Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile

High Field-Rate Losses in Cable-In-Conduit-Conductors Carrying Transport Current

Analytical and Numerical Studies

20th-24th September 2021

Virtual (St. Paul Lez Durance, France)

14th CHATS on Applied Superconductivity (CHATS-AS)

Gianluca De Marzi, ENEA FSN-COND

Acknowledgments

University of Roma Tre
Massimiliano Corradini

ENEA
Luigi Muzzi, Lorenzo Giannini, Antonio della Corte

University of Bologna
Marco Breschi, Lorenzo Cavallucci

Swiss Plasma Center - EPFL
Davide Uglietti

Politecnico di Torino
Roberto Bonifetto, Andrea Zappatore

Outline

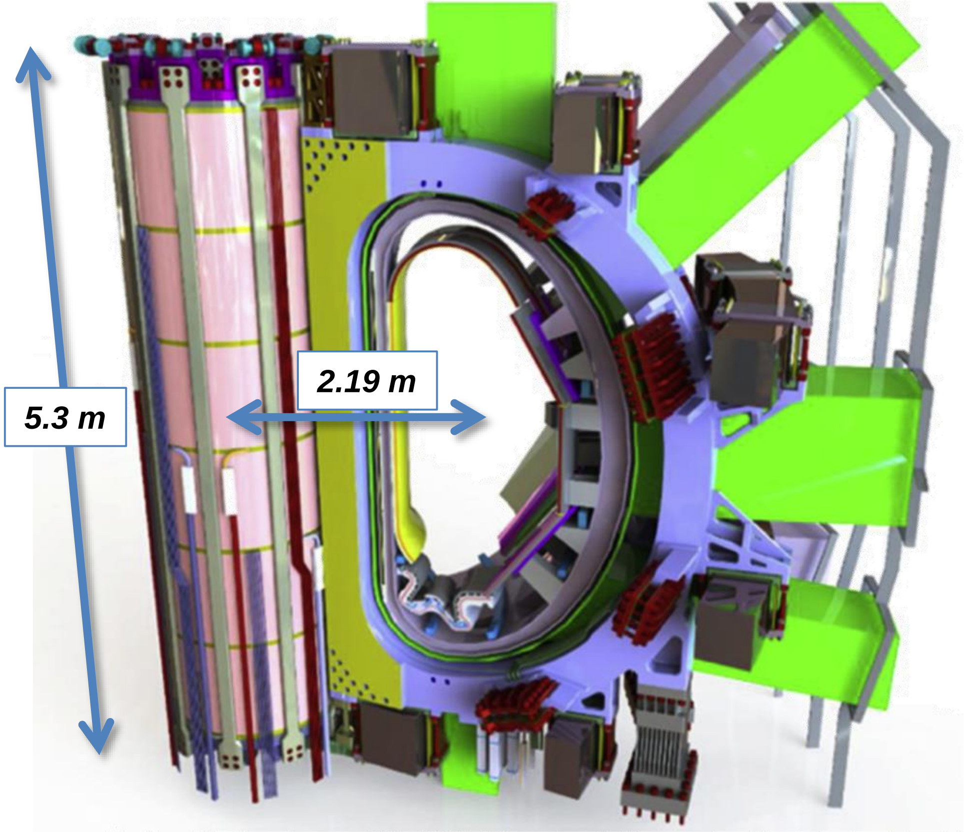
- Introduction: fast transients in Tokamaks
- New model for the calculation of AC losses due to fast varying fields
  - ✓ Analytical solution of the Osagawara equation
  - ✓ Coupling, magnetization, and dynamic resistance
- Model application: ac losses of a CS module of a Tokamak device (DTT):
  - ✓ Evaluated AC losses on central turn at peak field
  - ✓ Developed 2D FE model with variable $n\tau$
- Conclusions and future directions

Introduction – Divertor Tokamak Test @ ENEA

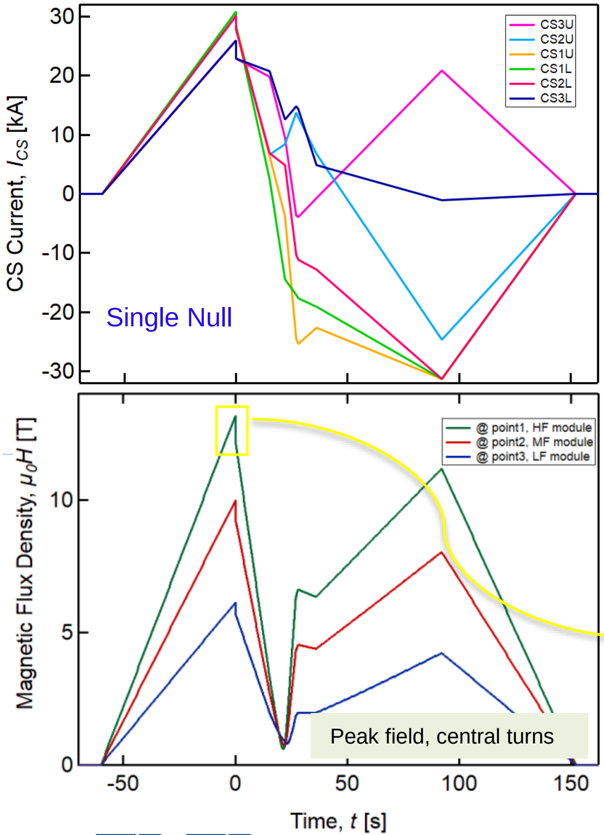
18 TF coils:
Nb_3Sn CICC: **42.5 kA – 11.9 T**
providing **6.0 T** over plasma major radius

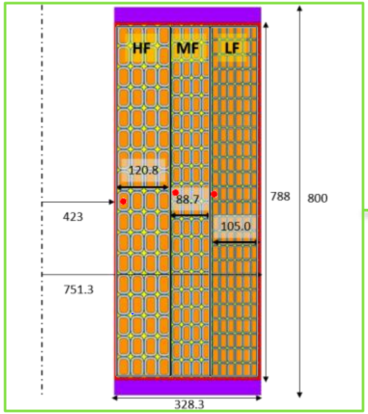
6 CS modules (indipendently fed):
Nb_3Sn CICC: **31.3 kA – 13.6 T**
providing **16.6 Weber** magnetic flux for plasma initiation at breakdown

6 PF coils:
Nb_3Sn (PF1 & PF6) CICC: **28.3 kA – 9.1 T**
NbTi (PF3 & PF4) CICC: **28.6 kA – 5.3 T**
NbTi (PF2 & PF5) CICC: **27.1 kA – 4.2 T**
Identical in pairs for full top/down symmetry

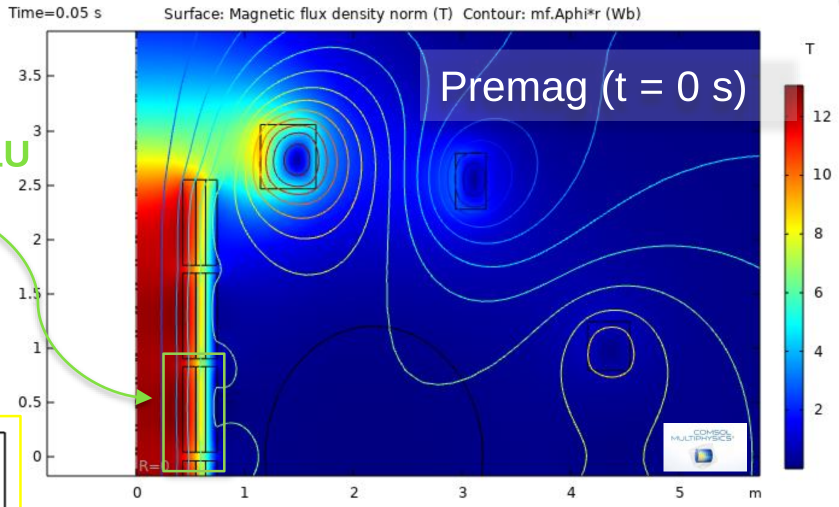


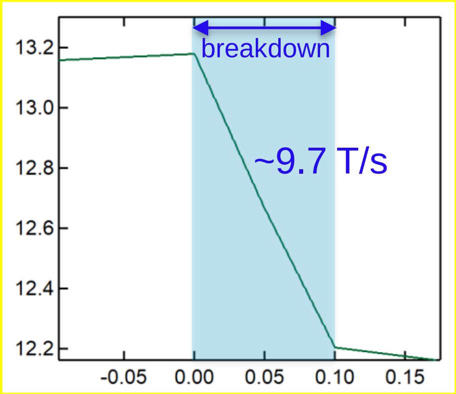
High Field-Rates in CS Modules





CS1U





$|\partial_t B|$ during breakdown:

9.7 T/s (CS1U, HF)

7.3 T/s (CS1U, MF)

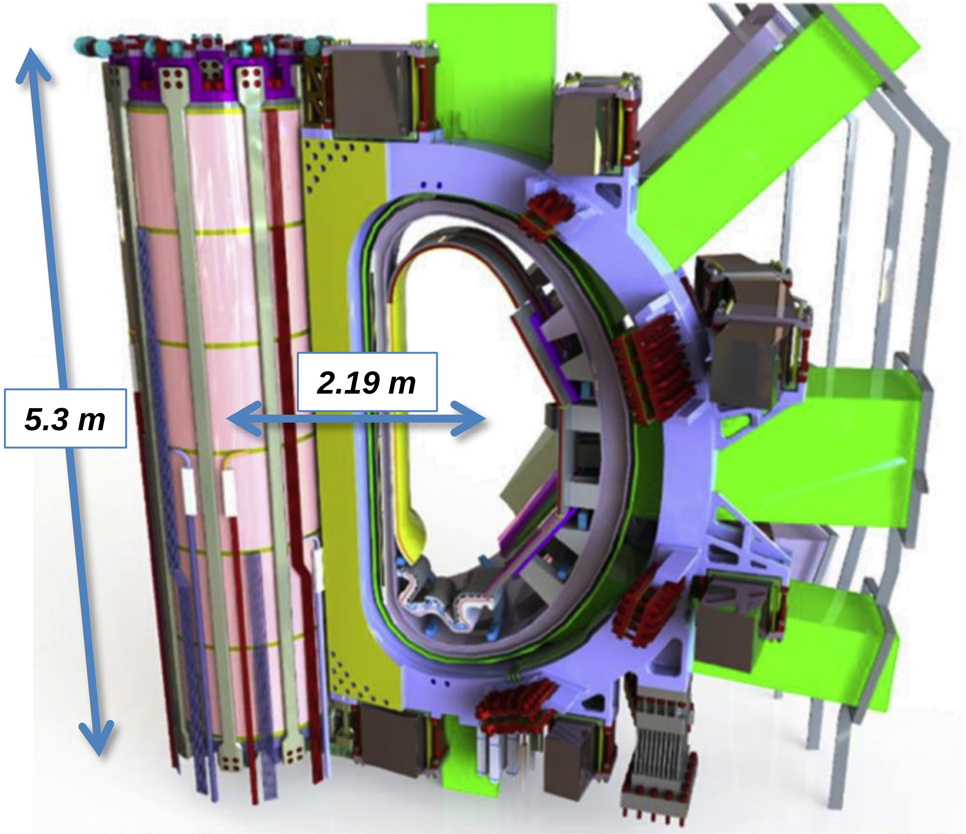
4.3 T/s (CS1U, LF)

Aim of the Work

Allocated **thermal budget** in SC magnet design

Need to estimate *e.m.* losses deriving from $\partial_t \vec{B}_{ext}$ and/or $\partial_t \vec{I}_{transp}$

The present work investigates the ac losses of conductors subjected to time-varying fields and carrying dc currents.



Coupling and Eddy Currents in Composites

1970s - Problem studied by several investigators [Morgan, Ries, Carr, Brandt, Clem, Murphy, Norris, *etc.*]

$$B_e - B = \tau \dot{B}$$

$$\tau = \frac{\mu_0}{\rho_{et}} \left(\frac{l_p}{2\pi} \right)^2$$

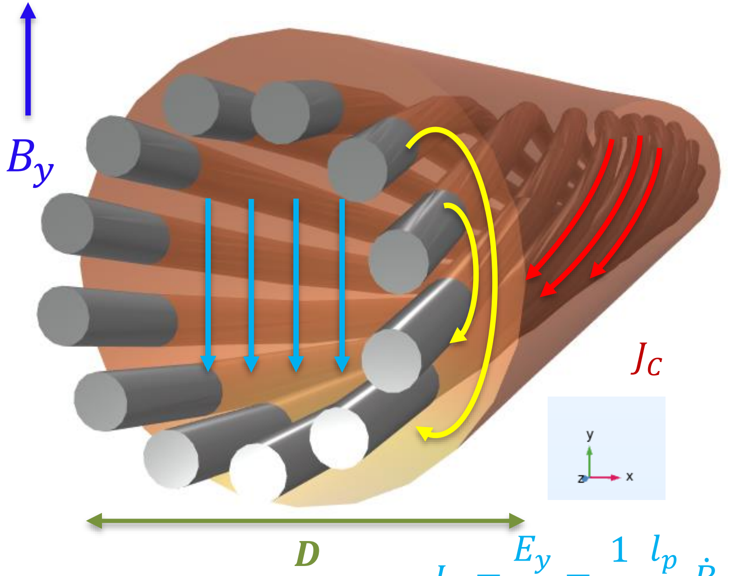
1978-79 - Extension to higher field-rates attempted by Soubeyrand&Turck

1980 - Ogasawara *et al*.: saturation layer δ depends on $\dot{B}$, and *Ries formula* no longer valid

$$B_e - B = \frac{\tau \dot{B}}{1 + \frac{\tau \dot{B}}{B_p}}$$

$$\frac{\delta}{R} = \frac{\tau \dot{B}}{B_p} \left(1 + \frac{\tau \dot{B}}{B_p} \right)^{-1}$$

$$B_p = \mu_0 J_C D/2$$



$$J_y = \frac{E_y}{\rho_t} = \frac{1}{\rho_t} \frac{l_p}{2\pi} \dot{B}$$

$$J_p(\theta) = \frac{1}{\rho_m} \frac{l_p}{2\pi} cos(\theta) \dot{B}$$

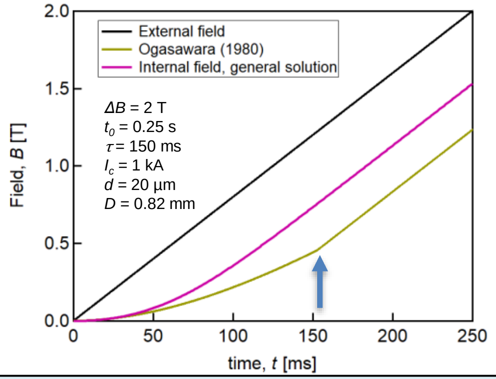
Solved for trapezoidal shaped $B_e(t)$, for two limiting cases:

$$\begin{cases} B_e - B = \tau \dot{B} \\ B_e - B = B_p \end{cases}$$

Solution of the Ogasawara Problem

- Differential equation slightly modified to include both *ramp-up* and *ramp-down*

$$B_e - B = \frac{\tau \dot{B}}{1 + \frac{\tau |\dot{B}|}{B_p}}$$



$$\beta_1 = -\left(1 + \frac{\tau}{t_0}\frac{|\Delta B|}{B_p}\right)$$

$$\beta_2 = \beta_1 - ln\left(\frac{\tau}{t_0}\frac{|\Delta B|}{B_p}\right)$$

$$\beta_1\left(\pm\frac{B(t) - \frac{|\Delta B|}{t_0}t}{B_p} + 1\right) - ln\left|1 + \beta_1\left(\pm\frac{B(t) - \frac{|\Delta B|}{t_0}t}{B_p} + 1\right)\right| = \frac{\beta_1^2}{\tau}t + \beta_2$$

