20T Target Solenoid Design & Optimization

J. Miller

Except for possibly one major issue, 20-T Target Solenoids are not only feasible but quite practical and for reasonable costs.

The one important R&D issue associated with feasibility is the radiation tolerance of the Resistive Magnet.

There are R&D issues for other subsystems that may affect overall costs and reliability (and therefore availability and maintenance costs).

Physics requirements

- Access (150-mm bore)
- Field profile (20 T over 800-mm length)
- Field quality (error < 5%)
- Service life (10 years)

System design: basic approach

- Review technology options
- Establish critical engineering constraints
- Perform benchmark design
  - Establish operating conditions
  - Choose design criteria
- Construct cost algorithms
- Optimize system design

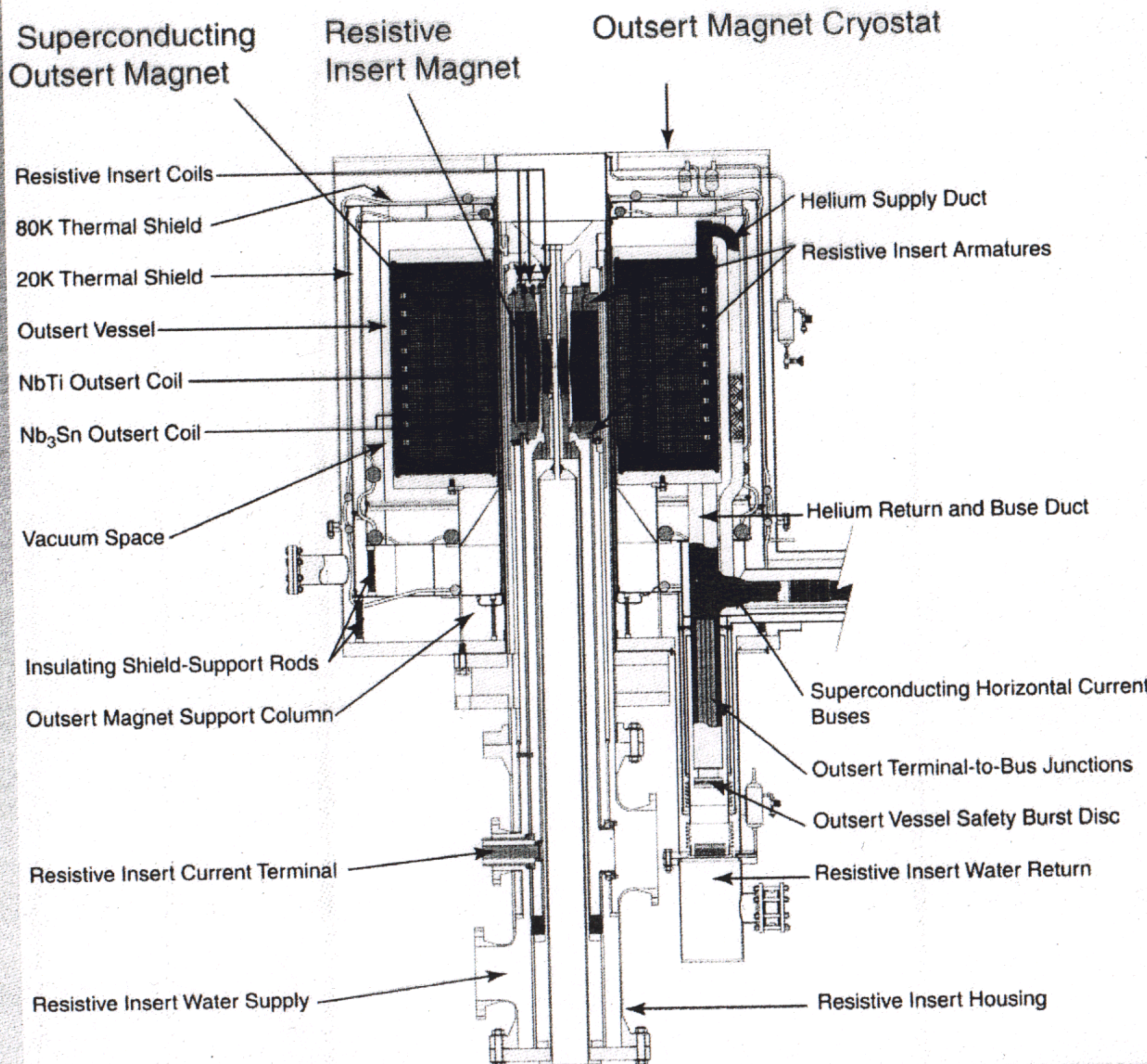
Technology options: resistive magnets

- Bitter magnets
  - Proven technology
  - Insulation mainly in compression
  - Limited life
- Hollow conductor
  - Simple construction
  - Long life
  - Limited current density
- Polyhelix
  - Complex stresses in insulation
  - "Newer" technology

