



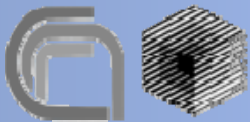
# Investigation of magnetization behaviour of $Nb_3Sn$ wires for the Next European Dipole Activity



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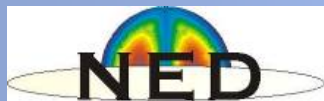
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## PROLOGUE



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<sub>3</sub>Sn wire (aiming at a non-copper critical current density of 1500 A/mm<sup>2</sup> 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-INFN Genova → magnetic characterization**

## 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<sub>3</sub>Sn volume

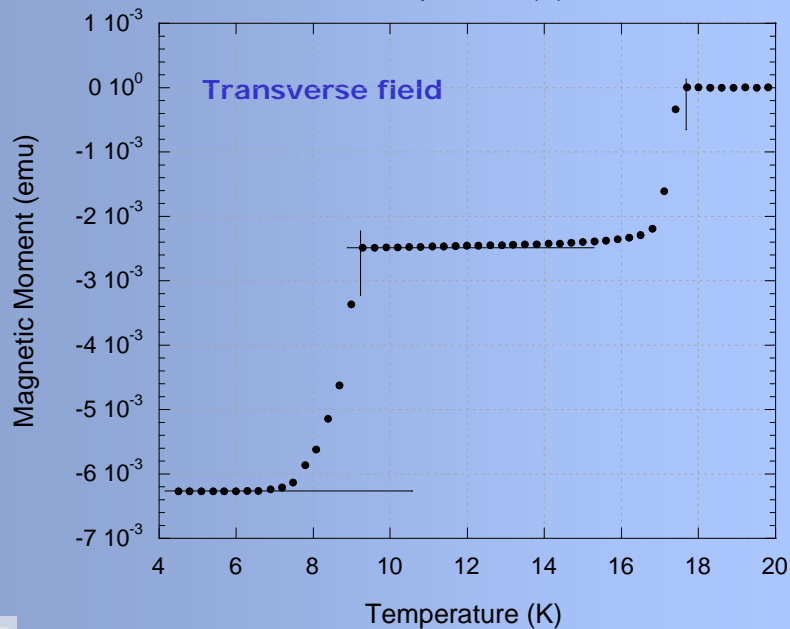
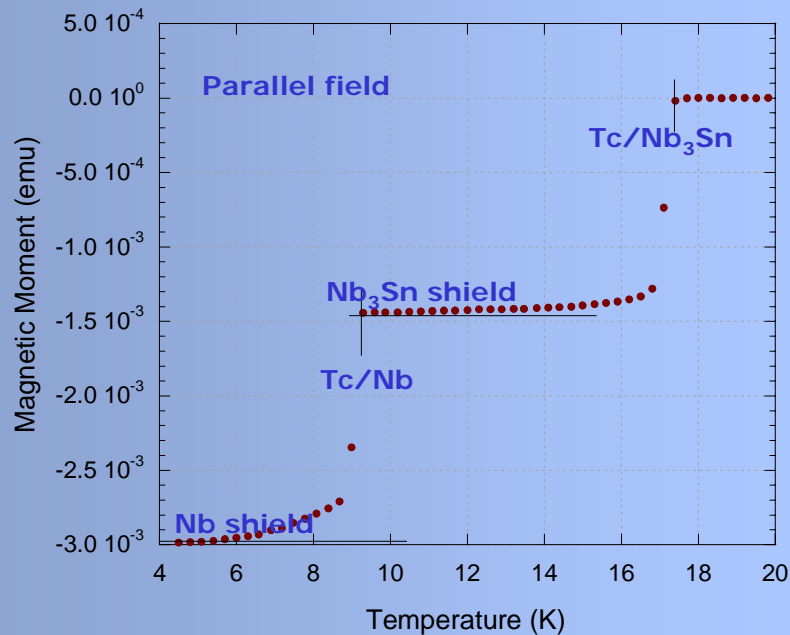
Nb<sub>3</sub>Sn inhomogeneity

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



Information coming from  $m(T)$

→  $T_c(B)$  & shielded volumes

$$m = \chi_0 B_a V$$

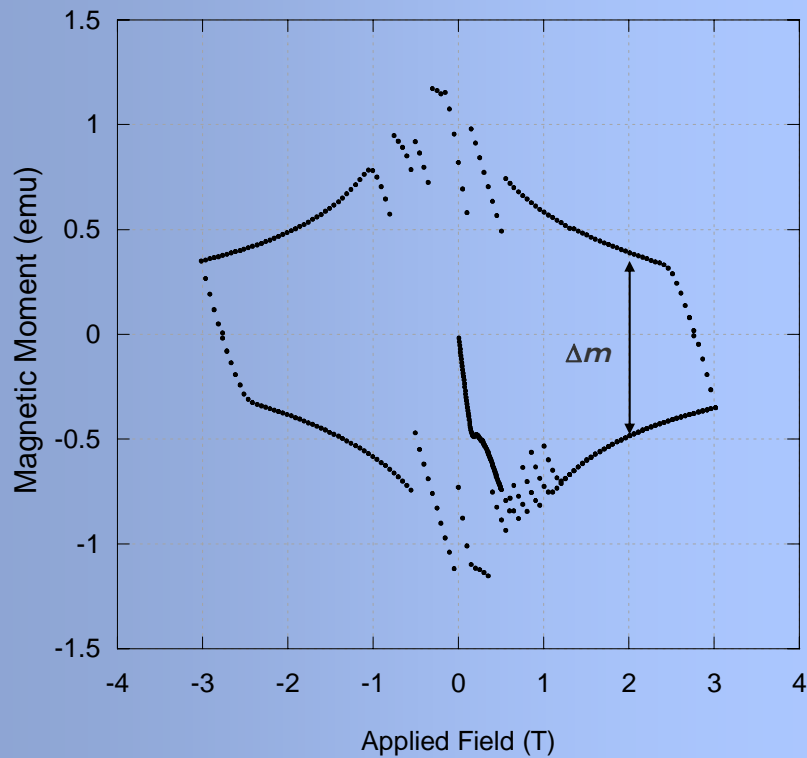
Susceptibility  $\chi_0$  can be calculated using FEM.

