Analysis of current distribution and AC losses in a RW2 prototype cable for the European DEMO TF coils

F. Bellina[1] M. Breschi[2] P. L. Ribani[2]

[1]Udine University, Italy, [2]Bologna University, Italy

2021 CHATS-AS Workshop, Sept. 2021

Summary

1. Introduction
2. The DEMO RW2 conductor
3. THELMA cable models
4. Models results
5. Contact and electromagnetic models
6. Lessons learned and conclusion

Introduction

- For the DEMO TF coil, Swiss Plasma Center (SPC) has proposed a R&W conductor with a high aspect ratio [1].
- This conductor is made of a set of small circular SC strand bundles *(petals)*, wound to form a *composite Rutherford-like* bundle.
- Stability is provided by two copper Rutherford bundles located on the two wide sides of the SC Rutherford bundle.

☞ The THELMA code is being used to model short SULTAN samples of this type of RW cable, in order to analyse:

  - the stabiliser interstrand resistances;
  - the cable behaviour as regards the total losses;
  - the induced currents distribution.

The DEMO RW2 conductor

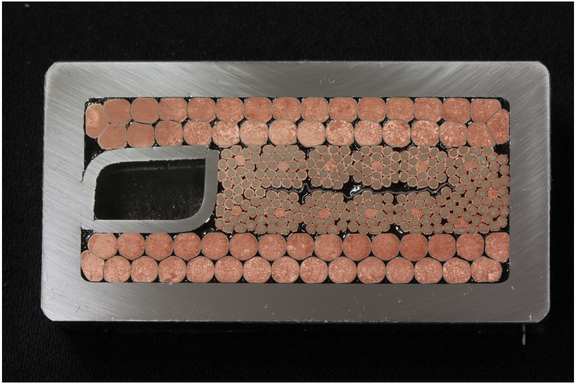


Figure: DEMO RW2 cross-section (Courtesy of SPC, from [2])

Go to cable data
Go to cable drawing

Experimental data I

The experimental data are taken from [2].
Available measurements:

- Rutherford stabilisers interstrand resistance;
- AC losses:
  - measured at 4.5 K and 20 K;
  - at 0° and 90° (**B** perpendicular/parallel to the cable broad face);
  - with sinusoidal and unipolar trapezoidal field;

Show SPC report

Experimental data II

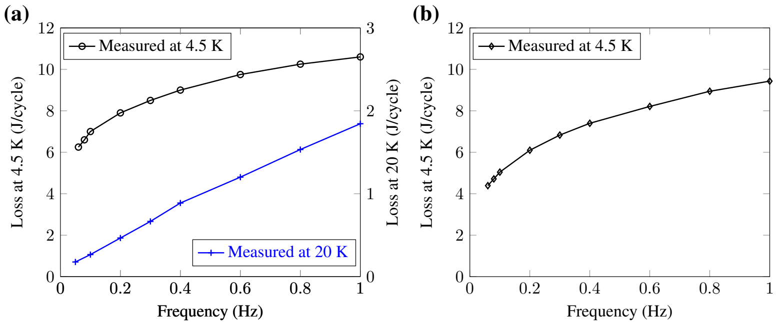


Figure: Measured AC losses, sinusoidal field. (a): perpendicular, (b): parallel. (from [2])

Cable models I: overview

Several cable models have been developed to study DEMO RW2:

- CEs geometry created according to UNIBO or UNIUD models;
- Inter-CE conductances computed from CEs geometry, according to UNIBO or UNIUD models;
- UNIBO distributed parameter model used for all AC losses analyses.

Go to cable drawing | Go to contact models | Go to UNIBO EM model

Cable geometric models I

Intra-CE: (4 Cu +54 Cu):

- models the Cu stabiliser *individual strand* in terms of 60 sub-cable elements,
- CEs axis modelled starting from 307 CE stabiliser strands geometry.

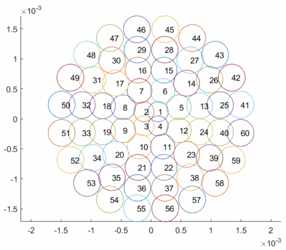


Figure: Intra-CE strand model.

Cable geometric models II

30 CE: (1 Cu)$\times$ 30:

- models the upper or the lower Rutherford Cu stabiliser.

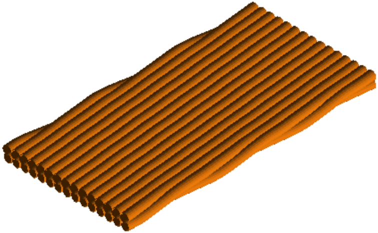


Figure: (1 Cu)$\times$ 30 cable model.

