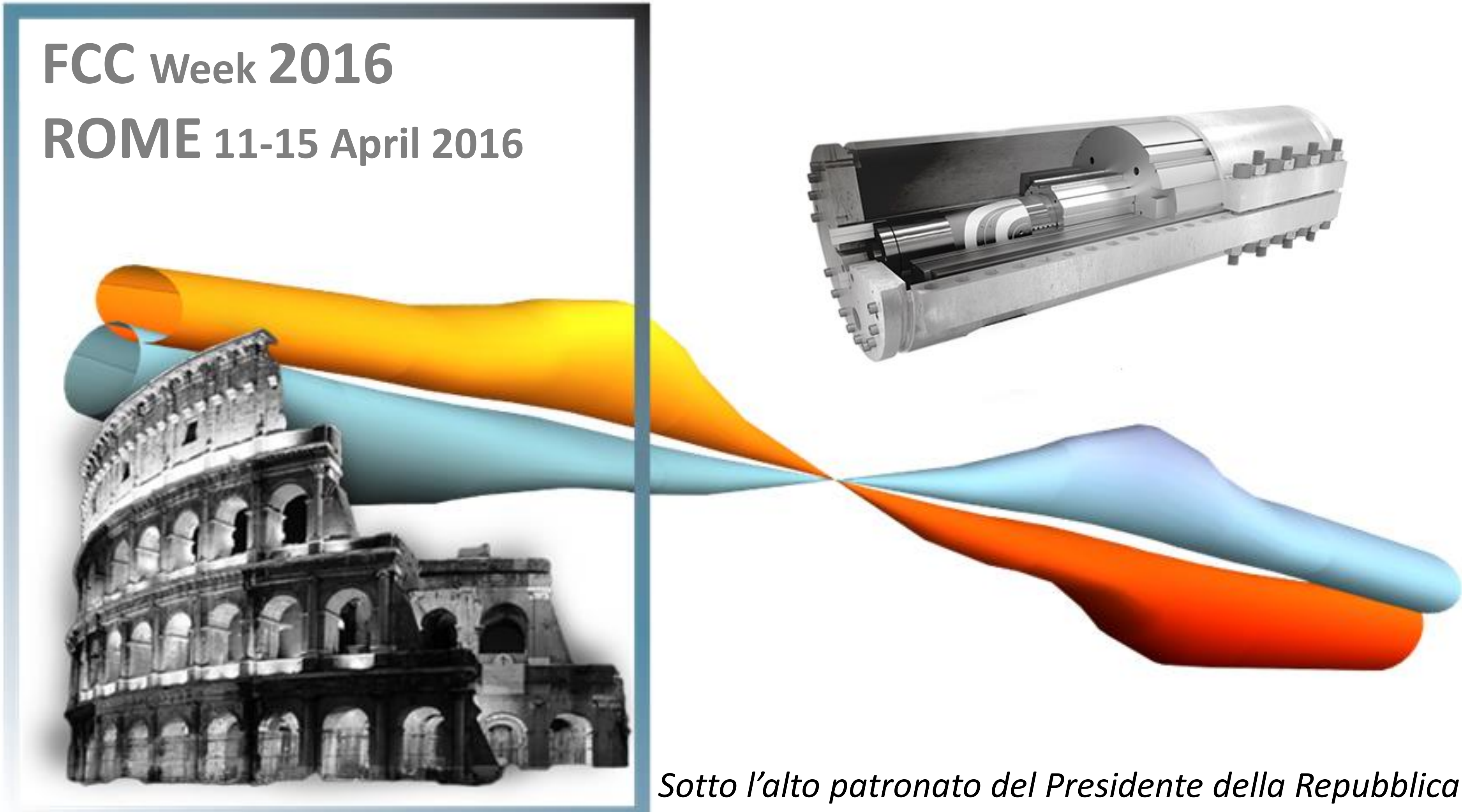
The FCC Conductor Development Plan

A. Ballarino, CERN



Sotto l'alto patronato del Presidente della Repubblica

Outline

- Nb_3Sn for FCC
  - Nb_3Sn for FCC vs ITER conductor
  - Nb_3Sn for FCC vs Hi-Lumi LHC conductor
- Nb_3Sn Conductor Development Program
- HTS potentials
- Conclusions

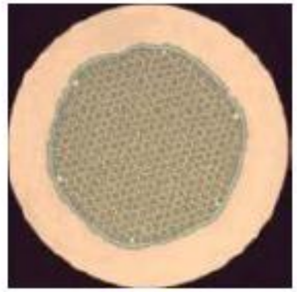
TF Strand Zoo: Nb_3Sn

~ 500 tons
Jc = 800 A/mm^2 (4.2 K, 12 T)

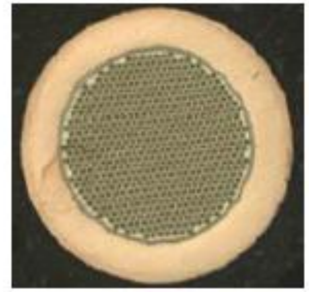
china eu india japan korea russia usa

Courtesy of A. Devred

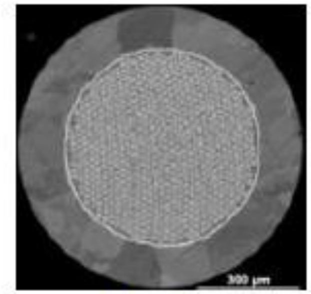
BAS
(Br; EU)



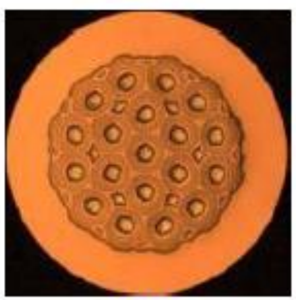
ChMP
(Br; RF)



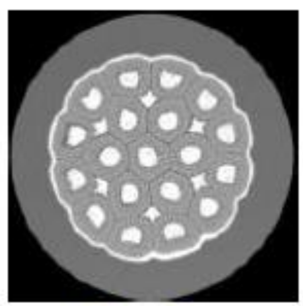
Hitachi
(Br; JA)



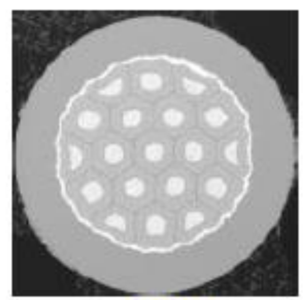
Jastec
(Br; JA)



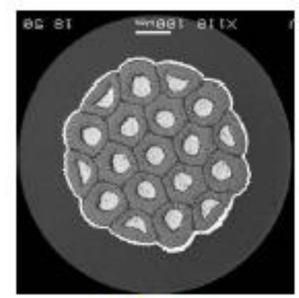
KAT
(IT; KO)



Luvata
(IT; US)



OST
(IT; EU & US)



WST
(IT; CN)

Worldwide production increased from 15 tons/year **up to 100 tons/year**

LHC High Luminosity Upgrade

The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

A peak luminosity of L_{peak} = **5×10^{34} $cm^{-2}s^{-1}$ with levelling**, allowing:

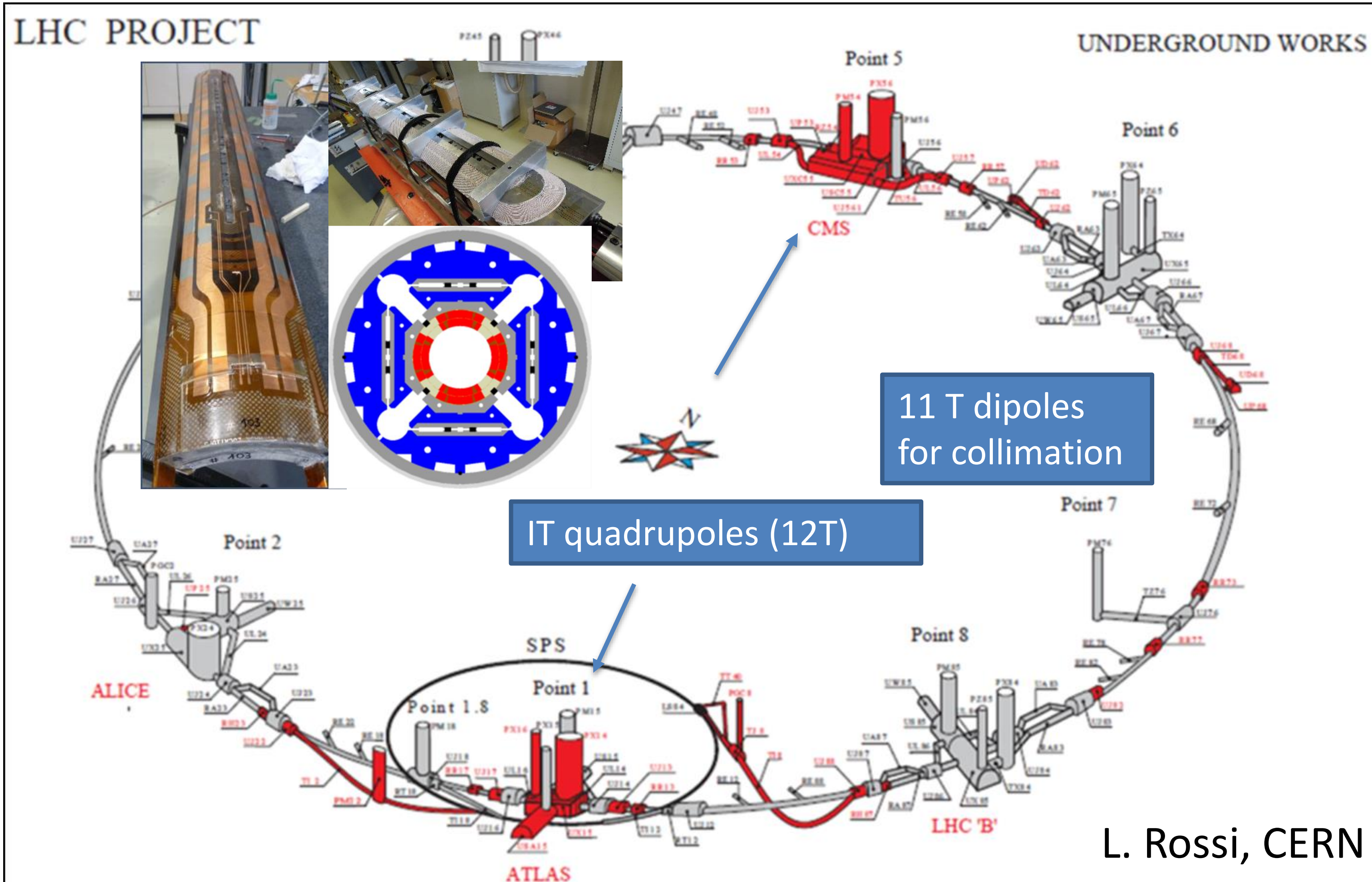
An integrated luminosity of **250 fb^{-1} per year**, enabling the goal of **L_{int} = 3000 fb^{-1}** twelve years after the upgrade.
This luminosity is more than **ten times the luminosity** reach of the first 10 years of the LHC lifetime. **Extension of Physics reach.**

Timeline: **Design Study** &R&D (2010-2016)
Construction and Installation (2017-2025)
Commissioning and Physics (2026 - **2035~40**)

L. Rossi, CERN

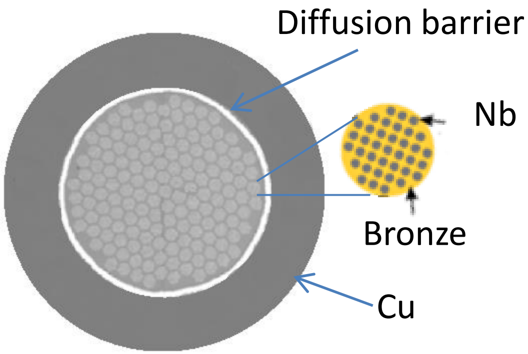
LHC High Luminosity Upgrade

Nb_3Sn for the first time in an operating accelerator



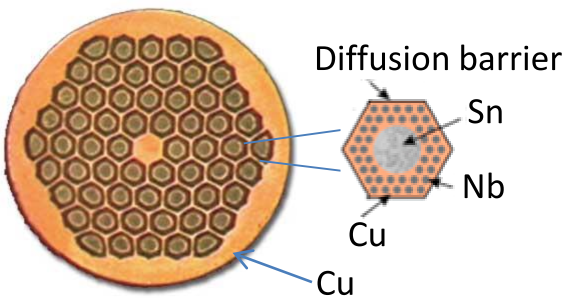
Nb_3Sn industrial wires

Bronze Route



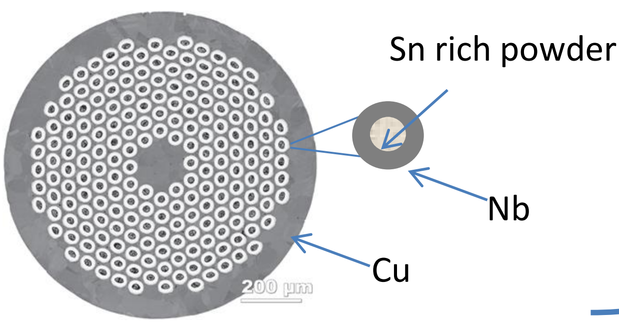
Small filaments ($\Phi < 5\ \mu m$)
Jc limited (~ 1-1.2 kA/mm^2 @ 12 T, 4.2 K) by the solubility of Sn in Cu (~15.5 wt %)

