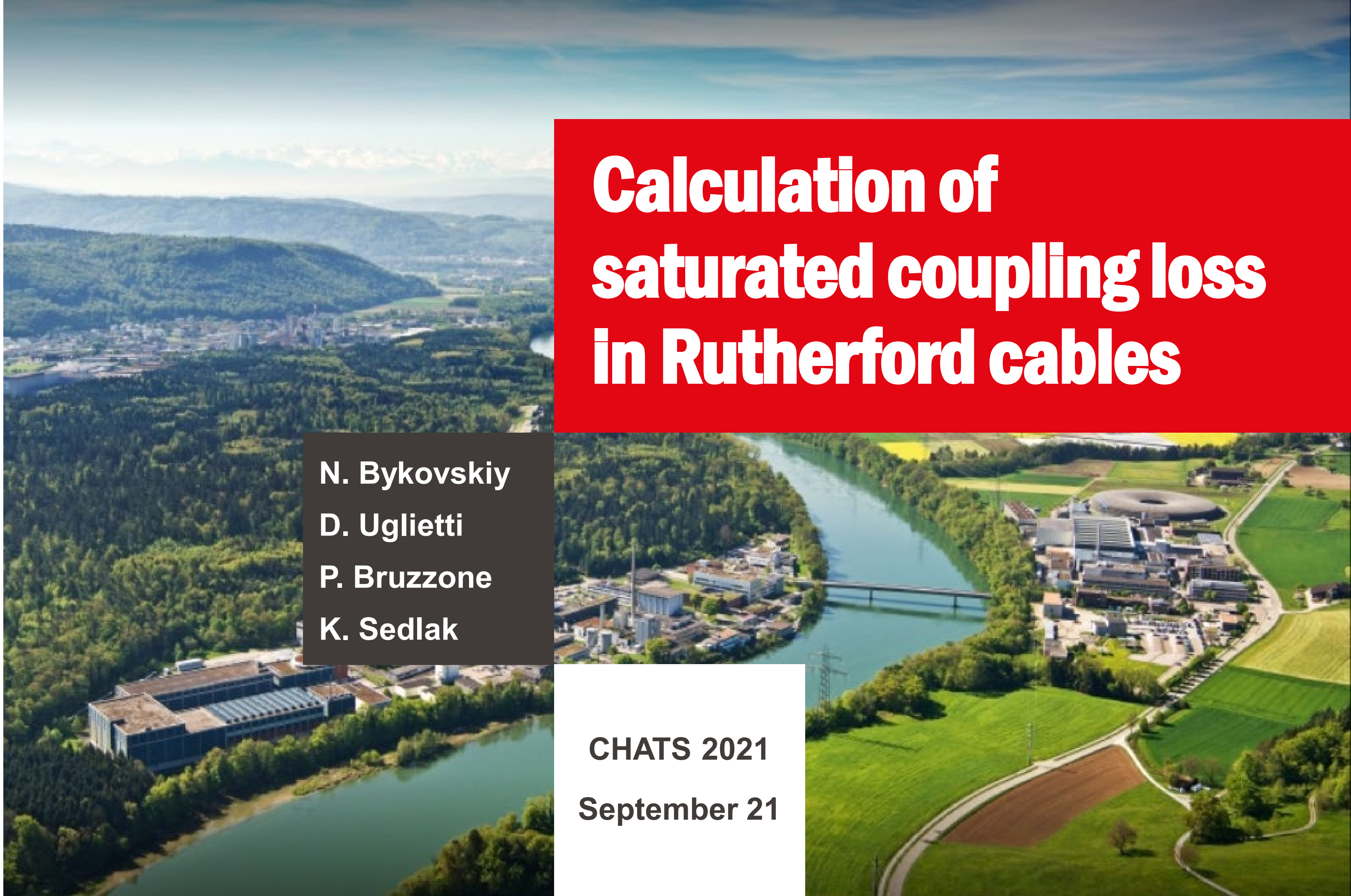
EPFL



Calculation of saturated coupling loss in Rutherford cables

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SWISS PLASMA CENTER

Outline

Introduction

Development of network models for Rutherford cables:

- 70's, Morgan et al: crossing strand coupling, weak excitation, analytical results
- 80's, Sytnikov et al: crossing and adjacent, weak and strong, analytical
- 90's, Verweij et al: complete numerical electromagnetic model
- 00's – p.t.: CUDI / JackPot / THEA / THELMA multi-physics modelling tools

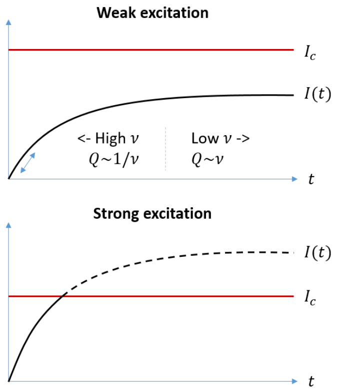
❖ LTS have low stability (low MQE), thus must be operated in weak excitation (coupling currents << Ic), therefore leading to small filaments and short twist-pitches.

