Lecture #2

Design Guide to Superconducting Magnet

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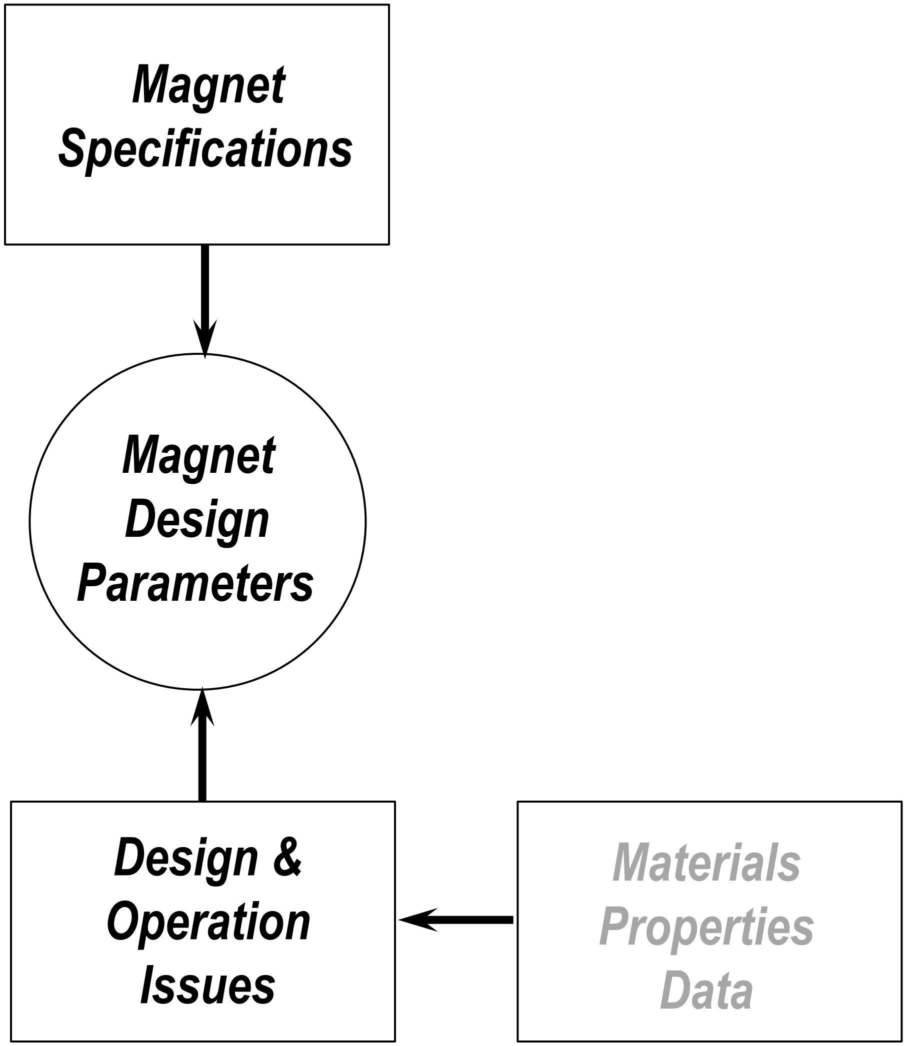
Design Block Diagram for a Superconducting Magnet



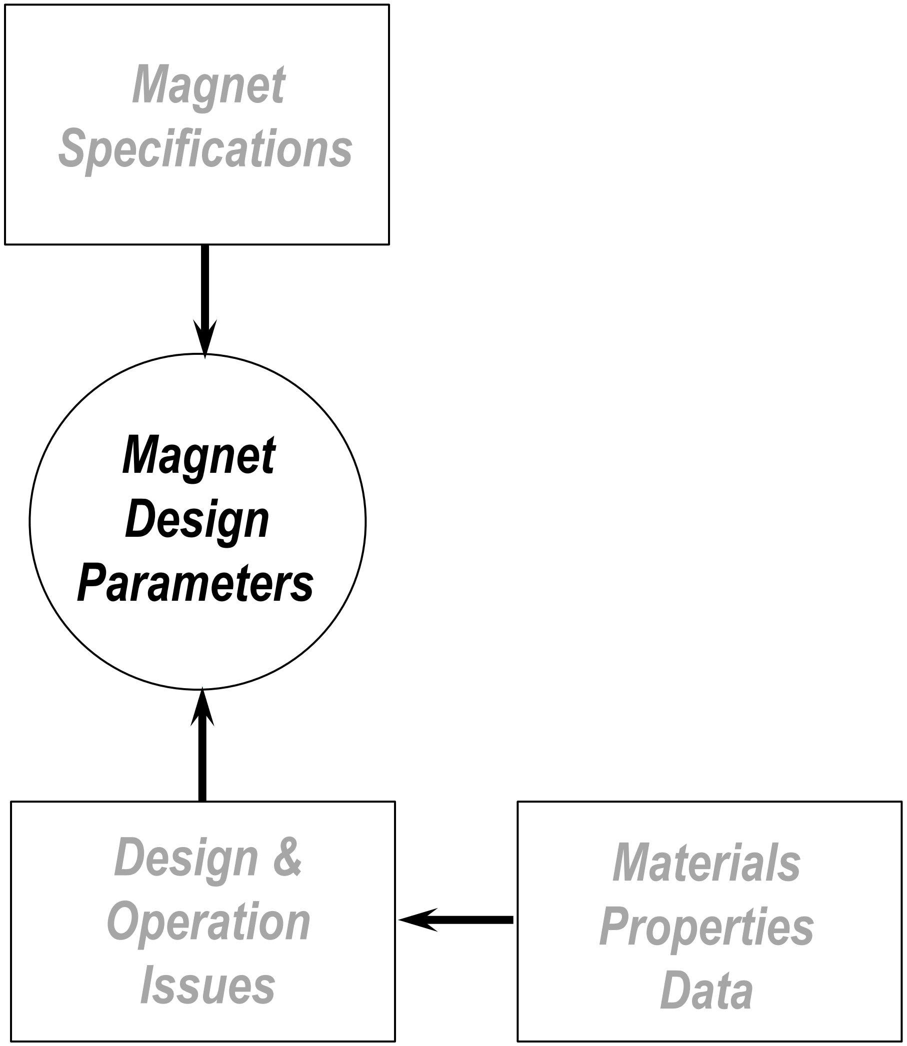
Magnet Specifications

Magnet Design Parameters

Design & Operation Issues

Materials Properties Data

Design Block Diagram for a Superconducting Magnet



Magnet Specifications

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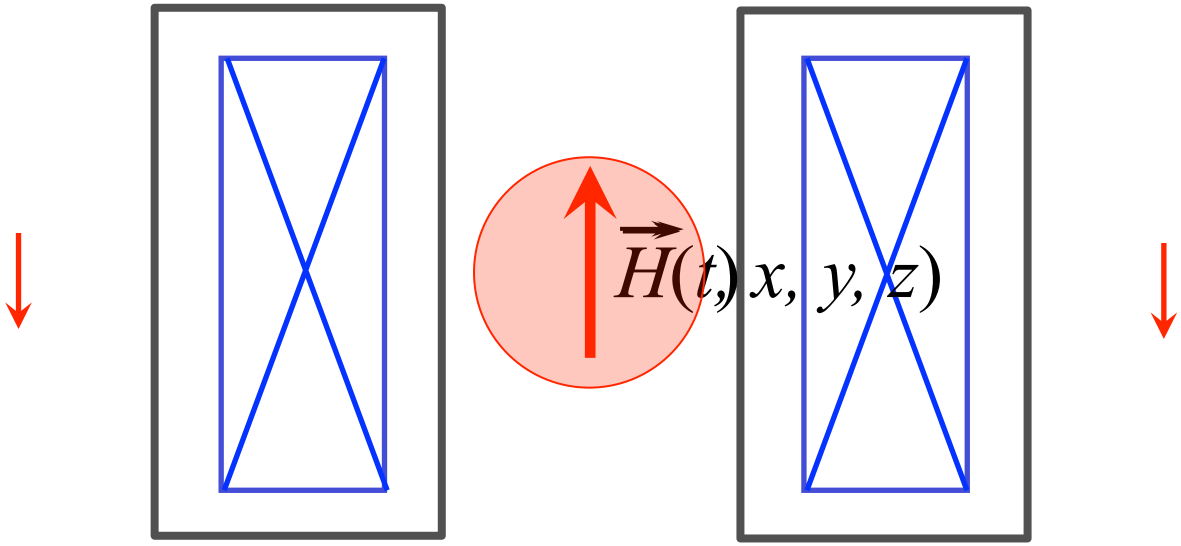
Magnet Specifications: 1—5

1. Center field vector: strength; direction—selected details in ***Lecture #3***
2. Room-temperature bore: orientation; dimensions
3. Field temporal function: driven vs. persistent mode—if *constant*, temporal stability limit
4. Field spatial function: field error limits over, e.g., 10-cm Diameter Spherical Volume (DSV)

