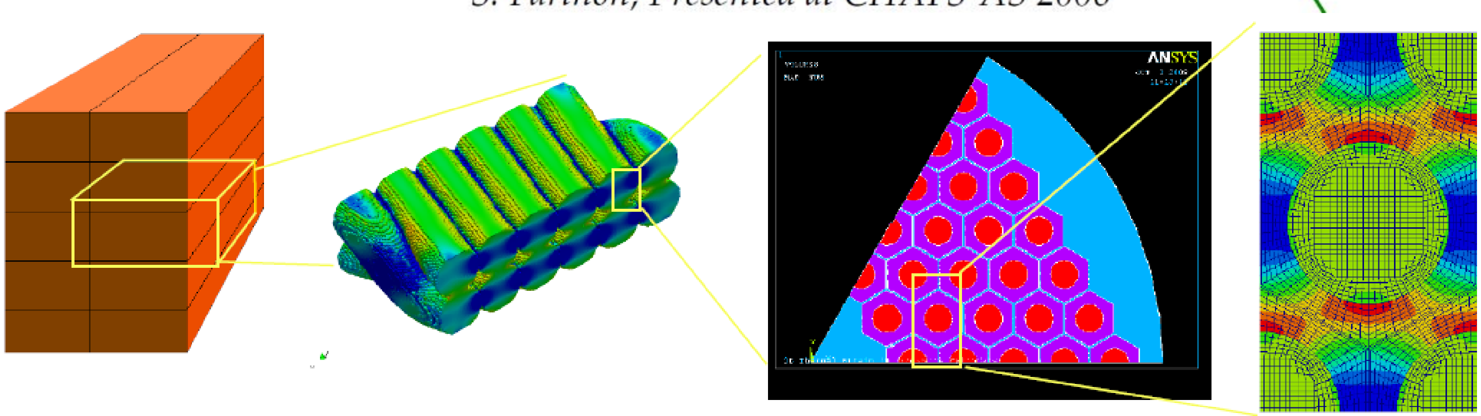
Modeling from magnets to filaments

A. Godeke





S. Farinon, Presented at CHATS-AS 2006



Coil Cable Strand RRP Filament

D. Arbelaez et al, "Cable Deformation Simulation and a Hierarchical Framework for Nb3Sn Rutherford Cables," EUCAS, pp. 1–11, 2009

HTS Accelerator Magnets?

Steve Gourlay

- LTS
  - 27 km of Nb-Ti accelerator magnets at near operational potential
  - First Nb_3Sn accelerator magnets to be installed in LHC
  - LHC Quads on the way
  - High field solenoids
  - Fusion magnets

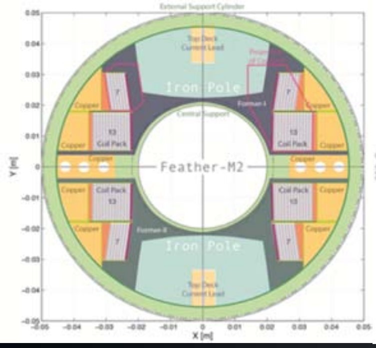
- HTS
  - MgB_2 links for LHC upgrade
  - Power cable demos
  - Power leads
  - > 1 GHz NMR magnets
  - And – 32T solenoid!
  - Several active R&D programs

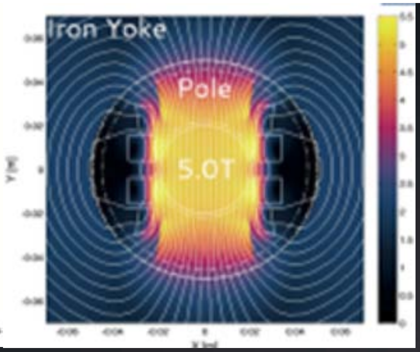
No accelerator magnets (yet)

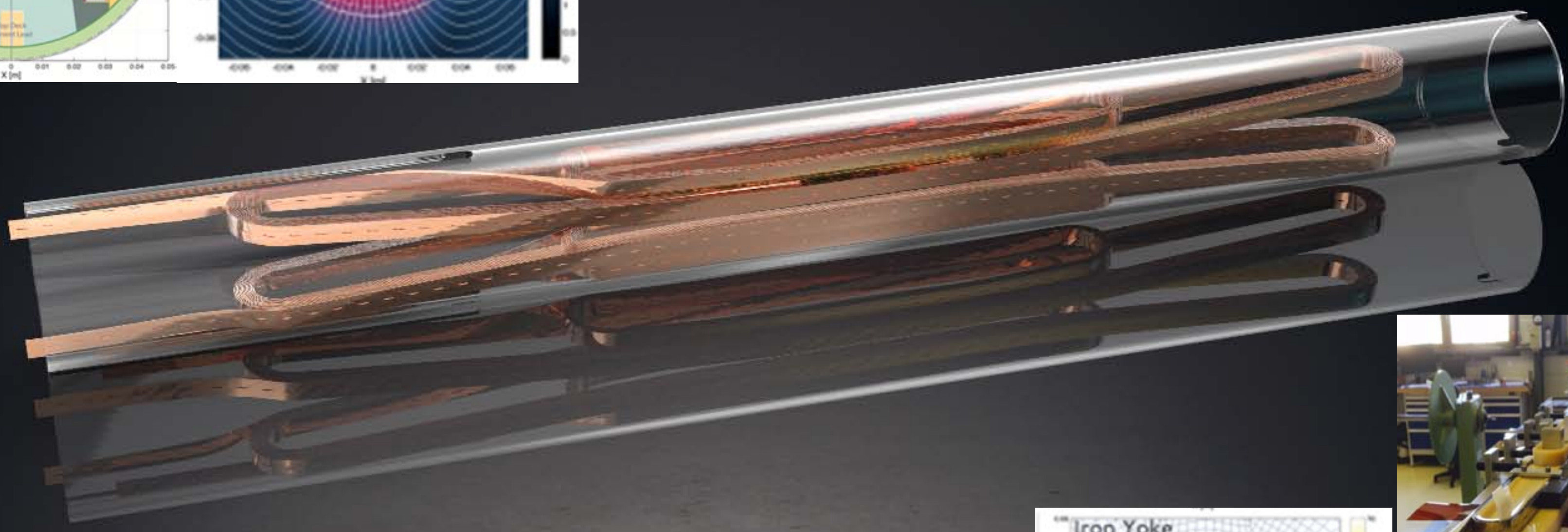
HTS Accelerator Magnets?

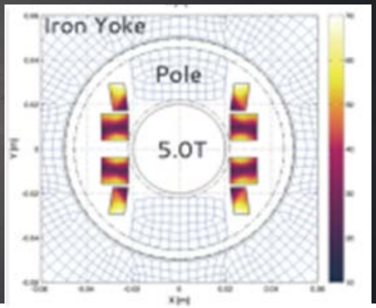
14+6=20T

Glyn Kirby et al, CERN





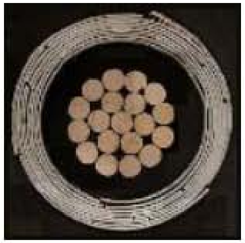




HTS Accelerator Magnets?

ReBCO

ACT CORC®

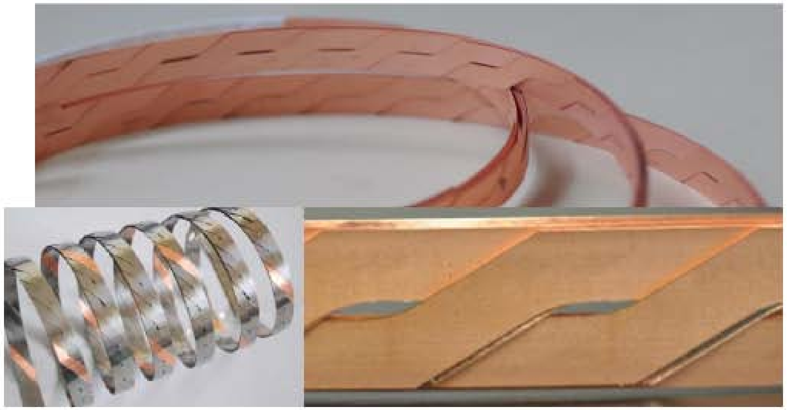


D C van der Laan et al.,
SuST, 24, 042001, 2011

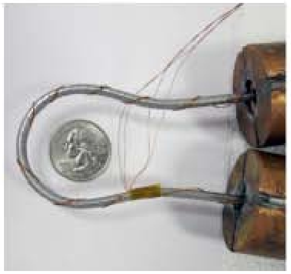
MIT Twisted Stacked-Tape Cable

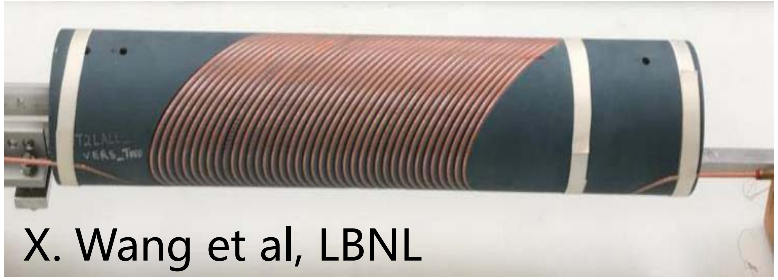
M. Takayasu et al.,
SuST, 25 (2012) 014011

KIT Roebel cable



A. Kario et al.,
SuST, 2013, 26 085019



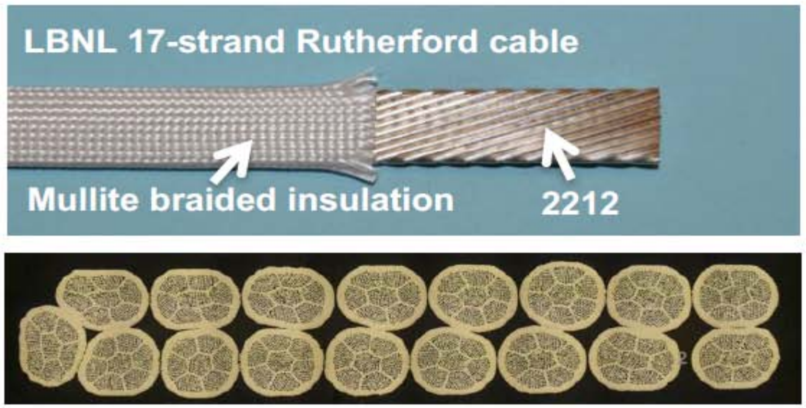


X. Wang et al, LBNL

HTS Accelerator Magnets?

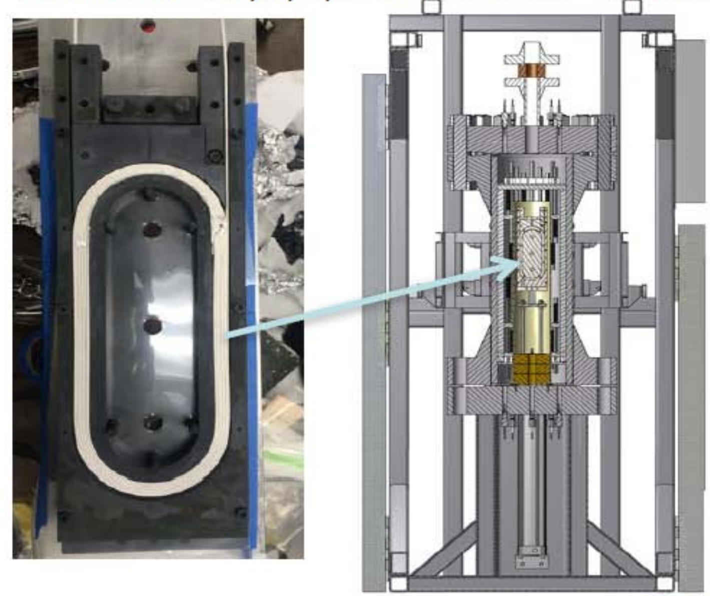
Bi-2212

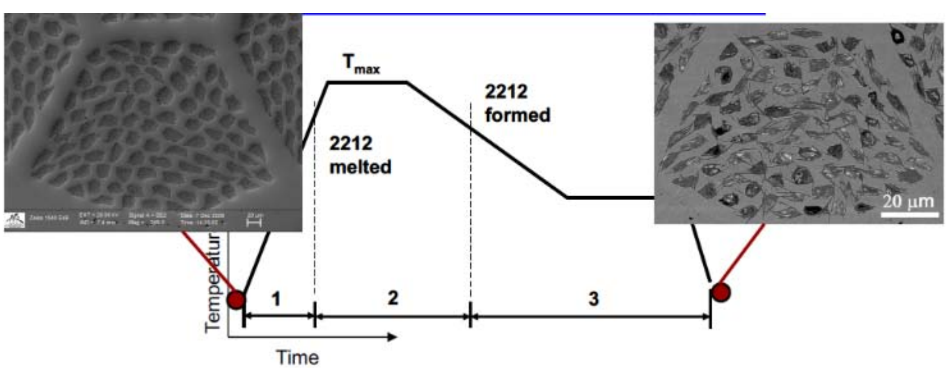
T. Shen et al, LBNL



Most recent insulation scheme is TiO_2 slurry (Chemically benign) + mullite sleeve

LBNL RC-1,2,3,5 in FSU OP furnace





2212 → Liquid + solid phases → 2212

HTS Accelerator Magnets?

and IBS ?

To be continued…

Summary of the 1st Section

Main challenges of the high field superconducting magnets for accelerators:

- ***Performance of Superconductors**: J_c, mechanical behaviors.*
- ***Stress control**: magnetic force in superconducting coils at high field $F \sim B^2$, and strain-sensitive conductors.*
- ***Quench protection**: High stored energy and operating current*
- ***Field quality**: magnetization effect, current distribution in tape conductors, iron saturation effect.*
- ***Cost**……*

Outline

- **Fundamental Principles of the Superconducting Accelerator Magnets**
  - PRINCIPLES of Particle Accelerators
  - CHARACTERISTICS and MAIN CHALLENGES of the Superconducting Accelerator Magnets

- **Case Study**
  - Progress of the High Field Magnet R&D at IHEP
  - Progress of the HL-LHC CCT Magnets

Acknowledgement

Team Members & Collaborators

IHEP-CAS: *Chengtao Wang, Yingzhe Wang, Zhan Zhang, Shaoqing Wei, Huanli Yao, Chunyan Li, Rui Kang, Juan Wang, Zhen Zhang, Jinrui Shi, Ze Feng, Xiangchen Yang, Xiaojuan bian, Quanling Peng, Lingling Gong, Ershuai Kong,…*

IEE-CAS: *Dongliang Wang, Xianping Zhang, Yanwei Ma,…*

HIPS-CAS: *Huajun Liu, Tao Zhao, Yanlan Hu,…*

IMP-CAS: *Wei Wu, Yu Liang, Wenjie Liang, Dongsheng Ni,…*

WST: *Bo Wu, Yanmin Zhu, Xiang Guo, Jianwei Liu, Jianfeng Li, Meng Li, Chao Li, …*

Toly Electric: *Yu Zhao, Hean Liao, Bingxing Lu,…*

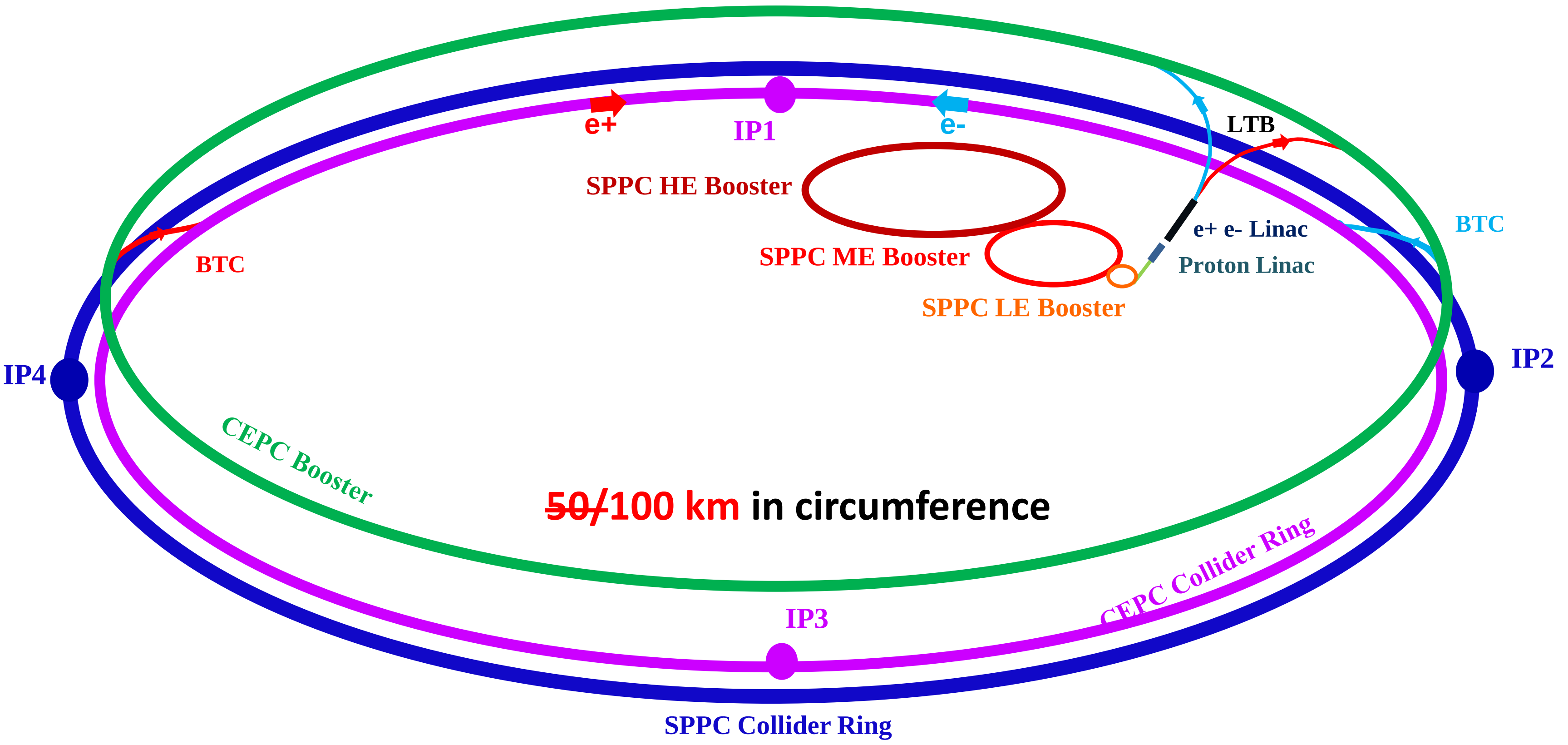
CERN**：** *Ezio Todesco, Glyn Kirby, Arnaud Devred,…*

……

**Work supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (CAS) Grant No. XDB25000000, the National Key Research and Development Program of China No. 2018YFA0704200, and National natural Science Foundation of China Grant No. 11675193, 11575214, 11604335.*

CEPC-SPPC

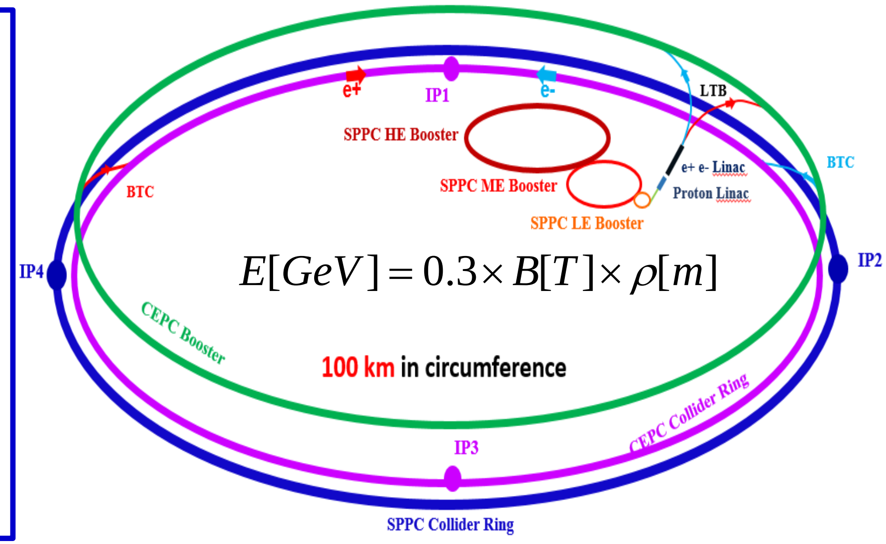
CEPC is an 240-250 GeV Circular Electron Positron Collider, proposed to carry out high precision study on Higgs bosons, which can be upgraded to a 70-150 (Upgrading phase) TeV pp collider SPPC, to study the new physics beyond the Standard Model.



