Technology challenges: Superconducting accelerator magnets
PART II/II

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Summer Student Lecture

Thanks to many colleagues, in particular Paolo Ferracin for the material they have given to me

Part II/II

Part I

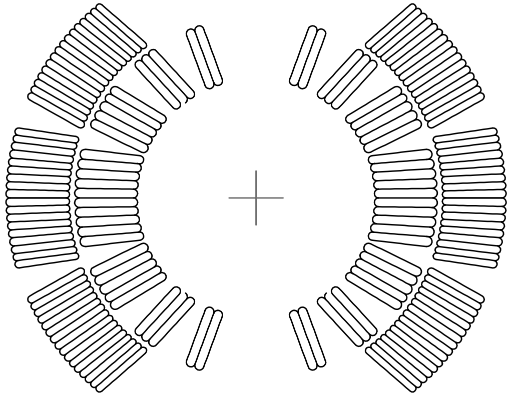
- Superconductivity
- Electromagnetic coil design
- Coil manufacture

Part II

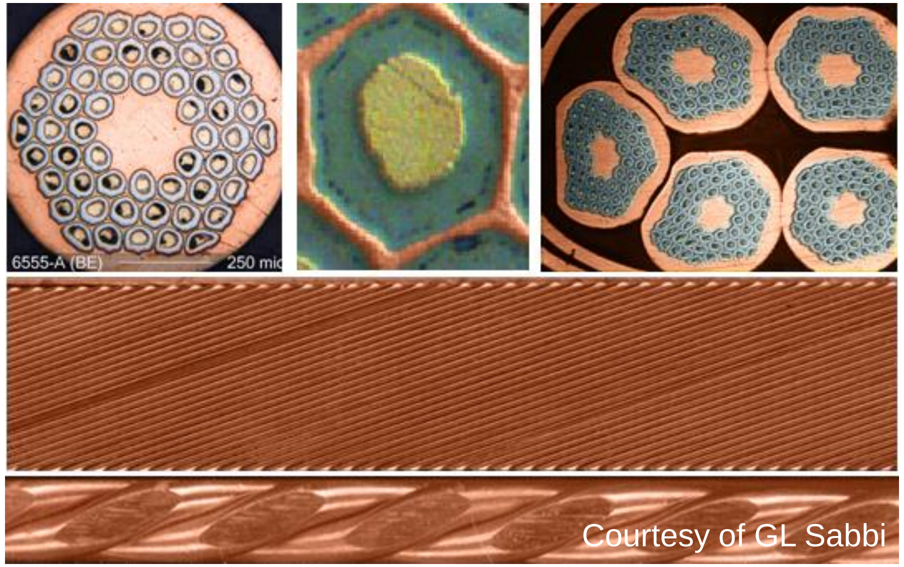
- Margins and quench protection
- Structural design and assembly
- Testing
- Outlook, what brings the future?

Recap from last lecture

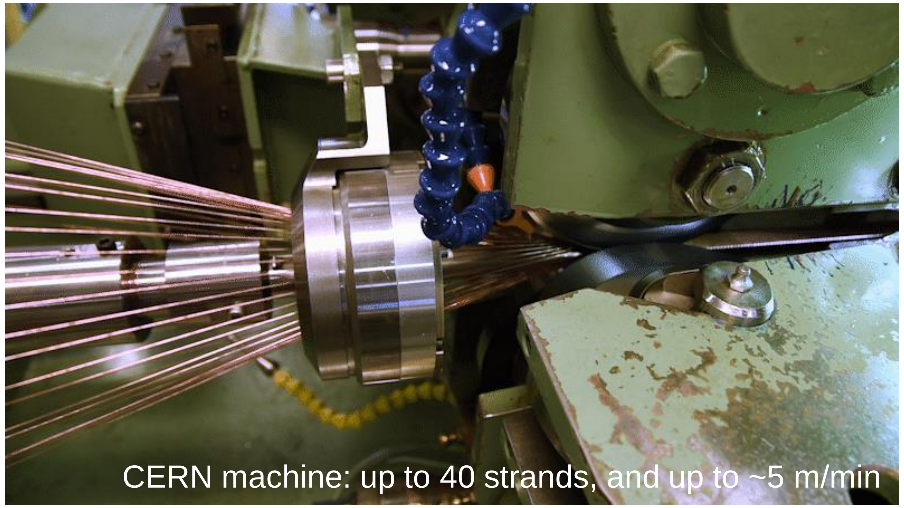
- Technical low-temperature superconductors (Nb-Ti, Nb_3Sn) are multifilamentary wires
- Rutherford cables are made of typically out of ~30-40 wires
- Insulation: polyimide (Nb-Ti), S2-glass/mica (Nb_3Sn)
- Electromagnetic coil design to optimize the field quality



LHC



Courtesy of GL Sabbi



CERN machine: up to 40 strands, and up to ~5 m/min

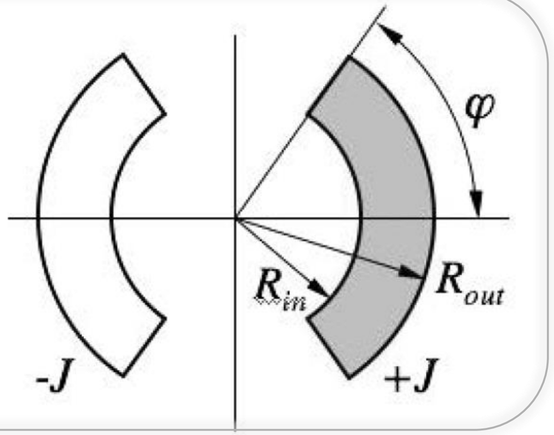
Recap Magnet design

The field can be expressed as (simple) series of coefficients
So, each coefficient corresponds to a "pure" multipolar field

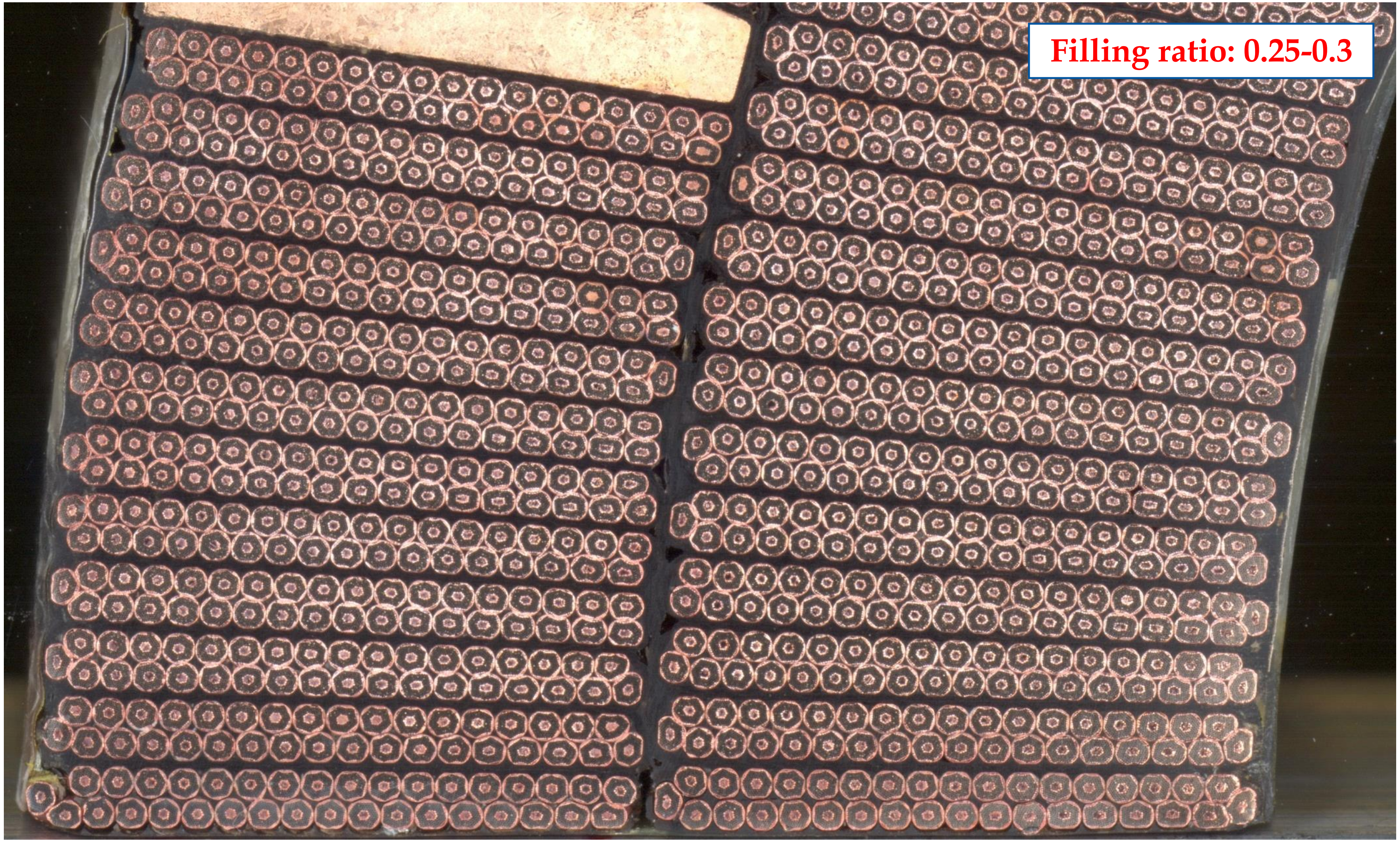
Dipole

$$B_1 = \frac{2\mu_0}{\pi} J(R_{\text{out}} - R_{\text{in}}) \sin\varphi = \frac{2\mu_0}{\pi} Jw \sin\varphi$$

$$B_n = \frac{2\mu_0}{\pi} J \frac{\left(R_{\text{out}}^{2-n} - R_{\text{in}}^{2-n}\right)}{n(2-n)} r_{\text{ref}}^{n-1} \sin(n\varphi)\,, n = 3, 5, 7, \ldots$$

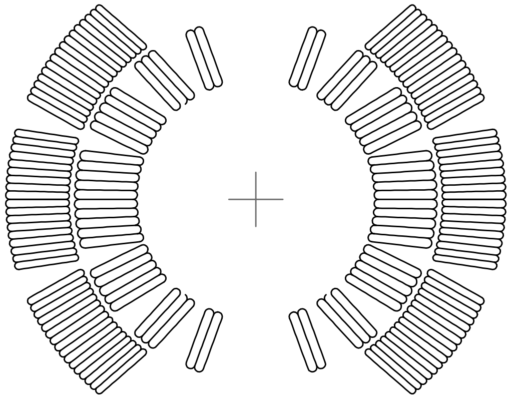


How much superconductor is in the cable?

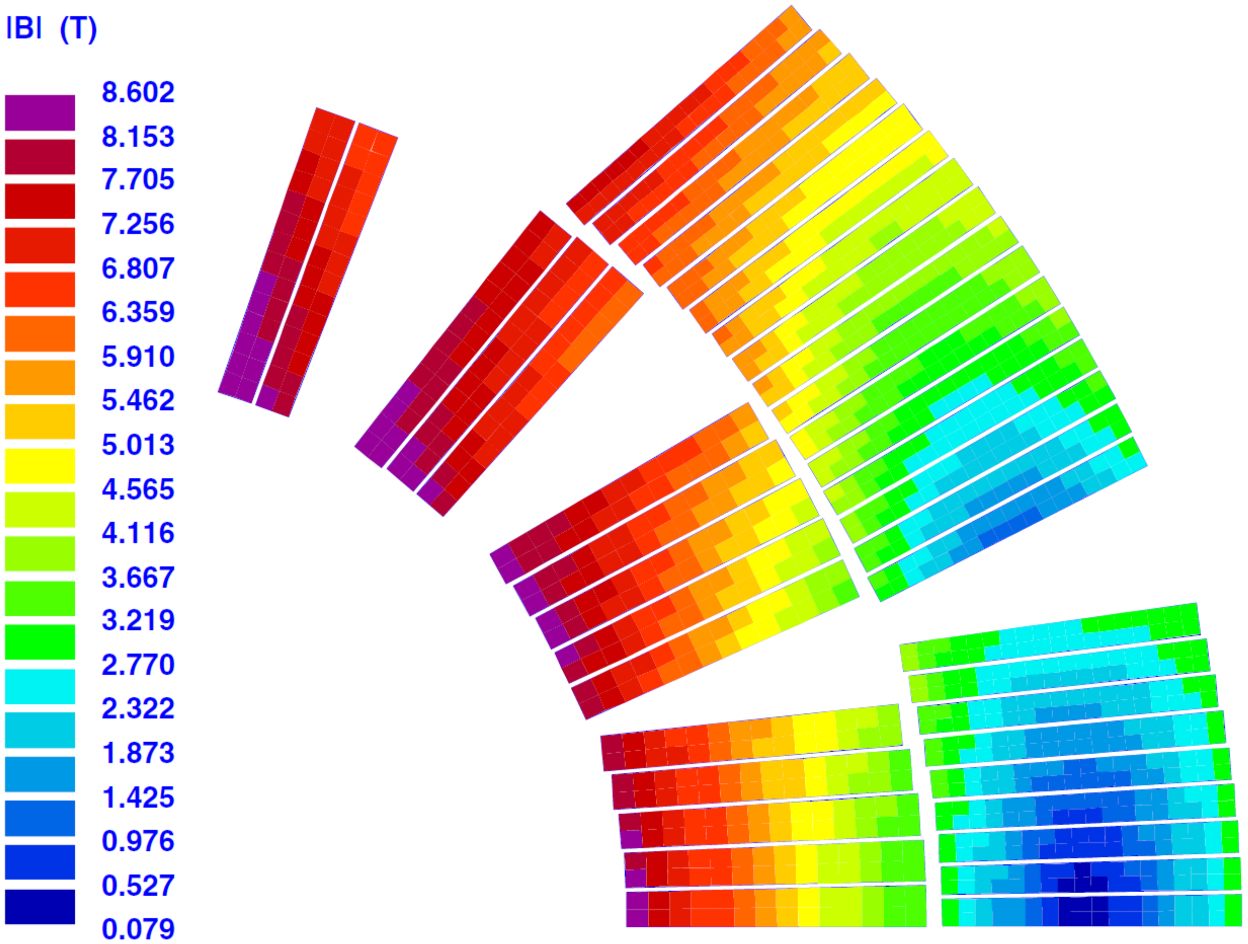


Filling ratio: 0.25-0.3

How to select the *J* in the coil?



LHC



- LHC main dipole at nominal operation: B_{op} = 8.33 T, I_{op} = 11 850 A, J_{eng} = ~450 A/mm^2

How to select the *J* in the coil?

Why margins?

