# Stellarator magnets

L. Bromberg

J.H. Schultz

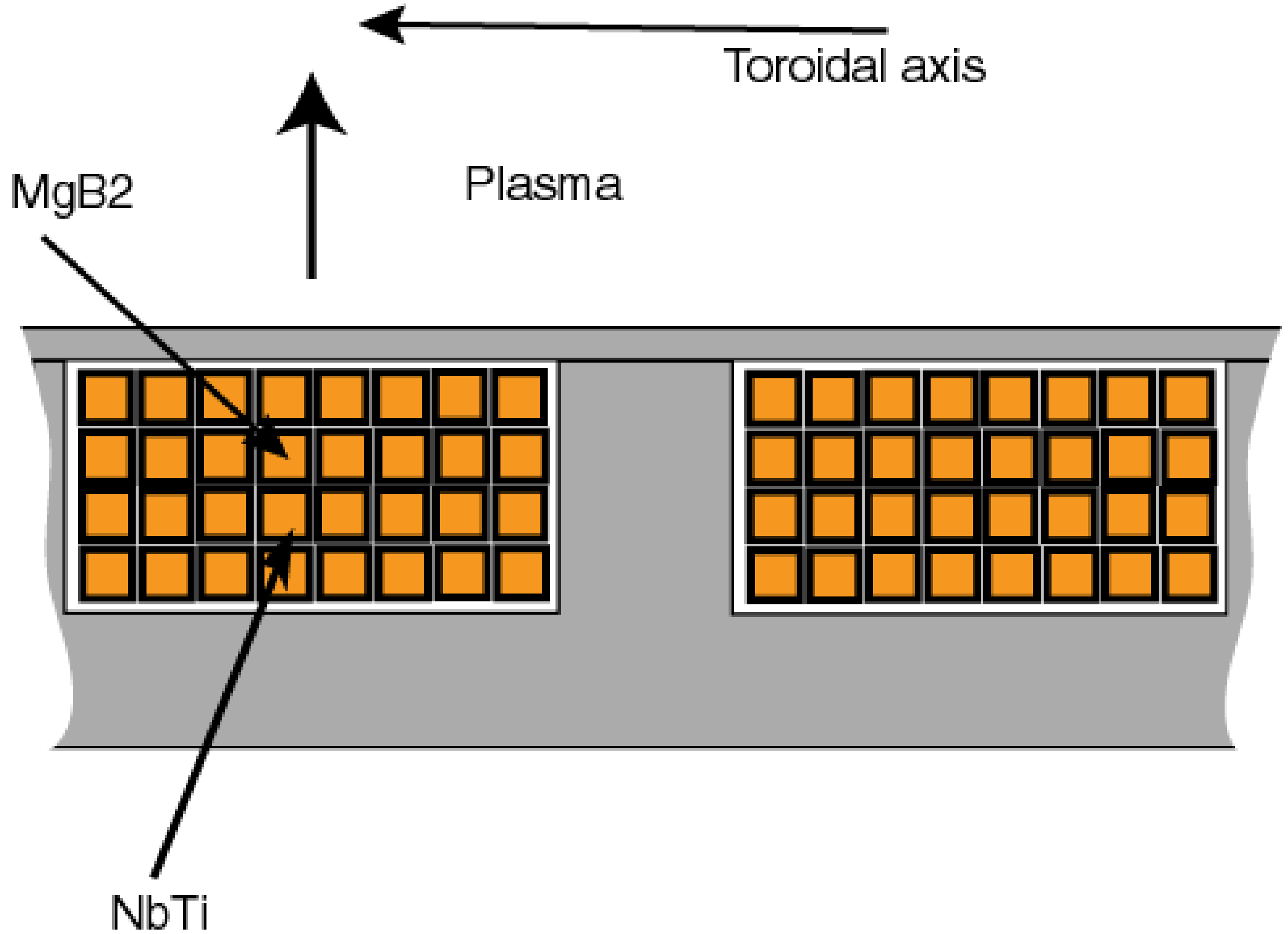
MIT Plasma Science and Fusion Center

ARIES meeting March 8-9, 2004

# Organization of talk

- Magnet design with dual temperature superconductor
  - $MgB_2$ and NbTi
- Costing algorithm
- Future work