Cable geometric models III

91 CE: (1 Cu + 6 CE)×13:

- considers only the last two cabling stages of the cable central Rutherford bundle,
- each *petal* is modelled as the central Cu strand and 6 SC macro CEs, each representing 3 SC strands,
- CEs axis geometry modelled analytically.

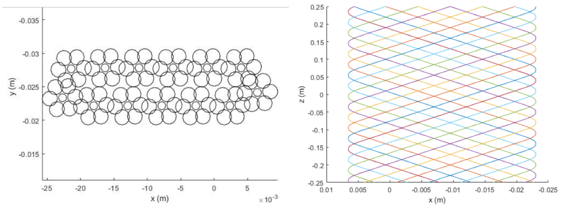


Figure: 91 CE cable model. Left: cable cross-section. Right: Cu core strands axis geometry.

Cable geometric models IV

307 CE: (1 Cu)$\times$ 30 + (1 Cu + 6 SC + 12 SC) $\times$ 13 +(1 Cu)$\times$ 30:

- considers all the cable strands (stabilisers and SC cable),
- SC Rutherford cable steel core modelled,
- Rutherford stabilisers coupled with the central SC Rutherford cable,
- *realistic* strands geometry. ▸ Show cable compaction

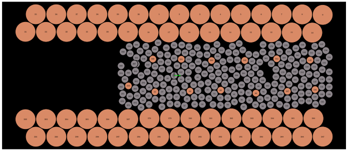
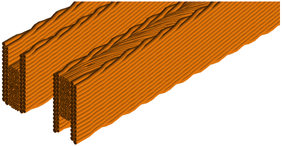



Figure: 307 CE cable model. Left: cable cross-section. Right: detail of the end of the two SULTAN sample cables.

Cable geometric models V

247 CE: (1 Cu + 6 SC + 12 SC) $\times$ 13 :

- same as 307 CE model, but SC cable strands only (no stabilisers).

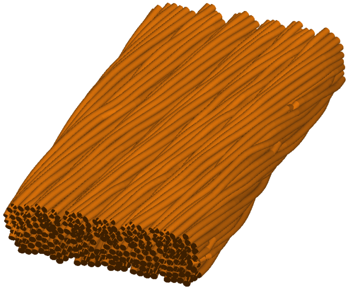


Figure: 247 CE cable model.

Models results

The analysis campaign has been subdivided into several interlinked subtasks:

- stabiliser interstrand resistances analysis,
- stabiliser AC loss analysis,
- SC Rutherford bundle AC loss analysis.

☞ According to the model adopted, different parameters have to be tuned to fit the experimental results.

Stabiliser interstrand resistances - I

- Some short samples of the Rutherford stabiliser were tested in DC at both 292 and 4.23 K [3, 1].
- Two strands of the sample were fed through two pin leads located at the sample middle length.

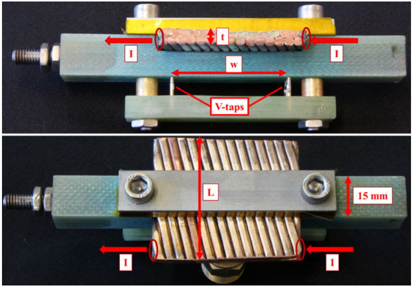


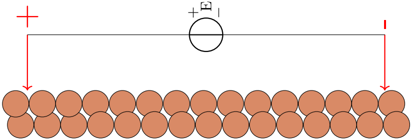
Figure: DEMO R&W RW2 stabiliser DC resistance test, from [2].

Stabiliser interstrand resistances - II

The measured resistance R_{meas} was used to determine the equivalent *resistivity in transverse direction*, defined as:

$$\varrho_{\text{eff}} = R_{\text{meas}} \frac{tL}{W} \qquad (\Omega \cdot \text{m}), \tag{1}$$

where t is the cable thickness, L is the stabiliser sample length, W is the distance between the two current leads.



Stabiliser interstrand resistances - III

- A **target value** $\bar{\varrho}_{\mathrm{eff}} = 1.96\ \mu\Omega\mathrm{m}$ has been assumed for a conductor model **100 mm long**, on the basis of the average values reported in [3].

☞ Actually, the updated measured value reported recently in [1] ($\rho_{\perp} = 631\ \mu\Omega\mathrm{m}$) is much greater.

- Using the target value $\bar{\varrho}_{\mathrm{eff}}$, the sample length and number of longitudinal elements have been changed parametrically.

