Geneva – 20th May 2008

WAMSDO 2008

Self-Field Instabilities in High-J_c Nb_3Sn Strands: the Effect of Copper RRR

Bernardo Bordini

OUTLINE

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- INTRODUCTION
- LESSON LEARNED FROM WIRES WITH LOW RRR
- THE EFFECT OF RRR AT 4.2 K AND 1.9 K
- PRELIMINARY RESULTS ON
  - THE EFFECTS OF CHANGING THE STRAND'S THERMAL BOUNDARY CONDITIONS THROUGH A 'THICK' LAYER OF STYCAST
  - SENSITIVITY TO MECHANICAL PERTURBATION
  - THE EFFECTS OF LOCAL STRAND DAMAGES
- CONCLUSIONS

MAGNETO-THERMAL INSTABILITIES

- High-J_c Nb_3Sn wires is the best candidate for next generation High Field (>10 T) accelerator magnets.
- Although very promising, state of the art high-J_c Nb_3Sn wires suffer flux jumps.
- Flux jumps can quench the superconductor and severely limit the strand performance.
- Flux jumps are caused by magneto-thermal instabilities:

1) 'Magnetization' instability depending on the J_c and D_{eff} ; at 4.2 K it can provoke premature magnet quenches in the very low field region (0 – 3 T) if the J_c and D_{eff} are not sufficiently low and the copper RRR is not sufficiently high;

2) 'Self field' instability depending on J_c and the strand diameter; at 1.9 K this phenomenon is the dominant magneto-thermal instability in high-J_c Nb_3Sn wires and it might be the primary cause of premature quenches of HF magnets.

SELF-FIELD INSTABILITY

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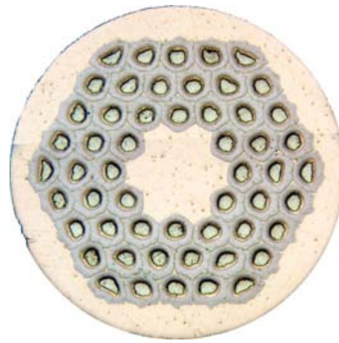
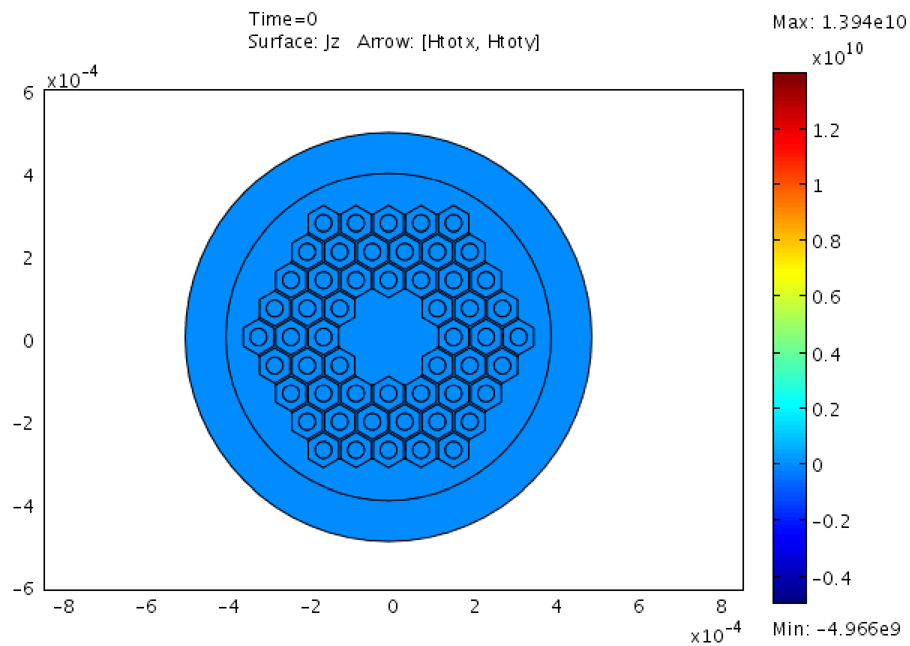
- Self field instability is caused by the uneven distribution of transport current (I) within the wire.



0.8 mm RRP Nb_3Sn strand

- While ramping up I at a fixed B_a , the multifilamentary strand acts as a large monofilament with a radius equal to the composite radius:

  The current only flows in the outermost sub-elements at the critical current density.



Distribution of the transport current while increasing the current from 0 to 1200 A in a fixed applied field, B_a=6 T

SELF-FIELD INSTABILITY :
Simulation of Premature Quench

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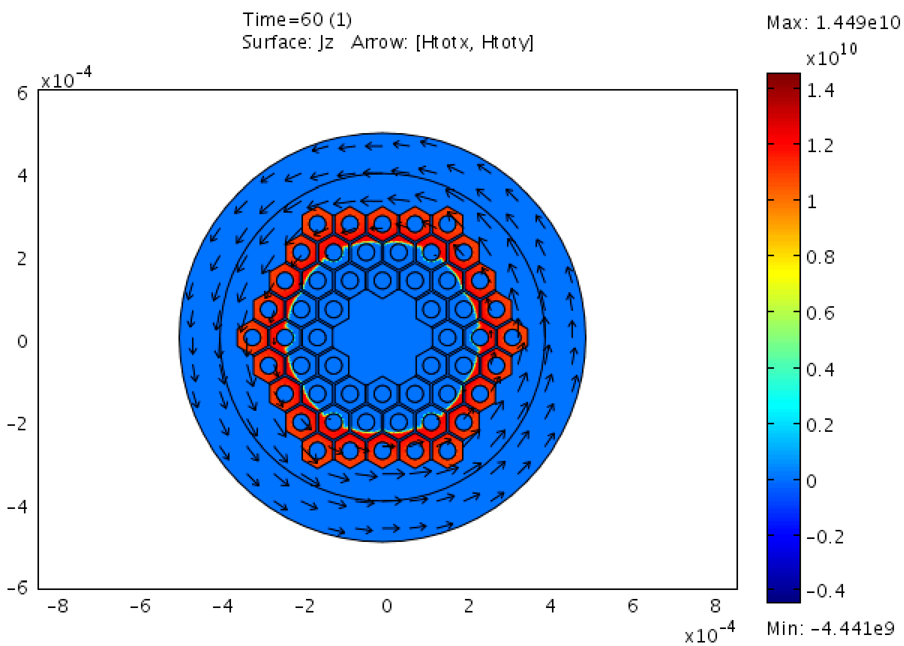
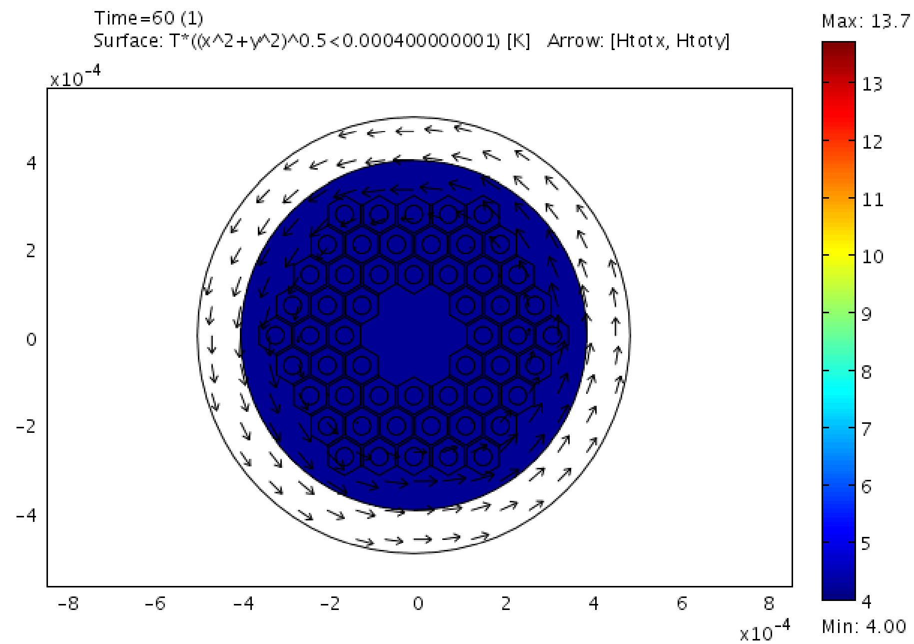
The color represents the Transport Current distribution

B_a=6 T -- I=1200 A -- T_i=4.2 K

The color represents the Temperature distribution





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MODEL SF INSTABILITY: a semi-analytical approach

