# Conclusion:
# A parade of magnet design

Ezio Todesco
European Organization for Nuclear Research (CERN)

Thanks to L. Bottura and G. de Rijk for proposing and supporting this initiative

*All the units will use International System (meter, kilo, second, ampere) unless specified*

v.1 – last updated 10 october 2020

# RULES OF THE PARADE

- We consider only magnets that have been built
  - Nothing about designs proposed but not realized
- We focus on the dipoles, plus few cases of quadrupoles
  - We do not present racetrack magnets without bore (HD1, RMC, …)
- Anyway, the list is far from being exhaustive

# RULES OF THE PARADE

- For each magnet we give
  - A first page with general list of parameters
    - Field, length, number, who built, who designed, size, material, dates
  - Here the reference field can be a controversial parameter
    - For installed magnets we refer to design/operational values
    - For R&D magnets the choice is much more difficult (example: D20, HD2, HQ have no explicit reference field, or they refer to short sample conditions) – I followed the text of the authors
    - Therefore in some cases the comparison can be not fair, since the loadline margin is very different
  - Even though these lectures are about design and not performance, I added few words about the level of field reached

# RULES OF THE PARADE

- For each magnet we give
  - A second page with an outlook of the main new features of the magnet
  - A third page with the detail of the coil cross-section and the specification on the conductor critical current density
  - A fourth page with the detailed list of design parameters, referred to the reference field
    - Current, loadline margin, temperature margin, stored energy, inductance, and last but not least, overall current density
  - A fifth page with details on mechanics and protection
    - I will use the equations for accumulated stress, not the ANSYS computations – for block design (HD2, Fresca2) I used the horizontal force given in the papers divided by the cable width

# RULES OF THE PARADE

- For each magnet we give
  - Some magnets have several iterations in the design, I took the “final” one (example: HQ reduced the strand diameter)
  - Some parts are missing, information retrivial in an organized way is a challenge, slides will be updated when missing parts will be recovered
  - If you find mistakes please tell me, they will be corrected
  - … and please be sympathetic to this effort, within its limits

# CONTENTS

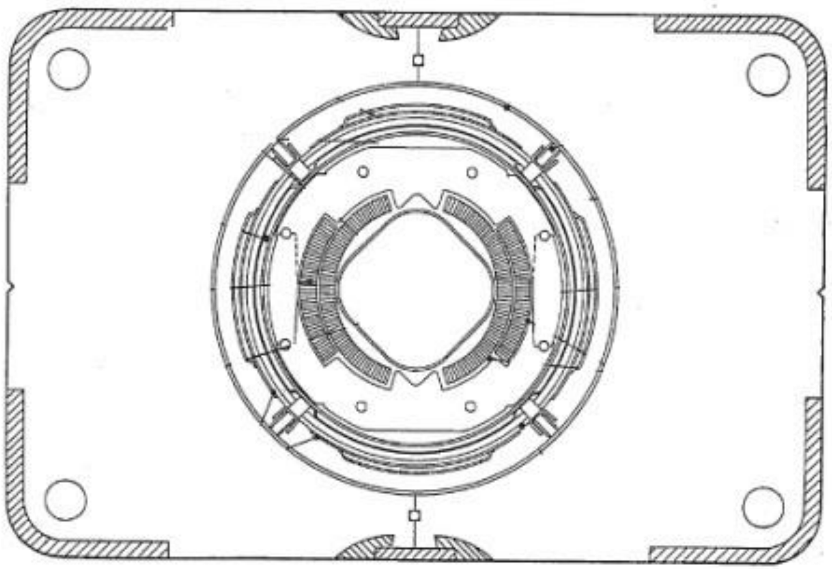
- Dipoles
  - Nb-Ti
  - $Nb_3Sn$

- A short selection of quadrupoles
  - Nb-Ti (ISR, MQY)
  - $Nb_3Sn$ (TQ/LQ, HQ, MQXF)
  - Not presented today, will be added in later in the slides

Thanks to many colleagues in this historical effort, in particular S. Izquierdo Bermudez, L. Bottura, A. Devred, P. Fabbricatore, P. Ferracin, E. Gautheron, L. Rossi, M. Sorbi, G. Spigo, X. Wang, and many others

# THE TEVATRON DIPOLE

- Scope: main dipole of the Tevatron
  - Name: Tevatron main dipole
  - Design: FNAL
  - Production: FNAL
  - Reference field: 4.3 T
    - Corresponding to 1 TeV operation
    - Tevatron operated at 0.98 TeV
  - Period: 1980-1986
  - Units: 774
  - Length: 6.1 m
  - Material: Nb-Ti
  - Operational temperature: 4.2 K
  - Aperture diameter: 76.1 mm
  - Dimension: 250×420 mm

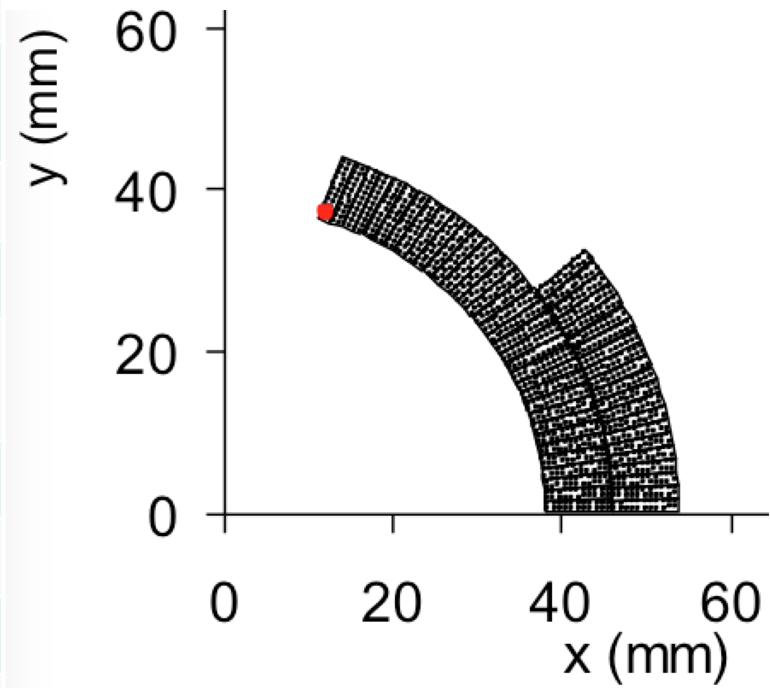


# THE TEVATRON DIPOLE

- Main features
  - First main superconducting dipole for accelerator
    - Note that first superconducting magnet installed in accelerator was the interaction region quadrupole of ISR
  - First dipole produced in large series
  - Rutherford cable
  - First accelerator magnet with stainless steel collars
  - Two layer coil
  - Iron yoke at room temperature

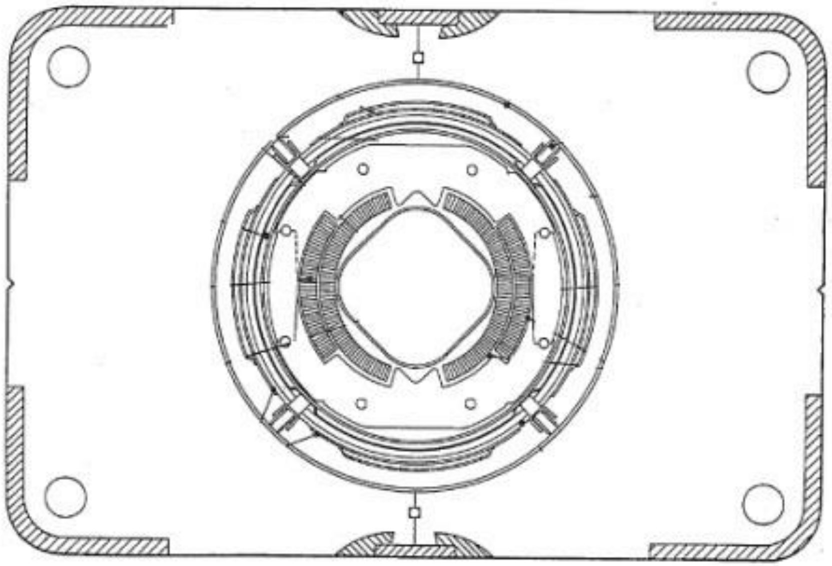
# THE TEVATRON DIPOLE

| | | Inner | Outer |
|---|---|---|---|
| Strand diameter | (mm) | 0.6807 | 0.6807 |
| Filament size | (μm) | | |
| N strands | | 23 | 23 |
| Cu/No_cu | | 1.8 | 1.8 |
| Critical current density | (A/mm$^2$) | 1790 (5 T, 4.2 K) | 1790 (5 T, 4.2 K) |
| Cable width | (mm) | 7.747 | 7.747 |
| Equiv. coil width | (mm) | 14.0 | |
| Cable mid thickness | (mm) | 1.243 | 1.243 |
| Keystone angle | (°) | 0.932 | 0.932 |
| N. turns | | 35 | 21 |
| N. blocks | | 1 | 1 |
| Insul. thickness (az/radial) | (mm) | 0.100/0.130 | 0.100/0.130 |



# THE TEVATRON DIPOLE

- Main parameters
  - Current: 4333 A
  - Loadline fraction: 0.90
  - Temperature margin: -- K
  - Inductance: ~32 mH
  - Stored energy: 0.300 MJ
  - Distance coil to iron: 36 mm
  - Iron contribution to field: 25%
  - Saturation: --%
  - Overall current density: 360 A/mm$^2$
    - Note: current density specified at 1500 A/mm$^2$, 6 T, 4.2 K even though 2200 A/mm$^2$ available



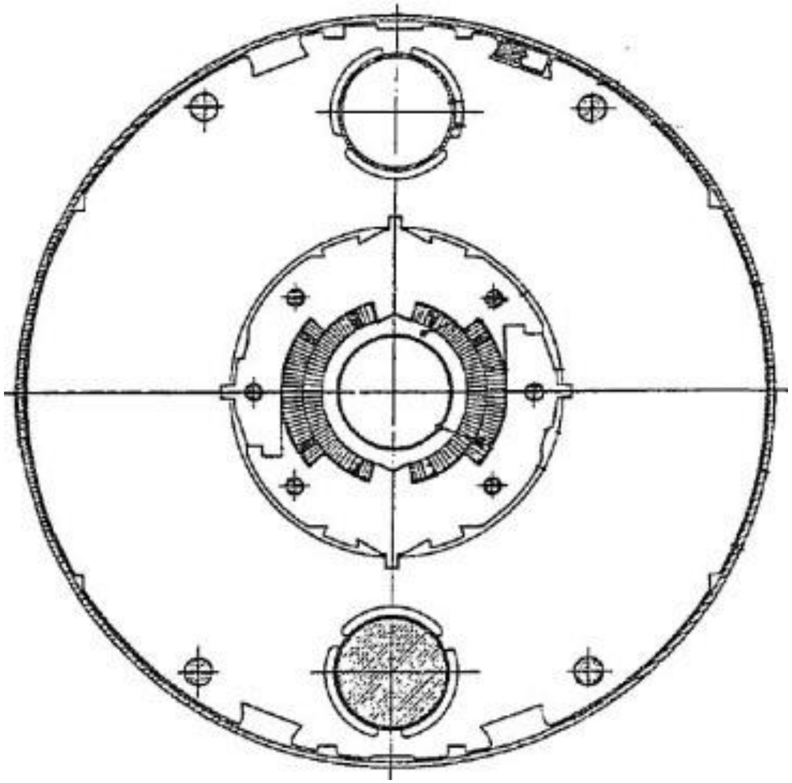
# THE TEVATRON DIPOLE

- Mechanical structure
  - Stainless steel collars, ~15 mm thick
  - Accumulated midplane stress: ~34 MPa
  - Radial stress: ~11 MPa

- Protection
  - Energy density over the insulated coil: 0.019 J/mm$^3$

# THE HERA DIPOLE

- Scope: main dipole of the HERA
  - Name: HERA main dipole
  - Design: DESY
  - Production: Ansaldo and ABB
  - Reference field: 4.68 T
  - Period: 1985-1990
  - Units: 416+38
  - Length: 8.8 m
  - Material: Nb-Ti
  - Operational temperature: 4.5 K
  - Aperture diameter: 75 mm
  - Outer diameter: *380* mm

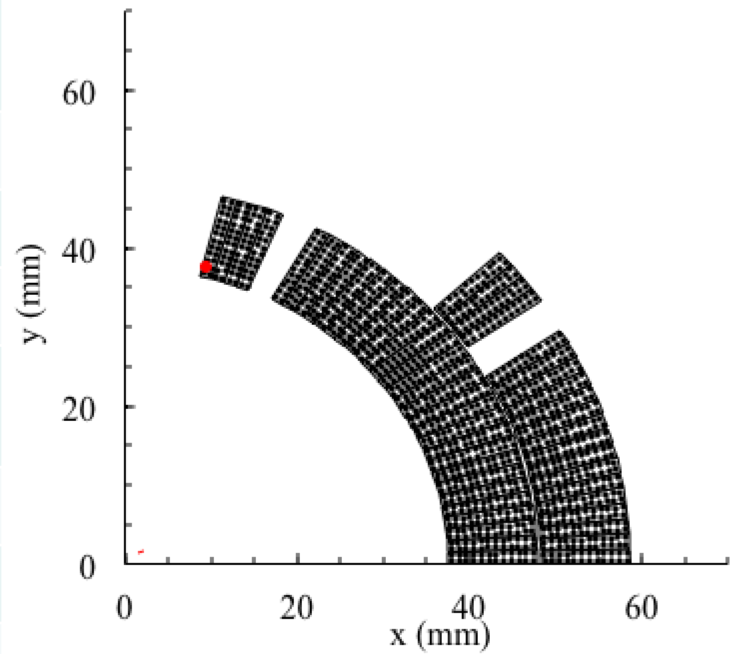


# THE HERA DIPOLE

- Main features
  - Iron included in the cryostat
  - First dipole with Al collars
  - First coil with wedges (true ?)

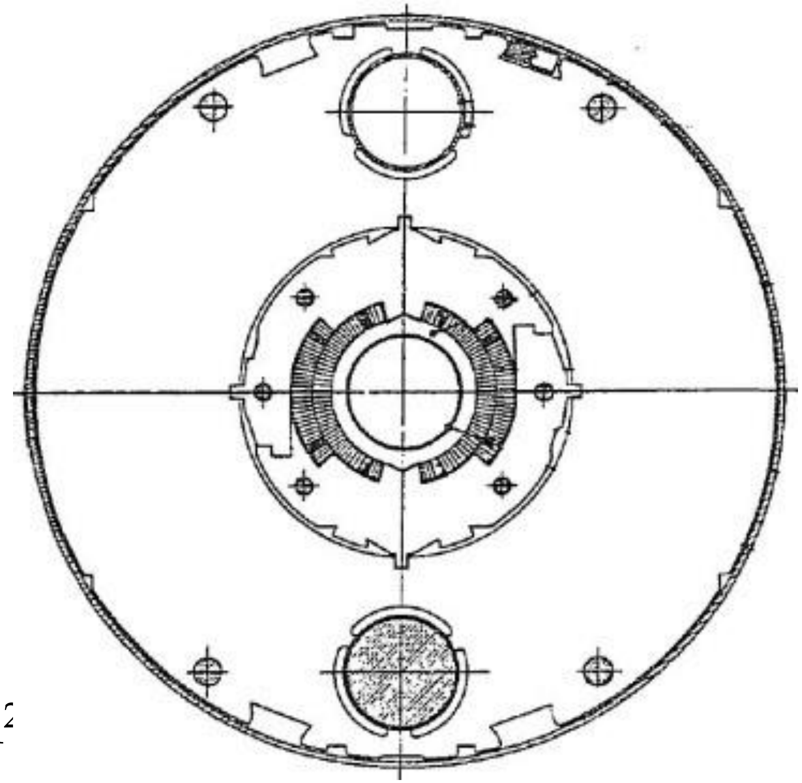
# THE HERA DIPOLE

| | | Inner | Outer |
|---|---|---|---|
| Strand diameter | (mm) | 0.833 | 0.833 |
| Filament size | (μm) | | |
| N strands | | 24 | 24 |
| Cu/No_cu | | 1.878 | 1.878 |
| Critical current density | (A/mm$^2$) | 1760 (5.5 T, 4.5 K) | 1760 (5.5 T, 4.5 K) |
| Cable width | (mm) | 10.000 | 10.000 |
| Equiv. coil width | (mm) | 19.0 | |
| Grading | | NO | |
| Cable mid thickness | (mm) | 1.4705 | 1.4705 |
| Keystone angle | (°) | 2.22 | 2.22 |
| N. turns | | 32 | 20 |
| N. blocks | | 2 | 2 |
| Insul. thickness (az/radial) | (mm) | 0.100/0.200 | 0.100/0.200 |



# THE HERA DIPOLE

- Main parameters
  - Current: 5027 A
  - Loadline fraction: 0.77
  - Temperature margin: -- K
  - Inductance: 58 mH
  - Stored energy: 0.733 MJ
  - Distance coil to iron: 30 mm
  - Iron contribution to field: 29%
  - Saturation: --%
  - Overall current density: 290 A/mm$^2$



