Quench Propagation in 1-D and 2-D Models of High Current Superconductors

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Superconductors & Quench

A typical **high current superconducting wire** can transport current densities in the range of 100 - 1000 A/mm², but this is not a stable condition: a small rise of the temperature in a limited section may force it in the normal state. The high Joule dissipation that takes place heats the nearby zones, creating a normal zone which becomes larger and larger, until it eventually encompasses the whole superconductor.

The description of this avalanche phenomenon, known as **quench,** is fundamental for the design of a SC magnet.

High Current Superconductors: wire

Thin (<50 μm) filaments of superconductor (here NbTi) are finely dispersed amid a pure copper matrix.

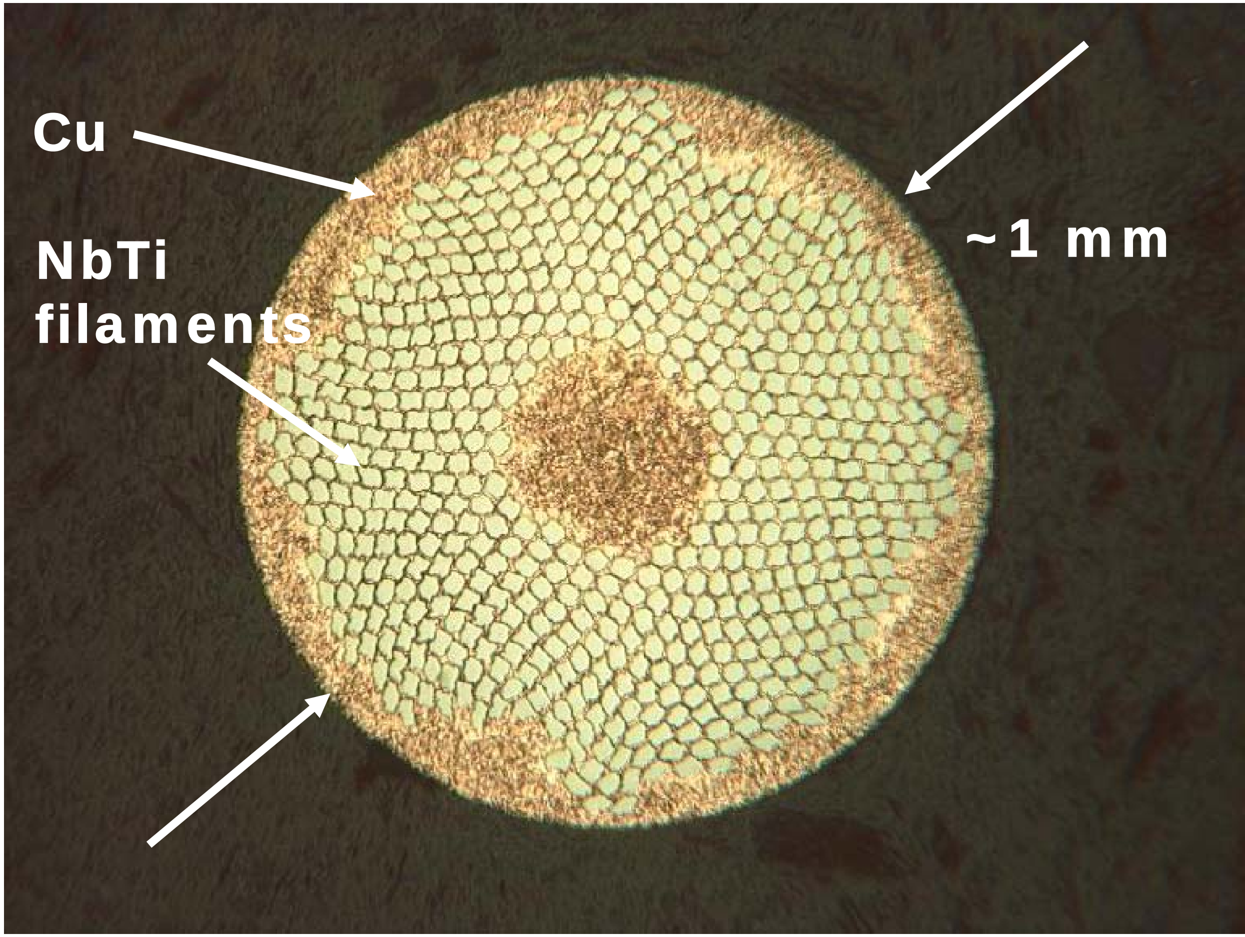
When the temperature exceeds the critical one, the current is forced into the copper resistive matrix (SC resistivity in the normal state is much higher than Cu)