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

→ comparison with  $I_c$  results

→ scaling law

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

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

$$\eta = r_{Sn} / r_{Nb_3Sn}$$

$$d = 2r_{Nb_3Sn}$$

$$S = \pi(r_{Nb_3Sn}^2 - r_{Sn}^2)$$

$$I_c = N_{fil} J_{c,sc}(B, T) S$$

## Information coming from $\chi(B, T)$

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

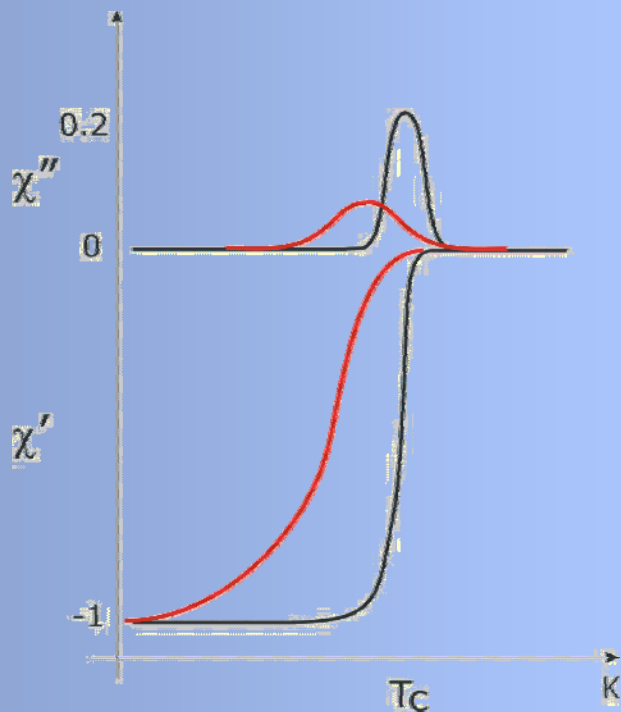
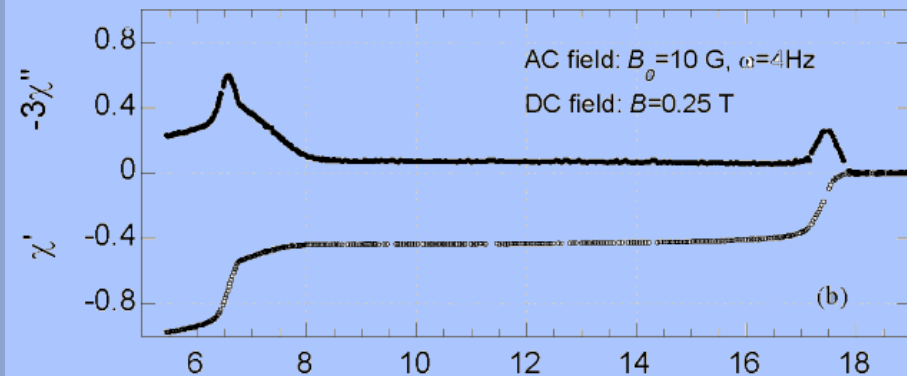
$\chi_0$  → external susceptibility under conditions of perfect screening (Meissner state)

$\chi''$  → dissipation, magnetic field really experienced by the sample

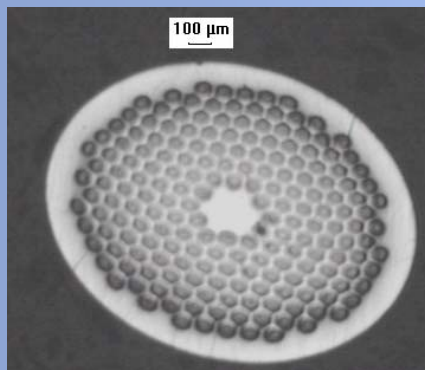
- $T_c(B)$
- Nb shielding volume
- $Nb_3Sn$  shielded volume

Sharp transition → homogeneous material

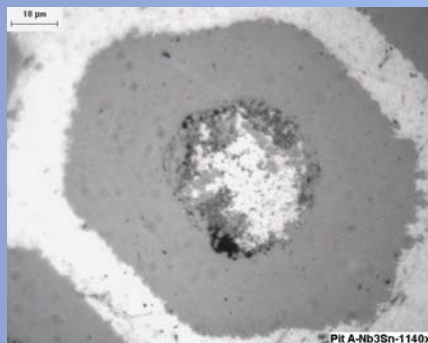
Smooth transition → key of dishomogeneity



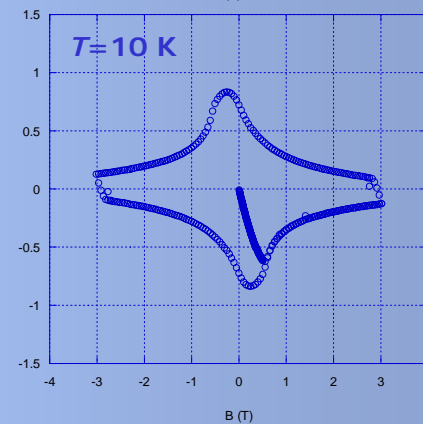
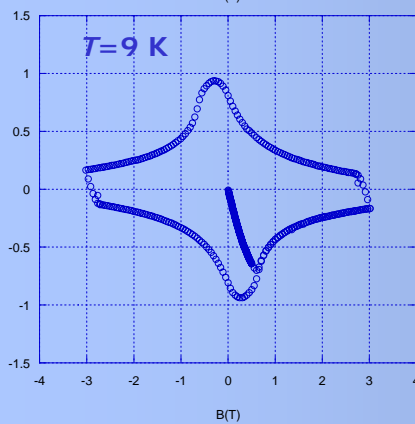
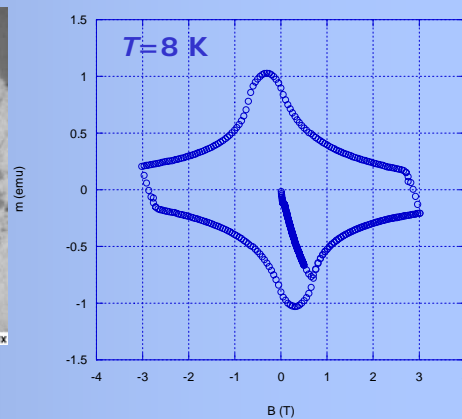
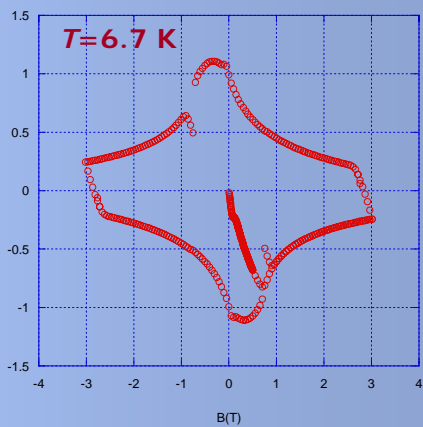
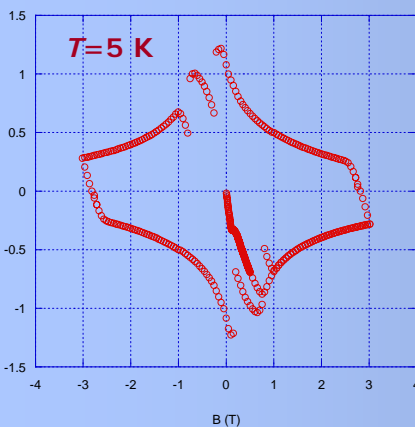
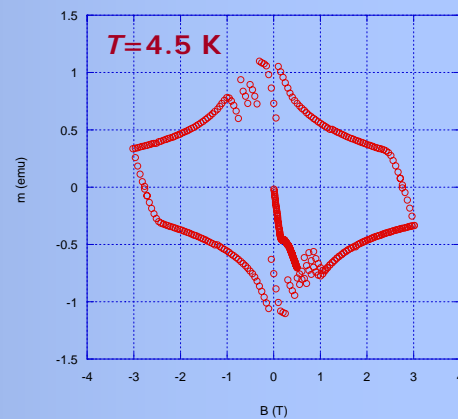
**Preliminary measurements on Internal TIN and "old" PIT samples showed flux jumps for  $T < 7\text{K}$  and  $B < 1\text{T}$**



