

DE LA RECHERCHE À L'INDUSTRIE



2/27/2019

# Stress induced current limit in $\text{Nb}_3\text{Sn}$ accelerator magnets

**E. Rochebault, A. Bord, H. Felice, C. Lorin**  
25/02/2019

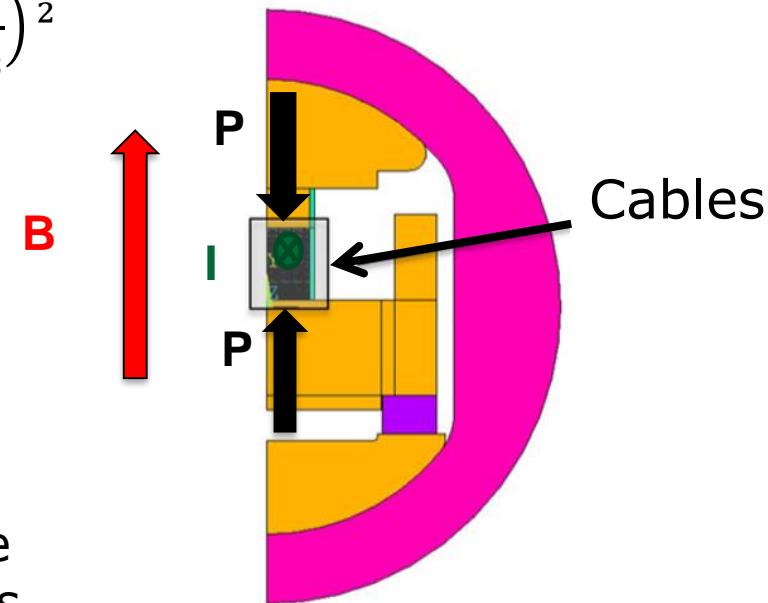
# CONSTITUTIVE LAW FOR THE CRITICAL CURRENT

$$\text{Classical scaling law : } I_c(B) = C \left( \frac{B}{B_{c2}} \right)^{-0.5} \left( 1 - \frac{B}{B_{c2}} \right)^2$$

Goal : Establish a constitutive law in the form  $I_c(B, S)$

→ transverse compression tests on Rutherford cables at CERN [1-2] and hopefully at Twente

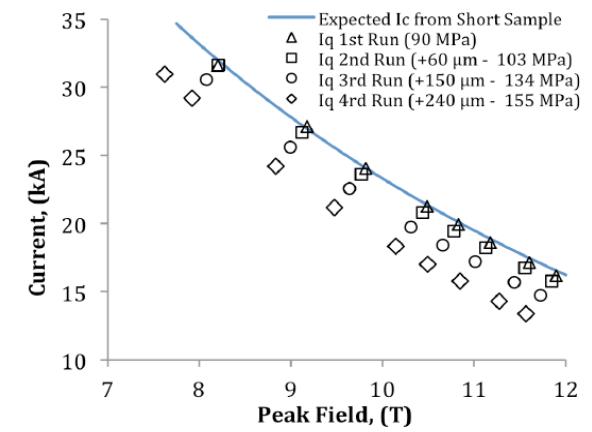
1st step: Relation between applied pressure P and maximum equivalent Von Mises stress S in the cable (Giorgio Vallone [3])



[1] B. Bordini, P. Alknes, A. Ballarino, L. Bottura and L. Oberli, "Critical Current Measurements of High-Jc Nb3Sn Rutherford Cables Under Transverse Compression", *IEEE Transactions on Applied Superconductivity*, vol. 24, no. 3, pp. 1-5, 2014.

[2] J. Duvauchelle, B. Bordini, J. Fleiter and A. Ballarino, "Critical Current Measurements Under Transverse Pressure of a Nb3Sn Rutherford Cable Based on 1 mm RRP Wires", *IEEE Transactions on Applied Superconductivity*, vol. 28, no. 4, pp. 1-5, 2018.

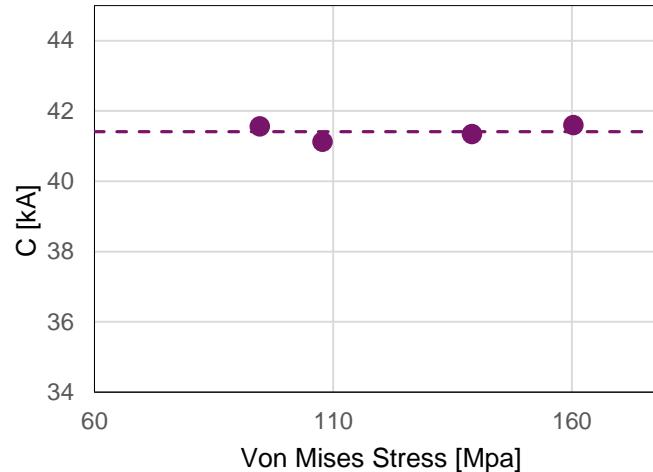
[3] G. Vallone, B. Bordini and P. Ferracin, "Computation of the Reversible Critical Current Degradation in Nb3Sn Rutherford Cables for Particle Accelerator Magnets", *IEEE Transactions on Applied Superconductivity*, vol. 28, no. 4, pp. 1-6, 2018.