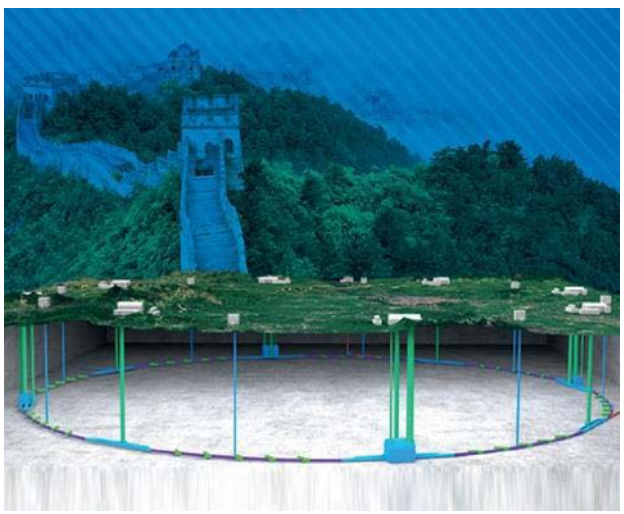
SPPC Magnet Design Scope

Main dipoles

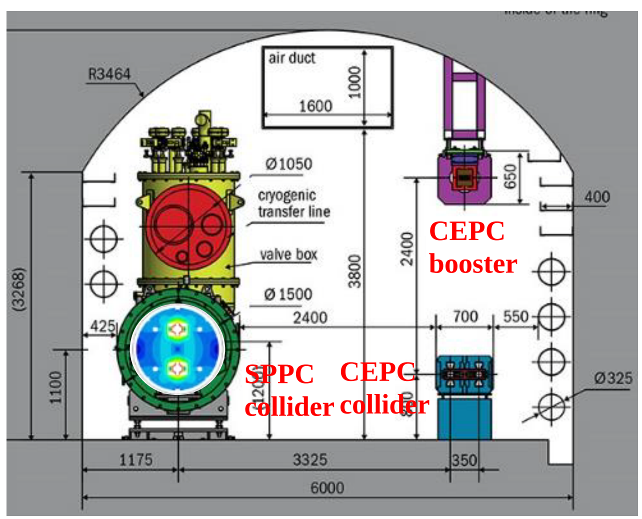
- *Field strength: 12-24 Tesla to get 75-150 TeV in a 100-km tunnel*
- *Baseline Iron-Based Superconductor (IBS), Nb_3Sn/ReBCO etc. as options*
- *Aperture diameter: 40~50 mm*
- *Field quality: 10^{-4} at the 2/3 radius*



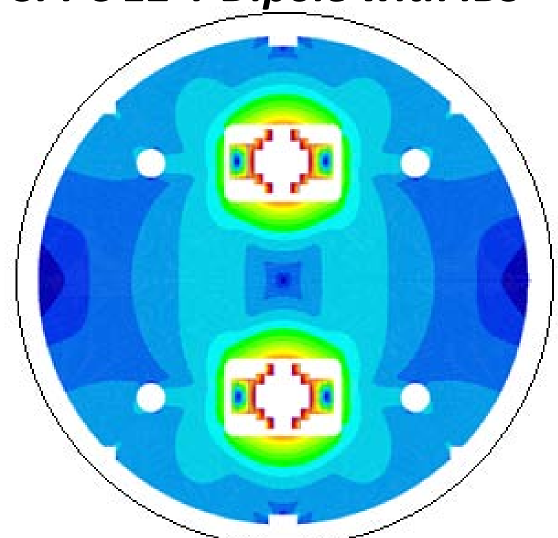
Site study of the CEPC-SPPC



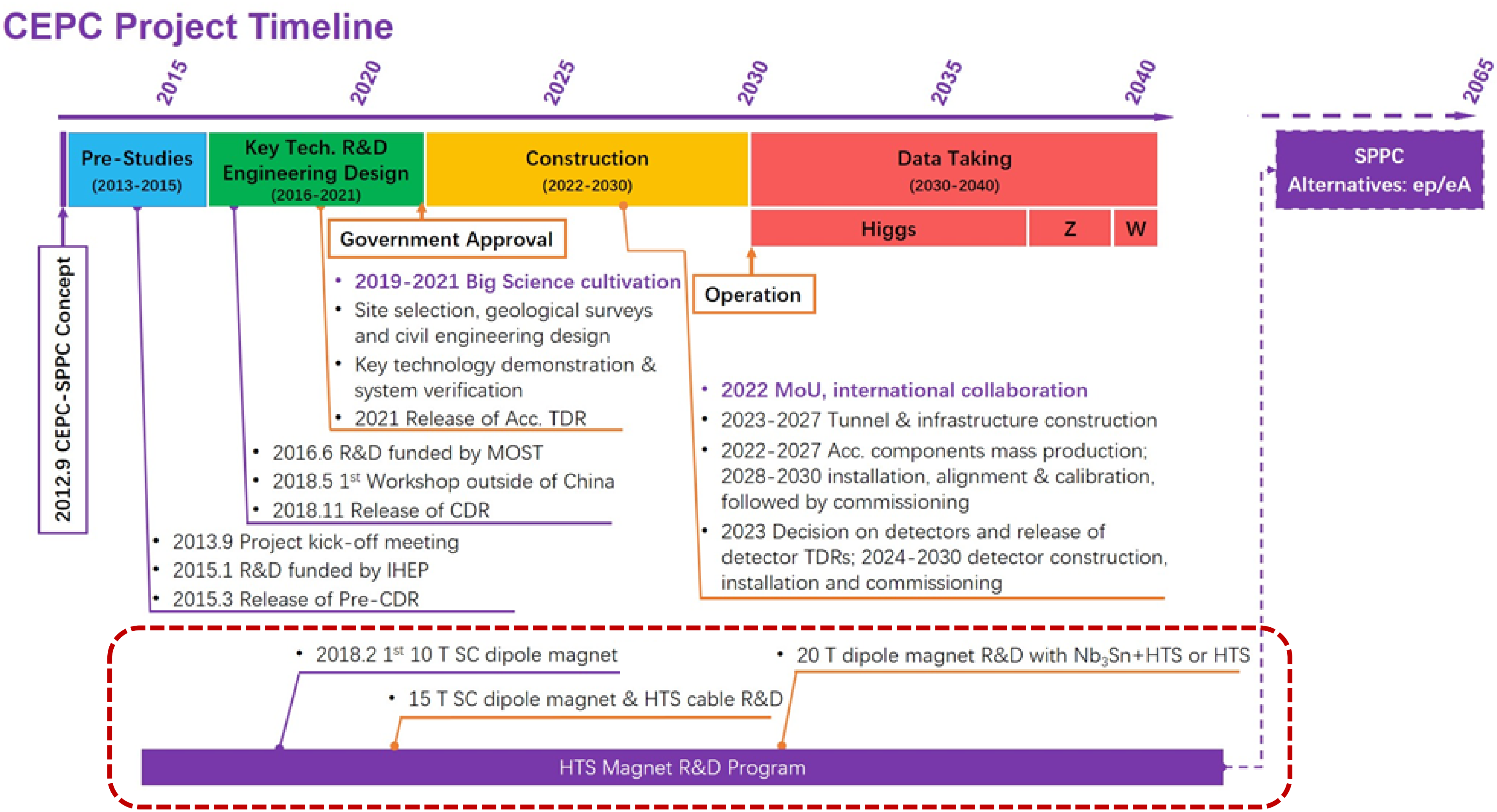
6-m width Tunnel for CEPC-SPPC



SPPC 12-T Dipole with IBS



CEPC-SPPC Project Timeline



Discovery of IBS Superconductor

Hideo Hosono
IBS (Tc 26K)
2008.02[1]

J|A|C|S
COMMUNICATIONS

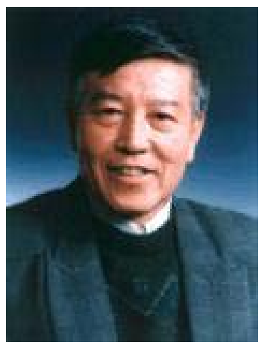
Published on Web 02/23/2008

Iron-Based Layered Superconductor $La[O_{1-x}F_x]FeAs$ ($x = 0.05-0.12$) with $T_c = 26$ K

Yoichi Kamihara,*,† Takumi Watanabe,‡ Masahiro Hirano,†,§ and Hideo Hosono†,‡,§

ERATO-SORST, JST, Frontier Research Center, Tokyo Institute of Technology, Mail Box S2-13, Materials and Structures Laboratory, Tokyo Institute of Technology, Mail Box R3-1, and Frontier Research Center, Tokyo Institute of Technology, Mail Box S2-13, 4259 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan

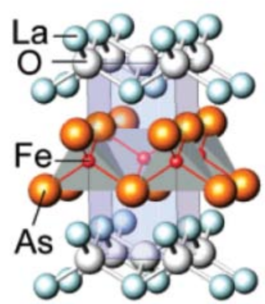
Received January 9, 2008; E-mail: hosono@msl.titech.ac.jp



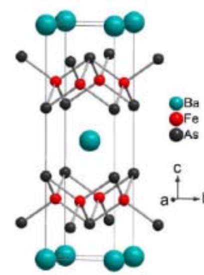
Z. Zhao
IBS (Tc 55K)
2008.04[2]

The three phases most relevant for wire applications are 1111, 122, and 11 types with a T_c of 55, 38 and 8 K, respectively.

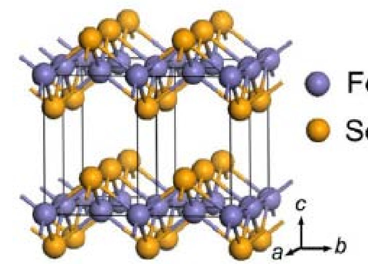
1111 Phase
LnOFeAs[2]



122 phase
AFe2As2



11 phase
FeSe[4]



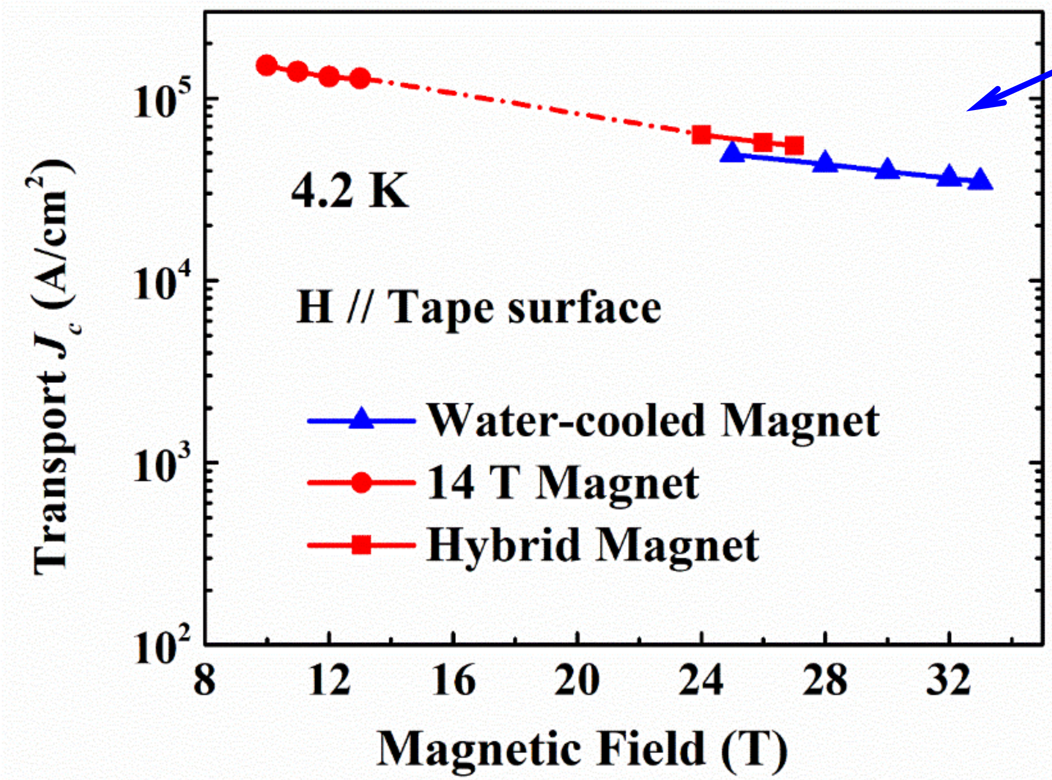
[1]Yoichi Kamihara, et al, 'Iron-Based Layered Superconductor La[O1-xFx]FeAs (x) 0.05-0.12) with Tc) 26 K', J. AM. CHEM. SOC. 2008, 130, 3296-3297
[2] Ren, Zhi-An , et al, ' Superconductivity and phase diagram in iron-based arsenic-oxides ReFeAsO1−δ (Re = rare-earth metal) without fluorine doping. EPL (Europhysics Letters). 2008, 83: 17002
[3] Marianne Rotter, et al, 'Superconductivity at 38 K in the Iron Arsenide (Ba1−xKx)Fe2As2', Phys. Rev. Lett. 101, 107006 – Published 5 September 2008
[4] Fong-Chi Hsu, et al, 'Superconductivity in the PbO-type structure α-FeSe', PNAS September 23, 2008 105 (38) 14262-14264

New record J_e 364A/mm^2 @ 4.2K, 10T

***Short sample** I_c**:** 437 A with 4-mm width and 0.3-mm thickness.*

J_e = 364A/mm^2 @ 4.2K, 10T

IEECAS
Yanwei Ma



At 30 T, J_c = 400 A/mm^2

Transport J_c of 100-m-class 7-filamentary Ba-122 IBS tapes was further improved to > 3×10^4 A/cm^2 at 10 T & 4.2 K (three times the value in 2016).