- The solution is an implicit function of B
- Good news! The solution is integrable, allowing analytical calculations of AC losses

Coupling Magnetization

Magnetization per unit volume, M_c, due to the coupling currents

Ogasawara 1980

Case (1) $\tau\dot{B}/B_p < (1-i)$ for $(0 \leq t \leq t_0)$

$$M_{c1} = \tau\dot{B} - \frac{1}{2B_p}\left(\tau\dot{B}\right)^2$$

Case (2) $\tau\dot{B}/B_p \begin{cases} < (1-i) \text{ for } (0 \leq t \leq t_1) \\ \geq (1-i) \text{ for } (t_1 \leq t \leq t_0) \end{cases}$

$$\begin{cases} M_{c2} = M_{c1} & 0 \leq t \leq t_1 \\ M_{c2} = \frac{1}{2}B_p(1-i^2) & t_1 \leq t \leq t_0 \end{cases}$$

De Marzi & Corradini 2021

Case (1) $\tau\dot{B}/B_p < \frac{(1-i)}{i}$ for $(0 \leq t \leq t_0)$

$$M_{c1} = \frac{\tau\dot{B}}{1+\tau|\dot{B}|/B_p} - \frac{1}{2B_p}\left(\frac{\tau\dot{B}}{1+\tau|\dot{B}|/B_p}\right)^2$$

Case (2) $\tau\dot{B}/B_p \begin{cases} < (1-i)/i \text{ for } (0 \leq t \leq t_1) \\ \geq (1-i)/i \text{ for } (t_1 \leq t \leq t_0) \end{cases}$

$$\begin{cases} M_{c2} = M_{c1} & 0 \leq t \leq t_1 \\ M_{c2} = \frac{1}{2}B_p(1-i^2) & t_1 \leq t \leq t_0 \end{cases}$$

Coupling Losses

Coupling losses per unit volume Q_c: analytical solution for ramping-up field

$$Q_c = \frac{1}{\mu_0}\int_0^{t_0} M_c \dot{B}_e \cdot dt$$

$$Q_c = \frac{1}{\mu_0}\frac{B_p \Delta B}{2t_0}\begin{cases} t_0 + \frac{\tau}{2\beta_1^2}(x_{t0}^2 - x_0^2) - \frac{\tau}{3\beta_1}(x_{t0}^3 - x_0^3) - \frac{t_0}{\beta_1^2} & \text{Case (1)} \\ (1-i^2)(t_0 - t_1) + t_1 + \frac{\tau}{2\beta_1^2}(x_{t1}^2 - x_0^2) - \frac{\tau}{3\beta_1}(x_{t1}^3 - x_0^3) - \frac{t_1}{\beta_1^2} & \text{Case (2)} \end{cases}$$

$$x_0 = \frac{B(t=0)}{B_p} + 1; \quad x_{t1} = \frac{B(t=t_1) - \Delta B/t_0\, t_1}{B_p} + 1; \quad x_{t0} = \frac{B(t=t_0) - \Delta B}{B_p} + 1; \quad \beta_1 = -1 - \frac{\tau}{t_0}\frac{\Delta B}{B_p}$$

Intrinsic Magnetization of SC Filaments

Intrinsic magnetization per unit volume, M_h, due to the shielding currents

Ogasawara 1980

Case (1) $\tau\dot{B}/B_p < (1-i)$ for $(0\leq t \leq t_0)$

$$M_{h1} = \frac{1}{2} b_p\left(1-\tau\dot{B}/B_p\right)\left(1-\frac{i^2}{\left(1-\tau\dot{B}/B_p\right)^2}\right)$$

Case (2) $\tau\dot{B}/B_p \begin{cases} < (1-i) \text{ for } (0\leq t \leq t_1) \\ \geq (1-i) \text{ for } (t_1 \leq t \leq t_0) \end{cases}$

$$\begin{cases} M_{h2} = M_{h1} & 0 \leq t \leq t_1 \\ M_{h2} = 0 & t_1 \leq t \leq t_0 \end{cases}$$

De Marzi & Corradini 2021

Case (1) $\tau\dot{B}/B_p < \frac{(1-i)}{i}$ for $(0\leq t \leq t_0)$

$$M_{h1} = \frac{1}{2} \frac{b_p}{1+\tau|\dot{B}|/B_p}\left(1-i^2\left(1+\tau|\dot{B}|/B_p\right)^2\right)$$

Case (2) $\tau\dot{B}/B_p \begin{cases} < (1-i)/i \text{ for } (0\leq t \leq t_1) \\ \geq (1-i)/i \text{ for } (t_1 \leq t \leq t_0) \end{cases}$

$$\begin{cases} M_{h2} = M_{h1} & 0 \leq t \leq t_1 \\ M_{h2} = 0 & t_1 \leq t \leq t_0 \end{cases}$$

Magnetization Losses

Magnetization losses per unit volume Q_h: analytical solution for ramping-up field

$$Q_h = \frac{1}{\mu_0} \int_0^{t_0} M_h \dot{B}_e \cdot dt$$

$$Q_h = \frac{1}{\mu_0} \frac{b_p \Delta B}{2 t_0} \begin{cases} \frac{\tau}{2\beta_1}\left(x_{t_0}^2 - x_0^2\right) - \frac{t_0}{\beta_1} - i^2 \frac{\tau}{\beta_1} ln\left(\frac{\left|1+\beta_1 x_{t_0}\right|}{\left|1+\beta_1 x_0\right|}\right) & \text{Case (1)} \\ \frac{\tau}{2\beta_1}\left(x_{t1}^2 - x_0^2\right) - \frac{t_1}{\beta_1} - i^2 \frac{\tau}{\beta_1} ln\left(\frac{\left|1+\beta_1 x_{t1}\right|}{\left|1+\beta_1 x_0\right|}\right) & \text{Case (2)} \end{cases}$$

$$x_0 = \frac{B(t=0)}{B_p} + 1; \quad x_{t1} = \frac{B(t=t_1) - \Delta B/t_0\, t_1}{B_p} + 1; \; x_{t0} = \frac{B(t=t_0) - \Delta B}{B_p} + 1; \quad \beta_1 = -1 - \frac{\tau}{t_0}\frac{\Delta B}{B_p}$$

Dynamic Resistance

Resistive voltage per unit length, V_t, due to dynamic resistance

Ogasawara 1980

Case (1) $\tau\dot{B}/B_p < (1-i)$ for $(0 \le t \le t_0)$

$$V_{t1} = \frac{1}{2} d\ i\ \dot{B}\left(1-\tau\dot{B}/B_p\right)^{-1}$$

Case (2) $\tau\dot{B}/B_p \begin{cases} < (1-i) \text{ for } (0 \le t \le t_1) \\ \ge (1-i) \text{ for } (t_1 \le t \le t_0) \end{cases}$

$$\begin{cases} V_{t2} = V_{t1} & 0 \le t \le t_1 \\ V_{t2} = \frac{1}{2} d\ \dot{B}_e + \frac{1}{2} D\ i\dot{B}_e\left(1-\frac{1-i}{(\tau/t_0)(\Delta B/B_p)}\right) & t_1 \le t \le t_0 \end{cases}$$