# CONSTITUTIVE LAW FOR THE CRITICAL CURRENT

2<sup>nd</sup> step: obtain  $C$  and  $B_{c2}$  for each value of stress, by fitting the experimental curves

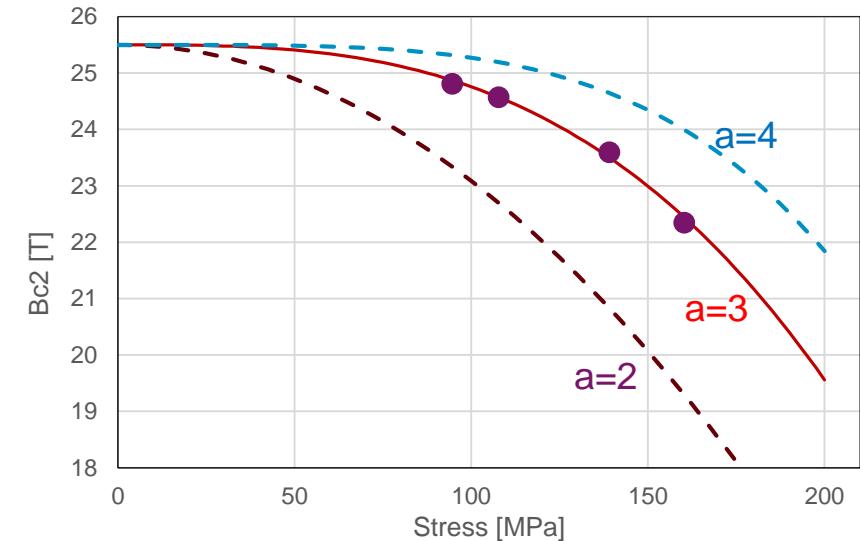
PIT



Proposed parameterization  
for a given T:

$$C(S) = \text{constant} = C^* = 41,4$$

Assumption:  $C$  does not depend on S



$$B_{c2}(S) = B_{c2}^* \left[ 1 - \left( \frac{S}{S_{max}} \right)^a \right]$$

→  $a$  and  $S_{max}$ : stress dependence

Assumption:  $a$  and  $S_{max}$  do not depend on T

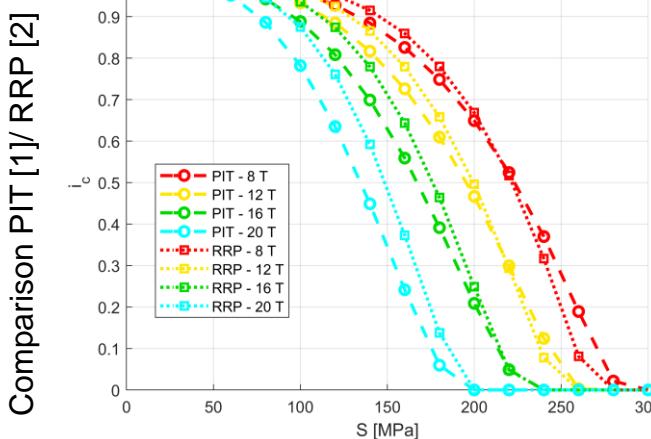
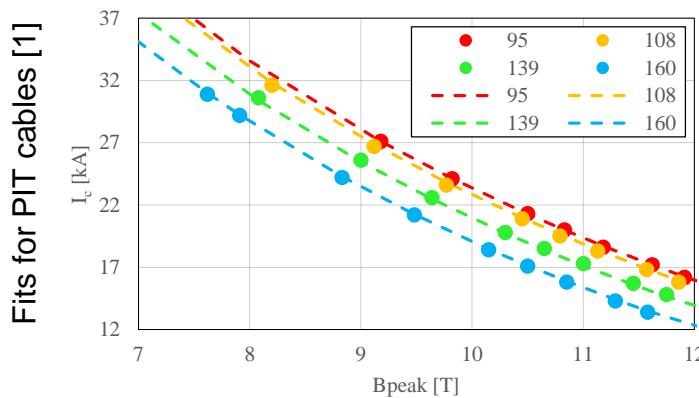
For a given T:

$$I_c(B, S) = C B^{-0.5} B_{c2}^{*0.5} \left[ 1 - \left( \frac{S}{S_{max}} \right)^a \right]^{0.5} \left( 1 - \frac{B}{B_{c2}^* \left[ 1 - \left( \frac{S}{S_{max}} \right)^a \right]} \right)^2$$

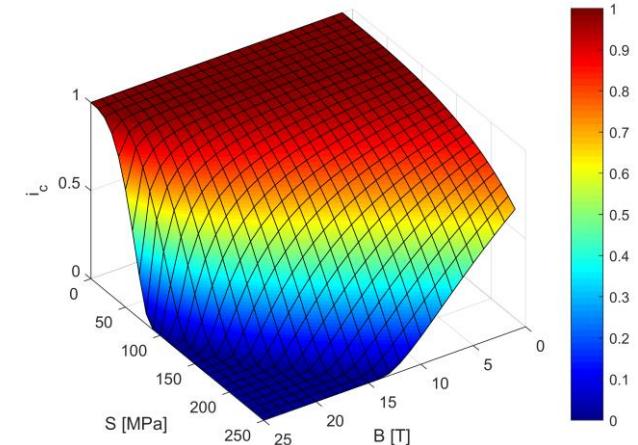
# CONSTITUTIVE LAW FOR THE CRITICAL CURRENT

Comparison of PIT and RRP cables  
**for data measured in [1-2] :**

Cable	$C$ [kA]	$B_{c2}^*$ [T]	$\alpha$	$S_{max}$ [MPa]
PIT	41,4	25,5	3,0	325
RRP	50,0	25,8	3,7	300