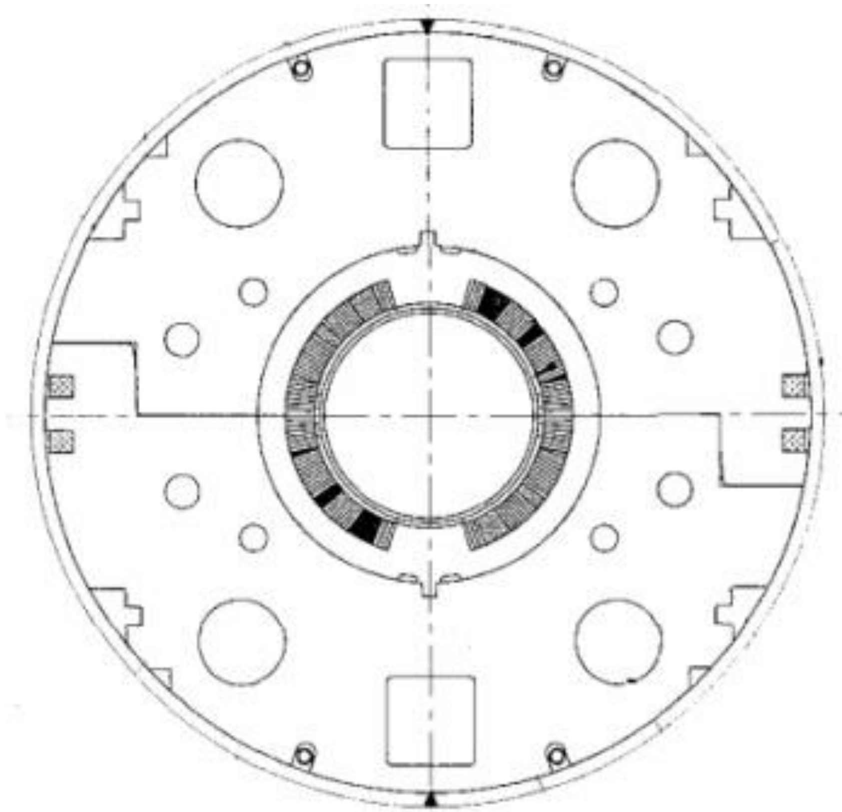
# THE HERA DIPOLE

- Mechanical structure
  - Al collars, 30 mm thick
  - Accumulated midplane stress: ~29 MPa
  - Radial stress: ~13 MPa

- Protection
  - Energy density over the insulated coil: 0.023 J/mm$^3$

# THE RHIC DIPOLE

- Scope: main dipole of the RHIC
  - Name: RHIC main dipole
  - Reference field: 3.46 T
  - Design: RHIC
  - Production: Northrop Grumman
  - Period: 1994-1996
  - Units: 264+32
  - Length: 9.45 m
  - Material: Nb-Ti
  - Operational temperature: *4.2* K
  - Aperture diameter: 80 mm
  - Outer diameter: *280* mm

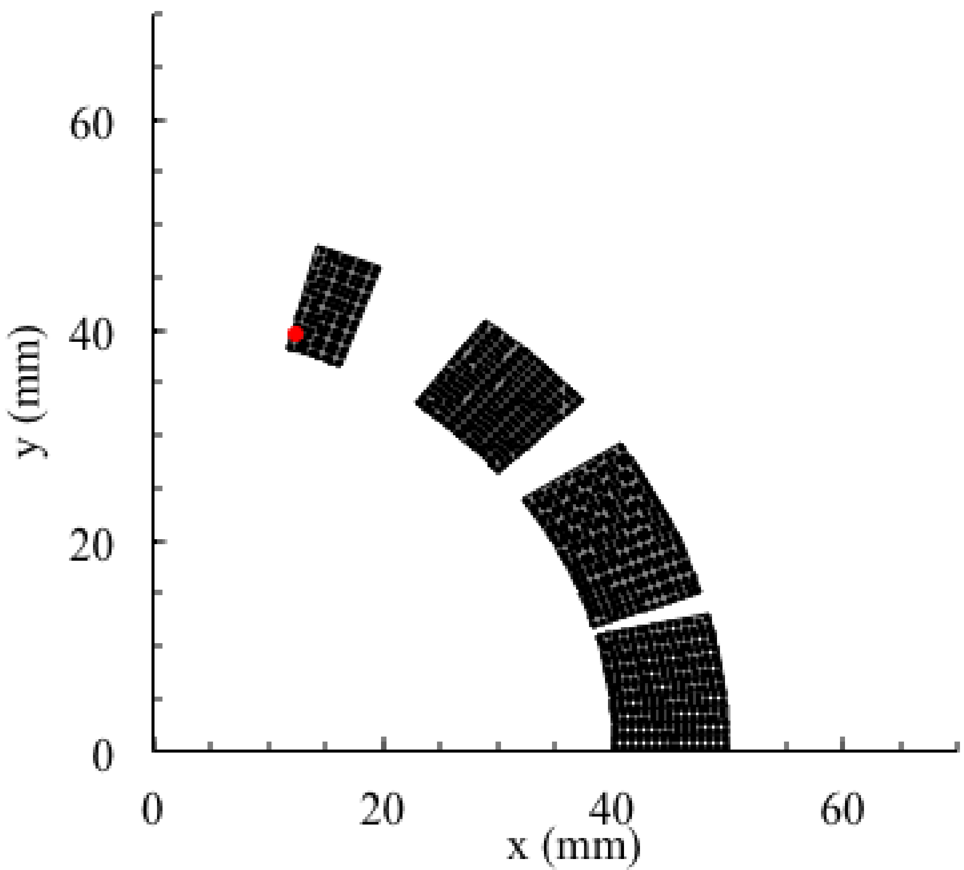


# THE RHIC DIPOLE

- Main features
  - An amazing exercise of cost optimization with the constraints imposed by Nb-Ti technology
  - Dipole aiming at minimizing the cost of integrated field
  - Support given by iron
  - Thin spacers between coil and iron to profit as much as possible of iron contribution
  - One layer to reduce manufacturing time
  - Only 10% of the magnets tested at 4.5 K

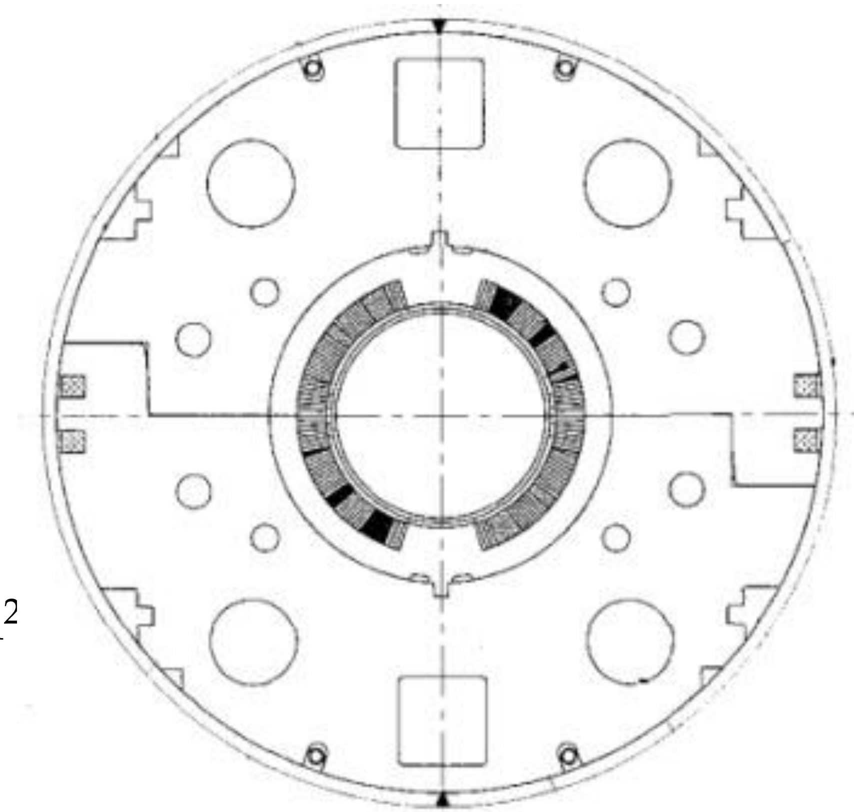
# THE RHIC DIPOLE

| | | Inner |
|---|---|---|
| Strand diameter | (mm) | 0.648 |
| Filament size | (μm) | |
| N strands | | 30 |
| Cu/No_cu | | 2.25 |
| Critical current density | (A/mm$^2$) | 2600 (5 T, 4.22 K) |
| Cable width | (mm) | 9.730 |
| Eq. coil width | (mm) | 9.2 |
| Cable mid thickness | (mm) | 1.166 |
| Keystone angle | (°) | 1.53 |
| N. turns | | 32 |
| N. blocks | | 4 |
| Insul. thickness (az/radial) | (mm) | 0.100/0.100 |



# THE RHIC DIPOLE

- Main parameters
  - Current: 5050 A
  - Loadline fraction: 0.60
  - Temperature margin: -- K
  - Inductance: 28 mH
  - Stored energy: 0.351 MJ
  - Distance coil to iron: 9.5 mm
  - Iron contribution to field: 57%
  - Saturation: 4%
  - Overall current density: 370 A/mm$^2$



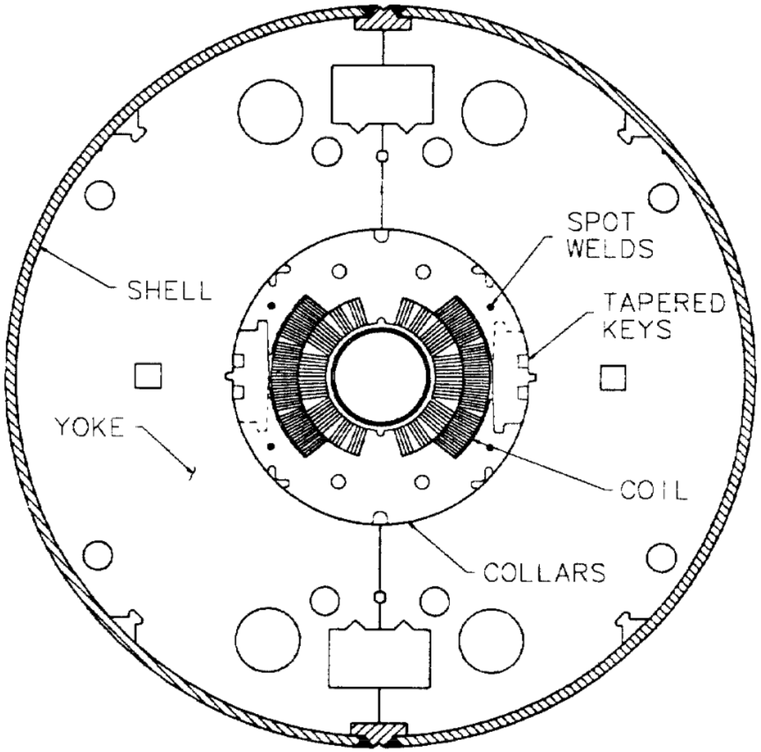
# THE RHIC DIPOLE

- Mechanical structure
  - Support given by iron
  - Accumulated midplane stress: ~28 MPa
  - Radial stress: ~7 MPa

- Protection
  - Protected by the diode
  - Energy density over the insulated coil: 0.022 J/mm$^3$

# THE SSC DIPOLE

- Scope: main dipole of the Superconducting Super Collider
  - Name: SSC dipole (main ring)
  - Reference field: 6.6 T
  - Design: SSC team
  - Production: several industries, labs
  - Period: 1985-1995
  - Units: several tens of short models
    nineteen 17-m-long magnets, 50 mm
    fifteen 15-m-long 40 mm aperture
  - Length: 17 m
    - Also 15 m built
  - Material: Nb-Ti
  - Operational temperature: 4.5 K
  - Aperture diameter: 50 mm
    - 40 mm in the first version
  - Outer diameter: 340 mm

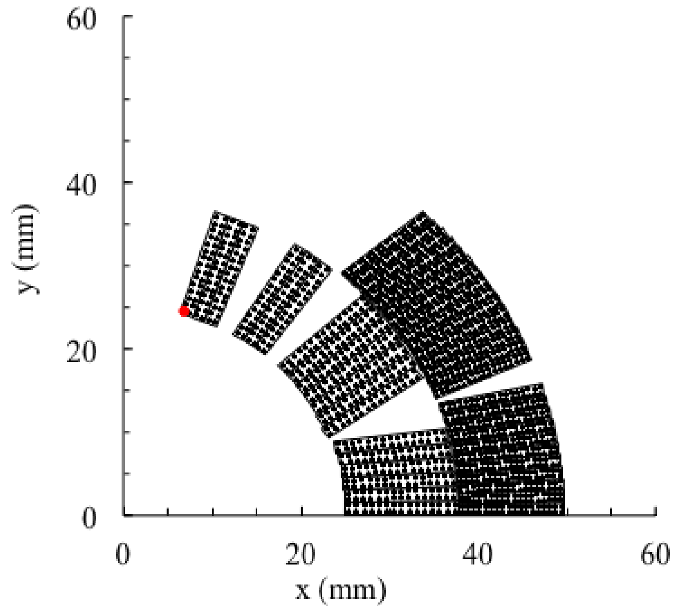


# THE SSC DIPOLE

- Main features
  - Two layers of 11-12 m width cable, with grading
  - Targeting a field above 6.5 T at 4.5 K

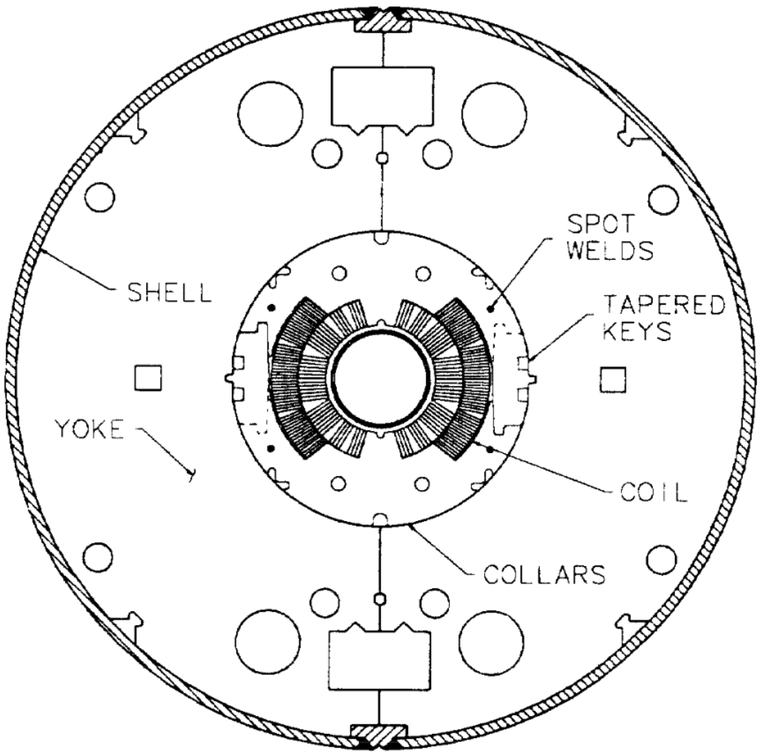
# THE SSC DIPOLE

| | | Inner | Outer |
|---|---|---|---|
| Strand diameter | (mm) | 0.808 | 0.648 |
| Filament size | (μm) | 6 | 6 |
| N strands | | 30 | 36 |
| Cu/No_cu | | 1.501 | 1.777 |
| Critical current density | (A/mm$^2$) | ~2200 A/mm$^2$ (at 5 T, 4.22K) | ~2200 A/mm$^2$ (at 5 T, 4.22K) |
| Cable width | (mm) | 12.603 | 11.645 |
| Eq. coil width | (mm) | 21.5 | |
| Grading | | 1.30 | |
| Cable mid thickness | (mm) | 1.454 | 1.153 |
| Keystone angle | (°) | 1.18 | 1.00 |
| N. turns | | 19 | 26 |
| N. blocks | | 4 | 2 |
| Insul. thickness (az/radial) | (mm) | 0.080/0.100 | 0.095/0.100 |



# THE SSC DIPOLE

- Main parameters
  - Current: 6600 A
  - Loadline fraction: 0.90
  - Temperature margin: ~0.7 K
  - Inductance:  75 mH
  - Stored energy: 1.58 MJ
  - Distance coil to iron: 17 mm
  - Iron contribution to field: 27%
  - Saturation: ~1%




  - Overall current density: 320/420 A/mm$^2$
    - Note: different mechanical structures were built, and variants of some design parameters (insulation, …)

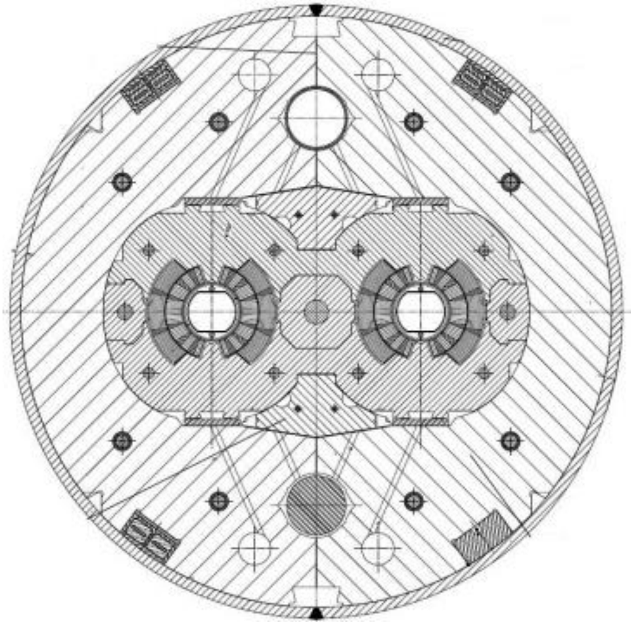
# THE SSC DIPOLE

- Mechanical structure
  - Stainless steel collars, 40 mm thick
  - Accumulated midplane stress: ~34 MPa
  - Radial stress: ~26 MPa

- Protection
  - Quench heaters
  - Energy density on the insulated coil: 0.032 J/mm$^3$