   —***Topics 3*** and ***4*** discussed a bit more later
5. Fringe field (strength space)***: shielded*** vs. ***unshielded***



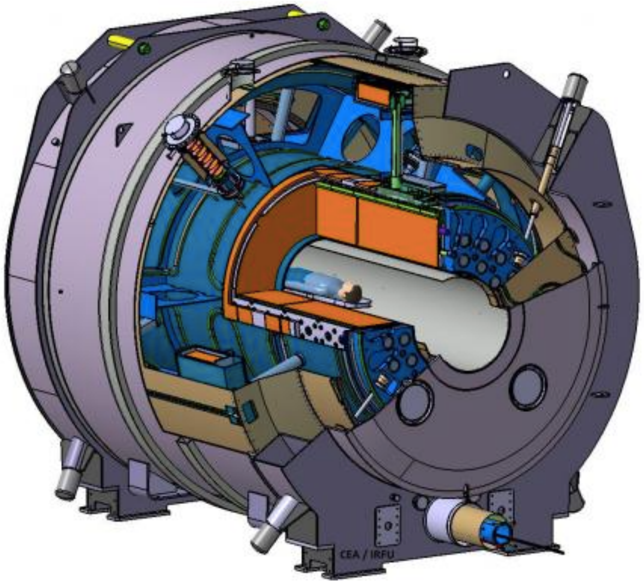
Magnet Specifications: 2

2. ***Room-temperature (RT) bore***; ***orientation***; dimensions
   - RT bore generally 20-50 mm greater than the innermost winding diameter—cryogenics
     - ➔ 50 mm for ≤ 4.2- K operation
     - ➔ 20 mm for >> 4.2-K operation
   - Field orientation

     Vertical*:* Most research and NMR magnets

     Horizontal*:* Most MRI magnets
     - Mechanical and cryogenic issues challenging

930-MHz NMR magnet (NIMS, 2002)
RT bore: 54 mm



ISEULT MRI magnet (CEA, 2017)
RT bore: 900 mm

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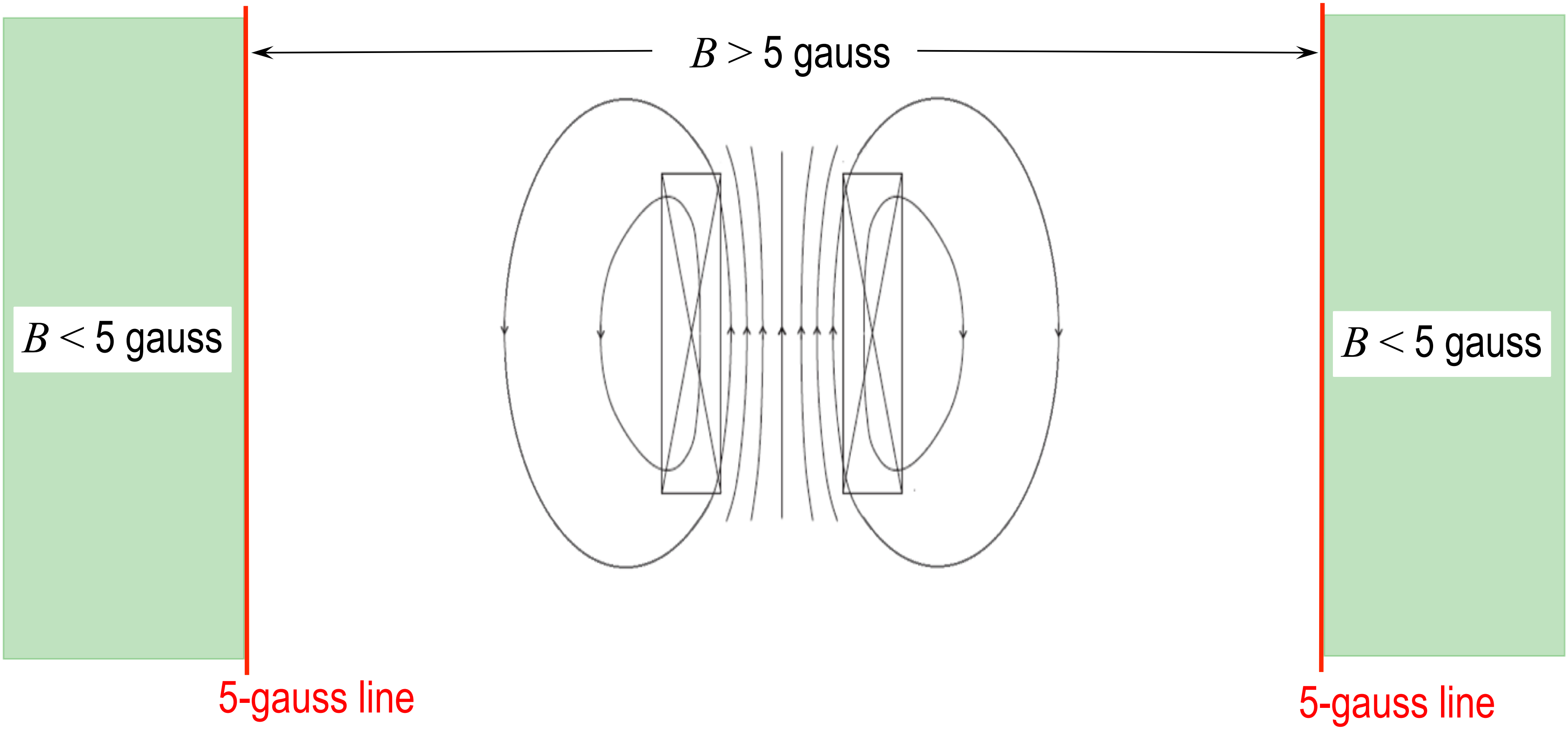
Magnet Specifications: 5

5. Fringe field (strength space): ***shielded*** vs. ***unshielded***

Fringe Field in Unshielded Magnet



$B > 5$ gauss

$B < 5$ gauss

$B < 5$ gauss

5-gauss line

5-gauss line

- For safety (people, devices, equipment) & convenience, a 5-gauss line closest to the magnet

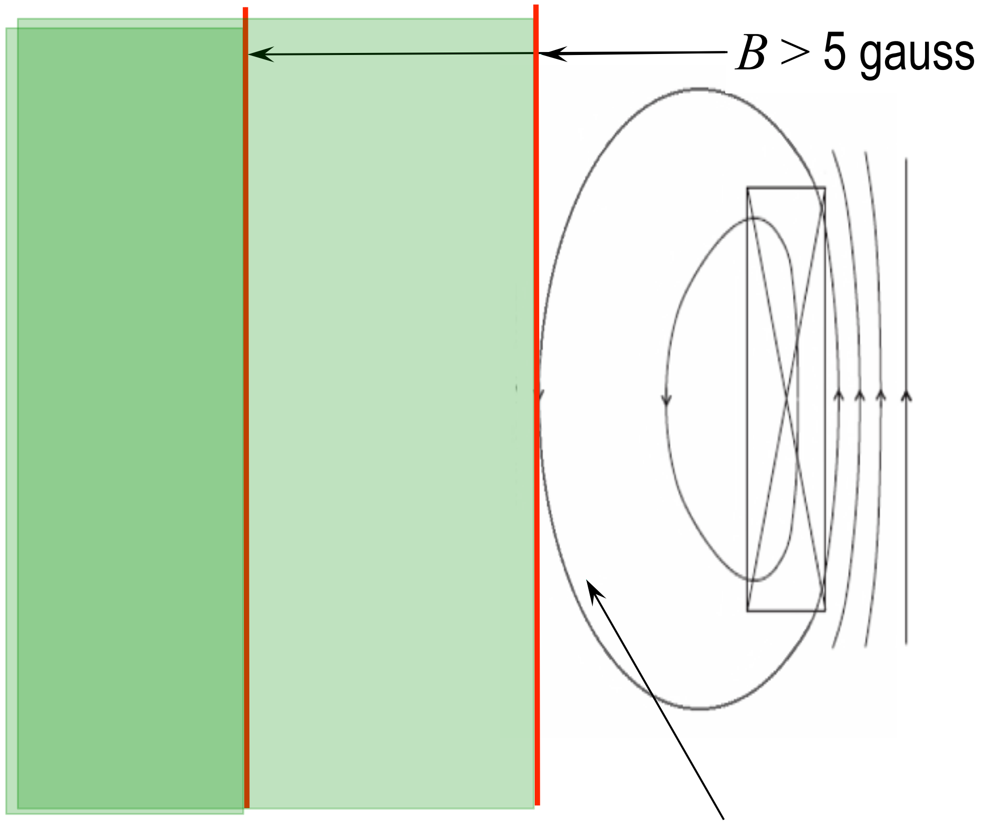
Magnet Specifications: 5

5. Fringe field (strength space): ***shielded*** vs. ***unshielded***

Fringe Field in Passively Shield Magnet

- Steel annulus an effective for passive shielding
- One ad often overlooked: it shields the magnet center from external magnet signals
- Big negative: can be *very massive*
  - ISEULT would have required a steel mass of 2000 tons

