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EASITrain

Electromechanical Properties of Technical Superconductors

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Outline

Forces, stress and strain in a magnet

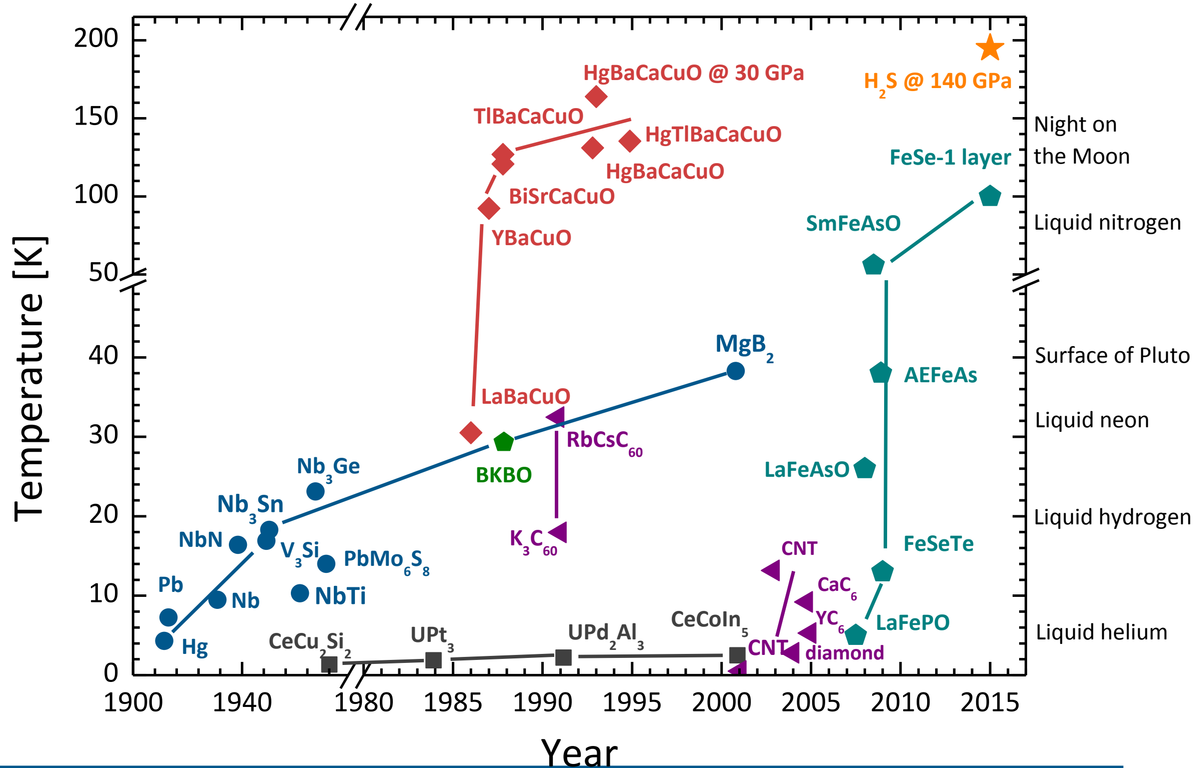
Technical superconductors under mechanical loads

- ***Reversible vs. irreversible effects***
- ***Mechanisms behind the irreversible degradation of the critical current***
- ***Intrinsic vs. extrinsic effects***

Focus on two materials: Nb_3Sn and YBCO

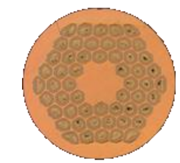
From superconducting materials…

…to technical superconductors



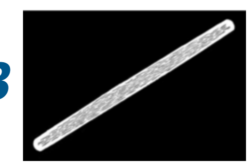
NbTi

Nb_3Sn



MgB_2

Bi2223



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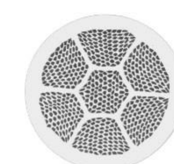
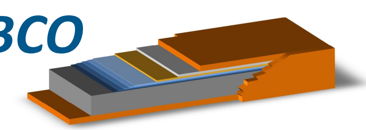


YBCO



1. ***Superconducting ?*** ***10’000***
2. ***T_c>4.2K & B_{c2}>10T ?*** ***100***
3. ***J_c>1000 A/mm^2 ?*** ***~10***

Operate at high current density is a necessary condition for applications, but it is not sufficient

Other crucial requirements:

- *Have high tolerance to stress* *Magnetic forces*
- *Be safe in case of magnet quench* *Quench detection, NZPV*
- *Have low magnetization* *Applications to NMR, MRI, HEP magnets*
- *Have a persistent joint technology* *Applications to NMR, MRI*

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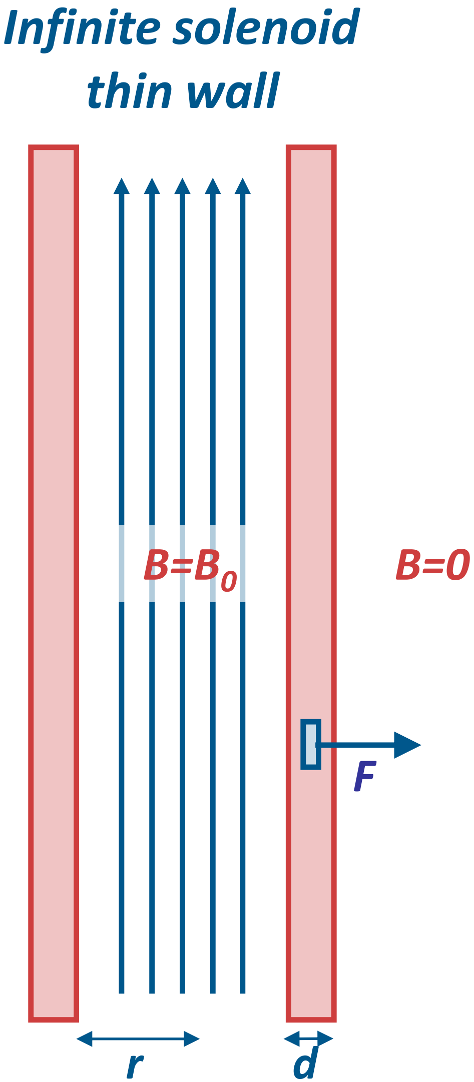
Introduction to Forces and Stresses in a Magnet



The magnetic field is $B_0 = \mu_0 J d$

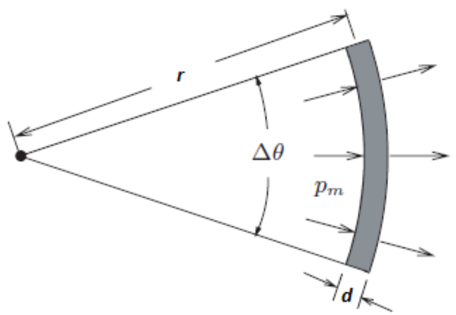
The expression of the magnetic force density (per unit of volume) is

$$f = J \times B$$

The average field in the winding is $\dfrac{B_0}{2}$

The (radial) force on a winding volume element is

$$\Delta F = J\frac{B_0}{2}\Delta v = J\frac{B_0}{2} r\Delta\theta\,\Delta z\, d = \frac{B_0^{\;2}}{2\mu_0} r\Delta\theta\,\Delta z$$

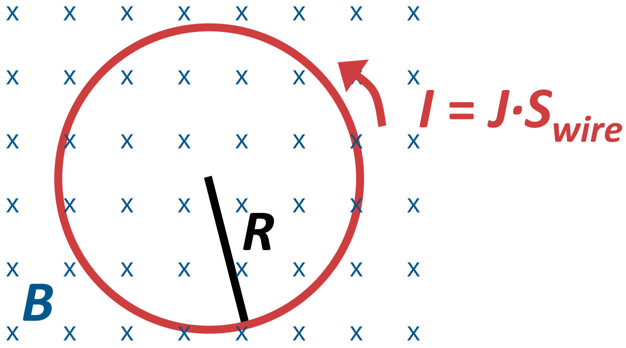


$$= \frac{B_0^{\;2}}{2\mu_0}\Delta s = p_m \Delta s$$

$$p_m(B_0 = 10T) = 400\ bar$$

Hoop stress in a ring

A ring carrying a current I in a field B



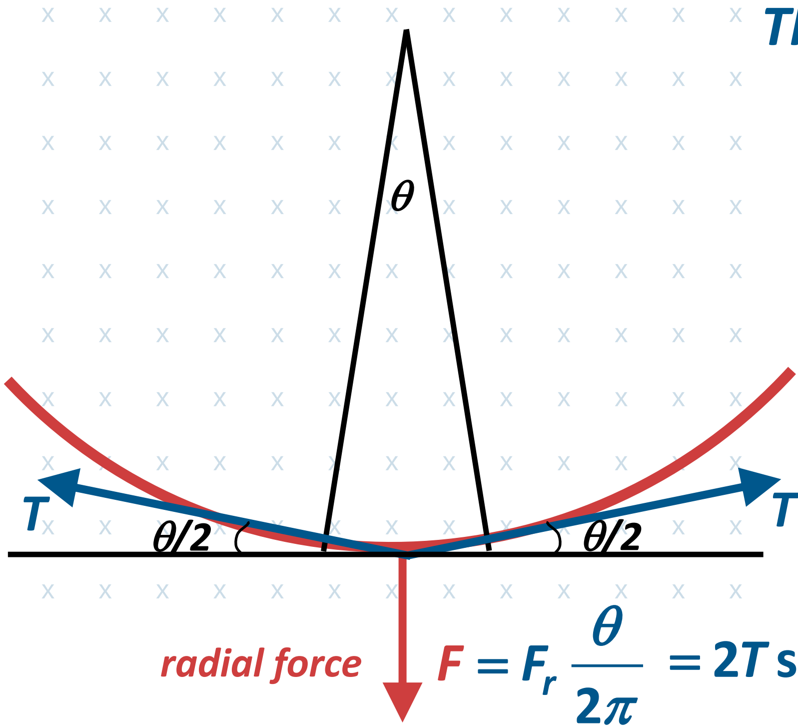
The total radial magnetic force on the ring is

$$F_r = \int_{loop} dv f = \int dv J \times B$$

$$= 2\pi \; R \; I \; B$$

Hoop stress in a ring

A ring carrying a current I in a field B



The total radial magnetic force on the ring is

$$F_r = \int_{loop} dv f = \int dv J \times B$$

$$= 2\pi \; R \; I \; B$$

A tension is developed within the ring

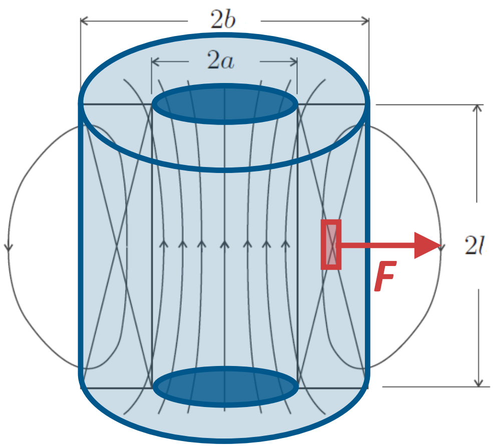
$$F = F_r \frac{\theta}{2\pi} = 2T \sin\frac{\theta}{2} \approx 2T\frac{\theta}{2} = T\theta \quad \Rightarrow \; T = \frac{F_r}{2\pi} = \; R \; I \; B$$

The so-called "hoop stress" on the wire is $\sigma_\theta = \frac{T}{S_{wire}} = \; R \; J \; B$

Hoop stress levels above 100 MPa are common, the NHMFL 32 T magnet operates at 400 MPa

Electromagnetic stresses in a finite solenoid

In a winding adjacent turns will press on each other and develop a radial stress σ_r which modifies the hoop stress σ_θ



Considering the solenoid as a continuous uniform medium, from the Hooke's law

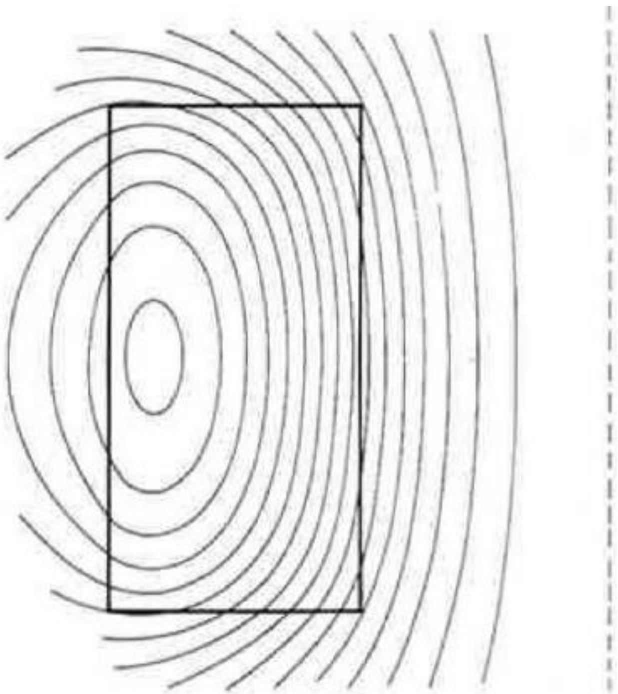
$$\sigma_r = \frac{E}{1-\nu^2}\left(\frac{du}{dr} + \nu\frac{u}{r}\right) \quad \text{and} \quad \sigma_\theta = \frac{E}{1-\nu^2}\left(\frac{u}{r} + \nu\frac{du}{dr}\right)$$

where u is the local displacement in the radial direction, E is the Young's modulus and ν is the Poisson's ratio

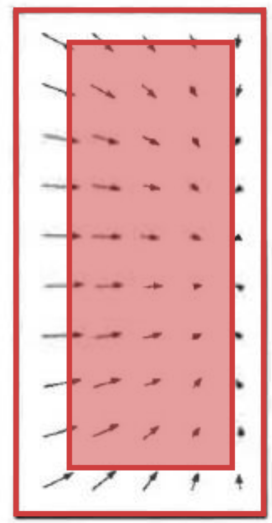
The condition for equilibrium between radial stress σ_r, hoop stress σ_θ and body force BJr is given by the equation

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{du}{dr}\right) - \frac{u}{r^2} = \frac{1-\nu^2}{E}BJ$$

Electromagnetic stresses in a finite solenoid



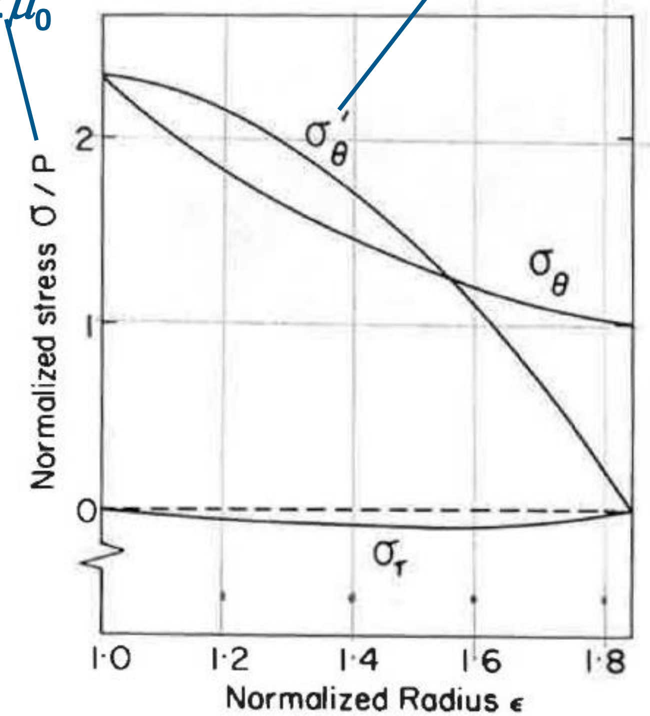
magnetic lines of force



vectors of electromagnetic force per unit volume

$$p = \frac{B_0^{\,2}}{2\mu_0}$$

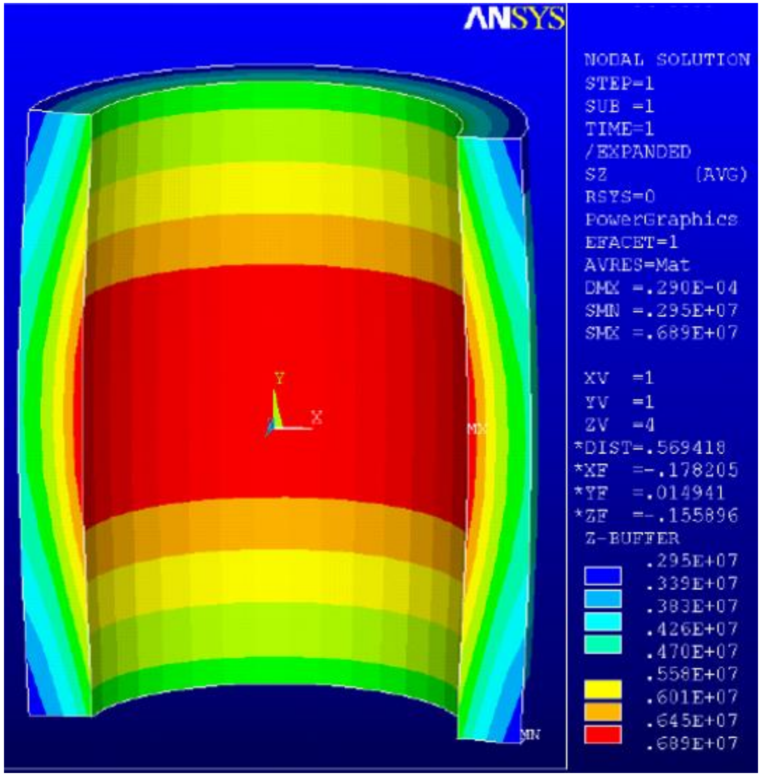
$$\sigma'_\theta = BJr$$



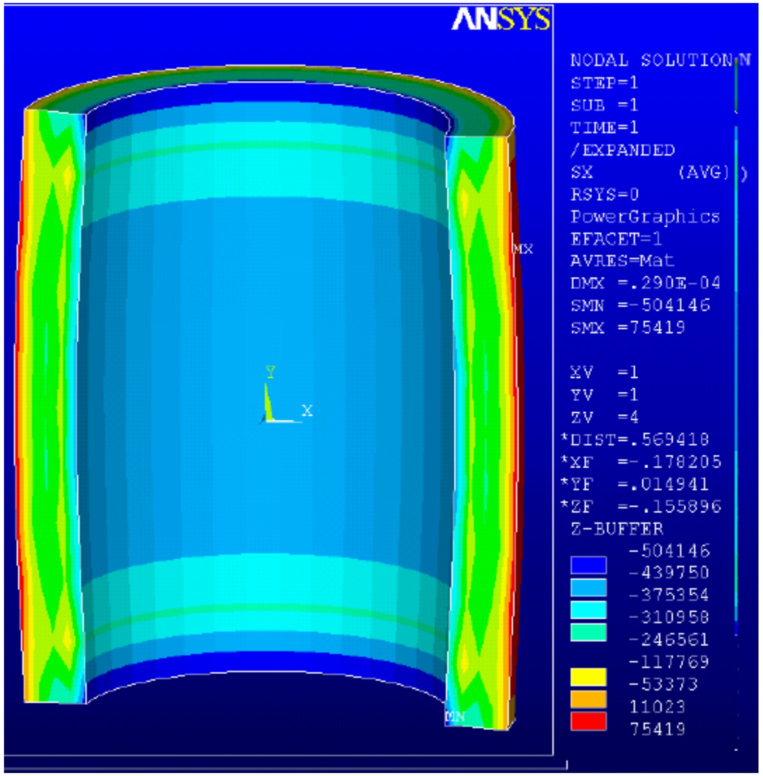
$$\varepsilon = \frac{r}{\text{bore radius}}$$

Example: for B_0 of the order of 10 T, on the winding σ_θ of > 200 MPa (> 2000 bar)

Colour mapping of σ_θ and σ_r in a finite solenoid

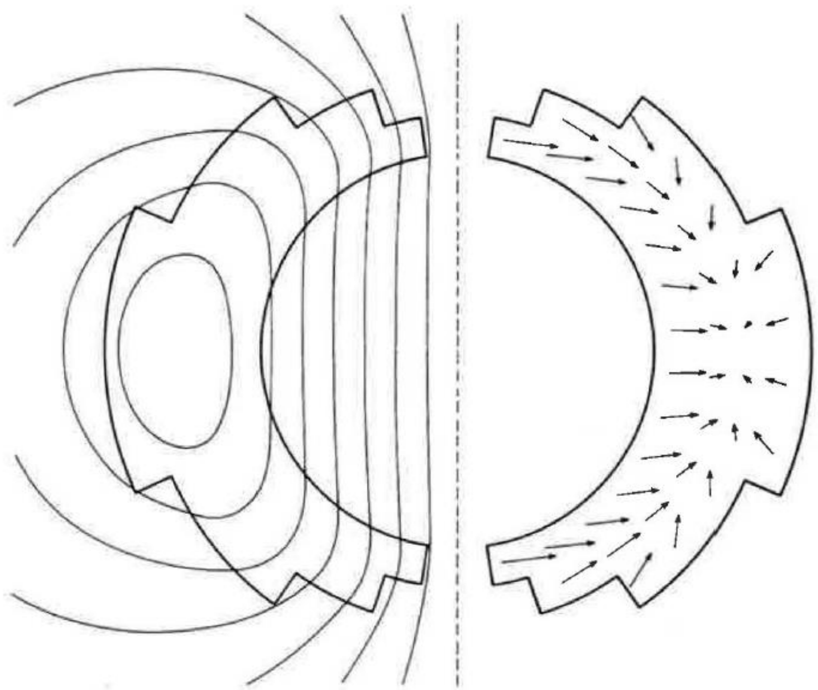


Hoop stress



Radial stress

Electromagnetic stresses in an accelerator dipole



magnetic lines of force

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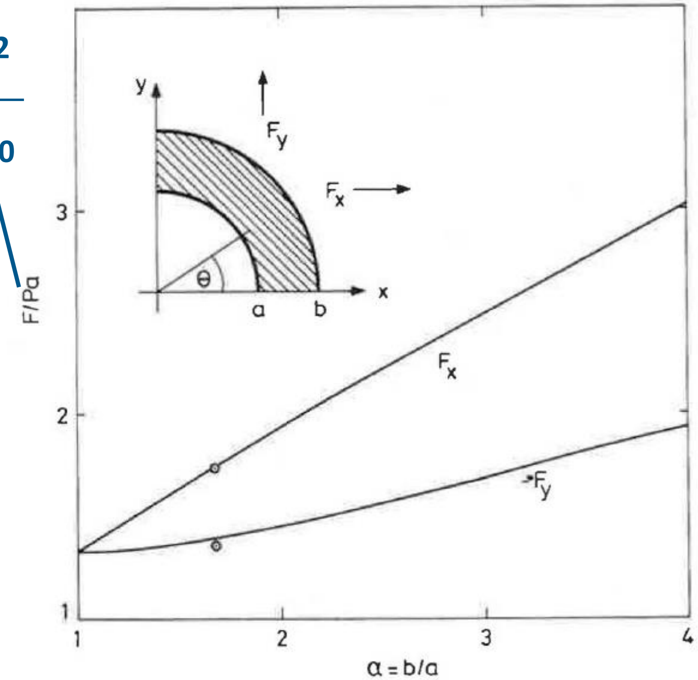
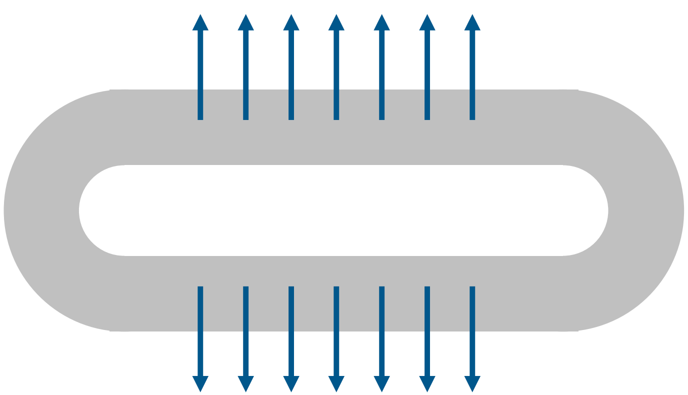