# THE LHC DIPOLE

- Scope: main dipole of the Large Hadron Collider
  - Name: LHC MB
  - Reference field: 8.3 T
    - Corresponding to 7 TeV operation
    - LHC operated until now at 6.5 TeV
    - Magnets are designed for ultimate field (9.0 T, corresponding to 7.5 TeV operation), and half of them were trained to that field
  - Period: 2000-2007
  - Units: 1232+46 spares
  - Length: 14.3 m
  - Material: Nb-Ti
  - Operational temperature: 1.9 K
  - Aperture diameter: 56 mm
  - Outer diameter: 570 mm

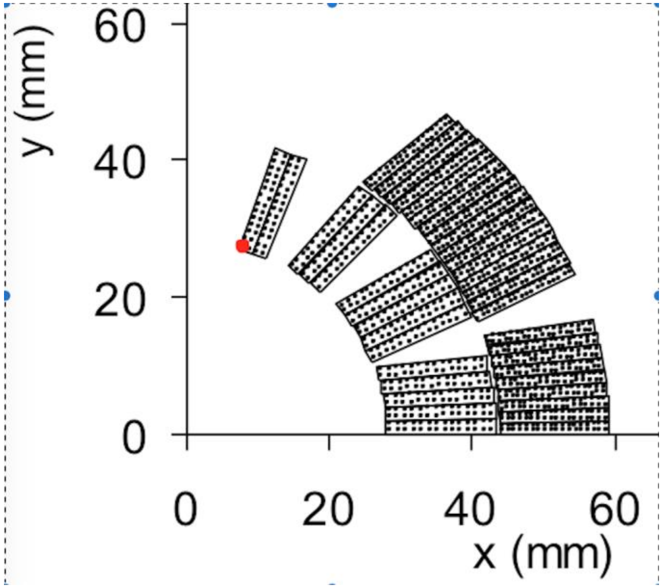


# THE LHC DIPOLE

- Main features
  - First accelerator magnet operated at 1.9 K
  - First accelerator magnet with double aperture
  - First accelerator magnet with twin collars
  - Largest series of accelerator magnets
  - Highest Nb-Ti field in large series dipoles
    - LHC prototypes (MFISC) and Fresca breached the 10 T barrier

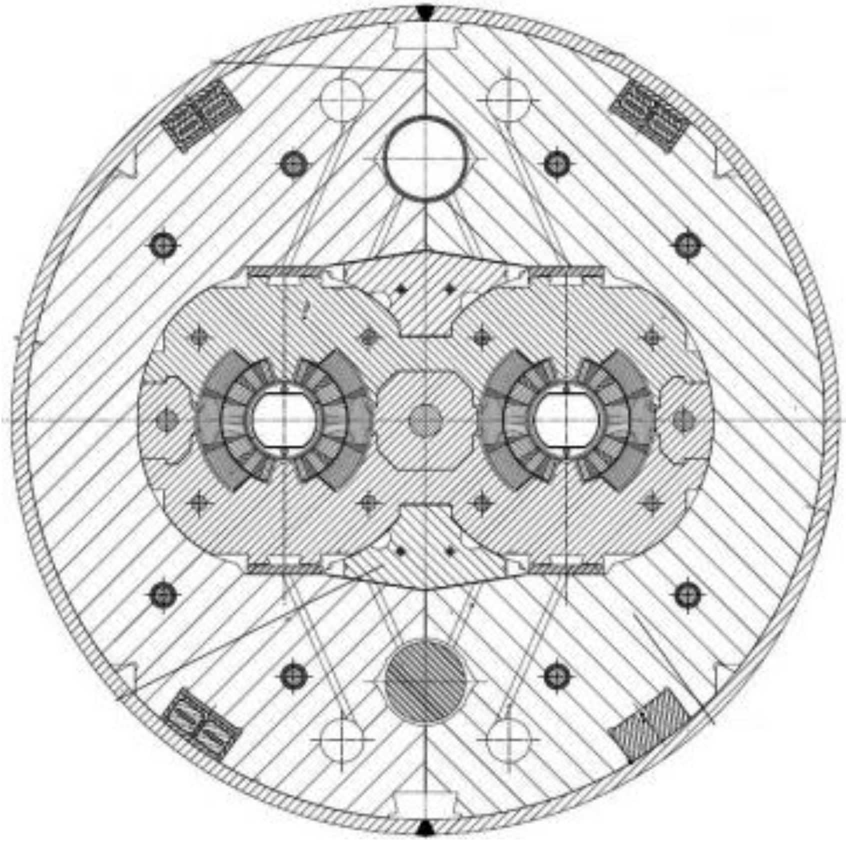
# THE LHC DIPOLE

| | | Inner | Outer |
|---|---|---|---|
| Strand diameter | (mm) | 1.065 | 0.825 |
| Filament size | (μm) | 7 | 6 |
| N strands | | 28 | 36 |
| Cu/No_cu | | 1.65 | 1.95 |
| Critical current density | (A/mm$^2$) | 1530 (10 T, 1.9 K) | 2100 (9 T, 1.9 K) |
| Cable width | (mm) | 15.1 | 15.1 |
| Eq. coil width | (mm) | 28 | |
| Grading | | 1.23 | |
| Cable mid thickness | (mm) | 1.900 | 1.480 |
| Keystone angle | (°) | 1.25 | 0.90 |
| N. turns | | 15 | 25 |
| N. blocks | | 4 | 2 |
| Insul. thickness (az/radial) | (mm) | 0.130/0.145 | 0.130/0.145 |



# THE LHC DIPOLE

- Main parameters
    - Note: values for two apertures
  - Current: 11850 A
  - Loadline fraction: 0.857/ 0.858
  - Temperature margin: 1.51/1.57 K
  - Inductance: 98.7 mH
  - Stored energy: 6.93 MJ
  - Distance coil to iron: 40 mm
  - Iron contribution to field: 18%
  - Saturation: 0.7%



  - Overall current density: 358 / 440 A/mm$^2$

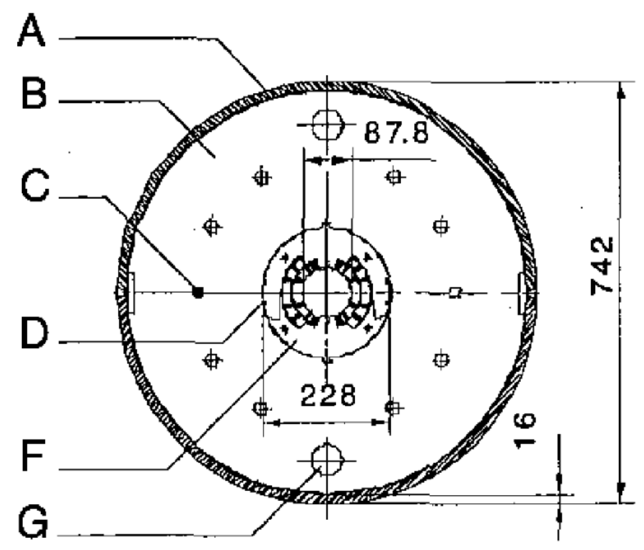
# THE LHC DIPOLE

- Mechanical structure
  - Stainless steel collars, 40 mm thick
  - Accumulated midplane stress: ~54 MPa
  - Radial stress: ~41 MPa

- Protection
  - Energy extraction (for busbars)
  - Quench heaters, two strips on outer layer
  - Time margin: 70 / 170 ms (inner/outer)
  - Energy density on the insulated coil: 0.052 J/mm$^3$

# FRESCA

- Scope: dipole for cable test station at CERN
  - Name: Fresca
  - Reference field: 9.5 T
    - Operated at 10.0 T, maximum field reached 10.07 T
  - Design: CERN
  - Production: CERN–HMA power systems
  - Period: 1998-2000
  - Units: 1
  - Length: 1.06 m
  - Material: Nb-Ti
  - Operational temperature: 1.9 K
  - Aperture diameter: 87 mm
  - Outer diameter: 742 mm



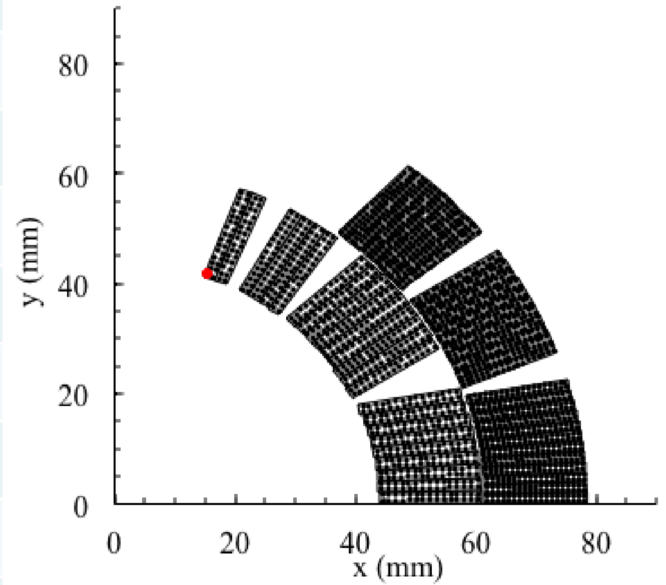

A) Shrinking Cylinder B) Yoke C) Alignment Key
D) Collar Key F) Collars G) Heat Exchanger Hole

# FRESCA

- Main features
  - Large aperture (43.9 mm radius), 50% more than LHC dipoles
  - One of the few Nb-Ti accelerator-like magnets above 10 T
  - Same mechanical concepts used for MFISC
    - Larger cable (1.5 mm more than LHC dipole)
    - Fit-to-fit mechanical structure, with full support from iron yoke to the collared coil (as in MFISC short model for LHC dipoles)

# FRESCA

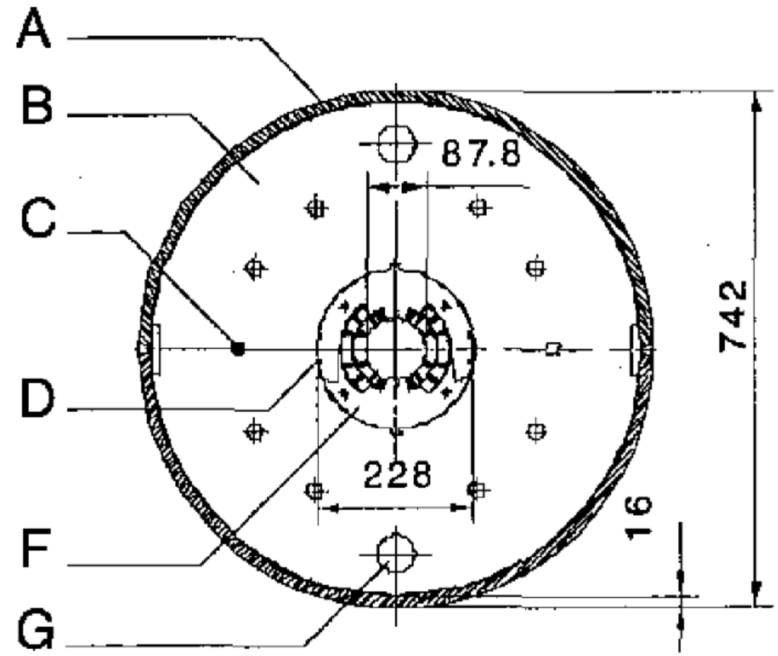
| | | Inner | Outer |
|---|---|---|---|
| Strand diameter | (mm) | 1.100 | 0.870 |
| Filament size | (µm) | 5 | 5 |
| N strands | | 30 | 38 |
| Cu/No_cu | | 1.6 | 1.87 |
| Critical current density | (A/mm$^2$) | 1503 (10 T, 1.9 K) | 1603 (10 T, 1.9 K) |
| Cable width | (mm) | 16.74 | 16.74 |
| Eq. coil width | (mm) | 30.4 | |
| Grading | | 1.24 | |
| Cable mid thickness | (mm) | 1.965 | 1.560 |
| Keystone angle | (°) | 1.20 | 0.83 |
| N. turns | | 24 | 32 |
| N. blocks | | 4 | 3 |
| Insulation thickness (az/radial) | (mm) | 0.130/0.145 | 0.130/0.145 |



# FRESCA

- Main parameters
  - Current: 12550 A
  - Loadline fraction: 0.93

  - Temperature margin: 0.8 K
  - Inductance: 7.5 mH
  - Stored energy: 0.623 MJ
  - Distance coil to iron: 35 mm
  - Iron contribution to field: 29%
  - Saturation: 4.5%
  - Overall current density: 338 (inner) 414 (outer) A/mm$^2$



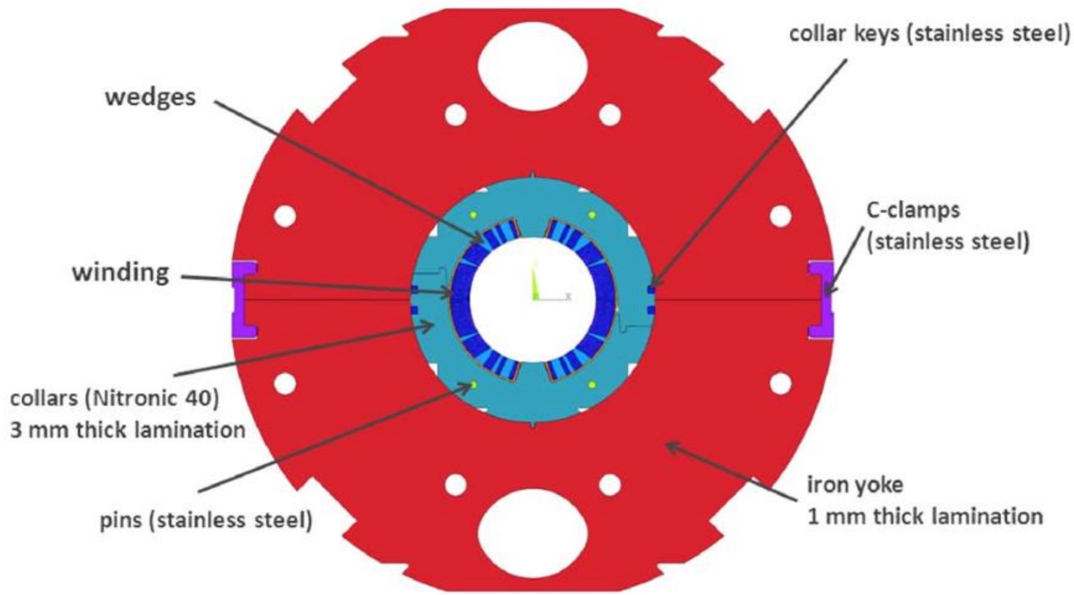

A) Shrinking Cylinder B) Yoke C) Alignment Key
D) Collar Key F) Collars G) Heat Exchanger Hole

# FRESCA

- Mechanical structure
  - Stainless steel collars, 35 mm thick, fit-to-fit yoke giving large rigidity
  - Accumulated midplane stress: ~85 MPa
  - Radial stress: ~54 MPa

# THE SIS 300 PROTOTYPE DIPOLE

- Scope: prototype dipole for SIS300 in GSI
  - Name: Discorap
  - Reference field: 4.5 T, ramped at 1 T/s
  - Design: INFN Genova and Milano
  - Production: ASG
  - Period: 2010-2014
  - Units: 1
  - Length: 3.88 m
  - Material: Nb-Ti
  - Operational temperature: 4.5 K
  - Aperture diameter: 100 mm
  - Outer diameter: 480 mm

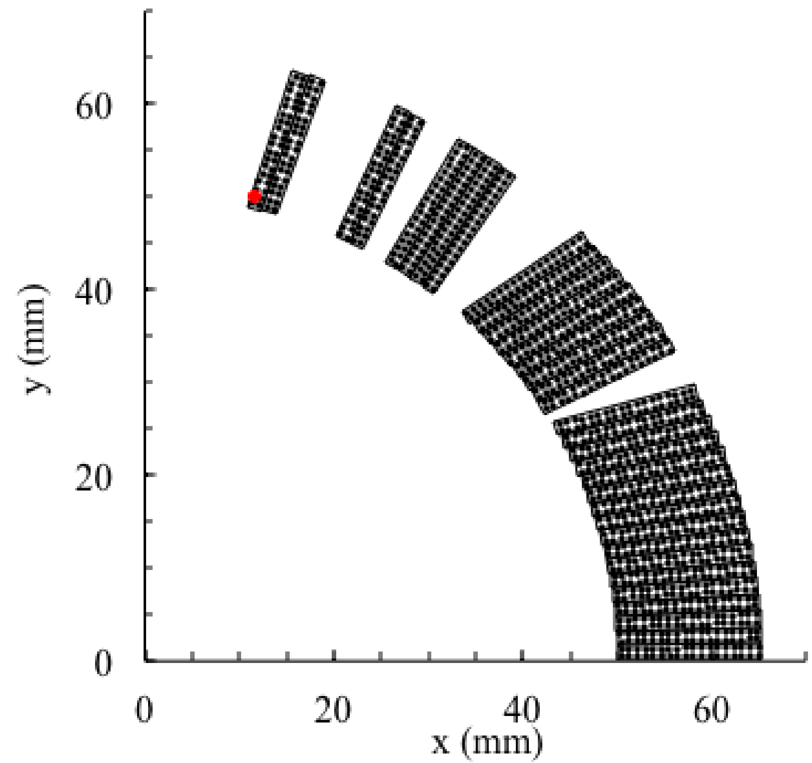


# THE SIS 300 PROTOTYPE DIPOLE

- Main features
  - Fast ramped dipole, low losses
    - Record of small filament (2-3 μm)
    - Cored cable (25-μm-thick steel core)
  - Curved dipole

