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W. Maurer, D.C. Larbalestier, and I. Sviatoslavsky

May 1980

UWFDM-361
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1. Introduction

The central cell field of the tandem mirror reactor (TMR) will be achieved with discrete solenoids spaced at regular intervals to provide space for feeding and diagnostic devices. The solenoids are superconducting and operate in a steady dc mode. To provide long term operation, the solenoid will be designed for cryostatically stable operation.

2. Stresses

The central cell solenoids for the TMR may be wound in pancakes or in disks similar to the NUWMAK conductor arrangement\(^{(1)}\). If the windings are mechanically independent, the hoop forces in the solenoids are given by the local Lorentz forces. The tangential stress in an unsupported conductor due to the magnetic force is given by

\[ \sigma(r) = j(r) \cdot B(r) \cdot r. \]  \hspace{1cm} (2.1)

The total force on the current carrying winding is distributed among the components of the conductor and the structural material. The stress is given by the rule of mixtures

\[ \sigma = \sum_{n} \sigma_{n} \alpha_{n} \]  \hspace{1cm} (2.2)

where the strain \( \varepsilon_{n} = \sigma_{n}/E_{n} \) is constant for all \( n \) components. \( \alpha_{n} \) is the relative volume fraction and \( E \) is Young's modulus. Eq. (2.2) is applicable in the elastic region of the materials, i.e. where Hooke's law is valid.
The NUWMAK conductor consists of five components:

1. NbTi superconductor
2. High purity Al-stabilizing material
3. High strength Al to encapsulate the first two components.

These three components form the conductor itself.

The fourth component is epoxy to electrically insulate the conductor and to couple the conductor mechanically with the fifth component, the structural material of the disk. In the case of the NUWMAK conductor, the structural material is high strength aluminum, Al-2219 T 87, the same as the third component of the conductor.

The maximum magnetic load for our solenoids under consideration is given in a simplified manner by

\[ F_{mag} = I \cdot B_{\text{max}} \cdot a_1 \]  \hspace{1cm} (2.3)

where I is the current, \( a_1 \) is the inner radius of the solenoid winding and \( B_{\text{max}} \) is the field at \( a_1 \). Other equations for the magnetic load may be found in Ref. (2).

The load is balanced by tangential hoop forces. In the case of a supported conductor this load is balanced by the conductor itself and the structural material. Therefore, we have a balance equation

\[ F_{mag} = F_c + F_s = \sigma_c A_c + \sigma_s A_s \]  \hspace{1cm} (2.4)
where the indices $c$ and $s$ denote conductor and structure, respectively. Dividing by $A_c$ gives

$$\sigma_{\text{mag}} = \frac{F_{\text{mag}}}{A_c} = \sigma_c + \sigma_s \frac{A_s}{A_c}.$$  \hspace{1cm} (2.5)

Together with Eq. (2.3) and the conductor current density

$$j_{\text{cond}} = I/A_c$$  \hspace{1cm} (2.6)

we get

$$j_{\text{cond}} \cdot B_{\text{max}} \cdot a_1 = \sigma_c + \sigma_s \frac{A_s}{A_c}.$$  \hspace{1cm} (2.7)

In the case under consideration we have

$$\sigma_c = \varepsilon (E_1 \alpha_1 + E_3 \alpha_3) + \sigma_2 \alpha_2$$  \hspace{1cm} (2.8)

and

$$\sigma_s = \varepsilon (E_4 \gamma_4 + E_5 \gamma_5)$$  \hspace{1cm} (2.9)

where the $\alpha_i$'s are the relative fractions of the $i$-th component in the conductor area only and the $\gamma_i$'s are the relative fractions
in the structure area only. Eq. (2.8) takes into account that
the high purity aluminum (component 2) in the conductor is in the
plastic region. For the \( \alpha \)'s and the \( \gamma \)'s we have

\[
1 = \alpha_1 + \alpha_2 + \alpha_3
\]  

(2.10)

and

\[
1 = \gamma_4 + \gamma_5.
\]  

(2.11)