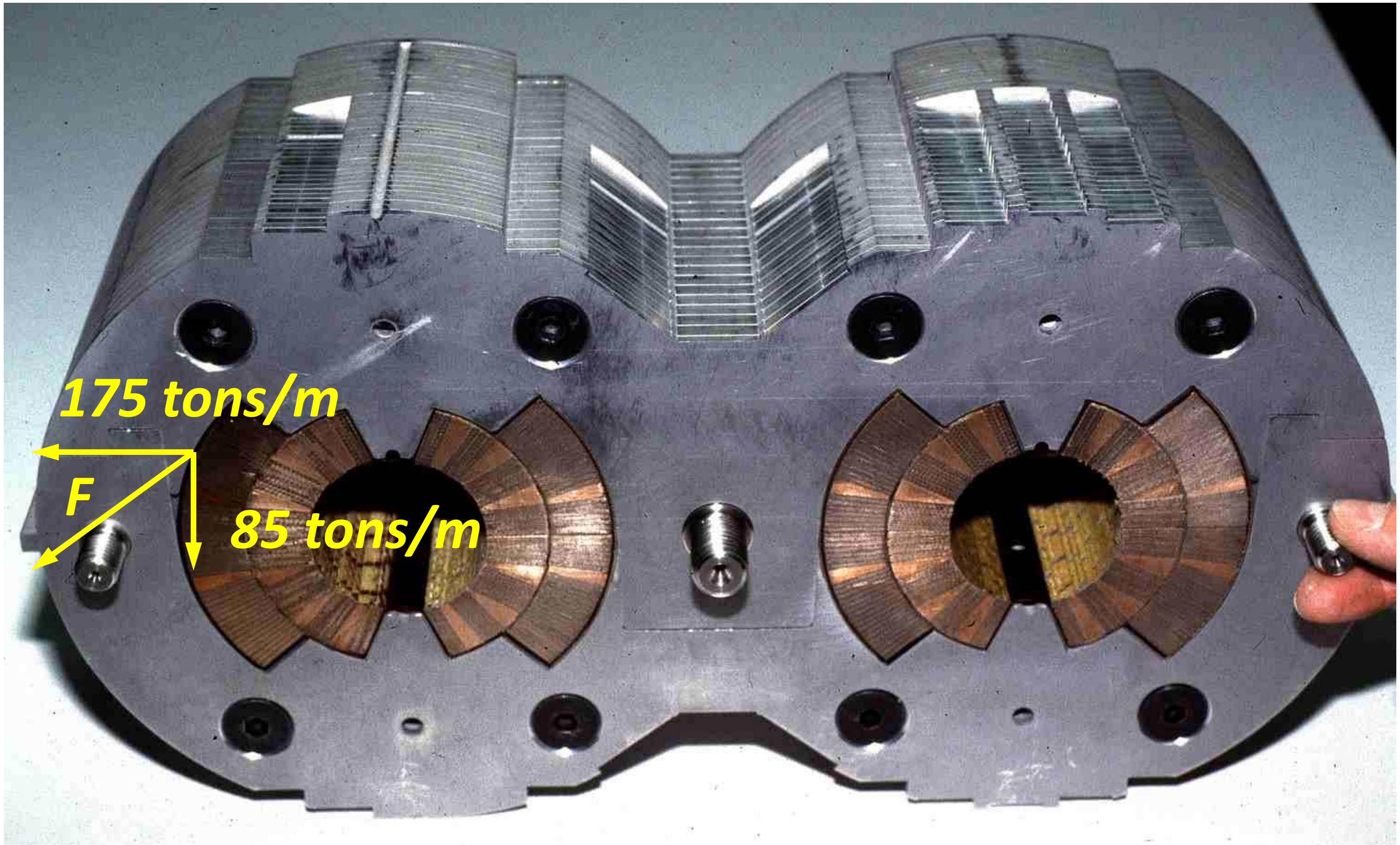
For B_0=6T and (a+b)/2=100 mm

F_x=200 tons/m



In straight-sided coils such as dipoles and quadrupoles the conductor is unable to support the magnetic forces in tension

Collaring and Pre-stress in accelerator magnets



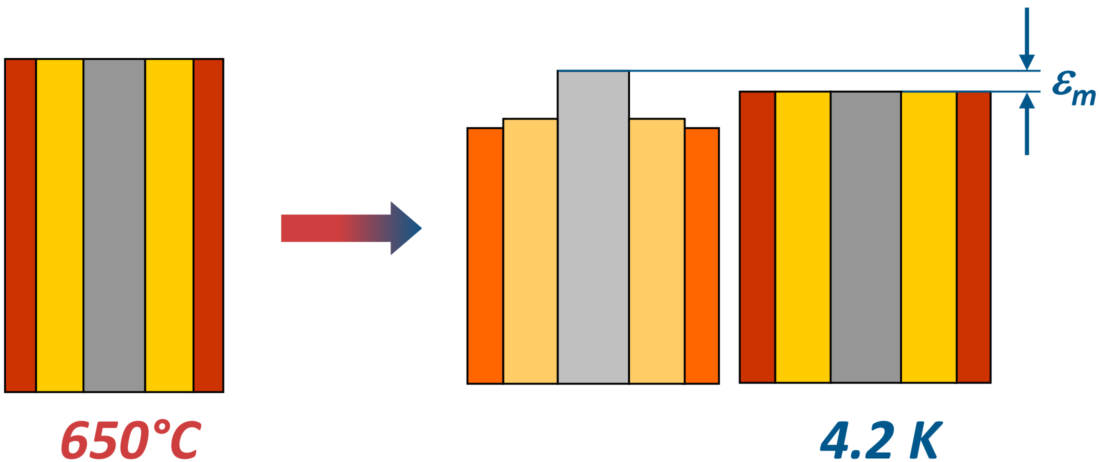
The windings of accelerator magnets are clamped in a solid collar

Collar provide pre-stressing to prevent the movement of the coil in the presence of electromagnetic forces

Thermal precompression of the superconductor

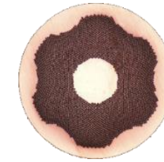
All technical superconductors are composite

Mismatch in thermal contraction within the composite induces a precompression in the SC

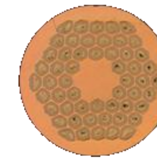


When the SC is cooled at the operating temperature, its crystal structure deforms and this induces changes on T_c , B_{c2} (and thus on J_c)

NbTi

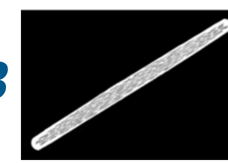


Nb_3Sn

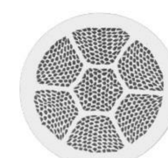


MgB_2

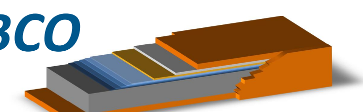
Bi2223



Bi2212



YBCO



In the following, the focus will be on

Nb_3Sn → Today high field superconductor, up to 23.5 T in solenoidal coils, the material for iter and HiLumi and only candidate material for the 16 T dipoles of FCC

YBCO → Tomorrow high field superconductor, more than 40 T demonstrated in solenoidal insert coils, the way to get 20 T dipoles and beyond EuCARD² ARIES

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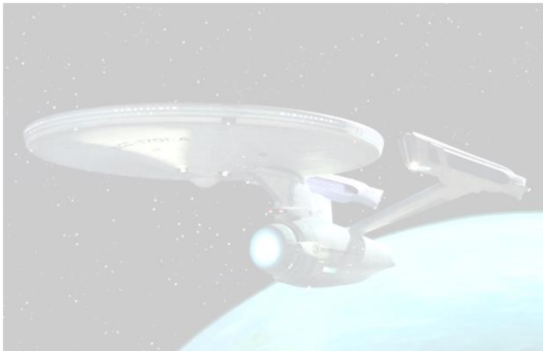
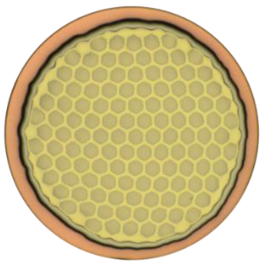
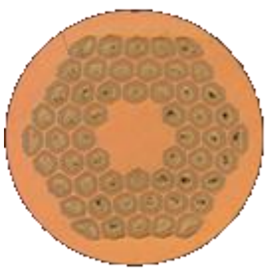


Industrial fabrication of Nb_3Sn wires

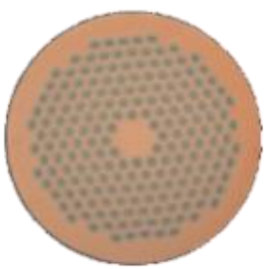
Three technologies have been developed at industrial scale



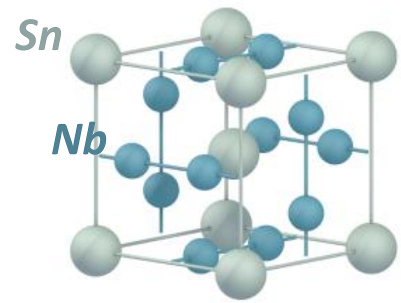
- Bronze route



- Internal Sn diffusion



- Powder-In-Tube (PIT)

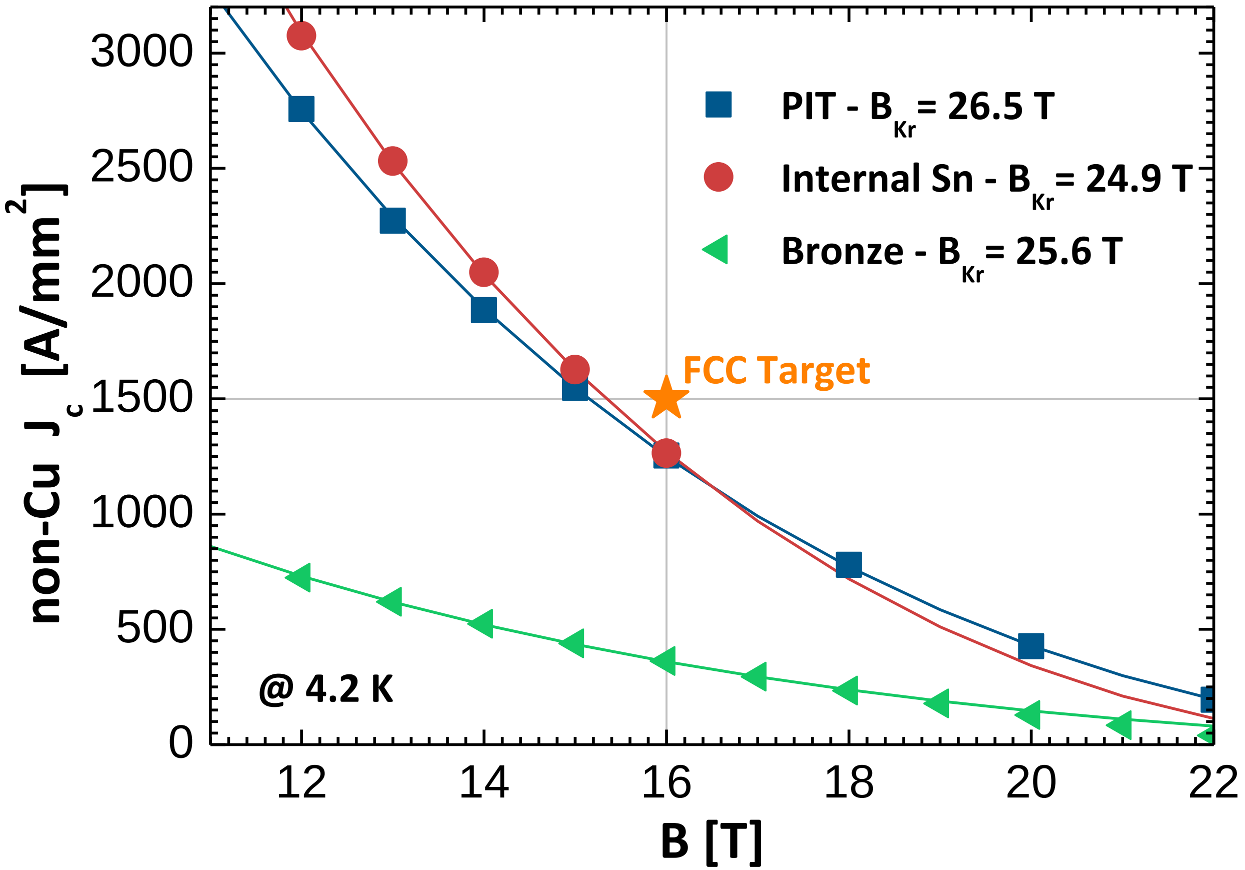


The Sn source is the main difference

Presently produced by BRUKER, LUVATA, Western Superconducting Technologies Co.,Ltd., BOCHVAR INSTITUTE OF INORGANIC MATERIALS JSC VNIINM, KISWIRE, KOBELCO KOBE STEEL, LTD., JASTEC SUPERCONDUCTOR

Critical current density vs. magnetic field

Best performance achieved so far in industrial wires



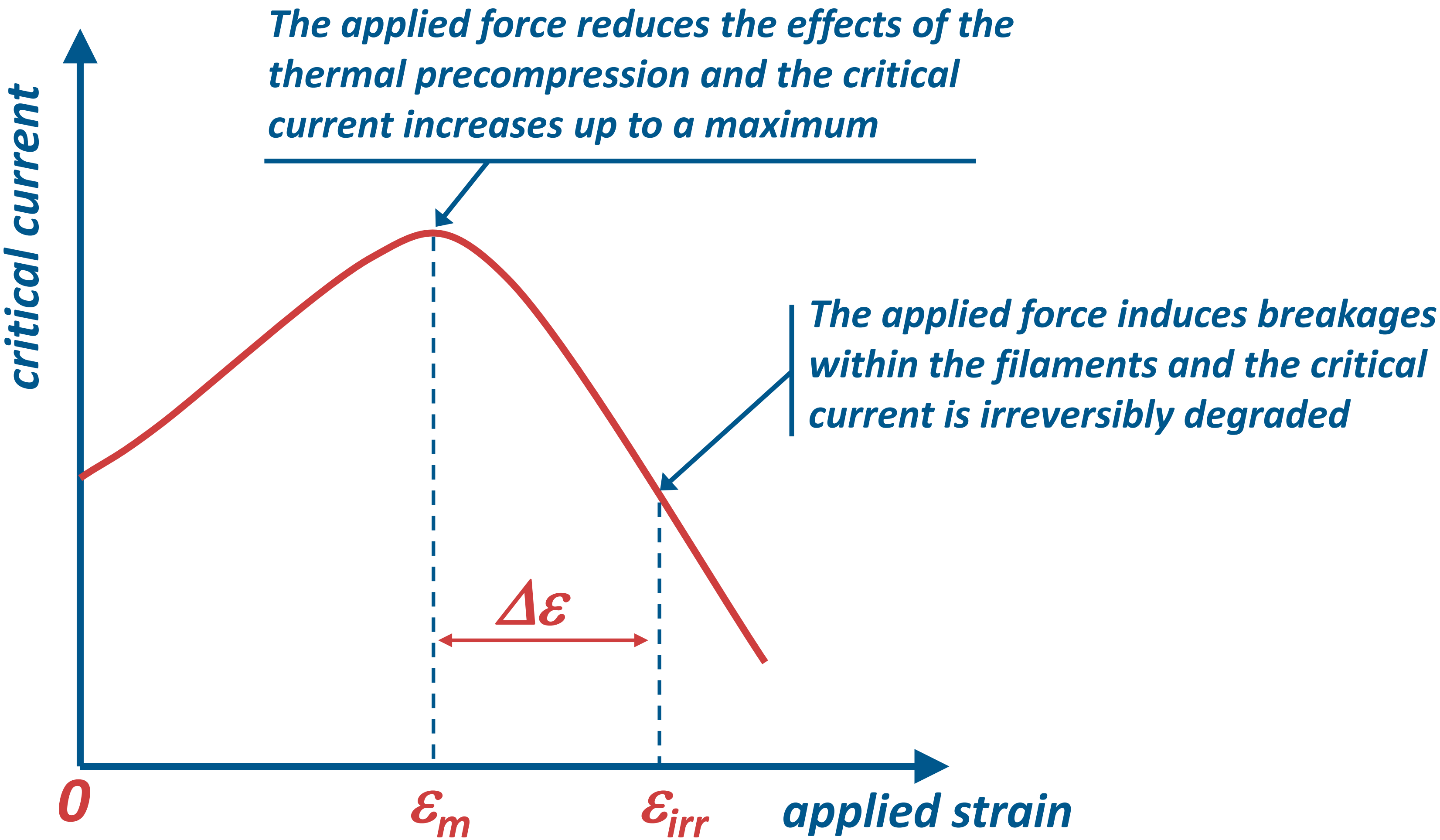
T. Boutboul et al., IEEE TASC 19 (2009) 2564

J. Parrell et al., AIP Conf. Proc. 711 (2004) 369

V. Abächerli et al., IEEE TASC 17 (2007) 2564

Strain-induced changes in the critical current

Effects of the longitudinal strain



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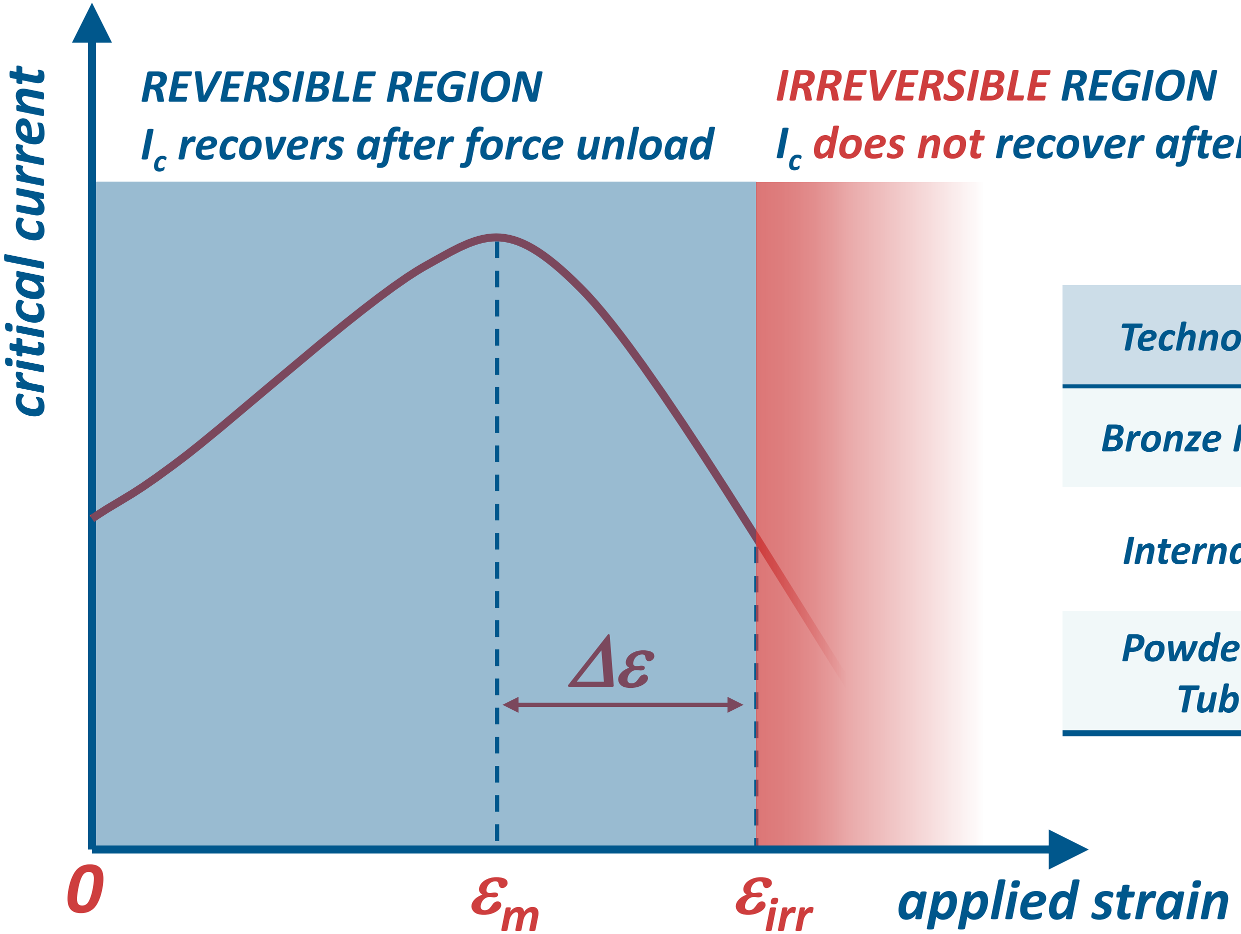
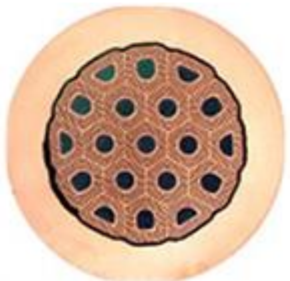
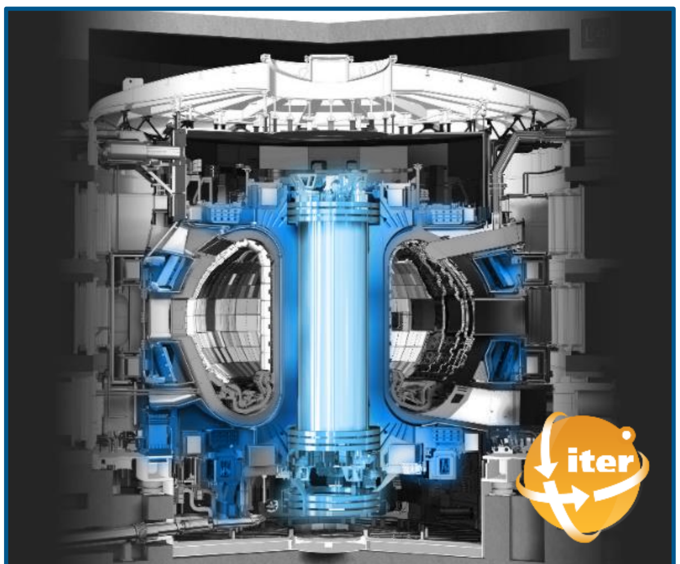


Technology	$\Delta\varepsilon = \varepsilon_m - \varepsilon_{irr}$ [%]
Bronze Route	0.4 – 0.6
Internal Sn	0.05 – 0.2
Powder-In-Tube	0.15 – 0.3

Wire cabling for the ITER coils

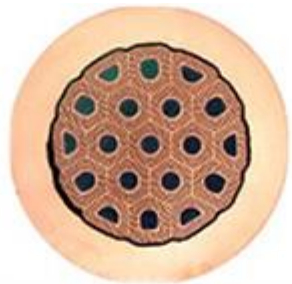


CICC = Cable-In-Conduit Conductor



Wire cabling for the ITER coils

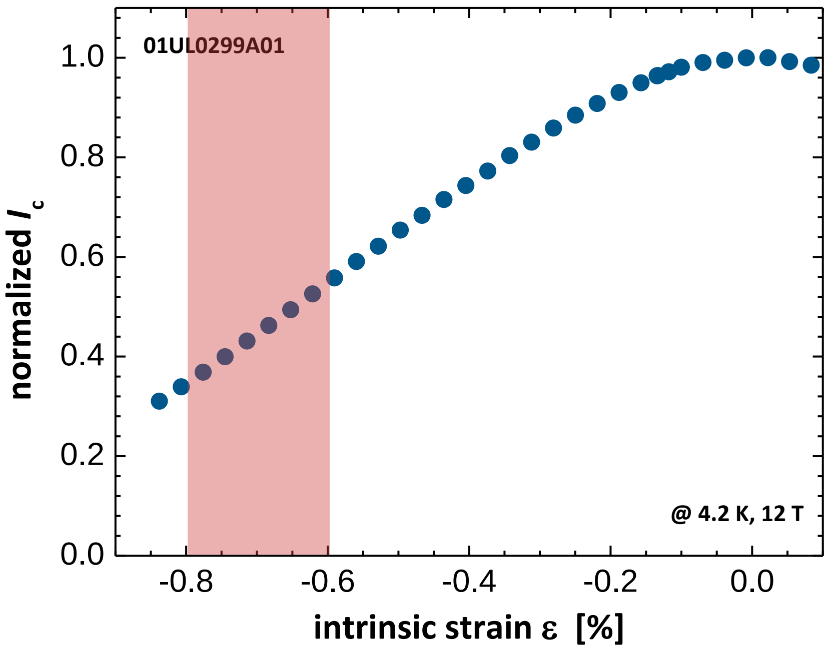
Reversible variation of I_c under strain matters



Because of the thermal precompression, wires in a CICC experience an effective axial compressive strain ranging between -0.6% and -0.8%

