Magnetic and Electromechanical Characterization of a High-J_C RRP Wire for the MQXF Cable

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ABSTRACT - In this work, we summarize the results of an experimental campaign of inductive and transport measurements aimed at the evaluation of the electromechanical performances of a 0.85 mm diameter RRP® wire relevant for the HiLumi LHC project [1]. SEM micrographs have been used to evaluate the sub-element diameter and Cu/non-Cu ratio, whereas the chemical composition across the sub-element sections has been studied via energy dispersive X-rays spectroscopy. The critical current dependence on the magnetic field and uniaxial applied strain (between -0.2% and 0.5%) has been investigated in a temperature range comprised between 4.5 K and 10 K. Furthermore, the strand magnetization up to 12 T has been measured at different temperatures (4.3 K-14 K) to determine the strand's effective filament diameter and to assess the critical current density in the temperature and field range where transport current measurements were not available. The experimental results have been analysed in the framework of a scaling law model, by using two different approaches for the data fitting. These results provide an accurate parameterization of the critical surface in terms of field, temperature and strain, to be used as a general reference for all purposes aimed at realizing a magnet sound design.

SAMPLE - The Nb_3Sn wire measured is a Ti-ternary RRP® 108/127 with a nominal diameter of 0.85 mm. **Table I** summarizes the wire's main characteristics. Heat Treatment (HT): RT to 210 °C for 48 h; 210 °C to 400 °C for 48h; 400 °C to 665 for 50h; ramp rates: 25 °C/h).

Table I. Characteristics of the MQXF wire.

Billet ID:	AO08S00142A02UY
Nominal Φ (mm)	0.850±0.003
Wire t. p. (mm)	19±3
Wire twist direction	Right-handed screw
Sub-element Φ (μm)	≤ 55
Cu/nonCu ratio	min: 1.10; max 1.30
Minimum J_C	632 A @ 12 T, 4.22 K 331 A @ 15 T, 4.22 K
RRR	> 150
n-value @ 15 T, 4.2 K	> 30

WITNESS STRAND - The critical current of a virgin witness strand has been measured at CERN in the field range 12 to 15 T, at 4.3 K (**Table II**). Critical current data have been analysed by means of an iterative procedure, where:

$$I_c = C\frac{b^{0.5}(1-b)^2}{B_p} \qquad B_p = B + \left(\frac{2}{R_{eff}} - hel\right)\cdot I_C \cdot 10^{-4}$$

$$R_{eff} = R\cdot C_R \qquad B_{c2} = B_{c20}(1-t^{1.52})$$

$$b = \frac{B}{B_{c2}};\ t = \frac{T}{T_{c0}} \qquad C = C_0(1-t^{1.52})(1-t^2)$$

The fitting parameters are reported in **Table III**.

Table II. Electrical characterization of the witness strand. I'_c values are temperature-corrected at 4.3 K and field-corrected at $B_p = \mu_0 H_p$.

$\mu_0 H$ [T]	$\mu_0 H_p$ [T]	T [K]	I_c [A]	I'_c [A]
12.00	12.32	4.30	690.5	690.81
12.00	12.33	4.29	693.2	692.28
13.00	13.27	4.30	576.1	576.38
14.00	14.22	4.30	472.0	472.26
14.00	14.22	4.30	471.6	471.86
15.00	15.18	4.31	379.8	380.65
15.00	15.18	4.31	381.8	382.42

Table III. Main fit parameters for the witness strand.

C_0 [A·T[	56450.1±1137.1	*Free*
B_{c20} [T]	29.17±0.42	*Free*
T_{c0} [K]	16.67±1.47	*Free*
C_R	0.84	*Constant*
R [mm]	0.425	*Constant*
hel	0.9	*Constant*

METALLOGRAPHY - Back-Scattered, Field Emission SEM (BS-FESEM) and detailed Energy Dispersive X-Rays (EDX) analyses have been carried out, see Figs 1-3. The wire diameter, averaged along two perpendicular directions, is 0.885/0.887 mm before/after the HT. An open-source software package (*Fiji*) has been used to measure the mean sub-element diameter, *d*. We found *d* = 48 ± 1 μm, and Cu/nonCu = 1.05.