Eq. (2.7) together with (2.8,9) results in:

\[
\frac{j_{\text{cond}} \cdot B_{\text{max}} \cdot a_1}{A} \leq \varepsilon (E_1 \frac{a_1}{A} + E_3 \frac{a_3}{A}) + \sigma_2 \frac{a_2}{A} \varepsilon (E_4 \frac{\gamma_4}{A} + E_s \frac{\gamma_s}{A}) \cdot \frac{S}{A_c}.
\]  

(2.12)

This relation means that the magnetic load has to be supported by
the conductor and the structure. Therefore, it is favorable to
consider Eq. (2.12) as an inequality.

According to Ref. (2) some other expressions can be used for
the circumferential stresses \( \sigma_c \), the left side of Eq. (2.12).
One relation is

\[
\sigma_c = \frac{j_{\text{cond}}}{4} (B_1 + B_2) (a_2 + a_1).
\]  

(2.13)
This is an average over the coil thickness. \( a_1 \) is the minor and \( a_2 \) is the major radius of the solenoid. \( B_1 \) and \( B_2 \) are the magnetic fields at \( a_1 \) and \( a_2 \). Two other relations for the stresses were considered; both are radius-dependent. The first one is

\[
\sigma_c = \frac{a_1^2 \cdot j_{\text{cond}}}{4a_1 \ln \alpha} \cdot (B_1 + B_2) (a^2 - 1) \quad (2.14)
\]

where \( a_1 < a < a_2 \) and \( \alpha = a_2/a_1 \). The second one is

\[
\sigma_c = a_1 \cdot j_{\text{cond}} \cdot \frac{B_1 (a^2 + a - 2) + B_2 (2a^2 - a - 1)}{6 \left( \frac{a}{a_1} \right)^2 \ln \alpha} \quad (2.15)
\]

A comparison of the different formulas for the stresses is given in section 7 for the central cell magnets.

3. Critical Current Density

The critical current density \( j_c \) in the superconductive material itself has to be taken at the maximum magnetic field \( B_{\text{max}} \), working at the conductor, and at the operating temperature \( T_{\text{op}} \). The critical current density in the composite conductor \( j_{\text{cond}} \) is given by
\[ J_{\text{cond}} = \alpha_1 \cdot f \cdot J_c \left( B_{\text{max}}^2 T_{\text{op}} \right) \]  

(3.1)

where \( \alpha_1 \) is the fraction of superconducting material in the conductor and \( f \) means the safety factor \((f < 1)\).

4. Stabilization

To protect the solenoids during a quench, the criterion of cryostatic stability must be fulfilled. It is given by\(^{(3)}\):

\[ I^2 \rho_n = \delta \cdot h \cdot \Delta T \cdot A_n \cdot S_n \]  

(4.1)

where \( I \) is the current, \( \delta \) is the stability parameter, \( h \) the heat transfer coefficient, \( \Delta T \) the temperature difference, \( A_n \) the area of the stabilizing material and \( S_n \) is the cooled surface area of the conductor. For \( \delta < 1 \) we have full stabilization.

Eq. (4.1) can be written in the form

\[ j_{\text{stab}}^2 \rho_{\text{stab}} = \frac{\rho_P}{\alpha_{\text{stab}} A_c} \cdot q_r \]  

(4.2)

which is more appropriate for our consideration. \( J_{\text{stab}} \) is the current density working in the stabilizing material. \( \rho_{\text{stab}} \) is the resistivity therein. \( \alpha_{\text{stab}} \) is the relative fraction of the stabilizing metal in the conductor area \( A_c \), \( \rho_P \) is the cooled portion of the perimeter \( P \) and \( q_r \) is the recovery heat flux. For pool boiling (bath cooling) a value of 0.3 W/cm\(^2\) at 4.2 K and 0.5 W/cm\(^2\) at 1.8 K is taken.
Considering the case of a 3-component conductor we have

\[ j_{\text{stab}} = j_{\text{cond}} \left( 1 + \frac{\alpha_1}{\alpha_2 + \alpha_3} \right) = \frac{j_{\text{cond}}}{\alpha_2 + \alpha_3} \quad (4.3) \]

