A Study of the Effect of a Strand Damage on the Operating Margin of a Nb_3Sn cable

G. Succi, L. Bottura, M. Breschi

Outline of the presentation

- Introduction
- Mathematical description of the problem
- Features of the THEA Model
- Current distribution during ramp-up & plateau
- Breakdown of the electrical network
- Characteristic times and lengths of the system
- Conclusion & Next steps

Outline of the presentation

- Introduction
- Mathematical description of the problem
- Features of the THEA Model
- Current distribution during ramp-up & plateau
- Breakdown of the electrical network
- Characteristic times and lengths of the system
- Conclusion & Next steps

Introduction

- It is an experimental evidence that current distribution and redistribution in multi-strand superconducting cables affects the operating margin, stable performance and field quality of particle accelerator magnets.

- The Nb_3Sn superconductor was selected for designing and building the magnets of the High-Luminosity project at CERN, profiting from its better superconducting properties compared to the *Nb-Ti* in the LHC.

  However, Nb_3Sn is brittle and excessive strain may result in conductor damage during the delicate manufacturing process of the Wind-and-React HL-LHC magnets.

- In this work, we wish to model current distribution and associated performance limits in a full-size, 40 strands Nb_3Sn cable for an HL-LHC magnet (11 T Dipole). The cable is subjected to a generic severe degradation of the current carrying capacity (*strand breakage*) in one strand (*broken strand*).

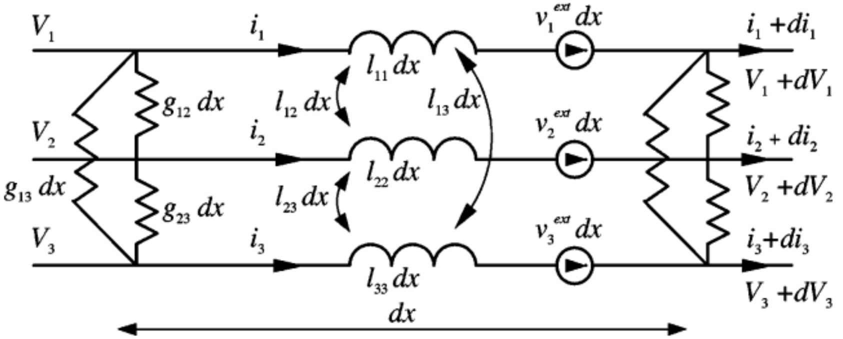
Mathematical description of the problem

Strands in the 11 T cable are made of Nb_3Sn superconducting filaments embedded in a stabiliser copper (Cu) matrix, and twisted to reduce AC currents and losses.

11 T Cable Specifications

Nominal cable current, I_{nom}	11.85 kA
Number of strands, N	40
Strand diameter, d	0.7 mm
Cu:Sc ratio	1.15
RRR of Cu	100
Adjacent contact resistance, R_a	0.5 $\mu\Omega$
Crossing contact resistance, R_c	180 $\mu\Omega$
Twist-pitch, t_p	100 mm
Keystone angle	0.79 °
Cable width, w	14.70 mm
Cable thickness, t	1.25 mm

The model adopted to describe the electrical network is based on a continuum description of longitudinal resistance, transverse conductance and inductance:



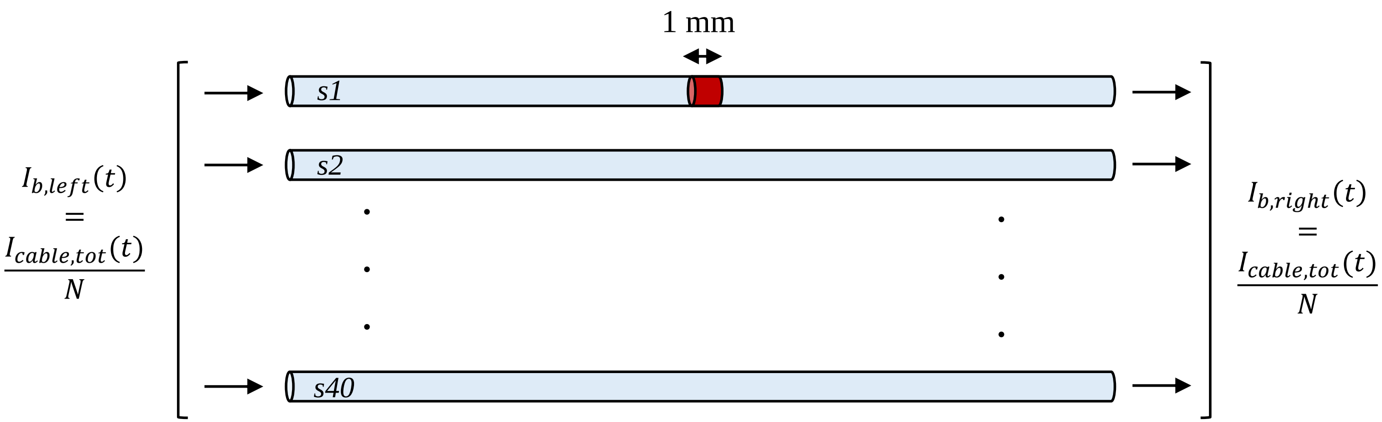
The governing equations are:

$$\frac{\partial^2 \vec{I}}{\partial x^2} + \vec{g}\vec{l}\frac{\partial \vec{I}}{\partial t} + \vec{g}\vec{r}\vec{I} - \vec{g}\vec{v}^{ext} = 0$$

Diffusion equations

Features of the THEA Model

- 40 electrical elements (40 strands) + 41 thermal elements (strands + insulation)