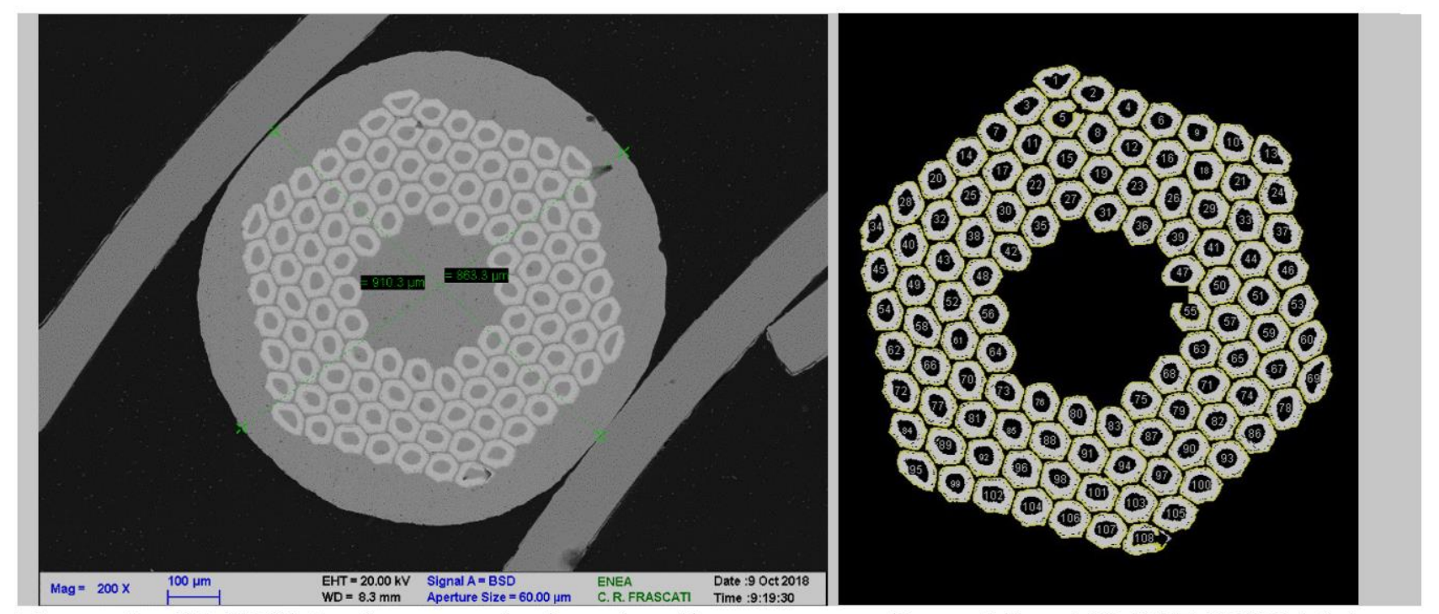
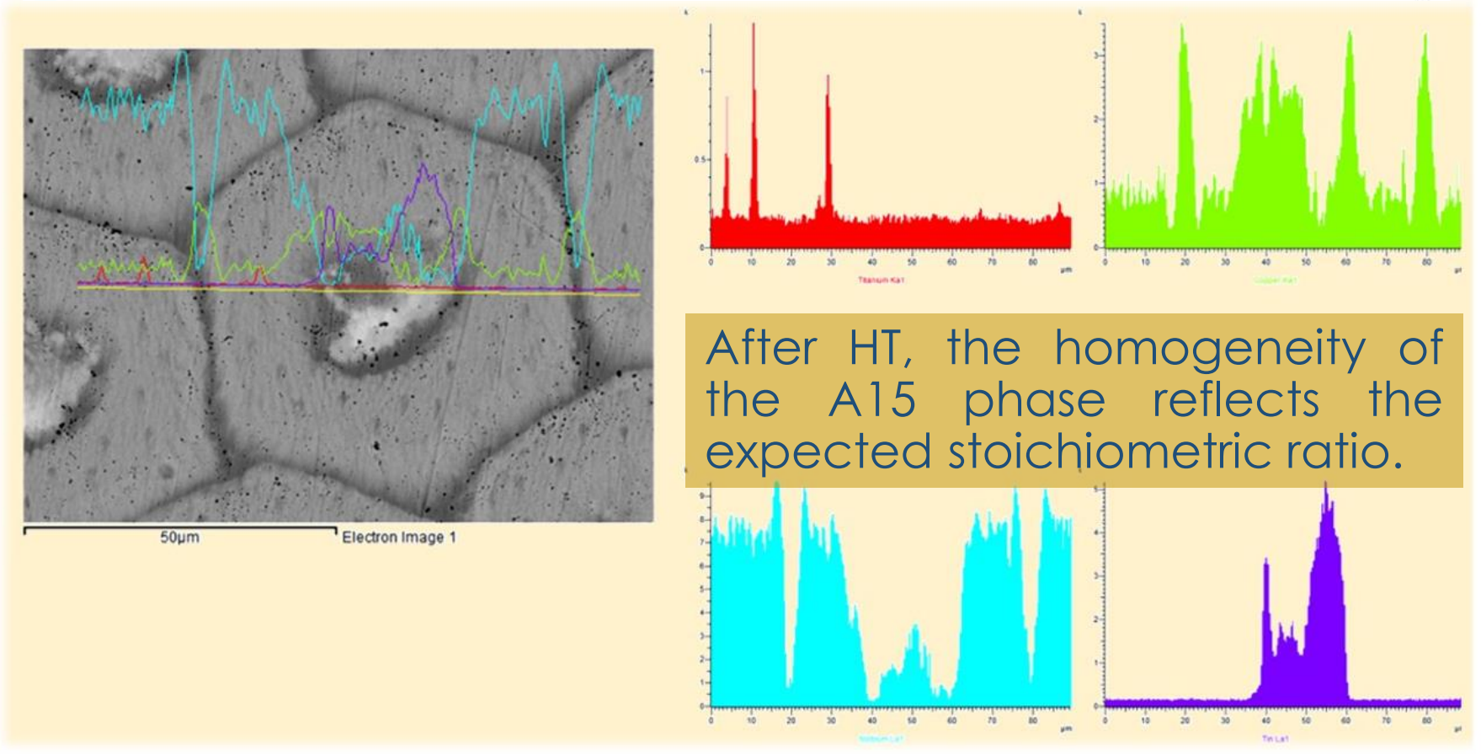