[Thierry Schild, CEA]



$B > 5$ gauss

Steel annulus surrounding the magnet

Magnet Specifications: 5

5. Fringe field (strength space): ***shielded*** vs. ***unshielded***

Fringe Field in Actively-Shield Coil

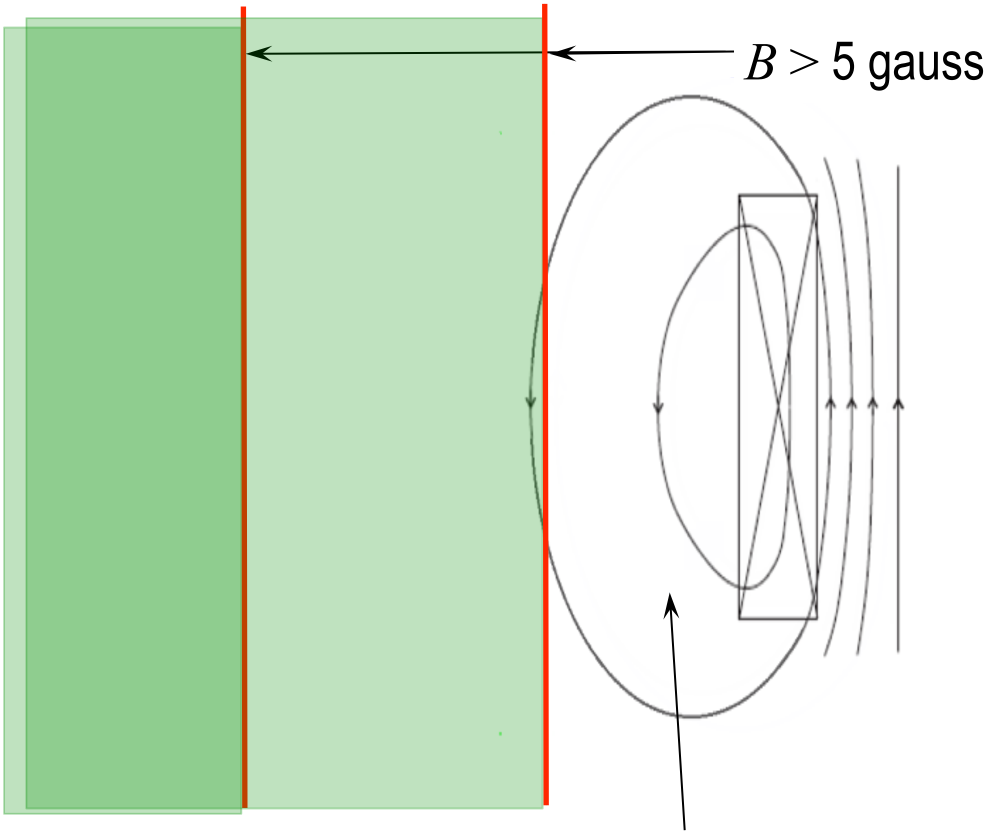
- Generally of superconducting
- Less massive than steel counterpart

Negatives

- Subtract field from the center field
- Large interaction forces
- Enlarges the system overall size

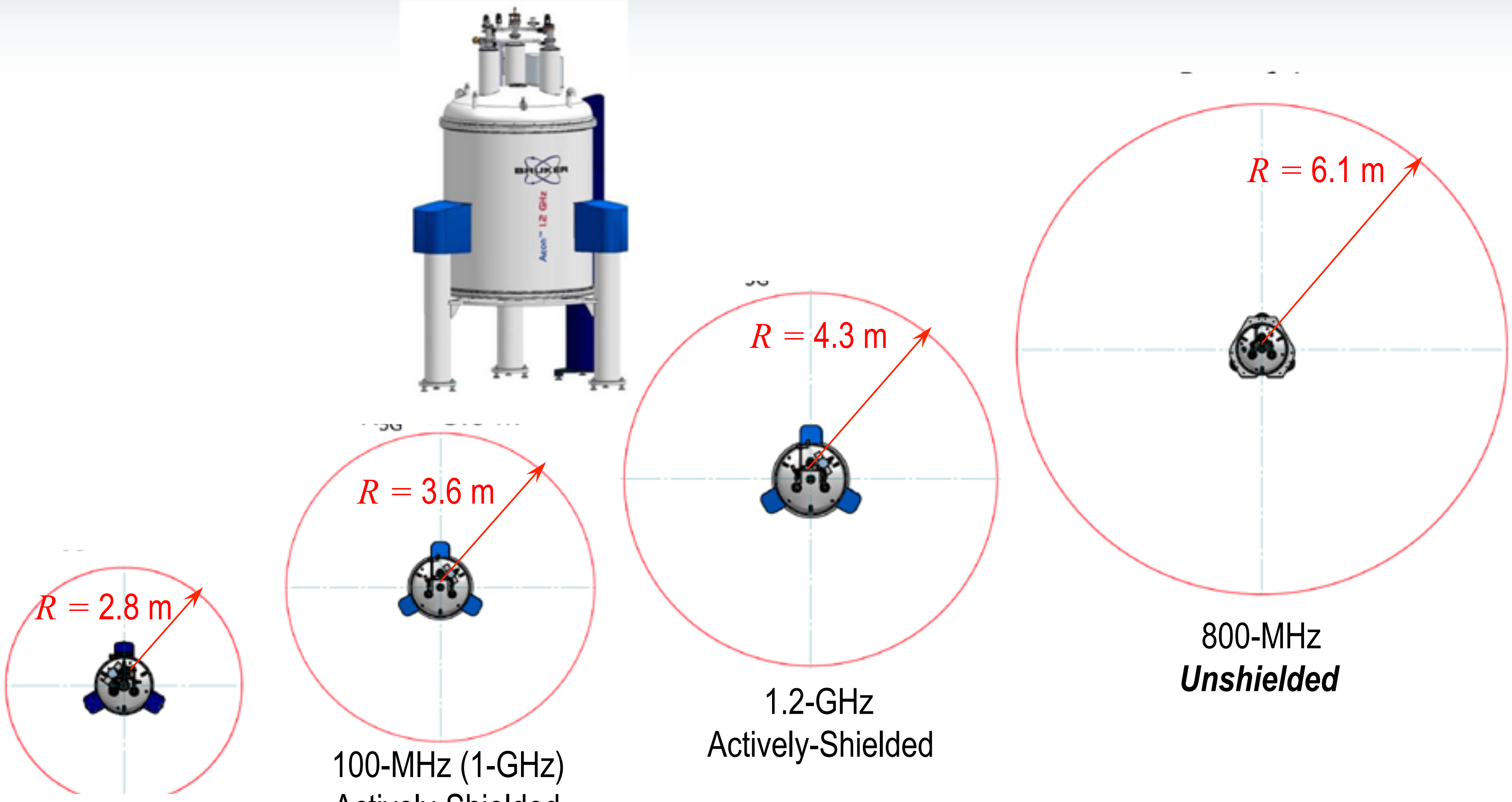
ISEULT active-shield coil pair

[Alain Payn, CEA]



Magnet Specifications: 5

Bruker NMR Magnet 5-Gauss Lines



800-MHz
Unshielded

1.2-GHz
Actively-Shielded

100-MHz (1-GHz)
Actively-Shielded

900-MHz Actively-Shielded

[Based on Bruker slide]