De Marzi & Corradini 2021

Case (1) $\tau\dot{B}/B_p < \frac{(1-i)}{i}$ for $(0 \le t \le t_0)$

$$V_{t1} = \frac{1}{2} d\ i\ \dot{B}\left(1+\tau|\dot{B}|/B_p\right)$$

Case (2) $\tau\dot{B}/B_p \begin{cases} < (1-i)/i \text{ for } (0 \le t \le t_1) \\ \ge (1-i)/i \text{ for } (t_1 \le t \le t_0) \end{cases}$

$$\begin{cases} V_{t2} = V_{t1} & 0 \le t \le t_1 \\ V_{t2} = \frac{1}{2} d\ \dot{B}_e + \frac{1}{2} D\ i\dot{B}_e\left(1-\frac{(1-i)/i}{(\tau/t_0)(|\Delta B|/B_p)}\right) & t_1 \le t \le t_0 \end{cases}$$

Losses due to Dynamic Resistance

Dynamic resistance losses per unit volume Q_d: analytical solution for ramping-up field

$$Q_d = \frac{1}{A}\int_0^{t_0} V_t I_t \cdot dt$$

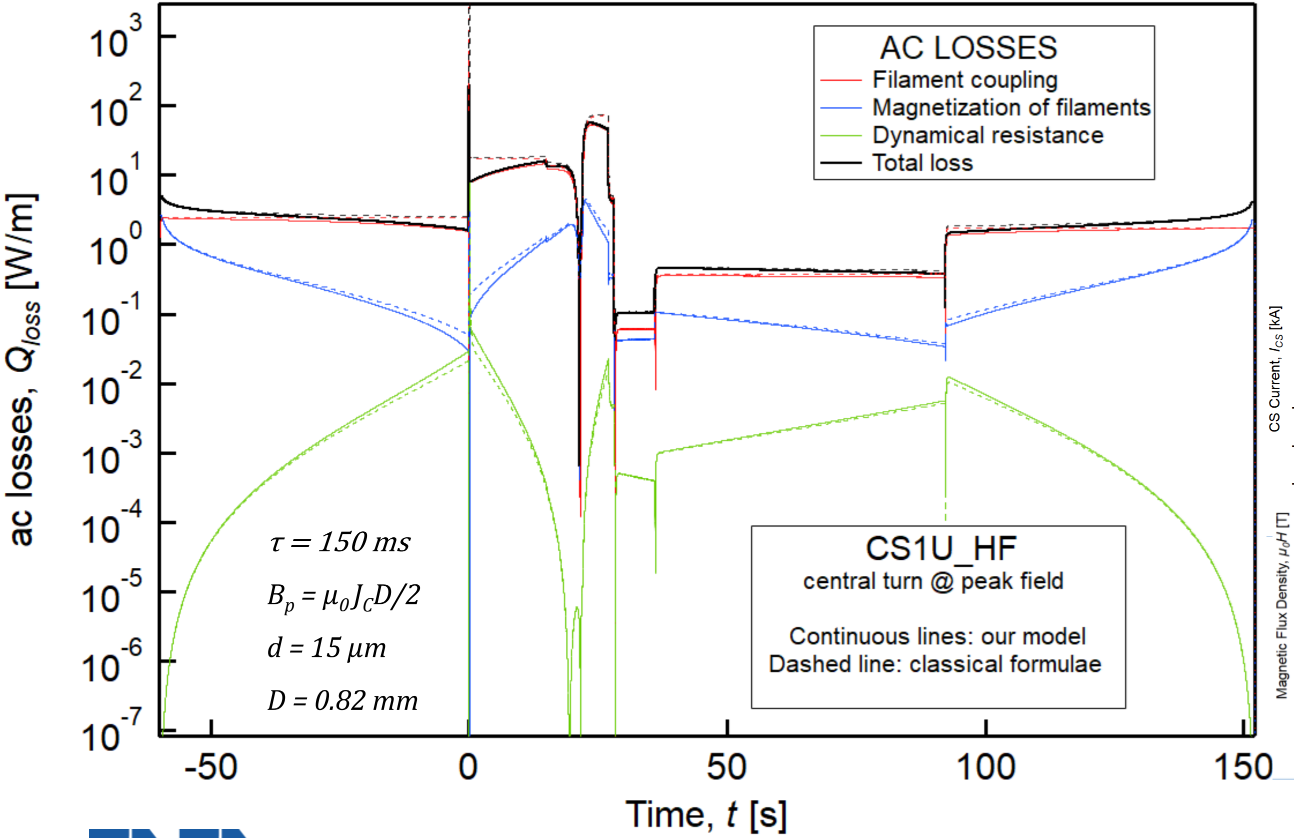
$$Q_d = \frac{i^2\, d\, I_c}{2\pi (D/2)^2} \begin{cases} y_{t_0} - y_0 + \dfrac{\Delta B^2}{B_p}\dfrac{\tau}{t_0} + \left(2\dfrac{\Delta B}{t_0}\tau + \beta_1\right)\left(x_{t_0} - x_0\right) + B_p ln\left(\dfrac{|x_{t_0}|}{|x_0|}\right) & \text{Case (1)} \\ y_{t_1} - y_0 + \left(\dfrac{\Delta B}{t_0}\right)^2 \dfrac{\tau}{B_p} t_1 + \left(2\dfrac{\Delta B}{t_0}\tau + \beta_1\right)\left(x_{t_1} - x_0\right) + B_p ln\left(\dfrac{|x_{t_1}|}{|x_0|}\right) + \dfrac{2}{d\, i}\Delta Q_d & \text{Case (2)} \end{cases}$$

$$\Delta Q_d = \frac{1}{2}\frac{\Delta B}{t_0}\left(d + D\, i\left(1 - \frac{1-i}{i}\frac{t_0}{\tau}\frac{B_p}{\Delta B}\right)\right)(t_0 - t_1)$$

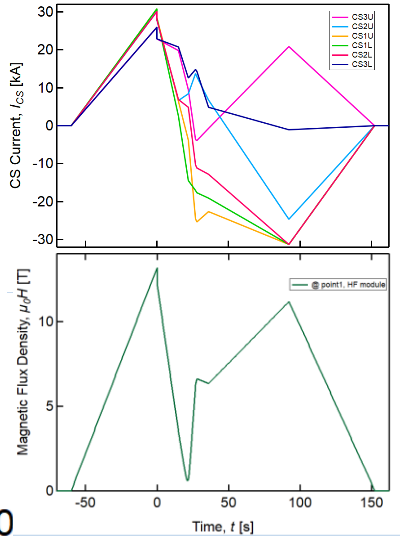
From Wires to Cables

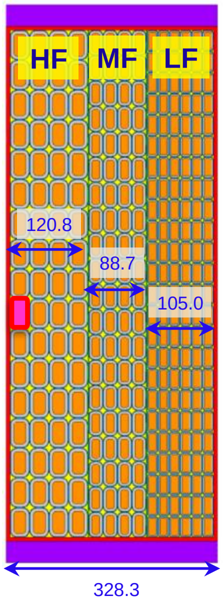
Can this model be applied to **CICCs** and **coils**?

