Thermo-Electric and Magnetic Problems in Superconducting Particle Accelerator Magnets

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09/10/2020 – EASISchool Student Workshop on Superconductivity and its Applications - Genoa

A few words about myself

- **Volontaire International** (Ministère de l'Europe et des Affaires Étrangères)   @ CERN
  - started Sept. 2019

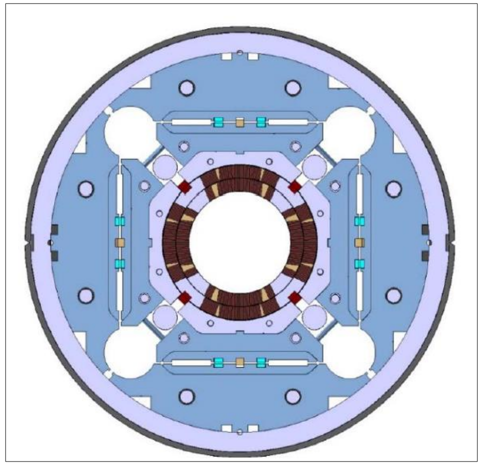
- Master's Degree in Energy/Nuclear Engineering   @ University of Bologna - March 2019

  Thesis: "Analysis *of Impregnated* Nb_3Sn *coils for the High-Luminosity LHC Magnets*"
  Supervisors: Prof. Breschi, Dr. Devred, Dr. Bottura

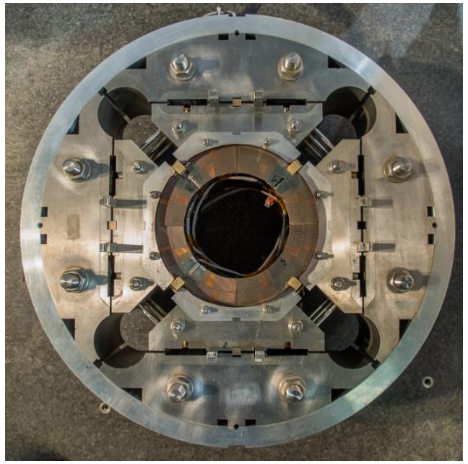
Just before moving on: This is my very first public presentation!

MSC Group – MQXF & 11 T Dipole

- Work in MSC (Magnets, Superconductors and Cryostats) Group ⇨ Design and Prototyping Magnets for the HL-LHC project
- 2 main ongoing projects: MQXF and 11 T Dipole



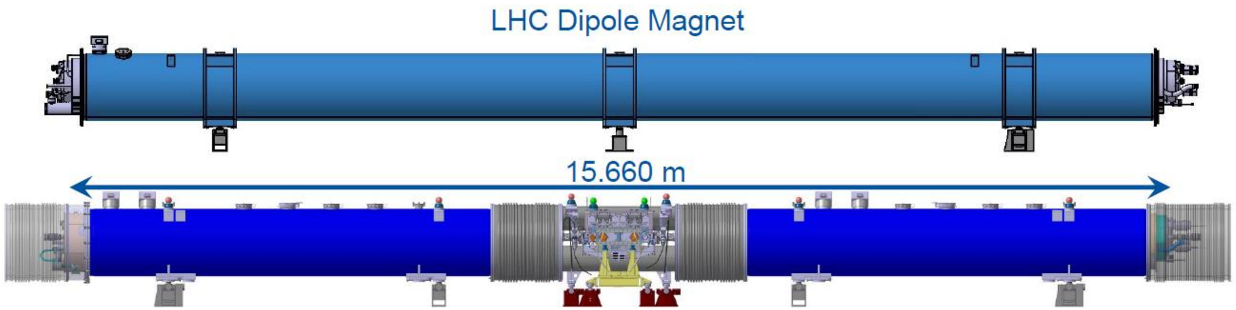
MQXF cross-sectional view, *single-aperture*