▸ Show SPC D'Auria report [3] ▸ Show article [1]

Stabiliser interstrand resistances - IV

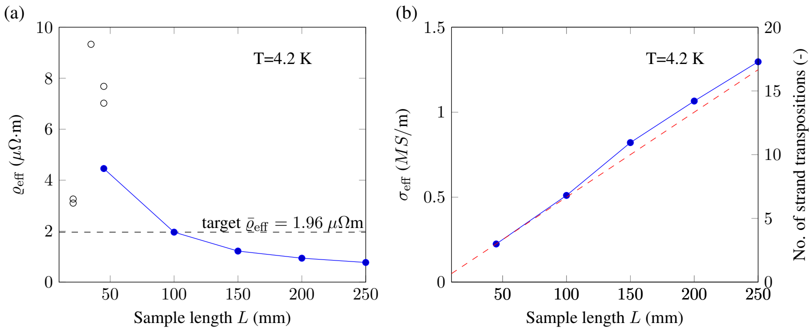


Figure: DEMO R&W RW2 stabiliser DC analysis: effect of the sample length. Left: resistivity $\varrho_{\rm eff} = R_{\rm meas} \cdot tL/W$. Right: conductivity $\sigma_{\rm eff}$ in transverse direction and no. of transpositions. Empty marks are the measured values [3].

Stabiliser interstrand resistances - V

Conclusions about stabiliser interstrand resistances parametric analysis.

- Computed σ_{eff} depends almost linearly with L.
- Possible reasons of this behaviour can be:
  - the current diffusion effects along the strands $\lambda = 1/\sqrt{r_\ell g_\mathrm{c}}$;
  - the strands geometry:

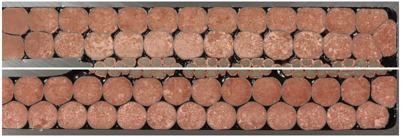


Figure: DEMO R&W RW2 stabiliser sections. (from [2])

Stabiliser AC loss analysis I

The stabiliser behaviour has been preliminarily studied with 30 CE model at 20 K considering $B(t) = 2.0 + 0.3\sin(\omega t)$ perpendicular to the cable ($B_\perp$).

- Cable losses are mostly made of intra-strand resistive losses, that can be estimated with a non inductive model of the strand [4]:

$$\mathcal{L}_\mathrm{J} = \frac{P_{\mathrm{J_{ave}}}}{f} = \pi^3 f \sigma_\mathrm{Cu} \frac{D_0^4}{32} B_\mathrm{M}^2 \quad (\mathrm{J/(cycle{\cdot}m)}). \tag{2}$$

This model is valid if the *penetration depth*

$$\delta = \sqrt{1/\left(\pi f \mu_0 \sigma_\mathrm{Cu}\right)} \tag{3}$$

is larger than the strand radius $r_0 = D_0/2 = 1.675$ mm.

Go to stabiliser AC analysis details

Stabiliser AC losses analysis II: 20 K

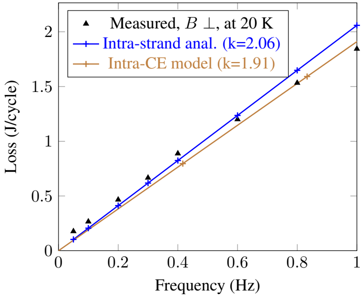


Figure: DEMO RW2 measured loss at 20 K, $B \perp$, intra-strand loss computed with Intra-CE model and loss analytically computed with (2).

☞ The analytical and Intra-CE models give quite similar values.

Stabiliser AC losses analysis II: 20 K

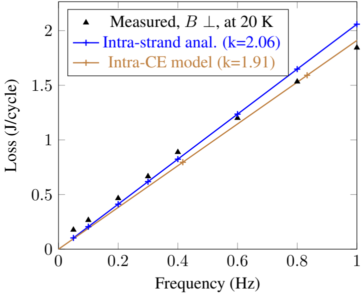


Figure: DEMO RW2 measured loss at 20 K, $B \perp$, intra-strand loss computed with Intra-CE model and loss analytically computed with (2).

☞ The computed loss almost equals measured values but it does not include the SC Rutherford bundle loss (≈ 1J/cycle)

Stabiliser AC losses analysis II: 20 K

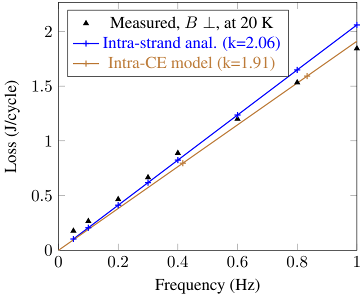


Figure: DEMO RW2 measured loss at 20 K, $B \perp$, intra-strand loss computed with Intra-CE model and loss analytically computed with (2).