Old PIT sample

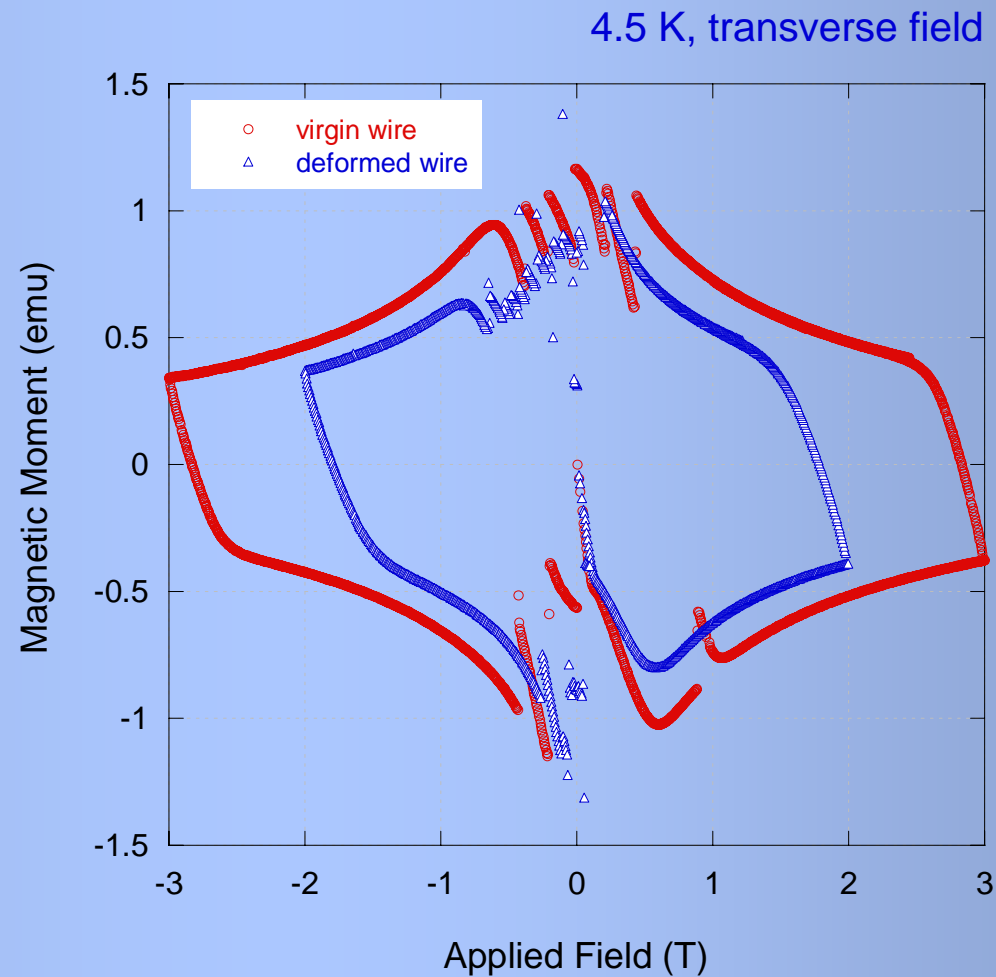
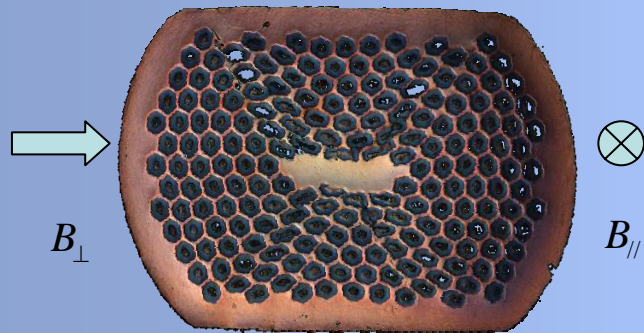