In this kind of wires we can assume that

i) temperature is constant throughout the cross section

ii) current moves istantaneously from SC to Cu matrix (radial current diffusion time constant is negligible)

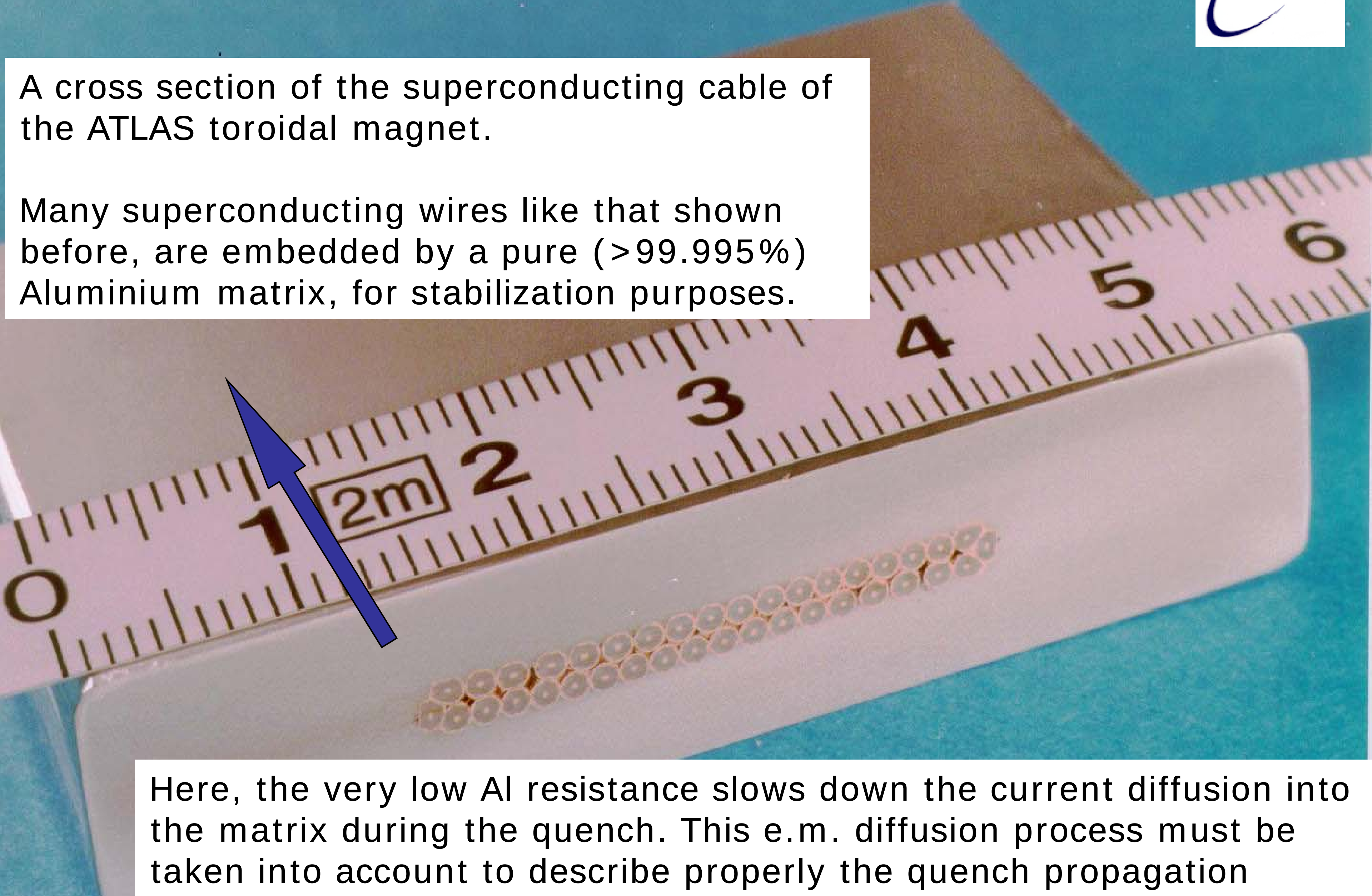
Cross section of a typical SC wire



High Current Superconductors: Al-stabilized conductors

A cross section of the superconducting cable of the ATLAS toroidal magnet.

