FCC Conductor Challenges
FCC Week 2015

A. Ballarino, CERN

Washington, 25/03/2015

A. Ballarino, B. Bordini, L. Bottura

Outline

- State of art performance of Nb_3Sn wire for LHC Hi-Lumi upgrade

- Nb_3Sn conductor for FCC
  - Targets for R&D development
  - Challenges

- Conclusions

Nb_3Sn Conductor for Hi-Lumi LHC

- Fresca 2 - 13 T @ 1.9 K, block-coils Nb_3Sn dipole (to be used in the Superconducting Cables Test Station at CERN)

- 11 T Dipoles – Accelerator magnets for Hi-Lumi LHC, Nb_3Sn 11 m long cosθ dipoles (upgrade of LHC collimation system)

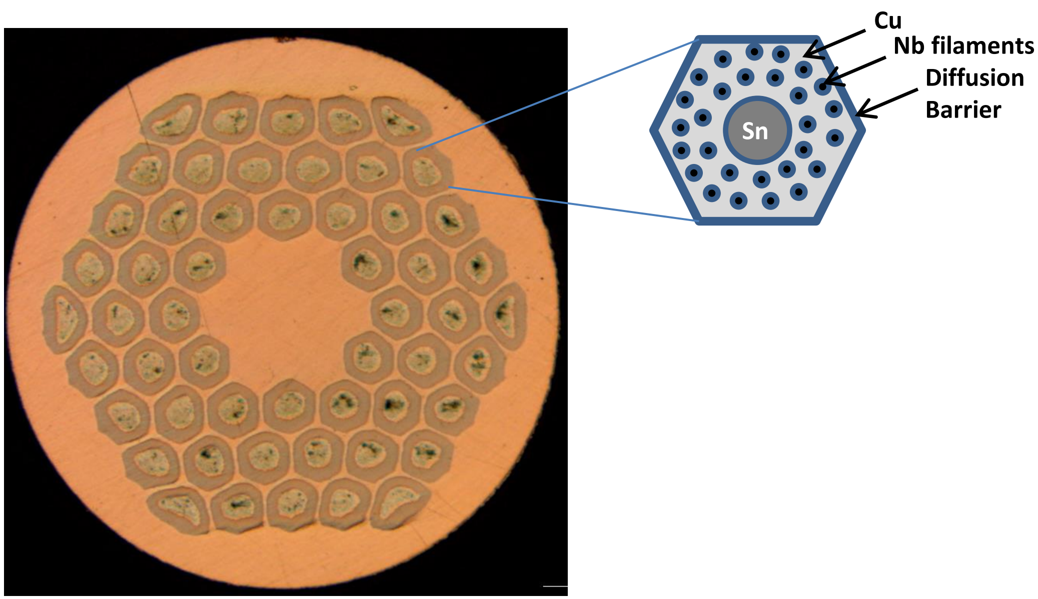
- Triplet Quadrupoles – Accelerator magnets for HL-LHC, Nb_3Sn cosθ Inner Triplet LHC quadrupoles (**CERN and USA LARP Program**)

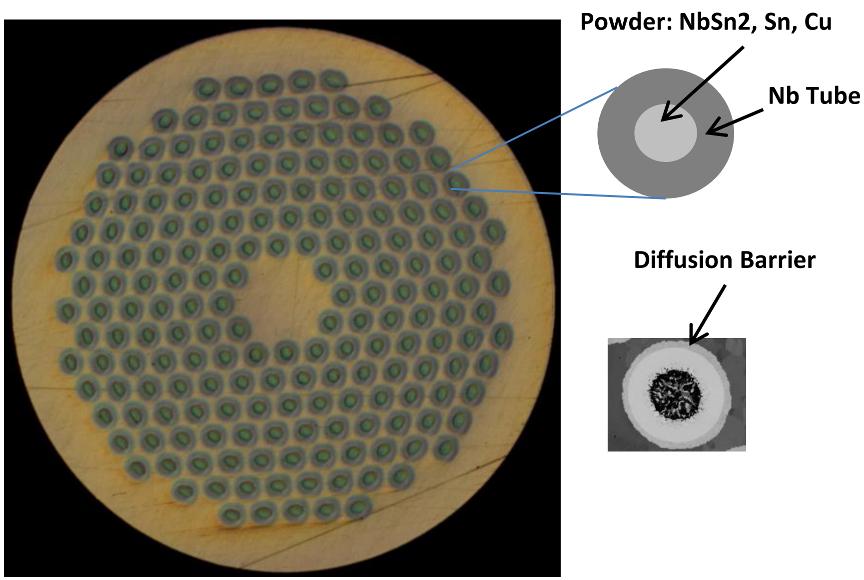
Hi-Lumi LHC magnets : integration in LHC in 2018 and in 2023.
Procurement of wire for magnet series production started

Nb_3Sn Conductor for Hi-Lumi LHC

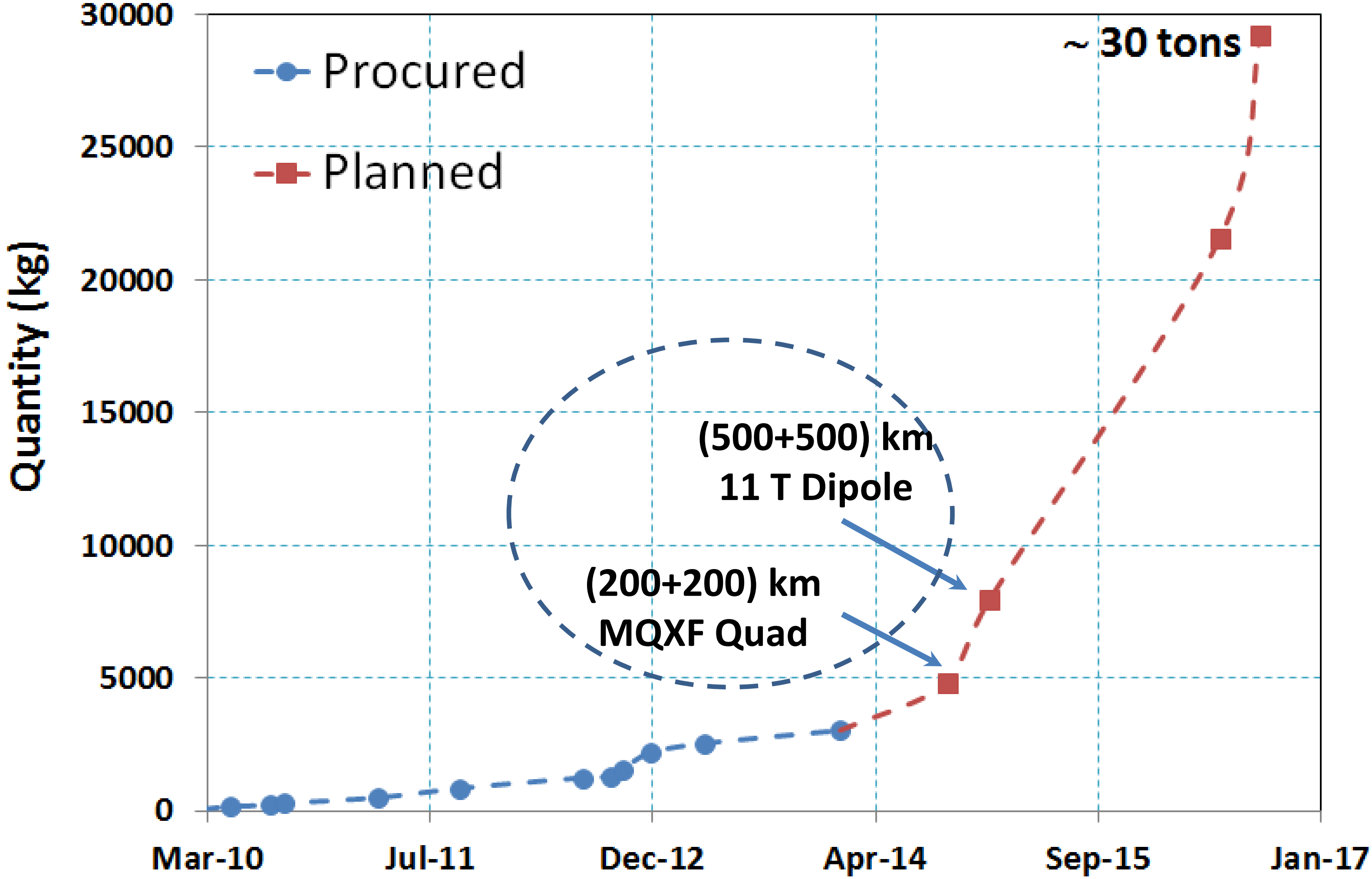
- Internal Sn (RRP®, OST)
- Powder in Tube (PIT, Bruker EAS)

