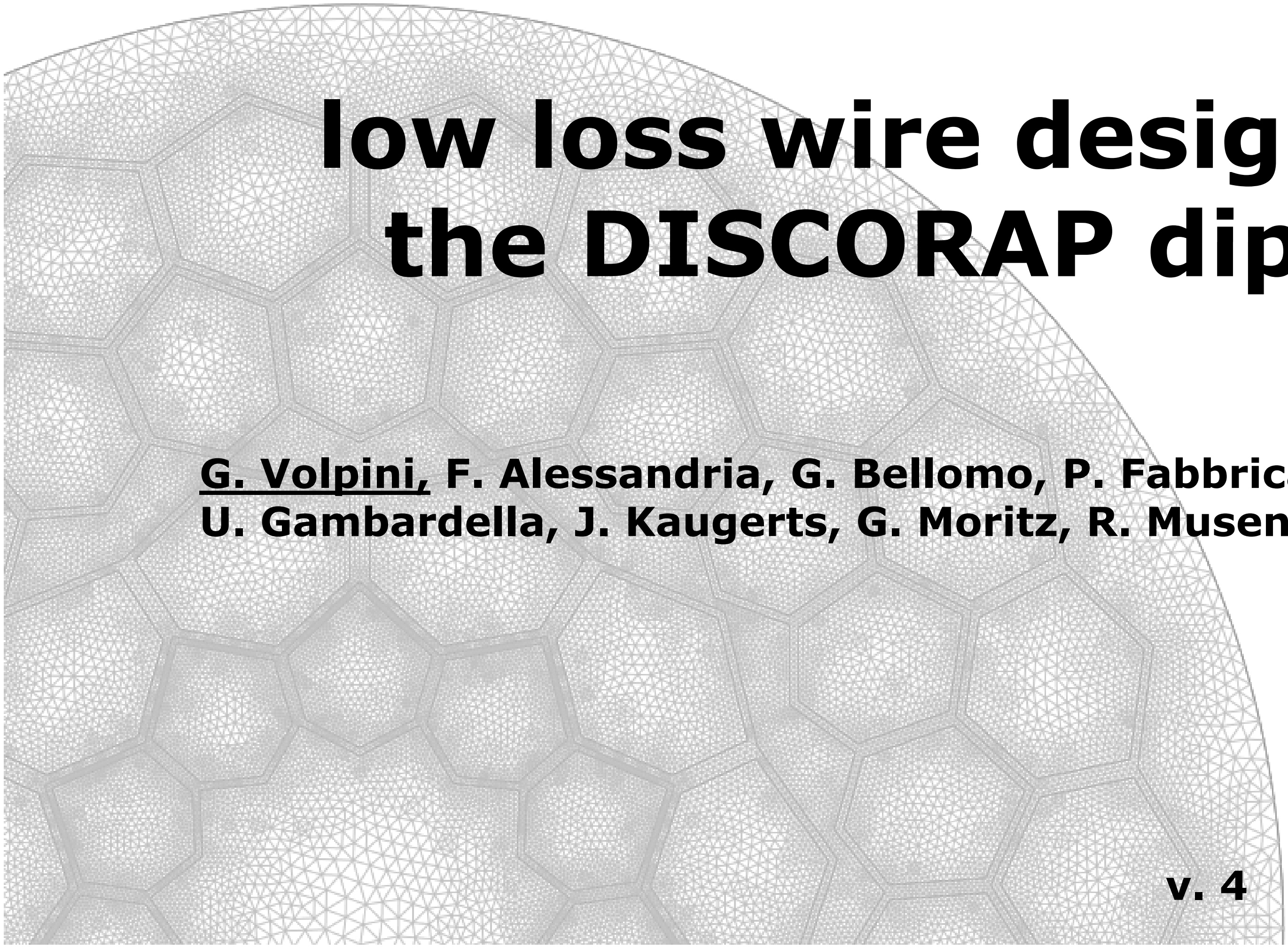

low loss wire design for the DISCORAP dipole

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v. 4

The DISCORAP project

The SIS-300 synchrotron of the new FAIR facility at GSI (Germany) will use fast-cycled superconducting magnets. Its dipoles will be pulsed at 1 T/s; for comparison, LHC is ramped at 0.007 T/s and RHIC at 0.042 T/s.

Within the frame of a collaboration between INFN and GSI, **INFN** has funded the project **DISCORAP** (***DI***_poli_ ***S***_uper_***CO***_nduttori_ ***RA***_pidamente_ ***P***_ulsati_, or Fast Pulsed Superconducting Dipoles) whose goal is to design, construct and test a half length (4 m), curved, model of one lattice dipole.

This presentation will focus on the low loss superconducting wire design

Thursday 22 **P. Fabbricatore** will give an overview of DISCORAP project

Rutherford cable development rationale

Main design choices:

Jc 2,600 A/mm2 @ 5 T, 4.2 K (achieved 2,700 A/mm2 on the prototype wire)
alpha 1.5 (Cu+CuMn)/NbTi
filament diameter 2.5 – 3.5 µm
CuMn interfilamentary matrix
stainless steel Rutherford cable core
redundancy

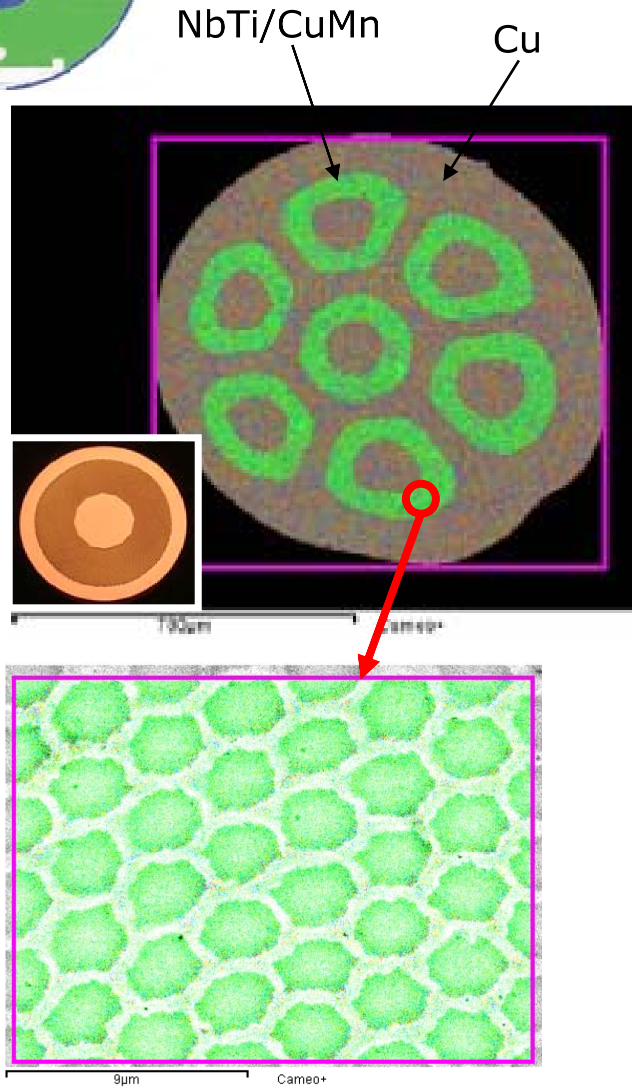
- more cable than required,
  in case difficulties are met in cable developement,
  or during the magnet construction
- to test different solutions in the wire design.

