Optimisation of CLIQ for HTS

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Thanks to H.H.J. ten Kate, G. Kirby and A.P. Verweij

Before we begin..

<u>I am not an expert of HTS!</u>

- What is CLIQ
- AC loss in HTS
- CLIQ optimization (valid for any magnet)
- Possible game changers
- First study case of CLIQ on HTS (Ravaioli & Van Nugteren)
- CLIQ with external excitation coils

HTS – Challenges for effective quench protection

Very low normal-zone propagation velocity (~cm/s): bad for detection, bad for protection

Very high margin to quench (~J/cm^3): good for stability, bad for protection

Slower quench detection

Faster rise of the hot-spot temperature

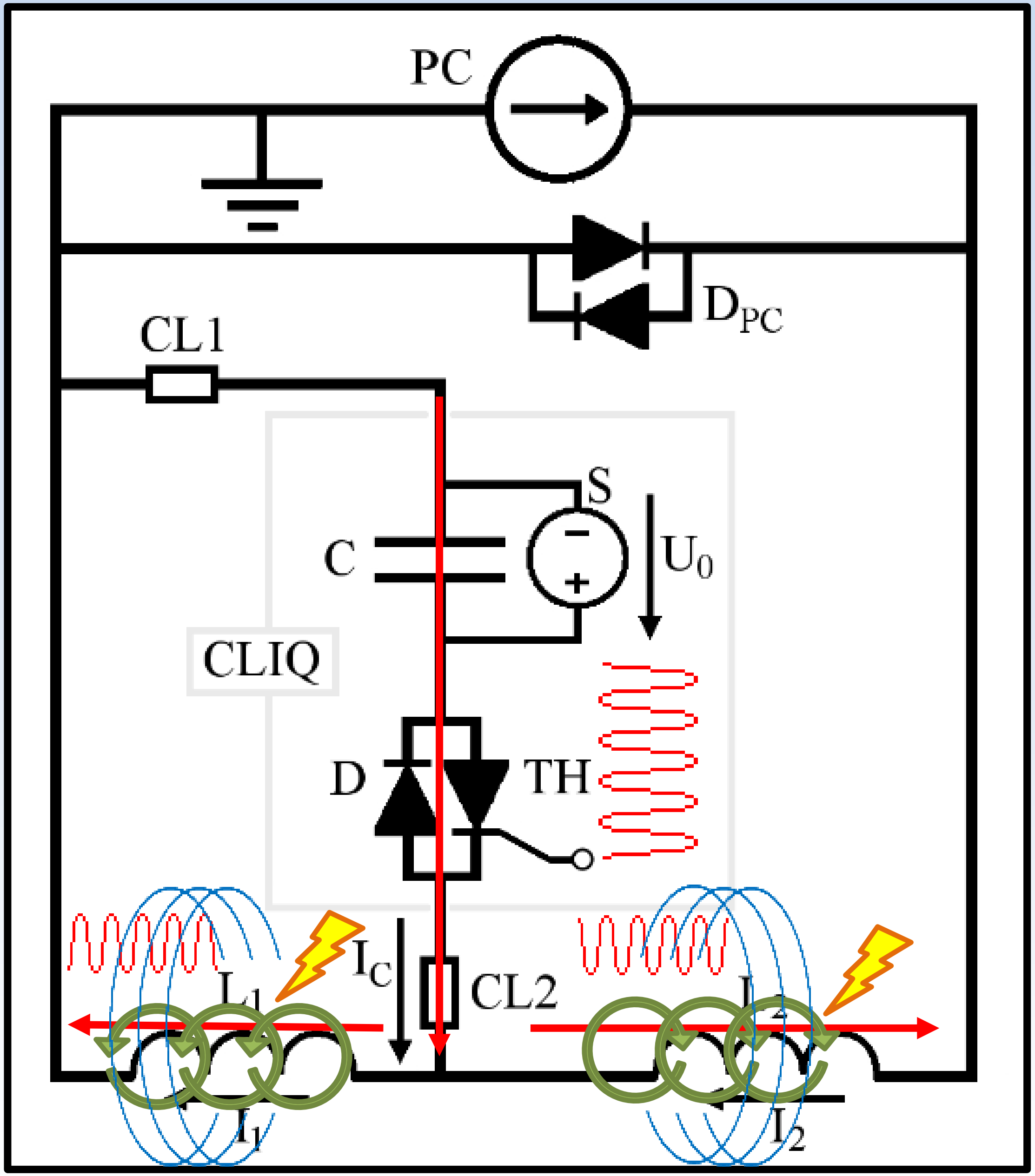
Less homogeneous transition to the normal state: Thermal stress (?), Less uniform coil-to-ground voltages