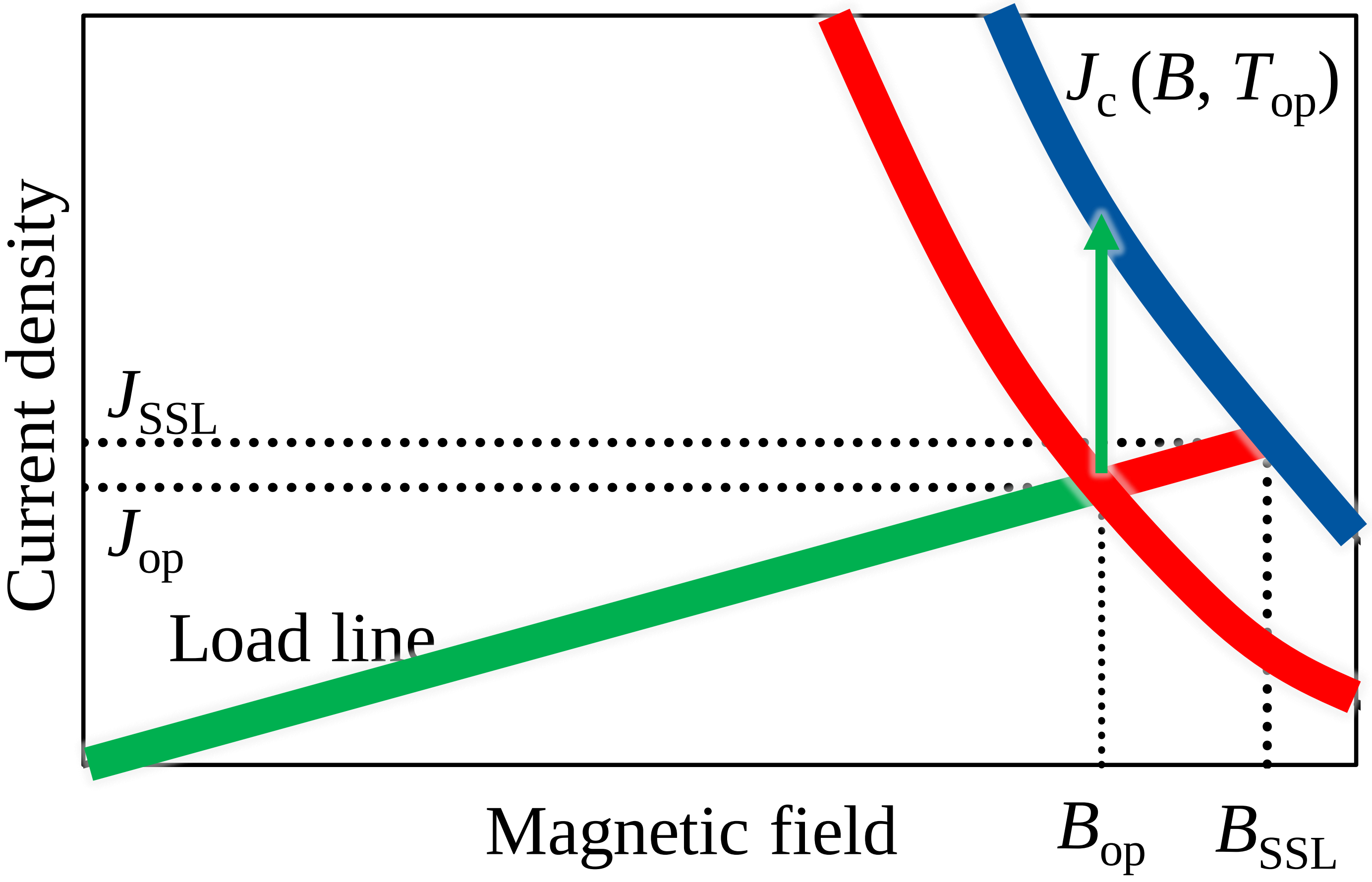
- Reach design field
- Limit number of training quenches
- Avoid quenches during operation

Margins:

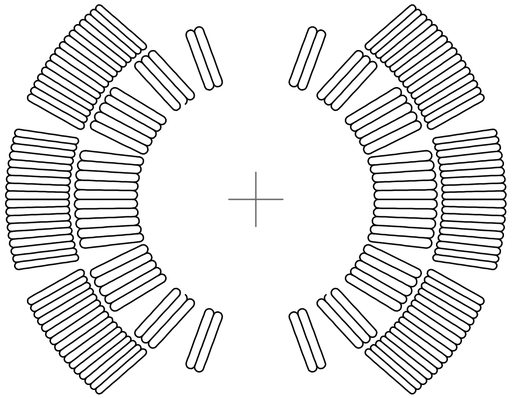
- Load line margin
- Temperature margin
- Current margin

How to select the margins? Typically, designs are done for load line margin (LHC & FCC: 14%)

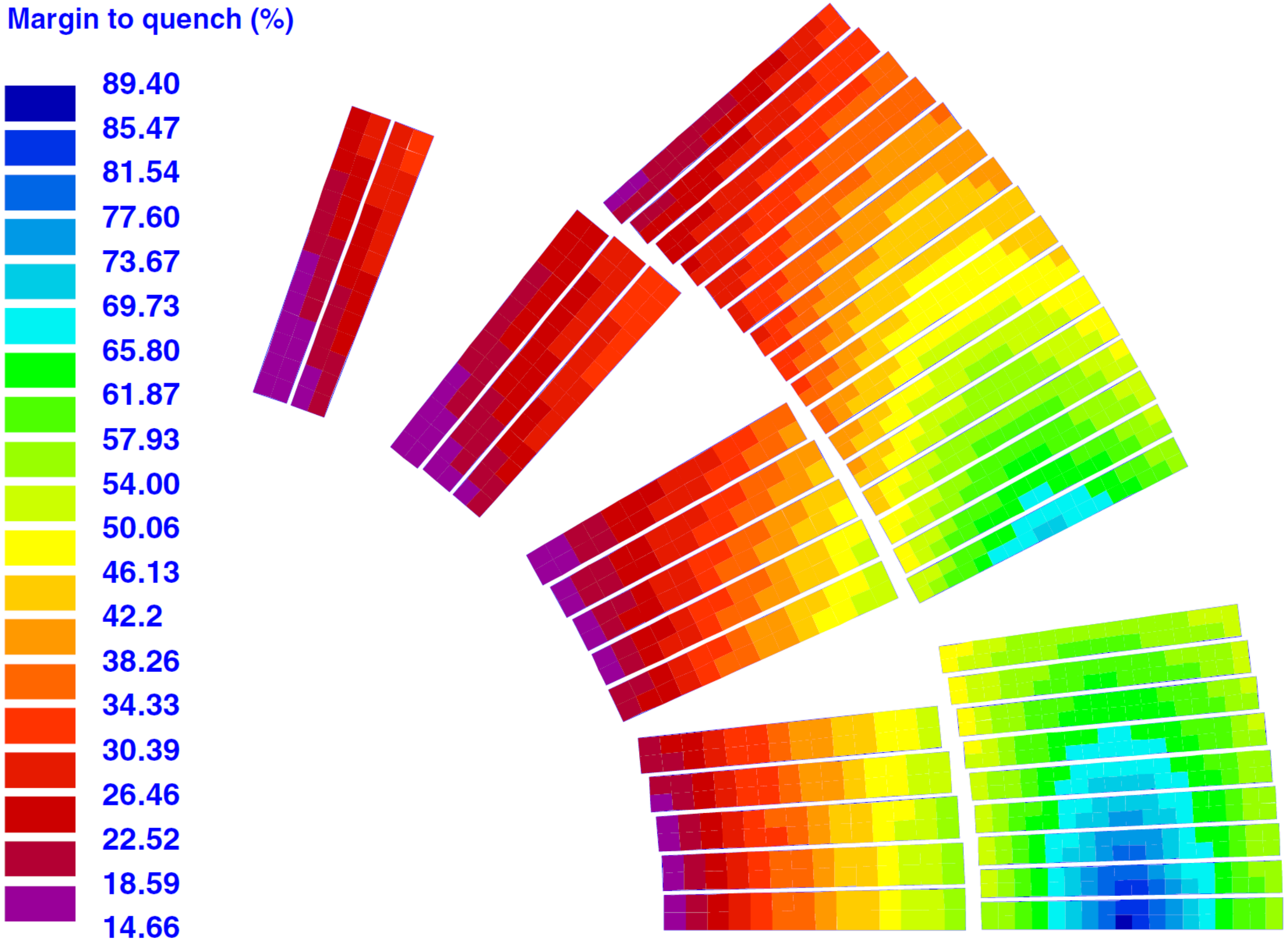
How is it selected? Empirically: long discussions and many prototypes!



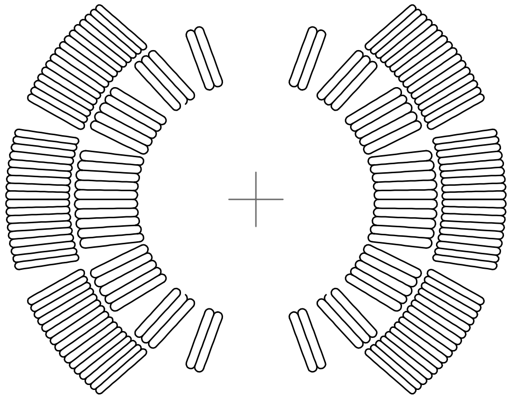
Margin on the load line



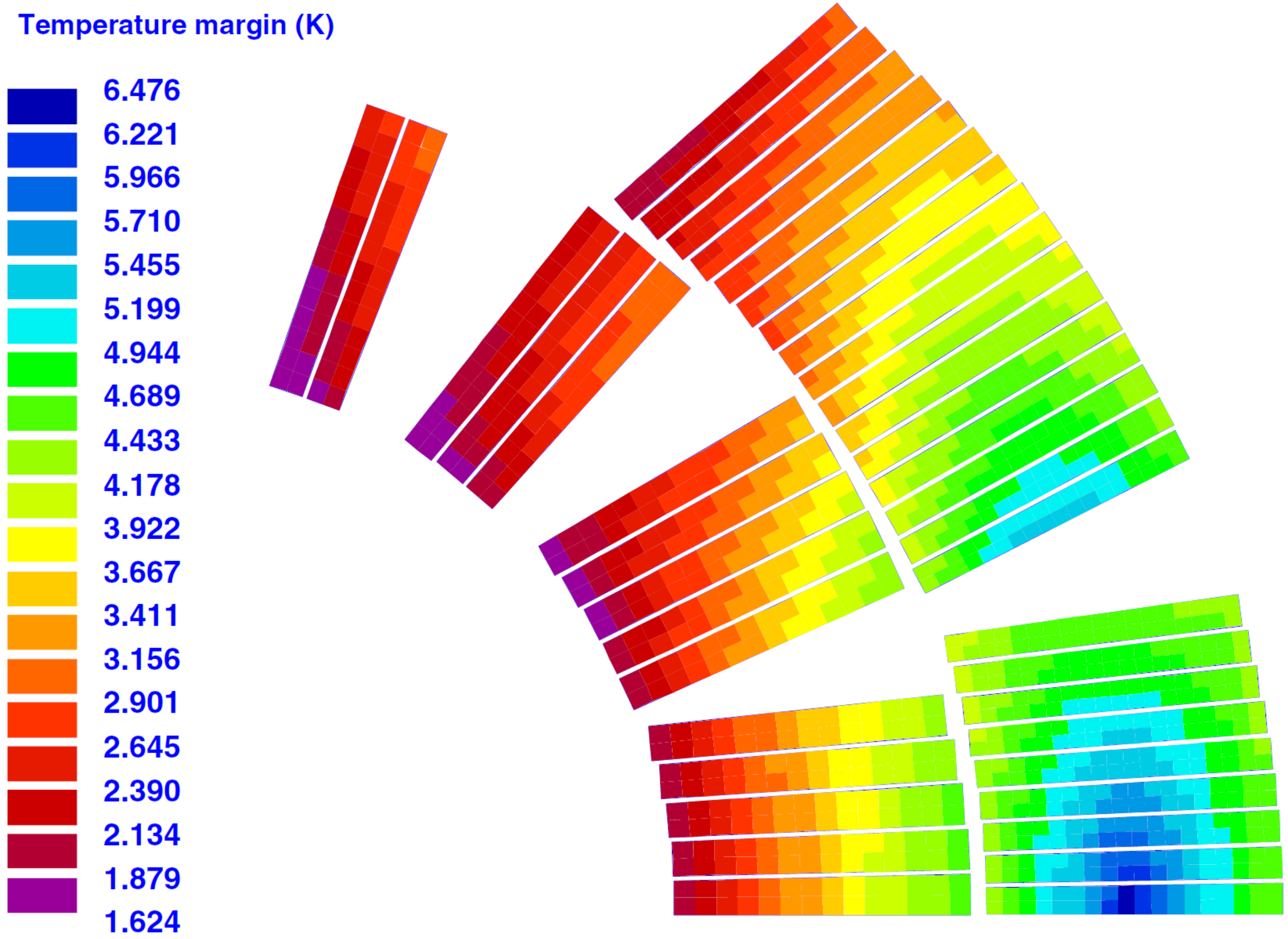
LHC



Temperature margin

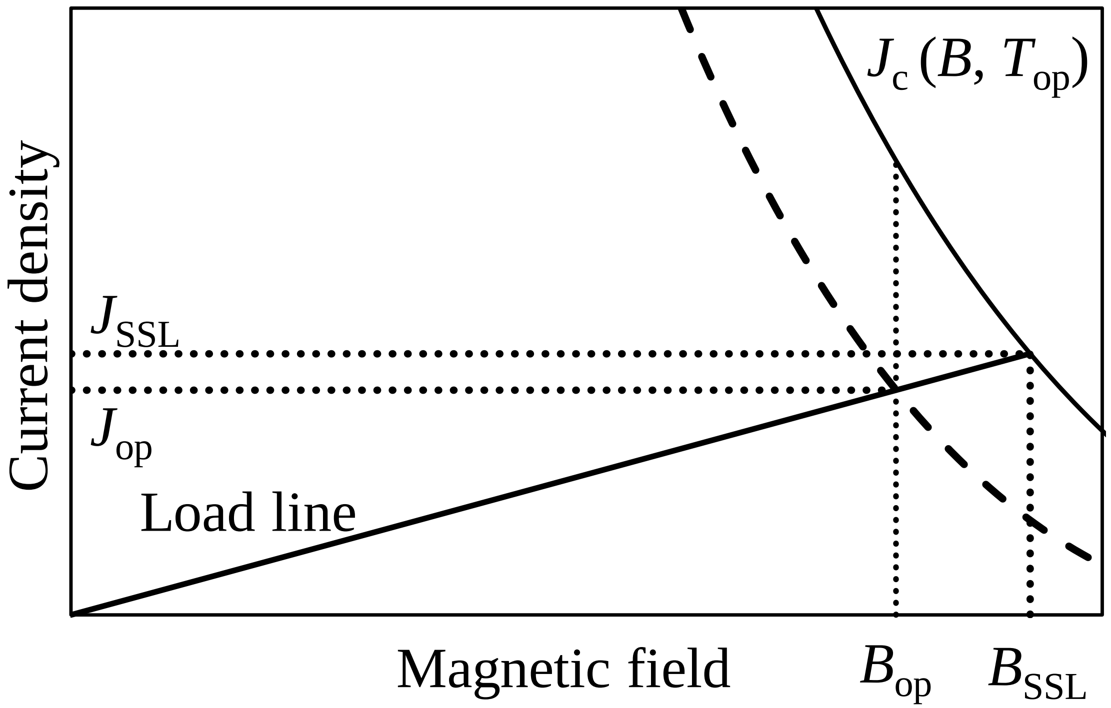


LHC



Coil design

Question: A magnet shall reach a bore field of 16 T with a load line margin of 14% (example of FCC). What is the field this magnet could potentially reach?

