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ASTRACT

Analysis of STRain Affected CharacTeristics of brittle SC cables

«Critical current evaluation of Nb_3Sn samples from m(B) curves by SEM image processing in ANSYS APDL using Space Claim import tools»

S. Burioli et al. on behalf of the ASTRACT collaboration

Chats 2023

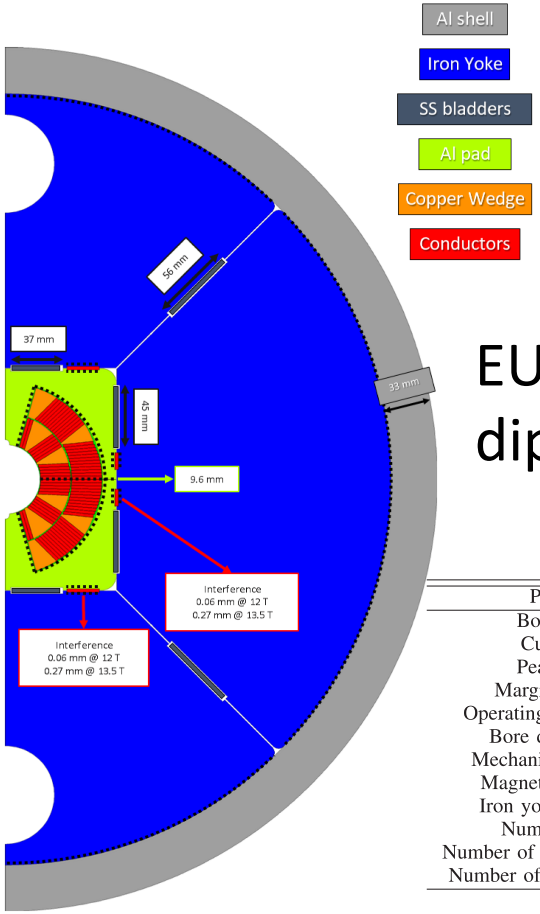
Applied Superconductivity

Outline

- Introducing the context
- The ASTRACT project
- Samples preparation
- Comparison of critical current and magnetization measurements
- ANSYS in our data analysis
- Results
- Summary

Introducing the contest

The next generation of Accelerator Magnets are targeting 16 T based on Nb3Sn cables. They need Jc up to 1500 A/mm^2 @ 16 T, 4.2 K

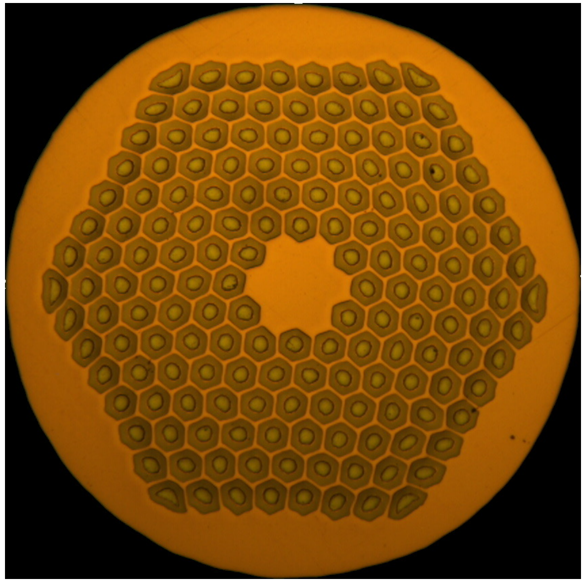


EUROCIRCOL -> FALCOND model: the first cosθ dipole with bladder & key assembly technique

Parameters	TDR	Review
Bore field [T]	12 / 14	12 / 13.5
Current [kA]	21.0 / 24.9	20.2 / 23.1
Peak field [T]	12.5 / 14.6	12.5 / 14.1
Margin on loadline	23.6% / 10.5%	24.6% / 14.7%
Operating temperature [K]	1.9	
Bore diameter [mm]	50	
Mechanical length [mm]	1500	
Magnetic length [mm]	1336	
Iron yoke radius [mm]	275	
Number of layers	2	
Number of blocks per quadrant	3+2	
Number of turns per quadrant	36 (5+5+2+12+12)	

F. Levi et al https://doi.org/10.1109/TASC.2023.3241832

FALCOND strand: RRP Ti-doped (162/169)



Diameter [mm]	1.0
Cu/non-Cu	0.9 ± 0.2
I_c at 4.22 K, 16 T [A]*	560 ± 14
d_{sub-el} (nom.) [µm]	58
Filament twist pitch [mm]	19 ± 3
RRR, rolled	159± 14
Heat treatment [°C]	665

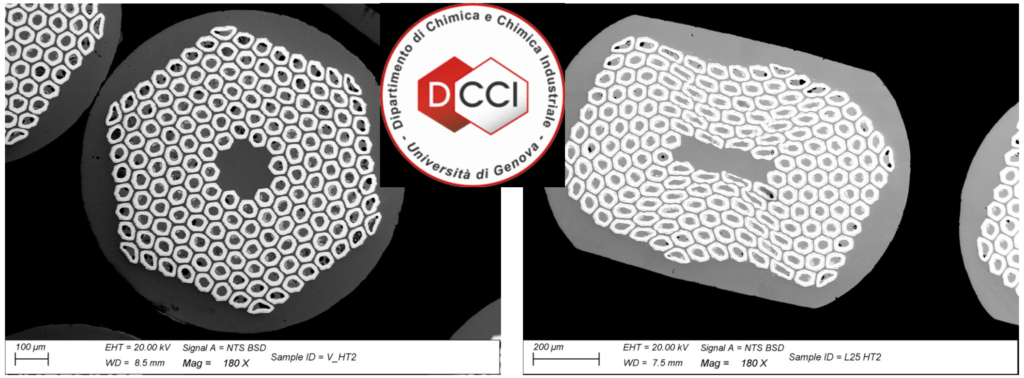
$*J_c = 1355\ A/mm^2$ (@16T, 4.2K)

Test laboratories

- INFN LASA (MI) – M . Prioli
- INFN Genoa – R. Musenich
- CNR/SPIN – A. Malagoli
- University of Genoa – Chemistry dip. – P. Piccardo
- ENEA – G. De Marzi
- INFN Salerno – G. Iannone

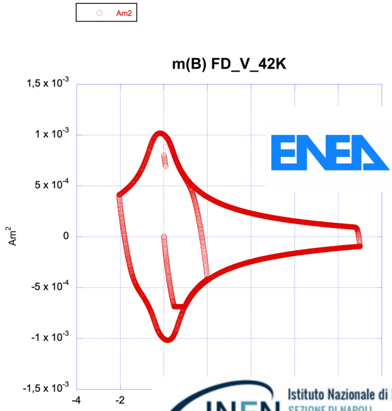
The ASTRACT project

A multidisciplinary approach to investigate the critical current degradation due to transverse strain in Nb3Sn strands.