Normalised current :  $i_c(B, S) = \frac{I_c(B, S)}{I_c(B, S=0)}$



Critical current is reduced at high stress and high magnetic field

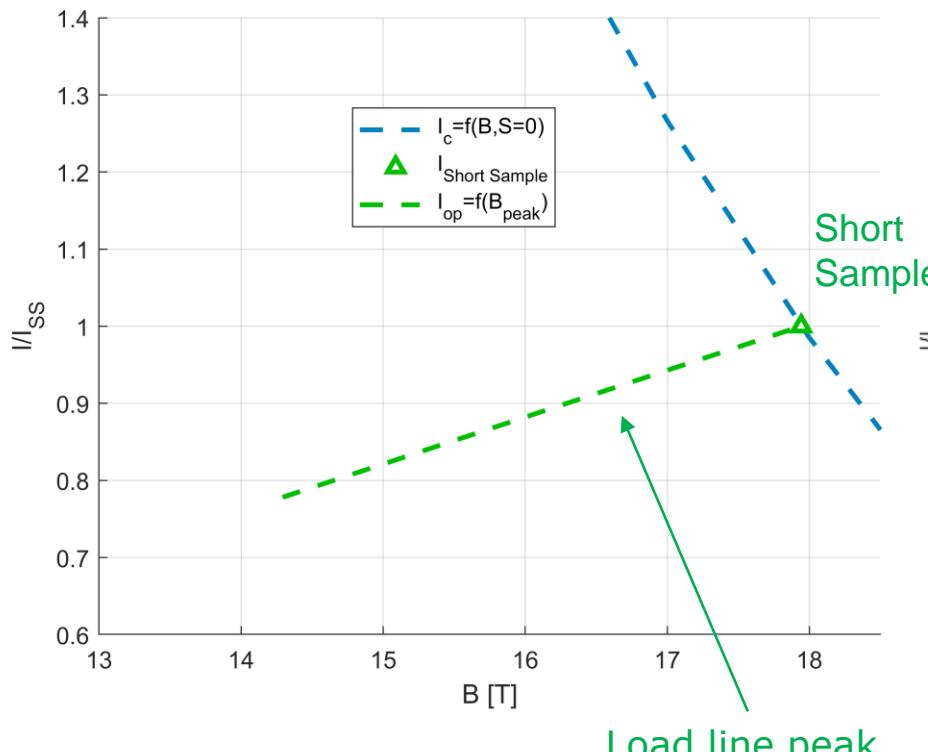


Application to a  $\text{Nb}_3\text{Sn}$  coil:  
 Estimate  $I_c$ , knowing B and S  
 at any point with the FEM

