Conceptual design of a 20T High Field Dipole Magnet

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Introduction

- Quest for higher fields in accelerator magnets
- New classes of superconducting magnets (HTS)

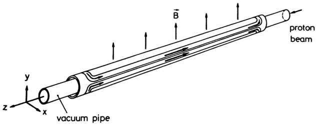
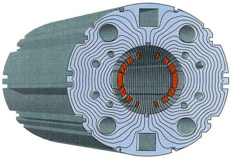


Figure 4.1: Schematic view of a superconducting dipole coil.

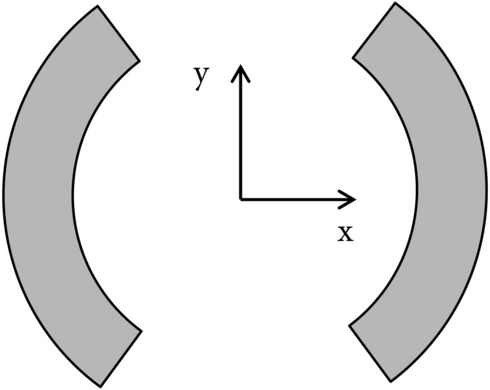


Aim of the study

- Investigate the feasibility of a 1 T HTS dipole coil within an existing 11 T dipole
- Design a concept of mechanical structure and a stress management solution for a HTS 5 T insert dipole within a 15 T Nb_3Sn dipole

a: internal radius

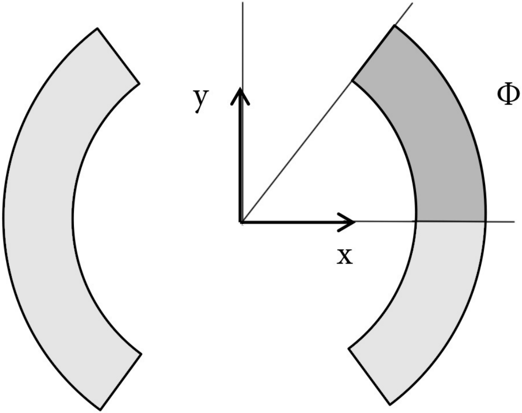
w: thickness



a: internal radius

w: thickness

ϕ: sector angle



1 Magnetic Model

2 Mechanical Model

3 Magnetic Optimization

4 First step

5 Second phase

Magnetic Model

Hypotheses:

- current shell distributions
- higher multipole terms neglected
- Yoke effects neglected
- $2D$ model

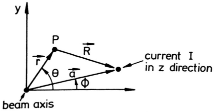
Analitical model of Magnetic Field

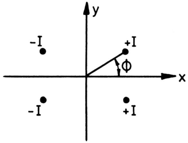
B can be expressed as the curl of the vector potential **A**:

$$\mathbf{B} = \nabla \times \mathbf{A}$$

For 2D problem: $\mathbf{A} = A_z \hat{k}$.

Four line currents with dipole symmetry:





$$\begin{cases} A_z(r,\theta) = \frac{2\mu_0 I}{\pi} \sum_{n=1,3,5..} \frac{1}{n} \left(\frac{a}{r}\right)^n cos(n\theta) cos(n\phi), & r > a \\ A_z(r,\theta) = \frac{2\mu_0 I}{\pi} \sum_{n=1,3,5..} \frac{1}{n} \left(\frac{r}{a}\right)^n cos(n\theta) cos(n\phi), & r < a \end{cases}$$

Magnetic Field contributions

1-Inside the aperture

$$A_z(r,\theta) = \frac{2\mu_0 J_0}{\pi} wr \; cos(\theta) sin(\phi_l)$$

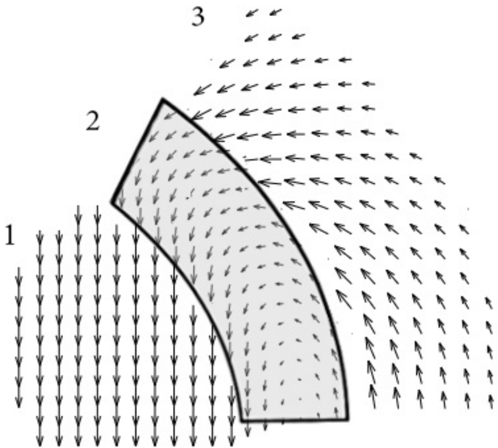
2-On the coil

$$A_z(r,\theta) = \frac{2\mu_0 J_0}{\pi} r \left[(a + w - r) + \frac{r^3 - a^3}{3r^2}\right] cos(\theta) sin(\phi_l)$$

3-On the external region

$$A_z(r,\theta) = \frac{2\mu_0 J_0}{\pi} r \left[\frac{r^3 - a^3}{3r^2}\right] cos(\theta) sin(\phi_l)$$