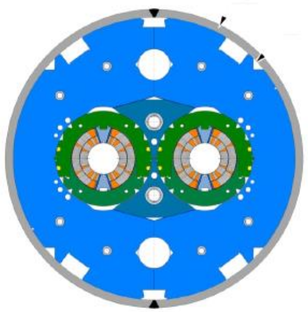


MQXF cross-sectional view, from real

Many issues related to Magnets

- Magnetic design
- Mechanics
- Protection
- Performance



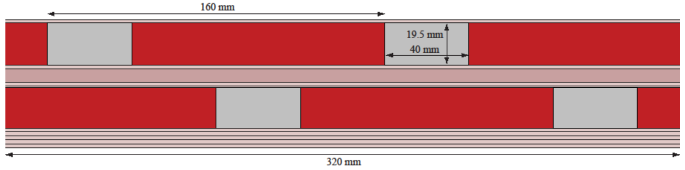


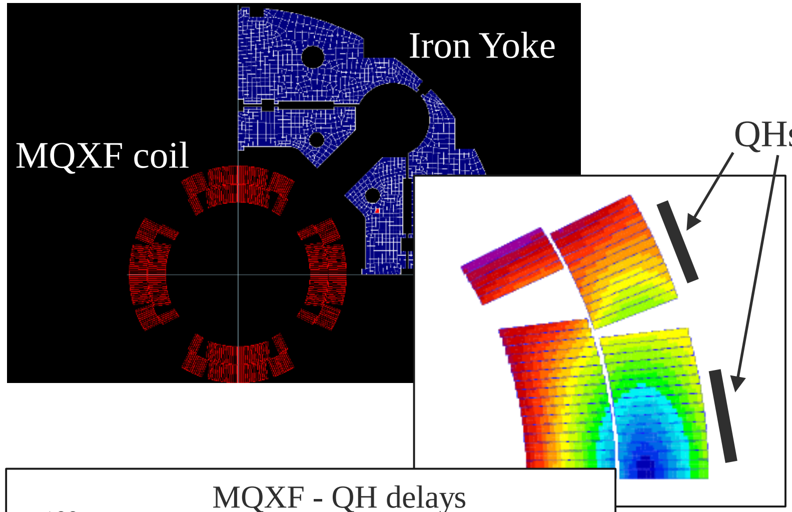
Cross-sectional view of the 11 T Dipole, *two-aperture*

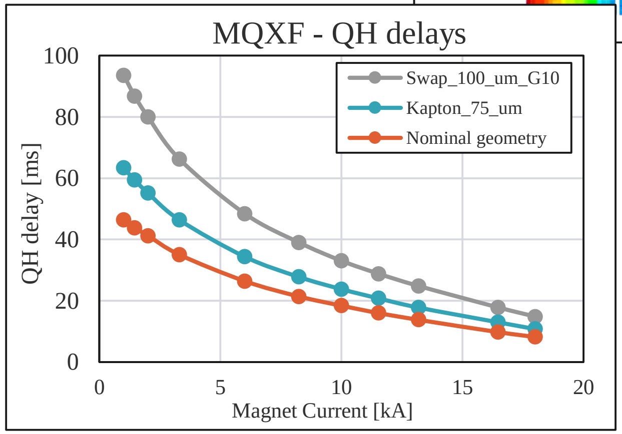
Topics of work

- Quench Heater Delays

Heater design (courtesy of S.Izquierdo Bermudez)

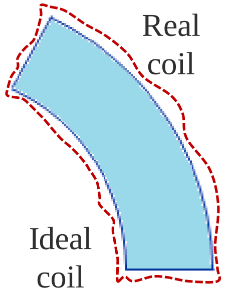


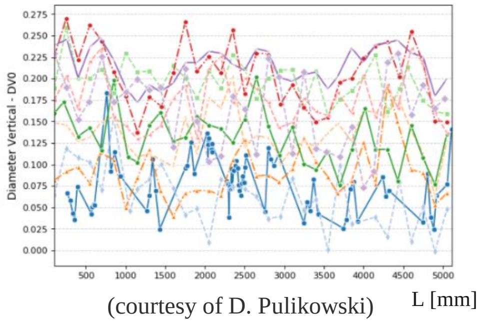




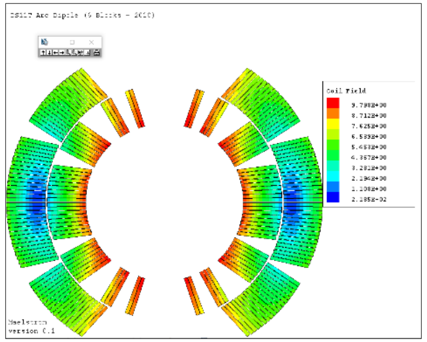
- Field Quality

$$\vec{B} = B_y + iB_x = 10^{-4} * B_0 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{r_0} \right)^{n-1}$$

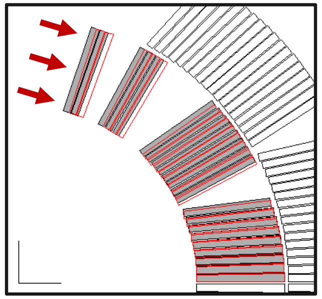




(courtesy of D. Pulikowski)



Example of field computation in MAELSTROM



a_2 → Midplane (top/bottom) asymmetry

a_3 → Midplane (left/right) asymmetry

b_3 → Oval deformation (?) → ongoing

- Effect of a Strand Breakage on Current Distribution and Stability

Broken strand
on a cable edge

- It is suspected that broken strands may be located also inside coils

Object of this presentation

A Study of the Effect of a Strand Breakage on the Operating Margin of a Nb_3Sn Cable

G.Succi, L.Bottura, M.Breschi

- Current distribution and redistribution phenomena in multi-strand superconducting cables have been studied for over 40 years, due to their impact on field quality and stability margin of accelerator magnets.