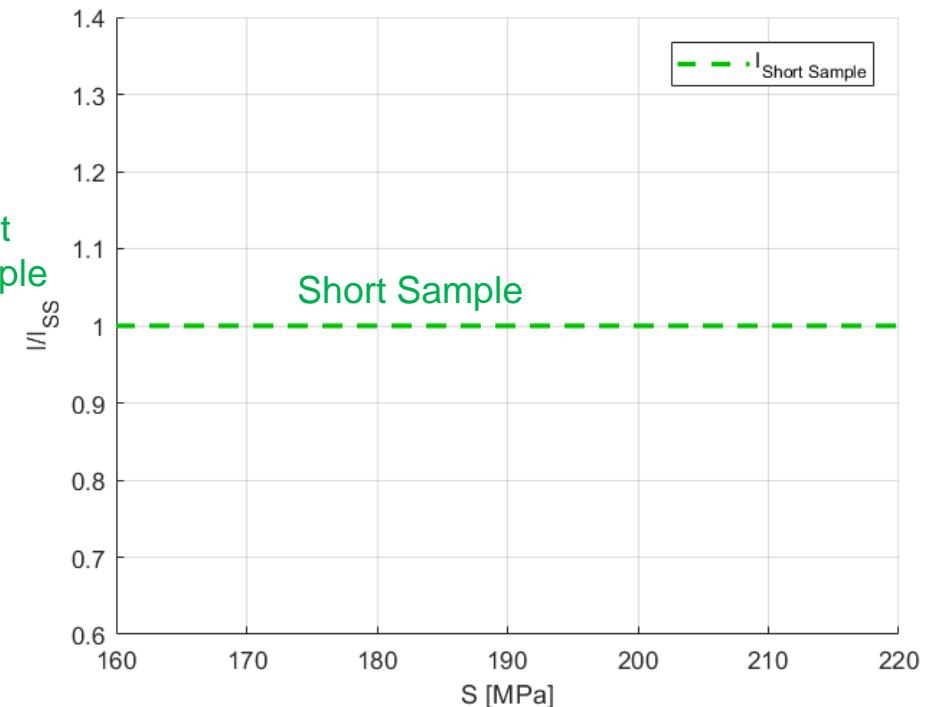
# STRESS INDUCED CURRENT LIMIT

**How to estimate the maximum admissible current due to stress?**

« Magnetic » load lines  $I=f(B)$



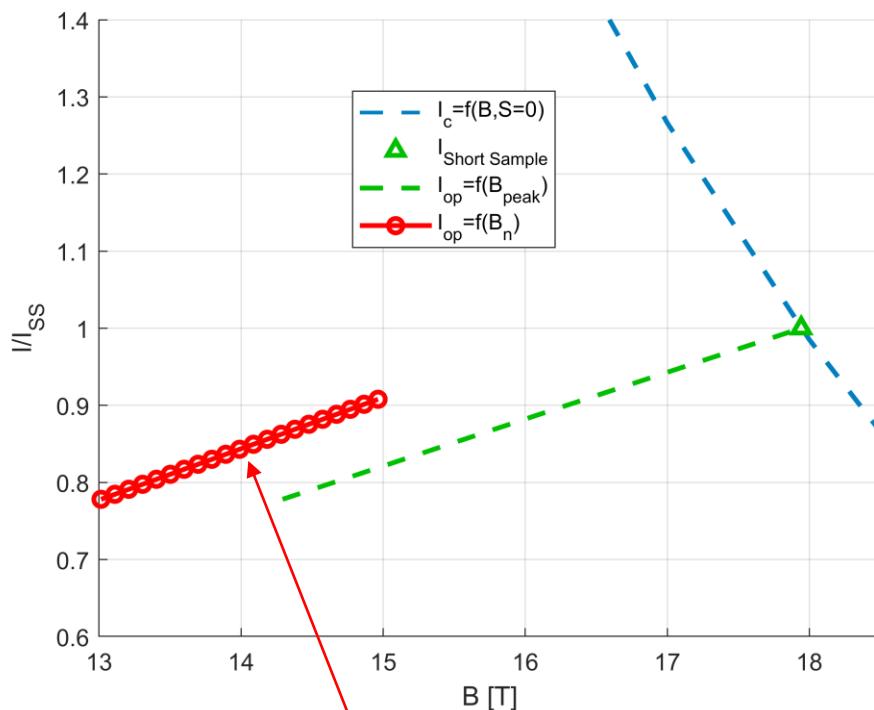
« Mechanical » load lines  $I=f(S)$



# STRESS INDUCED CURRENT LIMIT

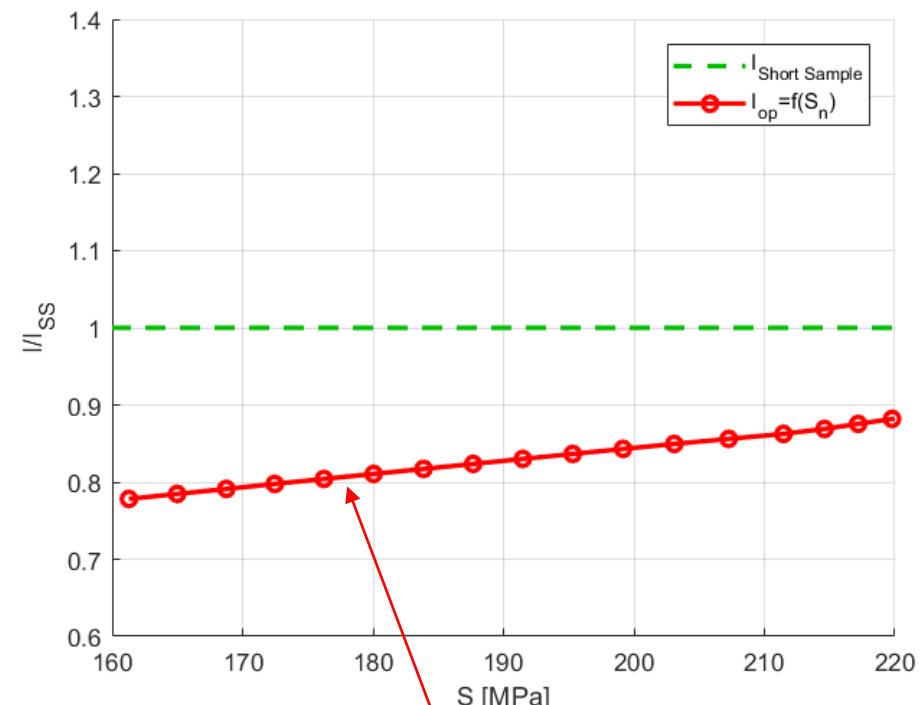
**How to estimate the maximum admissible current due to stress?**

« Magnetic » load lines  $I=f(B)$



Load line at a given point  $n$  of the coil  
 $I = f(B_n)$

« Mechanical » load lines  $I=f(S)$



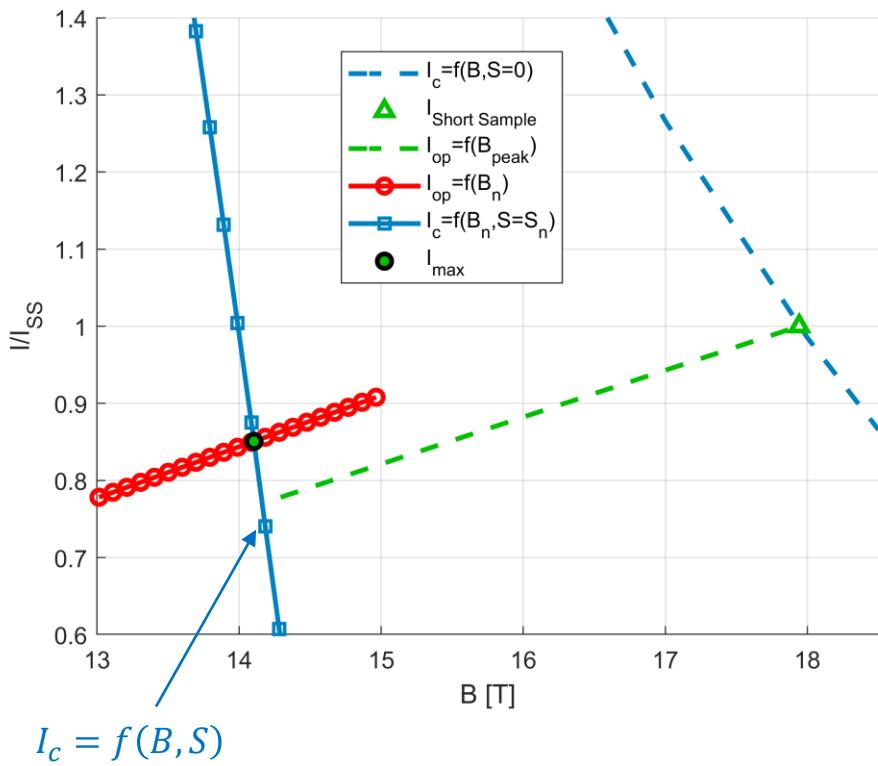
$I$  increases  
 $\downarrow$   
 $B$  et  $S$  increase

