# Engineering for Particle Accelerators - Magnets

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Education in Beam Physics and Accelerator Technology
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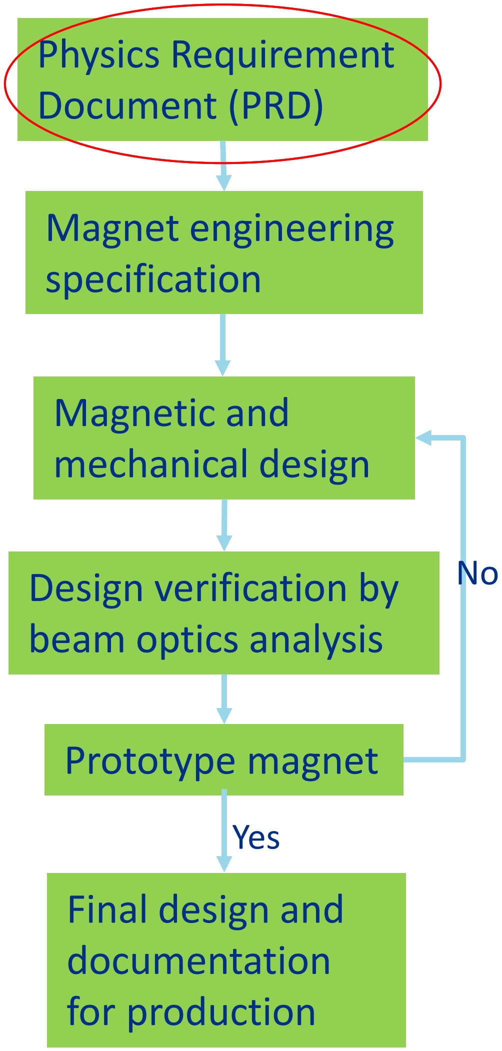
# Outlines

- Chapter 1: Basic Principle
- Chapter 2: Magnets in Accelerator
- Chapter 3: Magnetic Field Equations
- Chapter 4: Dipole Magnet Design and Manufacturing
- Chapter 5: Quadrupole Magnet Design and Manufacturing
- Chapter 6: Solenoid Design and Manufacturing
- Chapter 7: Superconducting Magnet Design and Manufacturing

# Chapter 4 Dipole Magnet Design and Manufacturing

# Functional Specification



Physics Requirement Document (PRD)

Magnet engineering specification

Magnetic and mechanical design

Design verification by beam optics analysis

Prototype magnet

No

Yes

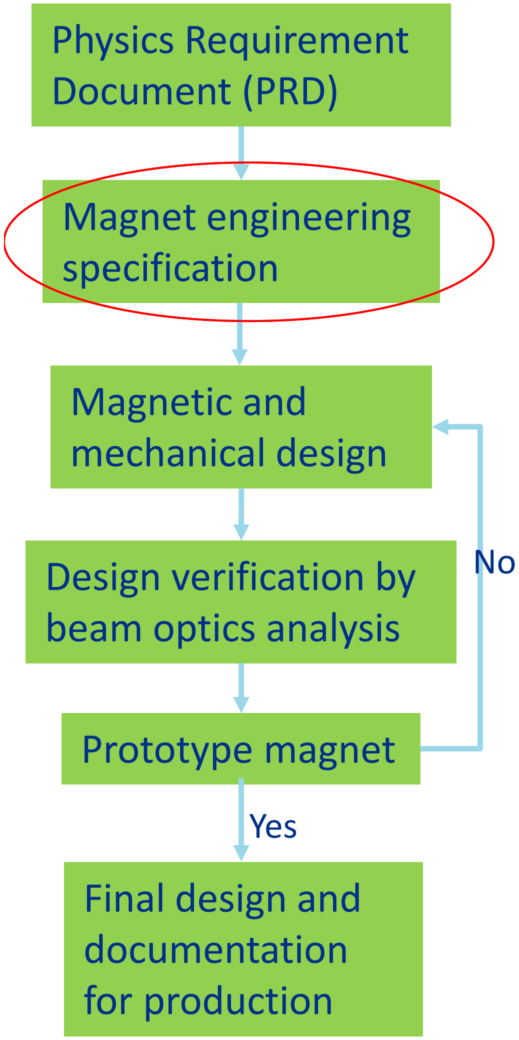
Final design and documentation for production

*The PRD is usually prepared by physicists responsible for the beam optics analysis.*

*The specification includes:*

- *Beam energy and type of particles: electrons, protons, muons…*
- *Magnet type: H-type dipole, C-type dipole, Shell-type dipole, Septum, Lambertson, Quadrupole, Sextupole, Octupole, Bump, Kicker, Solenoid, etc.*
- *Beam aperture dimensions;*
- *Field, or gradient strength in the magnet center;*
- *Magnet effective length;*
- *Good field area dimensions, and the field quality;*
- *Integrated field, or gradient along the beam path;*
- *Separation between beams for Septums, Lambertsons;*
- *Beam bending angle;*
- *Fringe field limitations.*

# Magnet Engineering Specification

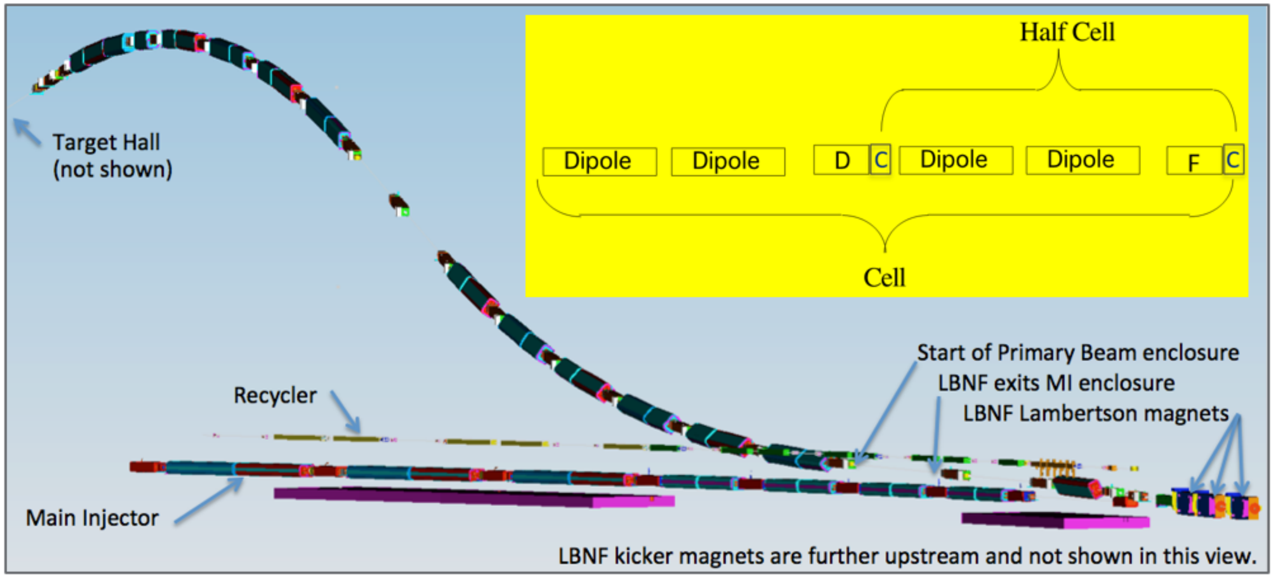


*The engineering specification is usually prepared by physicists and engineers responsible for the magnet design.*

*In general, the specification includes:*

- *Magnet physical aperture dimensions;*
- *Beam pipe dimensions;*
- *Magnet total length and space slot available for the magnet;*
- *Space and weight limitations;*
- *Magnet peak field, or gradient;*
- *Type of cooling: air, water, liquid Helium (Lhe), conduction;*
- *Cooling system parameters;*
- *Power supply parameters: peak current and voltage, AC, pulsed.*
- *Magnet protection and instrumentation;*
- *Radiation level;*
- *Number of magnets.*

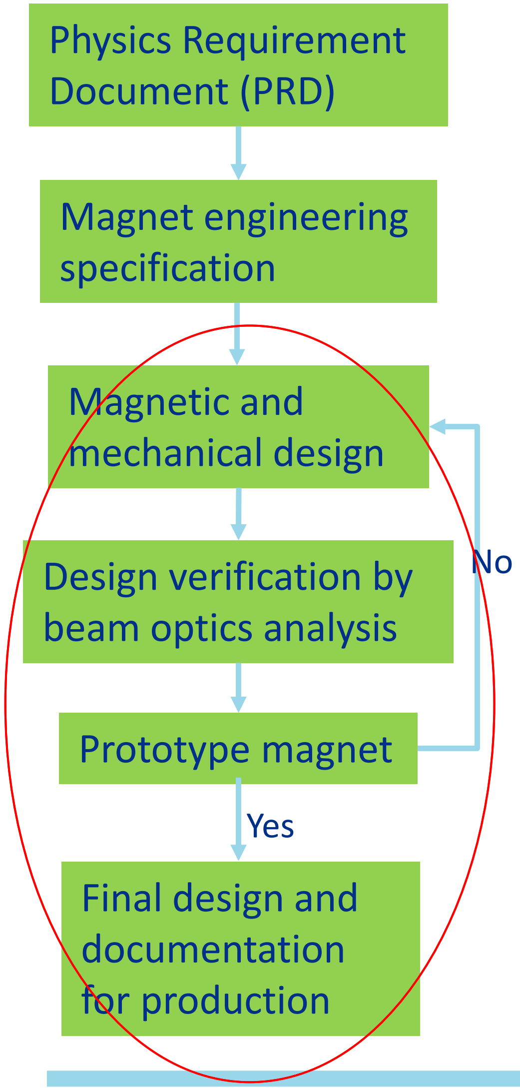
# LBNF Beamline Dipole Magnet Specification



LBNF kicker magnets are further upstream and not shown in this view.

| Property | Value (IDAL) | Value (IDDL) |
|---|---|---|
| Magnetic field (nominal at 120 GeV) | 1.604 T | |
| Integrated field (nominal at 120 GeV) | 10.03 T-m | 6.68 T-m |
| Gap | 50.80 mm | |
| Aperture dimension | 47 mm x 120 mm | |
| Good field area dimension | 44.45 mm x 44.45 mm | |
| Field homogeneity ΔB/B | 0.1% | |
| Color | Light blue | |

# Magnet Design and Fabrication Steps



Physics Requirement Document (PRD)

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Prototype magnet

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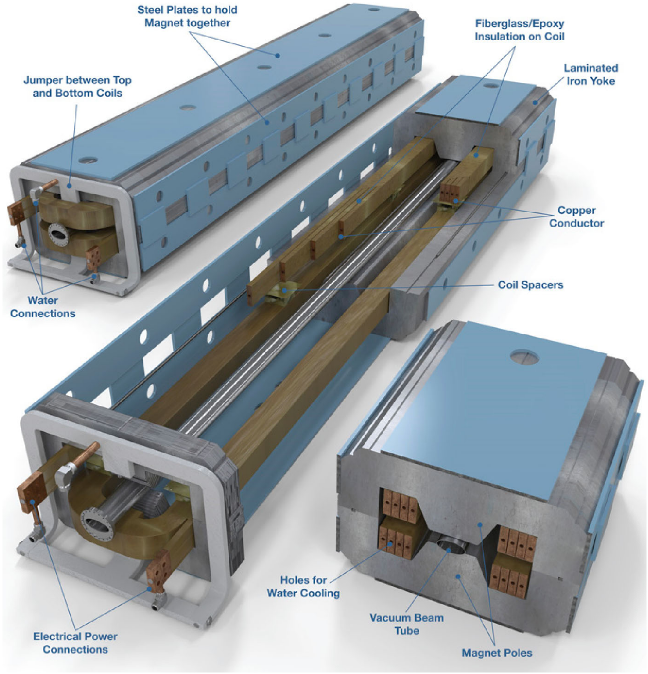
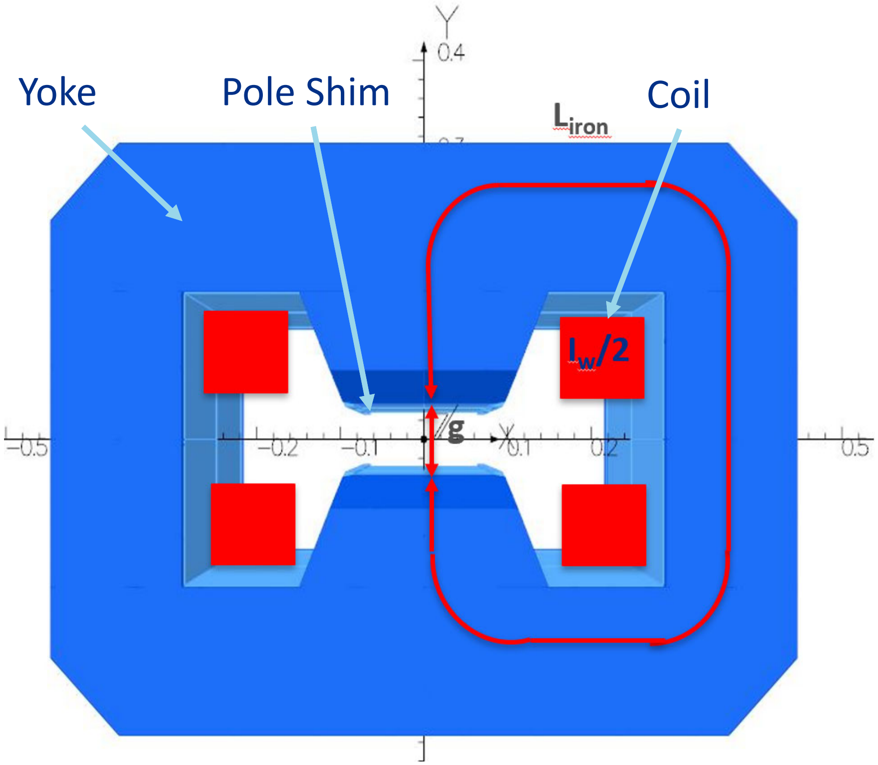
Final design and documentation for production



- *Conceptual Design*
  - *Coil*
  - *Core*
- ***Internal Review***
- *Prototype Design (drawing package)*
- *Manufacturing Plan*
- ***Prototype Readiness Review***
- ***Final Design Review***
- *Production*

# Coil Design



$$NI \cong \frac{B_{air}}{\mu_0} \cdot l_{air}$$

Given:

g = 0.0508 m, $B_{air}$ = 1.604 T

Obtain:

NI= $\frac{B_{air}}{\mu_0} \cdot g$ = 64842.3 A

| N (number of turns) | I (current per turn) |
|---|---|
| 2 | 32,422 A |
| 4 | 16,211 A |
| 8 | 8,106 A |
| 16 | 4,053 A |
| … | … |

g - magnet gap, m

$B_{air}$ – field density in the gap, T

$B_{iron}$ – field density in the iron yoke, T

$L_{iron}$ – the average flux path length in the iron yoke, m

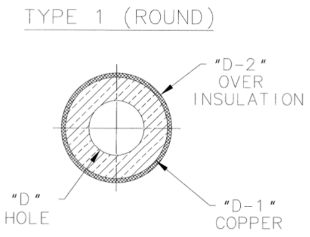
$I_w$ – total coils ampere-turns, A

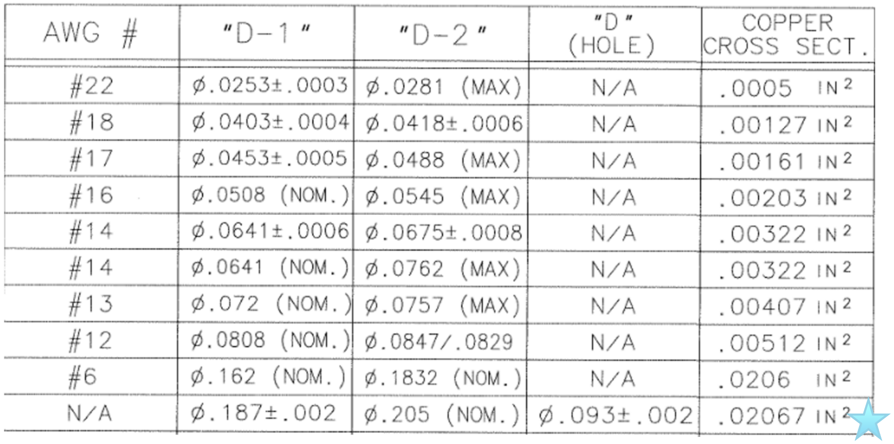
$\mu_0$= 4π x $10^{-7}$ T·m/A

# Coil Design_Conductor

| AWG | Diameter (mm) | Area (mm$^2$) | $\rho$(Ω/km) | Max Current (A) | Max Current Density (A/mm$^2$) |
|---|---|---|---|---|---|
| 1 | 7.348 | 42.4 | 0.406392 | 119 | 2.81 ☆ |
| 2 | 6.543 | 33.6 | 0.512664 | 94 | 2.80 |
| 3 | 5.827 | 26.7 | 0.64616 | 75 | 2.81 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| 38 | 0.102 | 0.00797 | 2163 | 0.0228 | 2.86 |
| 39 | 0.089 | 0.00632 | 2728 | 0.0175 | 2.77 |
| 40 | 0.079 | 0.00501 | 3440 | 0.0137 | 2.73 |

English unit in the table





| AWG # | "D-1" | "D-2" | "D" (HOLE) | COPPER CROSS SECT. |
|---|---|---|---|---|
| #22 | ø.0253±.0003 | ø.0281 (MAX) | N/A | .0005 IN$^2$ |
| #18 | ø.0403±.0004 | ø.0418±.0006 | N/A | .00127 IN$^2$ |
| #17 | ø.0453±.0005 | ø.0488 (MAX) | N/A | .00161 IN$^2$ |
| #16 | ø.0508 (NOM.) | ø.0545 (MAX) | N/A | .00203 IN$^2$ |
| #14 | ø.0641±.0006 | ø.0675±.0008 | N/A | .00322 IN$^2$ |
| #14 | ø.0641 (NOM.) | ø.0762 (MAX) | N/A | .00322 IN$^2$ |
| #13 | ø.072 (NOM.) | ø.0757 (MAX) | N/A | .00407 IN$^2$ |
| #12 | ø.0808 (NOM.) | ø.0847/.0829 | N/A | .00512 IN$^2$ |
| #6 | ø.162 (NOM.) | ø.1832 (NOM.) | N/A | .0206 IN$^2$ |
| N/A | ø.187±.002 | ø.205 (NOM.) | ø.093±.002 | .02067 IN$^2$ ☆ |

## Solid Conductor

- $I = J \cdot A_{\#1}$ = 2.81 (A/mm$^2$)·42.4 (mm$^2$) = 119 A
- To reach 64842.27 A, we need 546 turns of AWG#1

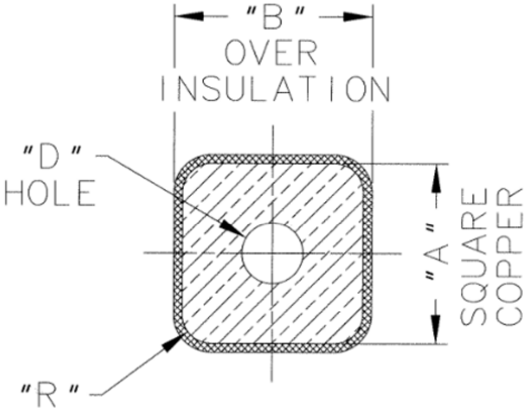
## Hollow Conductor

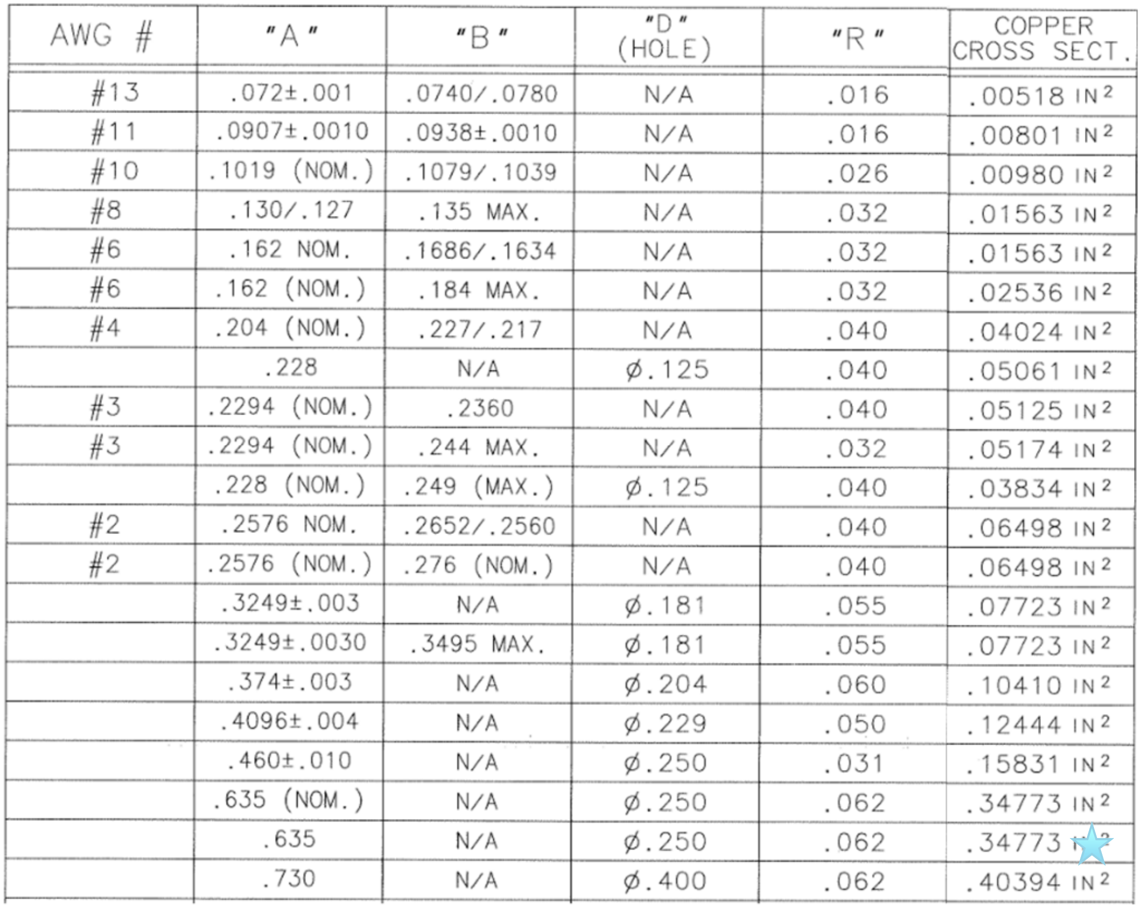
- With proper cooling, the conductor can carry max. 10 A/mm$^2$ current density (preferable below 4 A/mm$^2$ .
- $I = J_{max} \cdot A$ = 4 (A/mm$^2$)·13.34 (mm$^2$) = 53.36 A
- To reach 64842.27 A, we need 1216 turns of hollow round conductor

# Coil Design_Conductor Cont.

English unit in the table

TYPE 2 (SQUARE)





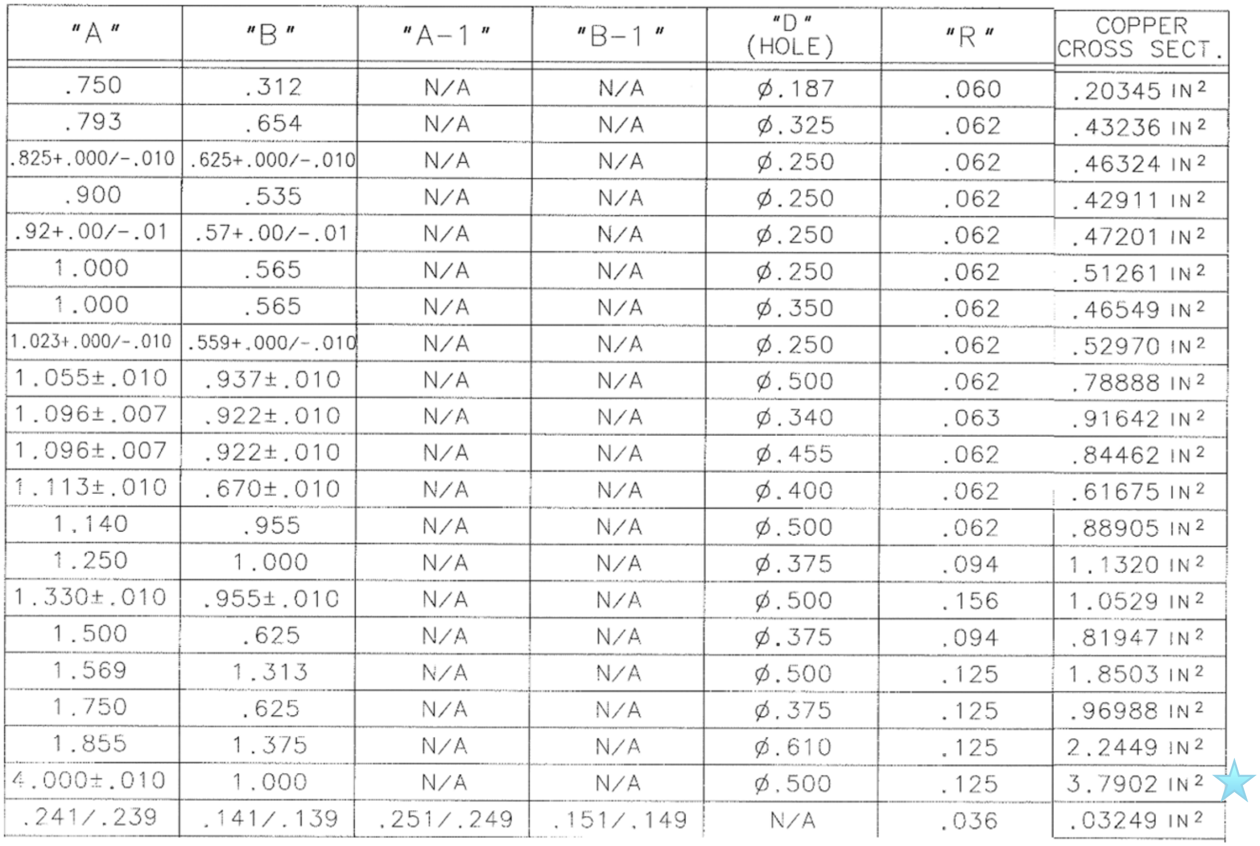
| AWG # | "A" | "B" | "D" (HOLE) | "R" | COPPER CROSS SECT. |
|---|---|---|---|---|---|
| #13 | .072±.001 | .0740/.0780 | N/A | .016 | .00518 IN$^2$ |
| #11 | .0907±.0010 | .0938±.0010 | N/A | .016 | .00801 IN$^2$ |
| #10 | .1019 (NOM.) | .1079/.1039 | N/A | .026 | .00980 IN$^2$ |
| #8 | .130/.127 | .135 MAX. | N/A | .032 | .01563 IN$^2$ |
| #6 | .162 NOM. | .1686/.1634 | N/A | .032 | .01563 IN$^2$ |
| #6 | .162 (NOM.) | .184 MAX. | N/A | .032 | .02536 IN$^2$ |
| #4 | .204 (NOM.) | .227/.217 | N/A | .040 | .04024 IN$^2$ |
|  | .228 | N/A | ø.125 | .040 | .05061 IN$^2$ |
| #3 | .2294 (NOM.) | .2360 | N/A | .040 | .05125 IN$^2$ |
| #3 | .2294 (NOM.) | .244 MAX. | N/A | .032 | .05174 IN$^2$ |
|  | .228 (NOM.) | .249 (MAX.) | ø.125 | .040 | .03834 IN$^2$ |
| #2 | .2576 NOM. | .2652/.2560 | N/A | .040 | .06498 IN$^2$ |
| #2 | .2576 (NOM.) | .276 (NOM.) | N/A | .040 | .06498 IN$^2$ |
|  | .3249±.003 | N/A | ø.181 | .055 | .07723 IN$^2$ |
|  | .3249±.0030 | .3495 MAX. | ø.181 | .055 | .07723 IN$^2$ |
|  | .374±.003 | N/A | ø.204 | .060 | .10410 IN$^2$ |
|  | .4096±.004 | N/A | ø.229 | .050 | .12444 IN$^2$ |
|  | .460±.010 | N/A | ø.250 | .031 | .15831 IN$^2$ |
|  | .635 (NOM.) | N/A | ø.250 | .062 | .34773 IN$^2$ |
|  | .635 | N/A | ø.250 | .062 | .34773 ★ |
|  | .730 | N/A | ø.400 | .062 | .40394 IN$^2$ |

## Square Conductor

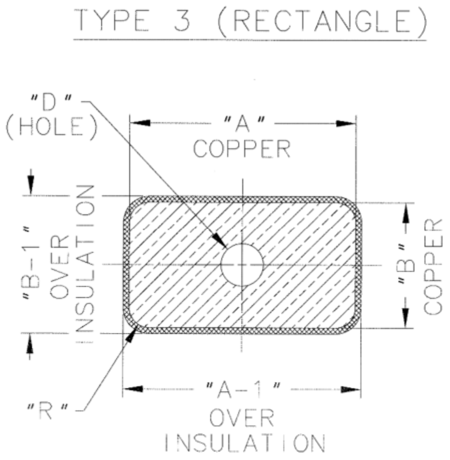
- I $= J_{max}$·A = 4 (A/mm$^2$)·260.6 (mm$^2$) = 1042.4 A
- To reach 64842.27 A, we need 62 turns of hollow square conductor

# Coil Design_Conductor Cont.

English unit in the table



| "A" | "B" | "A-1" | "B-1" | "D" (HOLE) | "R" | COPPER CROSS SECT. |
|---|---|---|---|---|---|---|
| .750 | .312 | N/A | N/A | ø.187 | .060 | .20345 IN² |
| .793 | .654 | N/A | N/A | ø.325 | .062 | .43236 IN² |
| .825+.000/-.010 | .625+.000/-.010 | N/A | N/A | ø.250 | .062 | .46324 IN² |
| .900 | .535 | N/A | N/A | ø.250 | .062 | .42911 IN² |
| .92+.00/-.01 | .57+.00/-.01 | N/A | N/A | ø.250 | .062 | .47201 IN² |
| 1.000 | .565 | N/A | N/A | ø.250 | .062 | .51261 IN² |
| 1.000 | .565 | N/A | N/A | ø.350 | .062 | .46549 IN² |
| 1.023+.000/-.010 | .559+.000/-.010 | N/A | N/A | ø.250 | .062 | .52970 IN² |
| 1.055±.010 | .937±.010 | N/A | N/A | ø.500 | .062 | .78888 IN² |
| 1.096±.007 | .922±.010 | N/A | N/A | ø.340 | .063 | .91642 IN² |
| 1.096±.007 | .922±.010 | N/A | N/A | ø.455 | .062 | .84462 IN² |
| 1.113±.010 | .670±.010 | N/A | N/A | ø.400 | .062 | .61675 IN² |
| 1.140 | .955 | N/A | N/A | ø.500 | .062 | .88905 IN² |
| 1.250 | 1.000 | N/A | N/A | ø.375 | .094 | 1.1320 IN² |
| 1.330±.010 | .955±.010 | N/A | N/A | ø.500 | .156 | 1.0529 IN² |
| 1.500 | .625 | N/A | N/A | ø.375 | .094 | .81947 IN² |
| 1.569 | 1.313 | N/A | N/A | ø.500 | .125 | 1.8503 IN² |
| 1.750 | .625 | N/A | N/A | ø.375 | .125 | .96988 IN² |
| 1.855 | 1.375 | N/A | N/A | ø.610 | .125 | 2.2449 IN² |
| 4.000±.010 | 1.000 | N/A | N/A | ø.500 | .125 | 3.7902 IN² ★ |
| .241/.239 | .141/.139 | .251/.249 | .151/.149 | N/A | .036 | .03249 IN² |



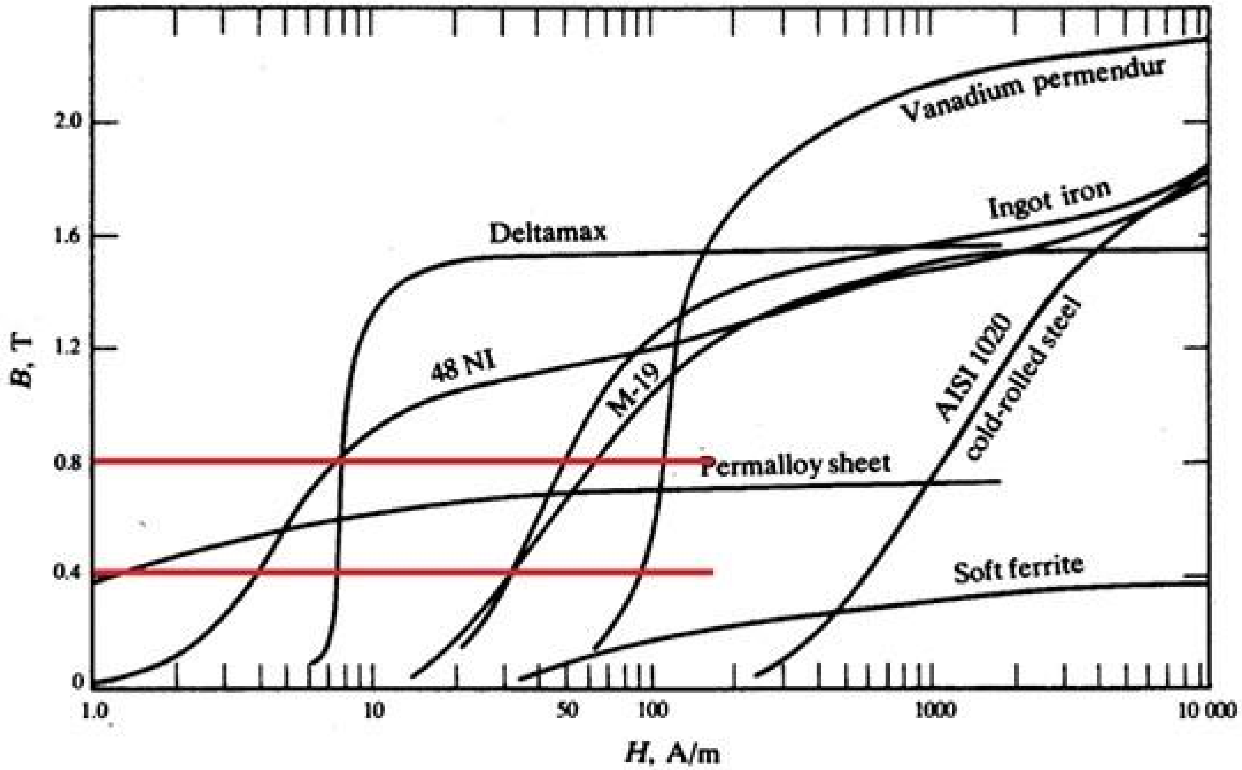
## Rectangle Conductor

- $I = J \cdot A$ = 4 (A/mm²)·2445.2 (mm²) = 9780.8 A
- With 8 turns, we can achieve the target, with $J = 3.3$ A/mm²
- How to fabricate the coil with such a “giant” cable ?