We awarded a contract to Luvata Fornaci di Barga Italy, to manufacture

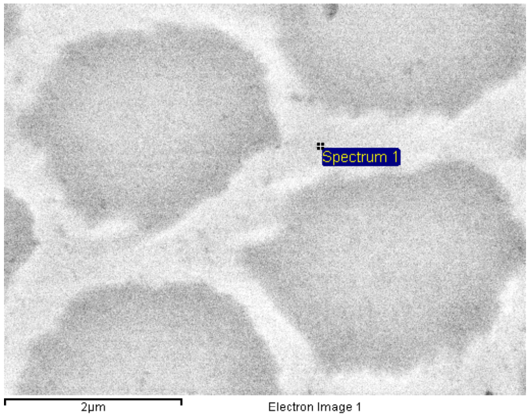
720 m (two unit lengths) of type-1 Cable (1st generation)
1080 m (three unit lenghts) of type-2 Cable (2nd generation)

1st generation 40K filaments, 2.6 µm geometrical (~3.5 µm effective)
2nd generation 58K filaments, 2.2 µm geometrical (~2.8 µm effective) + added CuMn barriers

Prototype wire



The “prototype wire” is based on cold drawing of seven elements of Luvata OK3900 wire already in stock.
Although significantly different from the final wire, it has allowed to assess which Jc and twist pitch can be realistically achieved on wires with NbTi fine filaments embedded in a CuMn matrix, with a diameter around 2 3 µm.



Geometrical filament diameter 2.52 µm
Small apparent deformation

Wire specifications

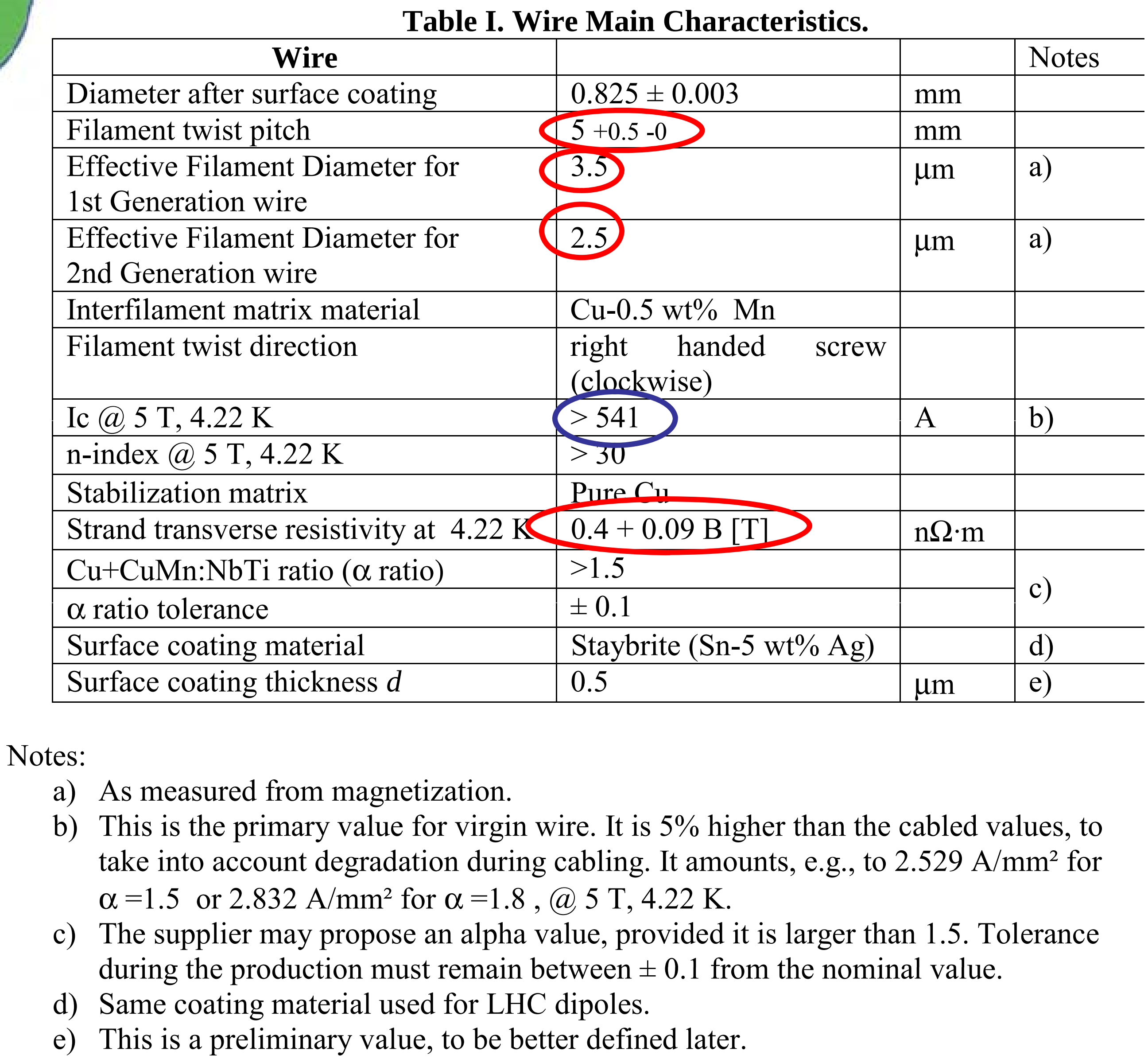


Table I. Wire Main Characteristics.