☞

- The stabiliser may have demagnetising effects on the SC Rutherford bundle (at 4.5 K this may not be true).
- Very low stabiliser inter-strand coupling currents are present.

Stabiliser AC losses analysis III: 4.5 K

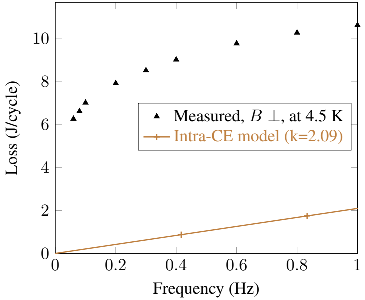


Figure: DEMO RW2 measured loss at 4.5 K, $B \perp$ and intra-strand loss computed with Intra-CE model.

☞ The computed AC loss in the stabilisers is almost the same at 20 K and 4.5 K.

Stabiliser AC losses analysis III: 4.5 K

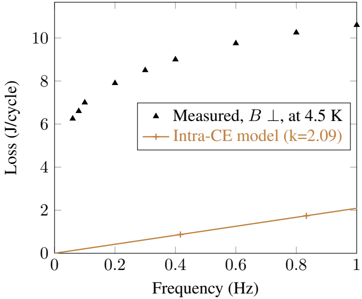


Figure: DEMO RW2 measured loss at 4.5 K, $B \perp$ and intra-strand loss computed with Intra-CE model.

☞ Hysteresis loss in SC Rutherford is dominant ($f \in [0.0 : 1.0]$ Hz).

Stabiliser AC losses analysis III: 4.5 K

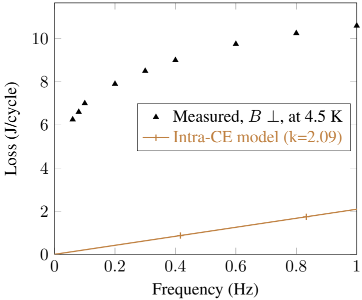


Figure: DEMO RW2 measured loss at 4.5 K, $B \perp$ and intra-strand loss computed with Intra-CE model.

☞ Coupling currents in SC Rutherford are by far larger than stabilisers coupling currents.

Stabiliser AC losses analysis III: 4.5 K

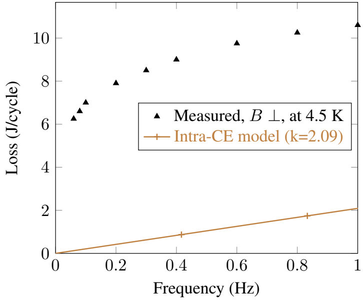


Figure: DEMO RW2 measured loss at 4.5 K, $B \perp$ and intra-strand loss computed with Intra-CE model.

☞ SC Rutherford may have a demagnetising effect on stabilisers.

Stabiliser AC losses analysis III: 4.5 K

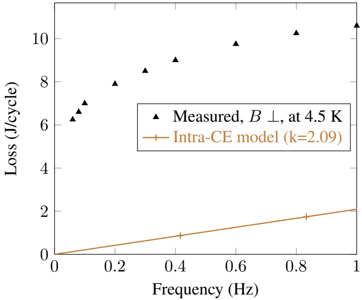


Figure: DEMO RW2 measured loss at 4.5 K, $B \perp$ and intra-strand loss computed with Intra-CE model.

☞ Stabilisers and SC Rutherford cable can be modelled separately as regards AC losses.

Stabiliser AC losses analysis III: 4.5 K

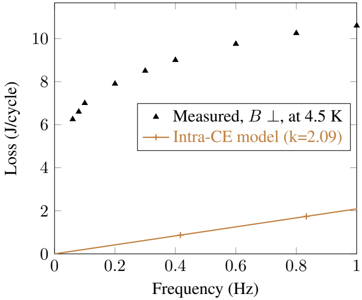


Figure: DEMO RW2 measured loss at 4.5 K, $B \perp$ and intra-strand loss computed with Intra-CE model.

☞ This enables the use of the 91 and 247 CE models to set-up the SC cable interstrand conductances through the THELMA AC losses.