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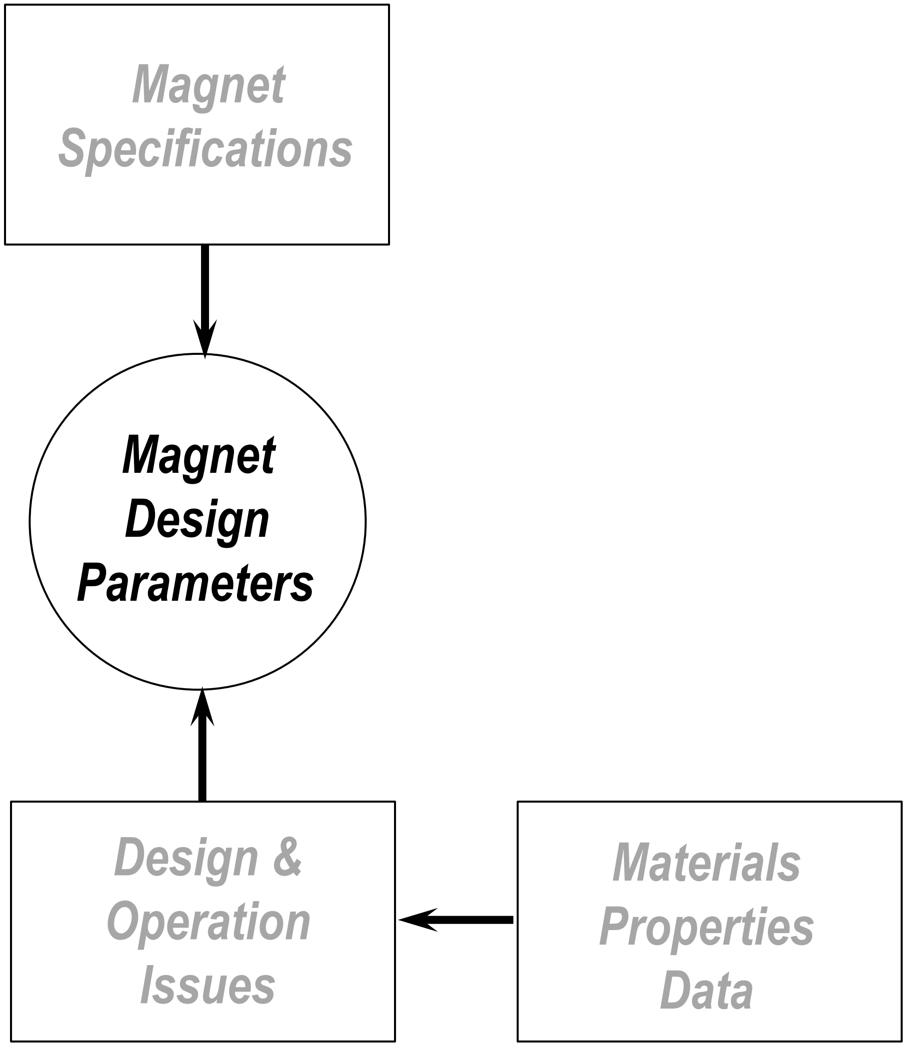
Design Block Diagram for a Superconducting Magnet



Magnet Specifications

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Magnet Design Parameters: Part 1

1. Superconductors (DC Magnets)

NbTi

- To ~10 T, 4.2 K: many superconducting magnets: *LHC*; most MRI magnets
- To ~12 T, < 4.2 K: *ISEULT*

NbTi* & *Nb_3Sn

- To ~18 T, 4.2 K: high-field magnets
- To ~24T, < 4.2 K: high-field magnets

NbTi*, *Nb_3Sn* & *Bi223* & *REBCO

- To ~31 T, 4.2 K: high-field magnets

Bi223* & *REBCO

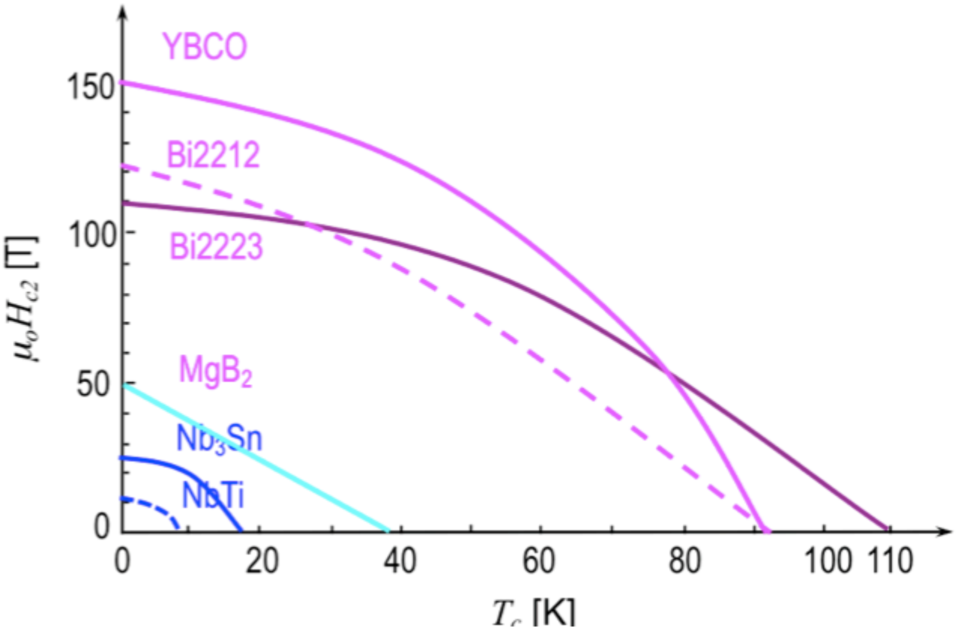
- > 10 K ➔ mostly *replacing*

REBCO

- To 100 T, 4.2 K: technically feasible

MgB_2

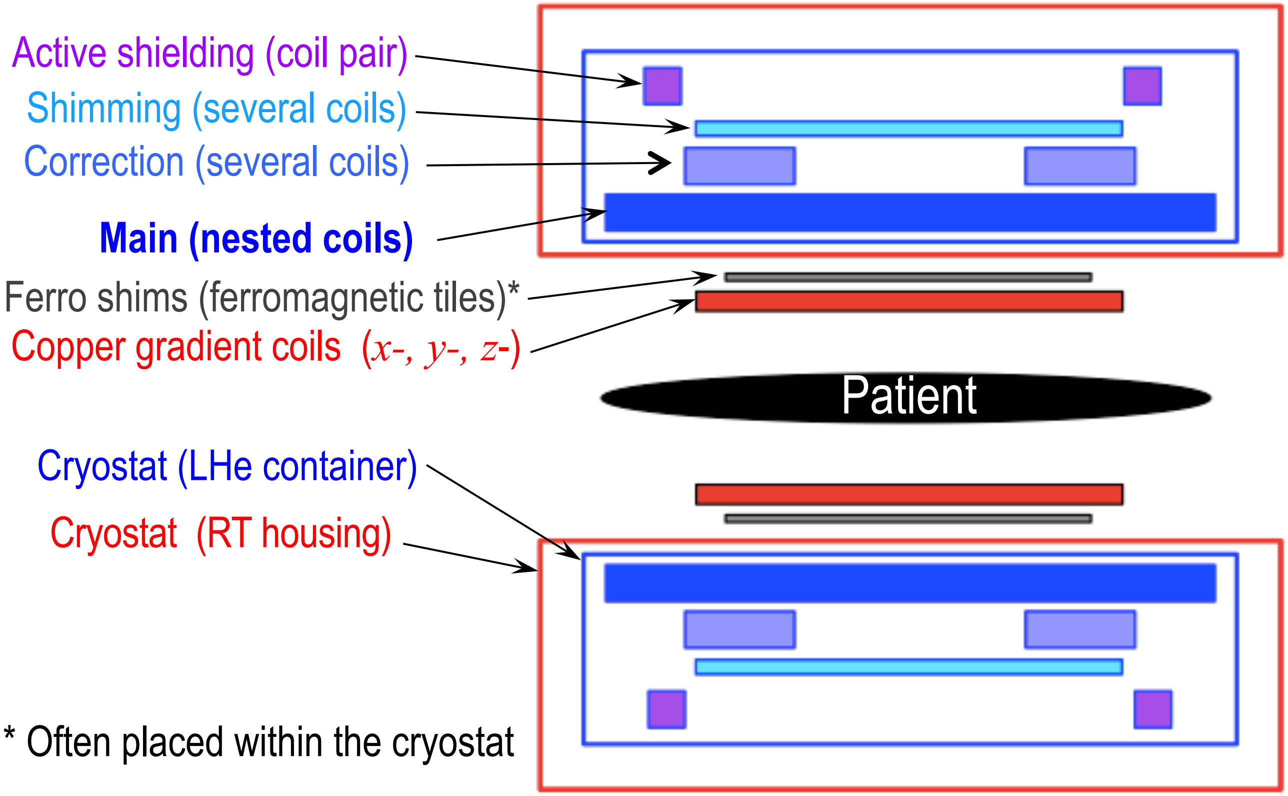
- To ~3 T, > 10 K: *promising*



Magnet Design Parameters: Part 2

2. Number of coils in the magnet;
   Each coil: winding dimensions and # of turns; matrix metal-SC ratio; conductor length

A Typical Superconducting Magnet—Here MRI



Active shielding (coil pair)

Shimming (several coils)

Correction (several coils)

Main (nested coils)

Ferro shims (ferromagnetic tiles)*

Copper gradient coils (x-, y-, z-)

Cryostat (LHe container)

Cryostat (RT housing)