❖ In contrast, HTS materials have high stability and could be operated in a strong excitation mode (coupling currents ~ Ic). No need for fine twisted filaments, for example Bi2223 tapes with non-twisted filaments, ReBCO monofilamentary tapes.

Large AC losses should then be properly evaluated and accounted in the design.

Impact of twisting stacks was found marginal for soldered stacks in fusion conductors, while transposing stacks (twisted or not) have a moderate effect, see https://doi.org/10.1016/j.cryogenics.2020.103118

response to constant $\dot{B}$



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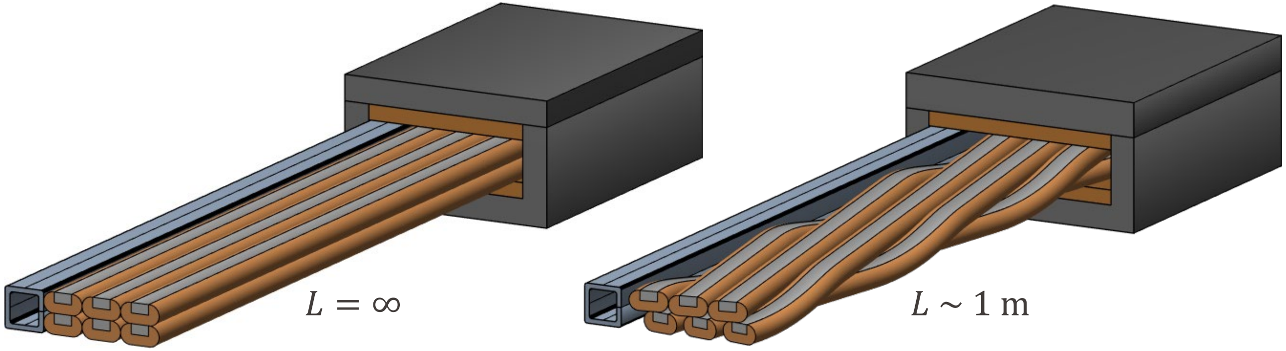
Motivation

ASTRA conductor concept for DEMO CS coils operated up to 18 T at 5 K, ≳0.1 T/s transients:



- Aligned Stacks Transposed in Roebel Arrangement
- Jacket pre-compression
- Separate cooling channel (conduction cooled stacks)
- Impregnation of cable space

Strong excitation mode features interplay between coupling current loops and superconducting loops, i.e. corresponding loss contributions are no longer independent.

Furthermore, effects of saturation and screening are counteracting.

Hence, detailed study on the actual AC loss performance is needed.

Analytical calculation: weak excitation

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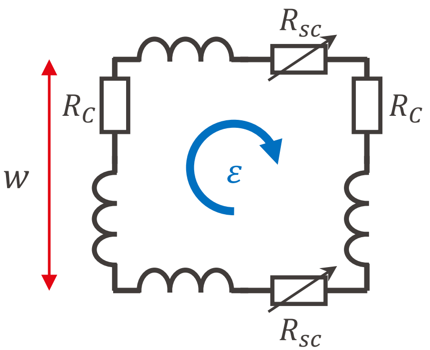
https://doi.org/10.1016/0011-2275(89)90207-5

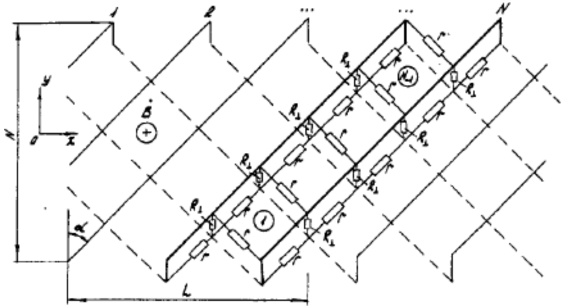


$R_{sc} \ll R_c$: inter-strand loss

$$P_\perp = P_{R_\perp} + P_{R_\parallel} = \frac{\dot{B}^2 H^2 L}{3}\left(\frac{N^2}{20R_\perp} + \frac{1}{NR_\parallel}\right) \text{ [W/m]}$$

$$H = Nw/2, R_a \sim N/L, R_c \sim N/L \rightarrow$$

$$P_c \sim N^3L^2, \qquad P_a \sim NL^2$$



→ R_{sc} increases with L, R_c decreases with L:

Limit of the model applicability in terms of the cable twist-pitch?