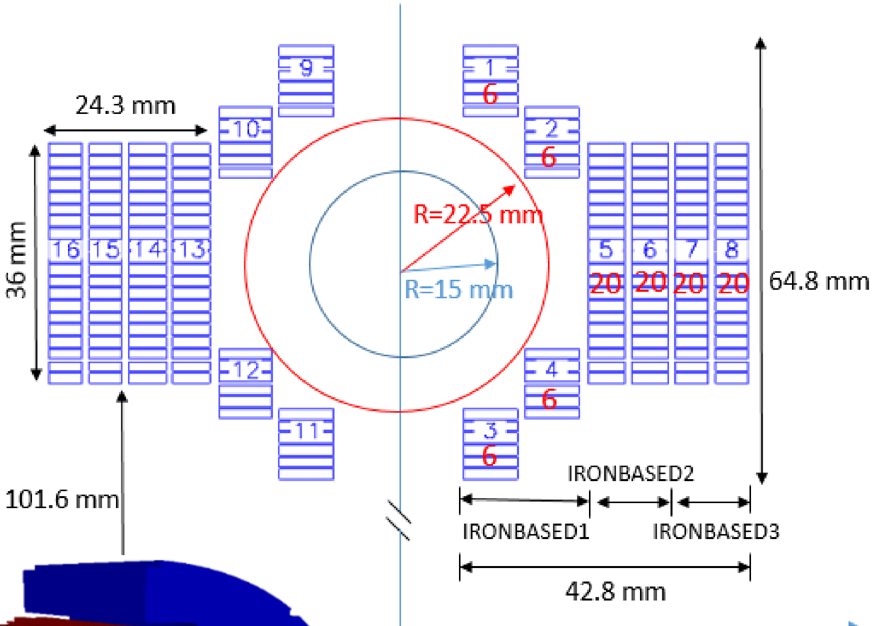
Domestic Collaboration for HTS R&D

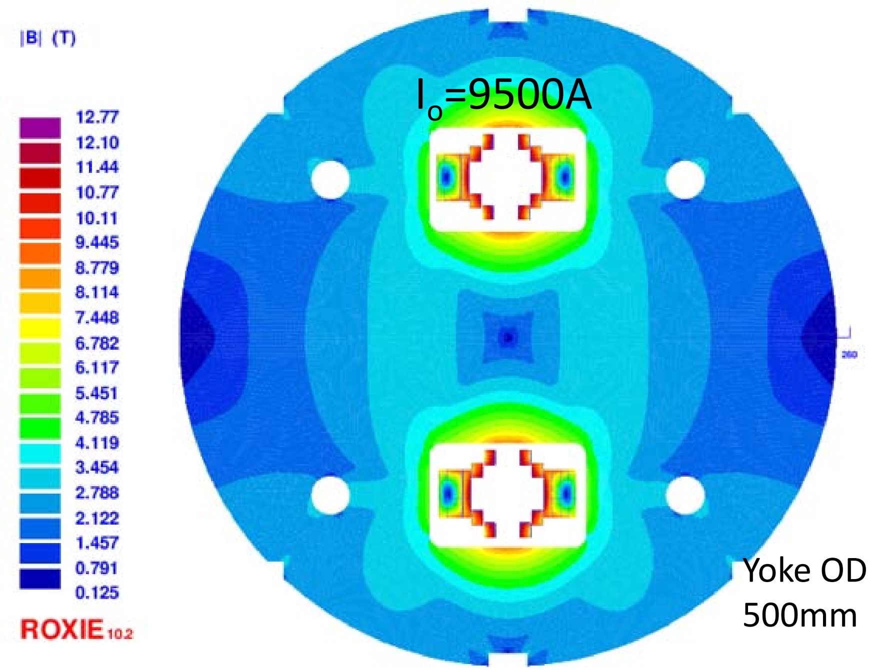
Applied High Temperature Superconductor Collaboration (AHTSC)

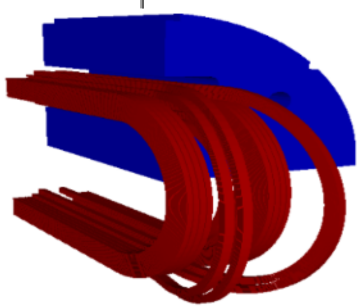
- R&D from **Fundamental sciences** of superconductivity, **advanced HTS superconductors** to **Magnet & SRF technology**.
- **Regular meetings every 3 months** from Oct. 2016
- **Goal：**

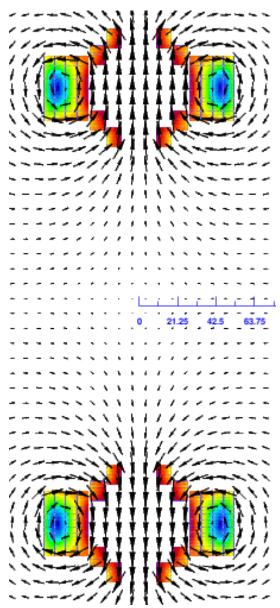
- **Increasing J_c** of iron-based superconductor **by 10 times**.
- **Reducing the cost** of HTS conductors to be **similar with "NbTi conductor"**
- Industrialization of the **advanced superconductors**, **magnets and cavities**

The 12-T Fe-based Dipole Magnet









Field quality	2D with R_f=13.3mm	3D with R_f= 8/13.3 mm
b3	0.45	0.79/1.91
b5	1.01	-0.65/-2.24
b7	0.46	0.08/0.67
b9	-0.27	-0.13/-0.22
a2	3.53	-1.00/-2.31
a4	0.49	-0.46/0.69
a6	0.33	0.26/2.49
a8	0.58	-0.12/0.84
a10	2.23	0.06/2.18

Conceptual design with expected J_e of IBS in 2025

Strand	diam.	cu/sc	RRR	Tref	Bref	Jc@ BrTr	dJc/dB
IBS	0. 802	1	200	4. 2	10	4000	111

- For 100-km SPPC, needs **3000 tons of IBS**
- Target cost of IBS: **20 RMB /kAm @12 T**
- Total cost for IBS conductors: **~10B RMB**

Performance of the 1^{st} IBS solenoid Coil

Fabrication and test of IBS solenoid coil at 24T

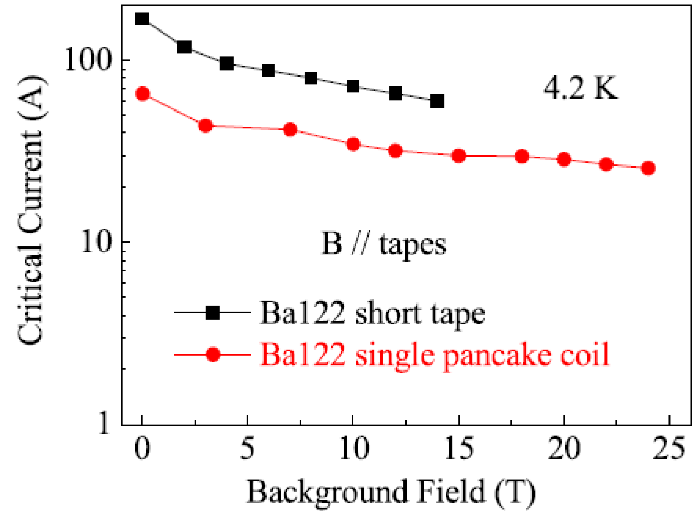
IOP Publishing Superconductor Science and Technology
Supercond. Sci. Technol. **32** (2019) 04LT01 (5pp) https://doi.org/10.1088/1361-6668/ab09a4

Letter

First performance test of a 30mm iron-based superconductor single pancake coil under a 24T background field

Dongliang Wang[1,2,5], Zhan Zhang[3,5], Xianping Zhang[1,2], Donghui Jiang[4], Chiheng Dong[1], He Huang[1,2], Wenge Chen[4], Qingjin Xu[3,6] and Yanwei Ma[1,2,6]

[1] Key Laboratory of Applied Superconductivity, Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, People's Republic of China
[2] University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China
[3] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, People's Republic of China
[4] High Magnetic Field Laboratory, Chinese Academy of Sciences, Hefei 230031, People's Republic of China



Viewpoint by NHMFL

'From a practical point of view, **IBS are ideal candidates for applications**. Indeed, some of them have quite a **high critical current density, even in strong magnetic fields**, and a low superconducting anisotropy.
Moreover, **the cost of IBS wire can be four to five times lower than that of Nb_3Sn**……

IOP Publishing Superconductor Science and Technology
Supercond. Sci. Technol. **32** (2019) 070501 (3pp) https://doi.org/10.1088/1361-6668/ab1fc9

Viewpoint

CrossMark

Constructing high field magnets is a real tour de force

Jan Jaroszynski
National High Magnetic Field, Laboratory, Tallahassee, FL, 32310, United States of America
E-mail: jaroszy@magnet.fsu.edu

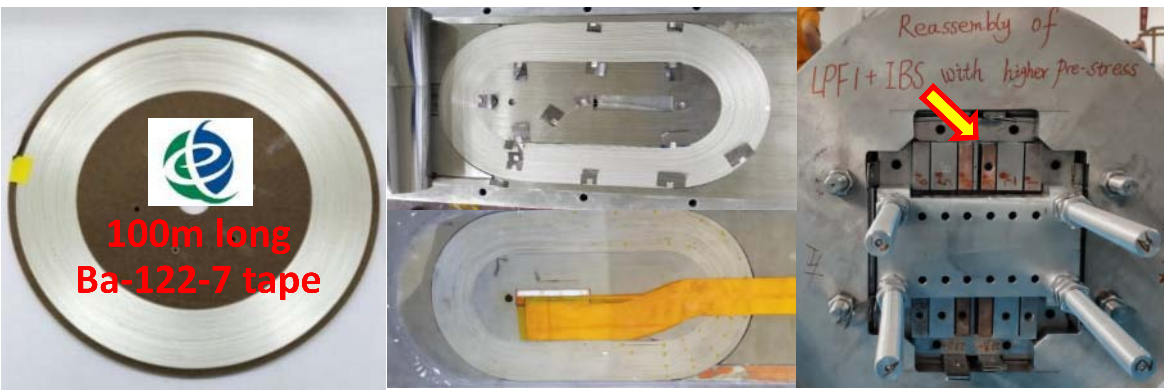
This is a viewpoint on the letter by Dongliang Wang *et al* (2019 *Supercond. Sci. Technol.* **32** 04LT01).

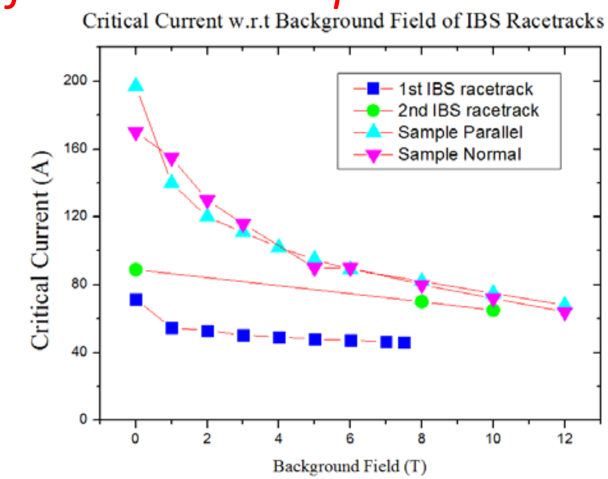
Following the discovery of superconductivity in 1911, Heike Kamerlingh Onnes foresaw the generation of strong magnetic fields as its possible application. He designed a 10 T electromagnet made of lead–tin wire, citing only the difficulty

Performance of the 1st IBS racetrack coil

Fabrication of racetrack coil with 100m IBS tape and test at 10T

- *Two racerack coils with 100m long IBS tapes have been fabricated and tested at 10T background field.*
- *The Ic in the coil reached 86.7% of the short sample at 10T.*





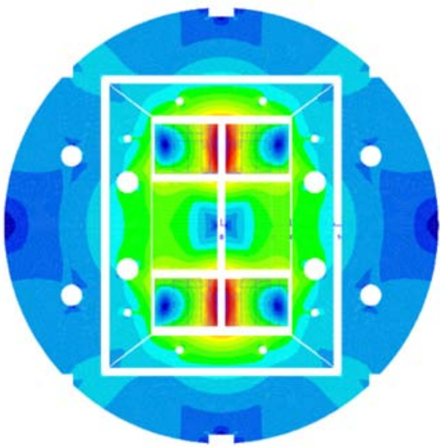
Comments from SUST reviewers :

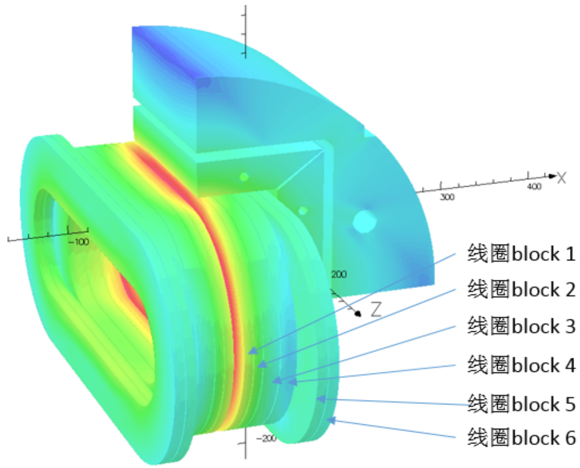
a) ...the new results that can have a strong impact on the conductor and magnet community.

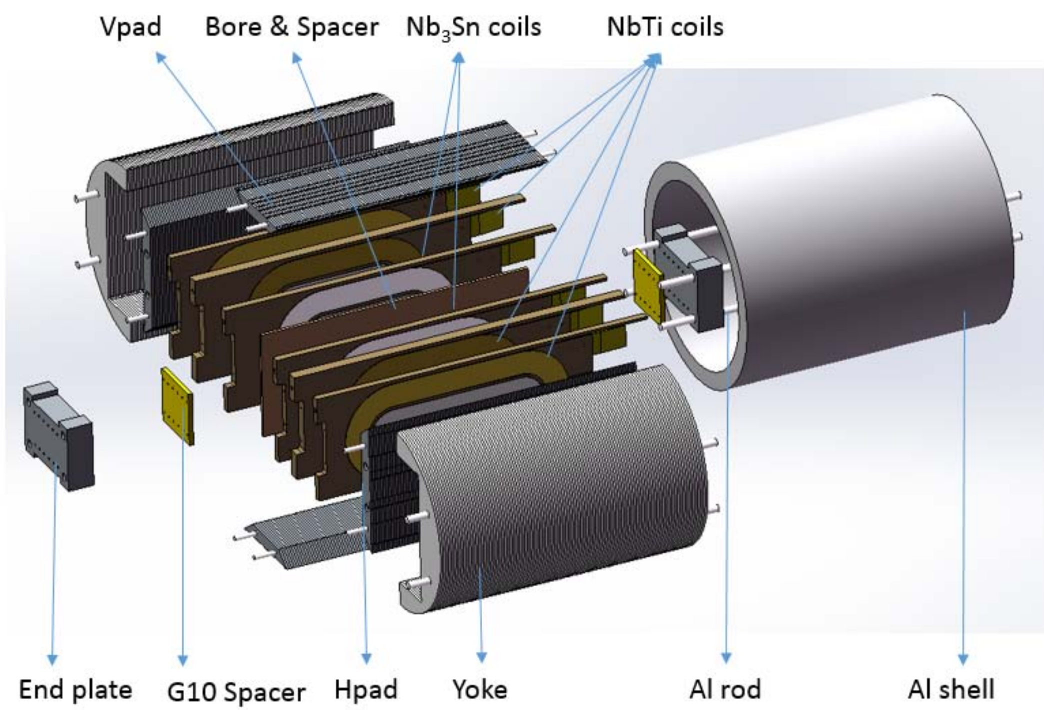
b) ...demonstrated the great potential of Iron-Based Superconductor in the development of next-generation accelerators.

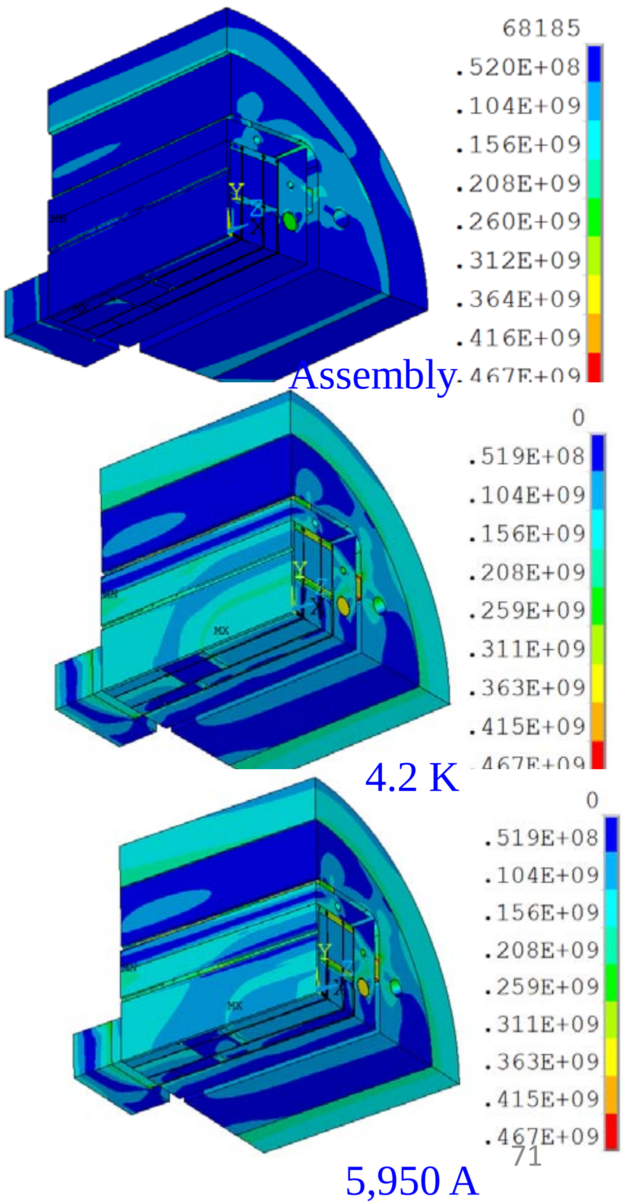
c) It is of certain significance in the path of applications of Iron-Based Superconductor...