Stabiliser AC losses analysis III: 4.5 K

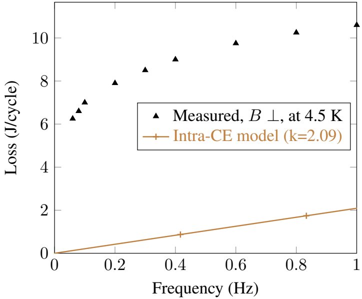
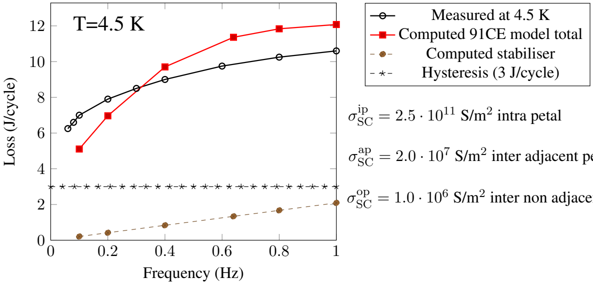


Figure: DEMO RW2 measured loss at 4.5 K, $B \perp$ and intra-strand loss computed with Intra-CE model.

☞ Very low transverse conductances (S/m) among the stabiliser strands used to fit the measured data at 20 K ($6 \cdot 10^3$ S/m).

SC Rutherford bundle AC losses analysis I: 91 CE model



$\sigma_{\mathrm{SC}}^{\mathrm{ip}} = 2.5 \cdot 10^{11}$ S/m^2 intra petal

$\sigma_{\mathrm{SC}}^{\mathrm{ap}} = 2.0 \cdot 10^{7}$ S/m^2 inter adjacent petals

$\sigma_{\mathrm{SC}}^{\mathrm{op}} = 1.0 \cdot 10^{6}$ S/m^2 inter non adjacent petals

Figure: DEMO RW2 measured loss at 4.5 K, B ⊥, total loss computed with 91 CE cable model, intra-strand loss computed with Intra-CE model and hysteresis loss.

☞ Hysteresis loss assumed constant with f, considering $\mathcal{L}_{\mathrm{hyst}} = \lim_{f \to 0} \mathcal{L}(f) \Rightarrow$ only estimated.

Go to hysteresis losses

SC Rutherford bundle AC losses analysis I: 91 CE model

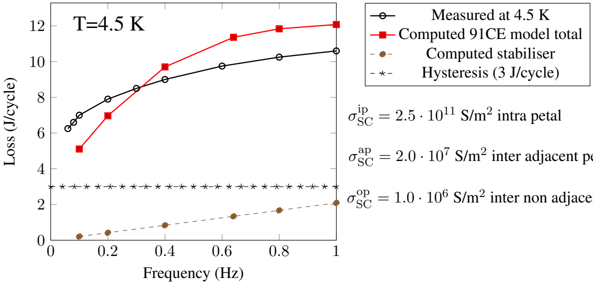


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Figure: DEMO RW2 measured loss at 4.5 K, $B \perp$, total loss computed with 91 CE cable model, intra-strand loss computed with Intra-CE model and hysteresis loss.

☞ Qualitative agreement between measured and computed losses, however $\varepsilon \in [-27\% : +14\%]$.

Go to hysteresis losses

SC Rutherford bundle AC losses analysis I: 91 CE model

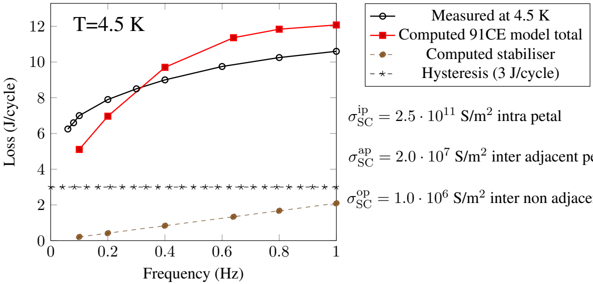

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Figure: DEMO RW2 measured loss at 4.5 K, $B \perp$, total loss computed with 91 CE cable model, intra-strand loss computed with Intra-CE model and hysteresis loss.

☞ Too steep total loss curve, esp. at low frequencies!

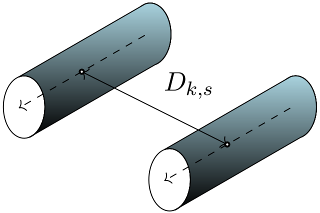
Go to hysteresis losses

SC Rutherford bundle AC losses analysis II: 91 CE model

Too steep total loss curve, possible reasons:

- inductive coupling between CEs;
- cable model too simple?
- interstrand and steel foil contact resistances values.