Both technologies are based on solid state diffusion to transport Sn from the source to the Nb and both require a diffusion barrier





Nb_3Sn Conductor for Hi-Lumi



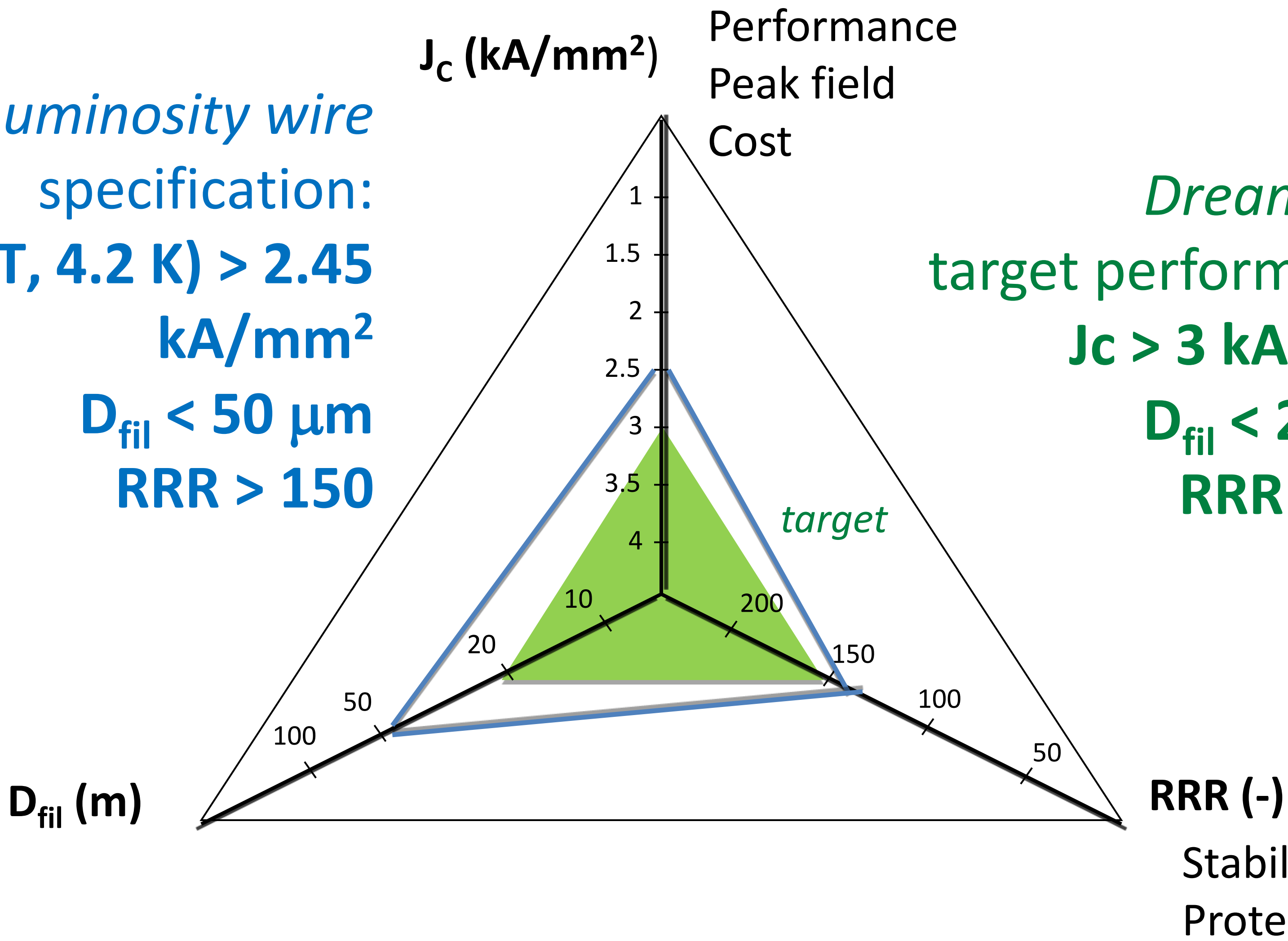
Nb_3Sn specification for Hi-Lumi LHC

Hi-Luminosity wire specification:

Jc(12T, 4.2 K) > 2.45 kA/mm²

D_{fil} < 50 μm

RRR > 150



Dream wire target performance:

Jc > 3 kA/mm²

D_{fil} < 20 μm

RRR > 150

+ Mechanical properties

Conductor procured BY CERN for Hi-Lumi LHC

	Sub-element size (μm)					
	Wire Φ (mm)	RRP® 108/127	RRP® 132/169	RRP® 192/217	PIT 114	PIT 192
FRESCA 2*	1	-	58	-	-	48
Hi-Lumi Quad	0.85	-	48	-	-	41
11 T	0.7	46	41	32	44	-

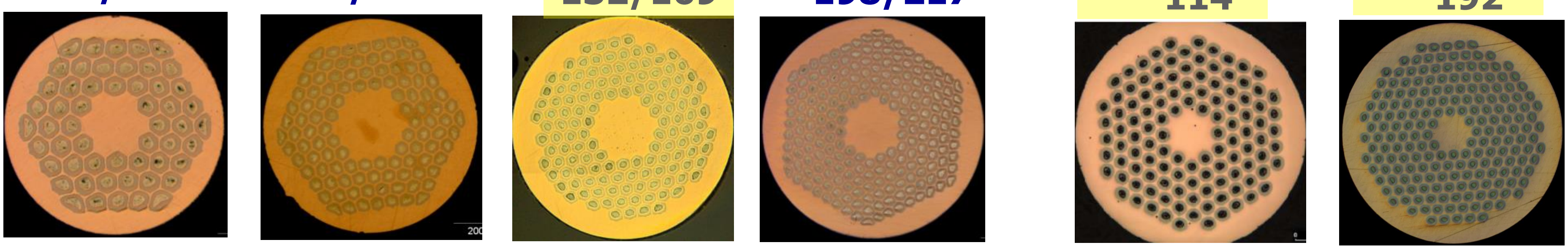
Smaller sub-element size →

RRP

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

PIT

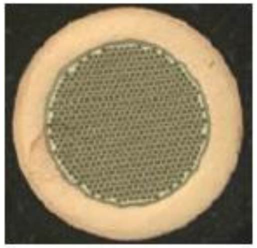
114 192

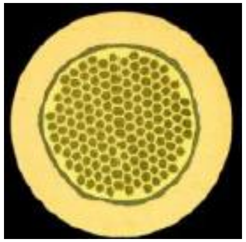


*Fresca 2 conductor: procurement by CERN and CEA – FP7 European Project

Conductor specification for Hi-Lumi LHC

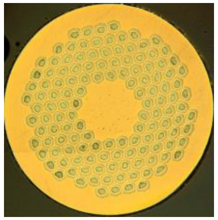
ITER strand: Non-Cu Jc ≥ 800 A/mm² (12 T, 4.2 K)