Many superconducting wires like that shown before, are embedded by a pure (>99.995%) Aluminium matrix, for stabilization purposes.



Here, the very low Al resistance slows down the current diffusion into the matrix during the quench. This e.m. diffusion process must be taken into account to describe properly the quench propagation

Goals

This talk presents two fairly simple models, which describe the quench in different conditions:

1-D model.

Here we describe the quench as governed by the longitudinal (i.e. along the wire axis) thermal diffusion only.

2-D model.

When the e.m. transverse time diffusion constant is large we must include the magnetic diffusion in the normal direction. The transverse geometry must therefore be introduced.

1-D model: PDE

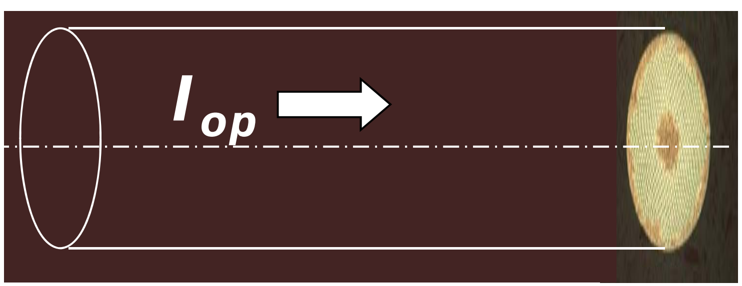
The quench propagation is governed by the longitudinal thermal diffusion (Eq. 1).

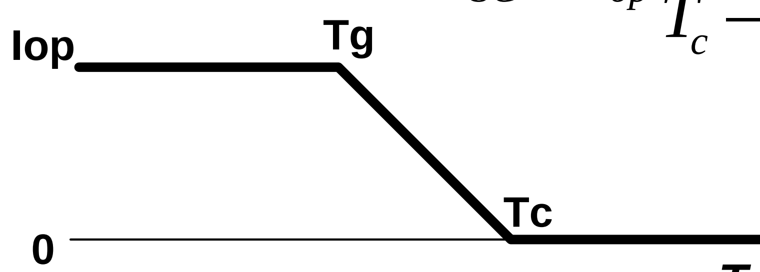
The superconducting dynamics is introduced by Eq. 2 which describes the current flowing without losses inside the SC filaments (I_{SC}); when the total current (I_{op}) exceeds I_{SC} the extra current is carried by the resistive matrix, giving origin to heating through Joule dissipation.

source term

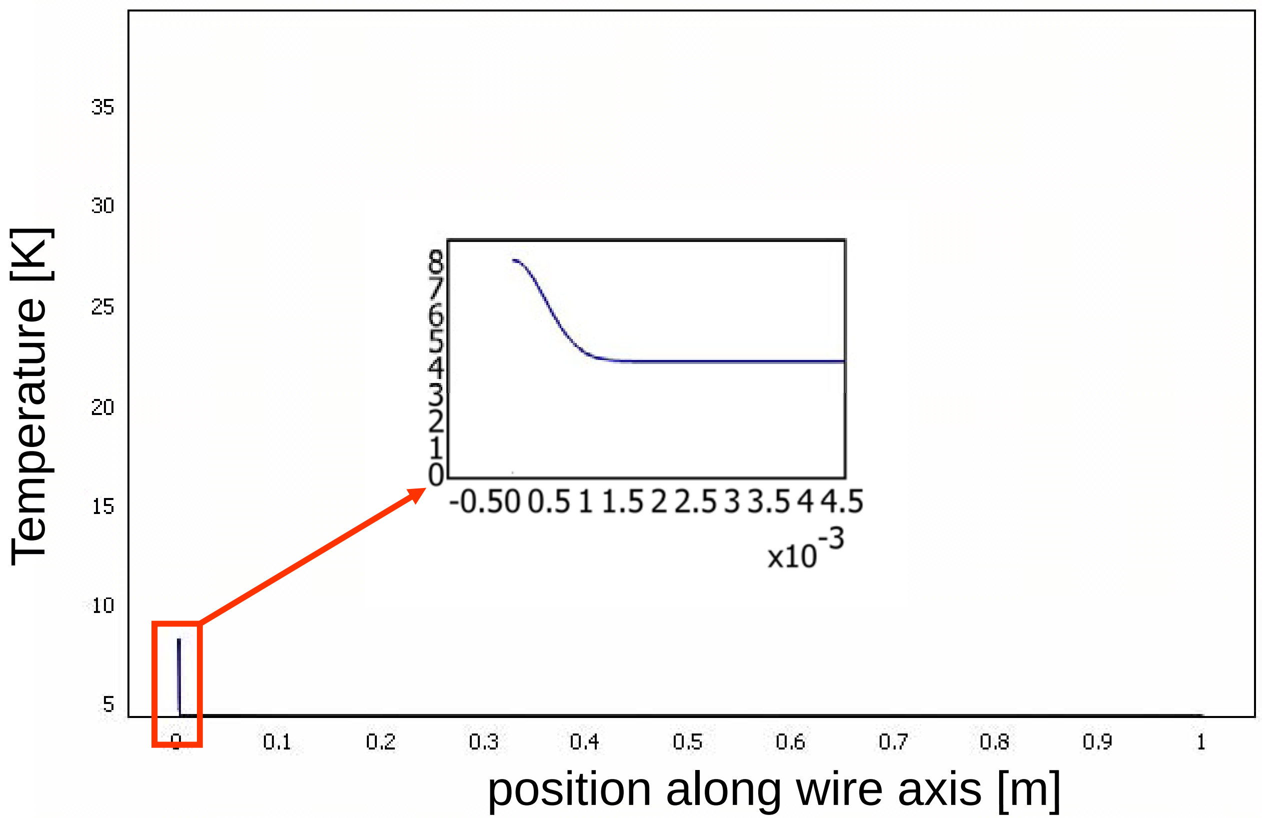
$$\rho_m C_p \, \partial_t T + \nabla \cdot (-k_{th} \nabla T) = \rho_{el} \underbrace{\frac{(I_{op} - I_{SC})^2}{A^2}}_{\text{source term}} \qquad \textbf{(1)}$$