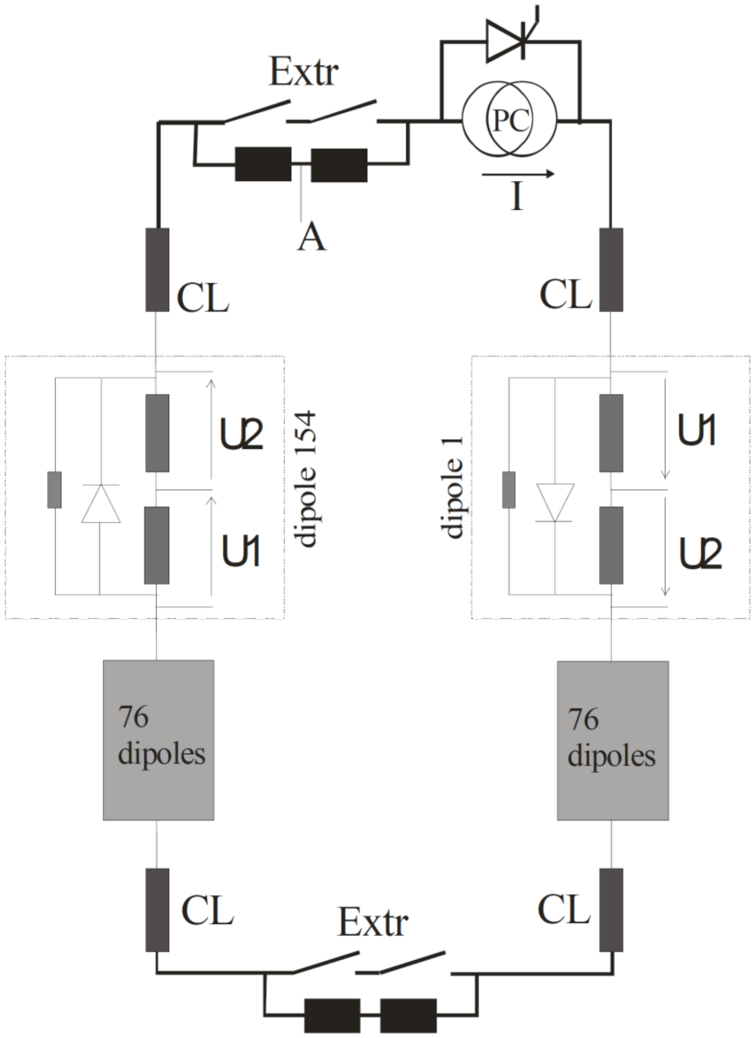


Circuit protection

- LHC MBs are powered in 8 sectors, each with 154 MBs
- The stored energy is 1.1 GJ:

→Corresponds to the kinetic energy of a fully loaded jumbo jet at start

$$E_m = \int_V \frac{B^2}{2\mu_0} dv = \frac{1}{2} L I^2$$



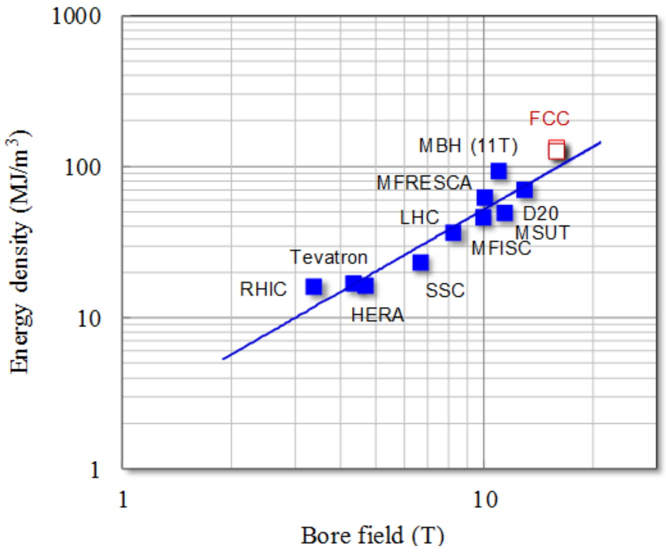
Magnet quench protection

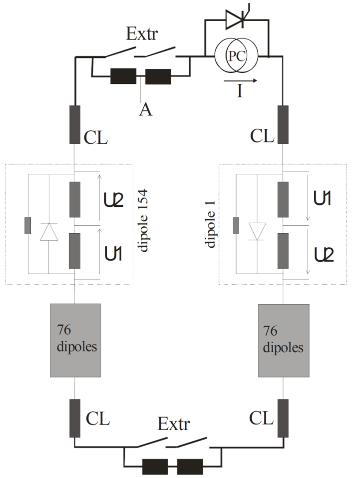
- In case a quench occurs, the stored energy does not allow to be extracted within the required time (few tens of ms): too large voltages (several kV-MV, depending on the circuit) would be required

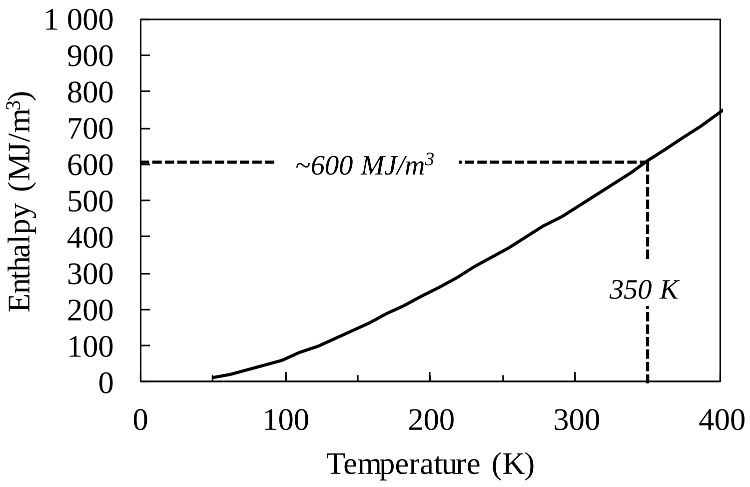
  $U = L\,dI/dt$ (LHC MB: L = 98.7 mH/magnet, I =11.85 kA)

  →A discharge in 0.1 s would yields a voltage of ~12 kV

- **Alternative:** stored energy is damped into the entire magnet by quenching it: upper theoretical limit can be calculated with adiabatic model

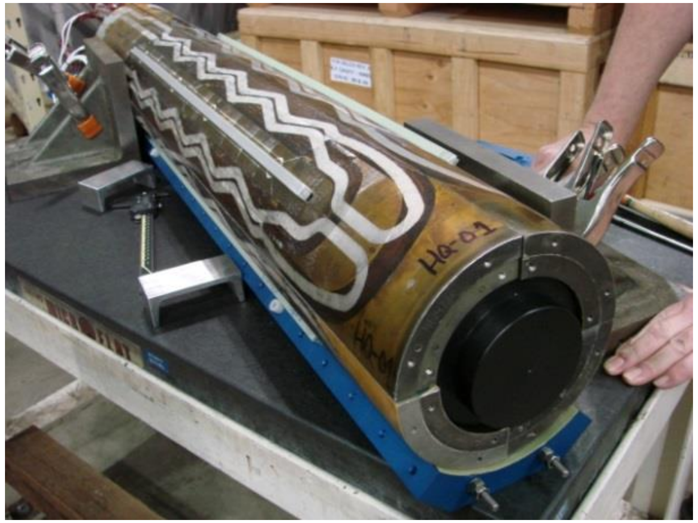






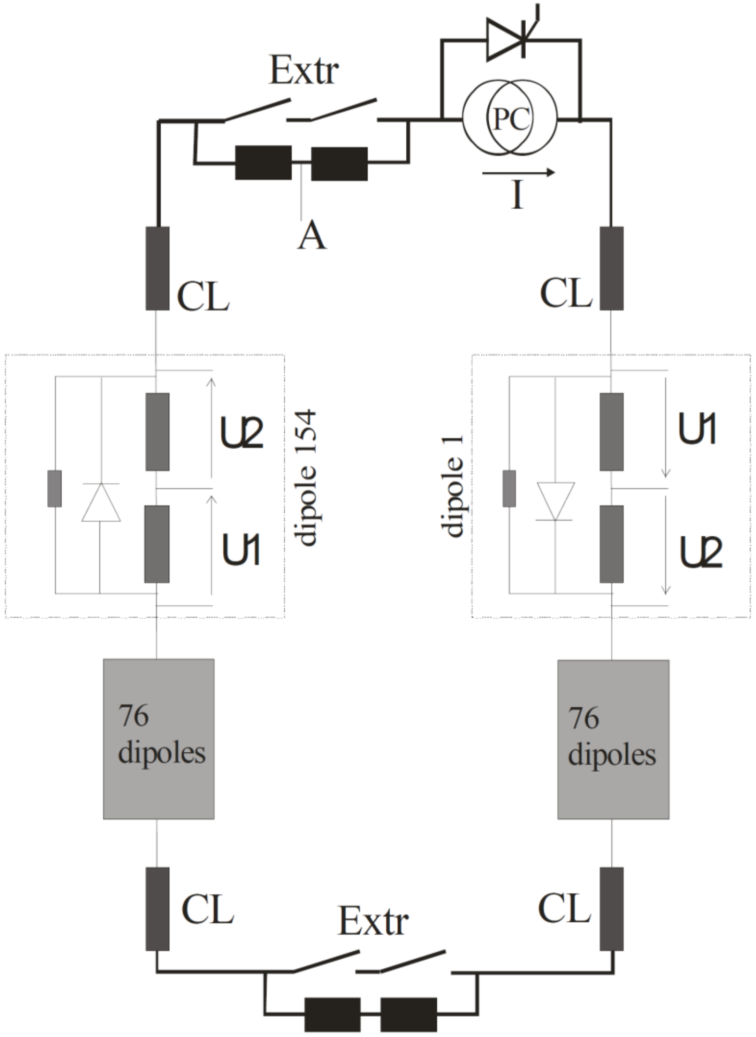
Quench heater

- In case a quench is detected, the magnet will be quenched (brought to normal conducting) within ~40 ms everywhere
- The final peak temperature for a given magnet depends on the time span to quench the magnet and the stored energy density



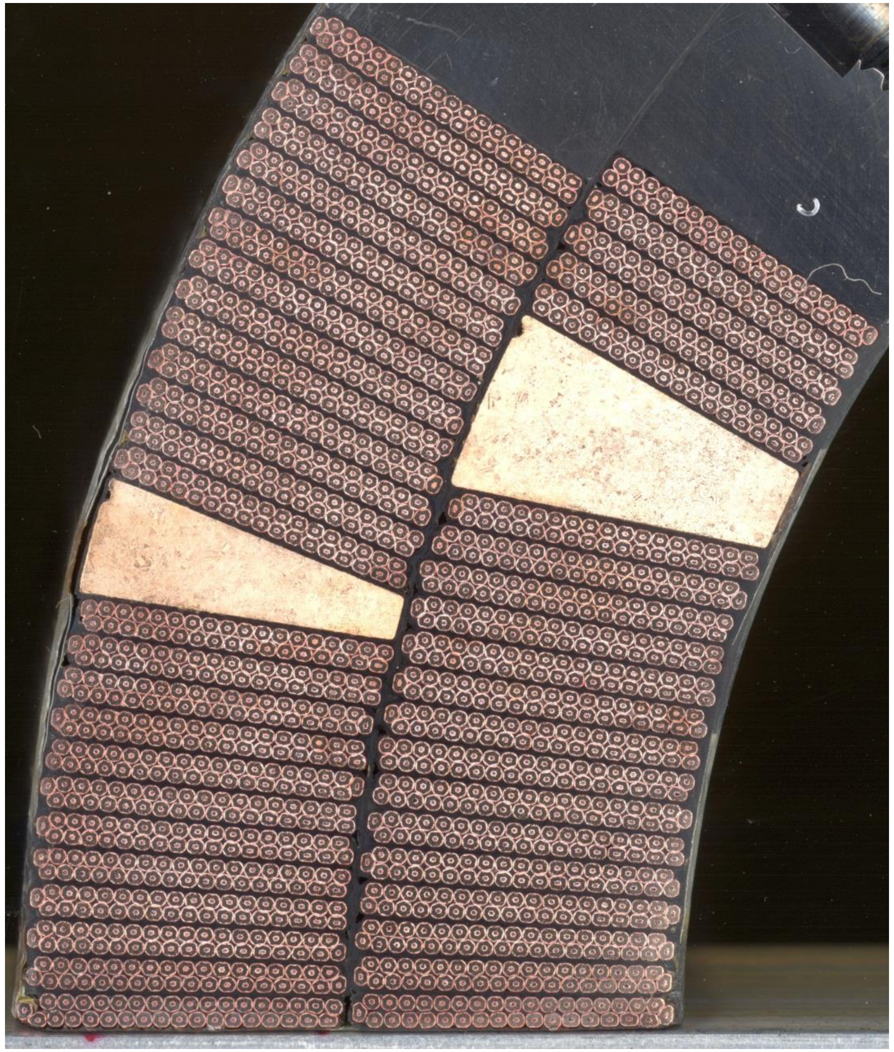
How to protect the magnets?

Which parameters determine the final temperature after quench of a magnet connected in series and operated at nominal field?



What is around the coils?

- How do keep the coils in place despite the large forces?
- How do we keep them cool?
- How we ensure that they perform well in the tunnel: testing!