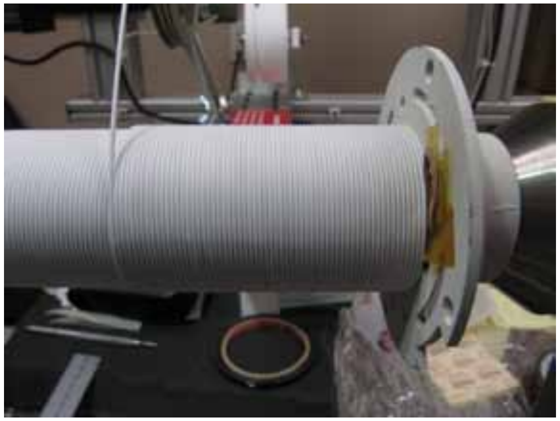
* Often placed within the cryostat

Magnet Design Parameters: Part 3a

3a. Winding options: ***layer*** vs. ***pancake***; epoxy-impregnated vs. none

Layer-Wound Coil

- Conductor, circular or rectangular sometimes tape, wound one turn a time on a plane (layer), and then to the next layer
- Dense winding pack, e.g., close-pack hexagonal formation



Negatives

- Can require a long continuous length conductor, e.g., up to ~15 km
- Entire wire may become useless

[Ulf Trociewitz, NHMFL, 2016]

Cowindings between turns

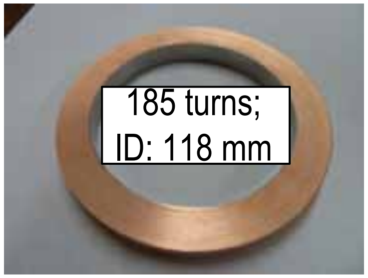
[Youngjae Kim, NHMFL, 2016]

Magnet Design Parameters: Part 3b

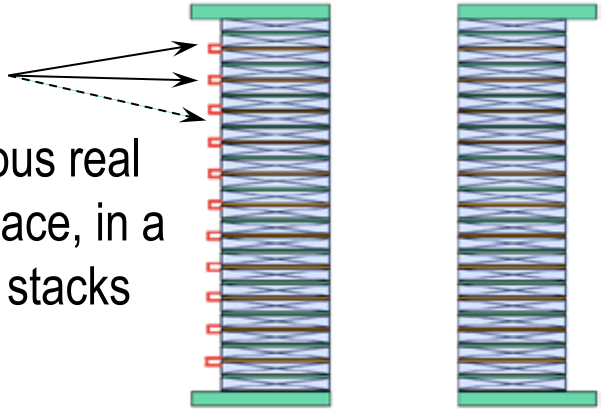
3b. Winding options: ***layer*** vs. ***pancake***; epoxy-impregnated vs. none

Pancake & Double-Pancake Coil

- DP magnet: a stack(s) of DP coils
- Modular approach—many "identical" coils
  - QC easier: one DP coil at a time
  - Mishaps often confined to one DP coil



Negatives



- Many DP-DP joints
- Joints take up precious real estate, i.e., radial space, in a magnet of many DP stacks

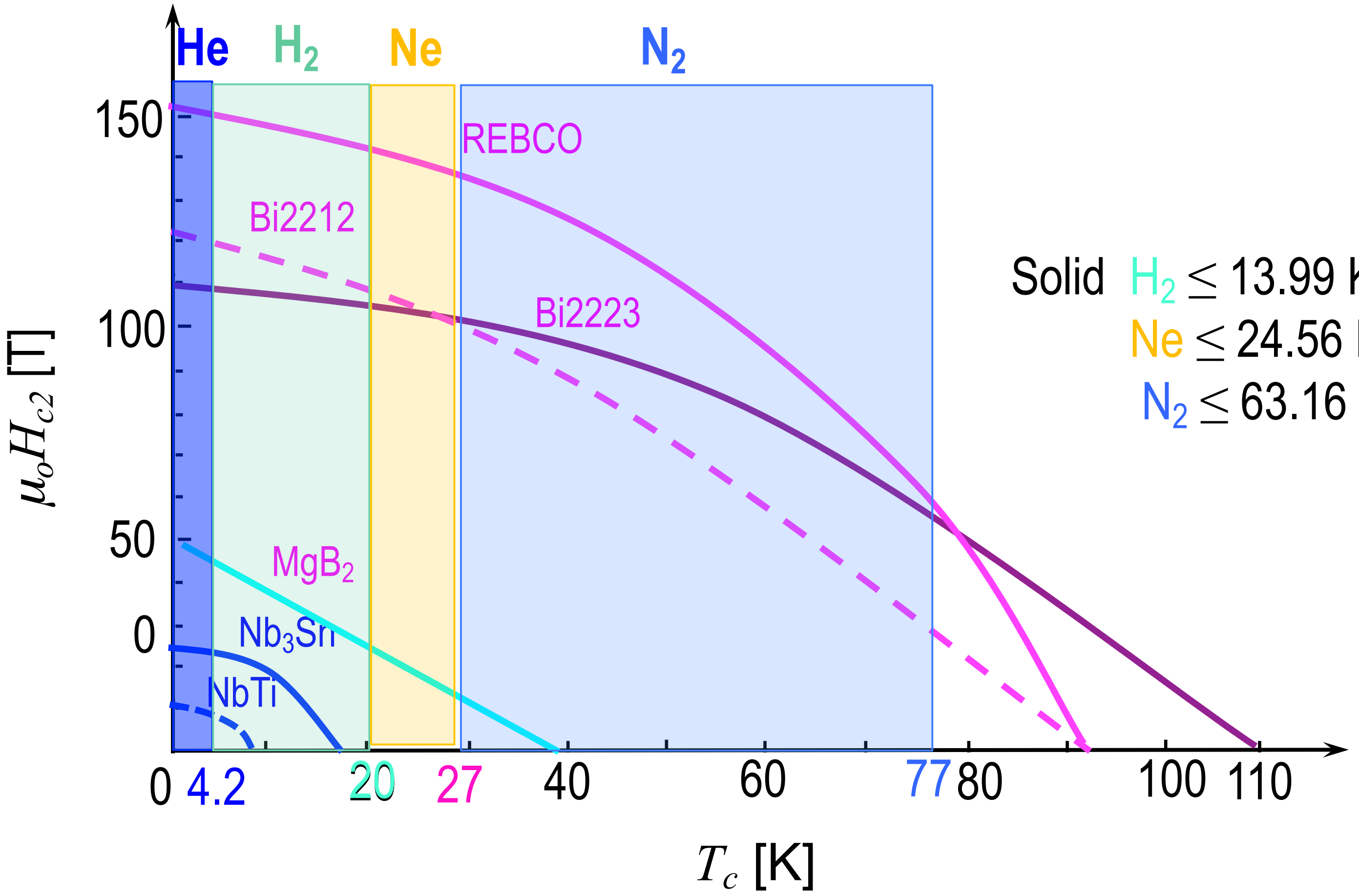
- Epoxy-impregnated vs. none:
  Discussed in ***Lecture 4: Stability & Protection***

Magnet Design Parameters: Parts 4—5a

4. Adiabatic vs. cryostable winding: Discussed in ***Lecture #4: Stability & Protection***

5a. Operating temperature ➔ cooling: ***cryogen*** & cryocooler

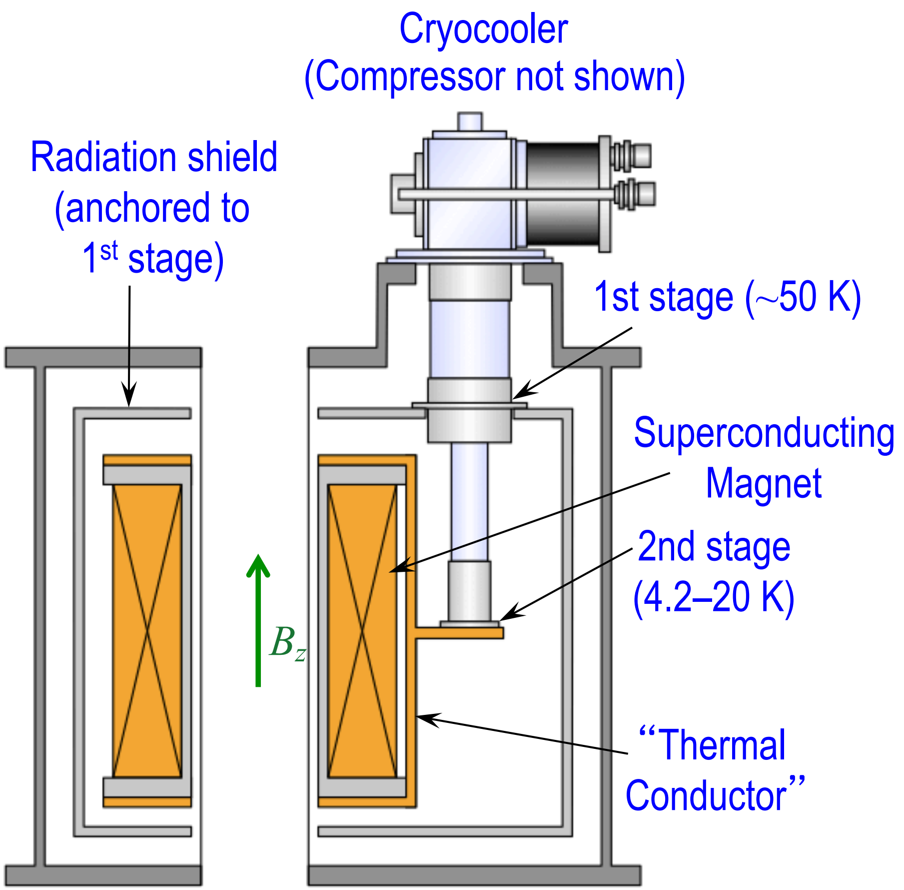
Cryogens for LTS & HTS magnets



Solid $H_2 \leq 13.99$ K
$Ne \leq 24.56$ K
$N_2 \leq 63.16$ K

Magnet Design Parameters: Part 5b

5b. Operating temperature ➔ cooling: cryogen & ***cryocooler***



Cryocooler
(Compressor not shown)