What is CLIQ

What is CLIQ	AC loss in HTS	CLIQ optimization (valid for any magnet)	Possible game changers	First study case of CLIQ on HTS (Ravaioli & Van Nugteren)	CLIQ with external excitation coils

CLIQ – Coupling-Loss Induced Quench system

Patent EP13174323.9



Current change

Magnetic field change

Transitory losses (Heat)

Temperature rise

QUENCH

What CLIQ offers...

A **different mechanism** for depositing **heat** in superconductors with respect to QH
(in multi-filamentary LTS strands, this mechanism is very effective)

An **electrically robust** system, mainly **external** to the coil, hardly interfering with the coil winding technology

...and what it requires

Study of complex interdependent **electro-magnetic** and **thermal** effects, on very **different scales** (filaments, strands, tapes, cables, main circuit)

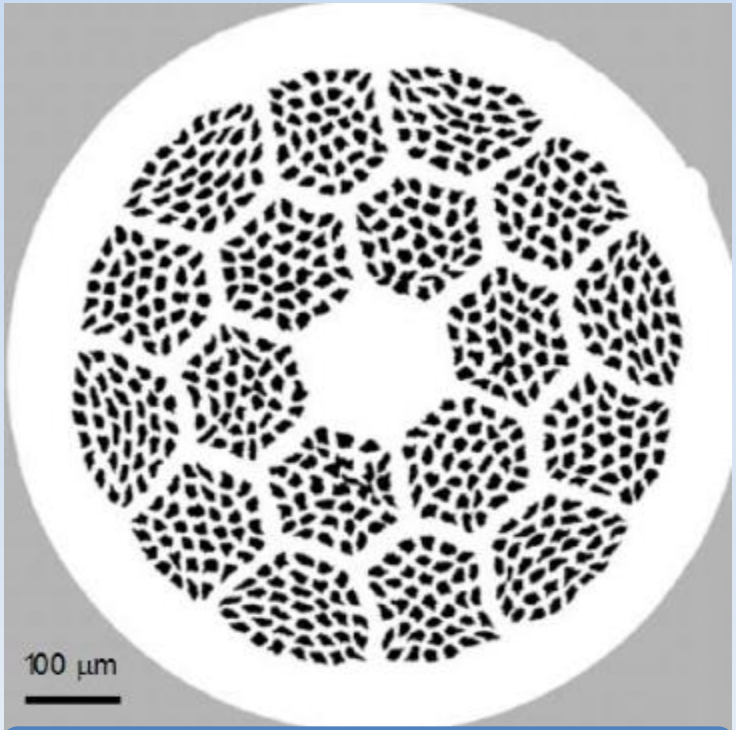
Additional **terminals** connected to the coil to protect

...and **"fast" transitory losses**!! (i.e. with small time constant)

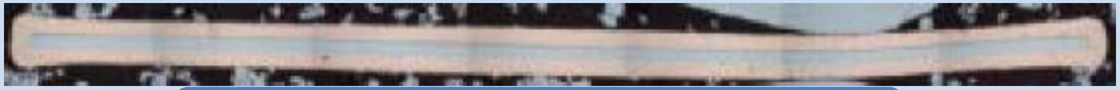
AC loss in HTS

What is CLIQ	**AC loss in HTS**	CLIQ optimization (valid for any magnet)	Possible game changers	First study case of CLIQ on HTS (Ravaioli & Van Nugteren)	CLIQ with external excitation coils

HTS strands/tapes



B-2212 strand (Ag matrix)