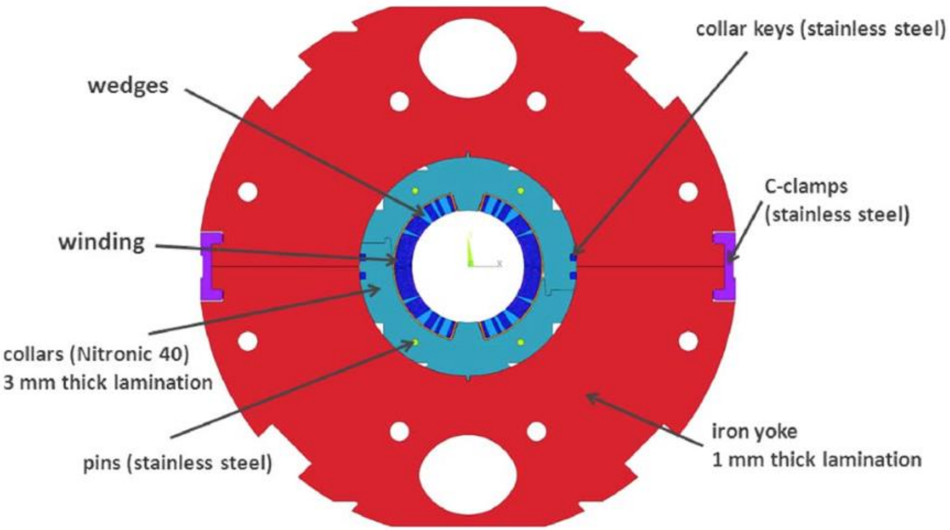
# THE SIS 300 PROTOTYPE DIPOLE

| | | Inner |
|---|---|---|
| Strand diameter | (mm) | 0.825 |
| Filament size | (μm) | 2.5 |
| N strands | | 36 |
| Cu/No_cu | | 1.5 |
| Critical current density | (A/mm$^2$) | 2530 (5 T, 4.22 K) |
| Cable width | (mm) | 15.10 |
| Eq. coil width | (mm) | 14.6 |
| Cable mid thickness | (mm) | 1.480 |
| Keystone angle | (°) | 0.90 |
| N. turns | | 34 |
| N. blocks | | 5 |
| Insulation thickness (az/radial) | (mm) | 0.100/0.125 |



# THE SIS 300 PROTOTYPE DIPOLE

- Main parameters
  - Current:  8926 A
  - Loadline fraction: 0.72
  - Temperature margin: --- K
  - Inductance: 12 mH
  - Stored energy: 0.459 MJ
  - Distance coil to iron: 31.5 mm
  - Iron contribution to field: 34%
  - Saturation: 60 units
  - Overall current density: 346 A/mm$^2$



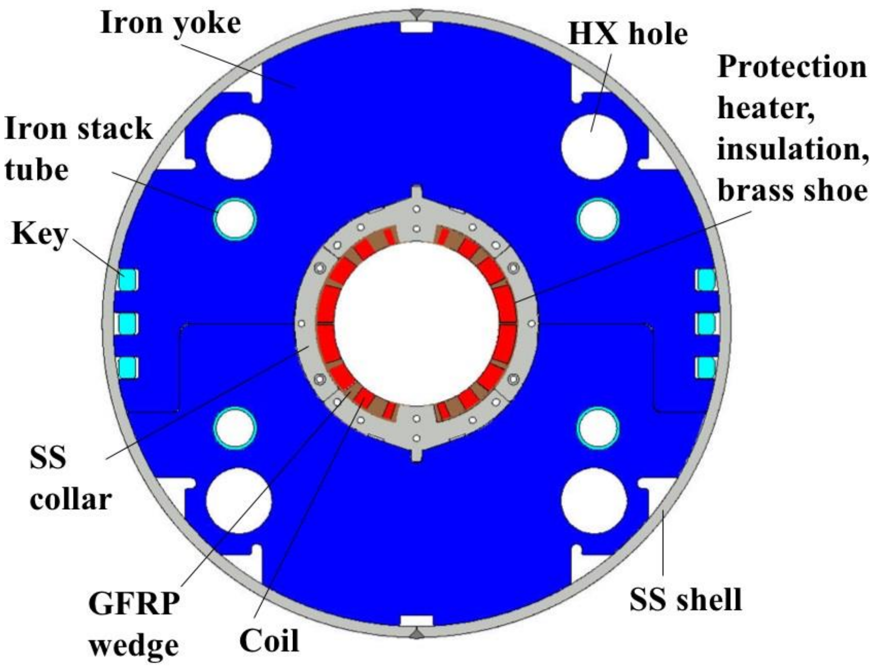
# THE SIS 300 PROTOTYPE DIPOLE

- Mechanical structure
  - Self supporting stainless steel collars, 30 mm thick
  - Accumulated midplane stress: ~42 MPa
  - Radial stress: ~12 MPa

- Protection
  - Quench heaters (same design of the LHC dipole)

# THE HL-LHC SEPARATION DIPOLE D1

- Scope: separation dipole for HL-LHC
  - Name: D1, MBXF
  - Reference field: 5.6 T
  - Design: KEK
  - Production: Hitachi
  - Period: 2011-2023
  - Units: 3 short models,
    1 prototype, 6 series
  - Length: 6.23 m
  - Material: Nb-Ti
  - Op. temperature: 1.9 K
  - Aperture diameter: 150 mm
  - Outer diameter: 570 mm

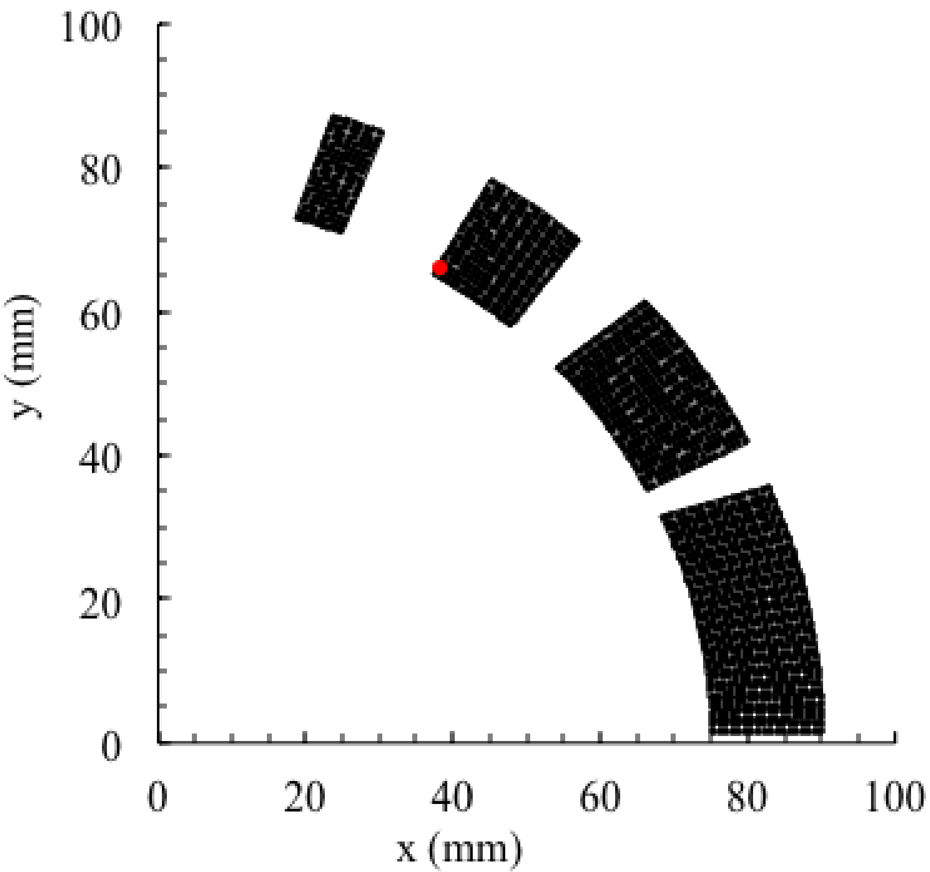


# THE HL-LHC SEPARATION DIPOLE D1

- Main features
  - Very large aperture dipole (150 mm diameter)
  - Unprecedented level of accumulation of azimuthal prestress in the midplane for Nb-Ti dipoles

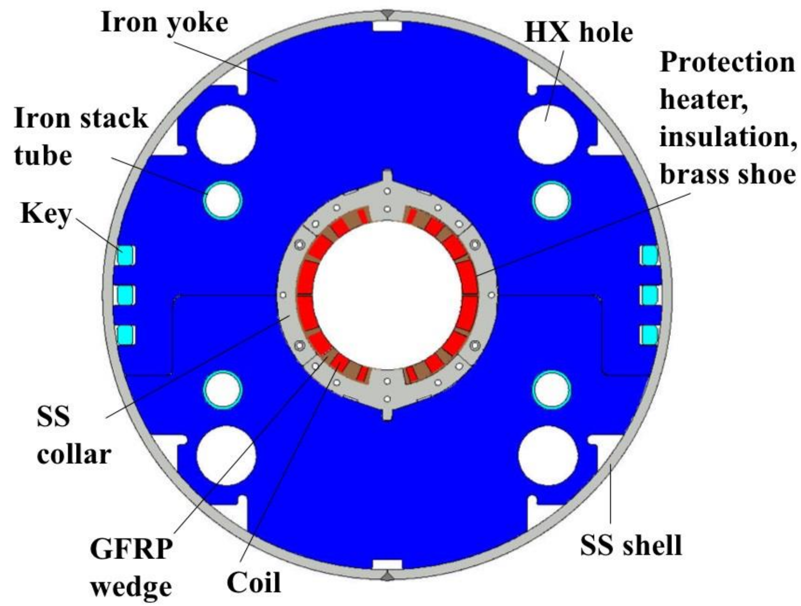
# THE HL-LHC SEPARATION DIPOLE D1

| | | |
|---|---|---|
| Strand diameter | (mm) | 0.825 |
| Filament size | (μm) | 6 |
| N strands | | 36 |
| Cu/No_cu | | 1.95 |
| Critical current density | (A/mm$^2$) | 2100 (9 T) |
| Cable width | (mm) | 15.1 |
| Eq. coil width | (mm) | 14.1 |
| Cable mid thickness | (mm) | 1.480 |
| Keystone angle | (°) | 0.90 |
| N. turns | | 44 |
| N. blocks | | 4 |
| Insulation thickness (az/radial) | (mm) | 0.135/0.155 |



# THE HL-LHC SEPARATION DIPOLE D1

- Main parameters
  - Current: 12070 A
  - Loadline fraction: 0.77
  - Temperature margin: 2.4 K
  - Inductance: 24.9 mH
  - Stored energy: 2.13 MJ
  - Distance coil to iron: 20 mm
  - Iron contribution to field: 34%
  - Saturation: 10%
  - Overall current density: 450 A/mm$^2$



# THE HL-LHC SEPARATION DIPOLE D1

- Mechanical structure
  - Support given by iron, stainless steel spacers 20 mm thick
  - Accumulated midplane stress: ~97 MPa
  - Radial stress: ~19 MPa

- Protection
  - Energy density on the insulated coil: 0.070 J/mm$^3$
  - Quench heaters (similar design of LHC dipole)

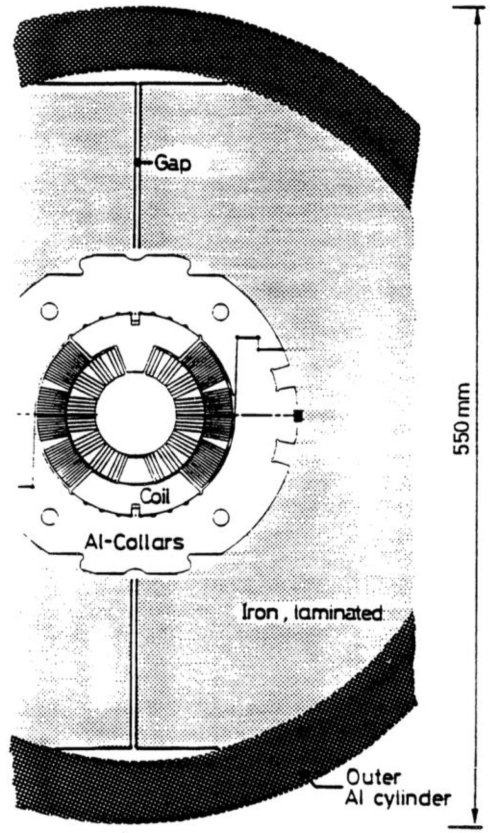
# CONTENTS

- Dipoles
  - Nb-Ti
  - $Nb_3Sn$

# CERN-ELIN

- Scope: $Nb_3Sn$ option for the LHC dipole
  - Name: CERN-ELIN
  - Reference field: 10 T at 4.3 K
  - Design: CERN
  - Production: ELIN
  - Period: 1989
  - Units: one short model
  - Length: 1 m
  - Material: $Nb_3Sn$
  - Op. temperature: 4.3 K
  - Aperture diameter: 55 mm*
  - Outer diameter: 550 mm
    - 9.5 T bore field reached at 4.3 K
    - 10.2 T maximum field reached at 4.3 K, mirror configuration, same results at 1.9 K

  * I found also 50 mm, to be clarified

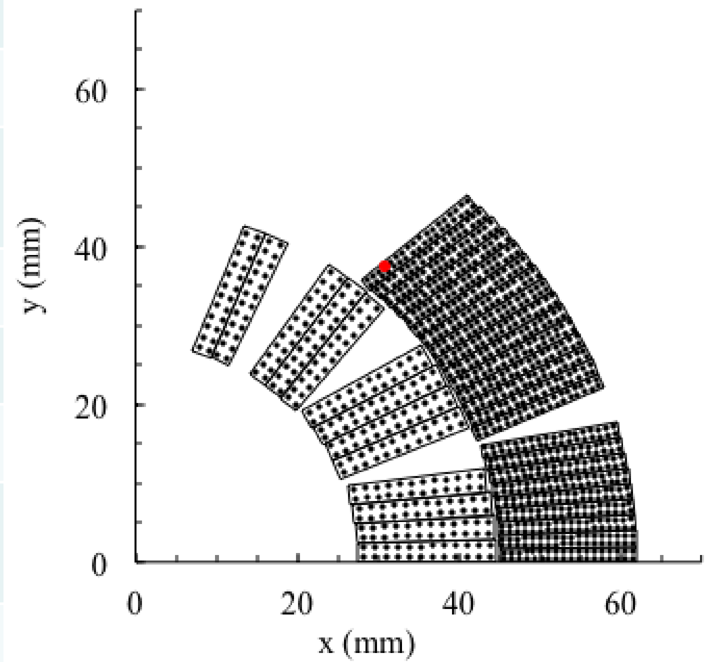


# CERN-ELIN

- Main novelties
  - Two layers with grading
  - Al collars and Al shell

# CERN-ELIN

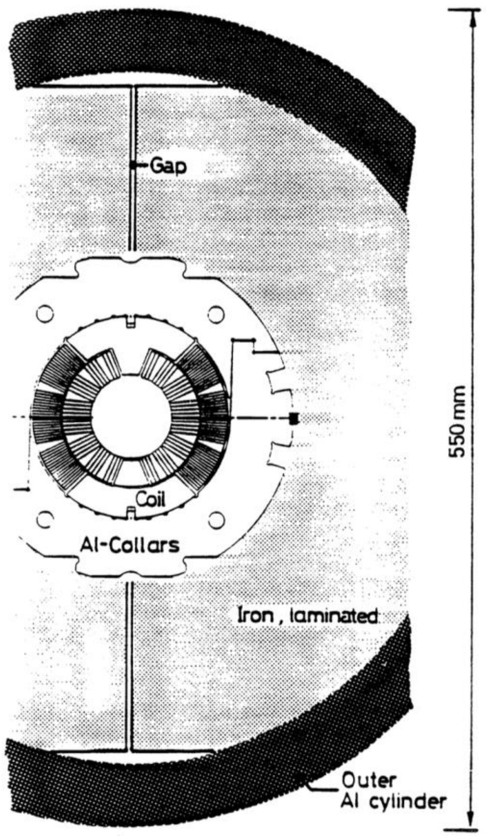
| | | | |
|---|---|---|---|
| Strand diameter | (mm) | 1.380 | 0.920 |
| Filament size | (μm) | | |
| N strands | | 24 | 36 |
| Cu/No_Cu | | 0.38 | 0.36 |
| Critical current density | (A/mm$^2$) | 810 (10 T, 4.22 K) | 850 (10 T, 4.22 K) |
| Cable width | (mm) | 16.81 | 16.81 |
| Eq. coil width | (mm) | 30.3 | |
| Grading | | 1.49 | |
| Cable mid thickness | (mm) | 2.440 | 1.630 |
| Keystone angle | (°) | 1.704 | 1.091 |
| N. turns | | 13 | 24 |
| N. blocks | | 4 | 2 |
| Insul. thickness (az/radial) | (mm) | *0.14/0.14* | *0.10/0.10* |



# CERN-ELIN

- Main parameters
  - Current:  16350 A
  - Loadline fraction: 0.90 (4.4 K)

  - Temperature margin: --
  - Inductance: -- mH
  - Stored energy: 0.316 MJ
  - Distance coil to iron: 35 mm
  - Iron contribution to field: 16%
  - Overall current density: 352 A/mm$^2$ 525 A/mm$^2$