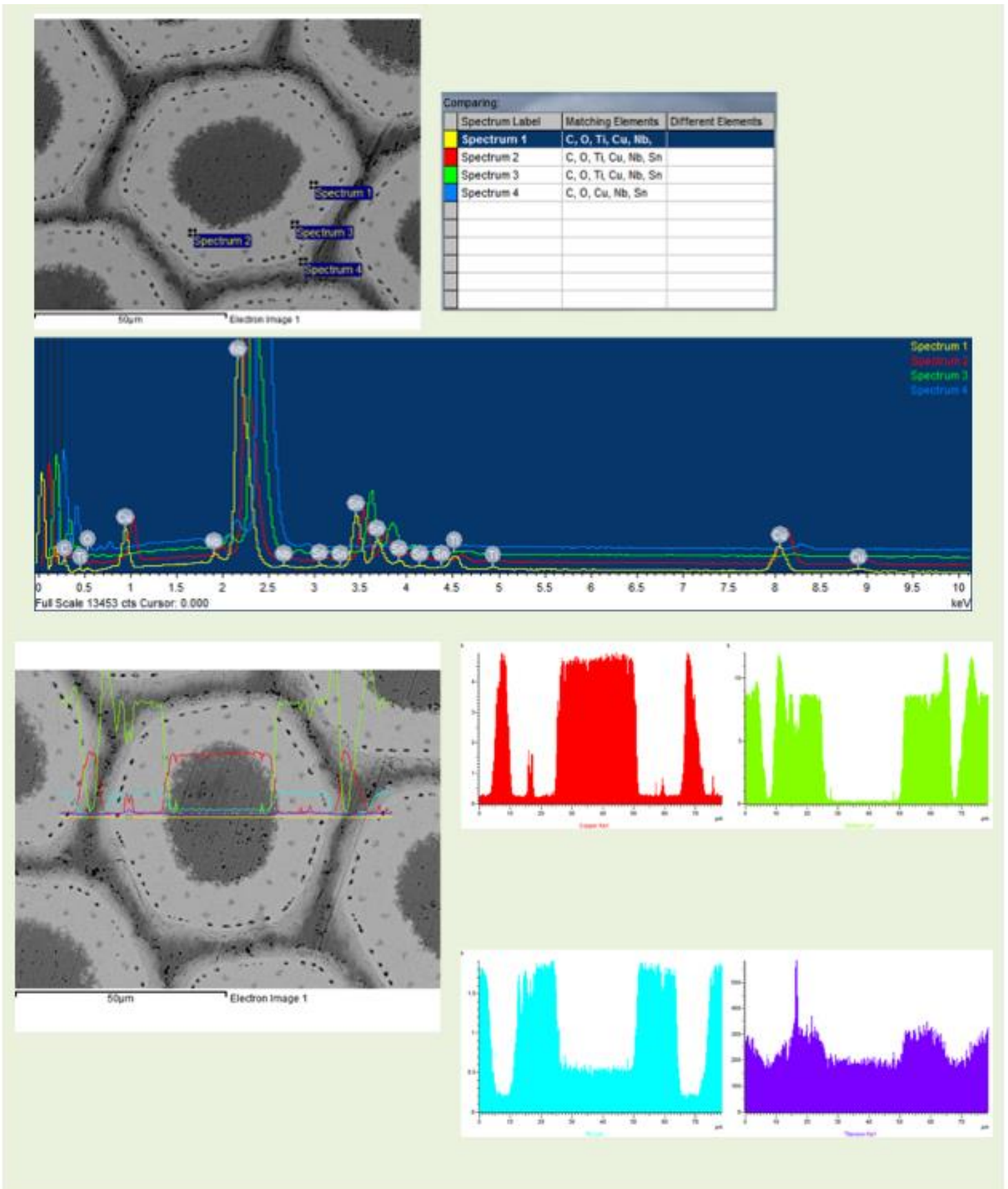


