



# manufacture of the superconducting Rutherford cable



# Rutherford cable development plan



## Luvata contract

5 unit lengths  $5 \times 360 \text{ m} = 1800 \text{ m}$   
filament geometrical diameter  $2.65 \mu\text{m}$   
two "generations", with increasing performances

first generation:

manufactured 2 unit lengths (now being wound)  
2 more unit lengths shall be delivered in January 2010

second generation:

1 unit length to be delivered in June 2010

## Brucker-EAS contract

80 km of low loss wire enough for 5 u.l.'s ,  
same spec's as Luvata contract, with  $2 \mu\text{m}$  filaments  
delivery in April 2010  
cabling (NOT included in the contract) being discussed



# Rutherford cable main characteristics



|                        |   |
|------------------------|---|
| Critical Current       | 18,540 A @ 5 T, 4.22 K (515 A/wire)<br>$J_c > 2530 \text{ A/mm}^2$            |
| n-value                | $> 30$  |
| Alpha                  | $> 1.5$   |
| Effective diameter     | 3.5 $\mu\text{m}$ (first generation)<br>2.5 $\mu\text{m}$ (second generation) |
| Transverse resistivity | $> 0.4 + 0.09 B \text{ n}\Omega \cdot \text{m}$                               |
| Ra                     | 200 $\mu\Omega$   |
| Rc                     | 20 m $\Omega$   |



# Luvata SC wire design



*Number of filaments  $55 \times 690 = 37,950$*

*Design filament diameter  $2.65 \mu\text{m}$*



# Ic measurements: virgin wire



| B [T] | Critical Current @ 4.22 K [A] : measured by Luvata Pori |     |     |     |     |     |     |  |     |
|-------|---|-----|-----|-----|-----|-----|-----|--|-----|
|       | 0.0%  |     |     |     |     |     |     |  |     |
|       | 4   | 5   | 6   | 7   | 8   | 9   | 15  |  | 25  |
| 6     | 383   | 386 | 390 | 391 | 391 | 392 | 393 |  | 394 |
| 5     | 475   | 479 | 482 | 484 | 485 | 486 | 488 |  | 489 |
| 4     | 574   | 578 | 582 | 584 | 585 | 586 | 588 |  | 588 |
| 3     | 701   | 704 | 708 | 711 | 711 | 713 | 714 |  | 715 |

Specified Ic before  
cabling 541 A @ 5  
T, 4.22 K

Measured values  
475-489 A  
@ 5 T, 4.22 K

| B [T] | n-index measured by Luvata Pori |    |    |    |    |    |    |    |    |
|-------|---------------------------------|----|----|----|----|----|----|----|----|
|       | 0.0%                            |    |    |    |    |    |    |    |    |
|       | 4                               | 5  | 6  | 7  | 8  | 9  | 15 | 15 | 25 |
| 6     | 30                              | 30 | 32 | 32 | 32 | 32 | 32 |    | 31 |
| 5     | 32                              | 32 | 33 | 33 | 33 | 34 | 33 |    | 32 |
| 4     | 33                              | 33 | 34 | 34 | 34 | 35 | 34 |    | 34 |
| 3     | 34                              | 34 | 35 | 35 | 35 | 36 | 34 |    | 34 |