SC Rutherford bundle AC losses analysis III: inductive coupling



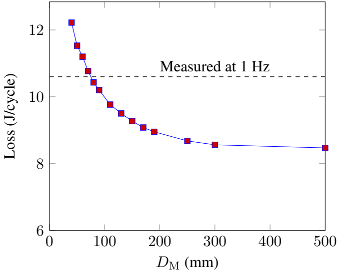


Figure: 91 CE cable model. Coupling loss in SC Rutherford at 1 Hz as a function of D_{M}.

$$\begin{cases} D_{k,s} \le D_{\mathrm{M}} \quad \Rightarrow \quad M_{k,s} = \int_{\tau_k} \int_{\tau_s} \dfrac{\mu_0}{I_k I_s} \dfrac{\mathbf{J}_k \cdot \mathbf{J}_s}{4\pi\, r_{k,s}} \, \mathrm{d}\tau_k \, \mathrm{d}\tau_s \\ D_{k,s} > D_{\mathrm{M}} \quad \Rightarrow \quad M_{k,s} = 0.0 \end{cases} \tag{4}$$

SC Rutherford bundle AC losses analysis IV: 247 CE model

With the 247 CE model:

- All strands are individually represented.
- Steel foil (SC Rutherford core) represented.
- *In principle* only these resistive parameters ($\Omega \cdot \mathrm{m}^2$) should be considered:
  - $\varrho^{\mathrm{d}}_{\mathrm{st}}$ SC strand;
  - $\varrho^{\mathrm{d}}_{\mathrm{Cu}}$ Cu strand;
  - $\varrho^{\mathrm{d}}_{\mathrm{core}}$ Steel foil addditional.

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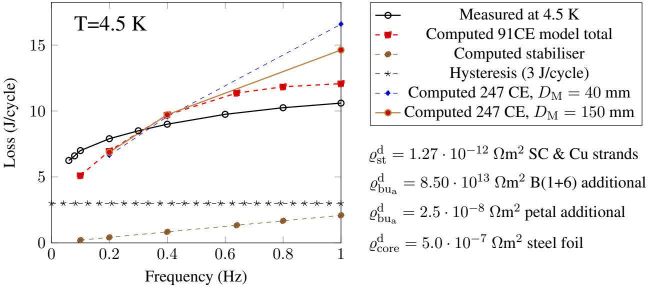
  - $\varrho^{\mathrm{d}}_{\mathrm{st}}$ SC strand;
  - $\varrho^{\mathrm{d}}_{\mathrm{Cu}}$ Cu strand;
  - $\varrho^{\mathrm{d}}_{\mathrm{core}}$ Steel foil addditional.
- However, there are also. . .
  - $\varrho^{\mathrm{d}}_{\mathrm{b}(1+6)_{\mathrm{a}}}$ Bundle (1+6) additional;
  - $\varrho^{\mathrm{d}}_{\mathrm{b}(12)_{\mathrm{a}}}$ Bundle (12) additional;
  - $\varrho^{\mathrm{d}}_{\mathrm{b}(1+6+12)_{\mathrm{a}}}$ Bundle (1+6+12) (petal) additional;

SC Rutherford bundle AC losses analysis VI: 247 CE model



$\varrho^{d}_{st} = 1.27 \cdot 10^{-12}\ \Omega m^2$ SC & Cu strands

$\varrho^{d}_{bu_a} = 8.50 \cdot 10^{13}\ \Omega m^2$ B(1+6) additional

$\varrho^{d}_{bu_a} = 2.5 \cdot 10^{-8}\ \Omega m^2$ petal additional

$\varrho^{d}_{core} = 5.0 \cdot 10^{-7}\ \Omega m^2$ steel foil

Figure: DEMO RW2 measured loss at 4.5 K, $B \perp$, total loss computed with 247 CE cable model, intra-strand loss computed with Intra-CE model and hysteresis loss.

☞ At present, the more detailed geometrical model seems not to give more accurate results.

SC Rutherford bundle AC losses analysis V: 247 CE model

☞ Bundles additional resistances in the absence of wraps and different coatings?

- DEMO RW2 has been manufactured by replacing the stabilisers of the existing and already tested *RW2 brass* sample.
- The Rutherford SC bundle is not cabled as usual CICCs, the petal has a concentric structure, so that it may be reasonable to consider additional distributed resistances e.g. for bundles B(1+6), B(12) and B(1+6+12)

☞ Large number of model parameters:

- optimisation (if any) requires a large computational effort;
- some different parameters sets give similar results with frequency;
- a given change of one parameter may give different results for different values of the other parameters.

Lessons learned and conclusion

- ☞ In DEMO RW2, the coupling losses dependence on frequency is different from that in CICCs.
- ☞ The magnetic coupling max distance D_{M} must be much bigger than in usual CICCs $\Rightarrow$ large size models.
- ☞ The inductive effects of the cable interstrand currents are important in the case of relatively high interstrand conductances.
- ☞ The results at 20 K and with parallel field must agree with the experimental ones.
- ☞ A large work is still to be carried out to investigate the effects of the interstrand and interbundle contact resistances.

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Thank you very much!

