FCC Week 2019
June 24th-28th
Bruxelles

# EuroCirCol Conductor Program

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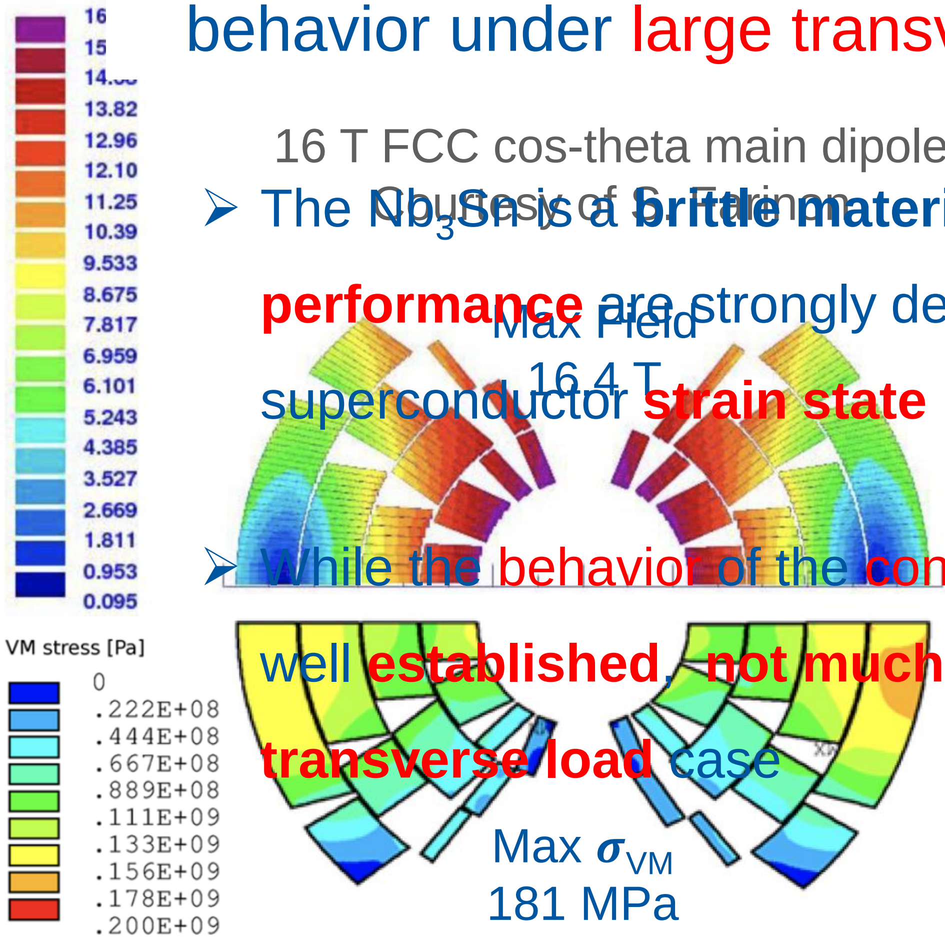
**On behalf of the EuroCirCol WP5**

# Introduction

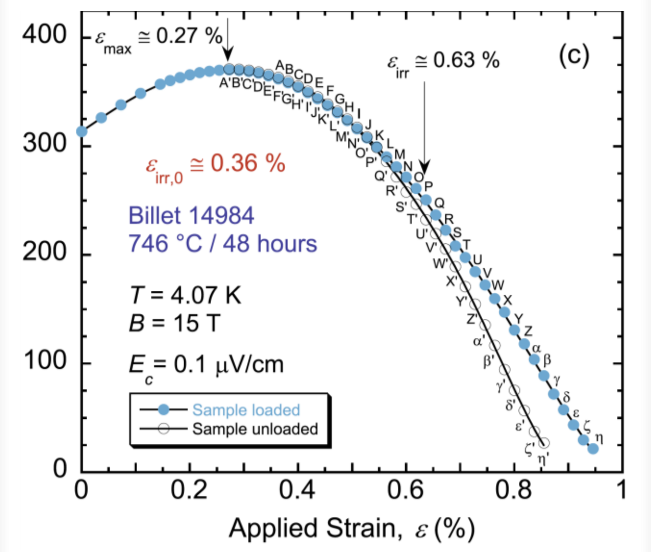
## $Nb_3Sn$ and Strain

- One of the major challenge for a 16 T $Nb_3Sn$ accelerator magnet is the conductor behavior under large transverse load: P∝B ➔ P (16 T) ≈ 150-200 MPa




- The $Nb_3Sn$ is a **brittle material** and its superconducting **performance** are strongly dependent on the superconductor **strain state**

- While the behavior of the conductor under **axial strain** is well **established**, **not much data** were available for the **transverse load** case