Figure 1. BS-FESEM micrograph showing the cross-section of the 108/127 RRP® high-J_C wire, and the same image after applying a *threshold* with Fiji software.



After HT, the homogeneity of the A15 phase reflects the expected stoichiometric ratio.

Figure 2. EDS analysis made on a selected Nb_3Sn sub-element before heat treatment.



Comparing:

Spectrum Label	Matching Elements	Different Elements
Spectrum 1	C, O, Ti, Cu, Nb,	
Spectrum 2	C, O, Ti, Cu, Nb, Sn	
Spectrum 3	C, O, Ti, Cu, Nb, Sn	
Spectrum 4	C, O, Cu, Nb, Sn	

Figure 3. EDS analysis made on a selected Nb_3Sn sub-element after heat treatment.

ELECTROMECHANICAL CHARACTERIZATION - The tests as a function of strain and temperature, at different magnetic field values, have been carried out using the ENEA Walters spring test rig. The wire was soldered over its entire length on the Cu-Be spring, in order to allow also the application of compressive strain values. Figs. 4-5 summarize all data collected on the MQXF high-J_c strand with the ENEA-WASP.

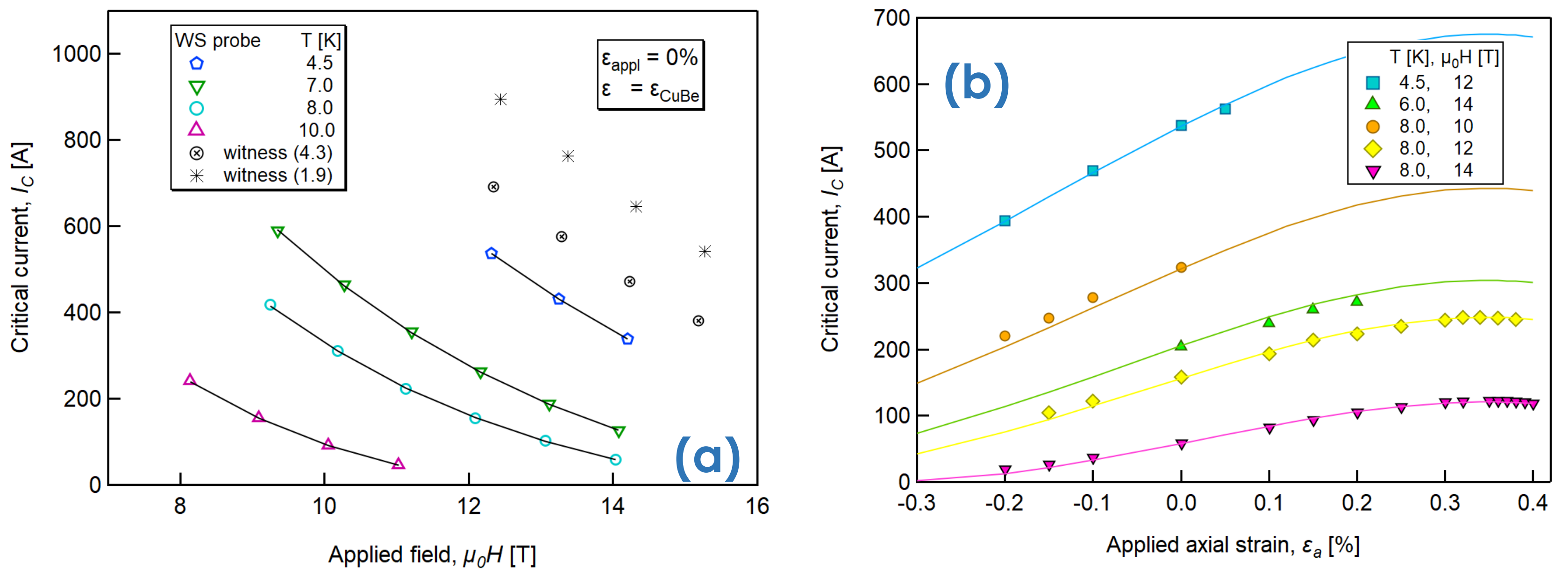


Fig. 4. I_C vs.: (a) peak field, at different temperatures and ε_{appl}=0%; (b) applied strain, at different temperature and external magnetic fields. The continuous lines represent fits to the ESE parameterization by a *Multi-Step Scaling* approach.