R&D of the 1st $NbTi+Nb_3Sn$ Model Dipole

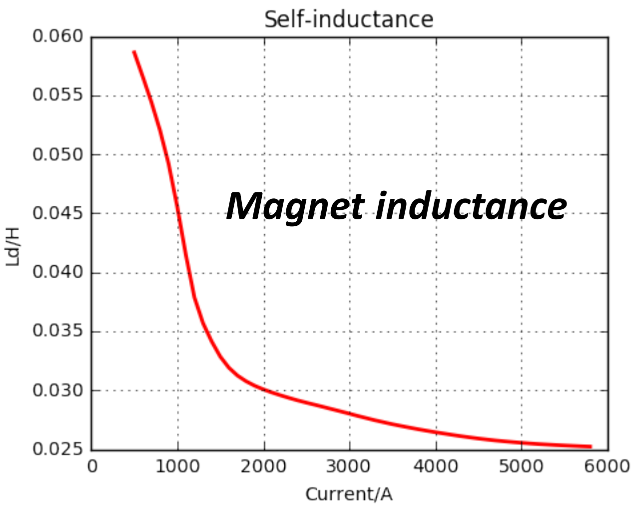


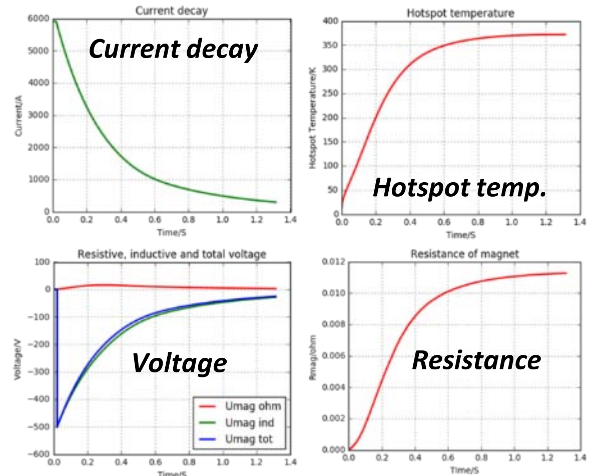


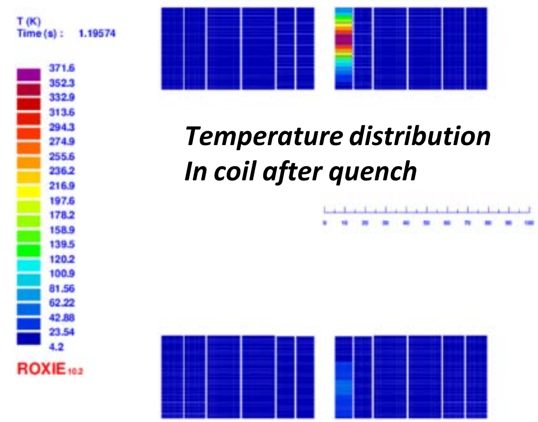




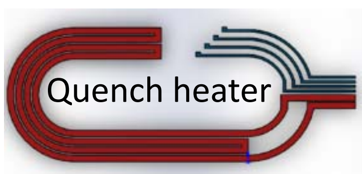
R&D of the 1st NbTi+Nb_3Sn Model Dipole



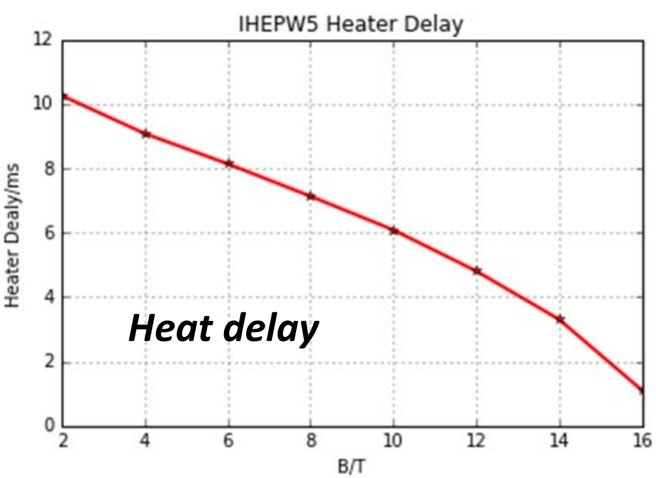


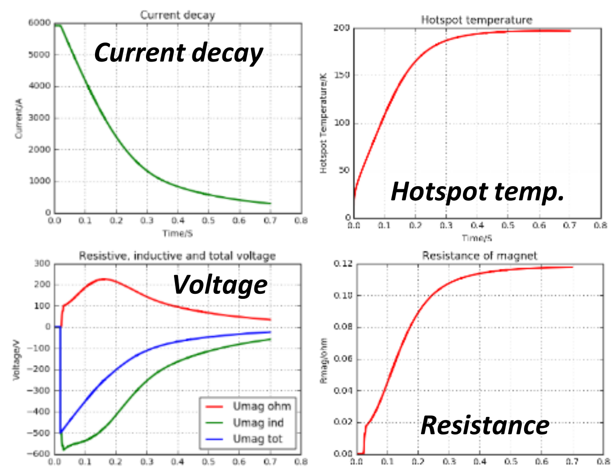


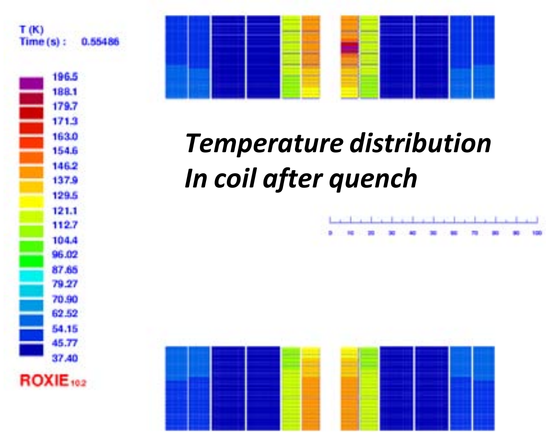
Quench simulation with dump resistor only



Thickness (µm)	Resistance （Ω）	Peak power （w/cm^2)	Charge voltage (V)	Max current (A)	Capacitance (mF)
50	3.1	100	341	110.07	9.67





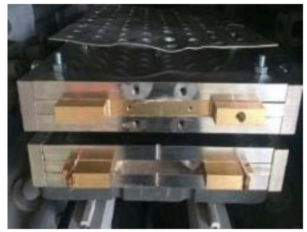


Quench simulation with dump resistor and heaters

R&D of the 1st $NbTi+Nb_3Sn$ Model Dipole

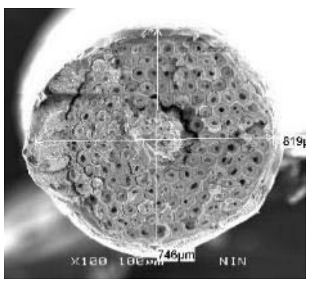
Tension control, deformation
J_c and RRR degradation,
Flux jump…

Temperature control, Thermal stress control
J_c and RRR degradation.

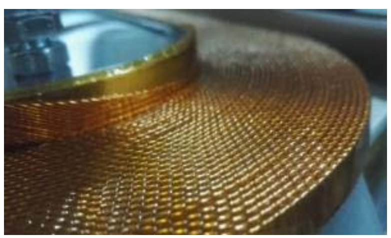


Pre-stress control
Stress of coils,
Mechanical Stability…

Cabling ➡ ***Coil winding*** ➡ ***HT*** ➡ ***VPI*** ➡ ***Magnet assembly*** ➡ ***Test***



Material, Structure, Processing,…
J_c, RRR, Cu ratio,
Filament size…



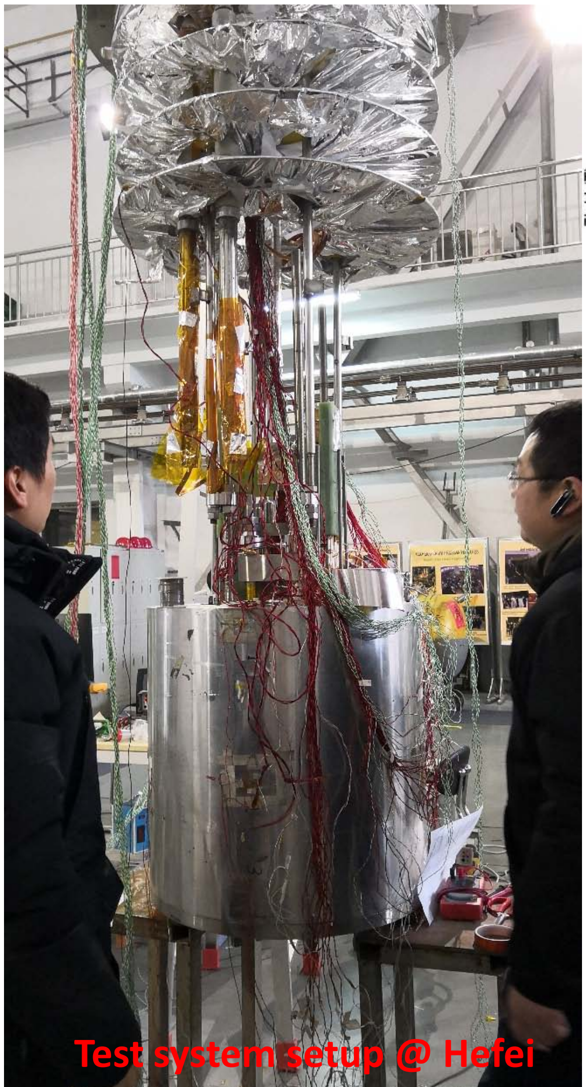
Stress control, Size control, Electrical insulation
J_c and Field quality degradation,
Electrical short…

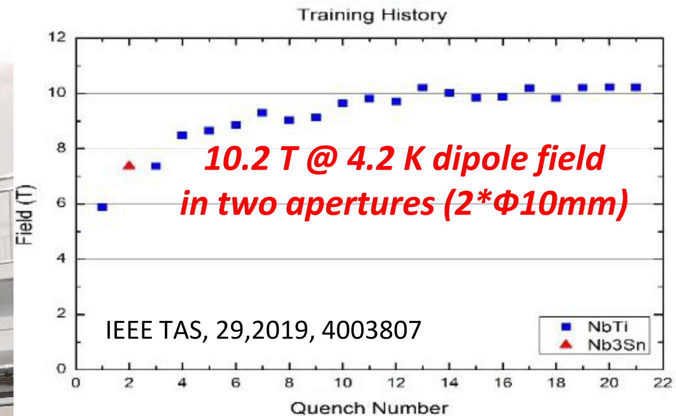
Impregnation quality control:
type of epoxy, procedures;
Mechanical strength and stability

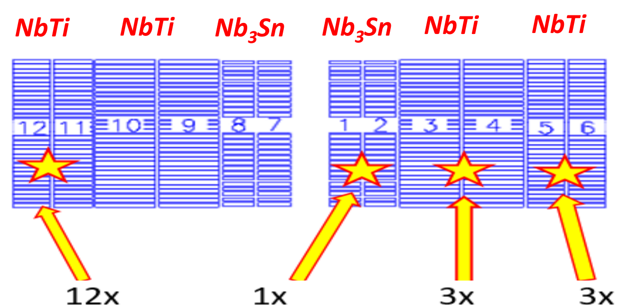
EM force, Quench protection
Training,
Strain of coils…

R&D of the 1^{st} NbTi+Nb_3Sn Model Dipole

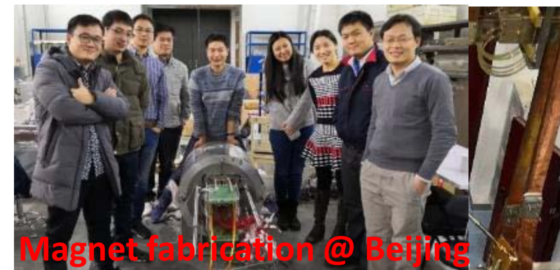
The 1^{st} test in 2018 in Hefei







- ***Performance** limited by the outermost NbTi coil.*
- ***Very possibly due to the** less of pre-stress.*



R&D of the 1st $NbTi+Nb_3Sn$ Model Dipole

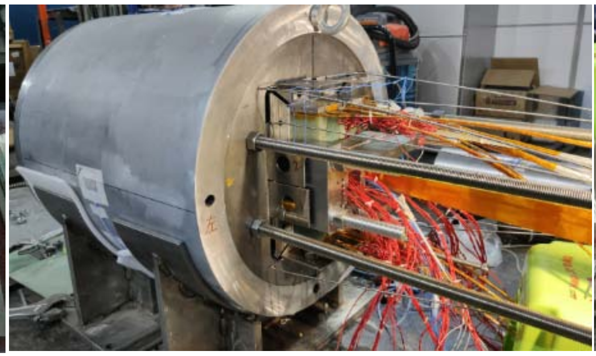
Reassembly of LPF1 with Increased Pre-stress

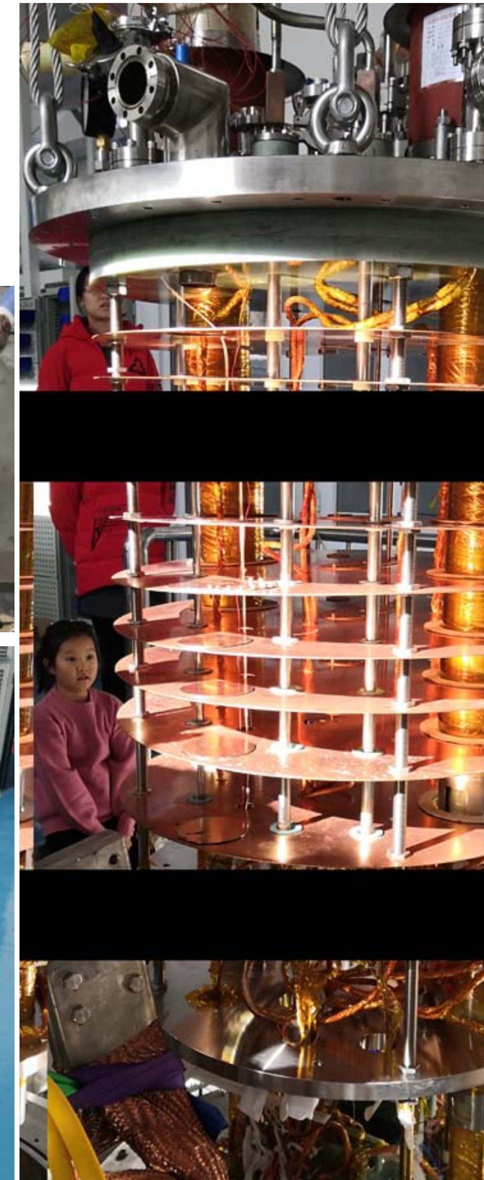
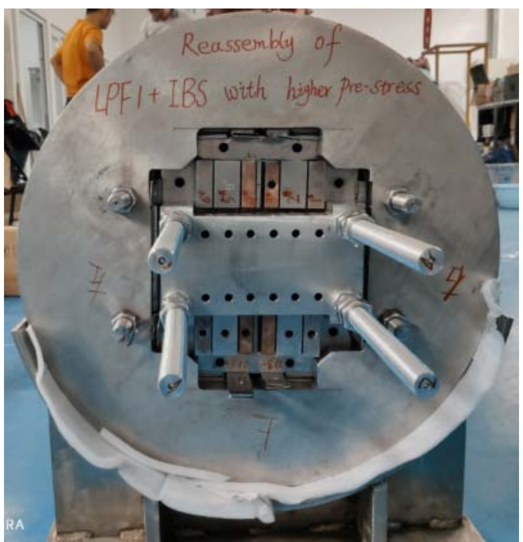
Pre-stress during assembly significantly increased.

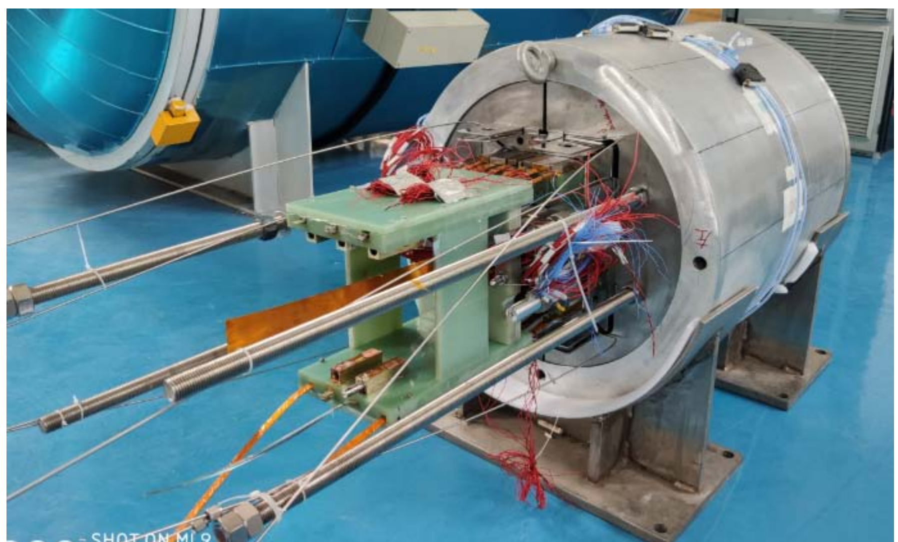
Horizontal：from previous 30 to 80 MPa;