Wire			Notes
Diameter after surface coating	0.825 ± 0.003	mm	
Filament twist pitch	5 +0.5 -0	mm	
Effective Filament Diameter for 1st Generation wire	3.5	µm	a)
Effective Filament Diameter for 2nd Generation wire	2.5	µm	a)
Interfilament matrix material	Cu-0.5 wt% Mn		
Filament twist direction	right handed screw (clockwise)		
Ic @ 5 T, 4.22 K	> 541	A	b)
n-index @ 5 T, 4.22 K	> 30		
Stabilization matrix	Pure Cu		
Strand transverse resistivity at 4.22 K	0.4 + 0.09 B [T]	nΩ·m	
Cu+CuMn:NbTi ratio (α ratio)	>1.5		c)
α ratio tolerance	± 0.1		
Surface coating material	Staybrite (Sn-5 wt% Ag)		d)
Surface coating thickness *d*	0.5	µm	e)

Notes:

a) As measured from magnetization.

b) This is the primary value for virgin wire. It is 5% higher than the cabled values, to take into account degradation during cabling. It amounts, e.g., to 2.529 A/mm² for α =1.5 or 2.832 A/mm² for α =1.8 , @ 5 T, 4.22 K.

c) The supplier may propose an alpha value, provided it is larger than 1.5. Tolerance during the production must remain between ± 0.1 from the nominal value.

d) Same coating material used for LHC dipoles.

e) This is a preliminary value, to be better defined later.

Rutherford cable specifications

Table II. Cable Main Characteristics.

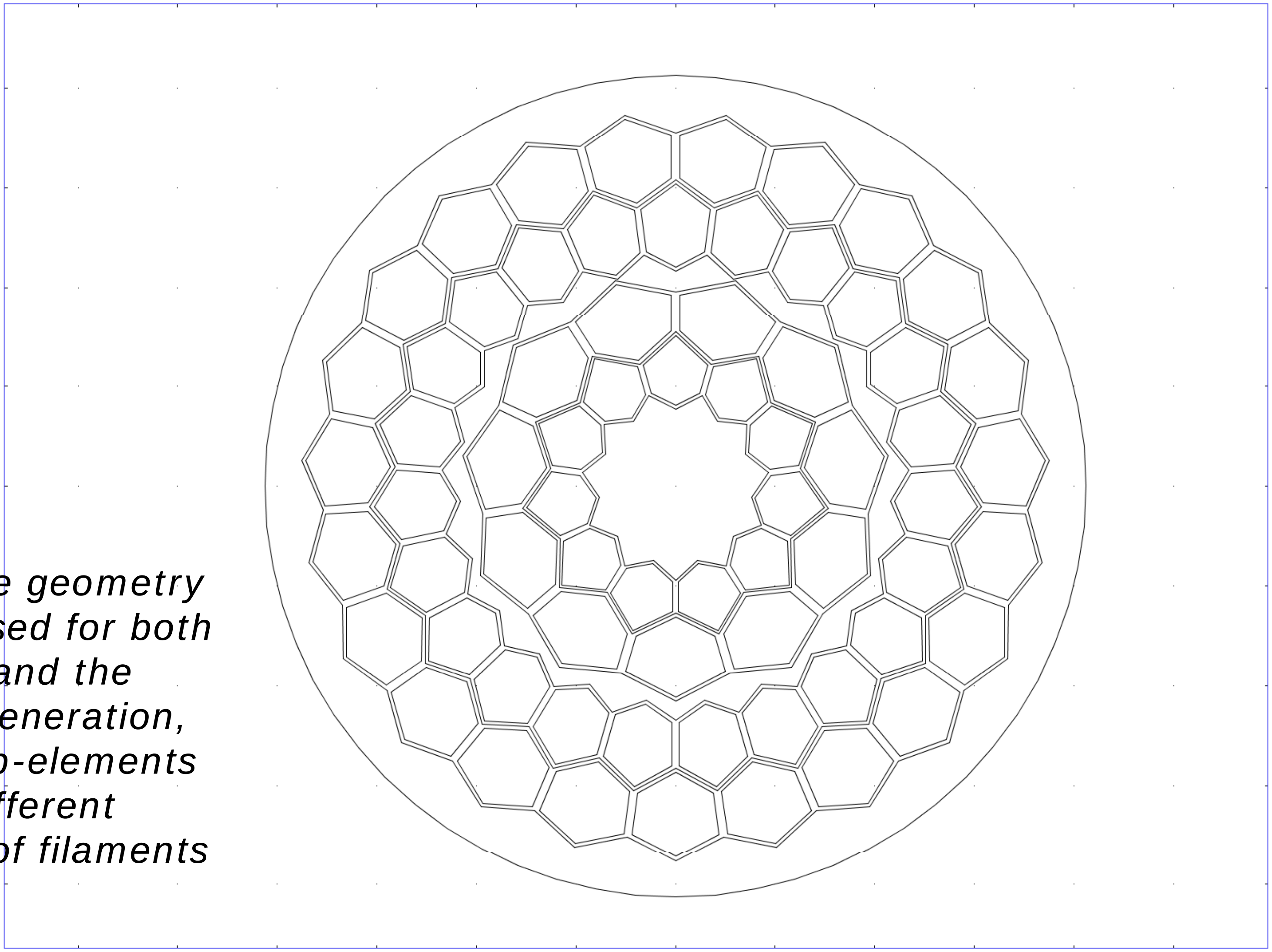
Geometrical			Not
Strand Number	36		a)
Width	15.10 +0 -0.020	mm	
Thickness, thin edge	1.362 ± 0.006	mm	
Thickness, thick edge	1.598 ± 0.006	mm	
Mid-thickness at 50 MPa	1.480 ± 0.006	mm	
Edge radius	≥ 0.30	mm	
Core material	AISI 316 L stainless steel, annealed		
Core width	13	mm	
Core thickness	25	µm	
Transposition pitch	100 ± 5	mm	
Cable transposition direction	left-handed screw thread		
Electrical			
Ic @ 5 T, 4.22 K	>18,540	A	b)
Stabilization matrix RRR	>70		

Notes:

a) The geometrical layout is the same as that of the LHC dipole outer cable design. Dimensions are specified at 20 °C.

b) Ic @ 5 T, 4.22 K for the extracted strand must be equal to or above 515 A.