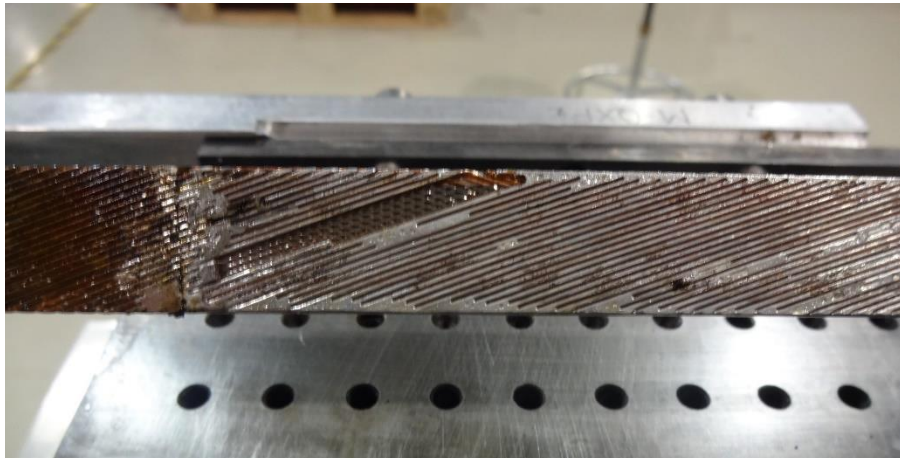
- This presentation addresses the problem of current redistribution in a 40-strand Nb_3Sn Rutherford cable subjected to a local strand damage.

- The aim is to evaluate the effect of strand breakages, originated for instance, during the fabrication stages of coils and magnets, on the operational margin of the magnets themselves. Such an evaluation is relevant to determine if non-conform coils could still be employed for the magnets of the High-Luminosity project.

Outline

The problem of current distribution in a Rutherford cable

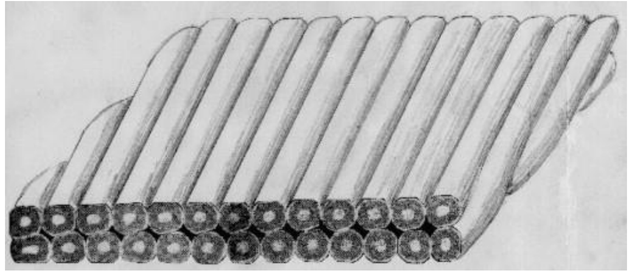
- Network Model & Governing Eqs.
- Model
- Current Distribution at Steady State
- Network Breakdown Mechanism
- Characteristic times and lengths of the system
- Recent developments
- Concluding Remarks



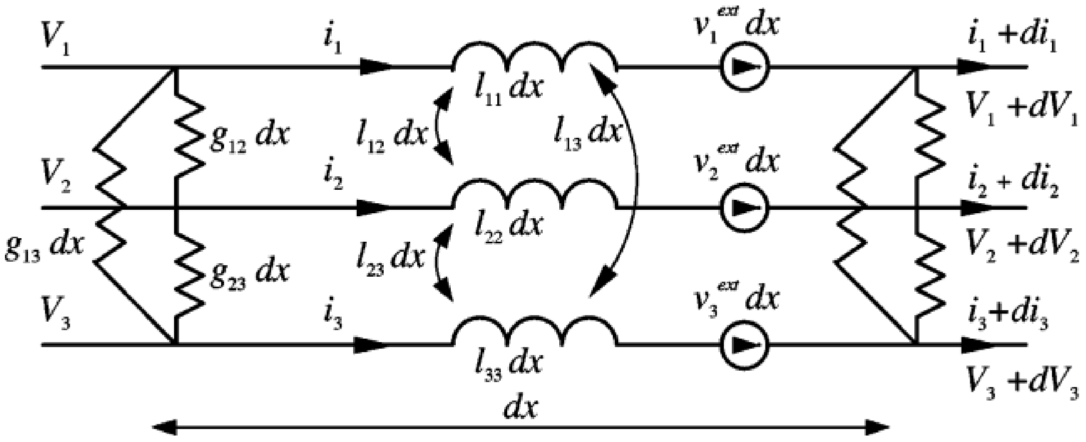
Example of broken strands in a cable splice

Network Model & Governing Equations

A **Rutherford cable** is a type of cable where superconducting strands are arranged in a twisted, two-layer, rectangular cross-section configuration.