taking into account Eq. (2.10). The resistivity \( \rho \) of the conductor is given by the relation

\[ \frac{1}{\rho} = \frac{\alpha_1}{\rho_1} + \frac{\alpha_2}{\rho_2} + \frac{\alpha_3}{\rho_3} \quad (4.4) \]

where \( \rho_1 \) is the resistivity of the superconductor after the transition to normal conduction. In general \( \rho_1 \gg \rho_2 \rho_3 \) and we get

\[ \frac{1}{\rho_{\text{stab}}} = \frac{\rho_2 \rho_3 (\alpha_2 + \alpha_3)}{\rho_2 \alpha_3 + \rho_3 \alpha_2} \quad \text{with} \quad \alpha_{\text{stab}} = \alpha_2 + \alpha_3 \quad (4.5) \]

With (4.3) and (4.5) we get from (4.2):

\[ j_{\text{cond}}^2 \cdot \frac{\rho_2}{\alpha_2 + \frac{\rho_2}{\rho_3} \alpha_3} < \frac{p^p}{A_c} \cdot q_r \quad (4.6) \]
This is the cooling condition for full stabilization.

5. Magnet Protection

The protection integral is given by

\[ \int_0^\infty j^2_{\text{cond}}(t) dt = \int_{T_b}^{T_{\text{max}}} \frac{c(T) \cdot \delta}{\rho(T)} dT \quad (5.1) \]

where \( c(T) \delta \) is the heat capacity of the normal conducting material\( (2) \). If we have \( n \) components in a composite conductor, then the protection integral is given by

\[ \int_0^\infty j^2_{\text{cond}}(t) dt = \int_{T_b}^{T_{\text{max}}} \left[ \sum_{k=1}^{n} \frac{\alpha_k}{\rho_k(T)} \right] \cdot \left[ \sum_{k=1}^{n} \alpha_k c_k(T) \delta_k \right] dt \quad (5.2) \]

We consider first the time integral on the left side of Eq. (5.1) or (5.2) for two different cases:

- Discharge in a constant resistor \( R_D \)
- Discharge with a constant voltage.

In the first case we suppose an exponential decay of the initial current density \( j \) of the conductor

\[ j(t) = j_0 e^{-t/\tau_R} \quad (5.3) \]
where the time constant $\tau_R$ is given by

$$\tau_R = \frac{2 \cdot E_S}{I_0 \cdot U_0} .$$  \hfill (5.4)

$E_S$ is the stored energy, $I_0$ is the initial current and $U_0$ is the voltage. Then the time integral is

$$\int_0^\infty j^2(t) dt = \frac{j_0^2 \tau_R}{2} = \frac{j_0^2 \cdot E_S}{I_0 \cdot U_0} \lesssim I_{RD} .$$  \hfill (5.5)

In the second case we consider the linear decay of the initial current density of the conductor given by

$$j(t) = j_0 \left(1 - \frac{t}{\tau_R} \right) \text{ for } 0 < t < \tau_R$$  \hfill (5.6)

where $\tau_R$ is given by (5.4). In this case the time integral is

$$\int_0^\infty j^2(t) dt = \frac{1}{3} j_0^2 \tau_R = \frac{2}{3} I_{RD} \lesssim I_u .$$  \hfill (5.7)
The time integral $I_u$ for constant voltage discharge is only two-thirds of the time integral $I_{RD}$ for constant resistor discharge.