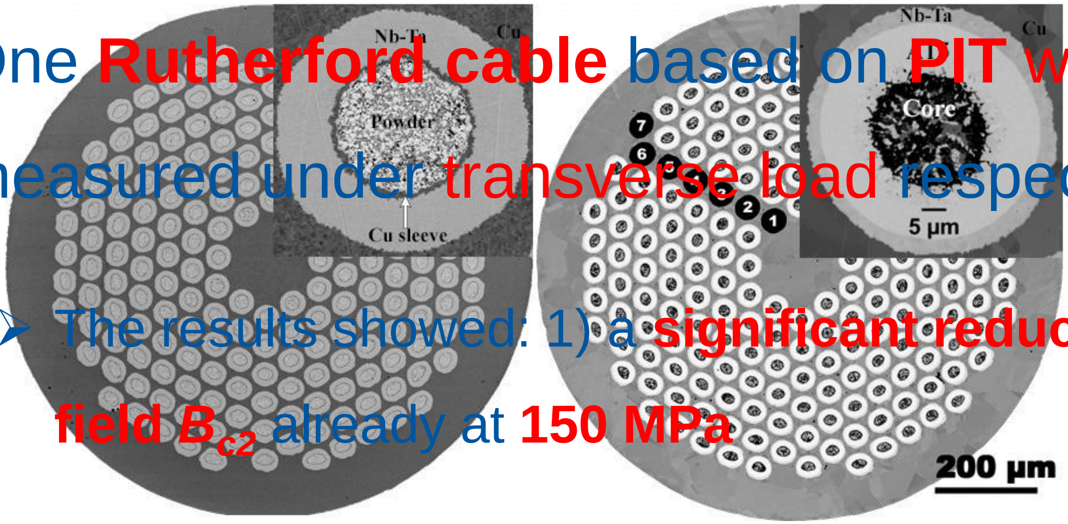



N. Cheggour et *al.* Scientific Reports | (2019) 9:5466

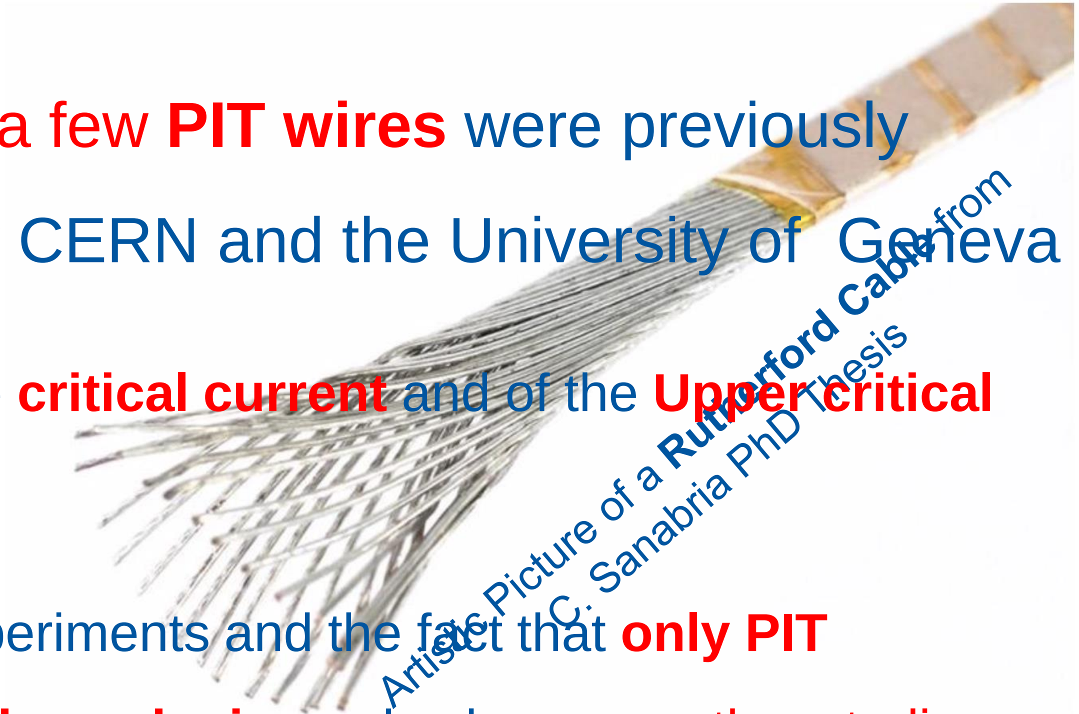
# Introduction

## Studies Preceding the EuroCirCol Conductor Program

- One **Rutherford cable** based on **PIT** wires and a few **PIT wires** were previously measured under transverse load respectively by CERN and the University of Geneva




Pictures of an Unreacted and a Reacted **Powder in Tube (PIT) $Nb_3Sn$ Strand** from C. Segal PhD Thesis



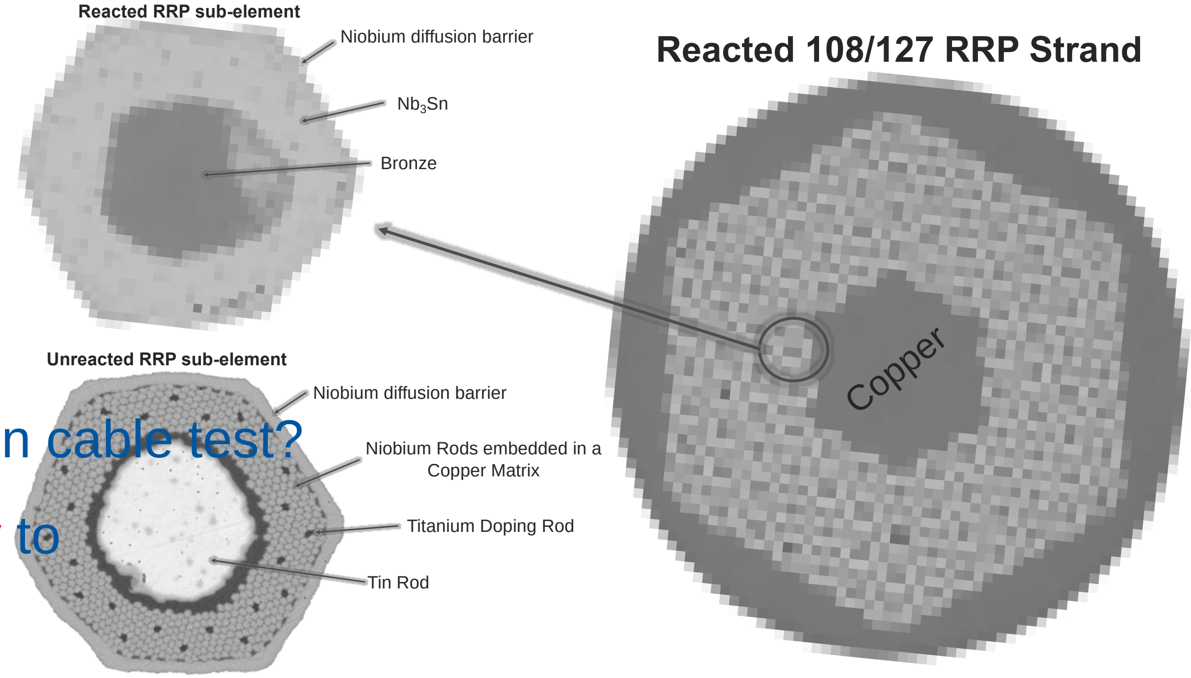
Artistic Picture of a **Rutherford Cable** from C. Sanabria PhD Thesis