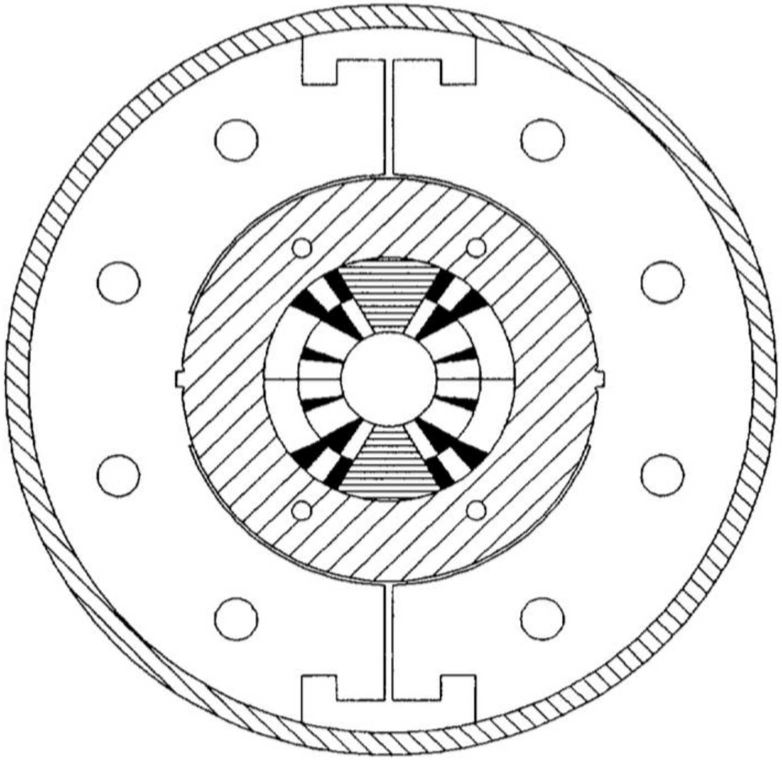
# CERN-ELIN

- Mechanical structure
  - Al collars and iron yoke
  - Accumulated midplane stress: ~66 MPa
  - Radial stress: ~60 MPa

- Protection
  - Energy density on the insulated coil: 0.057 J/mm$^3$

# MSUT

- Scope: R&D $Nb_3Sn$ magnet based on sector coil
  - Name: MSUT
  - Reference field: 11 T at 4.4 K
    - Initially at 11.5 T
  - Design: University of Twente
  - Production:
  - Period: 1992-1997
  - Units: one short model
  - Length: 1 m
  - Material: $Nb_3Sn$
  - Op. temperature: 4.4 K
  - Aperture diameter: 50 mm
  - Outer diameter: 395 mm
    - 11.03 T maximum field reached at 4.4 K

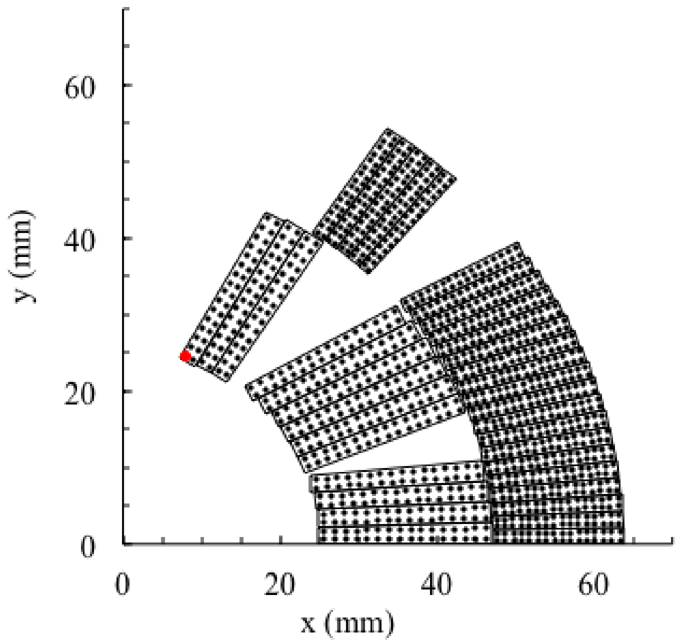


# MSUT

- Main features
  - Insulation based on mica U-shaped sheet and glass fiber tape
  - Two layers with grading
  - Al ring collars and iron yoke structure

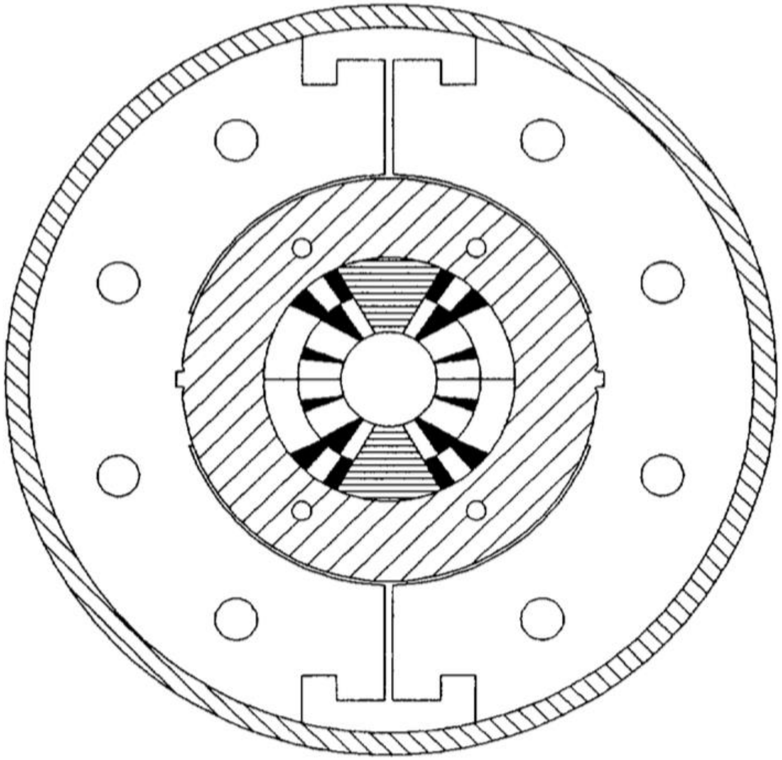
# MSUT

| | | | |
|---|---|---|---|
| Strand diameter | (mm) | 1.260 | 1.000 |
| Filament size | (μm) | 42 | 32 |
| N strands | | 33 | 33 |
| Cu/No_Cu | | 1.25 | 1.25 |
| Critical current density | (A/mm$^2$) | 1850 (10 T, 4.22 K) | 1850 (10 T, 4.22 K) |
| Cable width | (mm) | 21.7 | 17.4 |
| Eq. coil width | (mm) | 34.8 | |
| Grading | | 1.59 | |
| Cable mid thickness | (mm) | 2.225 | 1.680 |
| Keystone angle | (°) | 1.300 | 0.900 |
| N. turns | | 13 | 24 |
| N. blocks | | 3 | 3 |
| Insul. thickness (az/radial) | (mm) | 0.14/0.14 | 0.14/0.14 |



# MSUT

- Main parameters
  - Current: 18700 A
  - Loadline fraction: 0.90 (4.4 K)
  - Temperature margin: --
  - Inductance: -- mH
  - Stored energy: --- MJ
  - Distance coil to iron: 42.5 mm
  - Iron contribution to field: 13%
  - Overall current density: 340 A/mm$^2$ 540 A/mm$^2$



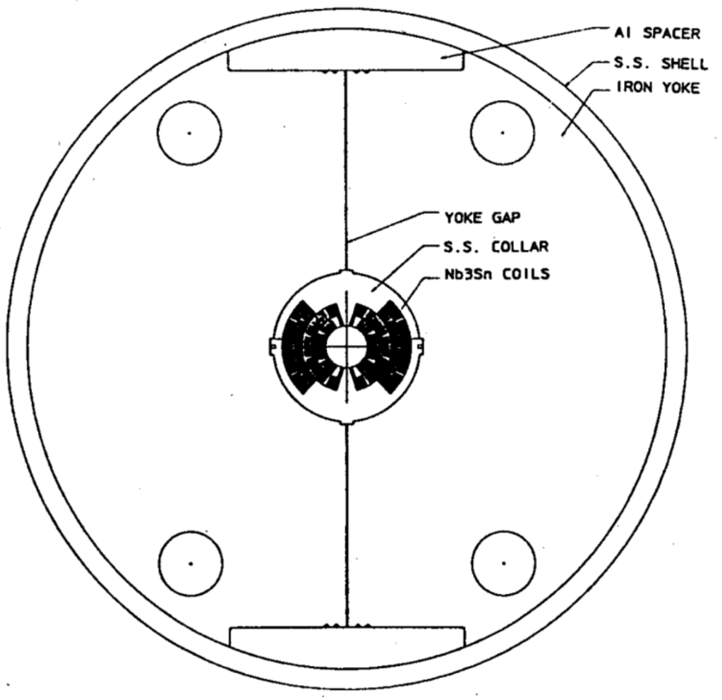
# MSUT

- Mechanical structure
  - Al ring, iron yoke
  - Accumulated midplane stress: ~69 MPa
  - Radial stress: ~72 MPa

- Protection
  - Energy density on the insulated coil: --- J/mm$^3$

# LNBL D20

- Scope: R&D $Nb_3Sn$ magnet based on sectoı
  - Name: D20
  - Reference field: 13 T at 4.35 K*
    - (14.5 T short sample at 1.9 K)
  - Design: LBNL
  - Production: LBNL
  - Period: 1993-1997
  - Units: one short model D20
  - Length: 1 m
  - Material: $Nb_3Sn$
  - Op. temperature: 1.9 K
  - Aperture diameter: 50 mm
  - Outer diameter: 600 mm
    - Note: reference field not defined, papers present the magnet target as >13 T short sample at 4.5 K
    - 13.5 T reached at 1.8 K, 12.8 T at 4.5 K

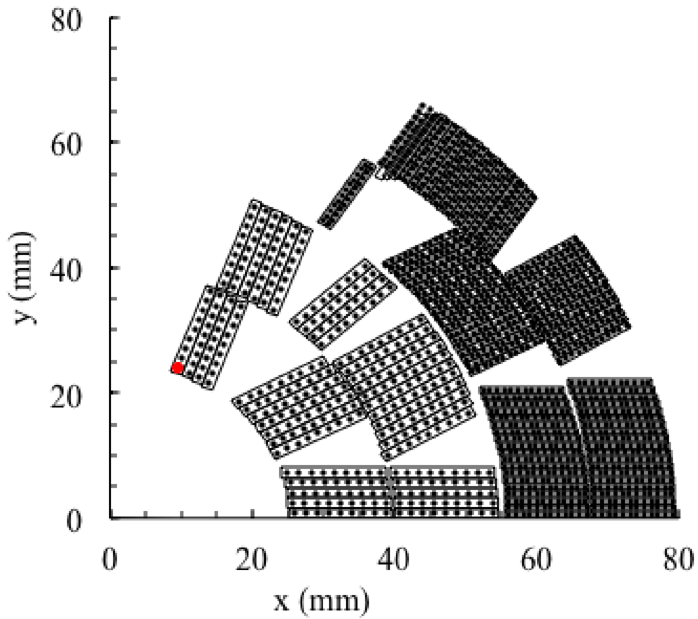


# LNBL D20

- Main features
  - Four layers
  - No keystoning to overcome degradation of keystoned cable
  - Largest grading: 1.80 (current density in the outer cable is 80% larger than in the inner cable)
  - Sector coil made with rectangular cable, 13 blocks and 9 wedges
    - Inner layer strand with extremely low quantity of copper (Cu/noCu 0.4), not protectable for long magnet

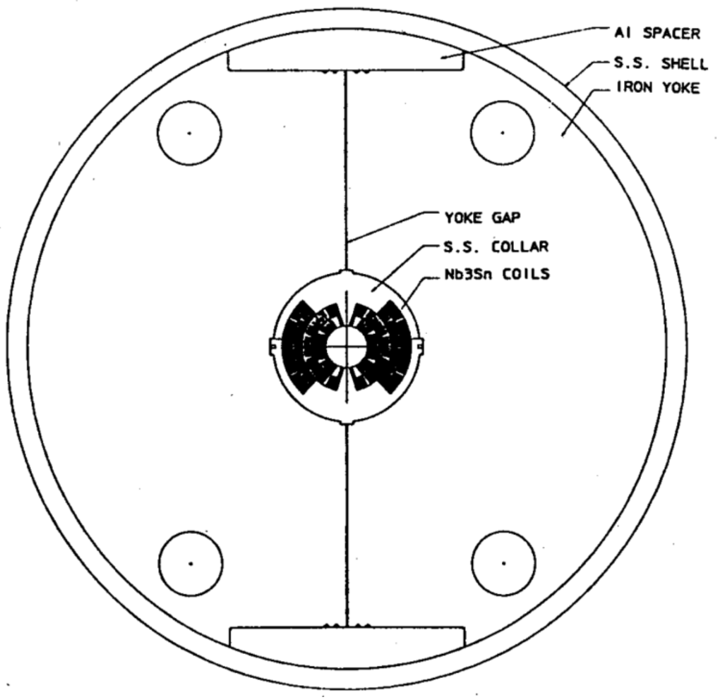
# LNBL D20

| | | | |
|---|---|---|---|
| Strand diameter | (mm) | 0.750 | 0.480 |
| Filament size | (μm) | | |
| N strands | | 37 | 47 |
| Cu/No_Cu | | 0.43 | 1.00 |
| Critical current density | ($A/mm^2$) | 515 (13.5 T, 4.22 K) | 1519 (10.5 T, 4.22 K) |
| Cable width | (mm) | 14.45 | 11.63 |
| Eq. coil width | (mm) | 44.8 | |
| Grading | | 1.80 | |
| Cable mid thickness | (mm) | 1.369 | 0.873 |
| Keystone angle | (°) | 0.000 | 0.000 |
| N. turns | | 42 | 96 |
| N. blocks | | 7 | 6 |
| Insul. thickness (az/radial) | (mm) | | |



# LNBL D20

- Main parameters
  - Current: 5800 A
  - Loadline fraction: 0.97 (4.5 K)
    0.90 (1.9 K)



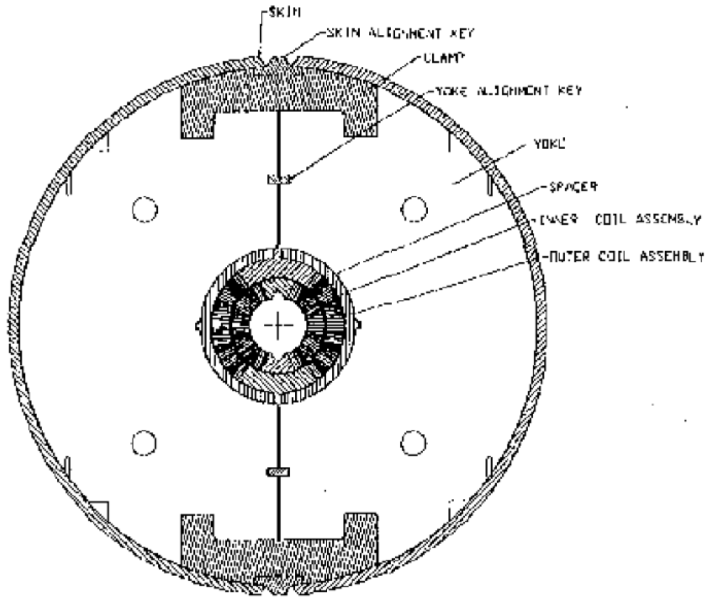

  - Temperature margin: --
  - Inductance: 45 mH
  - Stored energy: 0.75 MJ
  - Distance coil to iron: few mm
  - Iron contribution to field: 15%
  - Overall current density: 250 A/mm$^2$ 450 A/mm$^2$

# LNBL D20

- Mechanical structure
  - Bladder and keys and Al shell
  - Iron is very close to the coil (few mm)
  - Accumulated midplane stress: ~53 MPa
    - This estimate should be taken with some care since based on equation ignoring grading, and here the grading is very strong
  - Radial stress: ~101 MPa

- Protection
  - Energy density on the insulated coil: 0.103 J/mm$^3$
  - A very low Cu fraction in inner layer
  - Quench heaters and energy extraction

- Scope: cost-optimized dipole for VLHC
  - Name: HFDA, also 11 T
  - Reference field: 11 T
  - Design: FNAL
  - Production: FNAL
  - Period: 2000-2005
  - Units: three short models, two mirrors
  - Length: 1.0 m
  - Material: $Nb_3Sn$
  - Op. temperature: 1.9 K
  - Aperture diameter: 43.5 mm
  - Outer diameter: 420 mm
    - Limited to 40-60%, due to instabilities

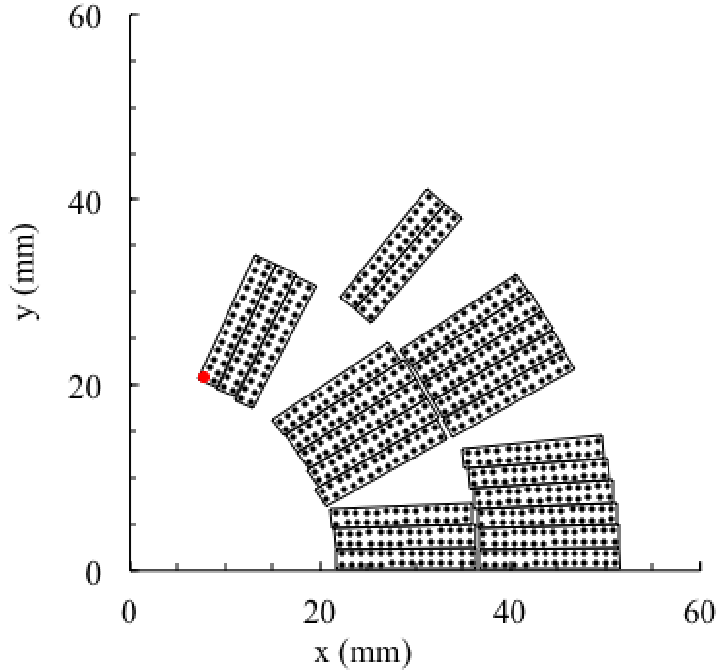


# FNAL HFDA

- Main novelties
  - Step back in field with respect to D20, HD2 to have a better optimized field versus cost (magnet is for a very large hadron collider, so lower field can be traded versus longer tunnel)
  - Very large overall current density to achieve the 11 T target (585 A/mm$^2$)