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[7] P. Bruzzone, K. Sedlak, X. Sarasola, B. Stepanov, D. Uglietti, R. Wesche, L. Muzzi, and A. della Corte, "A prototype conductor by React&Wind method for the EUROfusion DEMO TF coils," *IEEE Trans. Appl. Supercond.*, vol. 28, no. 3, p. 4202705, April 2018.

Cable interstrand contact models I: geometry

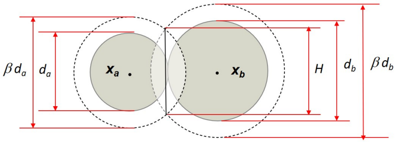


Figure: Contact geometry

$$\sigma_{\mathrm{a,b}}(\zeta) = \sigma^{\mathrm{s}}_{\mathrm{a,b}} H \quad (\mathrm{S/m}), \tag{5}$$

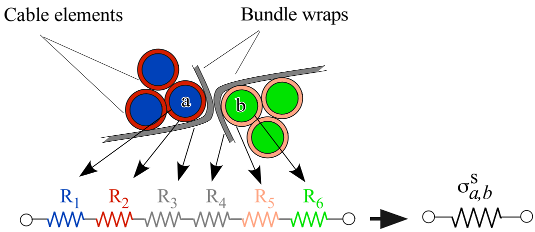
where:

- ζ cable axial coordinate (m);
- $\mathbf{x}_{\mathrm{a}}$, $\mathbf{x}_{\mathrm{b}}$ CEs centres 3D coordinates (m), $\mathbf{x} = \mathbf{x}(\zeta)$;
- d_{a}, d_{b} CEs diameters (m);
- $\sigma^{\mathrm{s}}_{\mathrm{a,b}}$ specific conductance between CEs a and b (S/m^2);
- β diameter magnification factor ($\beta \geq 1$) (–).

Cable interstrand contact models II: specific conductances

The two models differ as regards the specific conductance:

- In UNIBO $\sigma^{\mathrm{s}}_{\mathrm{a,b}} \in \boldsymbol{\sigma}^{\mathrm{s}}$, where $\boldsymbol{\sigma}^{\mathrm{s}}_{n_{\mathrm{CE}},n_{\mathrm{CE}}}$ is a model input matrix.
- In UNIUD $\sigma^{\mathrm{s}}_{\mathrm{a,b}}$ is computed considering the series resistance between the involved strands and bundles they belong to, including additional coatings:



Back to cable models

(Part of the) UNIBO electromagnetic model - I

- Cable made of N_{CE} cable elements, each made of N_{elem} longitudinal elements;
- CE current:

$$I_{\mathrm{ce}_k}(\zeta, t) = I_{\mathrm{u}_k}(t) + I_{\mathrm{d}_k}(\zeta, t), \quad k = 1 \dots N_{\mathrm{CE}},\ 0 \le \zeta \le \ell; \quad (6)$$

- Each CE is not electrically isolated and can exchange current among the CEs which are in contact with him:

$$\frac{\partial I_{\mathrm{ce}_k}}{\partial \zeta}(\zeta, t) = \sum_{h=1}^{N_{ce}} J_{\mathrm{cc}_{h,k}}(\zeta, t); \quad (7)$$

- The standard $\mathbf{A} - \mathbf{V}$ electromagnetic formulation is adopted:

$$\mathbf{E}(\mathbf{x}, t) = -\nabla V(\mathbf{x}, t) - \frac{\partial \mathbf{A}}{\partial t}(\mathbf{x}, t); \quad (8)$$

UNIBO EM model - II: system equations

- Inductive effects are considered both along each CE and along inter-CE contacts;
- the unknowns of the discretized problem are the $N_{\mathrm{ce}} \times N_{\mathrm{elem}}$ difference currents in the nodes of the cable segment:

$$\mathbf{I}_{\mathrm{d}} = \left(I_{\mathrm{d}_{k,w}}(t)\right), \quad \text{with} \quad k = 1, \ldots, N_{\mathrm{ce}}, \quad w = 1, \ldots, N_{\mathrm{elem}}; \tag{9}$$

- a linear distribution of current is present in the w-th CE element, changing from $I_{\mathrm{d}_{k,w}}$ to $I_{\mathrm{d}_{k,w+1}}$, with $\zeta \in [\zeta_w, \zeta_{w+1}]$;
- a first order non linear ODE is built and solved in time domain:

$$\mathbf{A}\frac{\mathrm{d}\mathbf{I}_{\mathrm{d}}}{\mathrm{dt}} = \mathbf{F}(t, \mathbf{I}_{\mathrm{d}}). \tag{10}$$

Back to cable models

Hysteresis loss calculation I

☞ To set in detail the interstrand conductances in SC cable, the hysteresis loss should be estimated and subtracted from the total measured loss.