Internal Tin



OXFORD INSTRUMENTS — RRP ®

Powder In Tube



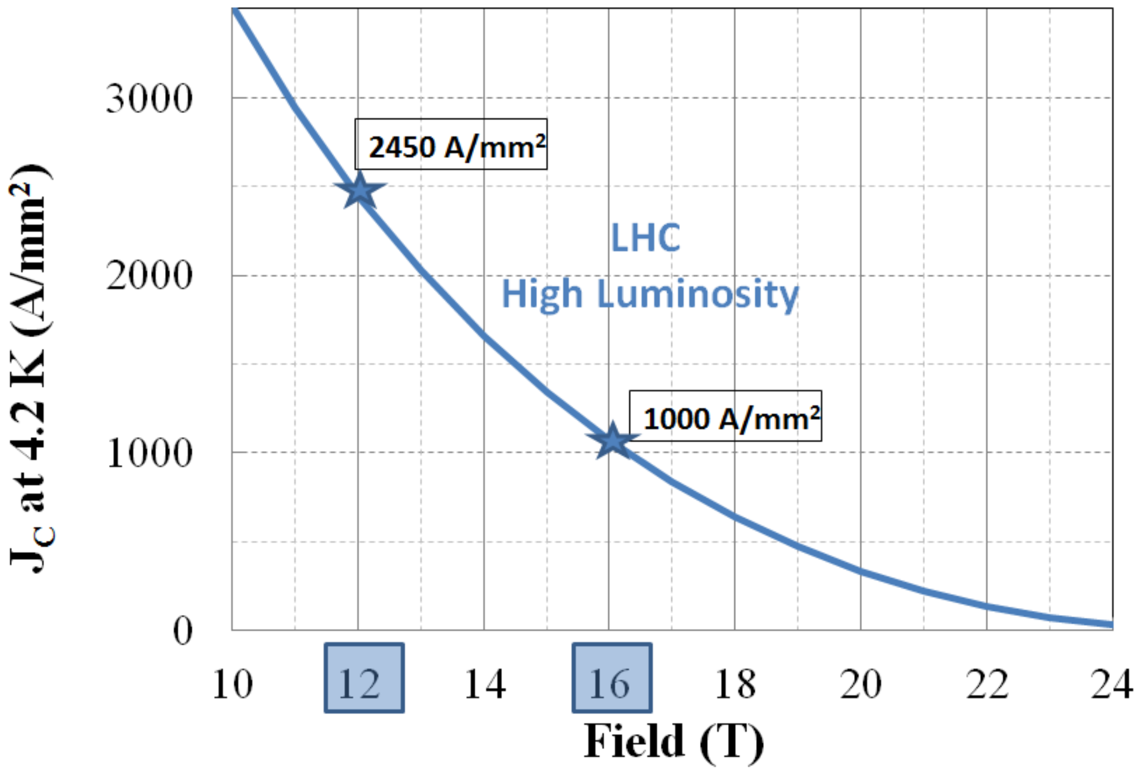
High Jc Nb_3Sn wires for accelerator magnets

BRUKER — PIT

High field Nb_3Sn: state-of-the-art of Hi-Lumi Nb_3Sn industrial production

- **PIT**(Bruker) and **RRP** (OST) technology
- Ternary **$(NbTi)_3Sn$** or **$(NbTa)_3Sn$** compounds $\rightarrow$ Bc2 enhanced by increasing ρ_n without sacrificing Tc and workability (1-2 % at Ti and 2-4 at % Ta)
- **Multi-filamentary wires**
  Φ = 0.7 mm and 0.85 mm, filaments/sub-elements size ~ 40-50 μm
- Total quantity: ~ **20 tons**

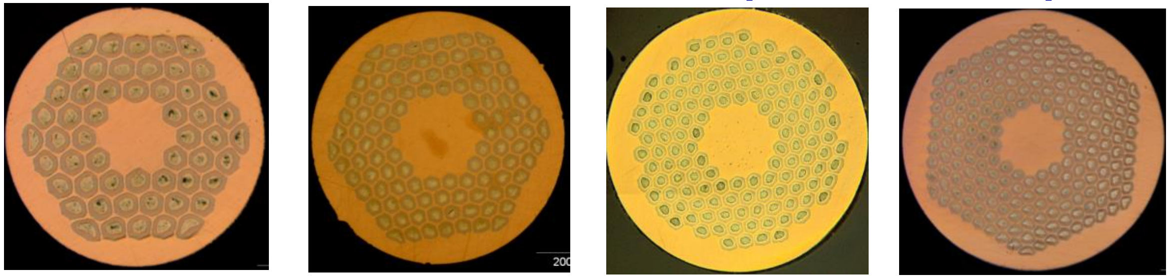
Nb_3Sn for Hi-Lumi LHC: Jc



CERN and USA LARP Collaboration

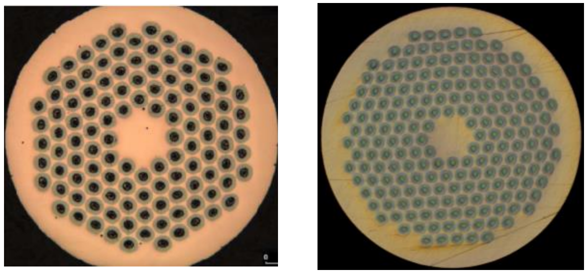
RRP

54/61 **108/127** **132/169** **198/217**



PIT

114 **192**



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Measurements – Nb_3Sn for Hi-Lumi

J_c & B_{c2} @ 4.22 K

This morning talks on Hi-Lumi conductor by B. Bordini and L. Cooley

	Layout	Sub-Element size	RRR	J_c (12 T), *RMS* [A/mm²]	J_c (15 T), *RMS* [A/mm²]	J_c (16 T), *RMS* [A/mm²]	J_c (17 T), *RMS* [A/mm²]	B_{c2}, *RMS* [T]	Sub-Element Shape
0.7 mm RRP	132/169	41 µm	**185**, *64*	**2508**, (2450) *125*	**1232**, *81*	**924**, *70*	**670**, *60*	**23.2**, *0.36*	Hex
	144/169		**172**, *30*	**2408**, *146*	**1186**, *104*	**888**, *91*	**644**, *80*	**23.2**, *0.52*	
	150/169								
0.85 mm RRP	132/169	50 µm	**235**, *52*	**2777**, (2450) *81*	**1427**, (1280) *55*	**1091**, *48*	**814**, *43*	**23.8**, *0.3*	
0.7 mm PIT	114	44 µm	**138**, *34*	**2426**, (2450) *66*	**1357**, *50*	**1089**, *45*	**845**, *40*	**25.9**, *0.32*	Circular
	120		**103**, *50*	**2302**, *101*	**1284**, *65*	**1027**, *57*	**804**, *49*	**25.8**, *0.36*	
0.85 mm PIT	192	41 µm	**175**, *30*	**2340**, (2450) *53*	**1306**, (1280) *41*	**1047**, *37*	**822**, *34*	**25.8**, *0.3*	

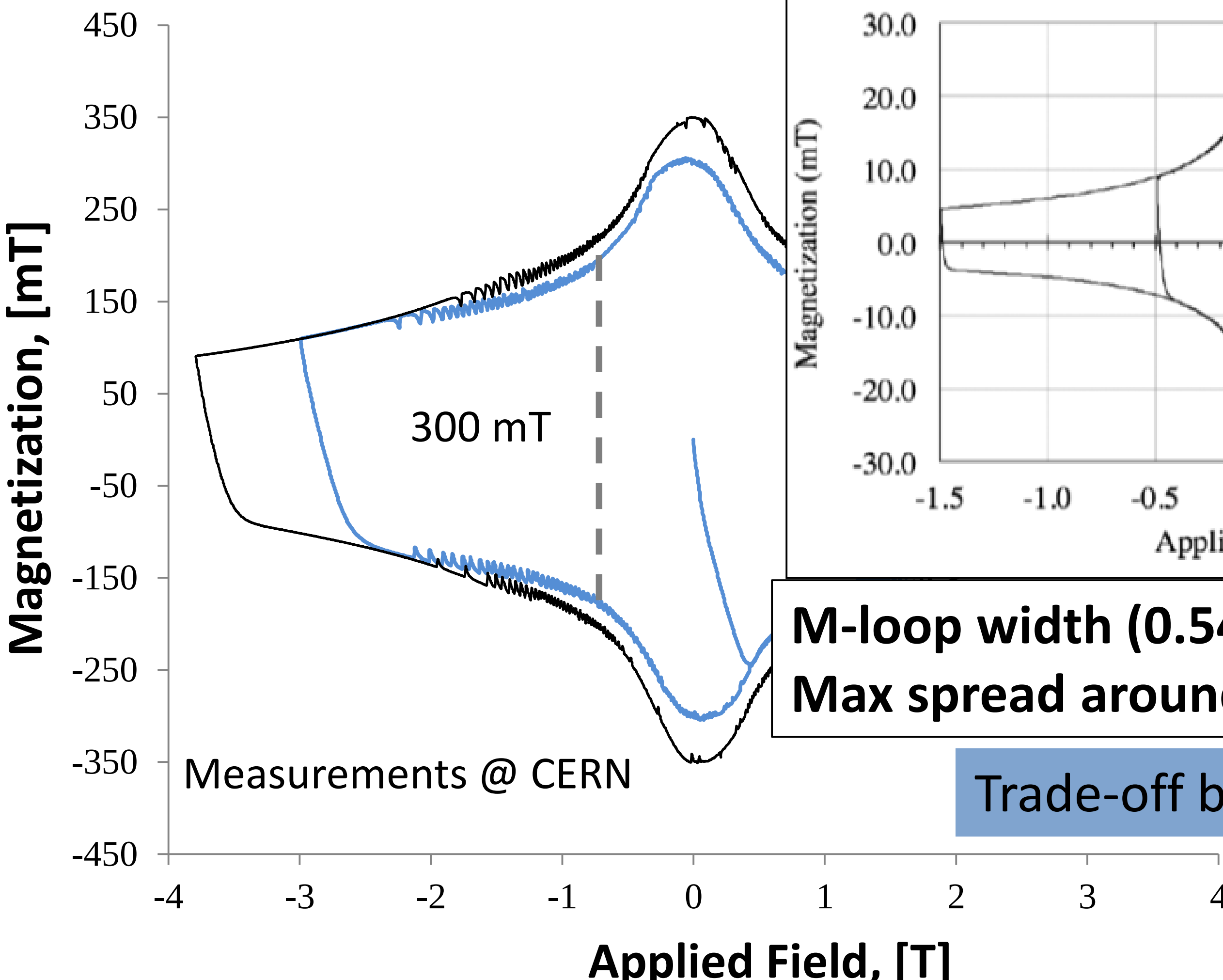
Review of the Performance of the Received wire for HiLumi-LHC – B. Bordini

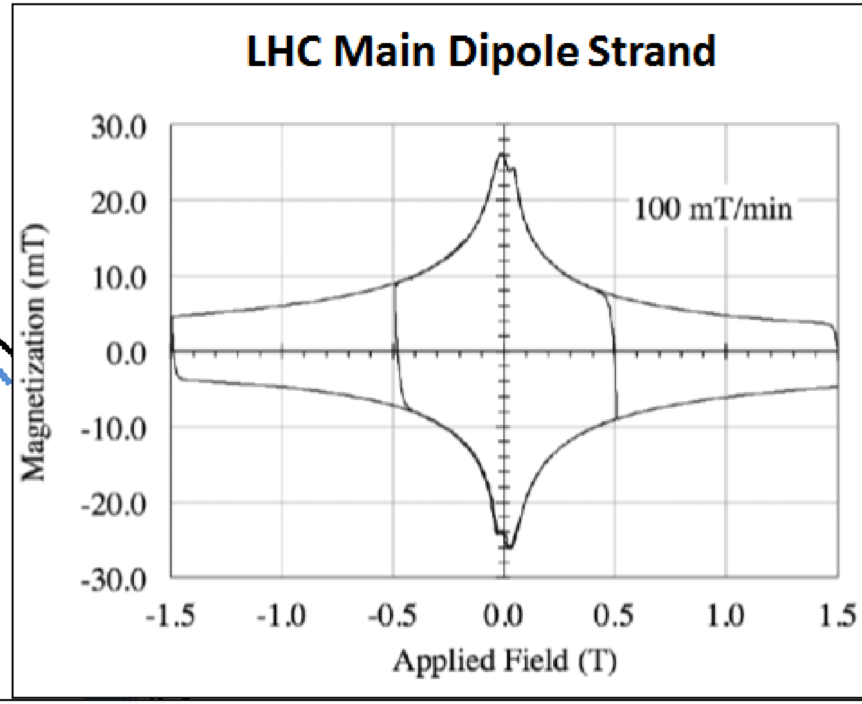
Nb_3Sn Hi-Lumi wire challenges: Deff

T = 1.9 K

Φ= 0.7 mm (11 T Dipole Project)

Reduce filaments size to reduce magnetization





M-loop width (0.54 T, 1.9 K) < 30 mT
Max spread around average ± 4.5 %

Trade-off between Jc and Deff

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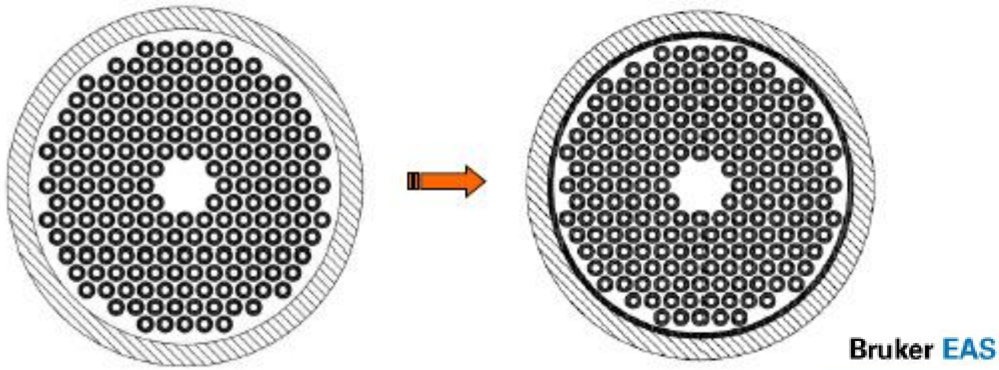
Nb_3Sn Hi-Lumi wire challenges: RRR

New generation of PIT Nb_3Sn for HE Physics



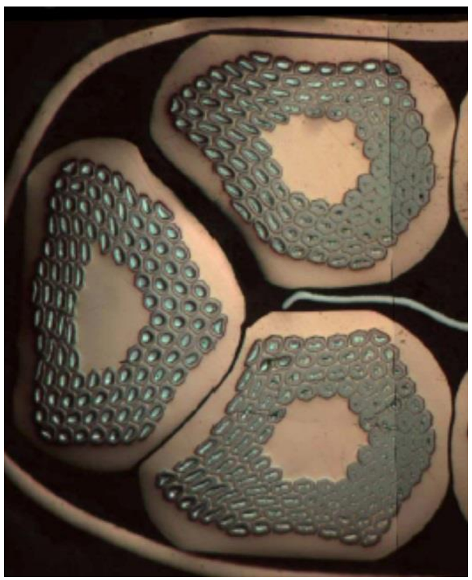
Nb barrier that protects the other shell of copper. It:

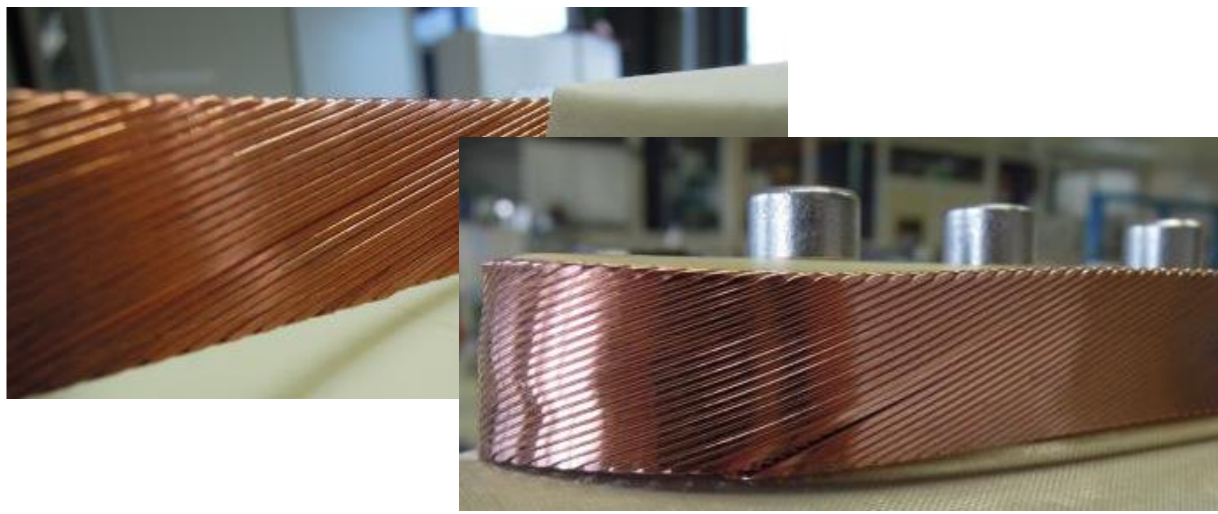
1) prevents RRR degradation after deformation;
2) enables use of higher Sn content

CERN-Bruker EAS R&D collaboration

Nb_3Sn for Hi-Lumi LHC: cabling

Operational current = 11 kA – 18 kA





Mechanical properties of PIT and RRP wires appropriate for cabling →
Ic degradation of wire < 5 %, RRR maintained above 100

Nb_3Sn for FCC: challenges

- Higher Jc at 16 T
- Aggressive Jc and small filaments size
- Industrial fabrication and scale-up for large scale production
- Cost effectives

Final Targets for FCC Conductor

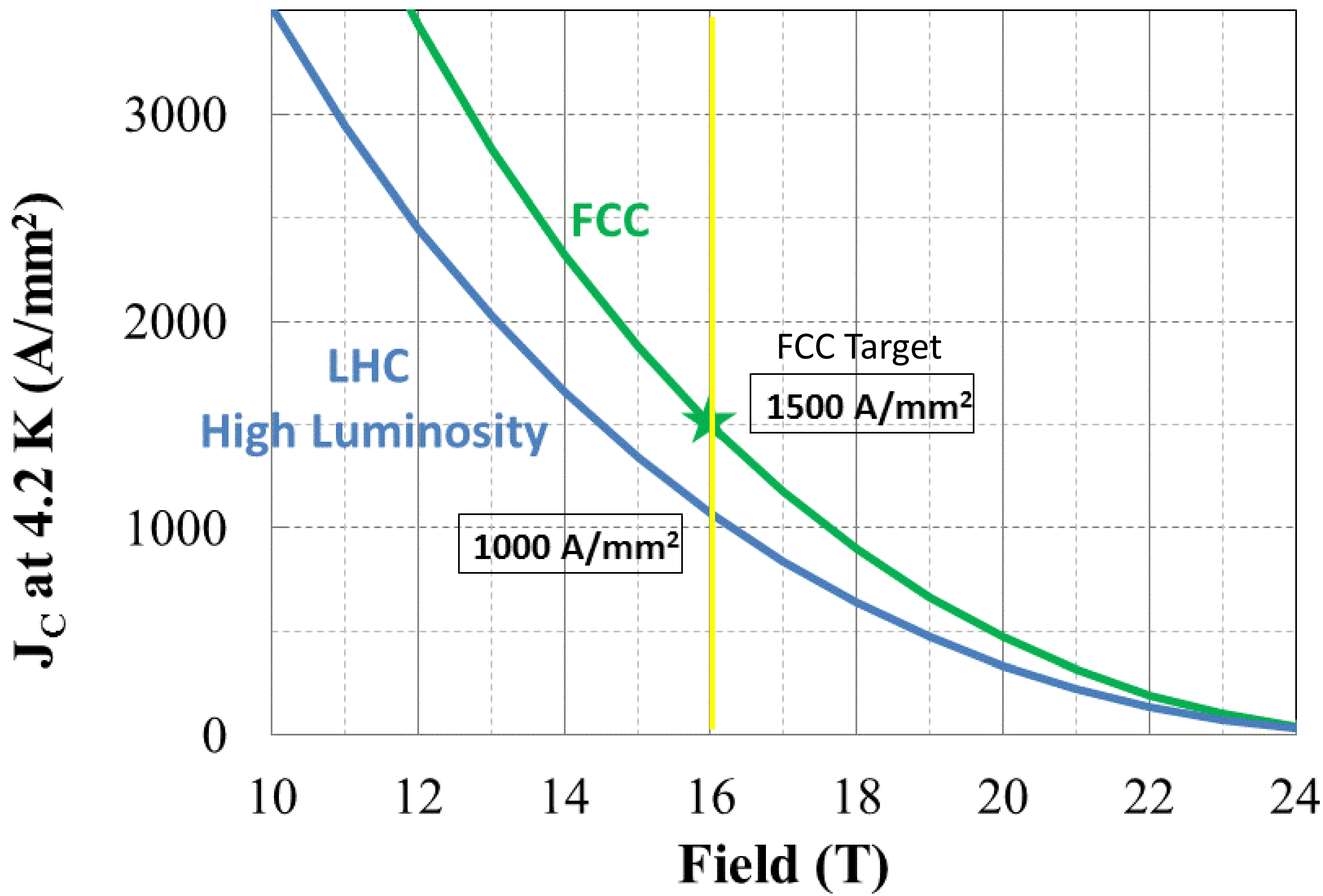
		Nb_3Sn
Wire diameter	mm	**~ 1**
Non-Cu Jc (16 T, 4.2 K)*	A/mm^2	**≥ 1500**
$\mu_o\Delta M$(1 T, 4.2 K)	mT	**≤ 150**
$\sigma(\mu_o\Delta M)$ (1 T, 4.2 K)	%	**≤ 4.5**
Deff	μm	**≤ 20**
RRR	-	**≥ 150**
Unit length	km	**≥ 5**
Cost	Euro/kA m**	**~ 5**

*Je ~ 600 A/mm^2
*Cu:non Cu ~ 1

** 16 T, 4.2 K

Targets derived from the larger context of magnet design requirements

Nb_3Sn - Jc Target for FCC



Application Needs vs Material Optimization

Application requirements

- High in-field **Jc**
- **High RRR** (>100)

Material optimization

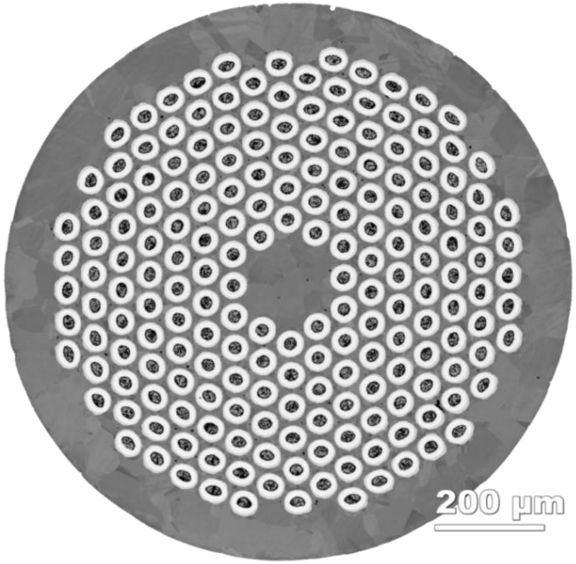
- Improved/optimized **pinning**
- Maximized rel. **A15 content**
- Optimized and homogeneous **A15 composition**
- **Homogeneous** grain morphology and small grain sizes
- **Integrity of** (Nb) **barrier**

Heat Treatment

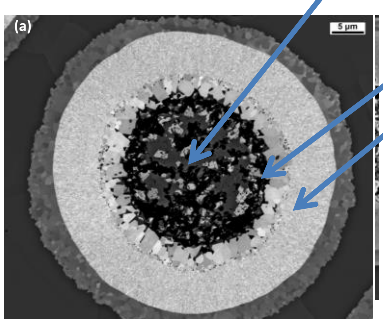
Delicate balance of conflicting requirements

Fully optimized Nb_3Sn conductor ?

PIT 192 – Nb7.5 wt% Ta



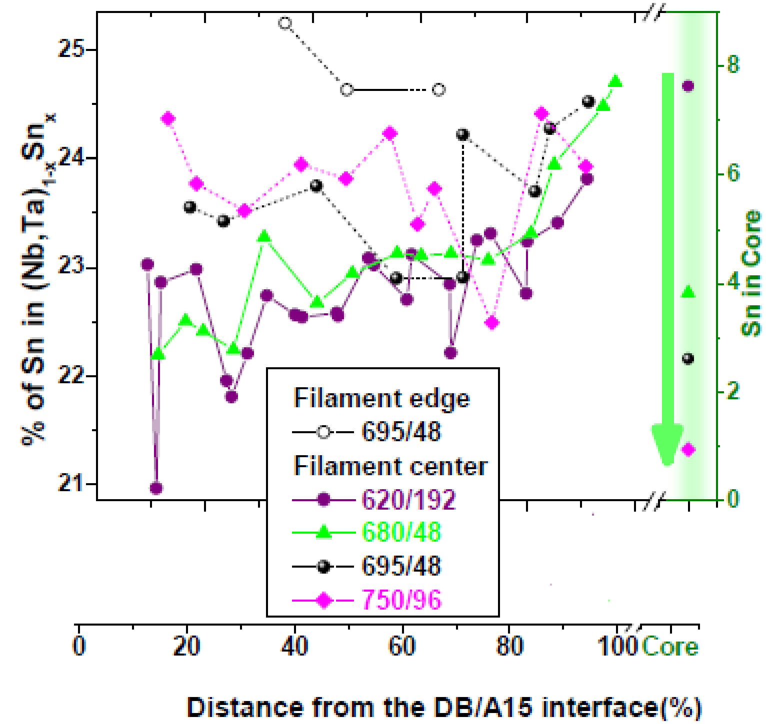
Residual core (~ 22 %)

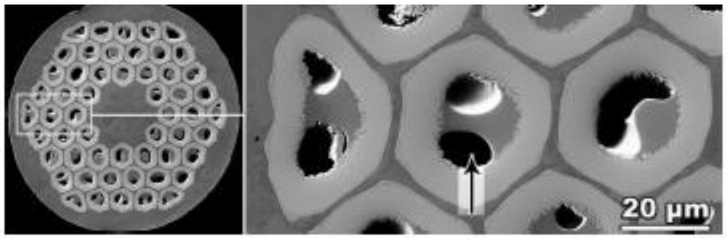


Large grains (~ 25 %)