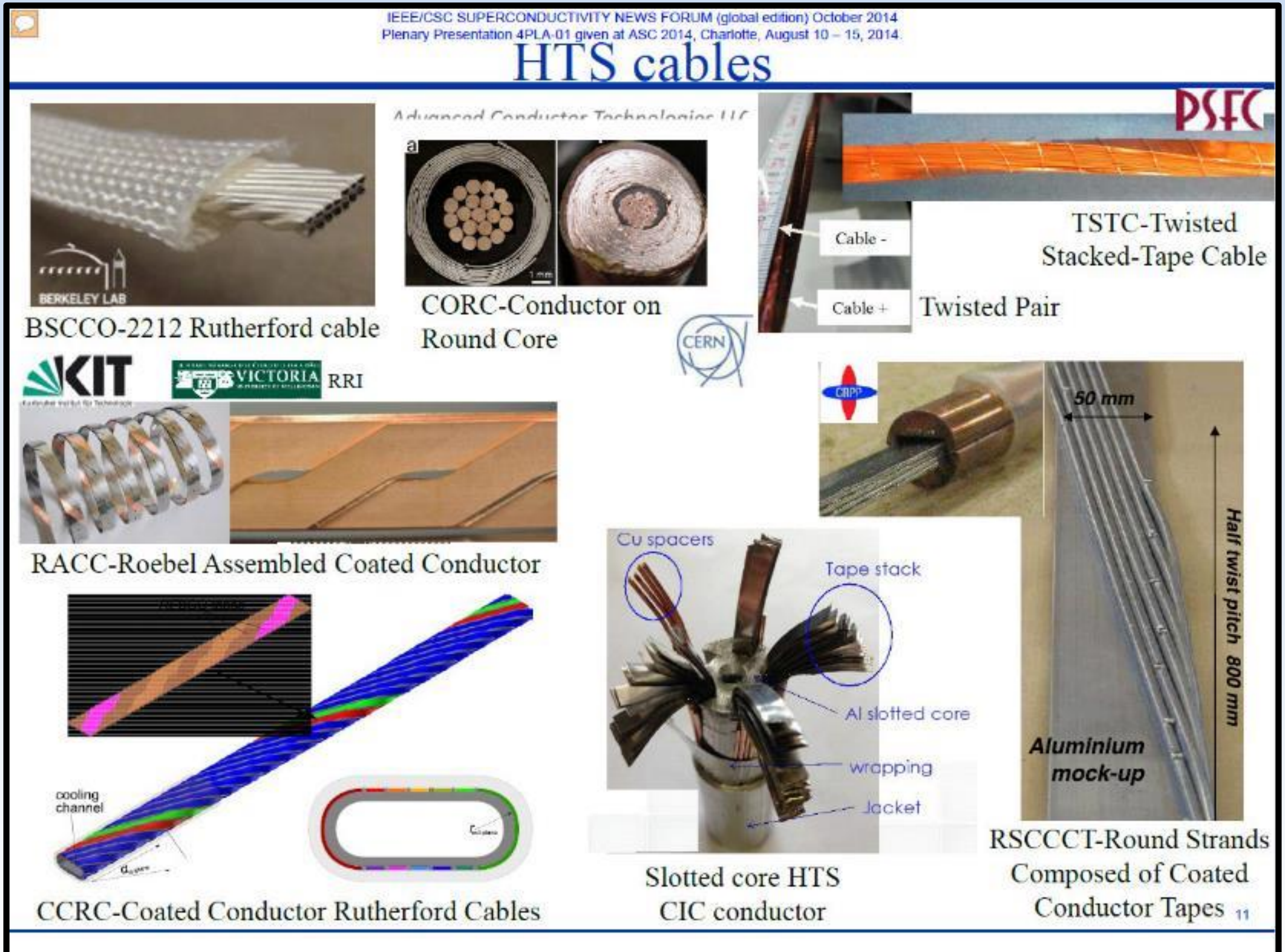


YBCO tape

MgB$_2$ strand (Cu matrix)

Figures and information from Luisa Chiesa's plenary talk at ASC 2014

HTS cables (Slide from Luisa Chiesa's talk at ASC2014)



Transitory losses in HTS conductors

The target of a CLIQ-based protection system is generating enough transitory losses to transfer most of the coil to normal state **in 10-20 ms**

Hence, "fast" losses are needed

Inter-filament coupling loss: Usually features an **ideal time constant** for heating up the superconductor very effectively with a CLIQ discharge

…but not present in tapes, by definition! (if not striated)

Inter-strand or inter-tape coupling losses: Whilst often higher in amplitude, they are typically too slow for heating up the coil in <20 ms

Too slow

Hysteresis losses (intentionally unspecific term here):
No time constant involved, potential for effective mechanism, but the amplitude of the oscillating field must be high

To measure and/or model on a case-by-case basis

CLIQ optimization (valid for any magnet)

What is CLIQ	AC loss in HTS	**CLIQ optimization (valid for any magnet)**	Possible game changers	First study case of CLIQ on HTS (Ravaioli & Van Nugteren)	CLIQ with external excitation coils