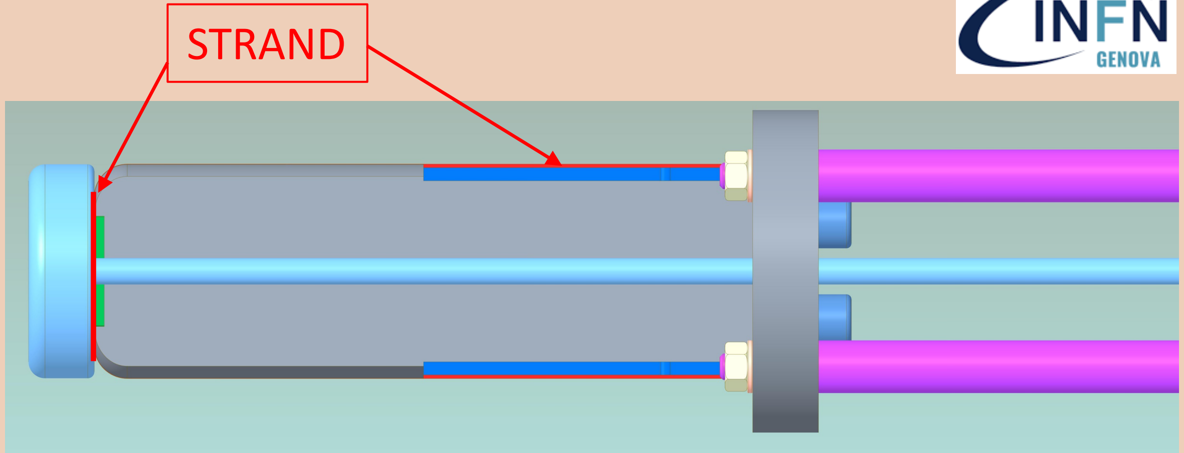


The first part: pre-HT lamination from 0 to 25% then measuring Ic by V-I (VAMAS) and m(B) VSM

The second part: measuring $I_c(B,T,\varepsilon_t)$ in a controlled transverse strain condition at 4.2 K from 11 to 13 T



The second part: measuring $I_c(B,T,\varepsilon_t)$ in a controlled transverse strain condition at 4.2 K from 11 to 13 T



We expect ε_t in the range 0 to -0.75%, i.e. 7.5 $\mu m/mm$

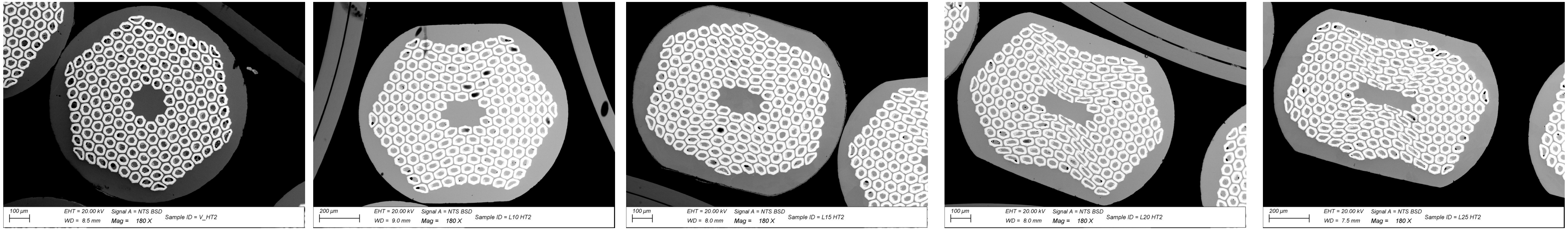
Considering E_{strand} = 80 GPa; Fmax = 30 kN; S = 50 mm^2

Samples preparation

We rolled 2 meter long strand up to 25% preparing VAMAS and VSM samples for the HT (CNR/SPIN)

VAMAS measured at LASA: 11 – 13 T @ 4.2K; VSM samples measured at ENEA VSM 18T @ 4.2 K

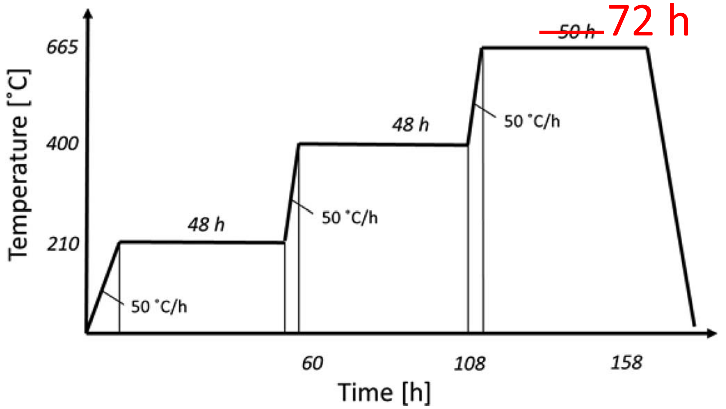
We collected around ten SEM images for any kind of lamination:



0% 10% 15% 20% 25%

What we try to understand:

A. Is there critical current degradation due to rolling?
B. Is there any effects due to shape changing of the sub-elements section?
C. Can we compare direct critical current measurements to critical current from magnetization curves?



F. Lackner *et al.*, doi: 10.1109/TASC.2016.2542339

Ic: VAMAS vs m(B)

1 – The Baumgartner's model

Evaluation of the Critical Current Density of Multifilamentary Nb_3Sn Wires From Magnetization Measurements

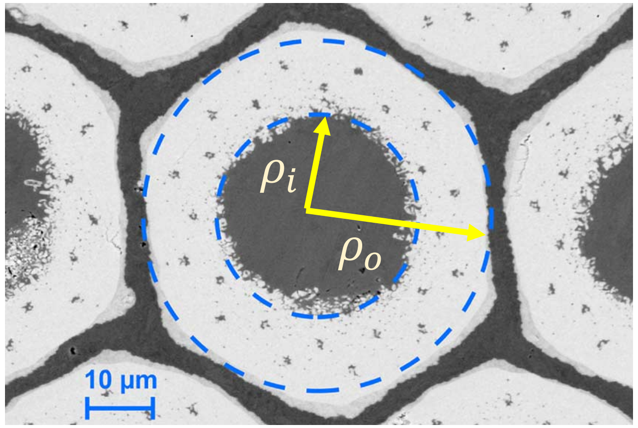
Baumgartner et al. 2012, DOI:10.1109/TASC.2011.2175350

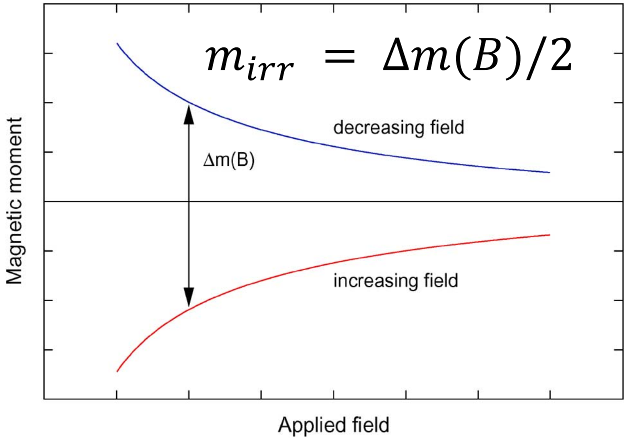
- Bean model, Jc constant over the sample and assuming no coupling between sub-elements in a strand:

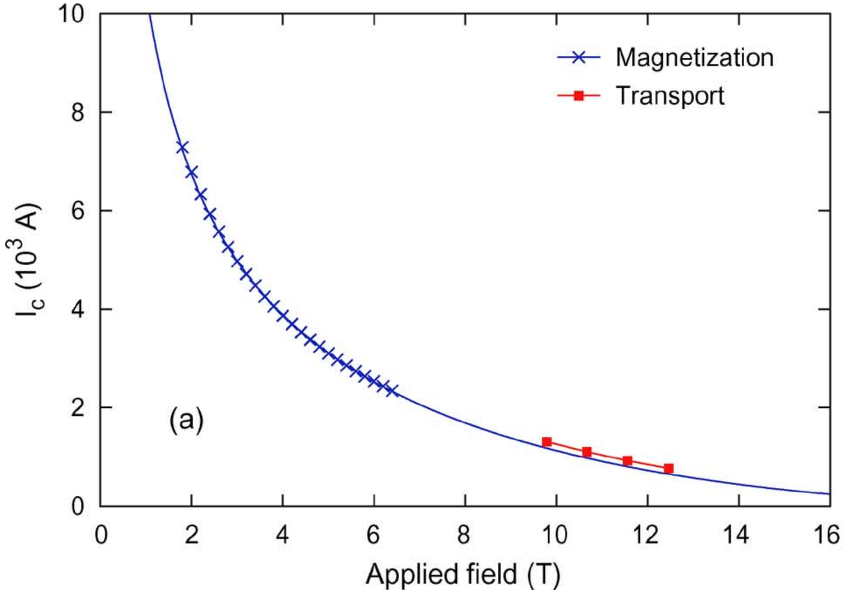
$$\left.\begin{array}{l}\vec{m} = \dfrac{1}{2}\displaystyle\int \vec{r}\times\vec{J}(\vec{r})\mathrm{d}^3r.\\[2ex] \vec{J}(\vec{r}) = J_\mathrm{c}\vec{e}_J(\vec{r}),\end{array}\right\} \quad \vec{m} = J_\mathrm{c}\cdot\underbrace{\frac{1}{2}\int \vec{r}\times\vec{e}_J(\vec{r})\mathrm{d}^3r,}_{\textit{shape factor}} \Rightarrow J_\mathrm{c} = \frac{3}{4}\cdot\frac{m_\mathrm{irr}}{NL\left(\rho_o^3-\rho_\mathrm{i}^3\right)},$$

#sub-elements

strand length







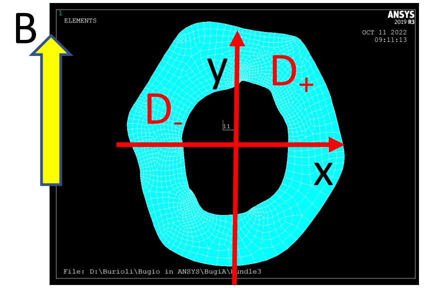
Ic: VAMAS vs m(B)

2 – Shape factor numerical calculation

We get the shape factor F by a first order numerical integration. For the i-th bundle:

Bean's model and current conservation ⇒ $\exists$ *a line* ∥ *to* $\vec{B}$ *leading to domains* D_+ *and* D_- *such that* $\int_{D_+} dS = \int_{D_-} dS$

Real bundle



We use the convention B || to the lateral side of the image. Starting from the bundle CM we look iteratively for the line parallel to B splitting the bundle in two equal areas D_+ and D_- -> this defines the domains of integration for the magnetic moment

$$\vec{m} = J_c \cdot \frac{1}{2} \int \vec{r} \times \vec{e}_J(\vec{r}) \mathrm{d}^3 r, \quad \Rightarrow$$

$$m_x^i = \frac{1}{2} J_c L \left(\int_{D_+^i} y dx dy - \int_{D_-^i} y dx dy \right) = 0$$

$$m_y^i = \frac{1}{2} J_c L \left(\int_{D_-^i} x dx dy - \int_{D_+^i} x dx dy \right) = J_c L F_y^i$$

$\Rightarrow$ We sum over the N bundles and we measure the intensity of $\vec{m}$

$$m_{irr} = J_c L \sum_{i=1}^{N} F_y^i = J_c L F$$

For the i-th real bundle, meshing the domain D_+ and D_- with N_+ and N_- elements we can approximate the shape factor as

$$F^i \approx \sum_{j=1}^{N_-} x_C^j \delta S_j - \sum_{j=1}^{N_+} x_C^j \delta S_j$$

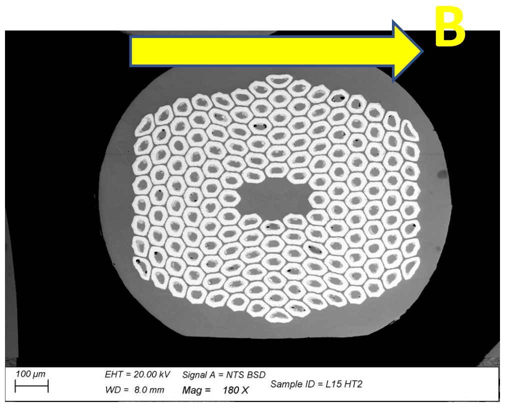
Perfect bundle	$f\ (m^3)$	F from ANSYS code (m^3)	$\lvert f - F \rvert / f$
Circular $f = 4/3(R_o^3 - R_i^3)$	$2.680311467\, 10^{-14}$	$2.680178946\, 10^{-14}$	$50\, 10^{-6}$
Elliptic $f = 4/3(a_o b_o^2 - a_i b_i^2)$	$2.46455893\, 10^{-14}$	$2.464592266\, 10^{-14}$	$14\, 10^{-6}$

Table 2. The shape factor evaluation for perfect bundles: theoretical value f vs numerical value F. $R_o = 29.6\, \mu m$; $R_i = 18\, \mu m$; $b_o = R_o$; $b_i = R_i$; $a_o = 26.2\, \mu m$; $a_i = 13.8\, \mu m$

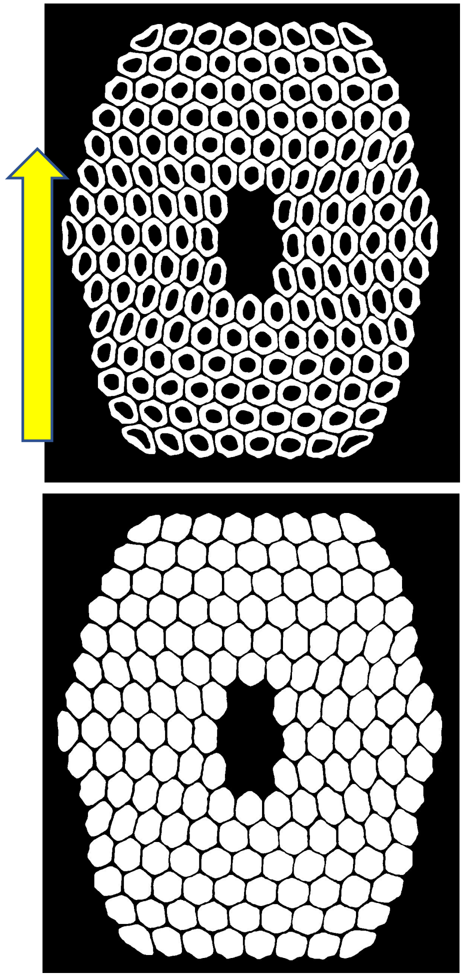
Ic: VAMAS vs m(B)

3 – SEM images elaboration

We averaged around 10 SEM images from different samples, in different position of the wire, per any kind of lamination.