# Medium Temperature Superconductor



# Preliminary design $MgB_2$

| | | | | |
|---|---|---|---|---|
| High field region | | | | |
| Outer radius of inner leg | m | 6.2 | | |
| Field | T | 12 | | |
| Thickness | | 0.17 | | |
| Composition | | | | |
| Structure (steel) | | 45% | | |
| Insulation | | 5% | | |
| Conductor pack | | 50% | | |
| Strands | | | 64% | |
| SC (Mg B2) | | | | 22% |
| Copper | | | | 78% |
| Helium | | | 17% | |
| Sheath (steel) | | | 19% | |
| | | | | |
| Low field region | | | | |
| Field | T | 6 | | |
| Thickness | m | 0.14 | | |
| Composition | | | | |
| Structure (steel) | | 45% | | |
| Insulation | | 5% | | |
| Conductor pack | | 50% | | |
| Strands | | | 70% | |
| SC (NbTI) | | | | 15% |
| Copper | | | | 75% |
| Helium | | | 24% | |
| Sheath (steel) | | | 6% | |
| | | | | |
| Structure (steel) | | | | |
| Thickness | m | 0.18 | | |

Needed for determination of radiation effects on magnet due to B in the SC

# Algorithm for low Tc coil

| Magnetic field | T | 6 | 12 | 14 | 16 | 18 |
|---|---|---|---|---|---|---|
| SC current density | A/m^2 | 1.50E+09 | 1.00E+09 | 2.00E+09 | 1.30E+09 | 8.00E+08 |
| | | | | | | |
| J2 tau | (A/m^2)s | 5.00E+16 | 5.00E+16 | 5.00E+16 | 5.00E+16 | 5.00E+16 |
| tau | s | 2.00E+00 | 2.00E+00 | 2.00E+00 | 2.00E+00 | 2.00E+00 |
| Current density in Copper | A/m^2 | 2.24E+08 | 2.24E+08 | 2.24E+08 | 2.24E+08 | 2.24E+08 |
| | | | | | | |
| Helium fraction | | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| | | | | | | |
| Sheathing thickness | | | | | | |
| B^2/2mu0 | Pa | 1.43E+07 | 5.73E+07 | 7.80E+07 | 1.02E+08 | 1.29E+08 |
| Stress in sheath | Pa | 8.00E+08 | 6.00E+08 | 8.00E+08 | 8.00E+08 | 8.00E+08 |
| Fractional thickness of sheath | | 1.79E-02 | 9.55E-02 | 9.75E-02 | 1.27E-01 | 1.61E-01 |
| | | | | | | |
| Sheath fraction in conductor | | 3.55E-02 | 1.82E-01 | 1.85E-01 | 2.38E-01 | 2.96E-01 |
| | | | | | | |
| Current density | A/m^2 | | | | | |
| Current density in strands | Conductor | 1.95E+08 | 1.83E+08 | 2.01E+08 | 1.91E+08 | 1.75E+08 |
| Strands + Helium | Conductor + helium | 1.46E+08 | 1.37E+08 | 1.51E+08 | 1.43E+08 | 1.31E+08 |
| Strands+helium+sheath | Conductor + Helium + | 1.41E+08 | 1.12E+08 | 1.23E+08 | 1.09E+08 | 9.22E+07 |