# Magnet Temperature

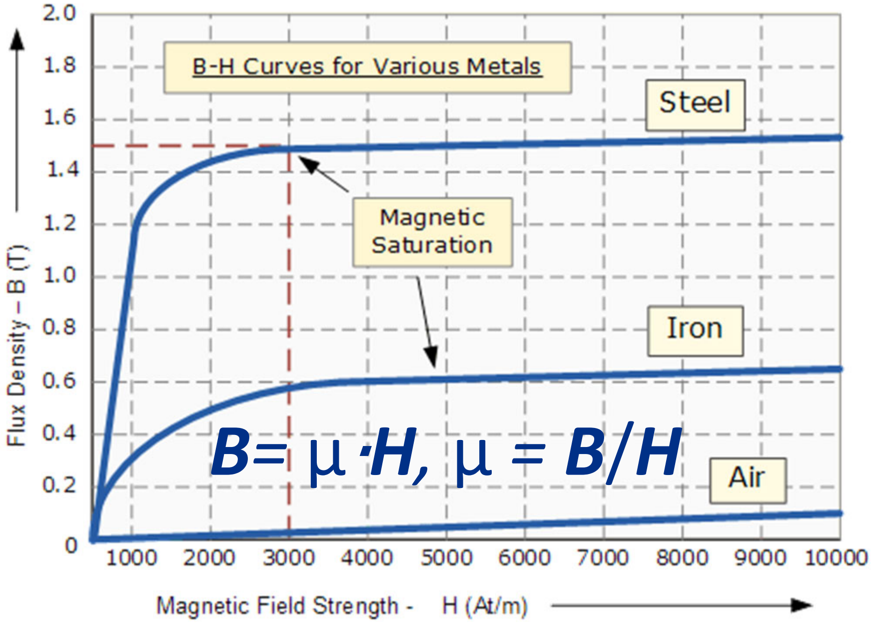
- If a solid conductor is used in a magnet, heat is generated due to the magnet power $P = I^2R\ (w)$, and the magnet is then air-cooled during the operation. Simulation may be needed to verify the magnet is not over-heated.
- If a hollow conductor is used, the magnet is water-cooled. The following formular can be used to estimate the magnet temperature rise.
  - Water velocity $v = \sqrt{\frac{p \cdot d^{1.33}}{0.5L}}$, where $p$ is the water pressure (unit in kg/cm$^2$), $d$ is the conductor cooling hole diameter (unit in mm), and L is the length of the coil (unit in m), the unit for $v$ is calculated in m/s.
  - Water flow rate $Q = S \times v \times 10^{-3}$, where $S$ is the cross-section area of the cooling hole (unit in mm$^2$), the unit for $Q$ is then Liter/s.
  - The temperature rise $\Delta T = \frac{0.24 \times P}{Q}$, where $P = I^2R\ (kw)$is the magnet power, the unit of the temperature is ℃.

# Yoke Material_Soft Magnetic Materials

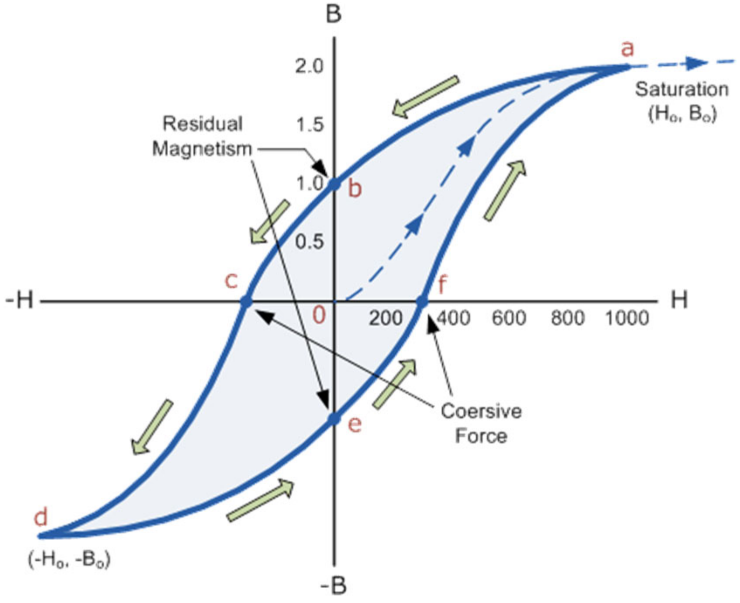


- For accelerator magnets, use low carbon steel: AISI 1006, AISI 1008, AISI 1010 with the low coercive force Hc < 2 Oe (160 A/m).
- Sometimes Vanadium Permendur is used for fields close to 2 T.
- Electrical type of steel is used in AC magnets has up to 4% Si to reduce AC losses. The lamination thickness for the yoke is 0.35 – 0.5 mm for 50-60 Hz applications.

# Ferromagnetic Material Properties

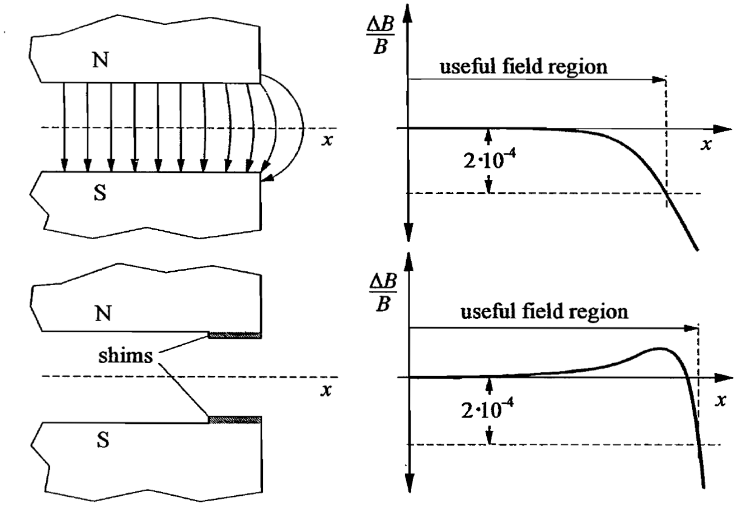


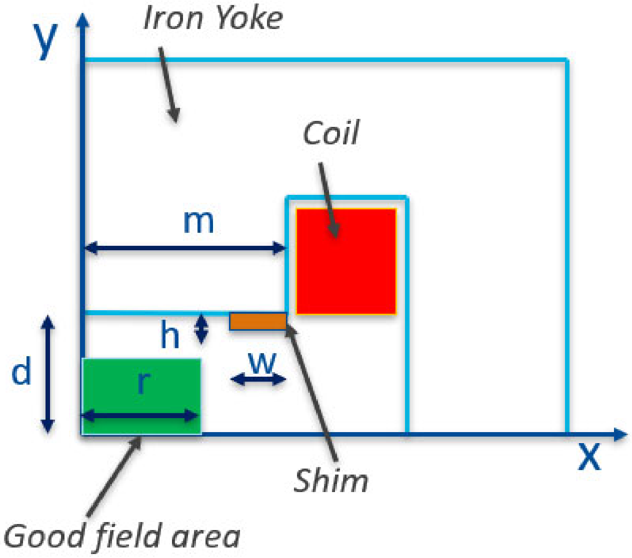
$B = \mu \cdot H$, $\mu = B/H$



- The typical steel is saturated when B is greater than 1.5 T
- The magnetic properties B-H Curve can be measured through the sample ring for solid yoke, and a closed magnetic circuit formed by thin steel strips for lamination-stacked yoke.

# Yoke Design_ Pole Dimensions





*For the shim size:*

- *The ratio of w/g is good from 0.2 to 0.6.*
- Shim area S= h·w = 0.021*d$^2$
- *If $B_{air}$ is over 0.8 T, the shim will need to be optimized smoothly to reduce the iron saturation effects in pole edges and shim areas.*

| Good Field Area Width r | ΔB/B < 1% | ΔB/B < 0.1% |
|---|---|---|
| w/o shims | m-d | m-2d |
| with shims | m-d/2 | m-d |

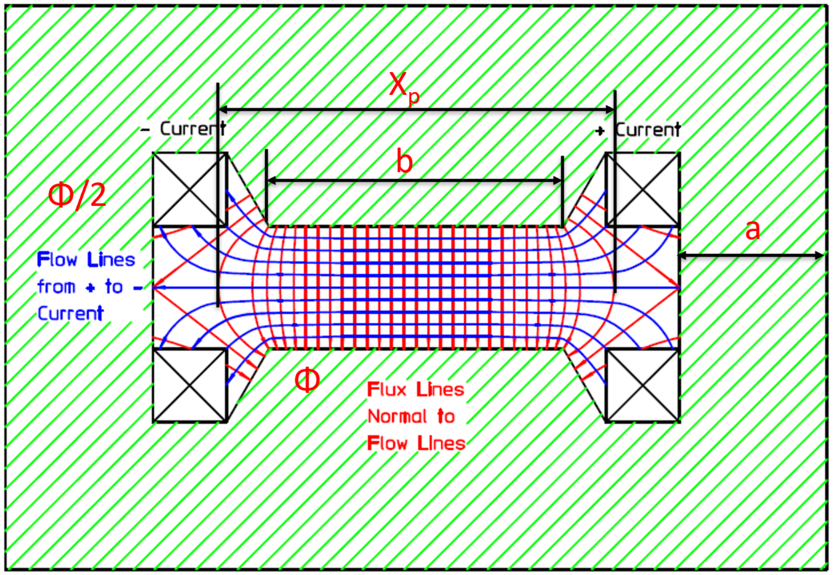
Given as requirement:

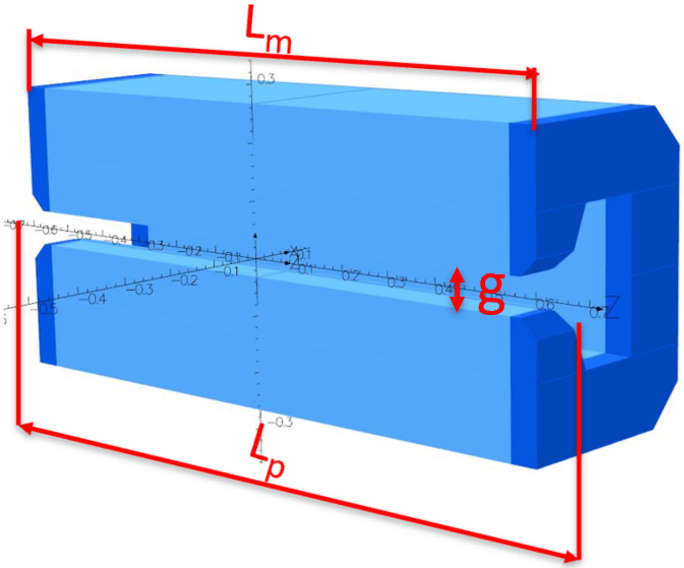
- Good field size 44.45 mm, ΔB/B < 0.1%
- Pole gap 50.8 mm
- Aperture dimension 47 mm x 120 mm

Calculate:

- r = m-d → $b = 2m = 2(r + d) = 2\cdot(r + g/2) = 95.25$ mm (if there is no aperture requirement)
- Shim width w/g = 0.5, w = 25.4
- $b = 120 + w = 145.4$ mm

# Yoke Design_ Yoke Dimensions





- *Pole effective width: $X_p = b + g$*
- *Pole effective length: $L_p = L_m + g$*
- *Pole effective area: $S_p = X_p \cdot L_p$*
- *Total flux in yoke: $\Phi = B_{air} \cdot S_p$*
- *Yoke leg area: $S_{iron} = a \cdot L_m$*

*Gauss's Law*

- *Flux density in yoke leg: $B_{iron} = \Phi/2 \cdot S_{iron}$*

Given:

$b = 145.4$ mm, $g = 50.8$ mm, $B_{air} = 1.604$ T, Integrated field 10.03 T·m

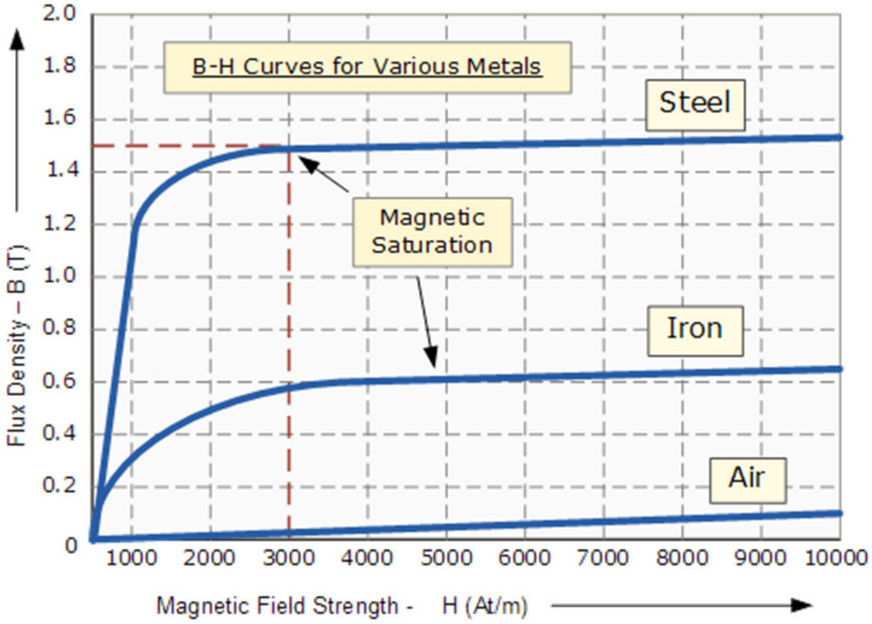
Calculate:

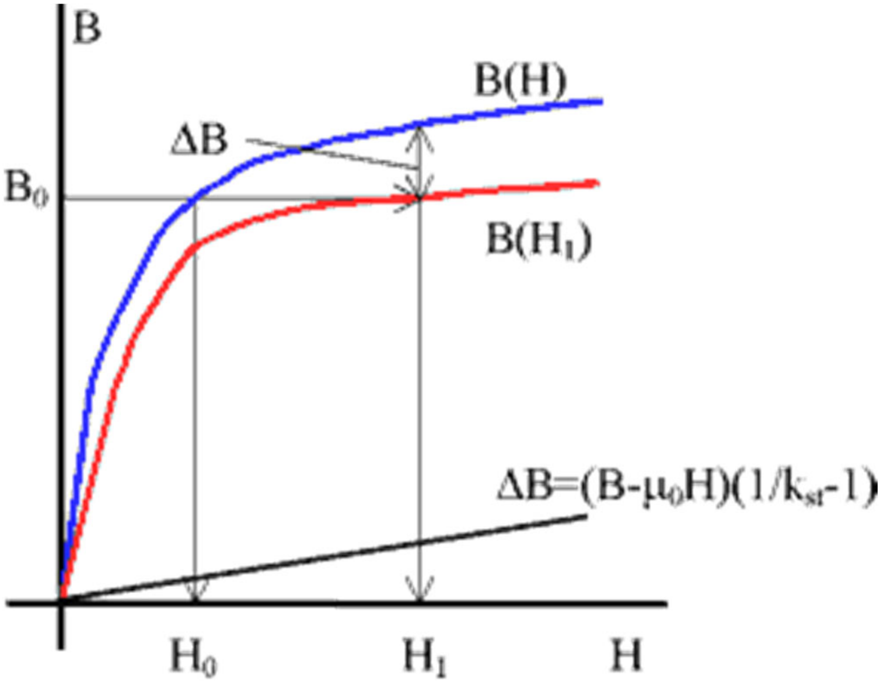
$X_p = 196.2$ mm, $L_p = 6.25$ m, $L_m = 6.2$ m, $S_p = 1.226\ \mathrm{m}^2$, *$\Phi = 1.97$ Wb*

*If, $a = X_p/2 = 98.1$ mm*

*$B_{iron} = \Phi/(2 \cdot a \cdot L_m) = 1.62$ T (Saturated)*

# Define $B_{iron}$ in the Yoke





- *Use B-H curve (blue) for solid yoke and B-H curve (red) for lamination-stacked yoke to defined* $B_{iron}$ *needed for the magnet parameters estimation.*
- *For lamination-stacked yoke, the flux density in the yoke is reduced due to the stacking factor* $k_{st}$ *(0.96-0.98), the formula is* $\Delta B = (B-\mu_0 H)(1/k_{st}-1)$

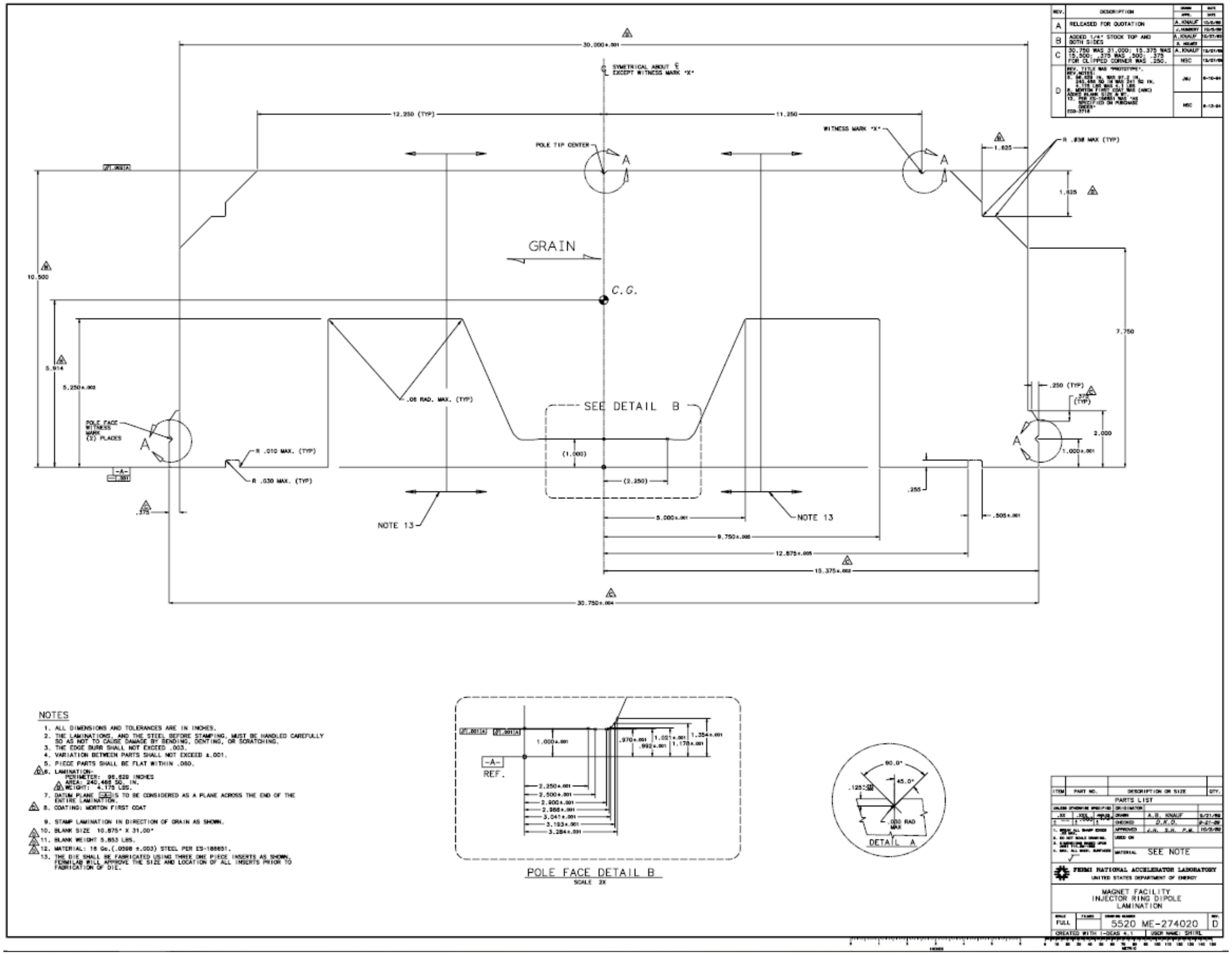
$B_0 = 1.2T$, for lamination-stacked yoke, $B_{iron} = B_0 - \Delta B = 1.17\ T$
$a = \Phi/(2 \cdot B_{iron} \cdot L_m) = 132\ mm$

# *Magnetic Field Simulations*

- Build or transfer from the CAD 2D or 3D model geometry;
- Input data for material properties and current sources;
- Specify type of field analysis: steady state, transient, current flow, motion, levitation, particles tracking;
- Specify multi physics combination: field-stress, field-thermal, quench for superconducting;
- Build the surface and volumetric meshes;
- Field calculation;
- Results analysis;
- Design Validation

*General 2D and 3D magnetic field simulation codes based on Finite Element Method. Commercial codes: OPERA, COMSOL, ANSYS, etc.*

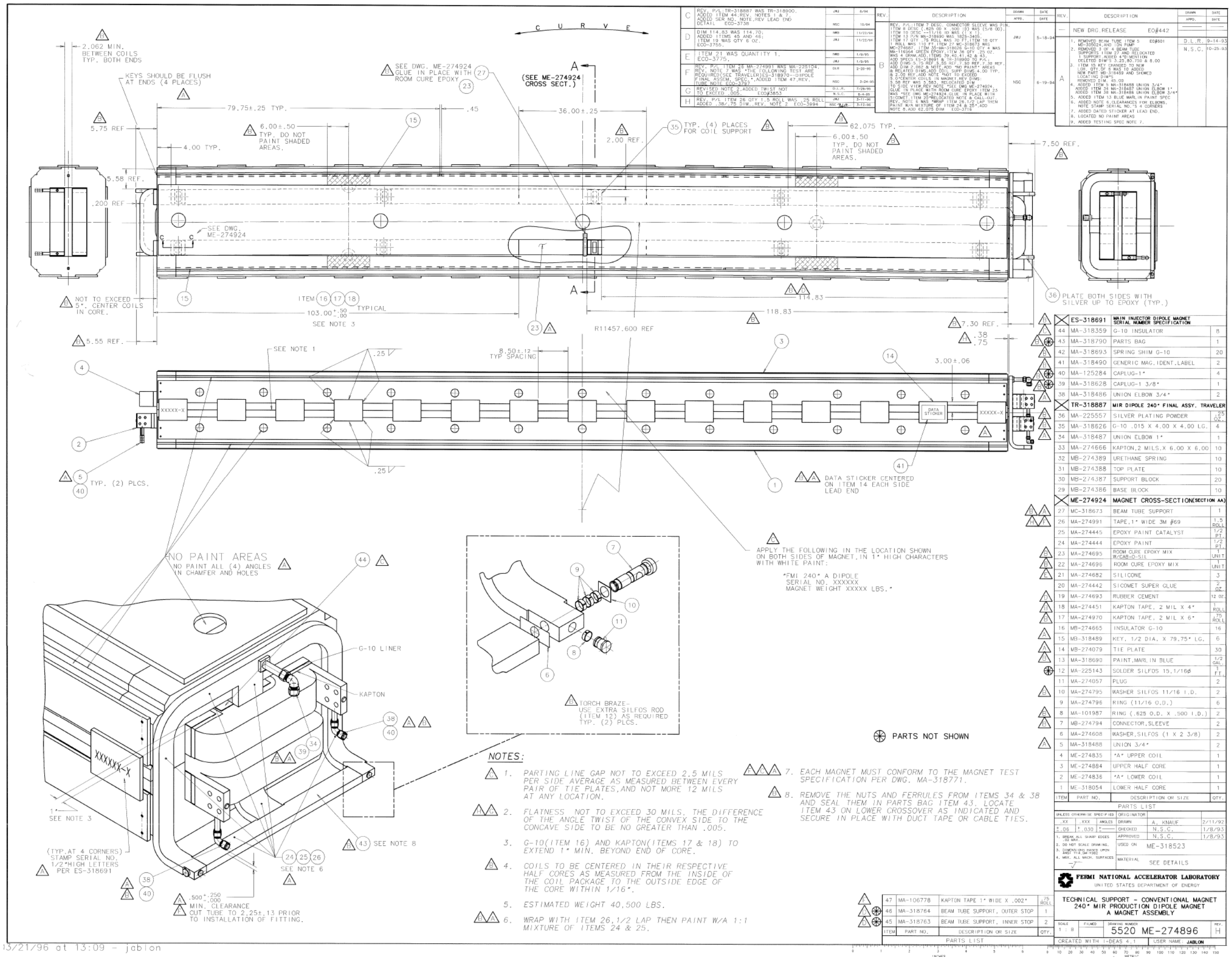
# Yoke Lamination Drawing



NOTES

1. ALL DIMENSIONS AND TOLERANCES ARE IN INCHES.
2. THE LAMINATIONS, AND THE STEEL BEFORE STAMPING, MUST BE HANDLED CAREFULLY SO AS NOT TO CAUSE DAMAGE BY BENDING, DENTING, OR SCRATCHING.
3. THE EDGE BURR SHALL NOT EXCEED .003.
4. VARIATION BETWEEN PARTS SHALL NOT EXCEED ±.001.
5. PIECE PARTS SHALL BE FLAT WITHIN .060.
6. LAMINATION–
   PERIMETER: 96.629 INCHES
   AREA: 240.468 SQ. IN.
   WEIGHT: 4.175 LBS.
7. DATUM PLANE -A- IS TO BE CONSIDERED AS A PLANE ACROSS THE END OF THE ENTIRE LAMINATION.
8. COATING: MORTON FIRST COAT
9. STAMP LAMINATION IN DIRECTION OF GRAIN AS SHOWN.
10. BLANK SIZE 10.875" X 31.00"
11. BLANK WEIGHT 5.853 LBS.
12. MATERIAL: 16 Ga.(.0598 ±.003) STEEL PER ES-186651.
13. THE DIE SHALL BE FABRICATED USING THREE ONE PIECE INSERTS AS SHOWN. FERMILAB WILL APPROVE THE SIZE AND LOCATION OF ALL INSERTS PRIOR TO FABRICATION OF DIE.

# Magnet Drawing

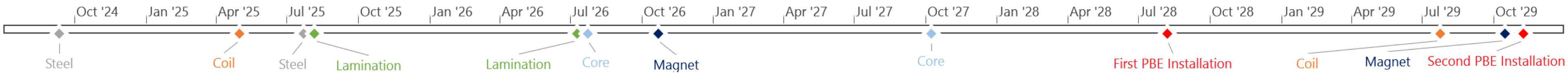


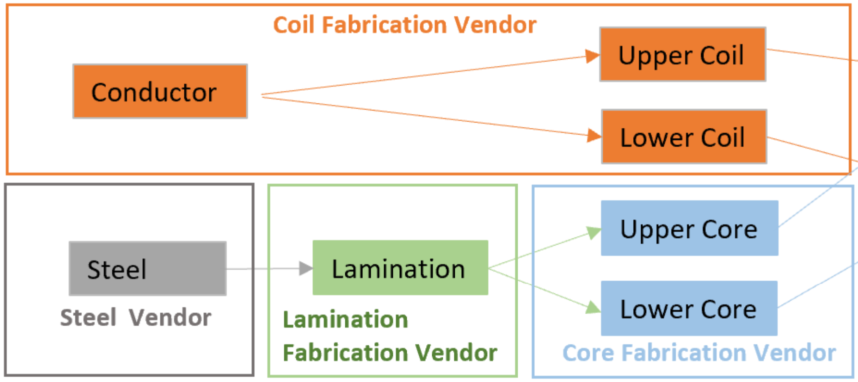
# Drawing Package

- IDA Magnet/Beam Tube Assembly (ME-318523)
  - Support Bracket-Ion Pump (MC-318241)
  - Insulator-Ion Pump BRKT (MC-318266)
  - Support Bar-Ion Pump (MC-318240)
  - **IDA Magnet (ME-274896 & ME-274924)**
    - Peripheral Parts
      - Union 3/4" (MA-318488) (Qt. 2)
      - Caplug-1" (MA-125284) (Qt. 2)
      - Washer, Silfos (MA-274608) (Qt. 2)
      - Connector, Sleeve (MB-274794) (Qt. 2)
      - Ring 0.625 OD x 0.5 ID (MA-101987) (Qt. 2)
      - Ring 11/16 OD (MA-274796) (Qt. 6)
      - Washer Silfos (MA-274795) (Qt. 2)
      - Plug (MA-274057) (Qt. 2)
      - Solder Silfos (MA-225143) (Qt. 1ft)
      - Paint, Marlin Blue (MA-318690) (Qt. 1/2 Gal.)
      - **Tie Plate (MB-274079)** (Qt. 30)
      - Generic Mag. Ident. Label (MA-318490) (Qt. 2)
      - **Key 1/2 Dia. x 79.75" LG (MB-318489) (Qt. 6)**
      - Insulator G10 (MB-274665) (Qt. 16)
      - Insulator G10 (MB-318359) (Qt. 8)
      - Kapton Tape 2mil x 6" (MA-274970) (Qt. 0.75 roll)
      - Kapton Tape 2mil x 4" (MA-274451) (Qt. 1 roll)
      - Rubber Cement (MA-274693) (Qt. 12 oz)
      - Sicomet super glue (MA-274442) (Qt. 2oz)
      - Silicone (MA-274682) (Qt. 3)
      - Room Cure Epoxy Mix (MA-274696) (Qt. 1 unit)
      - Room Cure Epoxy Mix W/Cab-o-sil (MA274695) (Qt. 1 unit)
      - Epoxy Paint (MA-274444) (Qt. 1/2 pt)
      - Epoxy Paint Catalyst (MA-274445) (Qt. 1/2 pt)
      - Tape, 1" wide (MA-274991) (Qt. 1.5 Roll)
      - **Beam Tube Support (MC-318673) (Qt. 1)**
      - **Base Block (MB-274386) (Qt. 10)**
      - **Support Block (MB-274387) (Qt. 20)**
      - **Top Plate (MB-274388) (Qt. 10)**
      - **Urethane Spring (MB-274389) (Qt. 10)**
      - Kapton, 2mil x 6 x 6 (MA-274666) (Qt. 10)
      - Spring Shim G10 (MA-318693) (Qt. 20)
      - Union Elbow 1" (MA-318487) (Qt. 2)
      - G-10 .015x4x4LG (MA-318626) (Qt. 4]
      - Silver Plating Powder (MA-225557) (Qt. 0.25 oz)
      - Union Elbow 3/4" (MA-318486) (Qt. 2)
      - Caplug - 1 3/8" (MA-318628) (Qt. 1)
      - Parts Bag (MA-318790) (Qt. 1)
    - Upper Half Core (ME-274884)
      - End Pack - Left (MD-318166)
        - Trimmed Lamination #P1 (MC-318168) (Qt. 3)
        - Trimmed Lamination #P2 (MC-318169) (Qt. 3)
        - Trimmed Lamination #P3 (MC-318170) (Qt. 3)
        - Trimmed Lamination #P4 (MC-318171) (Qt. 3)
        - Trimmed Lamination #P5 (MC-318172) (Qt. 3)
        - Trimmed Lamination #P6 (MC-318173) (Qt. 3)
        - Trimmed Lamination #P7 (MC-318174) (Qt. 5)
        - Trimmed Lamination #P8 (MC-318175) (Qt. 7)
        - Trimmed Lamination #P9 (MC-318176) (Qt. 9)
        - Trimmed Lamination #P10 (MC-318177) (Qt. 12)
        - Lamnination (ME-274020) (Qt. 51)
        - Epoxy Resin 826 (MA-116501) (Qt. 1000 g)
        - Hardner (MA-116503) (Qt. 900 g)
        - BDMA Curing Agent (MA-225565) (Qt. 10 g)
      - End Pack - Right (MD-318167)
        - Trimmed Lamination #P1 (MC-318168) (Qt. 3)
        - Trimmed Lamination #P2 (MC-318169) (Qt. 3)
        - Trimmed Lamination #P3 (MC-318170) (Qt. 3)
        - Trimmed Lamination #P4 (MC-318171) (Qt. 3)
        - Trimmed Lamination #P5 (MC-318172) (Qt. 3)
        - Trimmed Lamination #P6 (MC-318173) (Qt. 3)
        - Trimmed Lamination #P7 (MC-318174) (Qt. 5)
        - Trimmed Lamination #P8 (MC-318175) (Qt. 7)
        - Trimmed Lamination #P9 (MC-318176) (Qt. 9)
        - Trimmed Lamination #P10 (MC-318177) (Qt. 12)
        - Lamnination (ME-274020) (Qt. 51)
        - Epoxy Resin 826 (MA-116501) (Qt. 1000 g)
        - Hardner (MA-116503) (Qt. 900 g)
        - BDMA Curing Agent (MA-225565) (Qt. 10 g)
      - Lamnination (ME-274020) (Qt. ~3970)
      - Top Plate (MC-247888) (Qt. 1)
      - Side Bar (MC-274887) (Qt. 2)
      - Alignment Lug (MA-331902) (Qt. 1)
      - Split Pin (MA-331903) (Qt. 1)
    - Lower Half Core (ME-318054)
      - End Pack - Left (MD-318166)
        - Trimmed Lamination #P1 (MC-318168) (Qt. 3)
        - Trimmed Lamination #P2 (MC-318169) (Qt. 3)
        - Trimmed Lamination #P3 (MC-318170) (Qt. 3)
        - Trimmed Lamination #P4 (MC-318171) (Qt. 3)
        - Trimmed Lamination #P5 (MC-318172) (Qt. 3)
        - Trimmed Lamination #P6 (MC-318173) (Qt. 3)
        - Trimmed Lamination #P7 (MC-318174) (Qt. 5)
        - Trimmed Lamination #P8 (MC-318175) (Qt. 7)
        - Trimmed Lamination #P9 (MC-318176) (Qt. 9)
        - Trimmed Lamination #P10 (MC-318177) (Qt. 12)
        - Lamnination (ME-274020) (Qt. 51)
        - Epoxy Resin 826 (MA-116501) (Qt. 1000 g)
        - Hardner (MA-116503) (Qt. 900 g)
        - BDMA Curing Agent (MA-225565) (Qt. 10 g)
      - End Pack - Right (MD-318167)
        - Trimmed Lamination #P1 (MC-318168) (Qt. 3)
        - Trimmed Lamination #P2 (MC-318169) (Qt. 3)
        - Trimmed Lamination #P3 (MC-318170) (Qt. 3)
        - Trimmed Lamination #P4 (MC-318171) (Qt. 3)
        - Trimmed Lamination #P5 (MC-318172) (Qt. 3)
        - Trimmed Lamination #P6 (MC-318173) (Qt. 3)
        - Trimmed Lamination #P7 (MC-318174) (Qt. 5)
        - Trimmed Lamination #P8 (MC-318175) (Qt. 7)
        - Trimmed Lamination #P9 (MC-318176) (Qt. 9)
        - Trimmed Lamination #P10 (MC-318177) (Qt. 12)
        - Lamnination (ME-274020) (Qt. 51)
        - Epoxy Resin 826 (MA-116501) (Qt. 1000 g)
        - Hardner (MA-116503) (Qt. 900 g)
        - BDMA Curing Agent (MA-225565) (Qt. 10 g)
      - Lamnination (ME-274020) (Qt. ~3970)
      - Top Plate (MC-318055) (Qt. 1)
      - Side Bar (MC-274887) (Qt. 2)
      - Ball Tab (MB-318058) (Qt. 3)
    - Lower Coil (ME-274836)
      - Coil Fabrication A-Lower (ME-274800)
        - 1x4 Conductor (MB-274019) (Qt. ~150 ft)
        - 1x4 Conductor (MB-274019) (Qt. ~0.6 ft)
        - 1x2-3/8 Conductor (MB-274555) (Qt. ~2.1 ft)
        - Water Outlet 3/4" OD (MB-274834) (Qt. 1)
        - Silfos Ring, 3/4" OD (MA-274833) (Qt. 1)
        - End Plug (MA-274057) (Qt. 2)
        - Silfos Ring, 5/8" OD (MA-101987) (Qt. 20)
        - Sleeve (MA-318245) (Qt. 9)
        - Washer (MA-274016) (Qt. 9)
      - Thru Lead, A-Lower (MD-274831) (Qt. 1)
        - 1x4 Conductor (MB-274019) (Qt. ~21.10 ft)
        - Water Outlet 3/4" OD (MB-274834) (Qt. 2)
        - Silfos Ring, 3/4" OD (MA-274833) (Qt. 2)
        - End Plug (MA-274057) (Qt. 2)
        - Silfos Ring, 5/8" OD (MA-101987) (Qt. 2)
        - Wire, Silfos 15, 1/16 dia. (MA-225143) (Qt. 1 ft)
      - Fiberglass tape 7mil x 2" (MA-225574) (Qt. 50 Rolls)
      - G10 0.15x3.75x78 (MB-318295) (Qt. 26)
      - G10 0.15x3.75x80 (MB-318295) (Qt. 10)
      - G10 0.15x3.75x81.135 (MB-318296) (Qt. 6)
      - G10 0.15x4.00x23.75 (MB-318713) (Qt. 20)
      - G10 0.15x3.75x80.50 (MB-274726) (Qt. 6)
      - G10 0.15x4.00x81 (MB-274725) (Qt. 3)
      - TEDLAR 2mil x 2" (MA-116529) (Qt. 0.5 roll)
      - NMA Hardner (MA-116503) (Qt. ~40.5 kg)
      - 826 Resin (MA-116501) (Qt. ~45 kg)
      - DMP-30 Accelerator (MA-116500) (Qt. 675 g)
      - Start Tail Filler (MC-331504) (Qt. 1)
      - End Tail Filler (MB-331502) (Qt. 3)
    - Upper Coil (ME-274835)
      - Coil Fabrication A-Upper (ME-274799)
        - 1x4 Conductor (MB-274019) (Qt. ~172 ft)
        - 1x4 Conductor (MB-274019) (Qt. ~0.3 ft)
        - 1x2-3/8 Conductor (MB-274555) (Qt. ~6 ft)
        - Water Outlet 3/4" OD (MB-274834) (Qt. 1)
        - Silfos Ring, 3/4" OD (MA-274833) (Qt. 1)
        - End Plug (MA-274057) (Qt. 2)
        - Silfos Ring, 5/8" OD (MA-101987) (Qt. 22)
        - Sleeve (MA-318245) (Qt. 10)
        - Washer (MA-274016) (Qt. 10)
        - Water Outlet 1" OD (MB-274823) (Qt. 1)
        - Silfos Ring, 1" OD (MA-274824) (Qt. 1)
        - Wire, Silfos 15, 1/16 dia. (MA-225143) (Qt. 3 ft)
      - Fiberglass tape 7mil x 2" (MA-225574) (Qt. 50 Rolls)
      - G10 0.15x3.75x78 (MB-318295) (Qt. 28)
      - G10 0.15x3.75x80 (MB-318295) (Qt. 12)
      - G10 0.15x3.75x81.135 (MB-318296) (Qt. 2)
      - G10 0.15x4.00x23.75 (MB-318713) (Qt. 24)
      - G10 0.15x3.75x80.50 (MB-274726) (Qt. 6)
      - TEDLAR 2mil x 2" (MA-116529) (Qt. 0.5 roll)
      - NMA Hardner (MA-116503) (Qt. ~40.5 kg)
      - 826 Resin (MA-116501) (Qt. ~45 kg)
      - DMP-30 Accelerator (MA-116500) (Qt. 675 g)
      - Start Tail Filler (MC-331504) (Qt. 1)
      - End Tail Filler (MB-331502) (Qt. 1)
  - Beam Tube Assy. (MD-331589)
  - Beam Tube Support Block (MC-318672)
  - Beam Tube Support (MC-274687)
  - Riversible End Cover Assy. (MD-331898)
  - Center Plug Assy. (MB-331897)