AC Losses in CS1U, HF Module

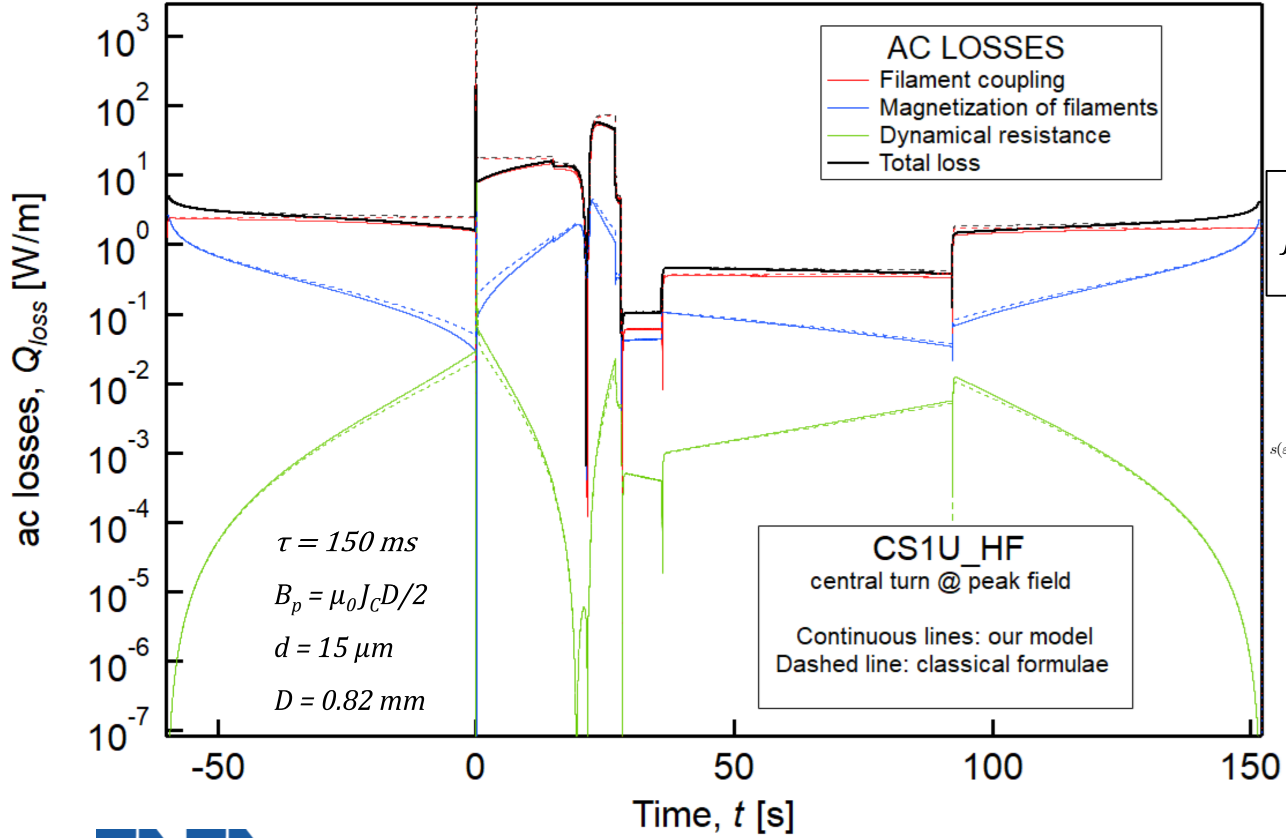


AC losses evaluated considering the **peak field on central turn**





AC Losses in CS1U_HF – J_C Parameterization



J_C parameterization

ITER-2008 with ε_{eff} = -0.55%

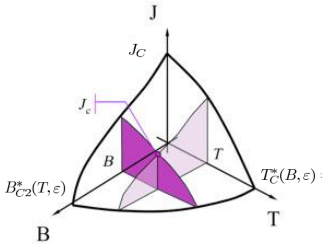
$$J_C = \frac{C_0}{B} s(\varepsilon)(1-t^{1.52})(1-t^2)b^p(1-b)^q$$

$$B^*_{C2}(T,\varepsilon) = B^*_{C20\,\max} s(\varepsilon)(1-t^{1.52})$$

$$T^*_C(B,\varepsilon) = T^*_{C0\,\max}[s(\varepsilon)]^{\frac{1}{3}}\left(1-\frac{B}{B^*_{C2}(0,\varepsilon)}\right)^{\frac{1}{1.52}}$$

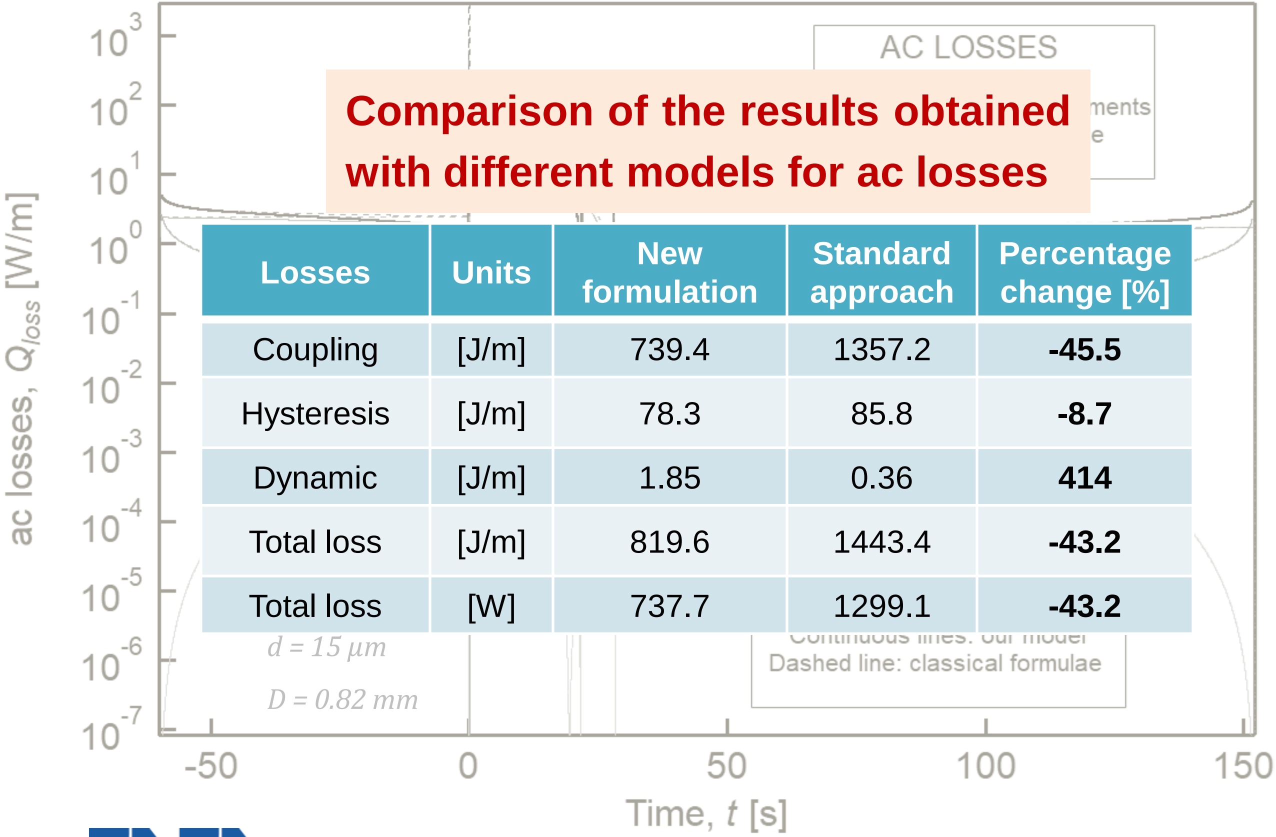
$$s(\varepsilon) = 1 + \frac{C_{a1}\left(\sqrt{\varepsilon_{sh}^2+\varepsilon_{0,a}^2}-\sqrt{(\varepsilon-\varepsilon_{sh})^2+\varepsilon_{0,a}^2}\right)-C_{a2}\varepsilon}{1-C_{a1}\varepsilon_{0,a}}$$

$$\varepsilon_{sh} = \frac{C_{a2}\varepsilon_{0,a}}{\sqrt{C_{a1}^2-C_{a2}^2}}$$



Coefficient	Value
C_0 [A T]	20918
C_{a1}	44.48
C_{a2}	0.0
$\varepsilon_{0,a}$ [%]	0.256
ε_m [%]	-0.049
$B_{c2,m}(0)$ [T]	32.97
$T_{c0,m}$ [K]	16.06
p	0.63
q	2.1