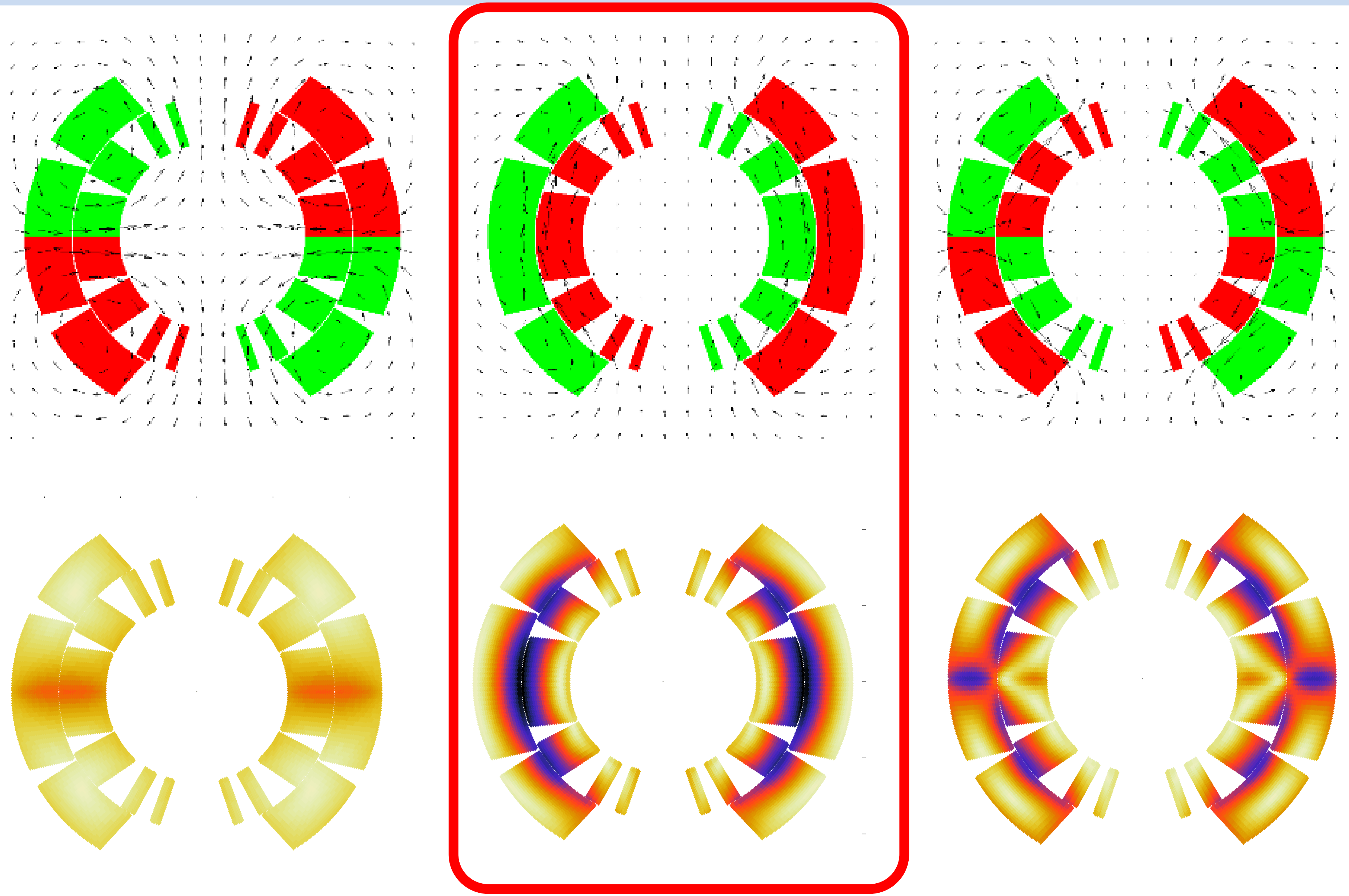
Some rules of thumb for CLIQ power and energy deposition

Coupling losses per unit volume are proportional to (dB/dt)^2	Hysteresis losses per unit volume are dependent on ΔB (α ΔB^3?)
dB/dt is proportional to U_0	ΔB is proportional to U_0
dB/dt is proportional to N_{CLIQ}	ΔB is proportional to (N_{CLIQ})^0.5
dB/dt is proportional to $1/L_{eq}$ and L_{eq} can be reduced by 10+ times by optimizing the discharge circuit	ΔB is proportional to $(1/L_{eq})$^0.5 and L_{eq} can be reduced by 10+ by optimizing the discharge circuit
dB/dt is independent of C	ΔB is proportional to C^0.5
dB/dt distribution can be optimized	ΔB distribution can be optimized