$$I_{SC} = I_{op} \frac{T - T_g}{T_c - T_g} \qquad \textbf{(2)}$$





1-D. Quench propagation



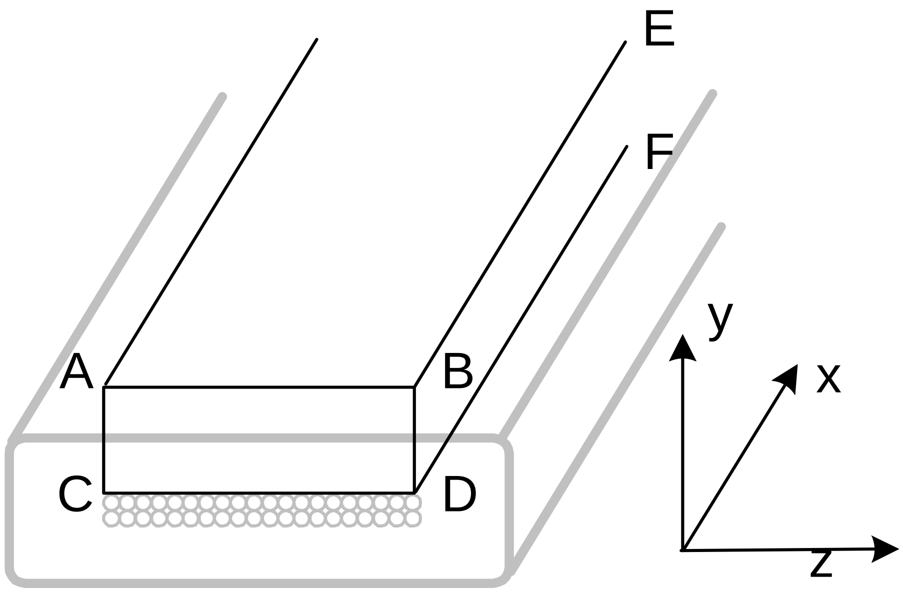
1-D. Conclusions

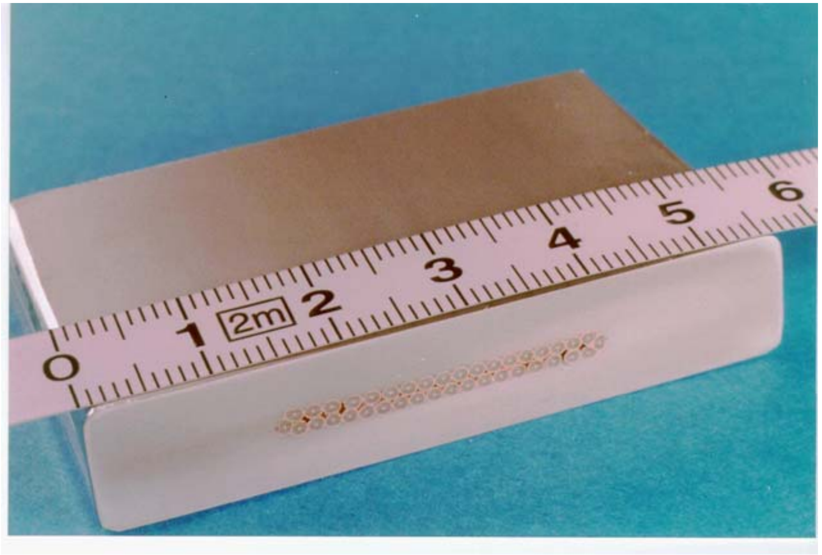
The quench speed and the minimum initial disturbance required to ignite a quench computed by means of COMSOL are well in agreement with the analytical formulae often used to describe quench.

Although reassuring, this is hardly surprising, since analytical formulae are determined from the approximate solutions of the same PDE's solved by COMSOL.

2-D model. Geometry

Geometrical model of the cable used in the 2-D simulations. The current flows along the *x* direction. The system is symmetric across the *x*-*z* plane; we also simplify the geometry assuming that the system is invariant along the *z* direction.





2-D. Governing Equations

Current is related to the B_z component of the magnetic field by means of Ampère's law (Eq. 3). Magnetic diffusion is described by Eq. 4. The heat diffusion equation and the current in the SC are described as in the 1-D case.