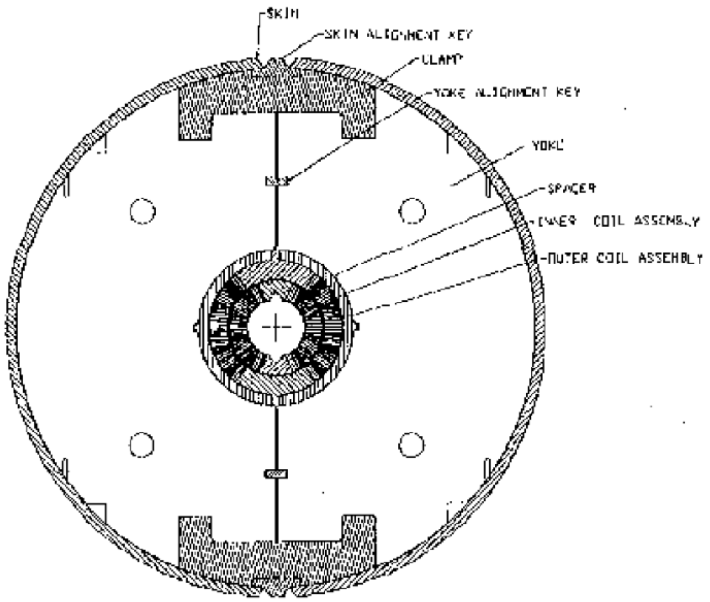
# FNAL HFDA

| | | |
|---|---|---|
| Strand diameter | (mm) | 1.000 |
| Filament size | (μm) | |
| N strands | | 28 |
| Cu/No_cu | | *0.83 (TBC)* |
| Critical current density | ($A/mm^2$) | (11 T, 4.22 K) |
| Cable width | (mm) | 14.232 |
| Eq. coil width | (mm) | 23.3 |
| Cable mid thickness | (mm) | 1.800 |
| Keystone angle | (°) | 0.9 |
| N. turns | | 24 |
| N. blocks | | 6 |
| Insul. thickness (az/radial) | (mm) | 0.250/0.250 |



# FNAL HFDA

- Main parameters
  - Current:  19800 A
  - Loadline fraction: --
  - Temperature margin: --
  - Inductance: 1.5 mH
  - Stored energy: 0.240 MJ
  - Distance coil to iron: 10 mm
  - Iron contribution to field: 24%
  - Overall current density: 585 A/mm$^2$



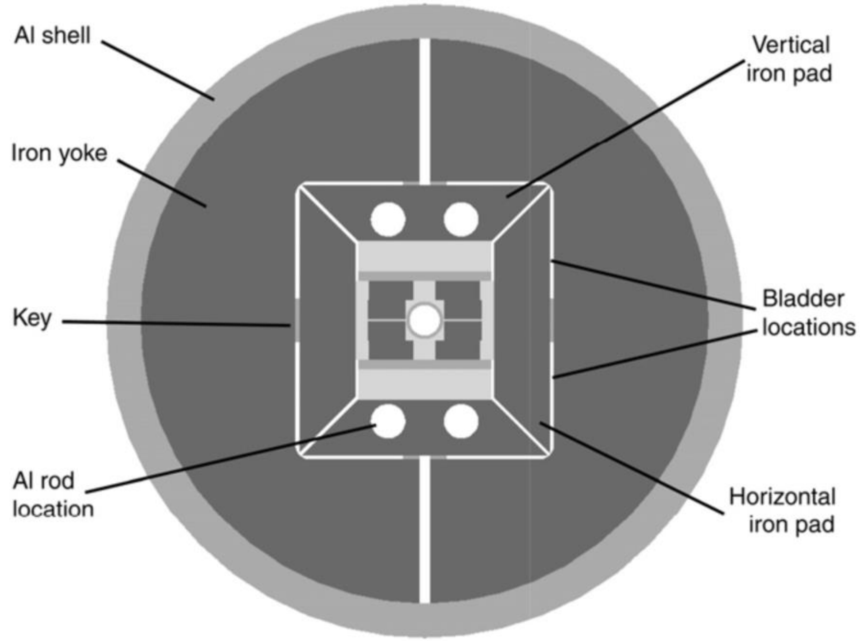
# FNAL HFDA

- Mechanical structure
  - Iron yoke based – thin spacers
  - Accumulated midplane stress: ~97 MPa
  - Radial stress: ~72 MPa

- Protection
  - Energy density on the insulated coil: 0.074 J/mm$^3$
  - Energy extraction and heaters

# LNBL HD2

- Scope: R&D $Nb_3Sn$ magnet based on block coils
  - Name: HD2
  - Reference field: 15 T*
  - Design: LBNL
  - Production: LBNL
  - Period: 2005-2010
  - Units: one short model HD2
    - a-b-c tests, plus d-e without cold bore, i.e. with 43 mm aperture
  - Length: 1 m
  - Material: $Nb_3Sn$
  - Op. temperature: tested only at 4.5 K
  - Aperture diameter: 35 mm
    - Including the inner structure
  - Outer diameter: 600 mm
    - Note: reference field not defined, papers establish a target of 15.0 T bore field
    - 13.74 T reached at 4.5 K
    - A second iteration on the design was done, named HD3 (2010-2014)

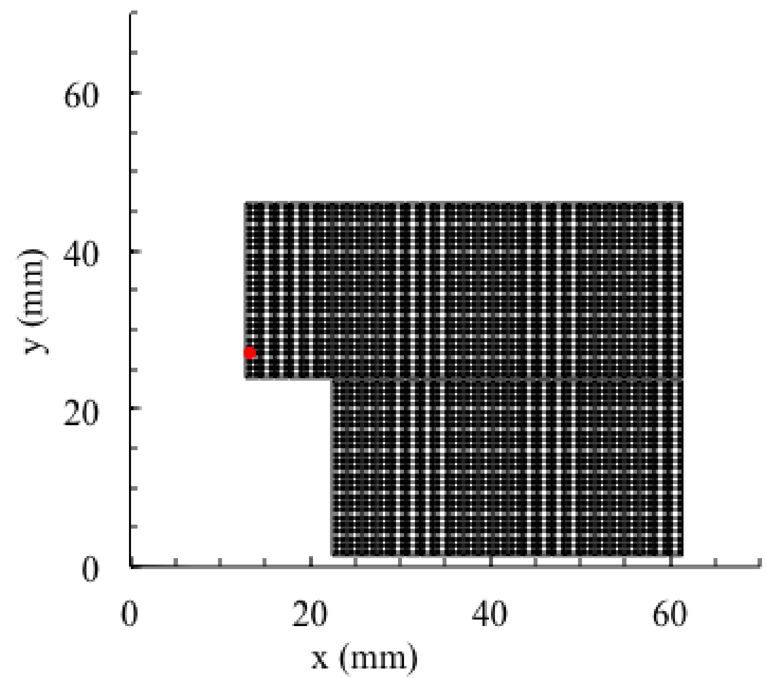


# LNBL HD2

- Main features
  - A dipole with accelerator features based on blocks
  - No wedges needed in the coil
  - Two layer coil, limiting the free aperture at 35 mm
  - Saddle ends to give space to the aperture
    - A similar paradigm adopted for FrescaII, but with four layers (no wedges, saddle ends

# LNBL HD2

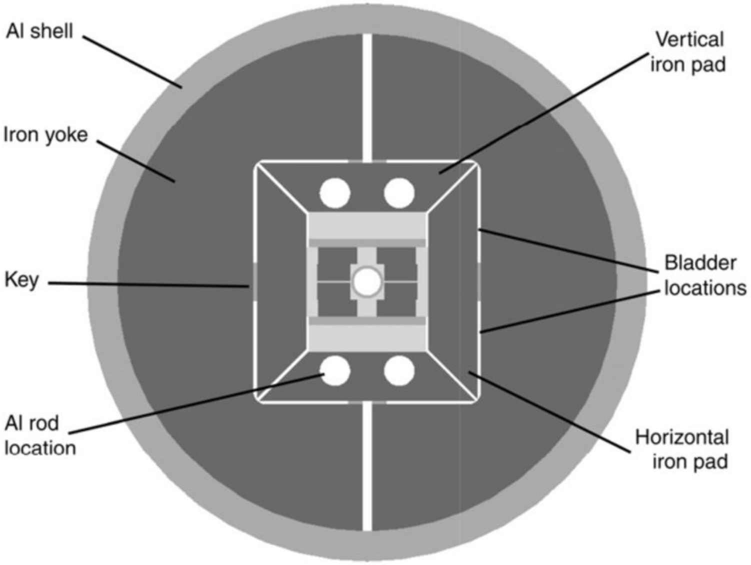
| | | |
|---|---|---|
| Strand diameter | (mm) | 0.800 |
| Filament size | (μm) | |
| N strands | | 51 |
| Cu/No_cu | | 0.95 |
| Critical current density | ($A/mm^2$) | 1250 (16 T, 4.22 K) |
| Cable width | (mm) | 22 |
| Eq. coil width | (mm) | 45.9 |
| Cable mid thickness | (mm) | 1.400 |
| Keystone angle | (°) | 0.000 |
| N. turns | | 54 |
| N. blocks | | 2 |
| Insul. thickness (az/radial) | (mm) | 0.11/0.11 |



# LNBL HD2

- Main parameters
  - Current:  17400 A
  - Loadline fraction: 0.96 (4.5 K)
    0.88 (1.9 K)*
  - Temperature margin: --
  - Equivalent coil width: 44.1 mm
  - Inductance: 5.6 mH
  - Stored energy: 0.75 MJ
  - Grading: no
  - Distance coil to iron: few mm
  - Iron contribution to field: 15%
  - Saturation: 10%
  - Overall current density: 483 A/mm$^2$

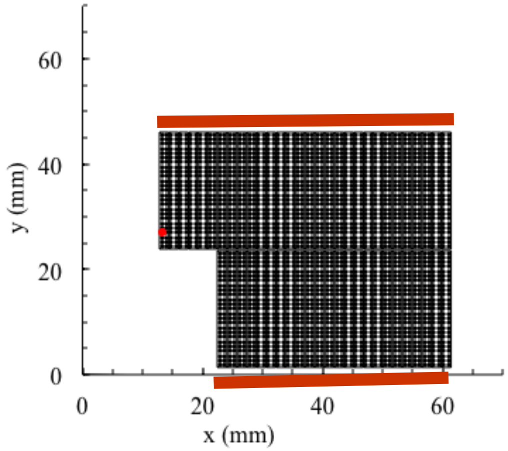
*never tested at 1.9 K



# LNBL HD2

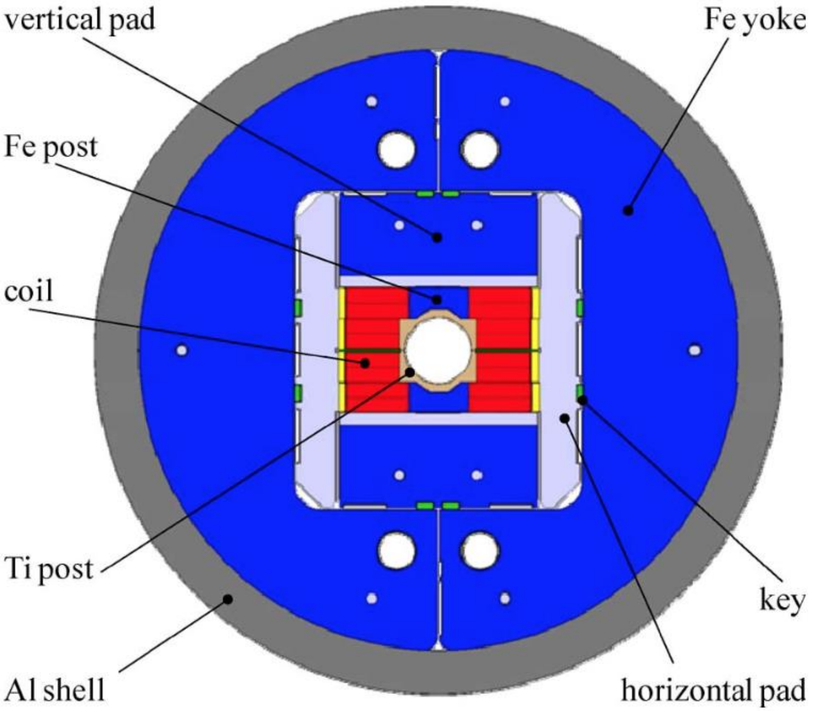
- Mechanical structure
  - Bladder and keys and Al shell
  - Iron is very close to the coil (few mm)
  - Radial (horizontal) stress: 107/154 MPa (lower/upper deck)
    - This estimated via the Fx value given in the literature divided by the cable width

- Protection
  - Energy extraction and quench heaters



# FRESCA2

- Scope: dipole for cable test station at CERN
  - Name: FRESCA2
  - Reference field: 13 T, with 15 T as ultimate
  - Design: CERN
  - Production: CERN and CEA
  - Period: 2012-2019
  - Units: one
    - Coil replacement
  - Length: 1.2 m
  - Material: $Nb_3Sn$
  - Op. temperature: 1.9 K
  - Aperture diameter: 100 mm
  - Outer diameter: 1030 mm
    - 14.6 T reached

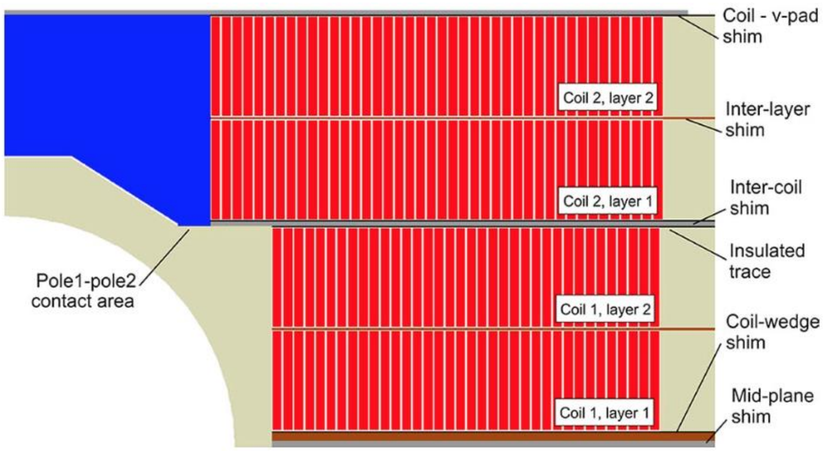


# FRESCA2

- Main features
  - Unprecedented coil width (80 mm equivalent)
  - Very low overall current density to achieve the 13 T target (220 A/mm$^2$)
  - A large aperture dipole with accelerator features based on blocks
  - No wedges needed in the coil
  - Four layers coil, required by the large aperture of 50 mm
  - Saddle ends to give space to the aperture
    - Same paradigm adopted for HD2

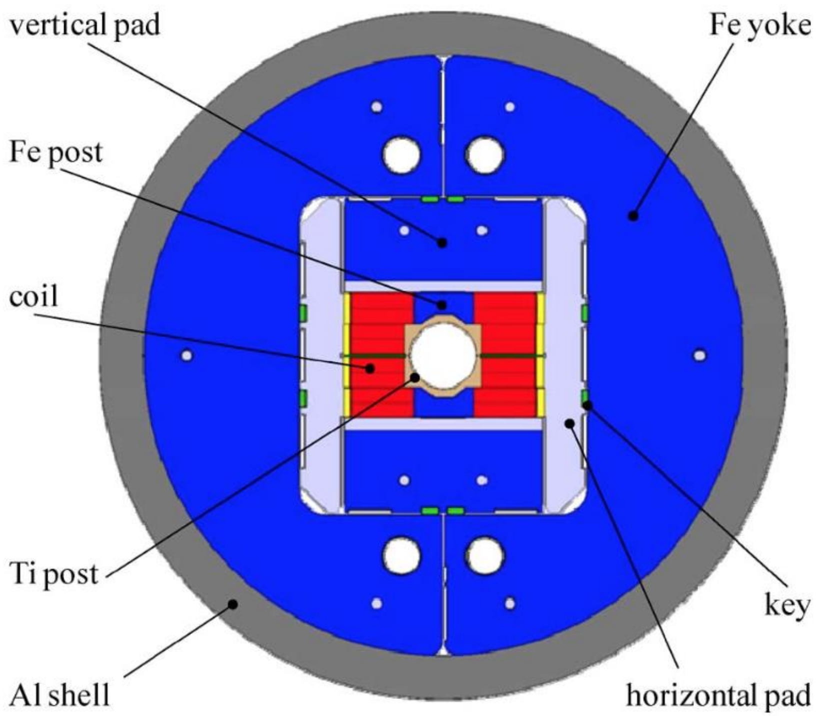
# FRESCA2

| | | |
|---|---|---|
| Strand diameter | (mm) | 1.000 |
| Filament size | (μm) | 48 |
| N strands | | 40 |
| Cu/No_cu | | 1.3 |
| Critical current density | (A/mm$^2$) | 1400 (15 T, 4.22 K) |
| Cable width | (mm) | 21.32 |
| Eq. coil width | (mm) | 81.6 |
| Cable mid thickness | (mm) | 1.890 |
| Keystone angle | (°) | 0.000 |
| N. turns | | 156 |
| N. blocks | | 4 |
| Insulation thickness (az/radial) | (mm) | 0.200/0.200 |