Vertical：from 30 to 40 MPa；

Test in 2019 in Beijing

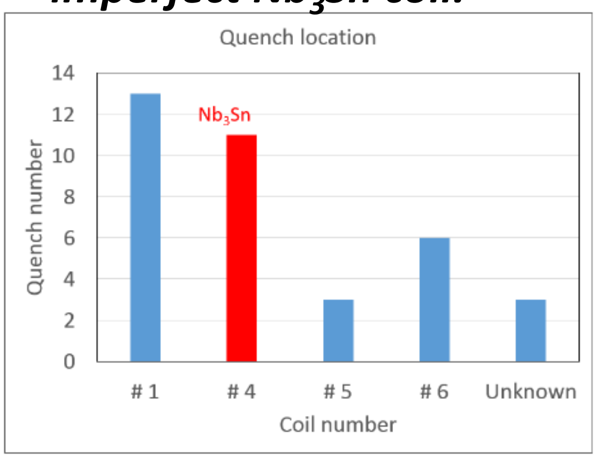



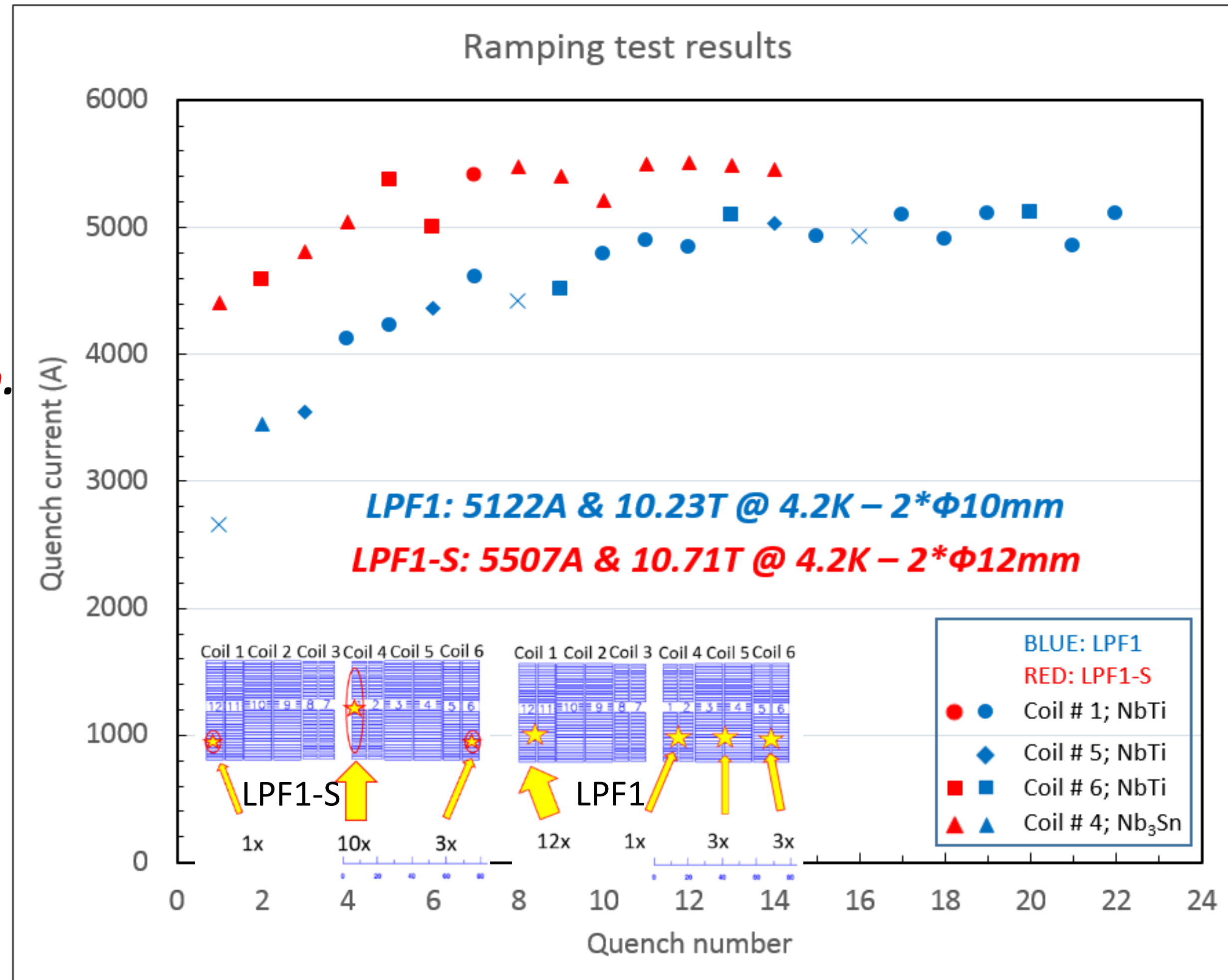


R&D of the 1st NbTi+Nb_3Sn Model Dipole

Performance with increased Pre-stress

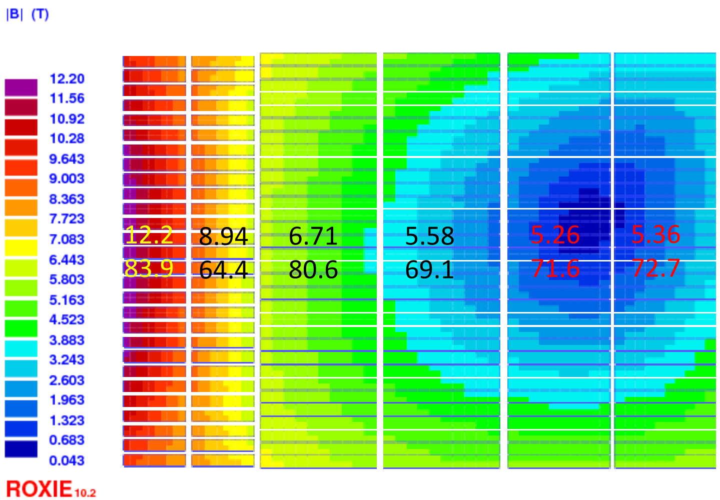
- ***The dipole field increased from 10.2 T to 10.7 T with larger apertures (2*ϕ12 mm) .***
- ***Performance limited by Nb_3Sn coil, possibly due to the imperfect impregnation.***
- ***Next step: replace the imperfect Nb_3Sn coil.***



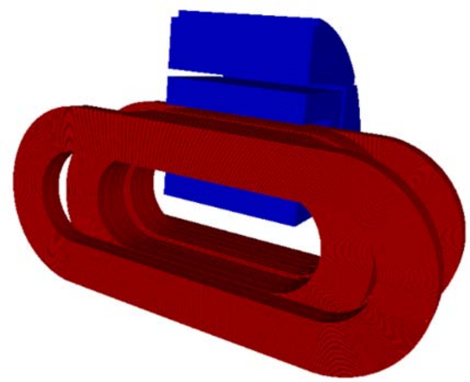


R&D of the 1st NbTi+Nb_3Sn Model Dipole

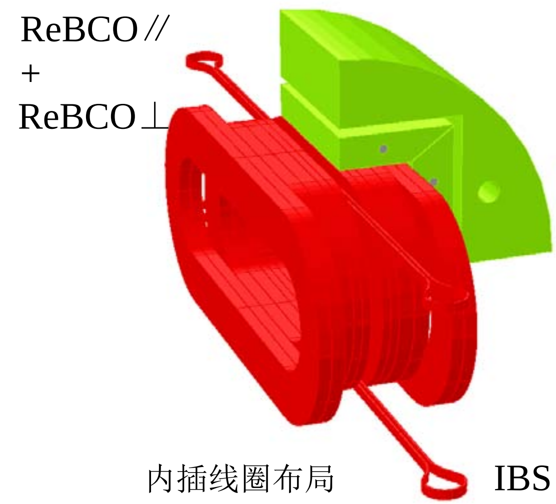
Upgrade with New Nb_3Sn and HTS Insert Coils



电流：6350 A；主场: 12 T



线圈及轭铁布局（3D）

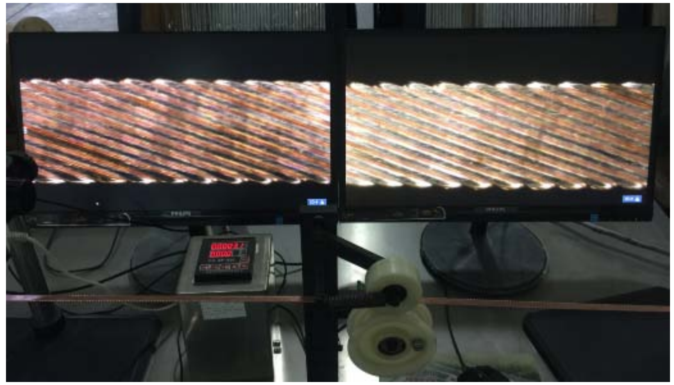


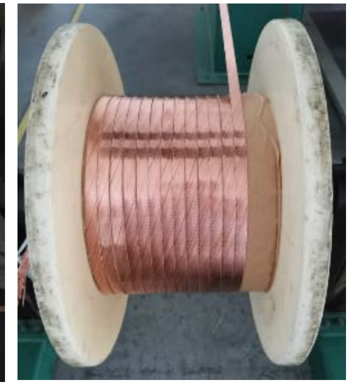
内插线圈布局

Main parameters of LPF1-U

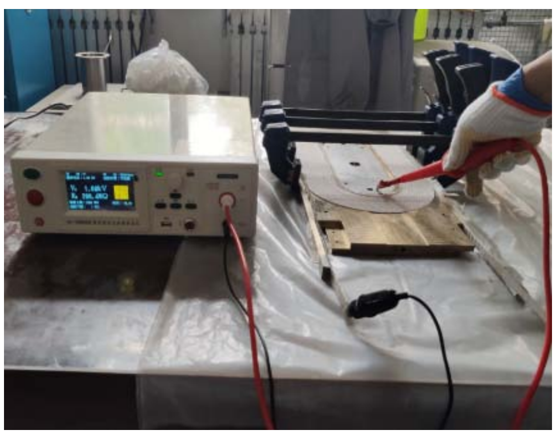
Results	Aperture (mm)	Current (A)	Main field (T)	Blocks	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6	ReBCO ⊥
2D	14	6350	12	Peak field (T)	12.20	8.94	6.71	5.58	5.26	5.36	12.74
				Load line ratio	83.9	64.40	80.58	69.05	71.59	72.7	-
3D	14	6575	12	Peak field (T)	12.20	8.65	7.20	7.00	6.11	6.16	12.7
				Load line ratio	84.6	63.51	86.01	83.98	81.25	81.79	-

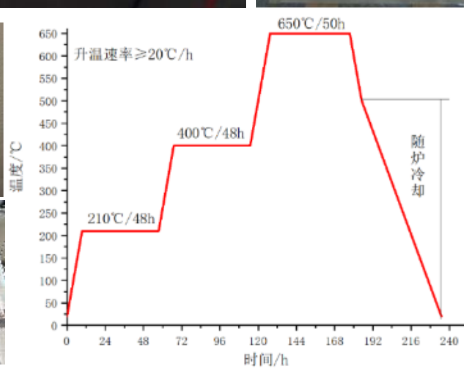
R&D of the 1st $NbTi+Nb_3Sn$ Model Dipole





在无锡统力电工完成卢瑟福电缆的绞制,绞制20芯铌三锡缆约125米；31芯铌钛缆约205米；铜缆共约250米



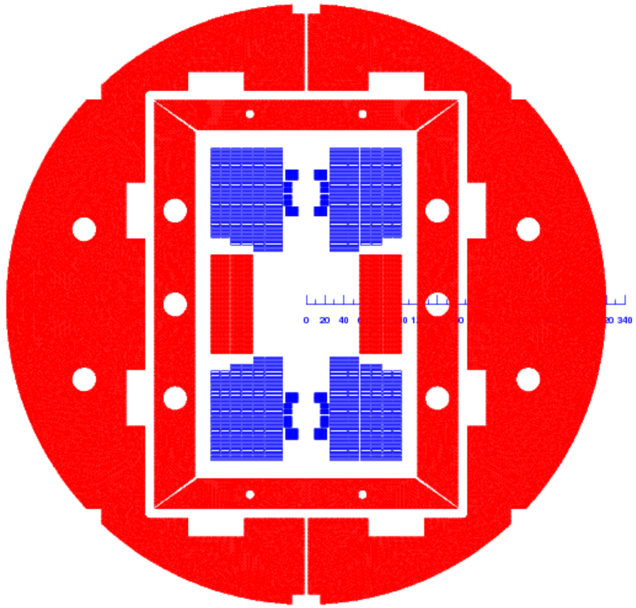


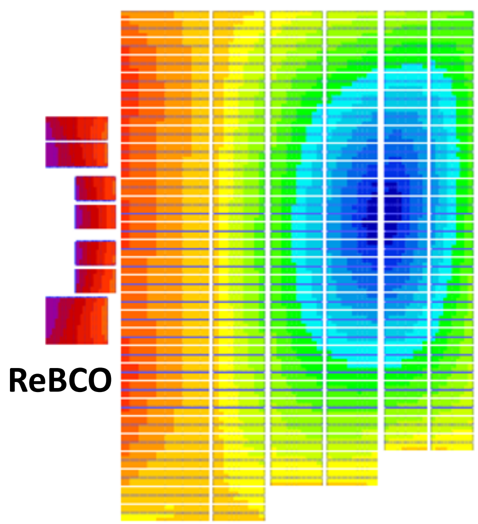
LPF 临界电流样品测试结果

种类	样品编号	超导线编号	位置识别号	Ic（A）	n	RRR
临界电流样品	1#	2024-19021A（原始）	BS1	606A，Quench		118
	2#	2024-19021A（截取）	BS2	644.5	39	64
	3#	2024-19017A-1（原始）	BS3	663.7	35	113
	4#	2024-19017A-1（截取）	BS4	646.7	66	74
	5#	2024-19021（截取）	BS5	541A，Quench		68