6. Design Procedure

We have the equations

$$1 = \alpha_1 + \alpha_2 + \alpha_3$$  \hspace{1cm} (2.1)

$$1 = \gamma_4 + \gamma_5$$  \hspace{1cm} (2.11)

$$\frac{A_s}{A_c} \cdot \varepsilon (E_4 \gamma_4 + E_5 \gamma_5) > j_{cond} \cdot B_{max} \cdot a_1 - \left[ \varepsilon (E_1 \alpha_1 + E_3 \alpha_3) + \sigma_2 \alpha_2 \right]$$  \hspace{1cm} (2.12)

$$j_{cond} = a_1 \cdot f \cdot j_c (B_{max}, T_{op})$$  \hspace{1cm} (3.1)

$$\frac{p^p}{A_c} \cdot q_r > j_{cond}^2 \frac{1}{\frac{\rho_2}{\alpha_2} + \frac{\rho_2}{\rho_3} \alpha_3}$$  \hspace{1cm} (4.6)

In addition we have

$$j_{cond} = j_{ov} \left( 1 + \frac{A_s}{A_c} \right)$$  \hspace{1cm} (6.1)
where \( j_{0v} \) is the overall density in the magnet. These equations connect geometrical data \((A_C, A_s, a_1, a_2, a_3, \gamma_4, \gamma_5, a_1)\) with mechanical material data \((E_1, \sigma_2, E_3, E_4, E_5)\), with electrical data \((\rho_2, \rho_3, j_c, j_{\text{cond}}, j_{0v}, B_{\text{max}})\) and cooling data \((T_{op}, q_r, p P)\). The working strain \( \varepsilon \) and the safety margin \( f \) have to be chosen.

A working strain of \( \varepsilon = 0.003 \) is chosen to keep the resistivity of the high purity Al below \( 10^{-8} \) ohm-cm\(^4\). The magnet system with given inner radius \( a_1 \) should be worked at \( T_{op} = 4.2 \) K which gives the recovery flux \( q_r \). If we choose the materials, then the data \( E_1, \sigma_2, E_3, E_4, E_5, \rho_2 \) and \( \rho_3 \) are fixed. The maximum magnetic field determines the critical current density of the superconductor together with the preselected \( T_{op} \). So the nine variables \( a_1, a_2, a_3, \gamma_4, \gamma_5, A_s/A_c, j_{\text{cond}}, p P/A_c, j_{0v} \) remain, connected by six equations. In principle six variables can be calculated in dependence of the three remaining.

In practice conductor current densities of some thousand \( A/cm^2 \) are convenient. We choose a conductor current density of \( 4000 \) A/cm\(^2\) and so \( a_1 \) is some percent of the conductor area for \( B_{\text{max}} \) from 6 T to 8 T (see Eq. 3.1). Now five equations remain to determine \( a_2, a_3, \gamma_4, \gamma_5, A_s/A_c, p P/A_c \) and \( j_{0v} \). We fulfill Eq. (2.10) by choosing a reasonable \( a_2 \), which means a reasonable stabilizer to superconductor ratio \( (a_2/a_1) \). Then we have the equations (2.11) and (6.1) and the inequalities (2.12) and (4.6) for \( \gamma_4, \gamma_5, A_s/A_c, p P/A_c \) and \( j_{0v} \), where Eq. (4.6) yields a lower limit of the cooling parameter \( p P/A_c \). If we fulfill Eq. (2.11) by choosing a reasonable value of \( \gamma_4 \) or \( \gamma_5 \), we can calculate a lower
limit of \( A_s/A_c \) from Eq. (2.12) and the corresponding overall current density \( j_{0v} \) from Eq. (6.1). The magnetic fields, the magnetic forces and the self and mutual inductance are calculated by means of the EFFI code\(^5\). In addition we have to calculate the stored self energy

\[
E_s = 0.5 L I^2 \quad (6.2)
\]

and the total energy in the central cell given by the relation

\[
E_{\text{tot}} = \frac{1}{2} \sum_{q=1}^{N} \sum_{p=1}^{N} L_{pq} I_q I_p \quad (6.3)
\]

7. Results

The result of such a calculation for a disk-conductor assembly (see Fig. 1) is given in Table 1. The resistivity of the high purity aluminum is

\[
\rho = 10^{-10} \ \mu\text{m}
\]

and of the high strength aluminum

\[
\rho = 1.5 \times 10^{-8} \ \mu\text{m}.
\]