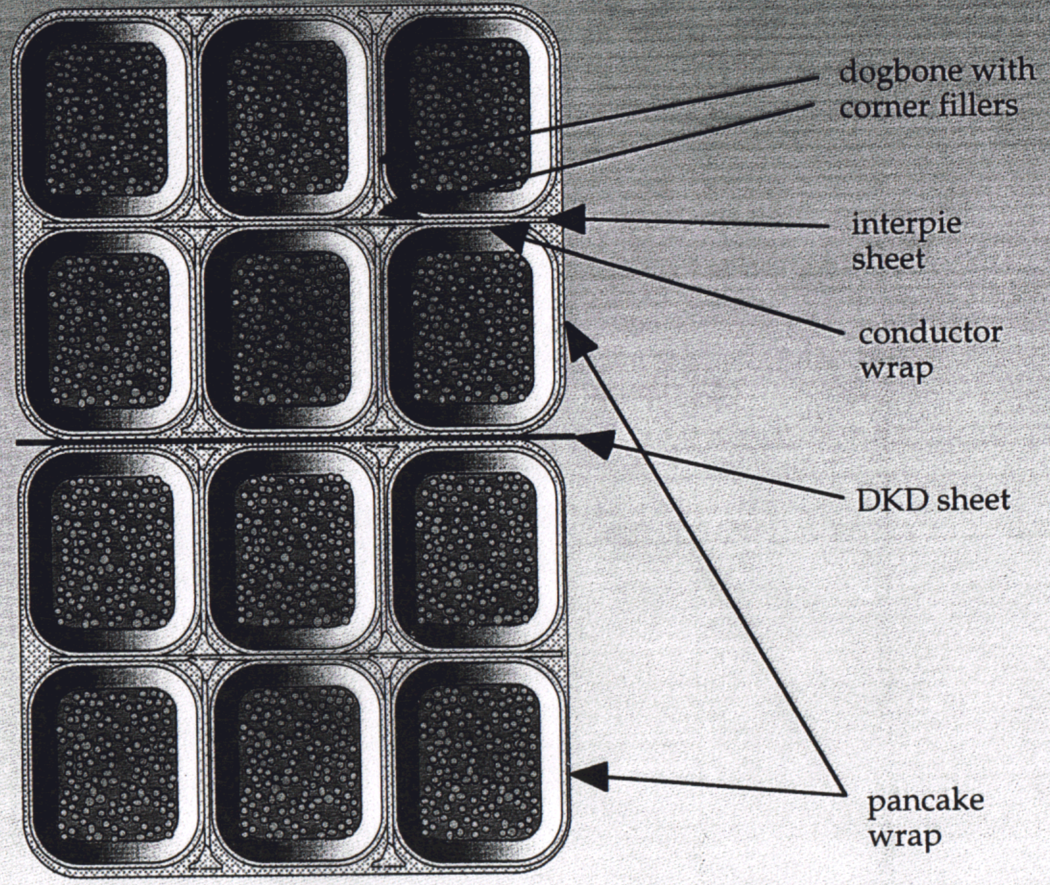
Technology options: superconducting magnets

- Bath-cooled
  - Simple
  - Passive
  - Essentially isothermal
  - Limited heat removal
- Force-cooled (CICC)
  - More complex
  - Active
  - Requires finite temperature margin
  - Capable of much higher heat removal (depends on T_C of superconductor)

