Investigation of magnetization behaviour of Nb$_3$Sn wires for the Next European Dipole Activity

P. Fabbricatore  
M. Greco, R. Musenich @ INFN-Genova

U. Gambardella @ INFN-Frascati

C. Bernini, C. Ferdeghini @ INFM-CNR-LAMIA
is aimed at the development of a large-aperture high field (up to 15 T) superconducting dipole magnet that will serve as a technology test bed for LHC luminosity upgrade

[about NED at ASC06 →1LL03, 2MC10, 4LX01, 4LX02, 4LX06]

Development of a high-performance Nb$_3$Sn wire (aiming at a non-copper critical current density of 1500 A/mm$^2$ at 4.2 K and 15 T) is carried out within the framework of the Collaborated Accelerator Research in Europe (CARE) project.

A Working Group on Conductor Characterization (WGCC)

CEA, CERN, INFN-Genova, INFN-Milano, University of Twente

was initiated to define and carry out reliable, reproducible methods for the measurement of electromagnetic properties

INFN-Genova and LNF +CNR-INFM Genova → magnetic characterization

PROLOGUE
THIS TALK

This talk has two aspects:

• To show the methodology for magnetic measurements and analysis on NED wires
  
  Critical Temperature (B)
  
  Evaluation of Nb\textsubscript{3}Sn volume
  
  Nb\textsubscript{3}Sn inhomogeneity
  
  Evaluation of critical current density
  
  Flux jump instabilities
  
• To underline the role of un-reacted Nb in flux jump instabilities at fields less than 1T

Three measurements methods (DC and AC): VSM, DC SQUID, AC Susceptibility

P.Fabbricatore, INFN-Genova
Information coming from $m(T)$

$\Rightarrow T_c(B)$ & shielded volumes

\[ m = \chi_0 B_a V \]

Susceptibility $\chi_0$ can be calculated using FEM. The samples measured can be assumed as cylinders. Parallel field, $\chi_0 \sim 1$; Transverse field, $\chi_0 \sim 2$

From the comparison of measurements in parallel and transverse field it is possible to evaluate demagnetization value $N$

\[ B_{\text{eff}} = B / (1 - N) \]

and compare with FEM calculation.
Information coming from $m(B)$

- Parallel and transverse field indication of shielding
- Flux jumps at low fields
- Estimation of $J_c(B)$ from $\Delta m$ from meas in transverse field
- Effective diameter

\[ \Delta m_{\text{wire}} = \frac{N_{\text{fil}}}{3} J_{c,sc}(B, T) \mu_0 l d^3 (1 - \eta^3) \]

\[ J_{c,sc}(B, T) = \frac{3\Delta m_{\text{wire}}}{N_{\text{fil}} \mu_0 l d^3 (1 - \eta^3)} \]

\[ \eta = \frac{r_{Sn}}{r_{Nb_2Sn}} \]

\[ d = 2r_{Nb_2Sn} \]

\[ S = \pi(r_{Nb_2Sn}^2 - r_{Sn}^2) \]

\[ I_c = N_{\text{fil}} J_{c,sc}(B, T) S \]
Information coming from $\chi(B,T)$

$$\chi = \frac{dB / dt}{dB_{\text{ext}} / dt} - 1 = \chi_0 (\chi' - i\chi'')$$

- $\chi_0 \rightarrow$ external susceptibility under conditions of perfect screening (Meissner state)
- $\chi'' \rightarrow$ dissipation, magnetic field really experienced by the sample

- $T_c(B)$
- Nb shielding volume
- Nb$_3$Sn shielded volume

Sharp transition $\rightarrow$ homogeneous material

Smooth transition $\rightarrow$ key of dishomogeneity
Preliminary measurements on Internal TIN and "old" PIT samples showed flux jumps for $T < 7K$ and $B < 1T$.

$m(B)$ at different temperatures, flux-jumps up to $T=6.7\, K$
Measurements on deformed wires showed correctly a critical current reduction (-30% to be compared with -40% of direct measurements) and flux jumps as well in the same field range.
Why Flux Jumps?