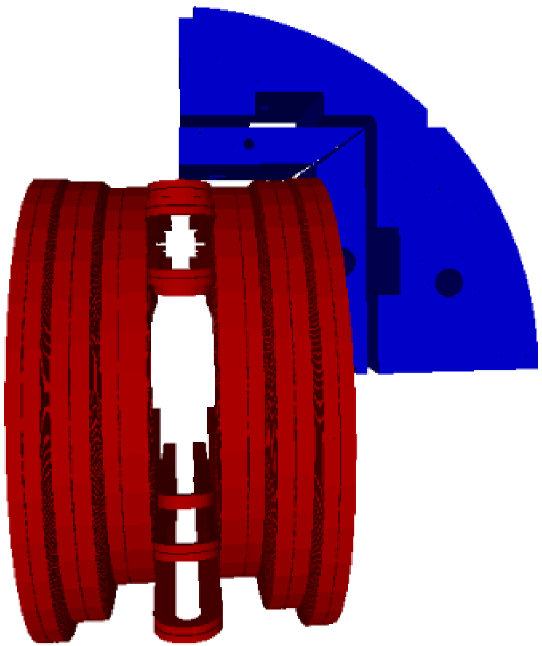
Next:16T Dipole Magnet with Nb_3Sn+HTS

Main field 16 (13+3) T in the two 30mm-diameter apertures

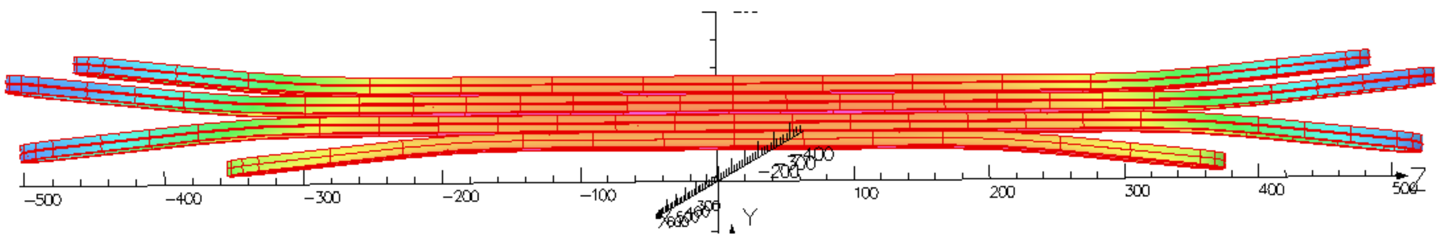




OD 640 mm AP 2*30 mm Nb_3Sn

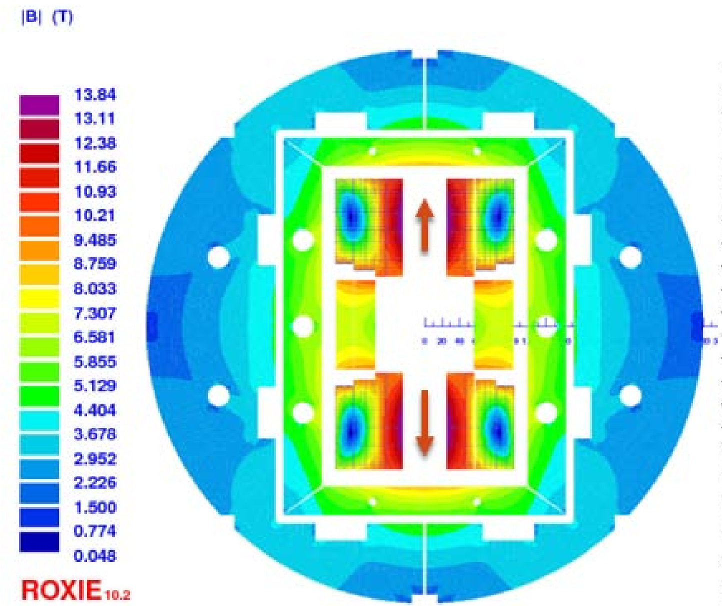


Nb_3Sn ReBCO Nb_3Sn

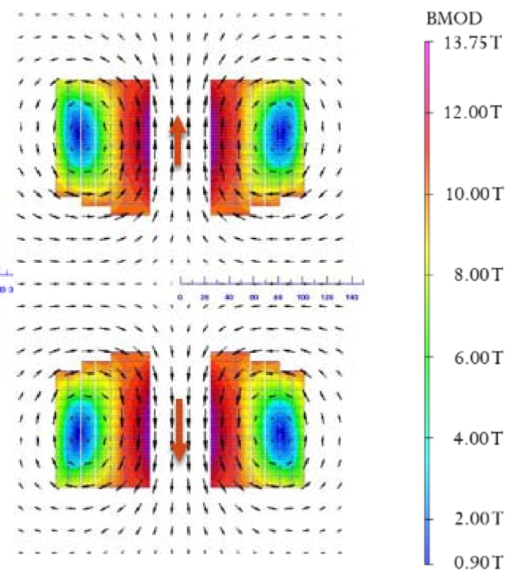


Next:16T Dipole Magnet with Nb_3Sn+HTS

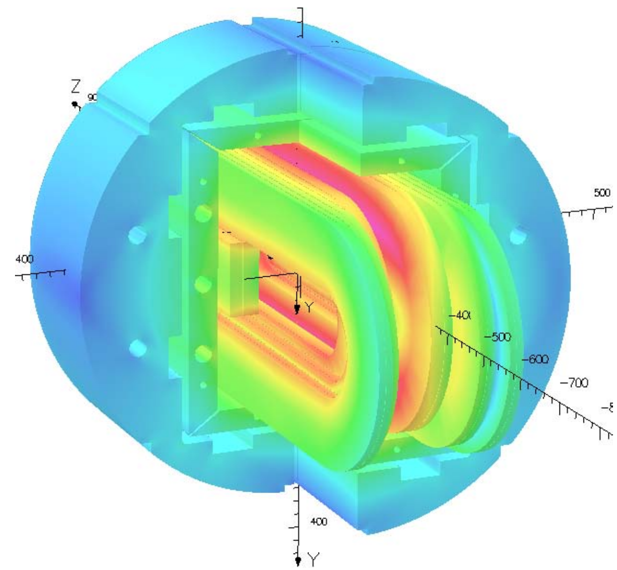
13T LTS design



Field distribution in the cross section



Flux distribution



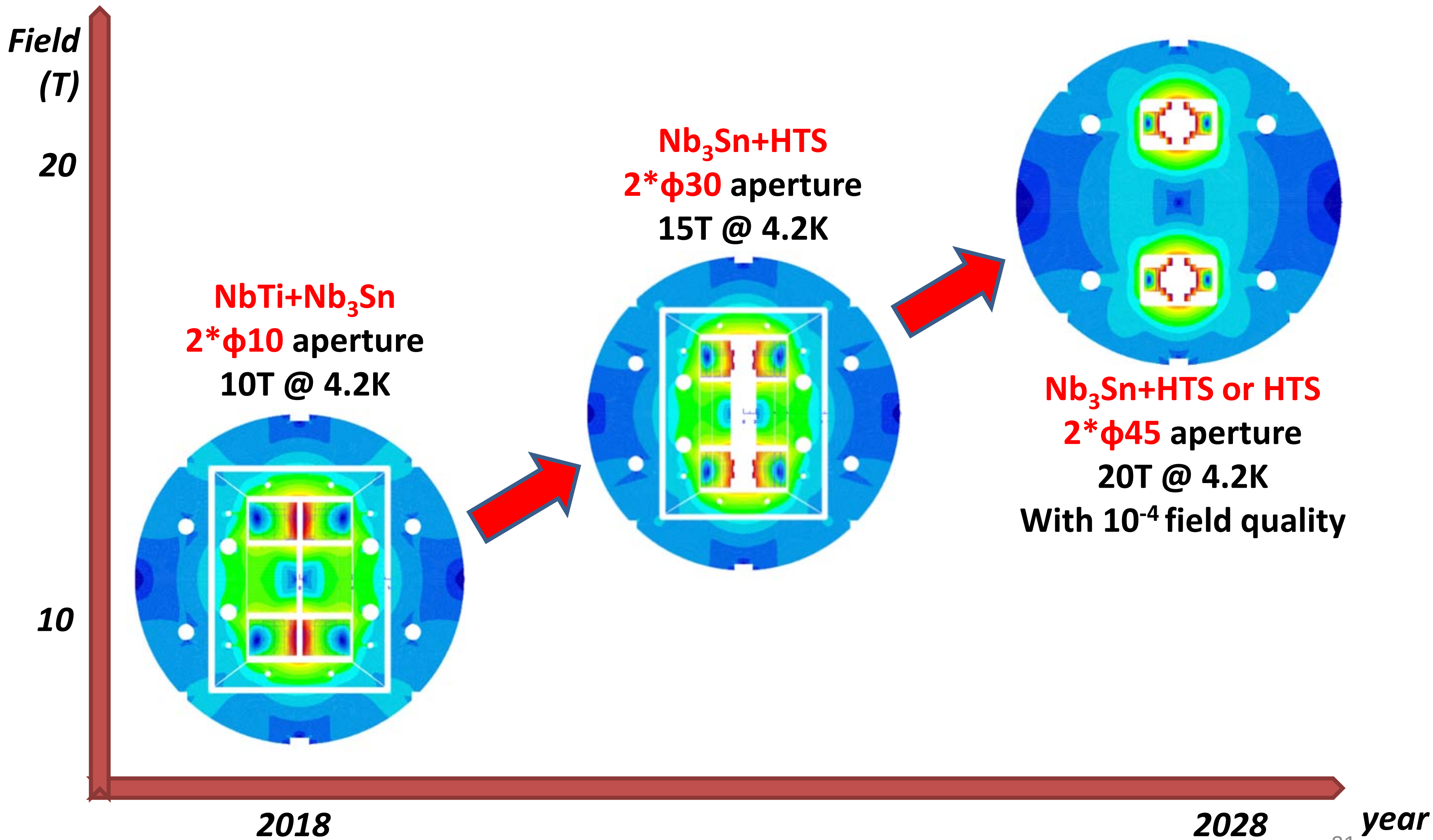
Cross-check with Opera -3D

Main parameters

Current - 3D	7630 A		Blocks	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6
Main field	13.02 T		Peak field (T)	13.85	11.13	10.95	11.21	10.57	10.47
			LL ratio (%)	82.91	78.16	77.18	78.6	78.63	78.09
Integral harmonics (-150-150mm); R-10	*b3: 102.76		b5: -0.08	b7: -0.01	b9: 0	*a2: -48.11	a4: -0.14	a6:-0.02	a8: 0
Integral harmonics (-150-150mm); R-15	*b3: 231.17		b5: -0.42	b7: -0.06	b9:0.01	*a2: -72.09	a4: -0.46	a6:-0.14	a8: 0.01

* Field harmonics to be improved with HTS insert coils

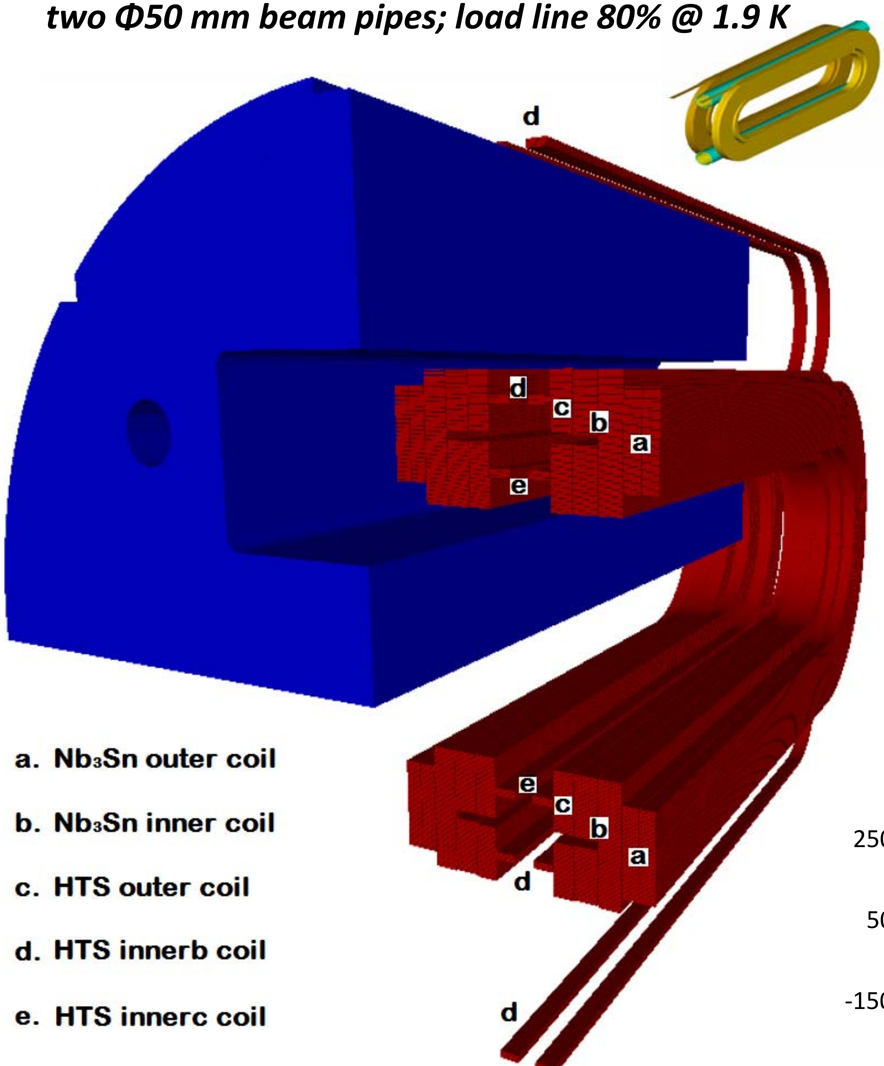
R&D Roadmap for next years

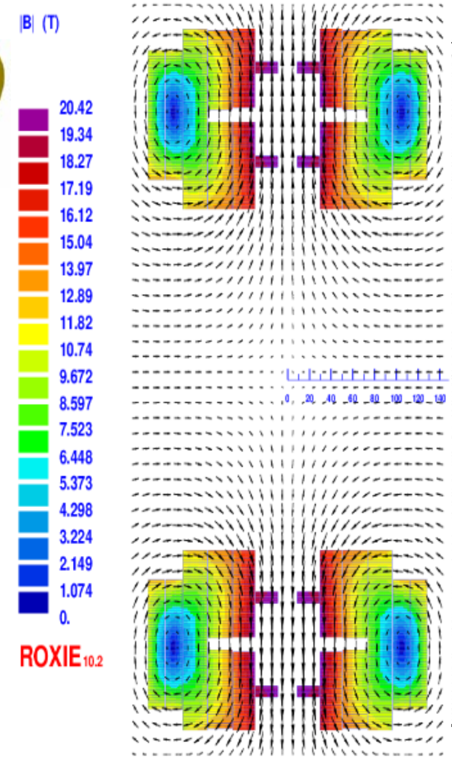


Conceptual Design of the 20T Dipole

20-T dipole magnet with common coil configuration

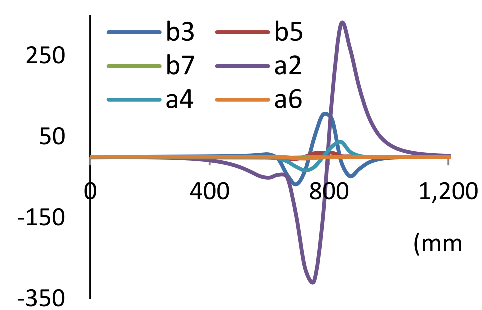
two Φ50 mm beam pipes; load line 80% @ 1.9 K





Main parameters of the magnet

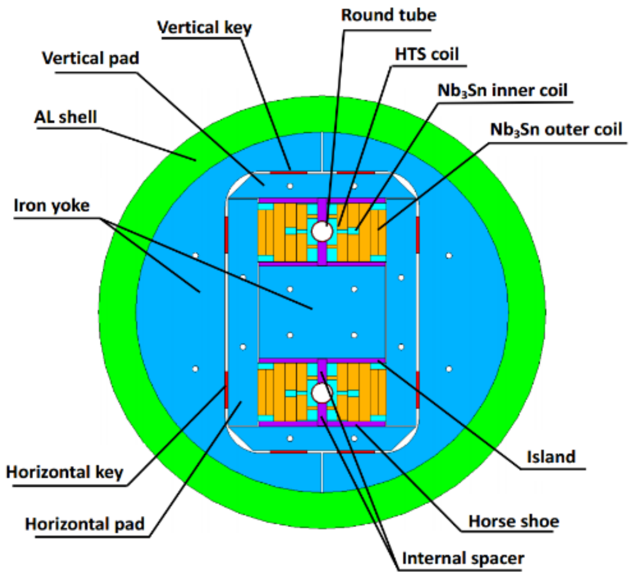
Number of apertures	2
Aperture diameter (mm)	50
Inter-aperture spacing (mm)	333
Operating current (A)	14700
Operating temperature (K)	4.2
Operating field (T)	20
Peak field (T)	20.4
Margin along the load line (%)	11
Stored magnetic energy (MJ/m)	7.8
Inductance (mH/m)	72.1
Yoke ID (mm)	260
Yoke OD (mm)	800
Weight per unit length (kg/m)	3200
Energy density (coil volume) (MJ/m^3)	738
Force per aperture – X / Y (MN/m)	23.5/4.4
Peak stress in coil (MPa)	240
Fringe Field @ r = 750 mm (T)	0.02

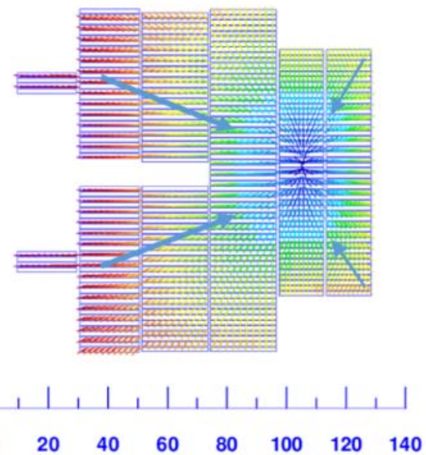


Integrated field quality

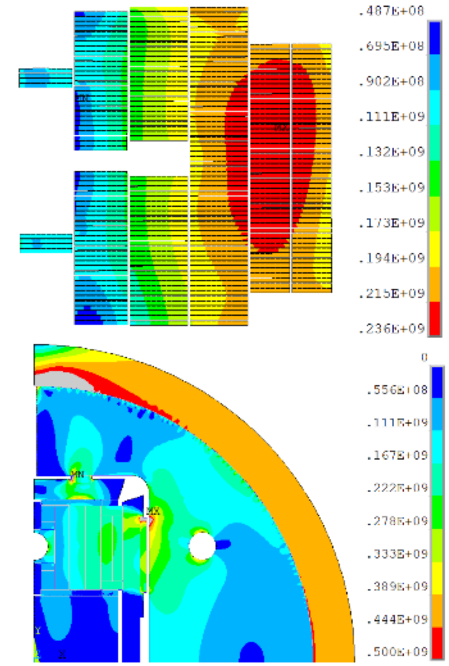
Integrated b_n & a_n	Value (10^{-4})
b3	0.14
b5	1.42
b7	-0.40
a2	-0.29
a4	-1.81
a6	0.03

Conceptual Design of the 20T Dipole



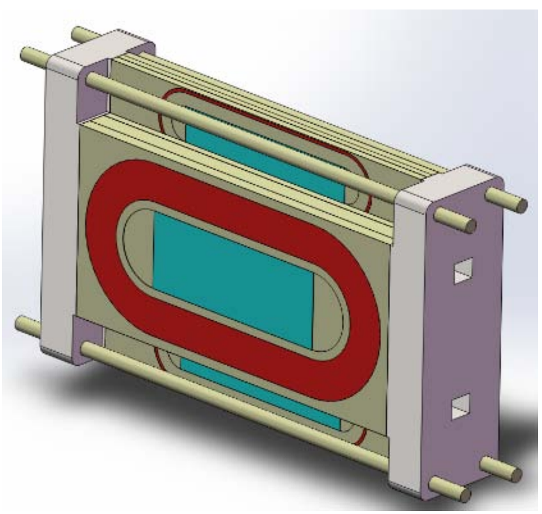


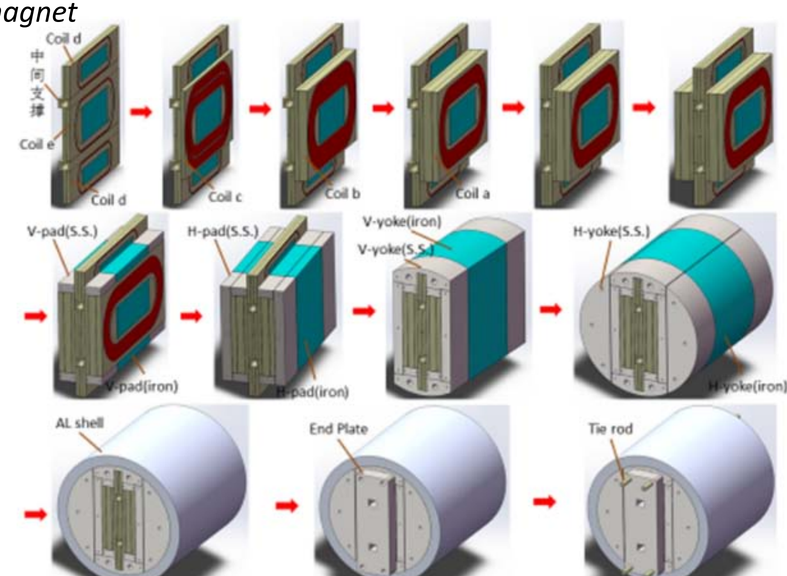
Lorentz force per aperture:
Fx=23.4 MN/m ; Fy=2.38 MN/m

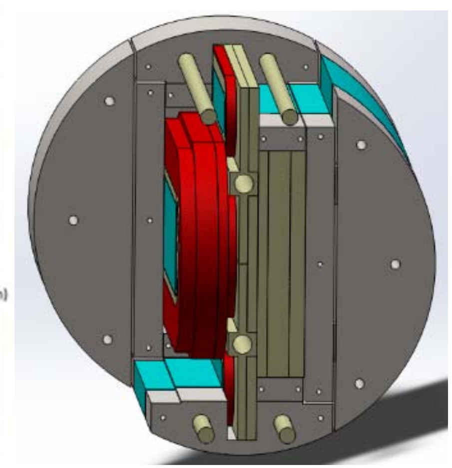


2D & 3D structure of the 20T dipole magnet

Stress distribution after excitation





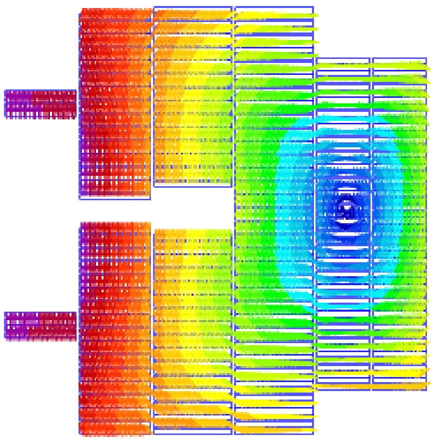


Conceptual Design of the 20T Dipole

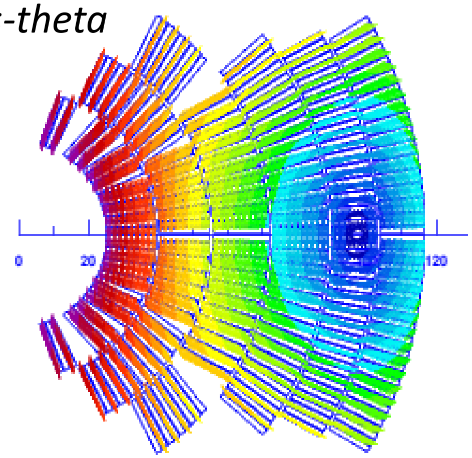
Comparison of different coil configurations

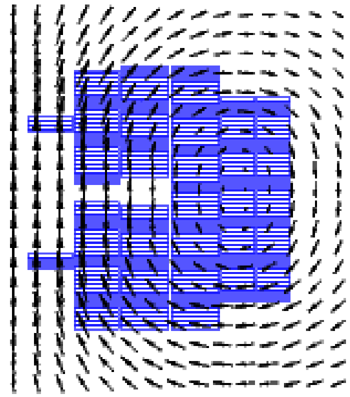
Common coil vs Cos-theta

Common coil



Cos-theta



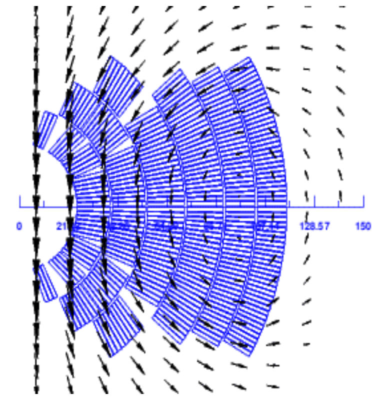


Common coil

Different coil configurations for 20-T dipole magnet

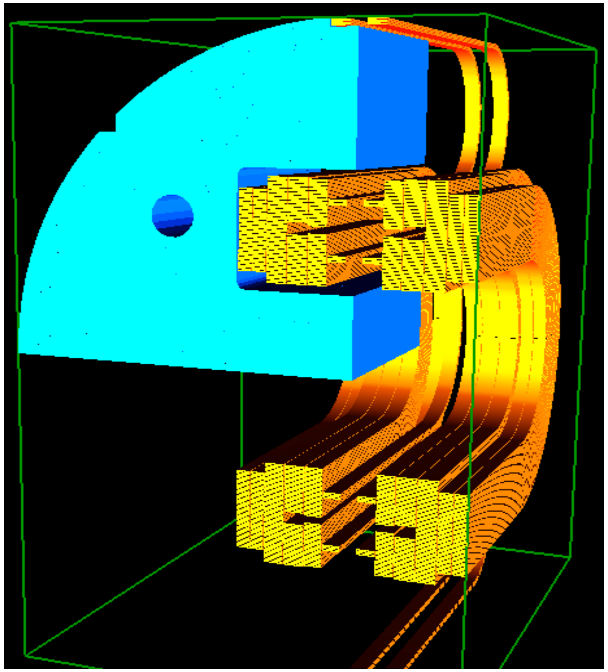
Left: Common coil

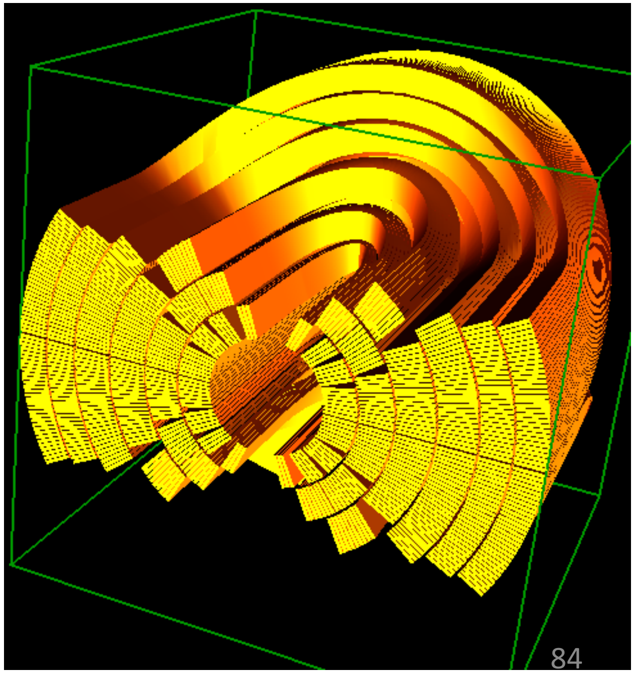
Right: Cos-theta



Cos-theta

Coil ends





SPPC vs. FCC

High Energy Circular Colliders for next decades		
Proposed institution	IHEP-CAS, China	CERN, Europe
Proposed dates	2012	2014
Site of the project	In China	Geneva
Baseline technology	IBS 12~24T to reach 75-150 TeV Nb_3Sn etc as options	Nb_3Sn 16T to reach 100 TeV
Timeline	2040s for construction	2050-60s for construction
Cost	*	**

All-HTS 20+ Tesla Accelerator Magnet?