Enlarged Filament Area



$m(B)$  at different temperatures, flux-jumps up to  $T = 6.7\text{ K}$

*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

$$\mu_0 J_c^2 d^2 / 4 \gamma C (T_c - T_{op}) > 3$$

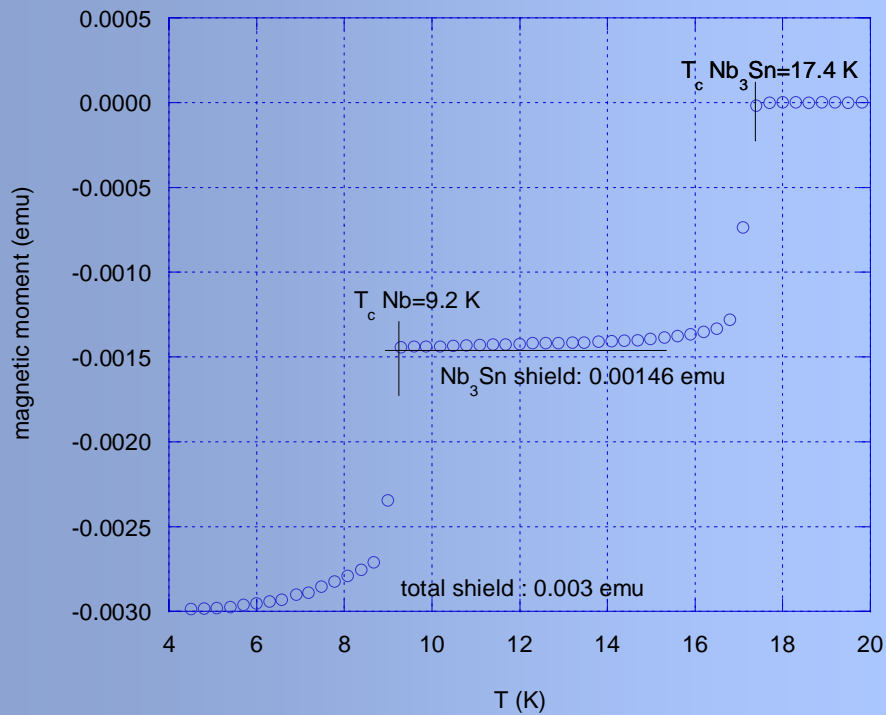
$J_c$  is the critical current density of the filaments

$d$  is the filament diameter

$C$  is the specific heat

$T_c$  is the critical temperature

The development of high  $J_c$  Nb<sub>3</sub>Sn wires requires very low  $d$



*Are only large Nb<sub>3</sub>Sn the sole responsible for instabilities?*

$$m = \chi_0 B_a V$$

$$m = 3 \cdot 10^{-3} \text{ emu} = 3.77 \cdot 10^{-12} \text{ Wb m}$$

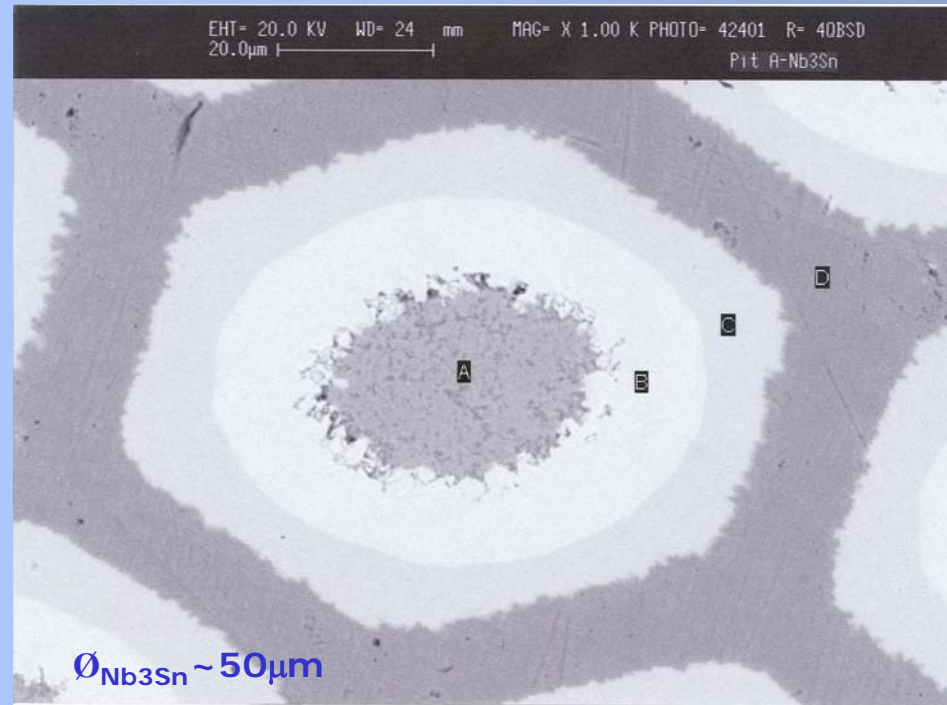
$$V_{\text{shielded Nb}} = 3.77 \text{ mm}^3$$

$$V_{\text{shielded Nb}_3\text{Sn}} = 1.83 \text{ mm}^3$$

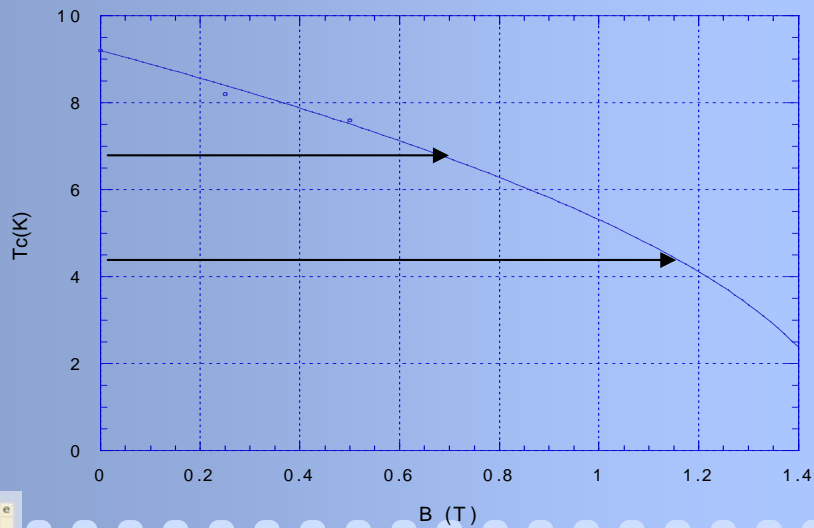
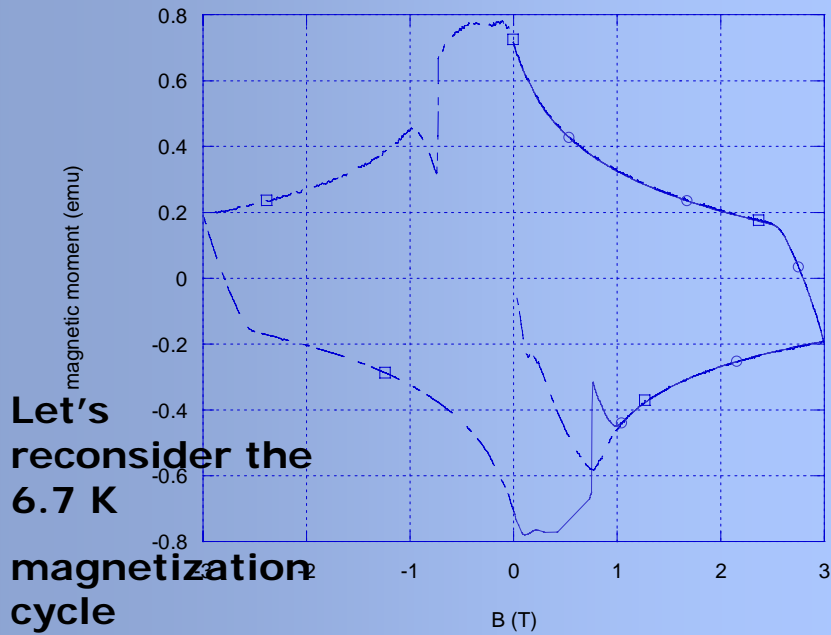
$$\varnothing_{\text{Nb}} = 65 \mu\text{m},$$