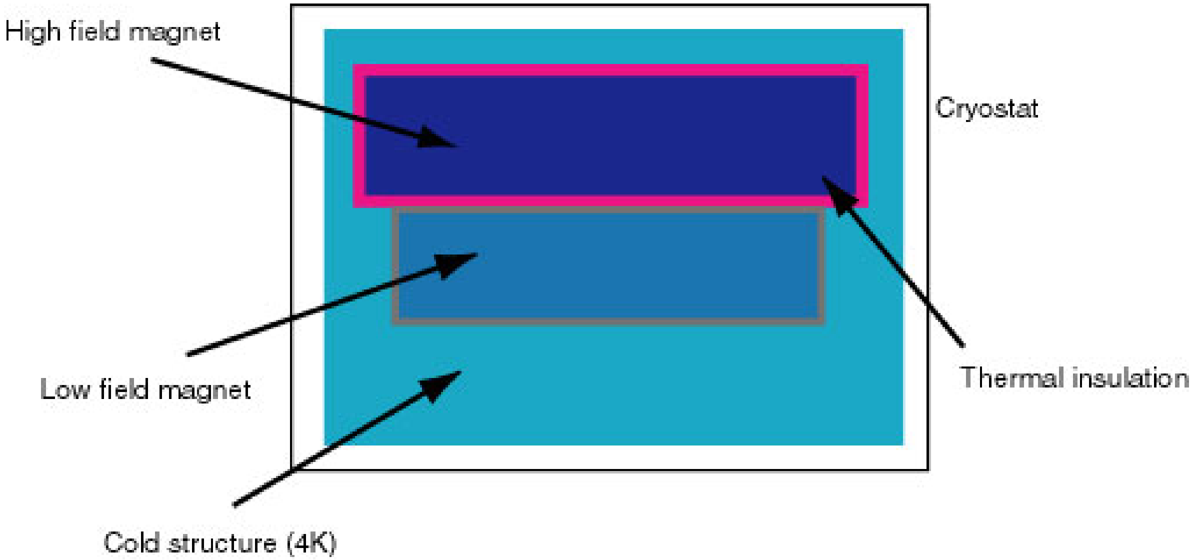
# Manufacturing

- Inserted from the plasma side into large structures.
- If wound. substantial amount of strain capability required for assembly
  - $Nb_2Sn$ requires low strain
  - $MgB_2$ has similar low strain capability
  - (both require react and wind)
- Stuck with either NbTi (at low temperature at high field) or high temperature superconductor.

# Multiple temperature operation?

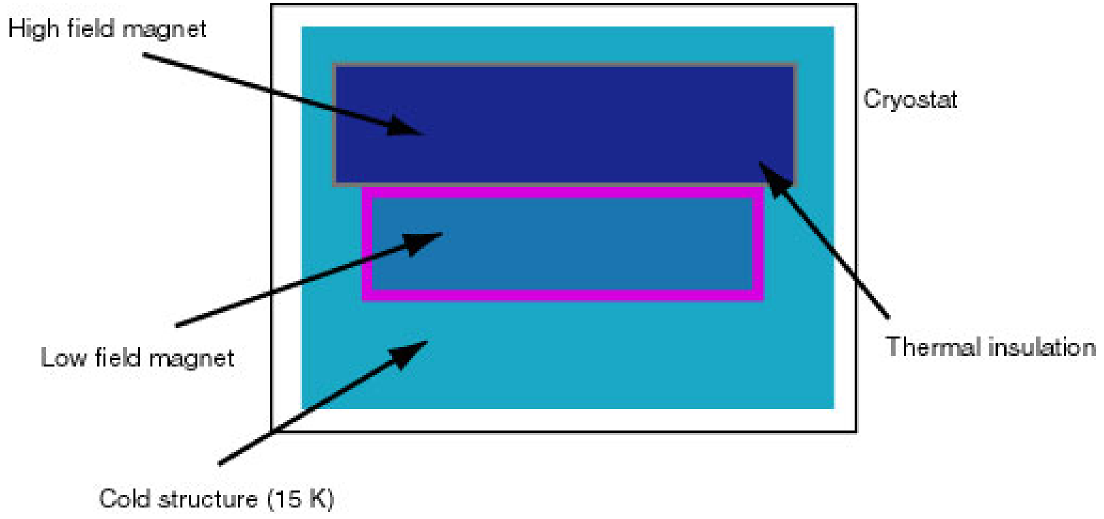
- By using either MgB2 or BSSCO, it is possible to grade the magnet for cost reduction
  - Use NbTi at 4 K for the low temperature region
  - The low field region is further removed from the plasma as is better shielded.

# Method for performing dual temperature - Option 1




- Radiation captured at the higher temperature
- Need to transfer loads through low temperature region (one insulation region required)

# Method for performing dual temperature - Option 2




- Substantially decreased thermal loads
- Need to transfer outward loads from high temperature region through low temperature region before getting to structure (if bucking): two insulation regions.