$$\vec{J} = \frac{1}{\mu_0}\nabla \times B_z\vec{k} \quad \textbf{(3)}$$

$$J_x = \frac{1}{\mu_0}(\partial_y B_z - \partial_z B_y) = \frac{1}{\mu_0}\partial_y B_z$$

$$J_y = \frac{1}{\mu_0}(\partial_z B_x - \partial_x B_z) = -\frac{1}{\mu_0}\partial_x B_z$$

$$\partial_t B_z + \nabla \cdot (-\frac{\rho_{el}}{\mu_0}\nabla B_z) = 0 \quad \textbf{(4)}$$

$$\rho_m C_p\, \partial_t T + \nabla \cdot (-k_{th}\nabla T) = \rho_{el}\left(\frac{1}{\mu_0}\nabla \times B_z\vec{k}\right)^2$$

$$I_{SC} = I_{op}\frac{T - T_g}{T_c - T_g}$$

superconductivity is introduced by...

this is a "multiphysics" problem, since the T and B variables are coupled in the heat diffusion equation

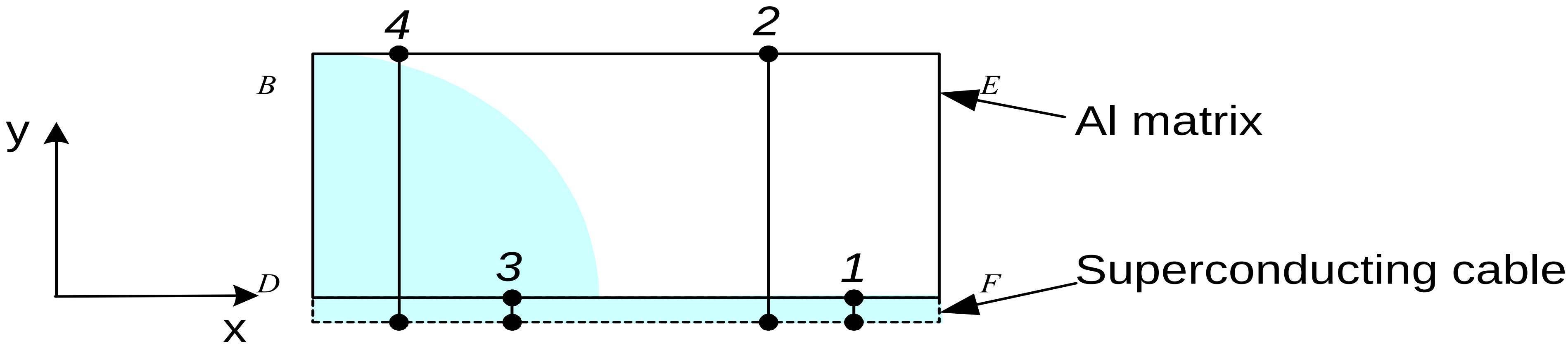
2-D. B_z boundary conditions

The superconducting cable itself is not part of the geometry, and the superconductor's properties are introduced by proper boundary conditions on the x-axis.