$$\varnothing_{\text{Nb}_3\text{Sn}} = 44 \mu\text{m}$$

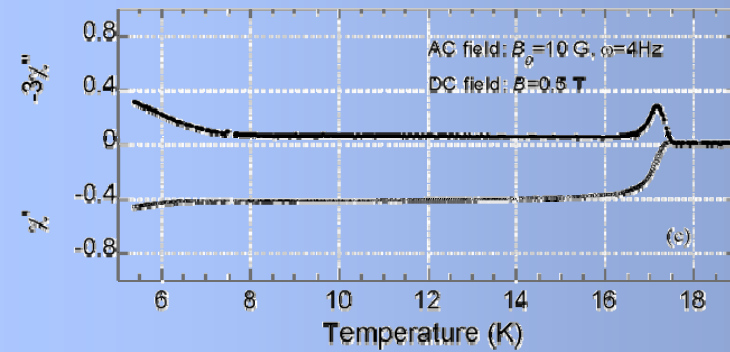
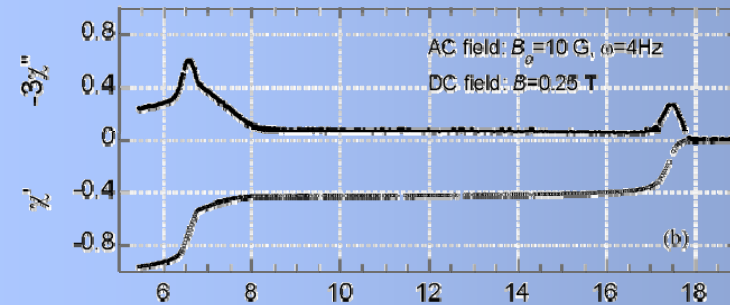
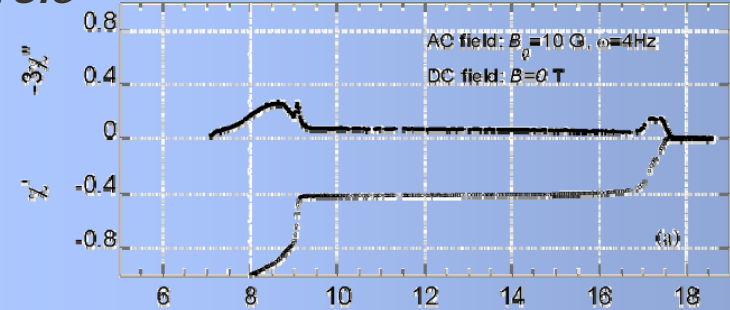
$$\text{Ratio } \varnothing_{\text{Nb}_3\text{Sn}} / \varnothing_{\text{Nb}} = 67\%$$



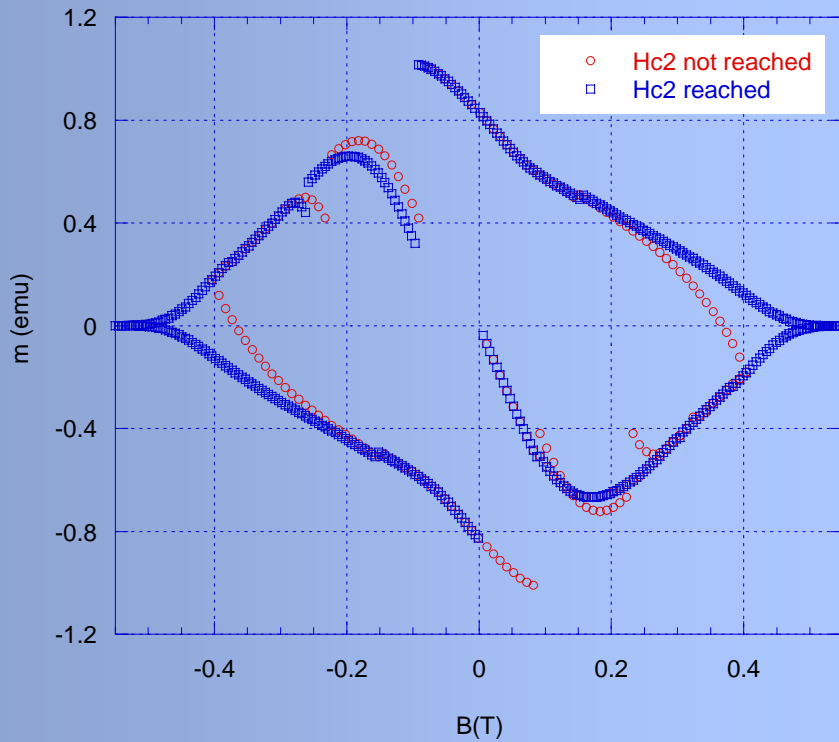
**There is a large amount of unreacted Nb in the conductor !!!**