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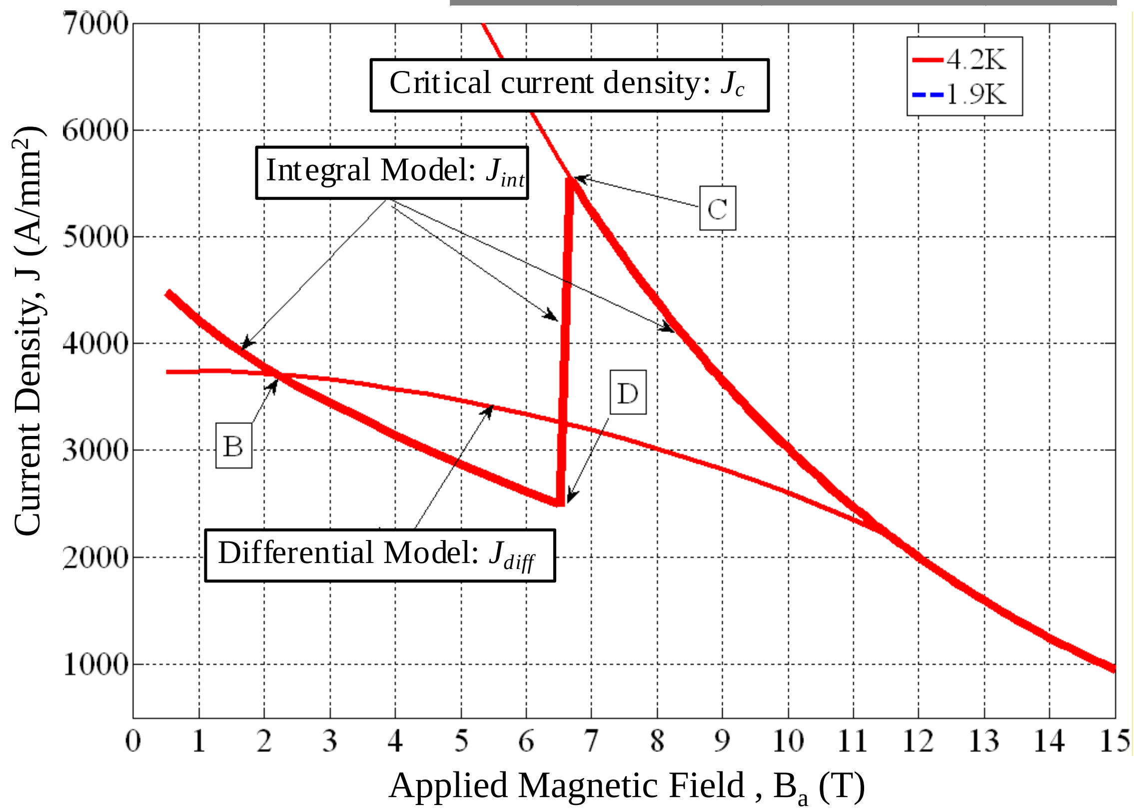
Strand diam. [mm]	Strand type	J_c @ 4.2 K-12 T [A/mm^2]	B_{c2} @ 4.2 K [T]
0.7	MJR 54/61	2000	22.73

- A semi-analytical 'Integral' model was developed [1] to predict the minimum quench current due to magneto-thermal instability
- The model, based on the adiabatic hypothesis, is well adapted to round wires with a low RRR
- In the plot the current densities are averaged over the non-Cu area and the curves represent:
  1. the intrinsic J_c values
  2. the 'integral' model
  3. the 'differential' adiabatic stability model of self-filed [2] adapted to our strand.



[1] B. Bordini, E. Barzi, S. Feher, L.Rossi, A.V. Zlobin, to be published in *IEEE Trans. Appl. Supercond.* 2008

[2] R. G. Mints, A. L. Rakhmanov, *Sov. Tech. Phys. Lett.*, vol 2, no. 6, Jun. 1976

V-I DATA AND SF INSTABILITY

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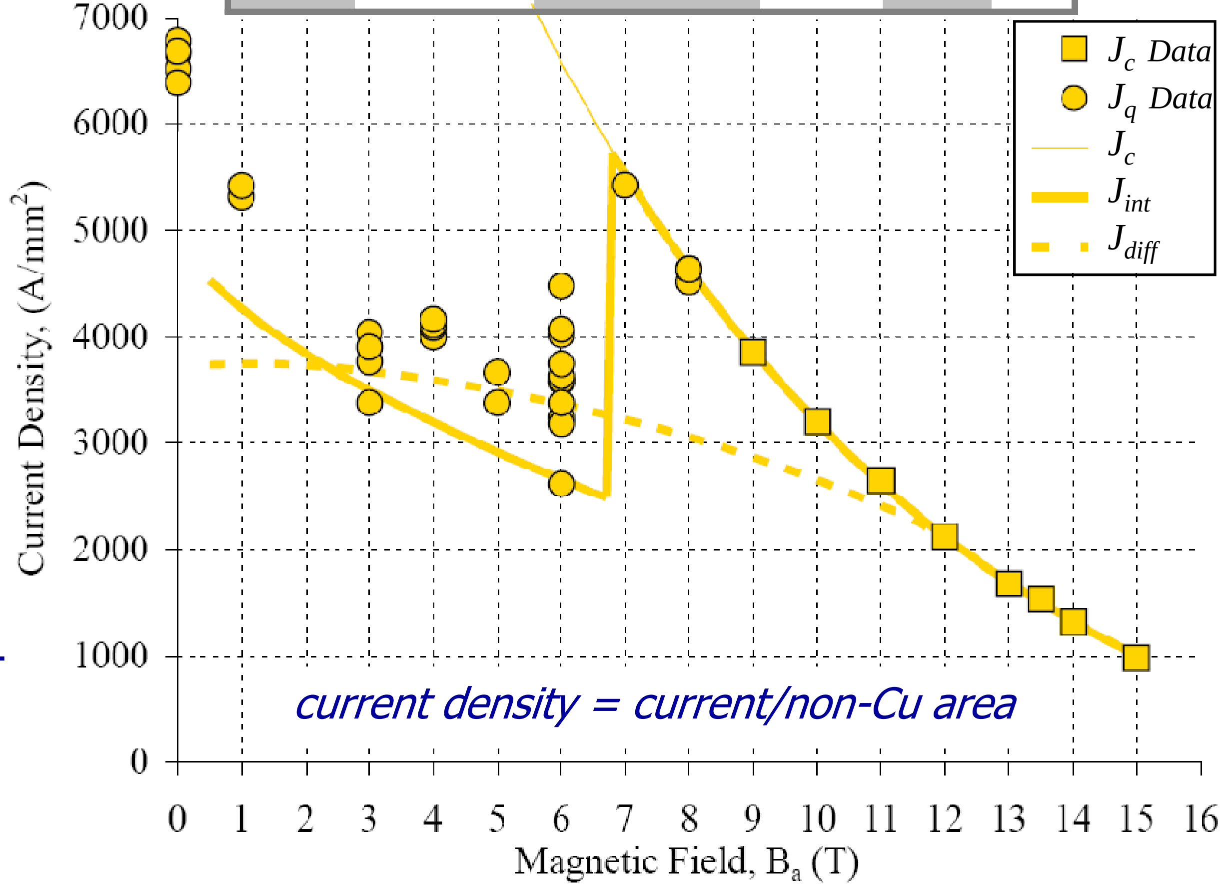
- J_q data ➔ V-I tests where premature quenches occurred .
- 3 stability regions:
  1. a high field stable region $B_a \geq 7$ T
  2. an intermediate field region 2 T<B_a<7 T where the min J_q follow the integral model
  3. a low field region B_a<2 T where min J_q data increases decreasing B_a.

Strand diam. [mm]	Strand type	J_c @ 4.2 K-12 T [A/mm²]	B_{c2} @ 4.2 K [T]	D_{eff} [μm]	RRR
0.7	MJR 54/61	2123	22.73*	70	7



V-I DATA AND SF INSTABILITY

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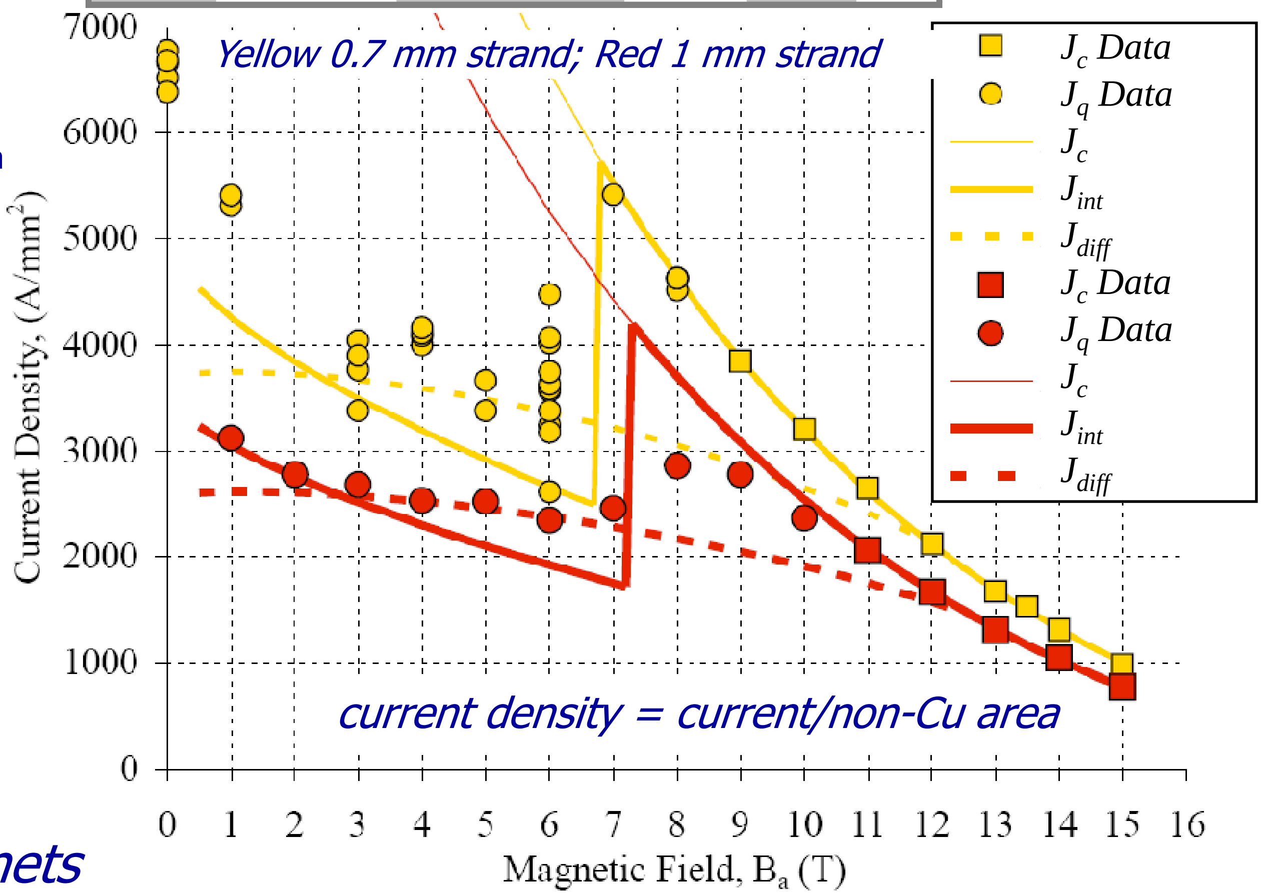
Strand diam. [mm]	Strand type	J_c @ 4.2 K-12 T [A/mm²]	B_{c2} @ 4.2 K [T]	D_{eff} [μm]	RRR
0.7	MJR 54/61	2123	22.73	70	7
1	MJR 54/61	1671	22.33	100	7