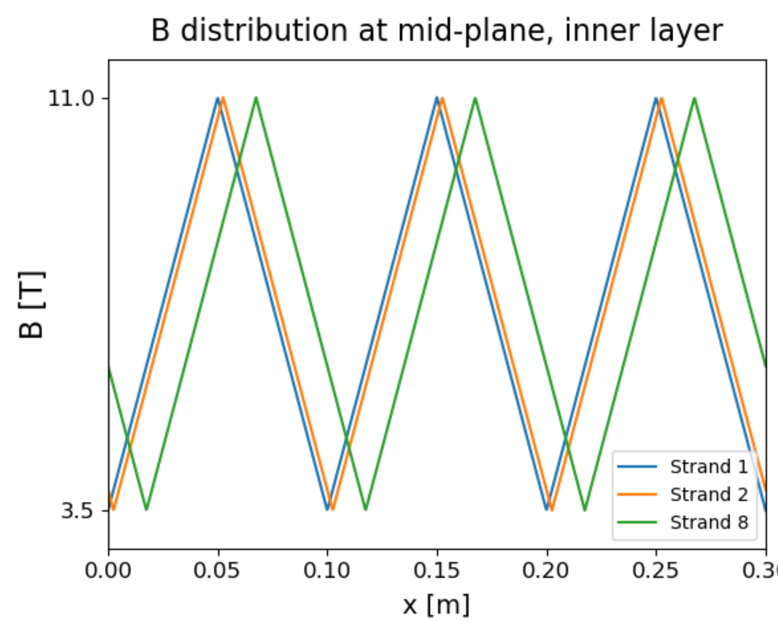
Strands are represented as cylinders, but they are actually treated as 1-D lines in the code

Domain length: 0.3 m

- J_c, B_c, T_c = 0 in the 1-mm broken region (red spot). No current can flow through the *Cu*, either.

- Current is equally distributed among the strands at the boundaries, at all times.

- Strands experience a *field variation* as they move alternatively between the inner and outer radius of a coil, due to twisting in Rutherford cables.

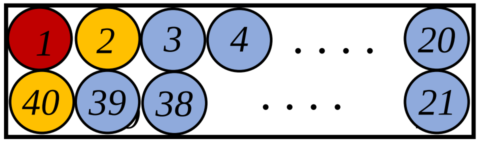


Outline of the presentation

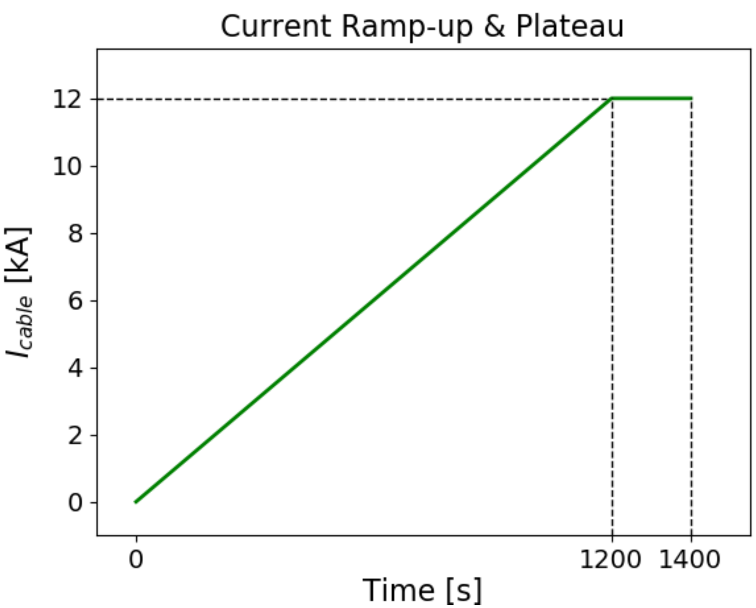
- Introduction
- Mathematical description of the problem
- Features of the THEA Model
- Current distribution during ramp-up & plateau
- Breakdown of the electrical network
- Characteristic times and lengths of the system
- Conclusion & Next steps

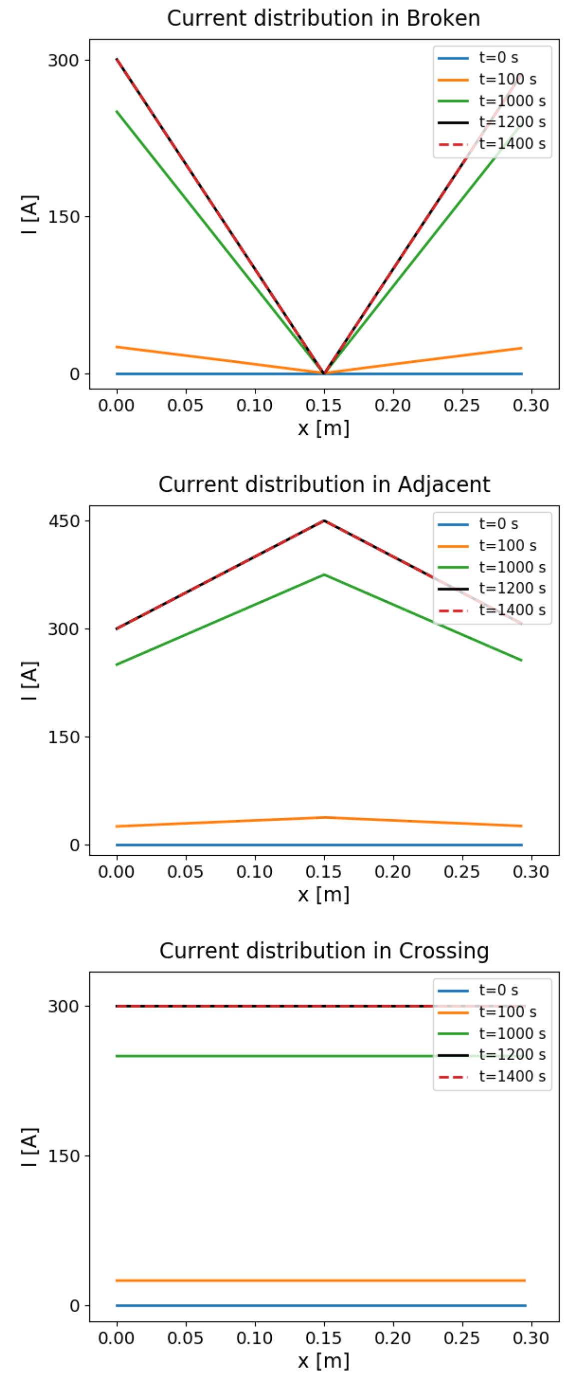
Ramp-up & Plateau

Strand numbering in the cable



s1: Broken
s2, *s40*: Adjacent
s3 – *s39*: Crossing



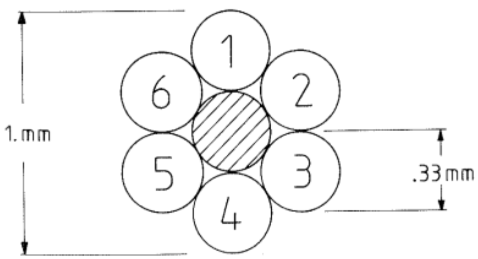


<u>Key facts</u>

- The current distribution is not uniform among the cable strands.
- Adjacent strands take 100 % of the current flowing out of the broken strand (*current overload* in the adjacent strands).
- Crossing strands do not take part in the process.