Scaling law - The Extrapolative Scaling Expression (ESE) relation [2] with the *Hybrid2* temperature and exponential $s(\varepsilon)$ parameterizations [3] is now being implemented at CERN for calculating the margin of the HL-LHC magnets.

$$I_c(B_p,T,\varepsilon) = \frac{C_0}{B_p}\cdot[s(\varepsilon)]^{\sigma}[(1-t^{1.5})\cdot(1-t^2)]^{\frac{\eta}{2}}b^p\cdot(1-b)^q \qquad \text{with } p = 0.5 \text{ and } q = 2$$

Reduced magnetic field → $b \equiv B_p/B_{C2}(T,\varepsilon)$

Reduced temperature → $t \equiv T/T_C(\varepsilon)$

$$B_{c2}(T,\varepsilon) = B_{c20}(\varepsilon_{CuBe})\cdot s(\varepsilon)\cdot(1-t^{1.5})$$

$$T_c(\varepsilon) = T_{c0}(\varepsilon_{CuBe})\cdot[s(\varepsilon)]^{\frac{1}{3}}$$

Data analysis – <u>*Multistep Scaling Method*</u> used to obtain the ESE parameters (**Table IV**):

1. From Kramer plots, data of Fig. 4a → extrapolate $B_{c2}(T, \varepsilon_{CuBe})$
2. Fit to $B_{c2}(T, \varepsilon_{CuBe}) = B_{c20}(\varepsilon_{CuBe})\cdot(1-t^{1.5})$ → get $T_{c0}(\varepsilon_{CuBe})$
3. Fit data of Fig. 4a to Eq. $I_C(B_p,\varepsilon_{CuBe}) = C/B_p\cdot b^{0.5}(1-b)^2$ → get C
4. Fit C *vs.* t to $C = C'(\varepsilon_{CuBe})[(1-t^{1.5})(1-t^2)]^{\eta/2}$ → get C', η
5. Fit of 8 K, 14 T dataset (Fig.4b) to ESE → get ε_{L0}

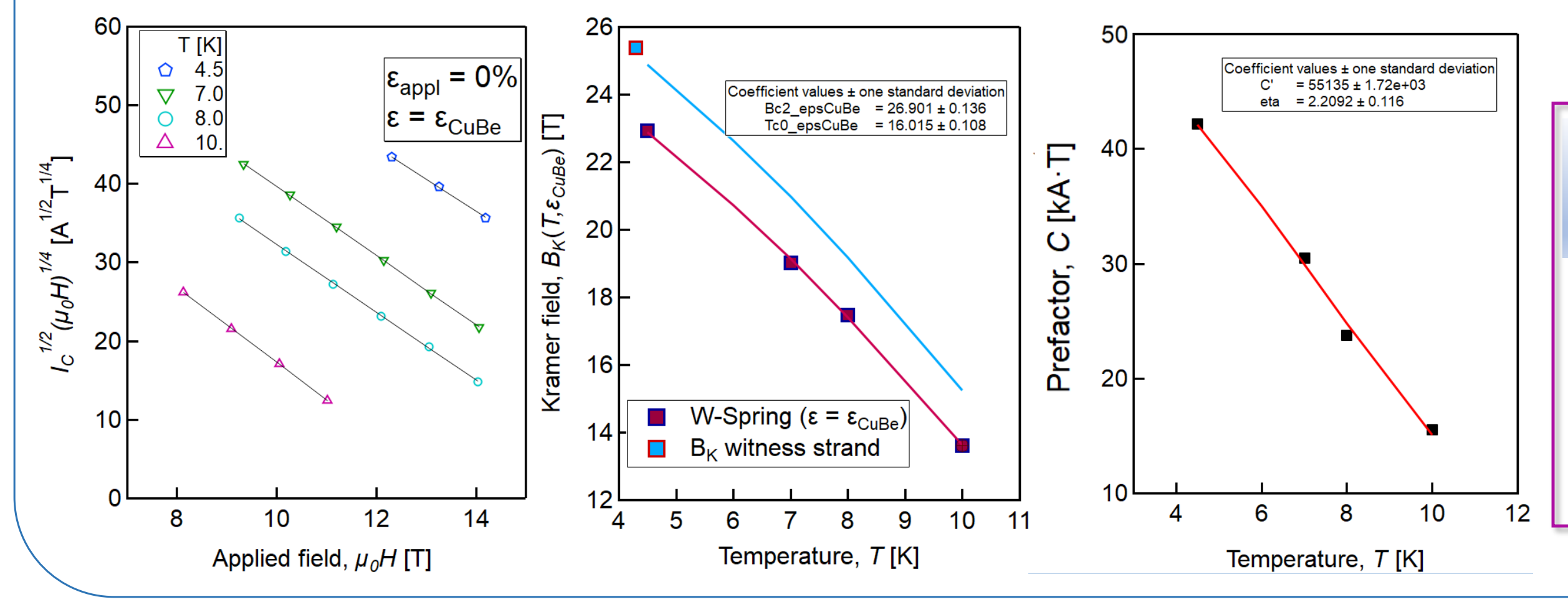


Table IV. ESE fit parameters for the high-J_c MQXF strand.

	value	unit
C_0	62590	A·T
$T_{c0,max}$	16.69	K
$B_{c20,max}$	30.4	T
C_1	0.75*	-
ε_{L0}	-0.3535	%
η	2.21	-
σ	1.07*	-

(*) fixed to the values from ref. 2.