We developed a elaboration protocol to avoid operator's dependencies



Software flow-chart:

- Rotates the strand image to be || to B in the meas.
- For bundle 1 to N
  - Meshing and finding D+ and D-
  - Evaluate F and Ssc
- Summing over the bundles to have total F and Ssc

With numerical integration we can also have the SC and NonCu total area thus the averaged radius R_e and R_i

$$F^i \approx \sum_{j=1}^{N_-} x_C^j \delta S_j - \sum_{j=1}^{N_+} x_C^j \delta S_j$$

$$m_{irr} = \frac{4}{3} J_c L N\left(R_e^3 - R_i^3\right) = J_c L f$$

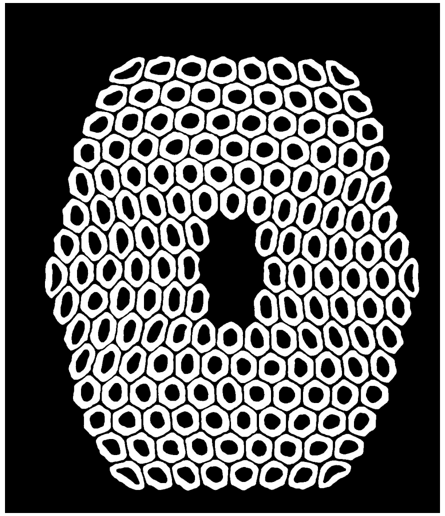
$$m_{irr} = J_c L \sum_{i=1}^{N} F^i = J_c L F$$

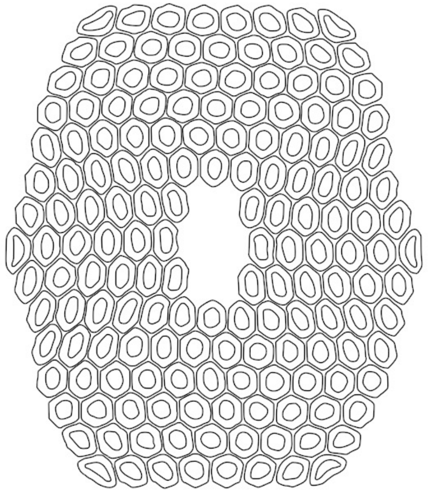
We expect $F \approx f$ for no rolled samples

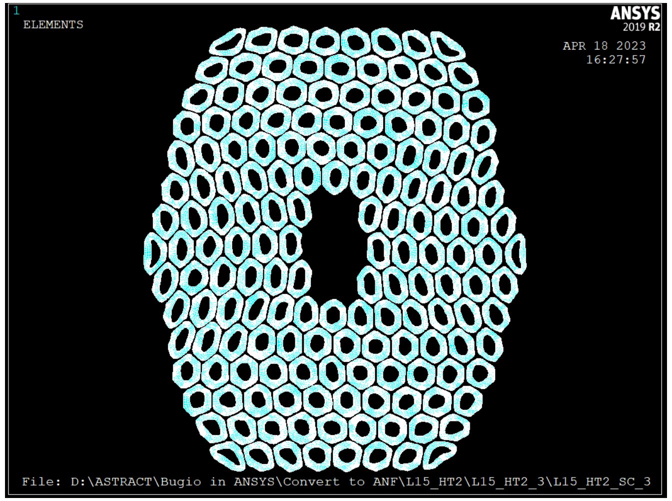
Ic: VAMAS vs m(B)

4 – ANSYS in our data analysis

SEM image BW .jpeg → DXF conversion → SpaceClaim → ANF conversion → ANSYS APDL image elaboration







Sample	# SEM images	F ($10^{-12}\,m^3$)	F rel.err. %	S_{SC} ($10^{-7}\,m^2$)	S_{SC} rel.err. %	f ($10^{-12}\,m^3$)	f rel.err. %	$\lvert f-F\rvert/f$ %
V_HT2	9	4.49474	1.08	3.10163	0.93	4.46737	1.12	0.6
L10_HT2	4	4.63332	1.49	3.27286	1.71	4.77351	0.86	2.9
L15_HT2	6	4.35757	2.41	3.08904	1.97	4.62882	2.50	5.9
L20_HT2	6	3.87951	2.02	2.89635	1.79	4.25102	2.10	8.7
L25_HT2	7	3.90966	1.36	2.96219	1.13	4.34611	1.24	10.0

F and f are the numerical and analytical shape factor averaged over the SEM images; S_{SC} is the mean effective SC section

Ic: VAMAS vs m(B)

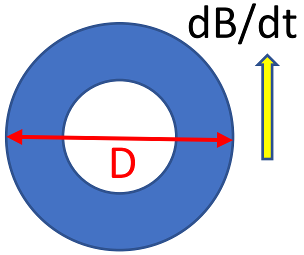
4 – Methodology

- From m(B) -> $I_{c;VSM} = \frac{m_{irr}(B)}{l\,F} S_{SC}^{L}$ with errors $\frac{\delta I_{c;VSM}}{I_{c;VSM}} = \sqrt{\left(\frac{\delta m_{irr}}{m_{irr}}\right)^2 + \left(\frac{\delta l}{l}\right)^2 + \left(\frac{\delta F}{F} + \frac{\delta S_{SC}}{S_{SC}}\right)^2}$

- From (V,I) data -> Recovering I_c^{VAMAS} by fitting $V = V_c \left(\frac{I}{I_c}\right)^n$ $where\ V_c = Voltage\ taps\ lenght\ x\ 10\,\frac{\mu V}{cm}$.
- I_c^{VAMAS} ***curves have to be corrected for self-field effects***

- **We scale original direct Ic to VSM electrical criteria**: $I_c = I_c^{VAMAS} \left(\frac{E_{VSM}}{10\ \mu V/cm}\right)^{\frac{1}{n}}$