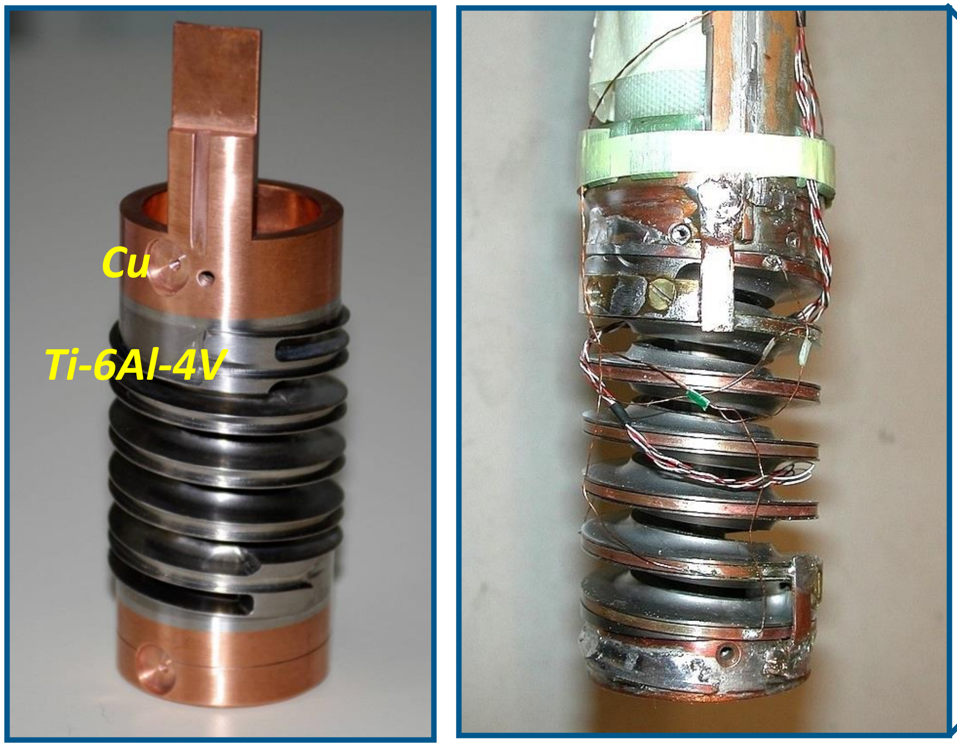
CICC = Cable-In-Conduit Conductor

The performance of the superconductor is limited to ~40% of the maximum achievable current

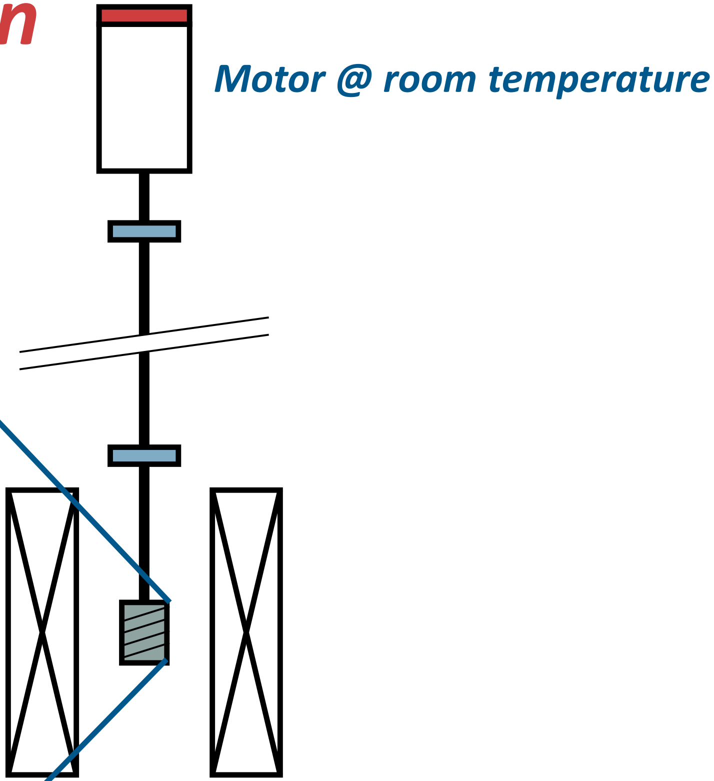


How to measure I_c vs. axial strain

The WASP (Walters Spring) probe



B. Seeber et al., Rev. Sci. Instr. 76 (2005) 093901



Max current	1000 A
Sample length	1.1 meter
Voltage taps distance	126 mm
Electrical field criterion	0.01 µV/cm
Strain (ε)	up to ± 1.2 %

Why do superconducting properties depend on strain ?

1. Reversible effects of strain

Reversible effects of strain

Why superconducting properties depend on strain

Nb_3Sn exhibits strong-coupling superconductivity

$\langle \omega \rangle$ *is an average phonon frequency*

electron-phonon coupling — *phonon DOS*

$$\lambda = 2\int_0^\infty d\omega \frac{\alpha^2(\omega)F(\omega)}{\omega} \propto \frac{N(E_F)}{\langle \omega^2 \rangle}$$

McMillan parameter

$$T_c = \frac{\hbar\langle\omega\rangle}{1.2k_B}\exp\left[-\frac{1.04(1+\lambda)}{\lambda-\mu^*(1+0.62\lambda)}\right]$$

μ^* gives the Coulomb repulsion at the Fermi surface

Strain induces change both in the phonon spectrum and the electronic bands

So far the question whether the strain sensitivity is due mainly to electrons or phonons has not been settled

Reversible effects of strain

Why superconducting properties depend on strain

Some recent theoretical studies

D. Markiewicz, Cryogenics 44 (2004) 767

This work emphasizes the role of anharmonicity as a source of the strain dependence in Nb_3Sn

D. Taylor and D. Hampshire., Supercond. Sci. Technol. 18 (2005) S241

Microscopic theory analysis suggests that the uniaxial strain effects are predominantly due to changes in the average phonon frequencies

G. De Marzi et al., J. Phys.: Condens. Matter 25 (2013) 135702

Investigation of the strain sensitivity of Nb_3Sn from first principle calculations based on the density functional theory

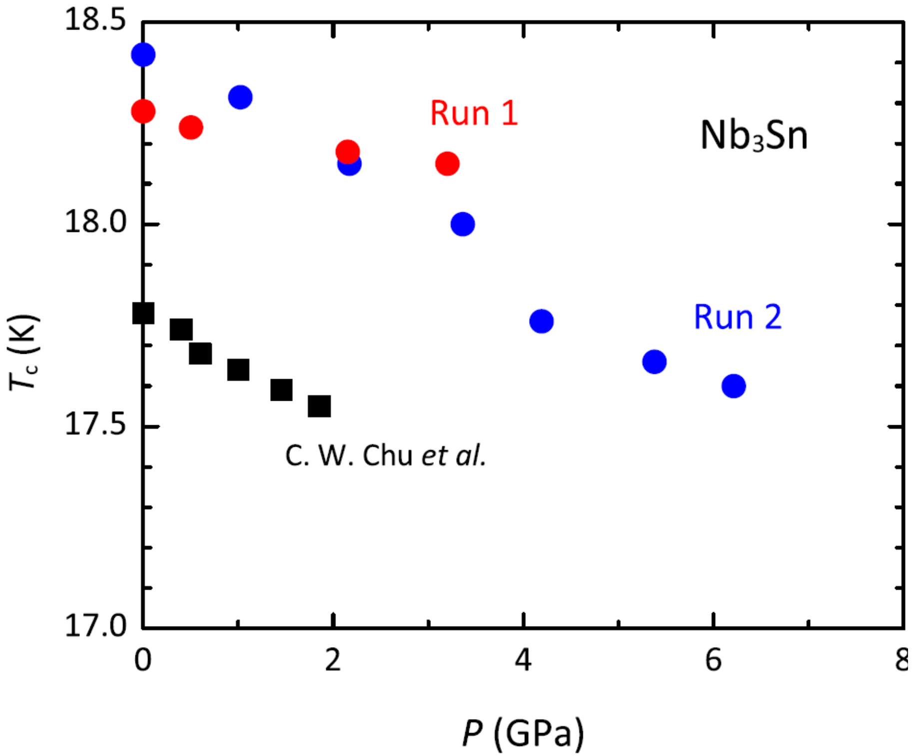
M. Mentink, PhD thesis (2014), University of Twente

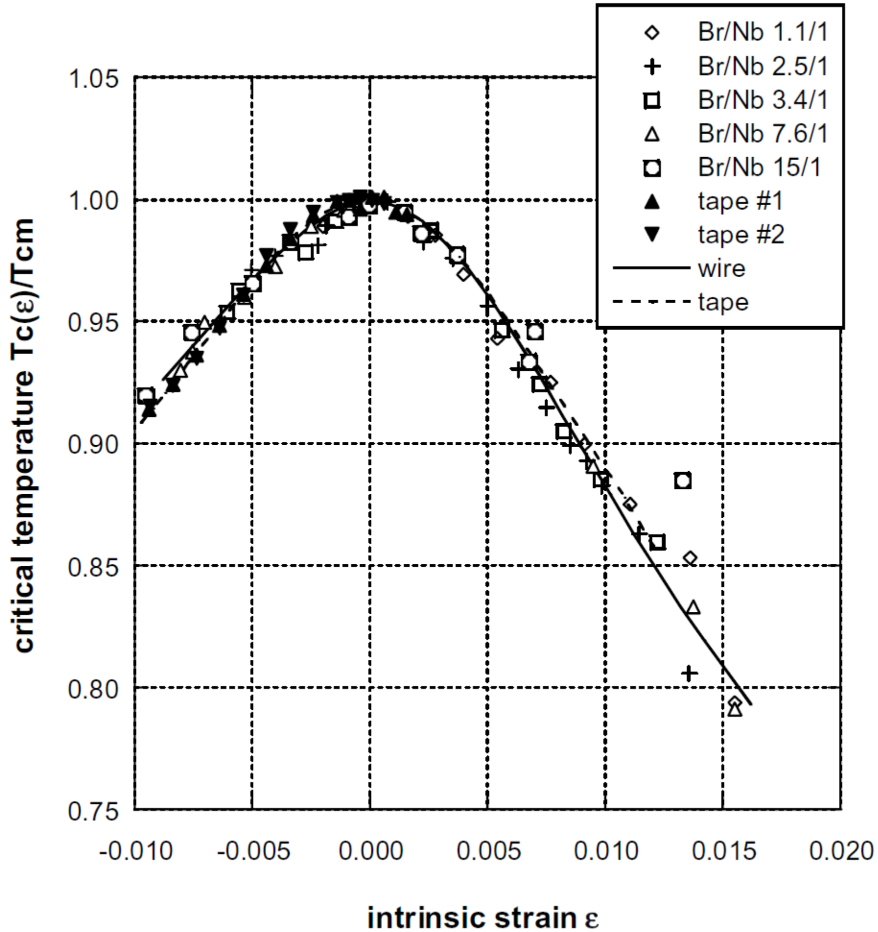
Ab-initio calculations used to evaluate electronic, and vibrational properties, as well as T_c and B_{c2} as a function of disorder, crystal orientation, and strain

D. Valentinis et al., Supercond. Sci. Technol. 27 (2014) 025008

A theory of the strain-dependent critical field in Nb_3Sn based on anharmonic phonon generation

Reversible effects of strain
Hydrostatic vs. uniaxial





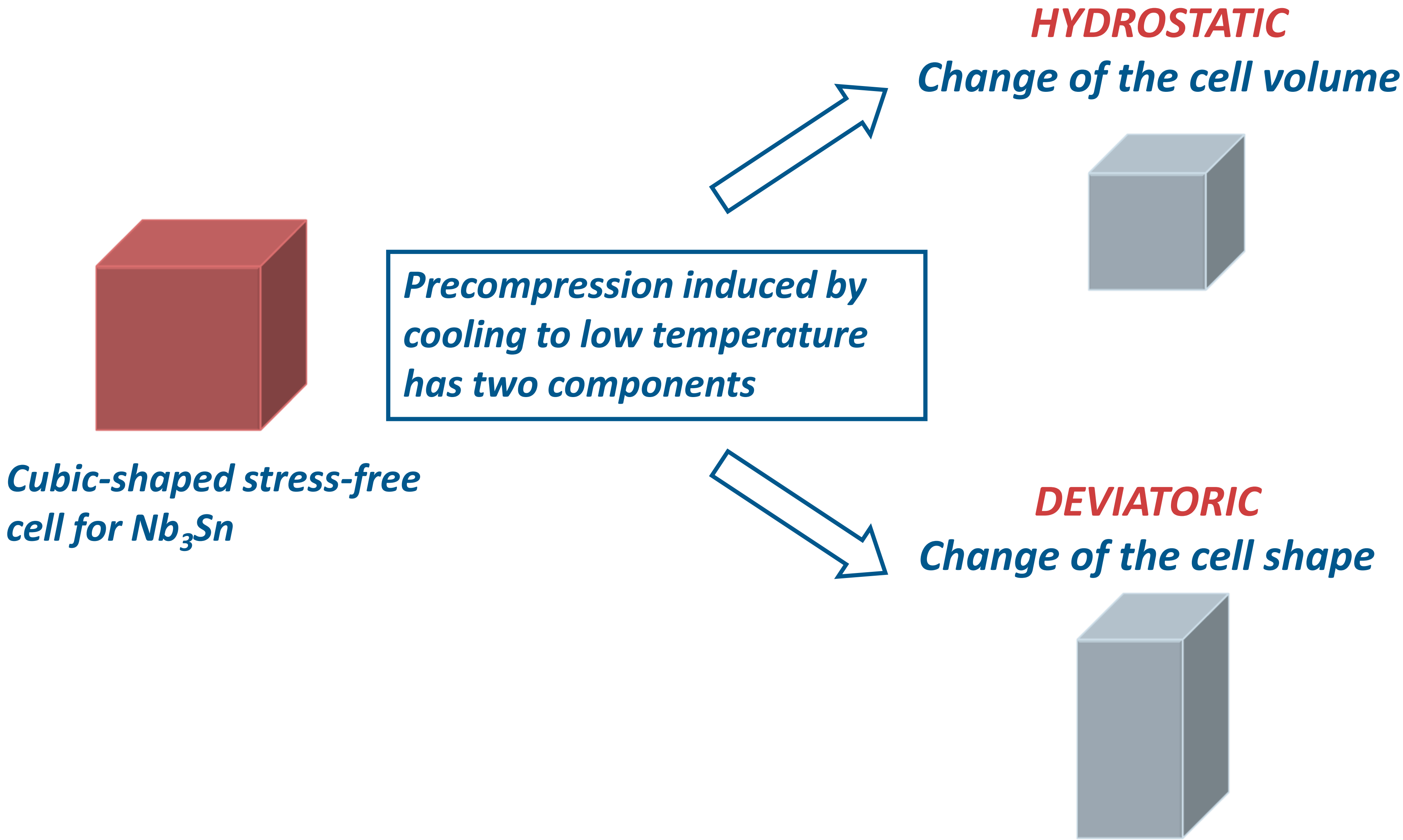
Critical temperature vs. hydrostatic compression

S. Tanaka et al., J. Phys. Soc. Jpn. 81 (2012) SB026

Reduced critical temperature vs. unaxial strain

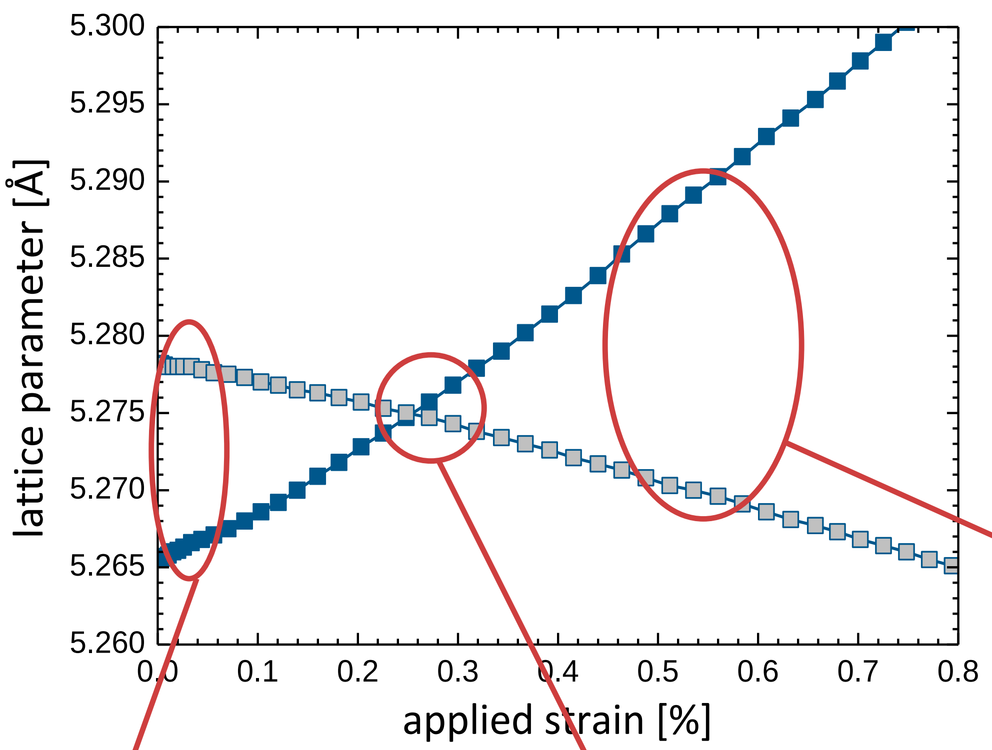
D. Markiewicz, Cryogenics 44 (2004) 767

Reversible strain effects in Nb_3Sn wires



Reversible strain effects in Nb_3Sn wires: lattice parameters

Bronze route wire: Nb_3Sn lattice parameters vs uniaxial strain @ 4.2 K



XRD experiments @ ESRF Grenoble

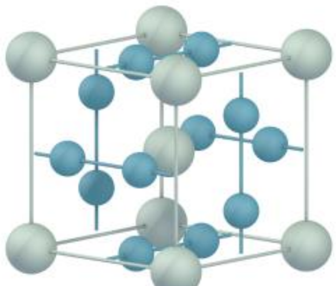
C. Scheuerlein et al., IEEE TAS 19 (2009) 2653

L. Muzzi et al., SUST 25 (2012) 054006

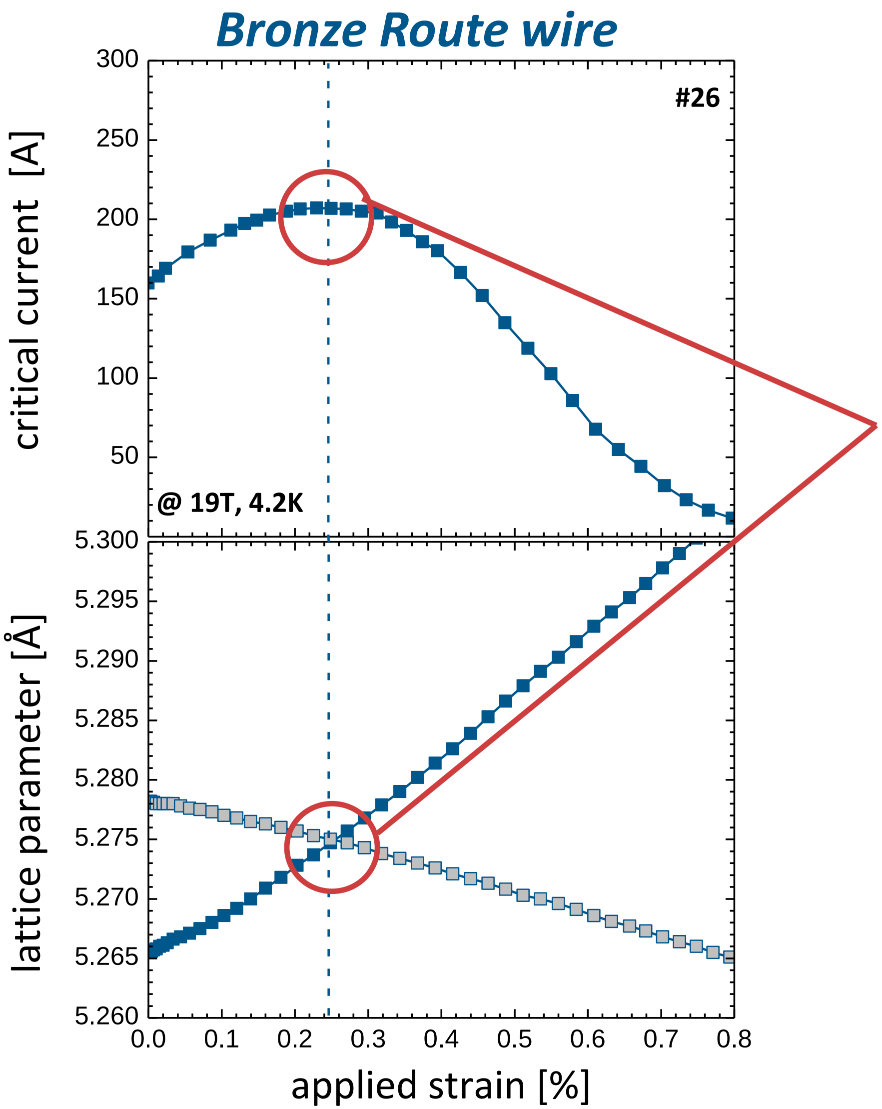
HIGH APPLIED STRAIN
Again Hydrostatic+Deviatoric

ZERO APPLIED STRAIN
Nb_3Sn is precompressed
Hydrostatic+Deviatoric

CROSSING POINT
Cubic cell recovered
Hydrostatic component still present



Lattice parameters and I_c under axial strain



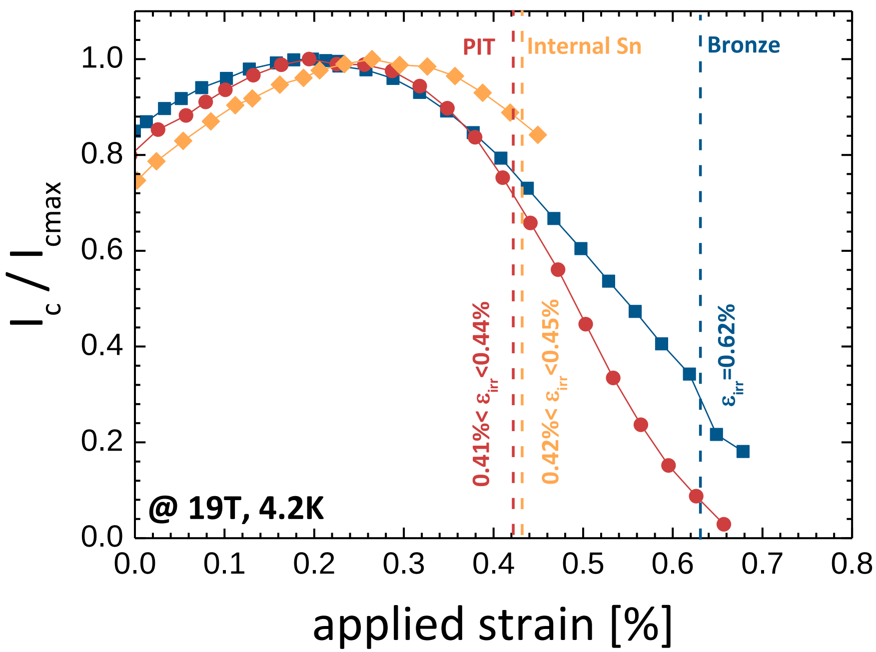
MAXIMUM OF I_c

The maximum of the critical current occurs when the cubic cell is restored

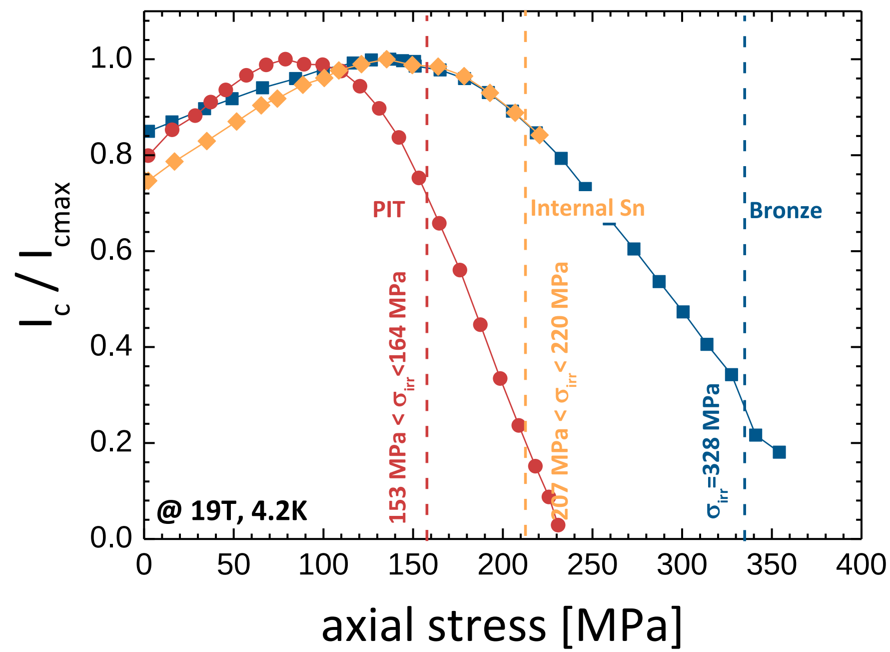
Bronze Route, Internal Sn and PIT

Reversible behaviour and irreversible limit

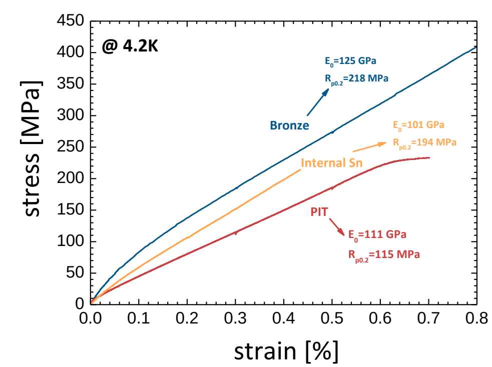
I_c vs. axial strain



I_c vs. axial stress



Technology	σ_{irr}
Bronze Route	330 MPa
Internal Sn	210 MPa
Powder-In-Tube	150 MPa



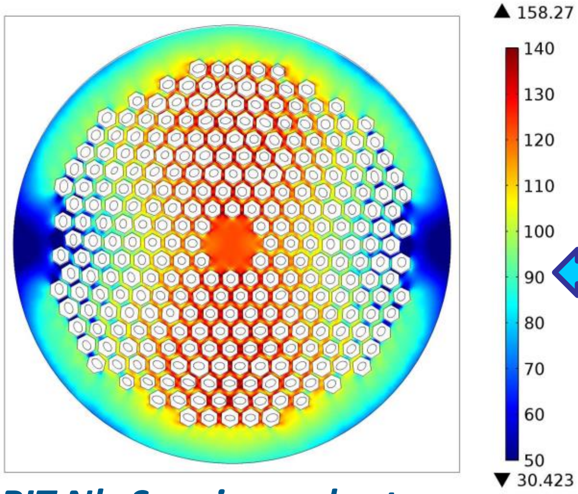
Why do superconducting properties depend on strain ?