Hundreds of drawings for the magnet, not including the tooling and the equipment for manufacturing.

# Manufacturing Plan





**Coil Fabrication Vendor**

Conductor

Upper Coil

Lower Coil

Steel

**Steel Vendor**

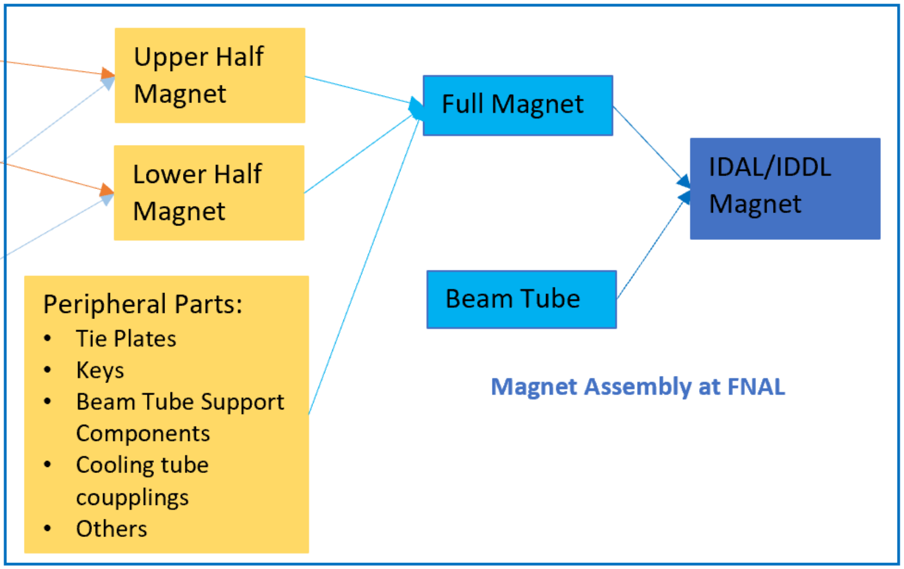
Lamination

**Lamination Fabrication Vendor**

Upper Core

Lower Core

**Core Fabrication Vendor**



Upper Half Magnet

Lower Half Magnet

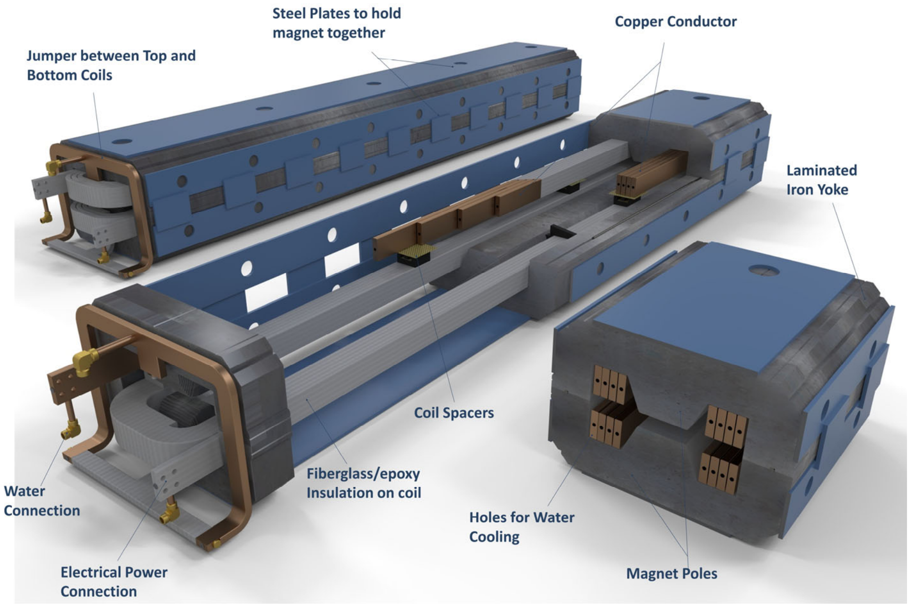
Full Magnet

IDAL/IDDL Magnet

Beam Tube

Peripheral Parts:
- Tie Plates
- Keys
- Beam Tube Support Components
- Cooling tube coupplings
- Others

**Magnet Assembly at FNAL**



- IDAL (6 m): Qt. 13 + 2 spares
- IDDL (4 m): Qt. 12 + 2 spares

# Manufacturing: Coil

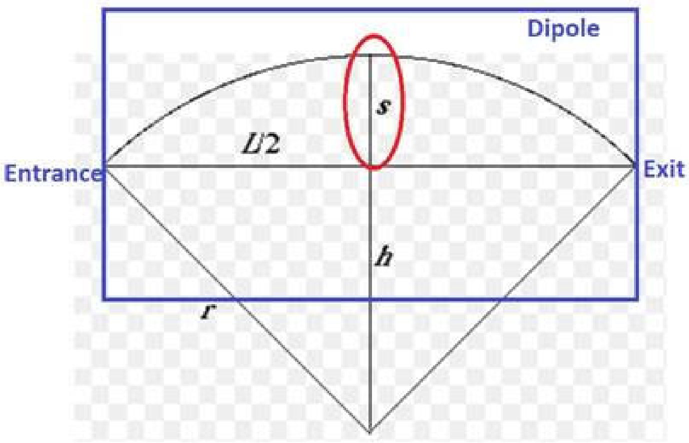
An Impregnated Coil

- The coil fabrication requires annealing and winding (conductor bending to shape), conductor joint brazing, insulation wrapping and coil epoxy impregnation.
- Risk: Each coil has as many as 9 brazing joints, any defect in the brazing joint will result in coil failure.
- The plan to reduce this risk is to use the design and in process QC, including approved induction brazing process, and do ultrasonic inspection on the brazing joints, helium leak check and water leak test with hydraulic pressure of 500 psi after the conductor sections are wound and brazed together.
- Electrical Test (Resistance and Inductance Measurement, Hipot Test and Impulse Test).

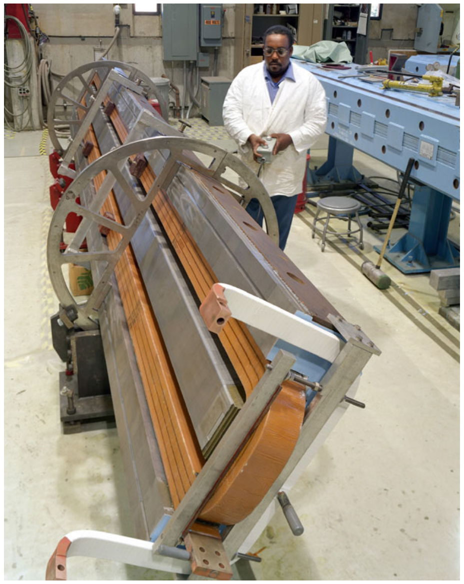
# Manufacturing: Core

A Stacked and Welded Core

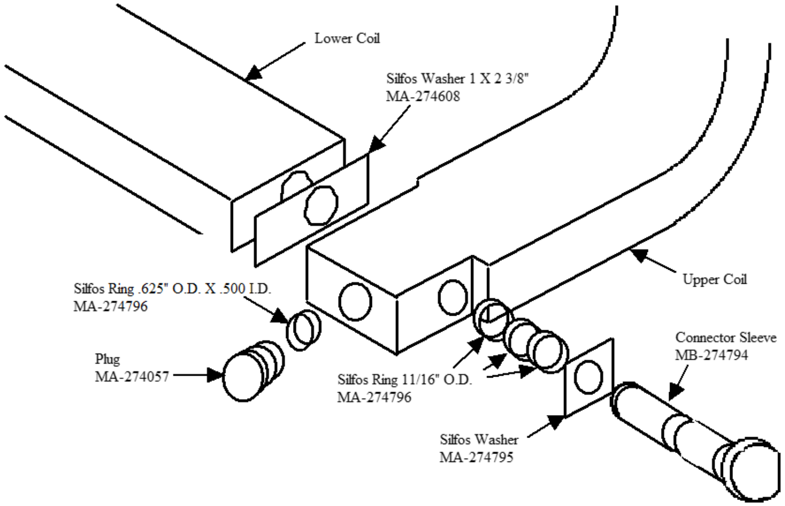
- The core laminations with 1.5 mm thickness are stamped using a stamping die.
- More than 4,000 laminations are stacked using hydraulic stacker to a half core and then the core is welded along its sides.
- Note that the core is not straight but curved to match the beam trajectory with the sagitta of 16 mm, which makes the fabrication process complicated.



# Manufacturing: Magnet Assembly



- The individual coil is placed to a half core (Upper and Lower, pay attention to the sagitta)
- Assemble the upper core and the lower core with coils inside using Hydraulic Clamping Table.
- Weld the strength plates along the two sides of the magnet.
- Electrical test (including coil resistance and inductance measurement, 5 kV Hipot to ground test and 100 V Ring test)
- Manifold assembly and brazing, and water flow test.



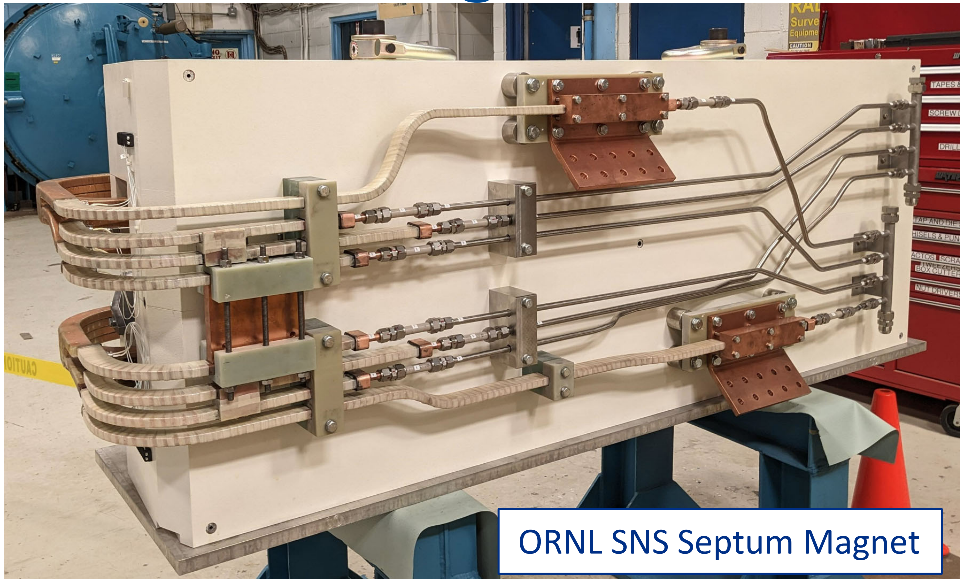
Manifold Assembly (Typical)

# Manufacturing: Magnet Test and Beam Tube Install

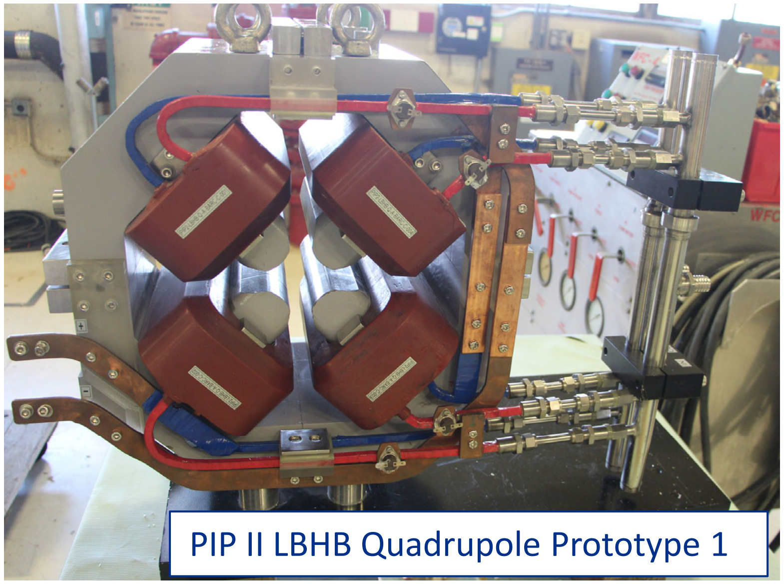
- The magnet is powered for magnetic measurement.
- The oval beam tube is due to protons of slightly different momenta bending differently in the magnetic field.
- Under vacuum, the beam tube's smaller dimension decreases to enough under 2.000 inches to allow its insertion into a magnet aperture and then to allow bending to match the beam sagitta.

# Manifold for other Water-Cooled Magnets

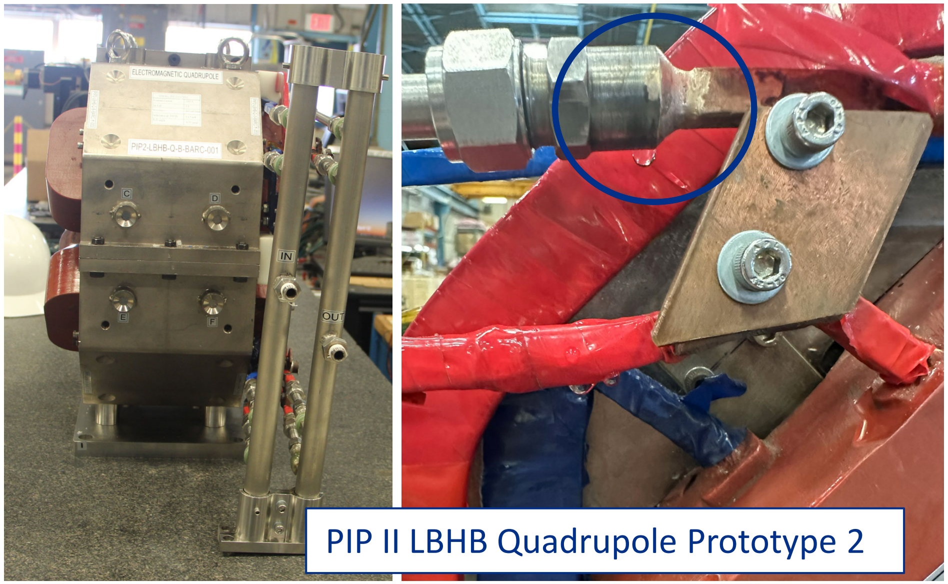
ORNL SNS Chicane Dipole Magnet



ORNL SNS Septum Magnet



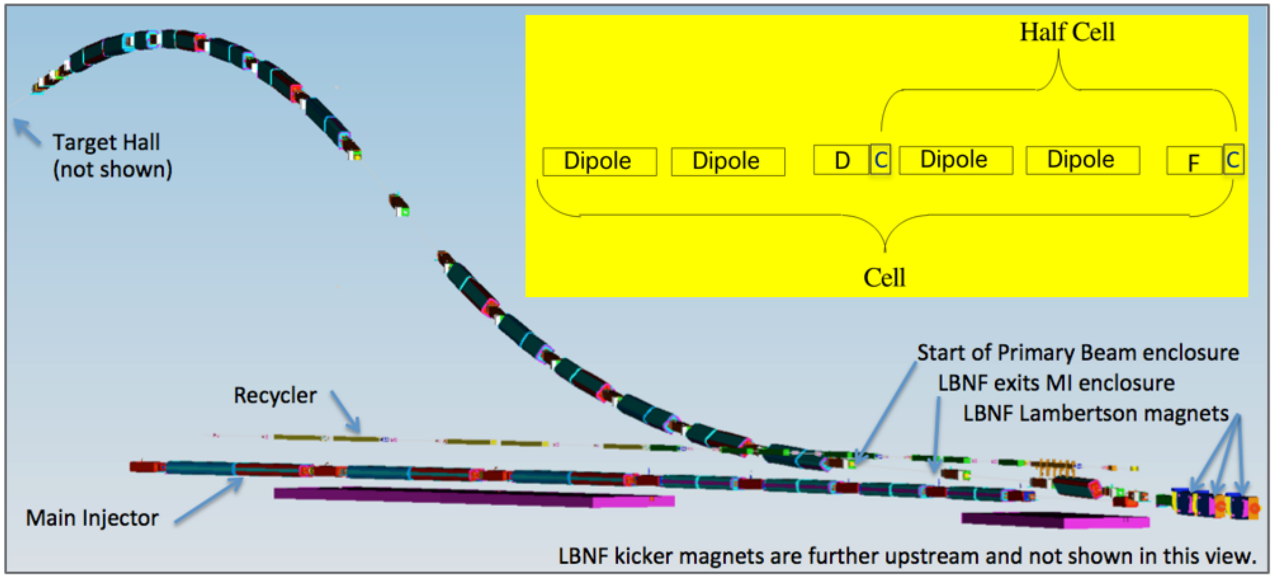
PIP II LBHB Quadrupole Prototype 1



PIP II LBHB Quadrupole Prototype 2

# Chapter 5 Quadrupole Magnet Design and Manufacturing

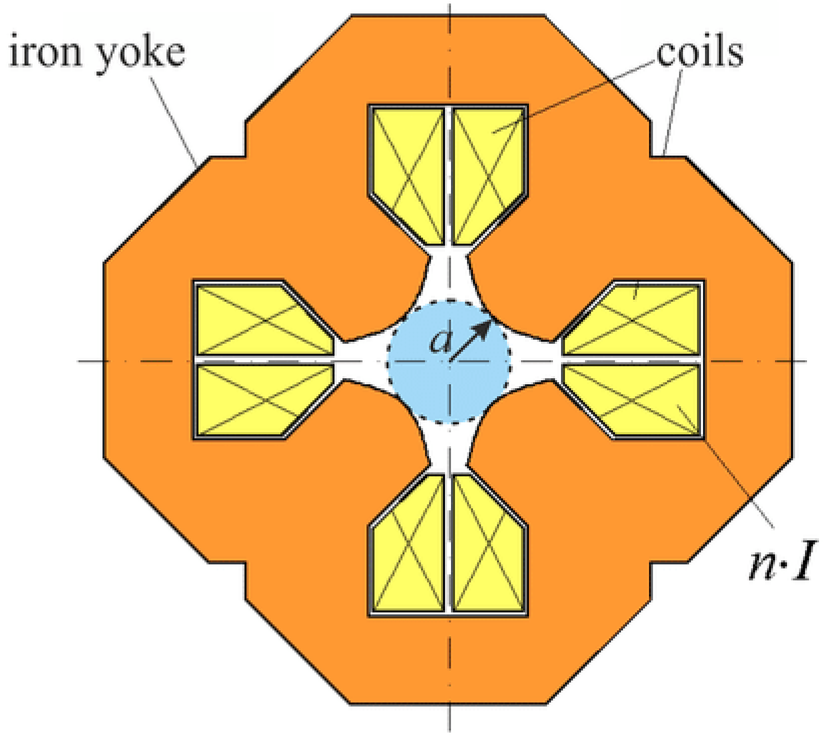
# LBNF Beamline Quadrupole Magnet Specification



LBNF kicker magnets are further upstream and not shown in this view.

| Property | Value (QQD) | Value (QQE) |
|---|---|---|
| Magnetic gradient (nominal at 120 GeV) | 16.546 T/m | 17.082 T/m |
| Integrated gradient (nominal at 120 GeV) | 50.43 T-m/m | 26.03 T-m/m |
| Pole diameter | 77.2 mm | |
| Aperture (with round beam tube) | minimum 72 mm | |
| Color | Orange | |

# Coil Design



$$g = \frac{2\mu_0 NI}{a^2}$$

Given:

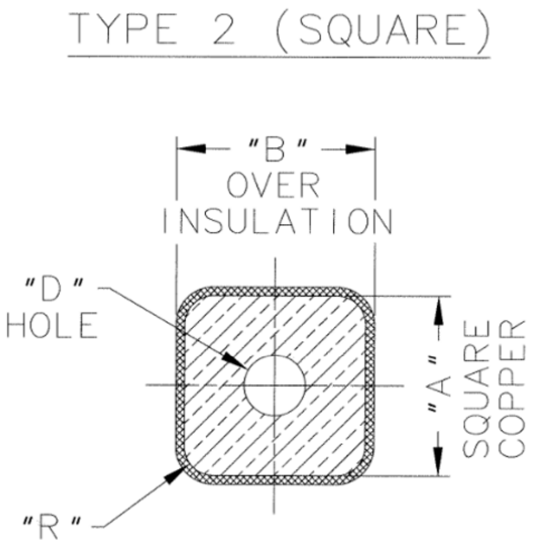
g = 16.546 T/m, a = 38.6 mm

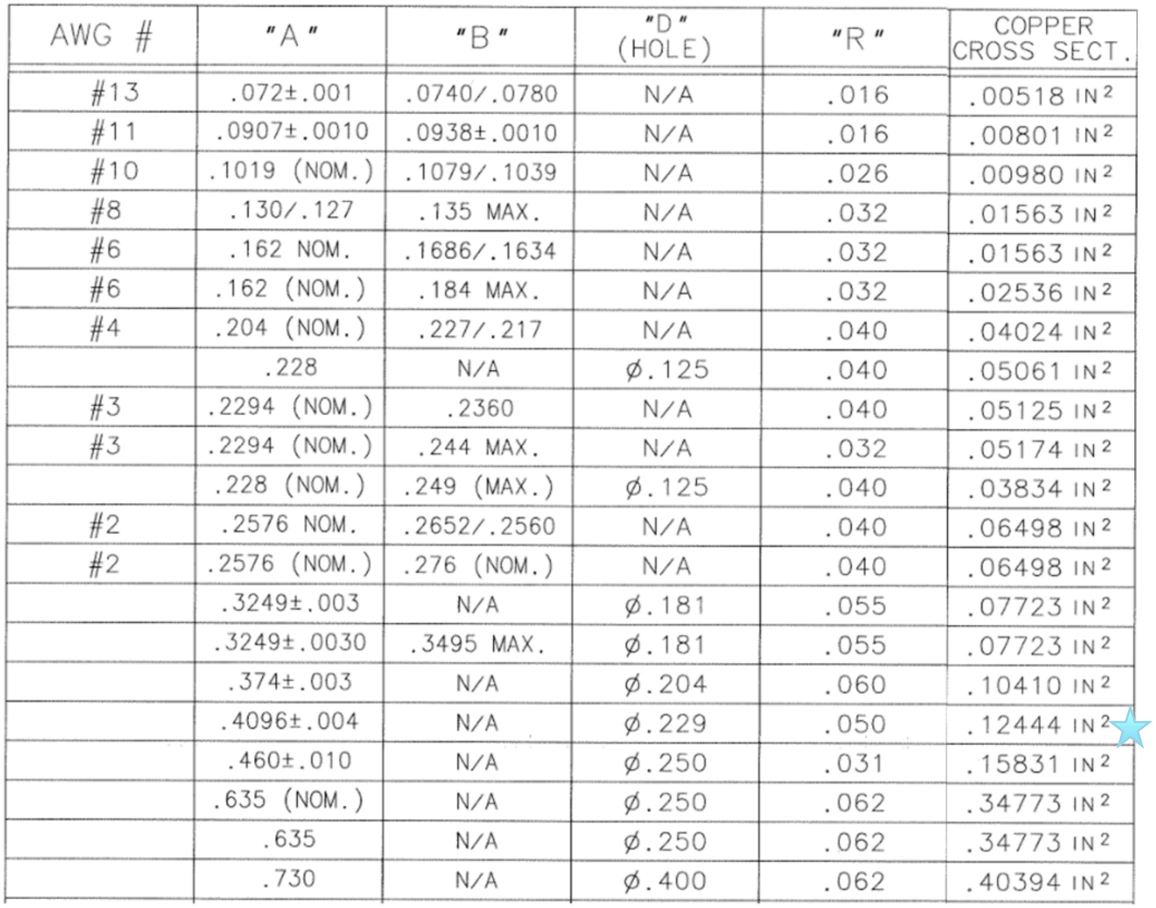
Obtain:

$\mathrm{NI} = \frac{g}{2\mu_0}\cdot a^2 = 9810\ \mathrm{A}$

| N (number of turns) | I (current per turn) |
|---|---|
| 8 | 1,226 A |
| 16 | 613 A |
| 28 | 350 A |
| 40 | 245 A |
| … | … |

# Conductor

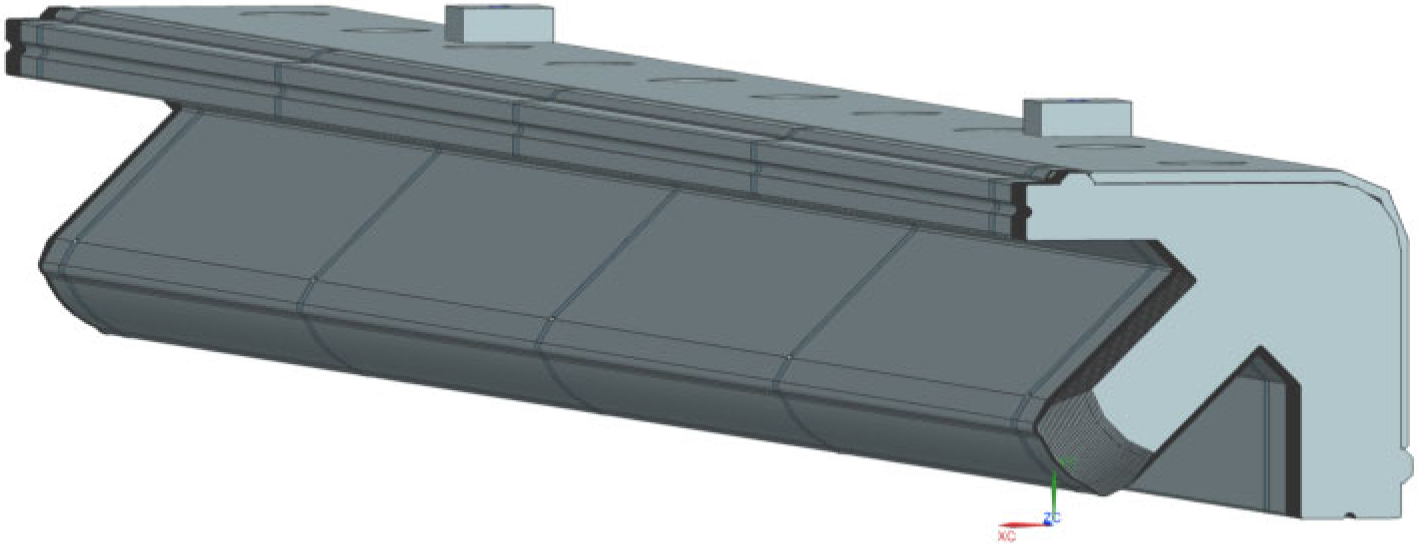




| AWG # | "A" | "B" | "D" (HOLE) | "R" | COPPER CROSS SECT. |
|---|---|---|---|---|---|
| #13 | .072±.001 | .0740/.0780 | N/A | .016 | .00518 IN$^2$ |
| #11 | .0907±.0010 | .0938±.0010 | N/A | .016 | .00801 IN$^2$ |
| #10 | .1019 (NOM.) | .1079/.1039 | N/A | .026 | .00980 IN$^2$ |
| #8 | .130/.127 | .135 MAX. | N/A | .032 | .01563 IN$^2$ |
| #6 | .162 NOM. | .1686/.1634 | N/A | .032 | .01563 IN$^2$ |
| #6 | .162 (NOM.) | .184 MAX. | N/A | .032 | .02536 IN$^2$ |
| #4 | .204 (NOM.) | .227/.217 | N/A | .040 | .04024 IN$^2$ |
|  | .228 | N/A | Ø.125 | .040 | .05061 IN$^2$ |
| #3 | .2294 (NOM.) | .2360 | N/A | .040 | .05125 IN$^2$ |
| #3 | .2294 (NOM.) | .244 MAX. | N/A | .032 | .05174 IN$^2$ |
|  | .228 (NOM.) | .249 (MAX.) | Ø.125 | .040 | .03834 IN$^2$ |
| #2 | .2576 NOM. | .2652/.2560 | N/A | .040 | .06498 IN$^2$ |
| #2 | .2576 (NOM.) | .276 (NOM.) | N/A | .040 | .06498 IN$^2$ |
|  | .3249±.003 | N/A | Ø.181 | .055 | .07723 IN$^2$ |
|  | .3249±.0030 | .3495 MAX. | Ø.181 | .055 | .07723 IN$^2$ |
|  | .374±.003 | N/A | Ø.204 | .060 | .10410 IN$^2$ |
|  | .4096±.004 | N/A | Ø.229 | .050 | .12444 IN$^2$ |
|  | .460±.010 | N/A | Ø.250 | .031 | .15831 IN$^2$ |
|  | .635 (NOM.) | N/A | Ø.250 | .062 | .34773 IN$^2$ |
|  | .635 | N/A | Ø.250 | .062 | .34773 IN$^2$ |
|  | .730 | N/A | Ø.400 | .062 | .40394 IN$^2$ |