An already-known problem

- The problem of the non-equal current distribution among strands of a superconducting cable is known from the past [3].



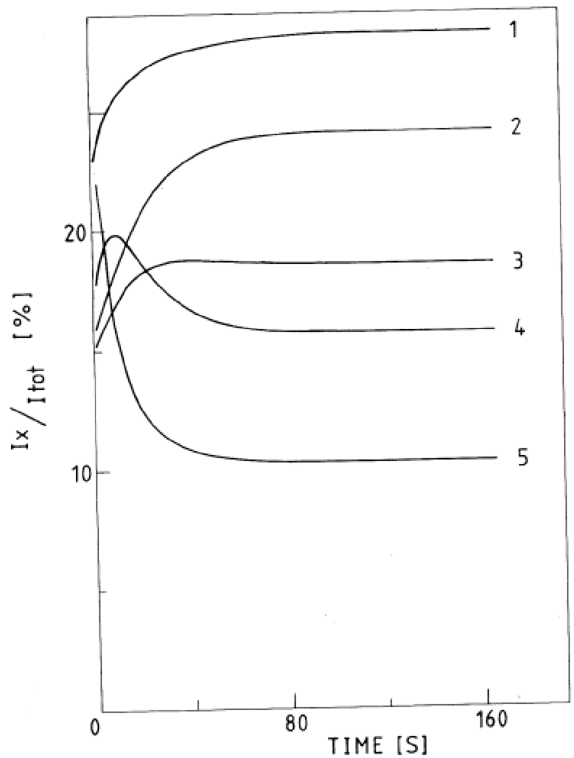
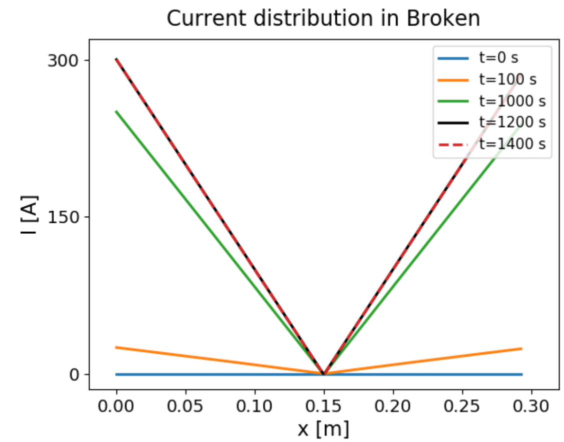
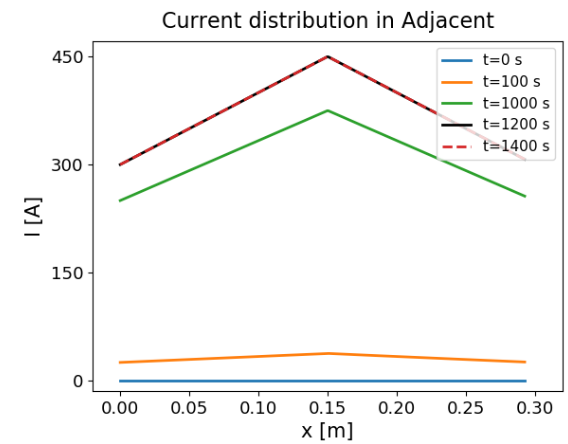
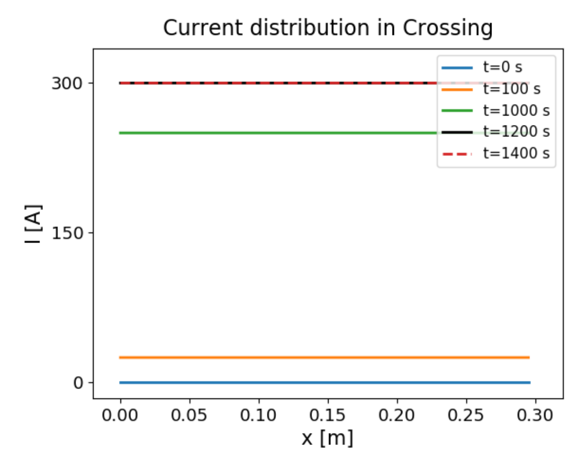


Fig. 7 The stationary current distribution versus time in the case of unequal resistances in the joints of the strands.

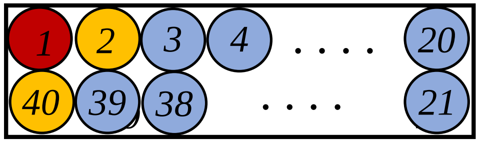






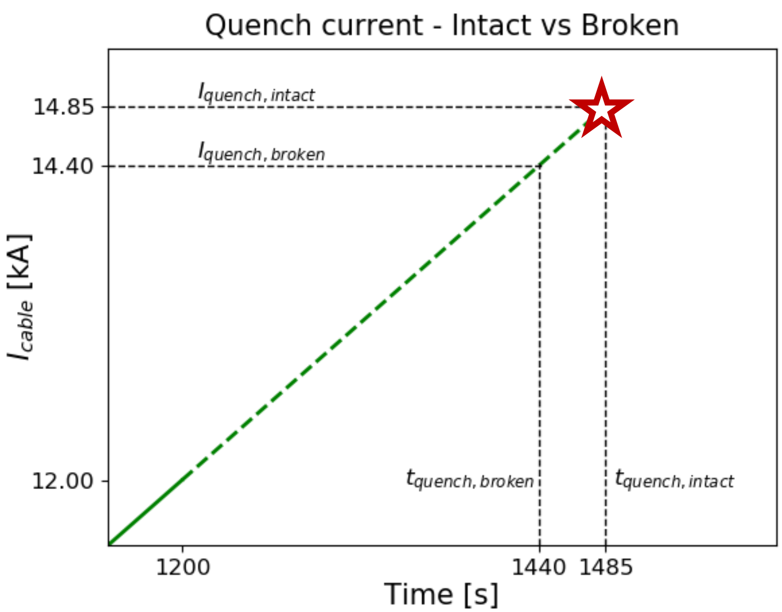
Breakdown of the electrical network (1)