2. Irreversible effects of strain

Irreversible degradation phenomena

Two irreversible phenomena play together

- *Plastic deformation of the Cu matrix*



PIT Nb_3Sn wire under transverse load
Stress map of the Cu matrix

Yield strength of Cu σ_y~ 90 MPa

What is the residual stress on Cu after unload ?

$$\sigma_{res}^{Cu} = \max(\sigma_{Mises}^{Cu} - \sigma_y , 0)$$

Plastically deformed Cu imposes a stress on Nb_3Sn after force unload (= lattice deformation)

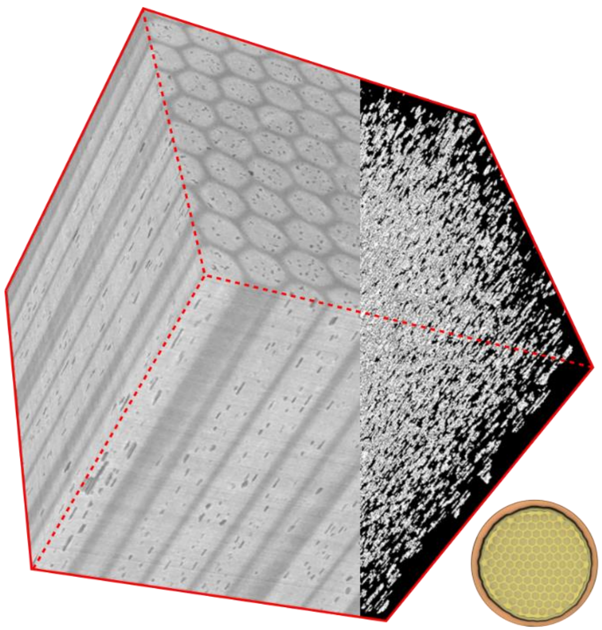
- *Crack formation in Nb_3Sn*

Nb_3Sn is a brittle material and is characterized by a strong propensity to fracture

Voids formed during the reaction cause localized stress concentrations where cracks nucleate

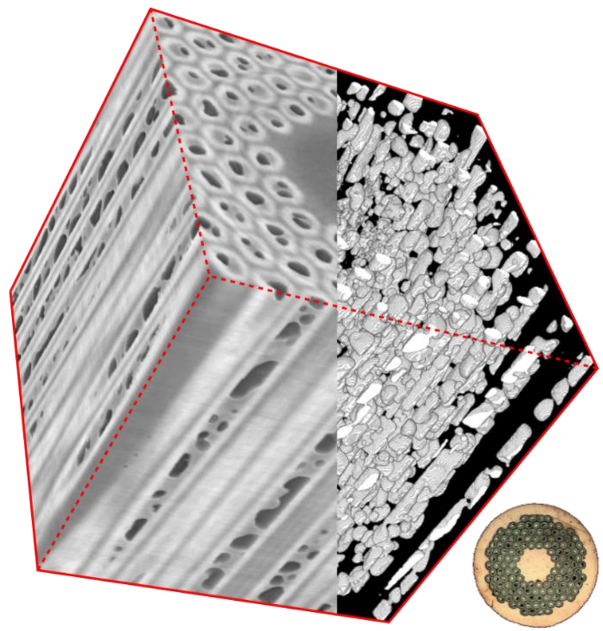
Voids in Nb_3Sn wires

XRD microtomography reconstruction



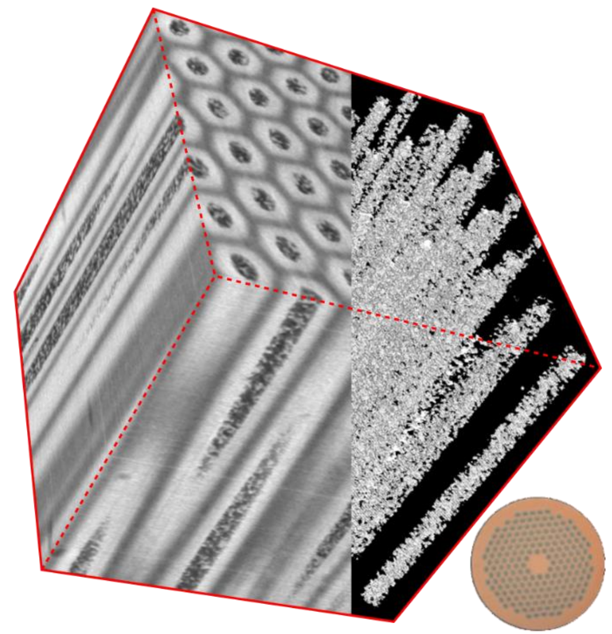
Bronze Route

121 x 121 filaments



Internal Sn

132/169 subelements

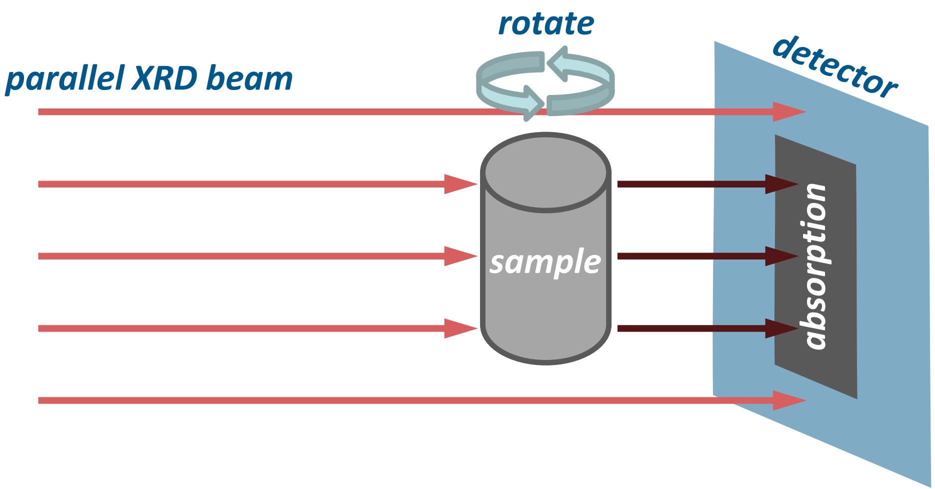


PIT

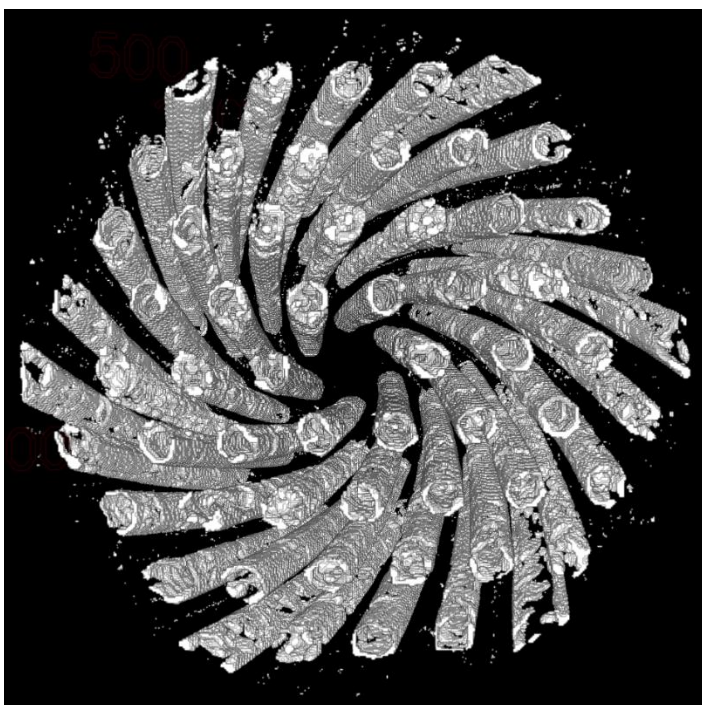
192 filaments

Can we quantify the impact of voids on the electromechanical limits?

XRD microtomography at ESRF Grenoble

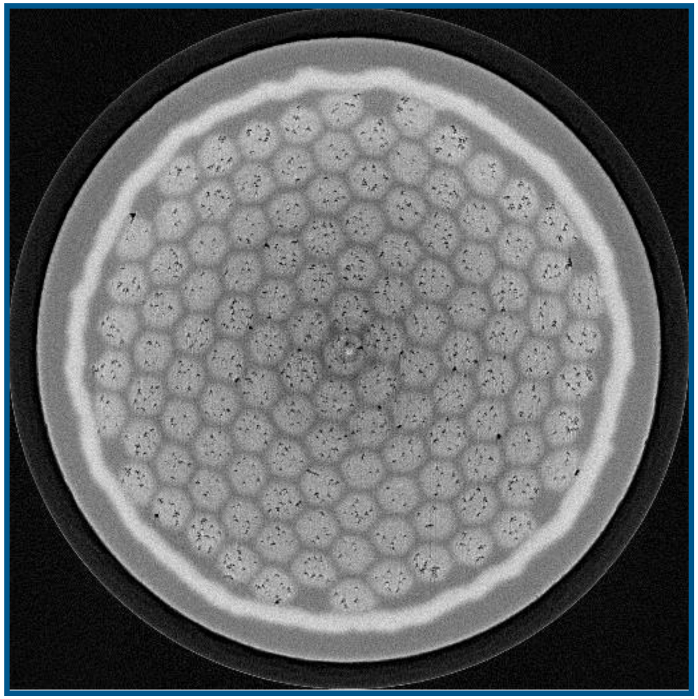


- XRD photon energy = 89 keV
- 360° rotation of the sample
- 30’000 projections
- 2560 x 2160 pixels
- 0.57 μm/pixel resolution

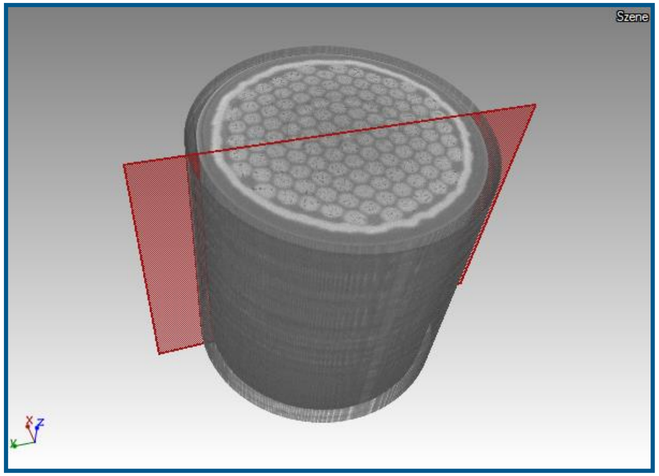


Non-destructive
3D volume reconstruction
with separation of internal features

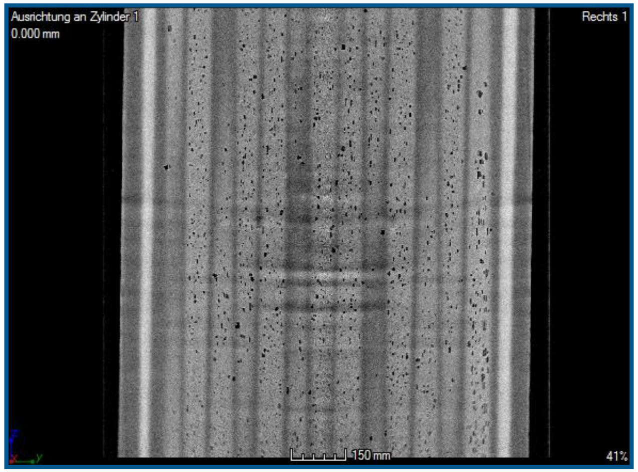
XRD microtomography at ESRF Grenoble



Bronze Route wire



Virtual longitudinal cut



A case study on Bronze Route Nb_3Sn wires

Why Bronze Route wires ?

Because by Hot Isostatic Pressing (HIP) treatment we can reduce the void fraction without degrading the critical current

Possibility to investigate the same wire type with and without voids

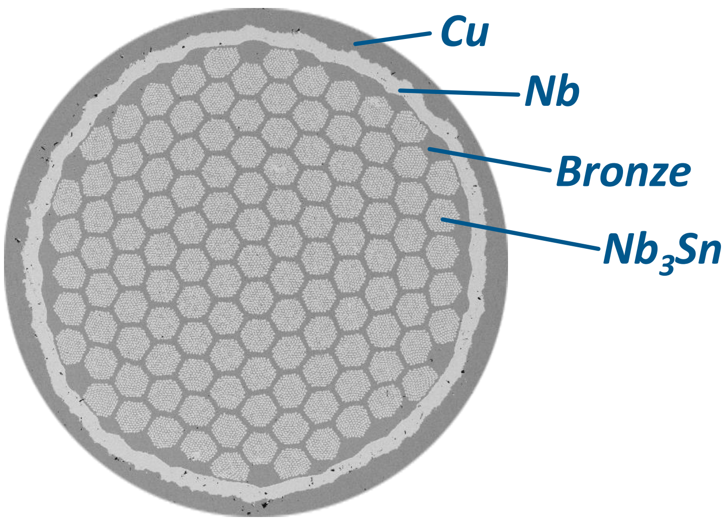
What did we do ?

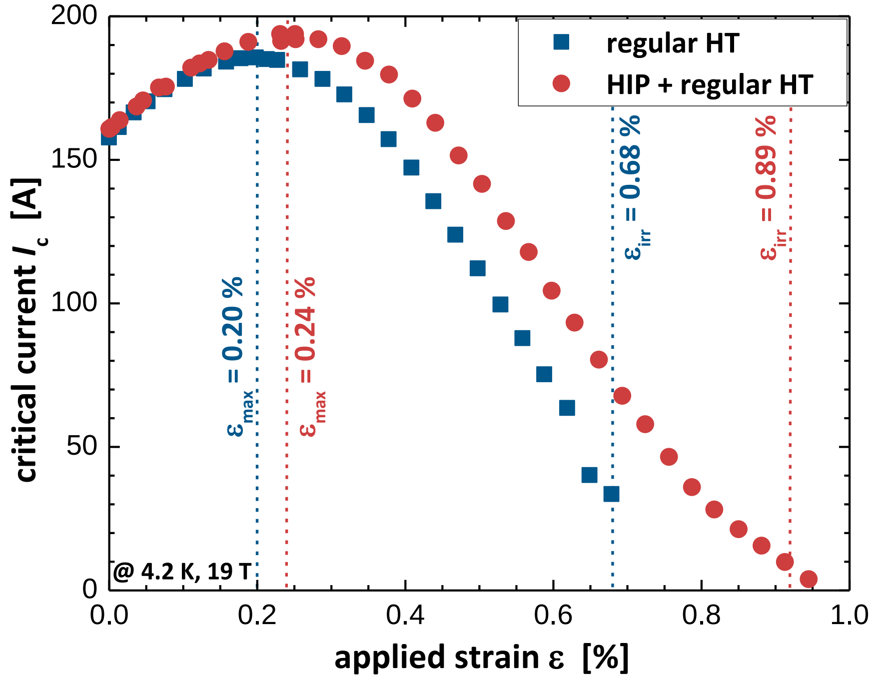
Experimental determination of the electromechanical limits

Statistical analysis of the voids size, shape and distribution

Finite Element Modelling (FEM) to quantify the impact of voids

A case study on Bronze Route Nb_3Sn wires





manufacturer	UNIVERSITÉ DE GENÈVE FACULTÉ DES SCIENCES
wire diameter	*1.25 mm*
# of filaments	*121 x 121*
filament size	*4.5 µm*

Regular HT: 600°C/100h + 670°/150h

$$\varepsilon_c = \varepsilon_{irr} - \varepsilon_{max} = 0.48\ \%$$

HIP 550°C/1h/200MPa + Regular HT

$$\varepsilon_c = \varepsilon_{irr} - \varepsilon_{max} = 0.65\ \%$$

With HIP treatment ε_c increases by +0.17 %

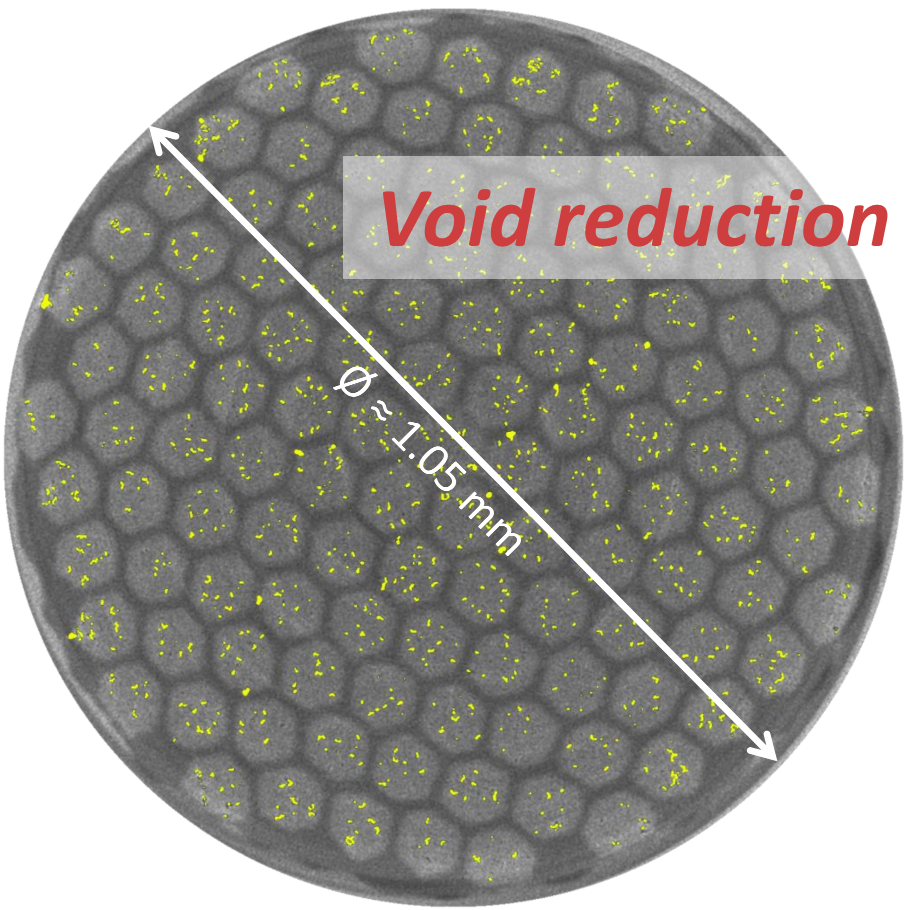
Bronze route wire: Void detection

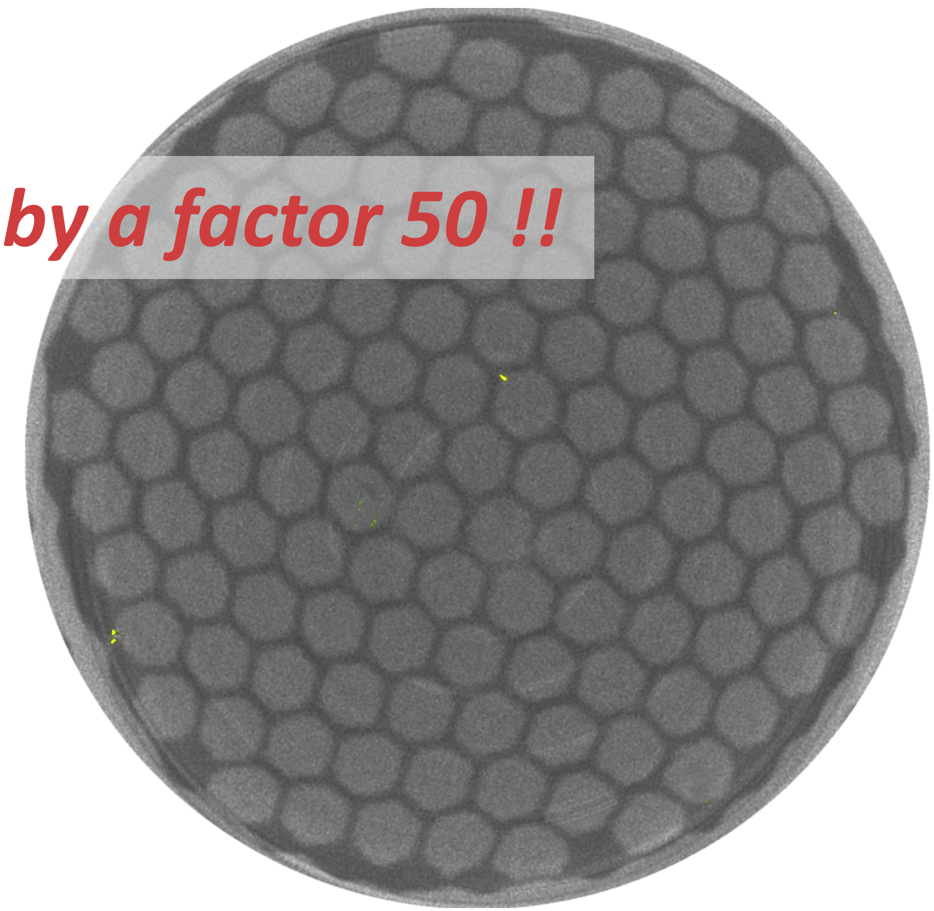
Without HIP treatment

Void fraction = 2.1 %

With HIP treatment

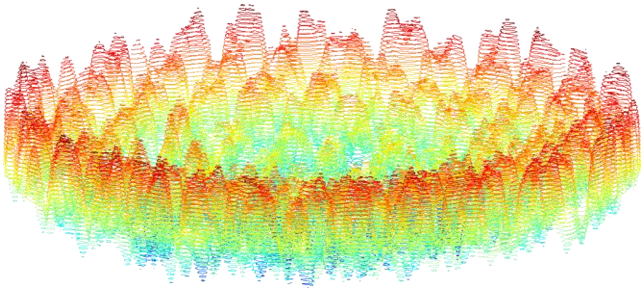
Void fraction = 0.05 %

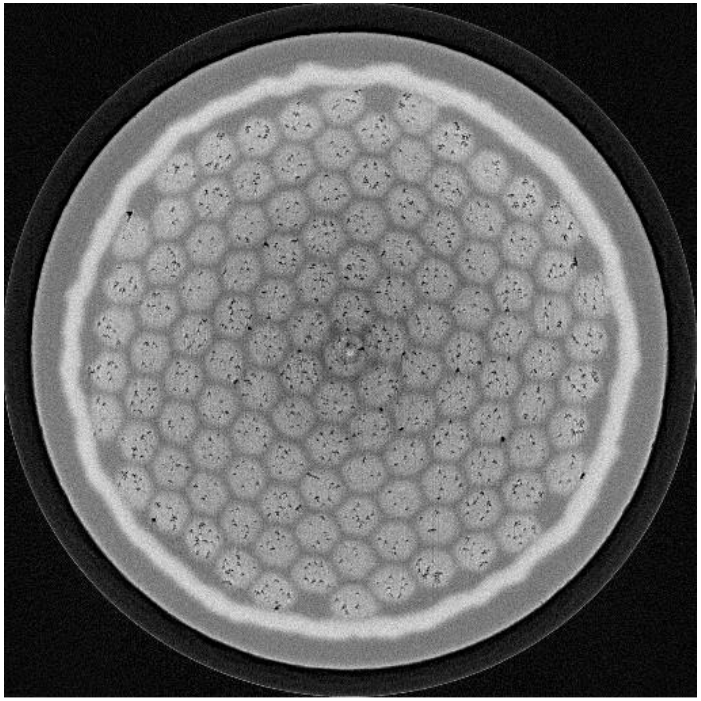




Void reduction by a factor 50 !!