# Dual temperature

- Impact mainly on cost.
- Tradeoff:
  - Much cheaper superconductor if using dual temperature
  - But
    - More complicated arrangement
    - Need for 4 K refrigerator
- Final design will investigate both

# Design/Costing algorithms

- Prepared simple spread sheet model for designing coils and costing
- Coil designs (conductor)
  - Simple coil (one type of conductor) and coils with multiple types of conductors
- Coil structure
- Coil cost
- Spread sheet transferred to Jim Lyon

# Using design by J. Lyon
## (presented in Dec. meeting)

| | | |
|---|---|---|
| Bo | T | 5.6 |
| Ro | m | 10 |
| Plasma ASPECT ratio | | 4.4 |
| INBOARD gap/blanket/shield thicknes | m | 1.5 |
| OUTBOARD gap/blanket/shield/gap | m | 2.5 |
| Coil height | m | 15 |
| | | |
| Outer radius of inner leg, Rin | | 6.23 |
| Inner radius of outer leg, Rout | | 14.77 |

- Coil aspect ratio small
  - There may be sufficient space between coils without having to change the winding pack shape

# Coil structure

| | | |
|---|---|---|
| sigma membrane allowable | Pa | 6.00E+08 |
| sigma bending allowable | | 9.00E+08 |
| | | |
| Thickness of inner leg, tin | m | 3.30E-01 |
| Thickness of outer leg, tout | m | 1.04E-01 |
| | | |
| Thickness of top/bottom | m | 0.44 |
| | | |
| Volume: | | |
| large ellipsoid | m^3 | 7570 |
| Small ellipsoid | m^3 | 6642 |
| Total | m^3 | 928 |

- Assumes that all space between coils is filled with structure
  - Regions for access ports need to be reinforced elsewhere
  - Conservative assumption
  - Subtraction of relatively large numbers for estimating the volume
  - Good for system code. Will be improved once design space is narrowed down.

# Calculation of external structure

- Using simple beam theory (good for system analysis)
  - $A = B_0^2 R_0^2 / 2 \mu_0$
  - $S_1 = A (R_2 \ln(R_2/R_1) - R_2 + R_1)/(R_1 (R_2 - R_1))$
  - $S_2 = A (R_2 - R_1 - R_1 \ln(R_2/R_1))/(R_2 (R_2 - R_1))$
  - $t_1 = S_1 / \sigma_m$ ; $t_2 = S_2 / \sigma_m$
  - $R_3 = (S_1 R_1^2 + S_2 R_2^2)/(A \ln(R_2/R_1))$
  - $a = \sqrt{3/8 \, S_2 R_2 (R_2 - R_3)/\sigma_b / R_3}$
  - $R_2$: outer external structure radius
  - $R_1$: inner external structure radius

# Design criteria for external support

- Use SS-316 because of the large amounts of materials required could have substantial cost penalty
- Cross section of support determined by bending
  - Maximum stress by lowest of 1.5 x greater of (2/3 $\sigma_y$ or 1/3 $\sigma_u$)
  - Use around 800 MPa (for SS-316)
    - SS-316: (1400 MPa yield, 1800 MPa ultimate)

# Bucking cylinder and total structure cost

| | | |
|---|---|---|
| Bucking cylinder | | |
| Inner pressure | Pa | 3.22E+07 |
| Force | Pa m | 2.00E+08 |
| thickness | m | 3.34E-01 |
| Volume | m^3 | 1.80E+02 |
| Total structure volue | m^3 | 1.11E+03 |
| Weight | tones | 8.87E+03 |
| Assume $50/kg | | 50 |
| cost of structure | | 4.43E+08 |

- Large structure with tight tolerances.
  - $50/kg may be an underestimate
  - Can we use rapid prototyping methods for manufacturing of these large structures?