Small grains

RRP 54/61 – Nb7.5 wt% Ta



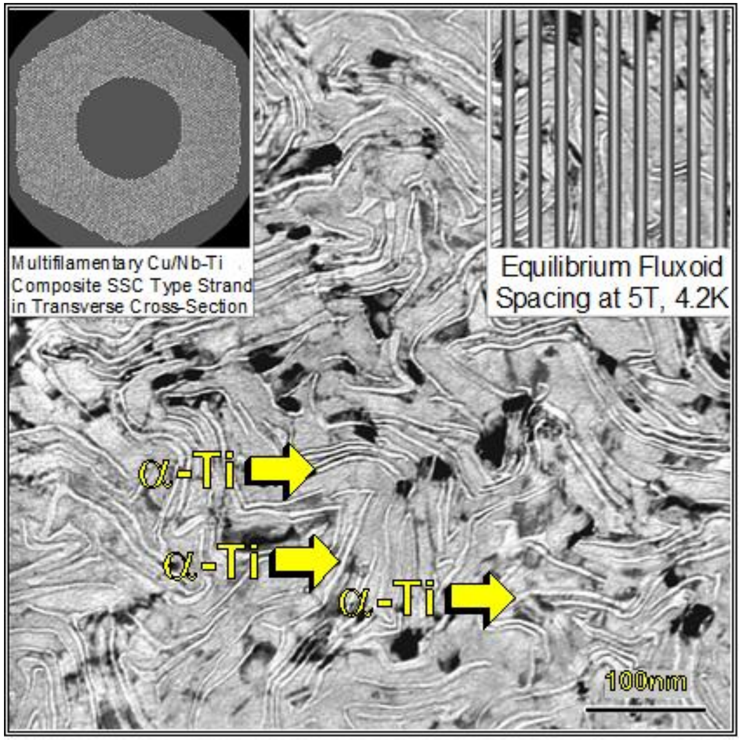


C. Tarantini et al, IoP, Vol 28, 095001 (2015)

C. Tarantini et al, IoP, Vol 27, 065013 (2014)

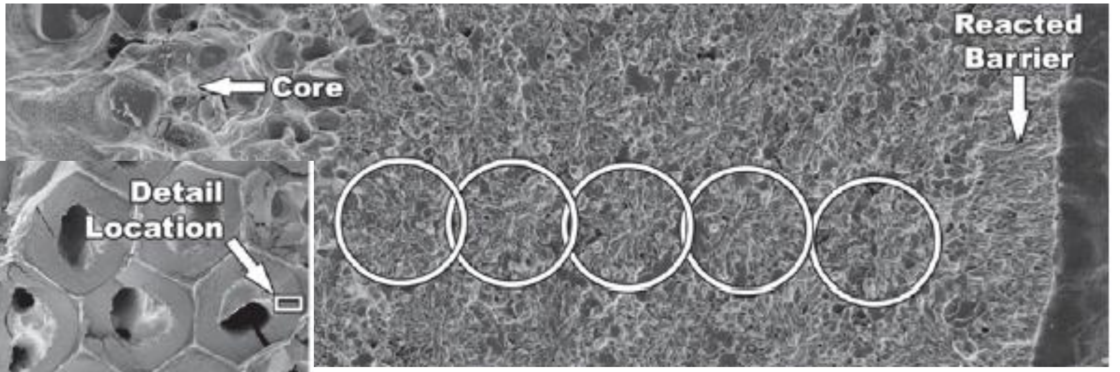
Pinning: Nb-Ti vs Nb_3Sn

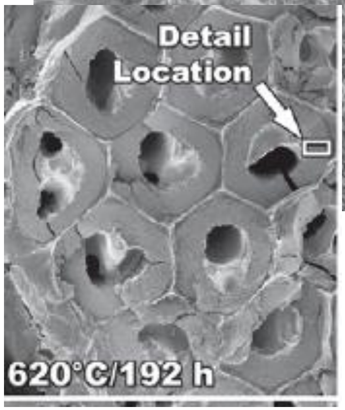
NbTi: α-precipitates



Meingast, Lee and DCL,
J. Appl. Phys. 66, 5971

Nb_3Sn: grain boundaries



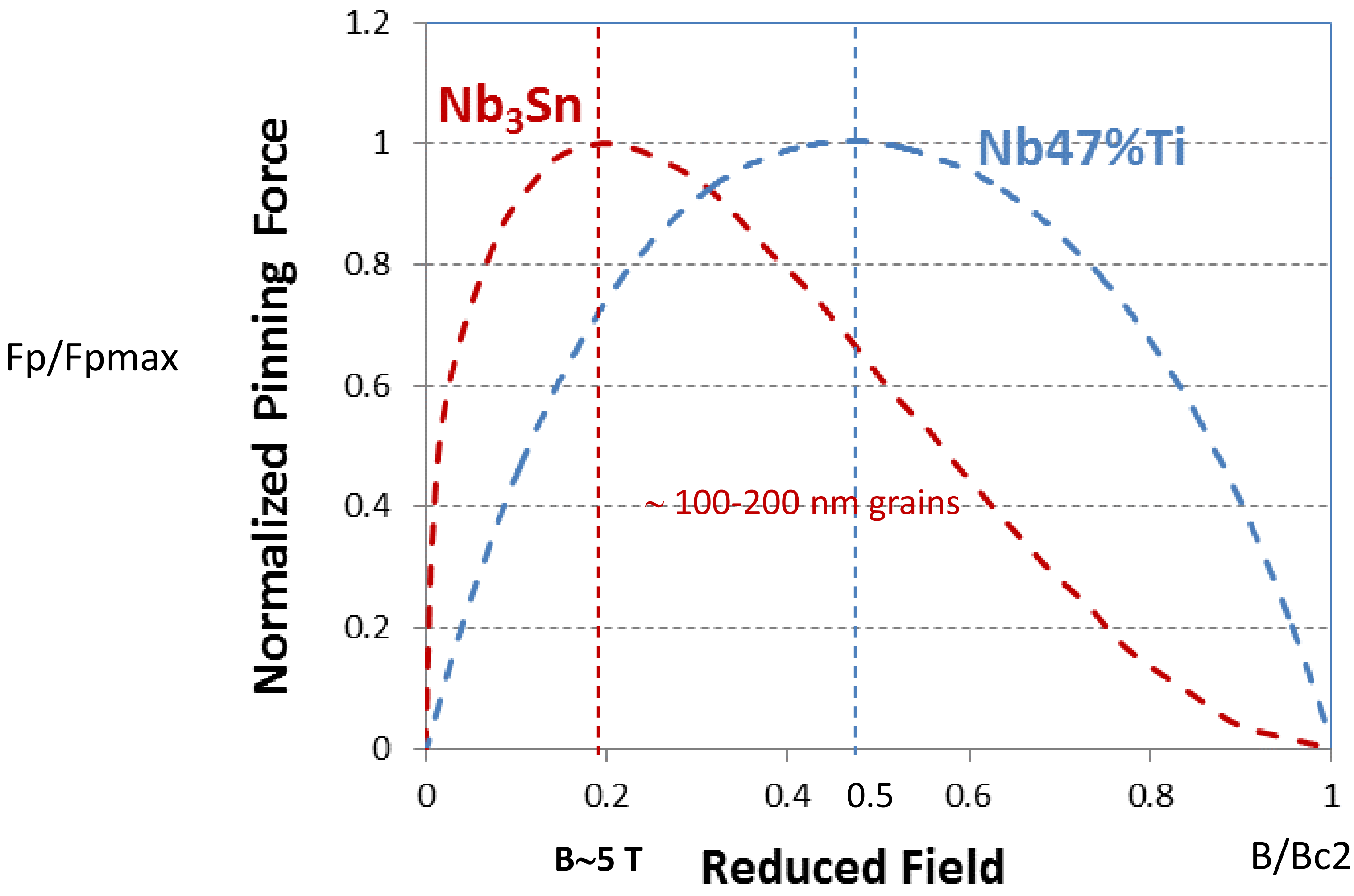


C. Tarantini et al, Supercond . Sci. Technol. 27 (2014)

Dominant **pinning mechanism**: **grain boundaries** (**vortex pinning**)

Diameter of Nb_3Sn grains = 100-200 nm

Pinning: Nb-Ti vs Nb_3Sn



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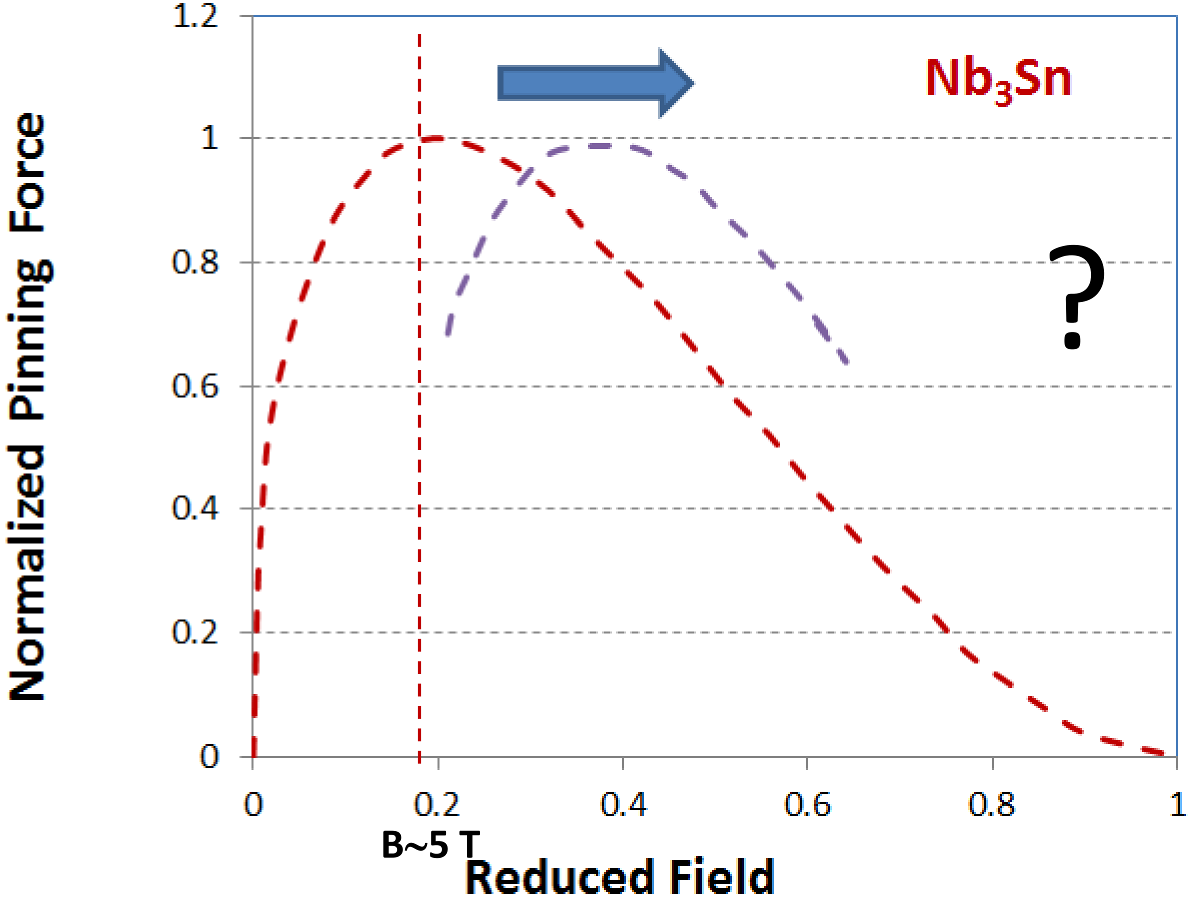
Nb_3Sn for higher fields

- Increase pinning force and efficiency



$Jc \propto GBD/d$

d = grain diameter

GBD = Grain boundaries Density

Nb_3Sn – Grain size refinement

- **Grain size** at optimized heat treatments (**150-200 nm**) vs **vortex spacing** at operational fields (~ **12 nm** at 16 T) . Needed matching of spacing of pinning sites to vortex spacing

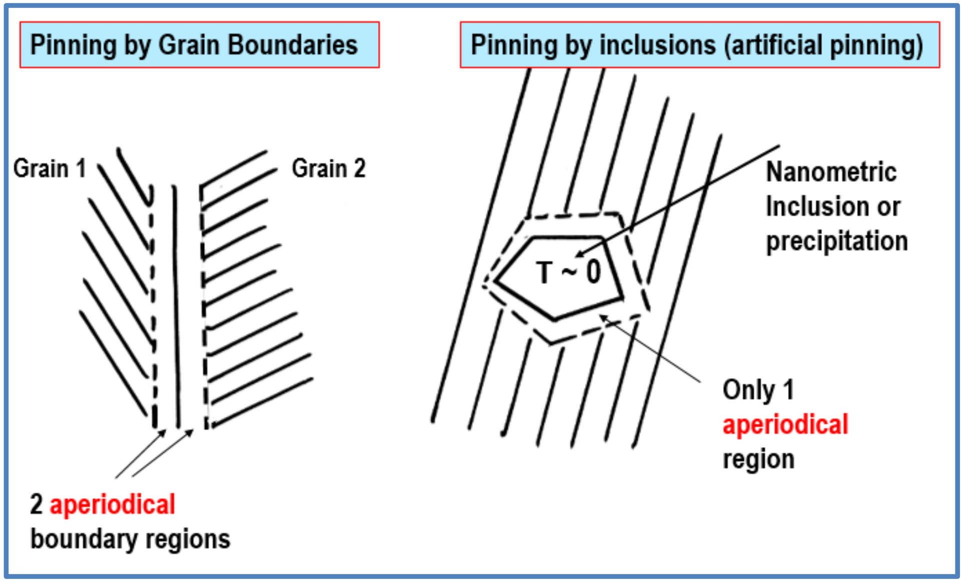
- **Grain refinement** possible by **lowering the reaction temperature**. **But** this is in conflict with the need of reaching stoichiometric Sn composition in the A15 phase → delicate interplay between A15 gain boundary density and compositional homogeneity

Nb_3Sn – Artificial Pinning

Introduction of a **nano-inclusions** in the Nb_3Sn → increase of the pinning strength by:

- **Reduction of grain size** (pinning by grain boundary)

- **Enhanced point pinning** induced by additional defects



Periodicity of lattice broken at the grain boundaries and/or at the interface with an inclusion/precipitation