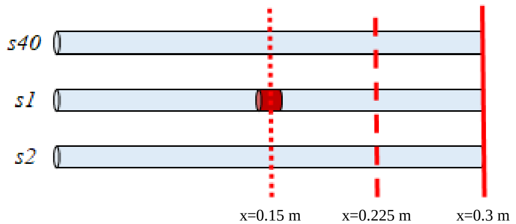
Strand numbering in the cable

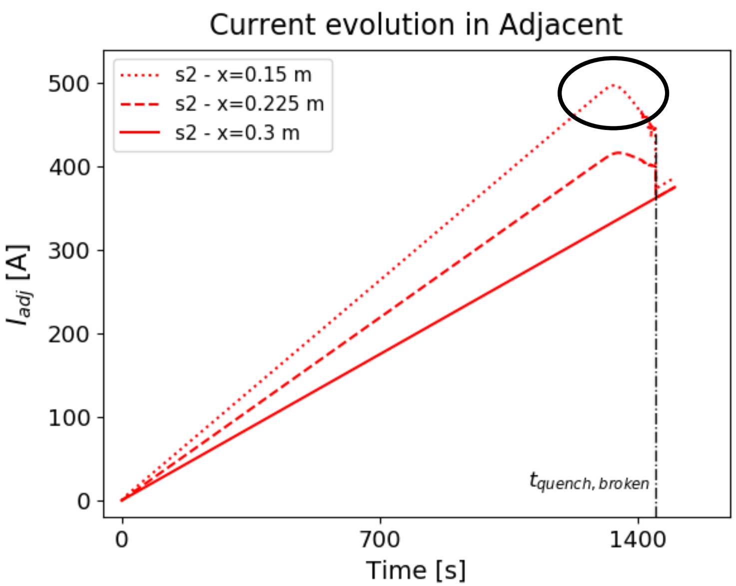


s1: Broken
s2, *s40*: Adjacent
s3 – *s39*: Crossing

- The pattern of the current distribution in the broken and adjacent strands can be extrapolated at higher cable currents: the slopes become steeper.
- Adjacent strands are the most stressed in terms of superconducting parameters.







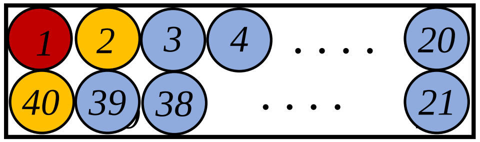
$$I_{quench,intact} = 14.85\ kA$$
$$= I_c(13.8\ T, \sim 2\ K)$$

$$I_{peak,\, x=0.15\ m} = 490\ A = I_c\ (12.9\ T, 2\ K)$$

Saturation: current redistributes to the other strands.

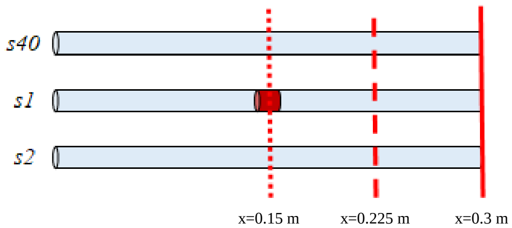
Breakdown of the electrical network (2)

Strand numbering in the cable



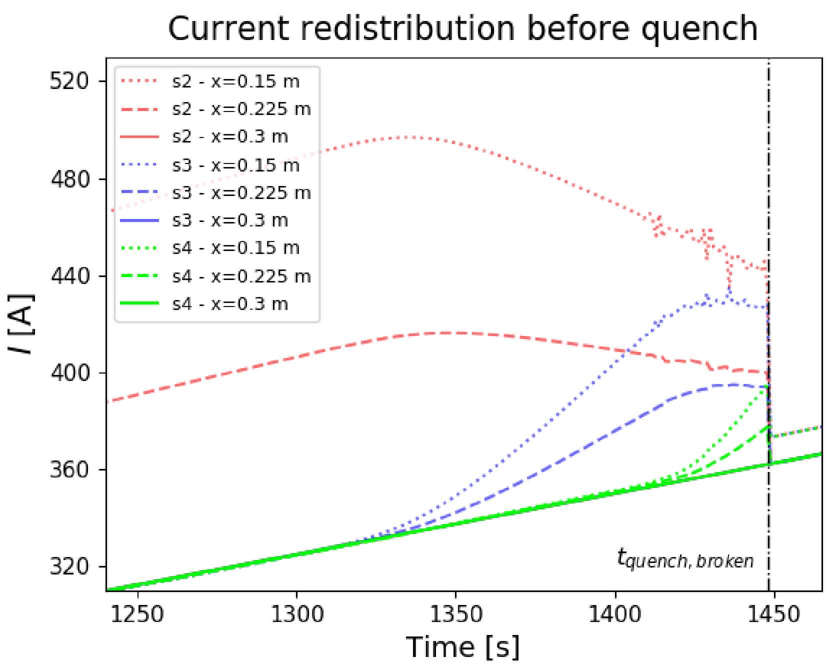
s1: Broken
s2, *s40*: Adjacent
s3 – *s39*: Crossing

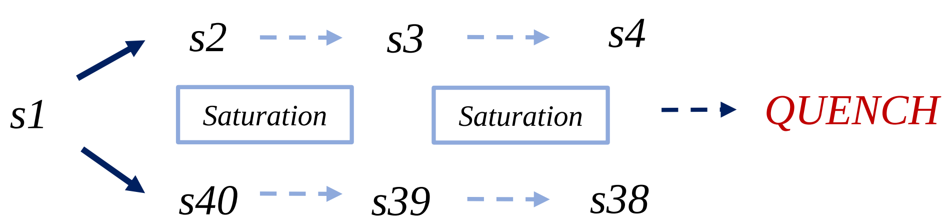
$$I_{quench,intact} = 14.85\ kA$$
$$= I_c(13.8\ T, \sim 2\ K)$$



$$I_{quench,broken} = 14.4\ kA$$

which is only a 3% loss in the quench current





Outline of the presentation

- Introduction
- Mathematical description of the problem
- Features of the THEA Model
- Current distribution during ramp-up & plateau
- Breakdown of the electrical network
- Characteristic times and lengths of the system
- Conclusion & Next steps

Characteristic times and lengths of the system (1)

- The current evolution in electrical circuits depends on time constants, as well as on diffusion lengths associated to the loops available for the circulation of current.