$$s(\varepsilon) = \frac{e^{-C_1\frac{J_2+3}{J_2+1}J_2} + e^{-C_1\frac{I_1+3}{I_1+1}I_1}}{2}$$

$$J_2 = \frac{1}{3}(\varepsilon_{L0} - \varepsilon_{T0} + (1+\nu)\varepsilon_a)^2$$

$$I_1 = (1-2\nu)\varepsilon_a + \varepsilon_{L0} + 2\varepsilon_{T0}$$

$\nu = 0.36$; $\varepsilon T_0 = -\nu\cdot\varepsilon_{L0} + K$ $(K = 0.1)$

MAGNETIC CHARACTERIZATION - Isothermal magnetization loops have been measured by means of an Oxford MAGLAB VSM provided with a 12 T superconducting magnet and a VTI (Fig- 5). The 5-mm sample is mounted on the sample-holder, with its axis perpendicular to the background field. Minor loops were also measured at 4.3 K at different ramp rate ranging from 0.2 T/min to 1 T/min (Fig. 6). No appreciable variation was detected in hysteresis loops areas, thus implying that the coupling time constant $n\tau$ is sufficiently low to neglect any coupling loss contribution for ramp rates up to 1.0 T/min.

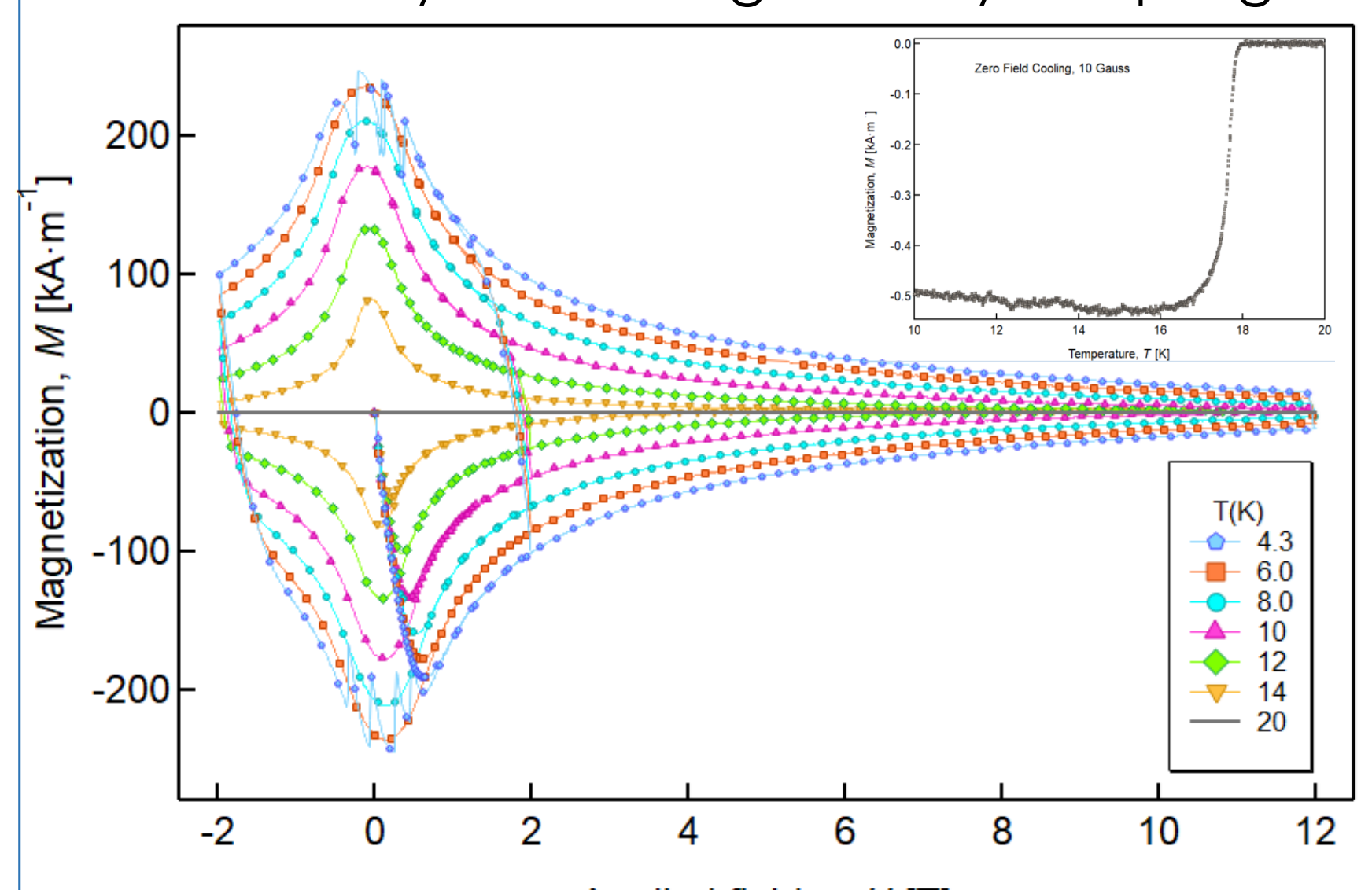


Fig. 5. The magnetization loops measured at different temperature as a function of field. Flux jumps are present at 4.3 K up to μ_0H = 0.5 T.