Load line at a given point  $n$  of the coil  
 $I = f(S_n)$

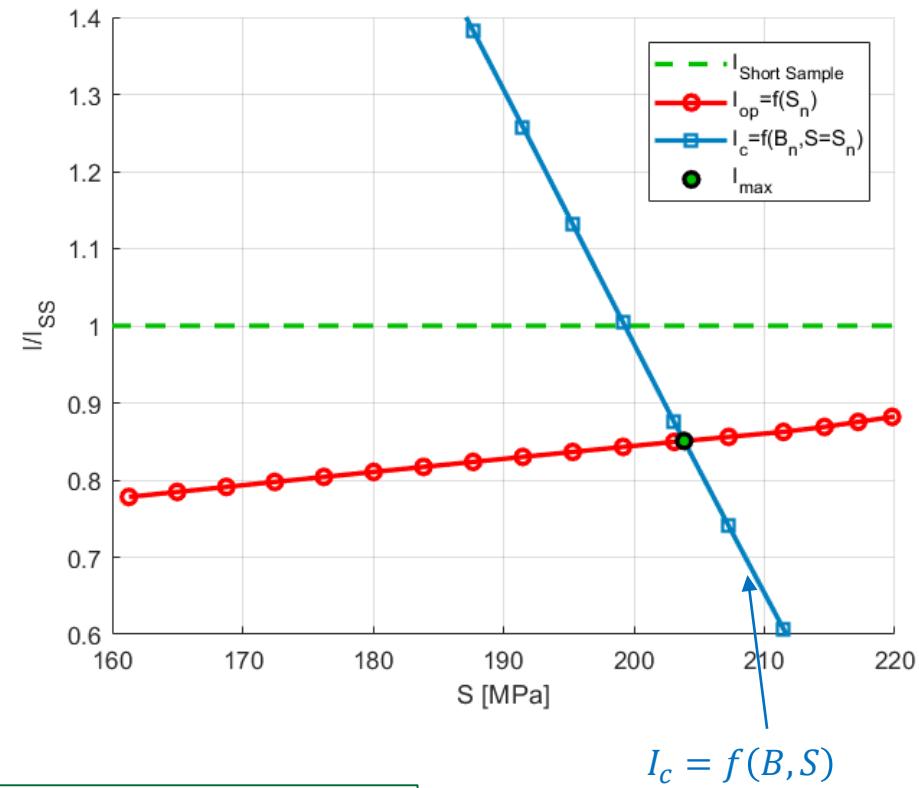
# STRESS INDUCED CURRENT LIMIT

**How to estimate the maximum admissible current due to stress?**

« Magnetic » load lines  $I=f(B)$



« Mechanical » load lines  $I=f(S)$



**Current limit =  $\min(I_{max,n})$**

# APPLICATION TO THE FCC BLOCK-COIL DIPOLE

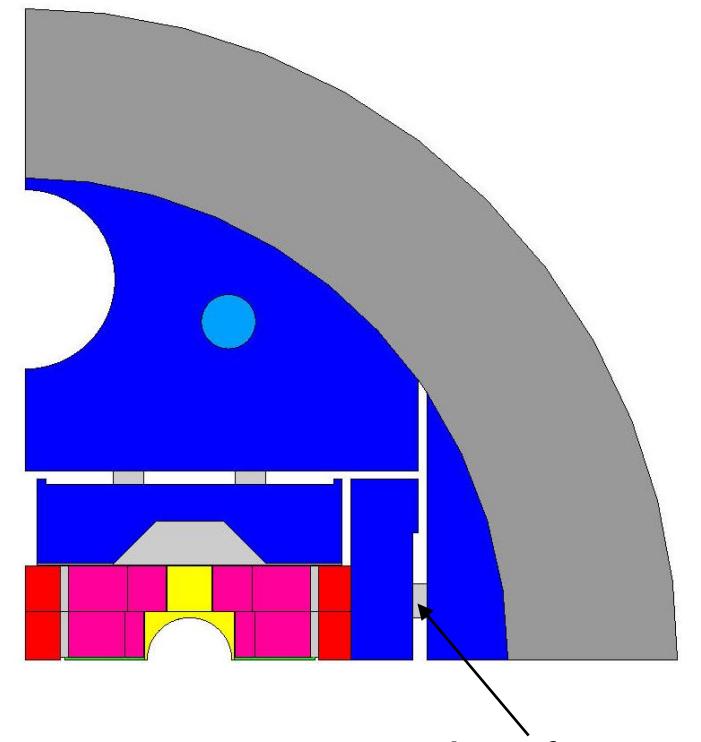
Eurocircol design [7]

- Double aperture
- 27 GPa coil modulus
- 1.9 K operating temperature
- Comparison attached/detached
- Different pre-loads explored

Fitting parameters:

- No FCC cable available for now
- Same  $a$  and  $S_{max}$  as measured RRP cable
- $C_0$  adapted to match spec. of 1500 A/mm<sup>2</sup>  
@ 16 T 4.2 K

Cable	$C_0$ [kA]	$B_{c20}$ [T]	$a$	$S_{max}$ [MPa]
RRP LF	40.5	28.2	3.7	300
RRP HF	102.9	28.2	3.7	300



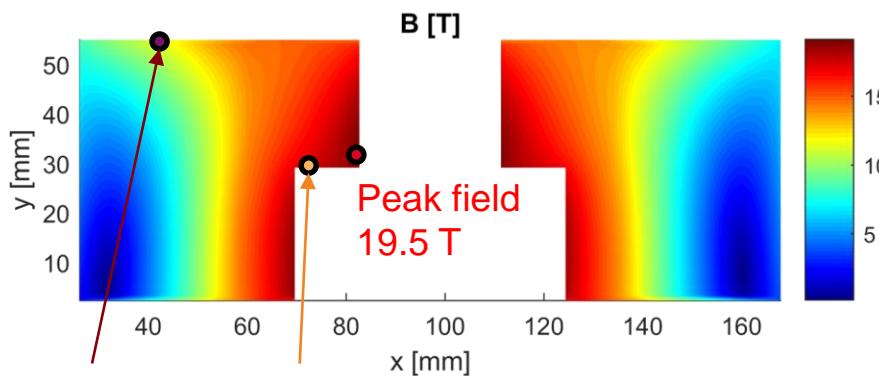
Interference  
for pre-load

[7] Lorin, « EuroCirCol 16 T Block-Coils Dipole Option for the Future Circular Collider », 2017.