- 28 turns of .4096” hollow square conductor
- $J = 350\ (\text{A})/80.28\ (\text{mm}^2) = 4.36\ \text{A/ mm}^2$

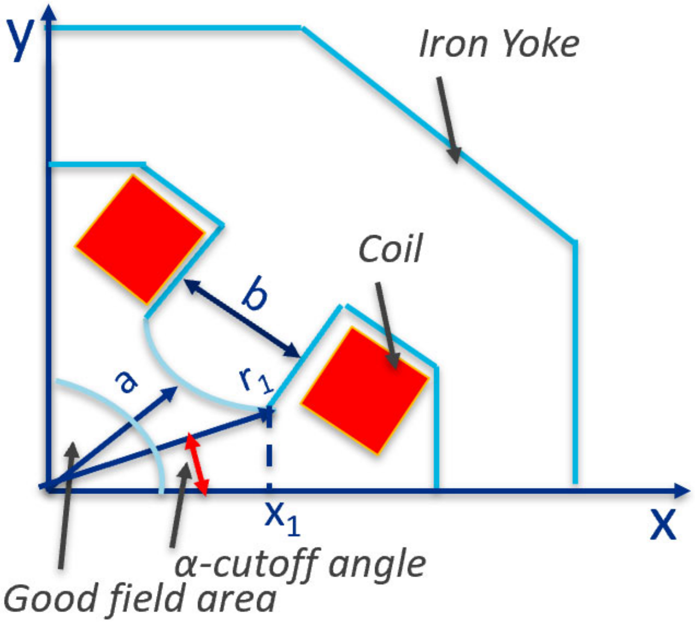
# Yoke Design_ Length

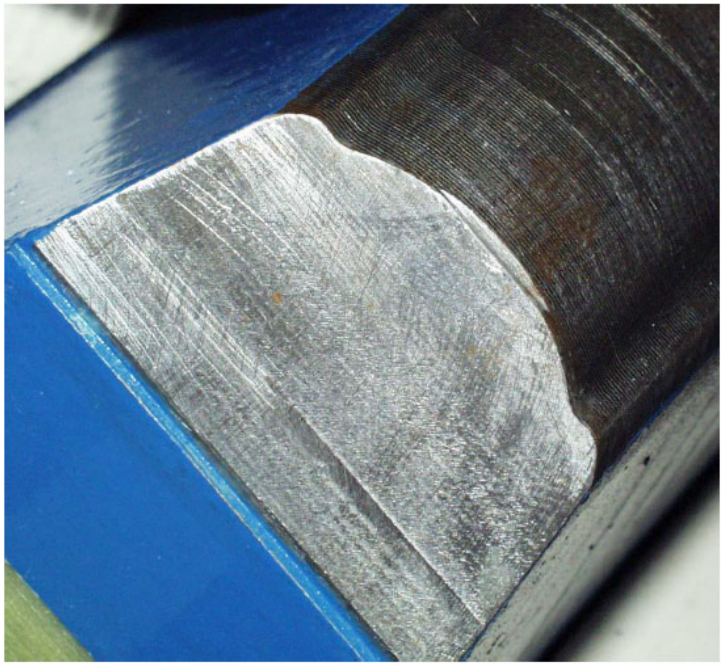


Given:
g = 16.546 T/m
Integrated gradient: 50.43 T-m/m

Calculate:
L=3.048 m

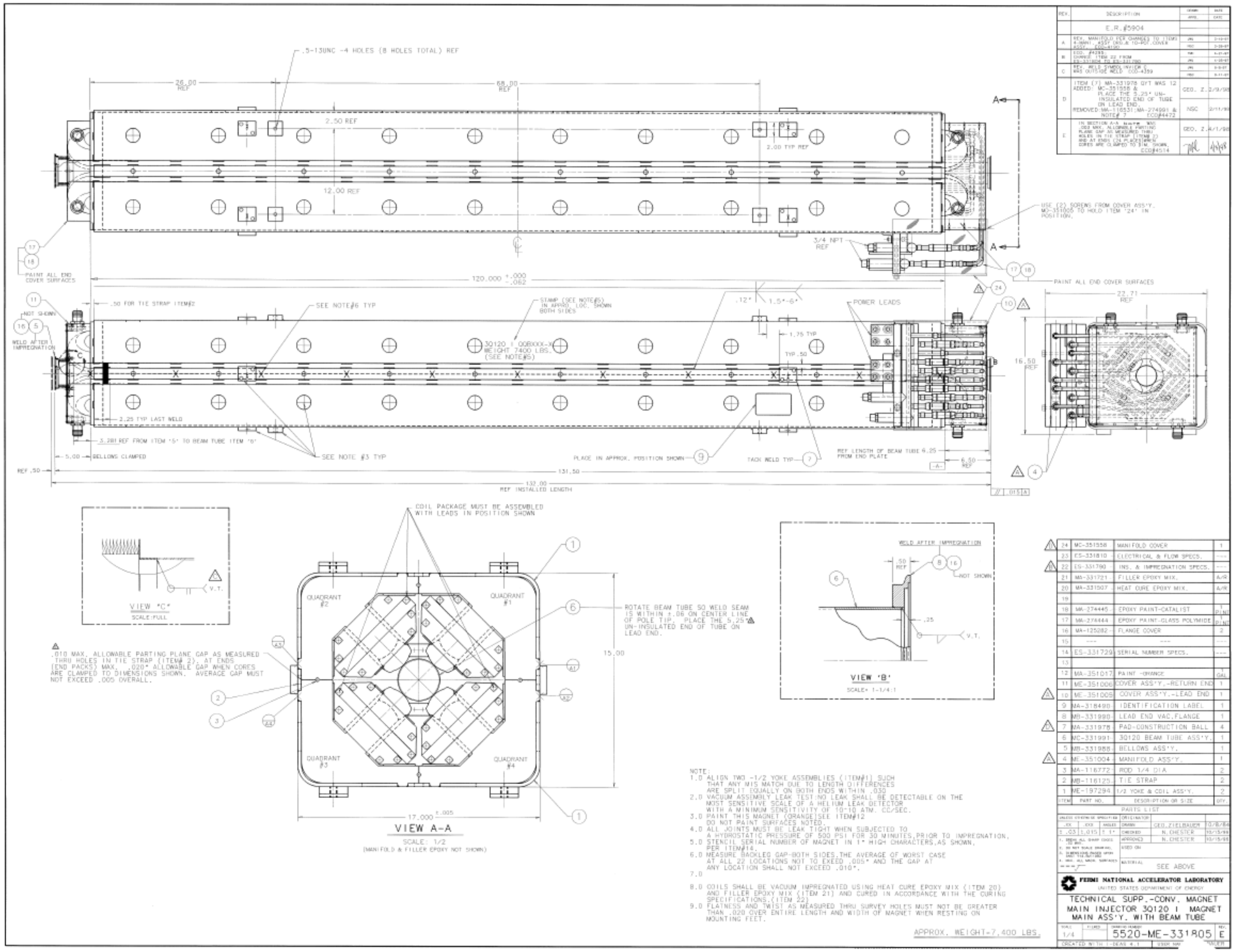
# Yoke Design_ Yoke Pole Dimensions





- The ideal quadrupole field is generated by a hyperbolic pole profile: $x \cdot y = \frac{a^2}{2}$
- Assume the radius of the good field region is $r_0$, initially set $b= a + r_0$
- Adding shims to compensate the pole cutoff. At $\alpha = 18°$, the first undesired $5^{th}$ order multipole vanished. $r_1$=1.122a.
- Need simulation to design the 2D shape of the yoke.

# Magnet Drawing



NOTE:
1.0 ALIGN TWO -1/2 YOKE ASSEMBLIES (ITEM#1) SUCH THAT ANY MIS MATCH DUE TO LENGTH DIFFERENCES ARE SPLIT EQUALLY ON BOTH ENDS WITHIN .030
2.0 VACUUM ASSEMBLY LEAK TEST:NO LEAK SHALL BE DETECTABLE ON THE MOST SENSITIVE SCALE OF A HELIUM LEAK DETECTOR WITH A MINIMUM SENSITIVITY OF 10⁻10 ATM. CC/SEC.
3.0 PAINT THIS MAGNET (ORANGE)SEE ITEM#12 DO NOT PAINT SURFACES NOTED.
4.0 ALL JOINTS MUST BE LEAK TIGHT WHEN SUBJECTED TO A HYDROSTATIC PRESSURE OF 500 PSI FOR 30 MINUTES,PRIOR TO IMPREGNATION.
5.0 STENCIL SERIAL NUMBER OF MAGNET IN 1" HIGH CHARACTERS,AS SHOWN, PER ITEM#14.
6.0 MEASURE BACKLEG GAP-BOTH SIDES.THE AVERAGE OF WORST CASE AT ALL 22 LOCATIONS NOT TO EXEED .005" AND THE GAP AT ANY LOCATION SHALL NOT EXCEED .010".
7.0
8.0 COILS SHALL BE VACUUM IMPREGNATED USING HEAT CURE EPOXY MIX (ITEM 20) AND FILLER EPOXY MIX (ITEM 21) AND CURED IN ACCORDANCE WITH THE CURING SPECIFICATIONS.(ITEM 22)
9.0 FLATNESS AND TWIST AS MEASURED THRU SURVEY HOLES MUST NOT BE GREATER THAN .020 OVER ENTIRE LENGTH AND WIDTH OF MAGNET WHEN RESTING ON MOUNTING FEET.

APPROX. WEIGHT=7,400 LBS.

| ITEM | PART NO. | DESCRIPTION OR SIZE | QTY. |
|---|---|---|---|
| 24 | MC-351558 | MANIFOLD COVER | 1 |
| 23 | ES-331810 | ELECTRICAL & FLOW SPECS. | --- |
| 22 | ES-331790 | INS. & IMPREGNATION SPECS. | --- |
| 21 | MA-331721 | FILLER EPOXY MIX. | A/R |
| 20 | MA-331507 | HEAT CURE EPOXY MIX. | A/R |
| 19 |  |  |  |
| 18 | MA-274445 | EPOXY PAINT-CATALIST | 1 PINT |
| 17 | MA-274444 | EPOXY PAINT-GLASS POLYMIDE | 1 PINT |
| 16 | MA-125282 | FLANGE COVER | 2 |
| 15 | --- | --- | --- |
| 14 | ES-331729 | SERIAL NUMBER SPECS. | --- |
| 13 |  |  |  |
| 12 | MA-351017 | PAINT -ORANGE | 1 GAL |
| 11 | ME-351006 | COVER ASS'Y.-RETURN END | 1 |
| 10 | ME-351005 | COVER ASS'Y.-LEAD END | 1 |
| 9 | MA-318490 | IDENTIFICATION LABEL | 1 |
| 8 | MB-331990 | LEAD END VAC.FLANGE | 1 |
| 7 | MA-331978 | PAD-CONSTRUCTION BALL | 4 |
| 6 | MC-331991 | 3Q120 BEAM TUBE ASS'Y. | 1 |
| 5 | MB-331988 | BELLOWS ASS'Y. | 1 |
| 4 | ME-351004 | MANIFOLD ASS'Y. | 1 |
| 3 | MA-116772 | ROD 1/4 DIA | 2 |
| 2 | MB-116125 | TIE STRAP | 2 |
| 1 | ME-197294 | 1/2 YOKE & COIL ASS'Y. | 2 |

PARTS LIST

| | | |
|---|---|---|
| DRAWN | GEO. ZIELBAUER | 10/8/84 |
| CHECKED | N. CHESTER | 10/15/98 |
| APPROVED | N. CHESTER | 10/15/98 |

MATERIAL: SEE ABOVE

FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

TECHNICAL SUPP.-CONV. MAGNET
MAIN INJECTOR 3Q120 I MAGNET
MAIN ASS'Y. WITH BEAM TUBE

SCALE 1/4
5520-ME-331805
REV. E

# Drawing Package

Hundreds of drawings for the magnet, not including the tooling and the equipment for manufacturing.

- **3Q120 Magnet/Beam Tube Assembly (ME-331805)**
  - Peripheral Parts
    - Tie Strap (MB-116125) (Qt. 2)
    - Rod 1/4 Dia. (MA-116772) (Qt. 2)
    - 3Q120 Beam Tube Assy (MC-331991)
    - Manifold Assy (ME-351004) (Qt. 1)
      - Swaged Coupling (MA-351353) (Qt. 12)
      - Swaged Reducing Coupling (MA-351355) (Qt. 4)
      - Swaged Tee (MA-351357) (Qt. 6)
      - Elbow-90° Street 3/8 (MA-197322) (Qt. 6)
      - Elbow-90° Reducing 1/2- 3/8 (MA-197321) (Qt. 6)
      - Tube Lead 1.25 LG (MA-351359) (Qt. 2)
      - Tube Lead 1.75 LG (MA-351035) (Qt. 3)
      - Tube Lead 2.75 LG (MA-351036) (Qt. 3)
      - Insulator (MC-14942) (Qt. 8)
      - Lead NO 1-13.00 LG (MB-351048) (Qt. 1)
      - Lead NO 2-9.16 LG (MB-351049) (Qt. 1)
      - Lead NO 3-7.80 LG (MB-351050) (Qt. 1)
      - Lead NO 4-14.34 LG (MB-351051) (Qt. 1)
      - Lead NO 5-8.91 LG (MB-351052) (Qt. 1)
      - Lead NO 6-12.73 LG (MB-351053) (Qt. 1)
      - Lower Manifold Tube Weld (MC-351018) (Qt. 1)
      - Upper Manifold Tube Weld (MC-351019) (Qt. 1)
      - Silver Plating Powder (MA-225557) (Qt. A/R)
      - Manifold Support Assy. (MB-351029) (Qt. 1)
      - Silfos #15 Rod 1/8x20 (MA-116256) (Qt. A/R)
    - Bellows Assy. (MB-331988) (Qt. 1)
    - Flange Cover (MA-125282) (Qt. 2)
    - Pad-construction Ball (MA-331978) (Qt. 4)
    - Lead End Vac. Flange (MB-331990) (Qt. 1)
    - Identification Label (MA-318490) (Qt. 1)
    - Cover Assy.- Lead End (ME-351005) (Qt. 1)
      - Side Plate-Lead Side (MC-351071) (Qt. 1)
      - Side Filler-Lead Side (MC-351072) (Qt. 1)
      - Side Plate-Blank Side (MC-351073) (Qt. 1)
      - Top Plate (MC-351075) (Qt. 1)
      - Bottom Plate (MC-351076) (Qt. 1)
      - Cover Plate (MC-351077) (Qt. 1)
      - Male Nipple 1-1/4" N.P.T (MA-331884) (Qt. 3)
      - Hardware
    - Cover Assy.- Return End (MD-351006) (Qt. 1)
      - Side Plate (MC-351084) (Qt. 2)
      - Bottom Plate (MC-351085) (Qt. 1)
      - Inner Cover Plate (MB-351086) (Qt. 1)
      - Cover Spacer Plate (MC-351087) (Qt. 1)
      - Outer Cover Plate (MC-351088) (Qt. 1)
      - Male Nipple 1-1/4" N.P.T (MA-331884) (Qt. 3)
      - Top Plate (MC-351562) (Qt. 1)
      - Hardware
    - Paint - Orange (MA-351017) (Qt. 1 Gal)
    - Epoxy Paint - Glass Polymide (MA-274444) (Qt. 1 pint)
    - Epoxy Paint - Catalist (MA-274445) (Qt. 1 pint)
    - Heat Cure Epoxy Mix (MA-331507) (Qt. A/R)
    - Filler Epoxy Mix (MA-331721) (Qt. A/R)
    - Manifold Cover (MC-351558) (Qt. 1)
  - 1/2 Yoke & Coil Assy (ME-197294) (Qt. 2)
    - 1/4 Yoke & Coil Assy Quad 1&3 (ME-331900)
      - 1/4 Yoke (MC-196834) (Qt. 1)
        - End Pack-L.H. (MC-196863) (Qt. 1)
          - Lamination (MD-116058) (Qt. 29)
          - Room Cure Epoxy Mix (MA-331638)
        - End Pack-R.H. (MC-196864) (Qt. 1)
          - Lamination (MD-116058) (Qt. 29)
          - Room Cure Epoxy Mix (MA-331638)
        - Lamination (MD-116058) (Notched Qt. 965)
        - Lamination (MD-116058) (Un-Notched Qt. 965)
        - Angle-1/4 Yoke (MC-116112) (Qt. 1)
        - Ball Mount Tab (MB-318058) (Qt. 2)
        - Lamination with pole tip notch (MD-331940) (Qt. 45)
        - Pad-Construction Ball (MA-331978) (Qt. 2)
      - Coil Assembly (MD-197278) (Qt. 1)
        - Half Coil Assy. (MD-197277) (Qt. 2)
          - Inner Coil (ME-197276) (Qt. 1)
            - Copper Conductor (MA-186587) (Qt. 200ft)
            - Sleeve Brazing (MA-186691) (Qt. 2)
            - Ring Braizing (MA-186692) (Qt. 4)
            - Washer Brazing (MA-351037) (Qt. 2)
            - Brazing Rod (MA-116256)
          - Outer Coil (ME-197275) (Qt. 1)
            - Copper Conductor (MA-186587) (Qt. 115ft)
            - Sleeve Brazing (MA-186691) (Qt. 2)
            - Ring Braizing (MA-186692) (Qt. 4)
            - Washer Brazing (MA-351037) (Qt. 2)
            - Brazing Rod (MA-116256)
          - Fiberglass tape 7mil x 1/2" (MA-351462) (Qt. 24 rolls)
          - Fiberglass tape 7mil x 2" (MA-225574) (Qt. 2 rolls)
          - G10 Strip 0.03 x 1.63 (MB-331799) (Qt. 2)
          - Filler (Straght Section) (MB-331800) (Qt. 6)
          - G10 (MB-331801) (Qt. 2)
          - G10 (MB-331802) (Qt. 2)
          - G10 (MB-331803) (Qt. 2)
          - Mylar (MA-116514) (Qt. 150")
        - Fiberglass tape 7mil x 2" (MA-225574) (Qt. 7 rolls)
        - G10 Sheet Insulator (MA-331831) (Qt. 2)
        - Tie Wrap (MB-318794) (Qt. 1)
      - G10 .375x1.5 (MB-331856) (Qt. 10)
      - Kapton 5 mil x 4" w/adhesive (MA-274452) (Qt. A/R)
    - 1/4 Yoke & Coil Assy Quad 2&4 (ME-331891)
      - 1/4 Yoke (MC-196834) (Qt. 1)
        - End Pack-L.H. (MC-196863) (Qt. 1)
          - Lamination (MD-116058) (Qt. 29)
          - Room Cure Epoxy Mix (MA-331638)
        - End Pack-R.H. (MC-196864) (Qt. 1)
          - Lamination (MD-116058) (Qt. 29)
          - Room Cure Epoxy Mix (MA-331638)
        - Lamination (MD-116058) (Notched Qt. 965)
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        - Angle-1/4 Yoke (MC-116112) (Qt. 1)
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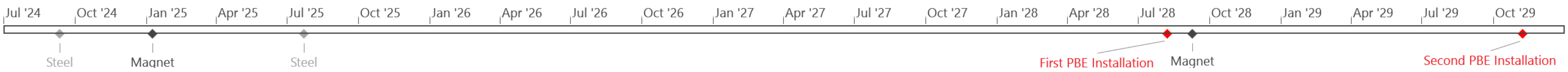
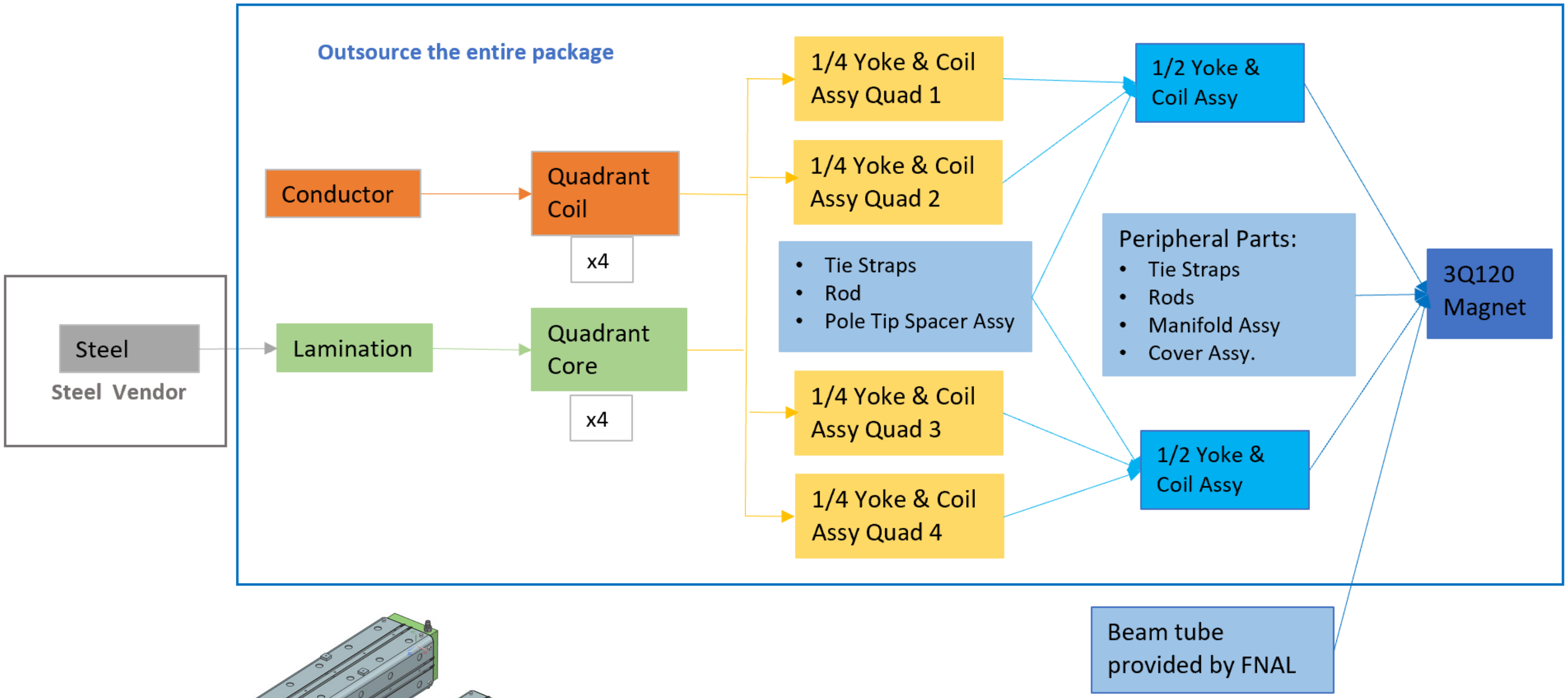
      - Coil Assembly (MD-197278) (Qt. 1)
        - Half Coil Assy. (MD-197277) (Qt. 2)
          - Inner Coil (ME-197276) (Qt. 1)
            - Copper Conductor (MA-186587) (Qt. 200ft)
            - Sleeve Brazing (MA-186691) (Qt. 2)
            - Ring Braizing (MA-186692) (Qt. 4)
            - Washer Brazing (MA-351037) (Qt. 2)
            - Brazing Rod (MA-116256)
          - Outer Coil (ME-197275) (Qt. 1)
            - Copper Conductor (MA-186587) (Qt. 115ft)
            - Sleeve Brazing (MA-186691) (Qt. 2)
            - Ring Braizing (MA-186692) (Qt. 4)
            - Washer Brazing (MA-351037) (Qt. 2)
            - Brazing Rod (MA-116256)
          - Fiberglass tape 7mil x 1/2" (MA-351462) (Qt. 24 rolls)
          - Fiberglass tape 7mil x 2" (MA-225574) (Qt. 2 rolls)
          - G10 Strip 0.03 x 1.63 (MB-331799) (Qt. 2)
          - Filler (Straght Section) (MB-331800) (Qt. 6)
          - G10 (MB-331801) (Qt. 2)
          - G10 (MB-331802) (Qt. 2)
          - G10 (MB-331803) (Qt. 2)
          - Mylar (MA-116514) (Qt. 150")
        - Fiberglass tape 7mil x 2" (MA-225574) (Qt. 7 rolls)
        - G10 Sheet Insulator (MA-331831) (Qt. 2)
        - Tie Wrap (MB-318794) (Qt. 1)
      - G10 .375x1.5 (MB-331856) (Qt. 10)
      - Kapton 5 mil x 4" w/adhesive (MA-274452) (Qt. A/R)
    - Peripheral Parts
      - Tie Strap (MB-116125) (Qt. 1)
      - Rod 1/4 dia (MA-116772) (Qt. 1)
      - Pole Tip Spacer Assy (MA-115391) (Qt. 10)
        - Spacer lamination (MC-115390) (Qt. 16)
        - Pin (MA-115392) (Qt. 2)

# Manufacturing Plan





Outsource the entire package

Steel

Steel Vendor

Conductor

Lamination

Quadrant Coil

x4

Quadrant Core

x4

1/4 Yoke & Coil Assy Quad 1

1/4 Yoke & Coil Assy Quad 2

- Tie Straps
- Rod
- Pole Tip Spacer Assy

1/4 Yoke & Coil Assy Quad 3

1/4 Yoke & Coil Assy Quad 4

1/2 Yoke & Coil Assy

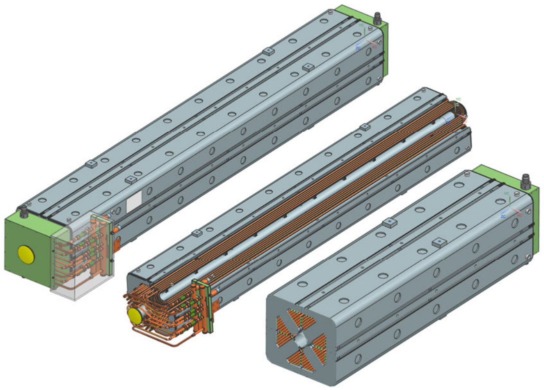
Peripheral Parts:

- Tie Straps
- Rods
- Manifold Assy
- Cover Assy.

1/2 Yoke & Coil Assy

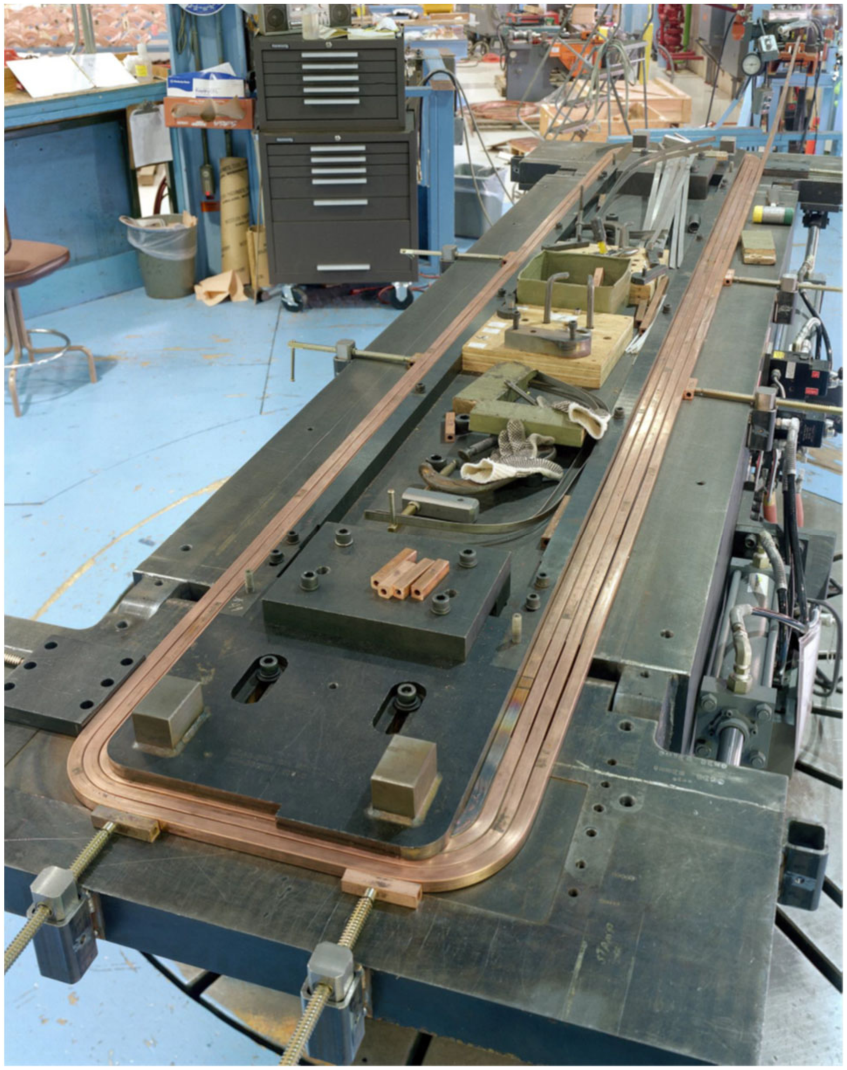
3Q120 Magnet

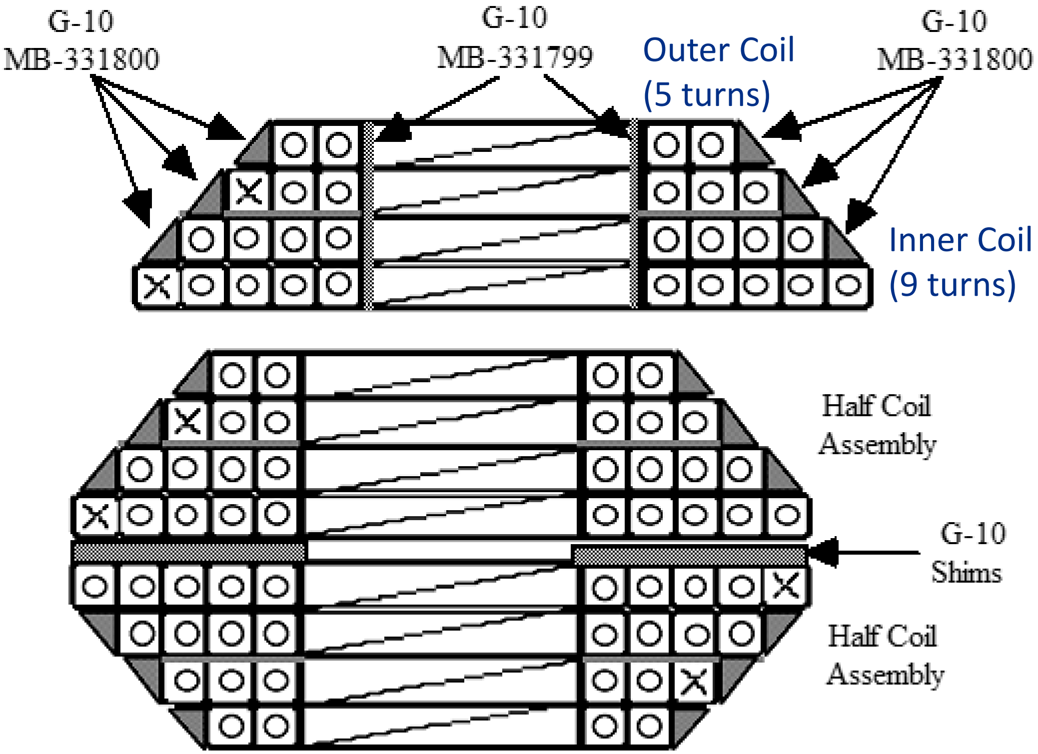
Beam tube provided by FNAL



- 3Q120 (120"): Qt. 17 + 2 spares
- 3Q60 (60"): Qt. 4 + 2 spares

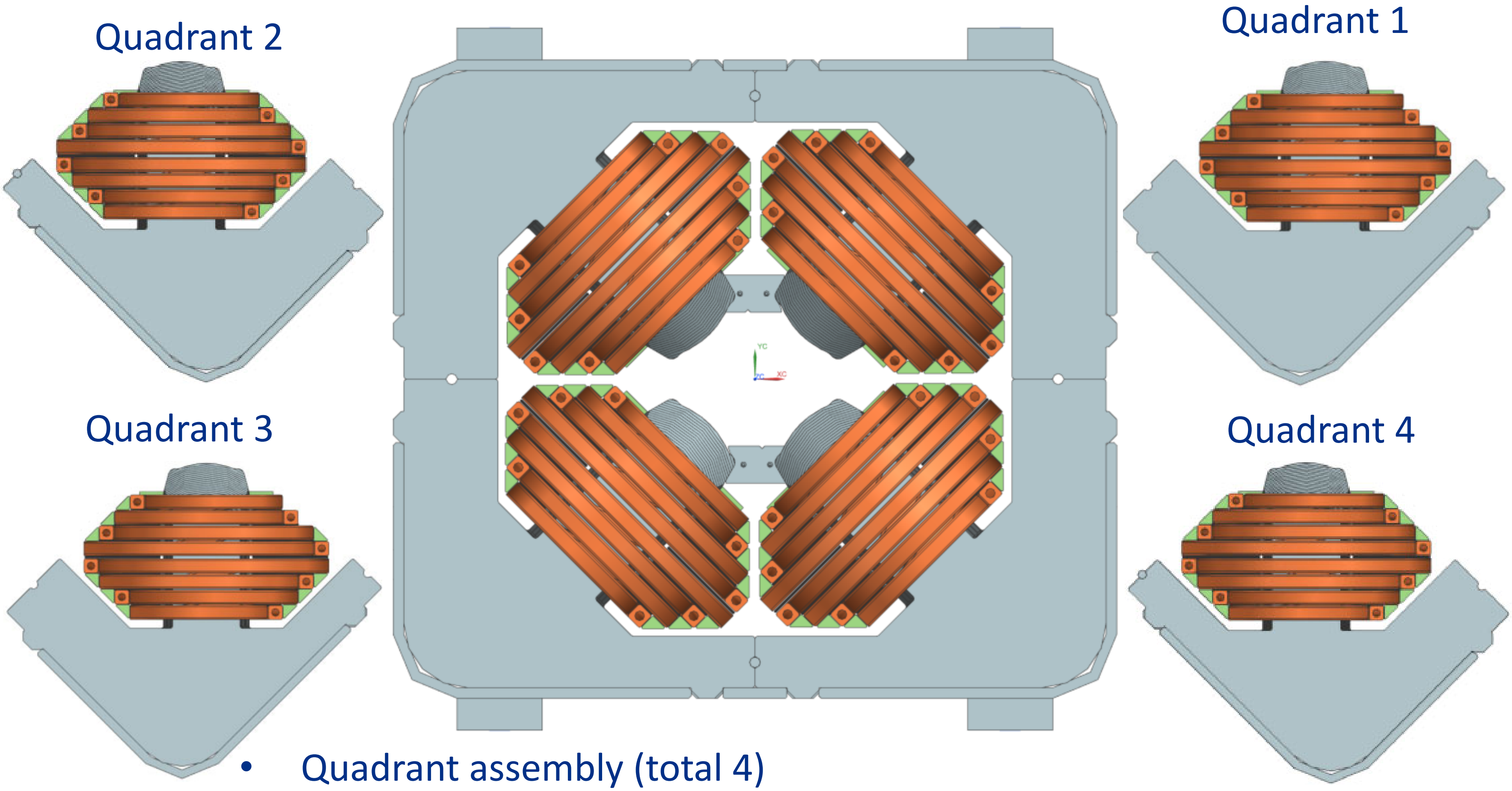
# Manufacturing: Coil





- The cable is wound around the winding tooling in two layers to a coil (inner and outer).
- Wrap the inner and outer coil into a half coil using fiber glass insulation.
- Wrap two half coils together.