Void detection and analysis



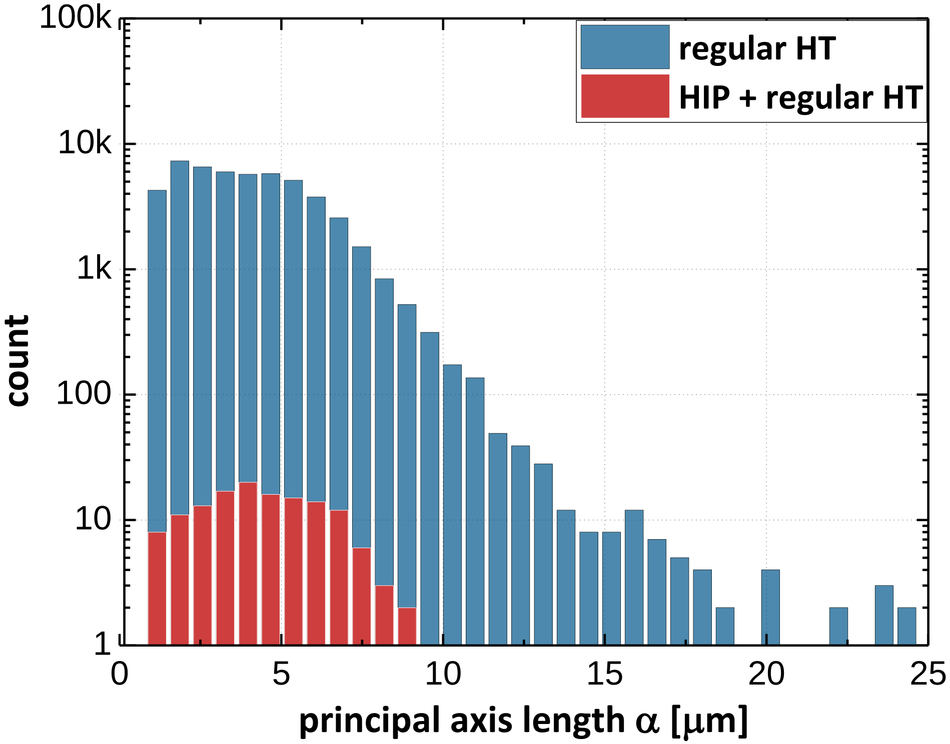


- *A brightness distribution analysis is used to detect voids*
- *Position is recorded, including distance to the nearest neighbors and location (matrix, filament bundle, interface)*
- *Voids are approximated with ellipsoids*
- *Size and orientation are determined*
    - *Major axis length*
    - *Major axis angles φ and θ*
    - *Eccentricity (sphericity)*

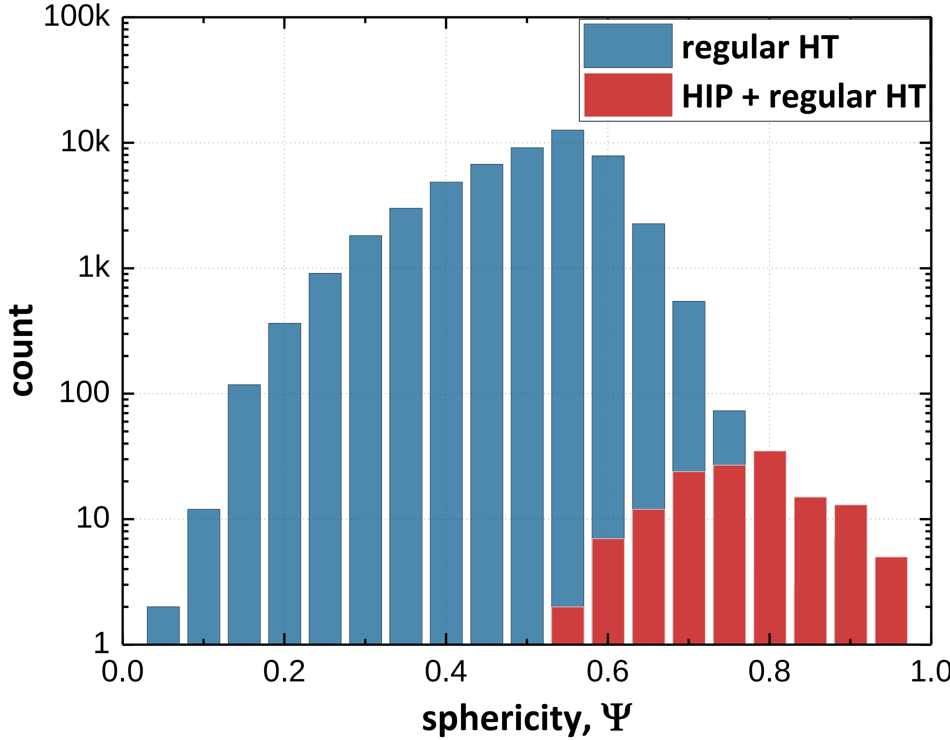
These data become input for FEM

Bronze route wire: Void analysis

Void size



Void shape

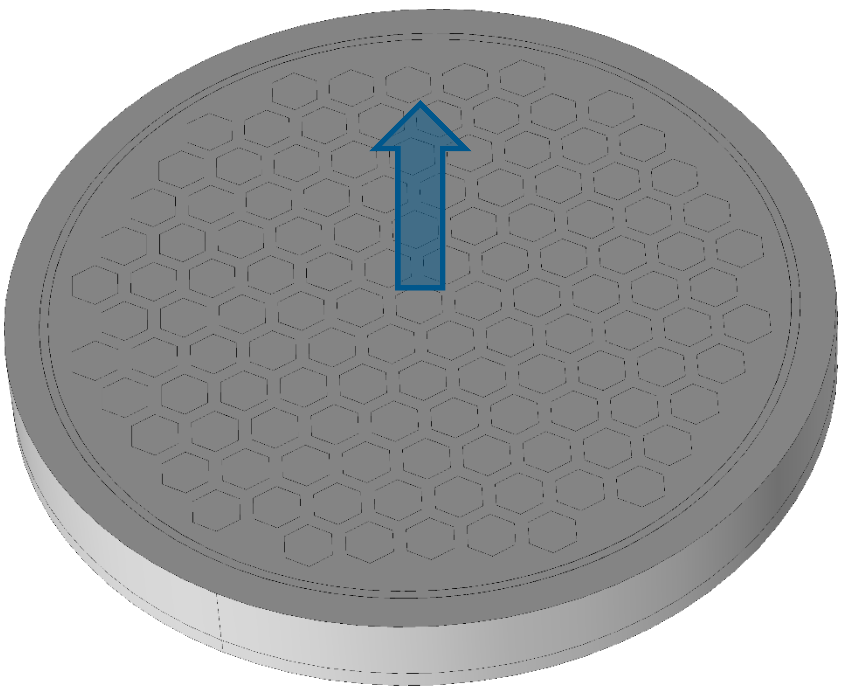


HIP ⇒ void size is reduced

HIP ⇒ voids are more spherical

Statistical FEM analysis

- ***3D model, real dimensions, 0.1 mm long wire***
- ***Bottom side is fixed, top side is displaced to apply a mechanical strain***



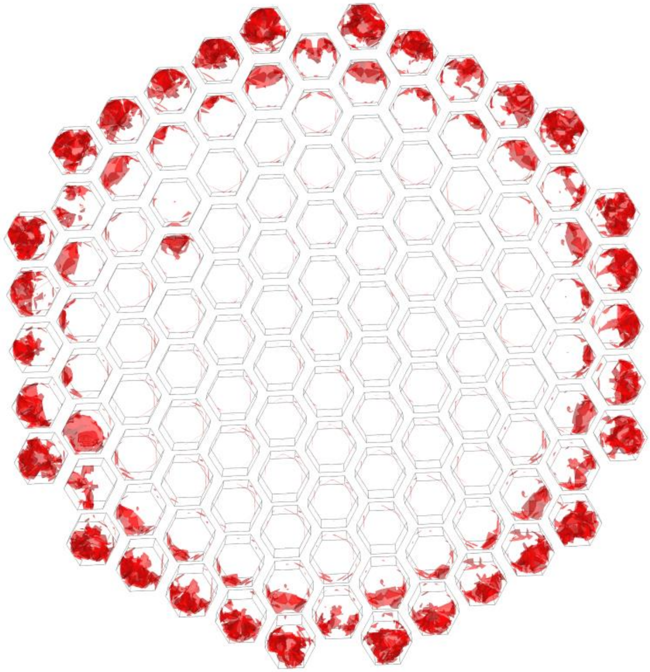
The output of the model is the von Mises stress distribution in the Nb_3Sn volume at a given strain

Statistical FEM analysis: 1) no voids

- *The experimental ε_c corresponds to an irreversible reduction of I_c by 5%*
- *Working hypothesis: 5% of I_c degradation ≡ damage in 5% of the filaments*

Wire with HIP treatment

SIMULATION done at ε_c = 0.65%



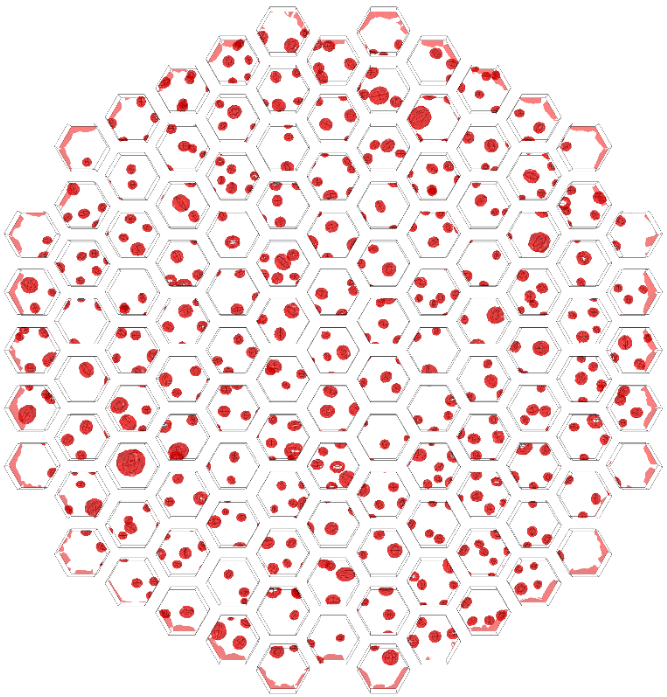
The 5% of the Nb_3Sn volume at the highest stress is highlighted in red

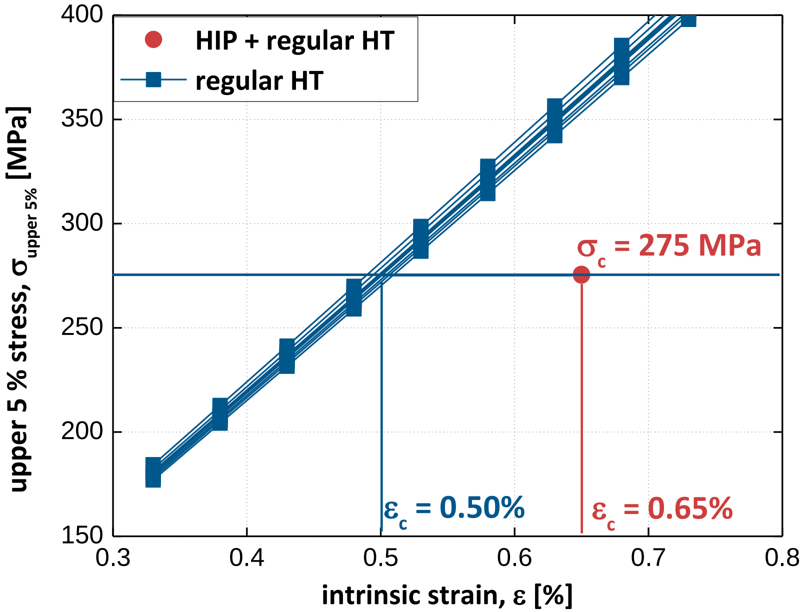
Here the red regions are at $\sigma \geq$ 275 MPa

The critical stress is thus σ_c = 275 MPa

Statistical FEM analysis: 2) with voids

- *Voids are generated from the statistical analysis until the void fraction of the wire is reached*
- *Simulation runs at increasing ε until $\sigma \geq \sigma_c$ in 5% of the filaments*
- *The goal is to predict the reduction of ε_c induced by the voids*



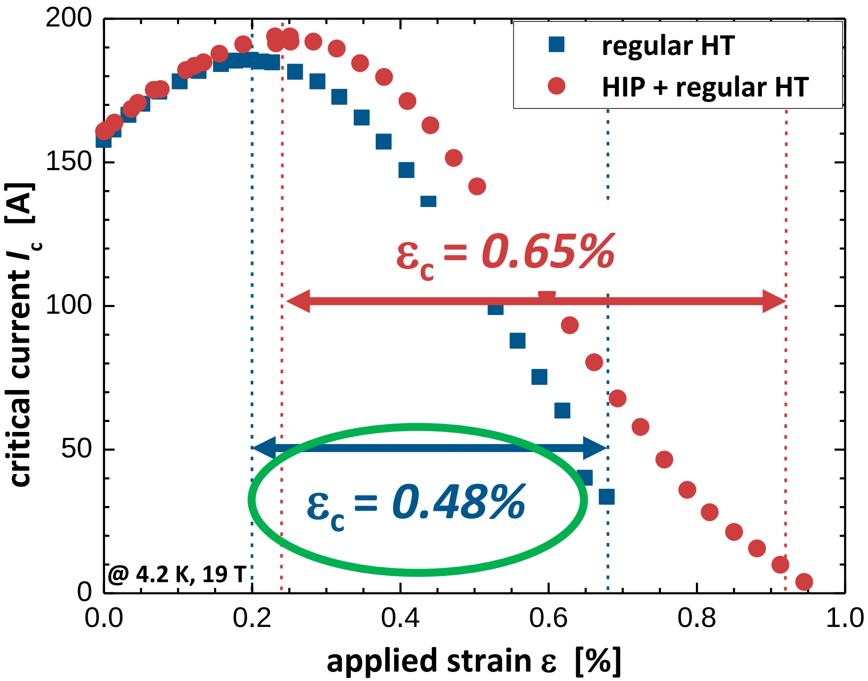


In the presence of voids the model predicts $\varepsilon_c = 0.50\%$

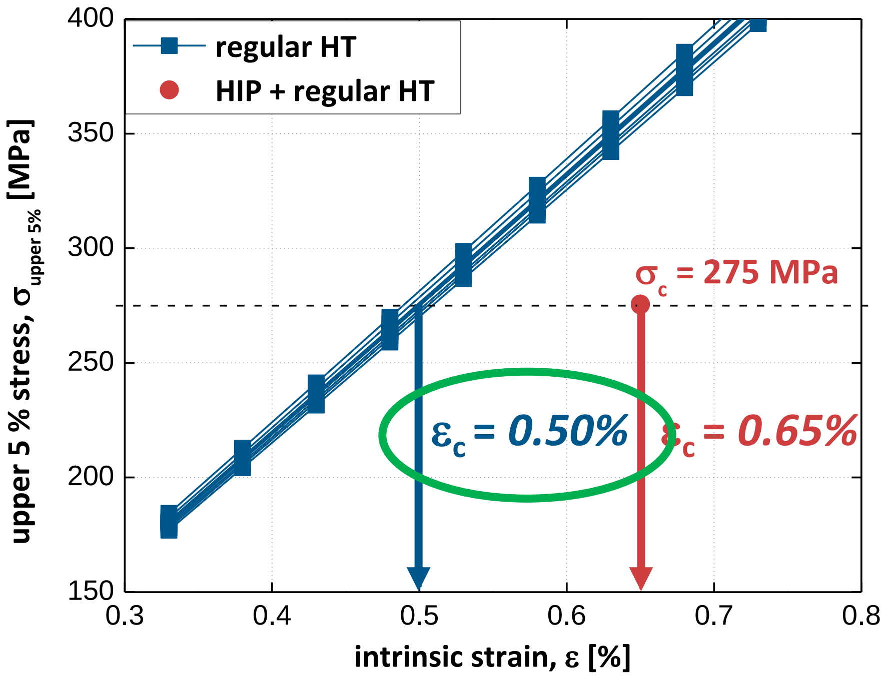
Irreversible limit in the presence of voids

Experiment vs Prediction

I_c vs strain measurement



FEM simulations



The simulations predict the correct value of ε_c when voids are introduced

What did we learn ?

Changes in the voids correlate quantitatively with the changes in the electromechanical limits

More details in SCIENTIFIC REPORTS

OPEN

Quantitative correlation between the void morphology of niobium-tin wires and their irreversible critical current degradation upon mechanical loading

C. Barth[1], B. Seeber[2], A. Rack[3], C. Calzolaio[1], Y. Zhai[4], D. Matera[1] & C. Senatore[1]

[1]Department of Quantum Matter Physics (DQMP), University of Geneva, Geneva, Switzerland. [2]Department of Applied Physics (GAP), University of Geneva, Geneva, Switzerland. [3]European Synchrotron Radiation Facility (ESRF), Grenoble, France. [4]Princeton Plasma Physics Laboratory (PPPL), Princeton University, Princeton, NJ, USA. Correspondence and requests for materials should be addressed to C.B. (email: christian.barth@unige.ch)

SCIENTIFIC REPORTS | (2018) 8:6589 | DOI:10.1038/s41598-018-24966-z

Case study on Bronze Route, what about Internal Sn and PIT ?

The same approach may lead to the prediction of how much ε_c can be increased by reducing the void fraction

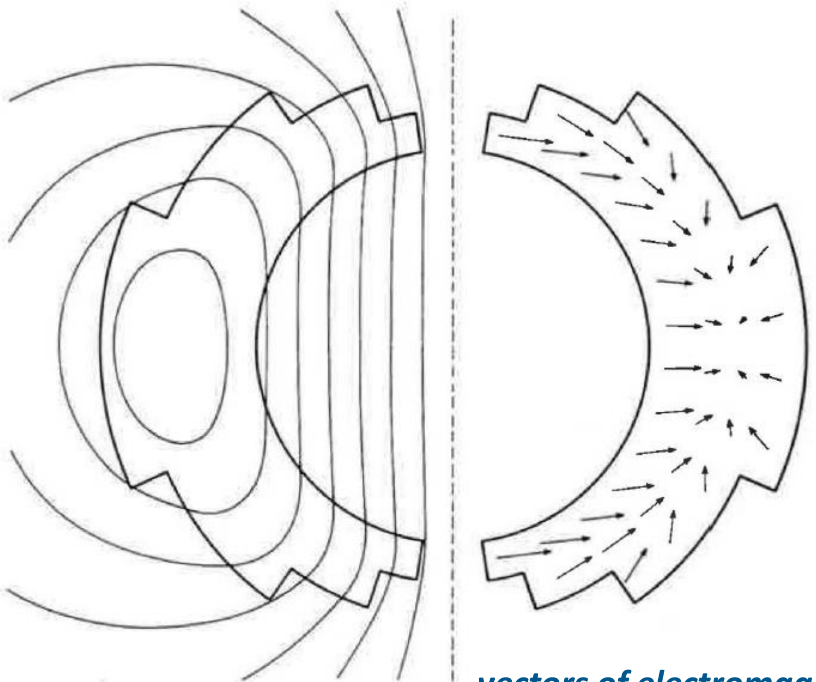
Strain-induced changes in Nb_3Sn wires

Reversible effects of strain ✓

Intrinsic mechanisms behind the irreversible degradation of the critical current ✓

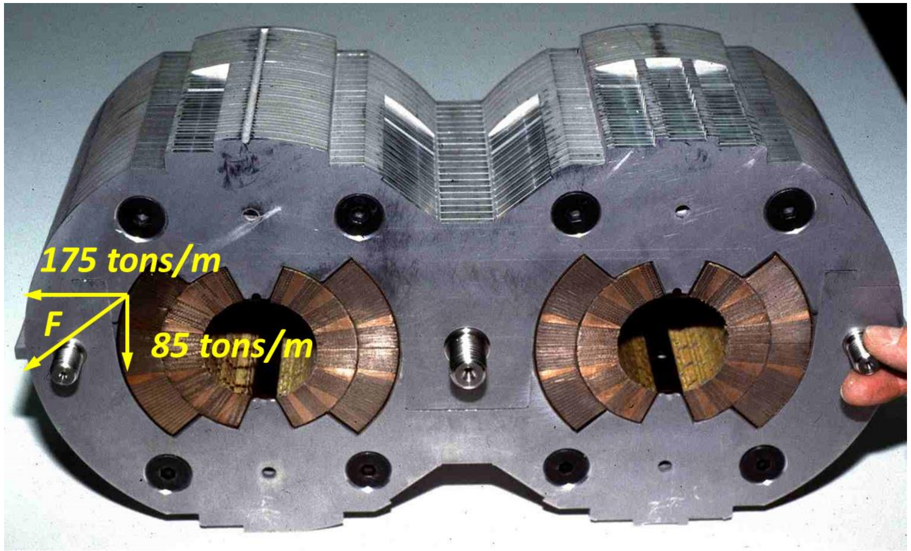
Influence on the stress tolerance of the way the mechanical stresses are exerted

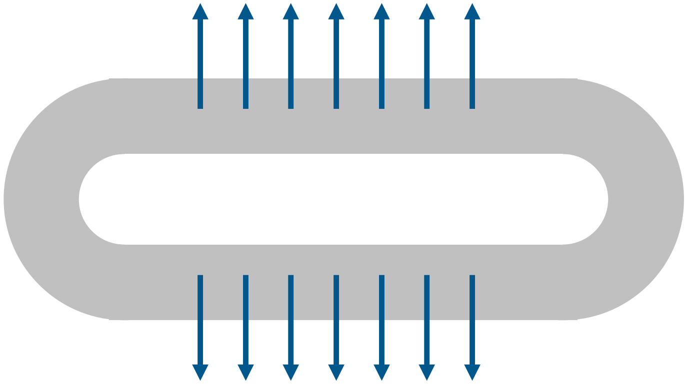
Electromagnetic stresses in an accelerator dipole



magnetic lines of force

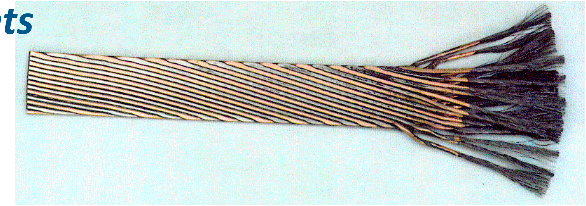
vectors of electromagnetic force per unit volume



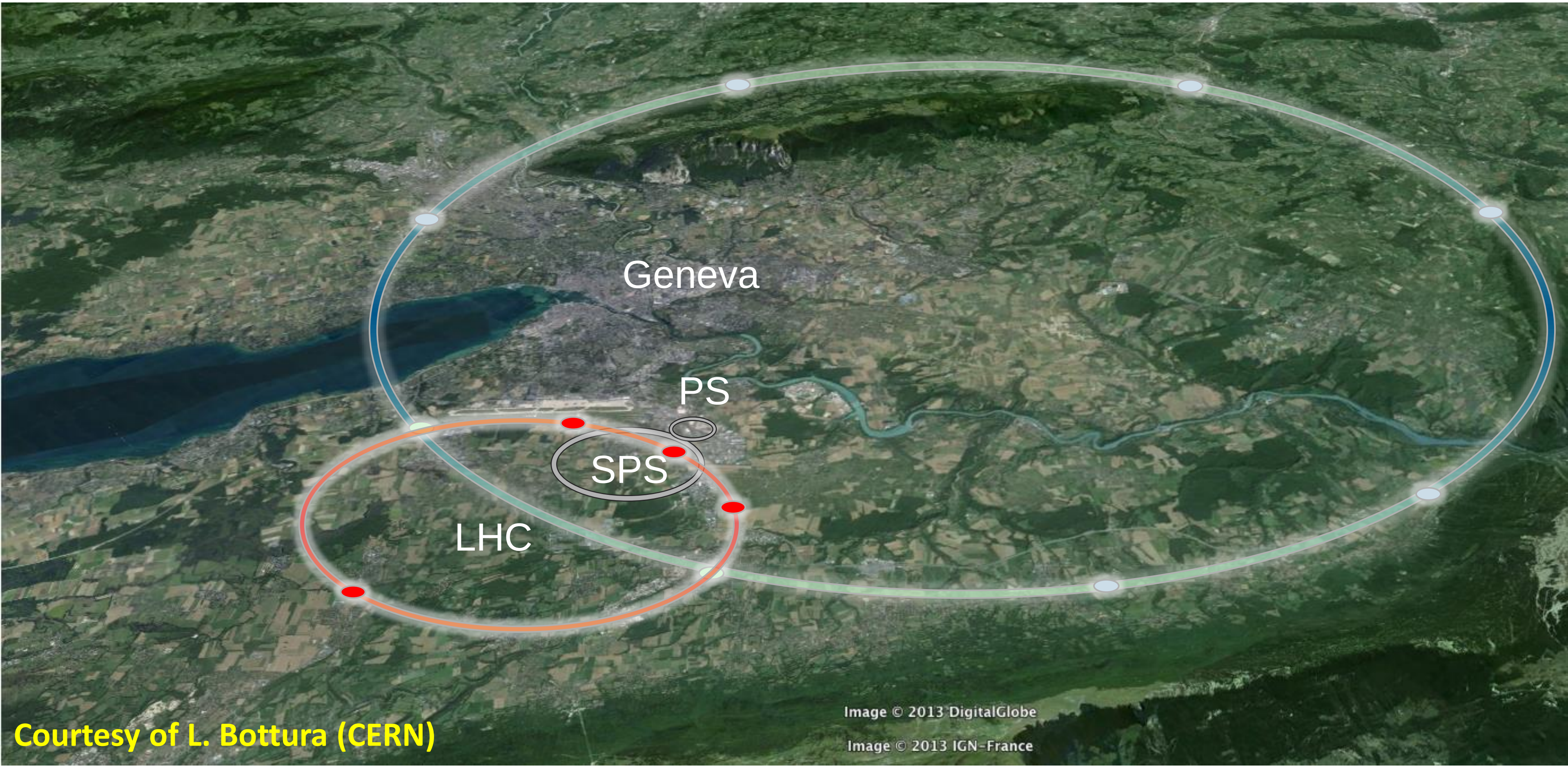


Accelerator magnets operate at ~10 kA to keep inductance low and ease magnet protection

Rutherford cables are used to get these large operating currents



The Future Circular Collider Study



LHC	HE-LHC	FCC-hh
27 km, 8.33 T	27 km, 16 T	100 km, 16 T
14 TeV (c.o.m.)	27 TeV (c.o.m.)	100 TeV (c.o.m.)
1300 tons NbTi	~3000 tons Nb_3Sn	~9000 tons Nb_3Sn

Degradation upon transverse loads

The 16 T FCC dipoles are being designed with a peak stress of 200 MPa at operation

Are the Nb_3Sn wires in the cable able to withstand such a high stress level? Which degradation is tolerable?