We have used these values in the temperature and magnetic field range considered\(^6\). The Young's moduli are:
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of solenoids</td>
<td>$N_s$</td>
<td></td>
<td>34</td>
</tr>
<tr>
<td>Coil separation (winding/winding)</td>
<td>$\Delta c$</td>
<td>m</td>
<td>3.23</td>
</tr>
<tr>
<td>Coil separation (midplane/midplane)</td>
<td>$\Delta z$</td>
<td>m</td>
<td>4.63</td>
</tr>
<tr>
<td>Axial coil length</td>
<td>$W$</td>
<td>m</td>
<td>1.4</td>
</tr>
<tr>
<td>Radial coil thickness</td>
<td>$T$</td>
<td>m</td>
<td>1.0</td>
</tr>
<tr>
<td>Inner coil radius</td>
<td>$a_1$</td>
<td>m</td>
<td>3.3</td>
</tr>
<tr>
<td>Outer coil radius</td>
<td>$a_2$</td>
<td>m</td>
<td>4.3</td>
</tr>
<tr>
<td>Mean coil radius</td>
<td>$\bar{A}$</td>
<td>m</td>
<td>3.8</td>
</tr>
<tr>
<td>Volume of one coil</td>
<td>$V_c$</td>
<td>$m^3$</td>
<td>33.427</td>
</tr>
<tr>
<td>Average density of a coil</td>
<td>$\rho_c$</td>
<td>$T/m^3$</td>
<td>2.64</td>
</tr>
<tr>
<td>Mass of one coil</td>
<td>$M_c$</td>
<td>T</td>
<td>88.087</td>
</tr>
<tr>
<td>Volume of N coils</td>
<td>$V_{tot}$</td>
<td>$m^3$</td>
<td>1136.502</td>
</tr>
<tr>
<td>Mass of N coils</td>
<td>$M_{tot}$</td>
<td>T</td>
<td>2994.968</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>$T_{op}$</td>
<td>K</td>
<td>4.2</td>
</tr>
<tr>
<td>Conductor current density</td>
<td>$j_{cond}$</td>
<td>$A/cm^2$</td>
<td>4000</td>
</tr>
<tr>
<td>Overall current density</td>
<td>$j_{ov}$</td>
<td>$A/cm^2$</td>
<td>950</td>
</tr>
<tr>
<td>Magnetic field on axis</td>
<td>$B_o$</td>
<td>T</td>
<td>3.6</td>
</tr>
<tr>
<td>Maximum field at conductor</td>
<td>$B_{max}$</td>
<td>T</td>
<td>6.14</td>
</tr>
<tr>
<td>Field ripple on axis</td>
<td>$\Delta B/B_o$</td>
<td>%</td>
<td>&lt; 3.5</td>
</tr>
<tr>
<td>Field ripple at plasma radius</td>
<td>$\Delta B/B_o$</td>
<td>%</td>
<td>&lt; 4.1</td>
</tr>
<tr>
<td>Operating current</td>
<td>$I$</td>
<td>A</td>
<td>12091</td>
</tr>
<tr>
<td>Number of turns</td>
<td>$N$</td>
<td></td>
<td>1100</td>
</tr>
<tr>
<td>Ampere-Turns</td>
<td>$NI$</td>
<td>A-turns</td>
<td>13.3 x 10^6</td>
</tr>
</tbody>
</table>

