CERN-HFM conductors rationale

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With thanks to L. Oberli, Th. Boutboul, B. Bordini
and "the crowd" in the Superconductors Laboratory

Meeting on 11T dipole conductor
CERN/FNAL
October 4th, 2011

By courtesy of Th. Boutboul

NED targets

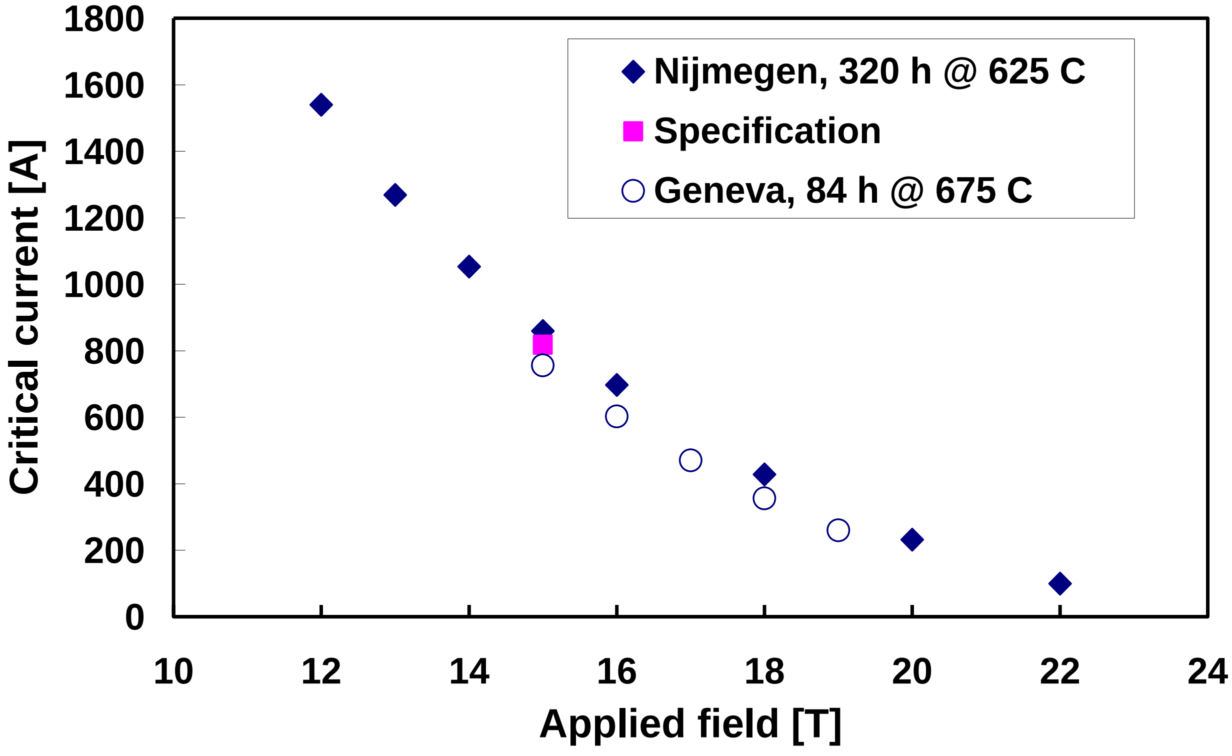
- The main goal of NED was to launch the R&D necessary to design and build a Nb_3Sn based 15 T magnet
- On basis of preliminary magnetic design and protection considerations, NED specifications for the strand were chosen:
  - **Diameter** **1.250 mm**
  - **Eff. filament diameter** **< 50 µm**
  - Cu-to-non-Cu ratio 1.25 ± 0.10
  - Filament twist pitch 30 mm
  - **non-Cu** J_C **1500 A/mm² @4.2 K & 15 T**
  - **minimum critical current** **818 A at 15 T**
  - RRR (after heat treatment) > 200

Very challenging specifications!