Nb_3Sn Rutherford cable for HL-LHC, 40 strands

- *Nb_3Sn wires are deformed during cabling*
- *Cables are braided with glass fiber*
- *The winding is impregnated with resin*

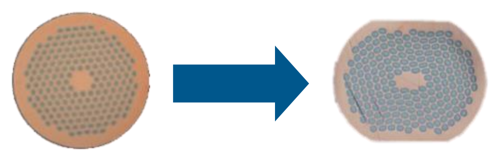
The irreversible limit under transverse stress is influenced by parameters <u>extrinsic to the wire</u>

- ***the type of impregnation (the elastic modulus of the resin)***

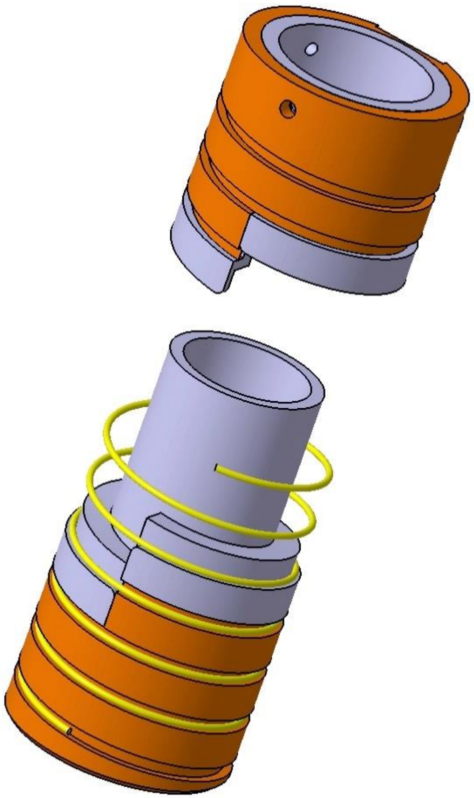
  Tested Epoxy L, Glass fiber + Epoxy L, Stycast

- ***the redistribution of the applied stress on the wire***

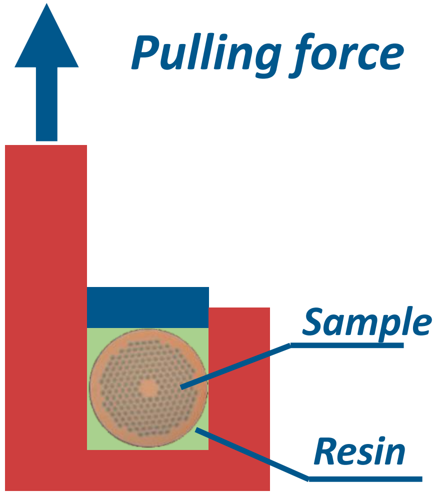
  i.e. the deformation of the wire during cabling



The WASP concept for I_c vs. transverse stress

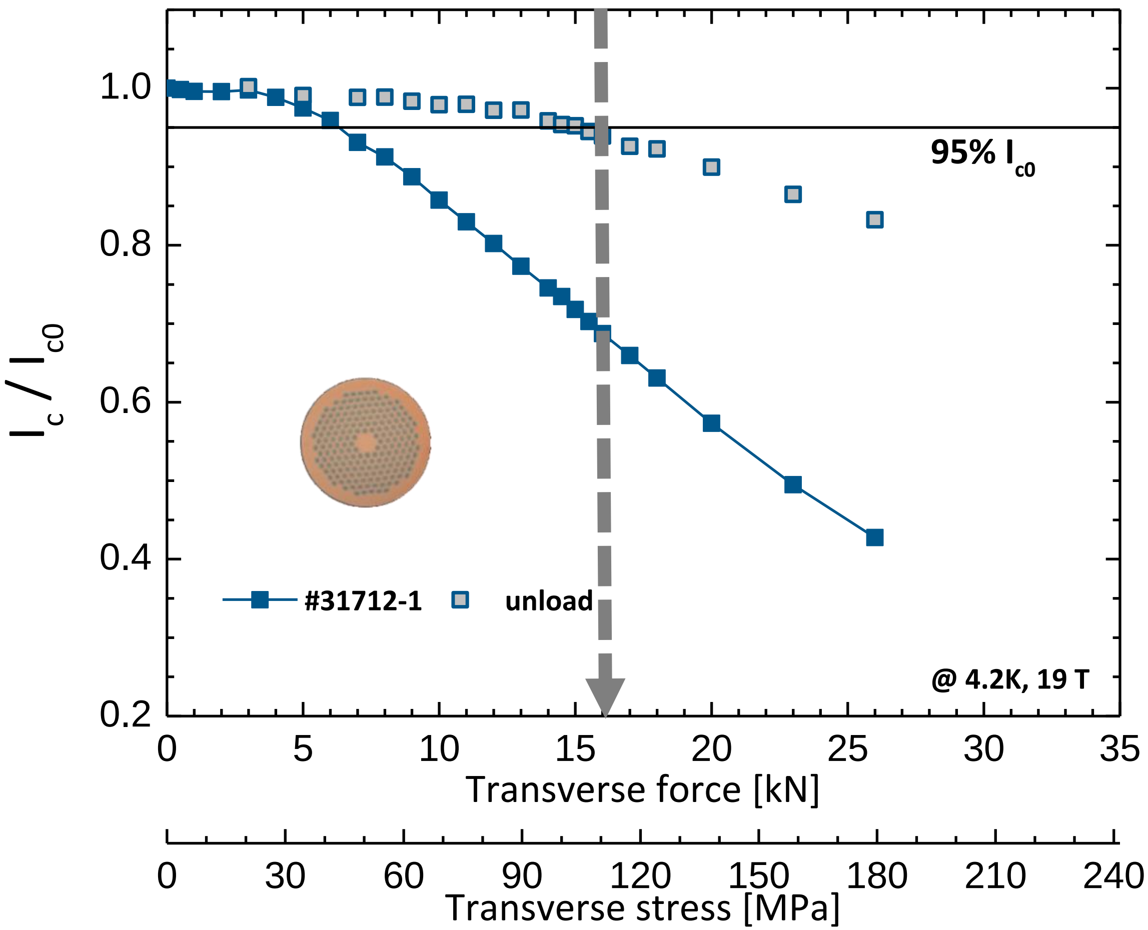


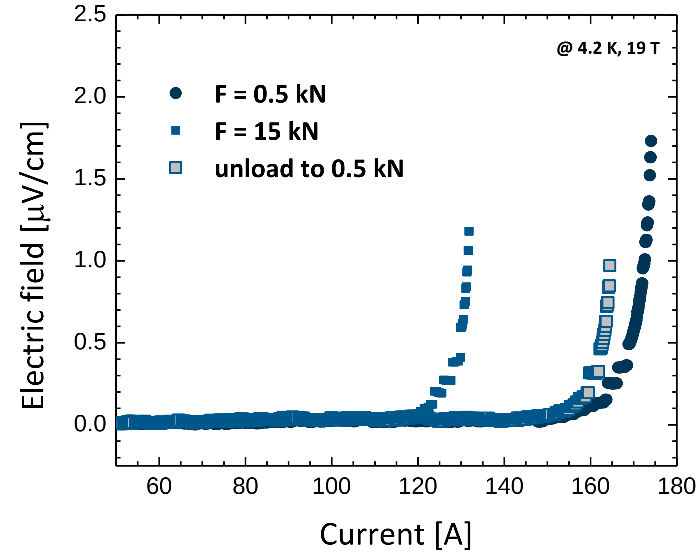
4-WALL + impregnation



UNIVERSITÉ DE GENÈVE FACULTÉ DES SCIENCES CERN collaboration agreement K1629/TE (2009-2012)

I_c vs. transverse stress PIT 192 + Epoxy L





The irreversible limit is defined at the force level leading to a 95% recovery of the initial I_c after unload

Here

$$F_{irr} = 16 \text{ kN}$$

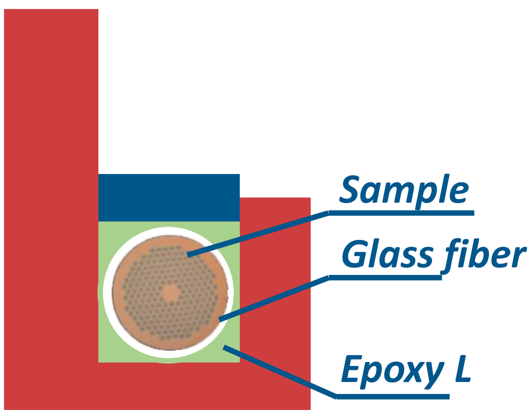
The corresponding irreversible stress limit is

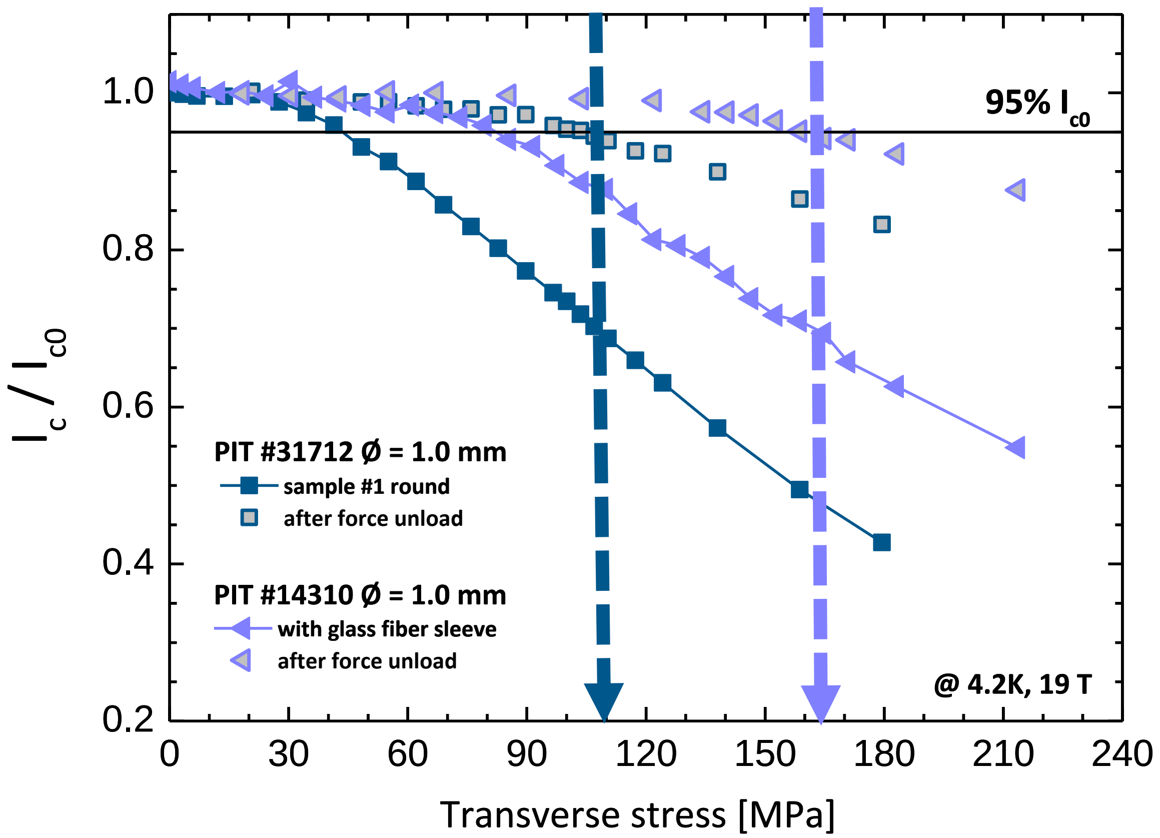
$$\sigma_{irr} = 110 \text{ MPa}$$

where

$$Stress = \frac{Force}{groove\ length \times groove\ width}$$

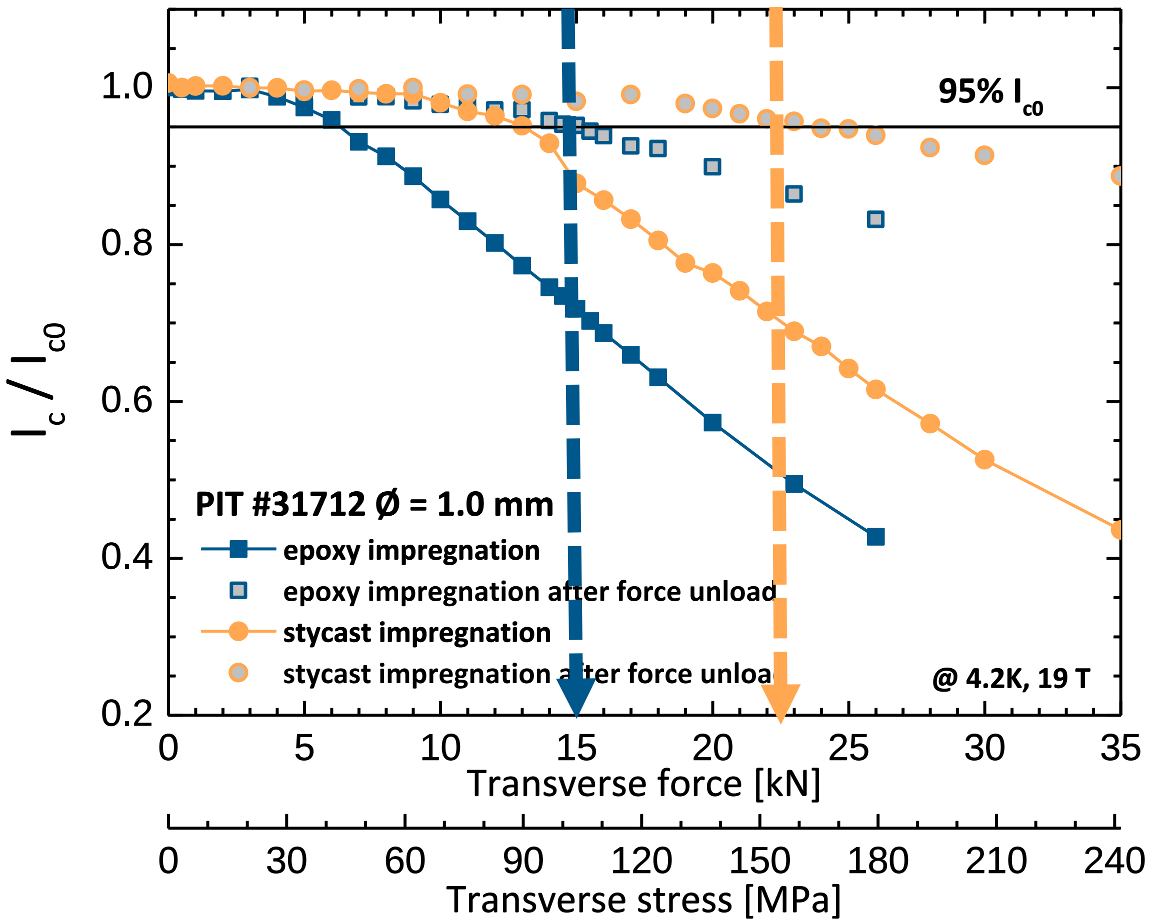
I_c vs. transverse stress: wire in a glass fiber sleeve





Glass fiber adds rigidity to the impregnation ⇒ Shift of σ_{irr} by > 50 MPa

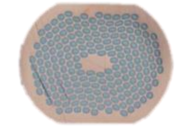
I_c vs. transverse stress: Epoxy L vs. Stycast



The Young modulus of Stycast is 3 to 4 times higher compared to the value of Epoxy L

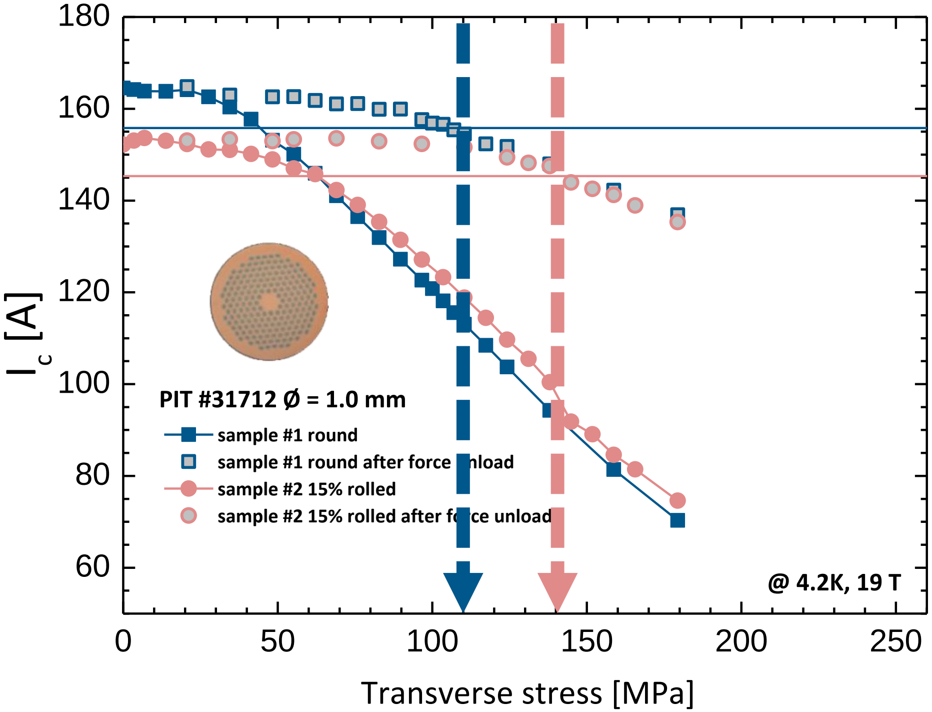
The change of resin, from epoxy to stycast, leads to an increase of σ_{irr} by > 50 MPa
The result is comparable to the value found with epoxy + glass fiber sleeve

I_c vs. transverse stress on flattened wires



Effects of the stress redistribution

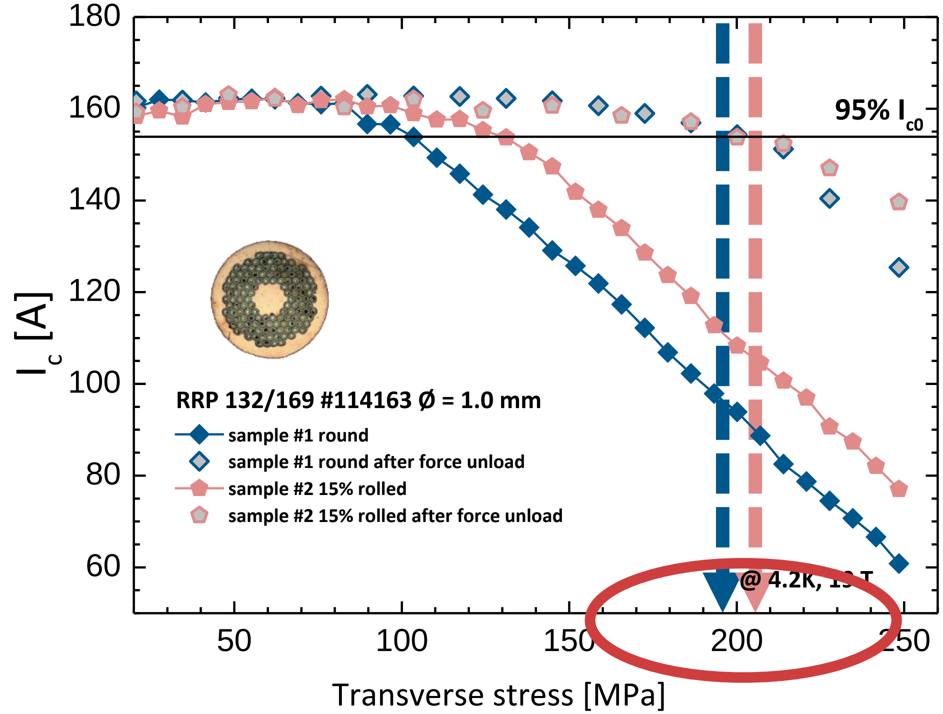
PIT 192



~7.5% I_c reduction by rolling

Shift of σ_{irr} by ~ 40 MPa

Internal Sn 132/169



NO I_c reduction by rolling

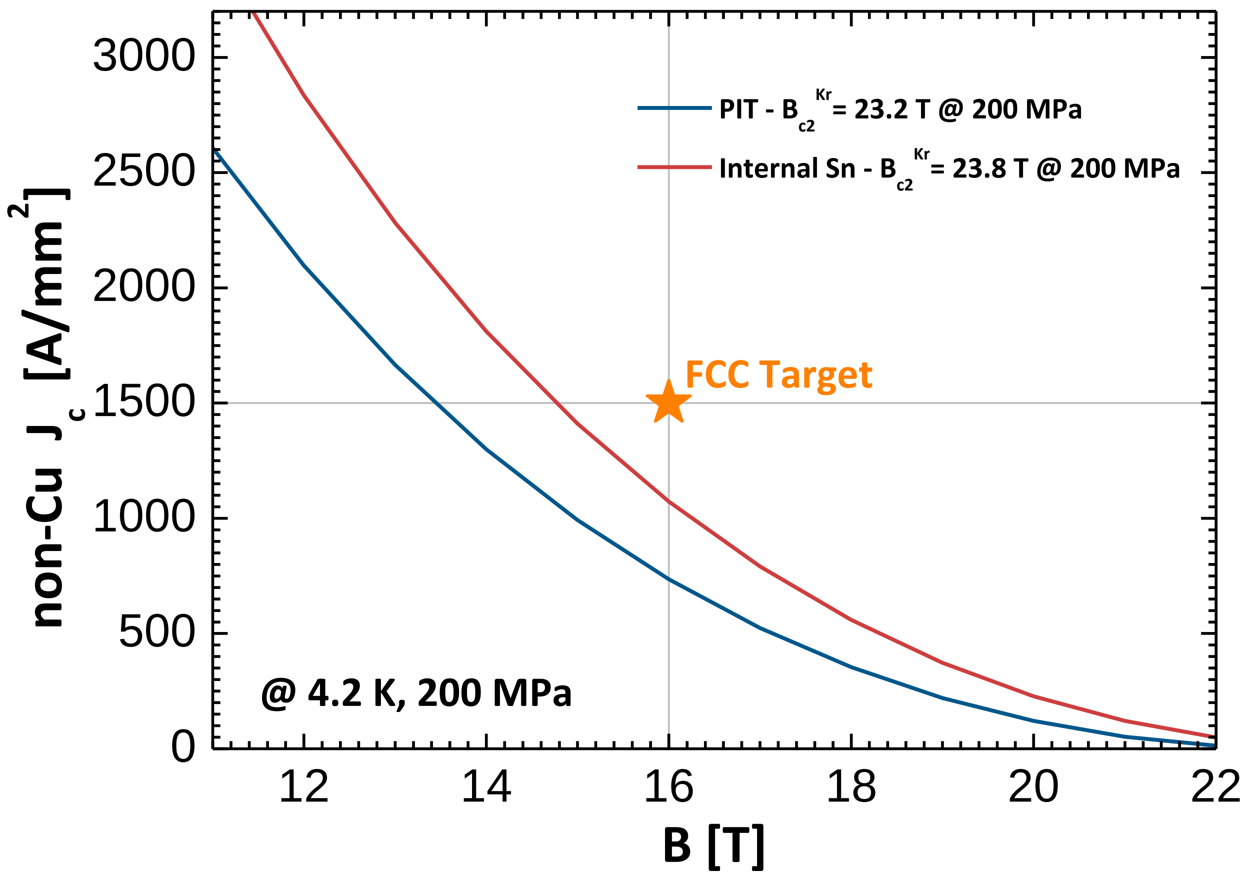
Shift of σ_{irr} by ~ 15 MPa

This wire can withstand the peak stress of the FCC dipoles !!