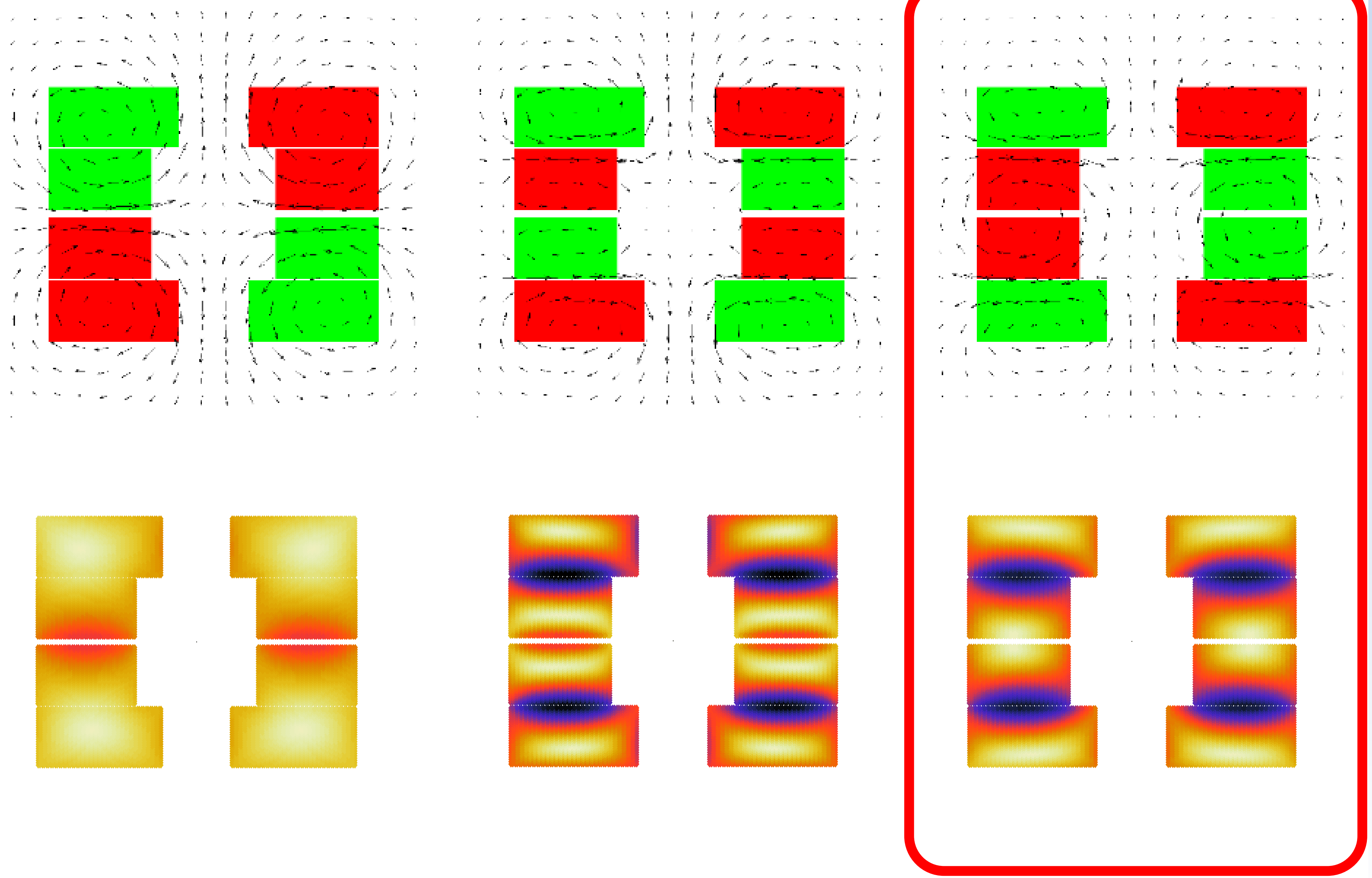
In any case, the total energy delivered to the coil is < 0.5 N_{CLIQ} C U_0^2

CLIQ typically introduces up to **dB/dt~10^2-10^3 T/s** and **ΔB~10^{-1}-10^0 T** and **orientation very different** from the field lines when powering in DC