# APPLICATION TO THE FCC BLOCK-COIL DIPOLE

- Example:
- Detached pole-coil contact
  - 1.6 mm interference
  - Current at 11.5 kA (98 % of  $I_{SS}$ )

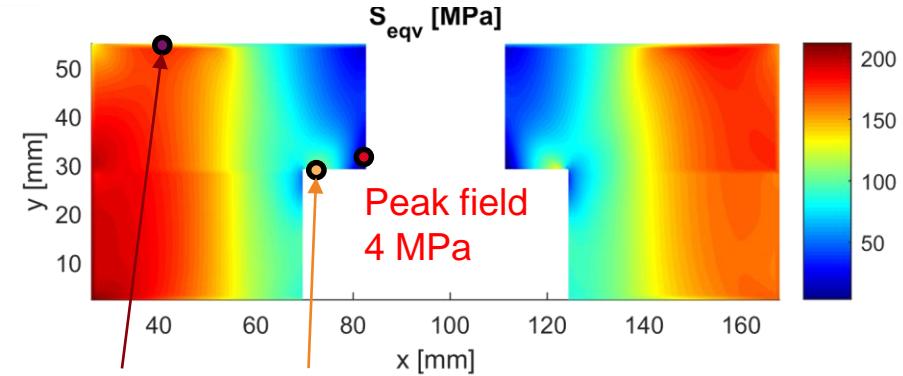
Nodal Field map  $B(x,y)$



Point 2  
13.0 T

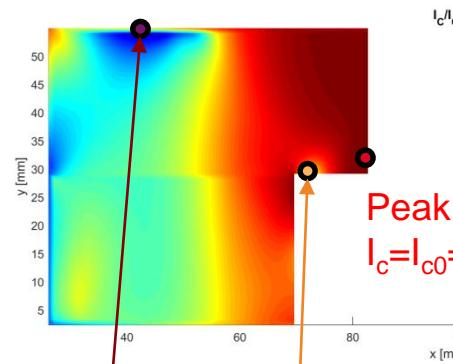
Point 1  
17.3 T

Nodal Stress map  $S(x,y)$



Point 2  
181 MPa

Point 1  
167 MPa



$I_c$  map  
 $I_c(B,S)/I_c(B,0)$

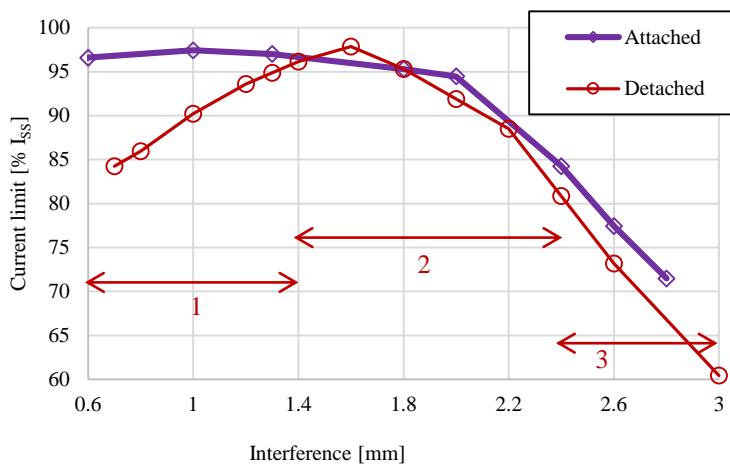
Point 2  
 $I_c = 11.5$  kA  
 $I_{c0} = 17.4$  kA