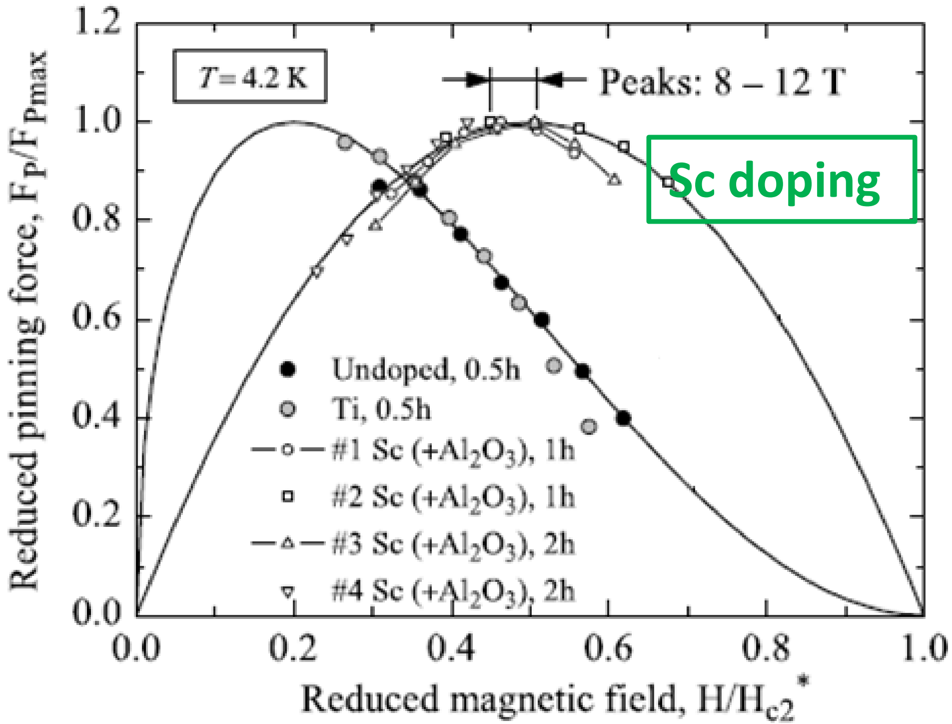
Nb_3Sn – Grain size refinement via AP

Thin films produced by electron beam co-evaporation

Grain size refined to **15-20 nm**

(Fp)max shifted to ~ **0.5 Birr**

Thin films



D. Dietrich and R. Scanlan, IEEE Trans.Appl. Supercon, 1997

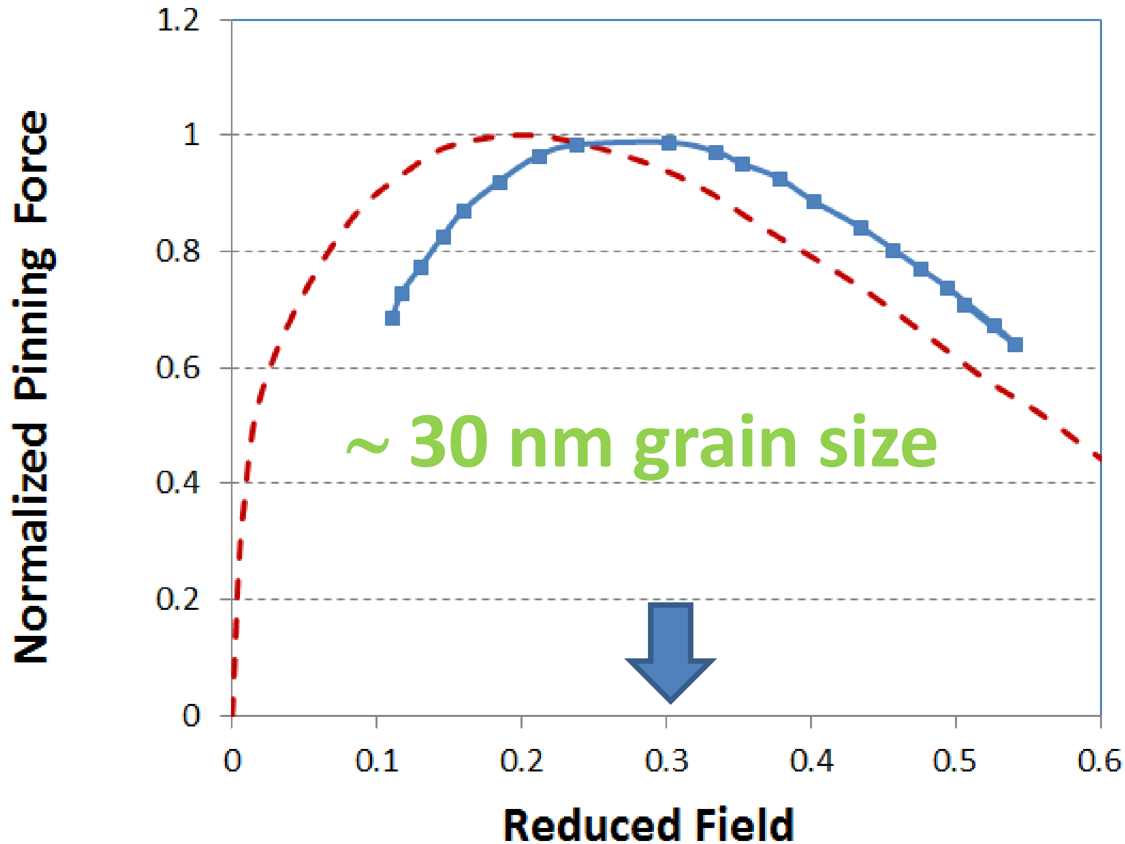
D. Dietrich and A. Godeke, Cryogenics, 48 (2008) 331-340

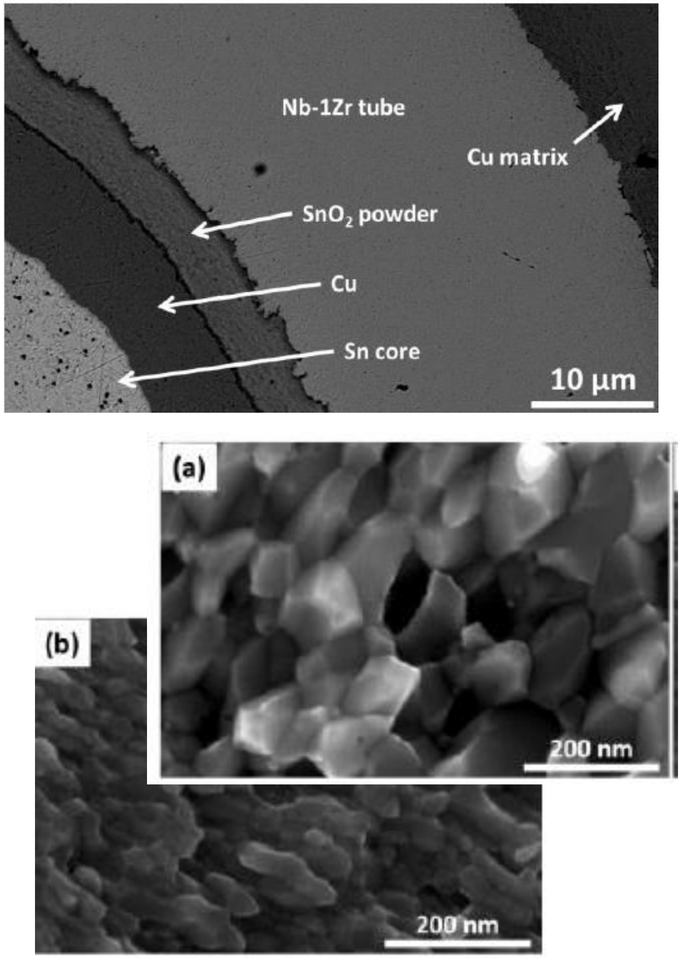
Nb_3Sn – Grain size refinement via AP

$(Nb\text{-}Zr)_3Sn$ wires produced by **Internal Oxidation method**

- ZrO_2 precipitates in Nb_3Sn wires

X. Xu, M. Sumption, X. Peng, E. W. Collins , Appl. Phys. Lett. **104** (2014)

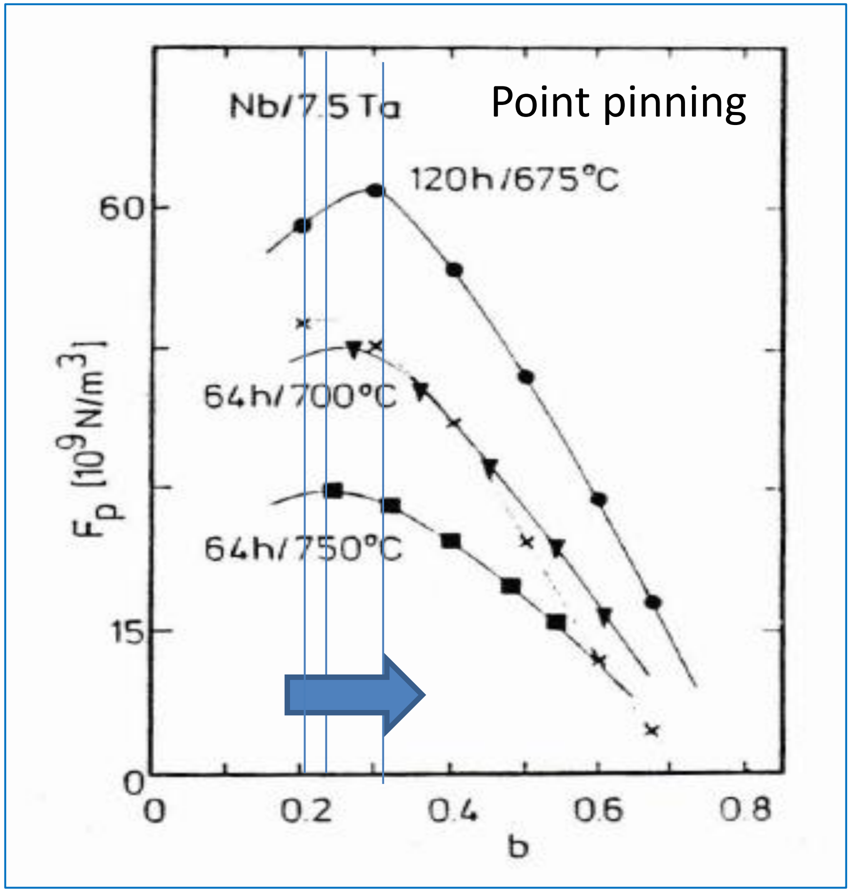


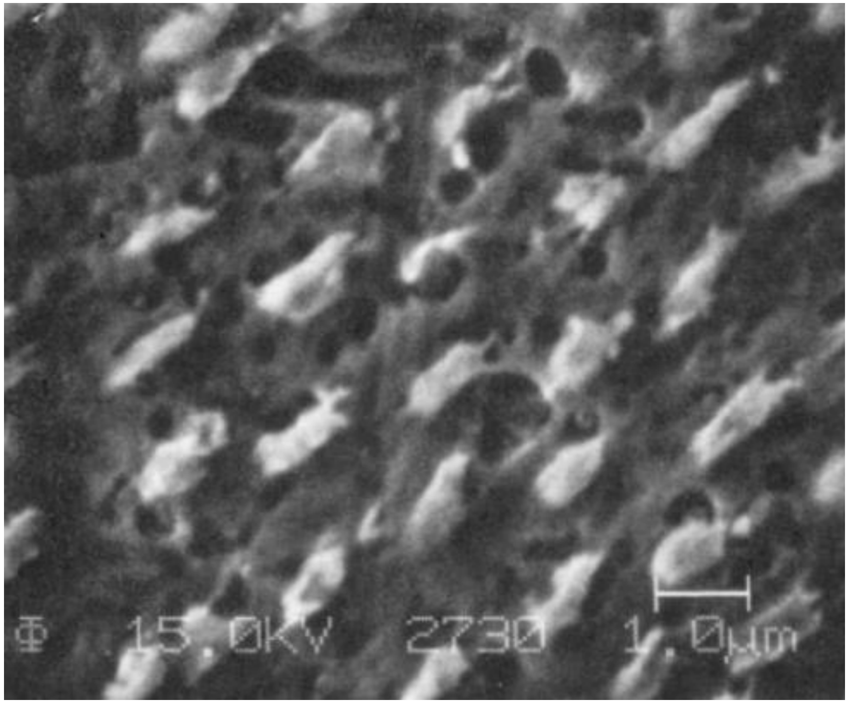


Artificial pinning via oxide nano-inclusions

Nb_3Sn –AP via Ta nanoinclusions

Bronze-route processed **wires**



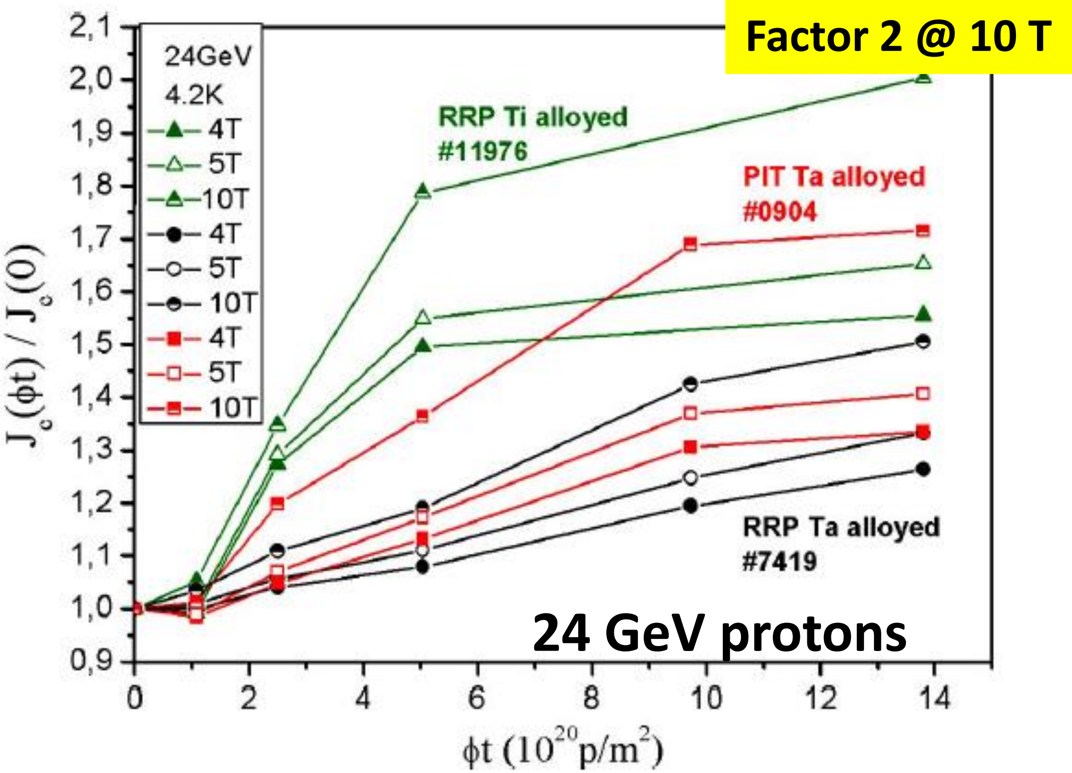


Nb matrix with ribbon-like Ta inclusions (Nb 8wt% Ta)