  - The results showed: 1) a **significant reduction** of the **critical current** and of the **Upper critical field $B_{c2}$** already at **150 MPa**
  - The **limited data** available, the **complexity** of the experiments and the fact that **only PIT** technology was tested, did **not allow** drawing **general conclusions** also because other studies indicated that up to a transverse load of 200 MPa, the effect on the superconducting performance was limited in $Nb_3Sn$ Rutherford cables

# Introduction

## Aim of the Study & Outstanding Questions

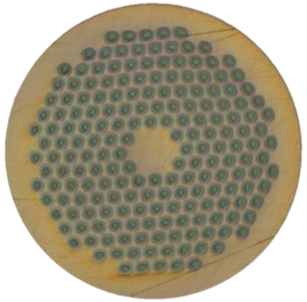
- If confirmed, CERN and UniGe conductor measurements would have had a significant **impact** on the **design** of $Nb_3Sn$ accelerator **magnets**
- In the framework of WP5, CERN coordinated a campaign of measurements in collaboration with the Universities of Geneva and Twente to **try answering the following questions**
  - Are CERN cable's measurements **reproducible?** Are the results reproducible **in a different set-up?**
  - Can we extend these results to the **Restacked Rod Process (RRP) $Nb_3Sn$ superconductor?**
  - At which pressure **permanent $I_c$ reduction** occurs in cable test?
  - Why **wire** measurements show a **larger sensitivity** to transverse load than **cable** measurements?



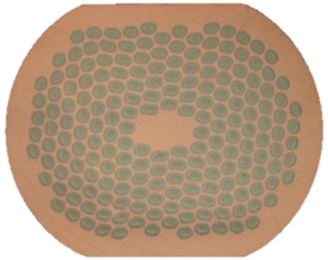
# Measurement Campaign

## Critical Current vs Transverse load

- The point of reference was the 10 mm wide Rutherford cable based on 1 mm $Nb_3Sn$ wires – that is the same cable geometry previously measured by CERN
- CERN and Twente University measured each:
  - **Two cable samples** based on the 192 **PIT** wires
  - **Two cable samples** based on the 132/169 **RRP** wires
- The University of Geneva measured at least two of the following wire samples
  - Round 192 PIT
  - 15% - rolled 192 PIT
  - Round 132/169 RRP
  - 15% - rolled 132/169 RRP