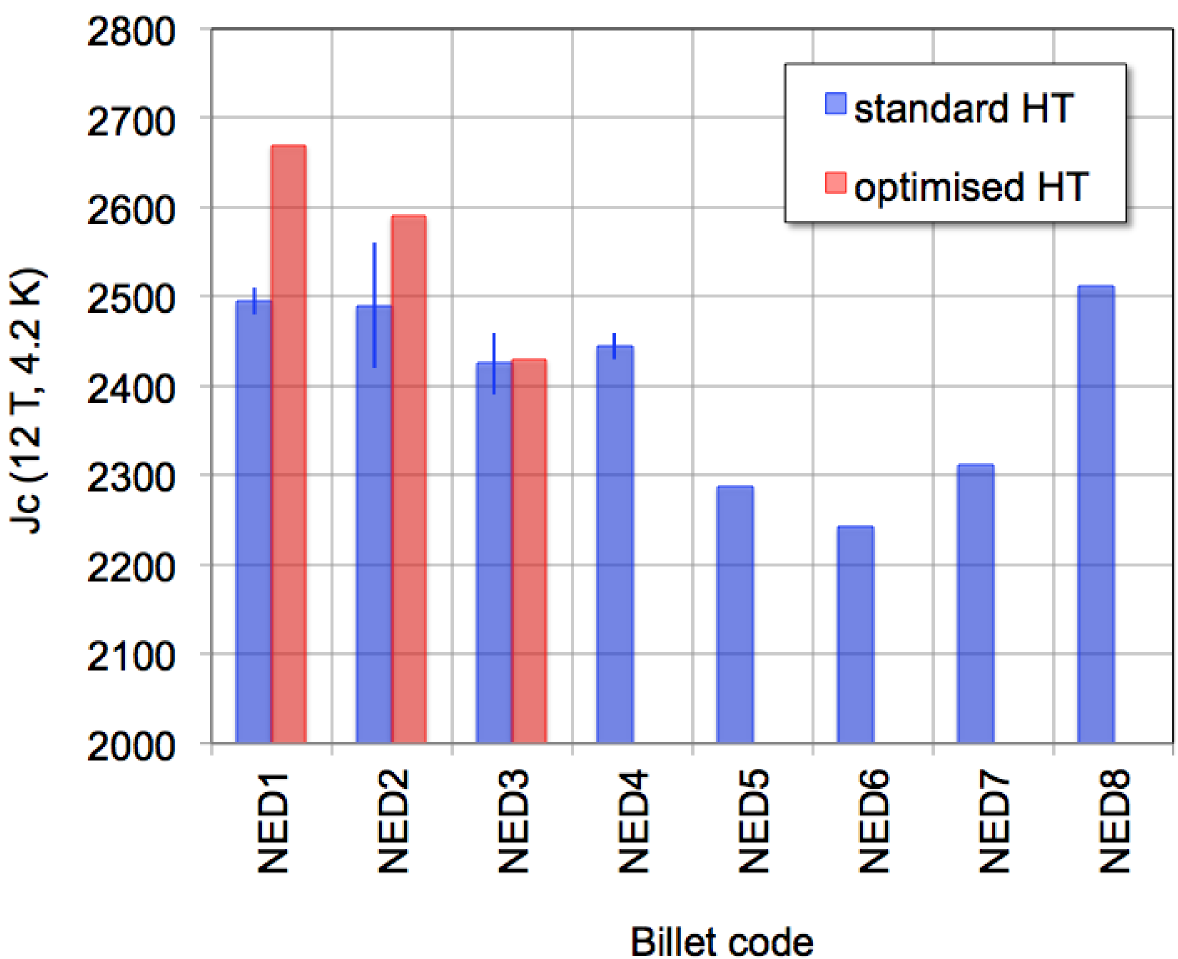
By courtesy of Th. Boutboul

NED promises

- PIT strand: I_c ~ *1400 A*, J_c ~ *2500 A/mm²* (12 T) for 675 °C/84 h
- Optimization launched at CERN. Results: 320 h @ 625 °C
  - 12 T and 4.2 K: ***I_c > 1500 A***, ***J_c > 2700 A/mm²***, **+ 10 %!!**
  - 15 T and 4.2 K: ***I_c > 818 A*** (NED spec.), ***J_c ~ 1500 A/mm²***



NED program results – 1/3



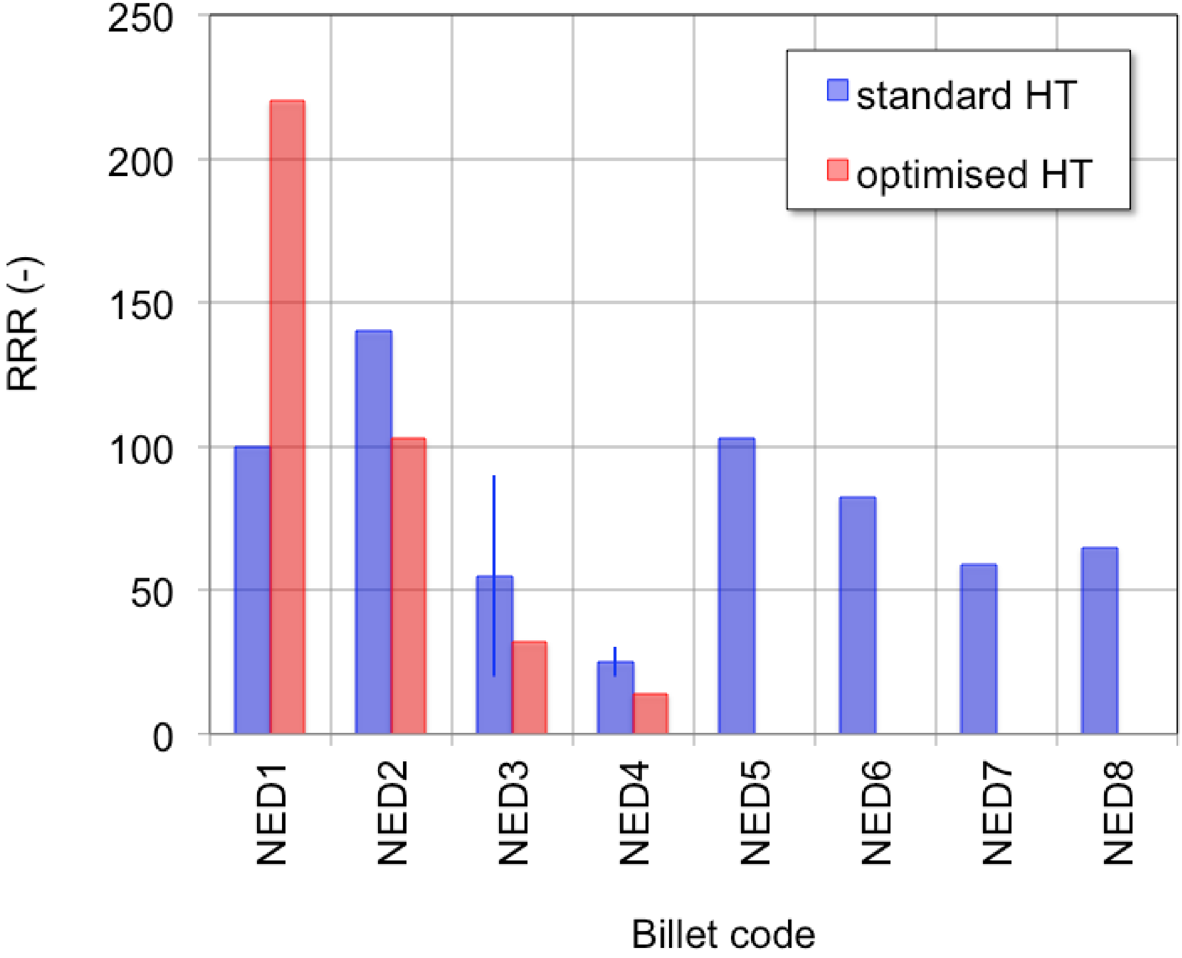
Jc of PIT wire produced within the scope of the NED R&D

Best performance was achieved optimizing the heat treatment for low plateau temperature (625 °C) and long times (320 hrs)

The production has gone through a technology transfer process clearly visible in the measured performance

Clear improvement with present stable manufacturing conditions

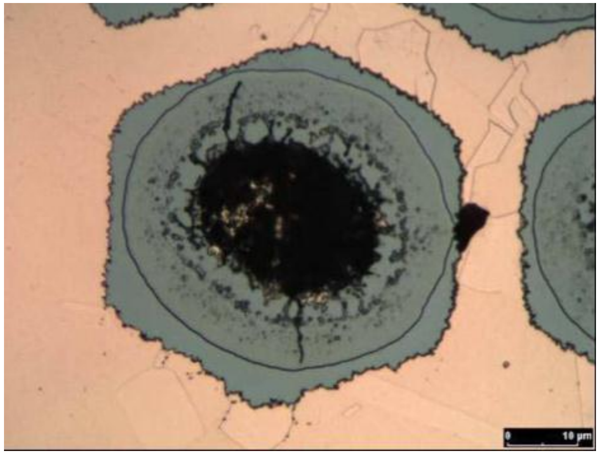
NED program results – 2/3



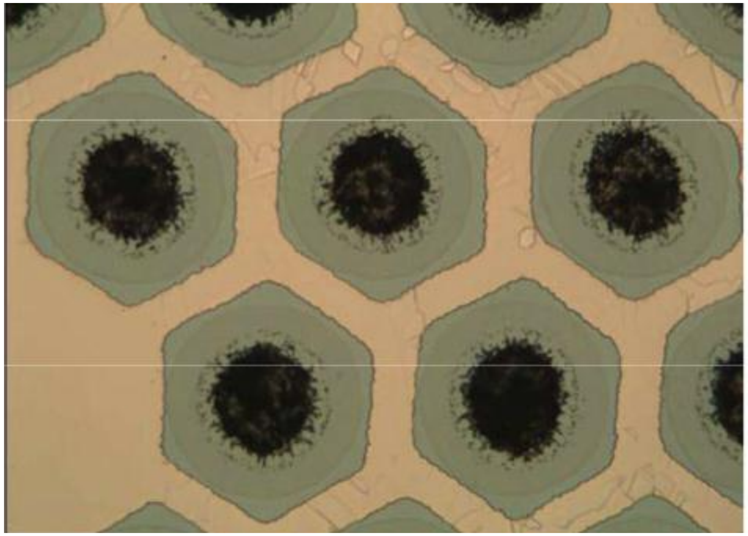
Excellent RRR values at the beginning of the R&D, much degraded at later times