Ex. An RL circuit $I(t) = I_0 e^{-\frac{t}{\tau}}$, $\tau = L/R$

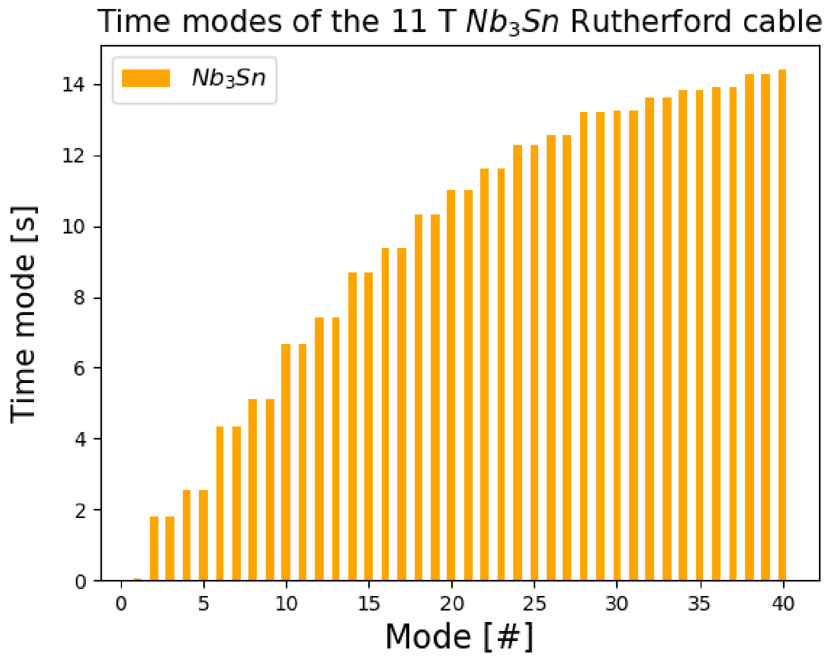
Fundamental mode

Ex. 2-strand system $I(x,t) = \sum_{k=1}^{\infty} b_k \left(1 - e^{-\frac{t}{\tau_k}}\right) sin\left(\frac{\pi k x}{L}\right)$, $\tau = \frac{l \cdot g \cdot L^2}{\pi^2}$

$\tau_k = \tau/k^2$

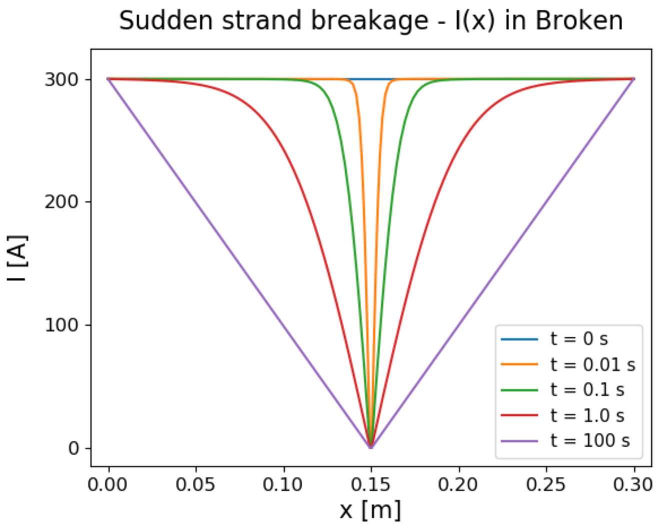
l: inductance
g: conductance
L: length

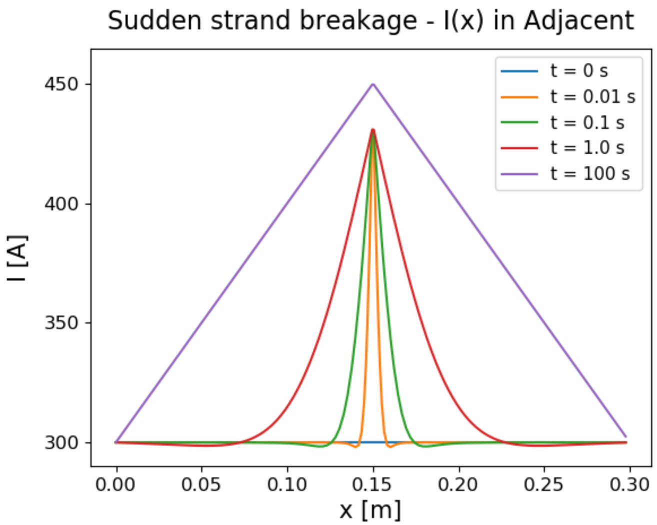
- An N-strand Rutherford cable is characterized by an entire set, or a *spectrum*, of modes, whose number is equal to the number of strands [1].