- **Precondition (Iron based conductor, ReBCO, Bi-2212,…)**
  - The Je of the HTS conductors is high enough for accelerator application
  - The cost is lower than or similar with the LTS conductors
  - Mechanical performance is qualified

- **Main challenges of the HTS technology**
  - Quench protection： quench propagation speed of HTS conductors is about two orders of magnitude lower than the LTS case
  - Cable fabrication： how to fabricate high-current cable with tapes?
  - Coil layout： compact, high efficiency, stress control, …
  - Field quality control： 10^{-4} field uniformity needed for accelerators

- **Advantages of the all-HTS magnet：**
  - Possibility of raising the operation temperature of the magnet（4.2K -> ?K）

Outline

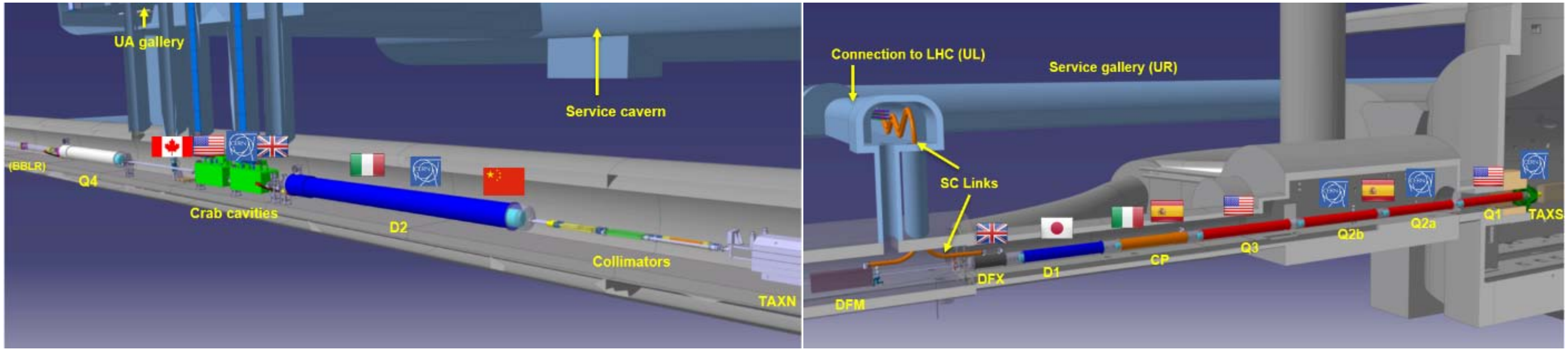
- **Fundamental Principles of the Superconducting Accelerator Magnets**
  - PRINCIPLES of Particle Accelerators
  - CHARACTERISTICS and MAIN CHALLENGES of the Superconducting Accelerator Magnets

- **Case Study**
  - Progress of the High Field Magnet R&D at IHEP
  - Progress of the HL-LHC CCT Magnets

China-CERN HL-LHC CCT Project

China provides 12+1 units CCT superconducting magnets for the HL-LHC project

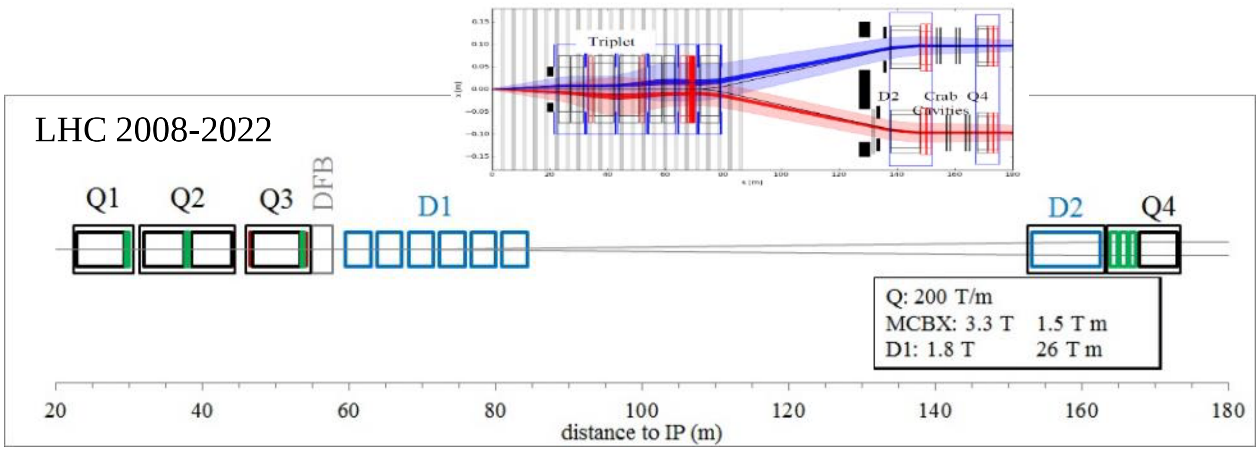
Agreement For HL-LHC CCT Magnets Signned in Sep 2018

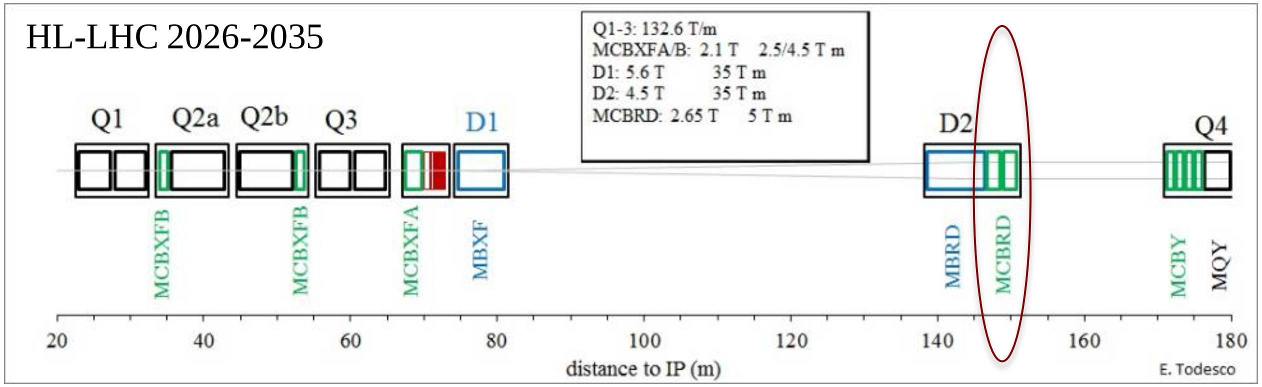


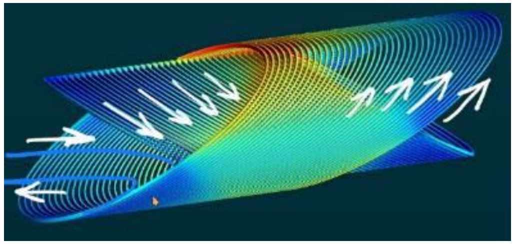
Layout of the HL-LHC Magnets and Contributors

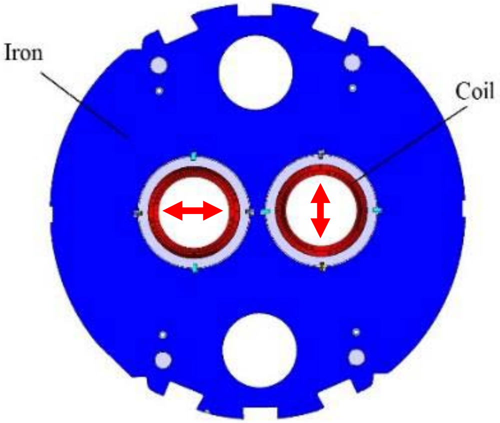
China-CERN HL-LHC CCT Project

MCBRD: the HL-LHC orbit correctors, providing a maximum 5 Tm integrated field in two apertures, vertical in one and horizontal in the other.