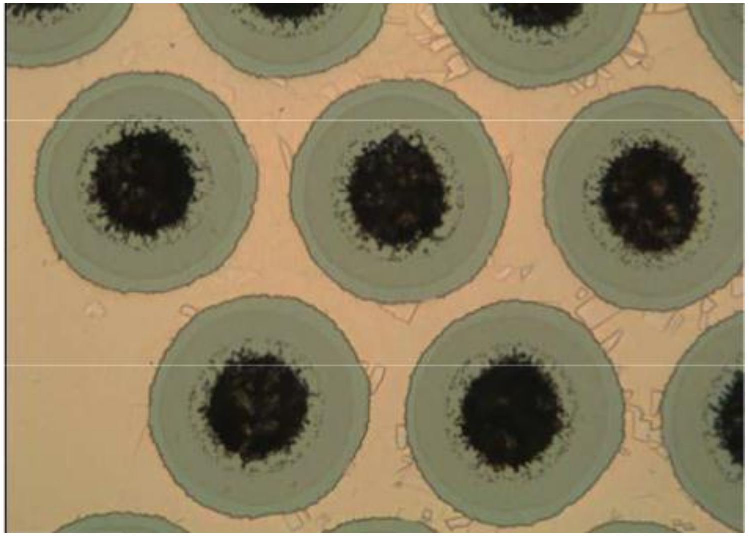
Optimization of Jc leads to a marked decrease of RRR

This has been traced to the presence of *hot-spots* in the strand



NED program results – 3/3



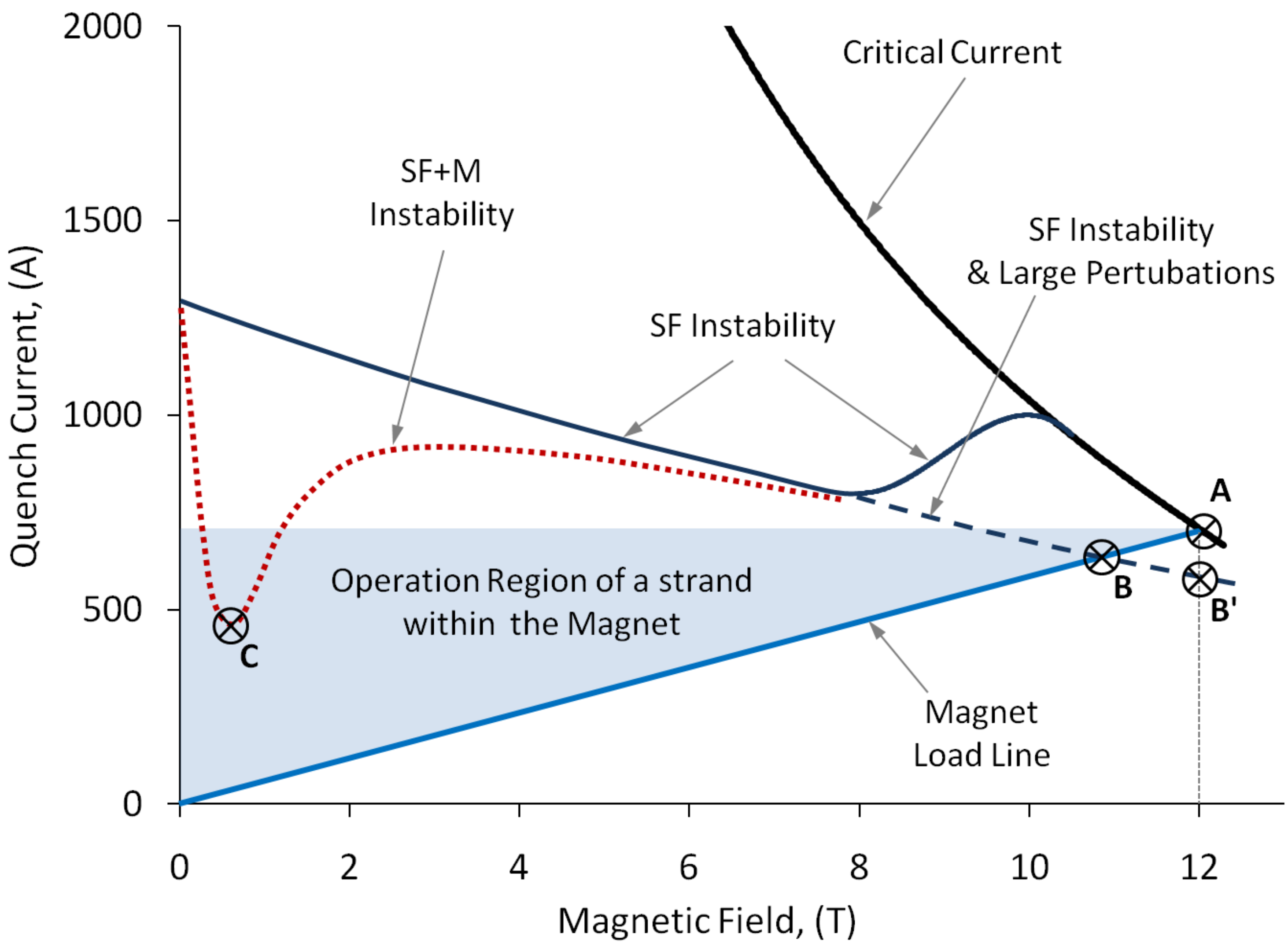


Modified strand architecture to improve the use of the *real estate*, and increase the optimization margin for J_C at acceptable RRR

For any given strand architecture based on react-able barriers there is an intrinsic limit in the maximum RRR achievable

By courtesy of B. Bordini

Magneto-thermal stability

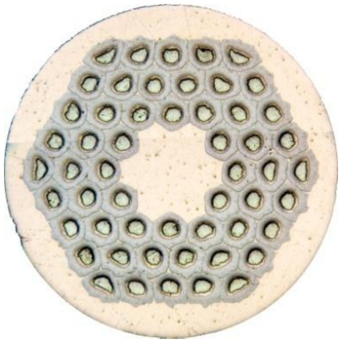


Magneto-thermal stability cook-book

- **Reduce the critical current** of the strand to the minimum required for magnet performance (range of 2500 A/mm^2, not much above)
- **Reduce the strand diameter** (1 mm and smaller) and the diameter of the multi-filamentary region
- Achieve a **local RRR of the order of 100**