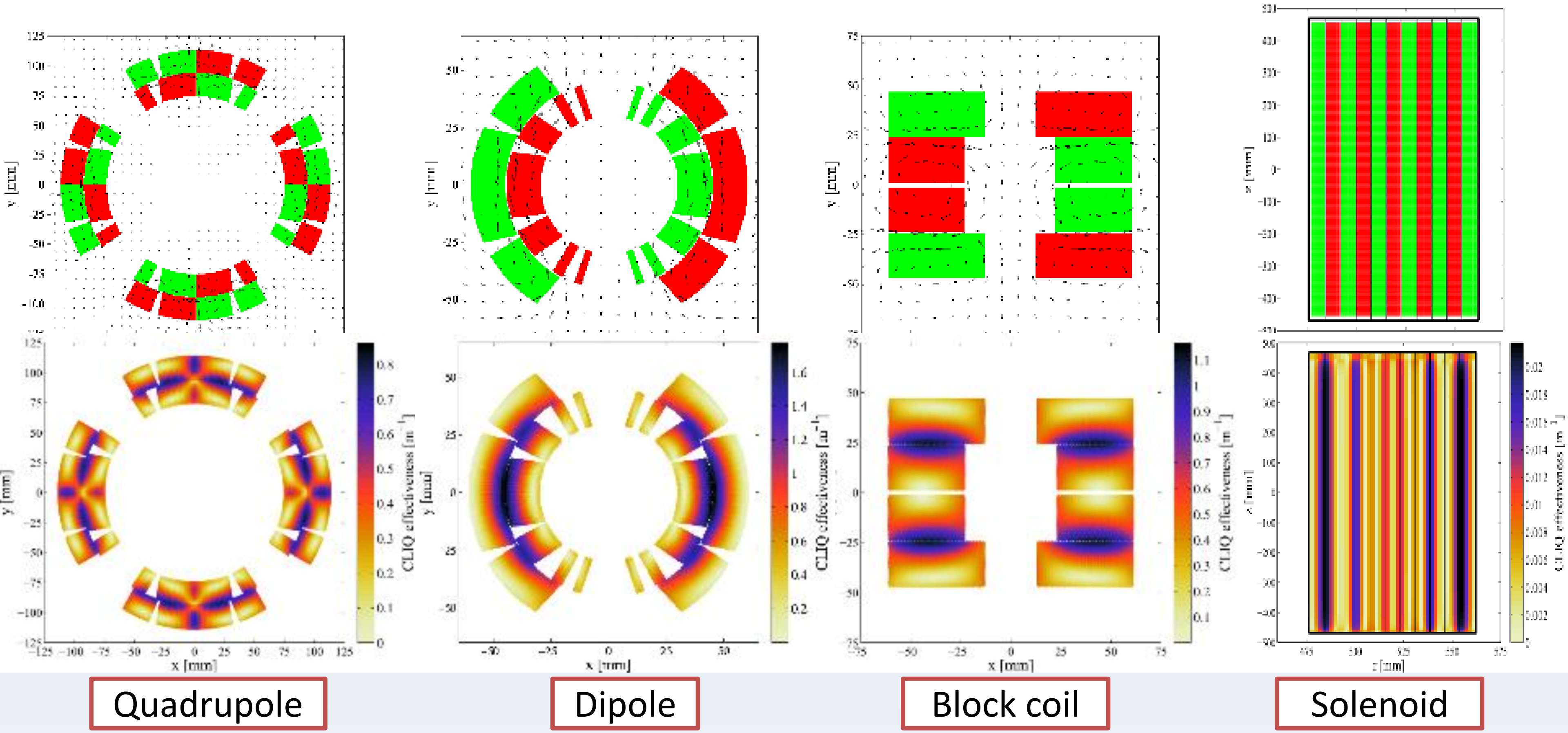
Example of CLIQ optimization (Dipole geometry)



Example of CLIQ optimization (Block-coil geometry)



Optimizing CLIQ – Different magnet geometries



Golden rules

Subdividing the coil in multiple sections

Introducing opposite current changes in coil sections that are physically adjacent

This looks beautiful… but where's the catch?