- Increasing the strand diameter:
  1. the premature quench current density at a certain B_a significantly decreases
  2. the intermediate field region extends towards larger B_a .

Increasing the strand diameter the self field instability gets more dangerous for Nb_3Sn magnets



V-I DATA: 4.2 K Vs. 1.9 K

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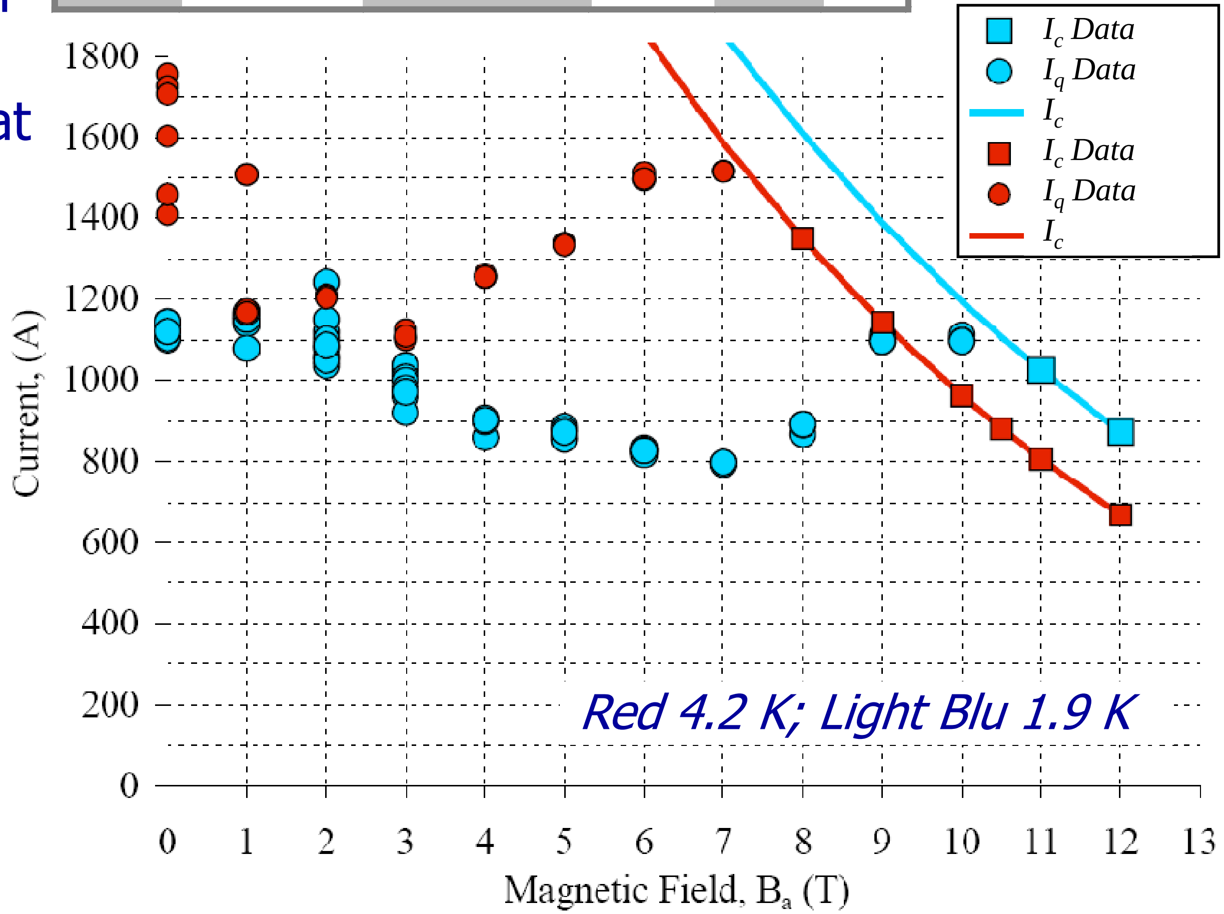
Strand diam. [mm]	Strand type	J_c @ 4.2 K-12 T [A/mm^2]	B_{c2} @ 4.2 K [T]	D_{eff} [μ m]	RRR
0.8	RRP 54/61	2602	24.54	80	8

- Comparing V-I tests at 4.2 K and 1.9 K, one can notice that, as predicted by our self field model, at the lower temperature:

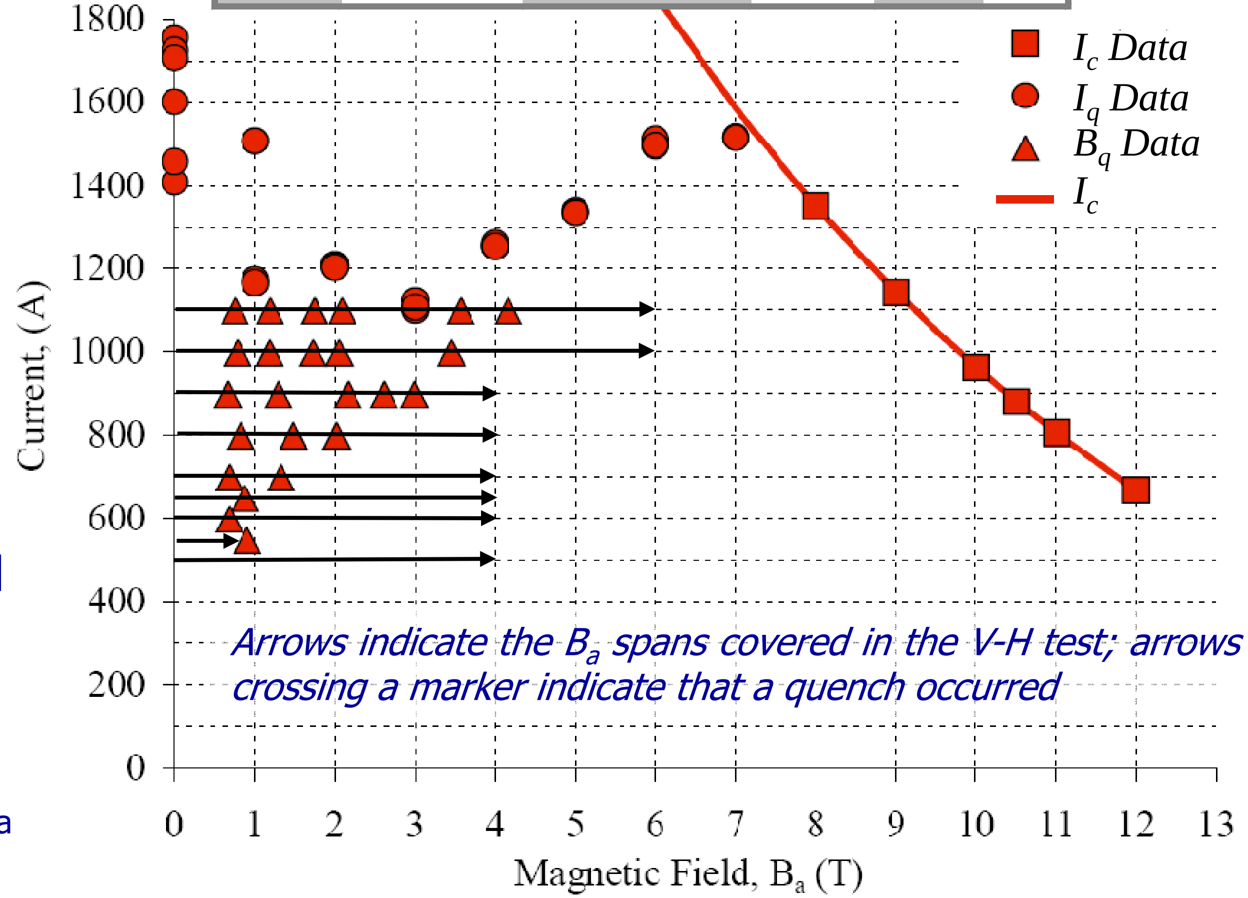
1. I_c can only be attained at higher field values (11 T instead of 8 T);
2. the minimum premature I_q moves towards higher fields (7 T instead of 3 T)
3. the minimum premature I_q is lower (800 A instead of 1100 A).