Point 1  
 $I_c = 11.5$  kA  
 $I_{c0} = 19.6$  kA

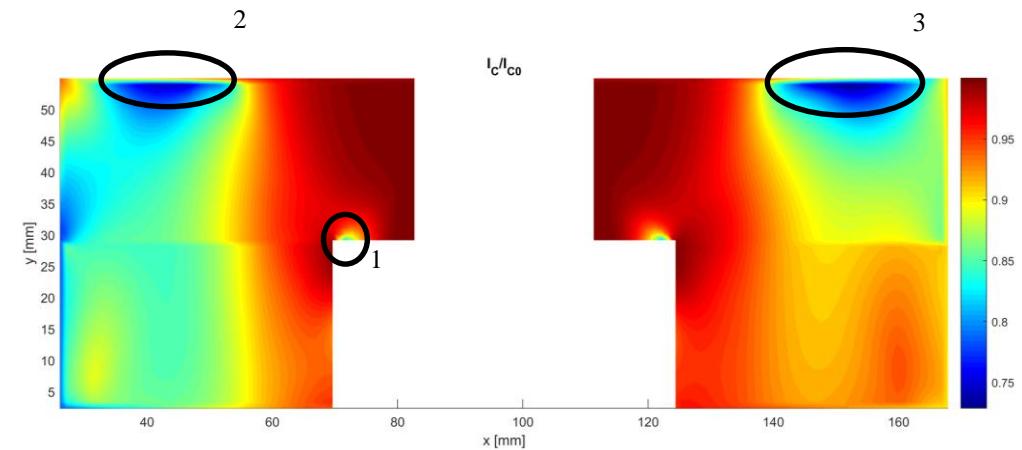
Current limit = 11.5 kA

# APPLICATION TO THE FCC BLOCK-COIL DIPOLE

Magnet Current Limit  
due to stress



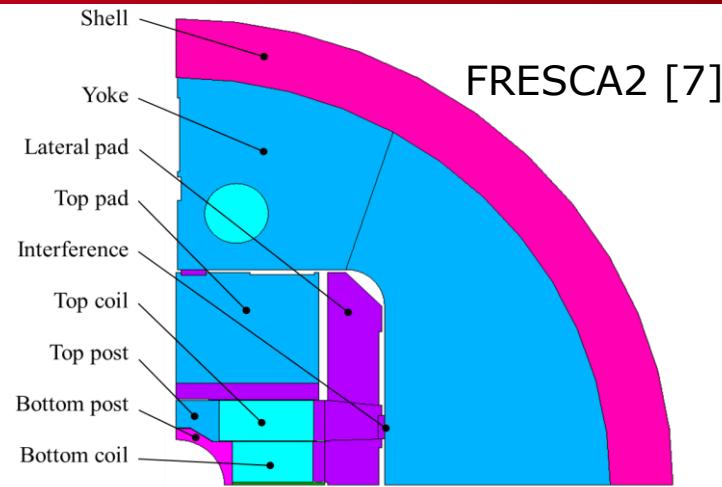
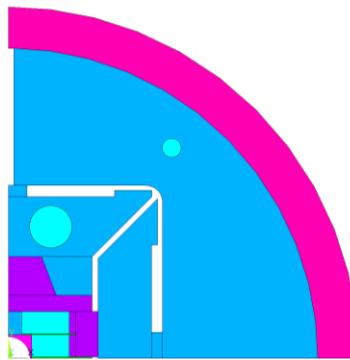
Detached case, 1.6 mm, 11.5 kA



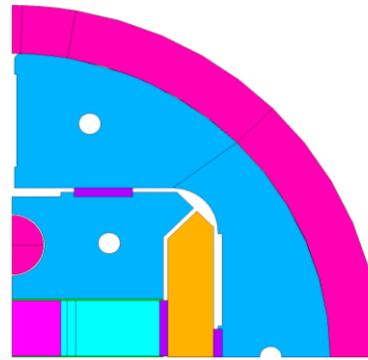
- The reduction zone depends in particular on:
  - The conditions attached/detached
  - The pre-load (interference)
- Optimum :**
  - 1.6 mm interference in the detached case → **98 % of  $I_{ss}$**
  - 0.6-1.3 mm interference in the attached case → **97 % of  $I_{ss}$**
- Limit for **irreversible degradation**: 200 MPa at cold
  - 1.2 mm interference
  - **94 % of  $I_{ss}$  in the detached case**
  - **97 % of  $I_{ss}$  in the attached case**

# SUMMARY ON SOME $\text{Nb}_3\text{Sn}$ DIPOLES

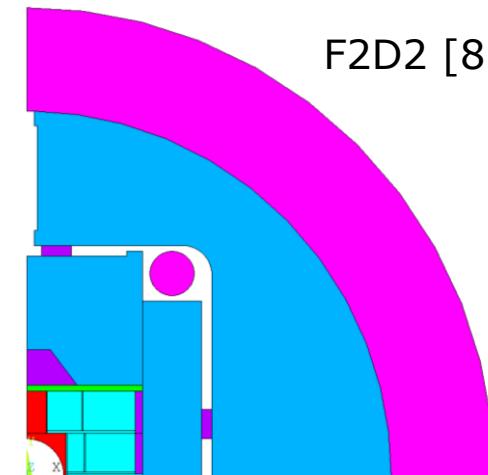
HD3 [5]:



RMC [6]:



F2D2 [8]



- [5] H. Felice, "Challenges in the Support Structure Design and Assembly of HD3, a  $\text{Nb}_3\text{Sn}$  Block-Type Dipole Magnet", IEEE Transactions on Applied Superconductivity, 2013
- [6] Perez, "16 T  $\text{Nb}_3\text{Sn}$  Racetrack Model Coil Test Result", IEEE Transactions on Applied Superconductivity , 2016
- [7] E. Rochepault et al., "Mechanical Analysis of the FRESCA2 Dipole During Preload, Cool-Down, and Powering", IEEE Transactions on Applied Superconductivity, vol. 28, no. 3, 4002905, 2018.
- [8] H. Felice et.al., « F2D2: a block-coil short-model dipole toward FCC », IEEE Transactions on Applied Superconductivity, 2019

# SUMMARY ON SOME $\text{Nb}_3\text{Sn}$ DIPOLES

Magnet	Goal	Nominal current [kA]	Nominal Field [T]	SS current [kA]	Achieved Field	% SS achieved	Estimated current limit (% of Iss)
FRESCA2	Test station	10,55	13	14,9 @ 4,2 K 13,8 @ 1,9 K	14,7 T @ 1,9 K	80 %	90-97 %
RMC	Short model	-	-	17,6 @ 4,2 K 19,4 @ 1,9 K	12,9 T @ 4,2 K	100 %	100 %
HD3	Short model		15,4	18,7 @ 4,3 K	13,4 T @ 4,2 K	86 %	93-100 %
F2D2	Dipole demonstrator	10,378	15,5	12,1 @ 1,9 K			~99 %
Eurocircol	Conceptual design for FCC	10,2	16	12 kA @ 1,9 K			94-98 %

→ No contradiction so far between estimated current limits and test results on existing magnets

# CONCLUSION

- New approach to **model the maximum current due to stress** in magnets:
  - However, **lack of experimental data** to establish proper constitutive laws
  - **Simplifying assumptions** regarding the fitting parameters : no dependence with cable geometry and temperature
- Study on tested dipoles:
  - FRESCA2 (80%  $I_{SS}$ ), HD (86%  $I_{SS}$ ), RMC ( $\sim 100\%$   $I_{SS}$ )
  - ... and future dipoles: RMM, F2D2, ECC → **negligible reduction if the pre-stress is adequate**
- Guideline for the design of high field Nb<sub>3</sub>Sn magnets:
  - Significant impact of the **preloading: trade-off between current reduction and pre-stress**
  - Necessity to **quantify the modulus of rigidity**: different estimate of the stress
  - **Influence of contact conditions** (attached/detached) on the coil stress
- Prospect : apply this method to other types of magnet (cos-theta dipoles, quadrupoles...)