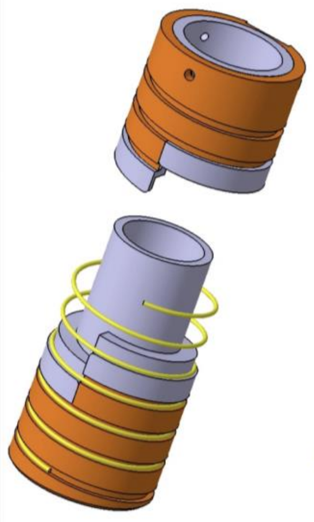


15% Rolling

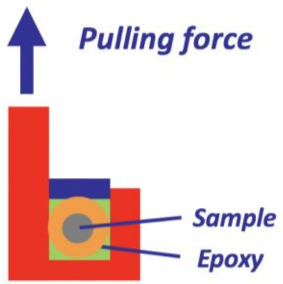


15% Rolling used to simulate the wire deformation during cabling

# Measurement Set-Ups



*4-WALL + impregnation*




*3 groove widths* — *1.30 mm*, *1.15 mm*, *1.00 mm*

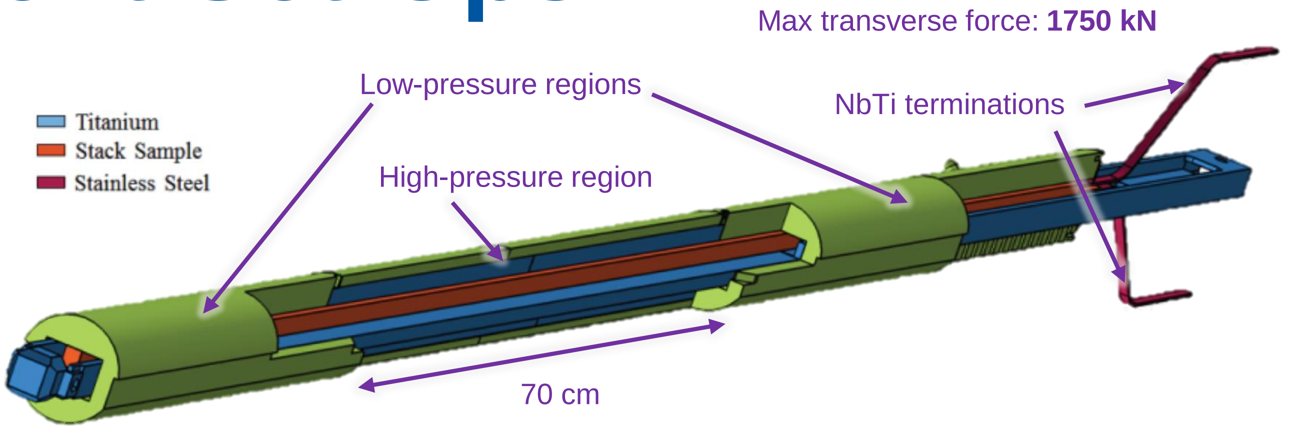
*Wire impregnated with epoxy applied stress uniformly distributed*

## UniGe wire sample holder

- Pro: Large transverse Loads, Rapid and Economic test campaigns
- Contra: single wire measurement

Courtesy of
Carmine Senatore

UNIVERSITÉ DE GENÈVE

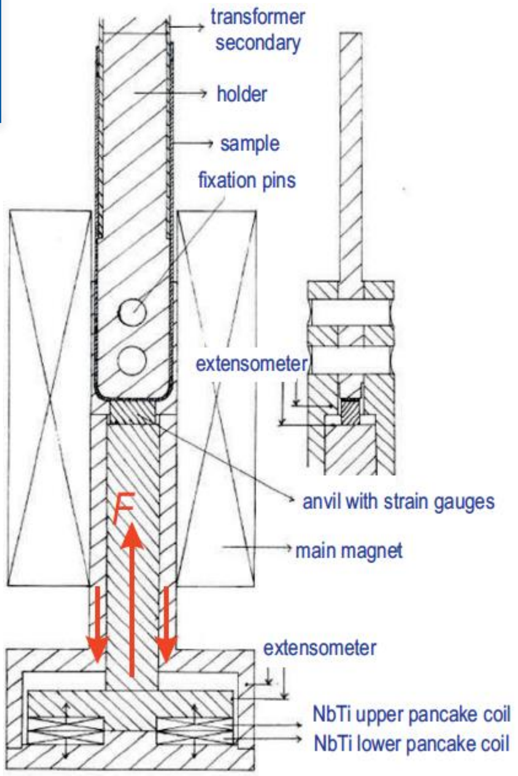


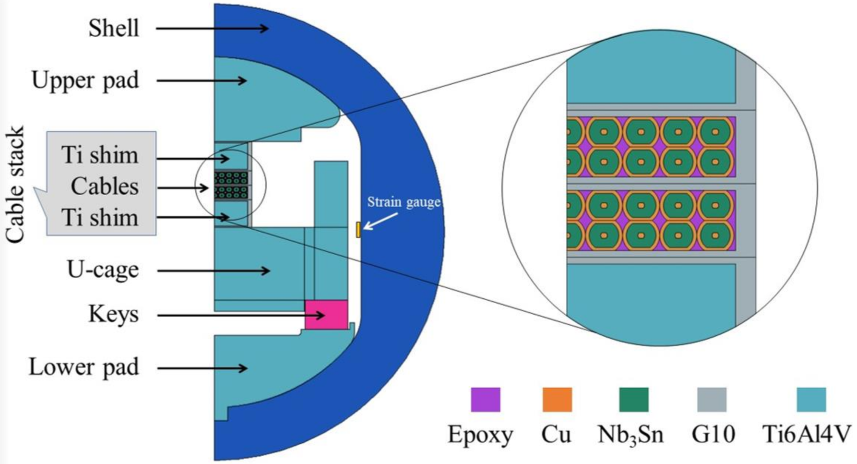

## TWENTE cable sample holder

- Pro: Large transverse loads and Rapid test campaigns
- Contra: short samples (45 mm), large magnetic fields gradients

Courtesy of
Marc Dhalle

UNIVERSITY OF TWENTE.