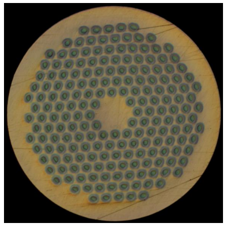


Hi-Lumi strand: Non-Cu Jc ≥ 2500 A/mm² (12 T, 4.2 K)

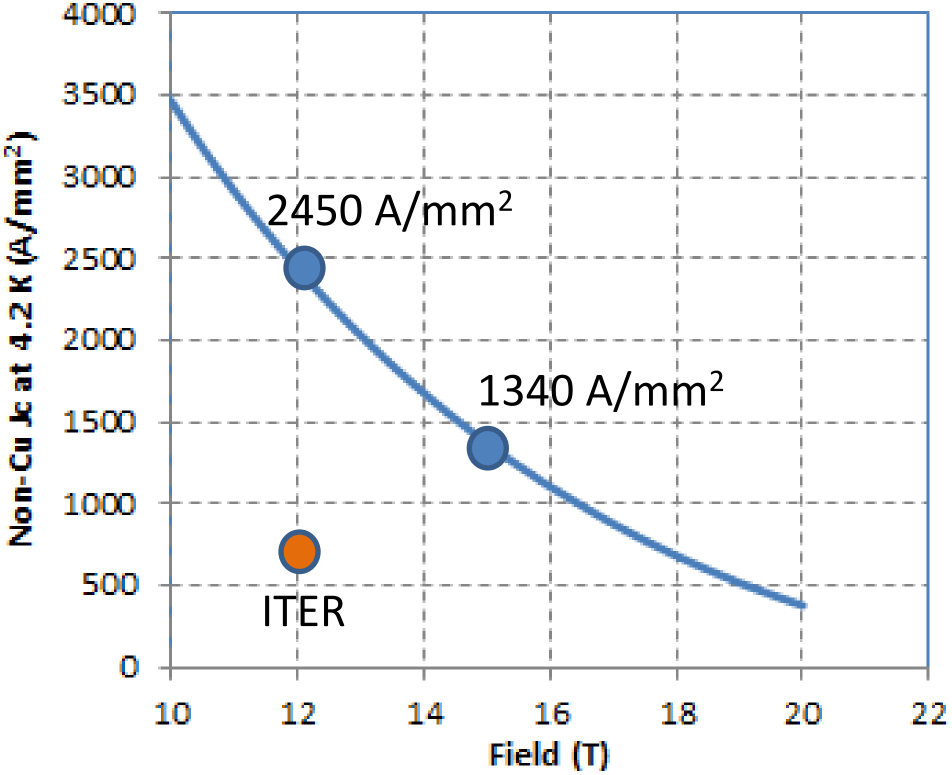
RRP 132/169



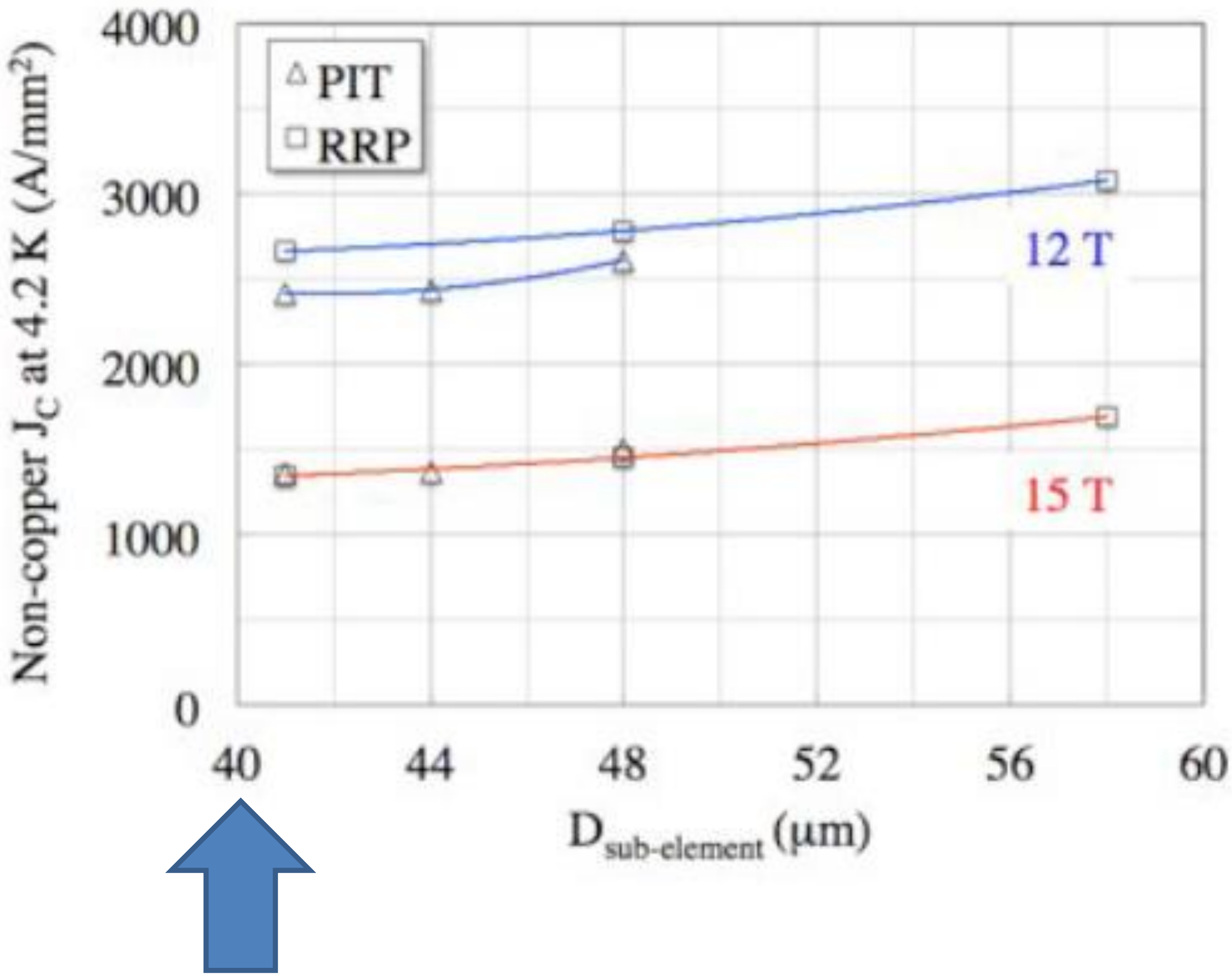
PIT 192



Critical current density versus field



Jc vs filament diameter



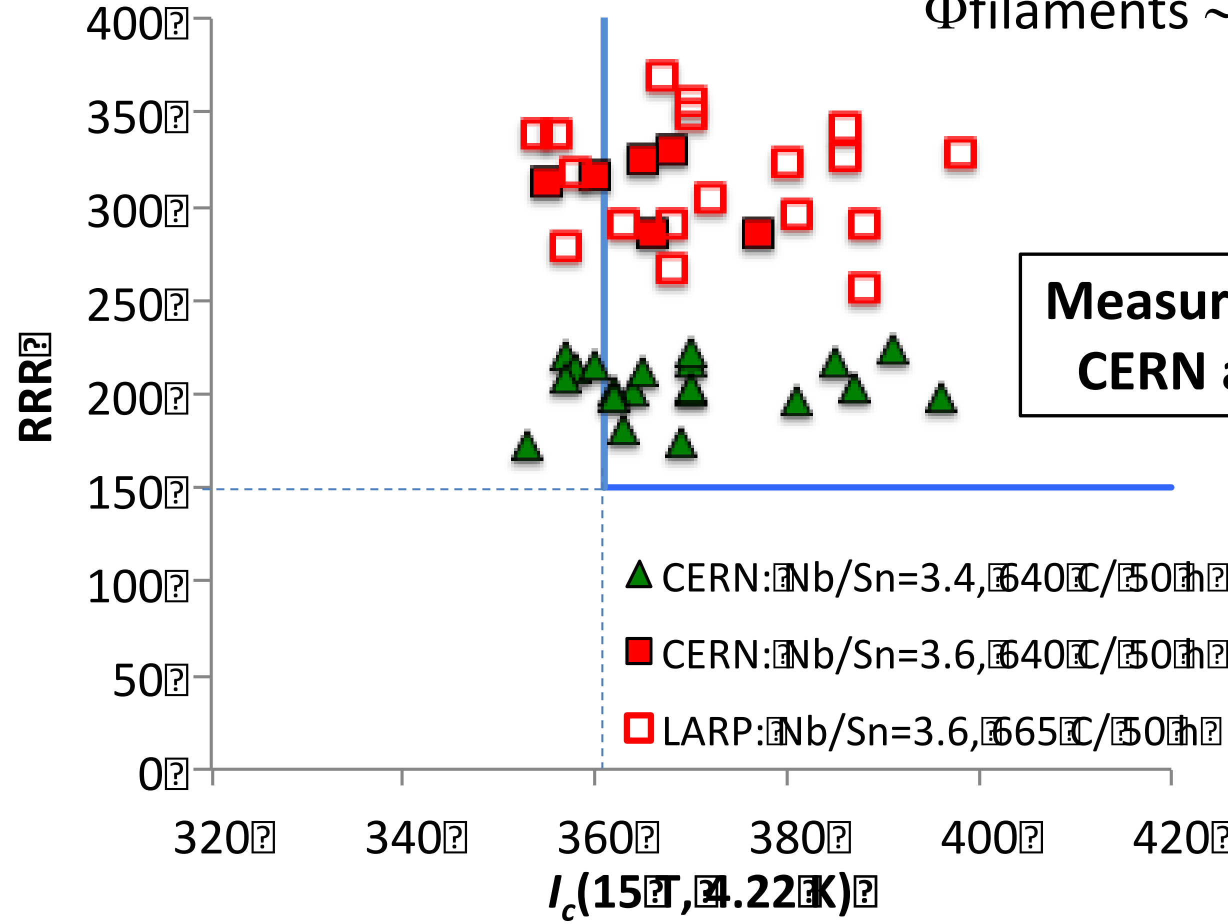