# Manufacturing: Magnet Assembly



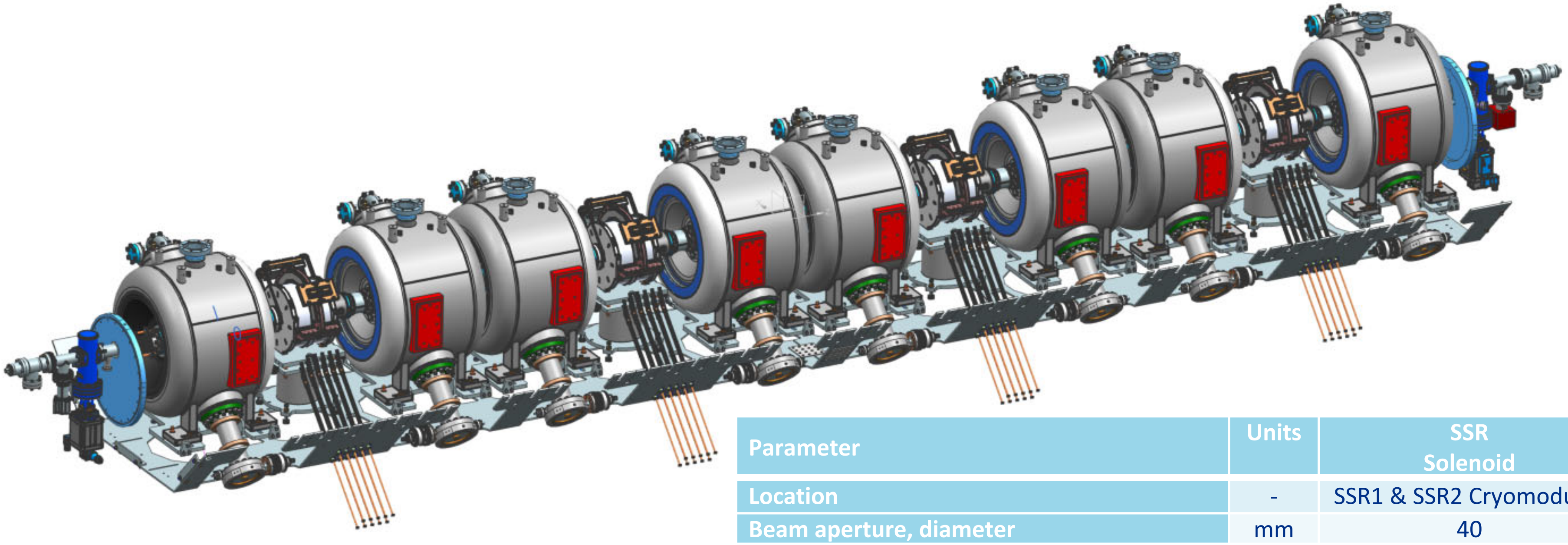
- Quadrant assembly (total 4)
- Two quadrants assembly (total 2)
- Quadrupole magnet assembly with beam tube in the center using Hydraulic Clamping System
- Manifold assembly and magnet impregnation

# Manufacturing: Final Magnet

3Q120 (120") Quadrupole Magnet

# Chapter 6 Solenoid Design and Manufacturing

# PIP II SSR Solenoid



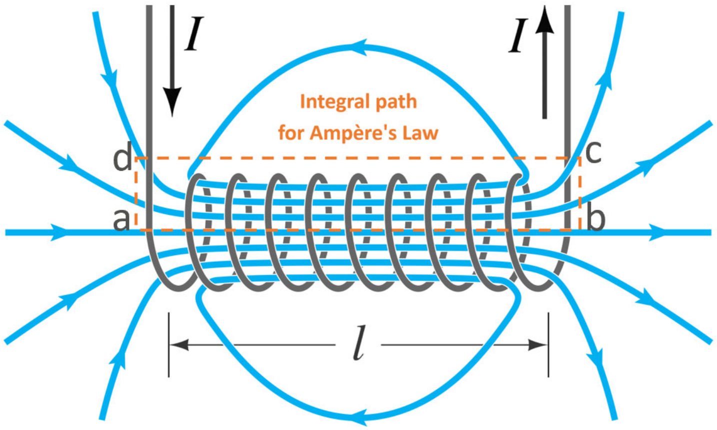
| Parameter | Units | SSR Solenoid |
|---|---|---|
| Location | - | SSR1 & SSR2 Cryomodules |
| Beam aperture, diameter | mm | 40 |
| Solenoid integrated focusing strength | $T^2 \cdot m$ | 3.2 & 4.5 |
| Solenoid effective length (approximate) | m | 0.185 |
| Solenoid strength operating range | % | 5 – 100 |
| Solenoid ramp rate | A/s | ≥1 |
| Beam loss | W | ≤1 |
| Integrated steering correctors | - | x and y |
| All 4 corrector coils powered independently | - | Yes |
| Corrector integrated strength | mT·m | ≥4.5 & ≥6.0 |
| Corrector field good field region (diameter) | mm | 24 |
| Corrector field uniformity | % | ±5 |
| Corrector field operating range | % | -100 – +100 |
| Corrector operational regime | - | DC |
| Corrector ramp rate | A/s | ≥5 |

Physics Requirement

- Integrated field strength: $I_2 = \int B_z^2 dz$ where $B_z$ is axial magnetic field in a solenoid, calculated ~5 T.

- Fringe field requirement: Fringe magnetic field on walls of superconducting cavities in the cryomodule must be less than 10 gauss.

# Coil Design



$$B_{inside} = \frac{\mu_0 NI}{l}$$

*Given:*

- *I* = 50 A
- *B* = 5 *T*
- *l* = 0.185 m

*First, without considering the fringe field requirement,*

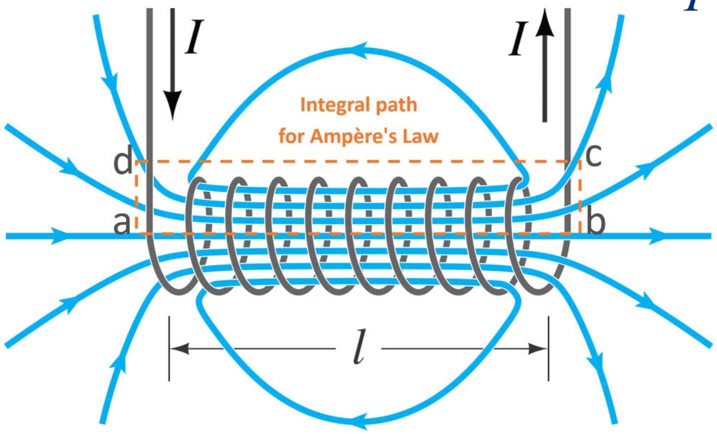
$$\mathrm{N} = \frac{Bl}{\mu_0 I} = \frac{5\, x\, 0.185}{4\,\pi\, x\, 10^{-7} x\, 50} = 14722 \text{ turn}$$

$$Area = \frac{I}{J} = \frac{50}{2.80} = 17.86\ mm^2$$

| AWG | Diameter (mm) | Area ($mm^2$) | $\rho$ (Ω/km) | Max Current (A) | Max Current Density (A/$mm^2$) |
|---|---|---|---|---|---|
| 1 | 7.348 | 42.4 | 0.406392 | 119 | 2.81 |
| 2 | 6.543 | 33.6 | 0.512664 | 94 | 2.80 |
| 3 | 5.827 | 26.7 | 0.64616 | 75 | 2.81 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| 38 | 0.102 | 0.00797 | 2163 | 0.0228 | 2.86 |
| 39 | 0.089 | 0.00632 | 2728 | 0.0175 | 2.77 |
| 40 | 0.079 | 0.00501 | 3440 | 0.0137 | 2.73 |

- *AWG 4 with diameter 5.19 mm satisfies the max. current density.*
- *0.185 m solenoid length needs 35 turns per layer by 420 layers, the OD of the solenoid will be over 4 m.* ✖

# Coil Design Continues



*First, without considering the fringe field requirement,*

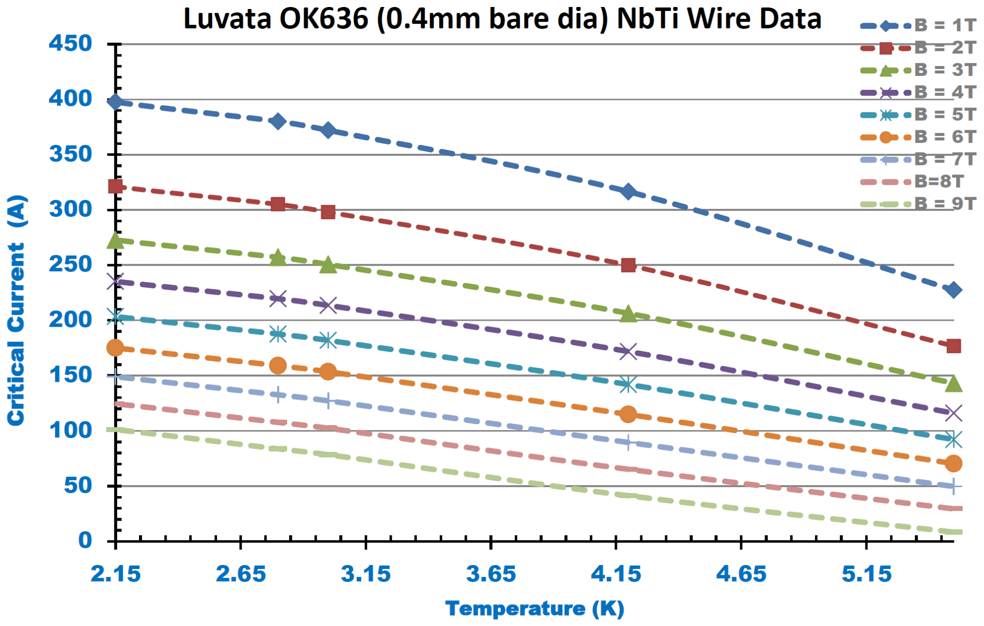
$$\mathrm{N} = \frac{Bl}{\mu_0 I} = \frac{5\,x\,0.185}{4\,\pi\,x\,10^{-7} x\,50} = 14722 \text{ turn}$$

- *With limited space, consider the superconductor NbTi wires with the diameter of 0.44 mm.*
- *0.185 m solenoid length needs ~400 turns per layer by ~36 layers, the OD of the solenoid will be around 78 mm.*
- *The coil requires cryogenic temperature as low as 2 K.*

$$B_{inside} = \frac{\mu_0 NI}{l}$$

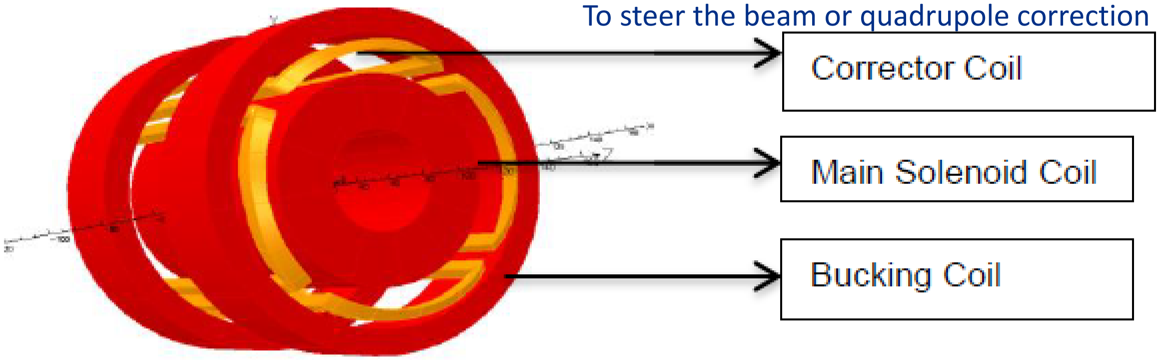
*Given:*

- $I = 50$ A
- $B = 5$ T
- $l = 0.185$ m



# Coil Design Continues

*When considering the fringe field requirement, we need bucking coils at both ends of the main solenoid. (simulation) to compensate the field at 0.5 m from the end of the solenoid.*

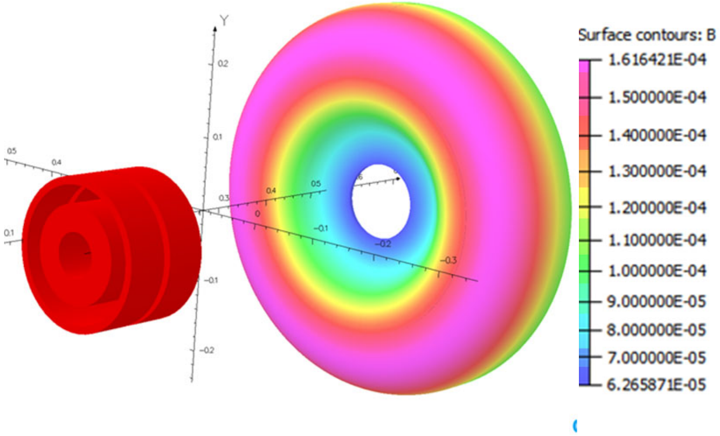


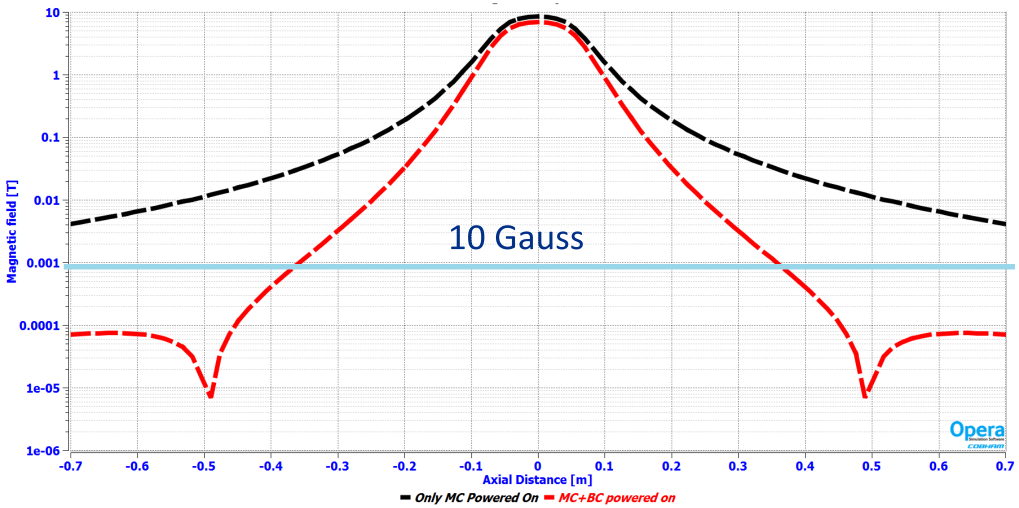
To steer the beam or quadrupole correction

Corrector Coil

Main Solenoid Coil

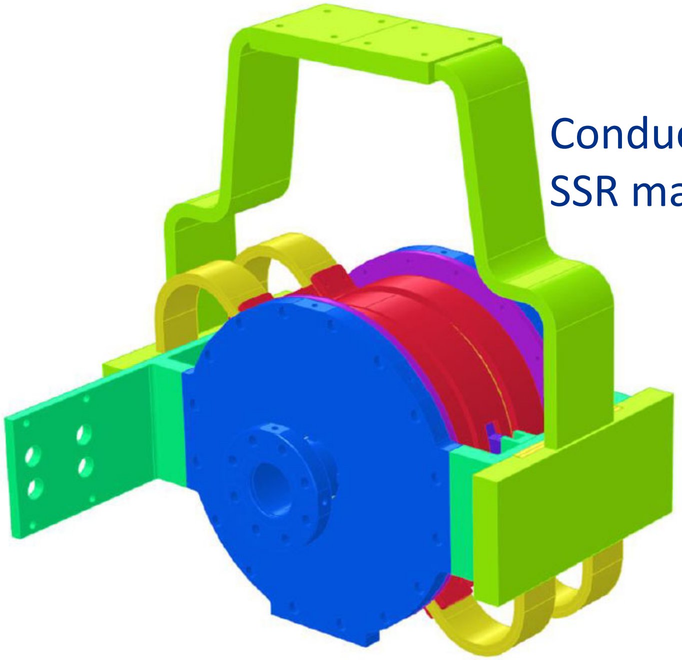
Bucking Coil



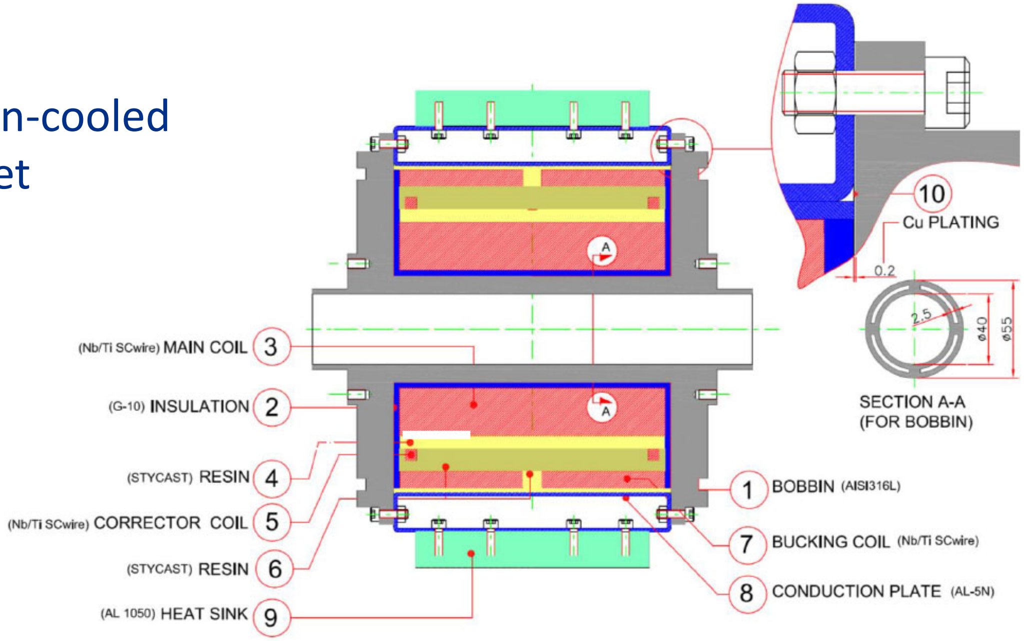


| | Total Turns | Total Layers | Coil OD (mm) |
|---|---|---|---|
| Main Coil | 18550 | 46 | 137 mm |
| Bucking Coil | 3600 | 20 | 203 mm |
| Corrector Coil | 300 | | |

# Magnet Design

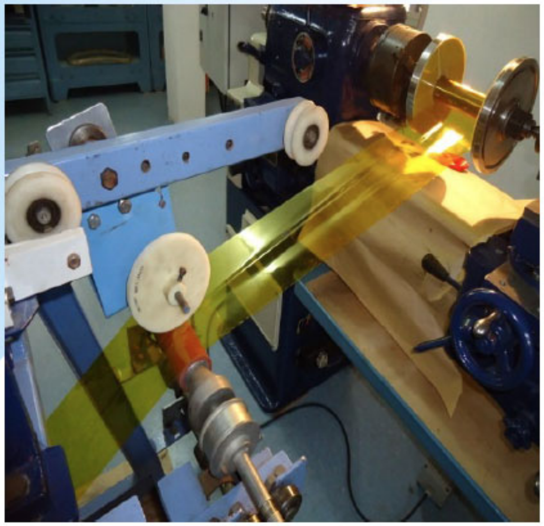


Conduction-cooled
SSR magnet

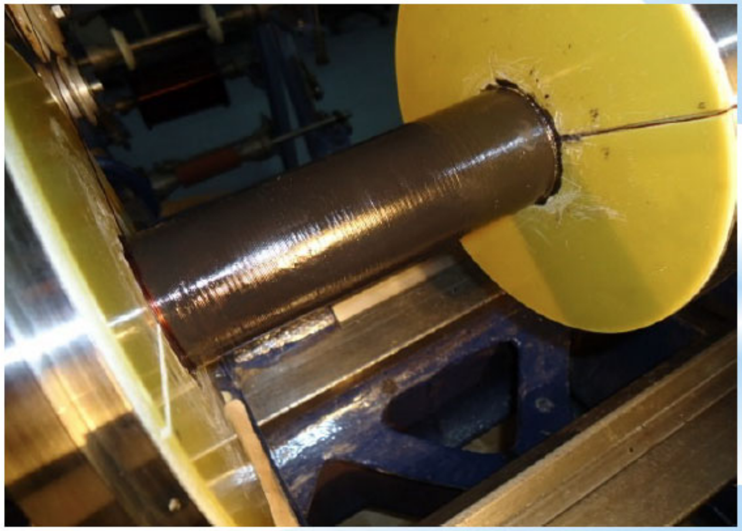


1. A non-magnetic magnet bobbin with Cu plating for good surface thermal conductivity.
2. Main coil is wound around the bobbin. Correct coils are housed inside an accurately machined cages. Bucking coils are wound on top of the cages. Room temperature epoxy is applied during coil fabrication.
3. C-shaped clamps surrounding the magnet, providing the stiffness to contain the electromagnetic forces.
4. Thermal straps and heat sinks around the magnet are the cooling paths.

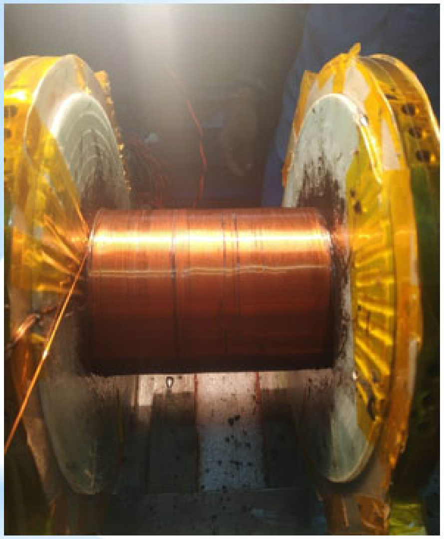
# Manufacturing_Main Coils Winding



Core insulation with Kapton



Wet winding with Stycast



MC1 last layer

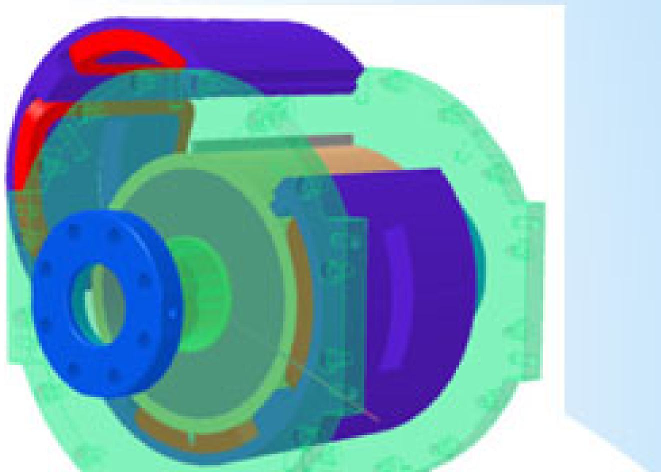
MC1 last layer with STYCAST

MC2 last layer with STYCAST

# Manufacturing_Dipole Corrector Coil Installation

Core insulation with Kapton

Corrector coil positioned inside cage



Corrector coil housed inside G-10 CR cage

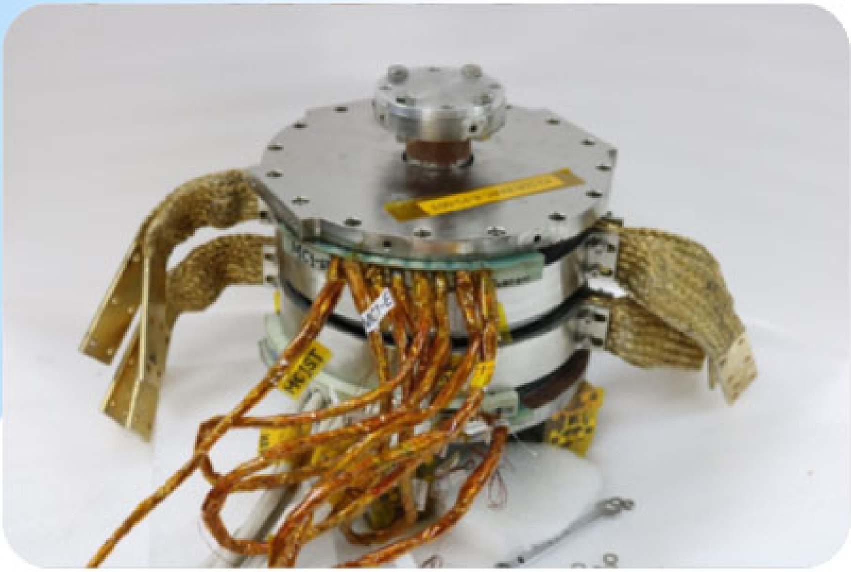
# Manufacturing_Bucking Coils


Surface before bucking coil winding


BC 1 winding first layer


Bucking coil 1 last layer after STYCAST

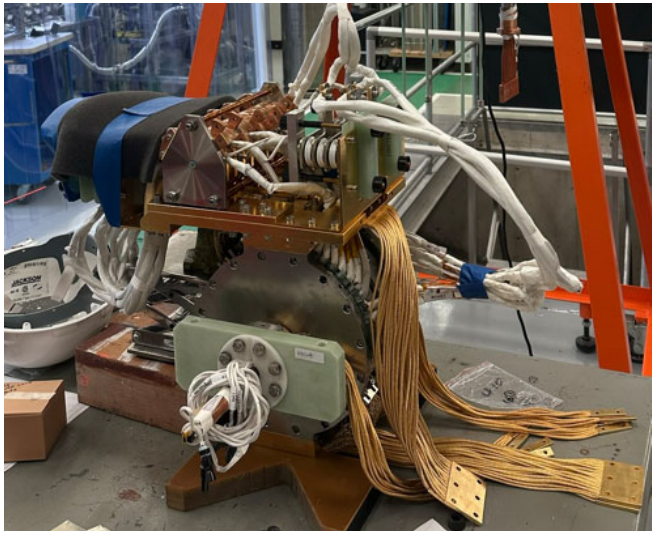

Bucking coil 2 first layer



# Prototype Magnet Assembly

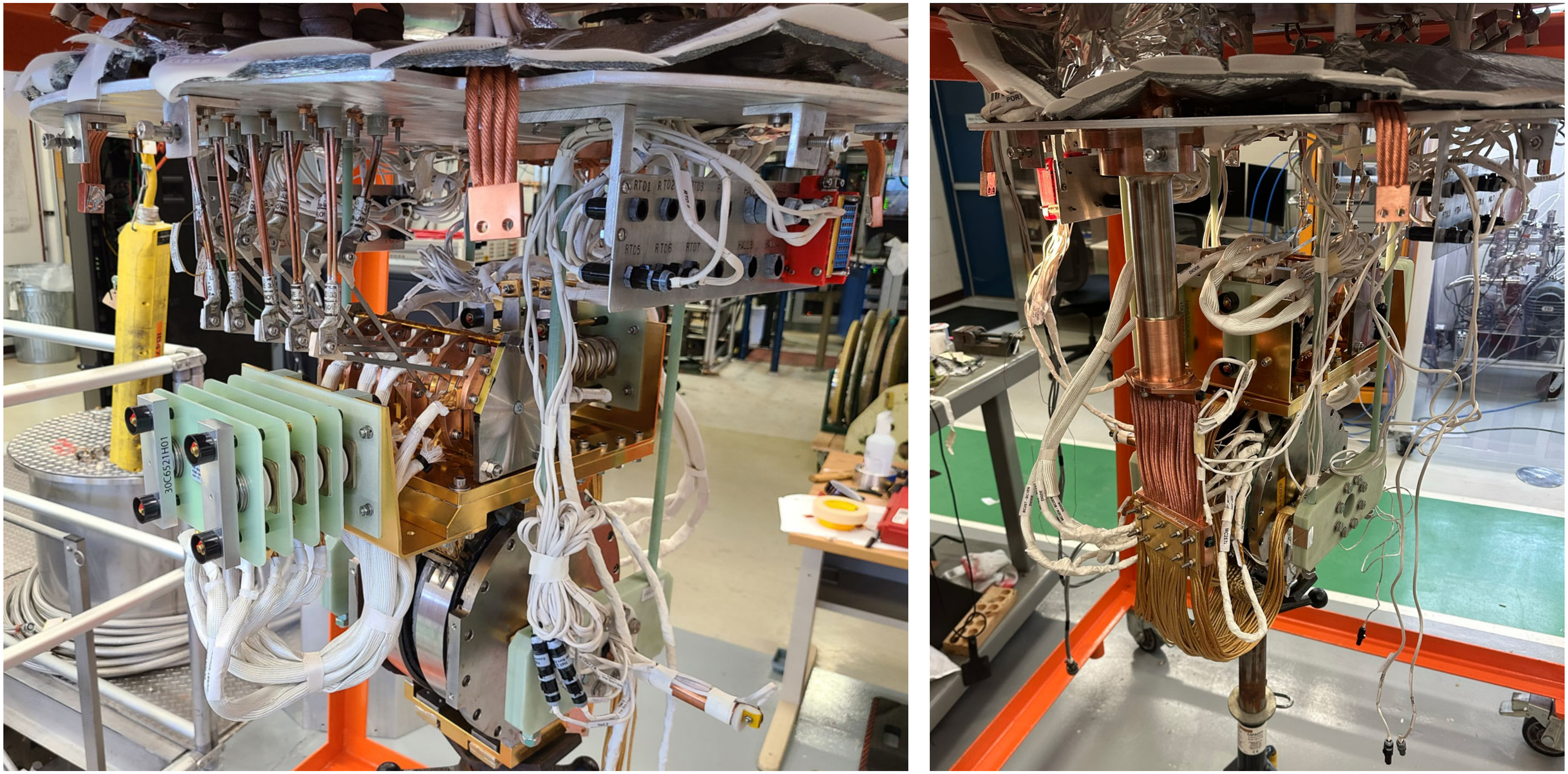
Install the thermal heat sink

Connect all the current leads



Install the diode racks for magnet protection

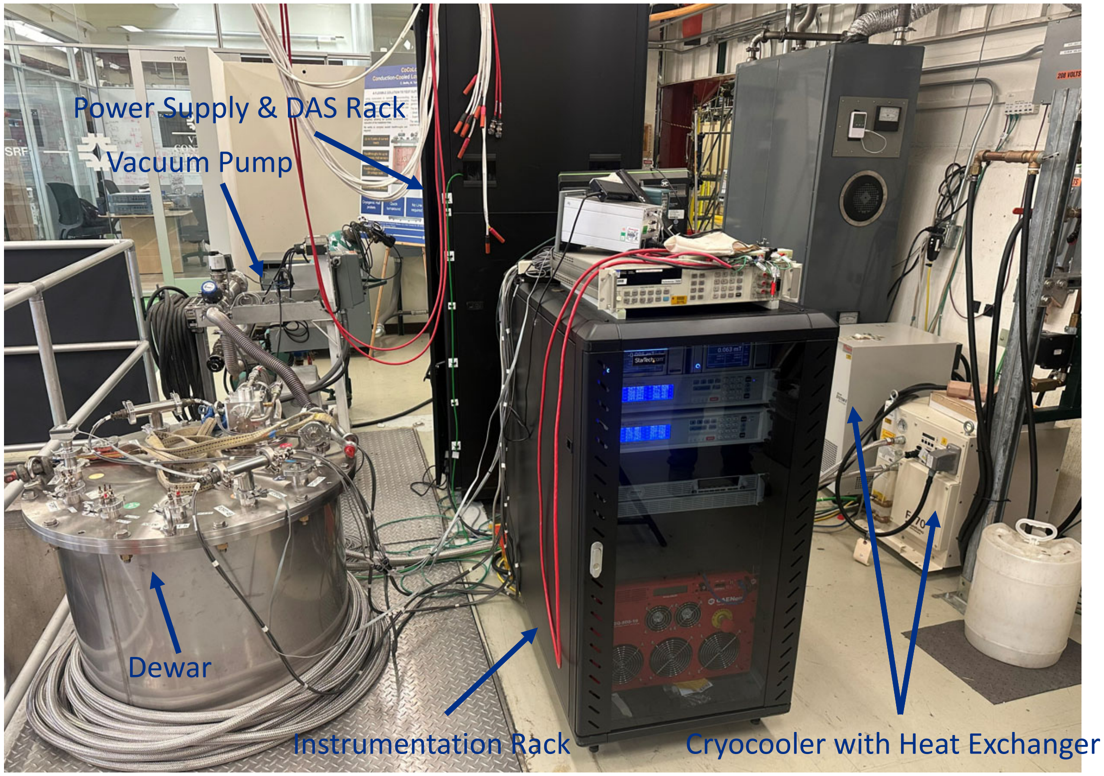
# Prototype Magnet Prepare for Test



Install the magnet to the top head of the test stand

- Connect the HTS leads to the magnet and the test stand
- Install temperature sensors and voltage taps to monitor the magnet
- Connect the thermal straps from the magnet side to the thermal strap from the cryocooler side
- Install the instrumentations (VTs, RTDs and hall probes)

# Magnet Test



## Install the magnet to Cryocooled Test Stand

- Put on the multi-layer insulation (MLI)
- Lower the top head into the test Dewar
- Vacuum pump down the magnet to 1x10$^{-4}$ mbar
- Cool down and Test

## Instrumentation Rack

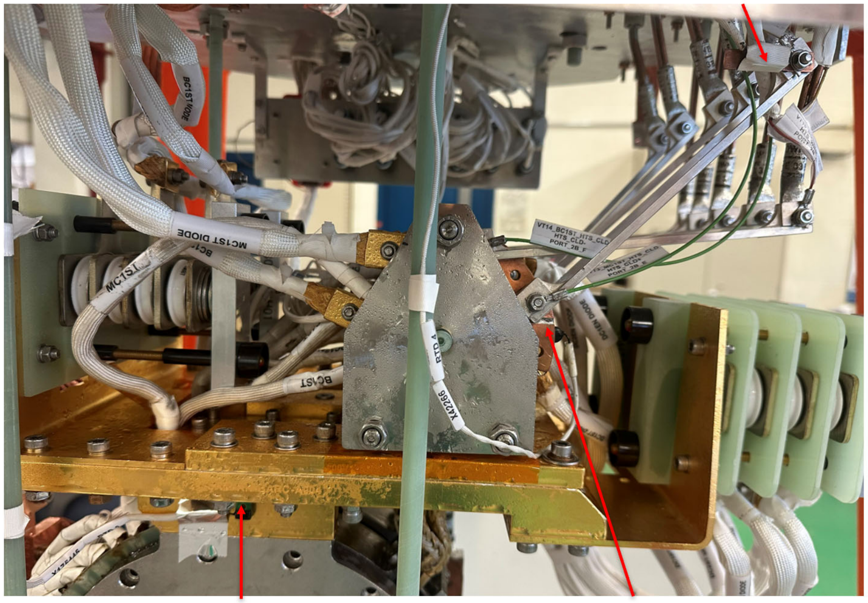
- 8 channels for temperature sensors
- 2 channels for magnetic hall probe

## Data Acquisition System

- Voltage & Current

# Test Results

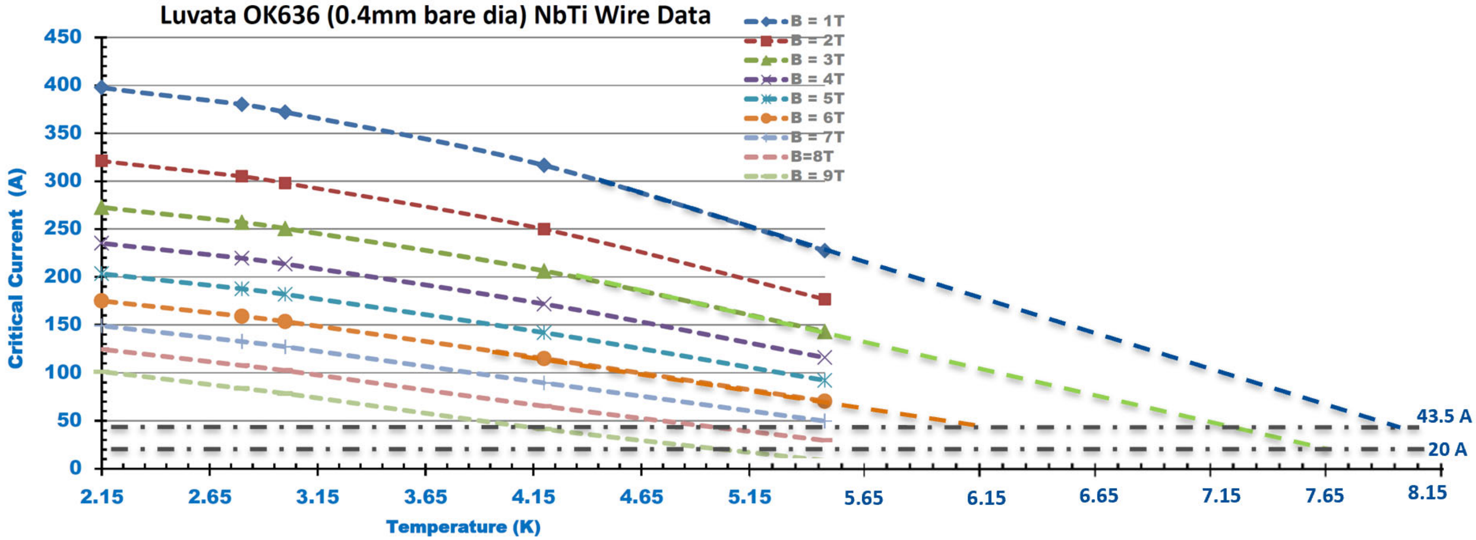
- The prototype magnet was powered with the ramp rate 0.01 A/s and quenched at ~21 A (nominal current ~45 A). The axial magnetic field was ~3.5 T.
- A quench is an abnormal termination of magnet operation that occurs when part of the superconducting coil enters the normal (resistive) state.
- Analysis pointed out that the temperature of the magnet current leads very likely were above the superconducting critical temperature.