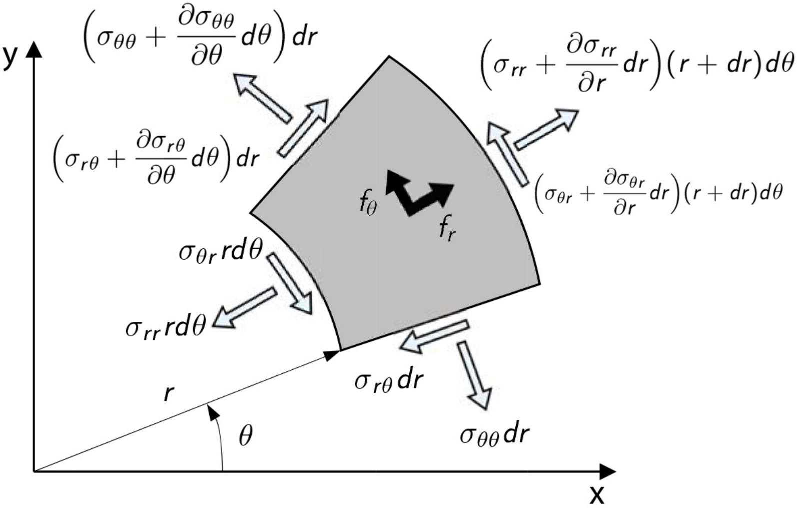
Magnetic Field generated by the coil



Mechanical Model

Hypotheses:

- Linear, Elastic, Omogeneous and Isotropic (IOLE) material
- $2D$ model
- thick membrane sector
- no thermal effects


y
$\left(\sigma_{\theta\theta} + \frac{\partial \sigma_{\theta\theta}}{\partial \theta} d\theta\right) dr$
$\left(\sigma_{rr} + \frac{\partial \sigma_{rr}}{\partial r} dr\right)(r + dr) d\theta$
$\left(\sigma_{r\theta} + \frac{\partial \sigma_{r\theta}}{\partial \theta} d\theta\right) dr$
$\left(\sigma_{\theta r} + \frac{\partial \sigma_{\theta r}}{\partial r} dr\right)(r + dr) d\theta$
f_θ
f_r
$\sigma_{\theta r} r d\theta$
$\sigma_{rr} r d\theta$
$\sigma_{r\theta} dr$
$\sigma_{\theta\theta} dr$
r
θ
x

Two equations from equilibrium along r and θ directions:

$$\begin{cases} \frac{\partial \sigma_{rr}}{\partial r} + \frac{\sigma_{rr} - \sigma_{\theta\theta}}{r} + \frac{1}{r}\frac{\partial \sigma_{r\theta}}{\partial \theta} + f_r = 0 \\ \frac{1}{r}\frac{\partial \sigma_{\theta\theta}}{\partial \theta} + \frac{\partial \sigma_{r\theta}}{\partial r} + 2\frac{\sigma_{r\theta}}{r} + f_\theta = 0 \end{cases}$$

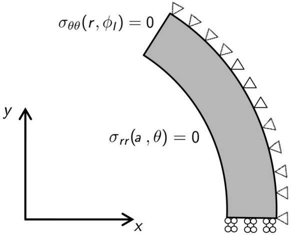
Based on previous studies (Bologna), a generalized plain strain model is considered.

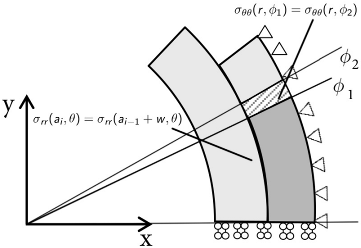
$$\sigma_{zz} = \nu(\sigma_{rr} + \sigma_{\theta\theta}) - \overline{\sigma_{zz}}$$

$$\overline{\sigma_{zz}} = \frac{1}{\pi[(a+w)^2 - a^2]\frac{(\phi_2 - \phi_1)}{2\pi}} \int_{\phi_1}^{\phi_2} \int_a^{a+w} \sigma'_{zz} r \, dr d\theta,$$

being $\overline{\sigma_{zz}}$ and σ'_{zz} the average axial stress and the axial stress for $\epsilon_{zz} = 0$.