# FRESCA2

- Main parameters
  - Current:  10900 A
  - Loadline fraction: 0.72
  - Temperature margin: 5.8
  - Inductance: 50 mH
  - Stored energy: 4.6 MJ
  - Distance coil to iron: 20 mm
  - Iron contribution to field: 15%
  - Overall current density: 220 A/n

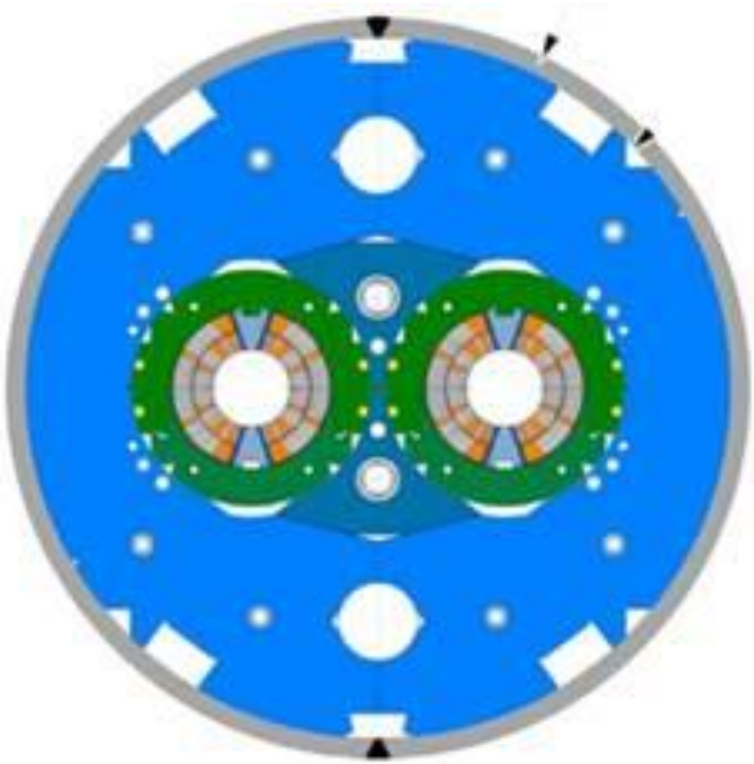


# FRESCA2

- Mechanical structure
  - Bladder and keys and Al shell
  - Radial (horizontal) stress: 80/100 MPa (lower/upper deck)
    - This estimated via the Fx  value given in the literature divided by the cable width
- Protection
  - Energy density on the insulated coil: 0.122 J/$mm^3$
  - Energy extraction and heaters

# HL-LHC 11 T

- Scope: dipole to make room for some collimators in the LHC lattice
  - Name: 11 T
  - Reference field: 11.24 T, with 12.04 T as ultimate (7.5 TeV operation)
  - Design: CERN
  - Production: CERN and GE
  - Period: 2011-ongoing
  - Units: six magnets
    - Plus 10 apertures build for short models
  - Length: 5.3 m
  - Material: $Nb_3Sn$
  - Op. temperature: 1.9 K
  - Aperture diameter: 60 mm
  - Outer diameter: 570 mm
    - >12 T reached

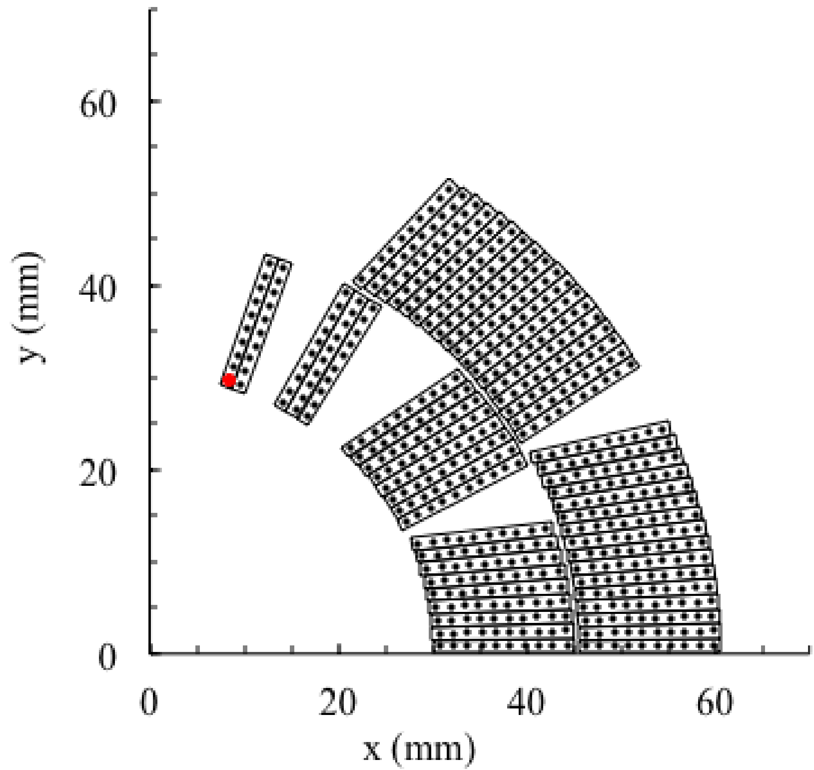


# HL-LHC 11 T

- Main features
  - First $Nb_3Sn$ magnet to be installed in an accelerator
  - First two-in-one $Nb_3Sn$ dipole
  - Design constrained by providing the same integrated field of the LHC dipole with the same current as in the LHC dipoles (11850 A)
    - SS Collars
    - Insulation based on mica sheet and glass fiber (as in MSUT)
    - Removable pole (as in MSUT)

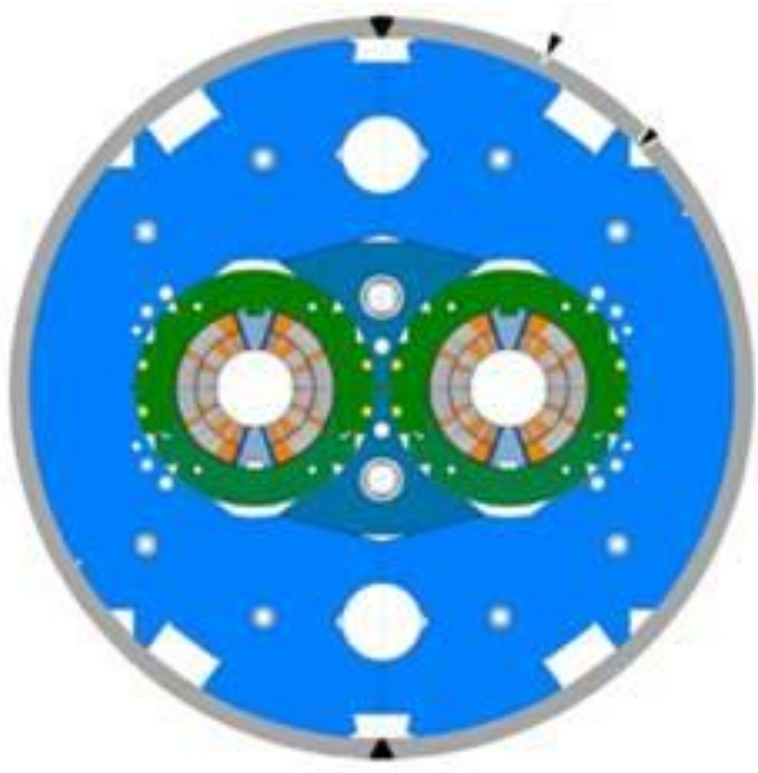
# HL-LHC 11 T

| | | |
|---|---|---|
| Strand diameter | (mm) | 0.700 |
| Filament size | (μm) | 50 |
| N strands | | 40 |
| Cu/No_cu | | 1.15 |
| Critical current density | (A/mm$^2$) | 2450 (12 T, 4.22 K) |
| Cable width | (mm) | 14.85 |
| Eq. coil width | (mm) | 81.6 |
| Cable mid thickness | (mm) | 1.288 |
| Keystone angle | (°) | 0.500 |
| N. turns | | 56 |
| N. blocks | | 6 |
| Insulation thickness (az/radial) | (mm) | 0.100/0.100 |



# HL-LHC 11 T

- Main parameters
  - Current:  11850 A
  - Loadline fraction: 0.80
  - Temperature margin: 4.5 K
  - Inductance: 50 mH
  - Stored energy: 4.6 MJ
  - Distance coil to iron: 25 mm
  - Iron contribution to field: 15%
  - Saturation: 5%
  - Overall current density: 530 A/mr



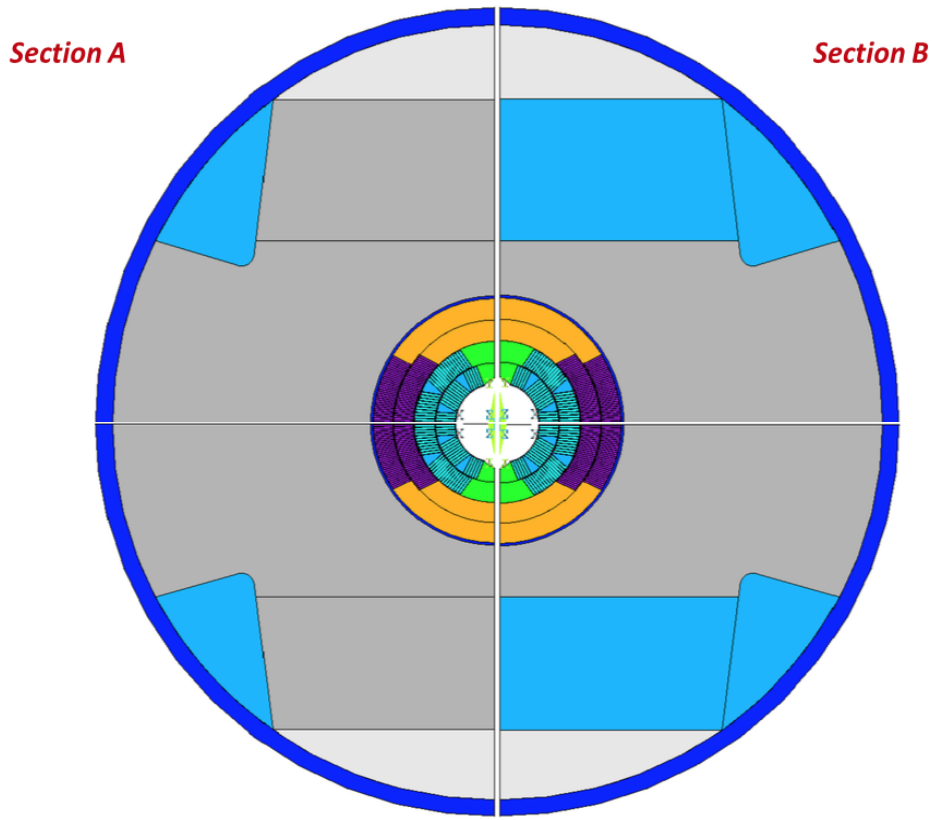
# HL-LHC 11 T

- Mechanical structure
  - SS collars
  - Accumulated midplane stress: ~114 MPa
  - Radial stress: ~75 MPa

- Protection
  - Energy density on the insulated coil: 0.089 J/mm$^3$
  - Quench heaters, no energy extraction (only for busbars as in the LHC dipoles)

# FNAL MDPCT1

- Scope: a 15 T dipole for Future Circular Collider
  - Name: MVPCT1
  - Reference field: 15 T
  - Design: FNAL
  - Production: FNAL
  - Period: 2016-ongoing
  - Units: one short model
  - Length: 1 m
  - Material: $Nb_3Sn$
  - Op. temperature: 1.9 K
  - Aperture diameter: 60 mm
  - Outer diameter: 612 mm
    - 14.1 T reached at 4.5 K

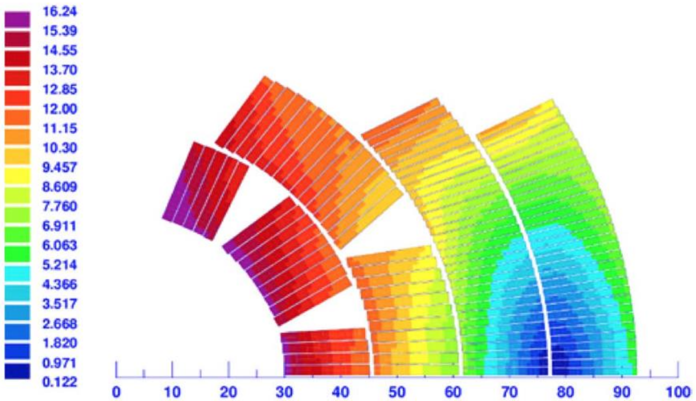


# FNAL MDPCT1

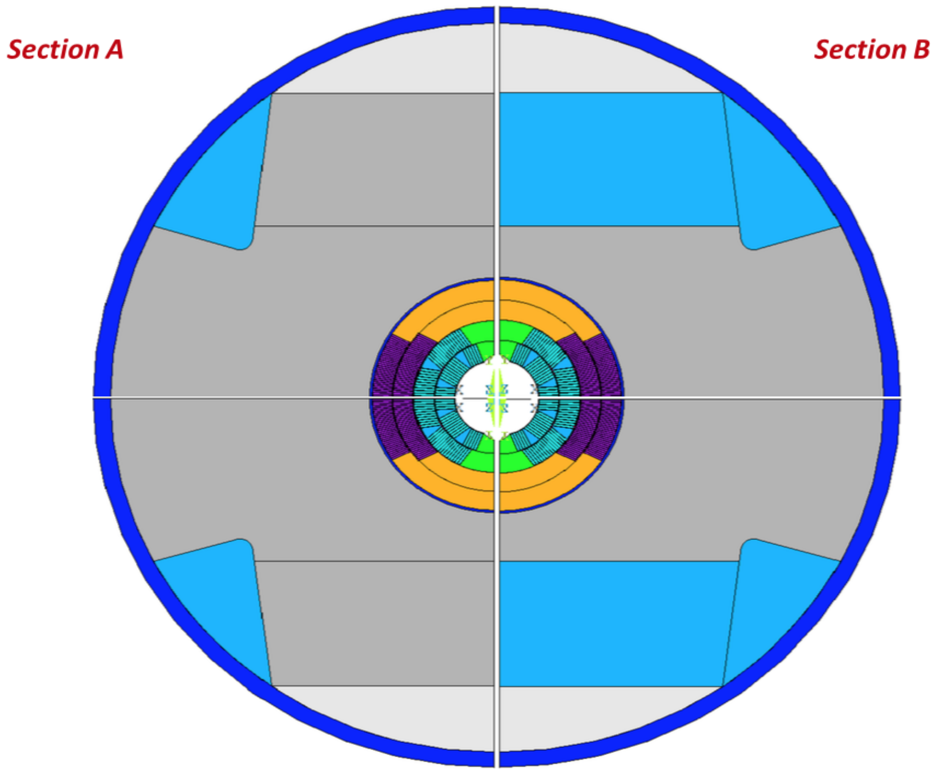
- Main novelties
  - Four layers
  - Full exploitation of iron contribution
  - A novel concept for mechanical structure, based on an Al clamp giving the preload

# FNAL MDPCT1

| | | Inner | Outer |
|---|---|---|---|
| Strand diameter | (mm) | 1.000 | 0.700 |
| Filament size | (μm) | | |
| N strands | | 28 | 40 |
| Cu/No_cu | | 1.13 | 1.13 |
| Critical current density | (A/mm$^2$) | 1500 (15 T, 4.22 K) | 1500 (15 T, 4.22 K) |
| Cable width | (mm) | 15.10 | 15.10 |
| Eq. coil width | (mm) | 52 | |
| Grading | | 1.345 | |
| Cable mid thickness | (mm) | 1.870 | 1.319 |
| Keystone angle | (°) | 0.805 | 0.805 |
| N. turns | | 44 | 65 |
| N. blocks | | 5 | 2 |
| Ins. thickness (az/radial) | (mm) | 0.---/0.--- | 0.---/0.--- |