Don't forget the reversible effects of stress !!

Critical current density vs. magnetic field @ 200 MPa

Best performance achieved so far in industrial wires

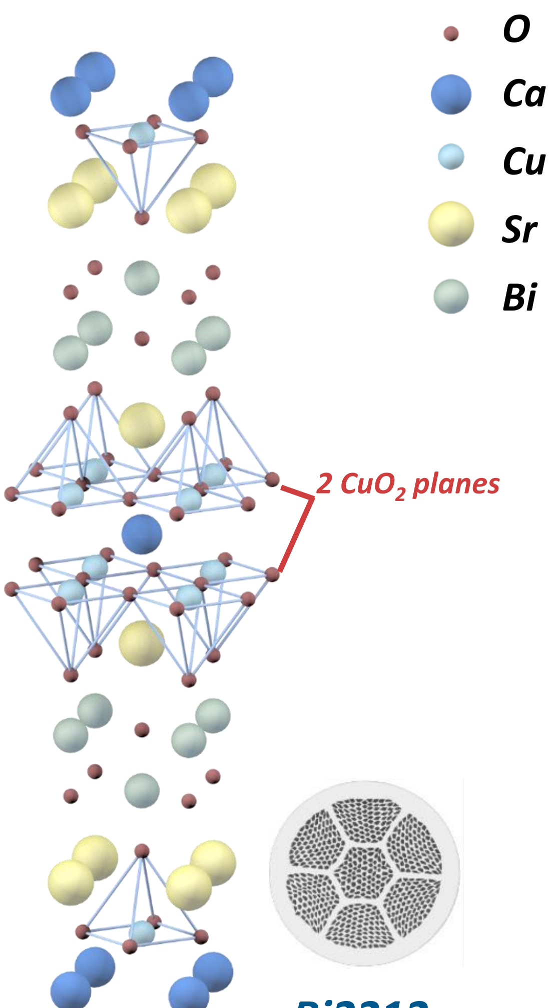


J. Parrell et al., AIP Conf. Proc. 711 (2004) 369

T. Boutboul et al., IEEE TASC 19 (2009) 2564

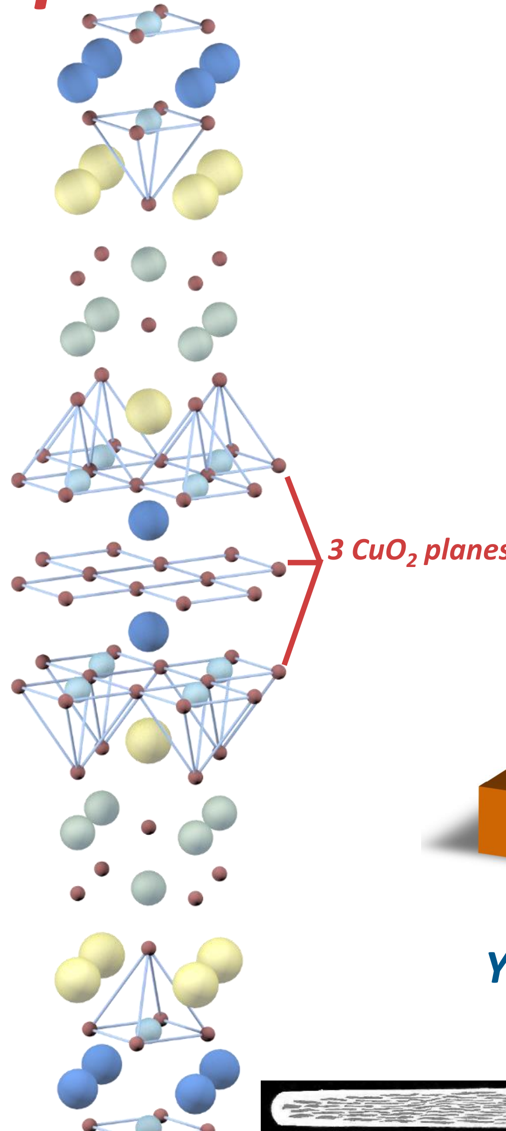
High Temperature Superconductors are different animals …

HTS materials for applications

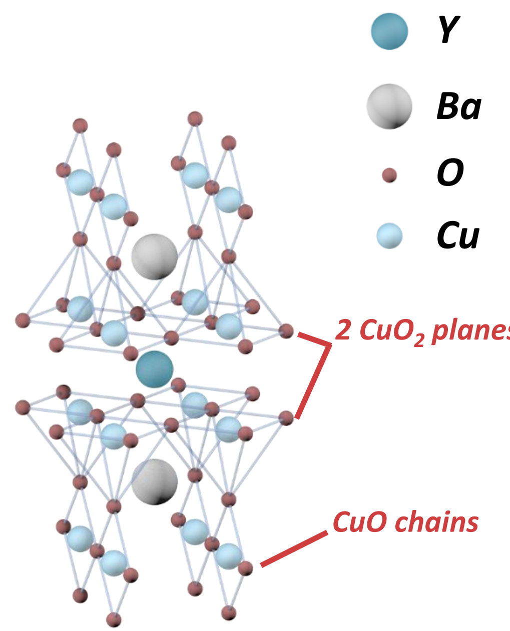


Bi2212
Powder-In-Tube wire

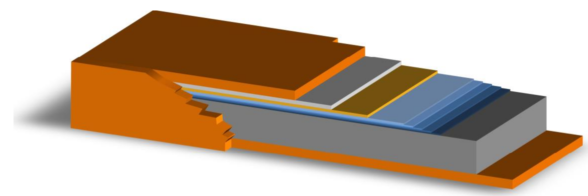
Bi2212
$Bi_2Sr_2CaCu_2O_{8+x}$



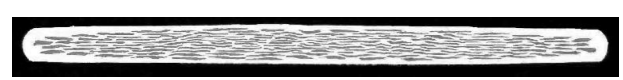
Bi2223
$Bi_2Sr_2Ca_2Cu_3O_{10+x}$



Y123
$YBa_2Cu_3O_{7-x}$

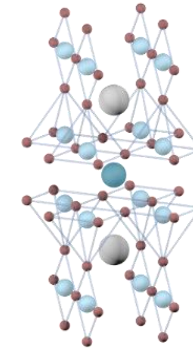


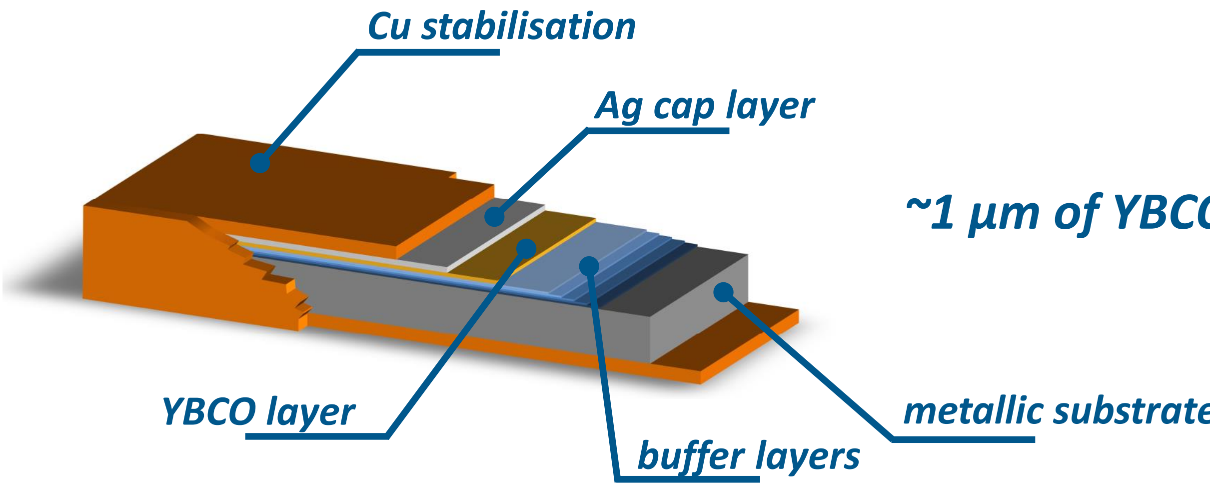
Y123 Coated Conductor



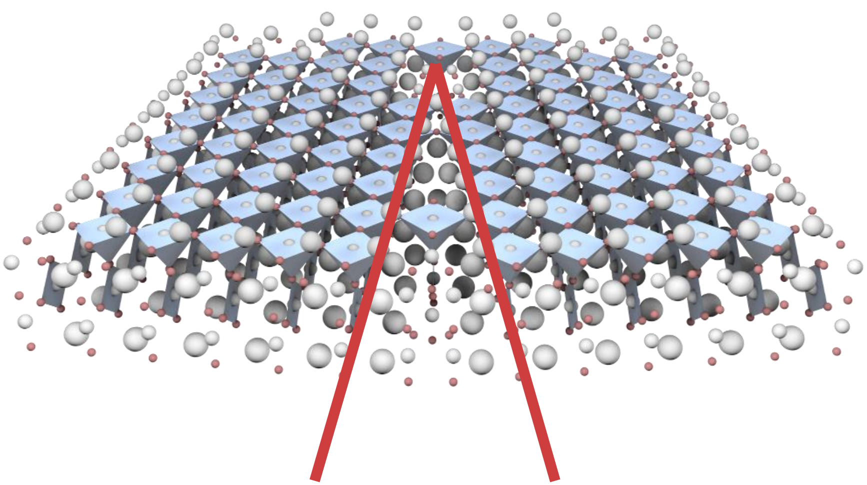
Bi2223 Powder-In-Tube tape

$YBa_2Cu_3O_{7-x}$ (YBCO) coated conductors

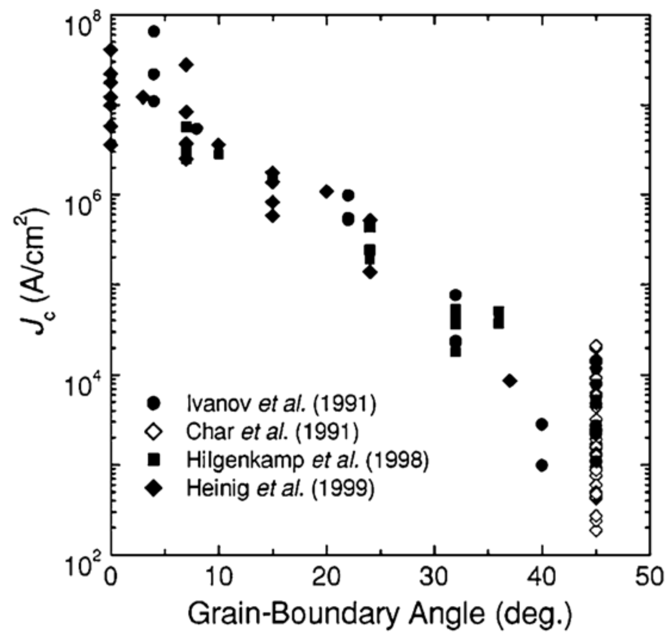




~1 μm of YBCO in a ~100 μm thick tape



[001] tilt grain boundary

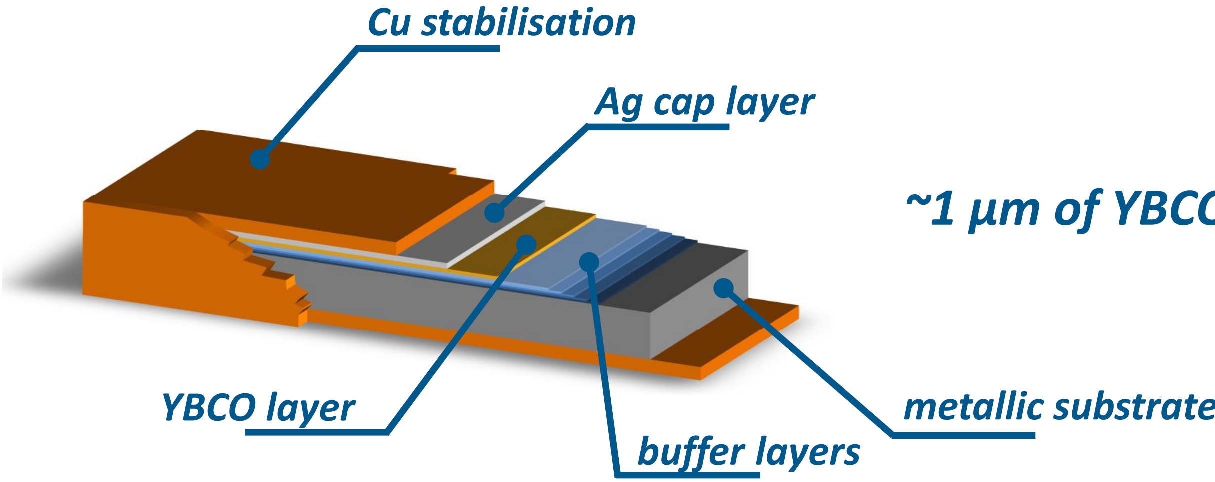


H. Hilgenkamp and J. Mannhart, RMP 74 (2002) 485

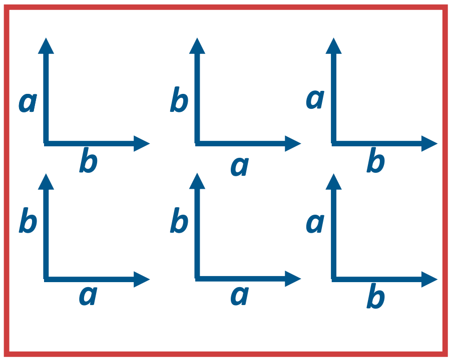
REBCO, RE = Rare Earth

$YBa_2Cu_3O_{7-x}$ (YBCO) coated conductors

Iijima et al., APL 60 (1992) 769
Goyal et al., APL 69 (1996) 1795



~1 μm of YBCO in a ~100 μm thick tape



Top view

The template is a metallic substrate coated with a multifunctional oxide barrier

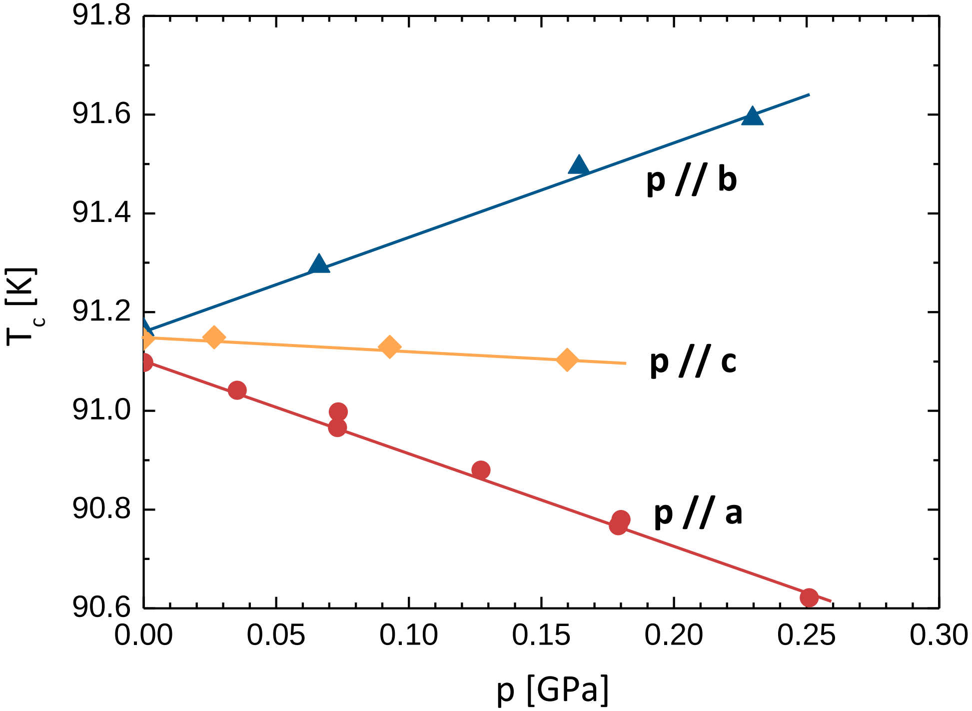
Biaxial texturing – within < 3° – is obtained

but with some also drawbacks:

- pronounced anisotropic behaviour
- complex and expensive manufacturing process

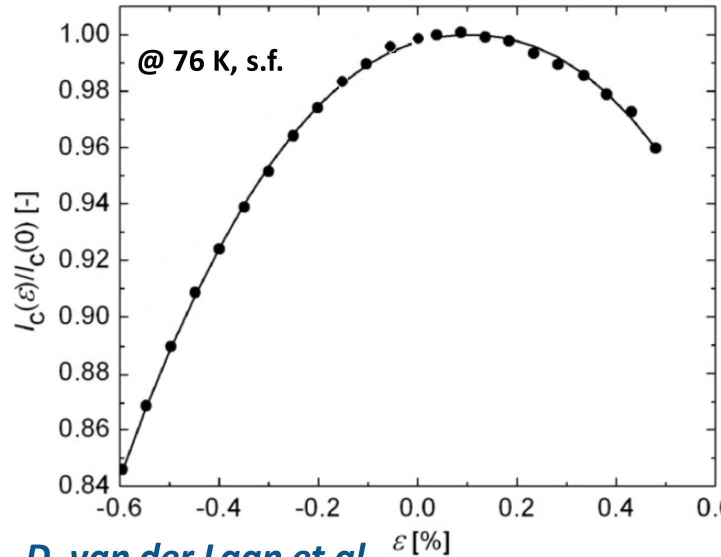
Presently produced by American Superconductor, BRUKER, Fujikura, SuNAM, SuperOx, SuperPower Inc. A Furukawa Company, STI, THEVA, Shanghai 上海超导 SHANGHAI SUPERCONDUCTOR, OXOLUTIA, deutsche nanoschicht, MetOx

Reversible effects of strain on YBCO



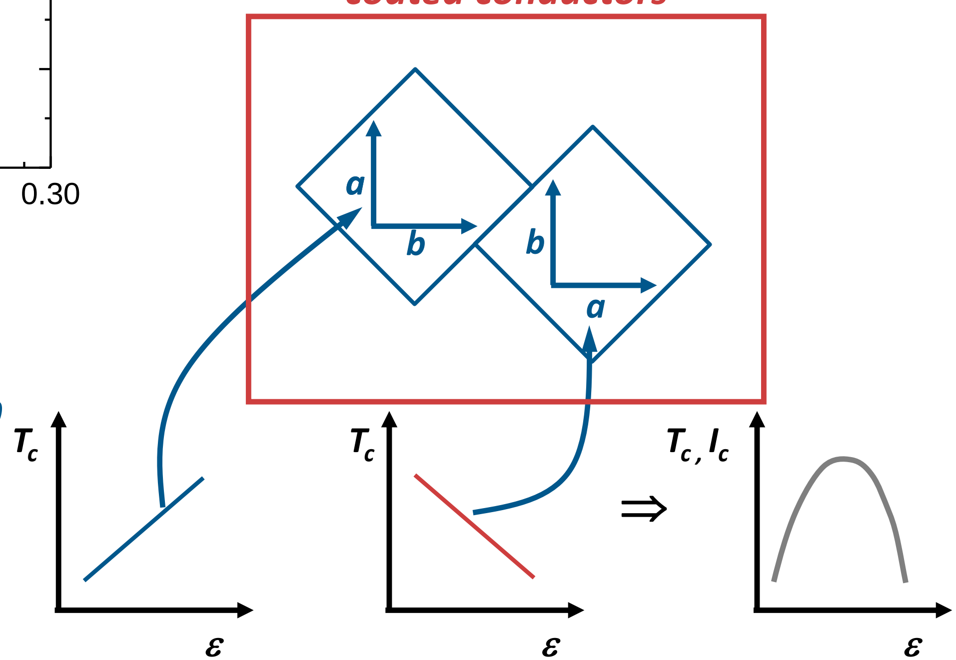
Critical temperature vs. uniaxial strain in single crystals

U. Welp et al., Phys. Rev. Lett. 69 (1992) 2130



D. van der Laan et al., Supercond. Sci. Technol. 24 (2011) 115010

Critical current vs. uniaxial strain in coated conductors



In the following, the focus will be on

Nb_3Sn* → *Today high field superconductor, up to 23.5 T in solenoidal coils, the material for and and only candidate material for the 16 T dipoles of

YBCO* → *Tomorrow high field superconductor, more than 40 T demonstrated in solenoidal insert coils*, the way to get 20 T dipoles and beyond

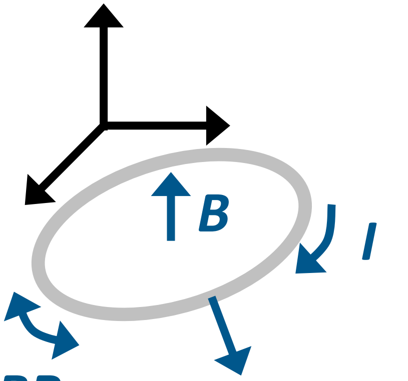
**tested in a resistive outsert*

All superconducting magnets beyond LTS

The World cup of high magnetic fields

	Maximum field [T]	HTS insert	HTS coil field [T]	Winding technology
	32	REBCO	17	DP
RIKEN	27.6	Bi2223 / REBCO	4.5 (Bi2223) 6 (REBCO)	LW
IEE CAS	27.2	REBCO	12.2	DP
SuNAM, MIT	26.4	REBCO	26.4	DP
IEE CAS	25.7	REBCO	10	DP
Université de Genève, Faculté des sciences; Bruker	25	REBCO	4	LW
HFLSM (Tohoku University)	24.6	Bi2223	10.6	DP
NIMS	24.2	Bi2223	3.66	LW