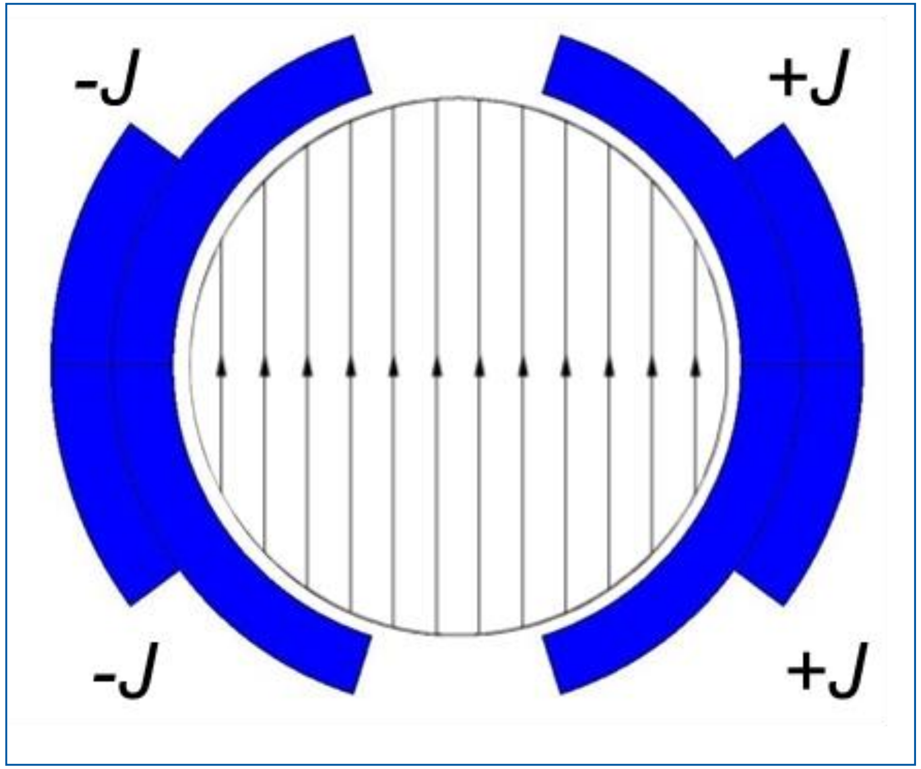


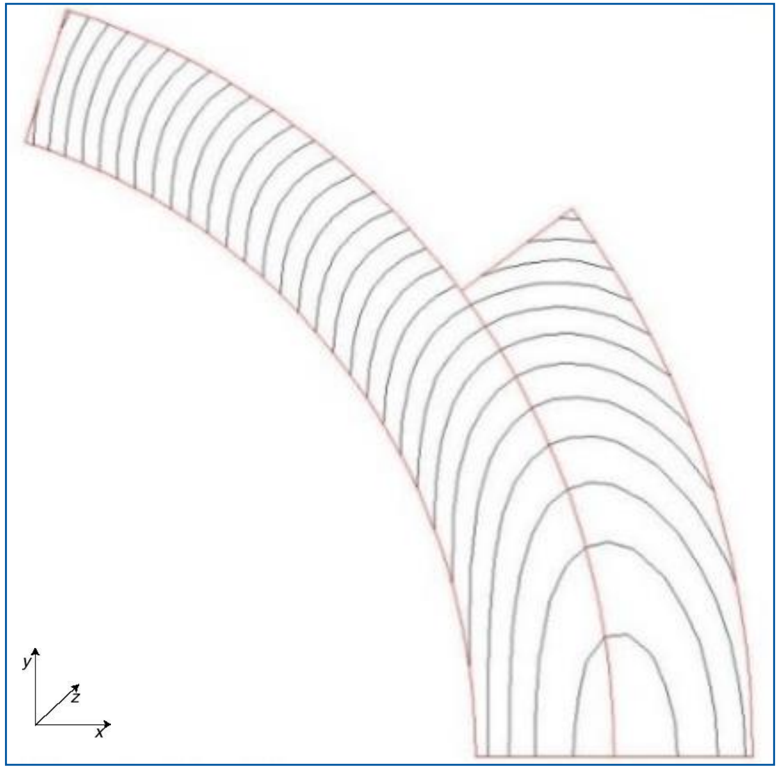
Mechanical structure

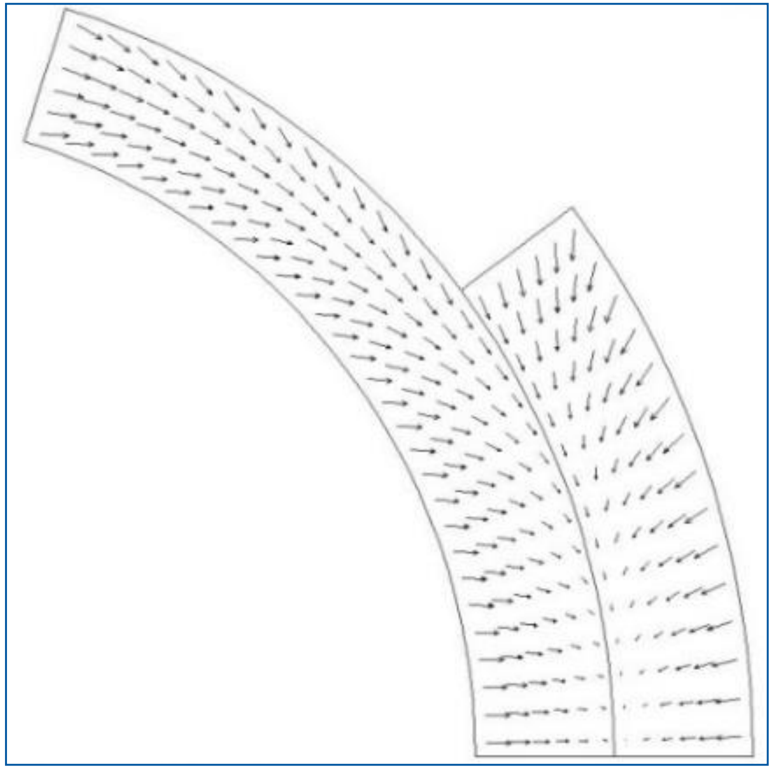
The e.m. forces in a dipole/quadrupole magnet tend to push the coil

- Towards the mid plane in the vertical-azimuthal direction (F_y , $F_\theta < 0$)
- Outwards in the radial-horizontal direction (F_x , $F_r > 0$)

$$F \propto B^2 a$$





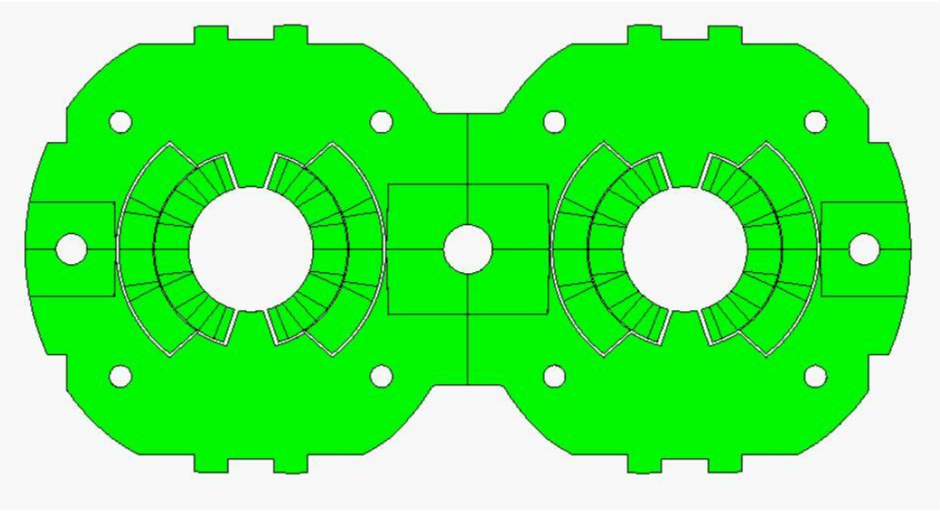


What to do to avoid movement and tensile stress?

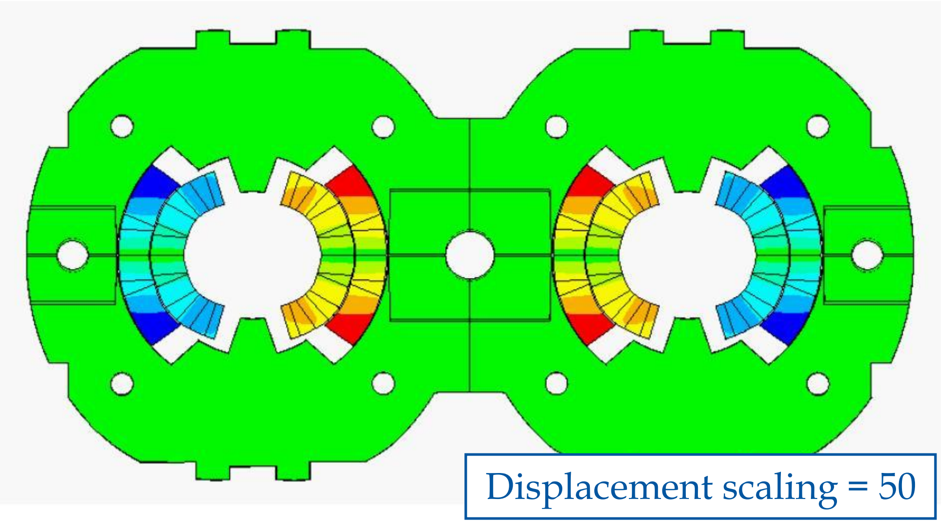
Effect of e.m forces

- change in coil shape: effect on field quality
- a displacement of the conductor: potential release of frictional energy
- Nb-Ti magnets: possible damage of polyimide insulation at~150-200 MPa.
- Nb_3Sn magnets: possible conductor degradation at about 150-200 MPa.
- All the components must be below stress limits.

LHC dipole at 0 T



LHC dipole at 9 T



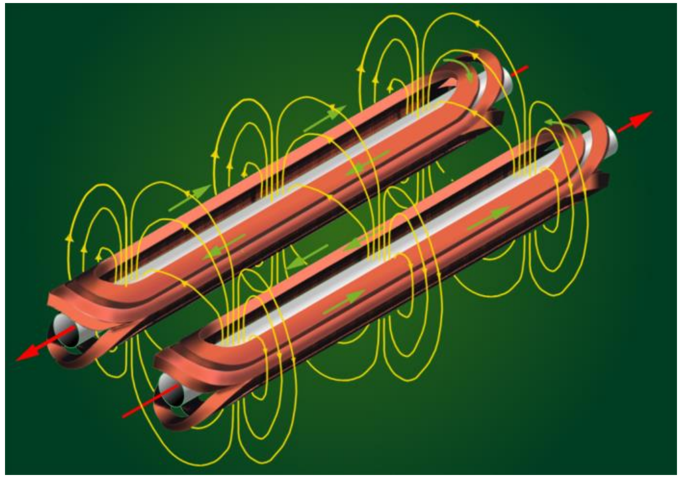
Displacement scaling = 50

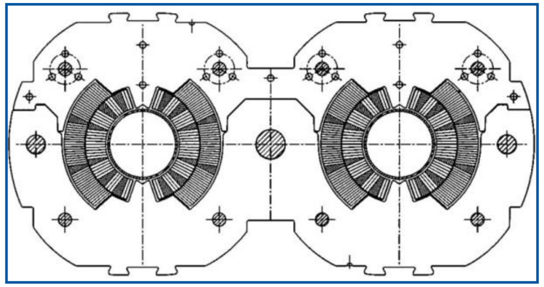
Mechanical structure: Examples

Nb-Ti LHC MB

Values for a central field of 8.33 T

- F_x = 340 t per meter: ~300 compact cars/m
- Precision of coil positioning: 20-50 μm
- F_z = 27 t: ~weight of the cold mass





Nb_3Sn dipole (Fresca-2)

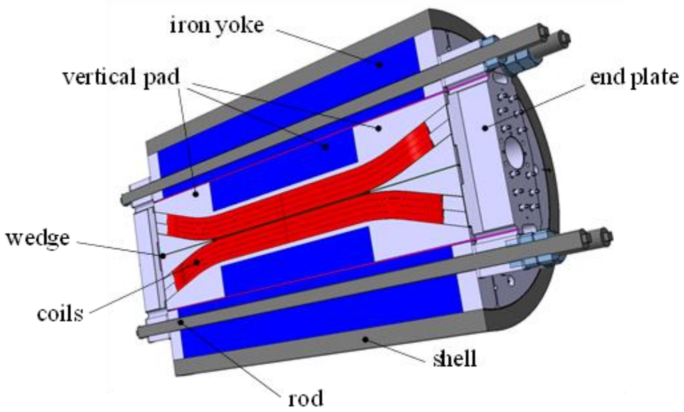
Values for a central field of 13 T

F_x = 770 t per meter and quadrant

F_z = 72 t/octant

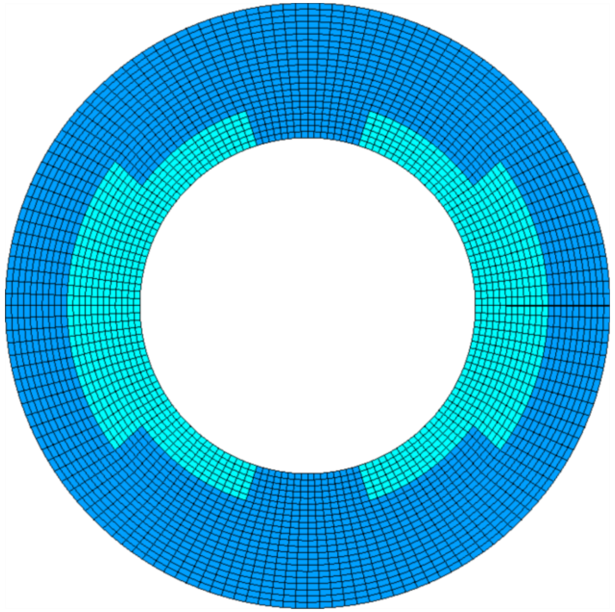
These forces are applied to an objet with a cross-section of 150x100 mm

and by the way, it is brittle

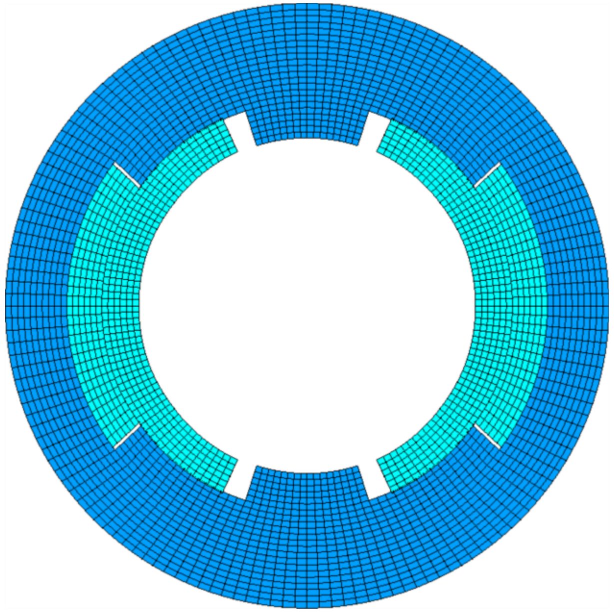


How to do to avoid movement and tensile stress?

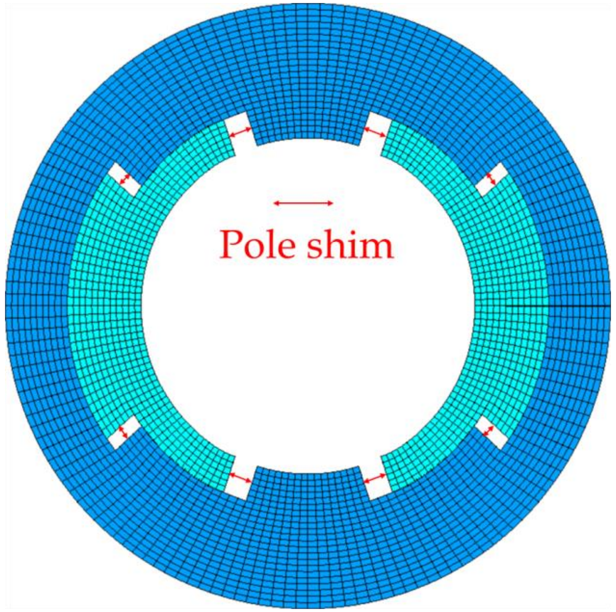
How to do to avoid movement and tensile stress?



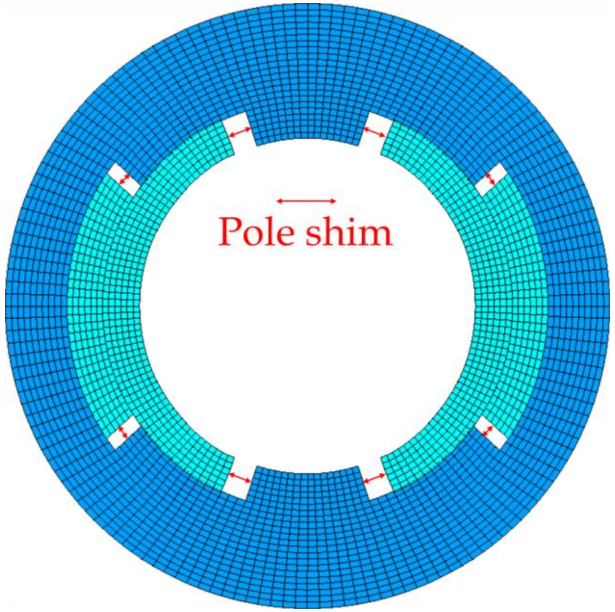
No pre-stress
No e.m. force



No pre-stress
With e.m. force



Pre-stress
No e.m. force



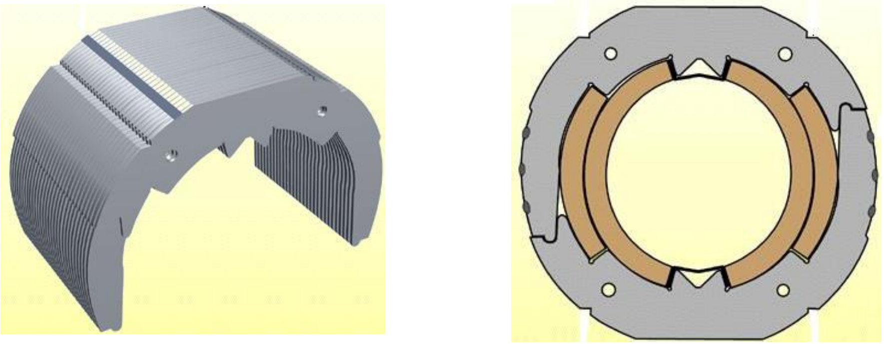
Pre-stress
with e.m. force

Mechanics of superconducting magnets: Collars

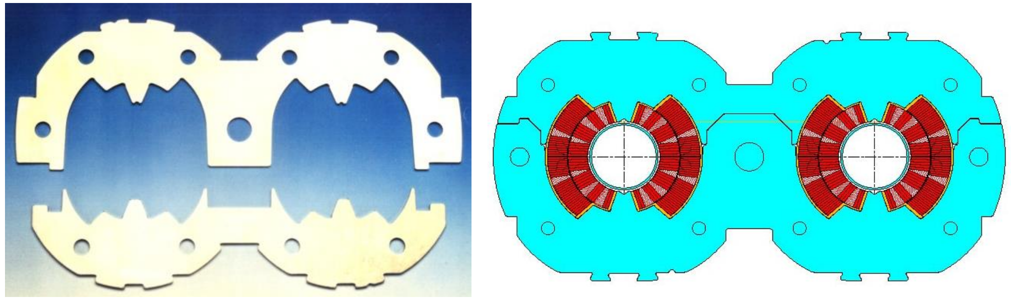
- Implemented for the first time in Tevatron, since then, almost always used

- Composed by stainless-steel or aluminium laminations few mm thick.