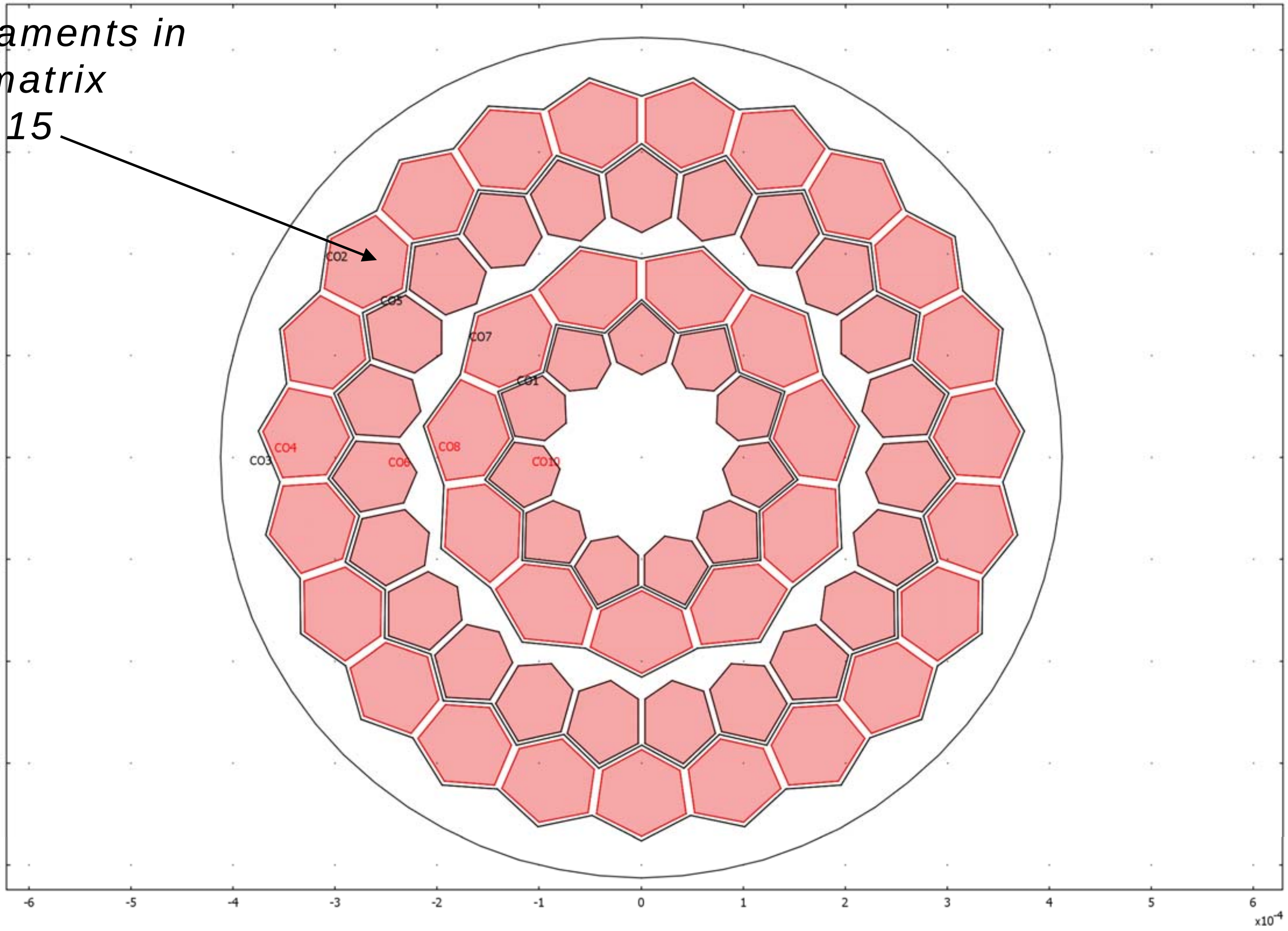
Wire cross section overall



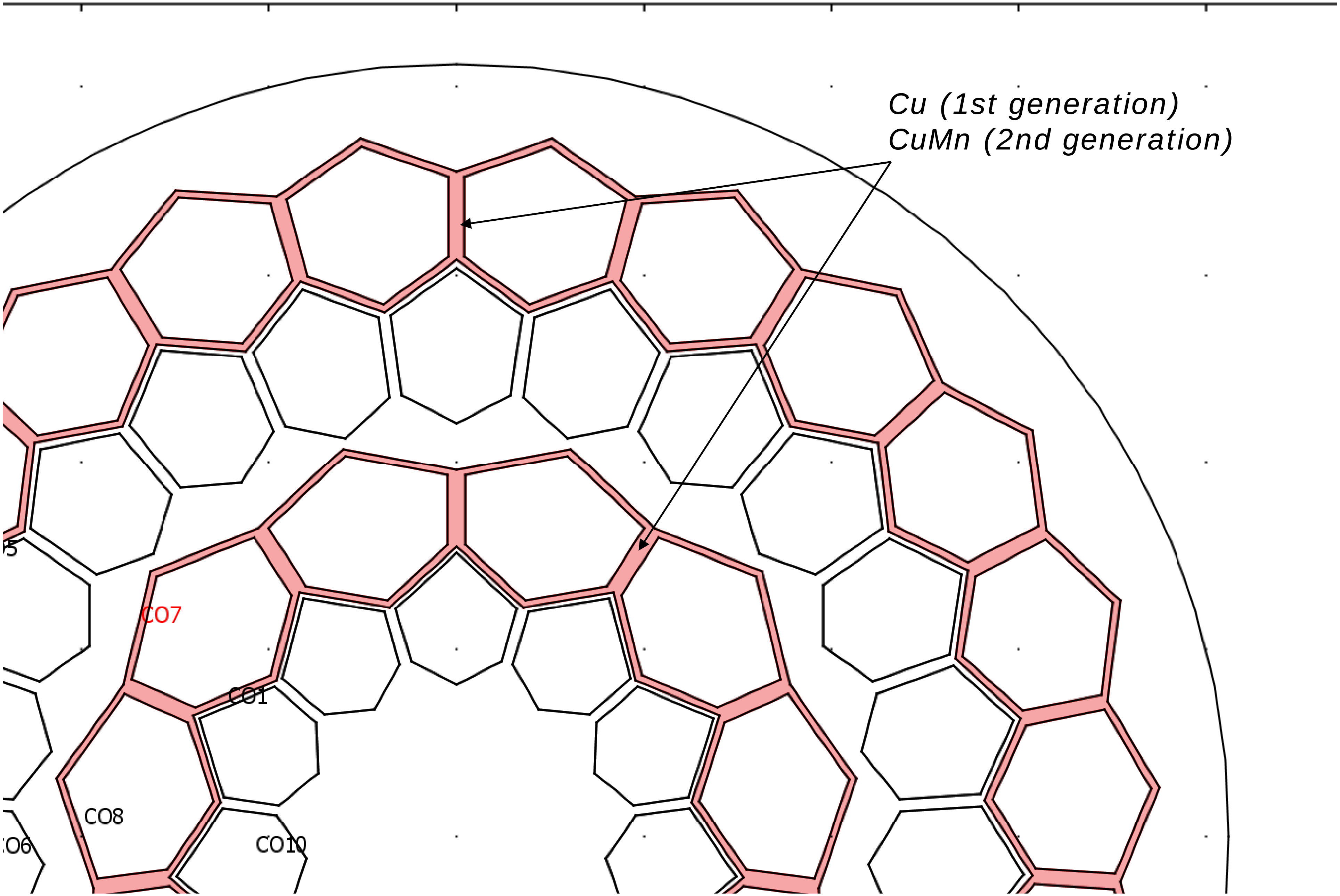
The same geometry will be used for both the first and the second generation, using sub-elements with a different number of filaments