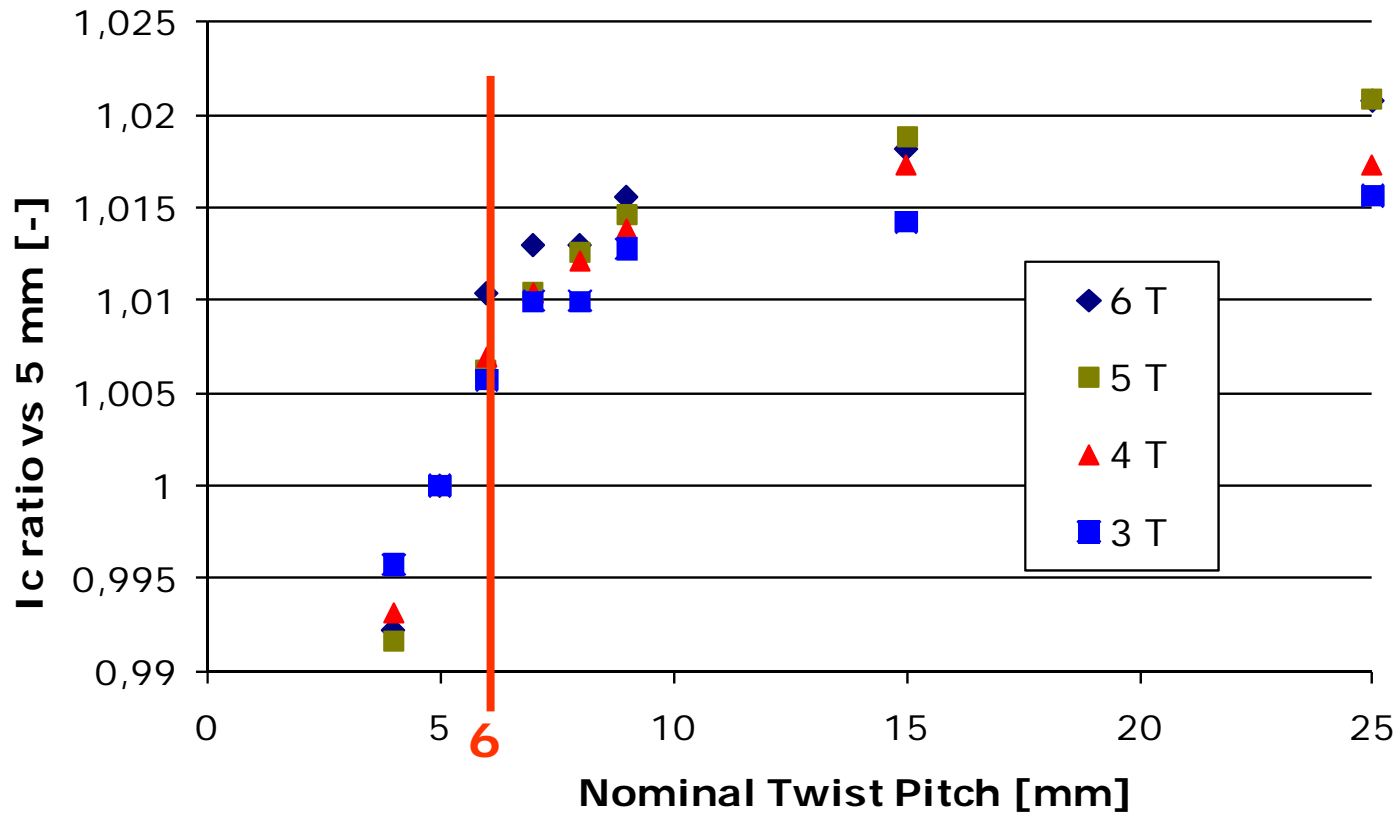
-10% w.r.t. specs

+ 3% w.r.t. LASA

| B [T]       | LASA vs Luvata Pori Ic results (LASA/Pori -1) |       |       |       |       |       |       |  |       |               |              |
|-------------|---|-------|-------|-------|-------|-------|-------|--|-------|---------------|--------------|
|             | 0.0%  |       |       |       |       |       |       |  |       |               |              |
|             | 4   | 5     | 6     | 7     | 8     | 9     | 15    |  | 25    | average       | std dev      |
| 6           | -2.2%   | -2.7% | -1.5% | -1.8% | -2.0% | -1.4% | -3.1% |  | -3.9% | -2.31%        | 0.86%        |
| 5           | -2.3%   | -2.5% | -1.7% | -1.9% | -1.9% | -1.0% | -3.4% |  | -3.9% | -2.30%        | 0.94%        |
| 4           | -2.8%   | -2.7% | -2.0% | -1.5% | -2.2% | -0.8% | -3.0% |  | -3.8% | -2.34%        | 0.93%        |
| 3           | -2.8%   | -2.5% | -2.7% | -2.0% | -1.9% | -1.1% | -3.3% |  | -3.9% | -2.53%        | 0.87%        |
| average     | -2.5%   | -2.6% | -2.0% | -1.8% | -2.0% | -1.1% | -3.2% |  | -3.9% | <b>-2.37%</b> | <b>0.86%</b> |
| standard de | 0.3%  | 0.1%  | 0.6%  | 0.2%  | 0.1%  | 0.2%  | 0.2%  |  | 0.1%  |               |              |



# Ic measurements: twist pitch effect



Final transposition pitch on the wire is 10% longer due to the final drawing step.