- By clamping the coils, the collars provide
  - coil pre-stressing;
  - rigid support against e.m. forces
  - precise cavity


Tevatron

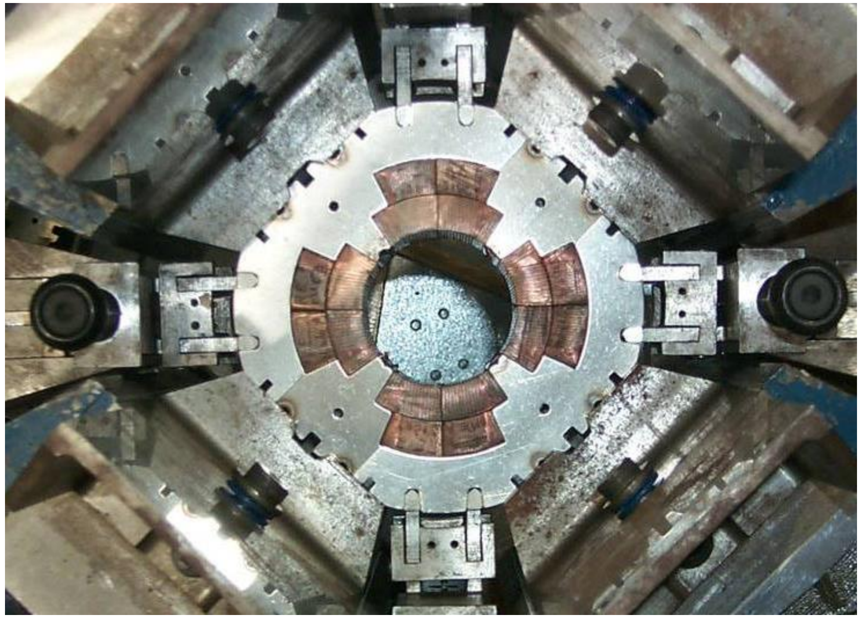

SSC


LHC

Mechanics of superconducting magnets: Collars

Collaring of a dipole magnet

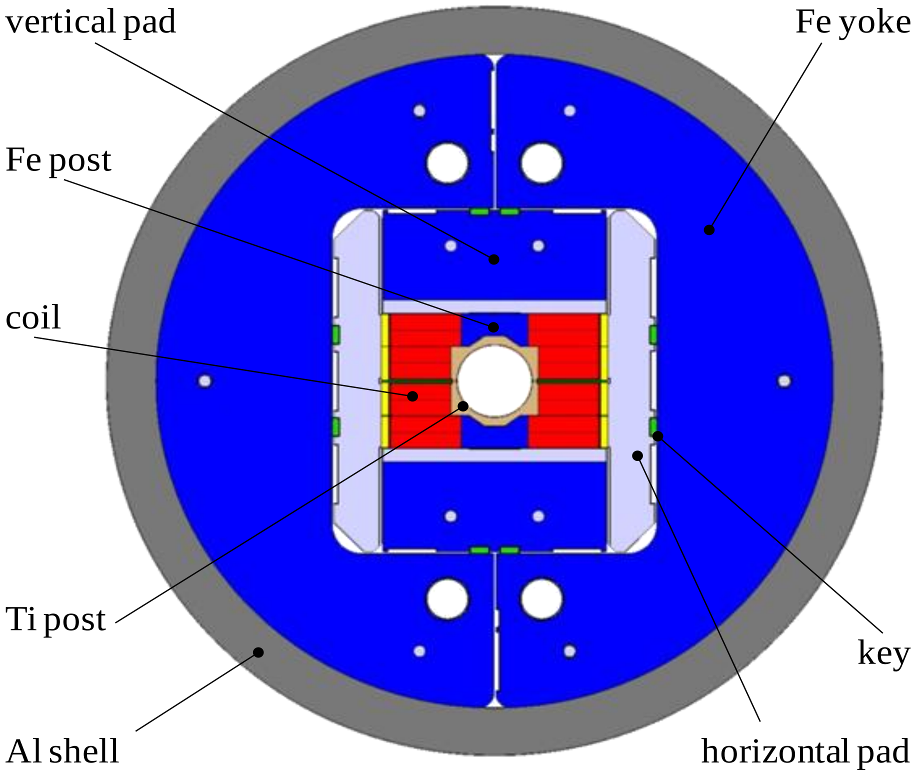
Collaring of a quadrupole magnet



Mechanics of superconducting magnets: Shell structure

Alternative structure, principle is based on different contraction coefficients:

- No large scale infrastructure required
- Only part of pre-stress is applied at ambient temperature



Material	α in mm/m
	293 K→4.2 K
Coil	3.88
Austenitic steel 316LN	2.8
Al 7075	4.2
Ferromagnetic iron	2.0
Pole (Ti6Al4V)	1.7

Mechanics of superconducting magnets: Iron yoke

- Iron yoke are also made in laminations (several mm thick)

Magnetic function:

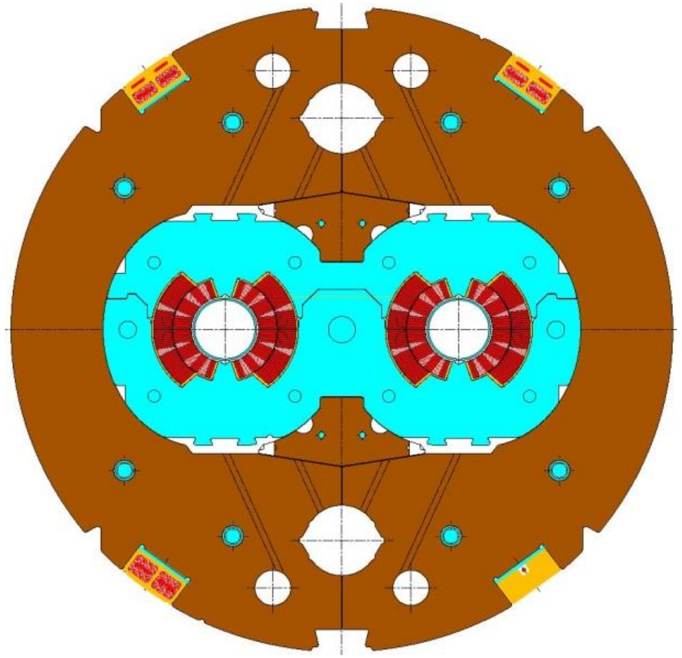
  - contains and enhances the magnetic field.

Structural function

  - tight contact with the collar
  - it contributes to increase the rigidity of the coil support structure and limit radial displacement.

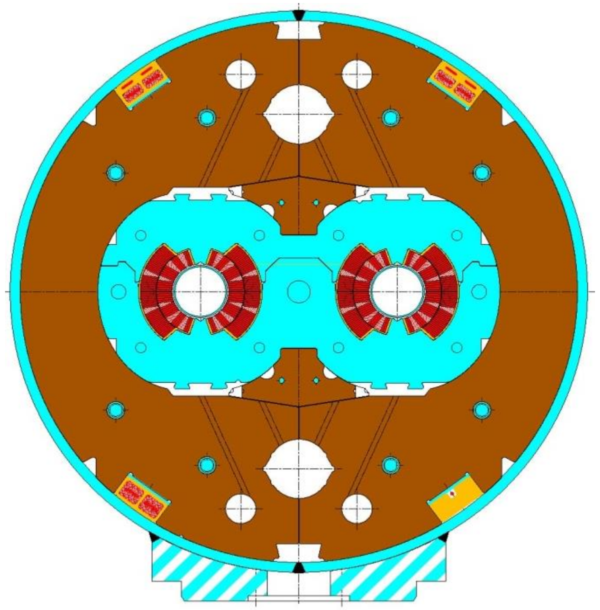
Holes are included in the yoke design for

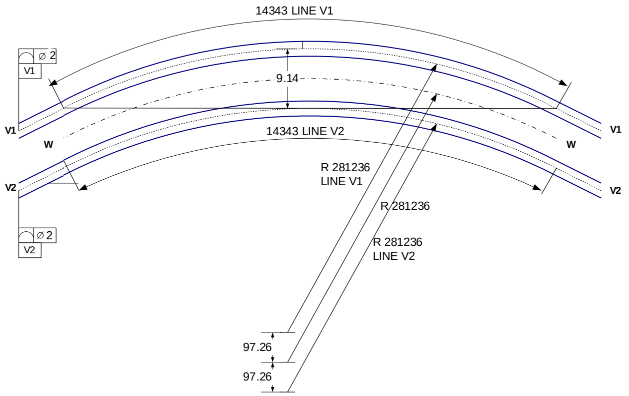
  - Correction of saturation effect
  - Cooling channel
  - Assembly features
  - Electrical bus



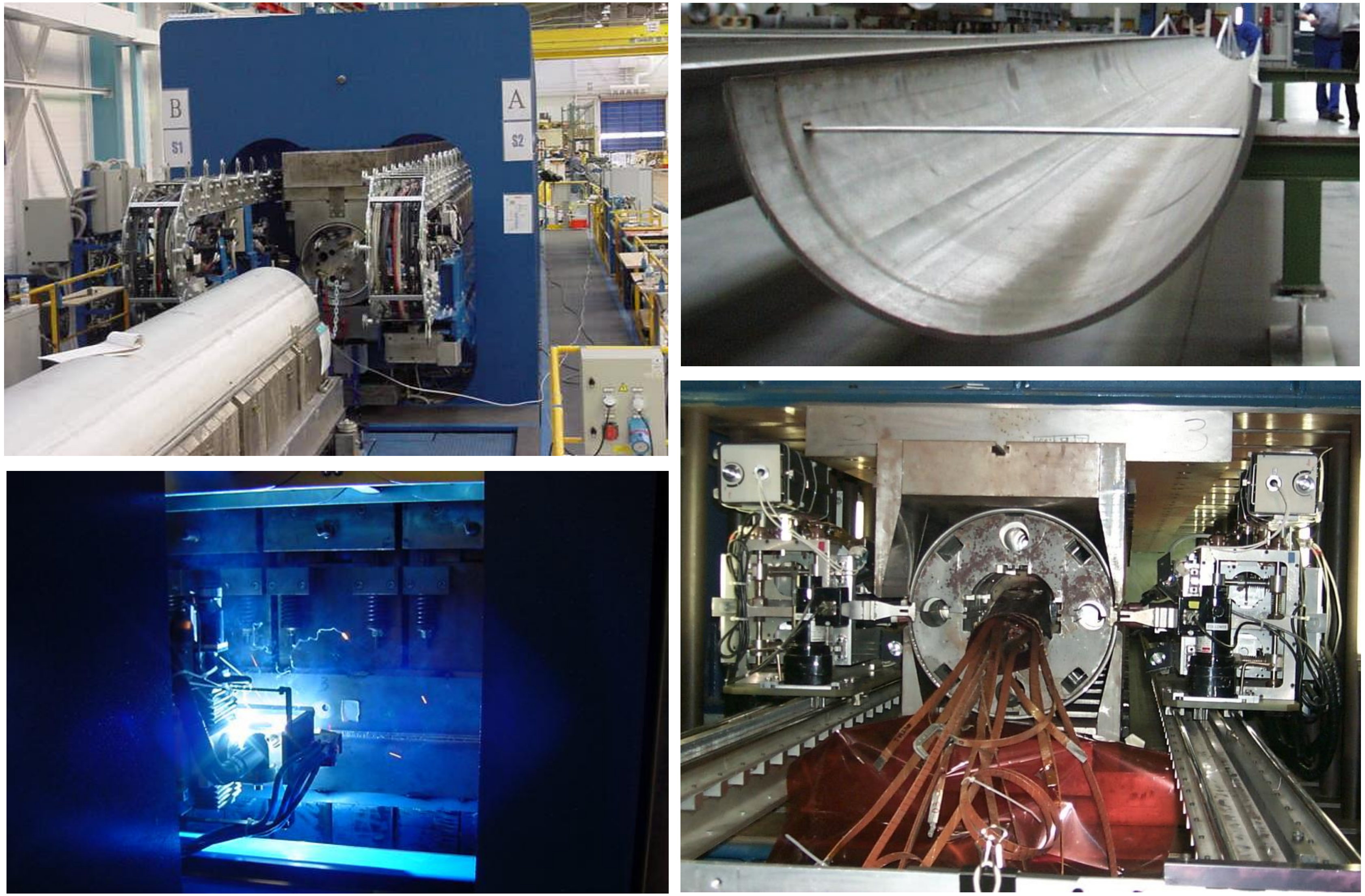
Cold mass

- The shell constitutes a containment structure for the liquid Helium.
- It is composed by two half shells of stainless steel welded around the yoke with high tension (about 150 MPa for the LHC dipole).
- With the iron yoke, it contributes to create a rigid boundary to the collared coil.
- If necessary, during the welding process, the welding press can impose the desired curvature on the cold mass
- In the LHC dipole the nominal sagitta is of 9.14 mm over ~14.3 m





Cold mass



An overview of the infrastructure (bldg. 180)…

Finishing benches
Geometrical measurements

15m Welding press

15m Collaring press

Pressure/leak bench

Nb_3Sn
Reaction
furnace

"Winding house"

Impregnation
chamber

Yoke assembly
bench

Welding press for 2m models

Half Yoke
returning
bench

Cold mass
assembly
bench

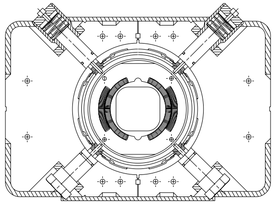
Collared coil
returning
bench

Collared coil magnetic
measurement bench

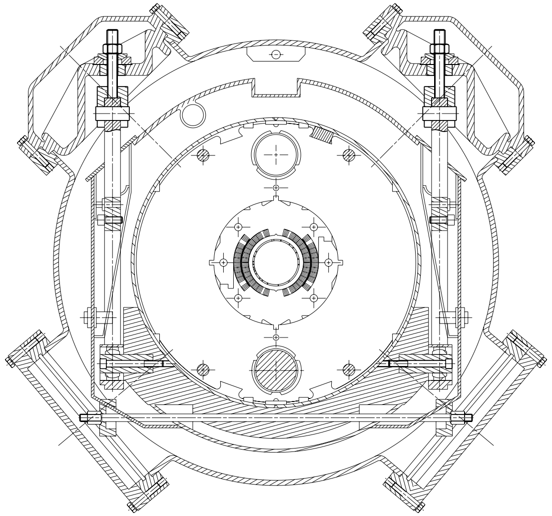
Cold mass magnetic
measurement bench

Cryo-magnets!