Wire cross section: Filamentary areas

NbTi filaments in
CuMn matrix
s/d ~0.15

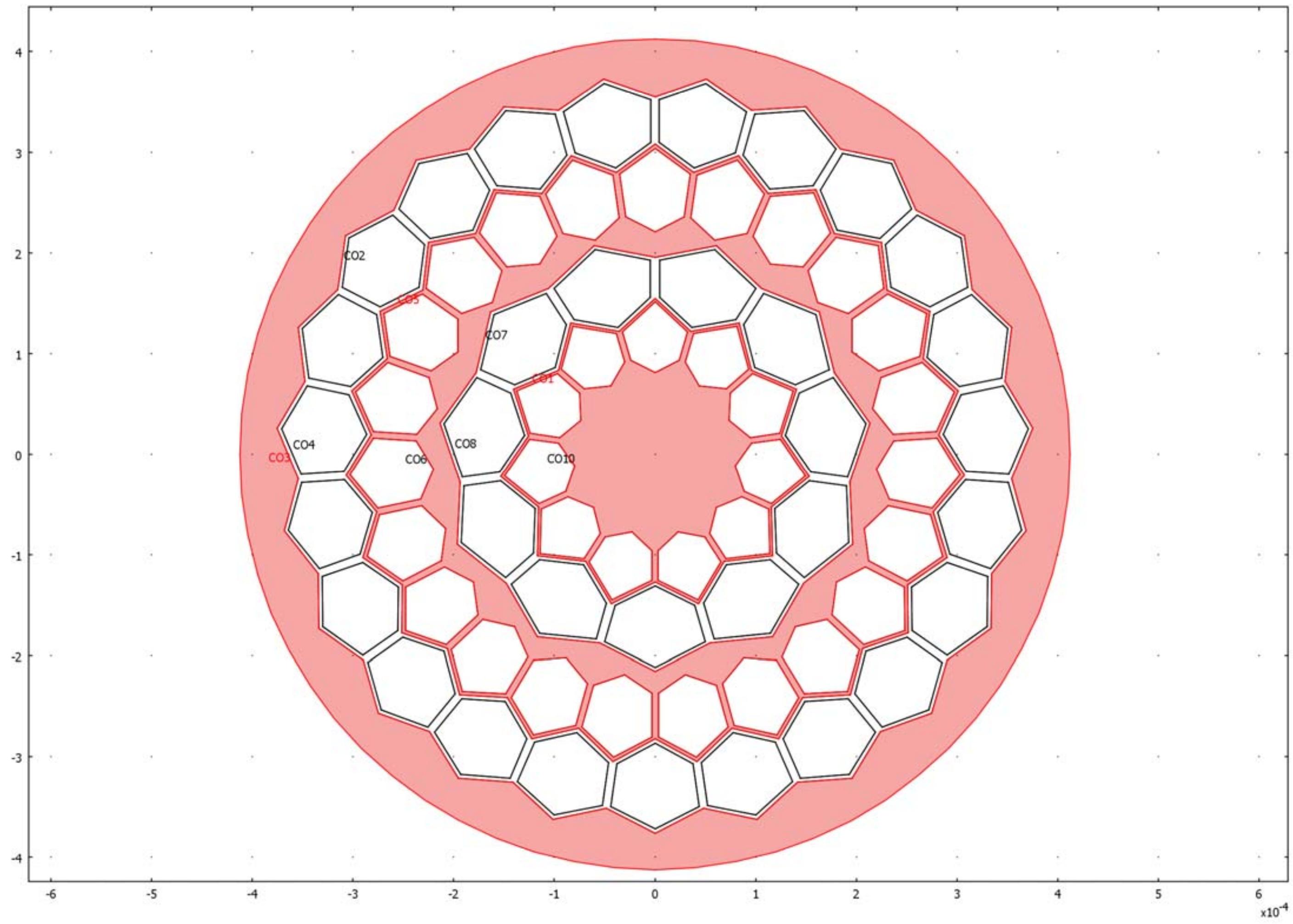


Wire cross section: Barriers

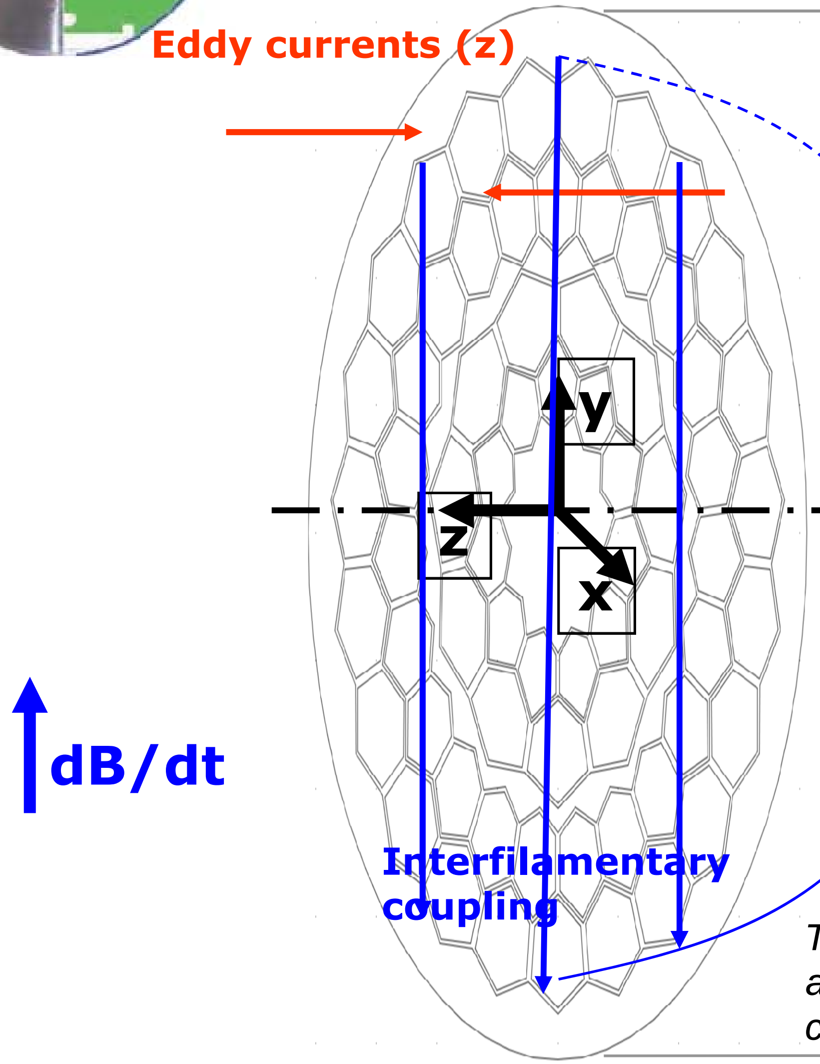


Cu (1st generation)
CuMn (2nd generation)

Wire cross section:
Cu areas



Eddy & Transverse Currents
Problem statement



$$\nabla^2\varphi(x,y)=0$$

Laplace Equation

$$\varphi(R,\vartheta)=\frac{\dot{B}\,L\,R}{2\,\pi}\cos(\vartheta)$$

Boundary condition around the filamentary areas

E.C. term

Interfil. term

$$Q=j^2/\sigma=\sigma\,[\dot{B}^2x^2+(\partial_x\varphi)^2+(\partial_y\varphi)^2]$$

$$\rho_t=\frac{\dot{B}^2}{Q}\left(\frac{L}{2\pi}\right)^2$$

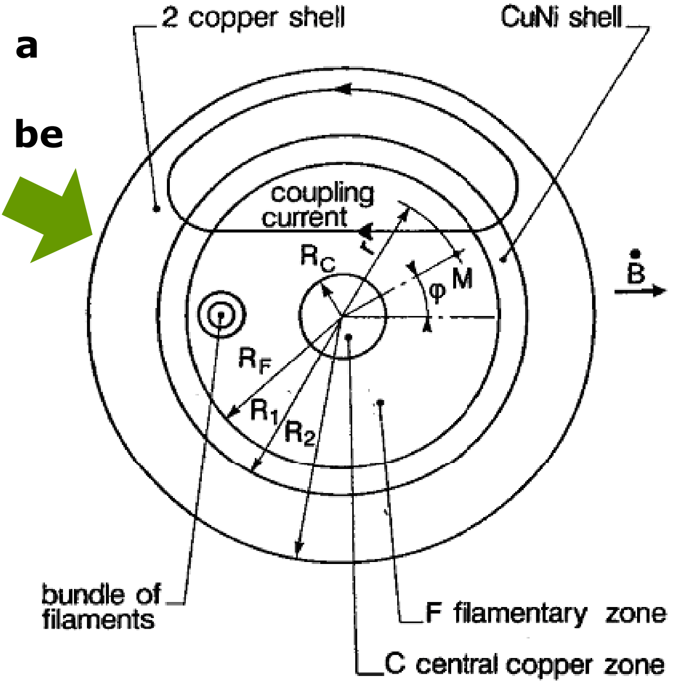
“effective” transverse resistivity

*Therefore we use the term **transverse resistivity** in a wider meaning; it describes both the transverse current and the EC losses.*

The EC’s contribute to 10-15% of the total losses

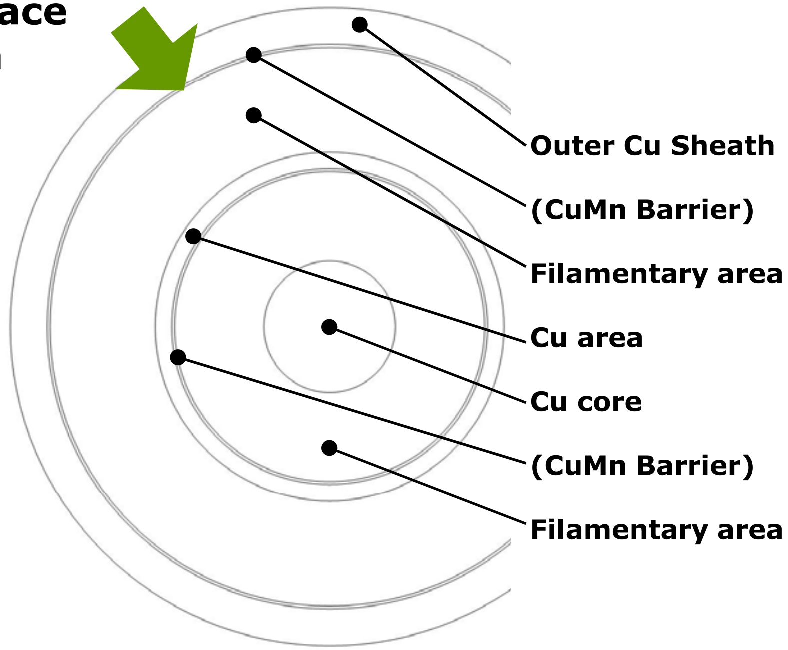
Solving the problem: analytical approach

Duchateau, J.L. Turck, B. & Ciazynski, D. have developed a model, based on a simplified geometry, with cylindrical symmetry. In this model, the above-seen equations may be solved analytically.



Duchateau, J.L. Turck, B. Ciazynski, D. “Coupling current losses in composites and cables: analytical calculations” Ch. B4.3 in “Handbook of Applied Superconductivity”, IoP 1998

We have improved their approach, to better suit our geometry, increasing the number of annular regions from 4 to 7. The Laplace equation has then been solved.



Outer Cu Sheath

(CuMn Barrier)

Filamentary area

Cu area

Cu core

(CuMn Barrier)

Filamentary area

Filamentary zone resistivity

Following an approach by M N Wilson, the resistivity of the filamentary is the averaged sum of the different zones:
bulk Cu, bulk CuMn, and filamentary zone.

For the filamentary zone we have considered the Carr approach, with the two extreme hypotheses of poor and good coupling.