$\varepsilon = \dot{B}wL_c \approx I_cR \sim \rho I_c/L_c \rightarrow L_c \sim \sqrt{\rho I_c/\dot{B}w}$ (e.g. missing geometry factor)

Geometry: slab (see Wilson's book, section 8.3.1)

$$L_c = \sqrt{\frac{8\rho I_c}{\dot{B}w}}$$

8.3. FILAMENTARY COMPOSITES IN TRANSVERSE FIELDS 175

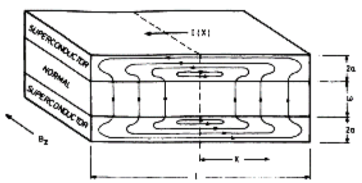
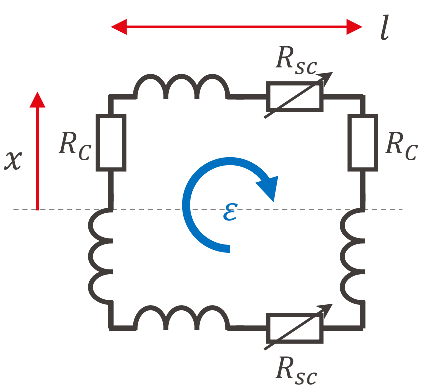


Fig. 8.14. Screening currents induced in a sandwich of superconductor and normal metal by a changing external field.

Geometry: Rutherford cable

$$L_c \approx \sqrt{\frac{96\rho I_c}{N\dot{B}w}}$$

Analytical calculation: strong excitation



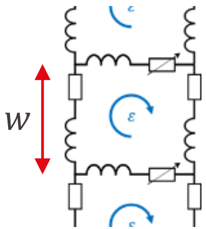
$R_{sc} \gg R_c$: saturated loss

$$\varepsilon = \dot{B}xl \approx E_c l (I/I_c)^n$$

$$I = I_c\left(\dot{B}x \,/\, E_c\right)^{1/n}$$

$$P_1/l = E \cdot I = E_c I_c (I/I_c)^{n+1}$$

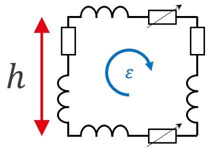
$$= E_c I_c \left(\dot{B}x/E_c\right)^{1+1/n} \quad [\mathrm{W/m}]$$



Perpendicular field (2 layers):

$$P_N/l = \Sigma\, P_1(x)/l = E_c I_c \left(\frac{\dot{B}w}{E_c}\right)^{1+\frac{1}{n}} F(N)$$

$$F(N) = 4 \cdot \sum_{k=0 \text{ or } 1/2}^{(N-2)/4} k^{1+\frac{1}{n}} \qquad (\text{min } N = 4)$$



Parallel field (N/2 layers):

$$P_N/l = E_c I_c \left(\frac{\dot{B}h}{2E_c}\right)^{1+\frac{1}{n}} N$$

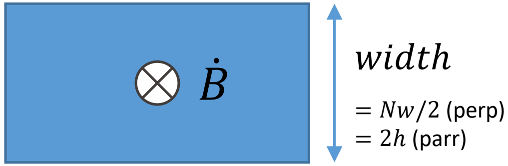
Critical-state model ($n = \infty$):

$$P/l = I_c w \dot{B} N^2/8 \quad \text{in perp field}$$

$$P/l = I_c h \dot{B} N/2 \quad \text{in parr field}$$

or simply

$$\boxed{P/l = I_{c\_total} \times width \times \dot{B}/4}$$



$$I_{c\_total} = N \times I_c$$

Generally, higher loss for finite n-value and same Ic:

$P/l \sim \dot{B}^2 N^3$ for $n = 1$ in perp field

Network modelling: integral formulation

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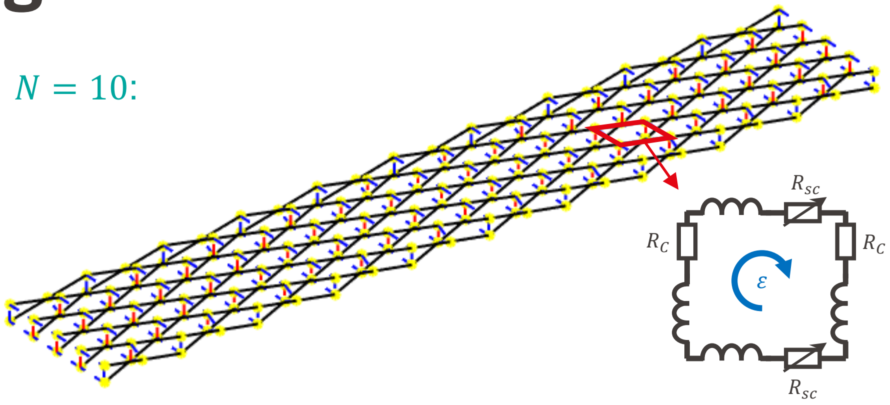
Model parameters			
Category	**Symbol**	**Description**	**Value**
Geometry	N	Number of strands	4 – 40
	W	Strand width	8 mm
	H	Strand height	4 mm
	L	Cable twist-pitch	0.1 m – inf
Electrical properties	ρ	Trans. specific resistance	1 – 100 µΩ.m
	I_c	Critical current	(strand props)
	n	Index of transition	1 – 1000
Operating conditions	$\dot{B}$	Ramp rate of external magnetic field	0.01 – 1 T/s
	φ	Field orientation	0 – 90 deg
	I_{op}	Operating current	0 to Ic

$N = 10$:



Find *current distribution* by solving:

- Kirchhoff current law for each node (yellow points)
- Kirchhoff voltage law for each elementary circuit
- Conservation of total operating current
- Specified boundary conditions:

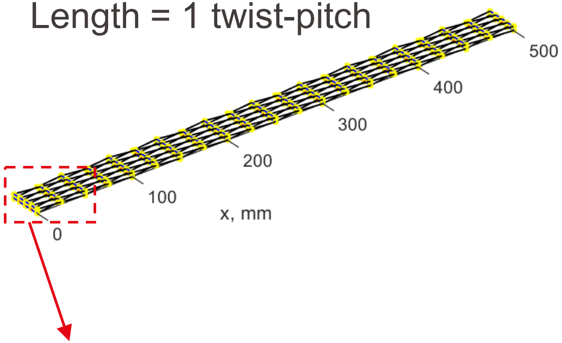
1. Dirichlet type: fixed input/output currents (i.e. 'insulated' strands outside the modeling region)
2. Neumann type: fixed current derivatives (zero derivatives → equipotential ends, i.e. short-circuited strands)
3. Periodic type: account for symmetry in current distribution (suitable to model infinitely long transposed strands) →

https://doi.org/10.1016/j.cryogenics.2018.10.003

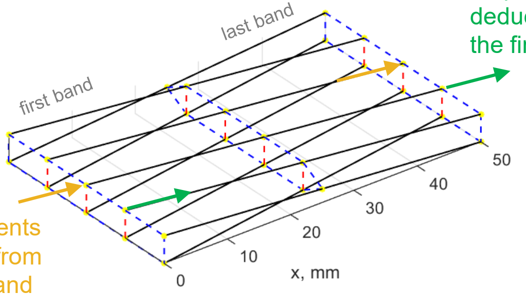
Network modelling: setup and benchmark

$N = 10$:

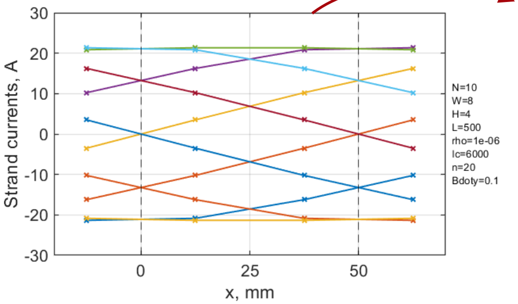
Length = 1 twist-pitch



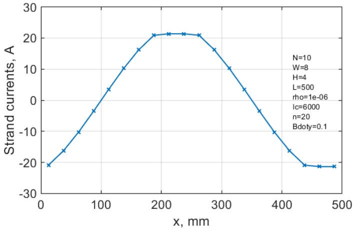
Length = 1 twist-pitch / N



Using periodic BC, L/N–long segment is sufficient for fast analysis *w/o accuracy loss.*