To be conservative, a 6 mm nominal t.p. has been selected for the mass production.



# Ic measurements: homogeneity along the billet



| DISCORAP PROJECT      |                                | M. Holm                       |                      | Nominal diameter   |      | 0,824 mm |      |      |      |      |      |      |      |                 |              |
|-----------------------|--------------------------------|-------------------------------|----------------------|--------------------|------|----------|------|------|------|------|------|------|------|-----------------|--------------|
| Billet ID             |                                | 09244                         |                      | Design alpha ratio |      | 1,67     |      |      |      |      |      |      |      |                 |              |
| OK 690                |                                | Multi II                      |                      |                    |      |          |      |      |      |      |      | n.m. |      | not measured    |              |
| Billet piece ID       | Twist measured in final dia mm | Cu/Sc                         | Measured dia AVG. mm | n-factor           |      |          |      | Ic   |      | Ic   | Jc   | Ic   | RRR  | Sharp bend test | Length m     |
|                       |                                |                               |                      | 3T                 | 4 T  | 5 T      | 6 T  | 3T   | 4 T  | 5 T  | 6 T  |      |      |                 |              |
| 1                     | 6,7                            | 1,626                         | 0,8235               | 36                 | 35   | 34       | 33   | 749  | 618  | 511  | 2524 | 411  | 121  | OK              | 3080         |
| 2                     | 6,6                            | 1,753                         | 0,824                | 34                 | 35   | 34       | 33   | 713  | 588  | 487  | 2522 | 393  | n.m. | OK              | 1295         |
| 3A                    | 6,7                            | 1,759                         | 0,824                | n.m.               | n.m. | n.m.     | n.m. | n.m. | n.m. | n.m. |      | n.m. | n.m. | OK              | 3370         |
| 3B                    | 6,6                            | 1,758                         | 0,8235               | n.m.               | n.m. | n.m.     | n.m. | n.m. | n.m. | n.m. |      | n.m. | n.m. | OK              | 975          |
| 4                     | 6,7                            | 1,763                         | 0,8235               | 35                 | 35   | 34       | 32   | 705  | 580  | 480  | 2494 | 386  | n.m. | OK              | 2485         |
| 5                     | 6,7                            | 1,751                         | 0,823                | 35                 | 35   | 34       | 32   | 707  | 583  | 484  | 2504 | 388  | 131  | OK              | 25200        |
| 6                     | 7,1                            | 1,785                         | 0,823                | 36                 | 35   | 33       | 32   | 698  | 574  | 475  | 2488 | 383  | 137  | OK              | 11045        |
|                       |                                |                               |                      |                    |      |          |      |      |      |      |      |      |      |                 | <b>47450</b> |
| machine setup twist   |                                | Twist calculated in final dia |                      |                    |      |          |      |      |      |      |      |      |      |                 |              |
| 6                     |                                | 6,6                           |                      |                    |      |          |      |      |      |      |      |      |      |                 |              |
| Twist at dia 0,867mm* |                                |                               |                      |                    |      |          |      |      |      |      |      |      |      |                 |              |

Average Ic on virgin wire    487 ± 14 A (± 3%)  
 Average Jc                            2,506 ± 16 A/mm<sup>2</sup> (± 0.6%)

*most variation comes from Cu content fluctuation*



# Ic degradation during cabling



Wire nominal Ic @ 4.2 K, 5 T is the specified final value after cabling 515 A

measured Ic by Luvata Pori on 5 extracted strands (**ave**, max, min) **466**, 463, 470 A

Measured Ic by LASA on 4 extracted strands (**ave**, max, min) **442**, 448, 435 A

## *How severe is the Ic reduction?*

|                               | design value | experimental |       |
|-------------------------------|--------------|--------------|-------|
|                               | Specs        | Luvata       | LASA  |
| Ic decabled [A]               | 515          | 466          | 442   |
| Ratio wrt specified           | 100%         | 90%          | 86%   |
| T current sharing [K]         | 5.67         | 5.53         | 5.45  |
| Margin wrt 4.7 K [K]          | 0.97         | 0.83         | 0.75  |
| Iop/Ic(Top,Bmax)              | 57.1%        | 63.1%        | 66.5% |
| Working point on<br>load line | 79.8%        | 82.8%        | 84.7% |