M. Klemm, E. Seibt, W. Specking , J. Xu, R. Flukiger, Supercon, Sci. Technol. 3 (1990)

Artificial pinning via metallic nano-inclusions

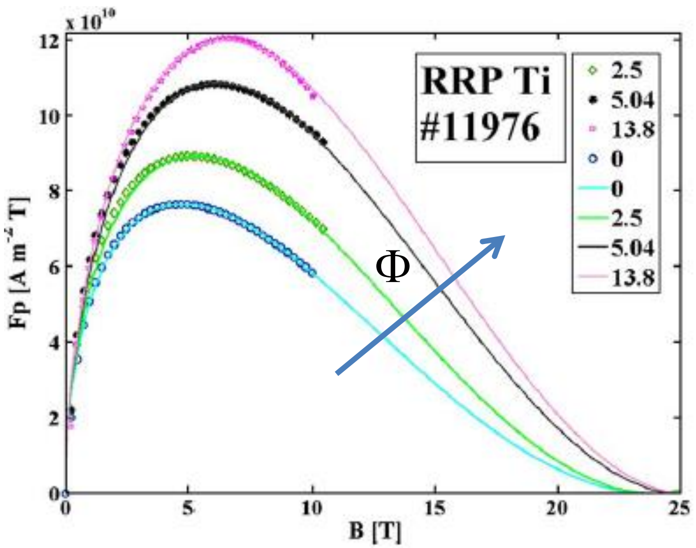
Nb_3Sn – AP via irradiation



$$F'_p = k(\alpha f'^{G.B} + \beta f'^{P.P})$$

GB Pinning

Point Pinning



Neutron irradiation at ATI

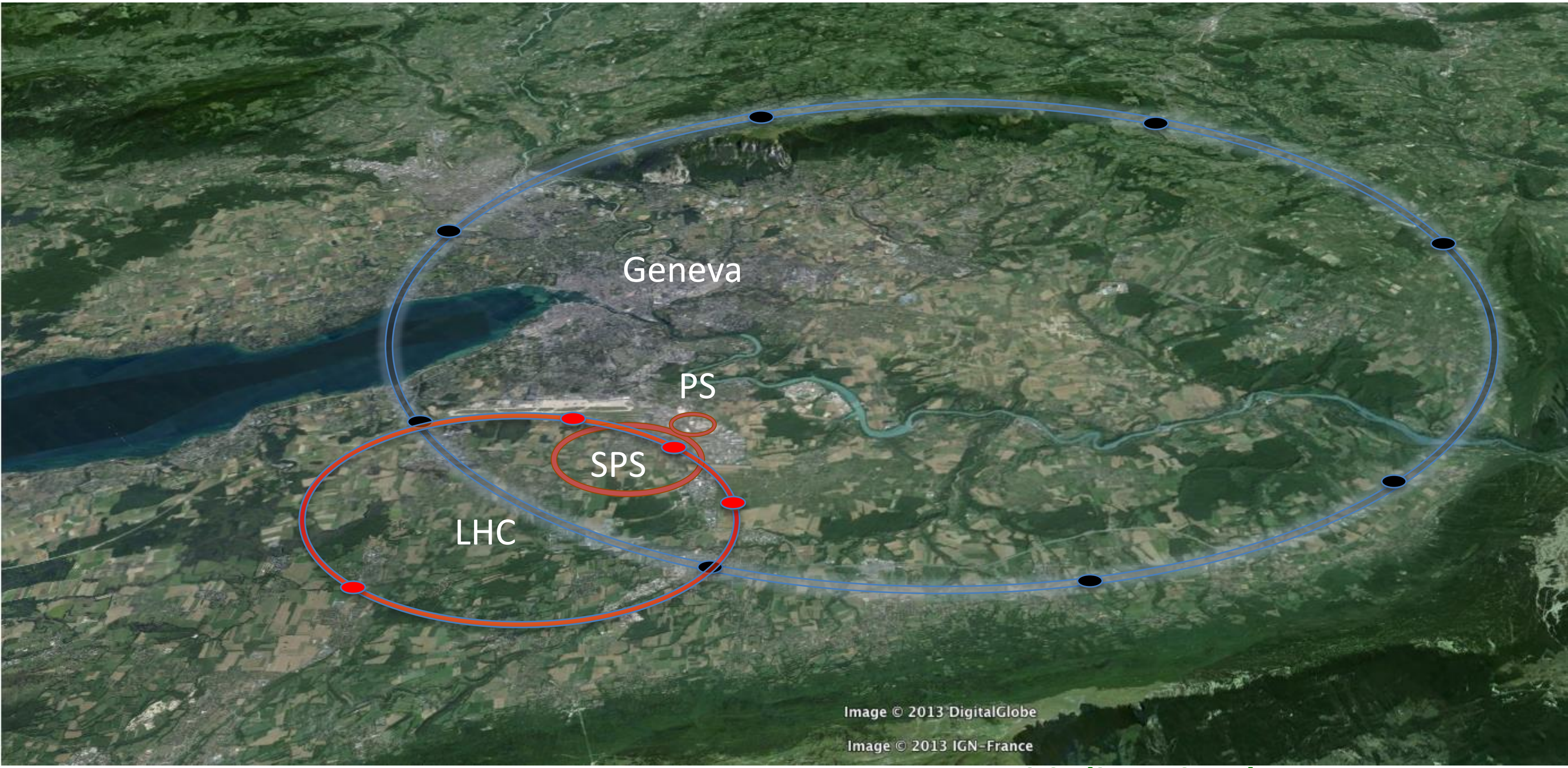
Radiation induced **nano-site defect clusters** acting as pinning enters → **enhancement of Jc**

T. Spina, C. Scheuerlein, D. Richter, B. Bordini, L. Bottura, A. Ballarino, and R. Flükiger IEEE Trans. on Appl. Supercond., 25, 2015

- **Nb_3Sn** has **potentials** **for higher Jc** at 16 T

- **AP** can enable achievement of the **target Jc performance** with the required margin required for assuring a large-scale and cost-effective production

Nb_3Sn Conductor for FCC - Quantity



LHC	FCC-hh (baseline)
27 km, 8.33 T	100 km, **16 T**
14 TeV (c.o.m.)	100 TeV (c.o.m.)
1200 tons Nb-Ti	6000 tons Nb_3Sn
200 kg HTS	3000 tons Nb-Ti

FCC Nb_3Sn conductor – Series production

- Total quantity of conductor – estimated on the basis of the present input from magnet design ~ **6000 tons**

- Required a total production world-wide of ~ **700 - 800 tons/year** over a period of ~ 7 years (if production by 8 companies)

- **ITER** production: world-wide production of up to **100 tons/year** (8 companies)

- Need for **industrial scaling-up** of facilities

FCC Nb_3Sn conductor - Cost

- **Target cost**: <u>< 5 Euro/kA m</u> (16 T, 4.2 K)
- Cost of **state-of-the-art accelerator-type Nb_3Sn** conductor (estimate based on procurement of relatively small – ~1 ton – quantities of material):

  $\geq$ 10 Euro/ kA m (12 T, 4.2 K) $\rightarrow$

  \> 20 Euro/kA m (16 T, 4.2 K)
- **Increase of Jc @ 16 T** (from 1000 A/mm^2 to 1500 A/mm^2): most effective way of decreasing cost. Importance of choice of technology, that should enable scale-up, and wire layout/composition
- Analysis and improvement of **both processing and manufacturing costs** (for raw materials and wire) required

Conductor development strategy

Intermediate goals (4 years program)

		Nb_3Sn	
Wire diameter	mm	**~ 1**	
Non-Cu Jc (16 T, 4.2 K)*	A/mm^2	**≥ 1500**	
~~**μoΔM(1 T, 4.2 K)**~~	~~mT~~	~~**≤ 150**~~	
~~**σ(μoΔM) (1 T, 4.2 K)**~~	~~%~~	~~**≤ 4.5**~~	
Deff	μm	~~**≤ 20**~~	**< 50**
RRR	-	**≥ 150**	
Unit length	km	~~**≥ 5**~~	**≥ 0.1**
Cost	Euro/kA m**	~~**~ 5**~~	

*Je ~ 600 A/mm^2

*Cu:non Cu ~ 1

** 16 T, 4.2 K

Scalability and potentials for large production

A. Ballarino, CERN

Conductor development program for FCC

- **Conductor development program** being launched by CERN :

  - **Four years** activity (2016-2019);
  - Focus is on **demonstration of current capability at 16 T** (Jc);
  - Production of wire in **industry world-wide**
  - Contribution of **external institutes** for material characterization and study
  - Production at CERN of **Rutherford cables** and possibly assembly and test of **short model coils**

Collaborations launched on Nb_3Sn development for FCC

- **CERN/KEK** – **Japanese** contribution. Japanese **industry** (JASTEC, Furukawa, SH Copper) and laboratories (Tohoku University and NIMS). **Kick-off meeting** at KEK in February 2016
- **CERN/Bochvar High-technology Research Inst.** – **Russian** contribution. Russian **industry** (TVEL) and laboratories
- Collaboration agreement with the **Technical University of Vienna** (TUW)
- Collaboration agreement with the **Applied Superconductivity Centre** at Florida State University

Collaborations to be launched
Nb_3Sn - Development for FCC

- **CERN/KAT** – **Korean** **industrial** contribution

- **CERN/Bruker**– **European** **industrial** contribution

Technologies being analysed by industry:

- Internal Tin Distributed Barrier
- Internal Tin Single Barrier
- Powder In Tube

CERN /KEK Collaboration Agreement

Task 1: Definition of the **manufacturing route(s) and technologies**

Task 2: Definition of the **billet(s) and wire(s) layout and composition**

Task 3: Fabrication of **R&D billets**

Task 4: **Characterization** of wire produced from R&D billets

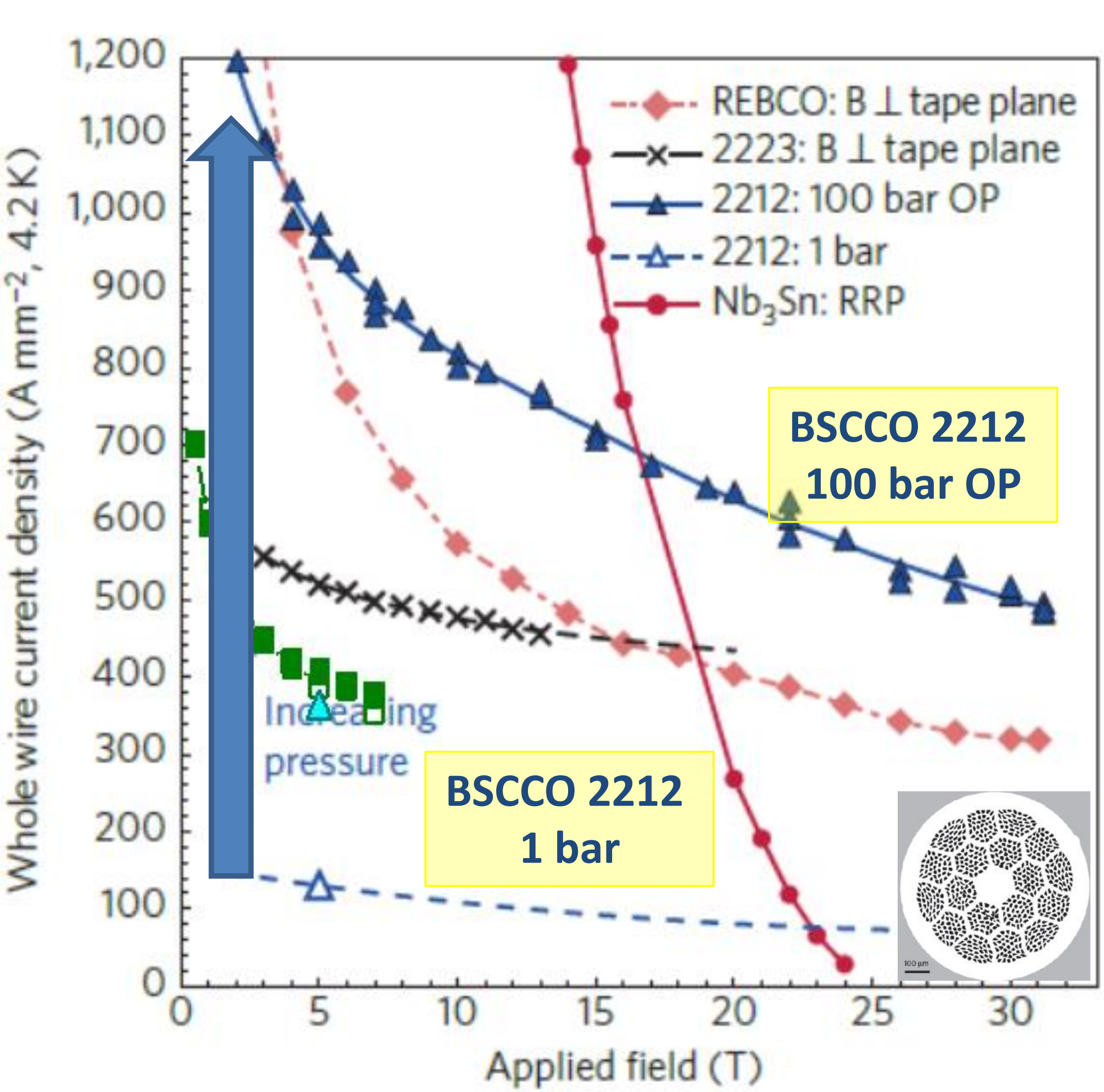
Afternoon talk by T. Ogitsu

Task 5: **Fabrication of HFM wire (~ 20 km**) that will be **cabled at CERN** and used at CERN for construction of prototype **short-model coils**

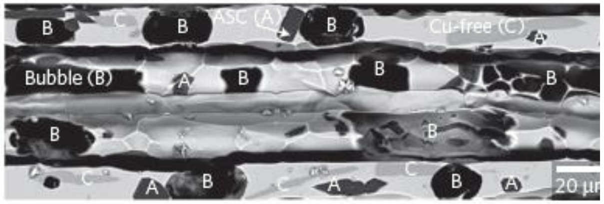
HTS for FCC ?

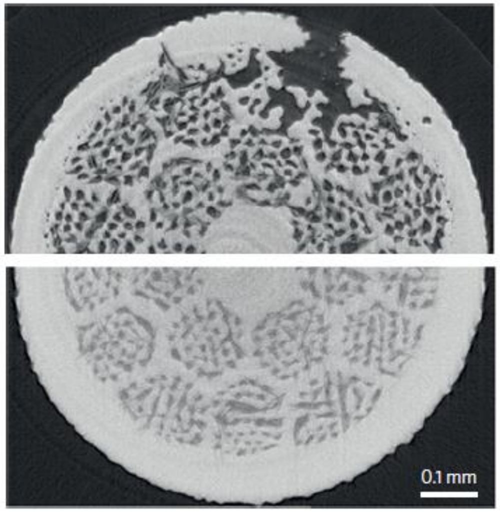
LHC	FCC-hh	FCC-hh
27 km, 8.33 T	100 km, 16 T	80 km, 20 T
14 TeV (c.o.m.)	100 TeV (c.o.m.)	100 TeV (c.o.m.)
1200 tons Nb-Ti	6000 tons Nb_3Sn	9000 tons LTS
200 kg HTS	3000 tons Nb-Ti	2000 tons HTS