45-T Hybrid Magnet

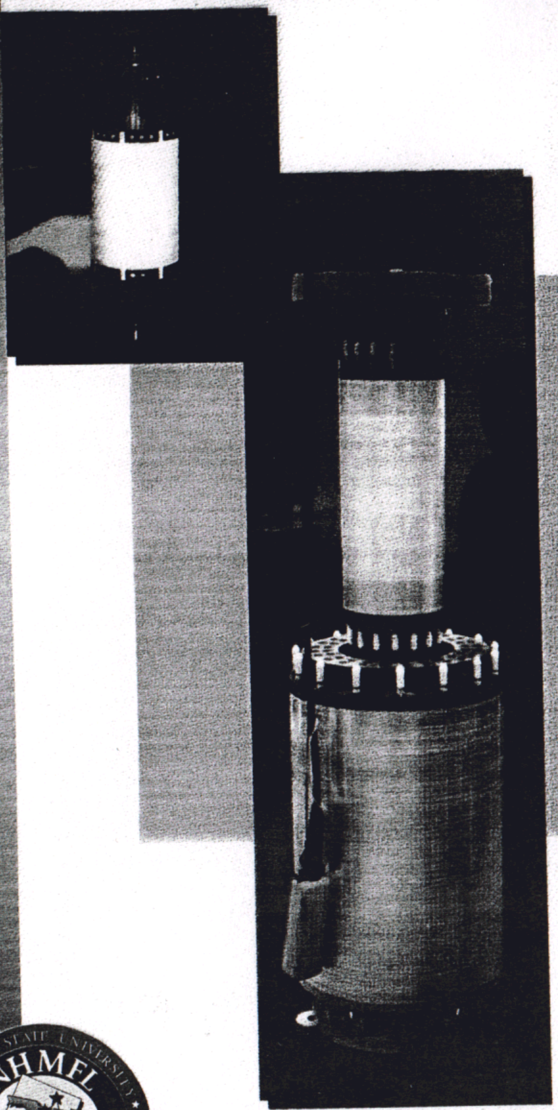


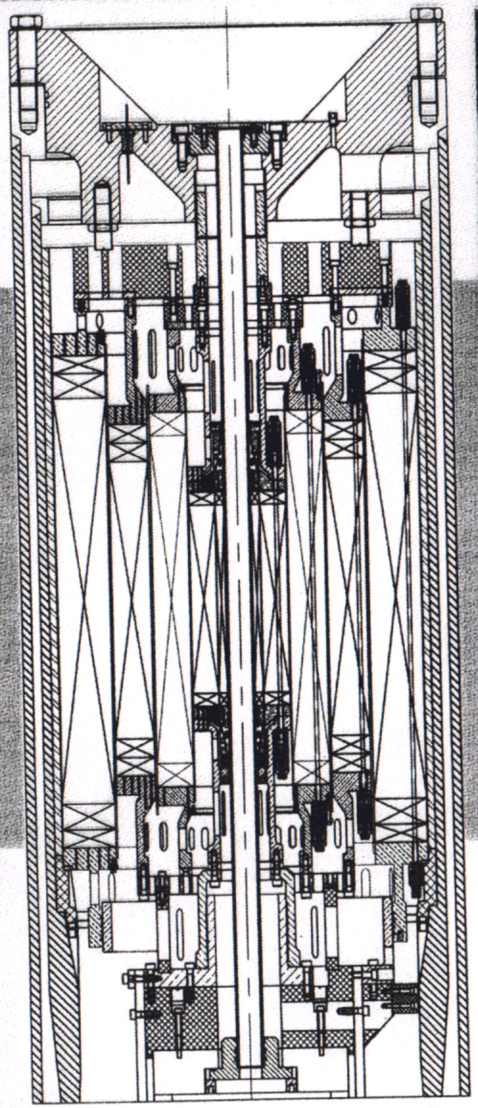
Pancake-wound CICC

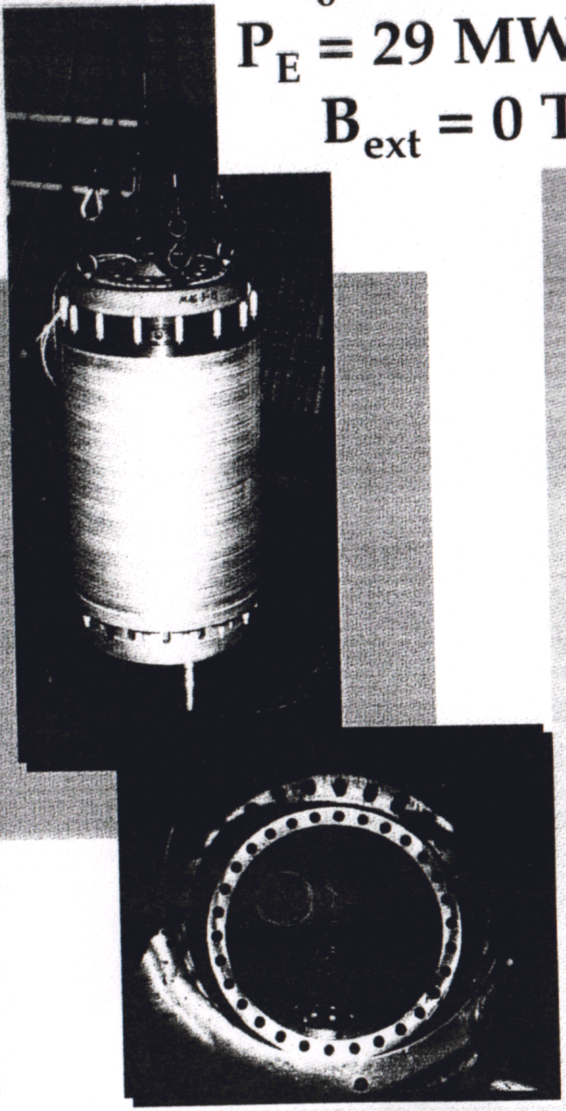


Resistive Insert

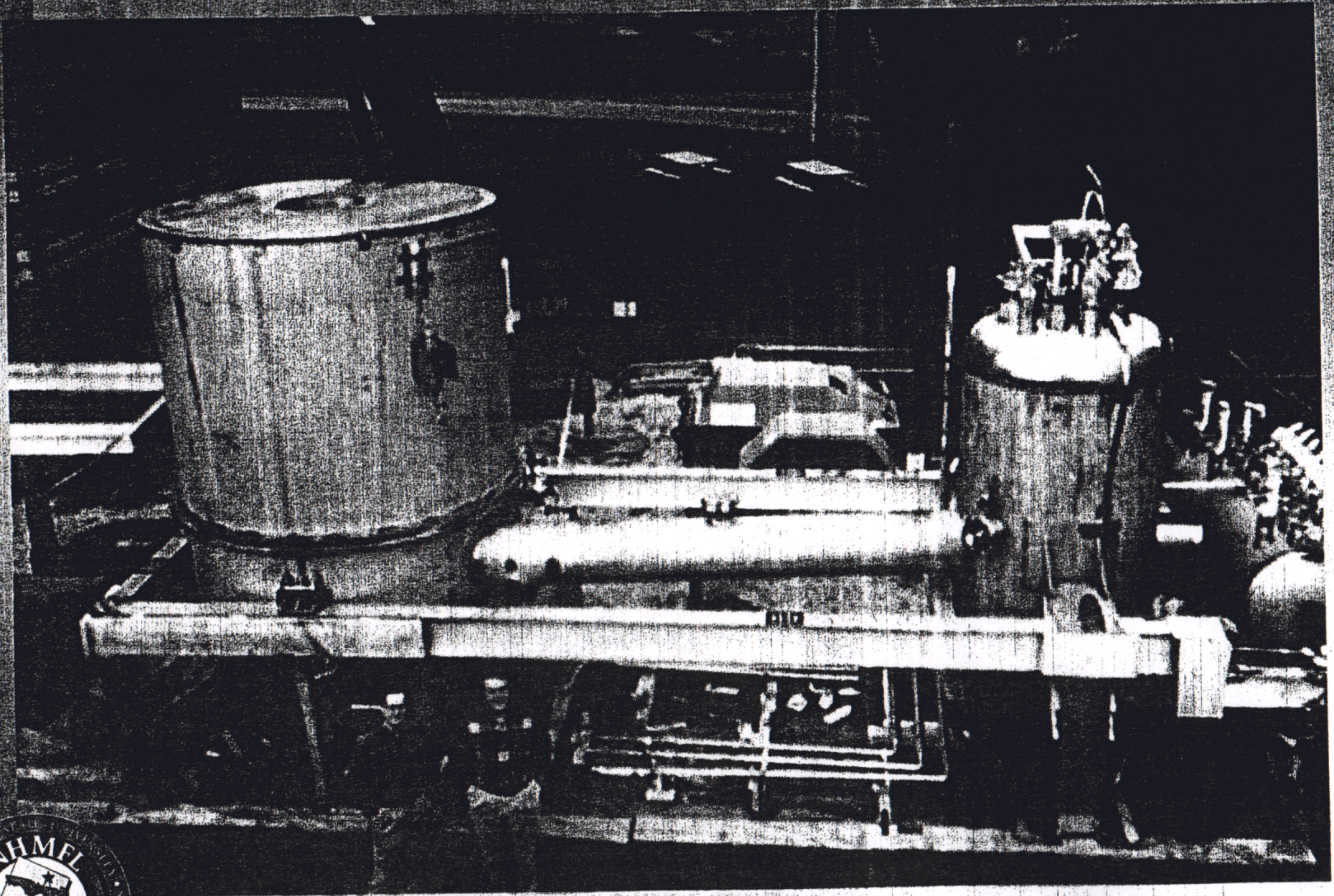
$B_0 = 32.5$ T
$P_E = 29$ MW
$B_{ext} = 0$ T







Outsert cryostat delivered to NHMFL, March 1995



Engineering constraints: resistive magnet

- Heating: < 5 W/mm^3
- Stresses: < 300 MPa
- Radiation damage: ? (no limit at present)

Engineering constraints: superconducting magnets

- Stresses/strains
  - Von Mises membrane in jacket < 800 MPa
  - Hoop strain < 0.3%
- Superconductor margins
  - $\Delta T_{cs} > 0.5$ K everywhere during heating
- Quench protection
  - $\tau_{discharge} = 5$ s
  - $t_{delay} = 1$ s
  - $T_{max} = 150$ K
- Radiation damage
  - ~10^8 Gy