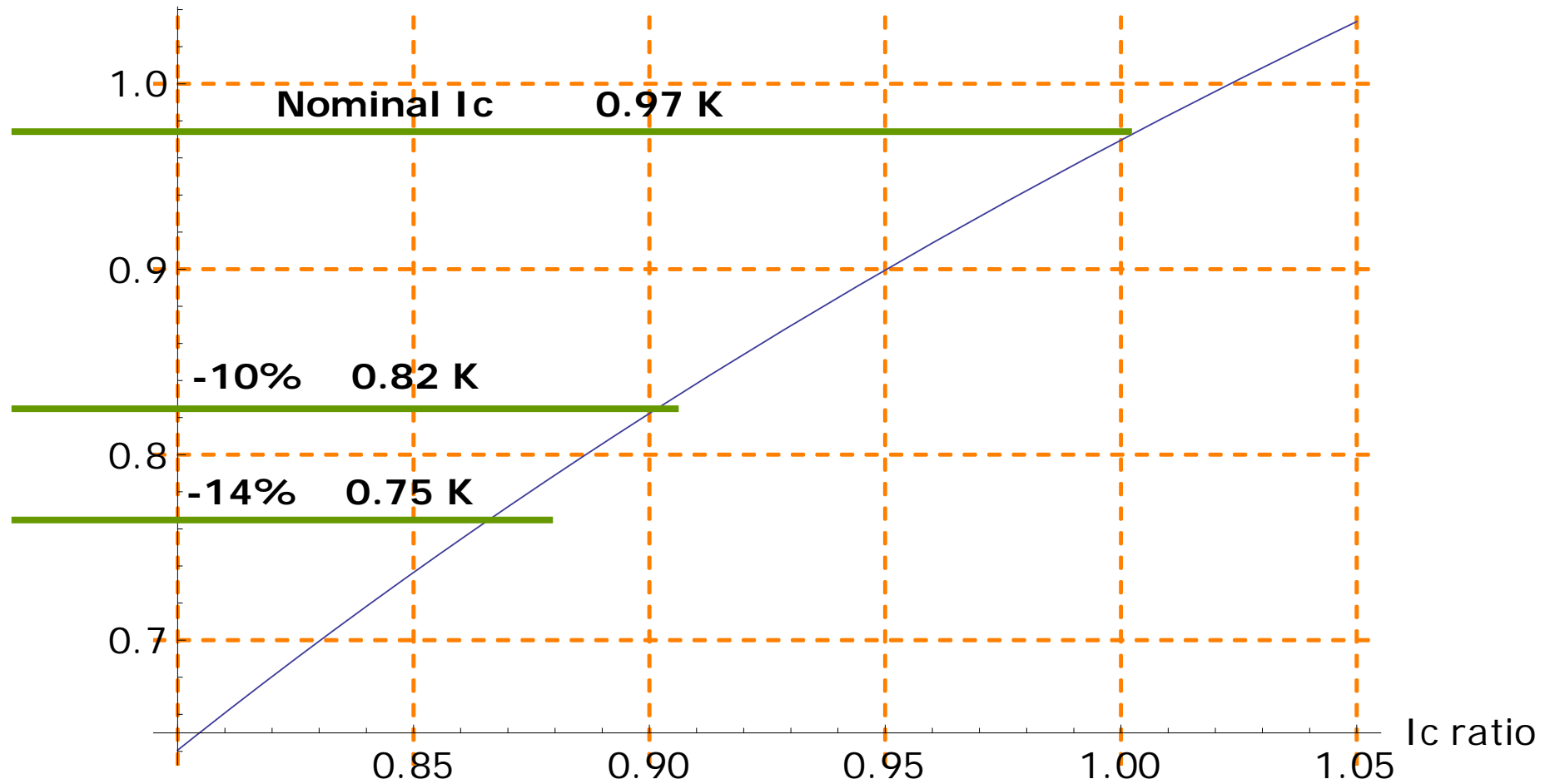




# Temperature Margin



Temperature margin [K]