**CONDUCTOR**

Dimensions (radial x axial)                        | cm x cm | 3.0 x 1.0 |
Superconductor                                     | NbTi    |
Superconductor, fraction in conductor               | %       | 3         |
| Table 1 (cont.) |
|-----------------|---------------------------------|
| Stabilizer      | High purity                     |
| Stabilizer, fraction in conductor | % | 75 | |
| Skin            | High strength                    |
| Skin, fraction in conductor | % | 22 | |
| Percentage of wetted perimeter | % | 24 | |
| Conductor assembly | Disk structure                   |
| Structural material | High strength                    |
| Working strain in structure | ε | 3.0x10^{-3} | |
| Working stress in structure | σ | 246 | |
| Yield stress at 4.2 K | MPa | 505 | |
| Number of conductors per disk | | 2x22 | |
| Number of disks per magnet | | 25 | |
| INDUCTANCES     |                                 |
| Inductance      | L/10^{-6} H/N^{2} | L/H | % coupling |
| Self           | 9.807                          | 11.86647 | |
| Mutual 1. Neigb. | 1.397                        | 1.6904 | 14.245 |
| 2.              | 0.3487                        | 0.4219 | 3.555 |
| 3.              | 0.1265                        | 0.1531 | 1.290 |
| 4.              | 0.05794                       | 0.0701 | 0.591 |
| 5.              | 0.0309                        | 0.0374 | 0.315 |
| 6.              | 0.01829                       | 0.0221 | 0.187 |
| 7.              | 0.01168                       | 0.0141 | 0.119 |
| 8.              | 0.007899                      | 0.0096 | 0.081 |
| Stored self energy in one central cell magnet | | | 0.8674 GJ |
Table 1 (cont.)

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total stored energy in the central cell</td>
<td>40.9625 GJ</td>
</tr>
<tr>
<td>DISK Cross section (radial x axial)</td>
<td>cm x cm</td>
</tr>
<tr>
<td>$Z_o$</td>
<td>cm</td>
</tr>
<tr>
<td>$Z_i$</td>
<td>cm</td>
</tr>
<tr>
<td>$Z_s$</td>
<td>cm</td>
</tr>
<tr>
<td>$Z_r$</td>
<td>cm</td>
</tr>
<tr>
<td>$Z_m$</td>
<td>cm</td>
</tr>
<tr>
<td>$R_m$</td>
<td>cm</td>
</tr>
<tr>
<td>Area of disk unit</td>
<td>552 cm$^2$</td>
</tr>
<tr>
<td>Superconductor</td>
<td>3.96 cm$^2$</td>
</tr>
<tr>
<td>Stabilizer</td>
<td>99.0 cm$^2$</td>
</tr>
<tr>
<td>Skin</td>
<td>29.04 cm$^2$</td>
</tr>
<tr>
<td>High strength structural Al</td>
<td>380.46 cm$^2$</td>
</tr>
<tr>
<td>Structural epoxy</td>
<td>20.03 cm$^2$</td>
</tr>
<tr>
<td>Space between disks</td>
<td>19.27 cm$^2$</td>
</tr>
</tbody>
</table>
For NbTi: \( 100 \times 10^9 \text{ N/m}^2 \)
For Al: \( 82 \times 10^9 \text{ N/m}^2 \)
And for epoxy: \( 10 \times 10^9 \text{ N/m}^2 \).

We have compared the stress relations (2.12, 13, 14, 15) and have found that the relation used in (2.12), \( J_{\text{cond}} B_{\text{max}} a_1 \) for \( \sigma_c \), gives the highest values for the stresses. The relation (2.13) gives 25% lower stresses and the radius-dependent relations (2.14) and (2.15) give respectively 15% and 13% lower stresses at the inner side of the solenoids, and 35% and 33%, respectively lower stresses at the outer side compared with the values used in our design (see Fig. 2). The protection integral is calculated for two cases.

In the case of our central cell solenoids we have a conductor current density of 4000 A/cm\(^2\), a stored self energy of 0.8674 GJ, a self inductance of 11.8665H and a current of 12091A. Then we get

\[
\frac{J_0^2 E_s}{I_0} = 1.148 \times 10^{20} \frac{A^2 s}{m^4} \cdot V
\]

discharge with a voltage of \( U_0 = 2 \text{ kV} \) gives

\[
I_{D} = 0.574 \times 10^{17} \frac{A^2 s}{m^4}
\]
FIG. 2. STRESS DISTRIBUTION
\[ I_u = 0.3826 \times 10^{17} \frac{A^2 s}{m^4}. \]

These correspond to a maximum temperature of about 60 K and 40 K, respectively. The time constant \( \tau \) of a coil is 72 s and the constant discharge resistor has to be 0.1654 ohm.

**Acknowledgement**

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**REFERENCES**