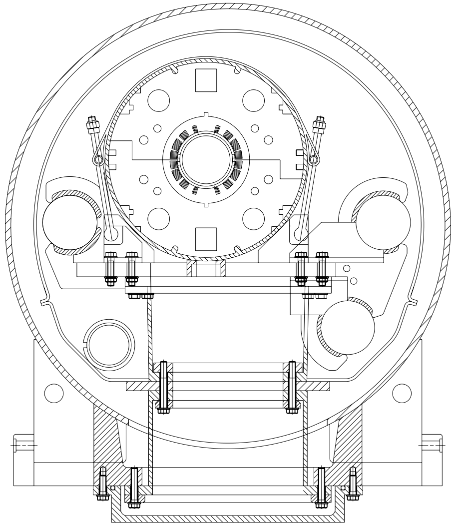
TEVATRON



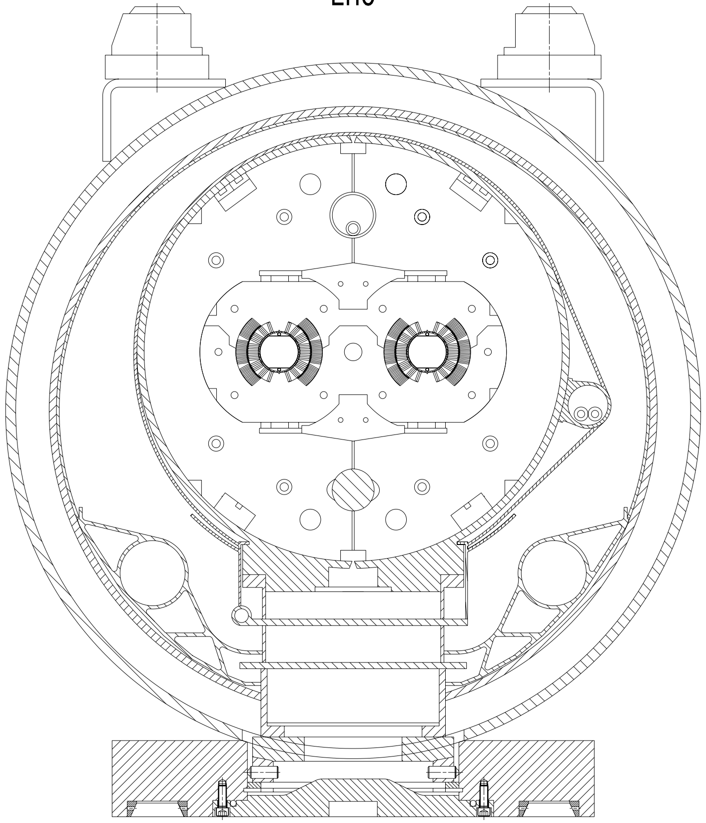
HERA



RHIC



LHC



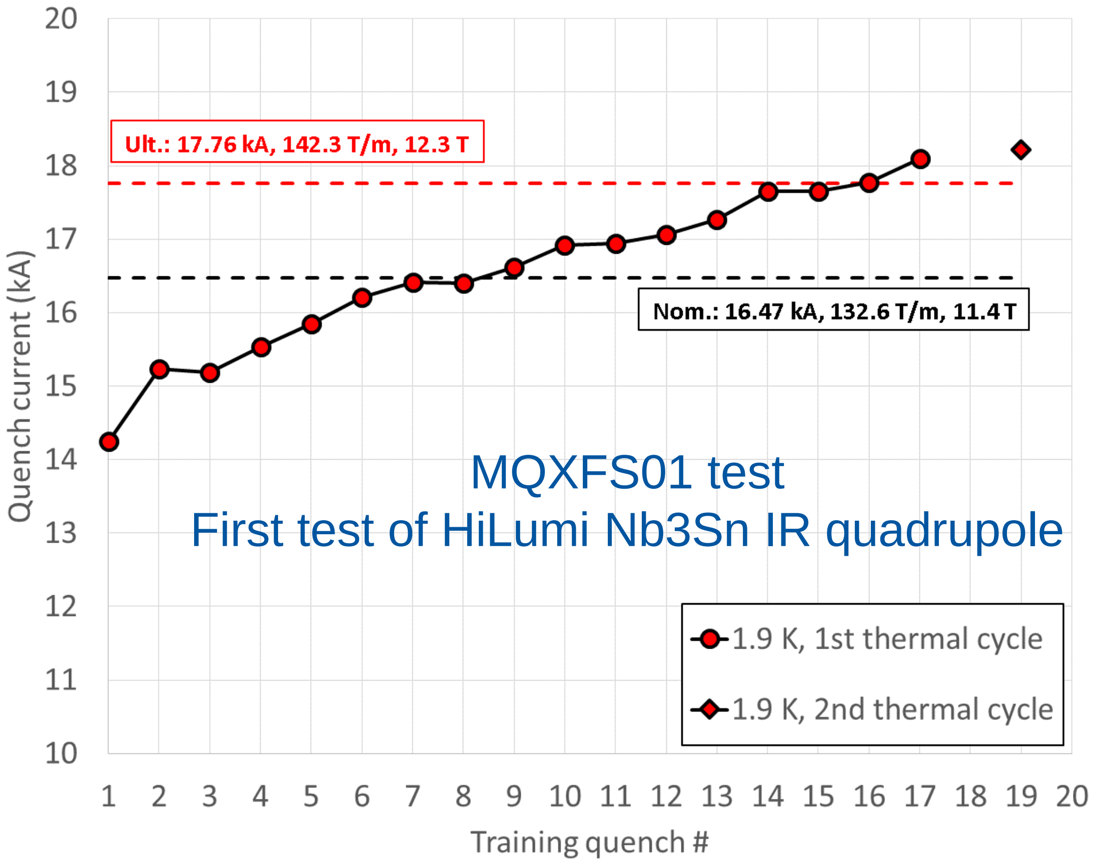
	Tevatron	HERA	RHIC	LHC
Operation period	1983-2011	1991-2007	since 2000	since 2008
Aperture (mm)	76	75	80	56
Magnetic length (m)	6.1	8.8	9.45	14.3
Nominal bore field (T)	4.3	5.3	3.5	8.3
Nominal current (kA)	4.3	5.7	5.1	11.9
Stored energy at I_{nom} (MJ)	0.30	0.94	0.35	6.93
Operation temperature (K)	4.6	4.5	4.3-4.6	1.9

Testing

All magnets to be installed in a machine have to go through testing.

A detailed test plan is elaborated. Main points:

- Electrical integrity (test voltage 1-2 kV)
- Performance (field, field quality): Reduce training!
- Memory after thermal cycle: Keep memory!



MQXFS01 test

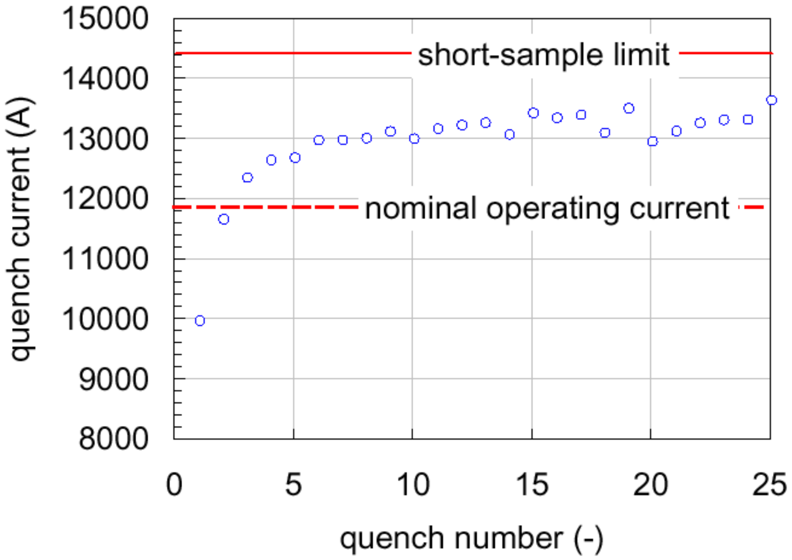
First test of HiLumi Nb3Sn IR quadrupole

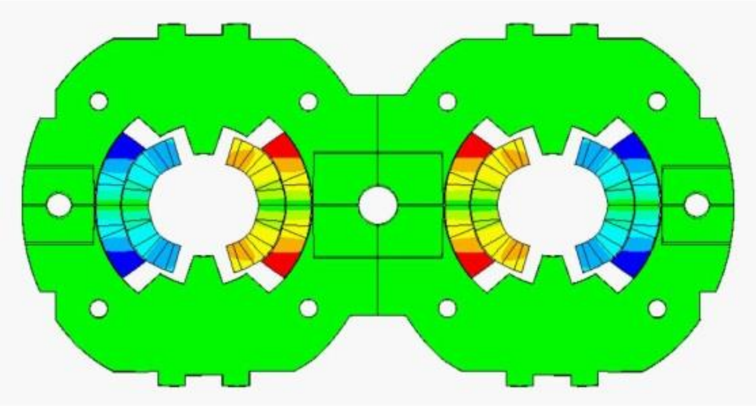
Training

Main causes

- Frictional motion
  - E.m. forces → motion → quench
  - Coil locked by friction in a secure state
- Epoxy failure
  - E.m. forces → epoxy cracking → quench
  - Once epoxy locally fractured, further cracking appears only when the e.m. stress is increased.
- Magnets operate with margin: Nominal current reached with few quenches.

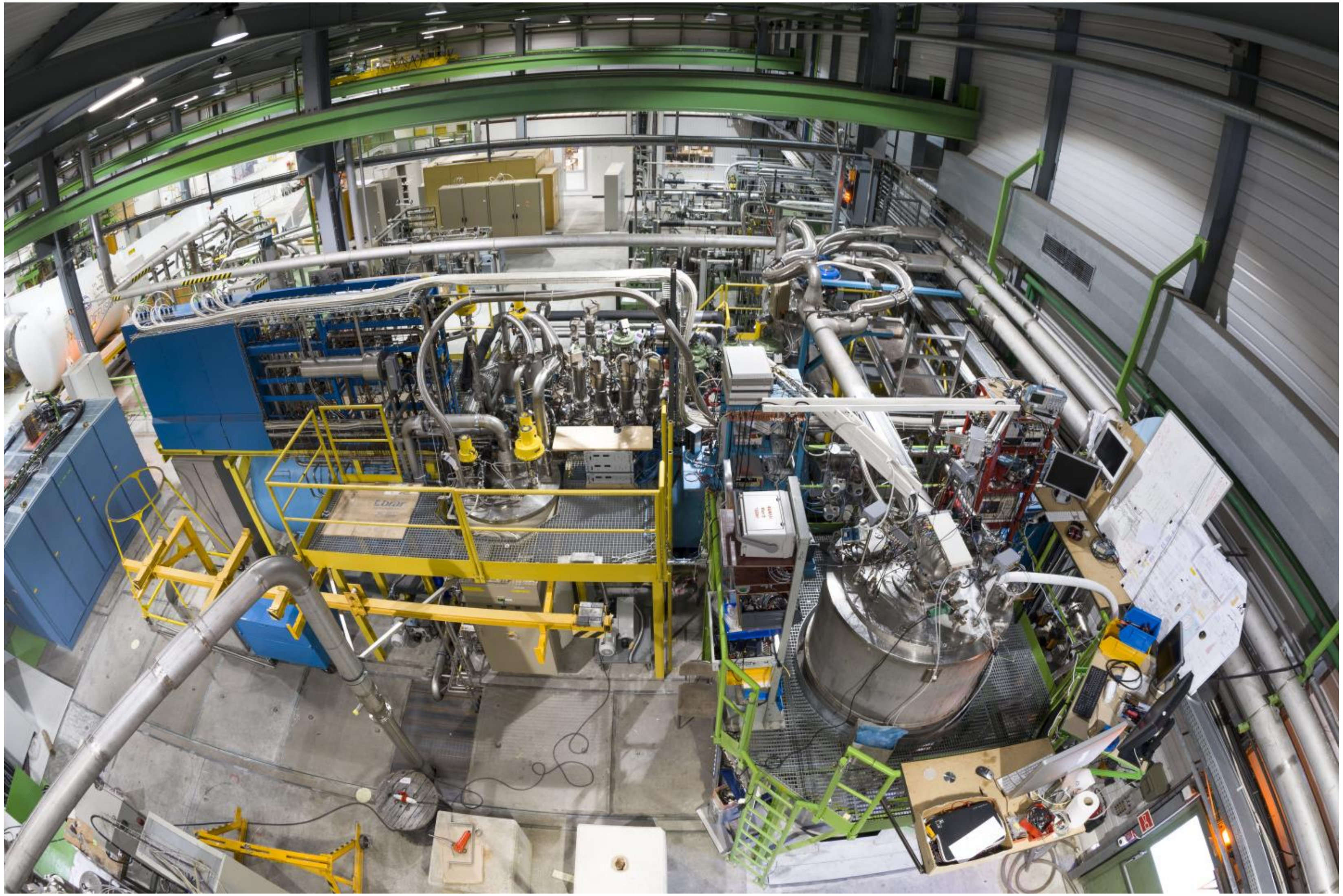
In general, very emotional process!





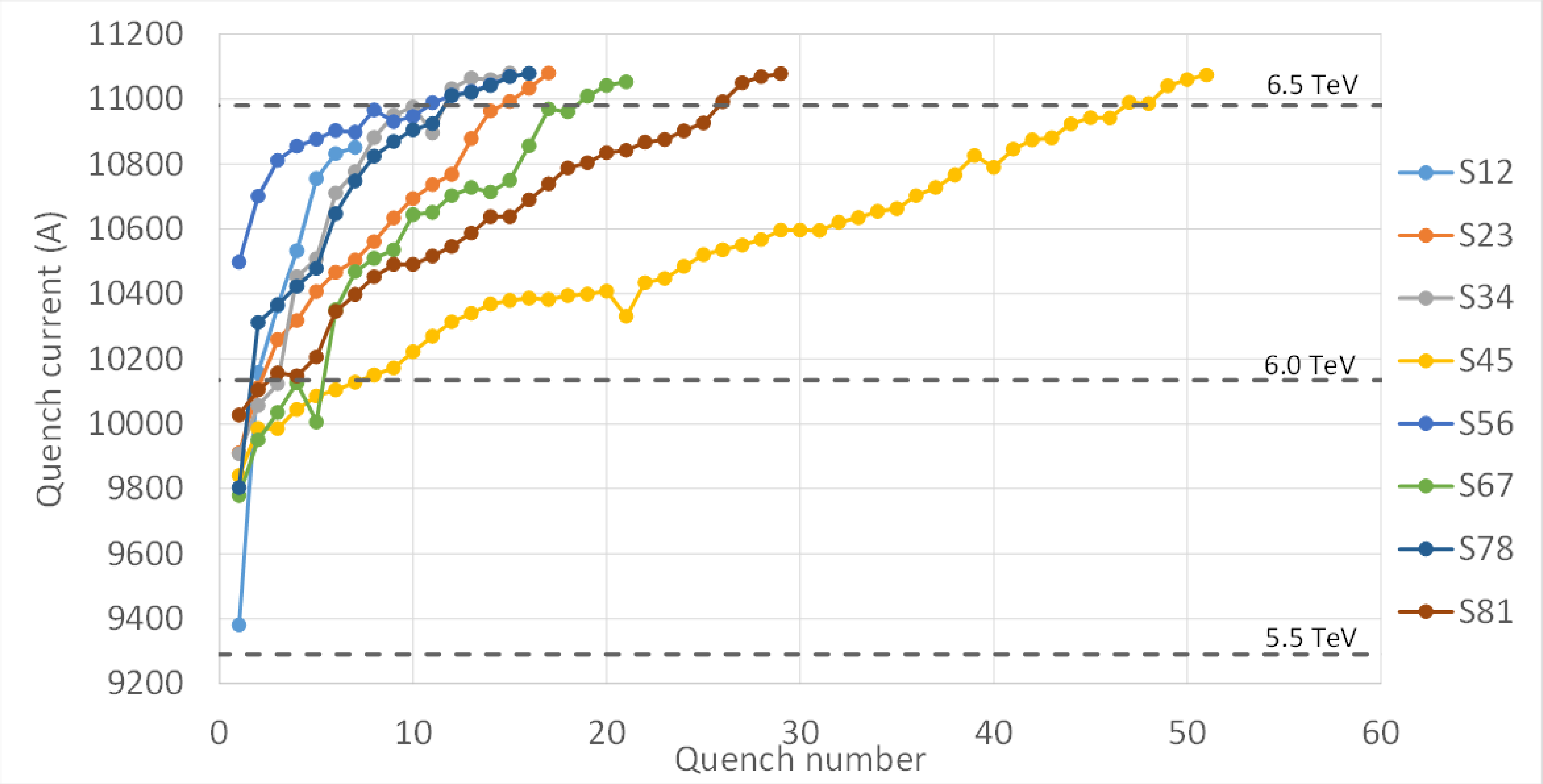
Testing of magnets: Horizontal test station