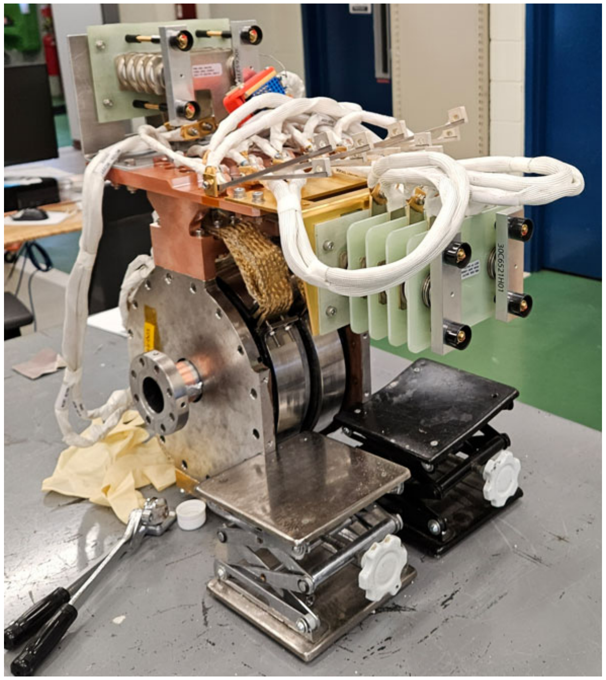
Bot C2 (HTS Lead) 44.7K

Top C1 (Top Heat Sink) 4.2K

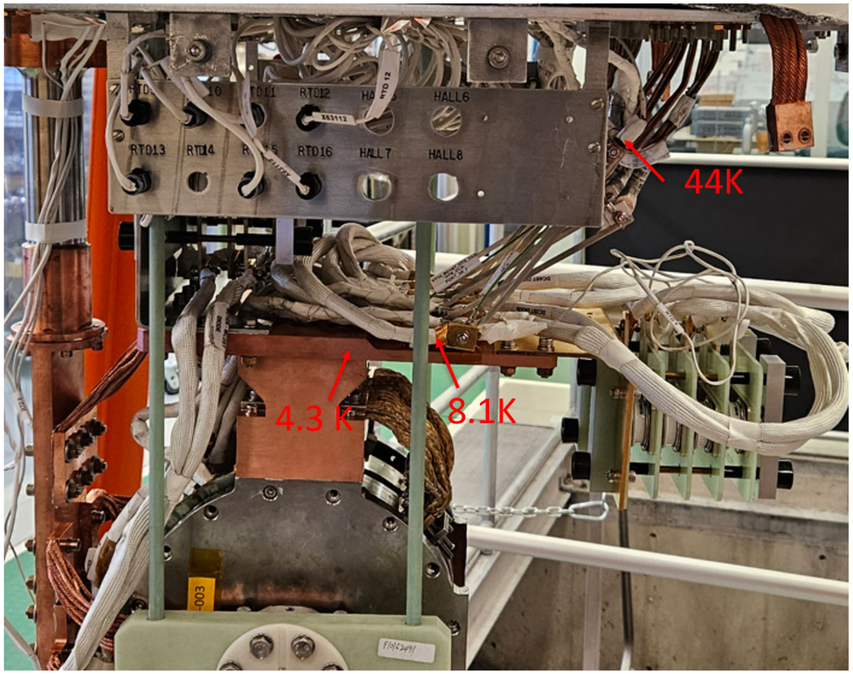
Top D1 (MC1 thermal intercept) 12.5K



# Improvement



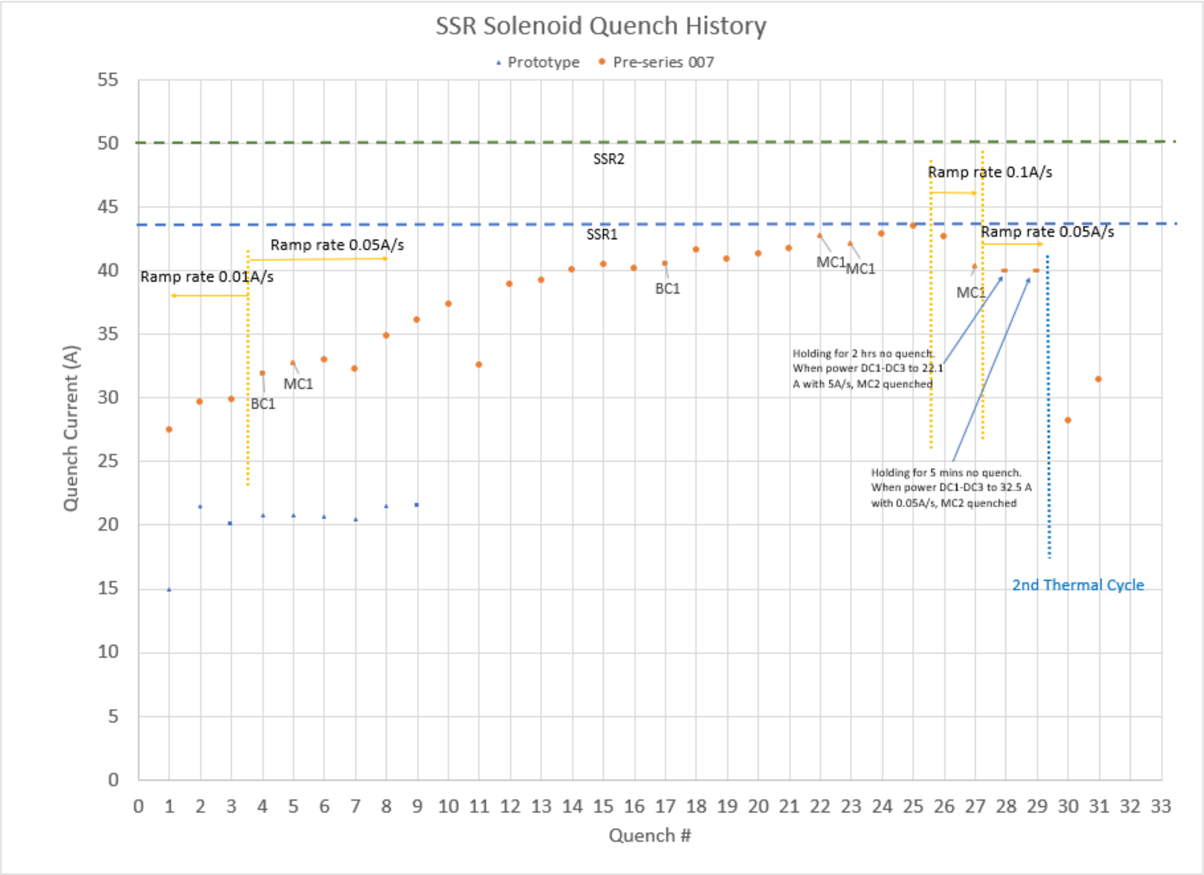
- The current leads were directed bolted to the thermal heat sink plate
- Change the thermal straps to copper bar at the cryocooler side.



- The temperature at the current leads was improved to 8.1 K, still losing ~4 K due to the joints.
- The prototype magnet was powered with the ramp rate 0.01 A/s and quenched at ~23 A (nominal current ~45 A).

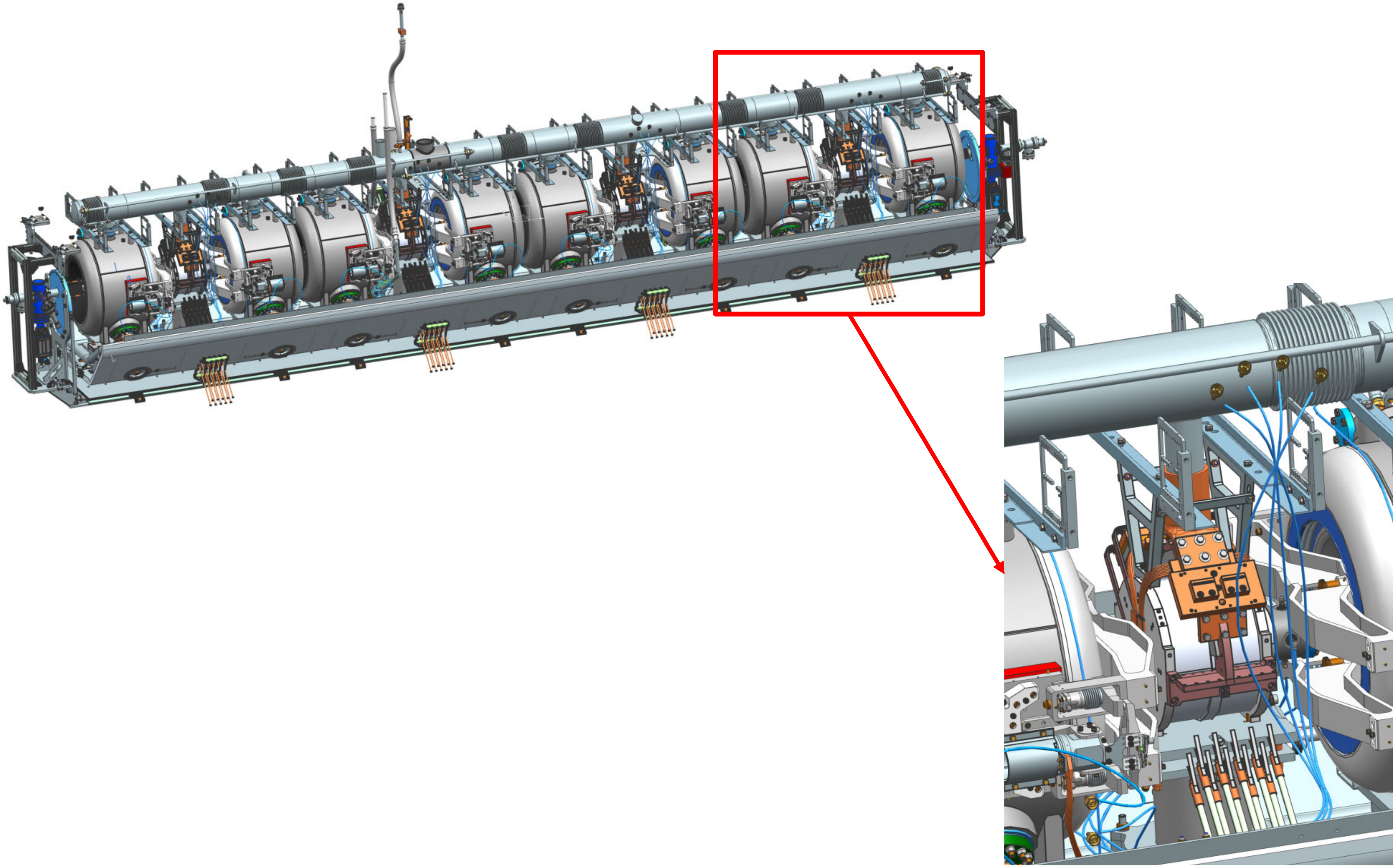
*!! Thermal transfer is very crucial to this magnet!!*

# Pre-series Magnet 007 Quench History at FNAL



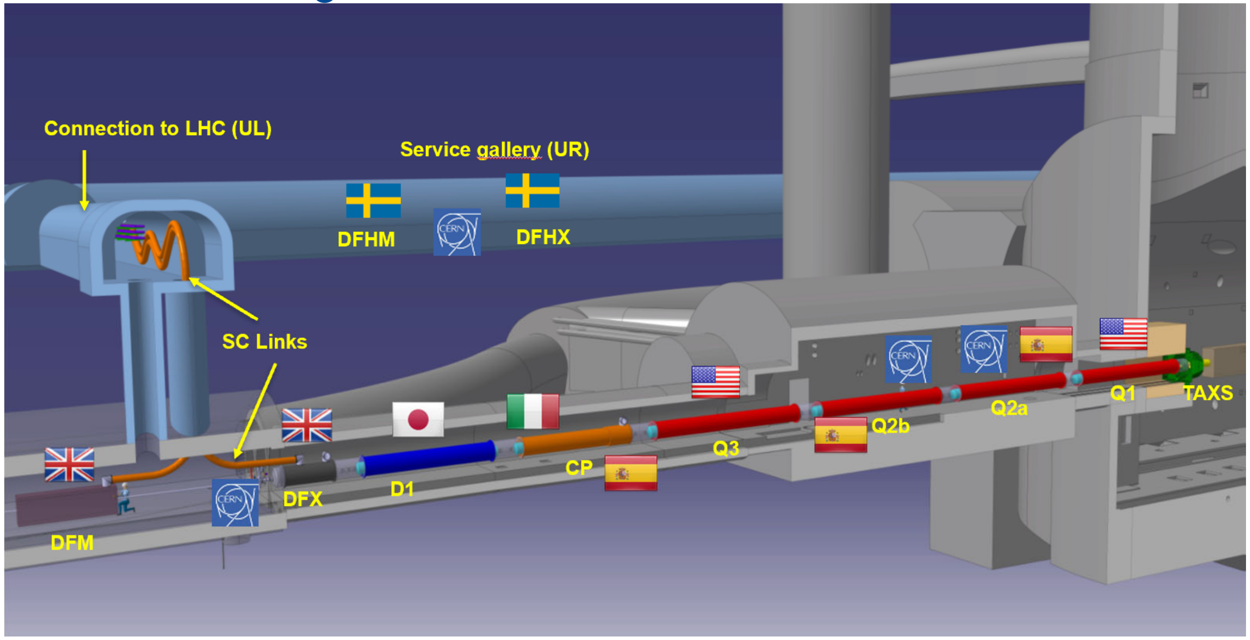
- DC: DC1-DC3 and DC2-DC4 were powered up to 42 A, with 5 A/s ramp rate, no quench.
- MC-BC: After each quench, the system need ~2 hrs for recovery.
  - Start with ramp rate of 0.01 A/s, 3 quenches up to 30 A. The first quench was at 27.5 A.
  - Increase the ramp rate to 0.05 A/s, 22 quenches up to 43.5 A. The magnet was under quench training.
  - Increase the ramp rate to 0.1 A/s, 2 quenches, little detraining.
  - Power the magnet to 40 A with 0.05 A/s, holding for 2 hrs (the temperature for the coils stabilized after ~2 mins), no quench. Then power DC1-DC3 coils with 5 A/s to 22.1 A, MC2 quenched.
  - Power the magnet to 40 A with 0.05 A/s, holding for 5 mins, no quench. Then power DC1-DC3 coils with 0.05 A/s to 32.5 A, MC2 quenched.
- Warm up and cool down the magnet 007 (0.7 K warmer than the 1st thermal cycle temperature on the coils)
  - 2nd thermal cycle test, power MC-BC coils with 0.05 A/s to 28.2 A, MC2 quenched.

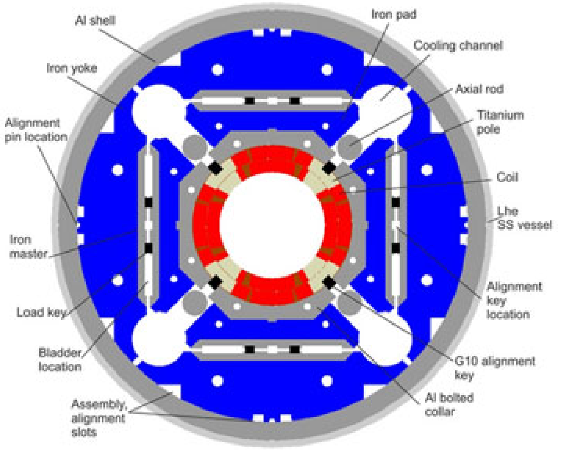
# Cryomodule Installation



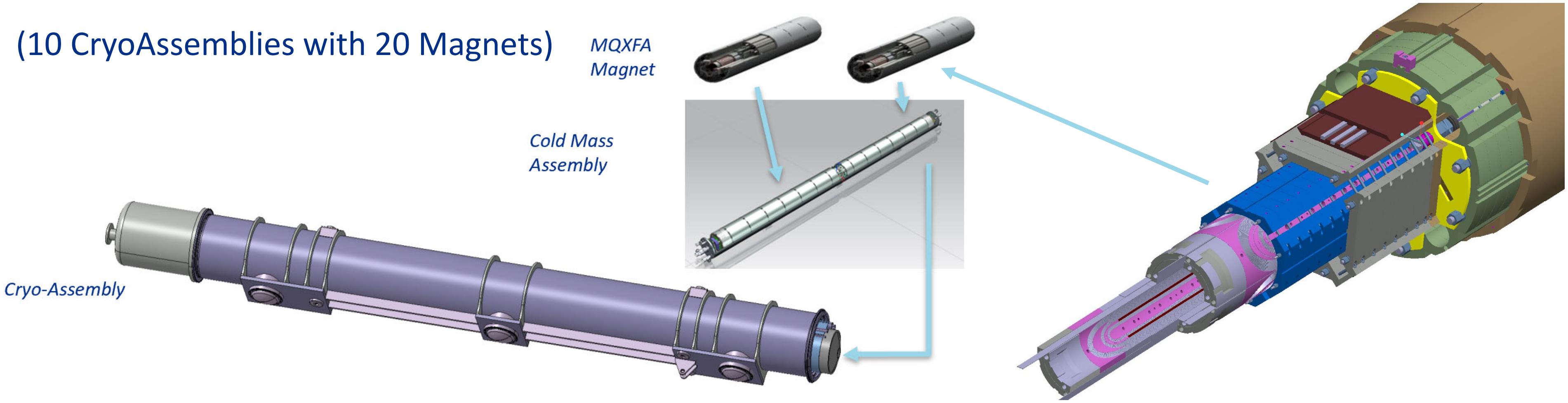
# Chapter 7 Superconducting Magnet Design and Manufacturing

# LHC $Nb_3Sn$ Superconducting Quadrupole Magnet





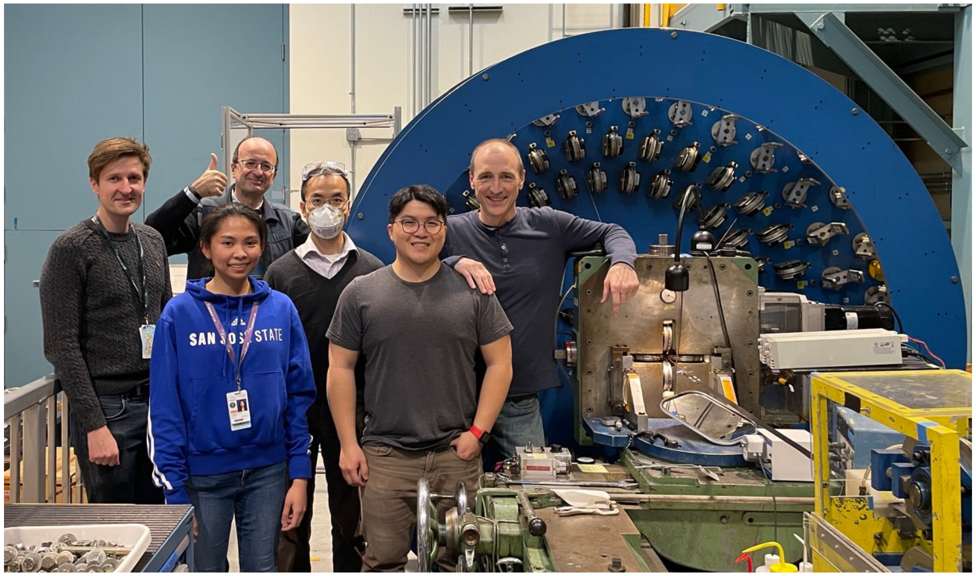
(10 CryoAssemblies with 20 Magnets)



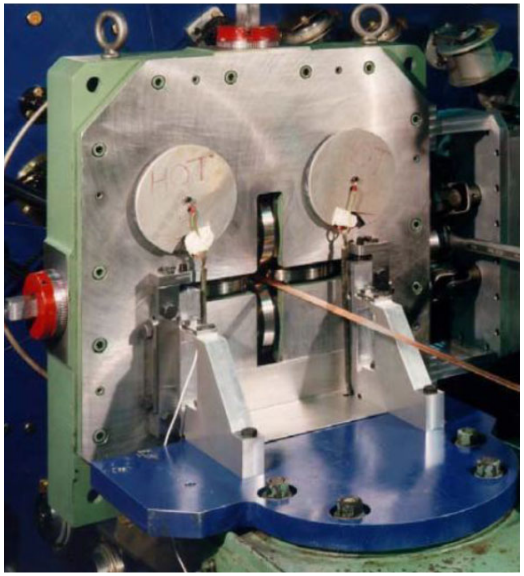
# LHC $Nb_3Sn$ Quadrupole Magnet Specification

| ID | Description |
|---|---|
| R-T-01 | The MQXFA coil aperture at room temperature without preload is 149.5 mm… |
| R-T-02 | The MQXFA nominal outer diameter without preload is 614 mm… |
| R-T-03 | The MQXFA magnet must be capable of operating at steady state providing an integrated gradient of 556.9 T in superfluid helium at (HeII) bath at 1.3 bar and at a temperature of 1.9 K |
| R-T-06 | The MQXFA cooling channels shall be capable of accommodating two (2) heat exchanger tubes running along the length of the magnet in the yoke cooling channels. The minimum diameter of the MQXFA yoke cooling channels that will provide an adequate gap around the heat exchanger tubes is 77 mm. |
| R-T-07 | At least 40% of the coil inner surface must be free of polyimide. |
| R-T-08 | The MQXFA structure shall have provisions for the following cooling passages: (1) Free passage through the coil pole and subsequent G-11 alignment key equivalent of 8 mm diameter holes repeated every 50 mm; (2) free helium paths interconnecting the four yoke cooling channels holes; and (3) a free cross-sectional area of at least 150 $cm^2$ |
| R-T-10 | The MQXFA magnet shall be able to survive a maximum temperature gradient of 50 K, during a controlled warm-up or cool-down, and to experience the thermal dynamics following a quench without degradation in its performance. |
| R-T-11 | The MQXFA magnets shall be capable of operating at any ramp rate within ±30 A/s. |
| R-T-13 | MQXFA magnets must be delivered with a (+) Nb-Ti superconducting lead and a (-) Nb-Ti superconducting lead, both rated for 18 kA and stabilized for connection to the LMQXFA cold mass electrical bus. |
| R-T-14 | Splices are to be soldered with CERN approved materials. |
| R-T-15 | Voltage Taps: the MQXFA magnet shall be delivered with three redundant (3x2) quench detection voltage taps located on each magnet lead and at the electrical midpoint of the magnet circuit; and two (2) voltage taps for each internal MQXFA $Nb_3Sn$-NbTi splice. Each voltage tap used for critical quench detection shall have a redundant voltage tap. |
| R-T-16 | The MQXFA magnet coils and quench protection heaters shall pass the hi-pot tests… |
| R-T-17 | After a thermal cycle to room temperature, MQXFA magnets shall attain the nominal operating current with no more than 3 quenches. |
| R-T-18 | MQXFA magnets shall not quench while ramping down at 150 A/s from the nominal operating current |
| R-T-20 | All MQXFA components must withstand a radiation dose of 35 MGy, or shall be approved by CERN for use in a specific location… |
| R-T-30 | MQXFA magnets will operate in the HL LHC era for an order of magnitude of 10000 cycles. The long-term reliability of the design will be proven by having a short model magnet submitted to 1,000 powering cycles during individual test. |
| R-T-22 | The MQXFA magnets shall meet the interface specifications with the following systems: (1) other LMQXFA Cold Mass components; (2) the CERN supplied power system; (3) the CERN supplied quench protection system; and (4) the CERN supplied instrumentation system. These interfaces are specified in Interface Control Documents. |
| R-T-23 | The MQXFA magnets must comply with CERN's Launch Safety Agreement (LSA) for IR Magnets (WP3). |
| R-T-24 | All travelers must be completed and delivered to CERN, and all NCR must be closed |
| R-T-29 | Splice resistance must be less than 1.0 nΩ at 1.9 K. |
| R-T-31 | MQXFA magnets must survive at least 50 quenches |

# Superconductor Cable



| Cable Parameter | |
|---|---|
| Number of Wires in Cable | 40 |
| Cable Mid-Thickness | 1.525 ± 0.010 mm |
| Cable Width | 18.15 ± 0.05 mm |
| Cable Keystone Angle | 0.40° ± 0.1° |
| Cable Lay Direction | Left |
| Cable Lay Pitch | 109 ± 3 mm |
| Cable Core Material | 316 L Stainless Steel |
| Cable Core Width | 12 mm |
| Cable Core Thickness | 0.025 mm |
| Cable Core Position | Biased towards the major edge |
| Maximum Cable Residual Twist | 150°/m |



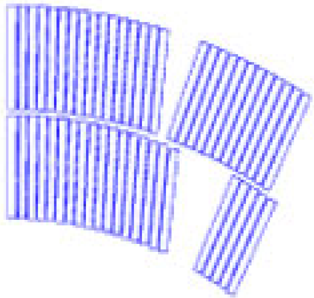
Cable fabrication

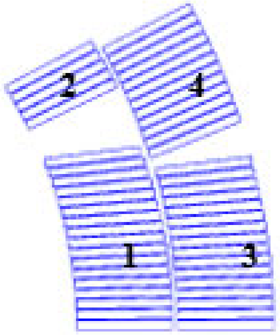
Cable Insulating

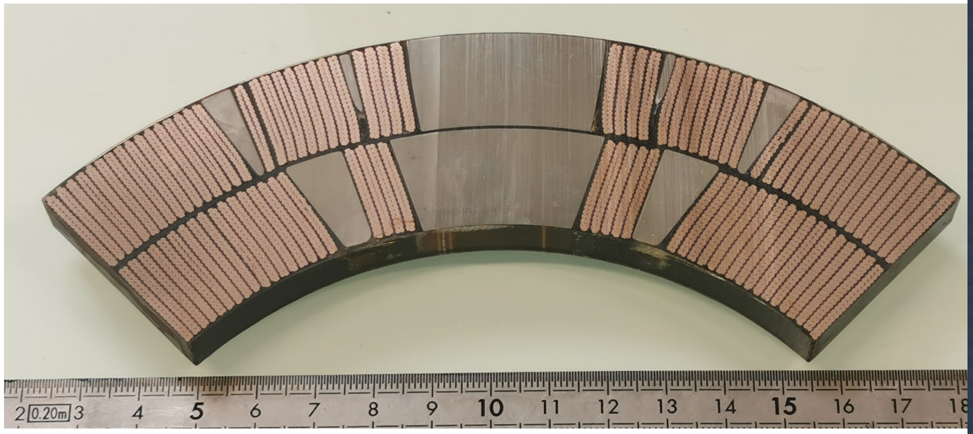
# Coil Magnetic Design

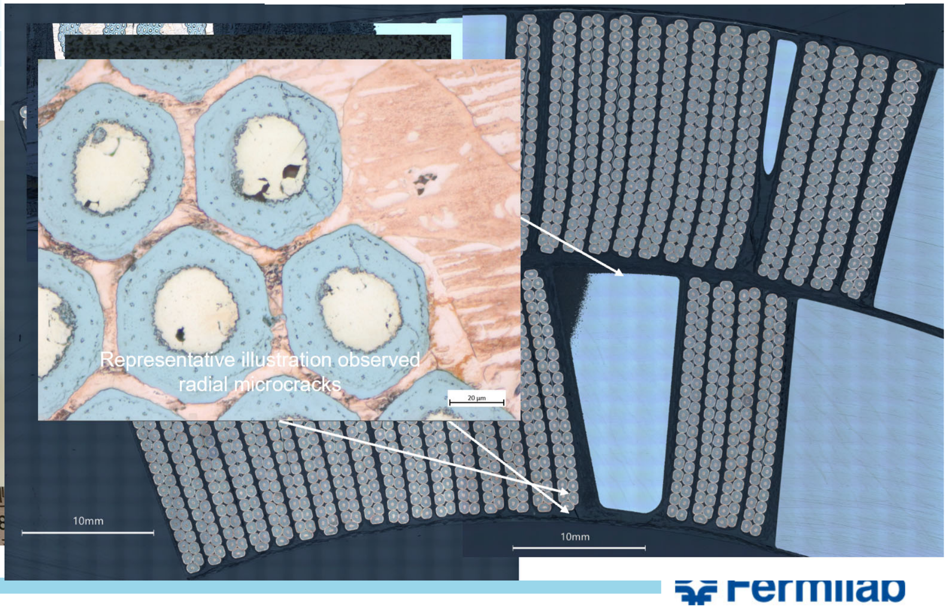
- The cross-section of the MQXFA is based on the cos2$\theta$-layout with two conductor blocks in each layer.

| | unit | |
|---|---|---|
| Coil aperture radius | mm | 75.000 |
| Layer 1 outer radius | mm | 93.653 |
| Inter-layer thickness | mm | 0.660 |
| Outer layer inner radius | mm | 94.313 |
| Outer layer outer radius | mm | 112.966 |
| Mid-plane shim thickness (per coil) | mm | 0.375 |
| Number of turns in block 1 | | 17 |
| Number of turns in block 2 | | 5 |
| Number of turns in block 3 | | 16 |
| Number of turns in block 4 | | 12 |
| Bare unreacted/reacted conductor width | mm | 18.150/18.363 |
| Bare unreacted/reacted conductor thickness | mm | 1.525/1.594 |
| Nominal keystone angle | deg | 0.40 |
| Nominal insulation thickness | mm | 0.145 |





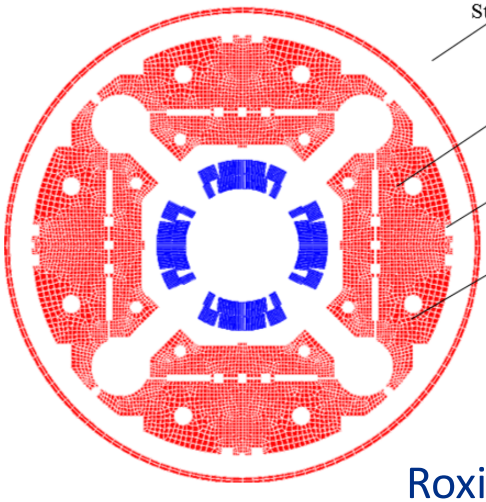




Representative illustration observed radial microcracks

# Coil Magnetic Simulation

| Parameters | Units | $I_{ss}$ |  | $I_{ult}$ | $I_{nom+margin}$ | $I_{nom}$ |
|---|---|---|---|---|---|---|
| Current | kA | 21.24 | 17.89 | 17.49 | 16.47 | 16.23 |
| $I/I_{ss}$ | % | 100 | 84 | 82 | 78 | 76 |
| Gradient | T/m | 168.1 | 143.2 | 142.1 | 132.6 | 132.2 |
| Coil peak field | T | 14.5 | 12.3 | 12.1 | 11.4 | 11.3 |
| Stored energy | MJ/m | 1.89 | 1.38 | 1.32 | 1.18 | 1.15 |
| Current sharing temperature | K | 1.9 | 5.8 | 6.0 | 6.8 | 7.0 |
| Differential inductance | mH/m | 8.13 | 8.18 | 8.23 | 8.21 | 8.26 |
| Superconductor current density ($j_{sc}$) | A/mm$^2$ | 2059 | 1734 | 1695 | 1596 | 1573 |
| Engineering current density ($j_{eng}$) | A/mm$^2$ | 936 | 788 | 771 | 726 | 715 |
| Forces x | MN/m | 3.83 | 2.85 | 2.74 | 2.47 | 2.41 |
| Forces y | MN/m | -5.68 | -4.08 | -3.94 | -3.48 | -3.41 |



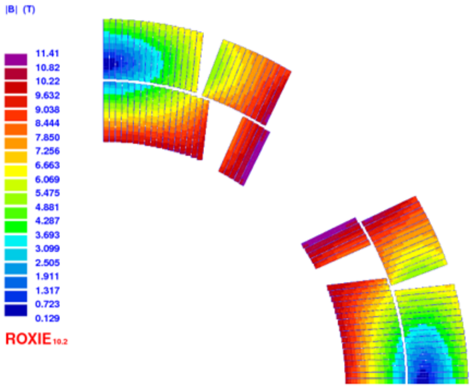
Stainless-steel vessel ($\mu_r$= 1.0025)

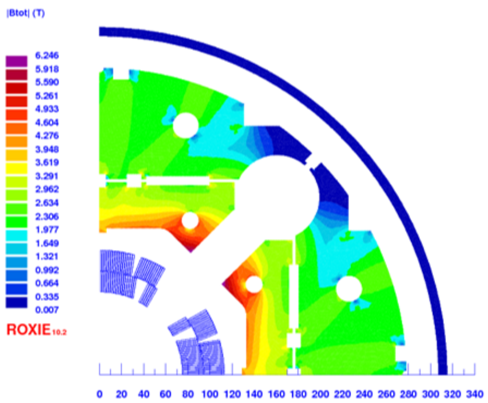
Pad (iron, *BHiron1* in the "*roxie.bhdata*" file)

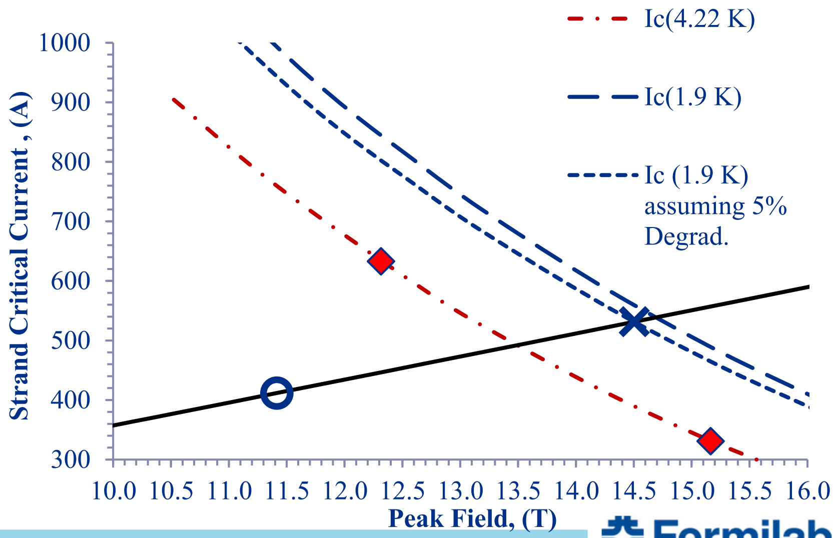
Yoke (iron, *BHiron1* in ROXIE)

Bladder slot (can be used for magnetic shimming).