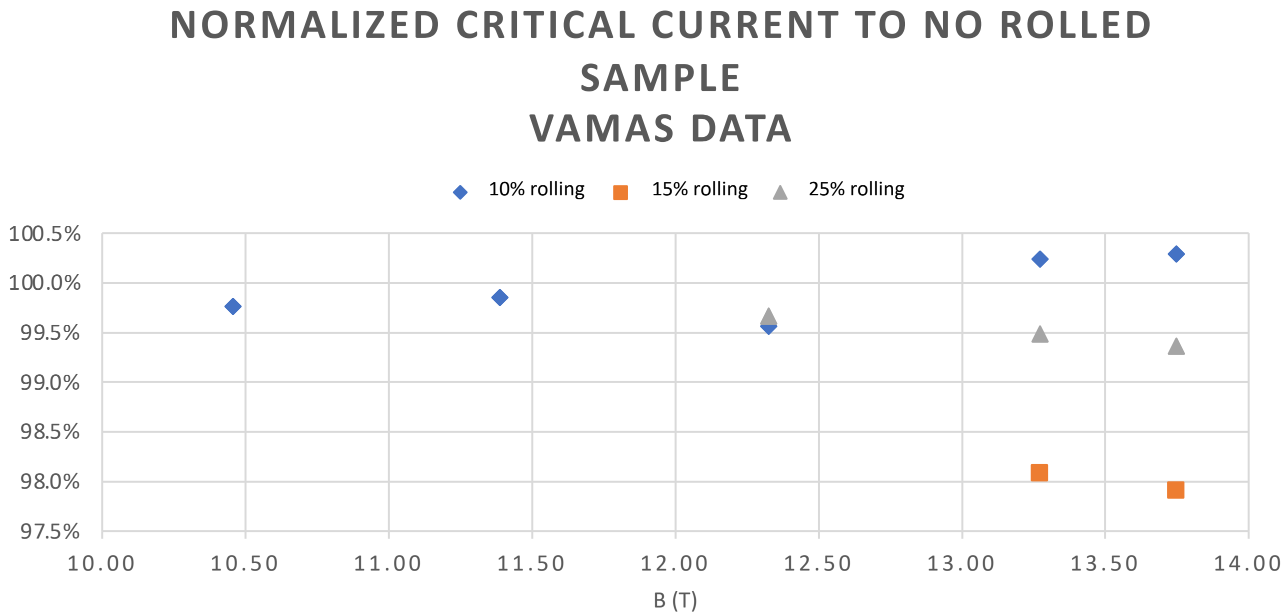
$where\ E_{VSM} \cong \frac{D}{2}\,\dot{B} \cong 2 \div 4\ 10^{-3}\,\frac{\mu V}{cm}$

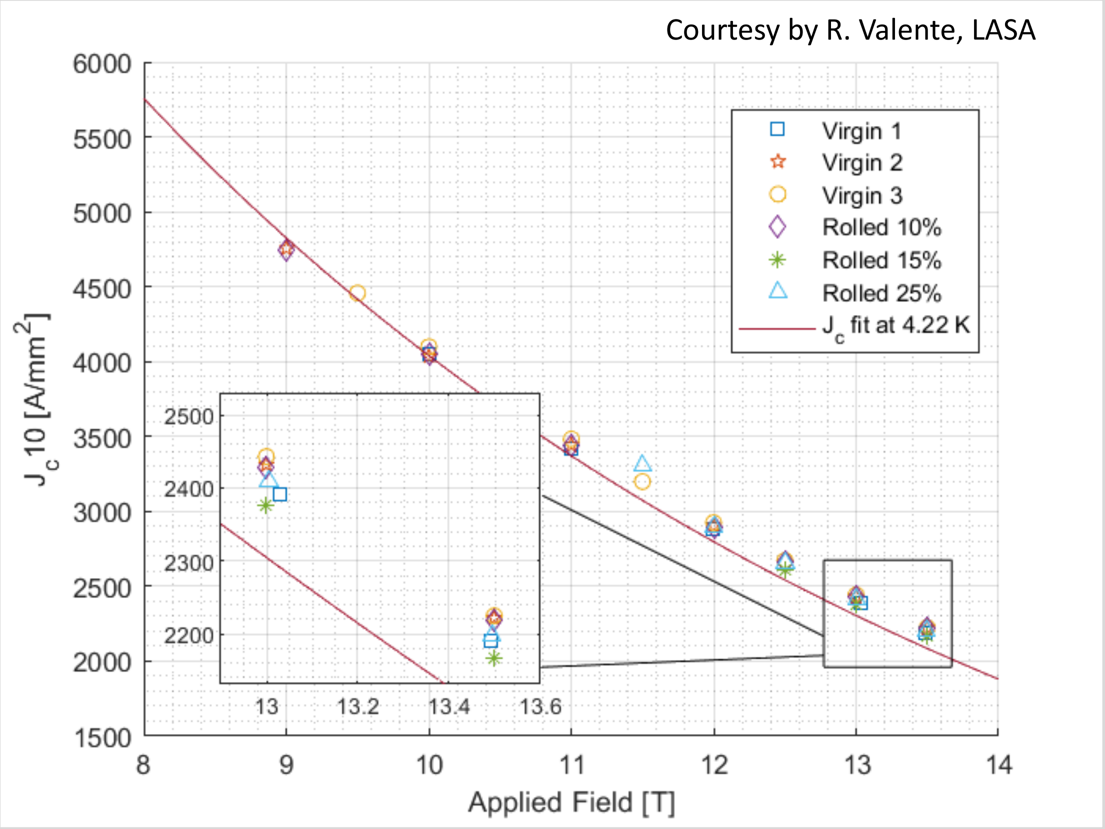


- For both VAMAS and VSM measurements we claim degradation if normalized Ic ($\frac{I_c^{rolled}}{I_c^{V}}$ $at\ same\ B\ and\ T$) is less than 95%