### Nb role



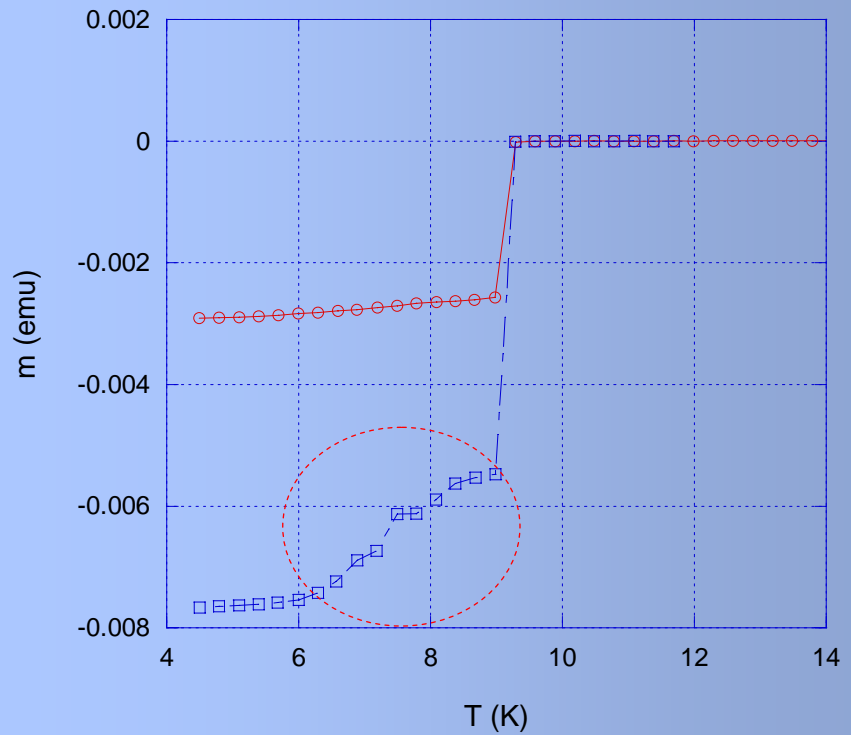
According to this extrapolation, at 4.2 K we can have strong effects on magnetization due to this *dirty* Nb phase



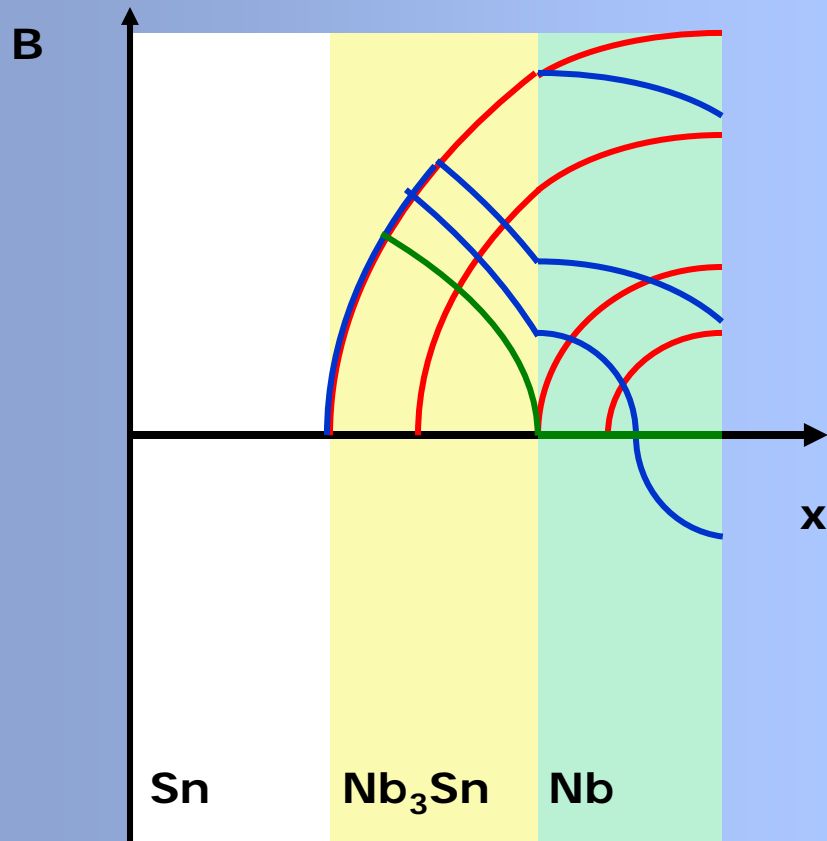
**Nb role:**  
*measurement on unreacted old PIT*

**$m(B)$  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 was suspected to be responsible for flux jumps at  $B < 1\text{T}$



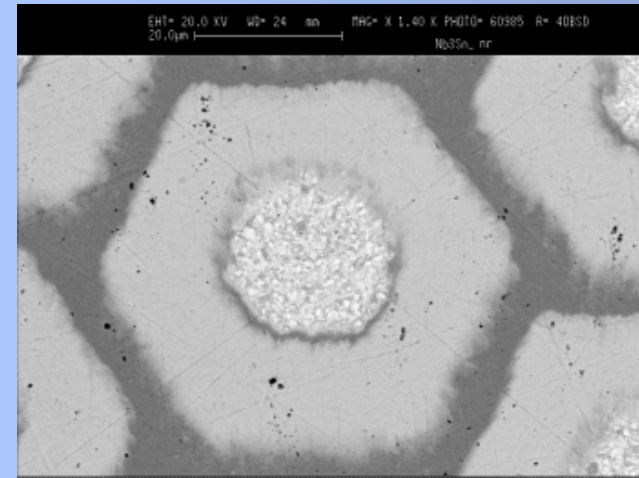
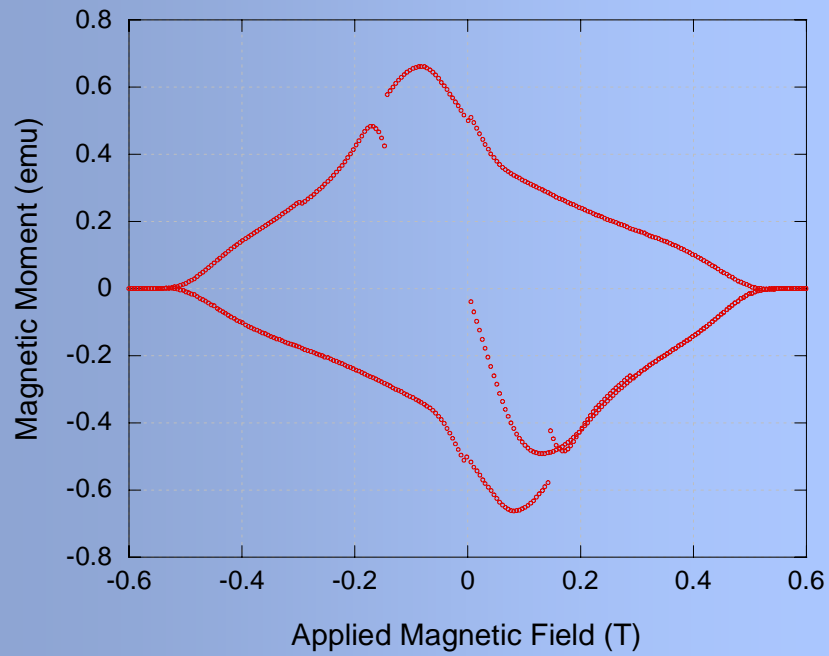
A simple scheme based on flux penetration according the critical state model shows how instabilities in Nb can drive flux jump in  $\text{Nb}_3\text{Sn}$