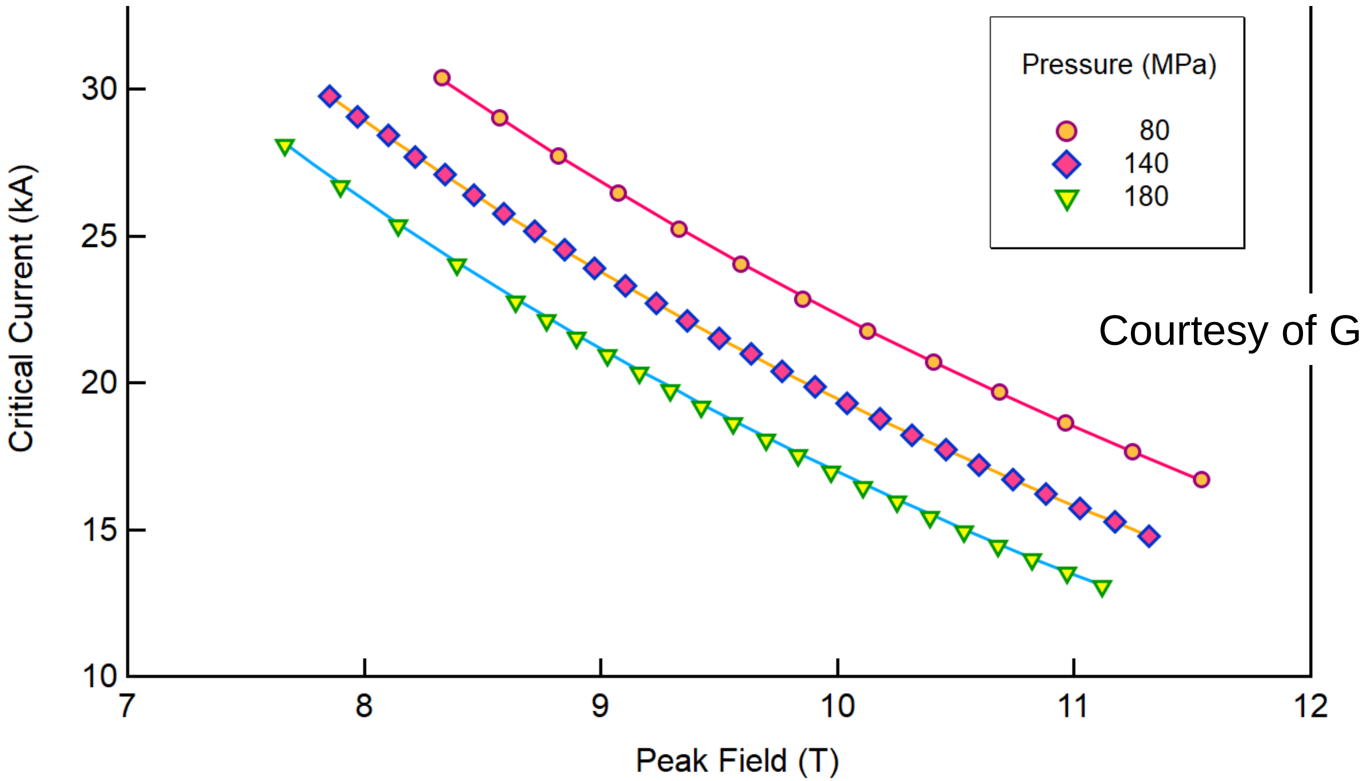

## CERN cable sample holder

- Pro: very representative of the conductor behaviour in a magnet
- Contra: long test campaigns, only narrow cables (~10 mm) can reach up to 250 MPa

# Main Results on Cable tests

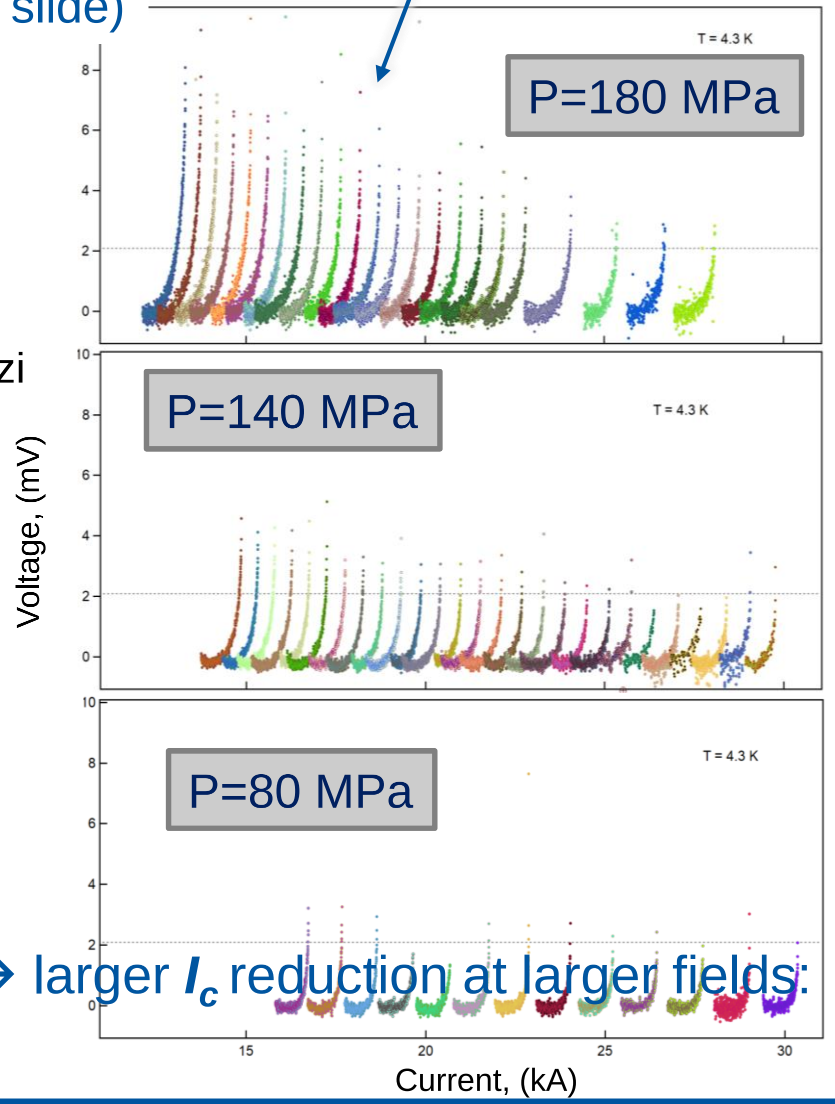
## $I_c$ Reduction Under Transverse Load

Typical results for a PIT Cable measured at CERN (full test sequence in next slide)