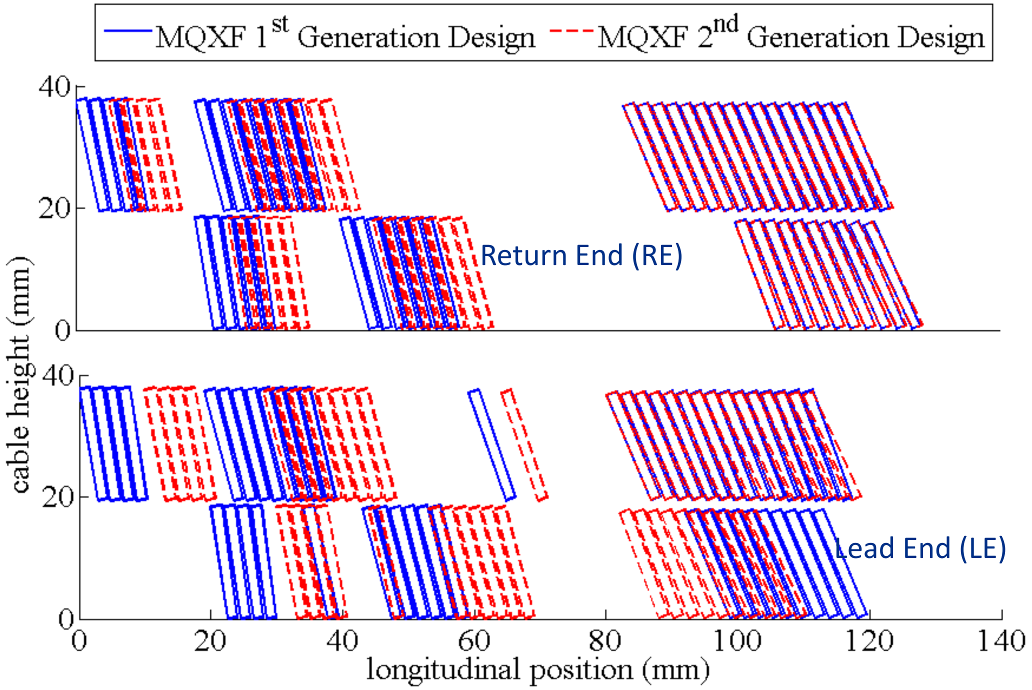
Roxie Model

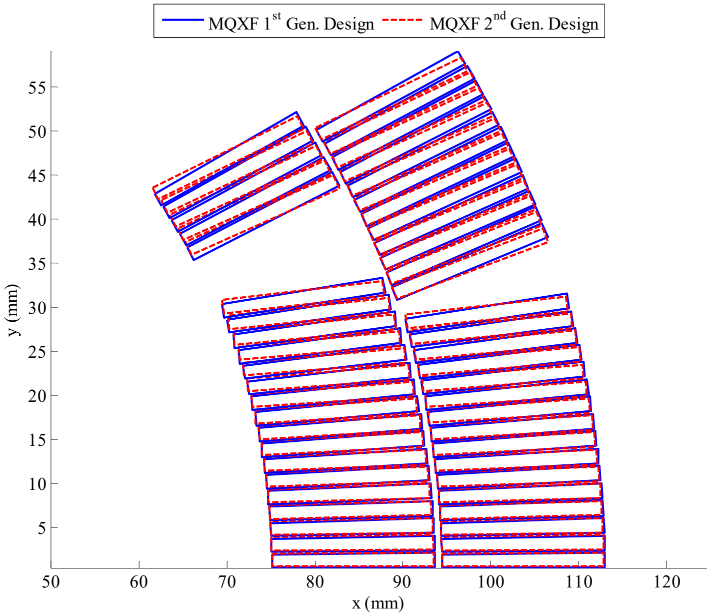






# Coil Design Optimization

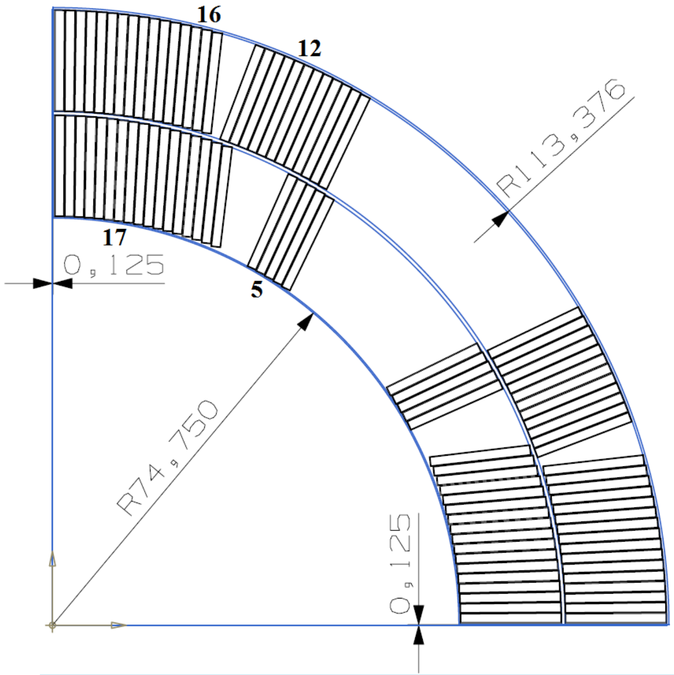


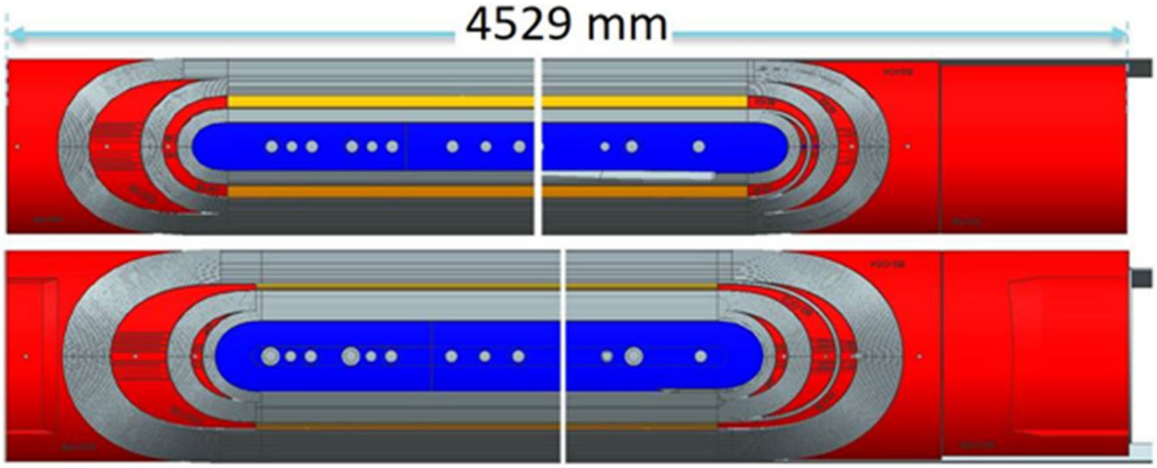


- Following the feedback from winding and inspection of the 1st generation coil, the coil ends (RE & LE) has been optimized
  - to limit the peak field enhancement in the ends;
  - to keep the coil end as compact as possible in order to increase the magnetic length for a given coil length;
  - to minimize the multipole content of the integrated field.
- Coil cross section has also been optimized to minimize the multipole field components.

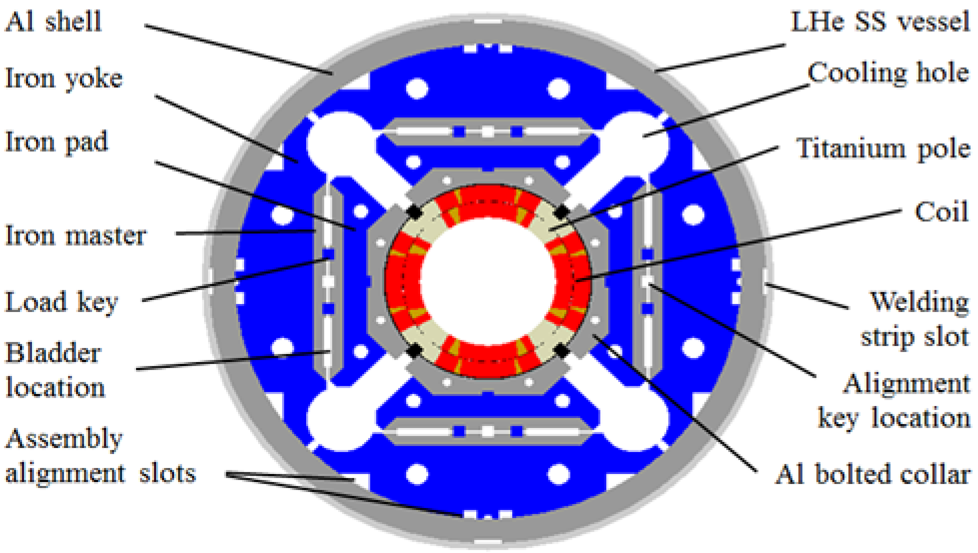
# Coil Mechanical and Fabrication Process Design

- The QXFA coil is a two-layer cos-$2\theta$ coil with saddle-shaped ends. The two-layer coil is wound continuously, without a splice at transition between the inner and outer layers, using the double-pancake technique. Both layers of the coil is temporarily cured to keep the compact shape as much as possible for the next fabrication process.
- The cured coil goes through a heat treatment cycle (reaction), the CuSn and Nb are heated to about 650-700 deg. C (require temperature homogeneity within +/- 3 deg. C) in inert gas (argon) atmosphere, and the Sn diffuses in Nb and reacts to form $Nb_3Sn$.
- The cable of $Nb_3Sn$ is brittle after reaction, so the coil is vacuum impregnated with epoxy.

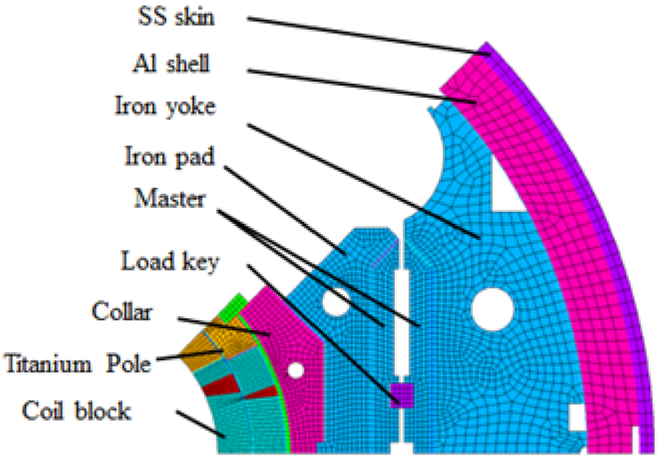




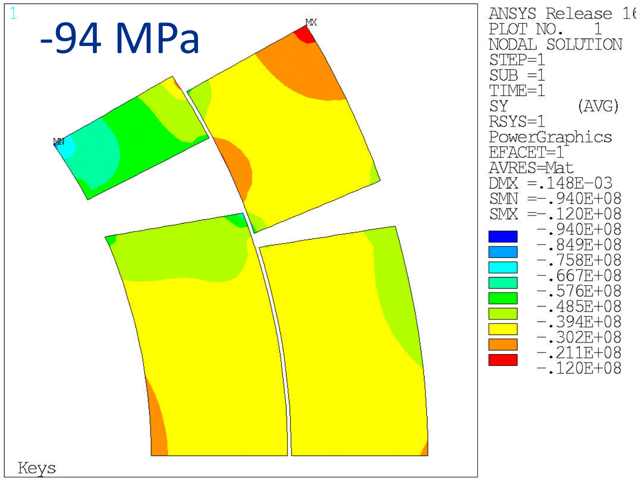
# Magnet Structure Design_2D



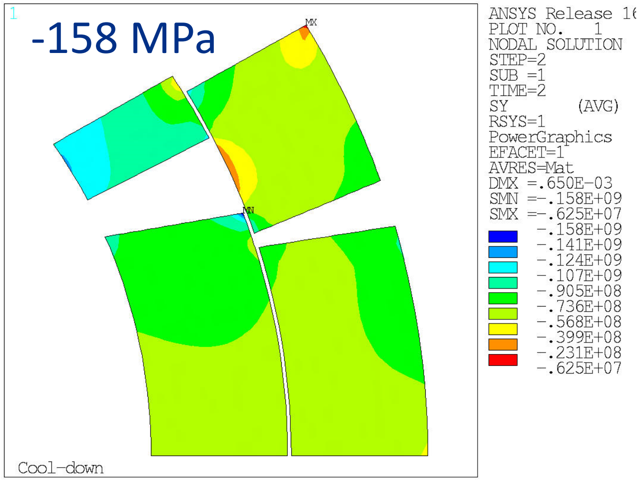
## ANSYS Model



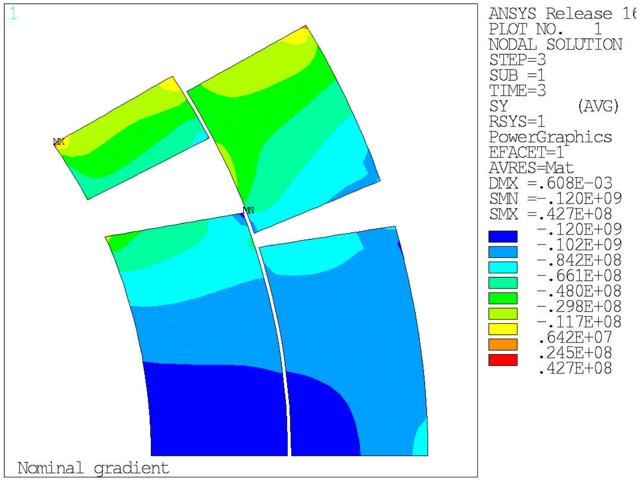
Keep the pole turn under compression



Room Temp. Assembly

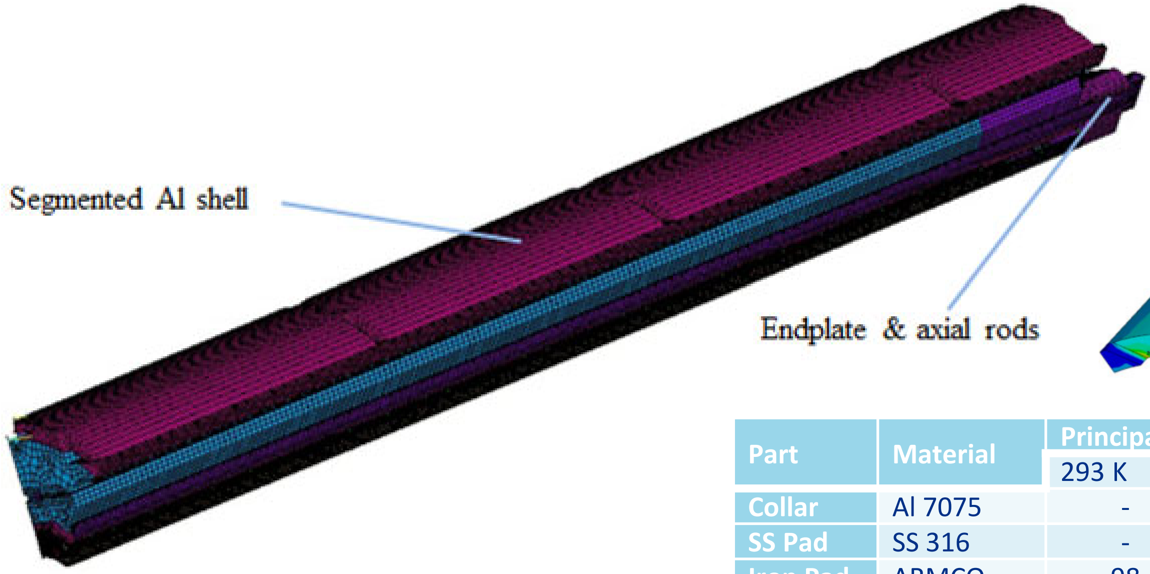


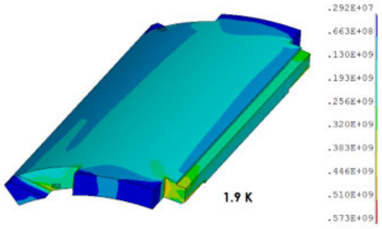
Cool Down to 1.9 K

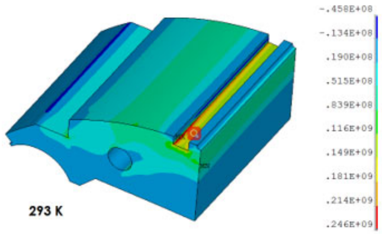


Magnet excitation at 16.5 kA

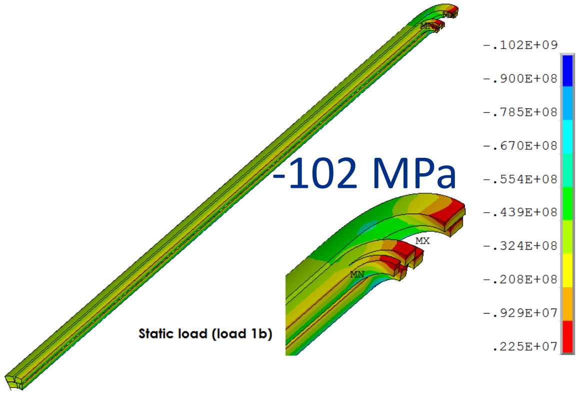
# Magnet Structure Design_3D

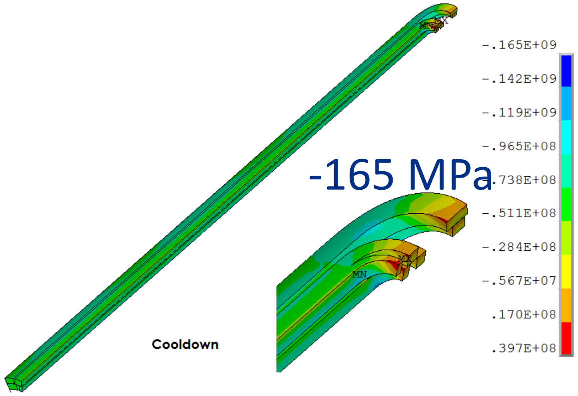


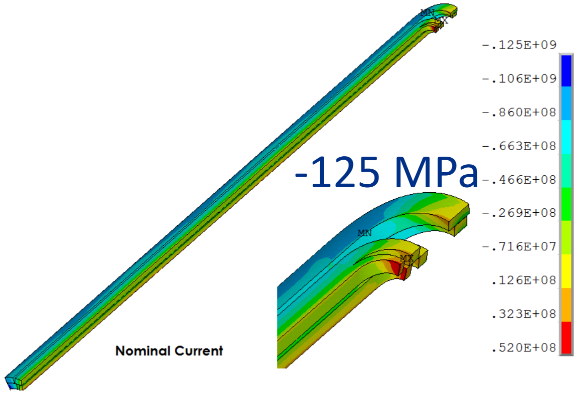




| Part | Material | Principal Stress (MPa) | | Von Mises Stress (MPa) | | $\sigma_y$ (MPa) | |
|---|---|---|---|---|---|---|---|
| | | 293 K | 1.9 K | 293 K | 1.9 K | 293 K | 1.9 K |
| Collar | Al 7075 | - | - | 121 | 273 | 420 | 550 |
| SS Pad | SS 316 | - | - | 82 | 277 | 289 | 375 |
| Iron Pad | ARMCO | 98 | 152 | - | - | 223 | - |
| Yoke | ARMCO | 246 | 306 | - | - | 223 | - |
| Shell | Al 7075 | 280 | 610 | 320 | 573 | 420 | 550 |
| Endplate | Nitronic 50 | - | - | 137 | 333 | 517 | 1120 |

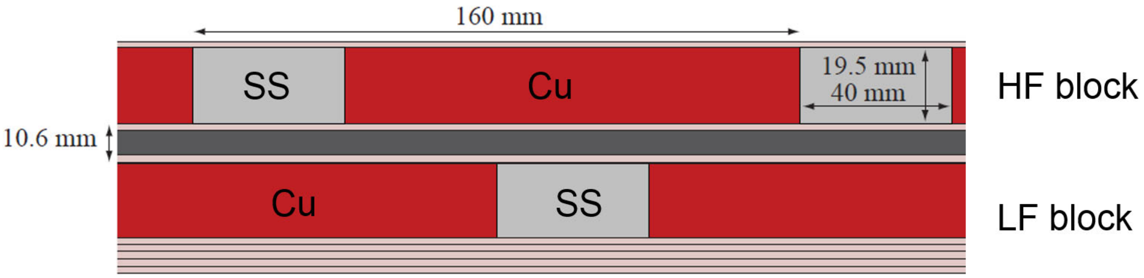


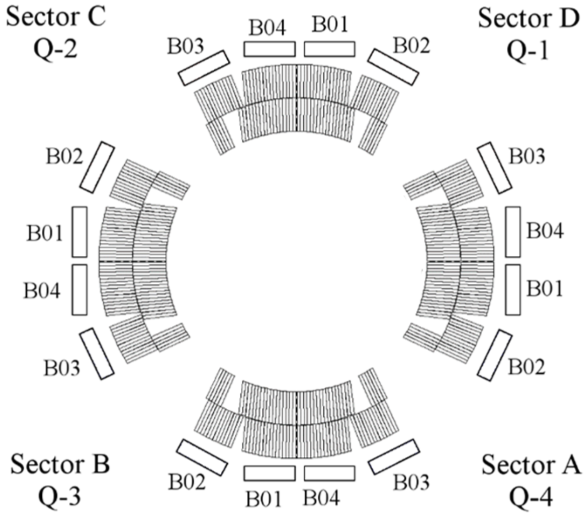




# Quench Protection

- The requirements for MQXFA magnets protection in operating conditions are: hot-spot temperature < 350 K, coil-ground voltages < 670 V and, turn-to-turn voltages < 160 V.
- The MQXFA is protected with a combination of quench heaters (QH) and Coupling-Loss Induced Quench (CLIQ) system. Upon quench detection, both QH and CLIQ units are triggered simultaneously.
- The QH units introduce a current through the QH strips attached to the coil and heat up the conductor by heat diffusion through a thin 50 µm insulation layer.
- The CLIQ units introduce oscillations in the magnet transport currents.



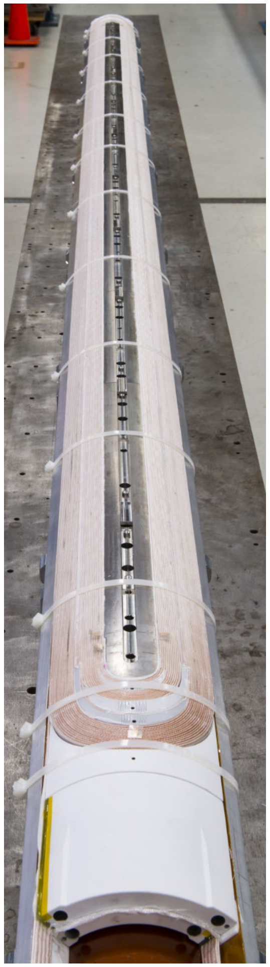


# Coil Manufacturing: Winding and Curing

- Coil winding tension is 15-25 kg depending on turn. Ceramic binder used at end turns to increase cable stability.
- Curing cycle 150° C for 90 minutes in closed cavity with ceramic binder.
- Hydraulic cylinders apply load to close the mold.
- Heated with electric cartridge heaters to cure the coil.

QXFA coil winding

FNAL curing press



QXFA Coil

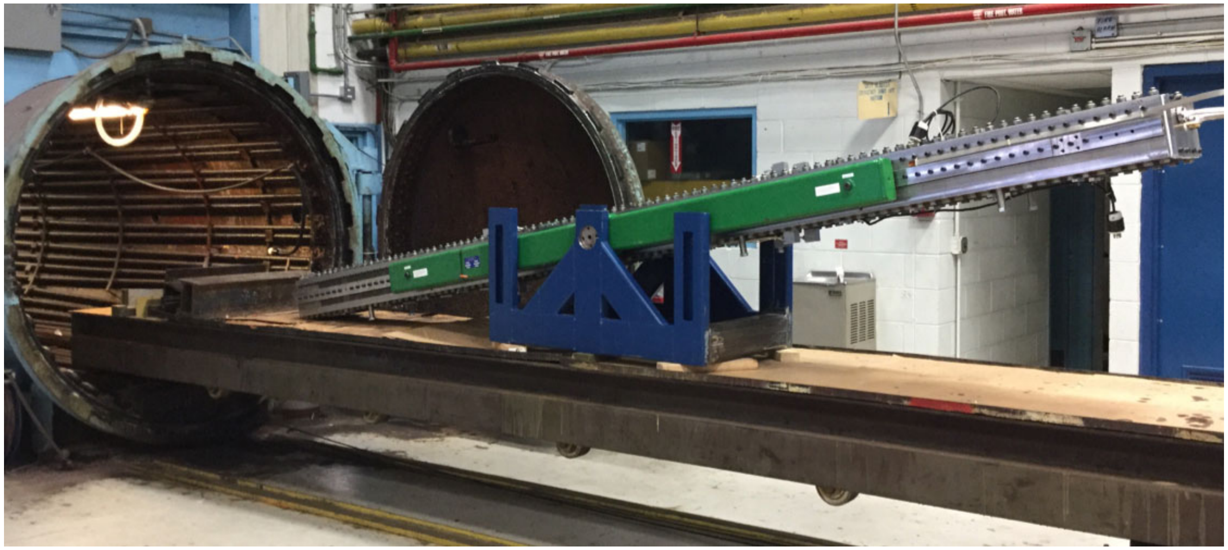
# Coil Manufacturing: Reaction

Reaction Oven & Coil in the Reaction Fixture

QXFA Coil after Reaction

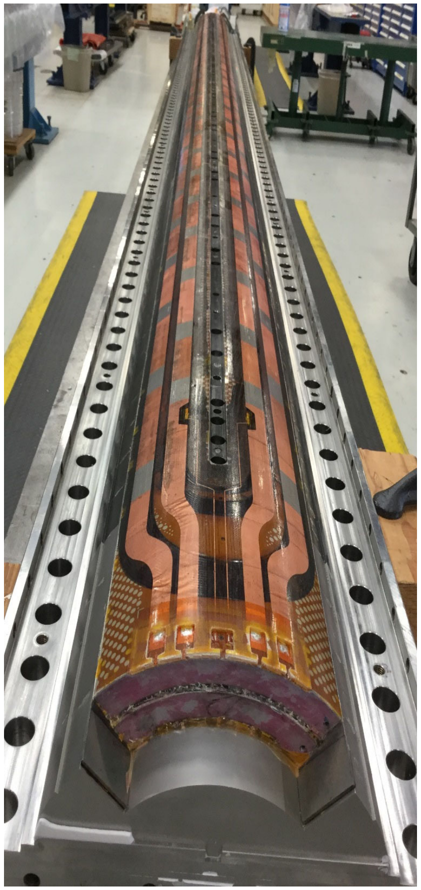
- Reaction cycle is in an argon atmosphere and lasts ~11 days including ramp up and cool down.
- Witness samples are at the end of the coil.
- Reaction tooling volume is identical to impregnation tooling.

# Coil Manufacturing: Impregnation



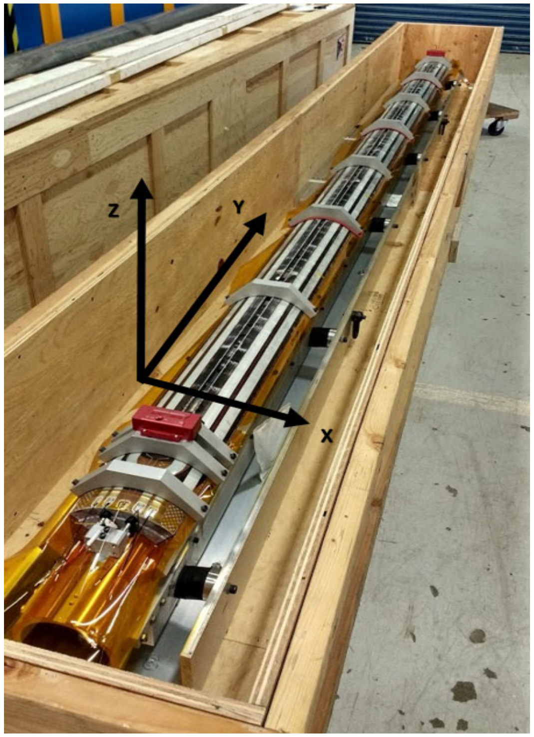
Vacuum Tank & QXFA Coil in the Impregnation Fixture

- The coil is vacuum epoxy impregnated at 50° C
- Epoxy cure is in the vacuum tank at 110° C for 5 hours then 125° C for 16 hours using external heaters mounted on the tooling.
- Material and process control is critical to reduce the coil failure.