V-I vs.V-H AT 4.2 K

Strand diam. [mm]	*Strand type*	*J_c @ 4.2 K-12 T [A/mm^2]*	*B_{c2} @ 4.2 K [T]*	*D_{eff} [μ m]*	*RRR*
0.8	RRP 54/61	2602	24.54	80	8

- The strand reached I_c for $B_a \geq 8$ T.
- The minimum premature quench current values were:
  1. ~1100 A at 3 T in J_q test (V-I)
  2. 550 A at ~0.9 T in B_q test (V-H).
- During V-H test when a quench occurred the power supply was tripped and the B_a ramp was stopped, then the same current value was restored and finally the B_a was ramped up again.



V-I vs.V-H AT 1.9 K

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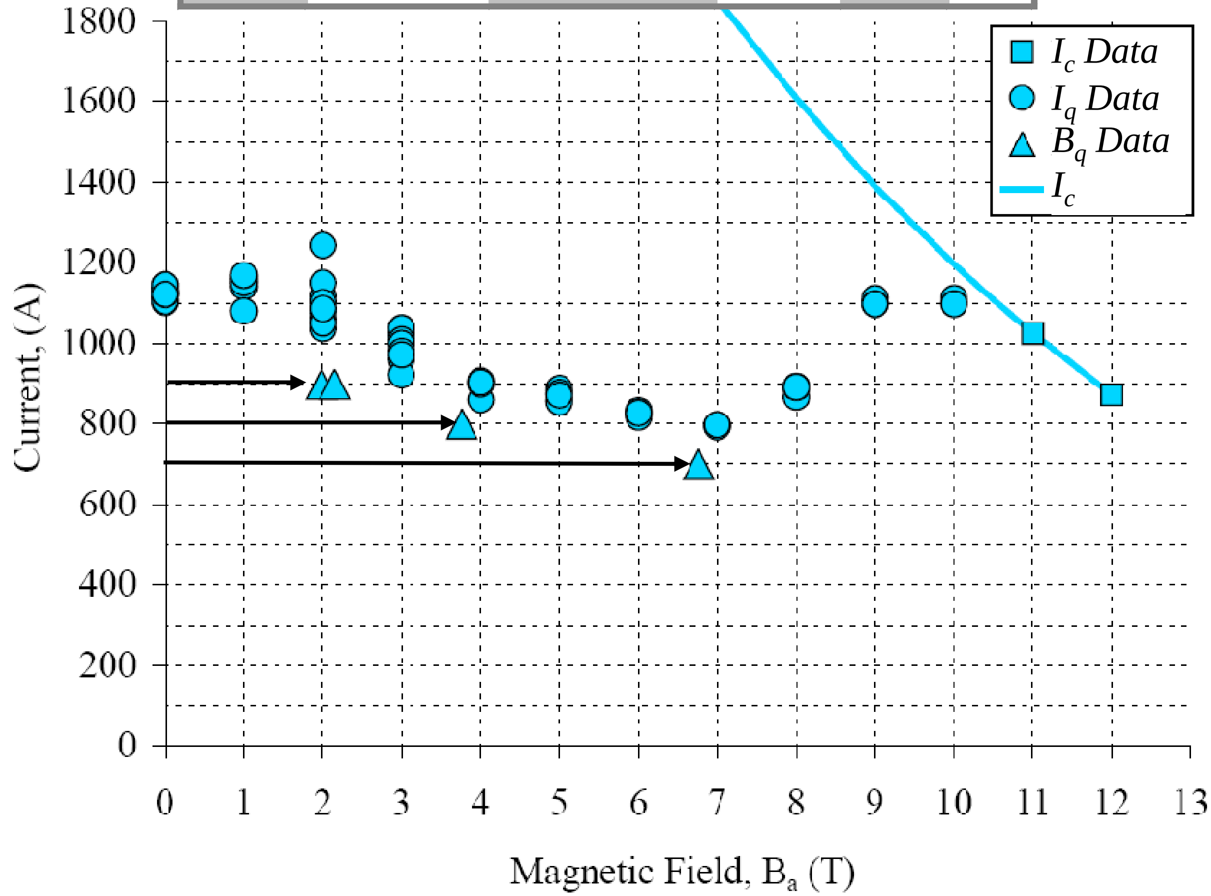
- In the V-H tests (B_q) at 1.9 K an unexpected behavior was observed: the quench current was not significantly lower than during V-I (I_q) tests.
- From this measurements one might conclude that the Self field instability is the predominant instability mechanism at 1.9 K.

Strand diam. [mm]	Strand type	J_c @ 4.2 K-12 T [A/mm^2]	B_{c2} @ 4.2 K [T]	D_{eff} [μ m]	RRR
0.8	RRP 54/61	2602	24.54	80	8



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STRAND TEST RESULTS @ 4.2 K:
RRR ranging from 8 to 120

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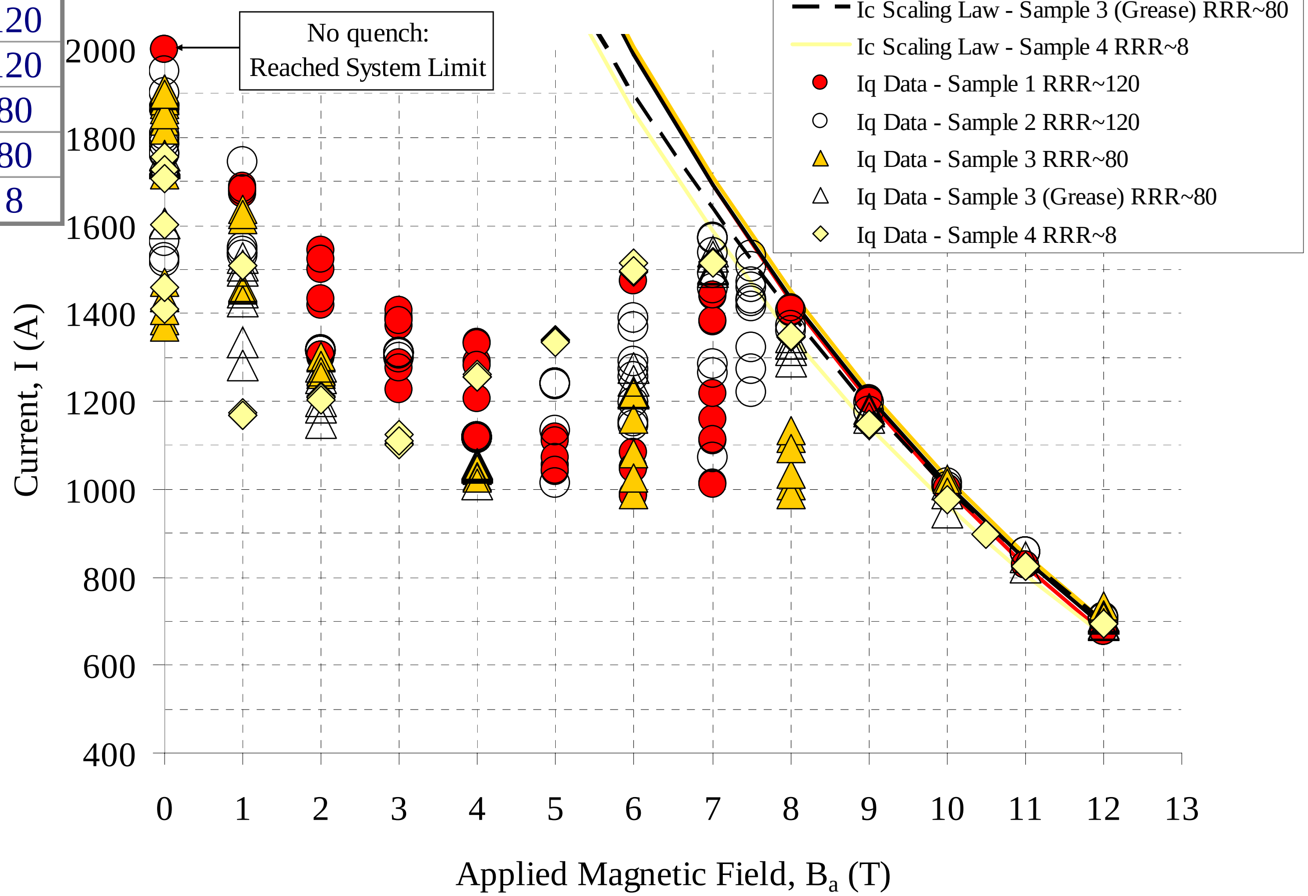
Sample Number	*J_c @ 4.2 K-12 T [A/mm^2]*	*B_{c2} @ 4.2 K [T]*	*D_{eff} [μm]*	*RRR*
1	2580	23.06	80	120
2	2645	23.56	80	120
3	2672	23.94	80	80
3 (Grease)	2683	24.72	80	80
4	2602	24.54	80	8

54 /61 RRP 0.8 mm

- The current values of premature quenches due to the self field instability are not much dependent on the RRR value



STRAND TEST RESULTS @ 4.2 K:

RRR ranging from 140 to 290

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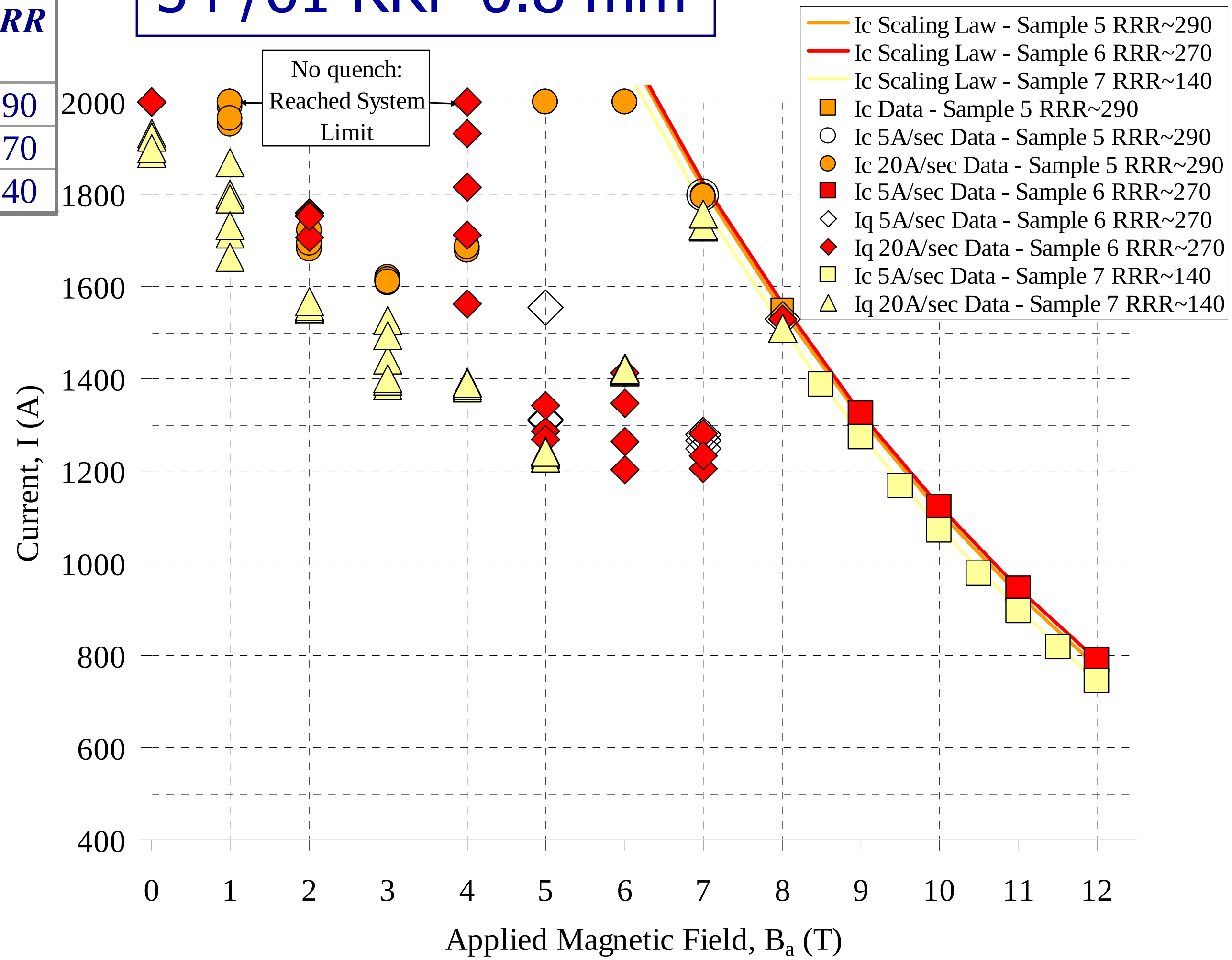
Sample Number	*J_c @ 4.2 K-12 T [A/mm²]*	*B_{c2} @ 4.2 K [T]*	*D_{eff} [μm]*	*RRR*
5	2978	24.5	80	290
6	3028	24.92	80	270
7	2852	24.13	80	140

54 /61 RRP 0.8 mm



- The current values of premature quenches due to the self field instability are not much dependent on the RRR value

STRAND TEST RESULTS @ 1.9 K:

RRR ranging from 8 to 120

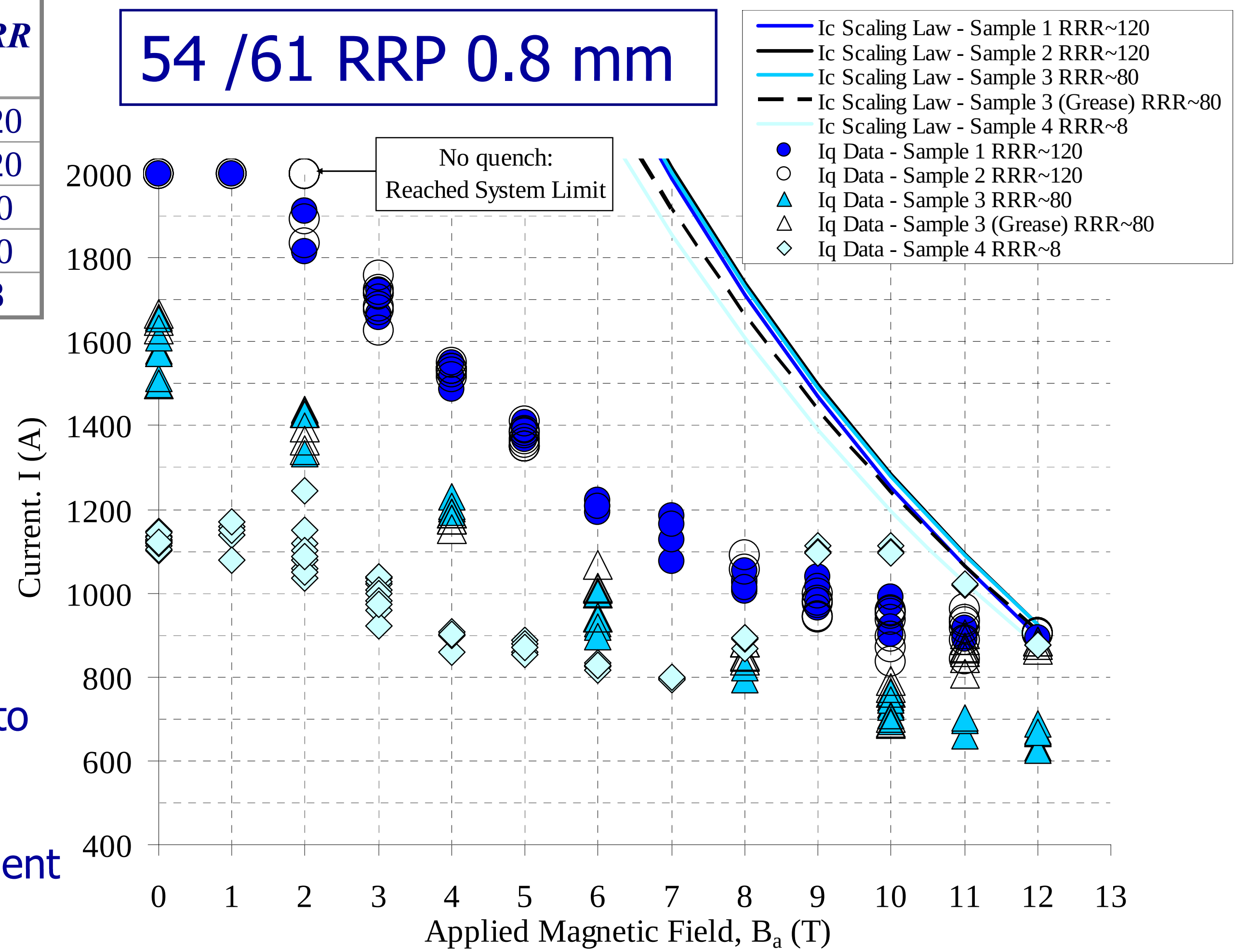
AT-MCS

WAMSDO 2008

Sample Number	*J_c @ 4.2 K-12 T [A/mm^2]*	*B_{c2} @ 4.2 K [T]*	*D_{eff} [μm]*	*RRR*
1	2580	23.06	80	120
2	2645	23.56	80	120
3	2672	23.94	80	80
3 (Grease)	2683	24.72	80	80
4	2602	24.54	80	8

- The current values of premature quenches due to the self field instability are dependent on the RRR value in the low field region (at 1.9 K ~ 0-7 T)

- At higher fields it is difficult to experimentally estimate the effect of RRR because the instability is strongly dependent on the initial perturbation