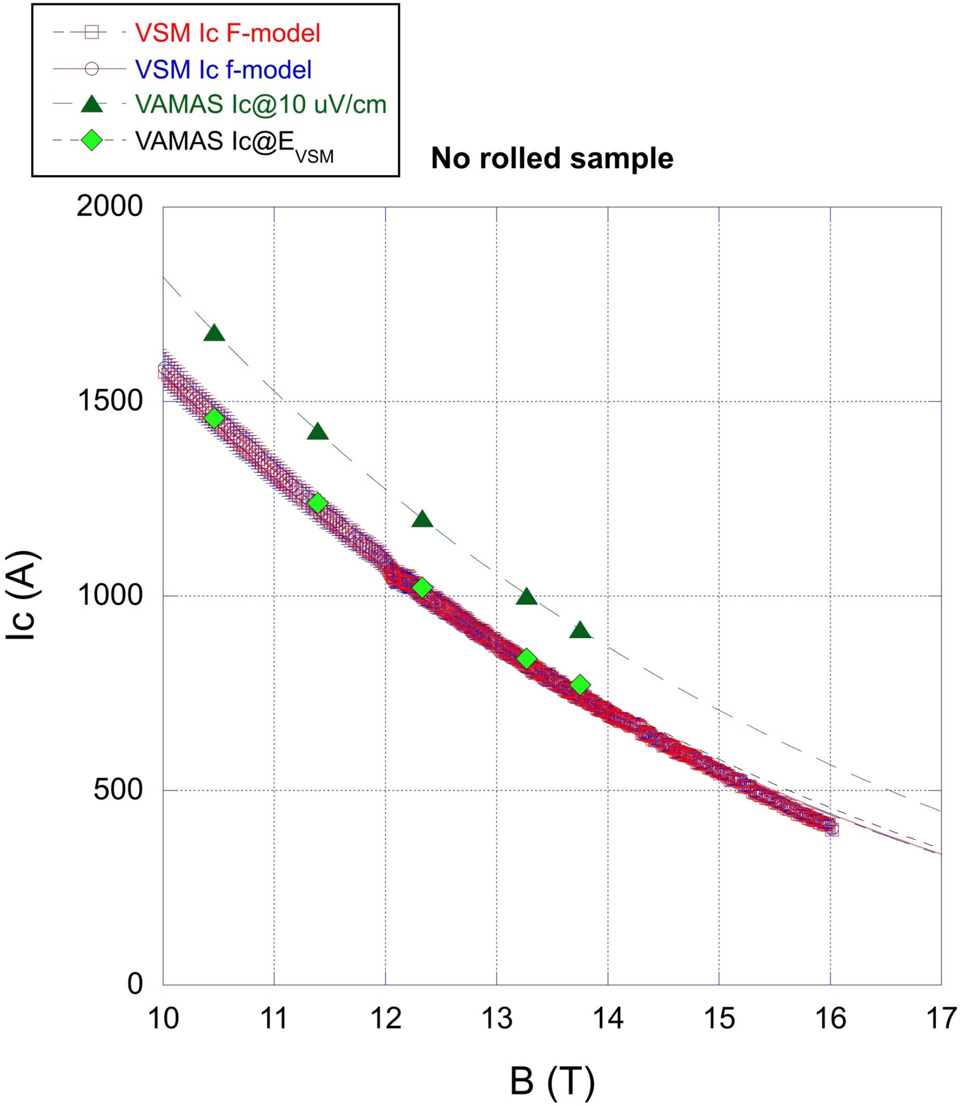
VAMAS results

- The red curve is the one used to simulate the Falcon Dipole wire $(J_c(4.2\ K, 16\ T) = 1300\ A)$;
- The data are not self field corrected
- Virgin 1 = virgin wire 14/10/2021
- Virgin 2 = FD_V_A
- Virgin 3 = FD_V_C
- **Rolled 20% was too much unstable to achieve Ic**




Courtesy by R. Valente, LASA

VAMAS vs VSM: 0% rolled



F-model = numerical shape-factor + VAMAS s.f. correction + VAMAS scaling

B (T)	n-value	VAMAS $I_c@E_{VSM}$ (A)	VSM I_c (A)	rel. diff.[1]	t*
10.5	55.4	1457.0	1456.2	0.1%	0.02
11.4	56.0	1238.8	1220.8	1.5%	0.58
12.3	53.1	1021.2	1002.5	1.8%	0.73
13.3	48.5	838.8	822.7	1.9%	0.77
13.7	50.3	771.1	739.0	4.2%	1.71

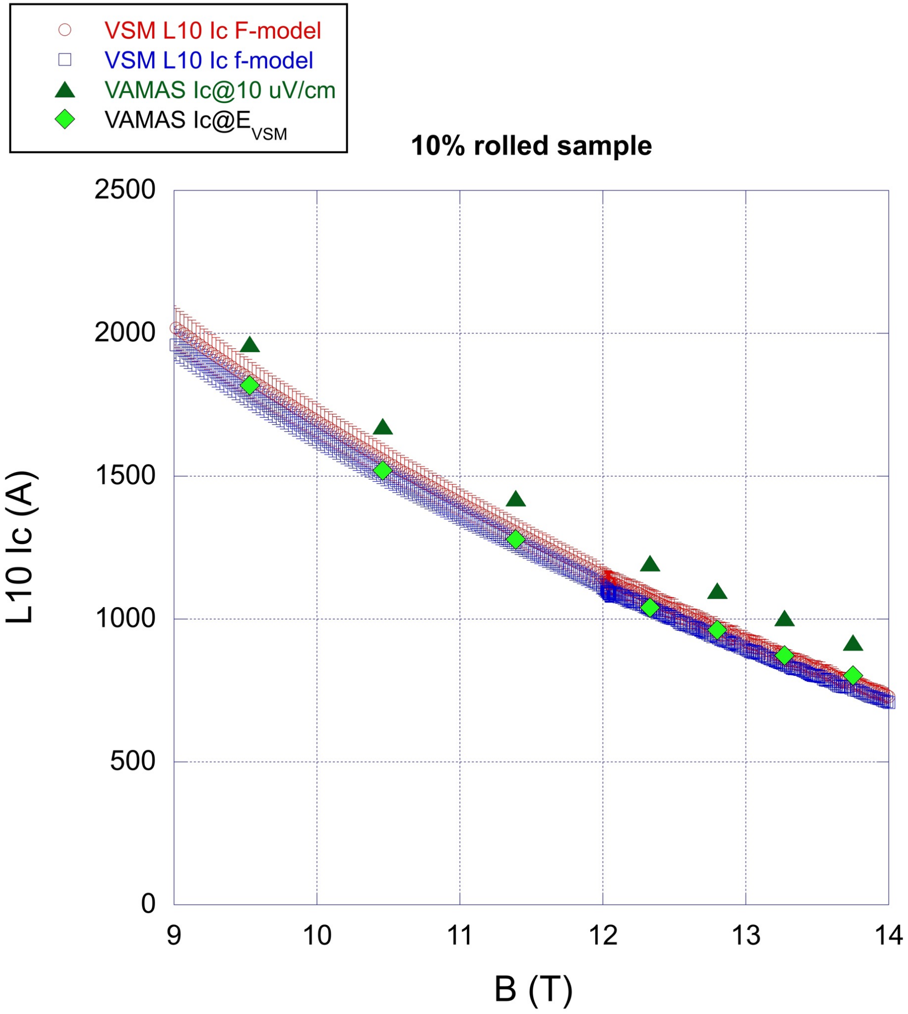
f-model = analytical shape-factor + VAMAS s.f. correction (Baumgartner's model)