Comparative Analysis of AC Losses Results



Comparison of the results obtained with different models for ac losses

Losses	Units	New formulation	Standard approach	Percentage change [%]
Coupling	[J/m]	739.4	1357.2	**-45.5**
Hysteresis	[J/m]	78.3	85.8	**-8.7**
Dynamic	[J/m]	1.85	0.36	**414**
Total loss	[J/m]	819.6	1443.4	**-43.2**
Total loss	[W]	737.7	1299.1	**-43.2**

Estimations using standard formulae lead to largely different values

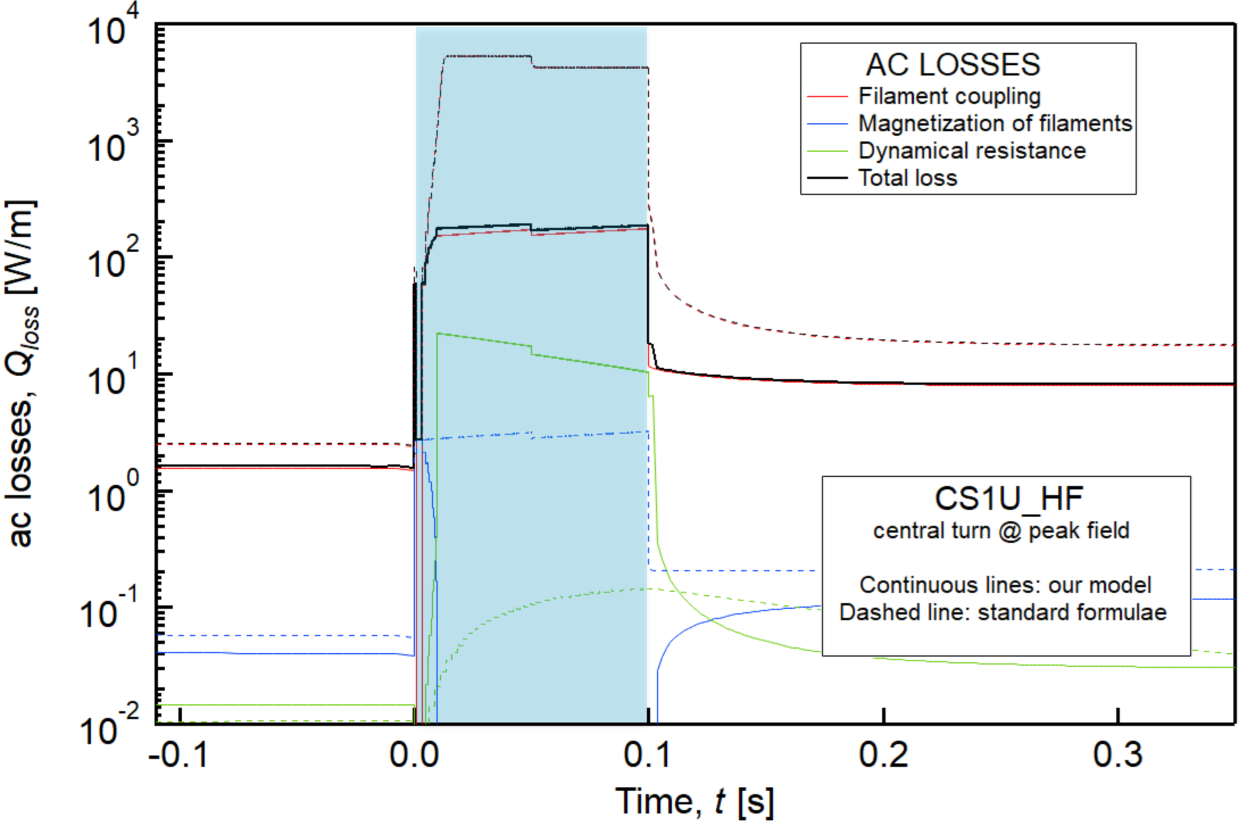
Coupling&magnetization

- AC losses tend to top-off to a maximum value $\propto (1-i^2)$
- Decrease of coupling (≈ **-46%**) and magnetization (≈ **-9%**) losses

Dynamic resistance

At high $\partial_t B$, a dynamic resistance appears against the transport current flow, causing a large increase in AC loss $\sim\propto i^2$: **+400%**!

AC Losses in CS1U_HF During Breakdown



During **breakdown**, where $\partial_t B$ peaks at ***9.7 T/s***, full saturation of strands occurs

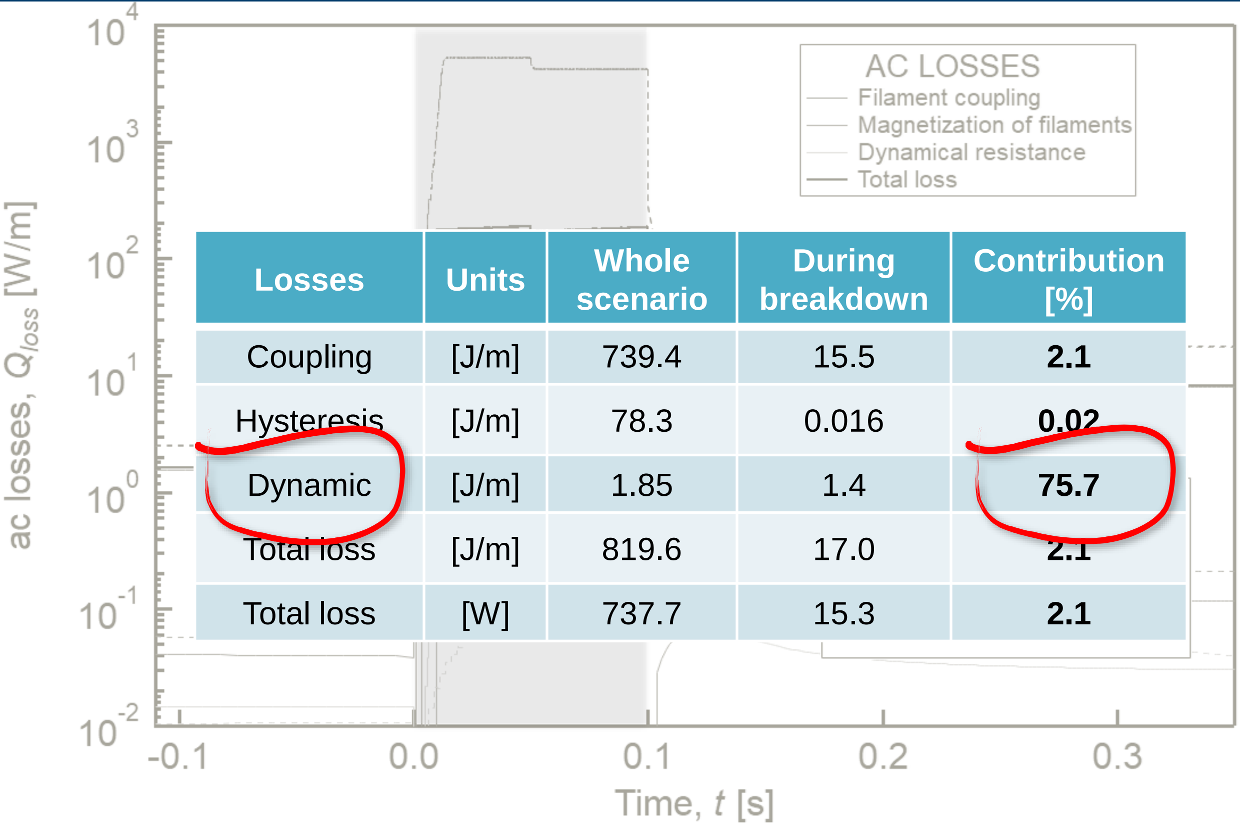
The strands behave like a solid conductor and a saturation effect takes place in both the magnetization and the ac losses.