STRAND TEST RESULTS @ 1.9 K:
RRR ranging from 140 to 290

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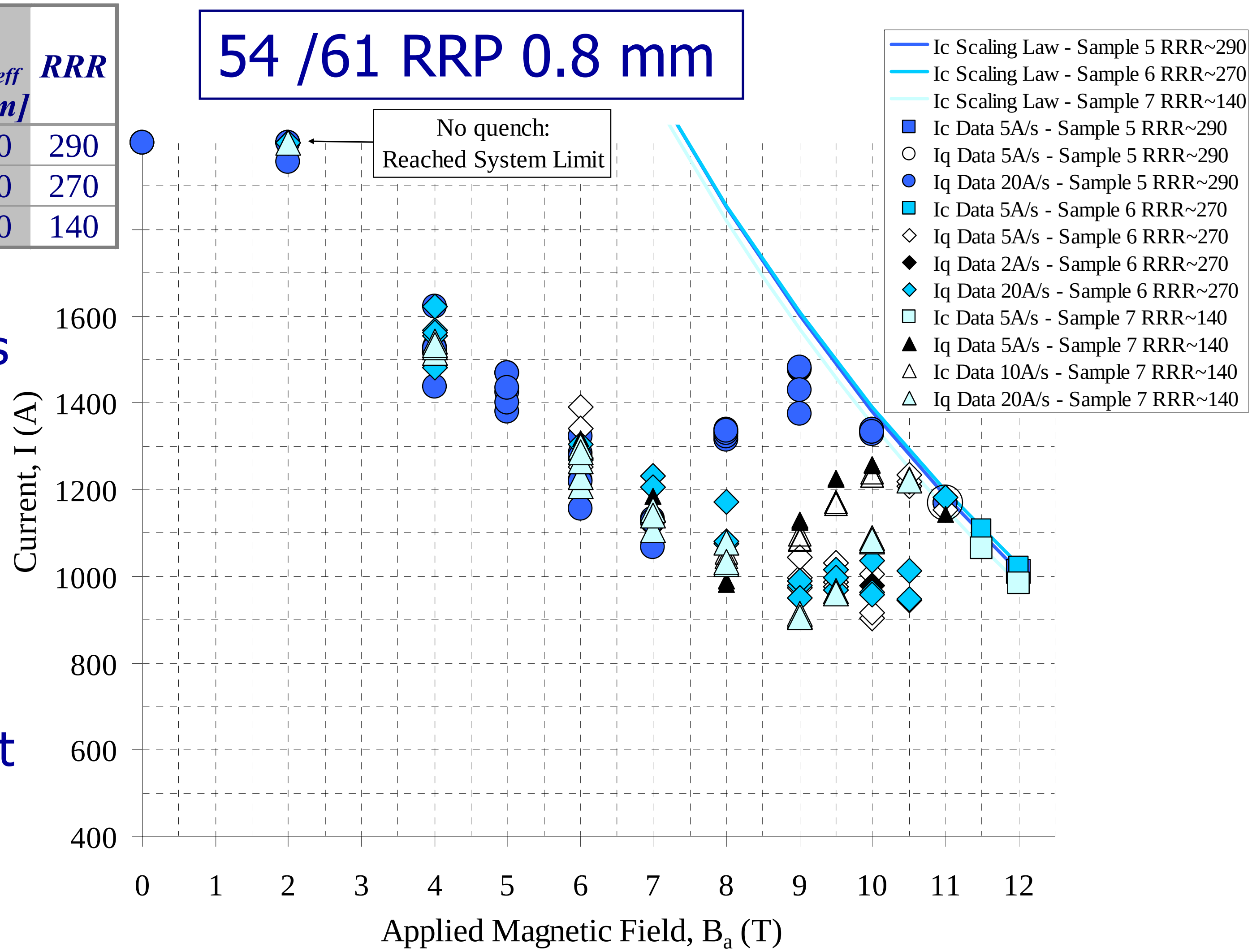
Sample Number	J_c @ 4.2 K-12 T [A/mm²]	B_{c2} @ 4.2 K [T]	D_{eff} [μm]	RRR
5	2978	24.5	80	290
6	3028	24.92	80	270
7	2852	24.13	80	140

- The current values of premature quenches due to the self field instability are not dependent on the RRR value in the low field region (at 1.9 K ~ 0-7 T)



STRAND TEST RESULTS @ 1.9 K: PIT Vs. RRP

AT-MCS

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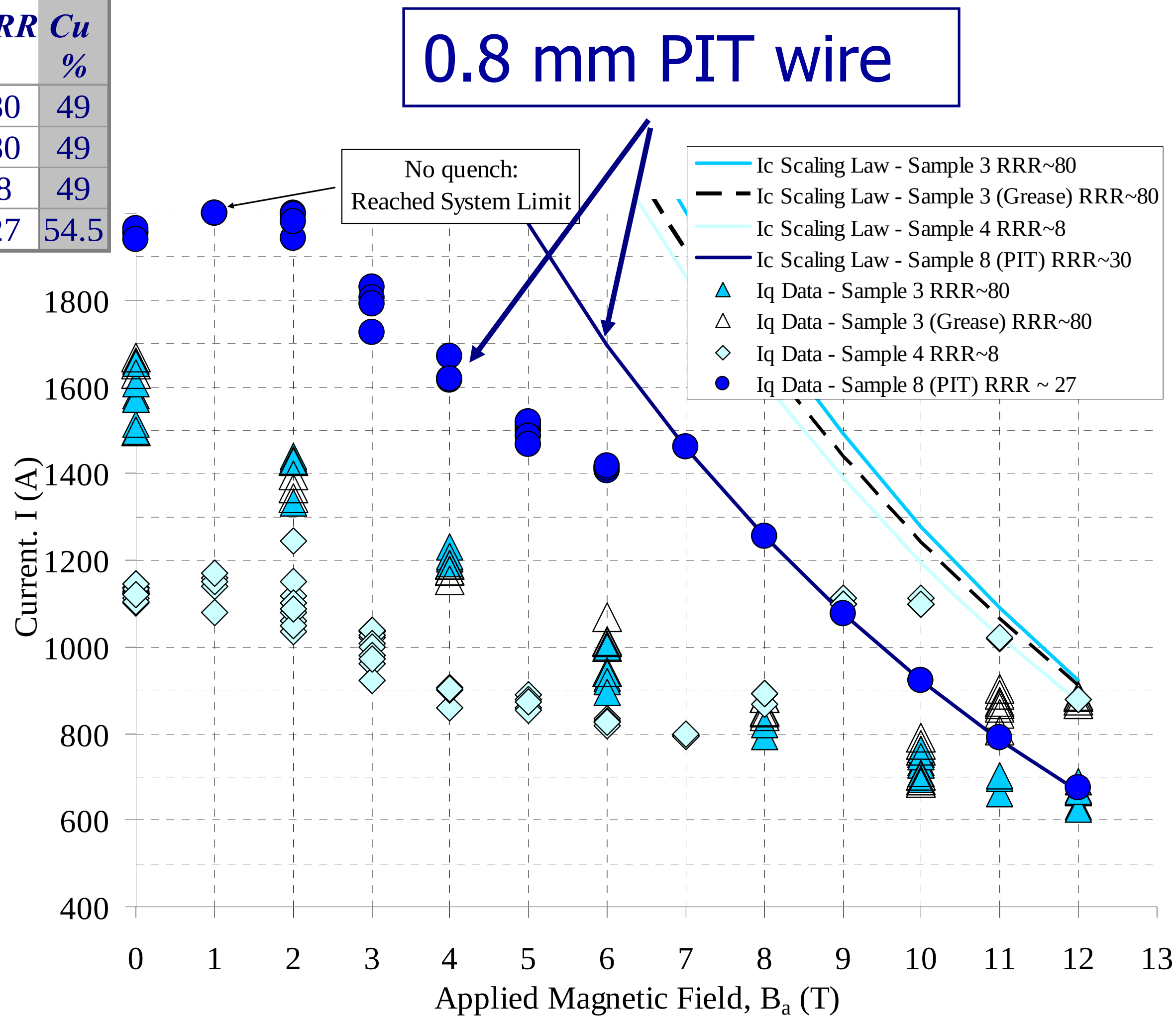
Sample Number	Strand type	Strand Diam. [mm]	J_c @ 4.2 K-12 T [A/mm^2]	B_{c2} @ 4.2 K [T]	D_{eff} [μm]	RRR	Cu %
3	RRP	0.8	2672	23.94	80	80	49
3 (Grease)	RRP	0.8	2683	24.72	80	80	49
4	RRP	0.8	2602	24.54	80	8	49
8	PIT	0.8	2224	24.27	30	27	54.5

- An high RRR is not sufficient to solve the problem of self field instability in record-J_c RRP OST strands at 1.9 K
- A possible solution might be to increase the overall Cu content and the Cu in between the superconducting sub-elements; PIT strands adopted these solutions and preliminary results show that they are much more self-field stable



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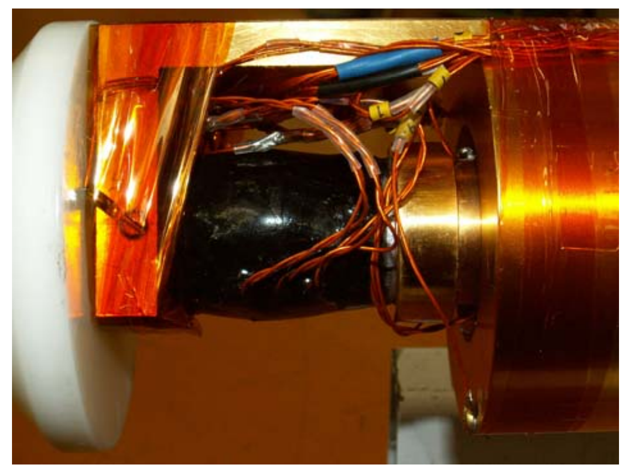
THE EFFECTS OF COVERING THE WIRE WITH 'THICK' LAYER OF STYCAST

- At first the strand was tested in direct contact with helium
- Then the same strand was covered by ~ 1 mm of stycast and retested
- The thermal diffusivity (D_{th}) of epoxy at 4.2 K and 1.9 K is respectively ~2.3 10^{-5} m^2s and ~ 2.03 10^{-4} m^2s (Cryocomp)
- The thermal penetration thickness δ_{th} is: $\delta_{th} = 4\sqrt{D_{th} \cdot t}$
- The time scale for a local flux jump is generally < 10^{-4} s