Courtesy of G. De Marzi

Different Curves at different applied magnetic fields

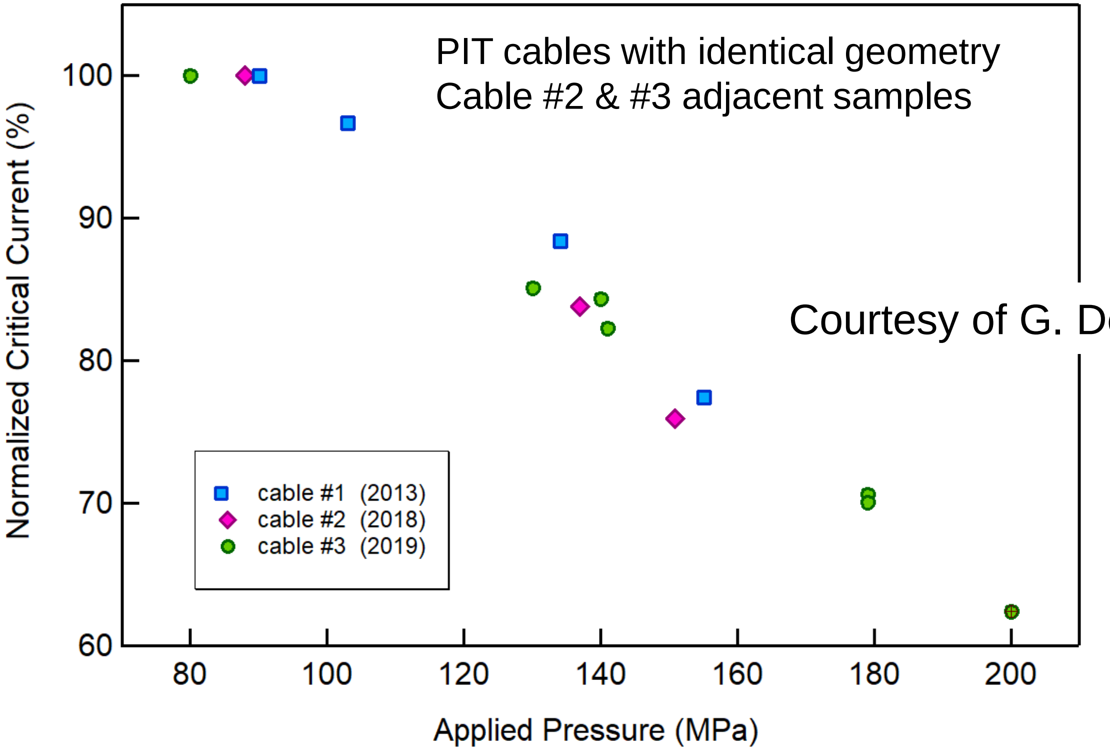



- **Significant Reversible Reduction** of the critical current $I_c$
- $I_c$ reduction mainly due to the decrease of the upper critical field $B_{c2}$ → larger $I_c$ reduction at larger fields: at **150 MPa and 1.9 K** ~ 20% at 12T and ~ 45% at 19 T