It is well known that we have flux jump instabilities in filaments when

\[ \frac{\mu_0 J_c^2 d^2}{4 \gamma C(T_c - T_{op})} > 3 \]

\( J_c \) is the critical current density of the filaments
\( d \) is the filament diameter
\( C \) is the specific heat
\( T_c \) is the critical temperature

The development of high \( J_c \) Nb\(_3\)Sn wires requires very low \( d \)
Are only large Nb₃Sn the sole responsible for instabilities?

\[ m = \chi_0 B_a V \]

\[ m = 3 \times 10^{-3} \text{ emu} = 3.77 \times 10^{-12} \text{ Wb m} \]

\[ V_{\text{shielded Nb}} = 3.77 \text{ mm}^3 \]

\[ V_{\text{shielded Nb₃Sn}} = 1.83 \text{ mm}^3 \]

\[ \varnothing_{\text{Nb}} = 65 \mu m, \]

\[ \varnothing_{\text{Nb₃Sn}} = 44 \mu m \]

Ratio \[ \varnothing_{\text{Nb₃Sn}} / \varnothing_{\text{Nb}} = 67\% \]

There is a large amount of unreacted Nb in the conductor !!!
Let’s reconsider the 6.7 K magnetization cycle.

According to this extrapolation, at 4.2 K we can have strong effects on magnetization due to this *dirty* Nb phase.

P. Fabbricatore, INFN-Genova
$m(B)$ in transverse field at 4.5 K $\rightarrow$ flux-jumps up to 0.3 T

$m(T)$ $\rightarrow$
very smooth transition of Nb down to 6 K

Nb role:
measurement on unreacted old PIT
Nb was suspected to be responsible for flux jumps at B<1T

A simple scheme based on flux penetration according the critical state model shows how instabilities in Nb can drive flux jump in Nb3Sn

Indications:
- Increase the cross section of Nb3Sn (i.e. reduce the unreacted Nb)
- Depress transport properties of Nb
**Nb role:**

*measurement on unreacted NED PIT*

\[ m(B) \] in transverse field at 4.5 K \( \rightarrow \) only one flux-jump at=0.1 T!

\[ m(T) \] \( \rightarrow \) smooth transition of Nb but in a narrower T range, down to 7 K

P. Fabbricatore, INFN-Genova
Measurements of SMI/NED wires with final design

\[ \varnothing_{\text{Nb}} = 58 \, \mu\text{m}, \]
\[ \varnothing_{\text{Nb3Sn}} = 46 \, \mu\text{m} \]

Ratio \[ \varnothing_{\text{Nb3Sn}} / \varnothing_{\text{Nb}} = 79\% \]

\[ \varnothing = 1.26 \, \text{mm} \]

\[ \varnothing_{\text{Nb}} \sim 60 \, \mu\text{m}, \]
\[ \varnothing_{\text{Nb3Sn}} \sim 46 \, \mu\text{m} \]

Flux jumps only in \([-0.4, 0.4 \, \text{T}]\)!

P. Fabbricatore, INFN-Genova
Scaling curve for $I_c$ using $m(B)$ measurements

$$I_c(B) = I_{c0}(a \cdot e^{-Bb} + 1)(c \cdot e^{-Bd} + 1)(1 - B / B^*)^g$$

Critical Current (A) vs. Applied Field (T)

$I_{c0} = 4081$ A
$a = 2.46$
$b = 0.23$ T
$c = 5.39$
$d = 1.91$ T

Next step: use of VSM for collecting data in the mean-field range

P. Fabbriatore, INFN-Genova
Combined AC and DC magnetization measurements provide several information about wire lay-out, transport properties and stability. In particular for NED developments we were interested in:

- content of Nb$_3$Sn with respect to other phases
- evaluation of critical current
- reduced transport capability due to deformation
- presence and range of instabilities

From our experimental results → strong warning on the importance of Nb

A better performance of unreacted wires combined with a larger extension of Nb$_3$Sn areas yield a better performance of PIT wires (having $d_{fil} \leq 50 \ \mu m$) for instabilities at $B<1 \ \text{T}$, but …

…it is not yet known how much could be worstened stability at higher fields.