Measurements @ CERN

Inner Triplets Quadrupole wire – Jc vs RRR

Maintain performance during large production

Φwire = 0.85 mm

Φfilaments ~ 48 μm



Measurements by CERN and LARP

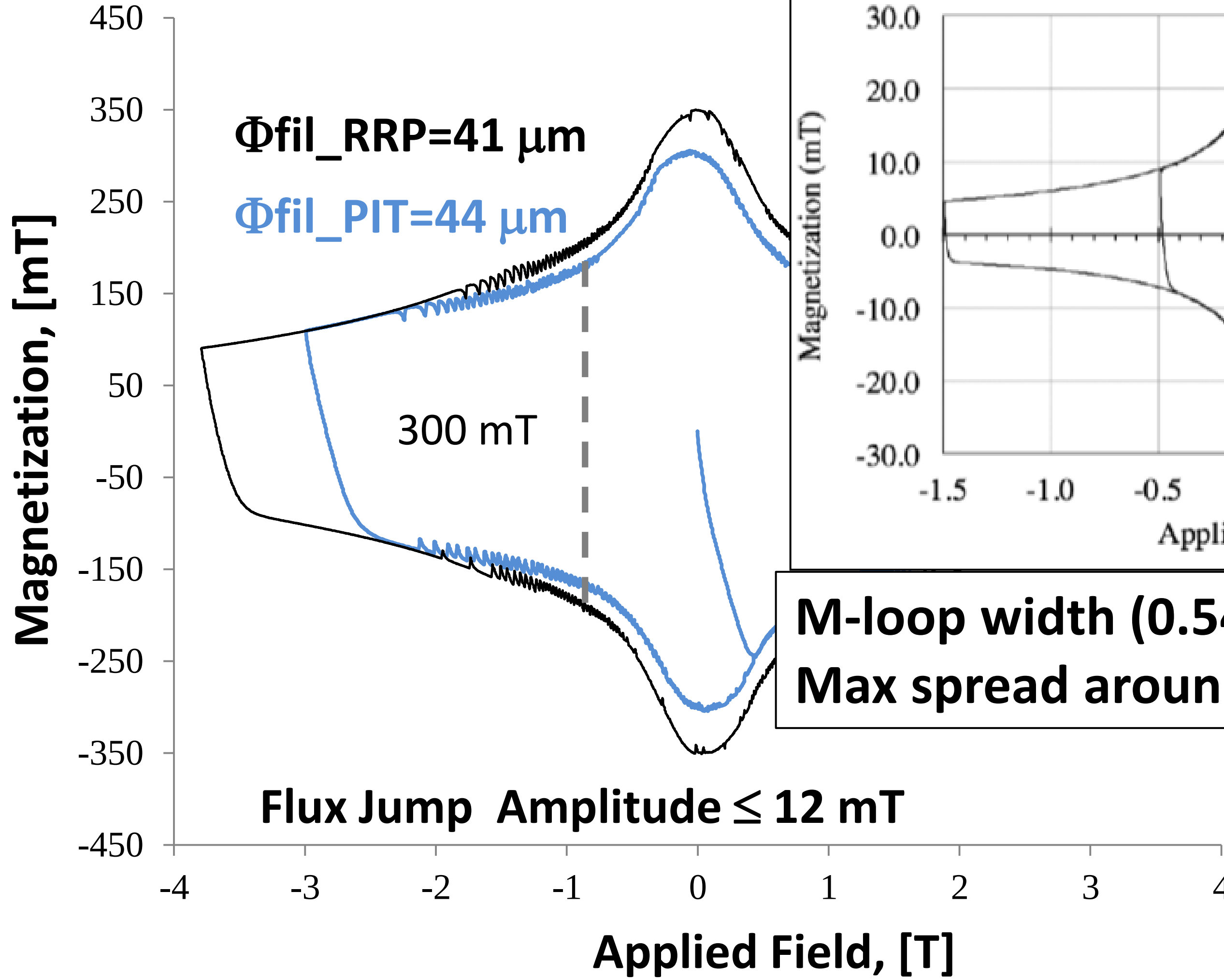
Ic(15 T,4.22 K)= 361 A → Jc(15 T, 4.2 K) = 1350 A/mm²