# magnetization curve

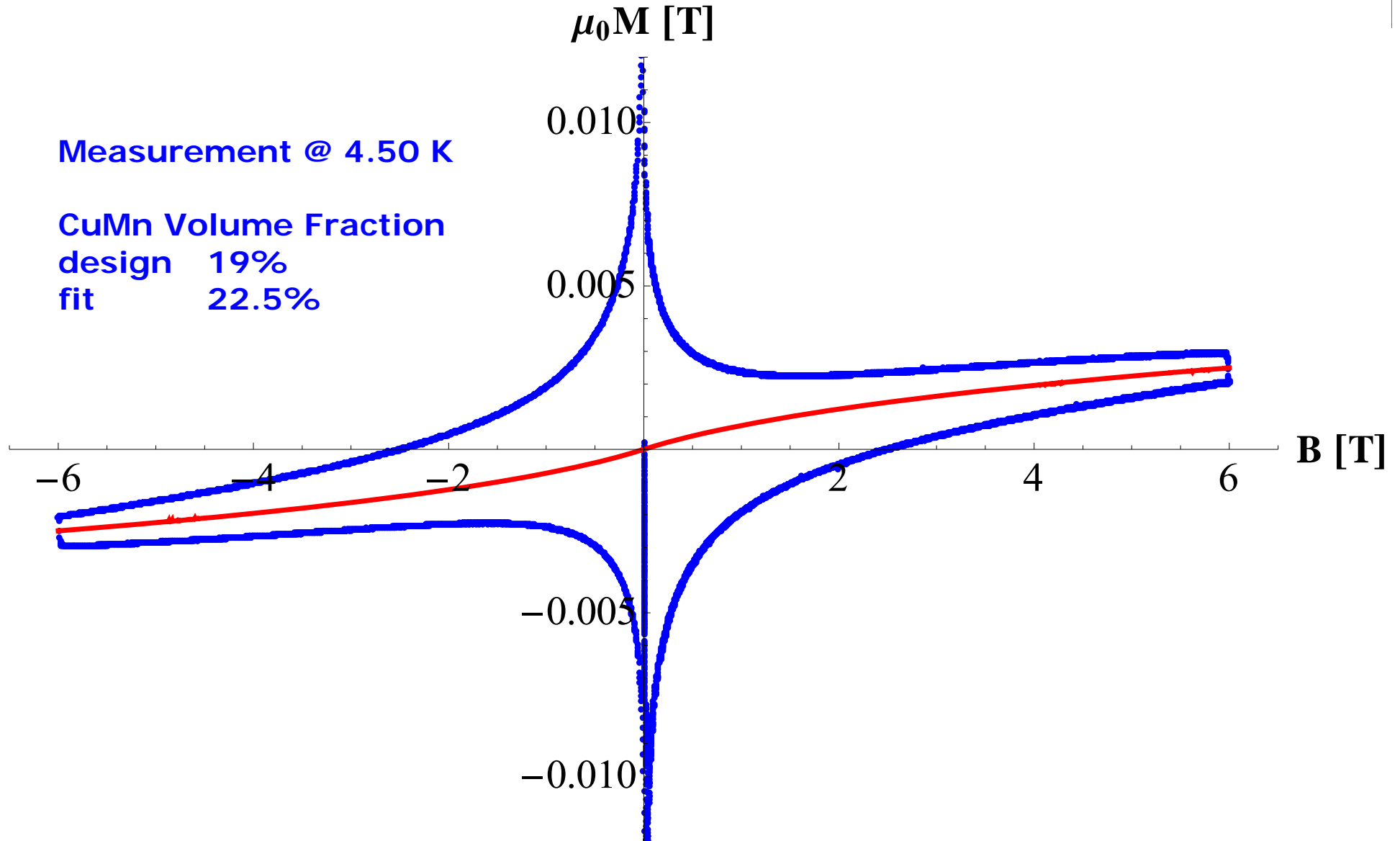


Measurement @ 4.50 K

CuMn Volume Fraction

design 19%

fit 22.5%





# effective diameter



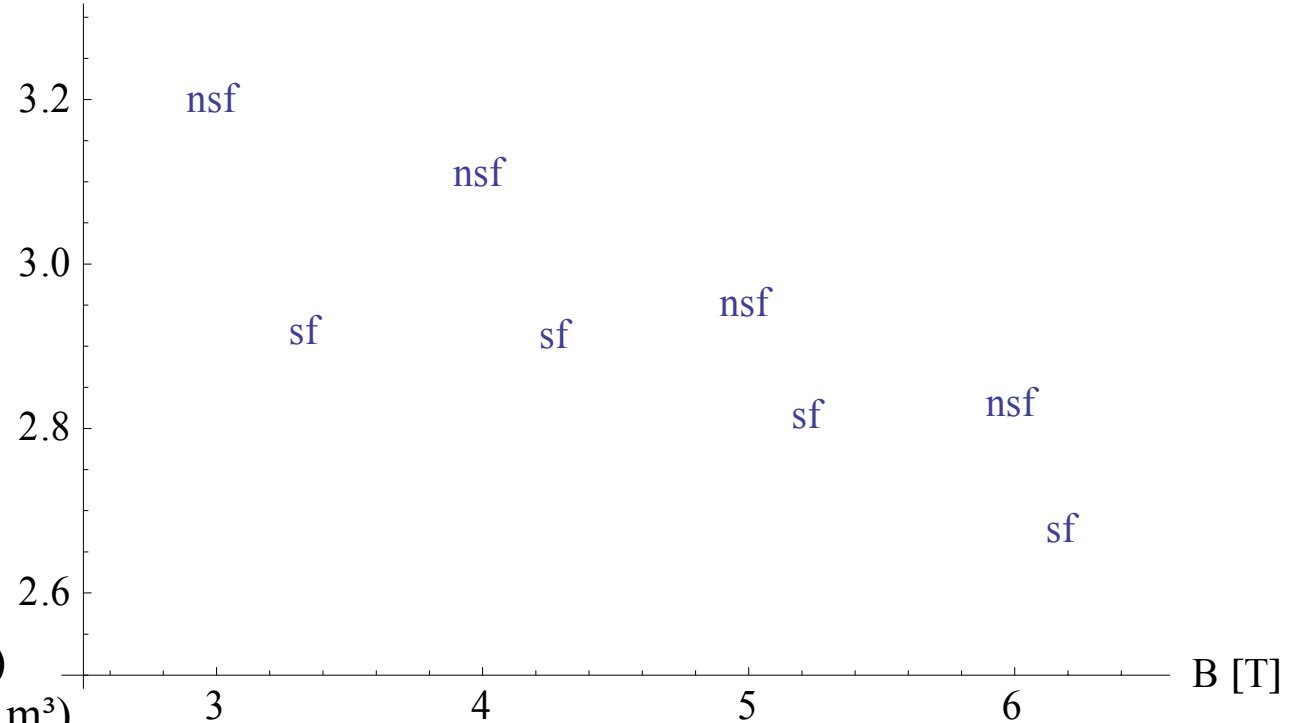
$$M = \frac{4\mu_0}{3\pi} J_c a$$

$$\frac{3\pi}{2\mu_0} \frac{m}{I_c l} = 2a$$

where:

- $M$  magnetization (T)
- $m$  magnetic moment ( $T \cdot m^3$ )
- $l$  sample length (m)
- $r$  wire radius (m)
- $a$  filament radius (m)
- $I_c$  critical current (A)
- $J_c$  critical current ( $A/m^2$ )

Effective diameter [ $\mu m$ ]