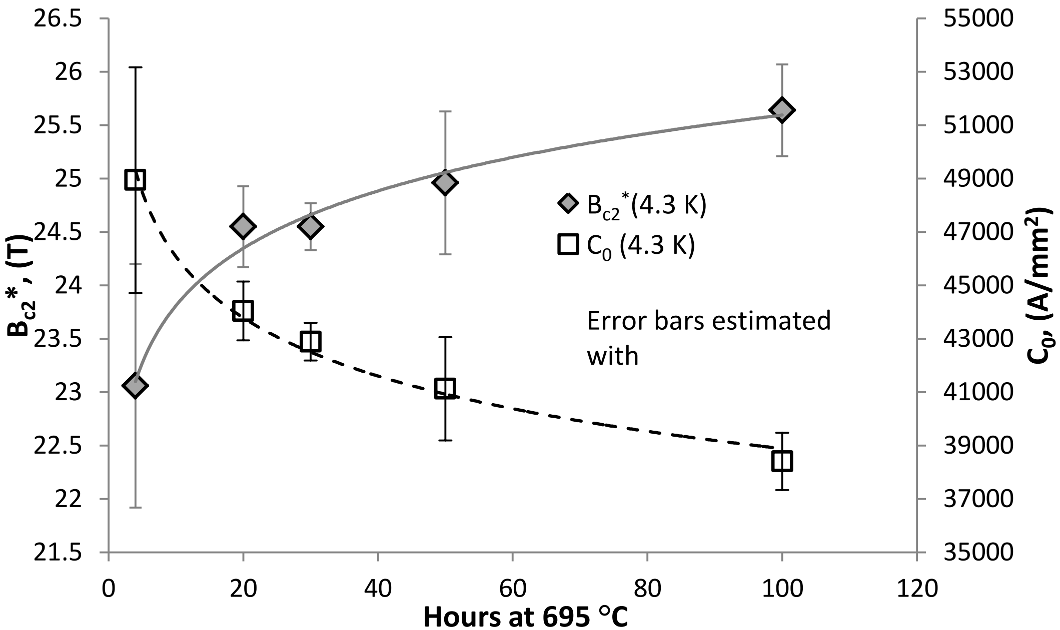
By courtesy of B. Bordini

Effect of RRR on stability – 1/4



0.8 mm 54/61
RRP® Nb_3Sn strand

Sample ID	Time at 695 °C [hrs]	*RRR*	I_c(4.3K-12T) [A]	J_c (4.3K-12T) [A/mm²]	B_{c2}^*(4.3 K) [T]
1	20	289±7	800	3068	24.55±0.38
2	30	264±8	778	2982	24.55±0.22
3	50	149±8	773	2963	24.96±0.67
4	70	81±7	732	2806	26.59±1.58
5	100	30±3	759	2909	25.64±0.43

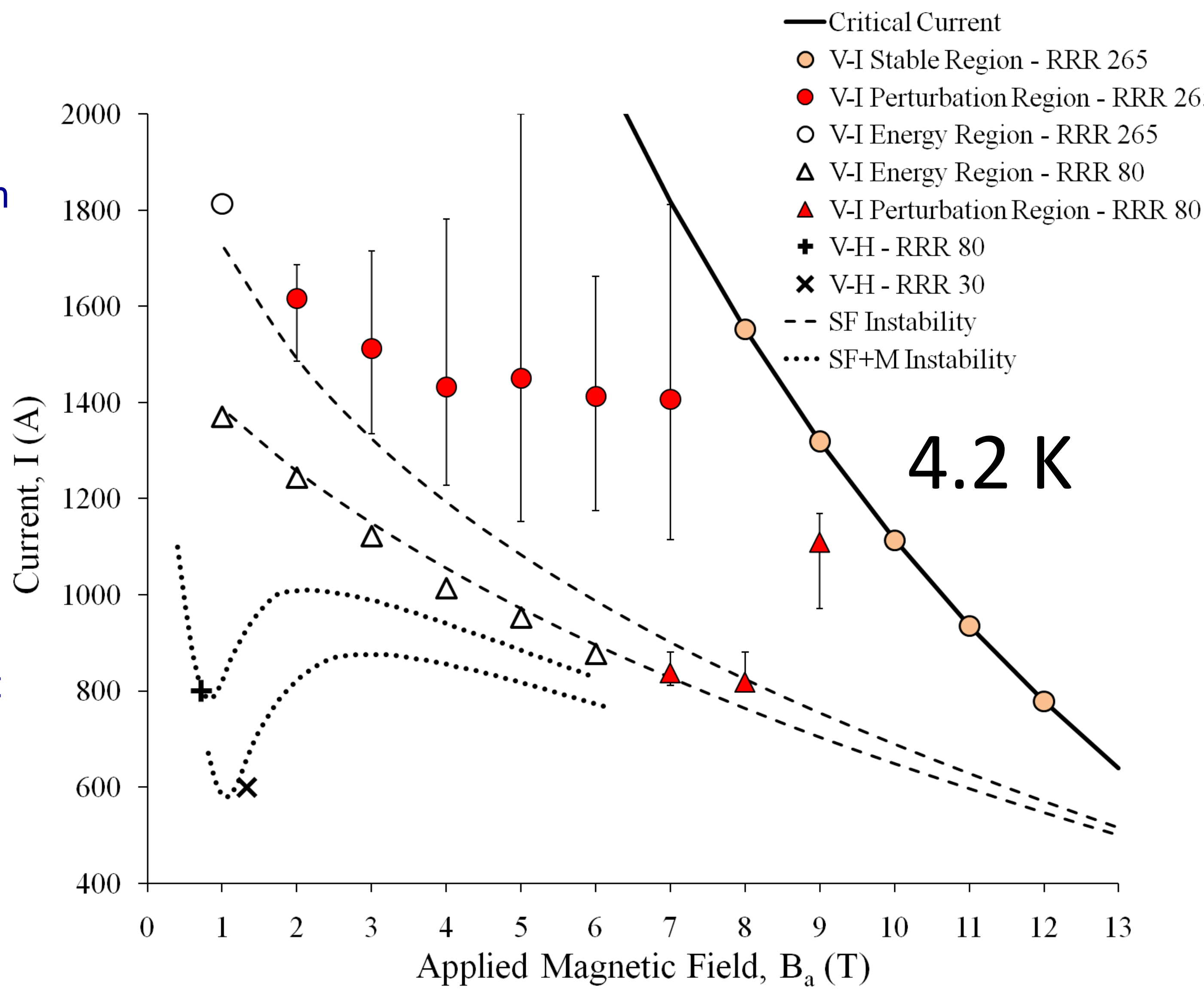


- Samples were prepared using the same strand (copper to non copper ratio ~ 0.92;effective filament size of ~ 80 µm)
- Heat treatment chosen in order to obtain different values of the RRR without significantly changing the critical current