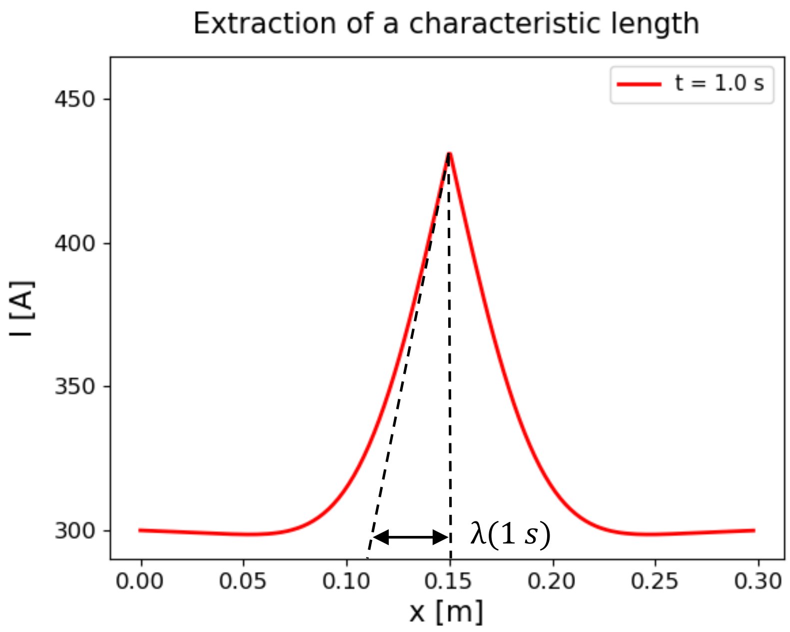
Characteristic times and lengths of the system (2)

- We propose a method to crosscheck the time modes with the numerical model in THEA.
- We induce a sudden strand breakage (at t = 0 s), thus current immediately starts avoiding the broken spot.





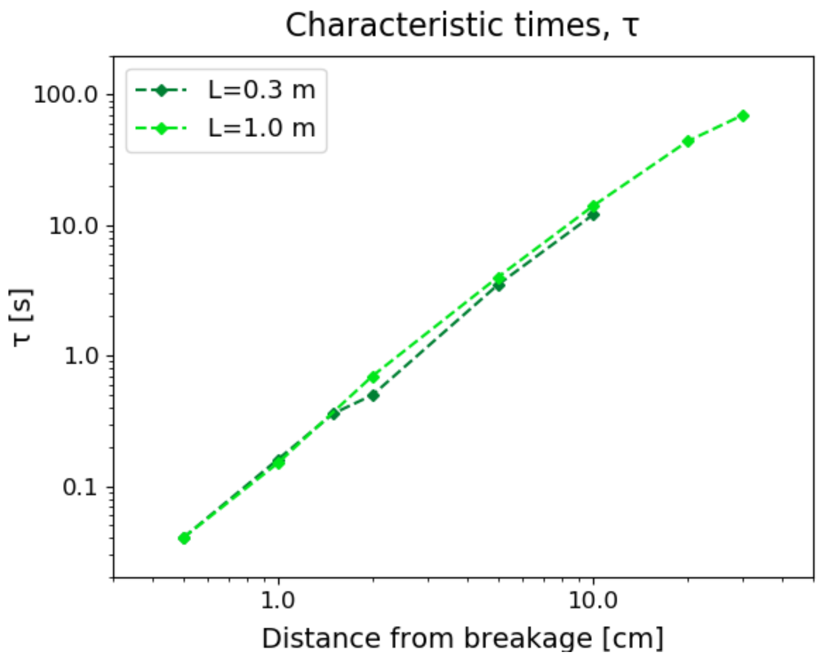
➢ *Extraction of characteristic times and lengths*

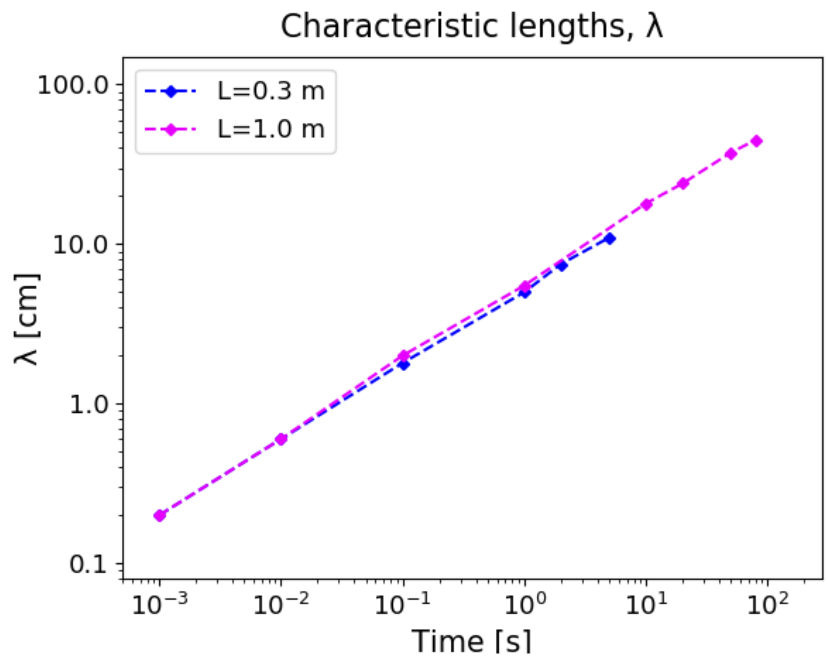


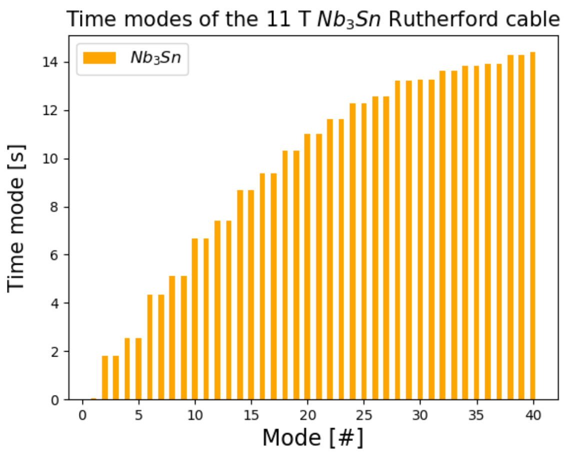
A similar way of proceeding is adopted for the extraction of characteristic times from $I(t)$ at a given spatial coordinate, x.