Electrical description of a Rutherford cable is based on the *distributed parameters model [1]*



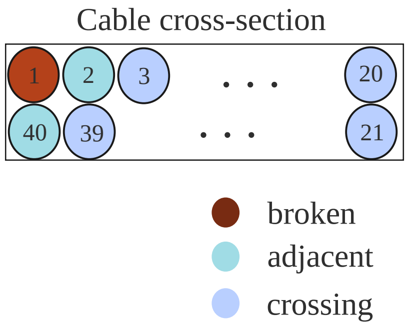
The relevant elements of the circuit are:

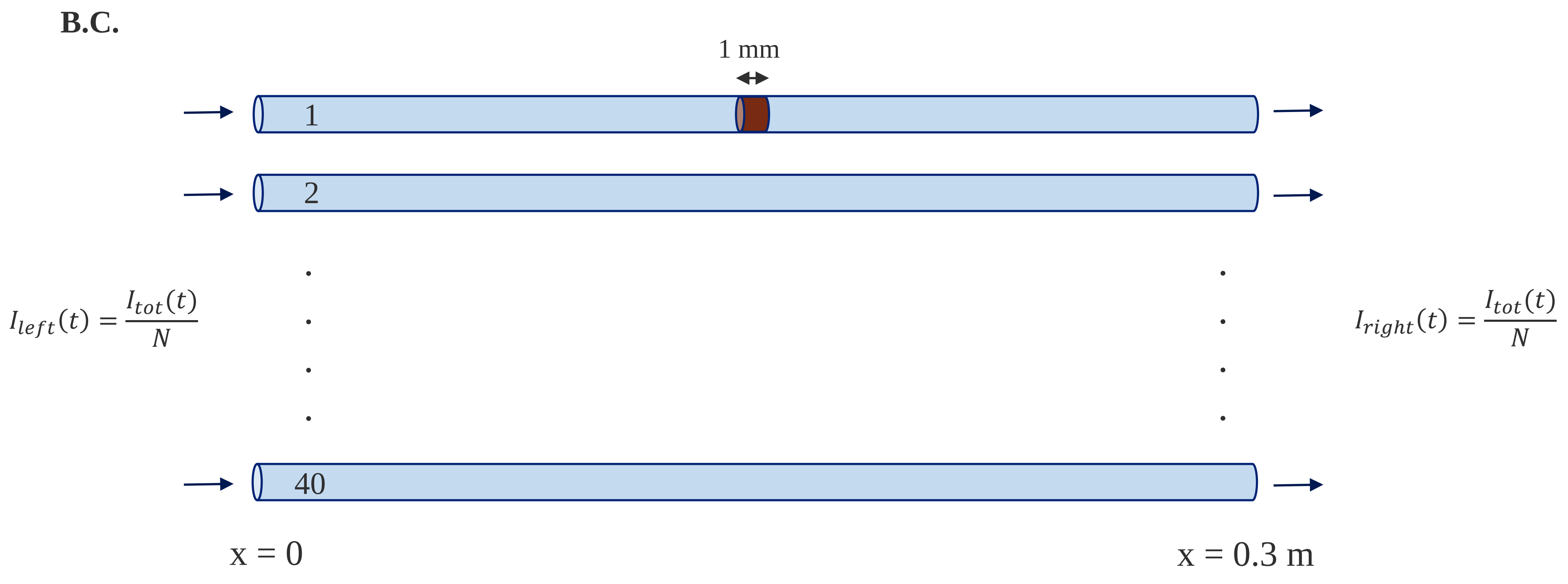
- Inductances $l_{i,j}$
- Transverse resistances R_a, R_c $\longrightarrow$ g_a, g_c

Governing equation :

$$\frac{\partial^2 \vec{\boldsymbol{I}}}{\partial x^2} + \vec{\boldsymbol{g}}\vec{\boldsymbol{l}}\frac{\partial \vec{\boldsymbol{I}}}{\partial t} + \vec{\boldsymbol{g}}\vec{\boldsymbol{r}}\vec{\boldsymbol{I}} - \vec{\boldsymbol{g}}\vec{\boldsymbol{v}}^{ext} = 0 \qquad (1)$$