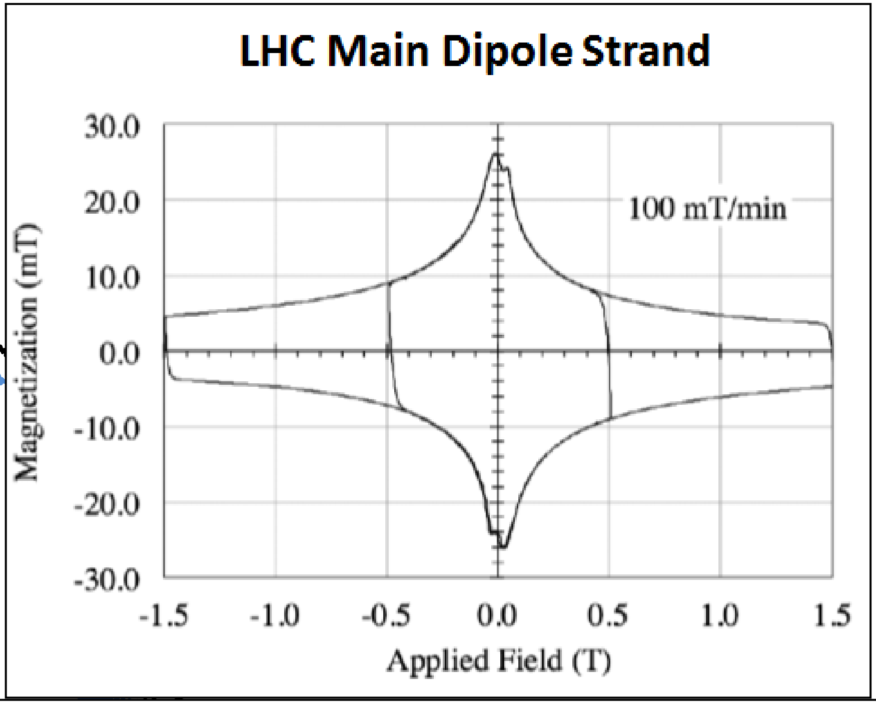
Magnetization measurements - Hi-Lumi Nb_3Sn wires

Reduce filaments size to reduce magnetization

T = 1.9 K

Φ= 0.7 mm (11 T dipole)





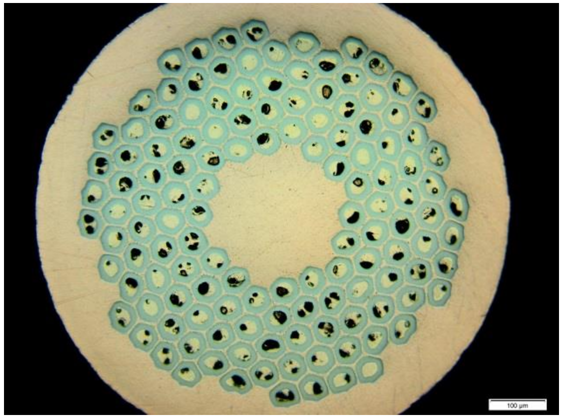
M-loop width (0.54 T, 1.9 K) < 30 mT
Max spread around average ± 4.5 %