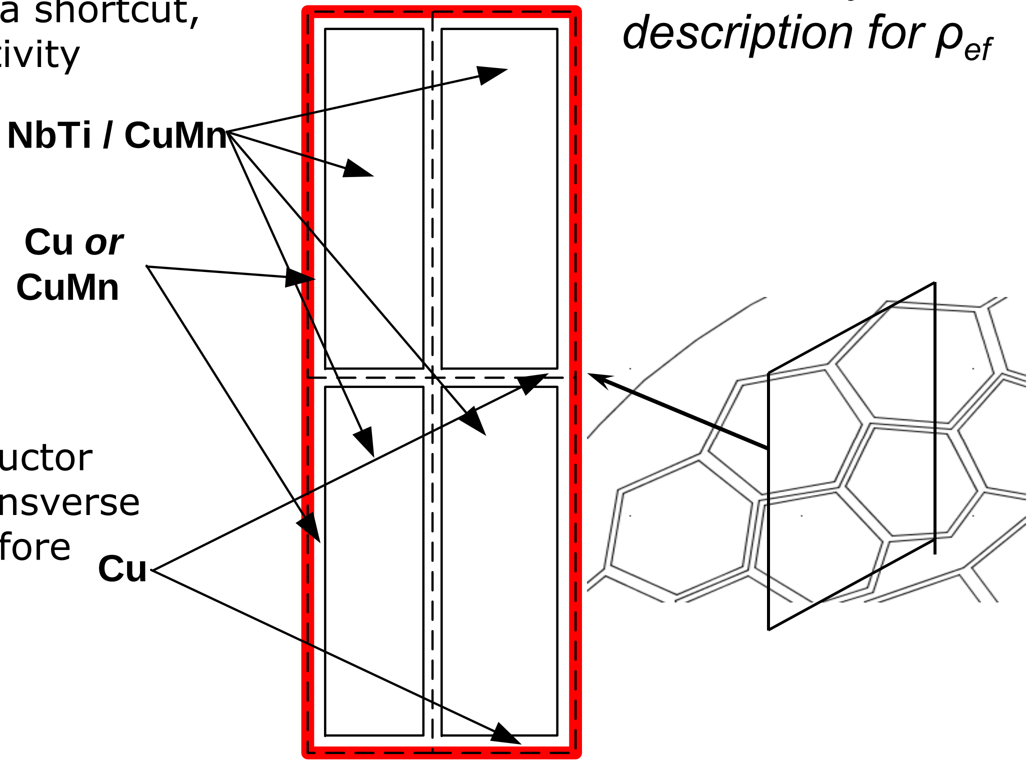
-good coupling
The superconductor effectively acts a shortcut, reducing therefore the matrix resisitivity

$$\rho_t = \rho_m \frac{1-\lambda}{1+\lambda}$$

-poor coupling
The high contact resistance between the matrix and the NbTi, prevents the current from flowing through the superconductor which does not contribute to the transverse current flow. The resistance is therefore enahanced.