Indications:

Increase the cross section of  $\text{Nb}_3\text{Sn}$  (i.e. reduce the unreacted Nb)

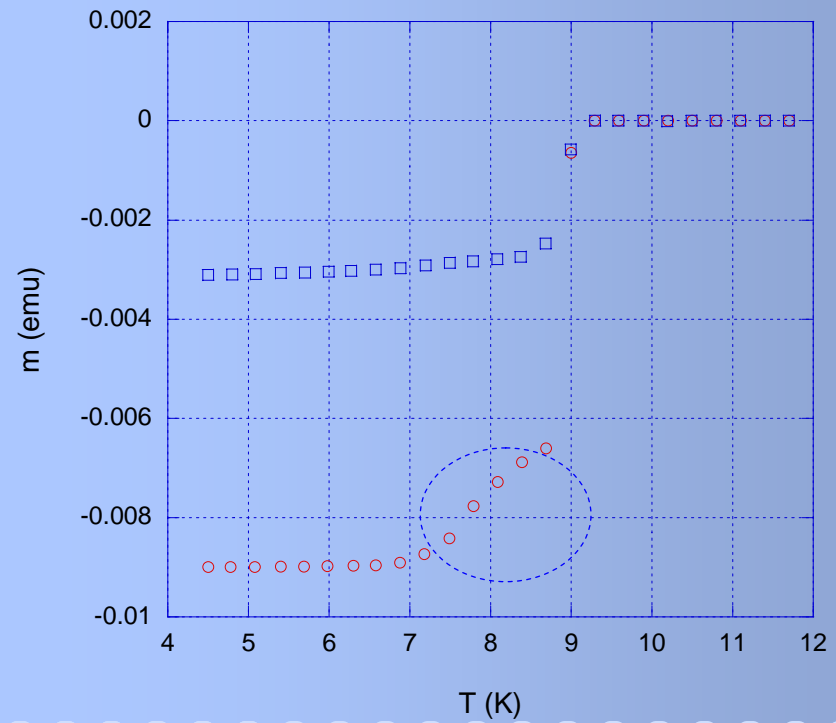
Depress transport properties of Nb

**Nb role:**  
**measurement on unreacted NED PIT**

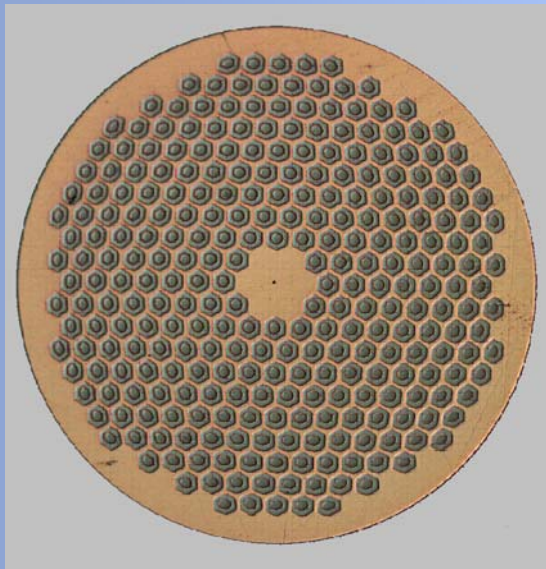


**$m(B)$  in transverse field at 4.5 K →  
only one flux-jump at =0.1 T!**

**$m(T)$  →  
smooth transition of Nb  
but in a narrower  $T$  range, down to 7 K**

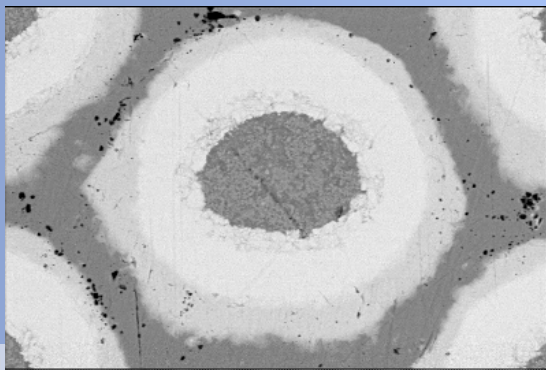


# Measurements of SMI/NED wires with final design

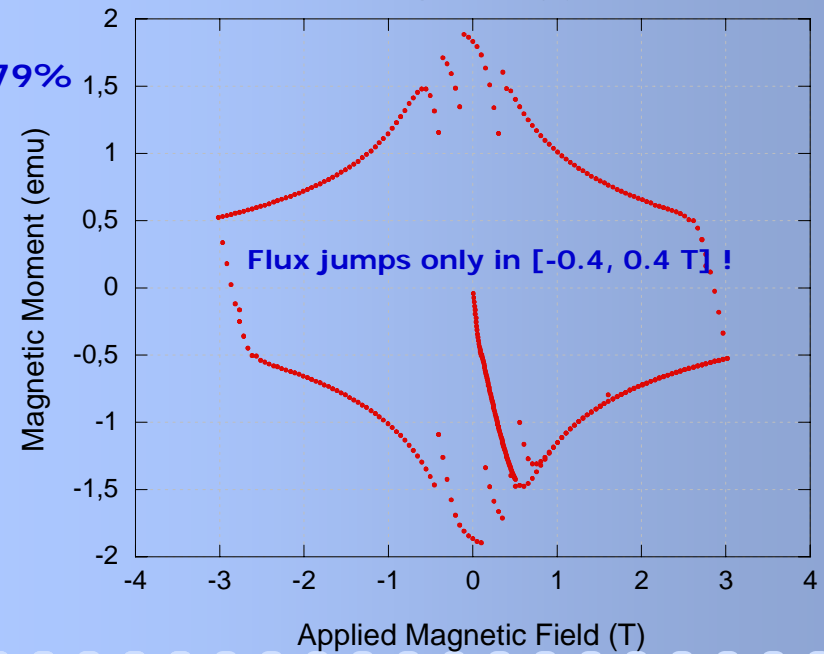
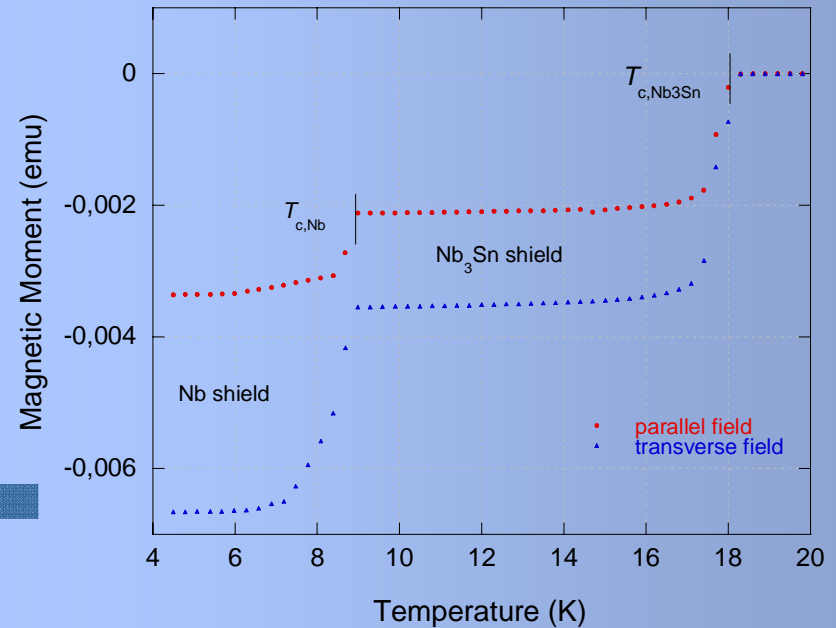


$\varnothing = 1.26 \text{ mm}$

$\varnothing_{\text{Nb}} = 58 \mu\text{m}$ ,  