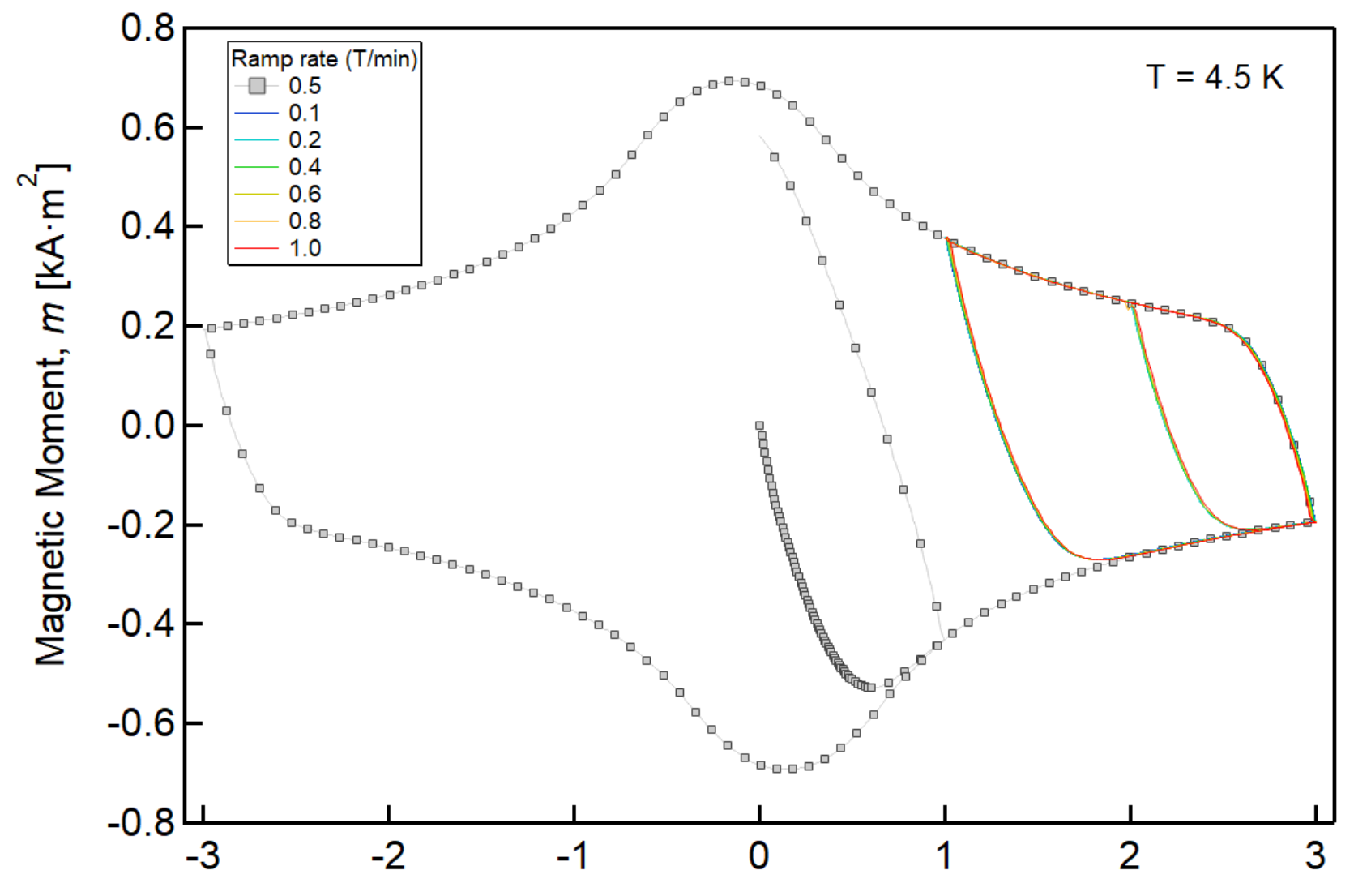


Fig. 6. Isothermal magnetization loop measured at T = 4.5 K, ± 3 T. Minor magnetization loops, centered at 2.0 T, have been measured at different field ramp rates.