Measurements @ CERN

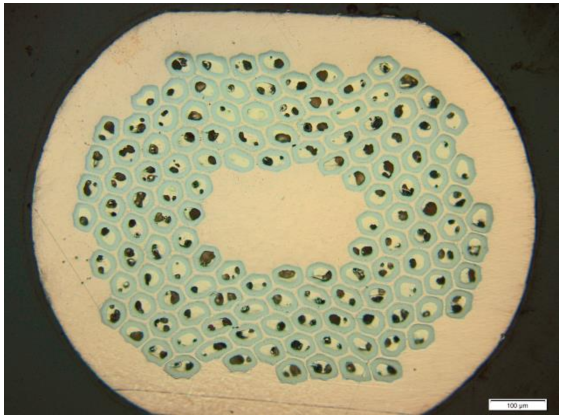
Effect of mechanical deformation

Rolled Wire

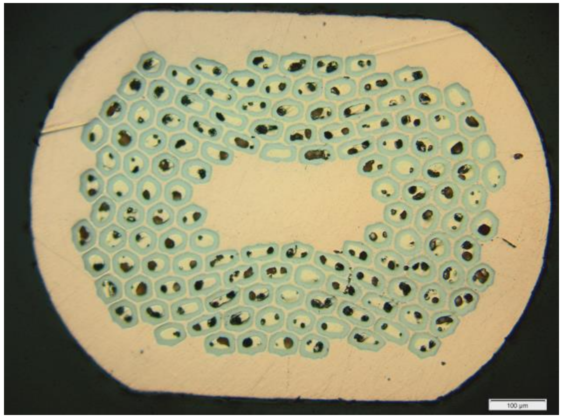
Round Wire



Rolled 15%

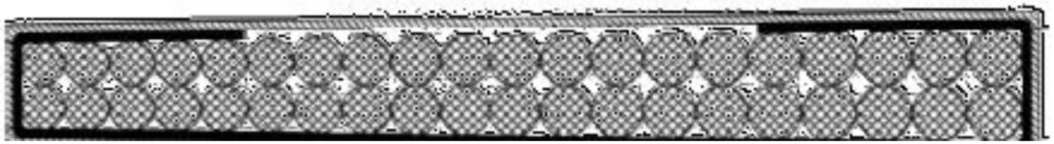


Rolled 20%

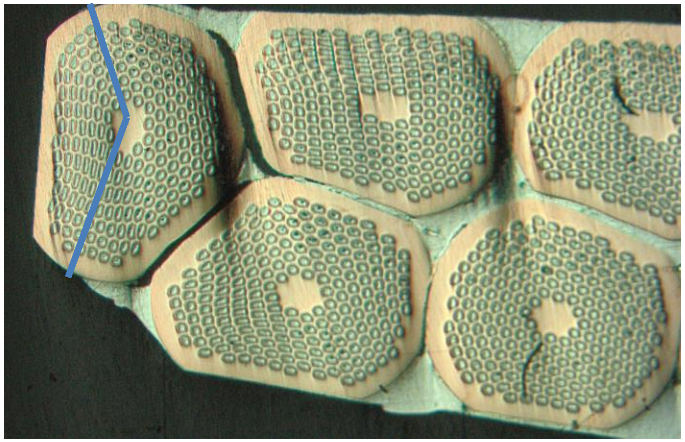


Rutherford Cable

Thin edge



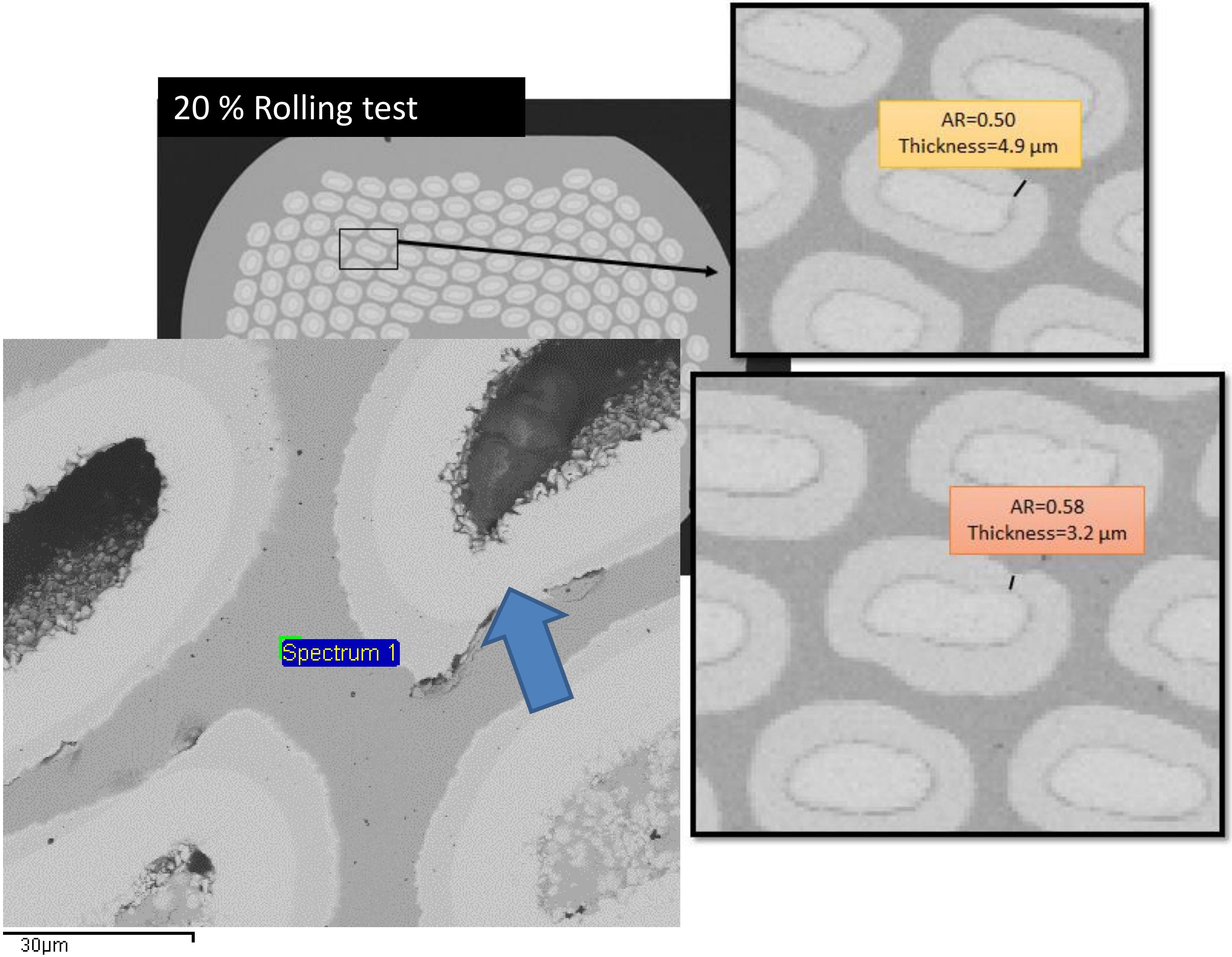
Packing factor ~ 86 %



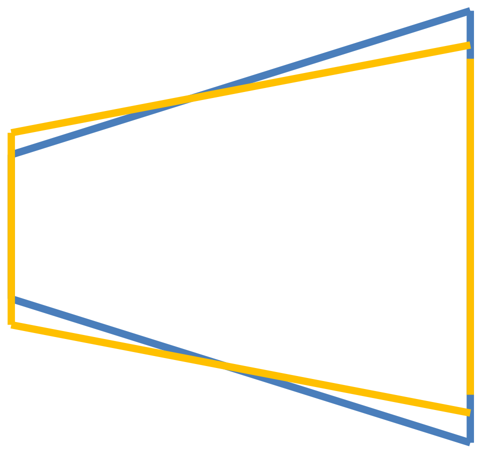
Assure mechanical properties of wires - as required for cabling

Cabling:
Ic degradation < 5 %
RRR > 100

Required homogeneous mechanical deformation



Nb_3Sn cable for Inner Triplet Quadrupoles



Width	mm	18.15	18.15
Keystone	deg	0.55	0.4
Thin Edge	mm	1.438	1.462
Thick Edge	mm	1.612	1.588
Mid Thickness	mm	1.525	1.525
ε_Thin Edge	%	15.4	14
Packing factor	%	86	86.5

Cable 1st iteration

Cable 2nd iteration

Try to cope with mechanical properties of wires

Ic cabling degradation achieved: < 3 %

Outline

- State of art performance of Nb_3Sn wire for LHC Hi-Lumi upgrade

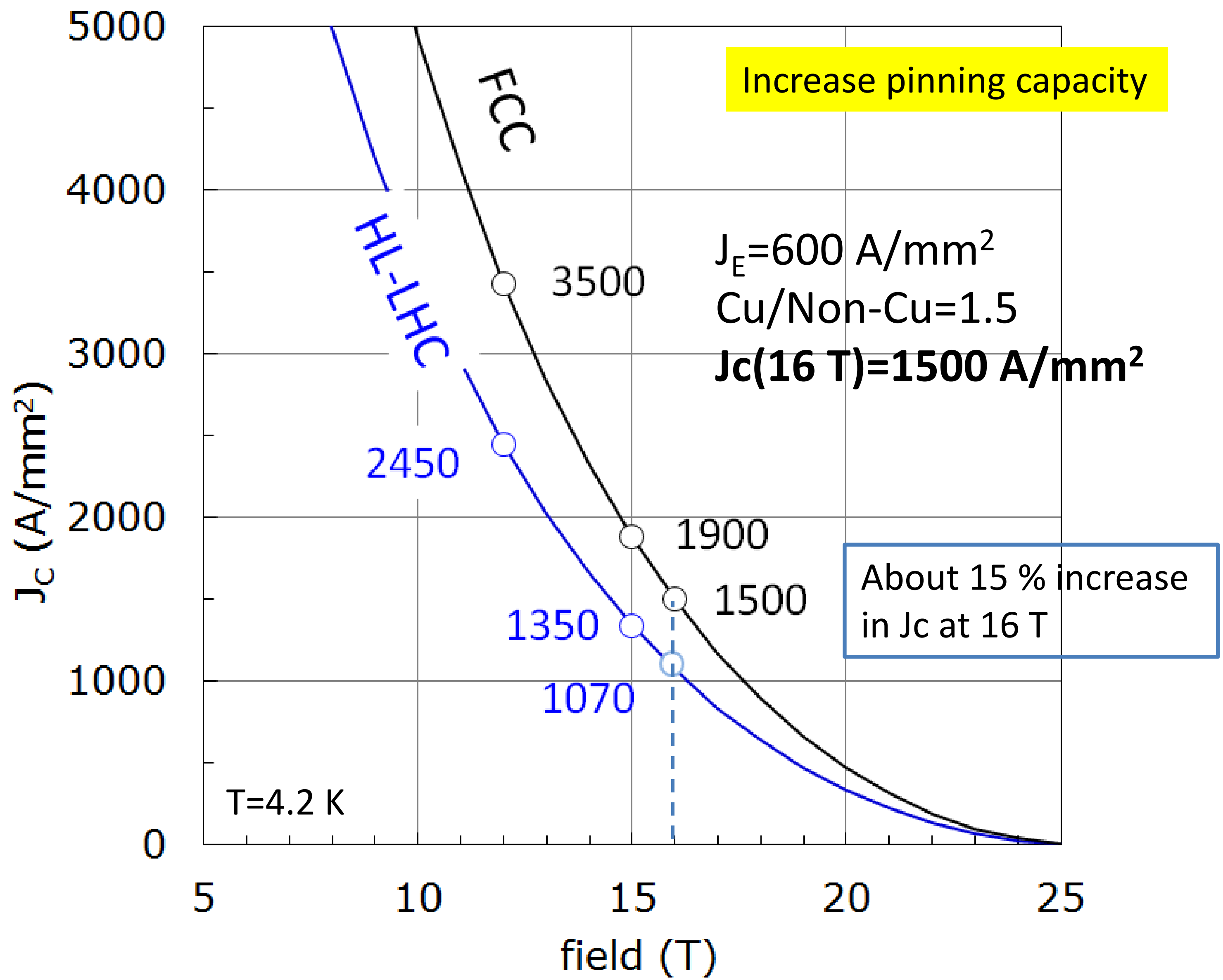
- Nb_3Sn conductor for FCC
  - Targets for R&D development
  - Challenges