$$\rho_b = \rho_m \frac{1+\lambda}{1-\lambda}$$

Filamentary area description for ρ_{ef}

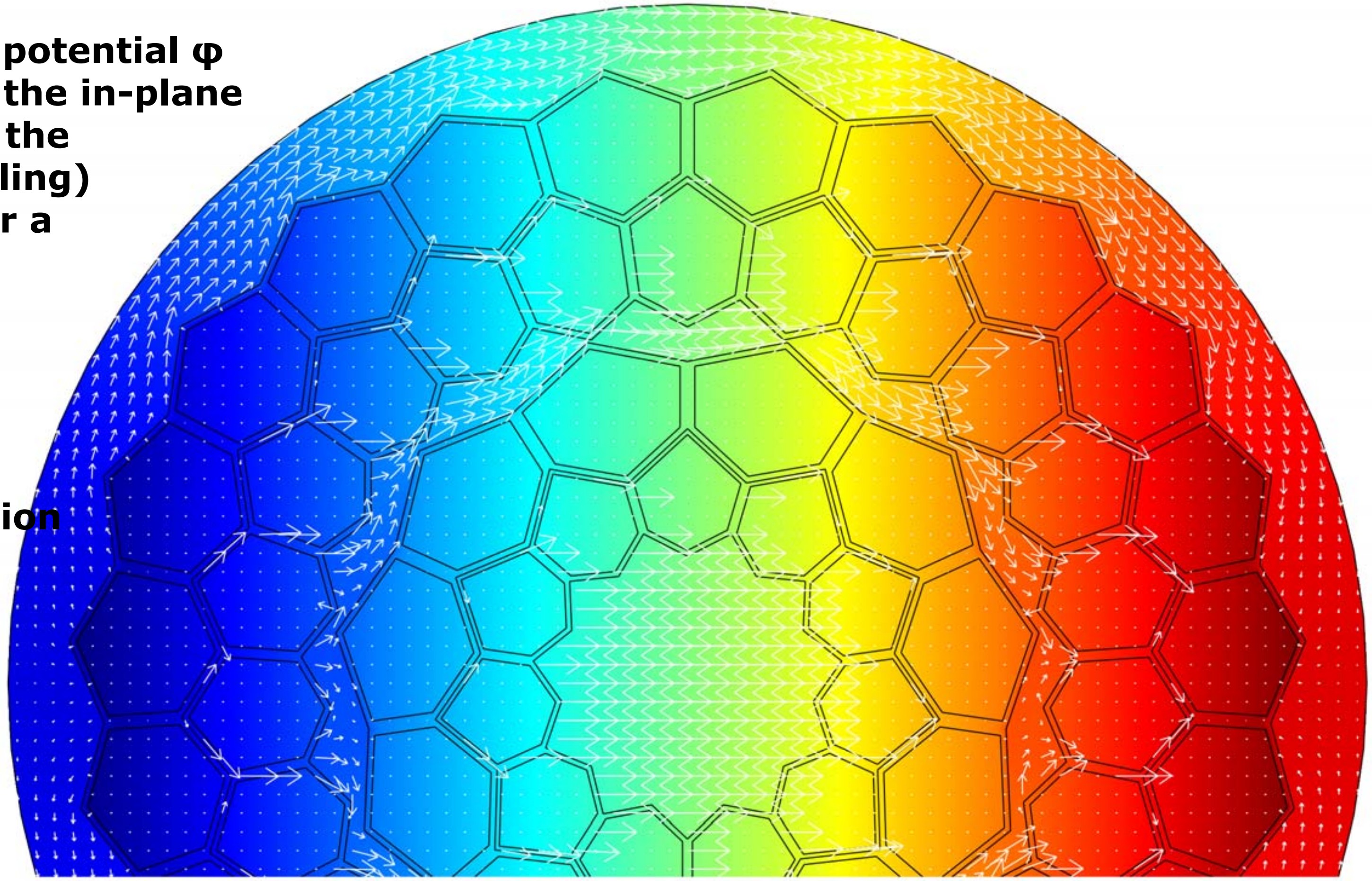


Solving the problem: FEM solution

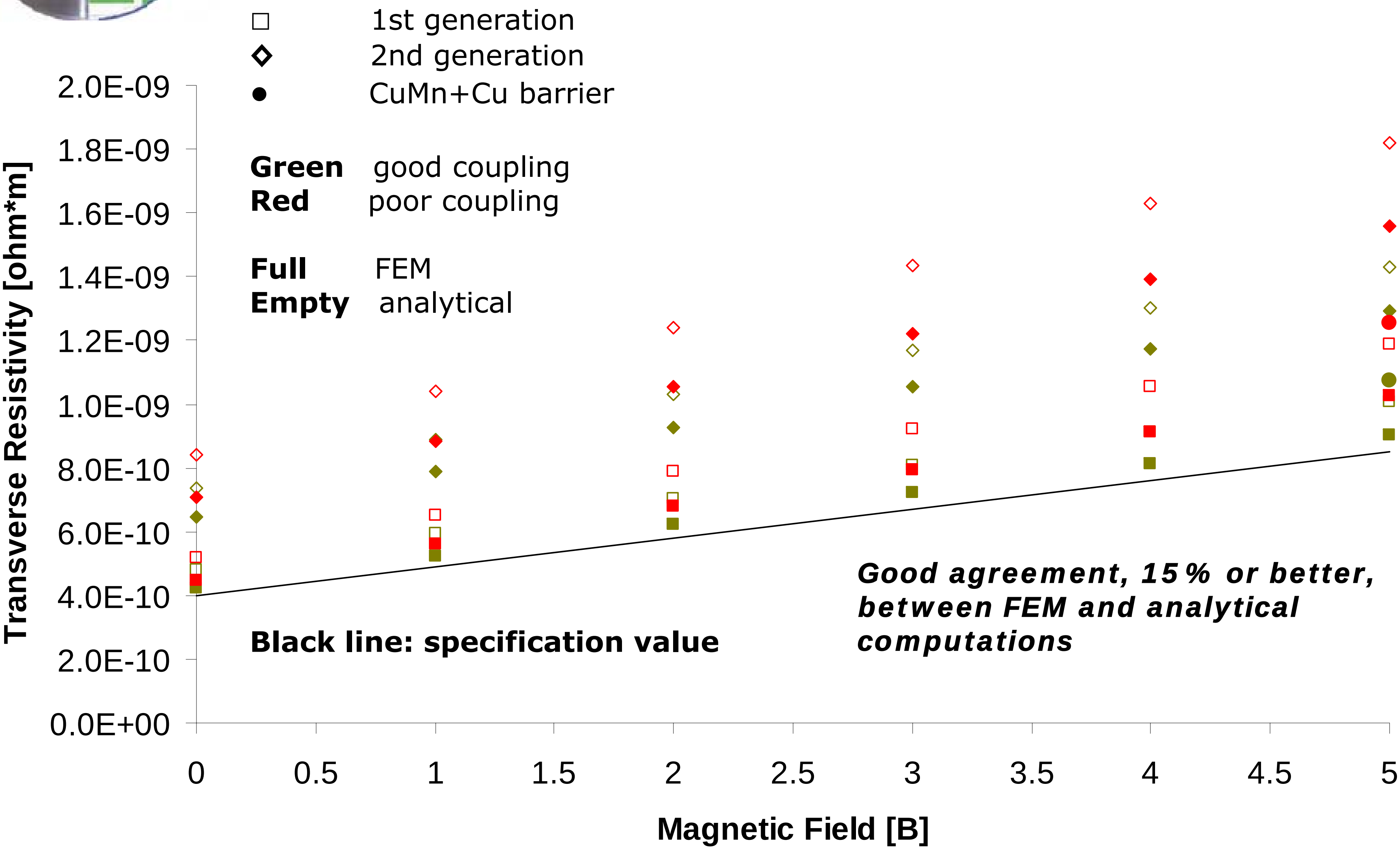
Given the geometry and the BC's, the Laplace solution can be solved with FEM as well.

Here we show the potential φ (colour map), and the in-plane x-y (i.e. related to the interfilament coupling) current density, for a second generation wire.

The total power dissipation Q is again found by numerical integration of E², and adding the EC term. From Q we compute the effective transverse resistivity.



Transverse resistivity from Analytical & FEM methods



Green good coupling
Red poor coupling

Full FEM
Empty analytical

Black line: specification value

Good agreement, 15% or better, between FEM and analytical computations

Dynamic stability

The stability criterion seems satisfied

0.1 W/mK

4.4 W/mK

Thermal conductivity

Weighed average beteween NbTi and CuMn 1.87 W/mK

Approach “à la Carr” 1.14 W/mK

λ (NbTi fill factor in the bundle) 0.588

Jc @ 4.2 K, 5 T 2700 A/mm^2

ρ_{Cu} @ 4.2 K, 5 T 3.5 · 10^{-10} ohm·m

$$d_{st} = \sqrt{\frac{k\cdot(\theta_c - \theta_0)\cdot(1-\lambda)}{\lambda\cdot J_c^{\,2}\cdot\rho}}$$

Characteristic length 32 µm

Round filament factor form 4√2 “ 137 µm

equivalent diameter << $4\cdot\sqrt{2}\cdot d_{st}$

Equivalent macrofilament diameter

Inner, Outer 60, 70 µm

So the margin for stability seems comparable to the layouts envisaged by MNW in Rep 29.

Conclusions

Low-loss, fine filaments NbTi Rutherford cable is now manufactured by Luvata Fornaci di Barga (Italy) for the pulsed dipole long model, under contract from INFN.

Two generations of wire are foreseen, the first with 3.5 μm filaments and the second with 2.5 μm filaments

Transverse resistivity has been computed by means of two different methods, one analytical and a FEM: they agree to 15% or less.

Larger uncertainties arise from unknown features, like the contact resistance between the matrix and the NbTi.

All the results comply with the transverse resistivity specified by DISCORAP

Credits

I wish to acknowledge

M N Wilson,	**whose approach has inspired the analytical solution**
P Fabbricatore,	**for cross-checking the FEM computations**
Luvata FdB,	**for their open collaboration during the wire design**