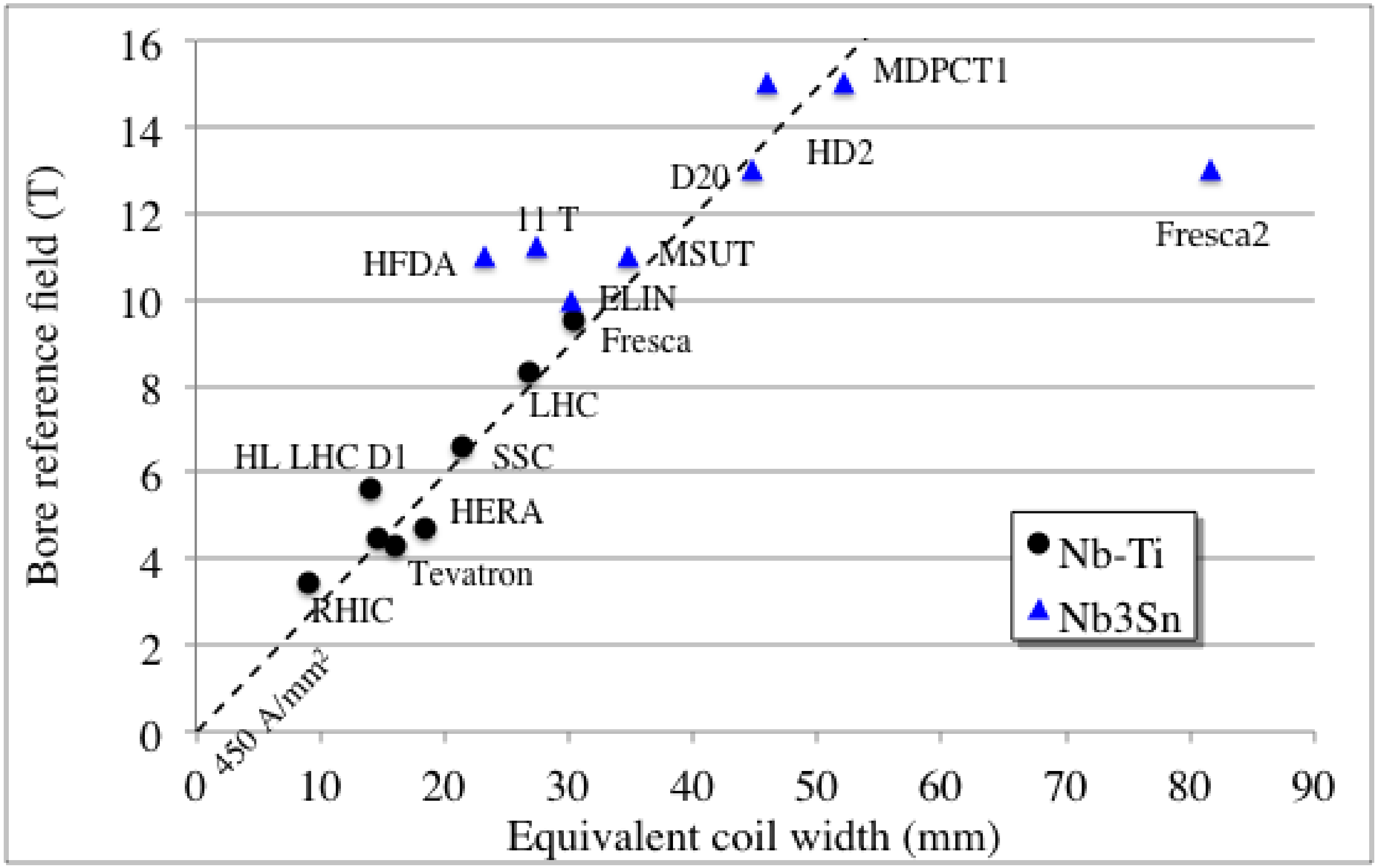
- Main parameters
  - Current: 10900 A
  - Loadline fraction:
    - 0.87 (1.9 K)
    - 0.96 (4.2 K)
  - Temperature margin: --- K
  - Inductance: 25 mH
  - Stored energy: 1.52 MJ
  - Distance coil to iron: 3 mm
  - Iron contribution to field: 28'
  - Saturation: 18%
  - Overall current density: 330/440 A/mm$^2$



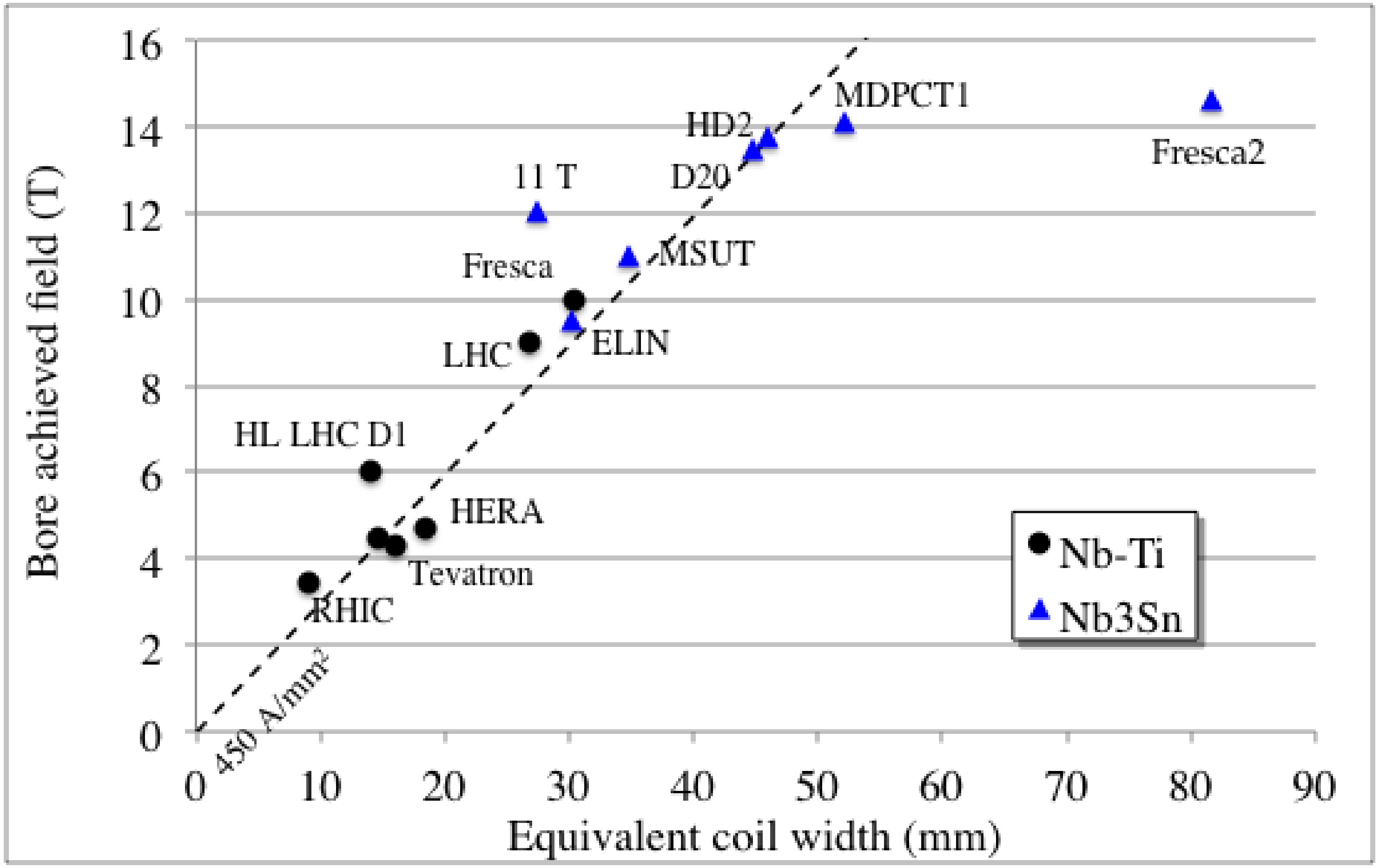
# FNAL MDPCT1

- Mechanical structure
  - Al clamps
  - Accumulated midplane stress: ~95 MPa
  - Radial stress: ~134 MPa
- Protection
  - Energy density on the insulated coil: 0.125 J/mm$^3$
  - Quench heaters

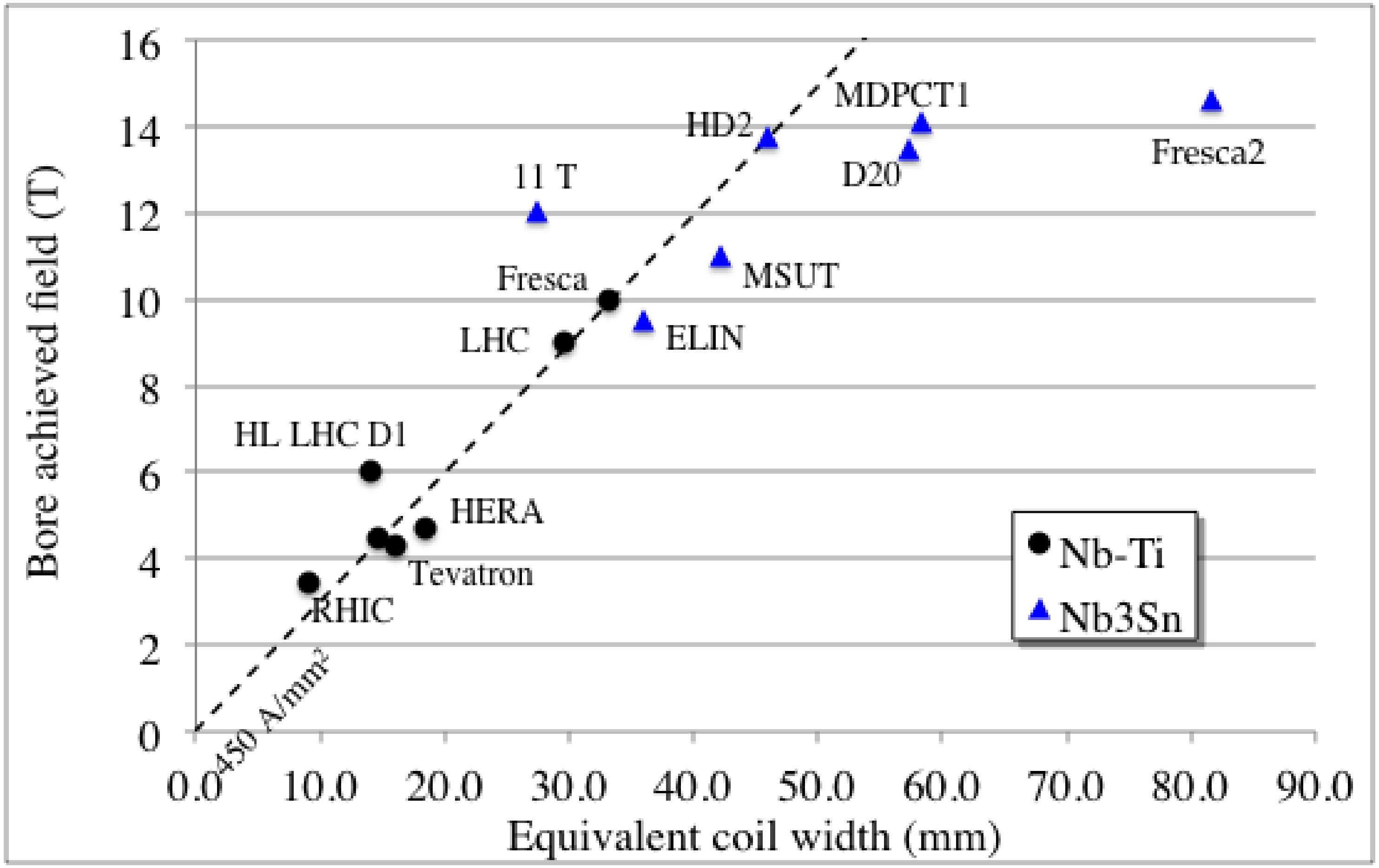
- Equivalent coil width versus reference field



- Equivalent coil width versus achieved field

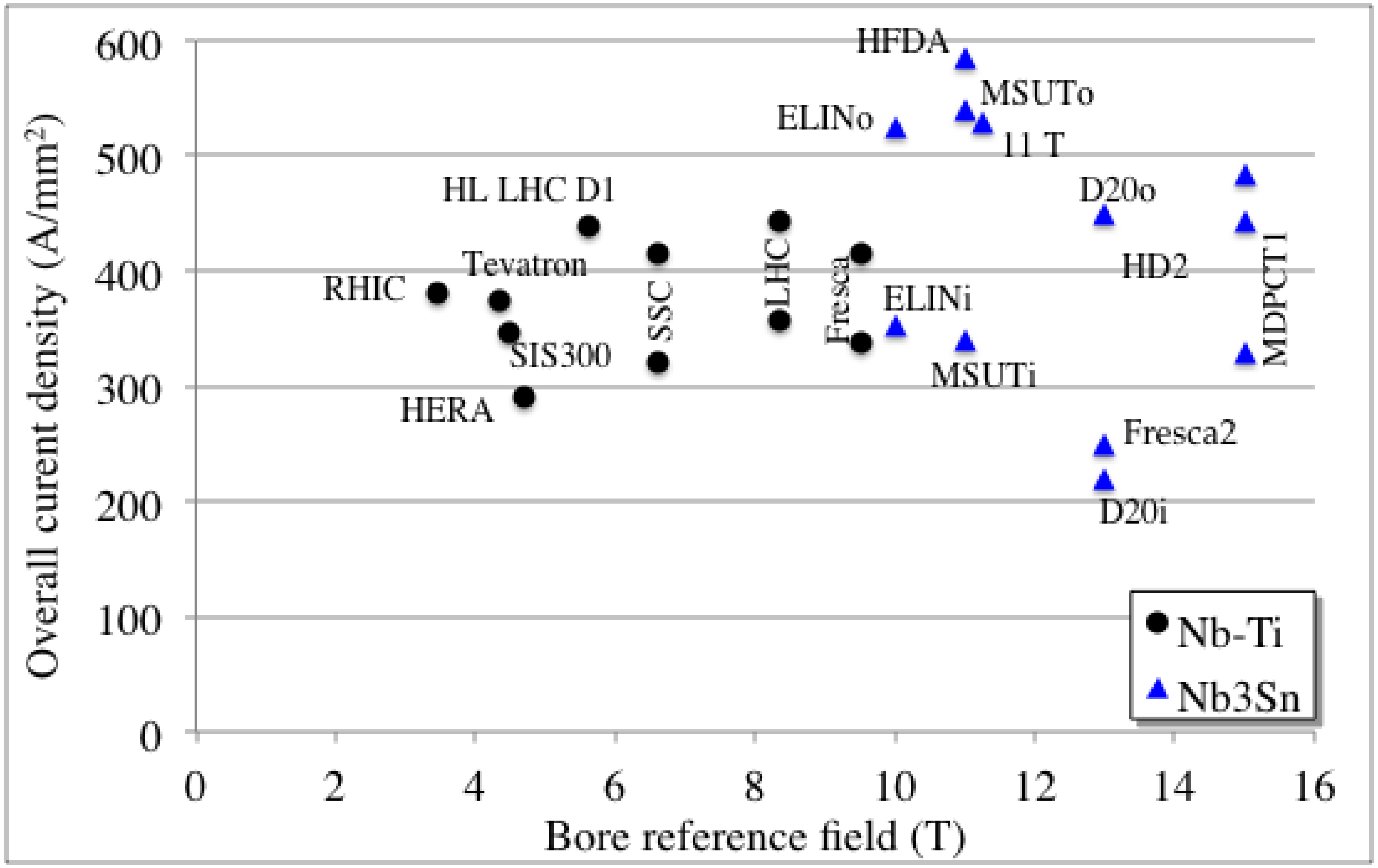


- Equivalent coil width (grading corrected) versus achieved field



# SUMMARY PLOTS

- Bore reference field versus reference overall current density



# A FEW REMARKS
# ON SOME FEATURES OUR WORK

- Time - first
  - The development time of superconducting magnets (design, fabrication of components, test) makes difficult, if not impossible, to go in series as everybody would like
  - An iteration on the design, even a fine tuning, is so long that many processes have to go in parallel
  - Making one model, testing, thinking about modification, implementing in a second model and having again the test result takes 1.5 to 3 years
    - Example: correction of the b6 in MQXF, 1.5 years to have first measurements
    - Example of the fine tuning of the wedges in the LHC dipoles to optimize field quality: decided after test of 15 magnets, first result visible in magnet 35
  - One has to make a continuous optimization between risk in making design iteration and schedule

# A FEW REMARKS ON SOME FEATURES OUR WORK

- Time - second
  - Our projects span over a 20-30 years range, from conceptual design, prototype, production, installation and commissioning
    - LHC: 1980-2010
  - It is natural to work on projects developed by others, or on projects that you will never see
  - This is difficult but also a beautiful features since it involves a hand-shaking between generations
  - The field has an incredible variety of aspects, so even if you work the whole life on the same project, you can always find new things

# A FEW REMARKS
# ON SOME FEATURES OUR WORK

- Literature - one
  - The knowledge of the literature is fundamental to be able to profit from the work of other colleagues, in different time and space
    - Read, read, read …
  - Literature is huge, and it can happen to ignore that the same problems have been already tackled in the past by other teams
  - Even though we are in a highly connected community, personal contact with colleagues is fundamental
    - Talk, talk, talk …

- Literature - two
  - When reading put in doubt the hidden assumptions to be able to have new ideas (thinking out of the box)

# A FEW REMARKS
# ON SOME FEATURES OUR WORK

- The toolbox
  - Our discipline has two relevant features: it is highly interdisciplinary and is rarely treated at University
  - When entering this field, we are usually « thrown in the cold water », and we miss formation in some specific fields
  - For each problem, and each phase of solution, be sure to use the rigth tool
    - Quick estimates based on simple equations
    - Computations carried on a worksheet
    - Integration of simple equations, still manageable if one knows how to program
    - Use of complex codes
  - These lectures were focussed on covering the first two steps, that are not enough developed in our community
    - Many things can be computed without a computer!
- Try to handle all tools, and do not be afraid of going by successive steps of approximation when studying a problem

# A FEW REMARKS
# ON SOME FEATURES OUR WORK

- Diversity
  - Different types of attitudes are present in the community
  - Example:
    - who carries out analysis of results should be neutral, to be able to read the reality between the numbers
    - who proposes a new concept has to be convinced that it works, otherwise he will not find motivation to develop it
  - The community strongly needs a mixture of all these profiles to produce good results
  - Scientific debate can be difficult, be aware of the challenges and do not be afraid

# A FEW REMARKS
# ON SOME FEATURES OUR WORK

- Setting the targets
  - We work on the gap between reality and dream
  - Developing new technologies means making possible what was previously impossible
  - If the targets are too conservative, you never develop anything new
  - If the targets are too far, you fail
  - Finding the correct balance between dreaming and reality is the main difficulty for our work, not only for our management, but in many cases at every level

# THANKS !

# CORRECTIONS

- V.1
  - Cross-section of 11 T changed
  - Corrections of radial stress in HERA and in SSC
  - Adding the saturation value in SIS300
  - Changing the vertical label in plot of slide 89