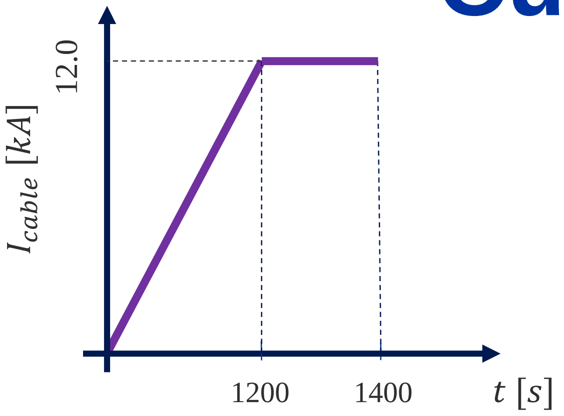
Model



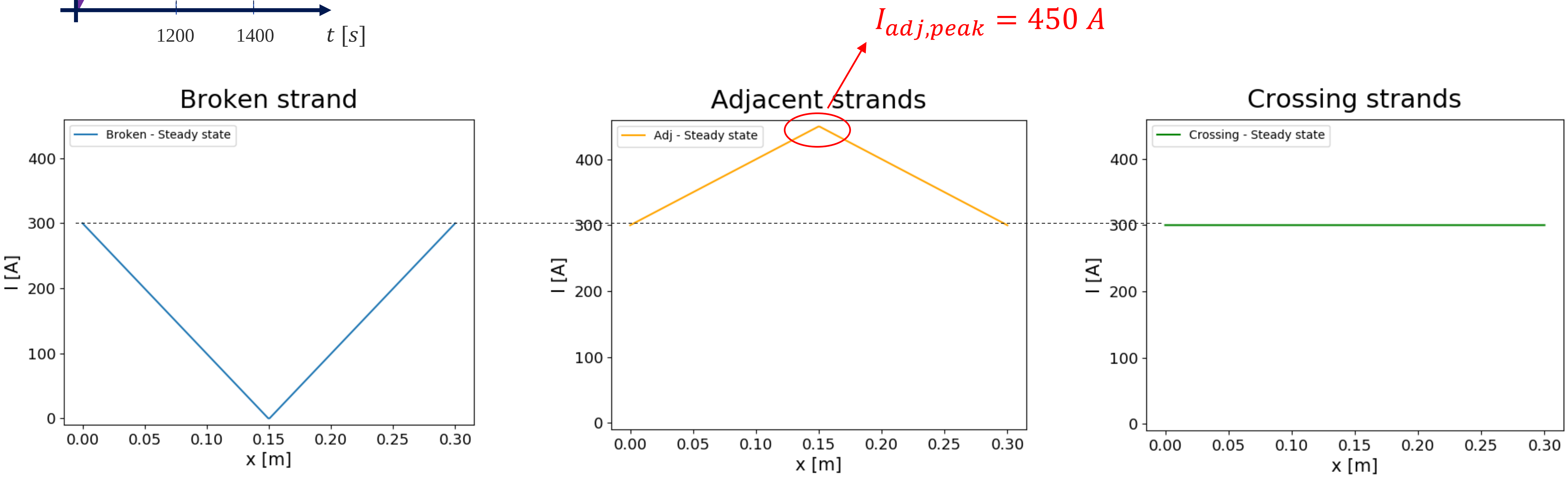


- Strands are represented here as 3-D elements, but they are actually treated as 1-D in the equations
- Thanks to adjacent and crossing contacts, strands are connected through a network of resistances (R_a, R_c), which allow *current sharing* among them.
- THEA software [2] has been used to perform the simulations

Current Distribution at Steady State

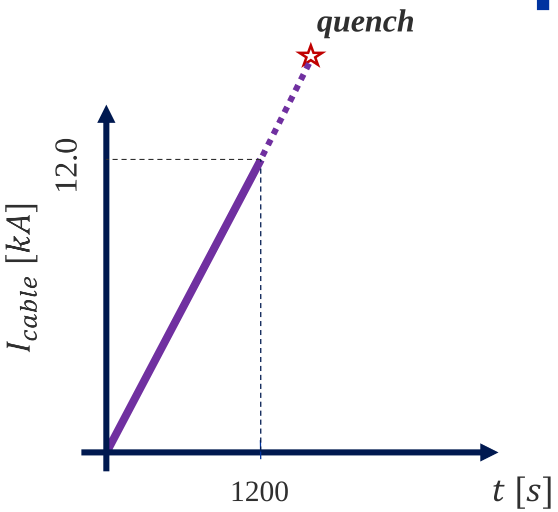


$$\frac{dI}{dt} = 10\ \frac{A}{s} \longrightarrow I_{plat.} = 12\ kA \longrightarrow \text{300 A/strand, on average}$$