$$\lim_{\dot{B}\to\infty} Q_c = \frac{1}{2\mu_0} B_p \Delta B (1 - i^2)$$

$$\lim_{\dot{B}\to\infty} Q_h = 0$$

$$\lim_{\dot{B}\to\infty} Q_d = \frac{1}{\mu_0} B_p \Delta B i^2$$

AC Losses in CS1U_HF During Breakdown



Losses	Units	Whole scenario	During breakdown	Contribution [%]
Coupling	[J/m]	739.4	15.5	**2.1**
Hysteresis	[J/m]	78.3	0.016	**0.02**
Dynamic	[J/m]	1.85	1.4	**75.7**
Total loss	[J/m]	819.6	17.0	**2.1**
Total loss	[W]	737.7	15.3	**2.1**

During **breakdown**, where $\partial_t B$ peaks at ***9.7 T/s***, full saturation of strands occurs

The strands behave like a solid conductor and a saturation effect takes place in both the magnetization and the ac losses.

$$\lim_{\dot{B}\to\infty} Q_c = \frac{1}{2\mu_0} B_p \Delta B (1 - i^2)$$

$$\lim_{\dot{B}\to\infty} Q_h = 0$$

$$\lim_{\dot{B}\to\infty} Q_d = \frac{1}{\mu_0} B_p \Delta B i^2$$

Field-Rate Dependent $n\tau$ in CICCs

- In multistage CICCs there exist multiple induced currents loops with a broad range of time constants, affecting different volume fraction of the cable conductors

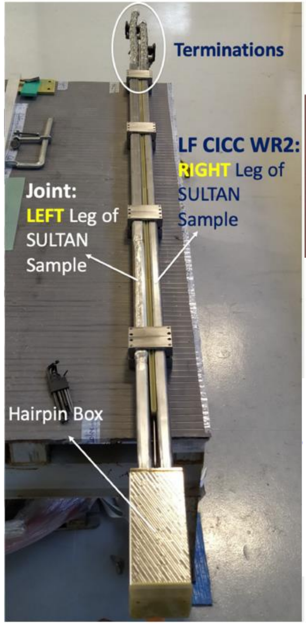
  Bruzzone et al., IEEE TAS 16, 827 (2006); Bruzzone et al., FED 146, 928 (2019)

- Depending on the frequency, a dominant time constant can be picked up
  - During plasma initiation, the $n\tau$ of the CICC approaches the range of the free standing strands
  - Lower field changes (i.e., coil charge) are associated with higher $n\tau$ values
- A single, but field-rate dependent coupling time constant, $n\tau(\partial_t B)$, has been introduced in AC loss models

Experimental Assessment of $n\tau(\partial_t B)$

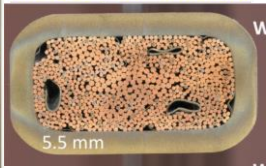
The behavior of nτ vs. $\partial_t B$ is based on the experimental results from recent SULTAN tests on the DEMO Low Field conductor (“*WR2*”), in which trapezoidal field pulses have been employed

For the procedure to obtain $n\tau_{pulse}$, please refer to P. Bruzzone *et al.*, FED 146, 928 (2019)

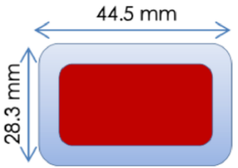


DEMO CICC

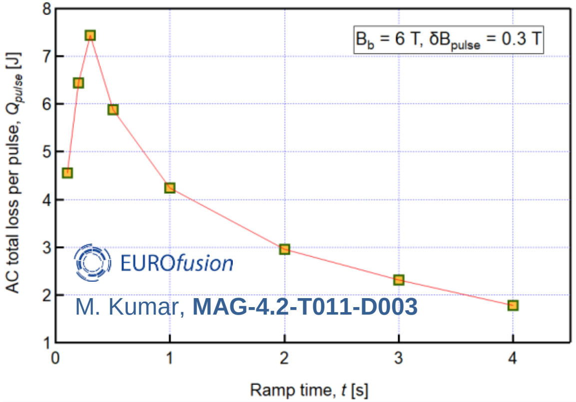
LF CICC (2020 prototype)



DTT-CS CICC

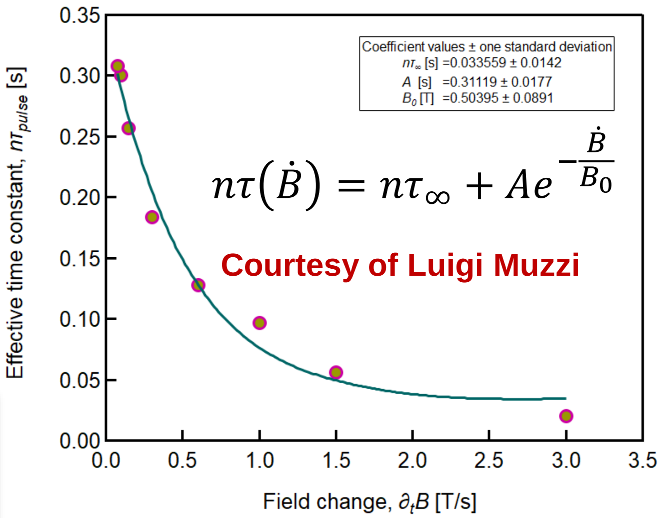


CS-HF, Nb_3Sn



DEMO WR2 vs. CS-DTT-HF

- Similar layouts (rectangular, long twist pitch, low void fraction, SS wrapping)
- Different number of SC strands



$$n\tau(\dot{B}) = n\tau_\infty + Ae^{-\frac{\dot{B}}{B_0}}$$

Courtesy of Luigi Muzzi

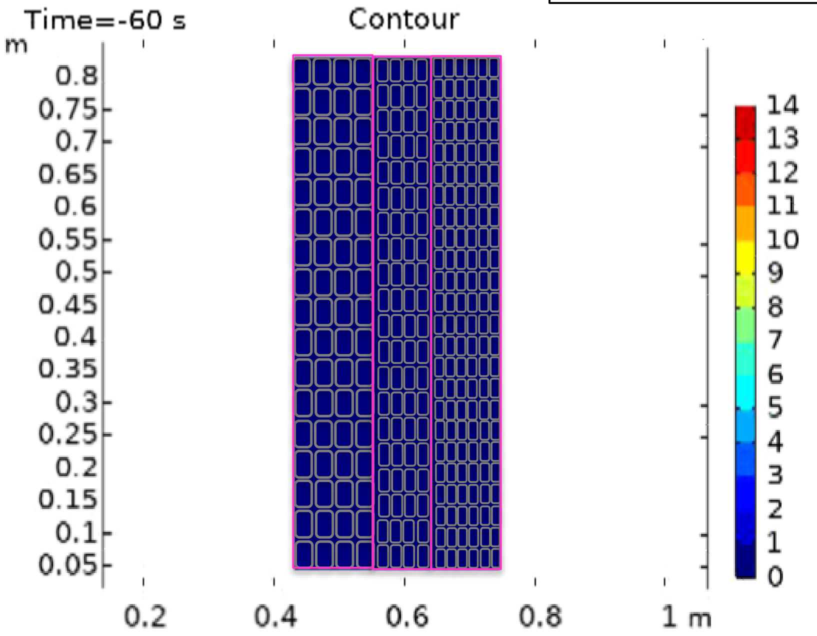
L. Muzzi *et al.*, IEE TAS **31**, 4201607 (2021)