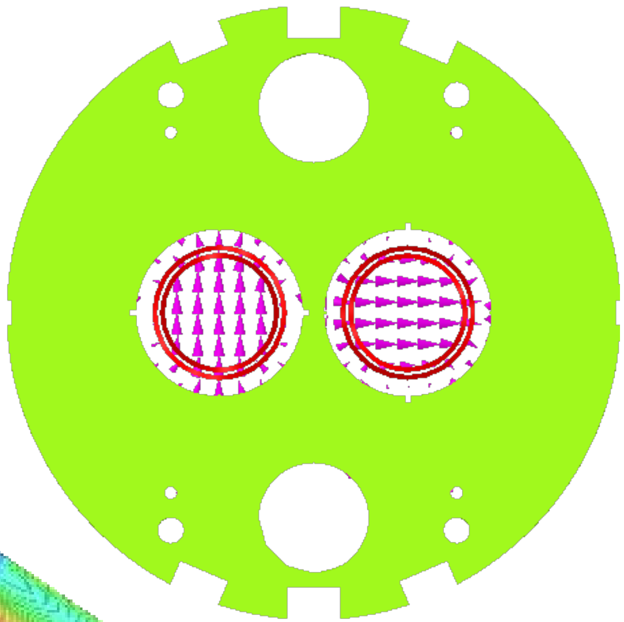


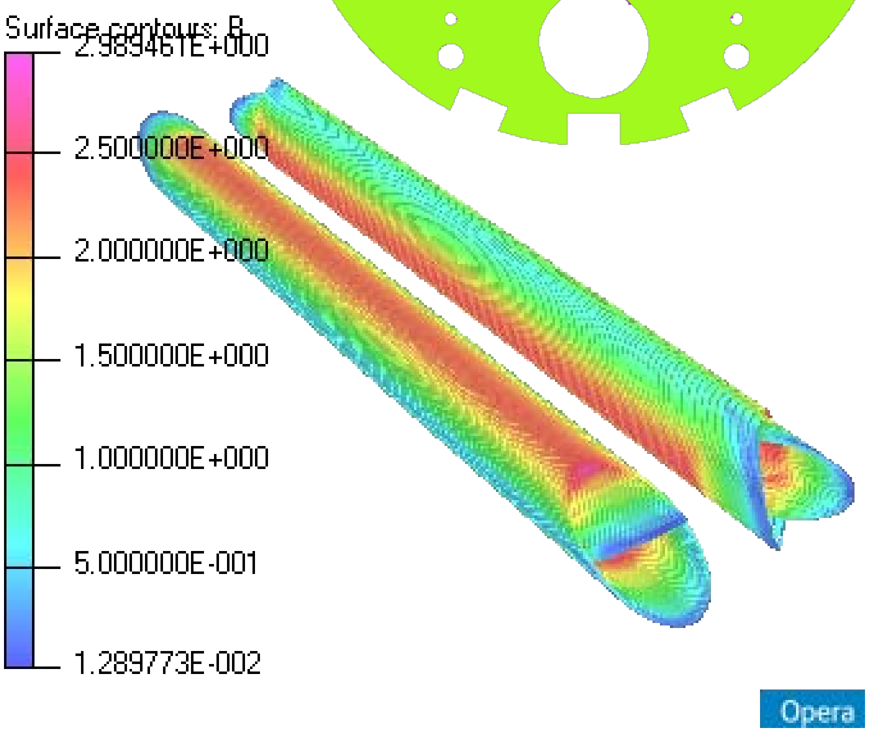


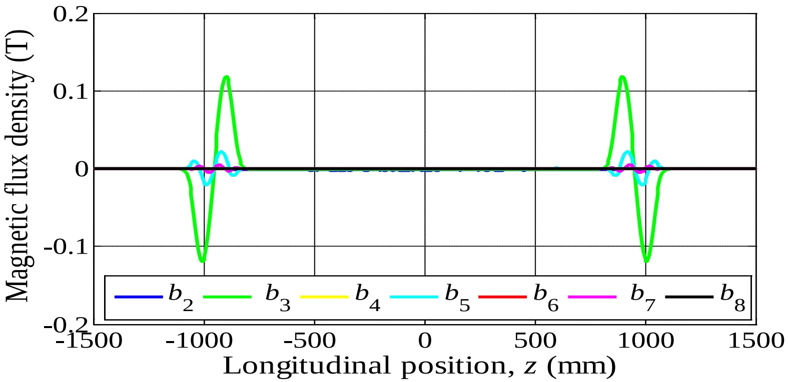


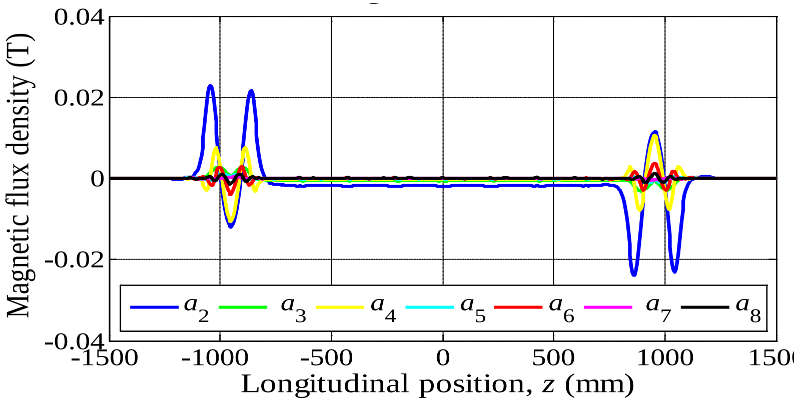
E. Todesco

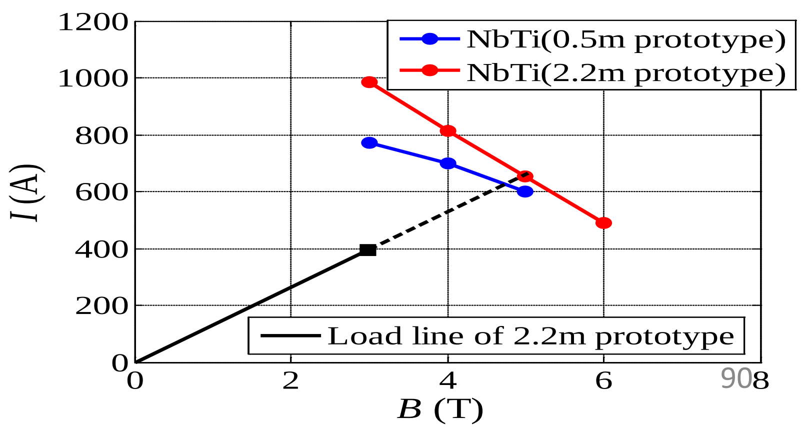
China-CERN HL-LHC CCT Project





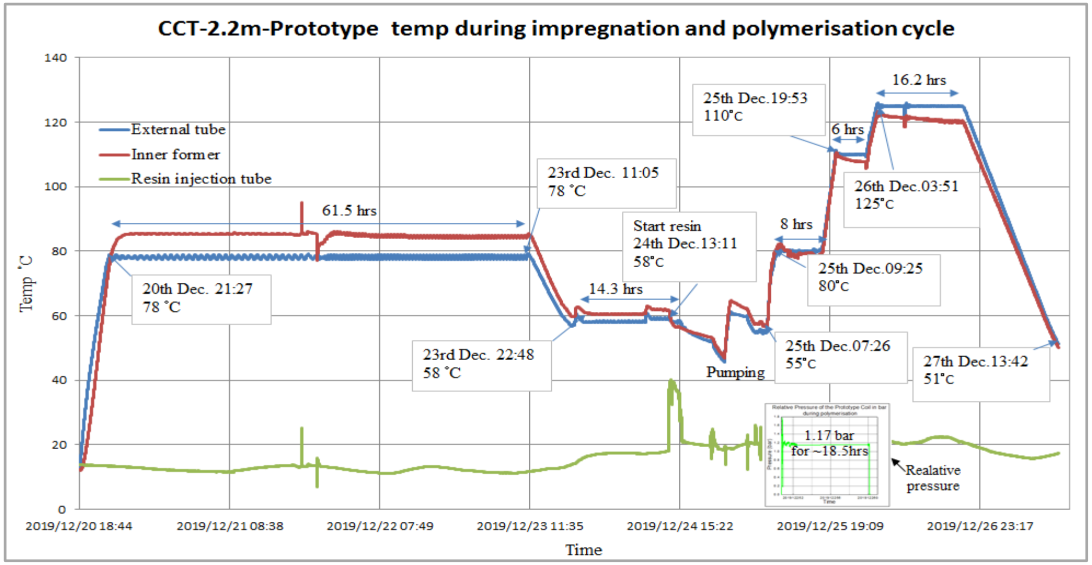


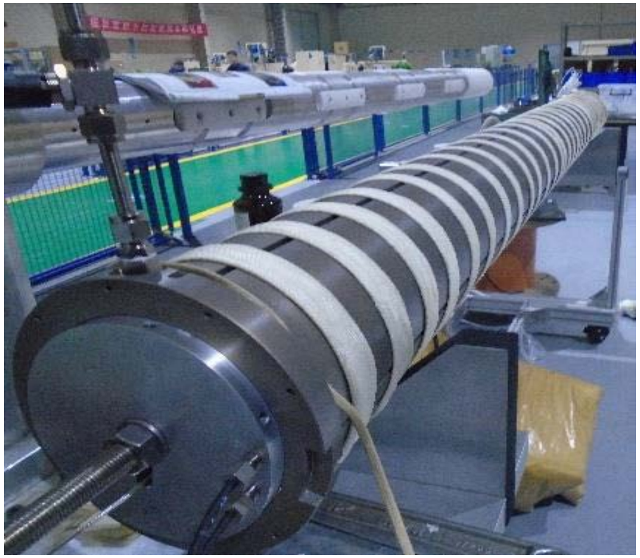


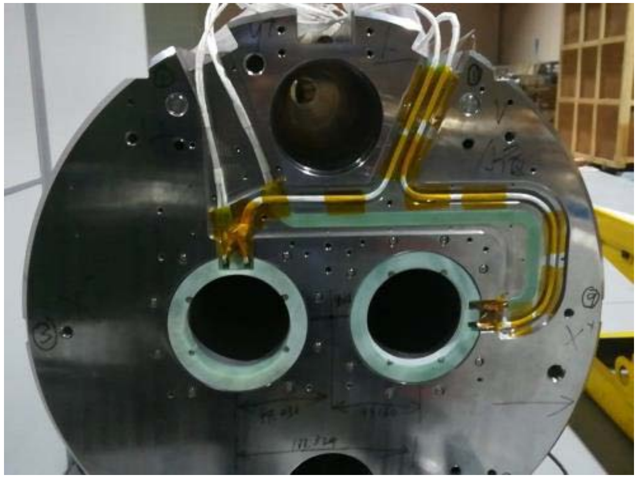


China-CERN HL-LHC CCT Project

Coil fabrication and Magnet Assembly

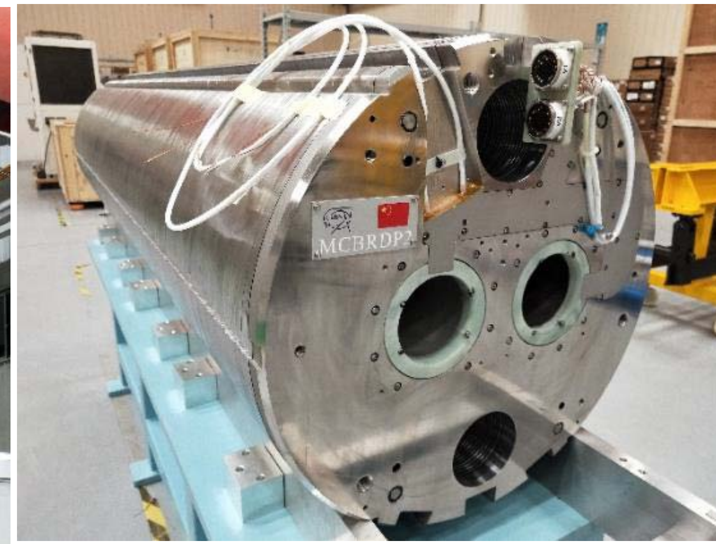






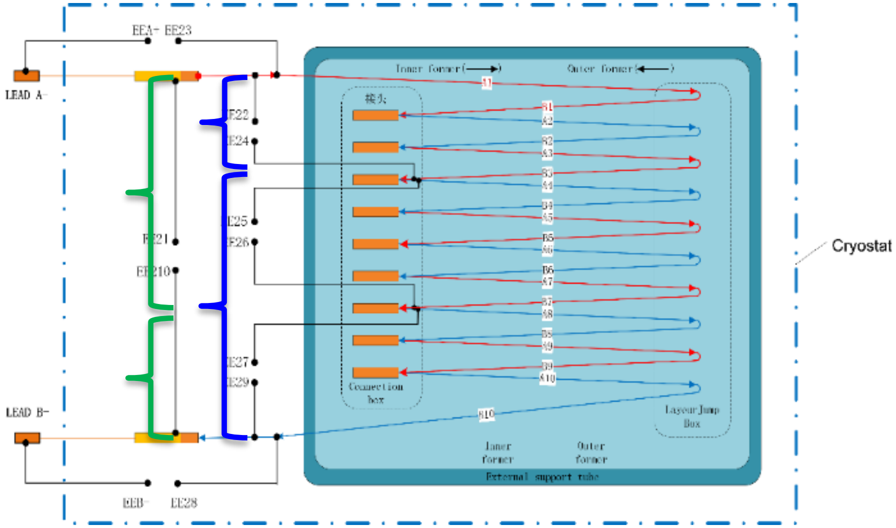
China-CERN HL-LHC CCT Project

Cold test at IMP



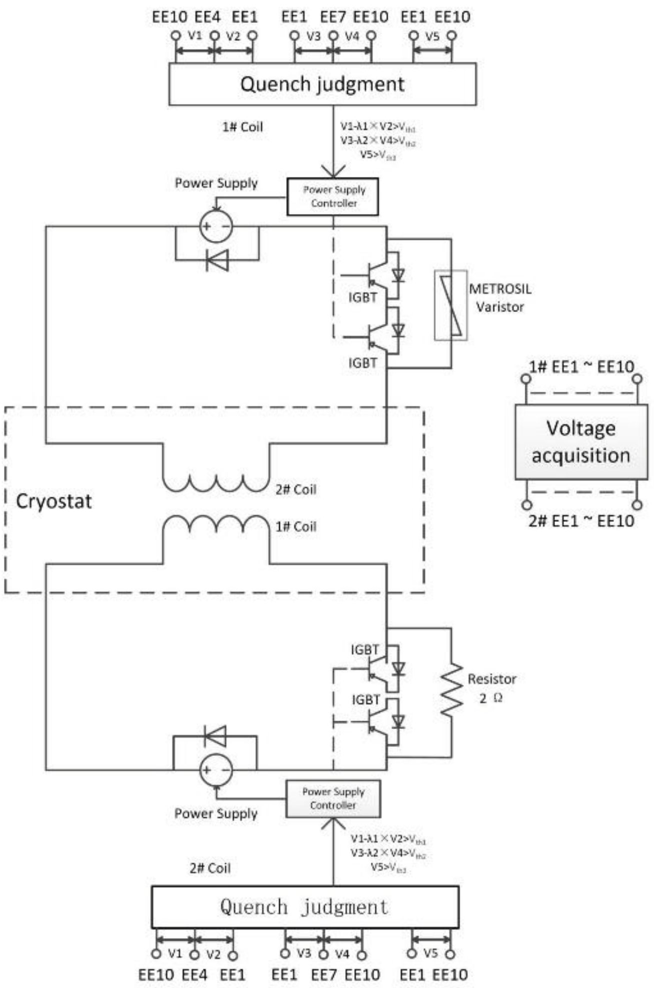
China-CERN HL-LHC CCT Project

Cold test at IMP



Quench detection

Metrosil varistor

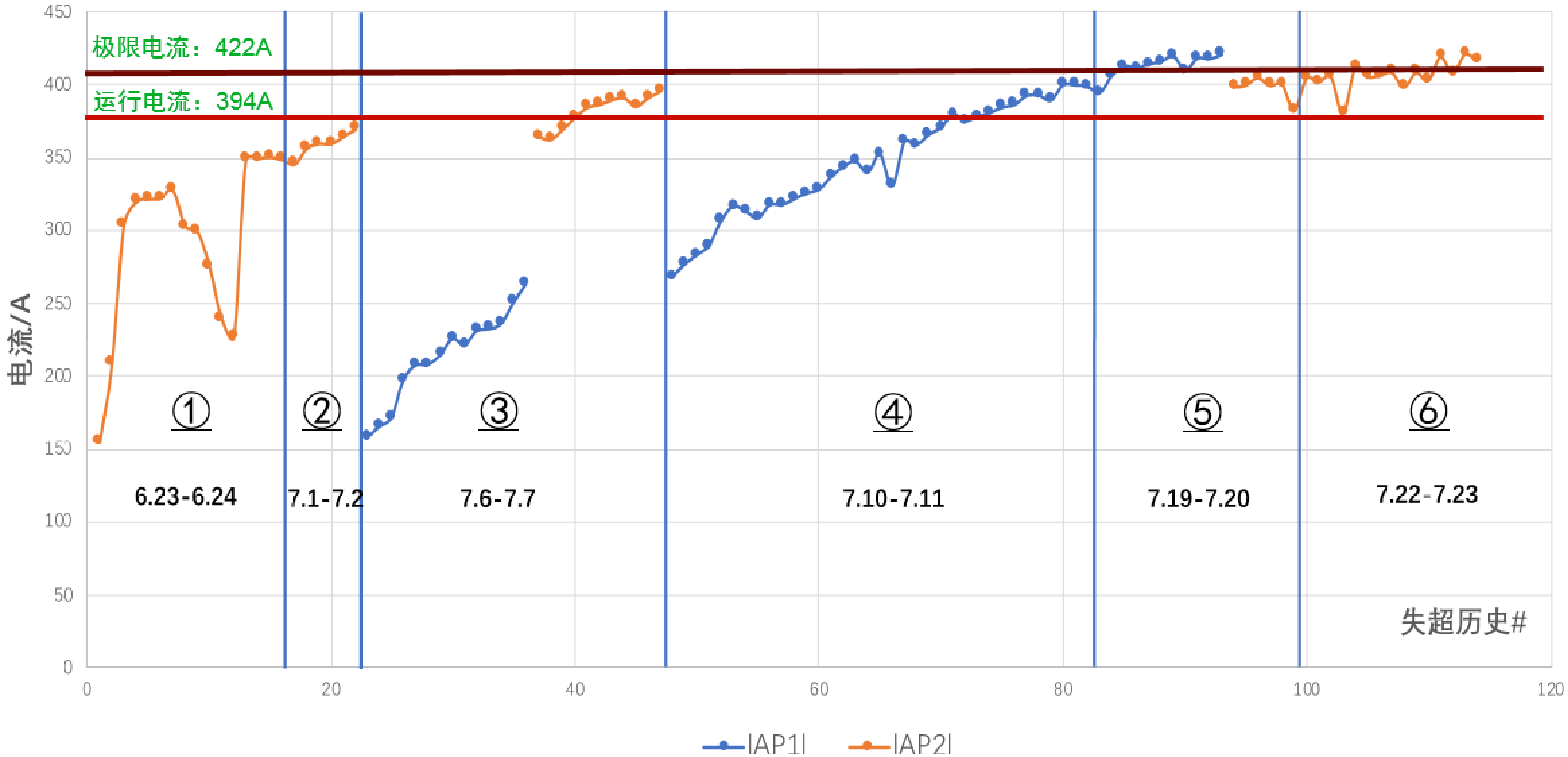


Quench protection scheme

China-CERN HL-LHC CCT Project

Cold test at IMP

After more than 1 month test and training at 4.2K, both apertures reached the design current and ultimate current, and the field quality is within the limit!



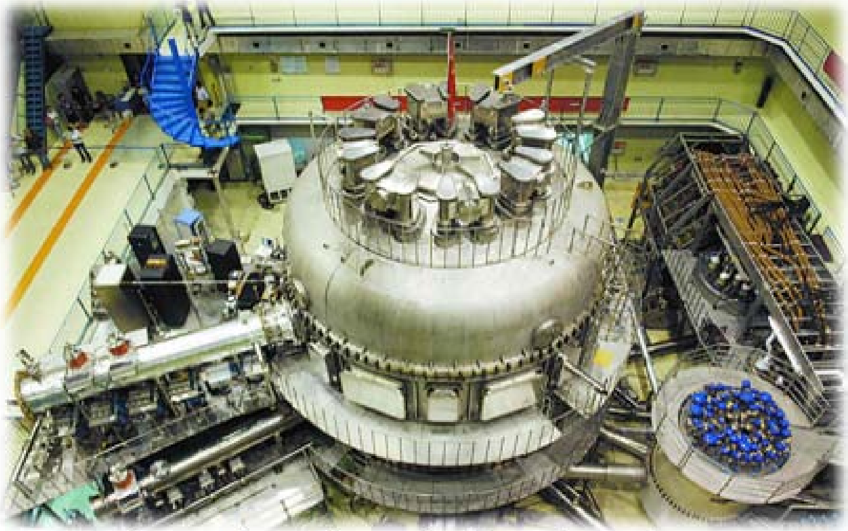
<u>A good start for the next series production!</u>

Summary of the 2nd Section

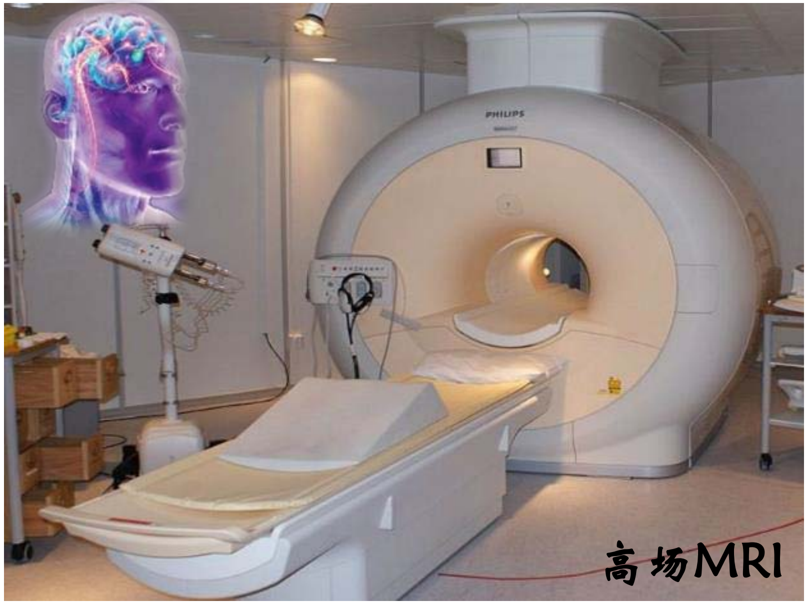
- *Advanced high field magnets are most crucial components for high energy circular colliders and accelerators.*
- *Strong domestic collaboration for the advanced superconductor R&D (HTS & Nb_3Sn): raising performance & lowering cost.*
- *Very good performance of the 1st IBS solenoid coil tested at 24T and the 1st IBS racetrack coil tested at 10T.*
- *10T+ model dipole magnets being developed at IHEP, aiming 16T (Nb_3Sn+HTS) in 3 years, and 20T in 10 years.*
- ***China & CERN Collaboration on accelerator technology:** started with HL-LHC CCT magnets, to be expanded in future.*

Application fields of Superconductivity

LHC的粒子加速器



合肥 先进实验超导托克马克

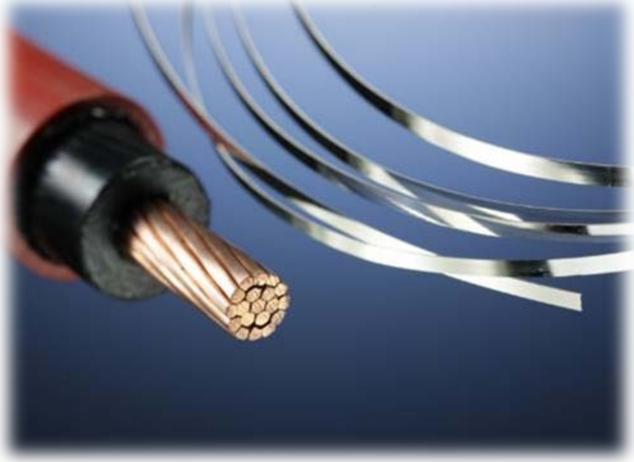


高场MRI

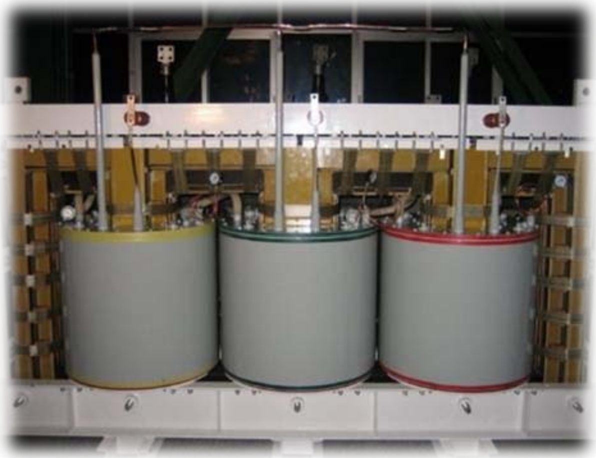
日本超导体磁悬浮列车试运行 最高时速505公里

2013年09月02日10:53

计划于2027年开通运行的日本Linear中央新干线于29日在山梨县内进行了长达42.8公里的试运行，试行车辆为超导磁悬浮原型车L0。



超导线缆/带材

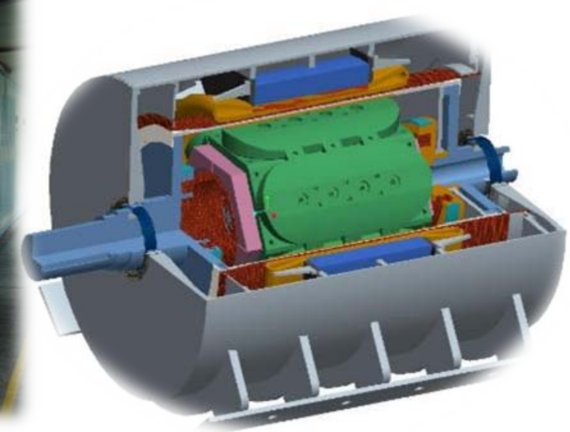


超导变压器

超导发电机

超导限流器

超导储能系统



超导电动机

Thanks

Questions and Discussions