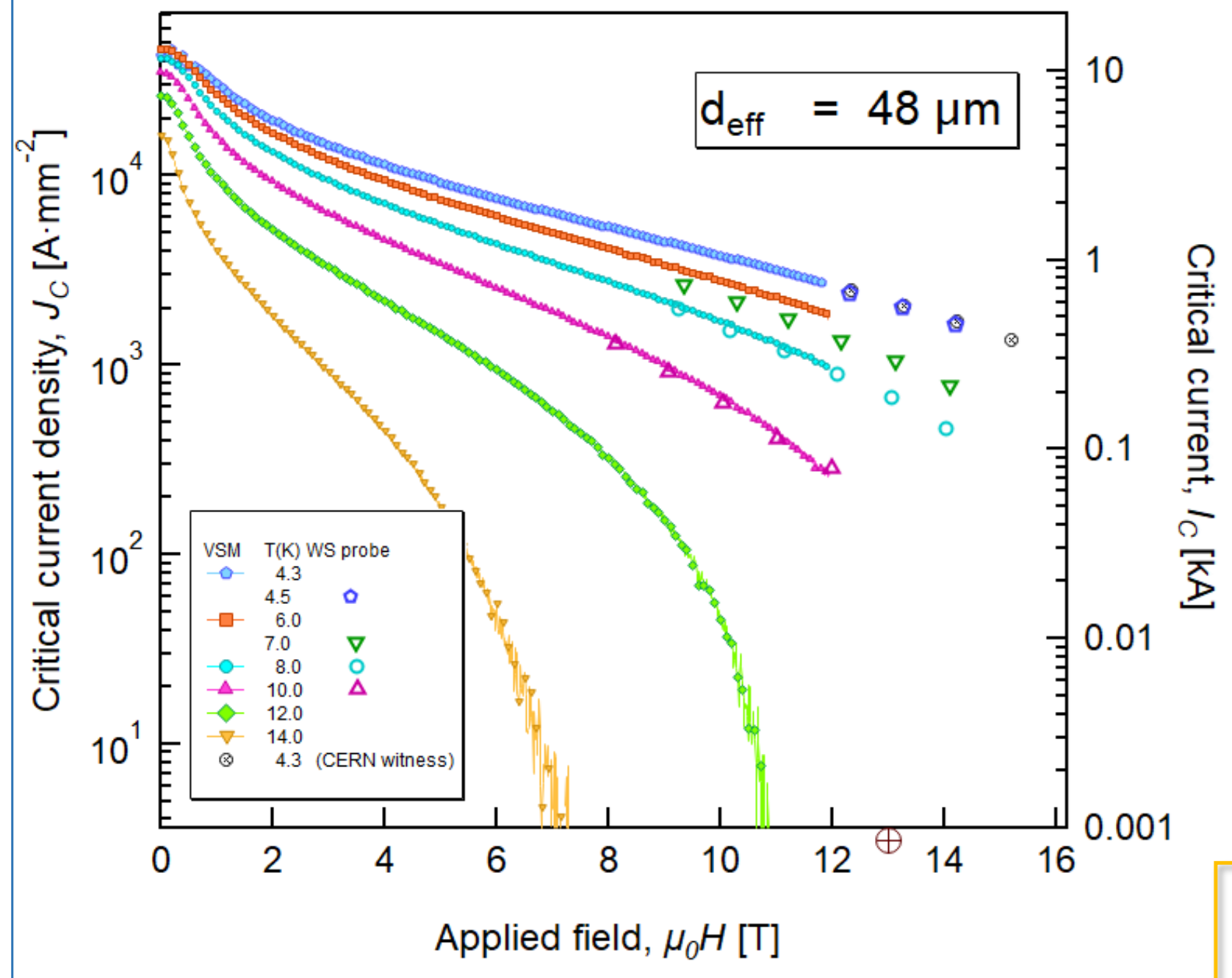


Fig. 7 The in-field behaviour of the critical current in the temperature range 4.3-14 K. Transport data have been rescaled with the ESE scaling law.

The critical current density is obtained by means of the Bean critical state model [4]:

$$J_c(B)[A/cm^2] = \frac{30}{4}\pi\frac{\Delta M(B)[k\,A/m]}{d_{eff}[cm]}$$

ΔM(B) is the width of the magnetization loop at a given applied field value *B*

d_{eff} = 48 μm is the effective diameter, in line with SEM analysis (Fig. 1)

With ***ESE***, transport data can be scaled on the inductive I_c curves with a proper strain value

CONCLUSIONS - A comprehensive experimental study was carried out to investigate the strain sensitivity of *high-J_c* Nb_3Sn wires to be used in the MQXF quadrupoles. The results have been analysed in terms of a novel Multi-Step Scaling method. For a reasonable estimate of the critical surface, magnet designers can assume the following ESE scaling parameters: C_0 = 62.5 kA·T; $T_{c0,max}$ = 16.69 K; $B_{c20,max}$ = 30.4 T; η = 2.2; σ = 1.07. These parameters are in line with those published previously [2]. For the exponential scaling law [3], the recommended parameters are: C_1 = 0.75; ε_{L0} = -0.3535; ν = 0.36; K = 0.1.

REFERENCES

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