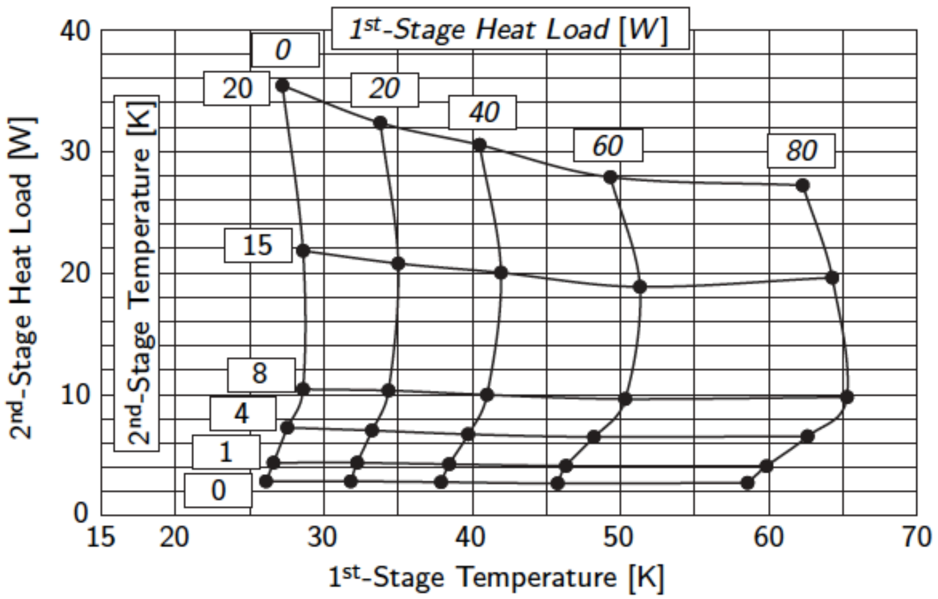
Radiation shield
(anchored to
1st stage)

1st stage (~50 K)

Superconducting
Magnet

2nd stage
(4.2–20 K)

"Thermal
Conductor"

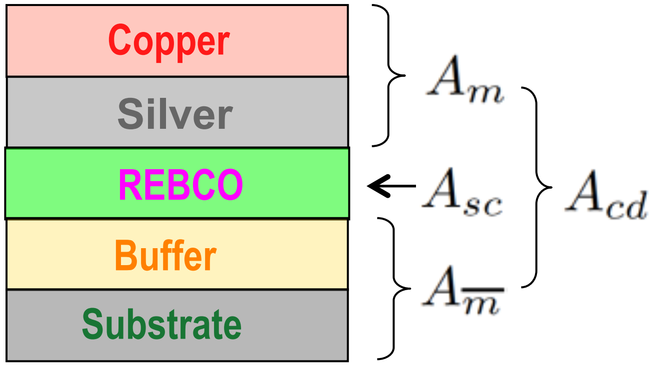


Magnet Design Parameters: Part 6

6. Operating current ➔ overall & matrix metal

Current Densities

Composite Conductor



Copper

Silver

REBCO

Buffer

Substrate

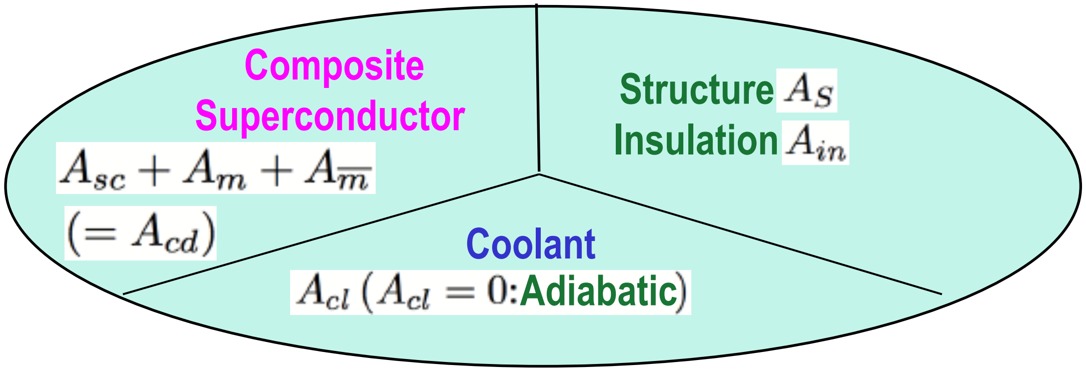
A_m

A_{sc}

$A_{\overline{m}}$

A_{cd}

Winding Pack



Composite Superconductor

$A_{sc} + A_m + A_{\overline{m}}$

$(= A_{cd})$

Structure A_S

Insulation A_{in}

Coolant

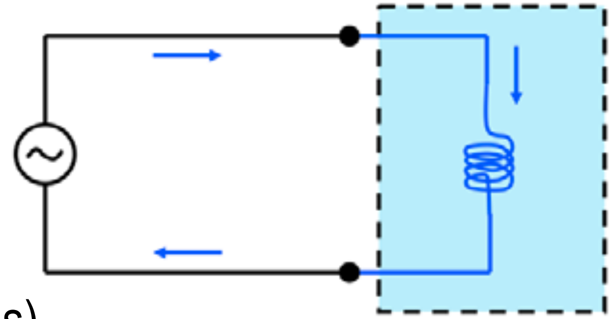
A_{cl} ($A_{cl} = 0$:**Adiabatic**)

Current Density	*Relevance*	*Definition*
Critical, J_c	Material development	$\frac{I_c}{A_{sc}}$
Engineering, $J_e (= J_{cd})$	Conductor development	$\frac{I_c}{A_{cd}} = \frac{I_c}{A_{sc} + A_m + A_{\overline{m}}}$
Matrix, J_m	Stability & Protection	$\frac{I_{op}}{A_m}$
Overall, $\lambda J (= J_{overall})$	Magnet efficiency	$\frac{I_{op}}{A_{wd}} = \frac{I_{op}}{A_{cd} + A_S + A_{in} + A_{cl}}$

- $J_c = \infty$ $(A_{sc} = 0)$ little impact on J_e or λJ

Magnet Design Parameters: Part 7a

7a. Operating mode: ***driven*** vs. ***persistent*** ➔ temporal stability
Driven: power supply; Persistent: joints, persistent-current switches, their locations

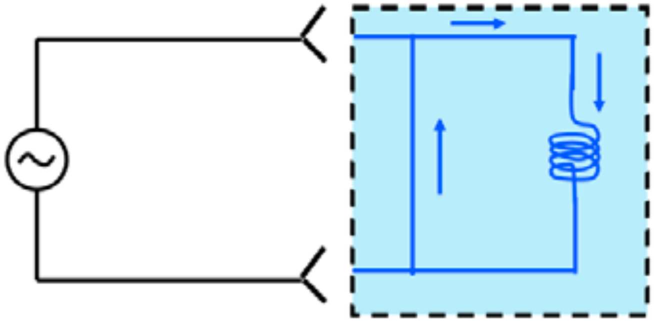


Driven-Mode

- MRI magnets generally operated in persistent-mode; a prominent exception: *ISEULT* (CEA)

ISEULT **Temporal Stabilities**

Long term (~hours): 0.05 ppm (± 0.006 gauss)
Short term (per scan time, ~30 min): 0.4 ppb (0.00005 gauss)