Increase of U_0	Increase of peak **voltages to ground** in the circuit (<1 kV?)
Addition of CLIQ units	Needs additional CLIQ **terminals**
Optimization of the discharge circuit (positioning of CLIQ leads, order of the coil sections, etc)	Typically requires addition of CLIQ terminals **between magnet layers** (less obvious to manufacture)

No real bottleneck for increasing dB/dt introduced with CLIQ by 10+ times, i.e. **increasing coupling loss by 100+ times** with respect to present CLIQ systems achieving very good performance on LTS coils

…providing the rules of the game don't change! →

Possible game changers

What is CLIQ	AC loss in HTS	CLIQ optimization (valid for any magnet)	**Possible game changers**	First study case of CLIQ on HTS (Ravaioli & Van Nugteren)	CLIQ with external excitation coils

Game changers

If filaments are present, but matrix has **very high transverse resistivity**, compensate with longer filament twist-pitch

If filaments are present, but matrix has **very low transverse resistivity**, not possible to compensate with shorter filament twist-pitch (IFCL time constant too large), compensate with filament-matrix barrier (?)

If **filaments** are not present, no inter-filament coupling loss

If very low/high **hysteresis losses** are generated for a given ΔB, performance can change dramatically (you'll see an example soon)

If current density depends on the **magnetic-field direction**, the transition to the normal state can be achieved with smart field-changes

Use a different type of CLIQ system based on **external excitation coils** (see last part of the presentation)

First study case of CLIQ on HTS (Ravaioli & Van Nugteren)

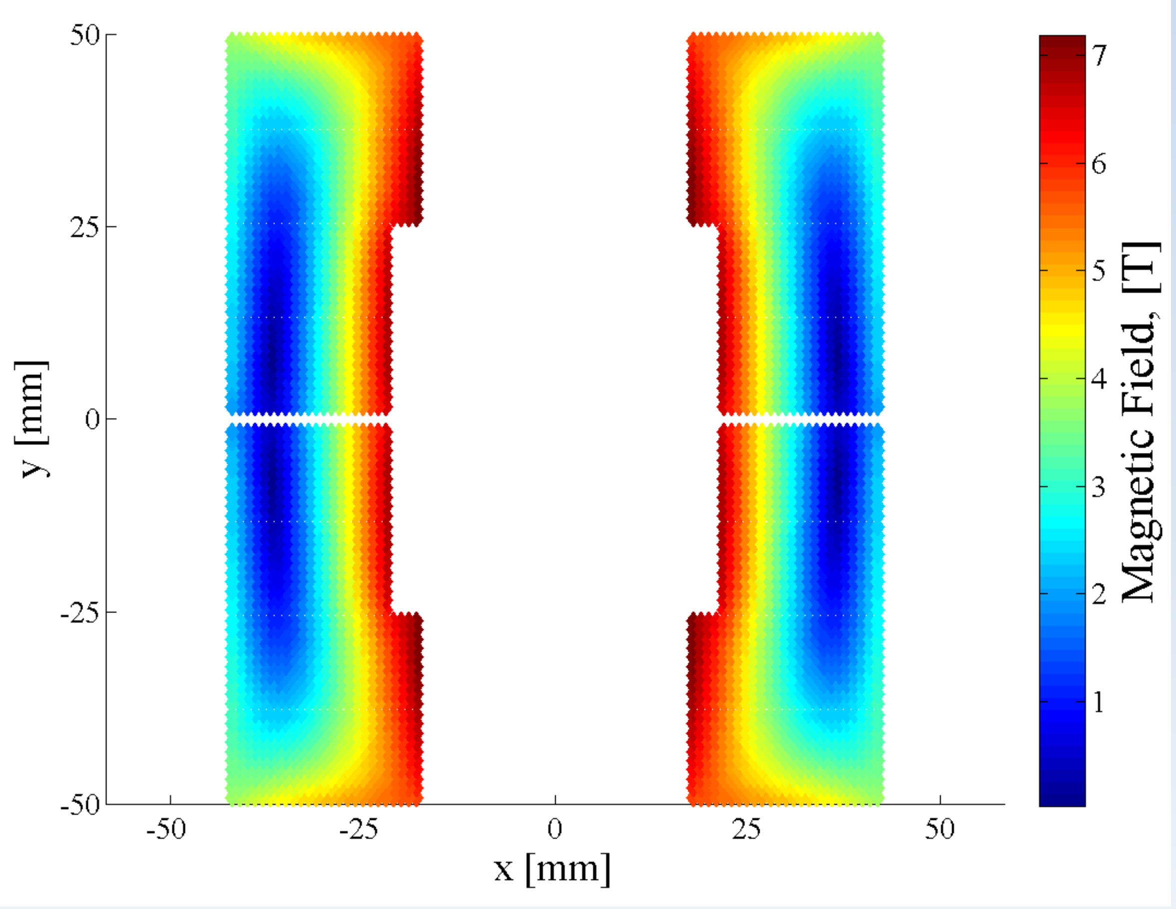
What is CLIQ	AC loss in HTS	CLIQ optimization (valid for any magnet)	Possible game changers	**First study case of CLIQ on HTS (Ravaioli & Van Nugteren)**	CLIQ with external excitation coils