Field profile in the mai
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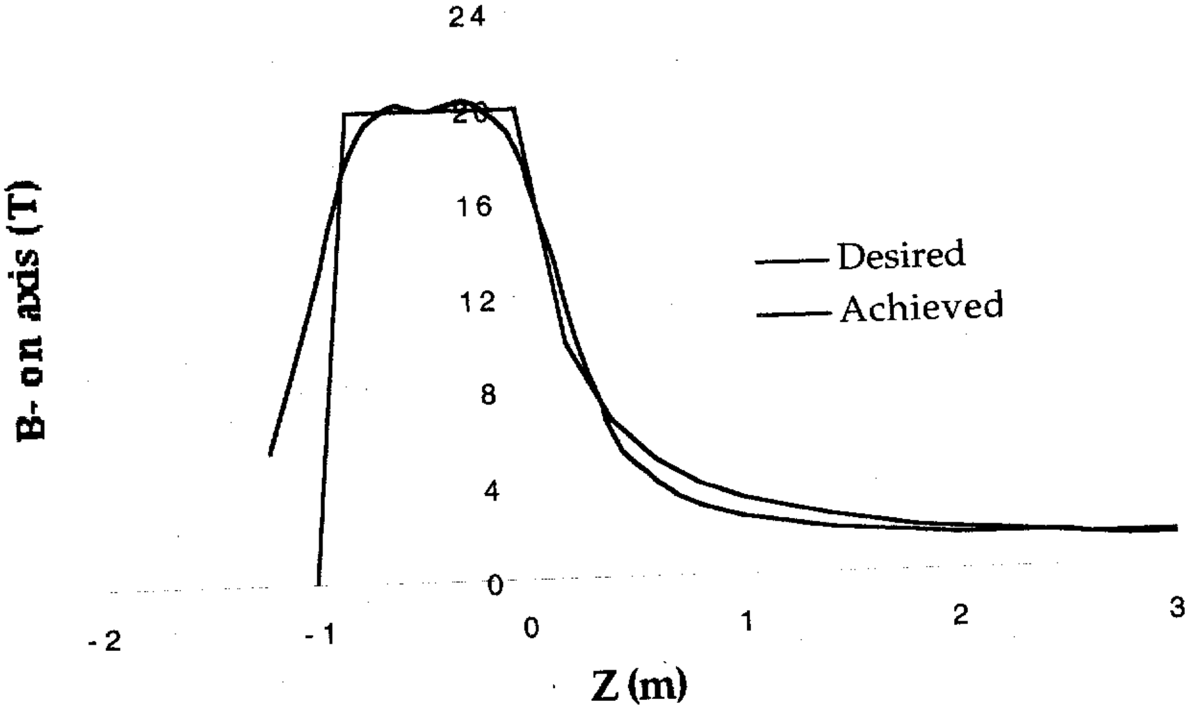


Winding-Pack Composition: Superconducting Magnet

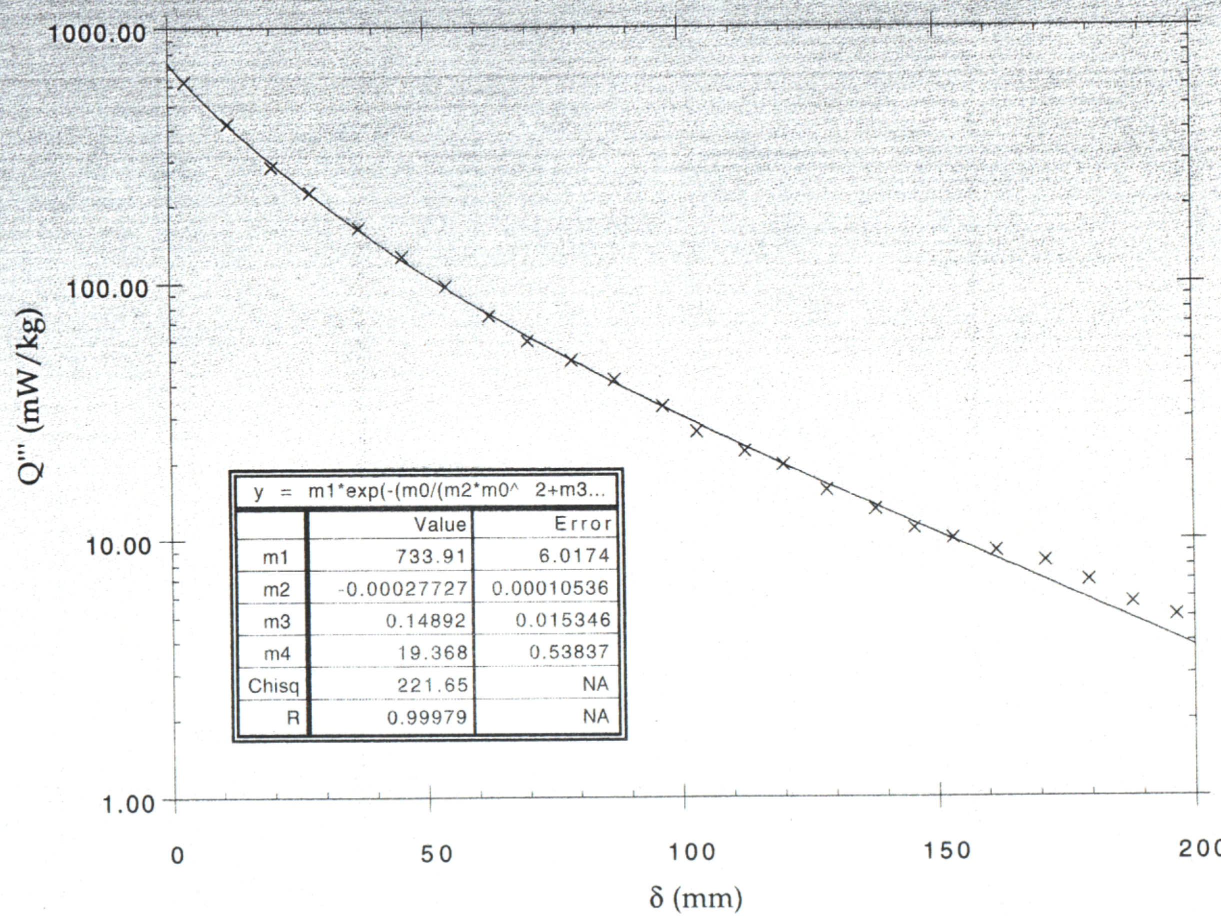
Material	Volume fraction	Density (kg/m^3)
Stainless steel	33%	7980
Copper	21%	8940
Non-Copper*	10%	8230
Helium (supercritical)	20%	140
GFRP insulation	16%	1940

