Analysis of losses in superconducting magnets based on the Nb$_3$Sn Rutherford cable configuration for future gantries

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Abstract - Proton therapy for the treatment of cancers adopts a rotating system called gantry to irradiate the tumor from any direction. The gantry system consists of different beamline magnets that bend the proton beam towards the patient. The use of superconducting magnets allows reducing the weight of the last bending section. During the gantry operation, the magnetic field of the last bending section is varied in time to tune the proton penetration depth. This change determines electrodynamic transients in the superconducting strands and cables that generate losses. This work describes the application of the THELMA code to compute the hysteresis and coupling losses in an innovative magnet system designed by PSI for future superconducting gantries.

Gantry magnet system configuration and working scenario

- The combined function magnet system configuration includes 8 main coils and two end quadrupoles [1]:

  - The reference working scenario of the gantry magnet system is characterized by a series of transport current ramps and plateaus:

    | 4 | 5 | 7 | 2 |
    |---|---|---|---|
    | Dipole + quadrupole + sextupole | Quads + sextupole |

- The power dissipated per unit volume is computed as:

  \[ P_{dc} = \frac{2}{3l} \int (B_d \cdot J_d) \, dl \]

Magnet system symmetry

- Coils #1 and #3, and coils #2 and #4 exhibit the same losses
- Coils #1 and #2 (#3 and #4) are identical exchanging the numbering of the turns
- Coils #5 and #6, and coils #7 and #8 exhibit the same losses
- Coils #5 and #7 (#6 and #8) are identical exchanging the numbering of the turns
- Coils #1 and #5 analyzed in detail

Impact of boundary conditions

- A uniform current and a short circuit boundary conditions at the turn ends were imposed to compare the losses
- The boundary conditions affect the coupling losses
- Hysteresis losses dominant
- No relevant effect of boundary conditions on total losses
- A Nb$_3$Sn bronze strand is selected for the magnet system design
- \( d_{eff} = 7.8 \mu m \)

Loss computation methodologies

- Coupling losses Coupling losses are computed by means of the THELMA code [2], which calculates the magnetic field distribution and current distribution between strands.
- The power dissipated per unit volume is computed as:

  \[ P_{dc} = \frac{2}{3l} \int (B_d \cdot J_d) \, dl \]

Magnetic flux density and losses

- High field locations with higher \( dB/dt \) but lower \( J_c \)
- Compensation effect
- The peak temperature in coil #1 is 8 K, the current sharing temperature at the peak field location is 9.7 K
- \( AT = 1.7 K \)
- Current sharing temperature

Thermal analysis: coil #1

- A collaboration between PSI and the University of Bologna was established to study power losses in Nb$_3$Sn Rutherford cables for future gantry magnet systems
- The THELMA code was adapted to the analysis of the Rutherford cable configuration and validated vs analytical formulae
- Two coils of the gantry magnet system were selected for detailed loss analysis due to symmetry conditions
- In this configuration the hysteresis losses in the strand are dominant with respect to the interstrand losses
- The computed losses were implemented in an adiabatic thermal model: the available temperature margin guarantees a safe magnet design

Summary

Reference:


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