- According to [5], the hysteresis loss can be obtained starting from the *penetration field* B_p:

$$B_\mathrm{p} = \frac{\mu_0 J_\mathrm{c}(B, T, \varepsilon) d_\mathrm{eff}}{\pi}, \tag{11}$$

where d_eff is the effective filament diameter (THELMA used $2.25 \cdot 10^{-5}$). If $\Delta B > 2B_\mathrm{p}$:

$$P_\mathrm{hyst} = \frac{2}{3\pi} J_\mathrm{c}(B, T, \varepsilon) d_\mathrm{eff} \left| \frac{\mathrm{d}B}{\mathrm{d}t} \right| \quad (\mathrm{W/m^3\ of\ SC}). \tag{12}$$

Hysteresis loss calculation II

However:

- in (11) B_{p} depends on J_{c} which, in turn, depends on B;
- eq. (12) is applicable if $\Delta B > 2B_{\mathrm{p}}$: this may not hold everywhere in the SC strands

Back to AC loss analysis

DEMO RW2 cable data

Table: DEMO RW2 cable (from [2],[6], [7]).

Operating Current (kA)	63.3
Peak Operating Field (T)	12.23
Jacket width × height (mm)	61.5×32.1
Cable Layout	(1 Cu +6+12)×13
Cable pitches τ_{Cbl_k} (mm)	+105, +390
SC cable size (mm)	35×11
Void fraction in cable	≈23%
Central steel strip in flat cable (mm)	25×0.2

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DEMO RW2 SC conductor data

Table: DEMO RW2 SC strand (from [2],[6], [7]).

Strand Diameter D_{St} (mm)	1.2
Cu/non-Cu (-)	1.0
J_{c} (A/mm^2)	1130
J_{Cu} (A/mm^2)	90
$J_{\mathrm{non-Cu}}$ (A/mm^2)	478
n index	18
$\varepsilon_{\mathrm{eff}}$ %	-0.35 : -0.40

DEMO RW2 stabiliser strand data

Table: DEMO RW2 stabiliser strand (from [2],[6], [7]).

External width $\times$ height (mm)	51$\times$6
Strand	CuNi clad
Strand Diameter D_{St} (mm)	3.35
Cable Layout 1 $\times$ N_{St}	1 Cu $\times$30
Cable pitches τ_{Cbl} (mm)	-450
Strand copper resistivity @ 292 K (Ω·m)	$1.66 \cdot 10^{-8}$
Strand copper *RRR* @ 4.2 K	415$\pm$11

DEMO RW2 cable THELMA model geometrical data

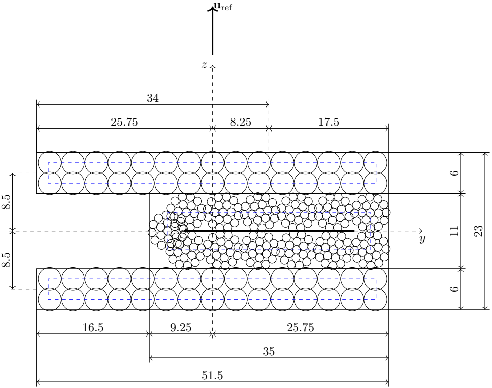

Figure: DEMO prototype cable RW2rutstab THELMA model cross-section sizes.

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Stabiliser AC analysis details I (analytical model)

Table: DEMO TF stabiliser intra-strand losses analytical model ($RRR = 415$).

T (K)	B (T)	σ_{Cu} (GS/m)	δ/r_0 at 1 Hz (–)	$\mathcal{L}_{\mathrm{J}}$ at 1 Hz J/cycle
4.5	2.3	7.64	3.44	2.01
4.5	2.0	8.45	3.27	2.23
4.5	1.7	9.44	3.09	2.49
20.0	2.3	7.12	3.56	1.88
20.0	2.0	7.81	3.40	2.06
20.0	1.7	8.64	3.23	2.28

For different frequency values, according to (2), losses per cycle $\mathcal{L}_{\mathrm{J}}$ are proportional to the frequency.

Stabiliser AC analysis details II (Intra-CE model)

The Intra-CE model was applied in this way:

- the Intra-CE model was applied at strands #1,4,7,10,13,16,19,22,25,28;
- the strands geometry was retrieved from the UNIUD 307 CE model;
- the *average* intra-strand loss was computed at 1 Hz, 4.5 K and 20 K;
- the stabiliser total intra-strand loss was computed from the average intra-strand loss.

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