BSCCO 2212



D. Larbalestier et al., Nat. Mat. ***13****, 375–381 (2014)*



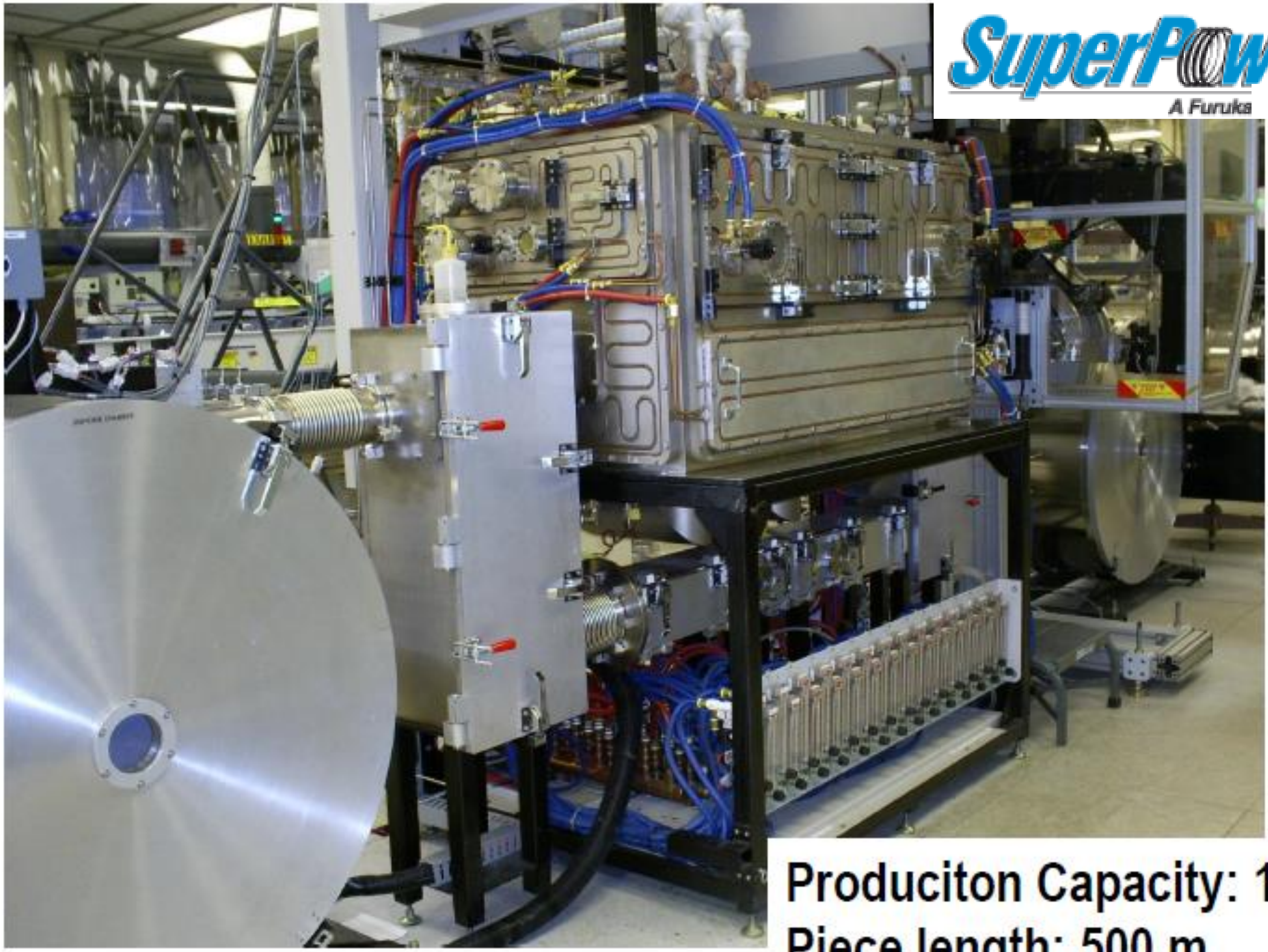


Isotropic material

D. Dietderich et al., LBNL

REBCO – Industrial Production

	REBCO layer					Template		
	PLD	MOD	MOCVD	RCE	CSD	IBAD ABAD	RABiTS™	ISD
SuperPower Inc. A Furukawa Company			+			+		
BRUKER	+					+		
SuNAM				+		+		
SuperOx	+					+		
American Superconductor		+					+	
"Tsunagu" Technology Fujikura	+					+		
THEVA				+				+
STI Superconductor Technologies Inc.				+		+		
OXOLUTIA					+	+		
MetOx			+				+	
deutsche nanoschicht					+		+	



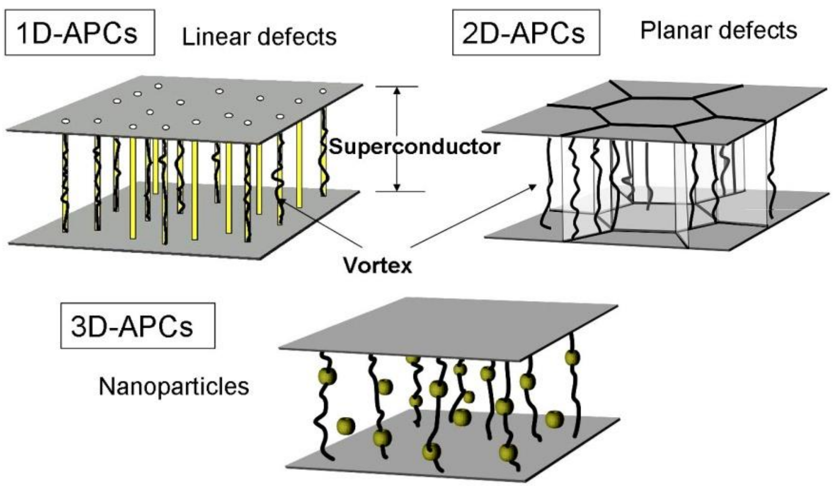
Produciton Capacity: 1000 Km/yr
Piece length: 500 m

Slide courtesy of T. Puig

REBCO – Nanocomposite materials

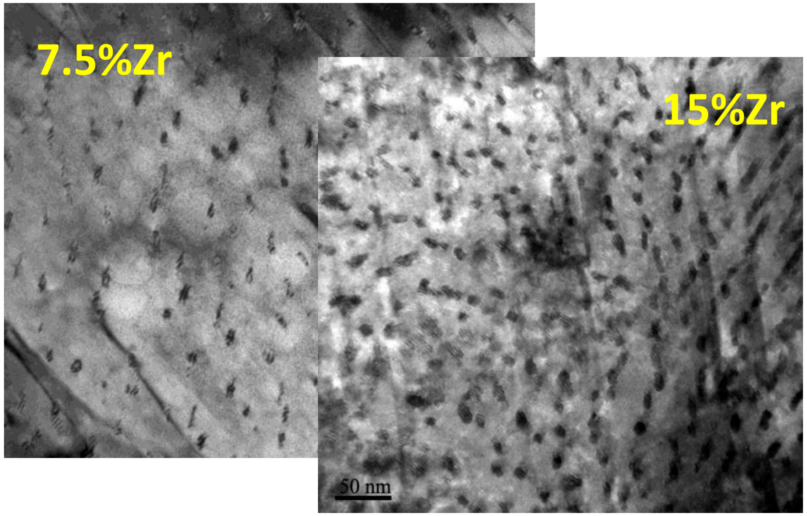
- **Nanoengineering of the defect structure** in the REBCO film

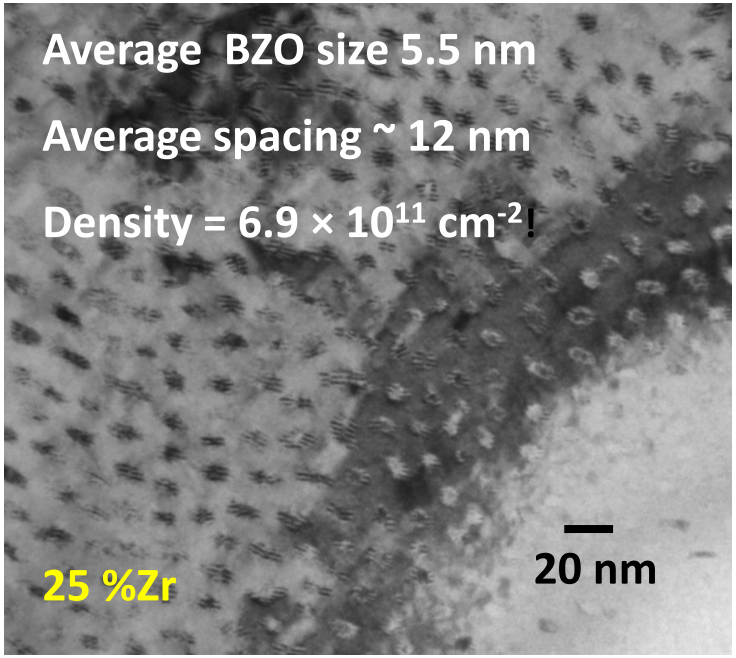
- **Optimization** of performance at the operating temperature and field:
  - **Jc(T, B)**
  - **Jc(T,B,θ)**

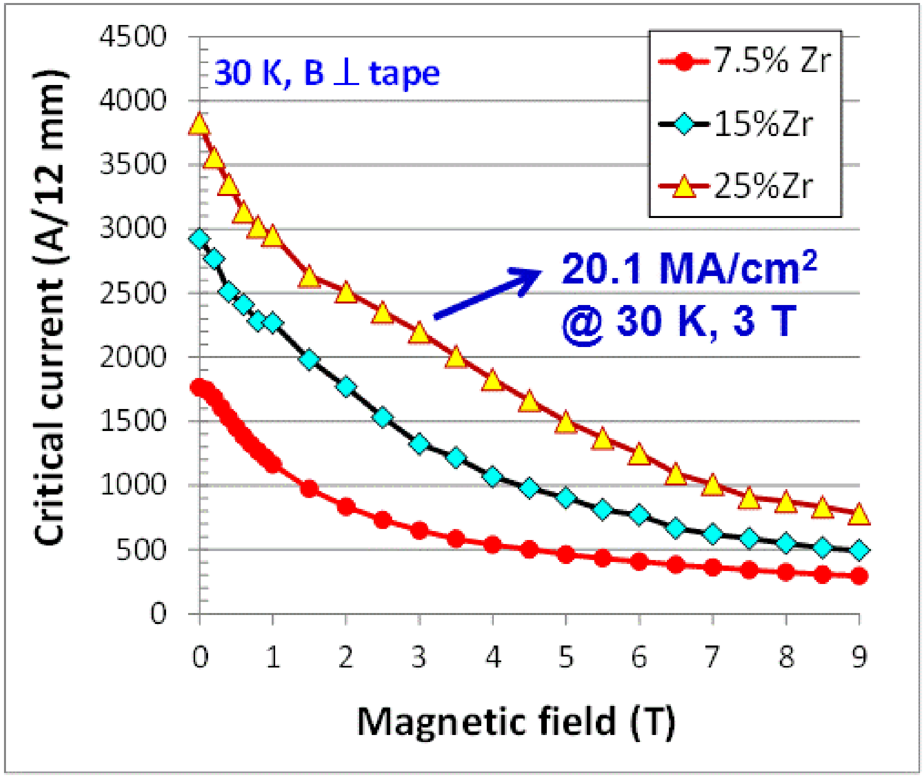


Nanoscale defects
for isotropic and strong flux pinning

UNIVERSITY of HOUSTON







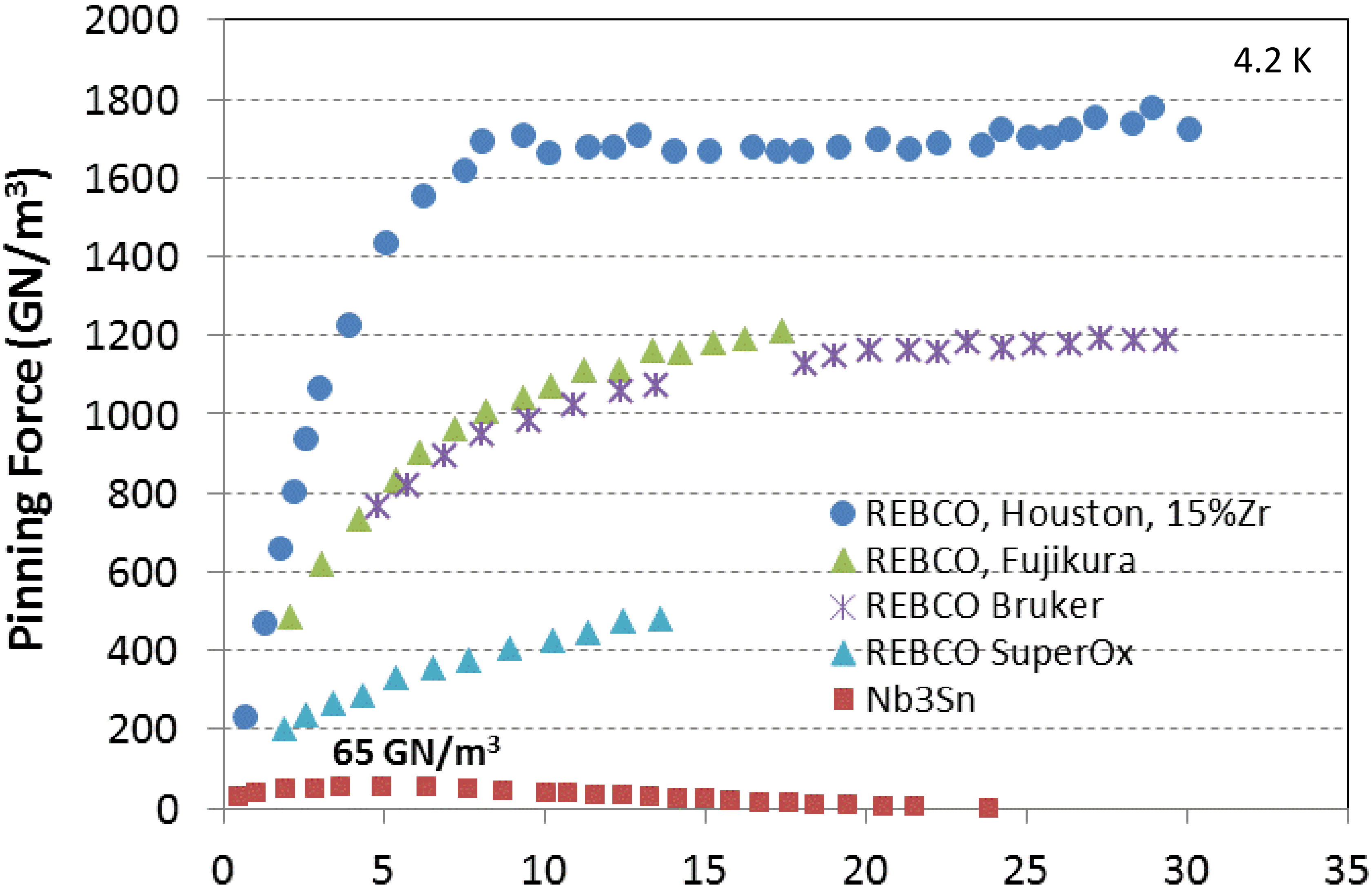
BZO size mostly 3 nm

Spacing 12 nm

Typical size of BZO in high lift factor tapes made in conventional MOCVD system: 5 – 6 nm