Persistent-Mode

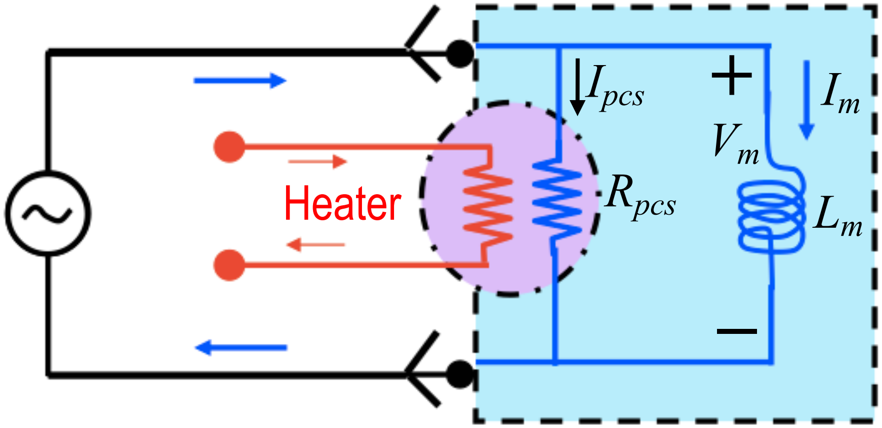
- Temporal stability of 0.5 ppb with persistent-mode, corresponding to a decay time constant of ~100,000 yrs
- Resistance of each joint typically < ~a few pico-ohms

Magnet Design Parameters: Part 7b

7b. Operating mode: driven vs. persistent ➔ temporal stability
Driven: power supply; Persistent: joints, ***persistent-current switches***, their locations

Requirements for Persistent-Current Switch (PCS)

- $I_{pcs} < \sim 0.1 \times I_m$: less than 10% of magnet current I_s through PCS
- $I_{pcs} = V_m / R_{pcs}$, where $V_m = L_m \times dI_m/dt$ ➔ Faster charging rate, greater R_{pcs}
- Minimum PCS heater power ➔ All PCS heater power becomes cryogenic load



Magnet Design Parameters: Parts 8—12

8. Stored magnetic energy: inductance matrix
   - Discussed in ***Lecture #4***: ***Stability & Protection***
9. Protection: active vs. passive

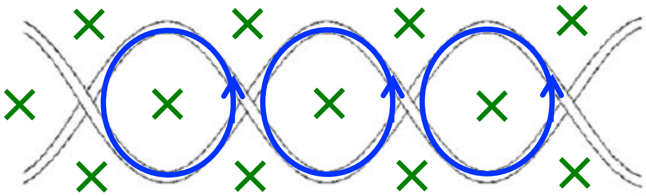
   Active Quench detection; discharge voltage; dump resistor; current switching; heater

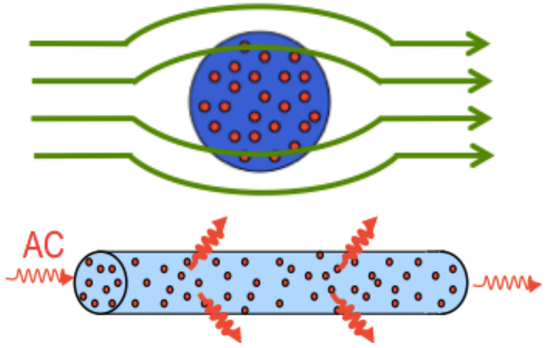
   Passive Normal-zone propagation; shunt resistors & locations
   - Discussed in ***Lecture #4***
10. Magnetic fields: center; peak; spatial field homogeneity ➔ Correction coils & shim coils
    Fringe fields: Shielded vs. non-shielded ➔ *Passive* vs. active
    - Selected topics in ***Lecture #3: Solenoidal, Dipole, Quadrupoles, Racetrack Coils***
11. Magnet support structure, within and outside the windings
    - Limited discussion in ***Lecture #5: Mechanical Issues***
12. Stresses (within windings) and strains (superconductors)
    —***Lecture #5: Mechanical Issues***

Magnet Design Parameters: Part 13

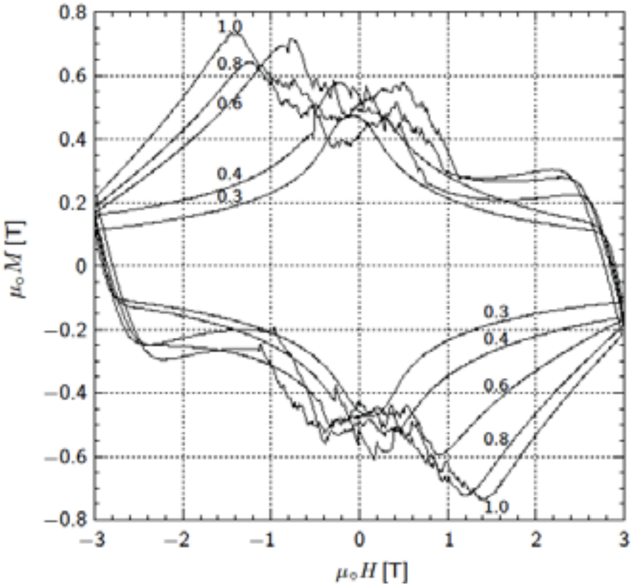
13. Time-varying field: AC losses in Type II Superconductors

- Hysteresis: manifestation of hysteretic magnetization
  - Smaller hysteresis area ➔ smaller loss, i.e., smaller filament size
- Coupling among filaments





  - Smaller loop size ➔ smaller loss, i.e., shorter twist pitch
- Eddy current in matrix metal and other metallic objects



Sources of AC Losses

- Time-varying magnetic field
- Time-varying current
- Time-varying field & current

AC losses one big obstacles for application of superconductivity to electrical devices

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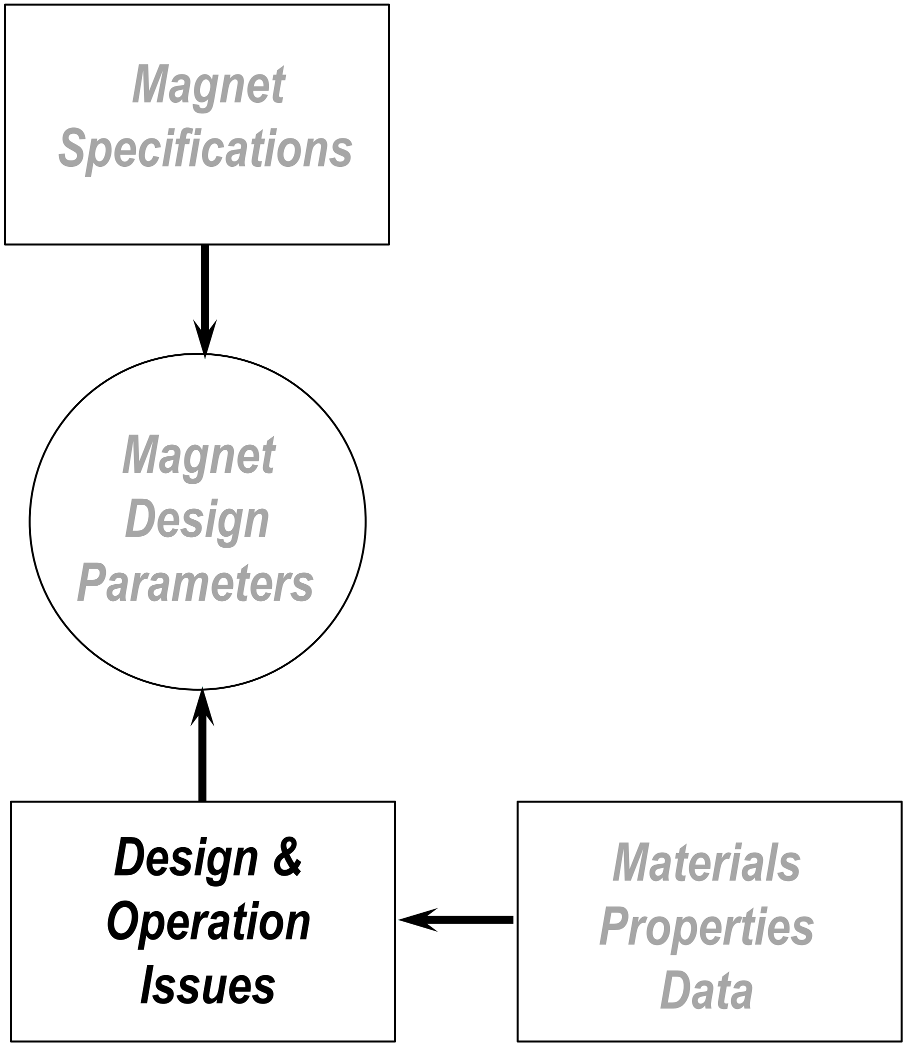