By courtesy of B. Bordini

Effect of RRR on stability – 2/4

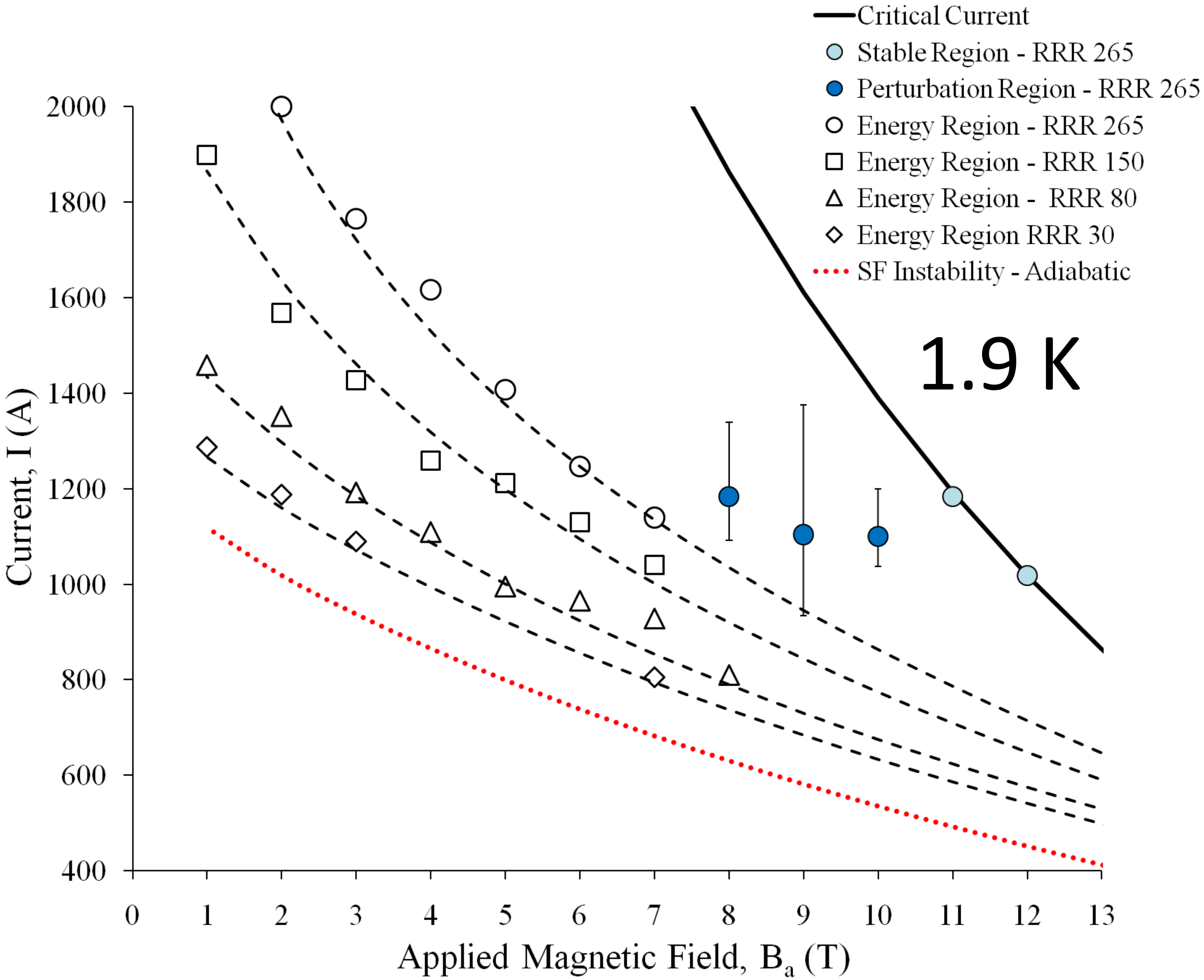
- 'Perturbation region': the quench current depends on the energy of the tiny perturbation acting on the strand (big variation of quench currents can occur)
- 'Energy Region': the quench current mainly depends on the potential energy stored in the current distribution
- V-H measurements at low fields shows that the minimum quench current significantly decrease by reducing the RRR below 100



By courtesy of B. Bordini

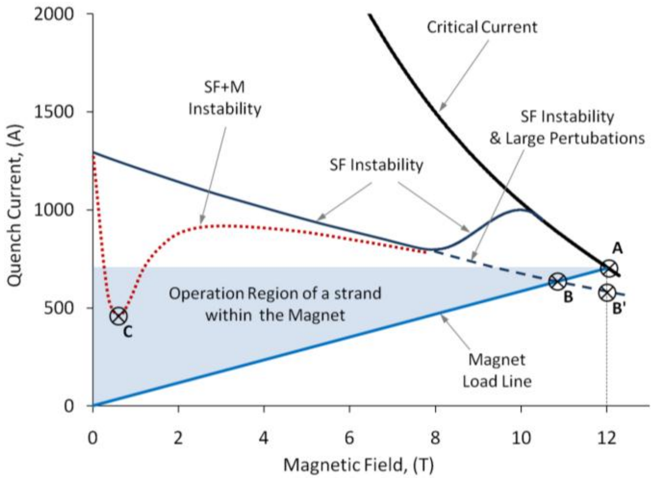
Effect of RRR on stability – 3/4

- At 1.9 K and with the same type of perturbation, the larger J_c and the smaller C_p of the wire (with respect to the values at 4.3 K) extend the 'energy region' and move the 'perturbation region' towards higher magnetic fields.
- The semi-analytical model is in good agreement with the experimental data in the 'energy region'