# transverse resistivity

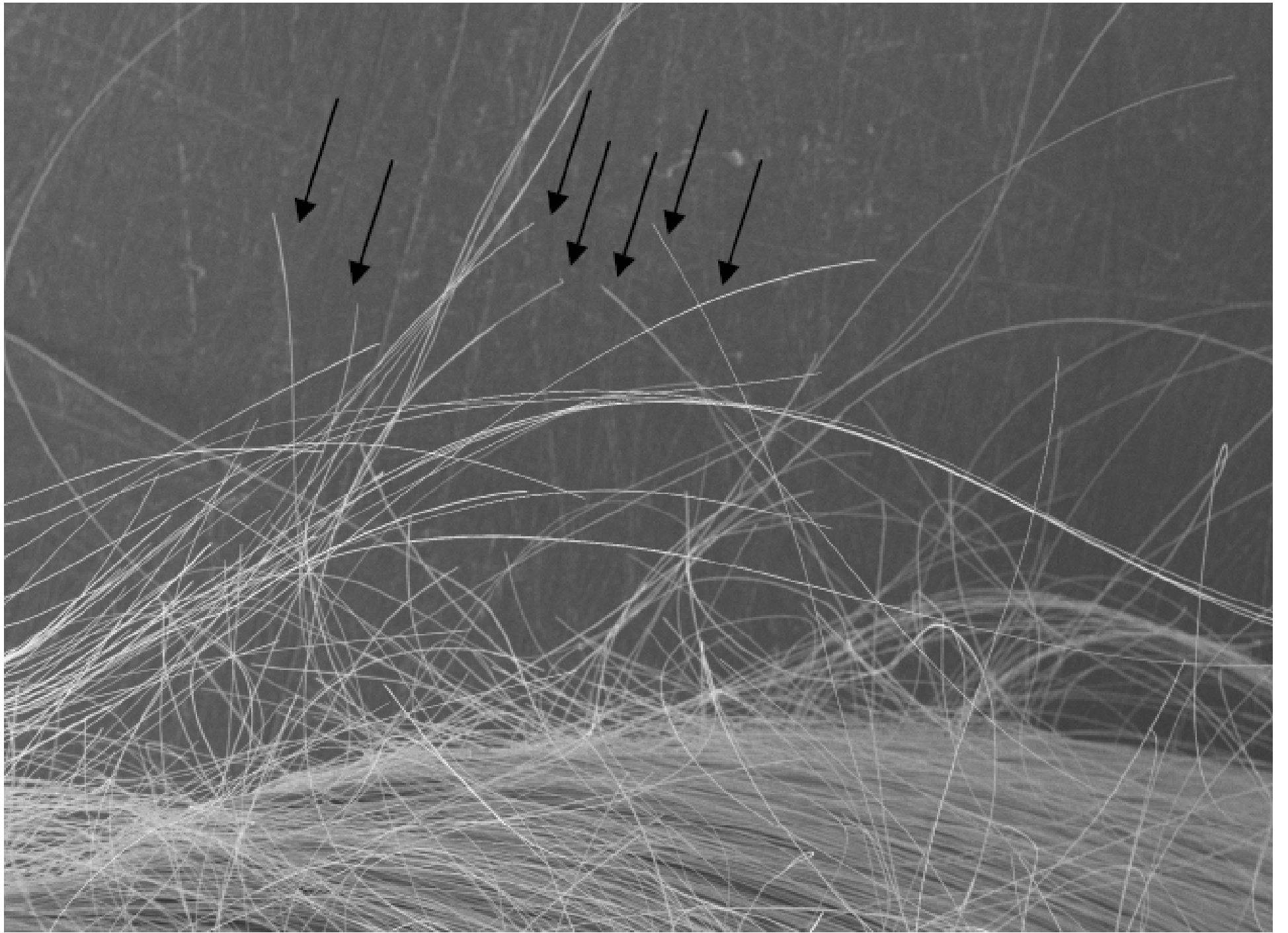


|                                 |  |      |
|---------------------------------|--|------|
| Alpha wire                      | 1.70   |      |
| Cu RRR=100 resistivity at 4.2 K | $1.53 \cdot 10^{-10}$ @ 0 T<br>$3.53 \cdot 10^{-10}$ @ 5 T | nΩ·m |
| CuMn resistivity at 4.2 K       | $2.5 \cdot 10^{-8}$  | nΩ·m |

| Contact type   | $\rho_t(B=0)$ |       | $d\rho_t/dB$ |       |
|----------------|---------------|-------|--------------|-------|
|                | nΩ·m          |       | nΩ·m/T       |       |
|                | Good          | Bad   | Good         | Bad   |
| <b>Designs</b> |               |       |              |       |
| A              | 0.463         | 0.492 | 0.097        | 0.117 |
| B              | 0.771         | 0.855 | 0.138        | 0.188 |
| C              | 0.496         | 0.530 | 0.109        | 0.134 |
| D              | 0.496         | 0.530 | 0.109        | 0.134 |