Magnet Specifications

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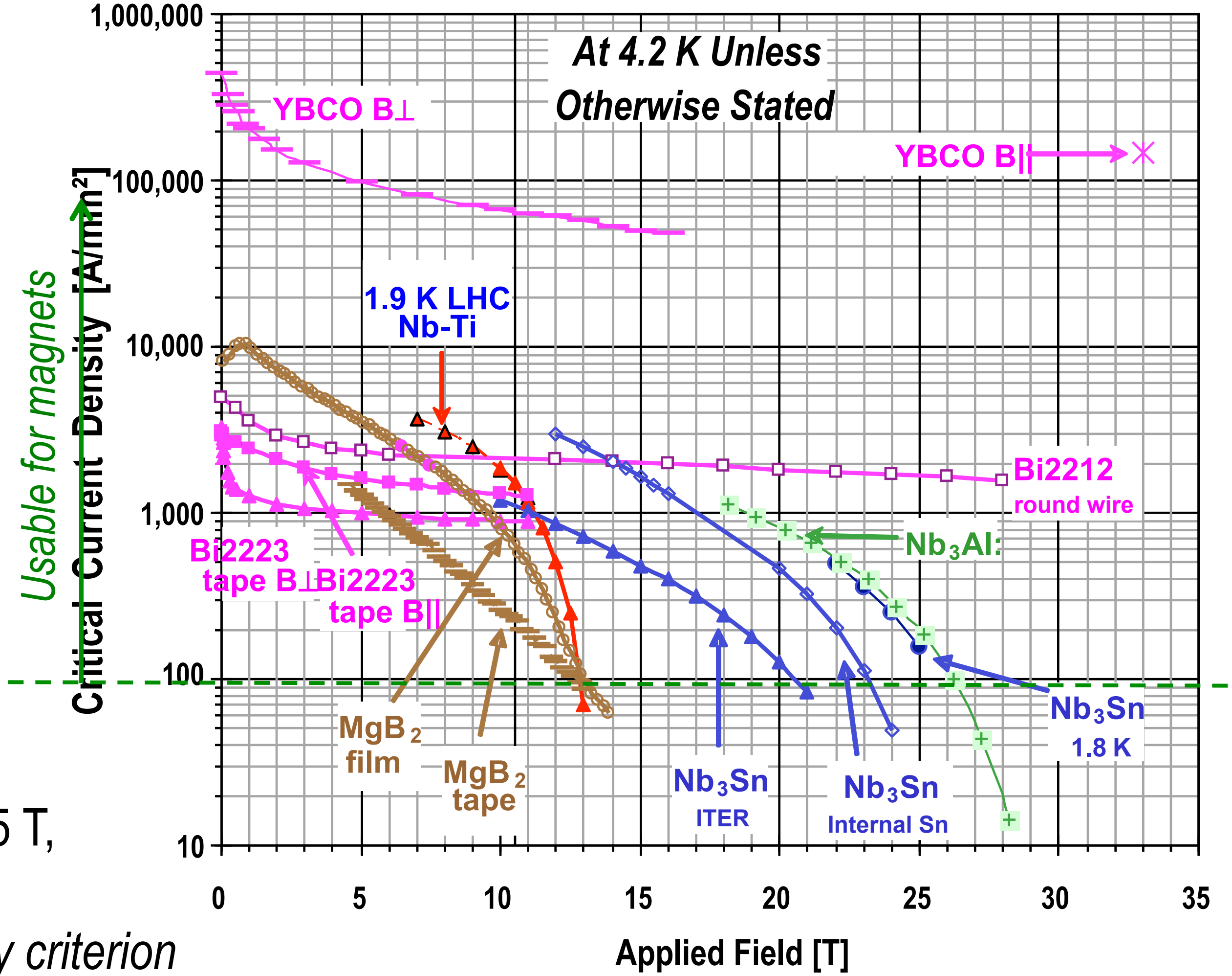
Design and Operation Issues: Part 1

1. Critical current densities of superconductors

- Nb_3Sn to ~20 T@ 4.2 K
  ~25 T@~2 K
- NbTi to ~10 T @4.2 K
  ~12 T @~2 K
- HTS, except MgB_2, ≥ 25 T, ***enabling*** *performance, not cost, primary criterion*
- HTS, except MgB_2, < 25 T, ***replacing,*** *cost, not performance, primary criterion*
- MgB_2 promising < 3 T @10-20 K



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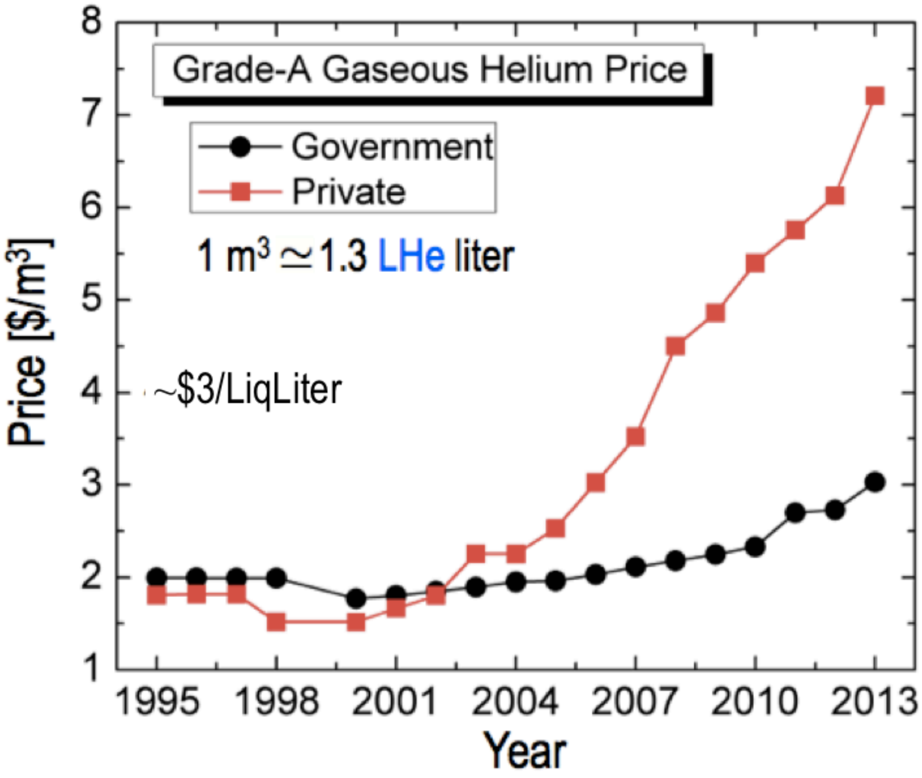
Design and Operation Issues: Parts 2 & 3

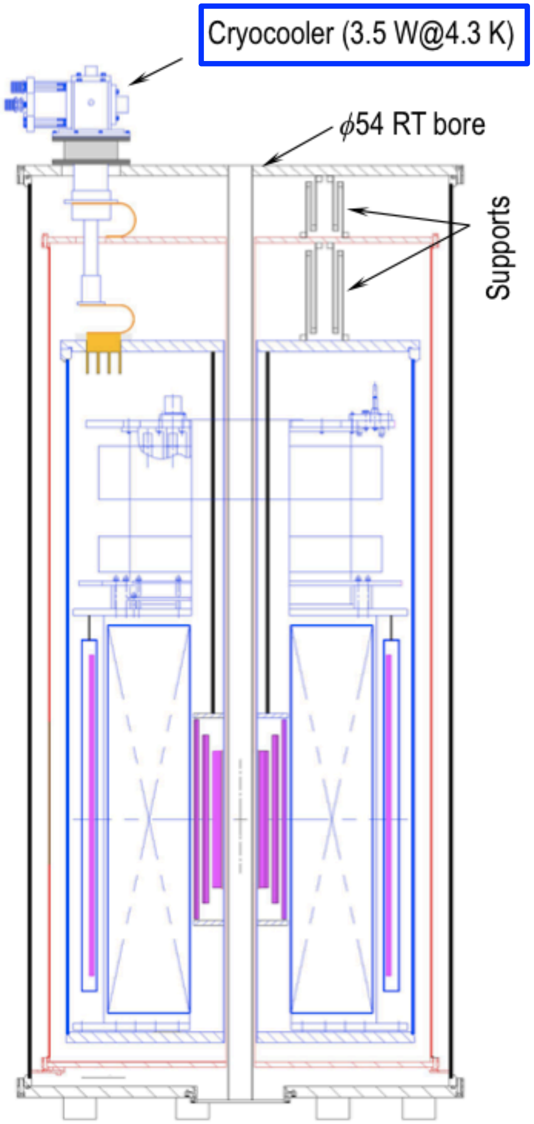
2. Mechanical integrity: axial, hoop, radial stresses
   strain tolerances of superconductors & other materials; "Gee," vibration; fault-mode forces
   Selected topics in ***Lecture #5: Mechanical Issues***

3. Stability: cryostable vs. adiabatic—***Lecture #4: Stability & Protection***

Design and Operation Issues: Part 4

4. Cryogenics: cryogen vs. cryocooler; ***LHe-free superconducting magnets***
   - Driving force on LHe-free magnets: world-wide helium scarcity
     - Easier solution: re-condense He vapor with a cryocooler
     - More challenging: No LHe bath





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Design and Operation Issue: Part 5

5. Protection: *passive* vs. *active*; quench detection; maximum winding temperature

   —***Lecture #4: Stability & Protection***

Joyeux Solstice d'été!