(Note that the above give a mean winding-pack density of 5680 kg/m^3.)

* The "core" of a MF-Nb_3Sn composite wire, a combination of Nb_3Sn, Cu-Sn bronze, barrier, and voids in the following approximate proportions: 23%, 69%, 6.5%, and 1.5%.

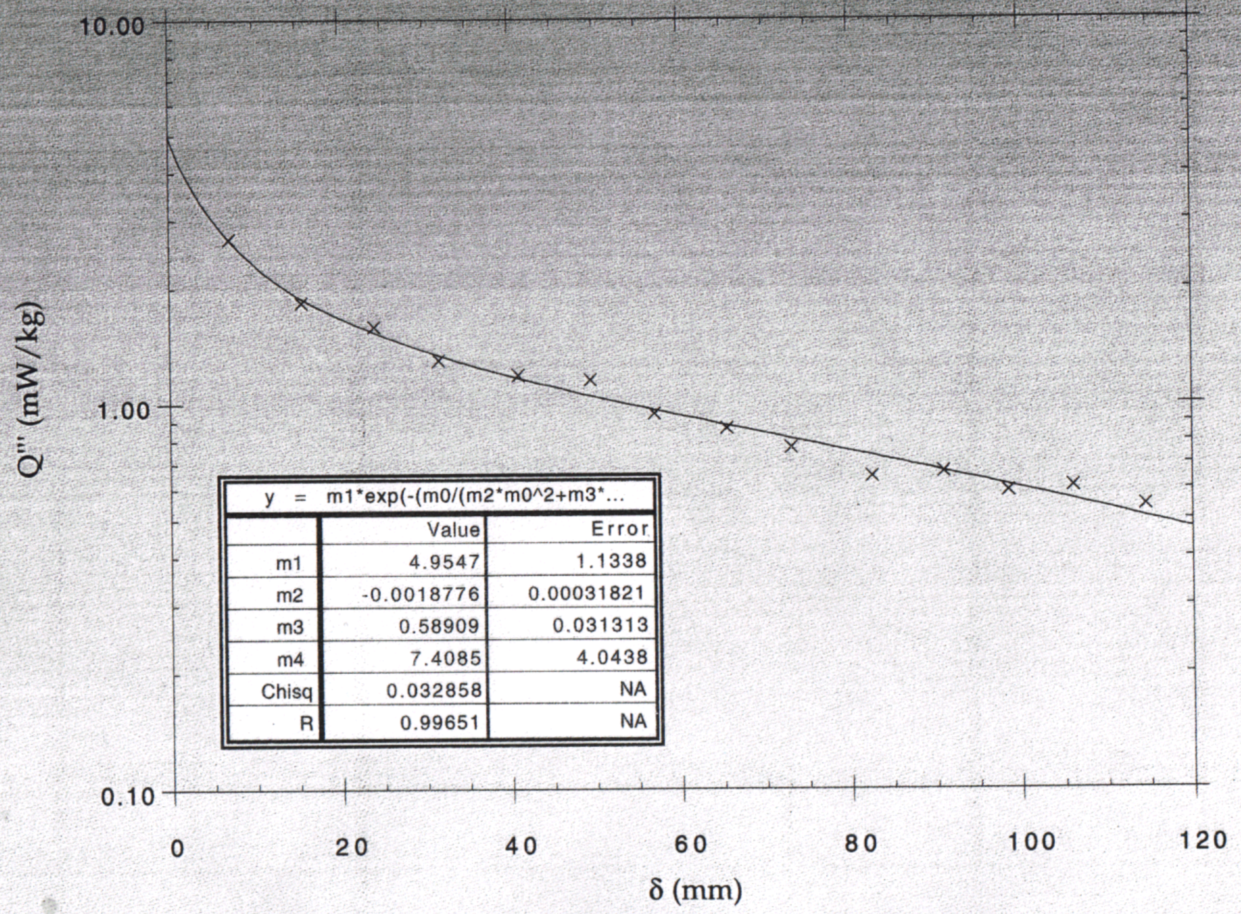
Operating conditions

Heating in the resistive coils



Operating conditions

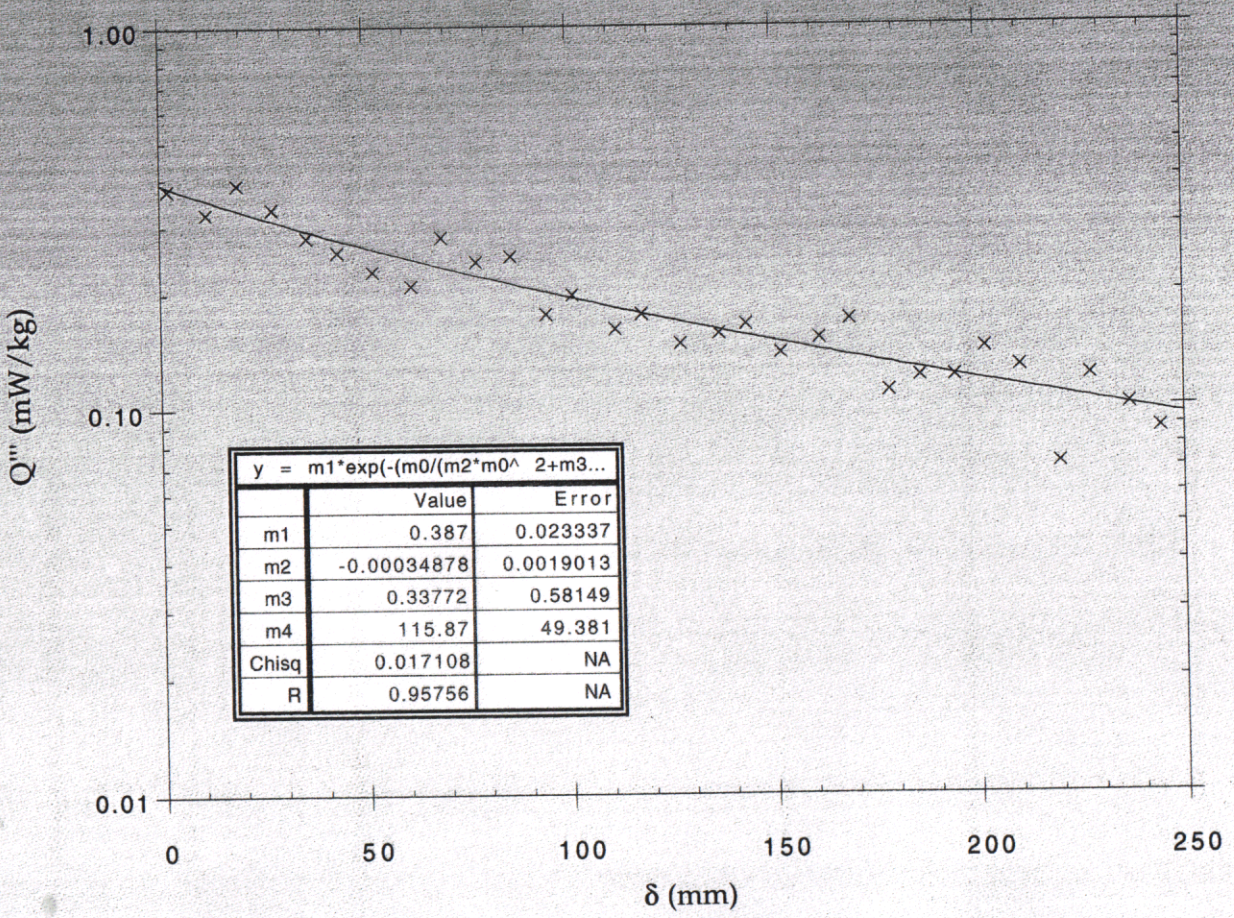
Heating in the tungsten shield



	Value	Error
m1	4.9547	1.1338
m2	-0.0018776	0.00031821
m3	0.58909	0.031313
m4	7.4085	4.0438
Chisq	0.032858	NA
R	0.99651	NA

Operating conditions

Heating in the superconducting magnet



Design choices: general

- Resistive magnet nearest the beam for more efficient field production
- Tungsten shield between resistive and superconducting magnets
- Common construction for resistive-magnet housing, shield vessel, and superconducting-magnet cryostat
- Assembly gaps fixed at minimum practical values

Design choices: superconducting magnet

- Single coil
- Force-cooled by supercritical He at 4.5 K
- CICC with 316LN jacket and MF-Cu/Nb_3Sn cable strands
- Pancake-wound construction with He inlets at the cross-over turns
- Radiation-tolerant insulations applied after heat-treatment

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System lifetime, availability, maintenance, and operation