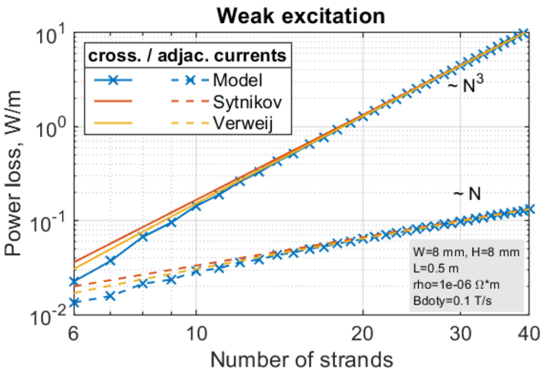


Full distribution can be obtained as well



→ $P = \sum I^2 R/l$ [W/m] $Q = \int P dt$ [J/m]

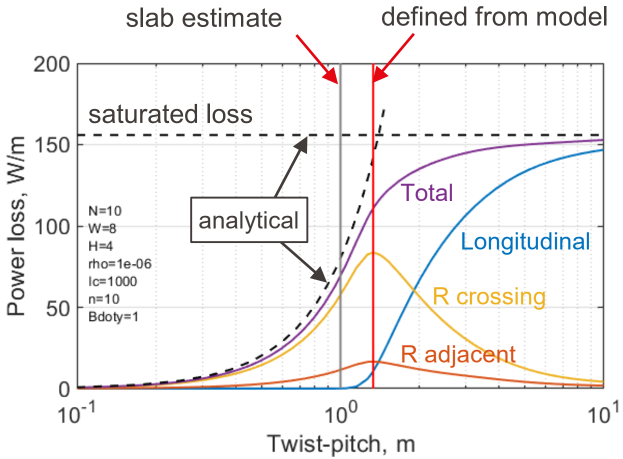
Note: intra-strand loss neglected



The model is validated wrt analytical solutions.

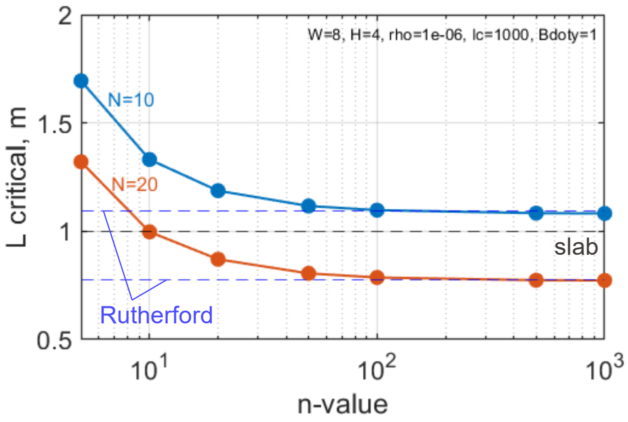
Network modelling: power loss

Study on twist-pitch:



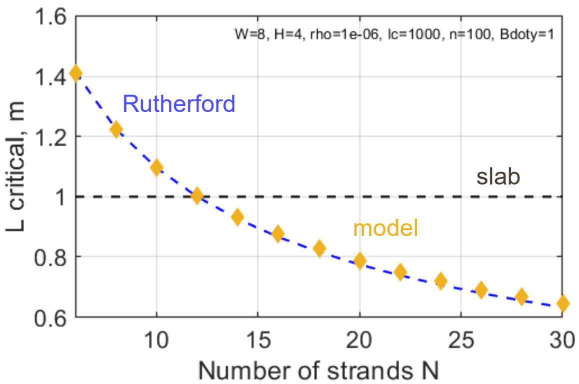
- Power loss at the critical value of twist-pitch ~ 50-70% of the saturated loss

Study on critical twist-pitch:



slab	Rutherford
$L_c = \sqrt{\frac{8\rho I_c}{\dot{B}w}}$	$L_c \approx \sqrt{\frac{96\rho I_c}{N\dot{B}w}}$

- Typically, n~10-20 for fusion conductors, thus its impact on L_c some 20 – 30%



- $L_c \sim N^{-0.5}$ scaling:

  less strands -> higher L_c -> lower P inter-strand, but higher P intra-strand

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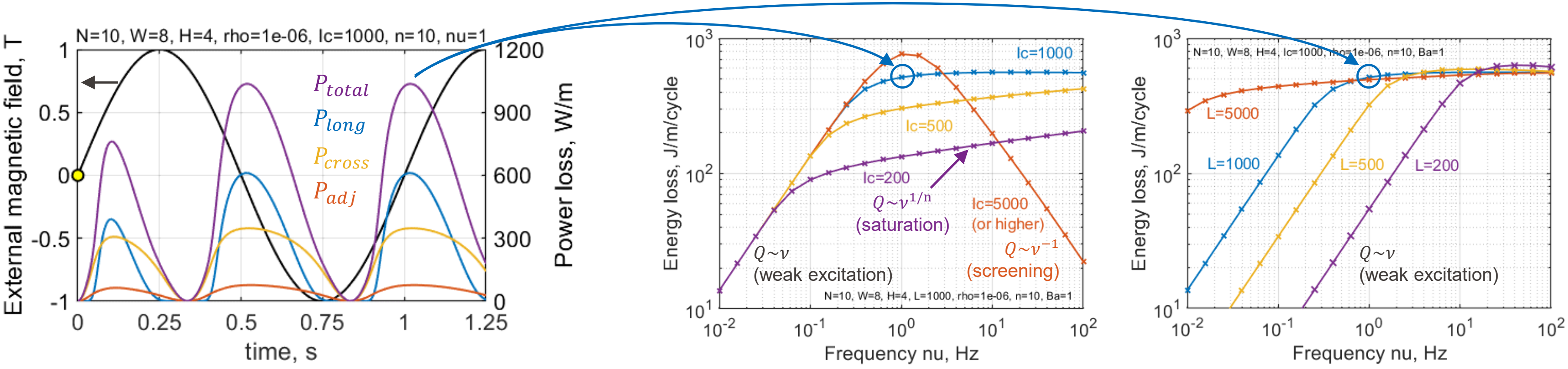
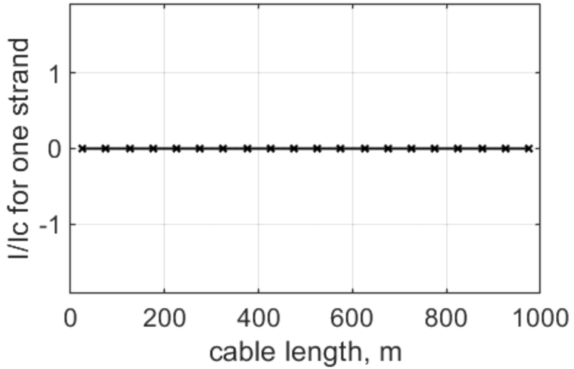
Network modelling: energy loss





* I/Ic for other strands are similar but phase-shifted

Mode	$I \ll I_c$	$I\sim I_c$
$\nu \ll 1/\tau$	Weak excitation: $Q\sim\nu$	Saturation: $Q\sim\nu^{1/n}$
$\nu \gg 1/\tau$	Screening: $Q\sim 1/\nu$	

Time constant:

$\tau \sim \mu_0 L^2/\rho$

- Typical AC loss cycles studied at zero transport current.
- However, changing of both transport current and produced magnetic field should be analyzed for actual coil operation →

DEMO CS graded coils: quick overview

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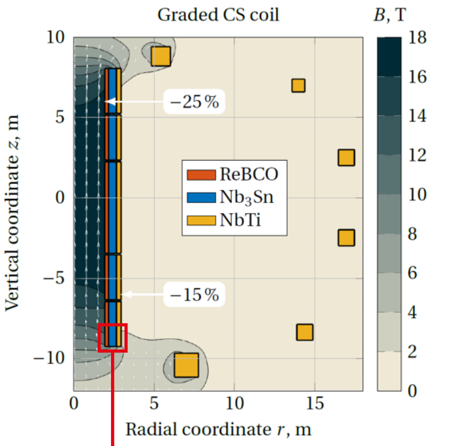
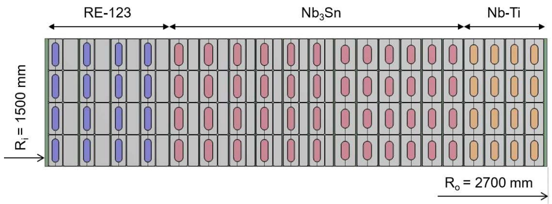
➢ Target: 60 kA / 18 T / 5 K, pulsed operation

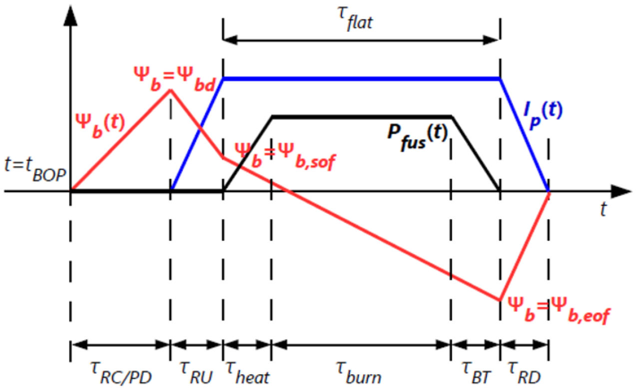
➢ R&D on HTS conductors for DEMO CS started this year: 4 concepts by SPC, ENEA and KIT; performance demonstration before 2024