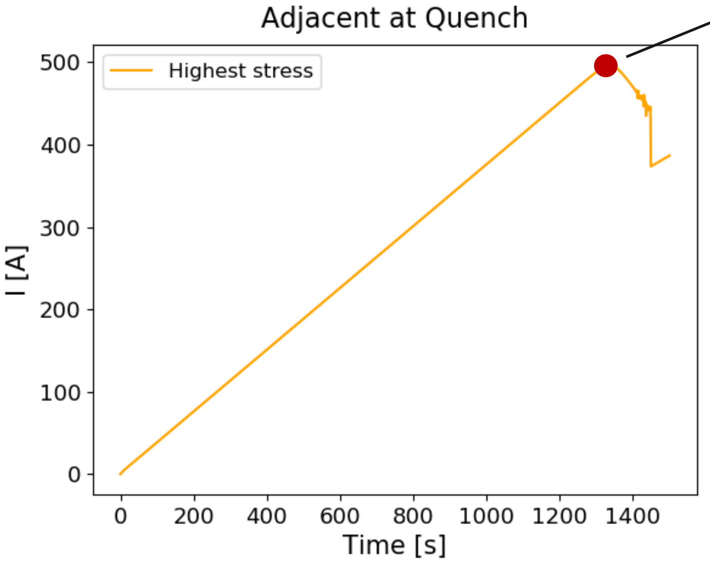
- Only adjacent strands take part in the current distribution
- Margin to critical curve is reduced by a factor 2

Network Breakdown Mechanism



$$\frac{dI}{dt} = 10\ \frac{A}{s} \longrightarrow I_{quench}$$

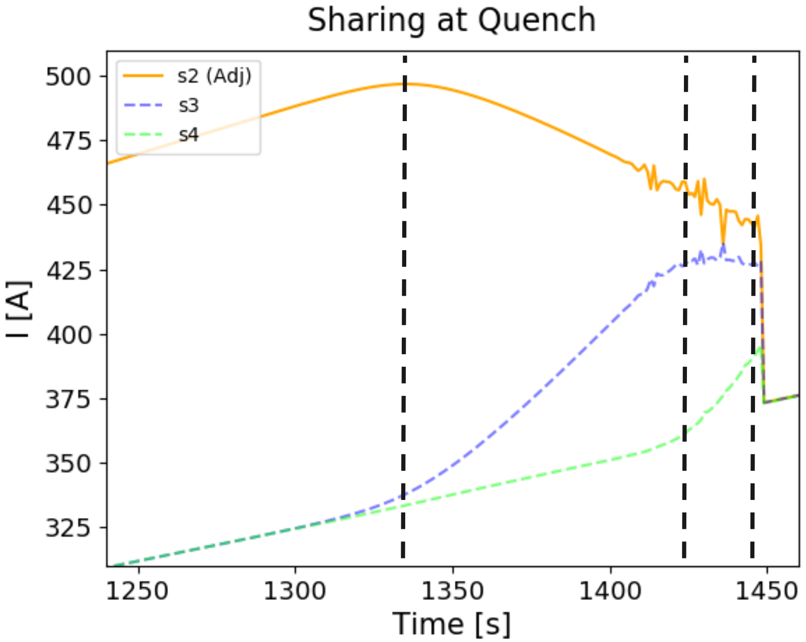
- $B_{max}(I_{cable}) = \frac{I_{cable}}{I_{nom}} * B_{max}(I_{nom})$

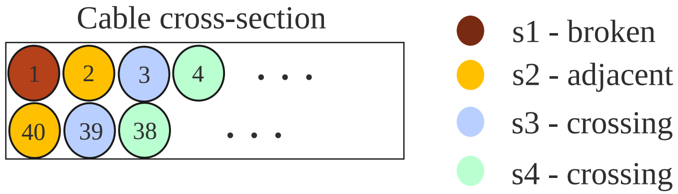


I = 490 A, B = 12.8 T → *margin = 0* !

- We “touch” the critical curve at *high I* and *B* levels
- In addition, *B* is increasing ⟶ *Sharing* to the crossing strands starts