Characteristic times and lengths of the system (3)

- Iterating the extraction over a set of times and spatial coordinates one gets:







$$\tau(5\,mm) = 0.03\,s$$
$$Mode\ 1 = 0.03\ \mathrm{s}$$
$$\ldots.$$
$$\tau(10\,cm) = 12\,s$$
$$Mode\ 40 = 14.4\ \mathrm{s}$$

- ➢ Time modes from the analytical formulae are in good agreement with the simulations.
- ➢ Extending the domain allows getting access to new sets of times and lengths (see above for L=1 m).

Outline of the presentation

- Introduction
- Mathematical description of the problem
- Features of the THEA Model
- Current distribution during ramp-up & plateau
- Breakdown of the electrical network
- Characteristic times and lengths of the system
- Conclusion & Next steps

Conclusion & Next steps (1)

- In this work, we developed a numerical model for the cable of the 11 T dipole magnet in THEA. The model describes strands as 1-D components, but it is capable of implementing 2-D and 3-D features (e.g. magnetic field non-uniformity, strand inductances).

- The aim of the modelling is to describe the effect of a local conductor damage on current distribution and margin to the critical curve. We investigated a 0.3-meter domain, but the findings could be extended to the full ~ 1000 m cable inside the 11 T dipole coil.

➢ Adjacent strands constitute the most convenient way for the current distribution in presence of a local damage in one strand, in particular for Rutherford cables with a core.

➢ At quench, current from the saturated strands redistributes to pairs of progressive adjacent strands (e.g. *s2*-*s3*-*s4*, *s40*-*s39*-*s38*). The remaining crossing strands, which constitute the vast majority of the cable strands, do not take part in the process.

➢ This behaviour can be attributed to the different values of the adjacent contact resistance, R_a, and the crossing contact resistance, R_c, given by the stainless steel core. Furthermore, this limits the potential for cable stability given by the actual number of strands in the cable.

Conclusion & Next steps (2)

- Characteristic times and lengths of the current distribution in Rutherford cables are typical of diffusion phenomena. Quench is ‘instantaneous’ with respect to current diffusion in a large magnet and sharing from the quenched strand to the other strands in the cable can hardly take place.

- A strand damage is responsible of two negative effects. First, it brings the system closer to the critical curve, increasing the quench risk. Second, the characteristic current diffusion phenomena do not act on fast time scales to help redistributing the current and recovering the superconducting state, in case the critical limit is overcome.

<u>To be investigated:</u>

- Parametrical study on the influence of the core design on the current distribution. Would a lower R_c given by a thinner core help improving stability, while keeping the AC losses to acceptable values ?

- Extend the study on the actual conditions to be imposed at the boundaries. Do joints act as equipotential surfaces or as current generators, or in between?

Thank you for
your attention !

Bibliography

[1] L. Bottura, M. Breschi, and M. Fabbri, “Analytical solution for the current distribution in multistrand superconducting cables,” *J. Appl. Phys.*, vol. 92, no. 12, 2002.

[2] R. Otmani, A. Devred, and P. Tixador, “Interstrand and AC-loss measurements on Rutherford-type cables for accelerator magnet applications,” IEEE Trans. Appl. Supercond., vol. 11, no. 1 III, 2001.

[3] H.G. Knoopers, H.H.J. ten Kate, L.J.M. van der Klundert, “Distribution of currents in a 6-strand superconducting cable”, Magnet Technology Conference, 1985.

[4] G. Ambrosio, E. Barzi, D. Chichili, I. Elementi, A.V. Zlobin, “Measurement of inter-strand contact resistance in epoxy-impregnated Nb_3Sn Rutherford cables, Fermilab Conf-03/290. Technology Conference, 1985.

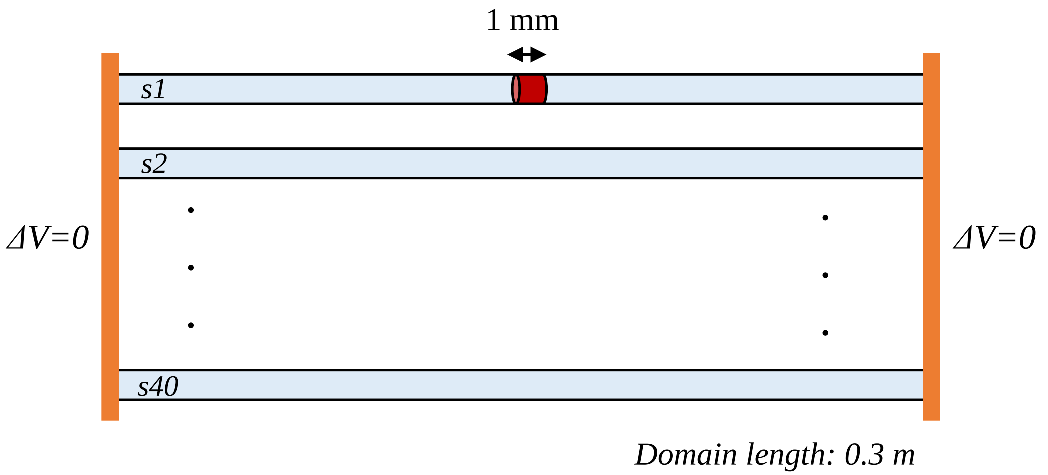
[5] V.E. Sumption, E.W. Collins, R.M. Scanlan, A. Nijhuis, H.H.J. ten Kate, “Core-suppressed AC loss and strand-moderated contact resistance in Nb_3Sn Rutherford cable, Cryogenics 39 (1999), 1-12.

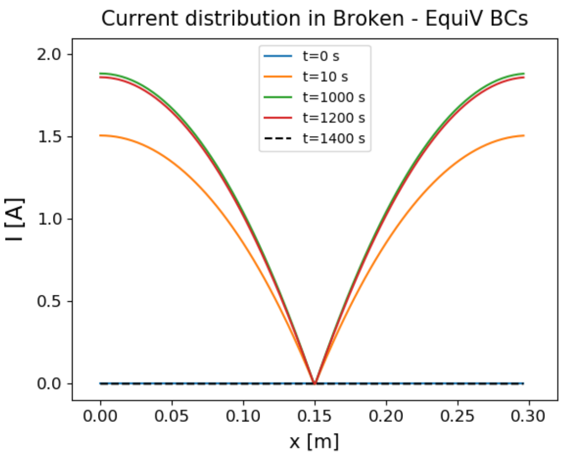
[6] A.A. Akhmethov, “Compatibility of two basic models describing the AC loss and eddy currents in flat superconducting cables”, Cryogenics 40 (2000), 445-457.