Experimental value at 0.2 T

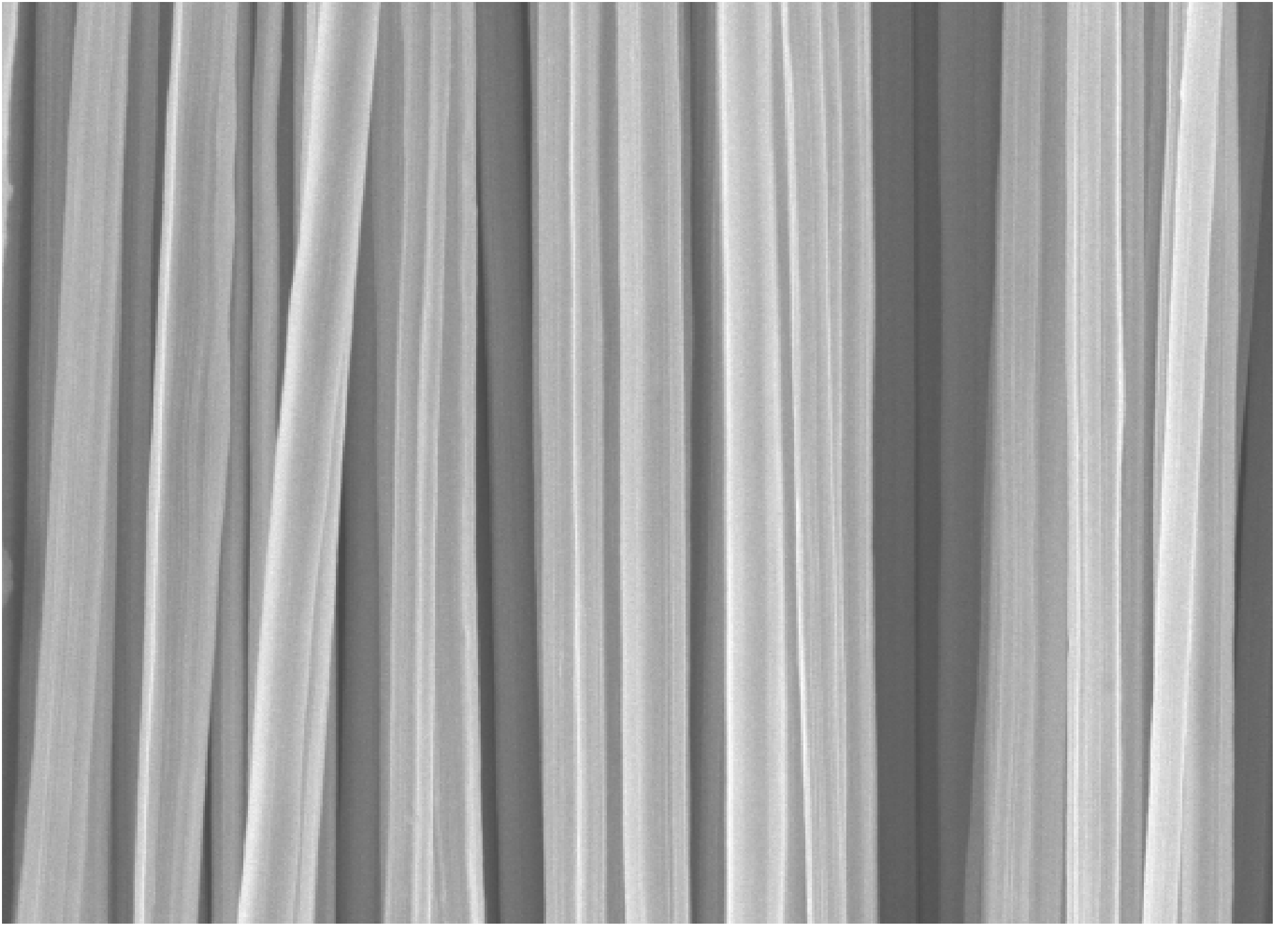
0.3 nΩ·m



2mm



100μm



40µm



# Comments



The low loss Rutherford cable for the DISCORAP magnet is there!

Low  $I_c$ , but no impact expected on this model performances

Partly because of the higher alpha ratio (1.74 measured, 1.67 target, 1.5 minimum specified)

Sensitive to degradation during cabling

Small(er) filament diameter

Lower transverse resistance and longer twist pitch

$R_a$  and  $R_c$  now being measured







## 2<sup>nd</sup> generation



### Ic improvement

we believe that the severe deformation of the external filaments of each sub-element, leads to locally reduced  $J_c$ . These filaments therefore do not contribute neither to the transport current nor to the magnetization

Luavata believes to be able to improve the filament quality.

### New lay-out

A new design, with more CuMn, will be adopted to increase the transverse resistivity



## Wire cross section 2<sup>nd</sup> generation



*The number of CuMn-sheath subelements will be increased in the second generation, to raise the transverse resistivity*

**Wire Component Volume Fractions.**

|                | Generation I | Generation II |
|----------------|--------------|---------------|
| (Cu+CuMn)/NbTi | 1.56         |               |
| NbTi           | 39.0%        | 39.0%         |
| Cu             | 42.3%        | 36.3%         |
| CuMn           | 18.7%        | 24.7%         |



**the end**