- Conclusions

Targets for Nb_3Sn conductor R&D

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**
RRR	-	**≥ 150**
Unit length	km	**≥ 5**

Target for Nb_3Sn conductor R&D (Jc)

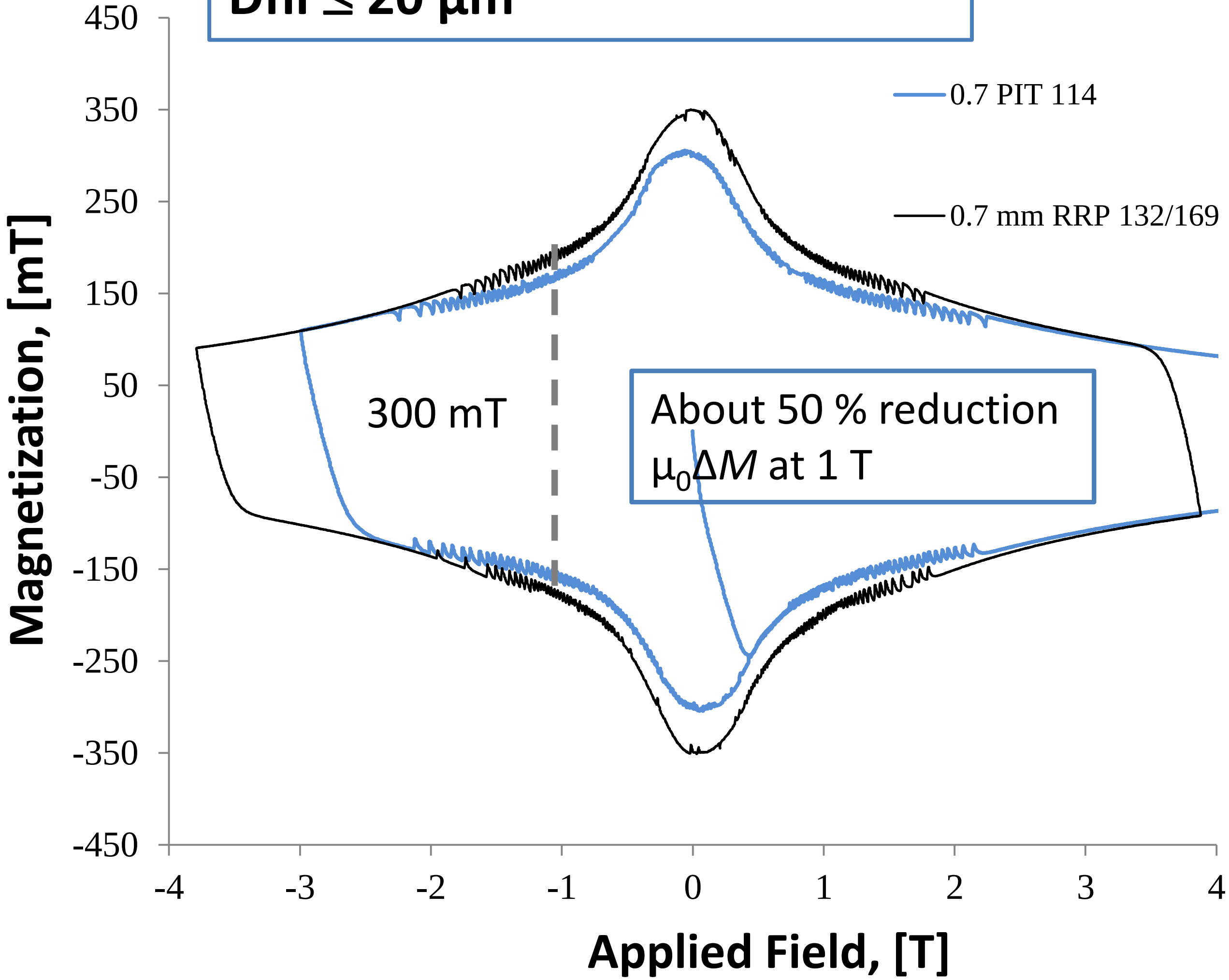


Target for Nb_3Sn conductor R&D (Dfil)

Injection field: 1 T

$\mu_0 \Delta M$ ≤ 150 mT (1 T and 4.2 K)

Dfil ≤ 20 µm

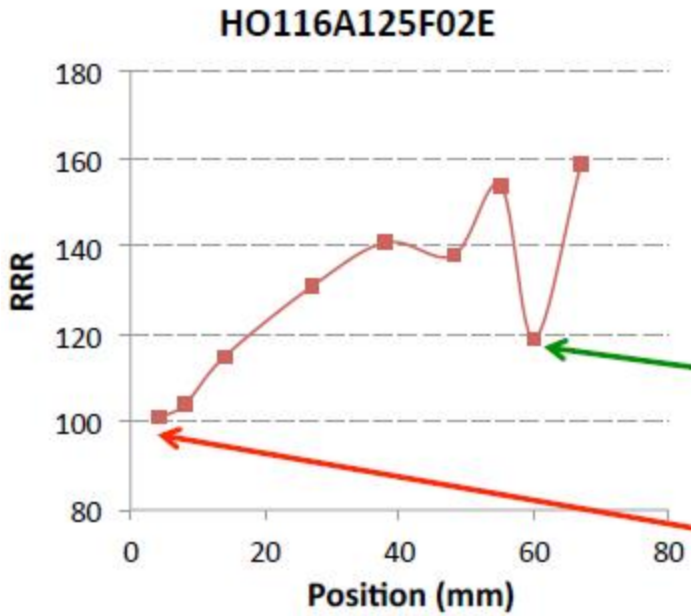


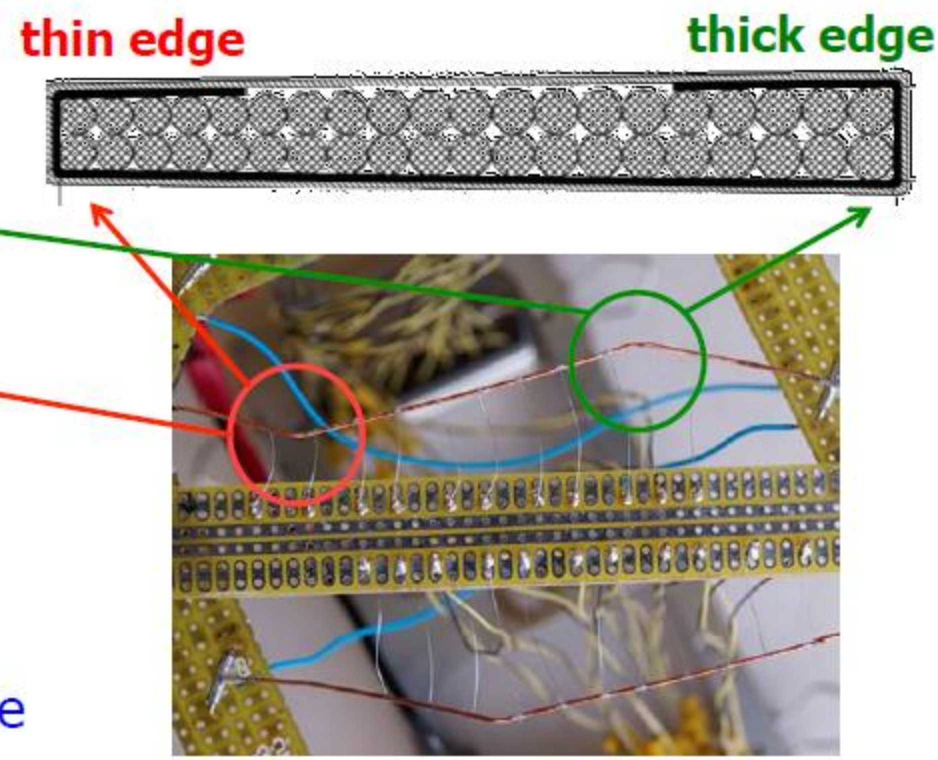
Target for Nb_3Sn conductor R&D (RRR)