By courtesy of B. Bordini

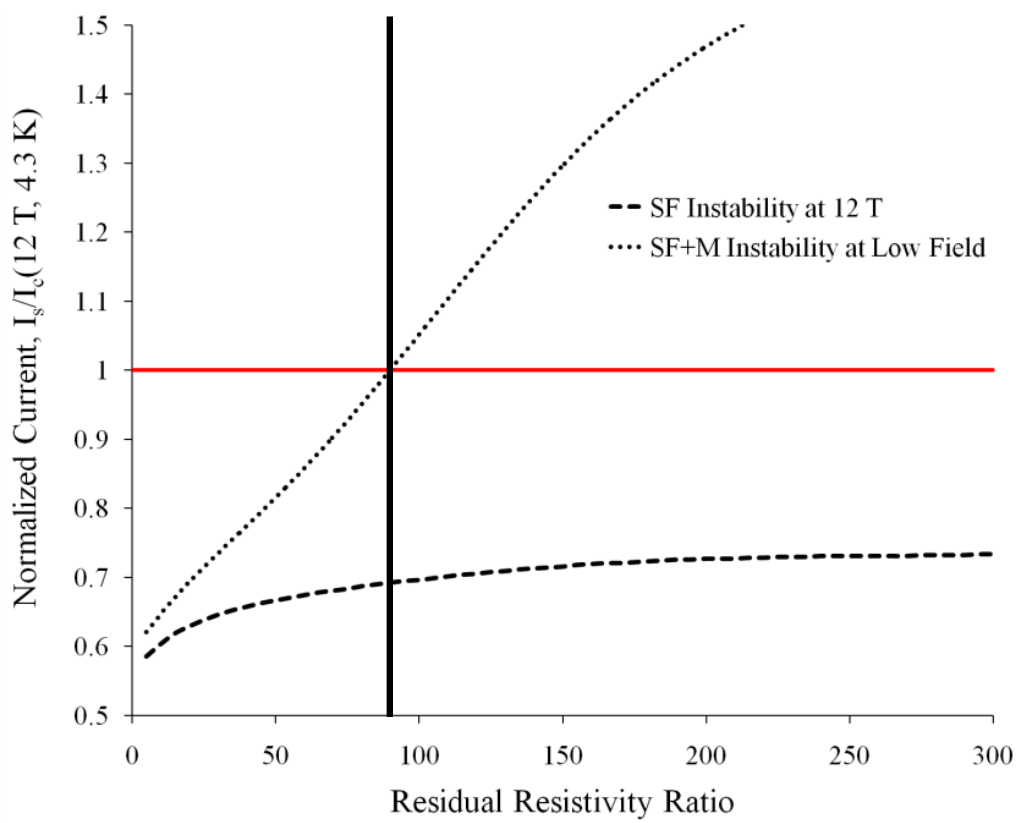
Effect of RRR on stability – 4/4



- The quench current at 4.3 K was computed for the minimum in the low field region (point C) and for 12 T in the case of self-field instability and large perturbations (point B′).

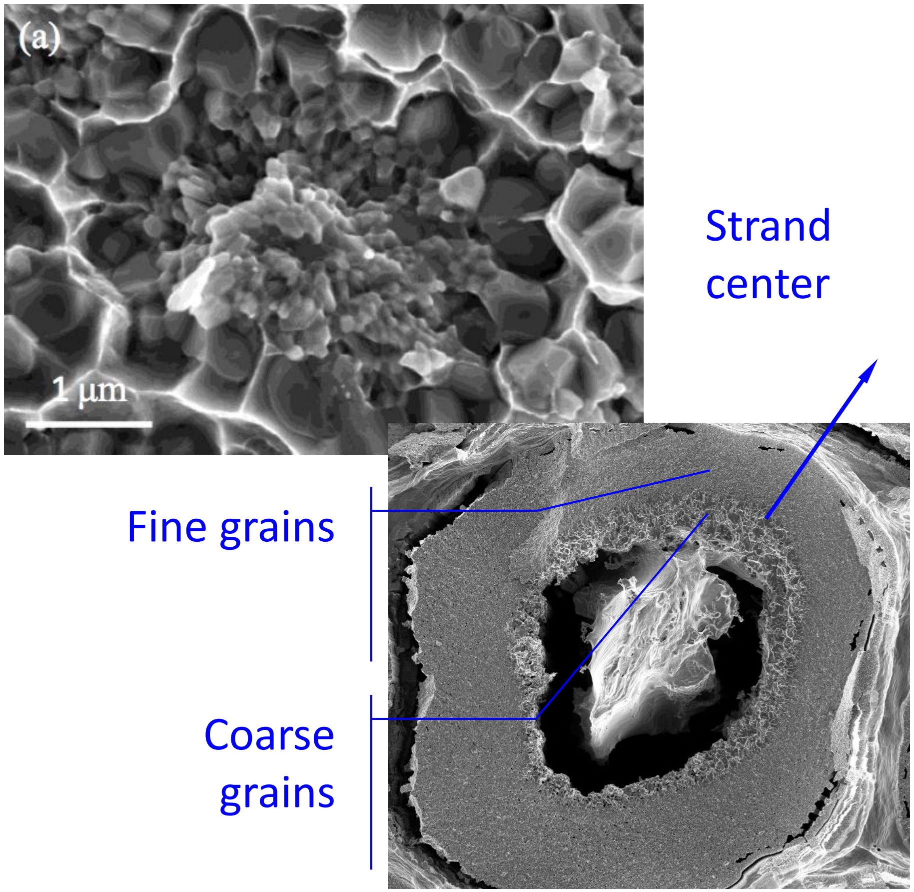
- For RRR larger than 100, the instability at low field (in the case of the considered conductor) is not a problem for a magnet designed to work at 12 T (or larger fields).

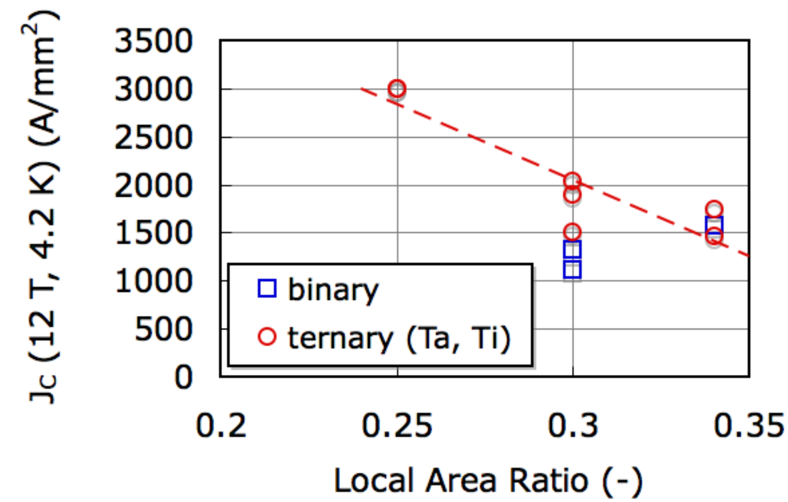
- The high field instability does not improve much increasing the RRR above 100.