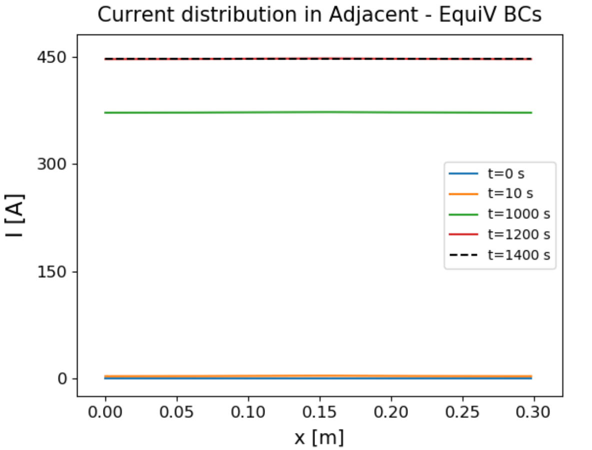
Back-up slides

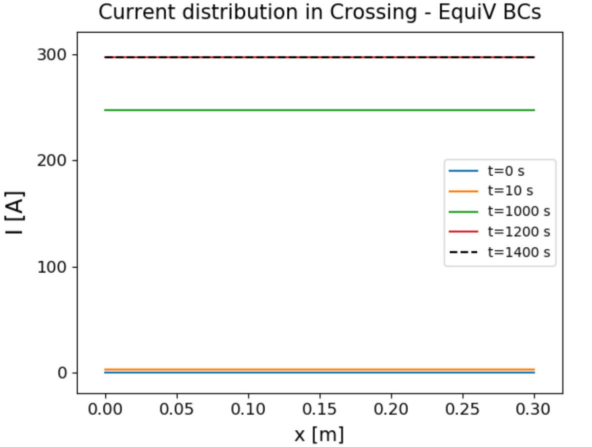
Boundary conditions

- Let us now analyse the case of short-circuited strands at the boundaries (equipotential joints).









- The broken strand is discharged in <u>any</u> location along the domain (a few amperes circulate during ramp due to the inductive effect, then current drops to zero at plateau).
- Adjacent strands experience 50 % higher current than in nominal conditions, along the entire domain.
- Margin is reduced by 23 % (i.e. from 53% to 30%, at $B_{peak} = 11\ T$) twice every twist pitch, regardless of the breakage location.

→ *Quench risk is much higher*

Macro vs Microscopic interpretation

- Results have shown that the 2 adjacent strands constitute the preferred path for the current distribution in presence of a strand breakage in the 11 T dipole cable.

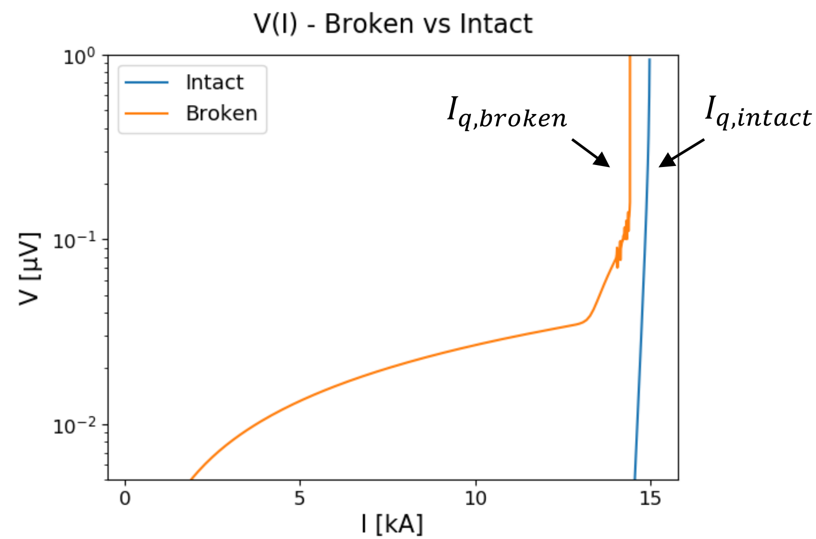
- There are 2 interpretations

  1) Macroscopic approach (cable as a 'black box')

  The heating generated by the *current transfer from the broken to the adjacent strands* is <1 mW/m, which could be withstood by the cooling system.

  $I_{op,11\,T} = 11.85\ kA$

  → Seems ok for operation

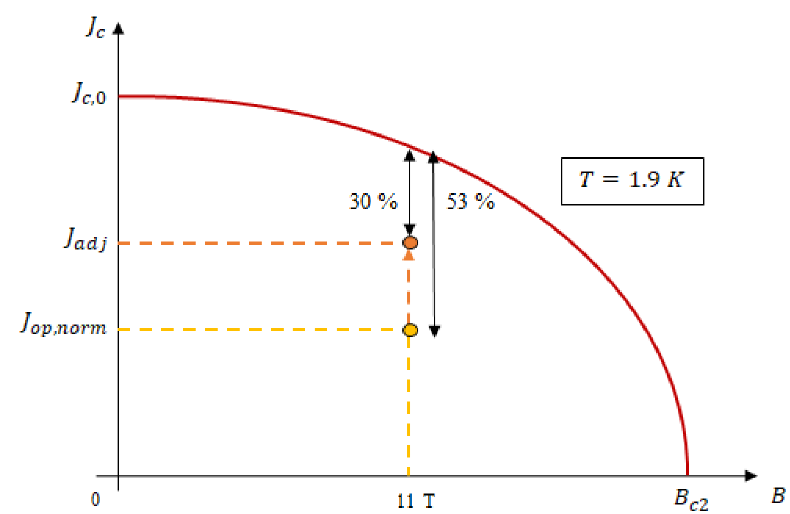


  2) Microscopic approach (cable detail)

  Current in the adjacent strands is 50 % higher at the breakage than in nominal conditions (450 A vs 300 A).

  Margin is reduced to 30 % (vs 53 %).

  → Dangerous for operation



➢ **The microscopic approach is the one to follow.**