Sample holder diameter ~ 32 mm



⬇

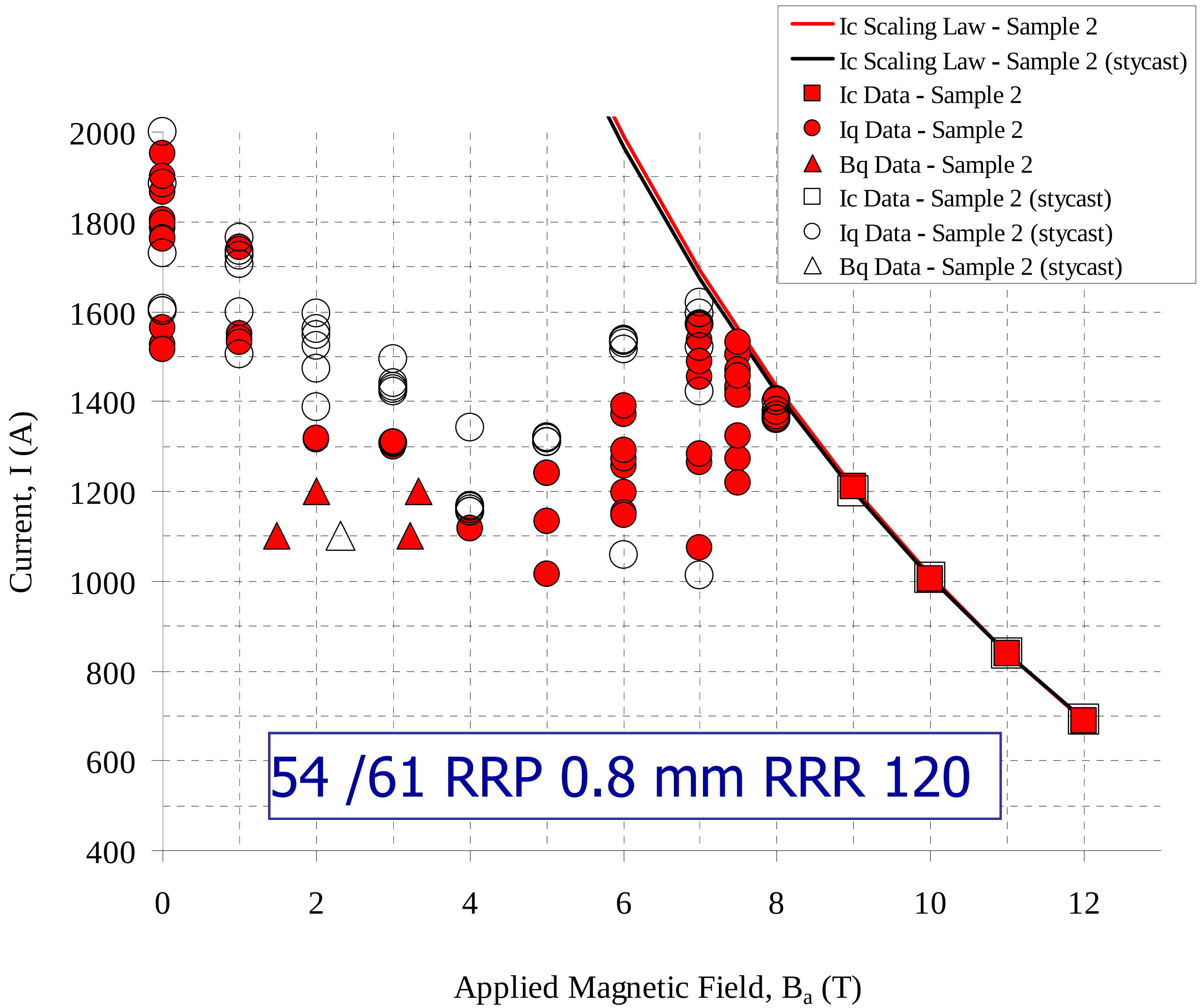
$$\delta_{th}(4.2\ K) < 0.19\ mm \qquad \delta_{th}(1.9\ K) < 0.57\ mm$$

⬇

Increasing the thickness of the stycast layer over 1 mm should not change the premature quench current values

THE EFFECTS @ 4.2 K OF COVERING THE WIRE WITH 'THICK' LAYER OF STYCAST

- The thick layer of stycast did not change the critical current values and did not significantly change the premature quench current values



THE EFFECTS @ 1.9 K OF COVERING THE WIRE WITH 'THICK' LAYER OF STYCAST

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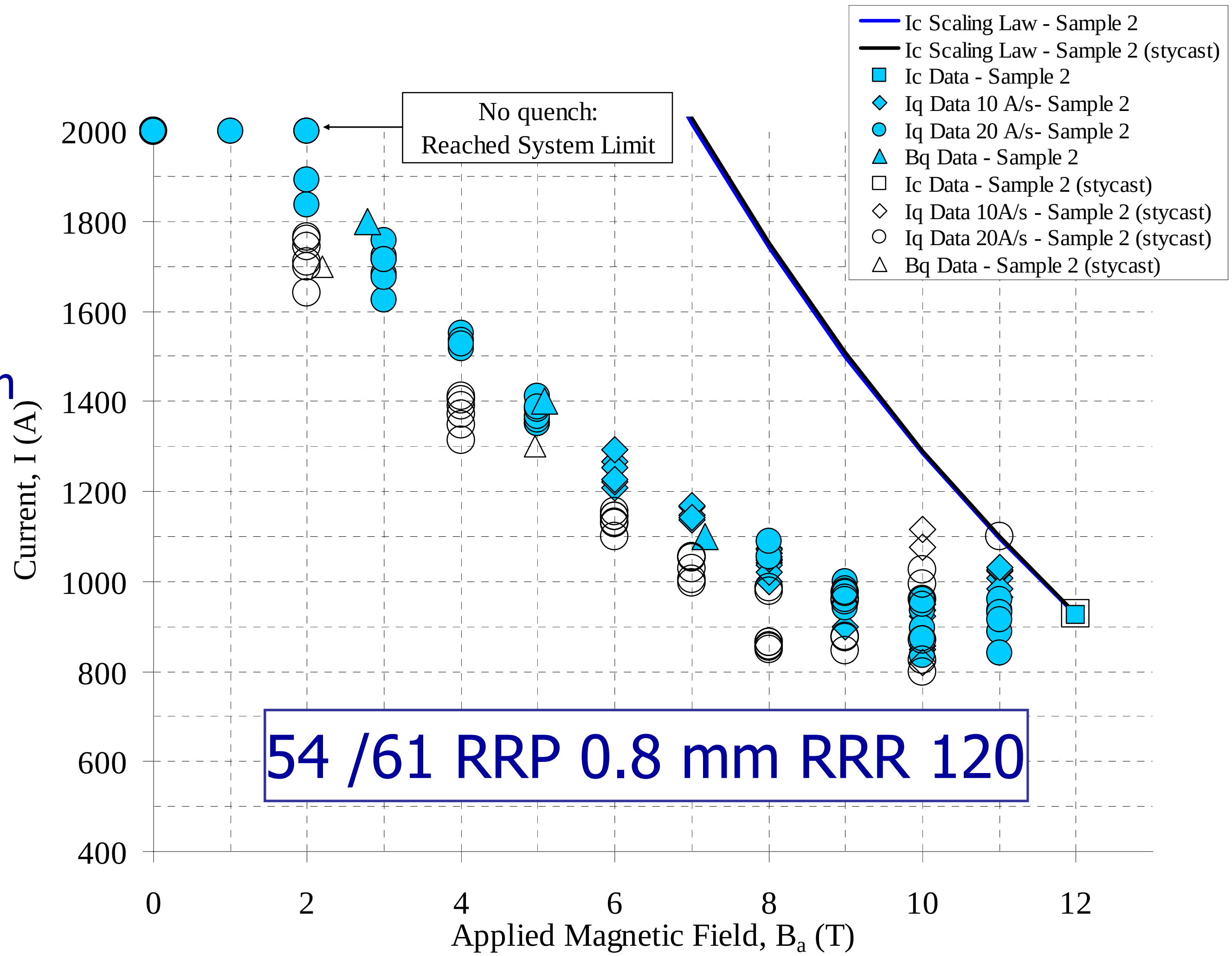
- The thick layer of stycast did not change the critical current
- In the low field region (~0-7 T at 1.9K) it decreased the minimum quench current of ~ 10%
- Also for strand with high RRR, the Self field instability is predominant instability mechanism at 1.9 K.