$$\Im_x(x,y) = \int_{-\Delta y}^{y} J_x(x,u)\,du = \frac{1}{\mu_0} B_z(y)$$

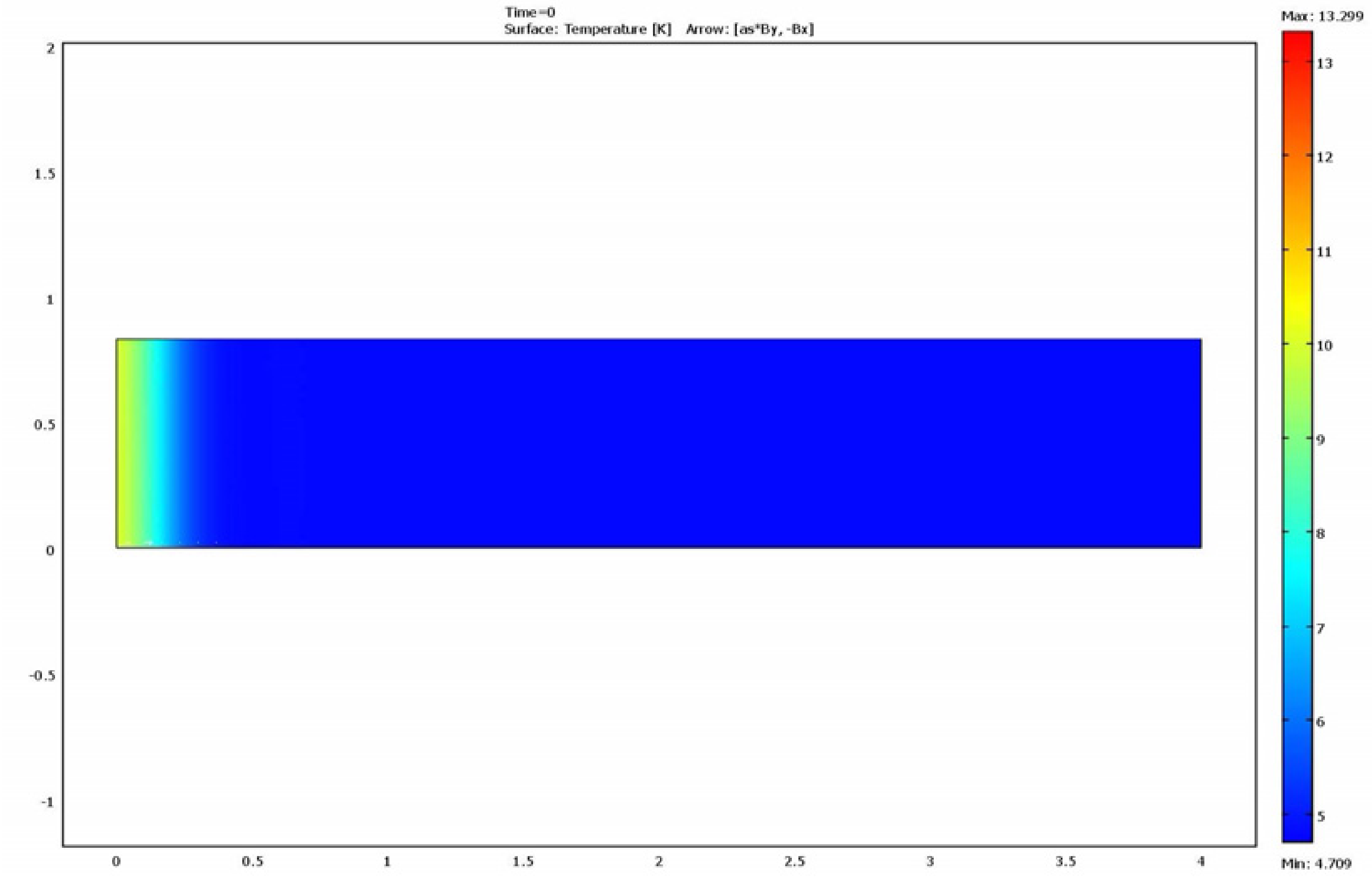
1,3 $\quad \Im_x(x,0) = I_{SC} = \frac{1}{\mu_0} B_z(0)$