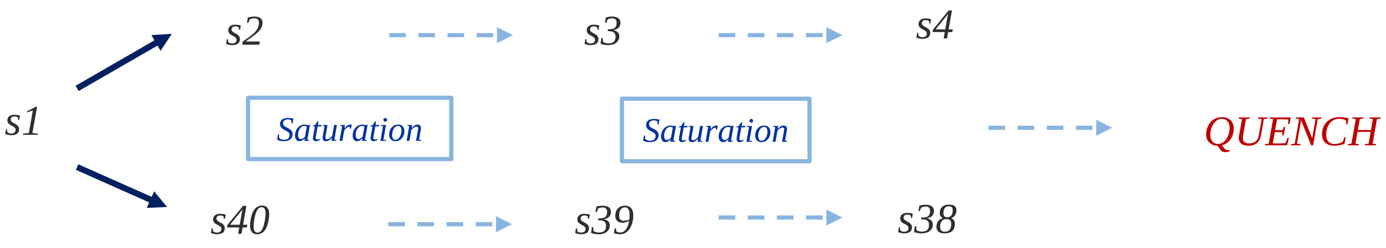
Network Breakdown Mechanism





Change in slope determines 3 relevant moments

1. Sharing to the first crossing strand (s3)
2. Sharing to the second crossing strand (s4)
3. Quench

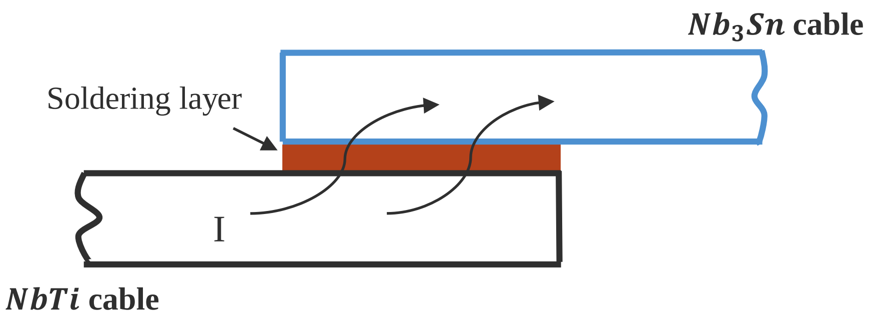


- Current distribution is highly non-uniform → Very bad effect on stability

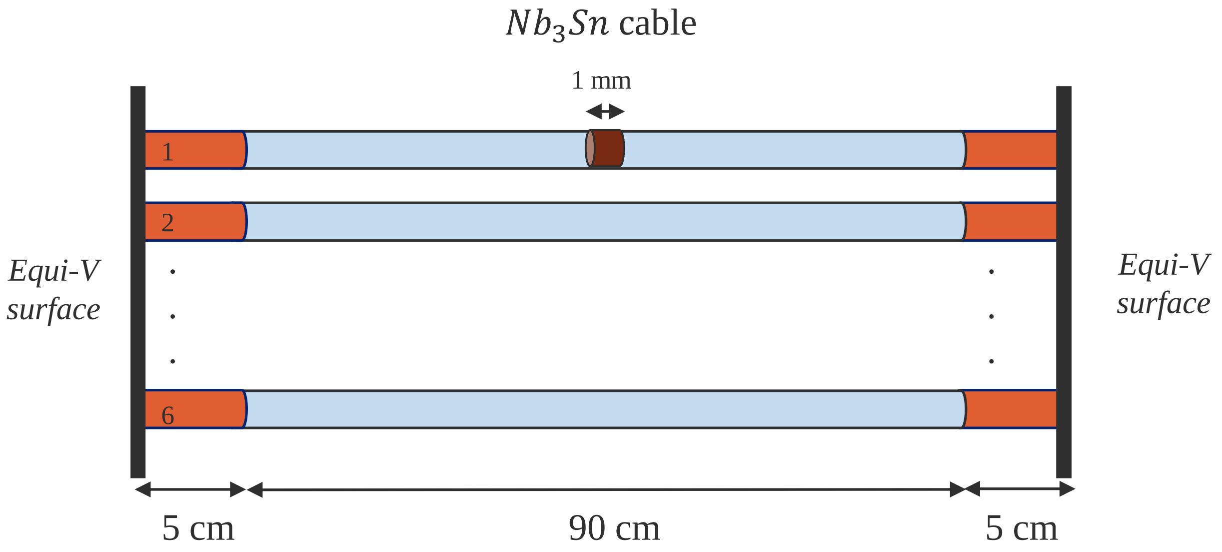
Recent developments

It has become clear that *the boundary plays a relevant role on the current evolution process*, and thus on the steady state current profile in each strand

→ Attention is now focused on the **cable joints**.



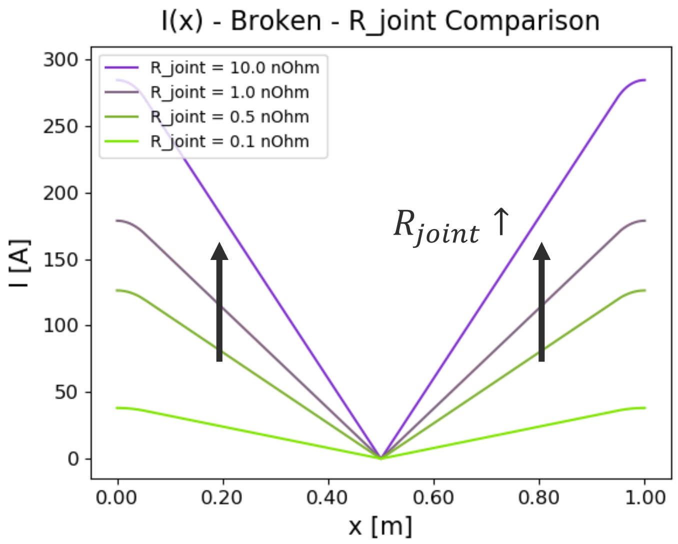
- Current is transferred from NbTi to Nb_3Sn strands through the resistive layer of the solder + Cu strand matrix