- The stabilizing effect of high Cu RRR in a wire saturates at values of about 100
- During cabling, filaments are distorted and local RRR decreases – Sn diffusion in the Cu matrix
- **RRR ≥ 150 in round wire** in order to assure a local RRR ≥ 100 in strands

Target for Nb_3Sn conductor R&D (RRR)

Local RRR on extracted strands





- RRR virgin wire ≈ 160
- Max value local RRR compatible with virgin wire
- Min value local RRR ≈ 100

Target for Nb_3Sn conductor R&D (Cost)

FCC-hh, 100 km, 16 T, 100 TeV (c.o.m.) : ~ **6000 tons Nb_3Sn** (and 3000 tons Nb-Ti) – to be compared with 1265 tons of Nb-Ti in LHC

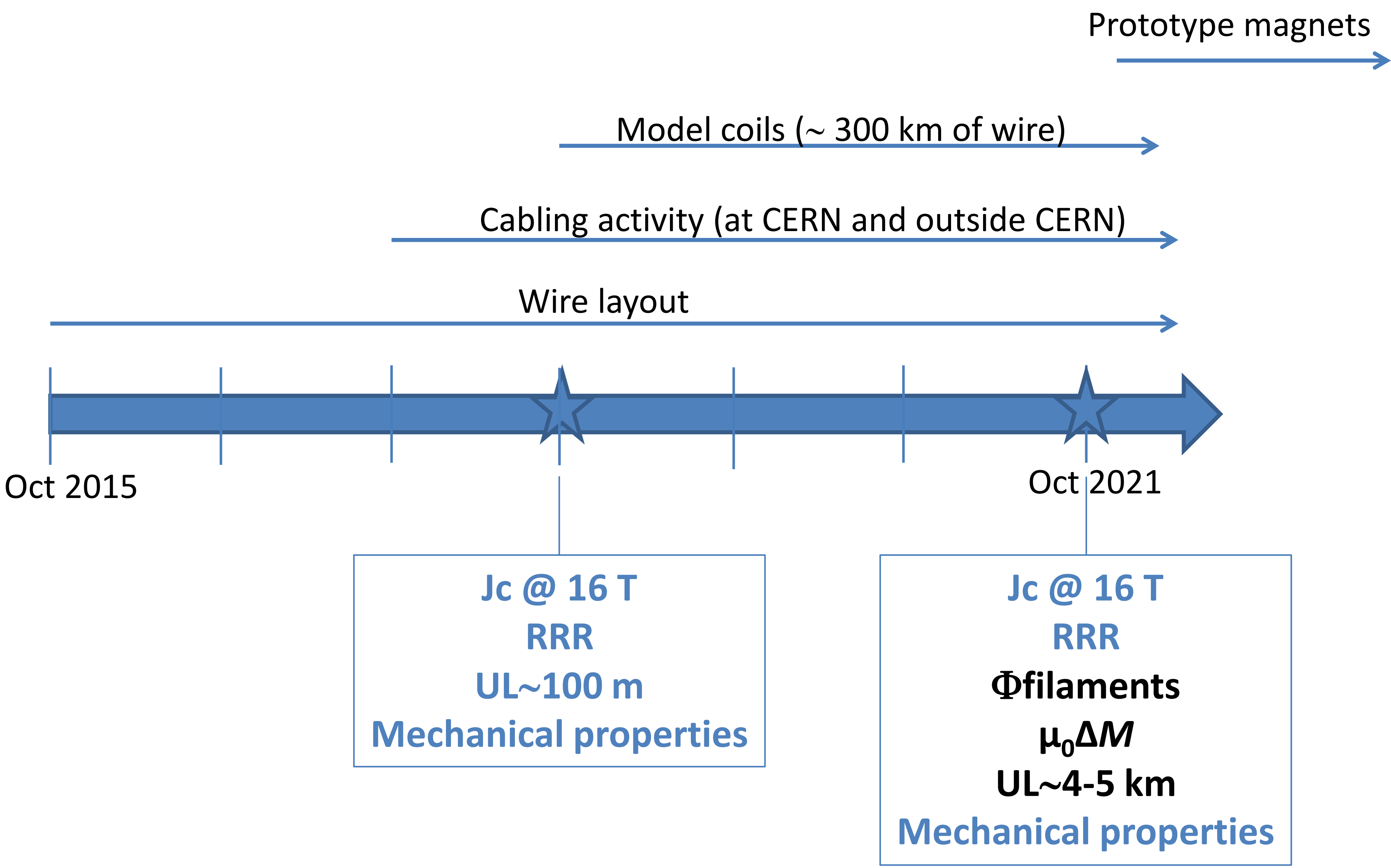
Wire architecture must be designed to ***scale*** **with high yield and commercial volumes**

Required:

Improvement of performance with respect to state of the art wire;
Scaling up of billet-size and yield for series production

Target cost: 5 Euro/kA at 4.2 K and 16 T

Timeframe for Nb_3Sn conductor R&D



Six years of R&D program

Characterization of Nb_3Sn conductor for FCC

- **Material studies** (optical, FIB, SEM, TEM, EDS,…)
- Test facilities for **Ic measurements of Nb_3Sn wires** at LHe temperature and at 16 T and above (16 T-18 T)
- Test facilities for **magnetization measurements of Nb_3Sn wires** at liquid helium temperature and at 16 T and above (16 T-18 T)
- Test facilities for Nb_3Sn **cable characterization**

Not to forget

- The Future Circular Collider will require other superconducting devices. Besides special (HTS) magnets, also:

  - **HTS Current Leads** (**BSCCO 2223** or **REBCO** based);

  - **Superconducting Links** (**MgB_2** or **HTS** based)

for feeding the magnet electrical circuits

Conclusions (1/2)

- **R&D** Program on Nb_3Sn conductor is **required** for achieving FCC performance targets. Simple extrapolation and improvement of existing strand architectures will not be sufficient – a quantum improvement in performance and an evolutionary change in technology is required

- Conductor development shall start well ahead of magnet development. Required **work with conductor manufacturers** to ensure that the developed wires meet performance/characteristics for accelerator quality magnets - and are of a sufficiently robust quality for large scale production

Conclusions (2/2)

- A very large quantity of Nb_3Sn conductor would be required, well above present production capability

- Conductor development shall start well ahead of magnet development

- Not to forget:

A magnet cannot perform better than the conductor it is made of

Thanks for your attention