QXFA Coil after Impregnation

# Coil Manufacturing: Handling and Shipping



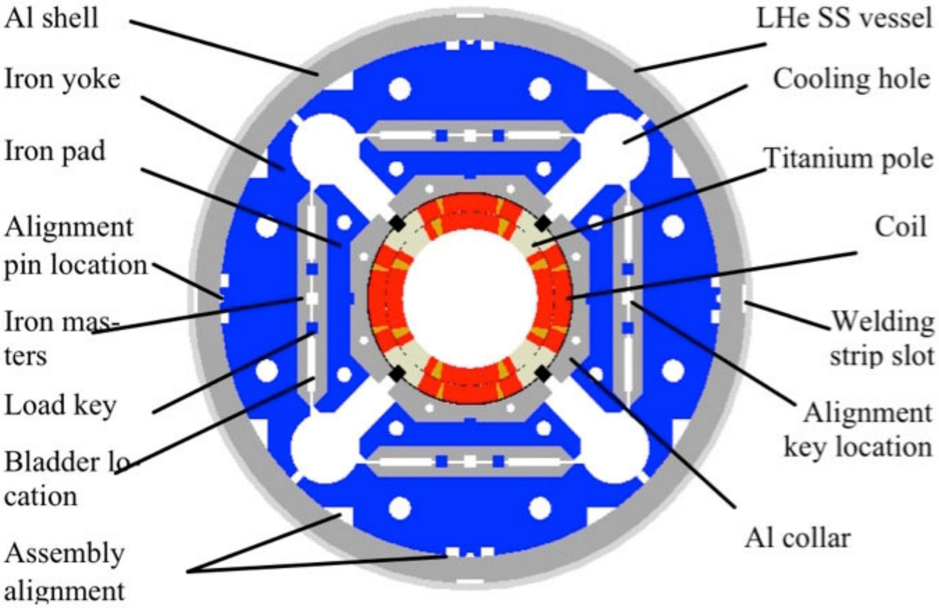
**Handling**

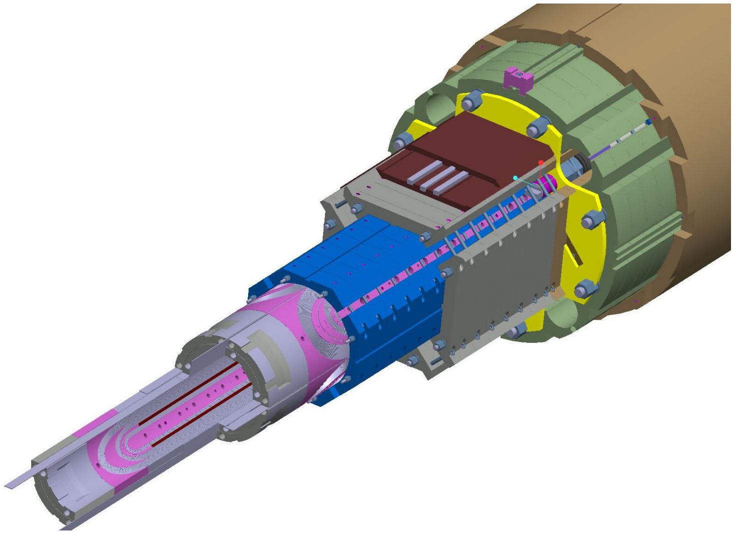
- <500 micro-strain
- dedicated lifting fixtures

**Shipping**

- dedicated shipping fixtures
- <500 micro-strain,  shocks <9 g
- 2 accelerometers on the LE and RE
- 5g and 10 g shock watches
- Air ride dedicated truck

# Magnet Assembly





Shell-Yoke Assembly

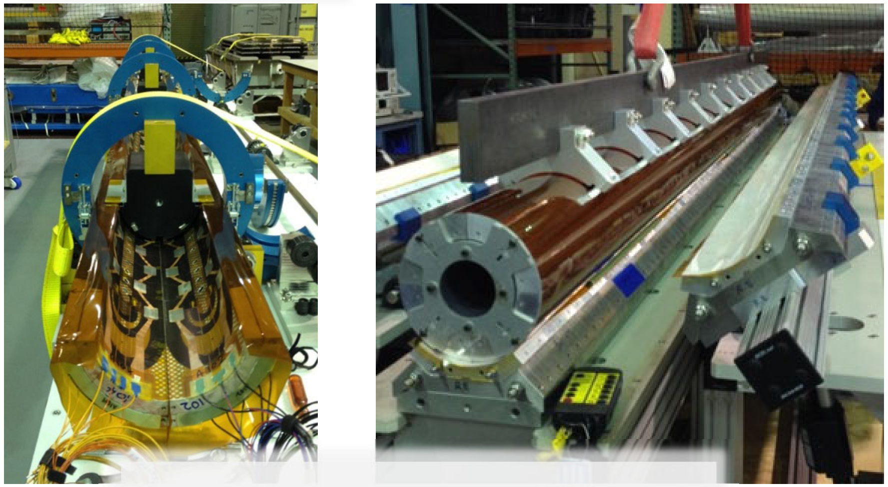
# Magnet Assembly Cont.

Coil Prep

Fuji Paper Exposure

Key shimming

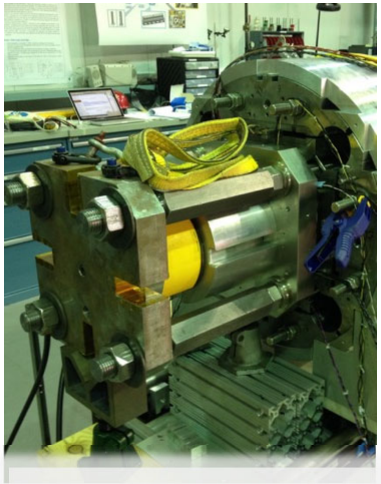
Radial Shim Prep



Coil Pack Assembly

# Magnet Assembly Cont.

Coil Pack Insertion

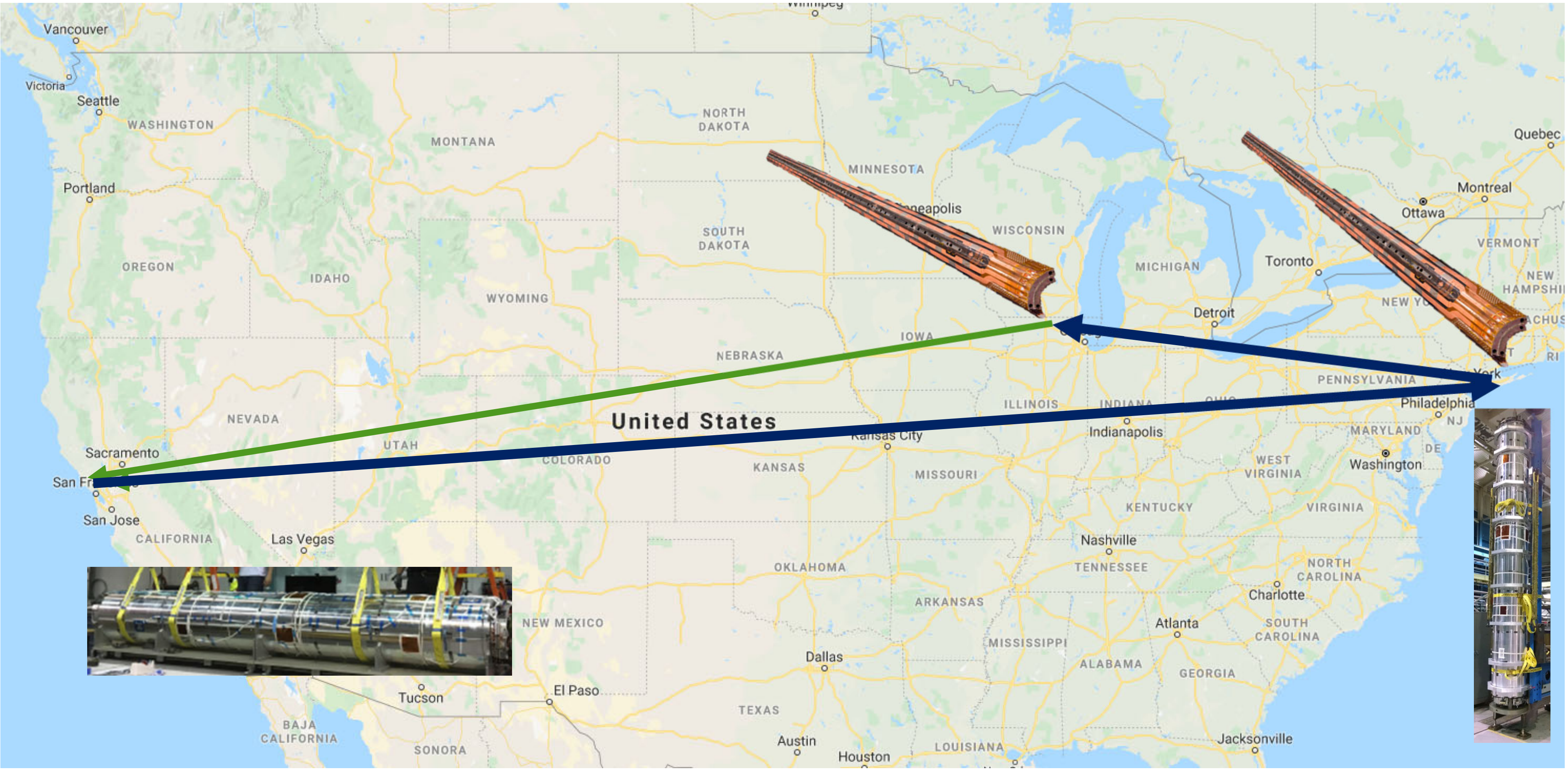


Preloading

Splicing and Connectorization

Fully assembled magnet

# Shipping



## HL LHC AUP: around 150 domestic shipments (coils + magnets)

# Magnet Testing

Test Plan

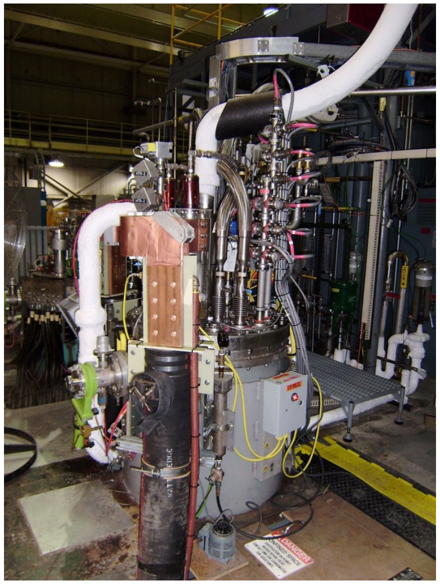
At room temperature before cool down
- Electrical checkouts and tests
- Magnetic measurements: integral field strength and field harmonics

After cool down to 1.9 K
- Electrical checkouts
- Quench test training – to 16.53 kA (nominal current plus 300 A
- Magnetic measurements
- Holding the nominal current plus 300 A margin for an extended period of time
- Quench Protection Heater tests to verify nominal operation
- Splice measurements

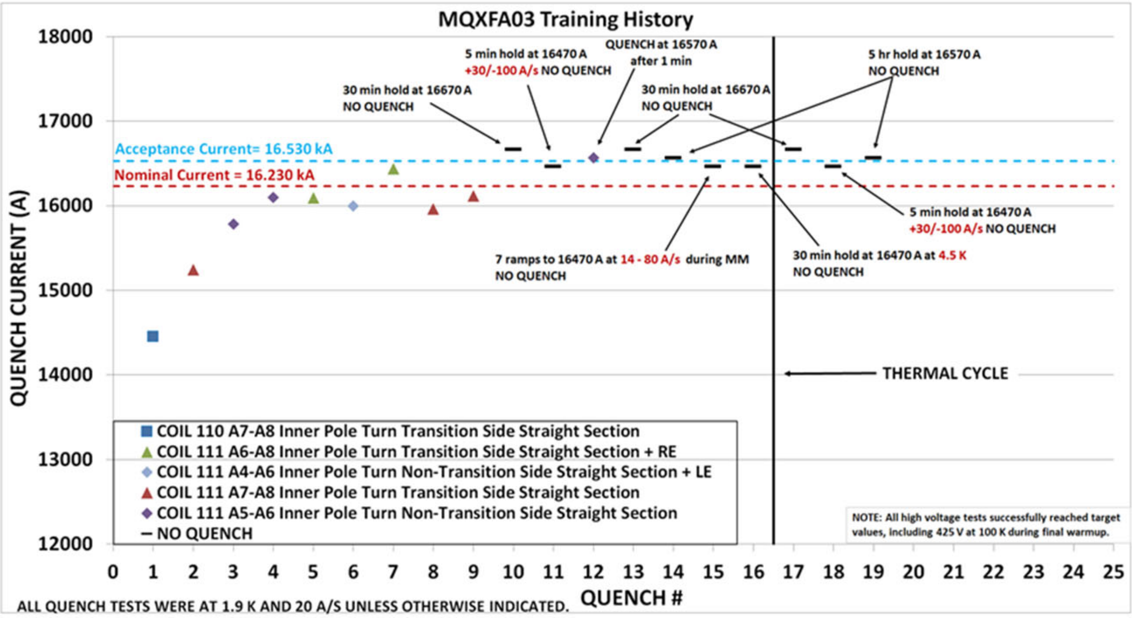
At room temperature after warm-up
- Magnetic measurements
- Electrical checkouts before shipping to FNAL

About magnet quench:

- ❖ When a superconducting magnet loses its superconducting state and abruptly transitions to a resistive state, leading to a rapid release of stored magnetic energy and a significant rise in temperature.
- ❖ This transition can be triggered by various factors such as excessive current, magnetic field fluctuations, mechanical disturbances, or temperature variations.

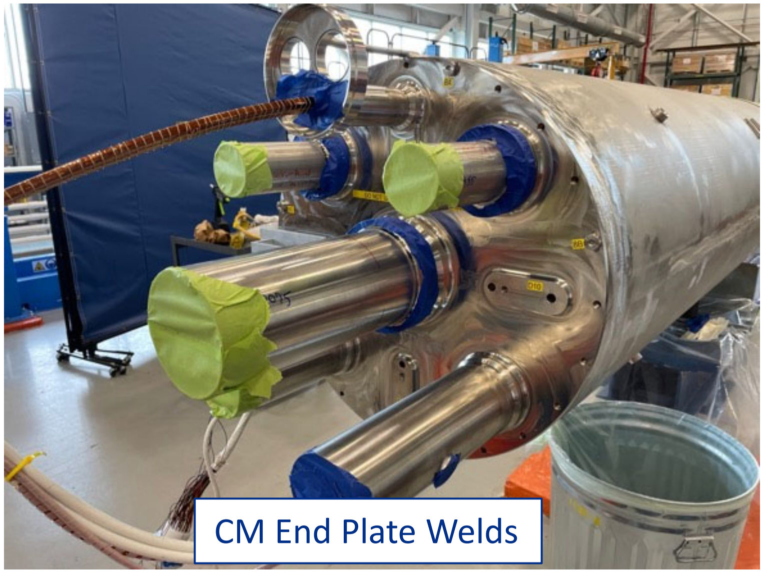


Vertical Test Stand at BNL



# Cold Mass (CM) Assembly

CM ready for Long. Welds

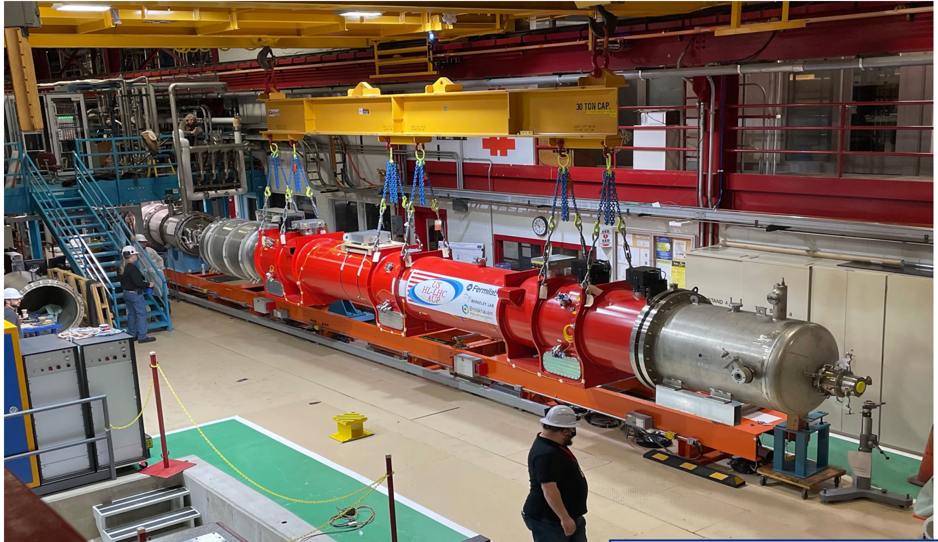


CM End Plate Welds

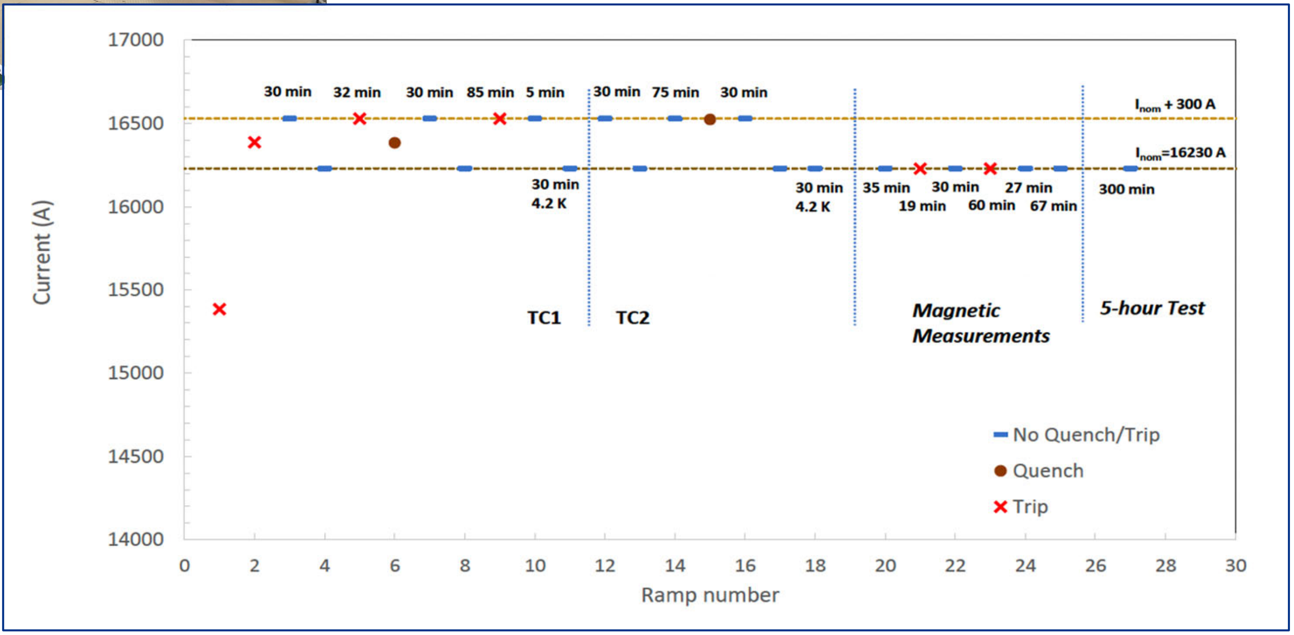
CM ready for Ultrasonic Inspection

Wrap with MLI and Insertion in Cryostat

# Cryo-assembly Testing


Installation in FNAL TS4

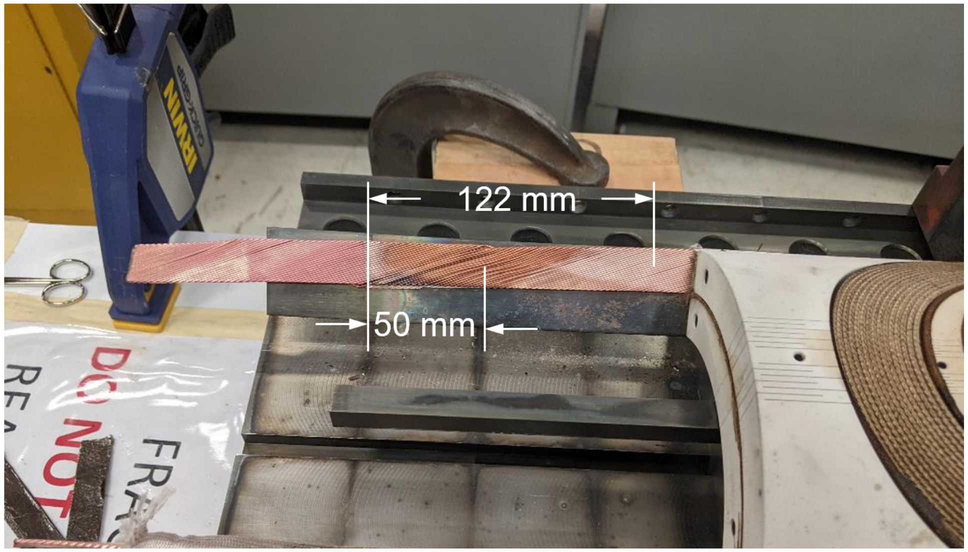
- Room temperature electrical checkout and initial setup
- Cool down and electrical checkout at 4.2 K, and high voltage test at 1.9 K.
- Perform magnetic measurements at 1.9 K for alignment.
- Setup for testing at 4.2 K and test the magnet at 1.9 K for quench(es).
- Holding current test at 1.9K.
- Magnetic field measurement using hall probe.
- Quench current temperature dependence study.
- Warm up and cool down, and then repeat the previous process as the 2nd thermal cycle verification.

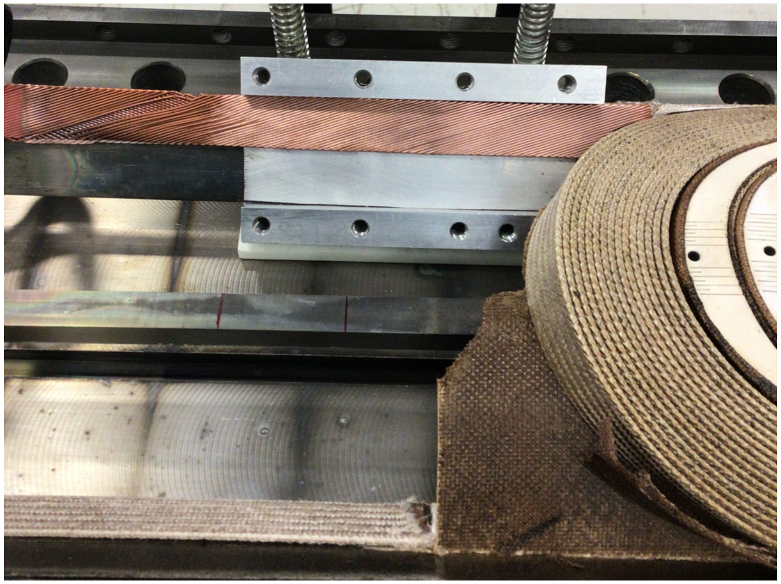


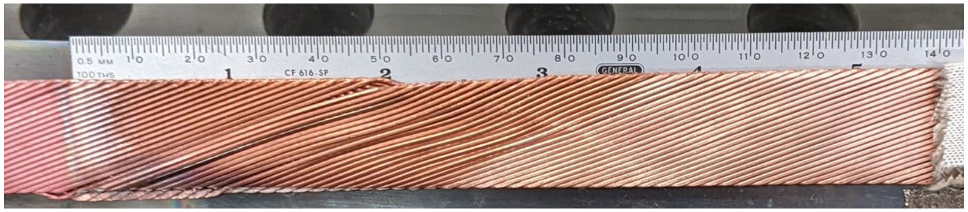
# Failure Case during Coil Winding

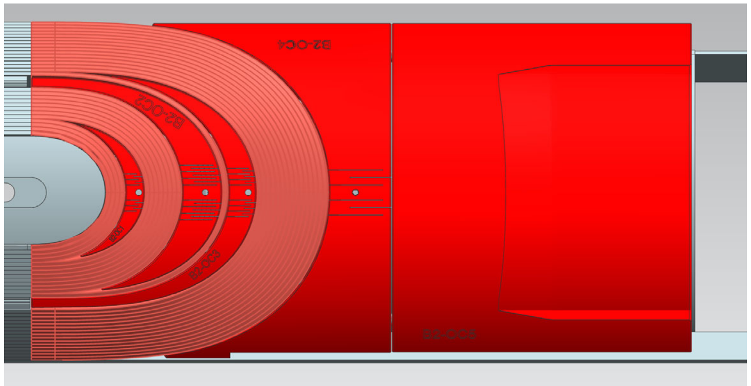
Cable roped and lost, ~$250k

# Failure Case during Coil Reaction

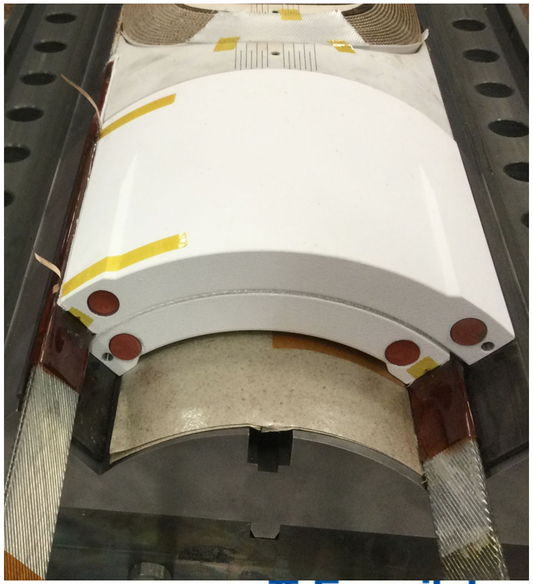




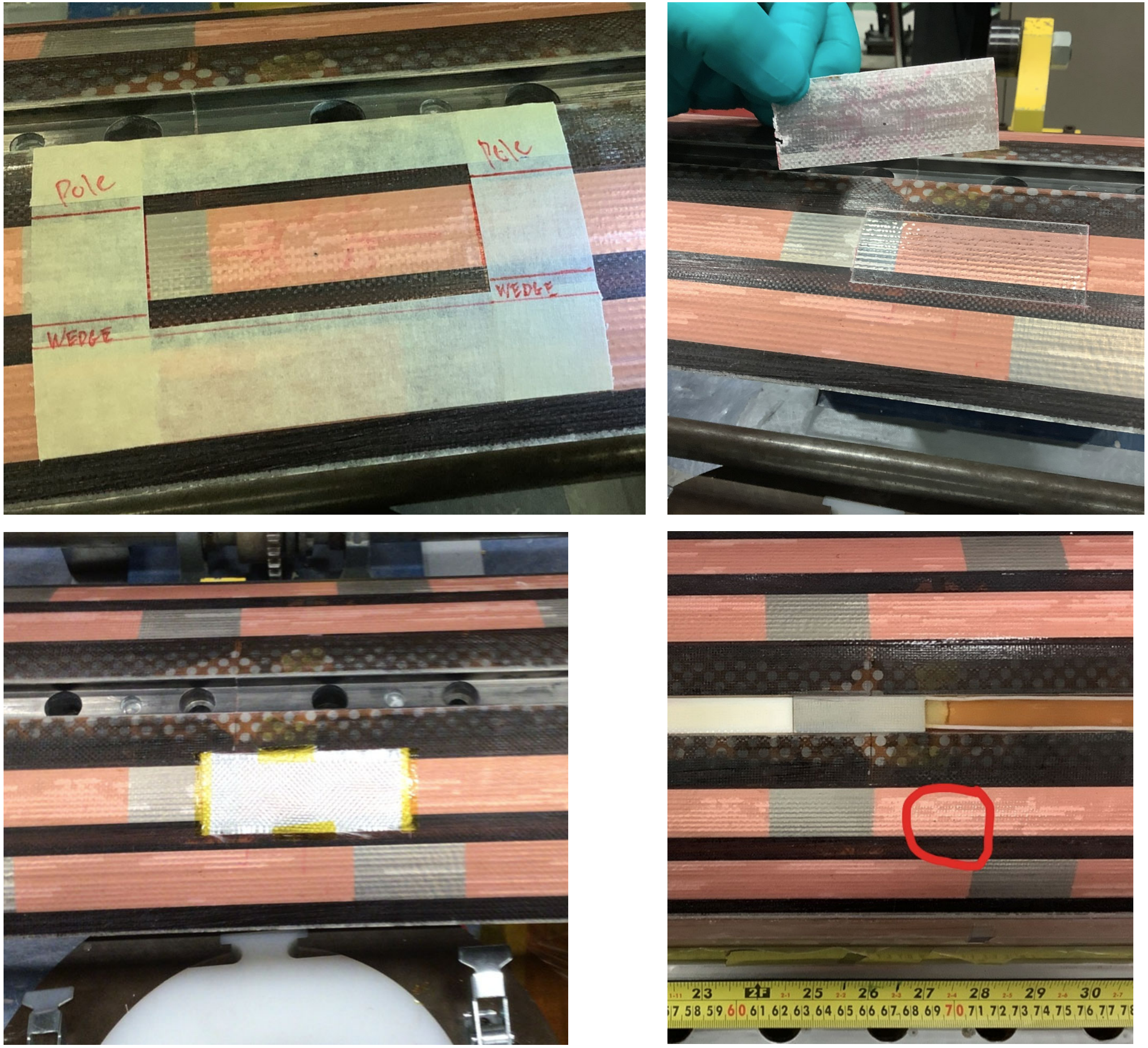




- Repaired by shifting the splice 75 mm into the coil.
- Tooling was replaced for future coils.



# Failure Case during Coil Impregnation

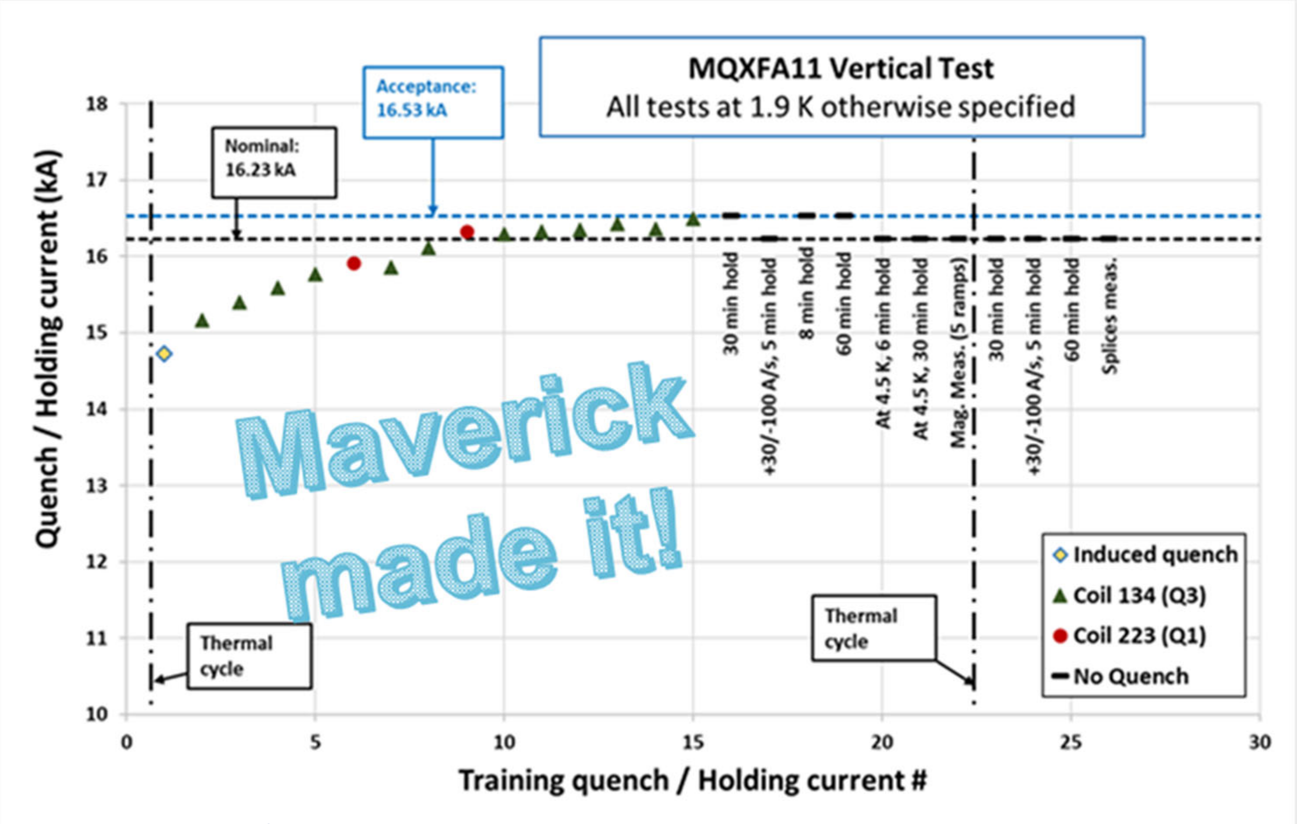


- Black object was impregnated into the coil, which may cause electric short in between the QH and the coil.
- Repaired by peeling off this section of impregnated cloth, patching a new insulation cloth and re-impregnation.

# Failure Case during Magnet Assembly

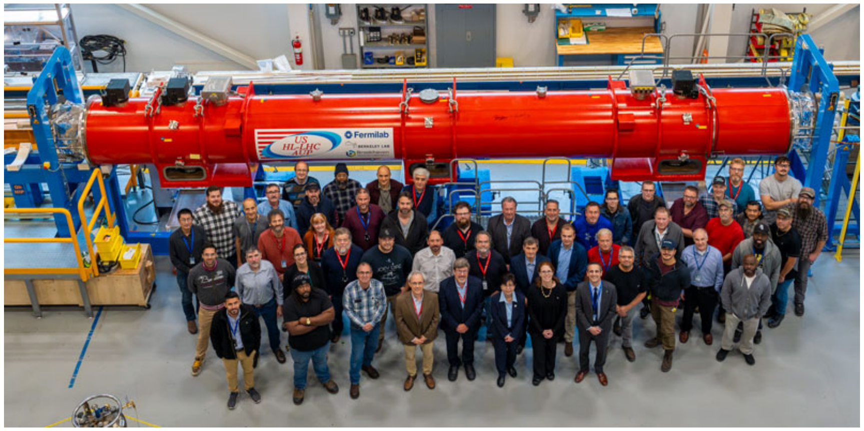
- In the process of shipping preparations, it was discovered that the GPI of Q2 Coil that was supposed to extend into the bore appeared to be folded in between Q3 Coil in two locations.
- These two coils were replaced in the magnet due to possible high stress during the assembly.

# Failure Case during Magnet Shipping



- The truck transporting the MQXFA11 magnet from LBNL to BNL was rear ended by another truck in 2022. The main hit took place on the right back corner. During the incident the truck rear axle disengaged as displayed.
- The magnet was moved to FNAL. Upon arrival a visual inspection was performed followed by electrical checkout, metrology survey, analysis of the fiber optic sensors and accelerometer data analysis (6-10 g vertical shock)
- All tests and analyses were OK. Magnet was shipped to BNL for magnet testing.

# Delivery



- Failure paves the way to success!
- It teaches us valuable lessons, strengthens our resilience, and provides opportunities for growth and improvement.
- Embracing failure as a natural part of the journey can lead to innovation, creativity, and ultimately, achievement.

Leaving FNAL

Arriving at CERN