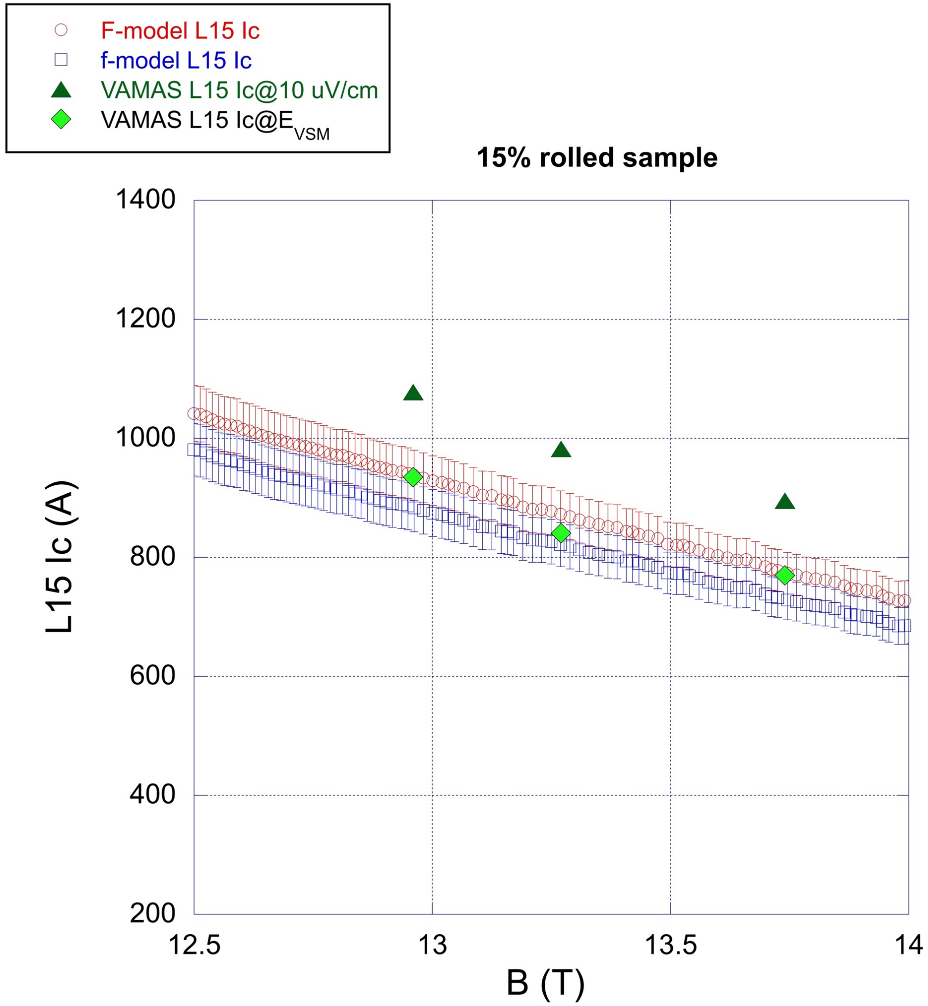
B (T)	n-value	VAMAS $I_c@10\,\mu V/cm$ (A)	VSM I_c (A)	rel. diff.[1]	t*
10.5	55.4	1678.5	1465.3	12.7%	5.73
11.4	56.0	1425.1	1228.5	13.8%	6.30
12.3	53.1	1200.2	1008.6	16.0%	7.48
13.3	48.5	1001.2	827.5	17.3%	8.26
13.7	50.3	914.4	743.4	18.7%	9.06