Calculation of saturated coupling loss in Rutherford cables

https://idm.euro-fusion.org/?uid=2M4P9J



Baseline 12 T DEMO CS:

Parameter (Symbol)	Unit	MIRA	PROCESS
Time to recharge the CS (τ_{RC})	[s]	363	30
Pump-down time (τ_{PD})	[s]	1800	1800
Time for CS recharge/pump-down ($\tau_{RC/PD}$)	[s]	1800	
Ramp-up time (τ_{RU})	[s]	157	30
Heating time (τ_{heat})	[s]	19	10
Burn time (τ_{burn})	[s]	4768	7200
Time for burn termination (τ_{BT})	[s]	123	
Flat-top time (τ_{flat})	[s]	4909	7230
Ramp-down time (τ_{RD})	[s]	157	30
Dwell time (τ_{dwell})	[s]	2256	1890
Total cycle duration (τ_{cycle})	[s]	7024	9103

https://dx.doi.org/10.5445/IR/1000095873

- Operating cycle in pulsed tokamaks: advanced 18 T CS graded coils allow increasing burn time, thus higher plant availability by ~10-20% compared to 12 T baseline option.
- Coils operated independently, but detailed scenario not yet specified.

Assuming 15 T sweep for RU:

Bdot	RU	Flat-top	RD
MIRA	0.1 T/s	0.004 T/s	0.1 T/s
PROCESS	0.5 T/s	0.003 T/s	0.6 T/s

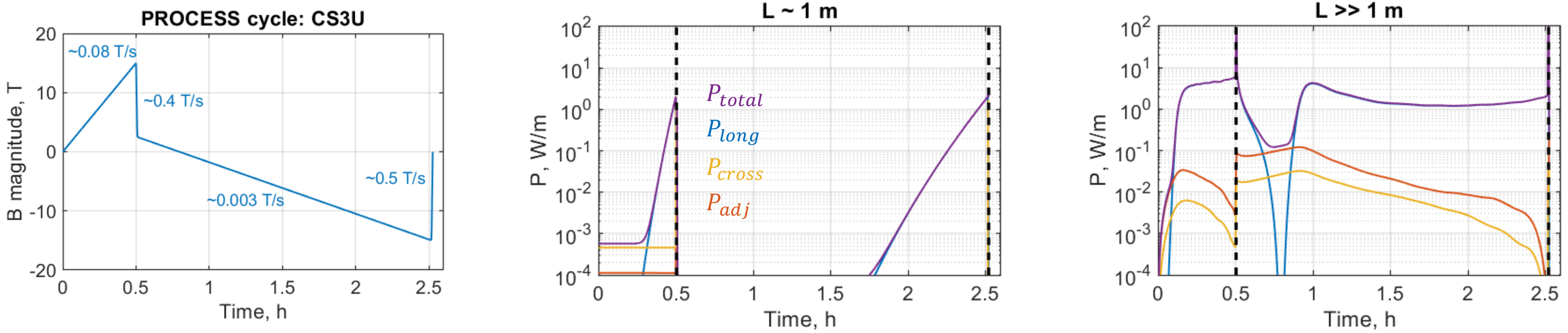
DEMO CS graded coils: power loss estimates

CS module	CS3L	CS2L	CS1	CS2U	CS3U
Most demanding operating conditions	PREMAG: 14.66 T / 70.1°	EOF: 12.59 T / 70.1°	PREMAG: 18.14 T / 83.7°	EOF: 13.16 T / 70.3°	PREMAG: 15.03 T / 70.2°
# of 3.3 mm tapes (aligned along z-axis)	~220	~200	~140	~200	~220
P max for L ~ 1 m	≈ 2.2 W/m	≈ 1.7 W/m	≈ 1.1 W/m	≈ 1.9 W/m	≈ 2.4 W/m
P max for L >> 1 m	≈ 110 W/m	≈ 80 W/m	≈ 60 W/m	≈ 90 W/m	≈ 120 W/m

For non-transposed strands, ~100 W/m applied to strands may increase their temperature above 10 K, thus need for higher T_{cs}.

Strands transposition may reduce losses by about 10 times.