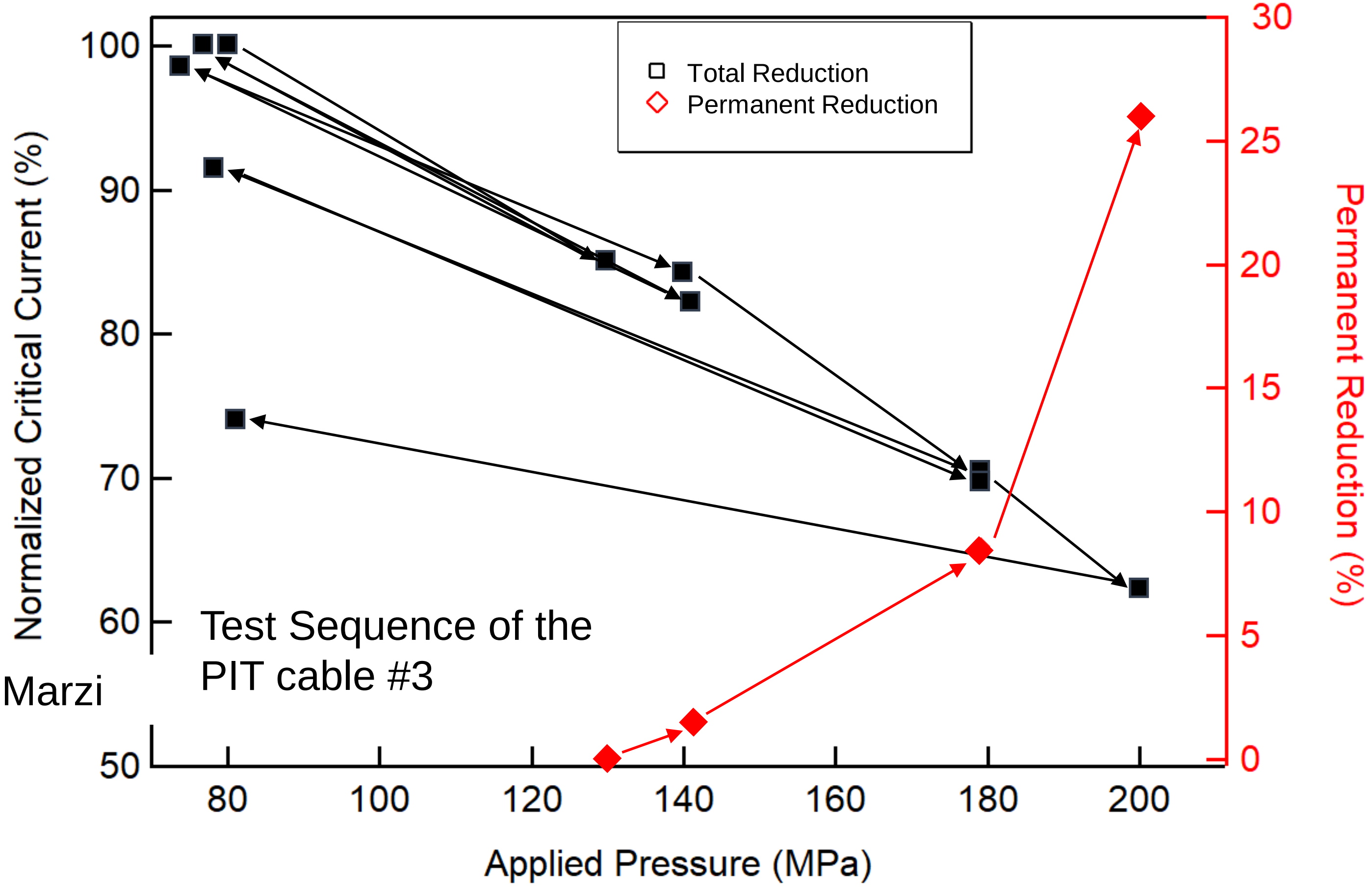
# Main Results on Cable tests

## Reproducibility at CERN

The new measurements **confirmed** and **consolidated** the results observed in 2013; furthermore they allowed **extending** our **understanding**




Courtesy of G. De Marzi



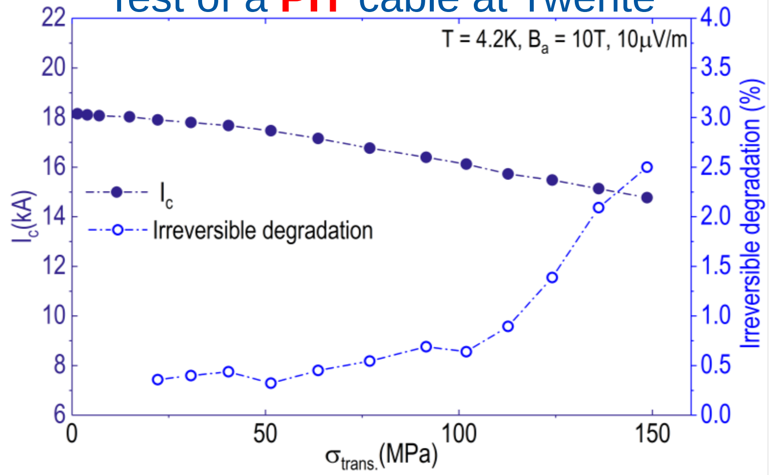

**Onset permeant** reduction **~130 MPa**, up to ~ 180 MPa most likely due to plasticization of copper afterwards, to cracks in the filaments

# Main Results on Cable tests

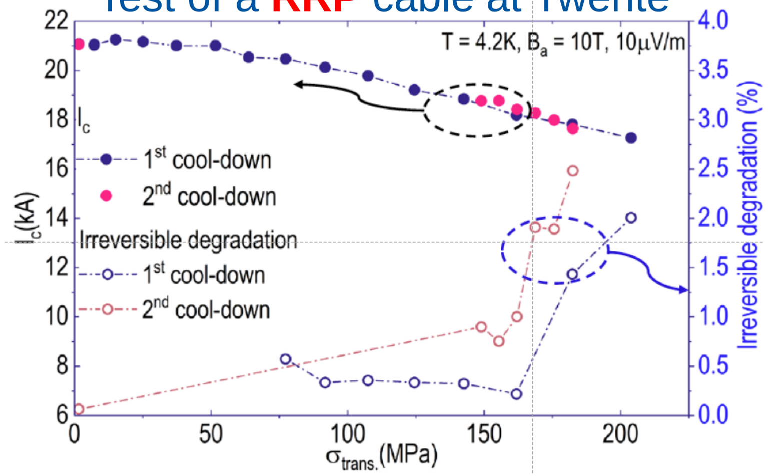
## Same Results in Twente's set Up? What about the RRP conductor? What is irreversible limit?

- Measurements carried out at Twente, confirmed the results found by CERN
- The **RRP** cable has still the same behavior of the PIT cable but it is **less sensitive** to transverse load
  - Onset **permanent** $I_c$ reduction
    1. **PIT**: **~130 MPa**
    2. **RRP**: **~170 MPa**
  - **Total** $I_c$ reduction at 11.6 T and **150 MPa**
    1. **PIT**: **~ 20 %**
    2. **RRP**: **~ 15 %**