# **Thank you for your attention !**

To cite this work:

E. Rochepault, A. Bord, H. Felice, C. Lorin,

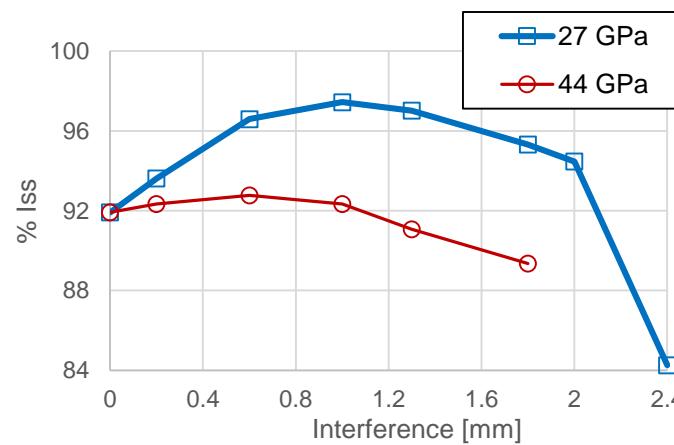
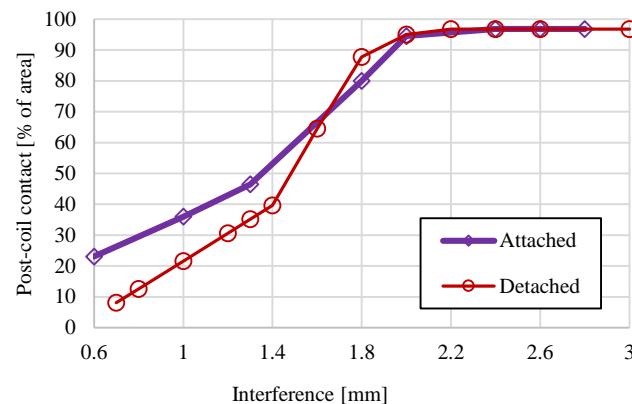
"Current Limits in Nb<sub>3</sub>Sn Superconducting Magnets Considering  
Magnetic Field and Stress",  
submitted to IEEE Trans. Appl. Supercond.

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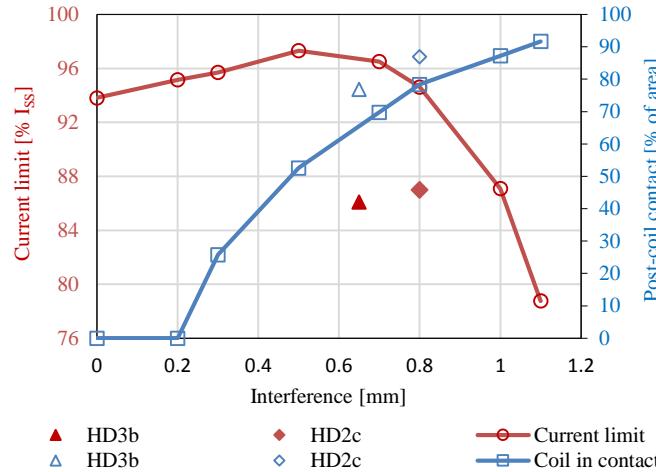
## BACKUP SLIDES

# APPLICATION TO THE FCC BLOCK-COIL DIPOLE

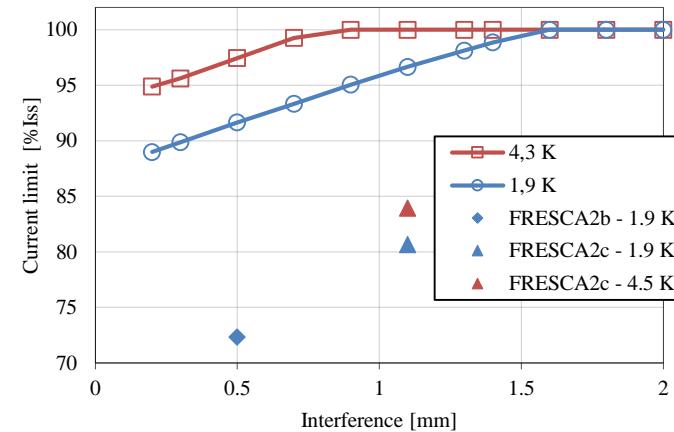


# SUMMARY ON SOME $\text{Nb}_3\text{Sn}$ DIPOLES

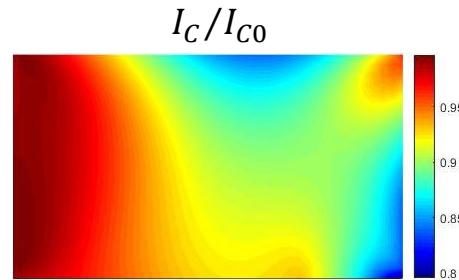
HD3 [5]:



FRESCA2 [7]



RMC [6]: no  $I_c$  reduction



F2D2 [8]