 $\varnothing_{\text{Nb}_3\text{Sn}} = 46 \mu\text{m}$   
 Ratio  $\varnothing_{\text{Nb}_3\text{Sn}} / \varnothing_{\text{Nb}} = 79\%$

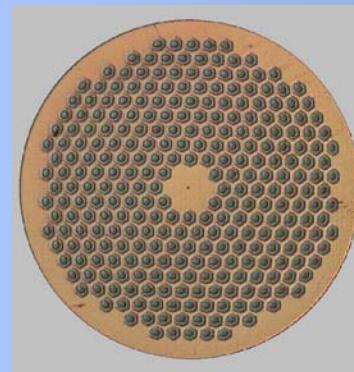
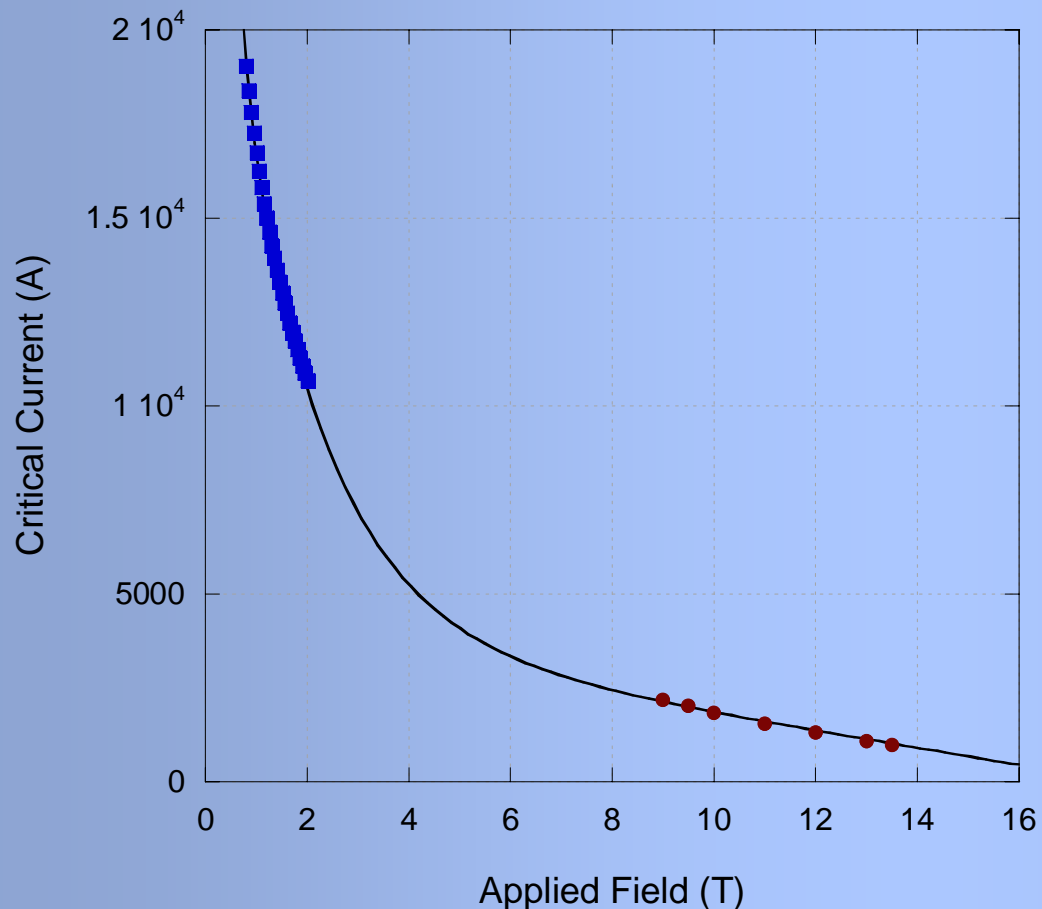


$\varnothing_{\text{Nb}} \sim 60 \mu\text{m}$ ,  
 $\varnothing_{\text{Nb}_3\text{Sn}} \sim 46 \mu\text{m}$



### Scaling curve for $I_c$ using $m(B)$ measurements

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



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

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



## CONCLUSIONS

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

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