# Total coil costing

| | | |
|---|---|---|
| Superconductor | | |
| Minor diameter of ellipse | m | 4.381183327 |
| Major diameter of ellipse | m | 7.717979729 |
| length of ellipse | m | 38.73687036 |
| Amp-turns | A | 2.80E+08 |
| | kA | 2.80E+05 |
| Superconductor | kA m | 1.08E+07 |
| | | |
| Cost (assuming all Nb3Sn) | $/kA m | 1.27 |
| Cost of SC | $ | 1.38E+07 |
| | | |
| With insulation and installation | x3 | 4.13E+07 |
| | | |
| Total cost of magnet | $ | 4.85E+08 |

- Cost of magnet dominated by winding assembly
- Cost of BSCCO would be larger than that of $Nb_3Sn$

# Magnet design

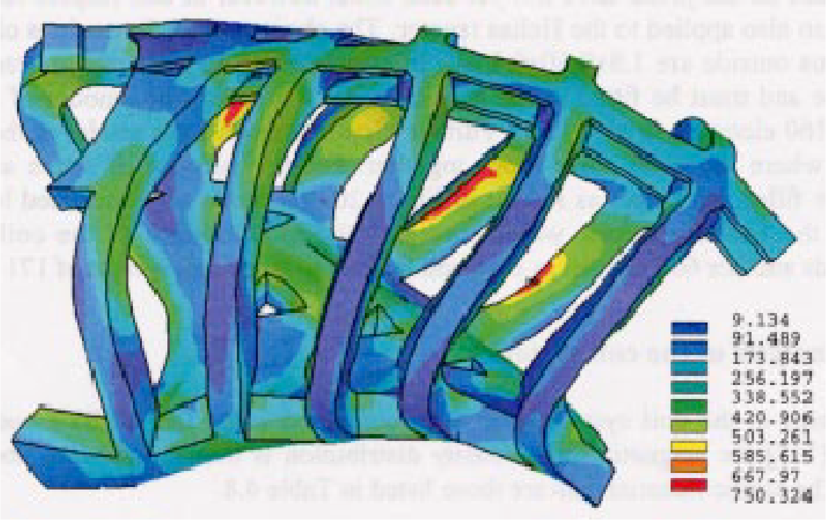
- Very aggressive IFE magnet design ran into a lot of resistance (from the reviewers of *Fusion Eng Design* article)
- I propose that the baseline be wound magnet
  - BSCCO and NbTi, if cost warrants
  - Else, just BSCCO
- Use aggressive design as option

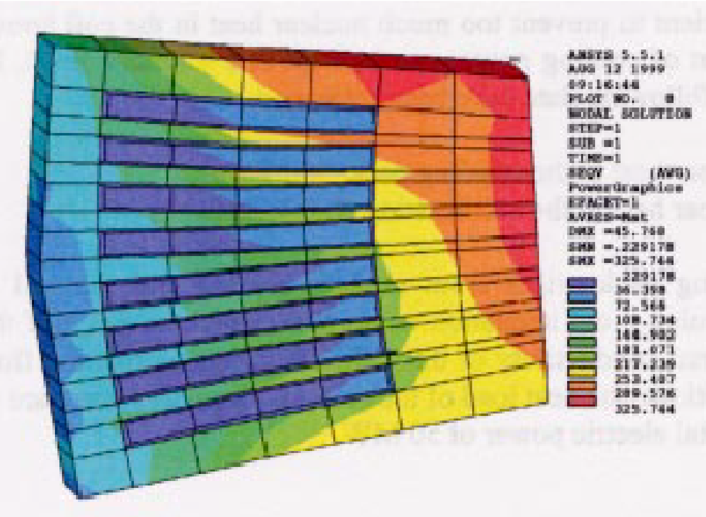
# Work to be done

- System design tools have been developed
- Detailed calculations need to be performed for a design point, in order to assure the appropriateness of the algorithms
  - Calculate stresses using actual currents and geometries
    - Structural considerations
    - Deformations and strains of the structure and superconductor
  - Superconductor characteristics
  - Power supplies
  - Cryogenic loads and cooling
- Need one design point to calculate some details
  - NCSX (??)
  - HSR

# HSR Coil Calculations

## Van Mises Stresses



**Coil housing ≤ 750 MPa**

**Coil ≤ 70 MPa**

**1.8K superfluid He, 10 T max on coils**

# Resources

- Can PPPL provide assistance with the calculations of the loads?
  - Stresses?
- P. Titus has been performing calculations for NCSX, but only earthquake analysis