DEPENDANCE ON THE ENERGY OF THE INITIAL PERTURBATION

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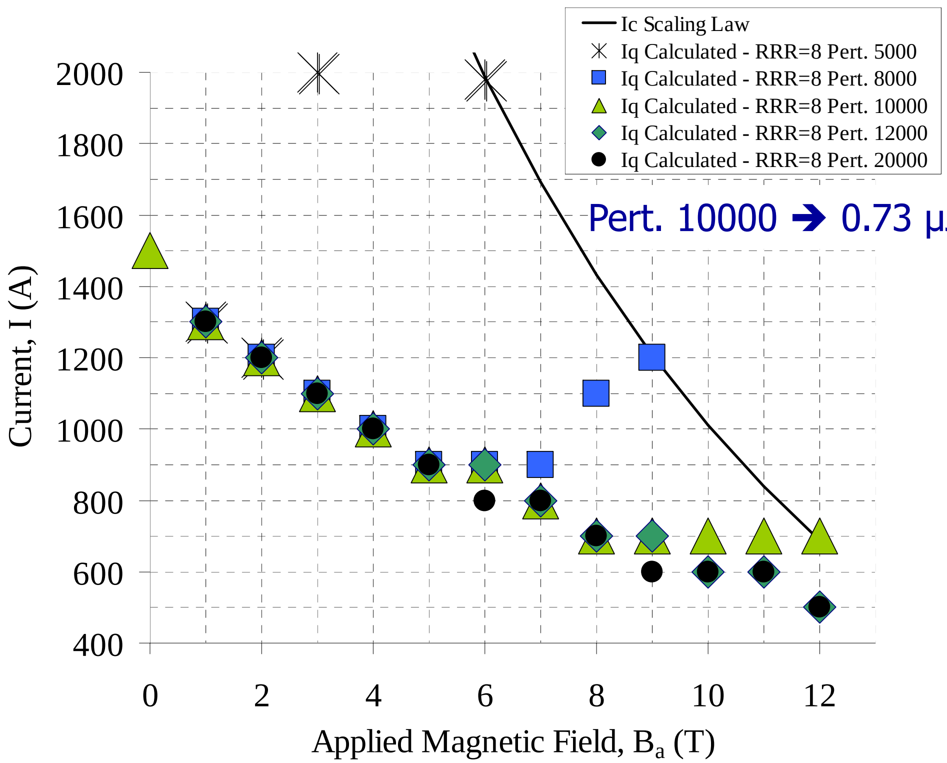
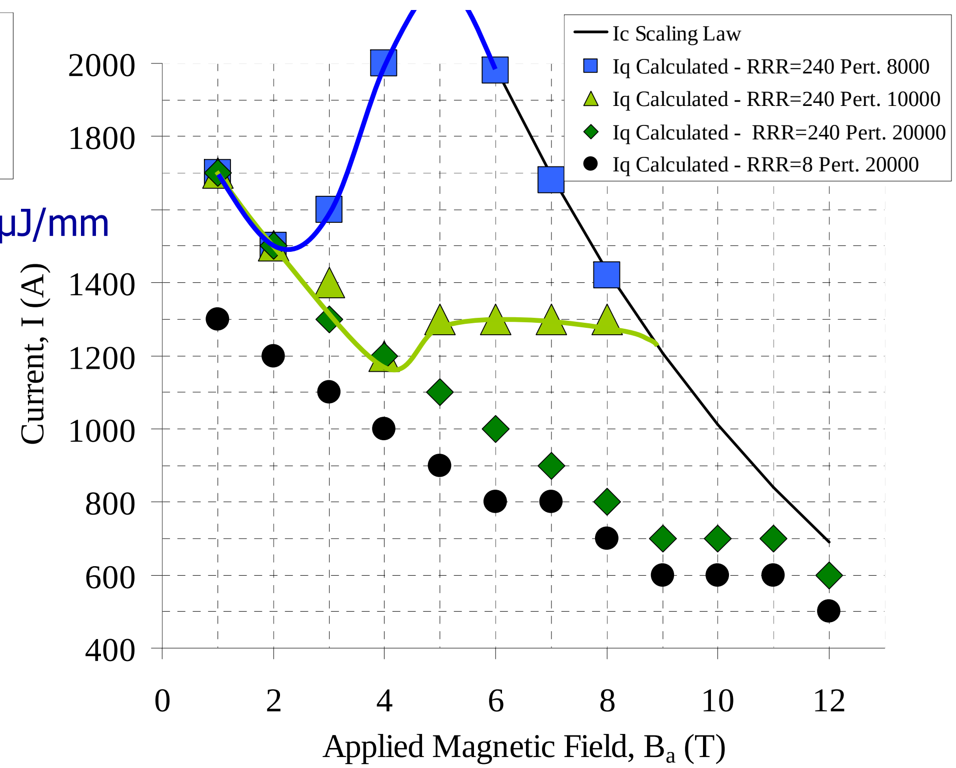
- The simulation of the self field instability by a Finite Element Model shows that the instability in the intermediate field region is sensitive to the amount of energy provided by the perturbation that initiates the flux-jump

Simulation of the quench current behavior at 4.2 K of a 0.8 mm 54 /61 RRP strand (J_c=2650 A/mm^2@12 T)





EFFECTS OF LOCAL STRAND'S DAMAGES

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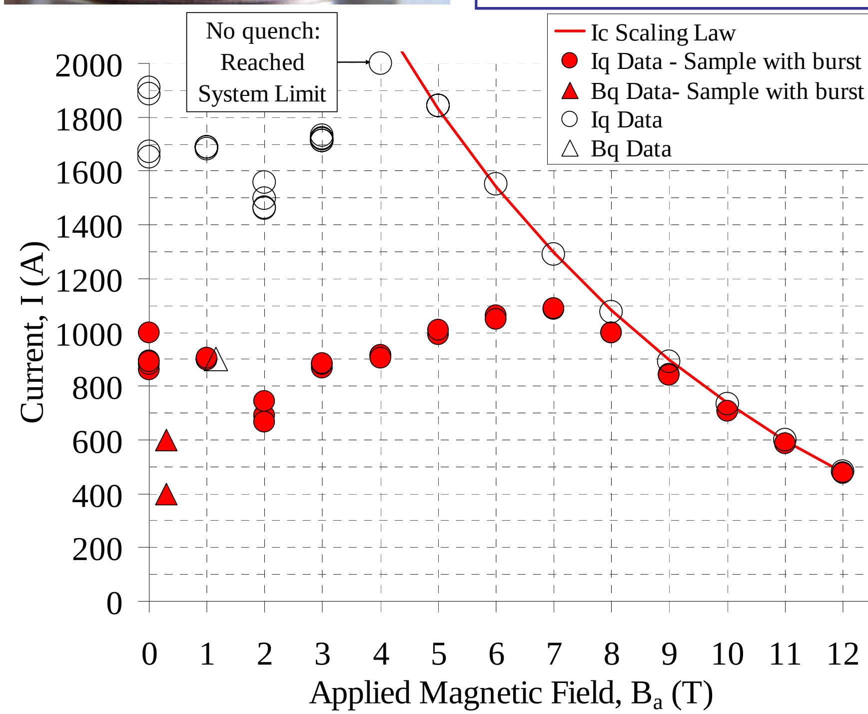
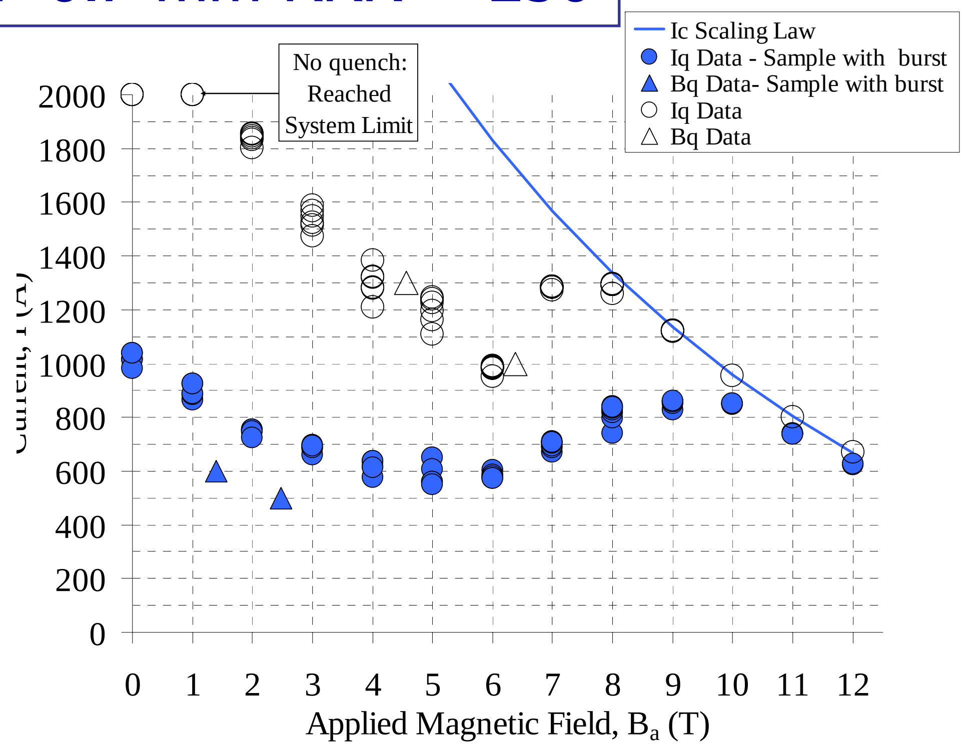
- A small local damage of the copper stabilizer can completely jeopardize the dynamic stabilization of a high J_c Nb_3Sn strand

LARP 54 /61 RRP 0.7 mm RRR > 250





CONCLUSIONS

- The self field instability is the predominant instability mechanism at 1.9 K.
- At 1.9 K, in the low field region (~0-7 T):
  1) the stability is improved by increasing the RRR in the range 8-120 while it was not observed a significant improvement in the range 140-290
  2) covering the strand sample with a 'thick' layer of stycast reduced the values of the premature quench current of ~ 10 %
- At 1.9 K, in the intermediate field region (~7-11 T) the quench current seems to be strongly dependent on the energy value of the perturbation that initiates the flux jump; in strand tests many times the minimum quench current was recorded in this field region and its value was lower than the critical current at 12 T
- An increase of the overall Cu content and the Cu in between the superconducting sub-elements might improve the self-field stability of record-J_c RRP strands; PIT strands adopted these solutions (they also have a lower J_c) and preliminary results show that they are much more self-field stable

ACKNOLEDGMENTS

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