- Overall system lifetime: 20 y
- Full system availability: ≈ 70% (6000 h/y)
- Resistive magnet lifetime: 4000 h, but replaced every 6 months with housing
- Resistive magnet/housing replacements: 39
- Extra ref.-sys. operation: 800 h/y
- Total system operation: 120,000 h
- Total ref.-sys. operation: 136,000 h

Resistive-magnet costs

- Coil-pack materials and supplies
  - Fixed: 300 k$
  - Variable: $0.075 \cdot L^{0.7}[(B_{max}+B_{ext})^2(D_o+D_i)^2]^{0.21}$ k$ (L and D in mm and B in T)
- Coil-pack assembly: $1.51 \cdot L^{0.7}$ k$ (L in mm)
- Magnet housing: 35 $/kg
- Power supply: 200 $/kW
- Cooling system: 200 $/kW
- Buswork: 24 $/kA•m
- Engineering & design: 20% of other contributions

Shield system costs

- Shielding: 80 $/kg
- Shield housing (one wall shared with cryostat): 35 $/kg
- Shield cooling system: 200 $/kW
- Engineering and design: 20% of other contributions

Superconducting magnet system costs

- Magnet
- Cryogenic subsystem
- Power/protection subsystem
- Engineering and design: 20% of other contributions

Superconducting magnet system costs: magnet

- Composite wire: (500 - f_{Cu}·250) $/kg
- Solid copper wire: 10 $/kg
- Cabling: 12 $/kg/stage
- Jacketing: 80 k$ (fixed) + 36 $/m + 26 $/kg (steel)
- Winding:
  - 50 k$ (fixed)
  - 50 k$/m3
  - 50 $/kg
  - 90 $/m
  - 100 $/kA·terminal
- Vessel/external structure: 20 $/kg

Superconducting magnet system costs: cryogenic subsystem

- Cryostat vessels: 40 k$/m^3 of cryostat envelope
- Cryostat shields: 1 k$/m^2 of cryostat envelope
- Refrigeration system: $23 \cdot Q^{0.7}$ k$ (Q is the design refrigeration load in W at 4.5 K)
- Design 4.5-K refrigeration load, Q:
  - Nuclear heating, Q_N
  - Pump work, Q_P ($0.03 \cdot Q_N$)
  - Current leads, Q_L (9 W/kA·pair)
  - Thermal radiation, Q_T (0.4 W/m^2)
  - Conduction, Q_C (0.1 W/t)
  - Margin, Q_M (50% of other contributions)

Superconducting magnet system costs: power/protection subsystem

- Power supply: 12 k$/kA
- Current interrupters: 7 k$/kA
- Dump resistor: 300 $/MJ
- Superconducting buswork: 250 $/kA·m
- Room-temperature buswork: 24 $/kA·m
- Instrumentation & controls: 100 k$

Operating costs: resistive-magnet system

- Total power: $P_{E,R}$
  - $= F \cdot [(\text{dc power}) + (\text{cooling power})]$
  - $\approx 1.25 \times (\text{dc power})$
- Electricity charge: 0.05 $/kW·h
- Replacement of coil-pack and housing at 3000-h intervals

Operating costs: shield system

- $P_{E,S} \approx 0.25 \cdot Q_N$ (where Q_N is total nuclear heat load in the shield)
- Electricity charge: 0.05 $/kW·h

Operating costs: cryogenic system

- Utilities:
  - Electricity: $P_{E,C} = 3.3 \cdot Q^{0.8}$ kW
  - GHe consumption:
    - Circulation: $0.15 \cdot Q$ g/s
    - Loss: (circulation)/300
  - LN_2 consumption
    - Refrigerator: $0.05 \cdot Q$ g/s
    - Cryostat: $0.005 \cdot (Q_T + Q_C)$ g/s
- Utility rates:
  - Electricity: 0.05 \$/kW-h
  - LN_2: 0.07 \$/liquid-L
  - GHe: 1.8 \$/equivalent-liquid-L

Costs for the "benchmark" system

Subsystem	Capital cost (k$)	10-year operating cost (k$)	Combined costs (k$)
Resistive/shield	6,166	25,777	31,943
Superconducting	8,759	11,025	19,785
Totals	14,925	36,802	**51,727**

Costs for the "optimized" system

Subsystem	Capital cost (k$)	10-year operating cost (k$)	Combined costs (k$)
Resistive/shield	6,633	29,471	36,104
Superconducting	6,605	6,622	13,227
Totals	13,238	36,094	**49,331**

Comparison of "Benchmark" and "Optimized" designs

Parameter	"Benchmark"	"Optimized"
Field contribution (T):		
Resistive	10.6	12.0
Superconducting	9.7	8.3
R_i, ΔR (mm):		
Resistive	100, 200	100, 250
Superconducting	500, 250	500, 211
Q_N (W):	1200	645

Conclusions

- Design tools have been assembled to quickly iterate conceptual designs for the Target Solenoid System
- Design variations appear to have significant cost differences
- 10-year operating costs appear to be the larger fraction of the total cost
- Support systems also comprise large fractions of the total capital cost