2,4 $\quad \Im_x(x,y_0) = I_{op} = \frac{1}{\mu_0} B_z(y_0)$

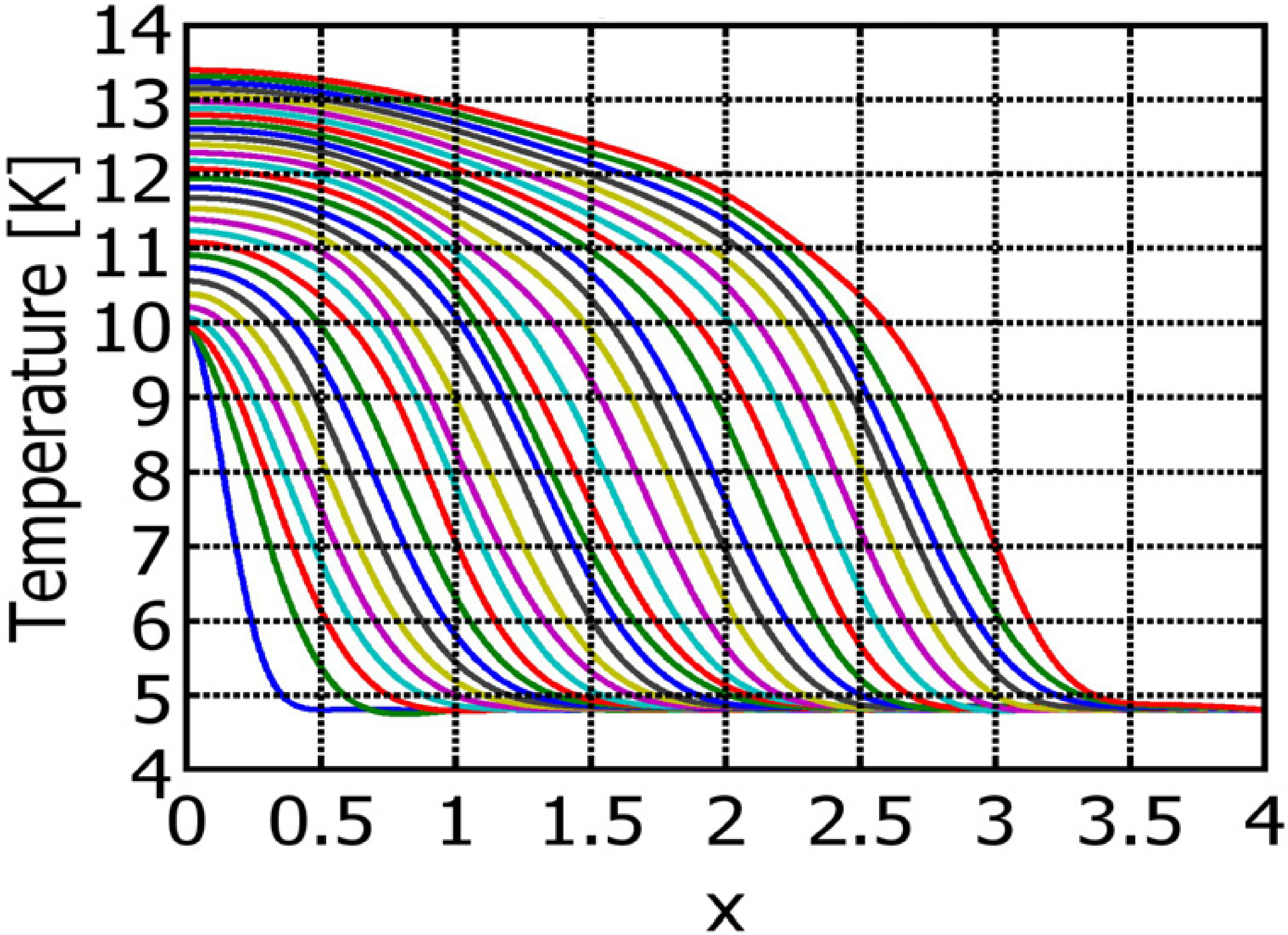


2-D. Quench Propagation

Stretched by a factor 100 to improve readibility



2-D. Quench Propagation



Simulations vs. Experiments

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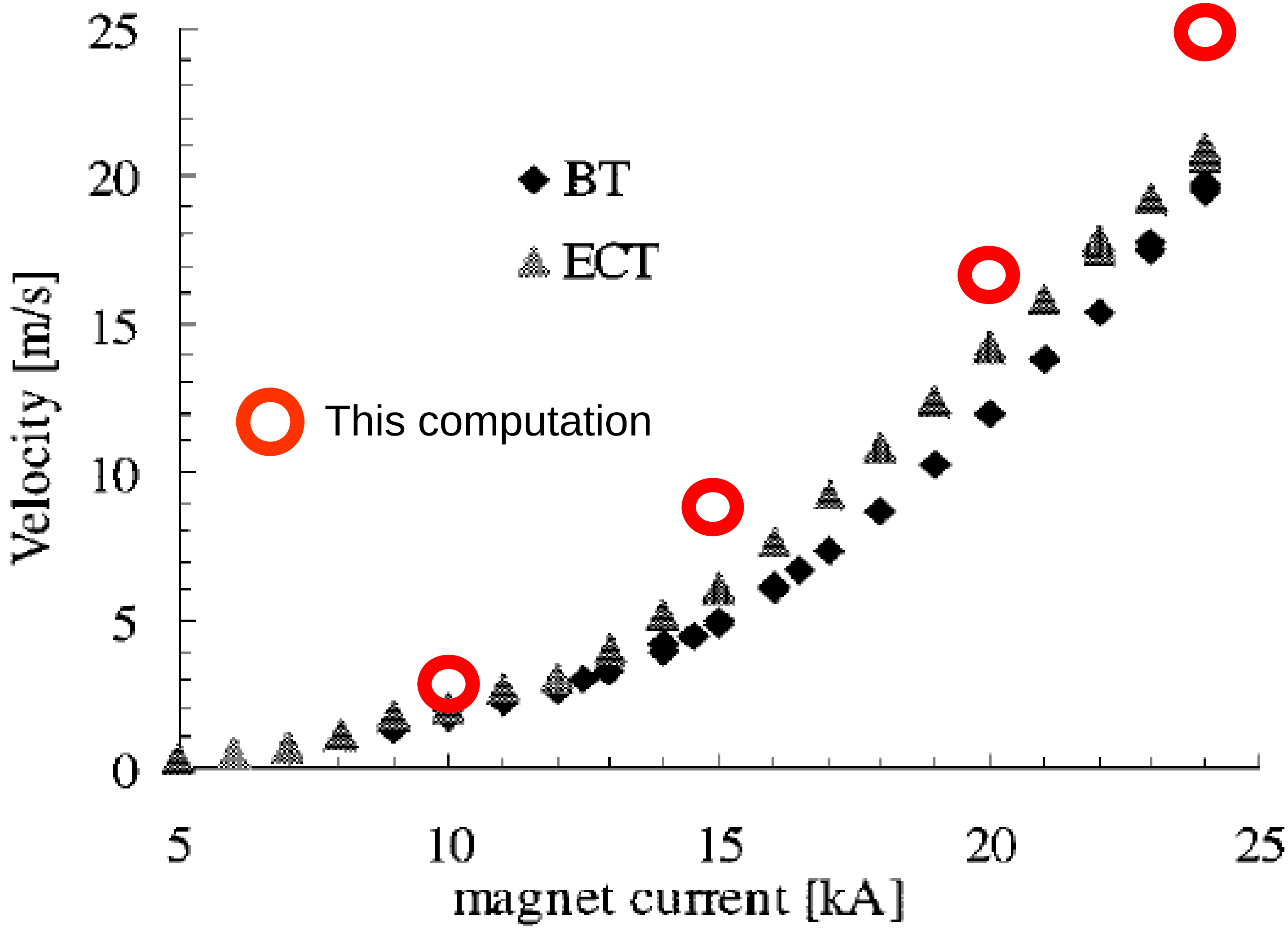
The Normal Zone Propagation in ATLAS B00 Model Coil

E. W. Boxman, A. V. Dudarev, and H. H. J. ten Kate



Conclusions

Despite its simplicity, the models shown in this talk have a remarkable predictive power when applied to real situations.

The 2D (thermal) + 2D (magnetic) could be replaced by a 1D (thermal) + 2D / 3D (magnetic), since the temeprature is homogeneous in the transverse direction.

More details (e.g. SC cable heat capacity) could be introduced, likely increasing the accuracy of the results.

Thank you!