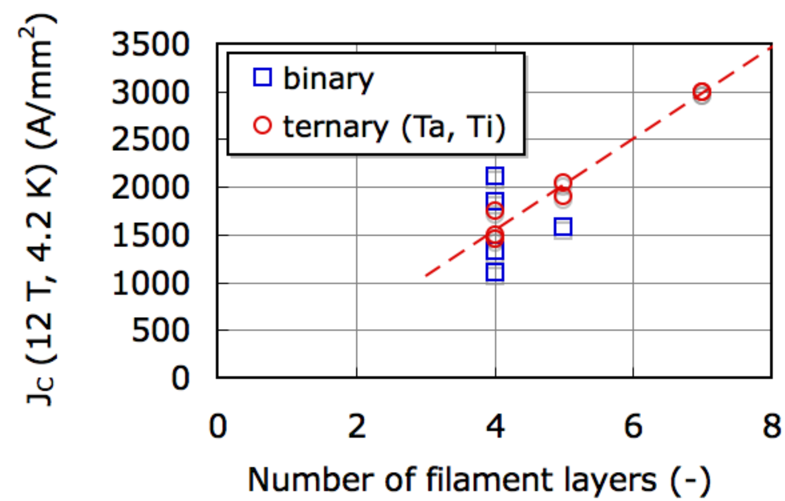


By courtesy of I. Pong and L. Oberli

Microstructure and *real estate*



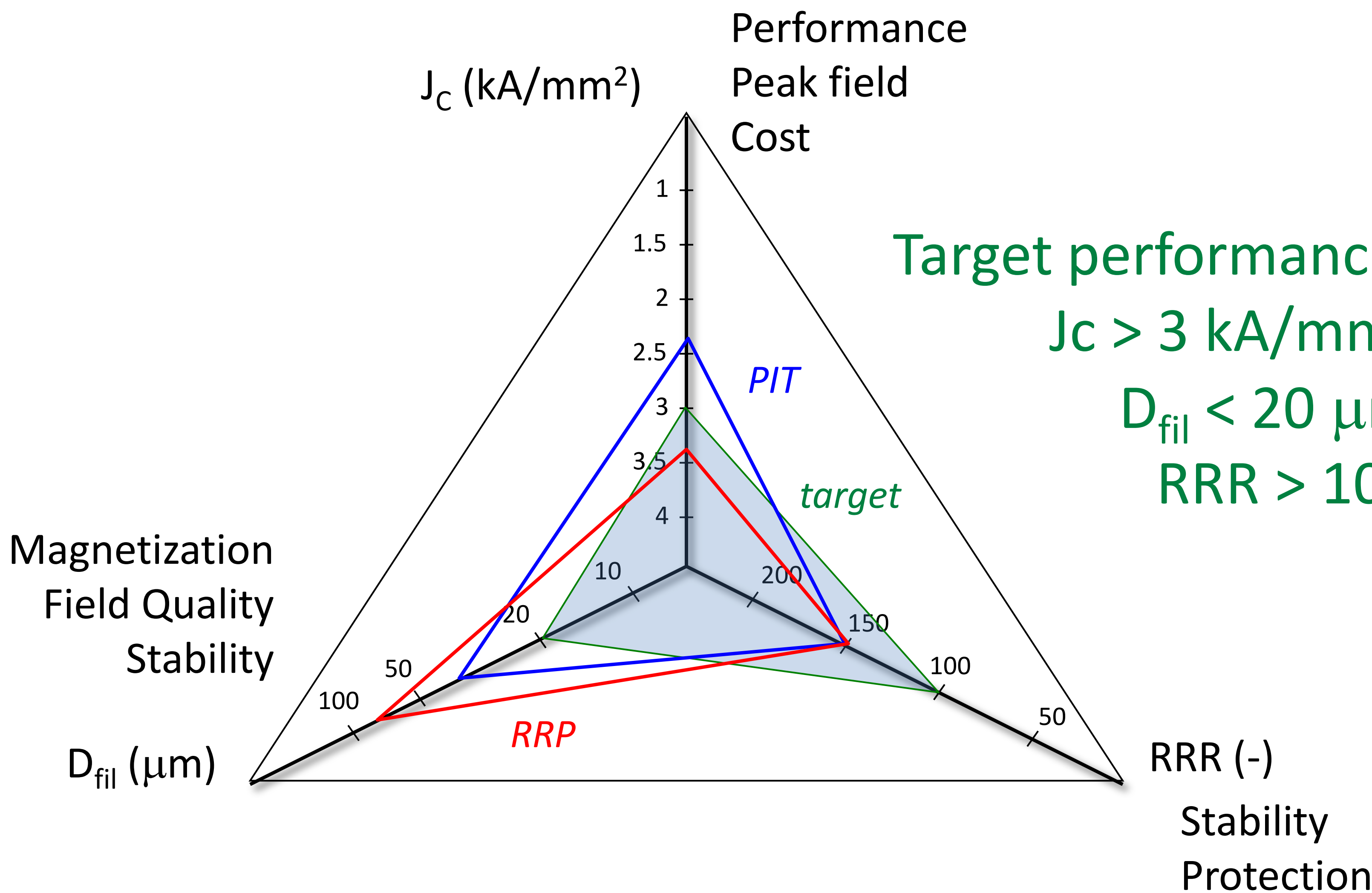




A summary of what (we think) we understood

- The initial NED specifications were possibly too demanding for stable performance in a magnet environment
- There is an intrinsic interplay of critical current density, filament diameter, and RRR, equivalent to a critical surface for the overall performance of a given strand

Performance targets for Nb_3Sn



Target performance:

$Jc > 3$ kA/mm^2

$D_{fil} < 20$ μm

RRR > 100

Present strand specifications

		NED (achieved)	FReSCa-II	DS-MB
Strand diameter	(mm)	1.25	1	0.7
Sub-element diameter	(μm)	50	50	**30***
Copper:non-Copper	(-)	1.25	1.25	1.15
J_C(12 T, 4.2 K)	(A/mm^2)	2740	2500	2650
J_C(15 T, 4.2 K)	(A/mm^2)	1530	1250	
n-index	(-)	> 30	30	30
RRR	(-)	220	150	100
Piece length	(m)	> 1000	800	800

(*) one of the main topics of the discussion today

Magnetization related matters

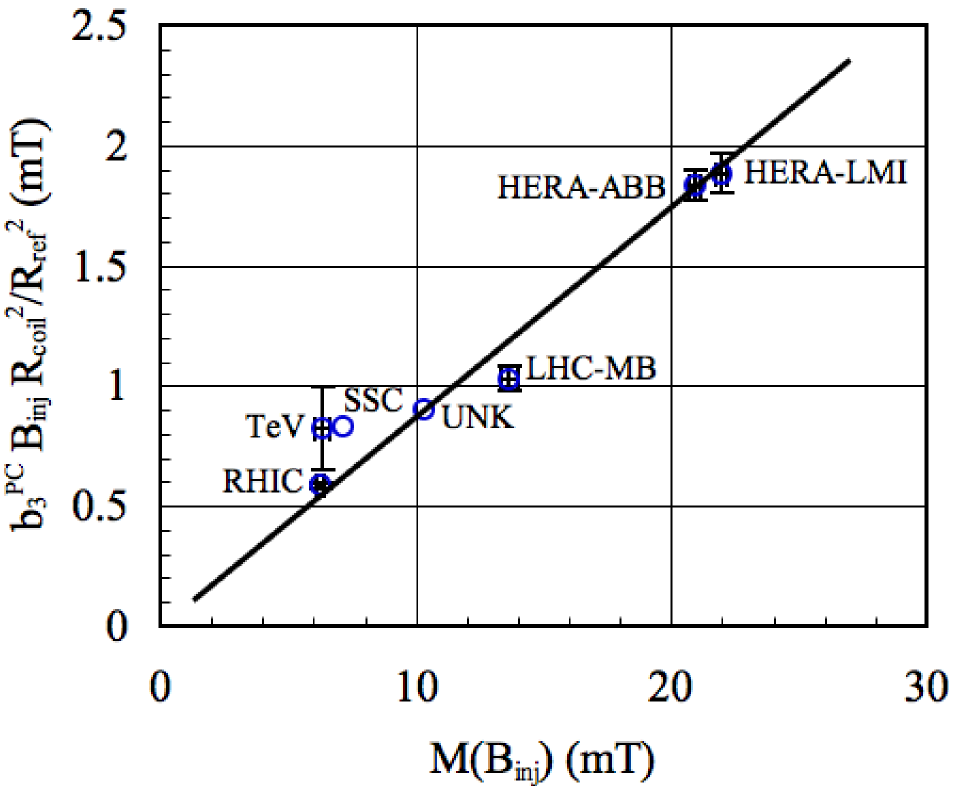
- Generic multipole (approximate integration in a coil of radius R_{coil}):

$$C_n \propto \mu_0 M(B)\left(\frac{R_{ref}}{R_{coil}}\right)^{n-1}$$

- Case of sextupole in a dipole magnet:

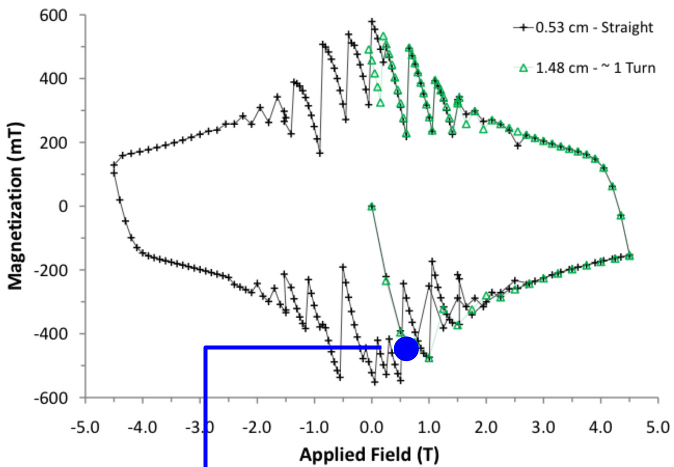
$$b_3^{PC} B_{inj}\left(\frac{R_{coil}}{R_{ref}}\right)^2 \propto M\left(B_{inj}\right)$$

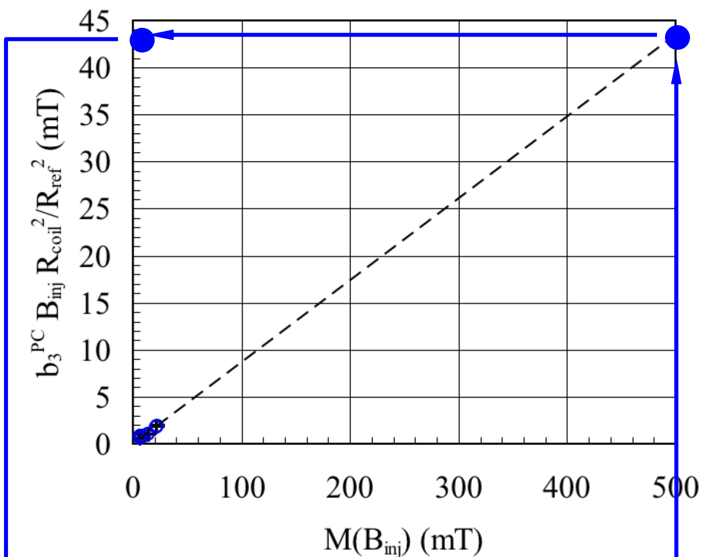
Scaled persistent current b_3^{PC} vs. strand M in dipoles for all SC synchrotrons to date

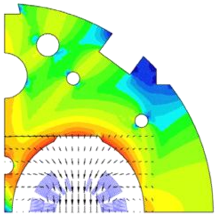


Expected field quality

OST-RRP 54/61







M ≈ 500 mT

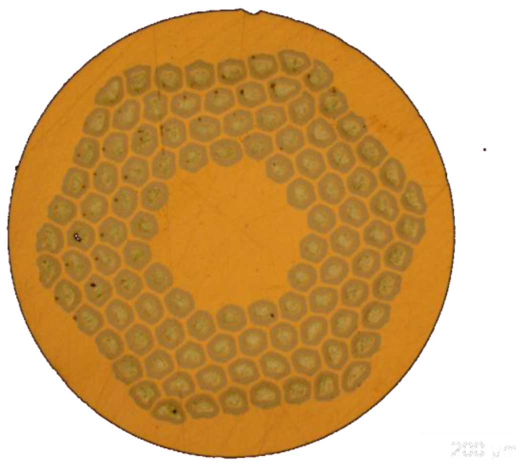
δM ≈ 200 mT

b_3 ≈ 300 units !!!

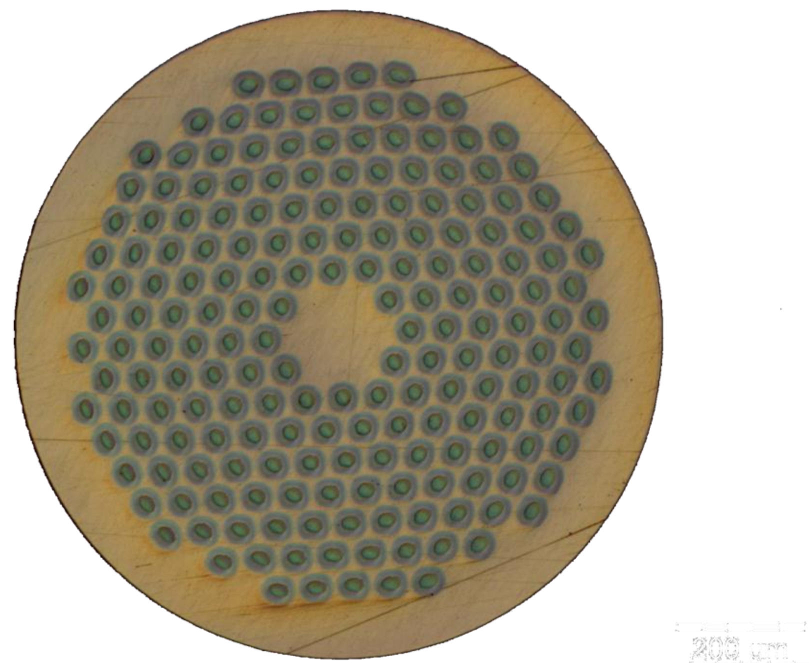
- What is the actual field error ?
- What can be tolerated and corrected ?

On-going strand work

0.7 mm, 108/127 stack RRP from OST



1 mm, 192 tubes PIT from Bruker EAS



Work is on-going on a new strand architecture (169 stack) to reduce the filament diameter to 52 μm at 1 mm strand diameter, and 35 μm at 0.7 mm strand diameter

R&D started for an alternative architecture with filaments of 30 μm at 0.7 mm strand diameter

Questions

- Do we agree on specifications (strand, cable) for magnet R&D and magnet production ?
- Material lead time is long (> 12 months), and we are already late. How do we manage/share the present stock ?
- What is the procurement strategy beyond the magnet R&D ?