FEM Analysis Using Commercial Software

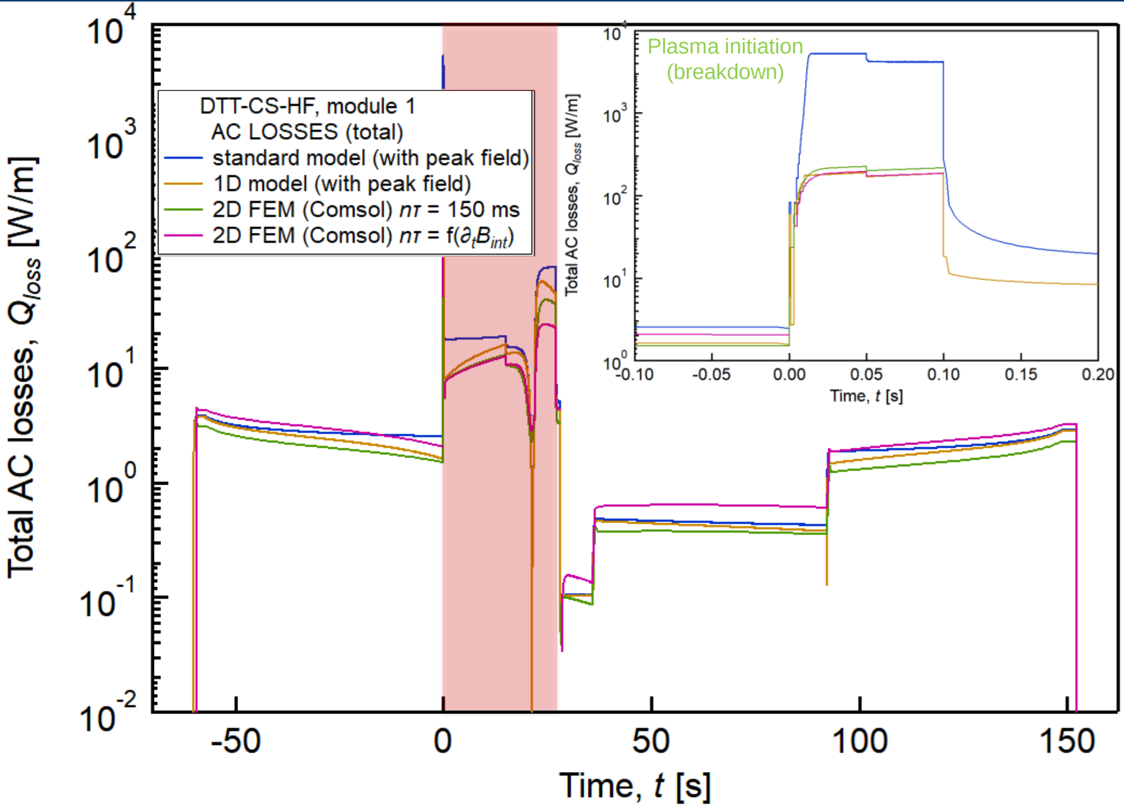
$$B_e - B = \frac{\tau \dot{B}}{1 + \frac{\tau |\dot{B}|}{B_p}}$$

Two-step procedure:

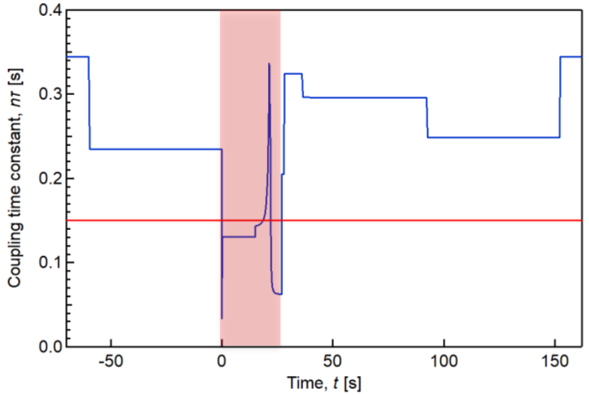
1) Evaluation of the external field map
   - 2D axisymmetric FE model
   - *Magnetic Field (mf)* interface, **AC/DC Module**)
   - Coil feature: homogeneized multiturn conductors
2) Evaluation of AC loss contributions
   - *Coeff Form PDE* interface, **Math module**
   - Time-dependent B_i map
   - Calculation of Q_c, Q_h, Q_d (surface averages)



Recap: AC Losses in CS1U Module, HF Sub-Module



Losses	nτ = 0.15 s			nτ=f(∂tB)
	Ries	*1 turn*	*FEM*	*FEM*
Coupling [J/m]	1357.2	739.4	584.5	639.9
Hysteresis [J/m]	88.7	78.3	76.9	73.6
Dynamic [J/m]	0.72	1.85	4.52	0.41
Total loss [J/m]	1446.6	819.6	665.9	713.9
Total loss [W]	1302.1	737.7	599.4	642.6

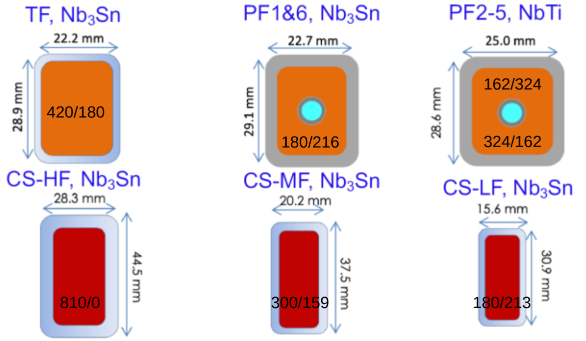


Future Directions

The qualification phase of the DTT CICC procurements will provide the information for the final choice of the 7 cable layouts

- Twist pitch cabling sequence; *e.m.* cyclic loading; ε_{eff}
- Coupling time constant $n\tau$
- Pressure drop, *MQE* tests and T_{cs}

TF Sample manufacturing scheduled Nov. 2021

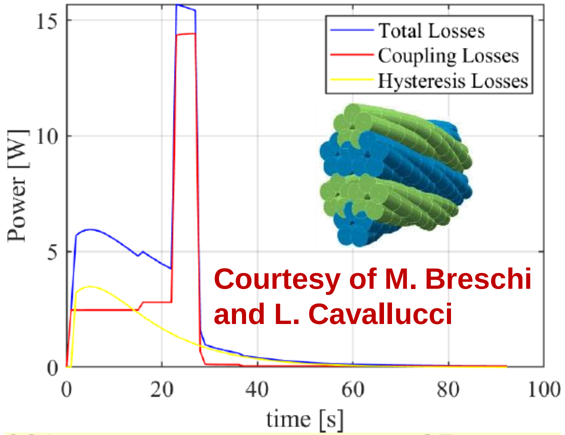


The outcome will constitute a test bed for model validation

- Analytical model - Unipolar trapezoidal pulses (ΔB = 0.3 T; t_0 = 0.1 to 4 s)
- Numerical model - Sinusoidal pulsing (128 ms, 600 V max)

AC loss model as input tool for thermo-hydraulic analyses (PoliTo)

THELMA numerical model based on σ[S/m^2] between cable elements - on going activity (UniBo)



Courtesy of M. Breschi and L. Cavallucci

Conclusion

- Proposed a novel model for the calculation of AC losses due to fast varying fields
  - ✓ Analytical solution of the Osagawara equation
  - ✓ Coupling, magnetization, and dynamic resistance
- Model applied to a Central Solenoid module of a Tokamak device (DTT):
  - ✓ Evaluated AC losses on central turn at peak field
  - ✓ Developed 2D FE model with variable $n\tau$
- Future directions: model validation
  - SULTAN tests with trapezoidal ramps
  - Benchmark with other approaches (UniBo)
  - Other off-normal scenario still to be analyzed, with special reference to quench and disruptions

Thank You
For Your Attention

Gianluca De Marzi
gianluca.demarzi@enea.it