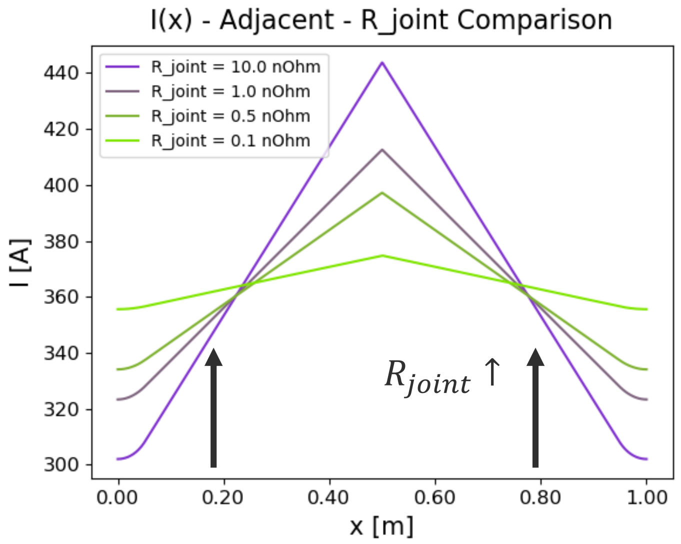


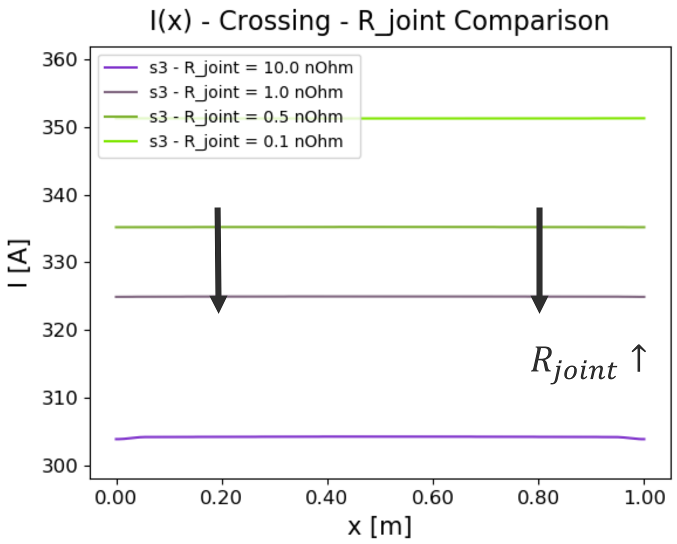
- Length and η_{Cu} in the boundary regions (depicted in orange) are set to have an overall $R_{joint} = 1.0\ n\Omega$.

Recent developments

Influence of R_{joint} on the current distribution in the cable







- A high R_{joint} means having a high voltage "pump" ($\Delta V = RI$), forcing current to flow into the broken strand.
- Current sharing worsens as R_{joint} ↑, having a negative effect on stability.

⟶ Low - R joints are preferable

Concluding remarks

- The dynamics of the current distribution in a 40-strand Rutherford cable (the same type used in the 11 T Dipole for the HL-LHC) subjected to a local breakage has been analysed.

- The first part was dedicated to the investigation of an intrinsic property of the network. The breakdown mechanism, showing that current sharing does not involve all strands, but it's rather a cascade effect from one strand to the next. This may be attributed to the high difference between R_a and R_c in a Nb_3Sn cable.

- The aim of the second part was to build a model of the conductor and the coil. A first step is the proper description of the joints, which behave as a mixed-BC (not stringent as a pure equal distribution of current, nor as a pure equi-V surface). Results show a much higher current uniformity in all non-broken strands for small values of R_{joint}.

- Next steps: Implementation of the field profile along the ~ 10^3 meter coil; Study the joint role in much longer domains; Go back to 40 strands to ensure full representation of the real system.

Thanks for your attention !!

For any doubt, explanation or complaint, please do not hesitate to contact me at:

giovanni.succi@cern.ch

Bybliography

[1] *Bottura*, *Breschi*, *Fabbri*, Analytical solution for the current distribution in multistrand superconducting cables, 2002.

[2] *Bottura*, *Rosso*, THEA Software, 1998