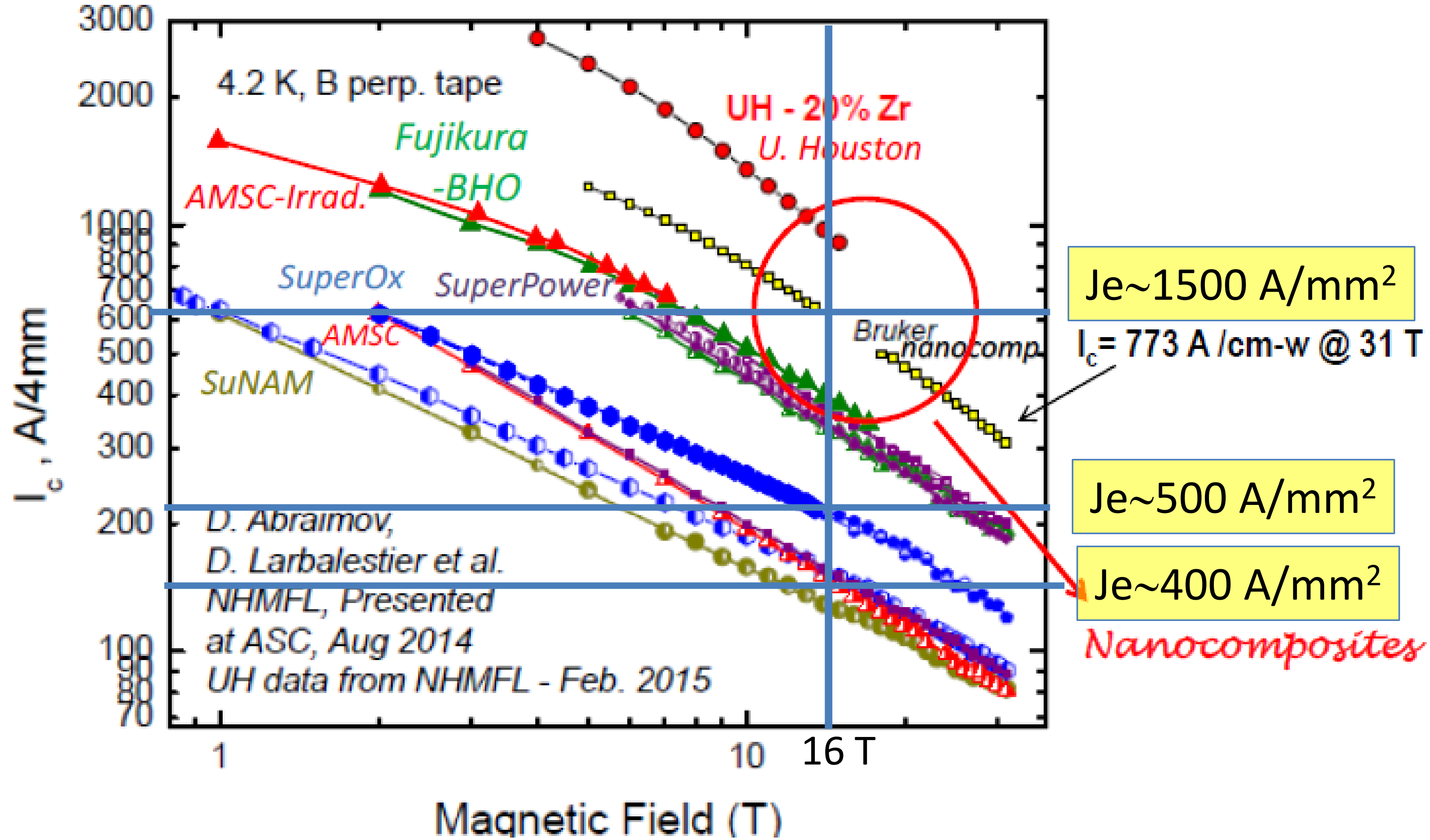
Courtesy of V. Selvamanickam

REBCO Tape for High Fields



Courtesy of T. Puig, adapted

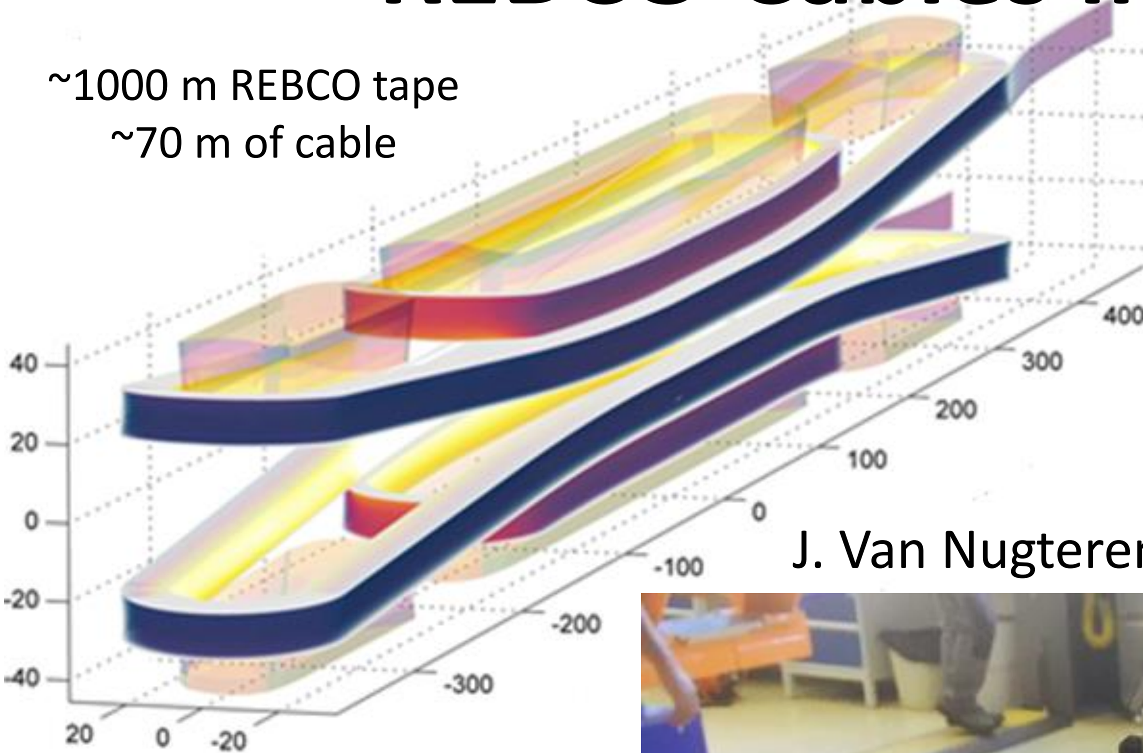
REBCO Tape for High Fields



Courtesy of V. Selvamanickam and T. Puig, adapted

REBCO Cables in Magnets

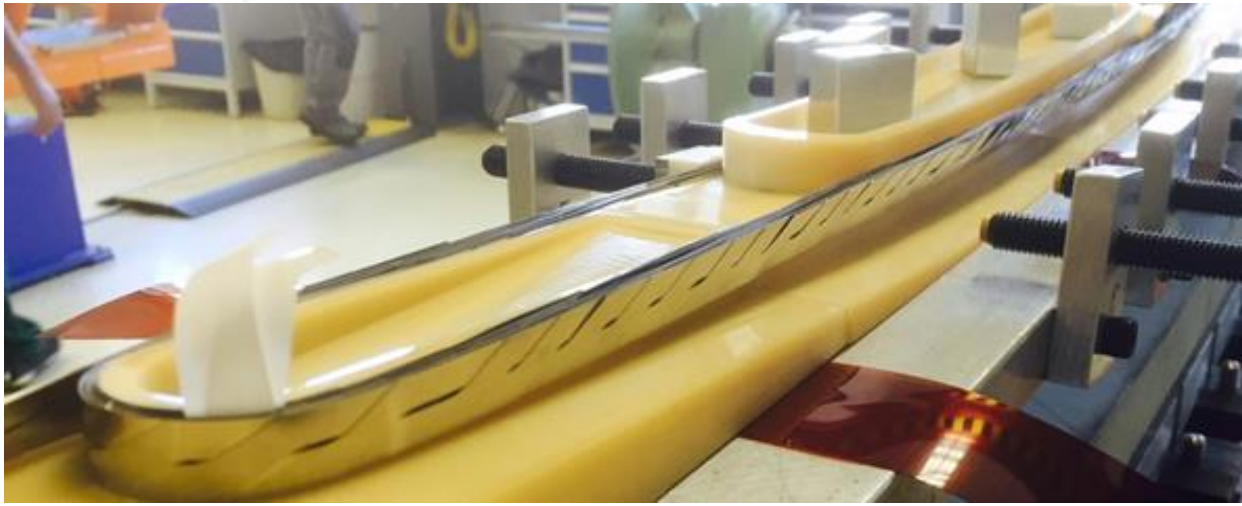
~1000 m REBCO tape
~70 m of cable



Aperture = 40 mm

5 T in a background field of 15 T

J. Van Nugteren and G. Kirby, CERN, **Eucard 2**



HTS use **in magnets** requires major **re-thinking** of existing technology and mode of operation – and prototype coils are needed

Conclusions

- **Performance** requirements for Nb_3Sn conductor are challenging
- A **large industrial effort** is needed in order to convince the community on performance and feasibility of a potential (very) large scale production
- **Synergy** between **magnet designers**, **superconductor experts**, **material scientists** and **industry** is required. This synergy is fostered via R&D Collaborations with both industrial partners and external laboratories

FCC Conductor development starts now !

Thanks for your attention !

MgB_2 for High Fields ?

- **Simple binary** composition
- **No weak links** at grain boundary
- **Low** electro-magnetic **anisotropy**
- Produced with known PIT technology as **round wire**
- Potentially **cheap**

But

- **Poor connectivity** (porosity, second phases at grain boundaries)
- Required **improvement** of **in-field performance**

MgB_2 for High Fields ?

- Doping **with C source** (nano-C, SiC, C nanotubes, B_4C,...) – to date C is the only element confirmed to be able to **enhance Bc2**. C substitutes B $\rightarrow$ increase ρ_N and pinning strength (fine grains $\rightarrow$ GB density)

- No effect of nano-particles additions

V Braccini, INFM, Italy
E W Collings, The Ohio State University, US
S X Dou, University of University of Wollongong, Australia
R Flukiger, DPMC, University of Geneve; Switzerland
W Goldaker, KIT, Germany
H Kumakura, NIMS, Japan
Y Ma, et al Chinese Academy of Sciences, China
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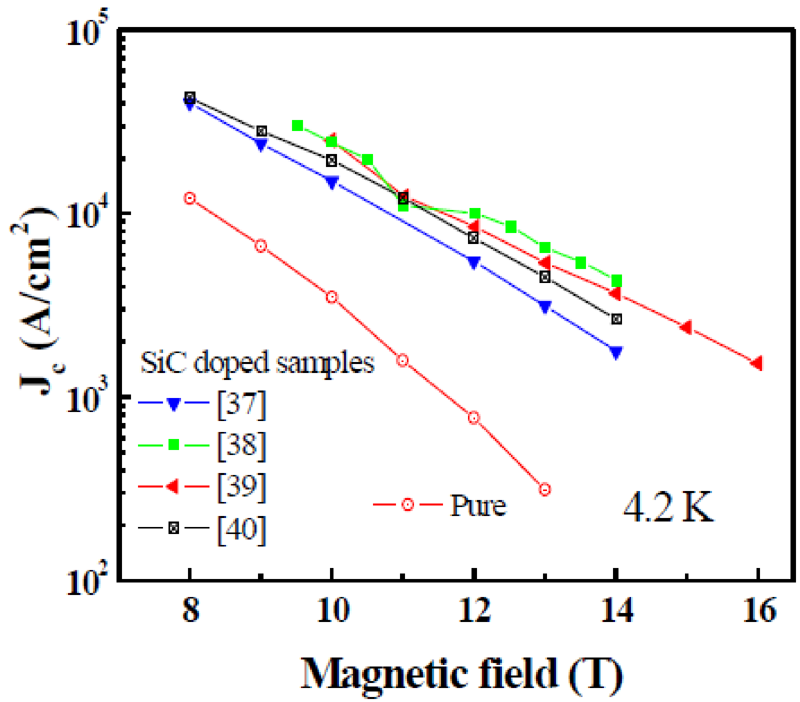


*IEEE Trans. on Appl. Superco.*1515 - 1520 (2010)

MgB_2 for High Fields?

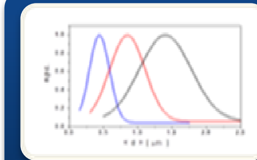
- MgB_2 roadmap for in field improvement in place
- Wire performance is expected to reach useful level at 10+Tesla in the next four years
- Activities are focusing on boron optimization, improved mechanical processing and wire architecture

Columbus Superconductors

Courtesy of G. Grasso

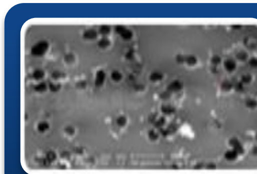
Boron

Boron of higher quality than presently used (99% and + compared to 95-98% of today) is known to allow for 50-100% performance improvement



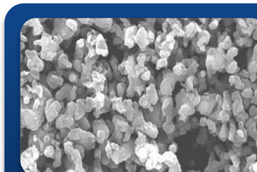
Particle size control

Control of particle size is fundamental to achieve high MgB_2 density, and increase in-field performance through grain boundary pinning



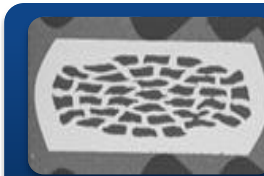
MgB_2 doping

Optimal Carbon doping concentration (3-8%) and vehicles for it will be introduced in production wire without segregation at grain boundaries



Connectivity

Higher MgB_2 density in final wire, and more clean MgB_2 powders thanks to the handling and treatment in controlled atmosphere will increase connectivity further



Superconductor filling factor

Increase in filling factor to > 40% will be allowed by optimized cold working processes

Year	-> 2014	2015	2016	2017	2018	2019
MRI	*Dedicated & low field* MRI	1,5 Tesla	1,5 Tesla & 3 Tesla *dedicated*	3 Tesla *total body*	7 Tesla *total body*	9 Tesla +
Field	*2-3 Tesla*	4-5 Tesla	6 Tesla	7 Tesla	8-9 Tesla	10 Tesla +