Testing of magnets: Vertical test station

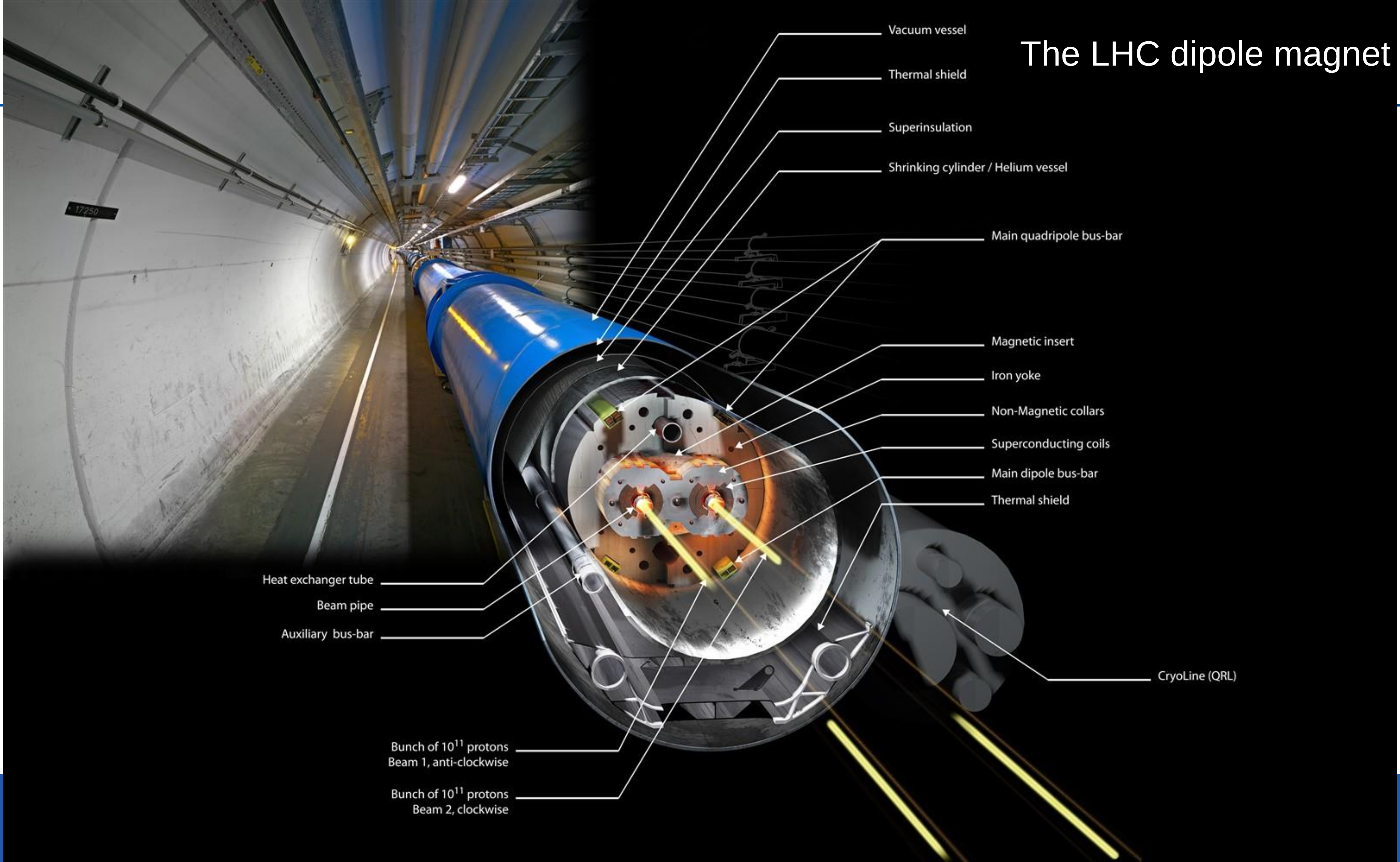


Testing of magnets: Vertical test station

Memory

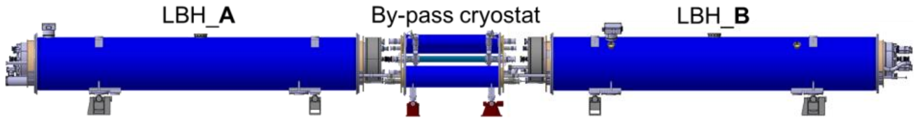

11200
11000
10800
10600
10400
10200
10000
9800
9600
9400
9200
Quench current (A)
0
10
20
30
40
50
60
Quench number
6.5 TeV
6.0 TeV
5.5 TeV
S12
S23
S34
S45
S56
S67
S78
S81

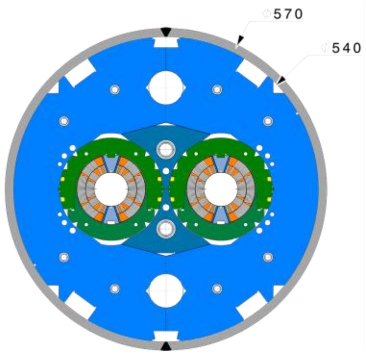
The LHC dipole magnet



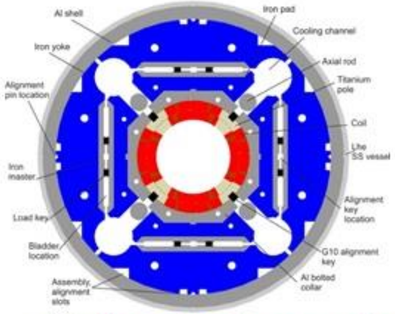
Hi-Lumi LHC at CERN

- Achieve instantaneous luminosities a factor of five larger than the LHC nominal value
- Enable the experiments to enlarge their data sample by one order of magnitude compared with the LHC baseline programme



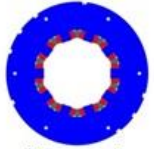


11 T dipole

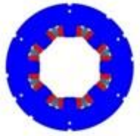


Triplet [G. Ambrosio, P. Ferracin et al.]

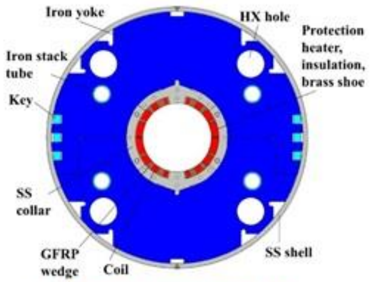
Dodecapole



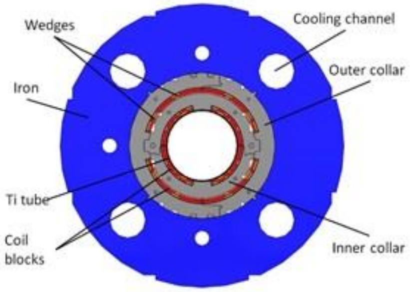
Decapole



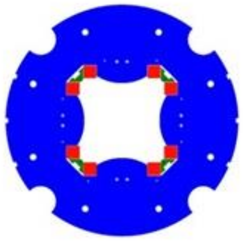
Octupole

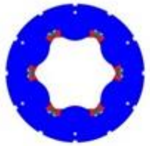


D1[T. Nakamoto, et al.]

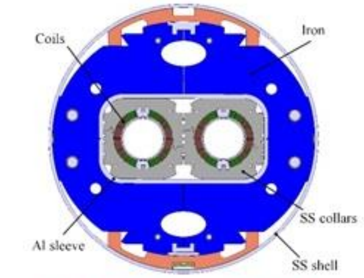


MCBXF [F. Toral, et al.]

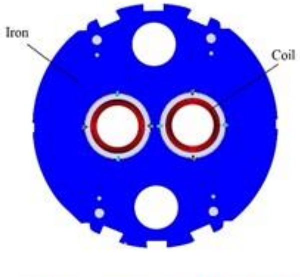




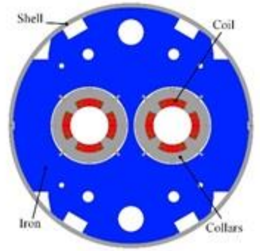
Skew quad
[M. Sorbi, M. Statera, et al.]



D2 [P. Fabbricatore, S. Farinon, et al.]



D2 correctors [G. Kirby]



MQYY [H. Felice, et al.]

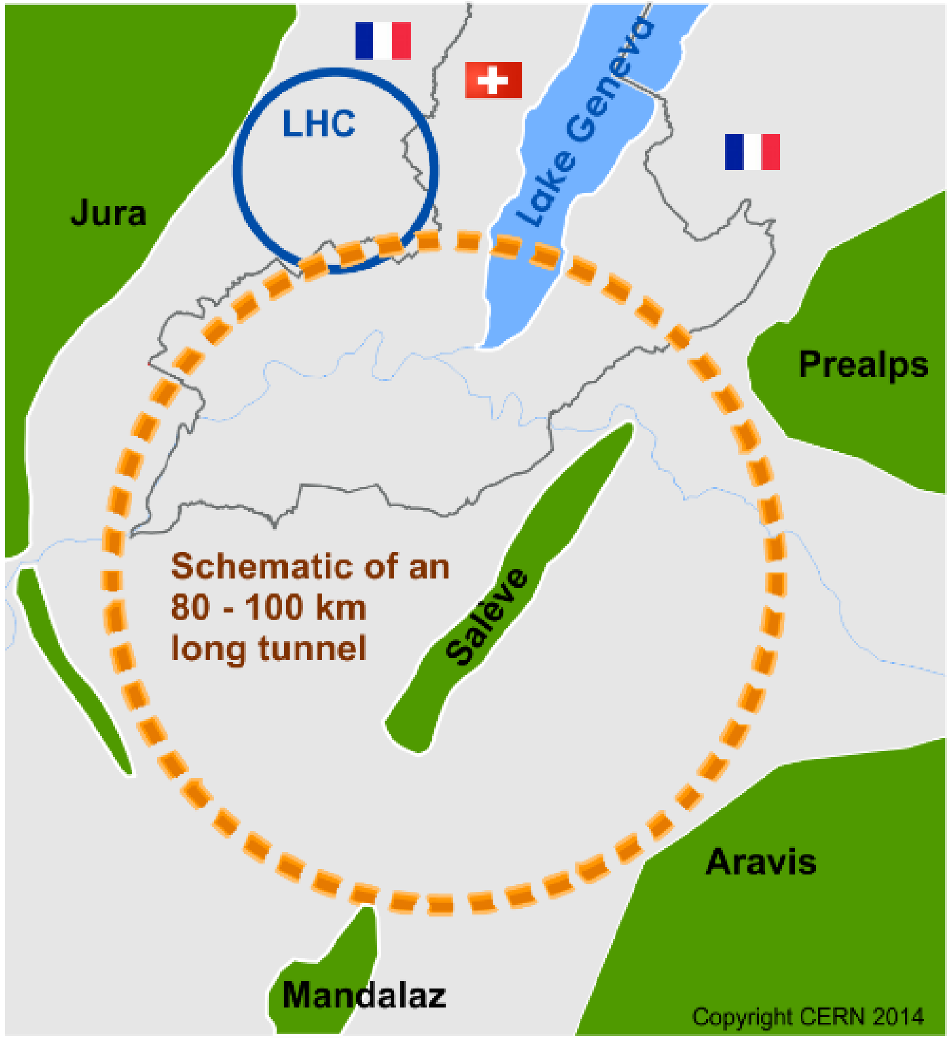
LHC, what next? FCC!

International FCC collaboration (CERN as host lab) to study:

80-100 km tunnel infrastructure

- *pp*-collider (*FCC-hh*)
- *e*$^+$*e*$^-$ collider (*FCC-ee*) as potential first step
- *p-e* (*FCC-he*) option

HE-LHC with *FCC-hh* technology



FCC versus LHC dipole

Twice the magnetic field →

- 2 x more Ampere turns
- 4 x higher forces/m
- ~6 x more stored energy/m

4 x more magnets

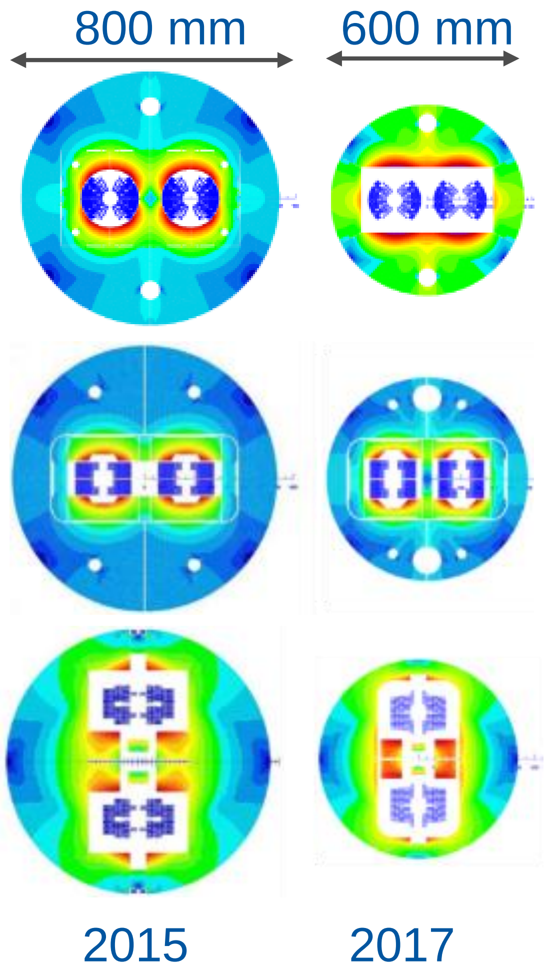
Prototypes will be built.