2.4 W/m + intra-strand loss = 10–20 W/m?



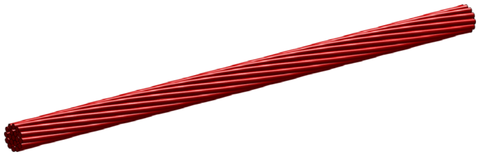
Operating current $\sim B$ during the cycle

Intra-strand loss should be accounted…

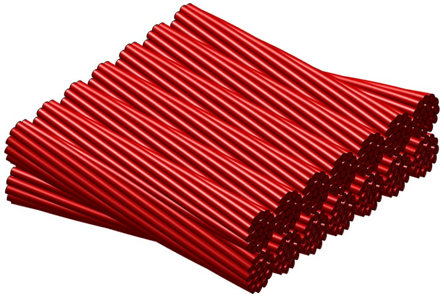
Intra-strand loss is negligible

Outlook on network modelling

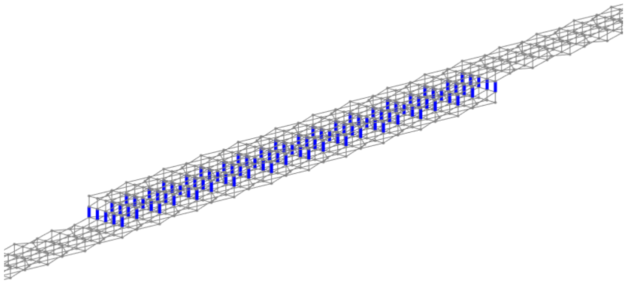
DEMO R&W sub-cable



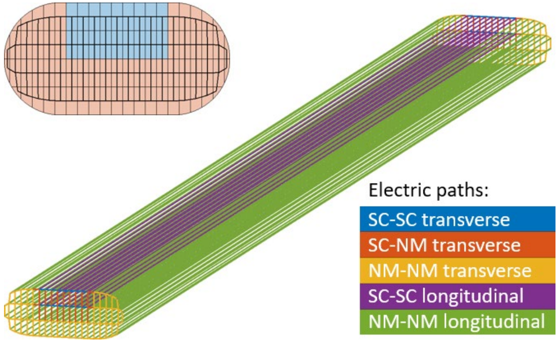
DEMO R&W cable



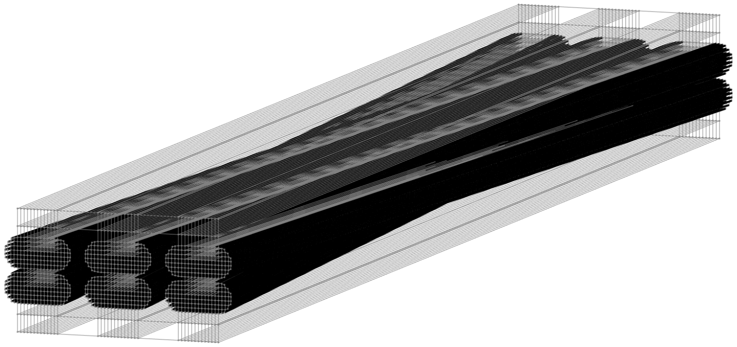
Cable splices



HTS stacked tapes strand

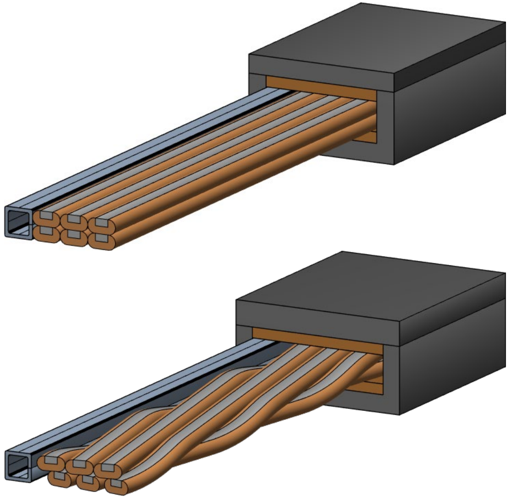


ASTRA conductor



Conclusion

- Analytical and numerical models are developed to analyze saturated coupling loss in Rutherford cables.
- Relatively low loss is obtained by keeping twist-pitch below its critical value expressed as $L_c \approx \sqrt{96\rho I_c \,/\, N\dot{B}w}$.
- Transposition of strands is needed to avoid their overheating during fast transients in the DEMO CS coils.
- Network modelling approach is being used to simulate electromagnetic behavior of various cable layouts.



THANK YOU FOR YOUR ATTENTION!