Load boundary conditions and constraints



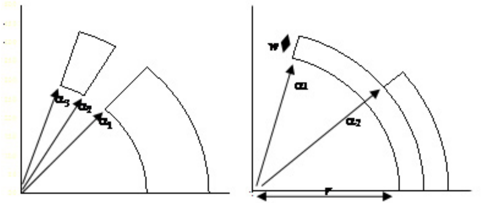


Volume forces (Lorentz's forces)

$$f_r = -B_\theta J_0 = J_0 \frac{\partial(\sum A_{z,i})}{\partial r} \qquad f_\theta = B_r J_0 = J_0 \frac{1}{r}\frac{\partial(\sum A_{z,i})}{\partial \theta}$$

Field Quality requirements

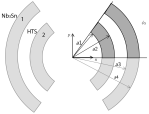
From multipole series:
Skew multipoles $a_n \Longrightarrow$ cancelled by symmetry
Normal multipoles $b_n \Longrightarrow$ can be made to vanish by coil geometry (sector angles and wedges)



$$b_n \propto sin(n\phi_l)\left(\frac{1}{a^{n-2}} - \frac{1}{(a+w)^{n-2}}\right), \quad n = 3, 5, 7, 9, \ldots$$

First step: 1T HTS standalone insert within 11TNb_3Sn coil

HTS loadline



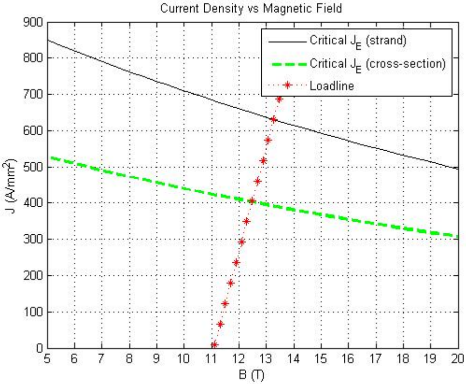
HTS: BSCCO-2212

$$J_{0,Nb_3Sn} = 800\frac{A}{mm^2}$$

$$a_{HTS} = 15mm$$

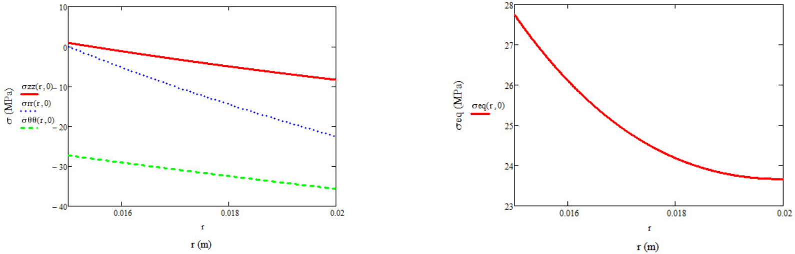
$$w_{HTS} = dcd$$

$$\phi_I = 60^o$$



First step: 1 T HTS standalone insert within 11 TNb_3Sn coil

$J_{0,HTS} = 300 \frac{A}{mm^2}$
Stress field for $\theta = 0$ (critical section):

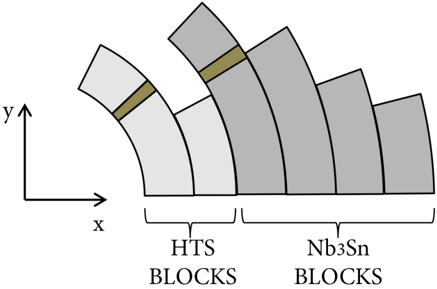


Results

With stresses below the $BSCCO - 2212$ stress limit of about 50 MPa the HTS insert results feasible

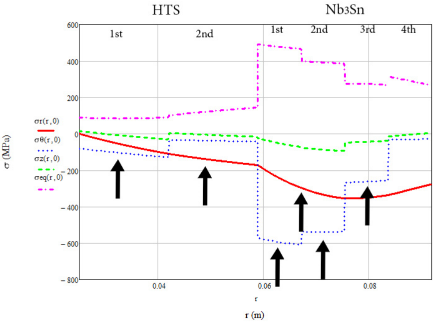
HTS 5 T insert within a 15 T dipole

- Field quality optimization (multipoles made to vanish until b_9);
- Material saving;
- 11 angles and 10 constraints $\Longrightarrow$ 1 parameter



Stress Field

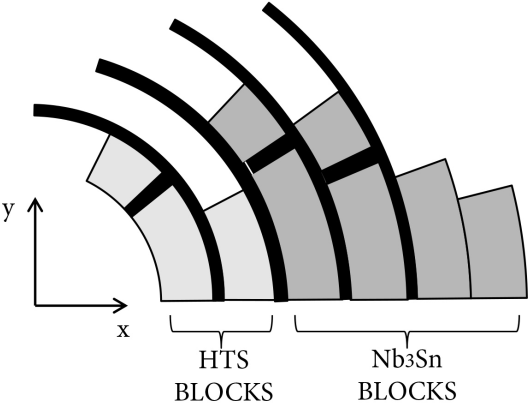
$J_{0,HTS}$	$250\,\frac{A}{mm^2}$
J_{0,Nb_3Sn}	$800\,\frac{A}{mm^2}$
a	$25\,mm$



Need for Stress Managemet structures

Azimuthal stress management provided by structural wedges.
Radial stress management provided by Stainless Steel shells.

Proposed structure - Slotted shells



Conclusions

- Field quality optimization on the proposed structure (performed)
- FEM simulation of the entire structure
- Need for $BSCCO - 2212$ material characterization