[1] rel.diff = (VAMAS – VSM)/VAMAS

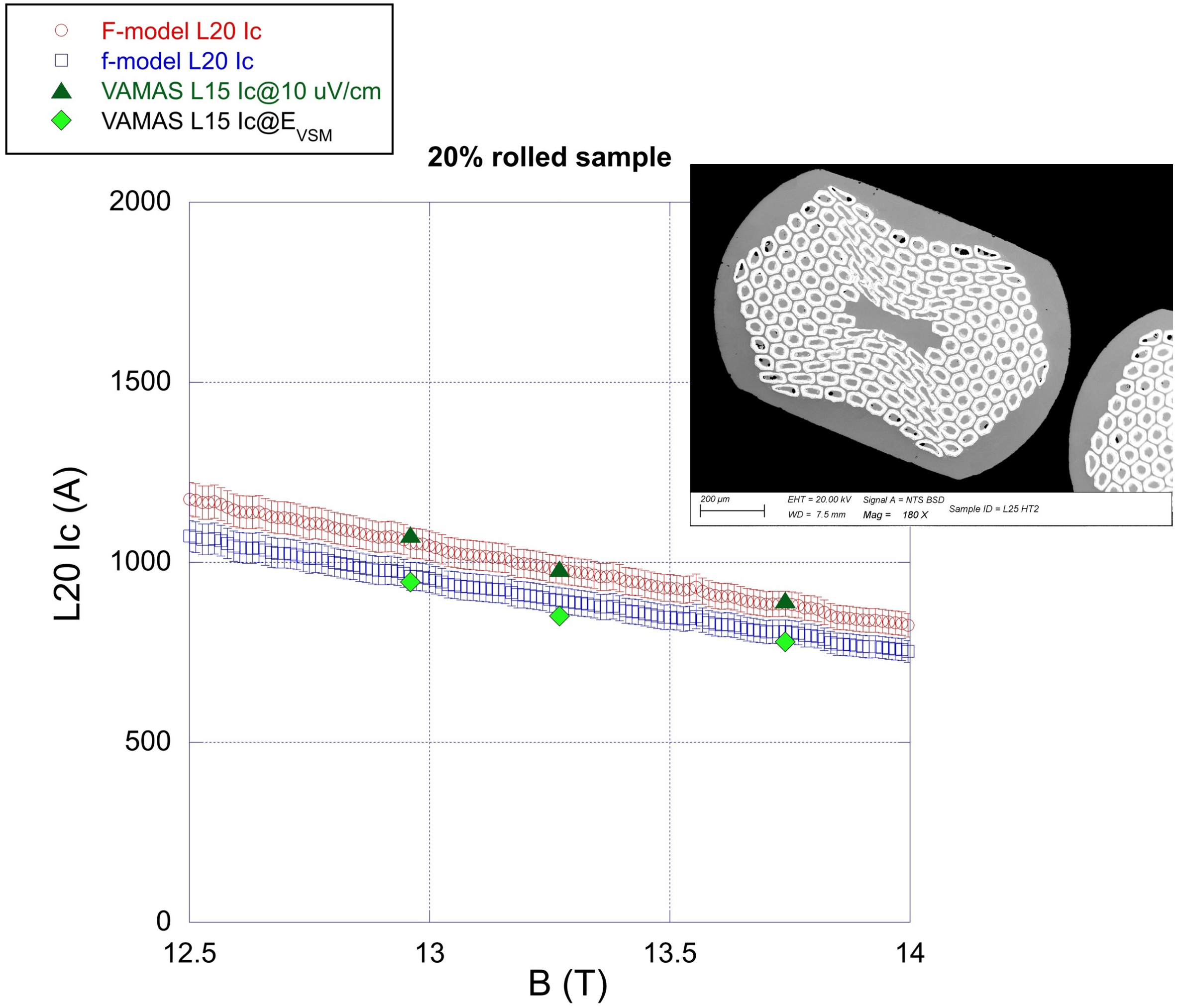
*t = |VAMAS – VSM|/δVSM

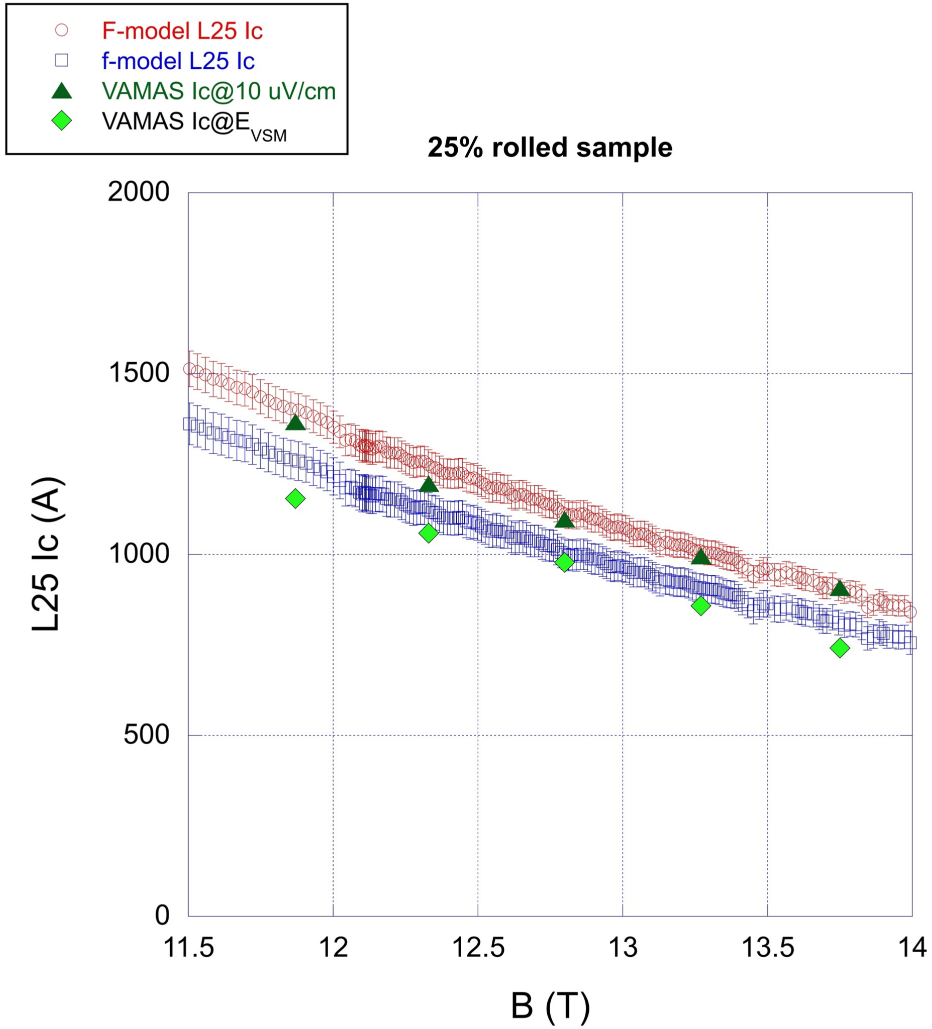
VAMAS vs VSM: 10 and 15 % rolled





VAMAS vs VSM: 20 and 25 % rolled



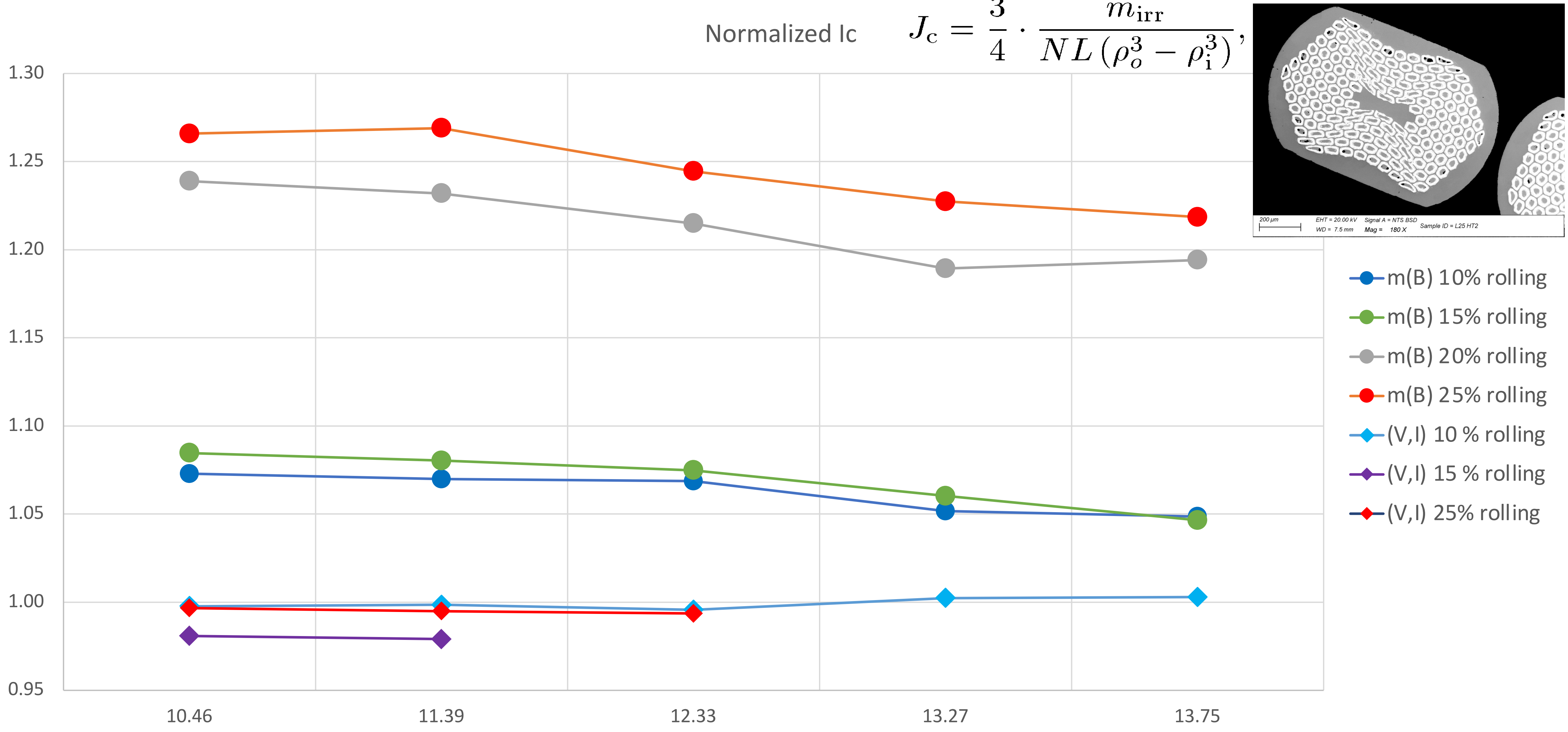


WARNING: no L20 VAMAS data available –> compared to L15 VAMAS

VAMAS vs VSM: Ic degradation?

Normalized Ic

$$J_c = \frac{3}{4} \cdot \frac{m_{\mathrm{irr}}}{NL\left(\rho_o^3 - \rho_i^3\right)},$$



Summary

- We presented a way to use ANSYS to extract critical current data from magnetic moments curves.
- Defining a database of strand SEM images is possible to achieve Ic values independently from transport data
- Testing the compatibility between VAMAS and VMS techniques requires to scale VAMAS data to the E_c^{VSM}
- Our method is compatible with transport data at 0, 10 and 15% of rolling.
- Both VAMAS and VSM show no critical current degradation due to rolling up to 25%. VSM normalized Ic seems to improve with a boost in performance at 25% of rolling (more than 115% Ic). This effect has been already observed in RRP rolled samples as a consequence of bundles merging and it could lead to a falling of our working hypothesis.

In the next future we will

- test the method respect to other Nb_3Sn strand layouts or SC material as BSSCO
- improving the ANSYS code adding magnetic simulations
- find a way to determine the shape factor in case of merged bundles
- setup an experimental method to measure the n-value from m(B), which would allow to derive Jc from m(B) at any value of Ec

Thanks for your attention!