Test of a **PIT** cable at Twente




Test of a **RRP** cable at Twente

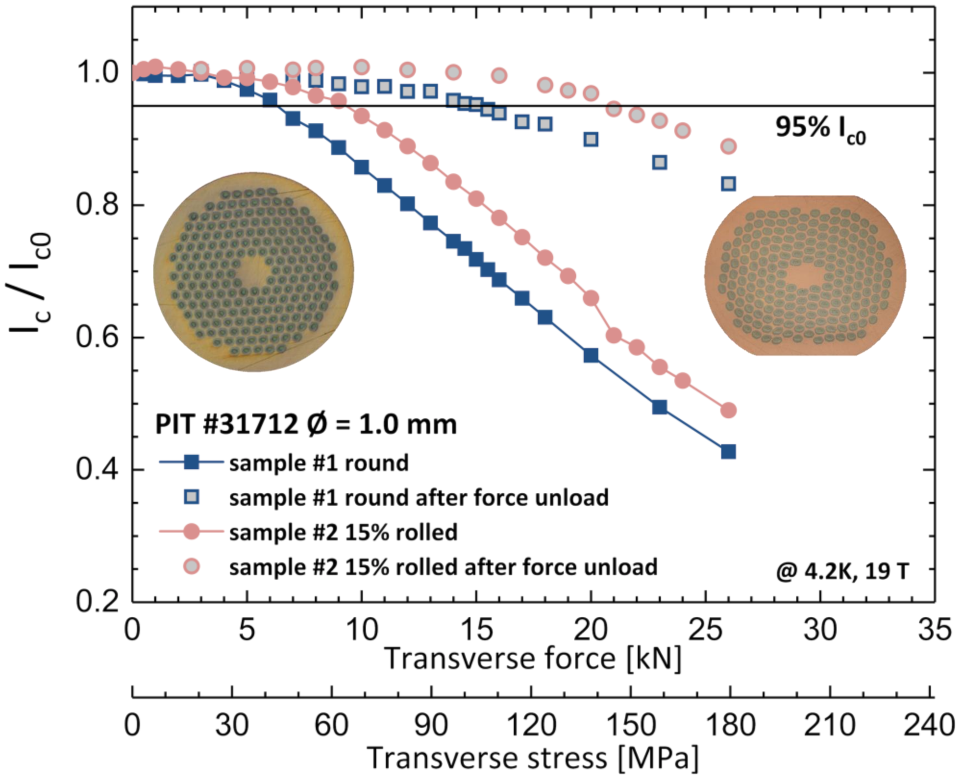



Courtesy of M. Dhalle

# Main Results on Strand tests

## Why wire measurements show a larger sensitivity to transverse load than cable measurements?

- **15%-rolled** wire samples are **less sensitive** than **round wire** samples
  - The same performance reduction is obtained at **40 MPa larger** loads
- It was proved that the **stress concentration** in round wires is at the origin of the difference
  - $I_c$ Measurement of rolled wires under transverse load are significantly more representative of the cable behavior

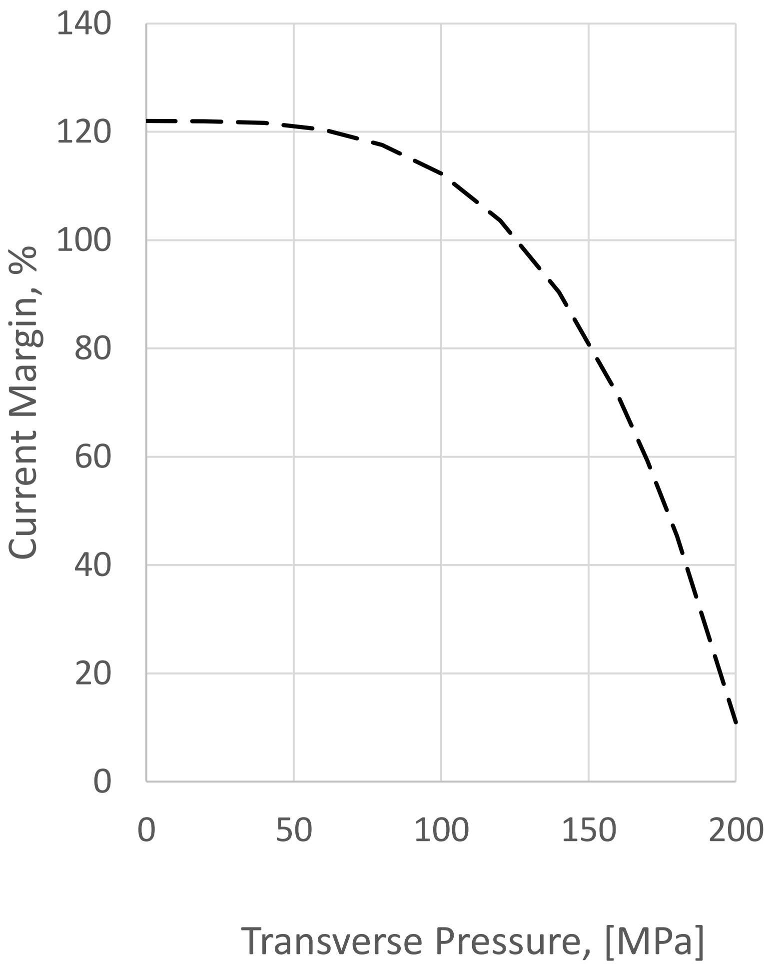



Courtesy of C. Senatore

# Impact of the Study

- The conductor study proved that the **reversible reduction** of the critical current due transverse load must be taken **into account** in the **design** of high field $Nb_3Sn$ magnets

- The study **sensitized** the **magnet international community** and there now several efforts to account for the transverse load in the design of the magnets




Estimate of the Current Margin in the mid-plane of a 11 T $Nb_3Sn$ cos-theta dipole magnet

# Conclusion

- The **EuroCirCol Conductor program**, coordinated by CERN in collaboration with the Universities of Geneva and Twente, **successfully answered** the **outstanding questions** set at the beginning of the study

- The **effect** of the **transverse load** on the **superconducting performance** of $Nb_3Sn$ cables and wires was **understood** and **quantified**
  - This effect is **relevant** at **high fields** and has to be taken into account for the design of High Field $Nb_3Sn$ magnets

- There now **several efforts** in different magnet groups **to account** for the **transverse load** in the **design** of **High Field $Nb_3Sn$ magnets**

# Thank you for your attention