Stress management in Ultra High Field magnets

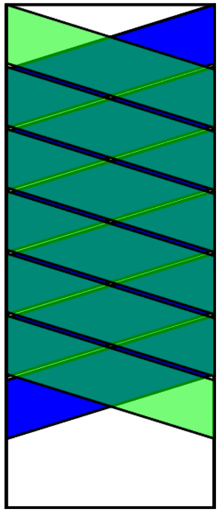


Hoop stress levels above 100 MPa are common, the NHMFL 32 T magnet operates at 400 MPa

$$\sigma_{hoop} = \frac{I}{S_{wire}} BR$$

$$F = I \times B$$

Other constrains to the winding come from the tape geometry of the conductor

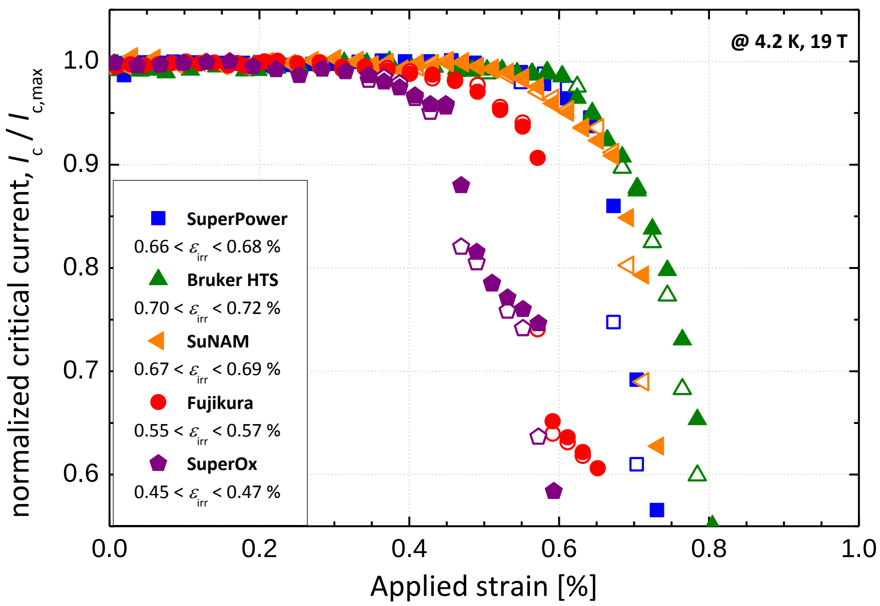


In the case of layer winding the direction changes going from one layer to the next impose in-plane hard bending of the tape

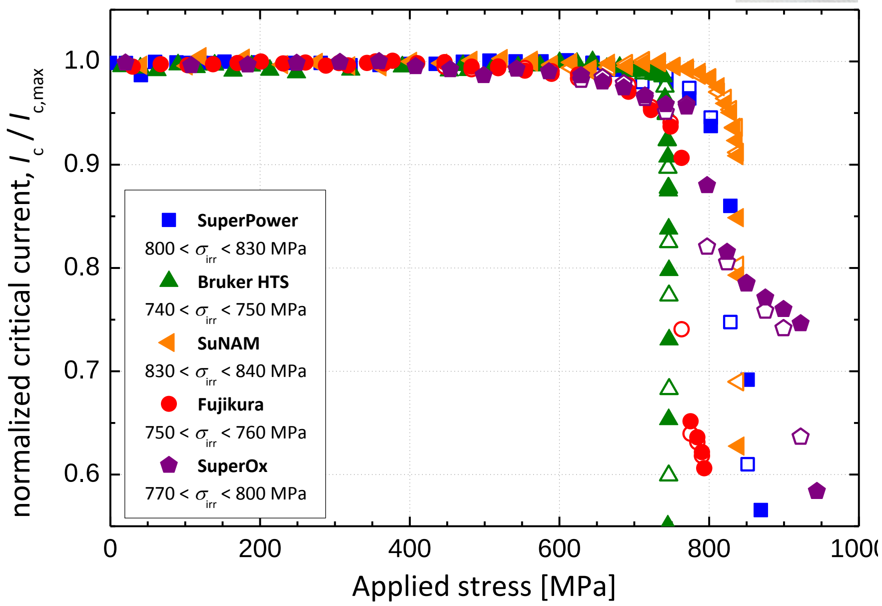
REBCO CCs: Dependence of I_c on axial loads

Reversible behaviour and irreversible limit

I_c vs. axial strain



I_c vs. axial stress

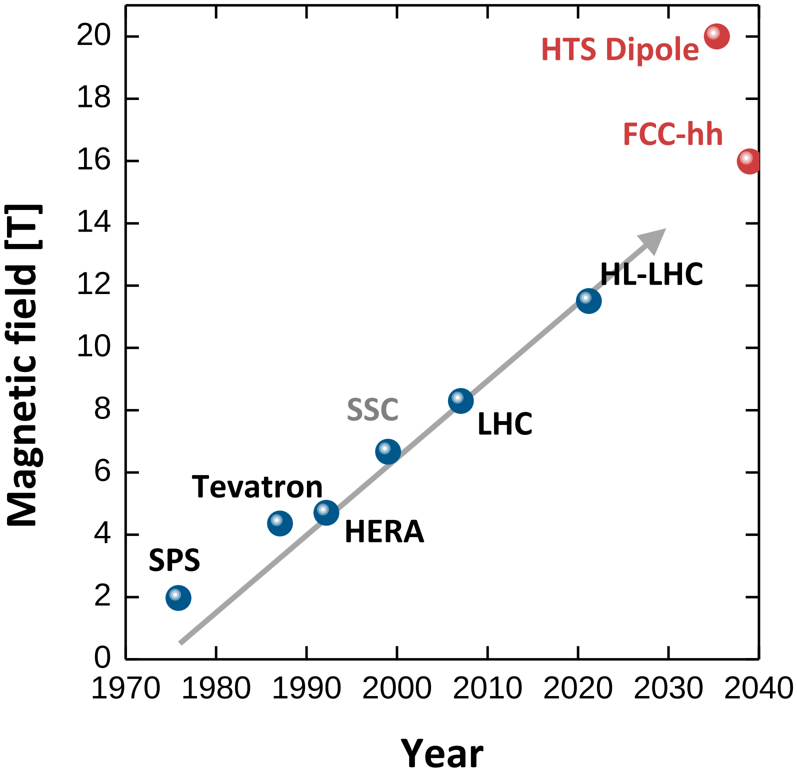


- *REBCO CCs are inherently strong, ~50% is a high strength alloy*
- *Very low stress effect → curves are flat in rev. region*
- *Irreversible stress limits above 500 MPa*
- *The only weakness is delamination...*

C. Barth, G. Mondonico and CS, Supercond. Sci. Technol. 28 (2015) 045011

HTS for accelerator magnets

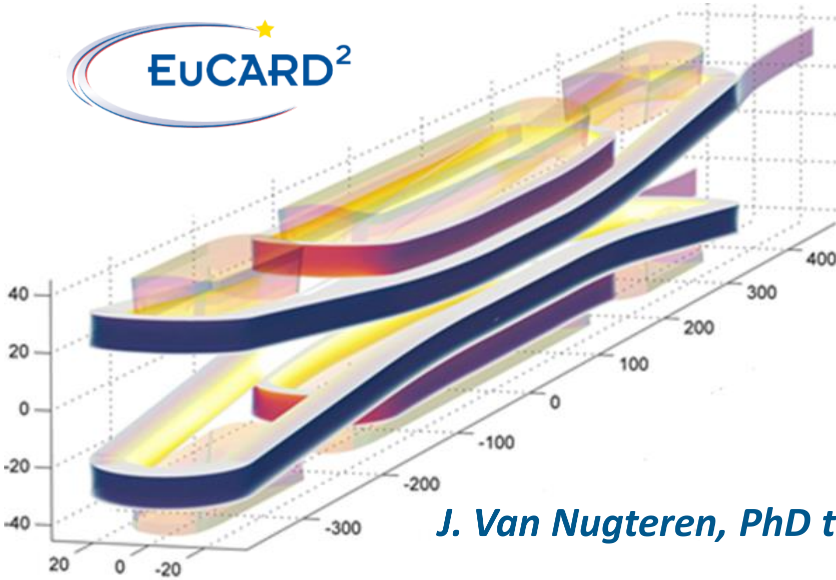
The goal of 20 T in an accelerator quality dipole calls for HTS

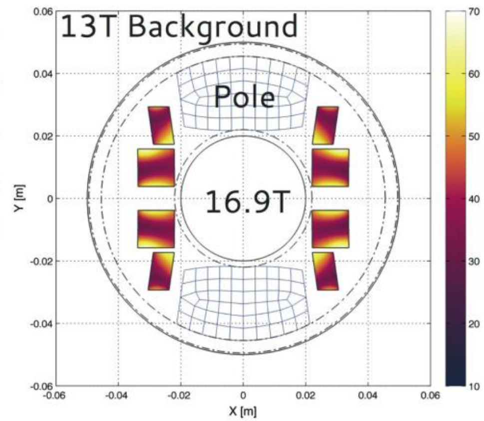


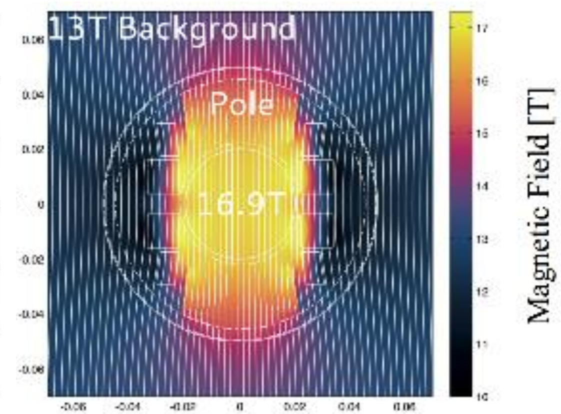
Accelerator magnets operate at ~10 kA to keep inductance low and ease magnet protection

The most promising HTS CONDUCTOR for accelerator magnets is the Roebel Cable (10 kA-class cable)

A coil of Roebel cable: a Short Dipole Demonstrator







J. Van Nugteren, PhD thesis, 2016

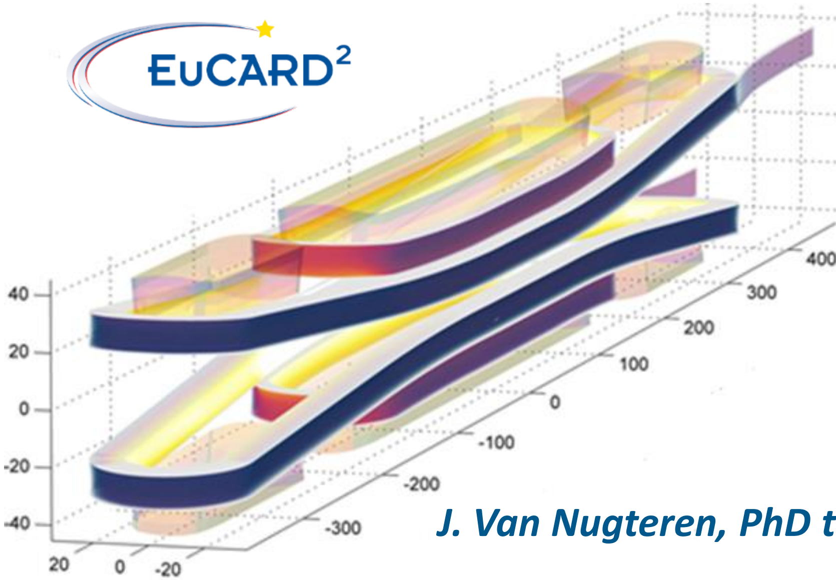
~1000 m of REBCO tape

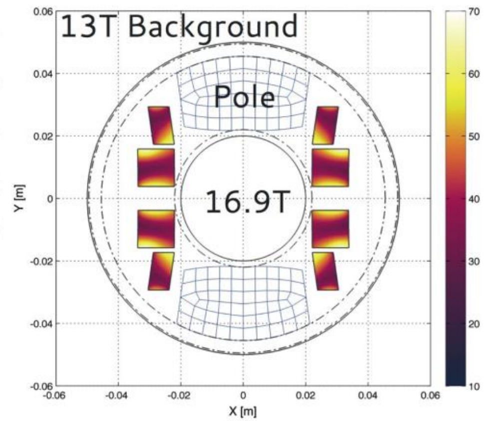
~70 m of Roebel cable

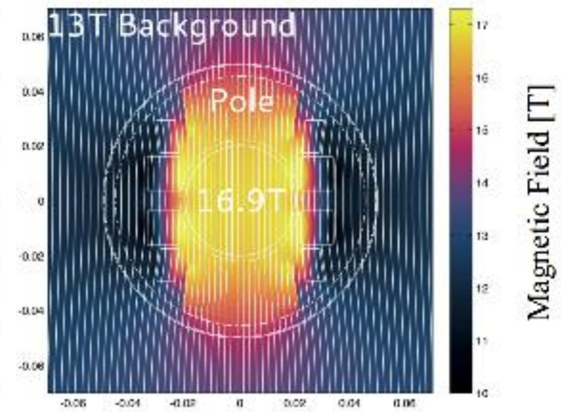
5 T in standalone configuration

40 mm aperture

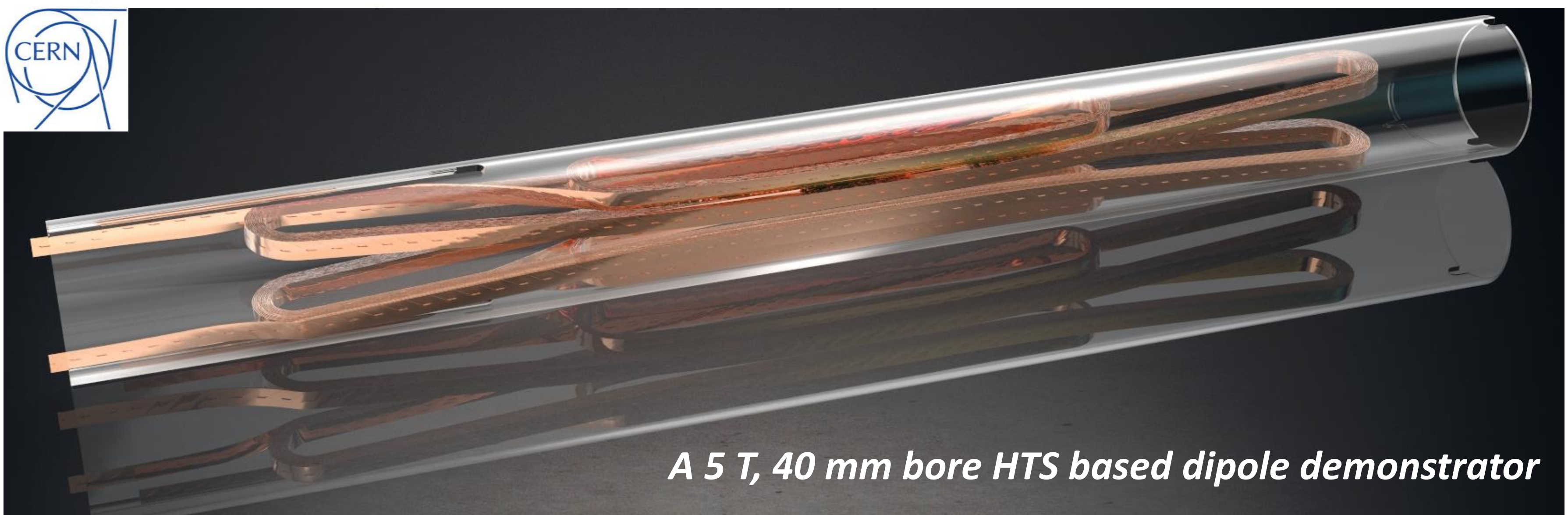
A coil of Roebel cable: a Short Dipole Demonstrator





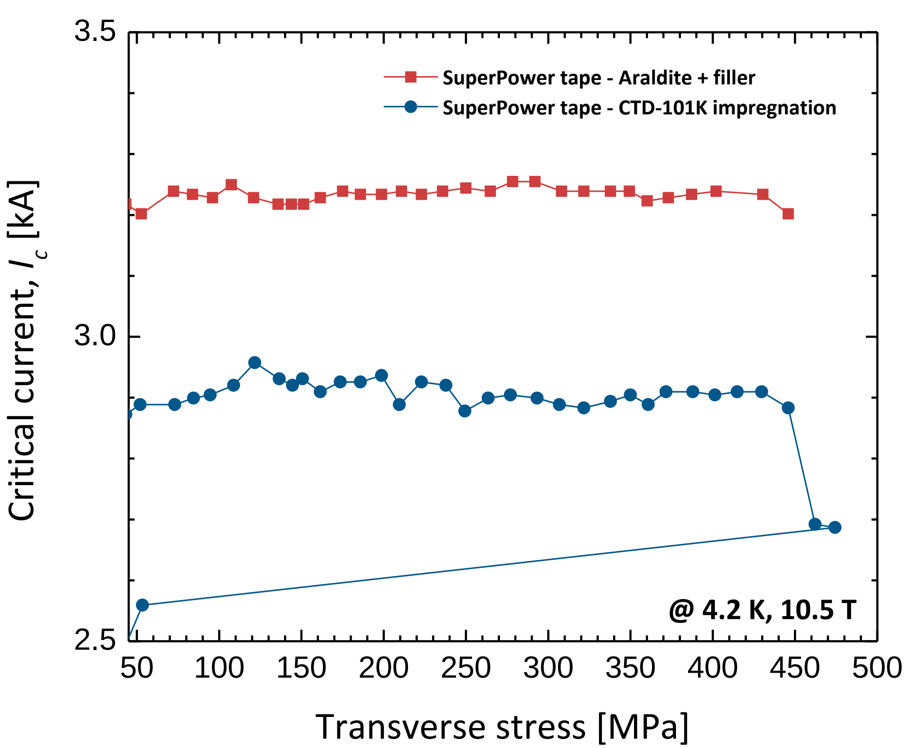


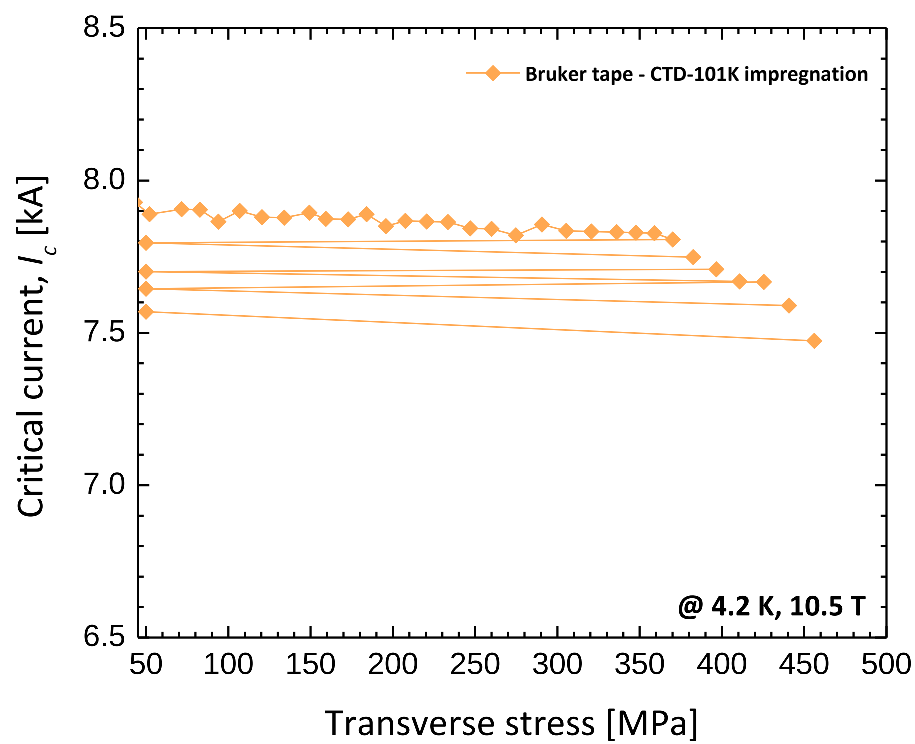
J. Van Nugteren, PhD thesis, 2016



A 5 T, 40 mm bore HTS based dipole demonstrator

Are Roebel cables able to withstand large transverse loads?



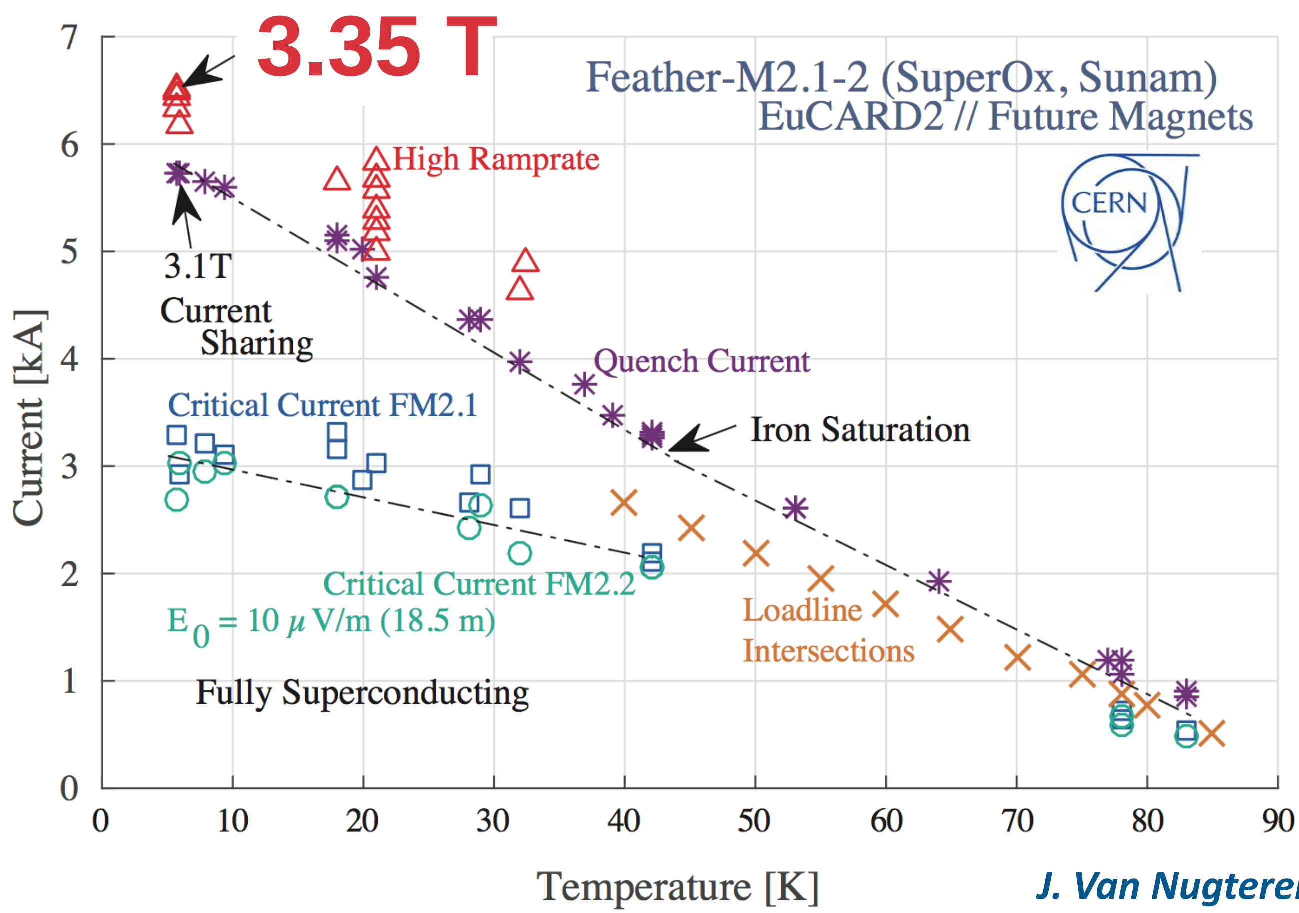


The answer is YES: Irreversible stress limit ≥ 400 MPa

EuCARD² UNIVERSITEIT TWENTE. KIT Karlsruher Institut für Technologie CERN

Short Dipole Demonstrator results

1^{st} coil wound with moderate I_c SuNAM cable (~40% of the Bruker cable)



J. Van Nugteren @ EUCAS2017

New coil with ultra-high I_c cable from Bruker already wound

Expected field in stand-alone test ~7T

What we have learned…

- ***Why we care about mechanical loads***
  Electromagnetic forces in solenoids and accelerator magnets
- ***What hides behind the reversible degradation of I_c***
  Deviatoric strain, intrinsic anisotropy,…
- ***Which are the intrinsic mechanisms that lead to the irreversible degradation of I_c***
  Detailed study of the stress concentration at the voids in Nb_3Sn
- ***How the stress tolerance depends also on factors extrinsic to the wire***
  Load geometry, impregnation…
- ***An overview of the electromechanical properties of Nb_3Sn and YBCO***

Thank you for the attention !

…time for questions…

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