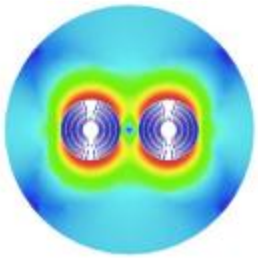
Magnet Design Options: Future Circular Collider

Cosine-theta (baseline)

Block-type coils

Common-coils



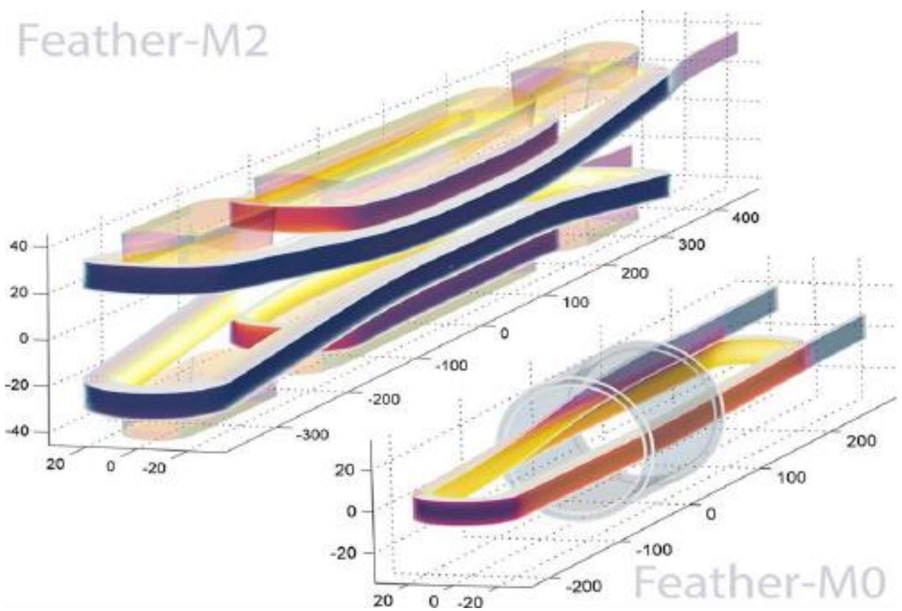


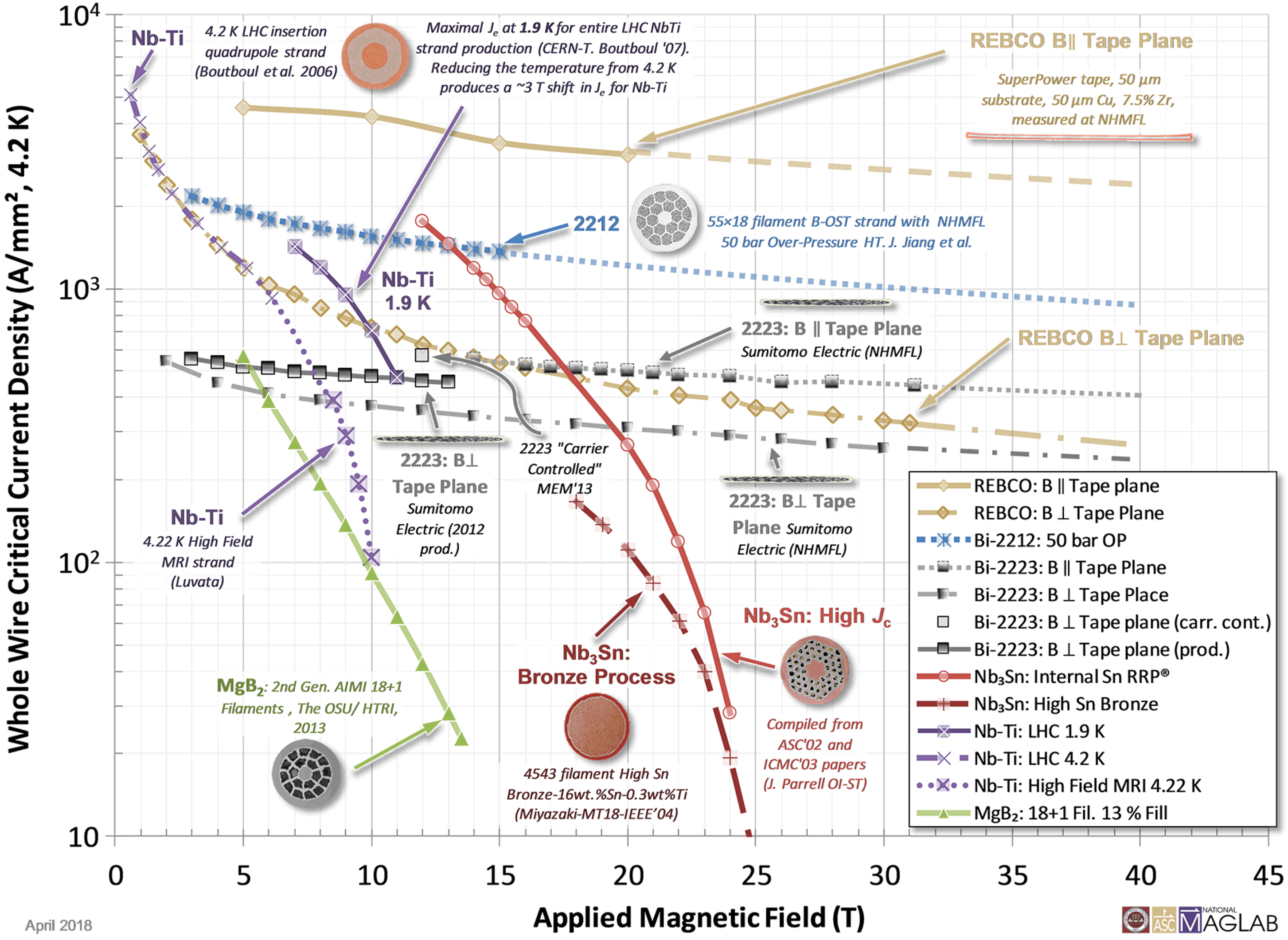
CCT (PSI with LBNL and CERN)

Magnet length	14.3 m
Free physical aperture	50 mm
Inter-beam distance	204 mm
Field amplitude	16 T
Margin on the load-line @ 1.9K	14 %

High-Temperature Superconductors

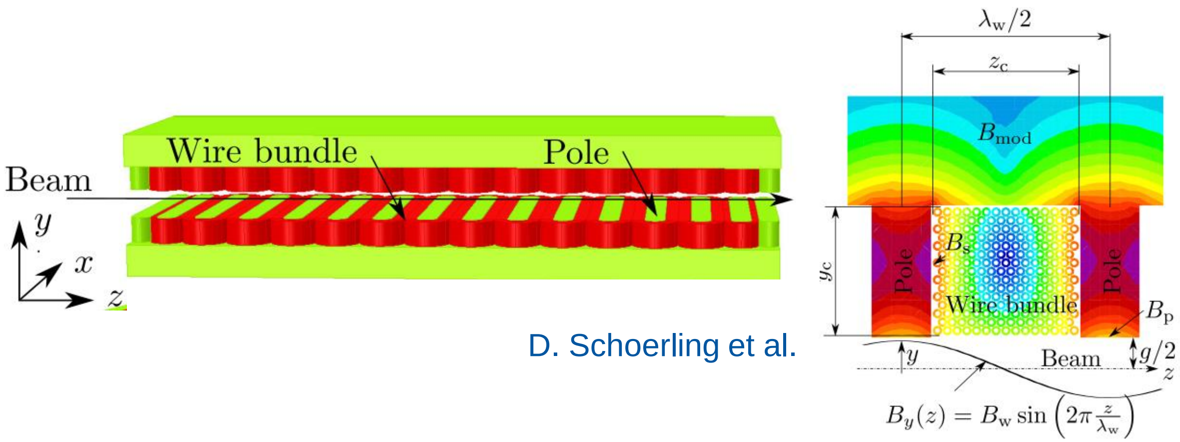
- High-temperature superconductor promise much higher fields
- Technology is currently being developed
- Main challenge: Reduce cost!



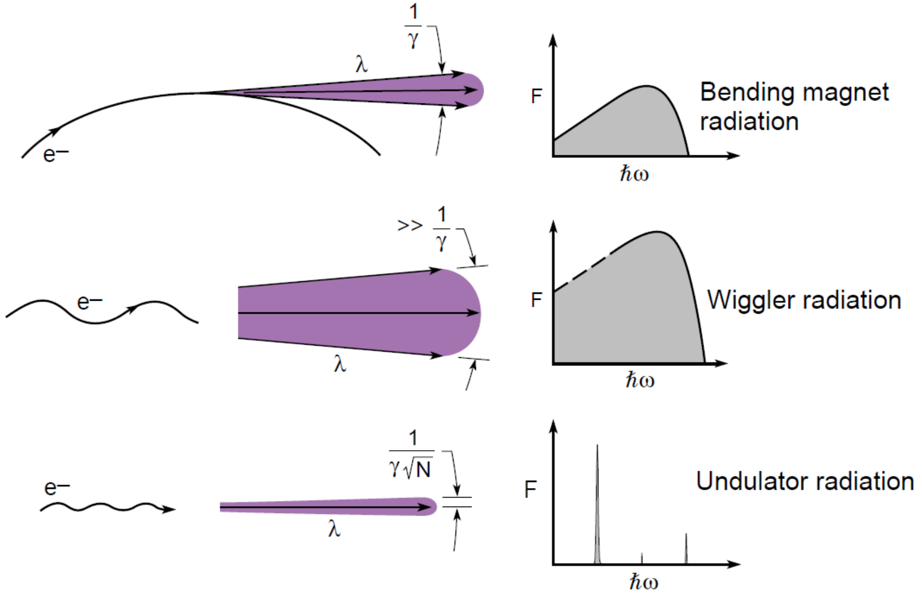


Other superconducting magnets in accelerators

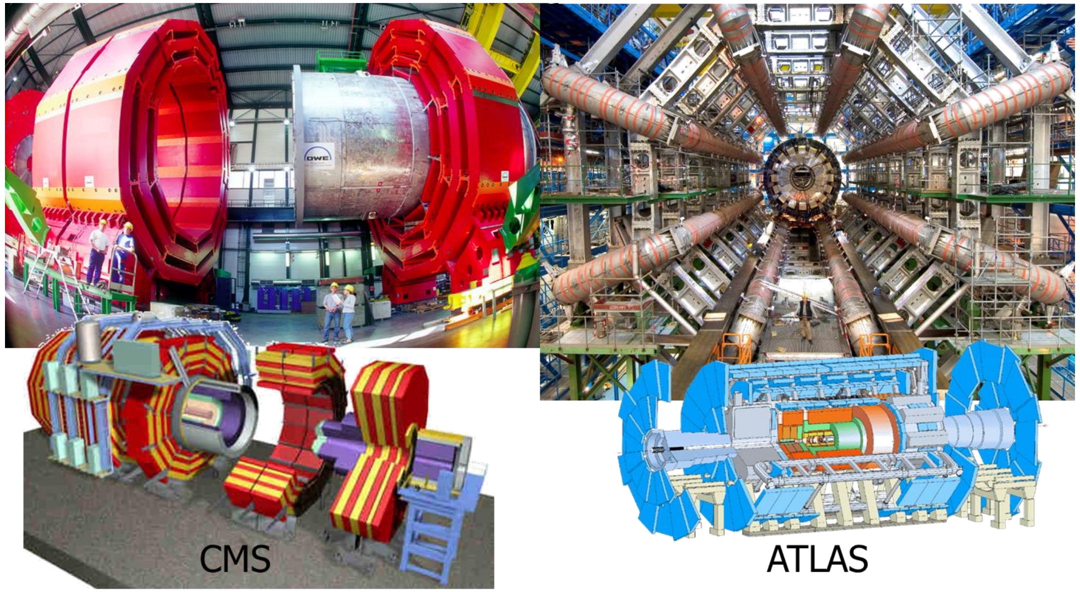
- Experimental magnets (large solenoids)
- Insertion devices for reducing the beam emittance and creating synchrotron radiation: Very active field of R&D for storage rings and FELs (ESRF, Soleil, etc.… and European XFEL, SwissFel,…)



D. Schoerling et al.



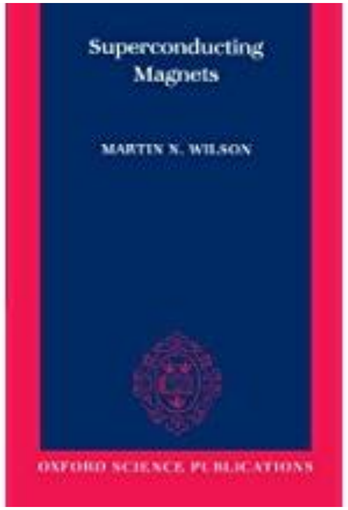
David Attwood, Soft X-Rays and Extreme Ultraviolet Radiation: Principles and Applications



Concluding remarks

- Superconducting magnet design and manufacture is a very diverse field. It starts with superconductors (materials, wires, cables, and their electric and thermal properties), continues with electromagnetic design, thermal calculations, mechanics, protection, stability, etc…
- Cooling requires cryogenic, a field of applied science by its own
- The manufacture requires cost modelling, industrialization, complex project management, etc.
- We live in exciting times for superconducting accelerator magnets: First Nb_3Sn magnets to be installed in HL-LHC, new field record of 14.6 T achieved with Fresca-2, first 16 T magnets for FCC to be manufactured from now on, first HTS dipole to be tested in background field, HTS undulator to be build, …

Literature

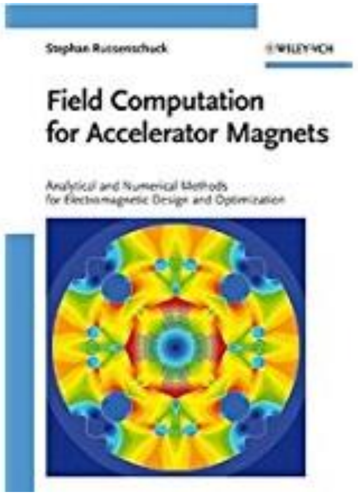


Superconducting Magnets

MARTIN N. WILSON

OXFORD SCIENCE PUBLICATIONS

Martin N. Wilson, Superconducting Magnets, 1983: The classical book! Excellent introduction to the engineering of superconducting magnets.



Stephan Russenschuck

WILEY-VCH

Field Computation for Accelerator Magnets

Analytical and Numerical Methods for Electromagnetic Design and Optimization

Stephan Russenschuck, Field computation, 2010: The book for all questions related to electromagnetic calculations!

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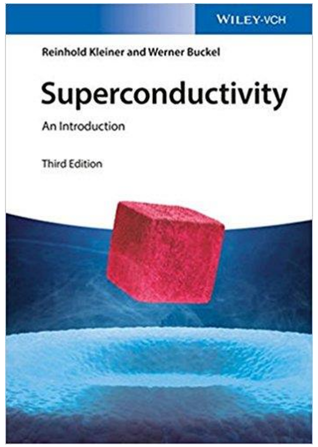

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Reinhold Kleiner and Werner Buckel

Superconductivity

An Introduction

Third Edition

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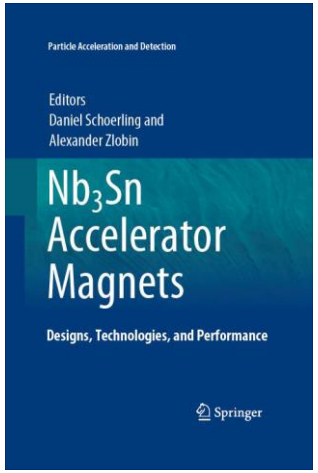

Particle Acceleration and Detection

Editors
Daniel Schoerling and
Alexander Zlobin

Nb_3Sn Accelerator Magnets

Designs, Technologies, and Performance

Springer

Daniel Schoerling and Alexander Zlobin, Nb_3Sn accelerator magnets: Designs, technologies, and performance, 2018 (to be published): Review of all so far built Nb_3Sn dipole magnets.

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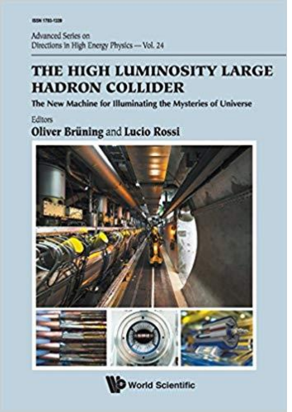

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Oliver Bruning, Lucio Rossi (editors), High Luminosity Large Hadron Collider, The New Machine For Illuminating The Mysteries Of Universe: Introduction to HL-LHC

The LHC dipole magnet