Study case: 7 T block-coil dipole insert, YBCO Roebel cable

- Block-coil
- 4 layers
- R=25 mm aperture
- 5 meter long

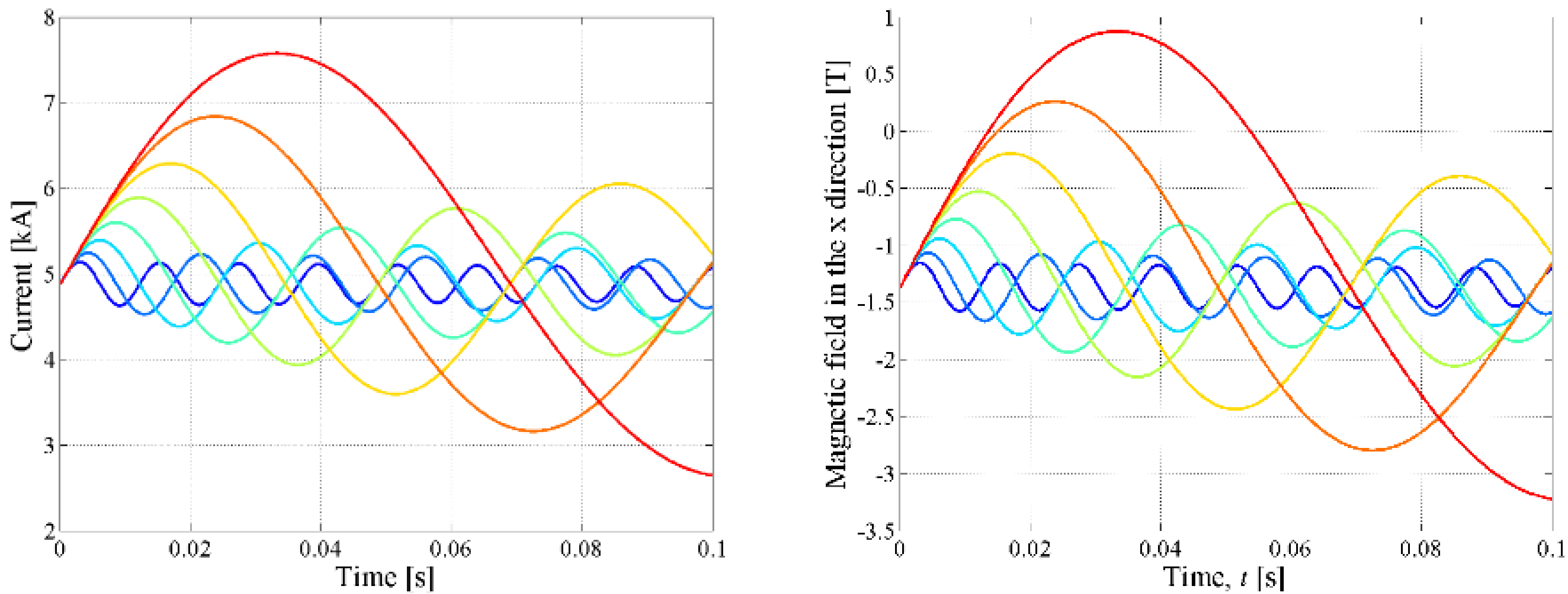
- Nom current 4880 A
- Peak dipole field ~7 T
- Background field 13 T
- Insulation 0.1 mm

- YBCO, Roebel cable
- 15 tapes
- 12x0.8 mm^2
- Je=400 A/mm^2



Study jointly performed by
E. Ravaioli and J. Van Nugteren

Current and magnetic-field changes introduced by CLIQ



Only **1 CLIQ unit** and 2 CLIQ terminals
U_0=1 kV (±500 V to ground)
C varying between 1 and 128 mF

CLIQ configuration optimized to maximize the **magnetic-field changes** in the direction **perpendicular** to the cable broad faces

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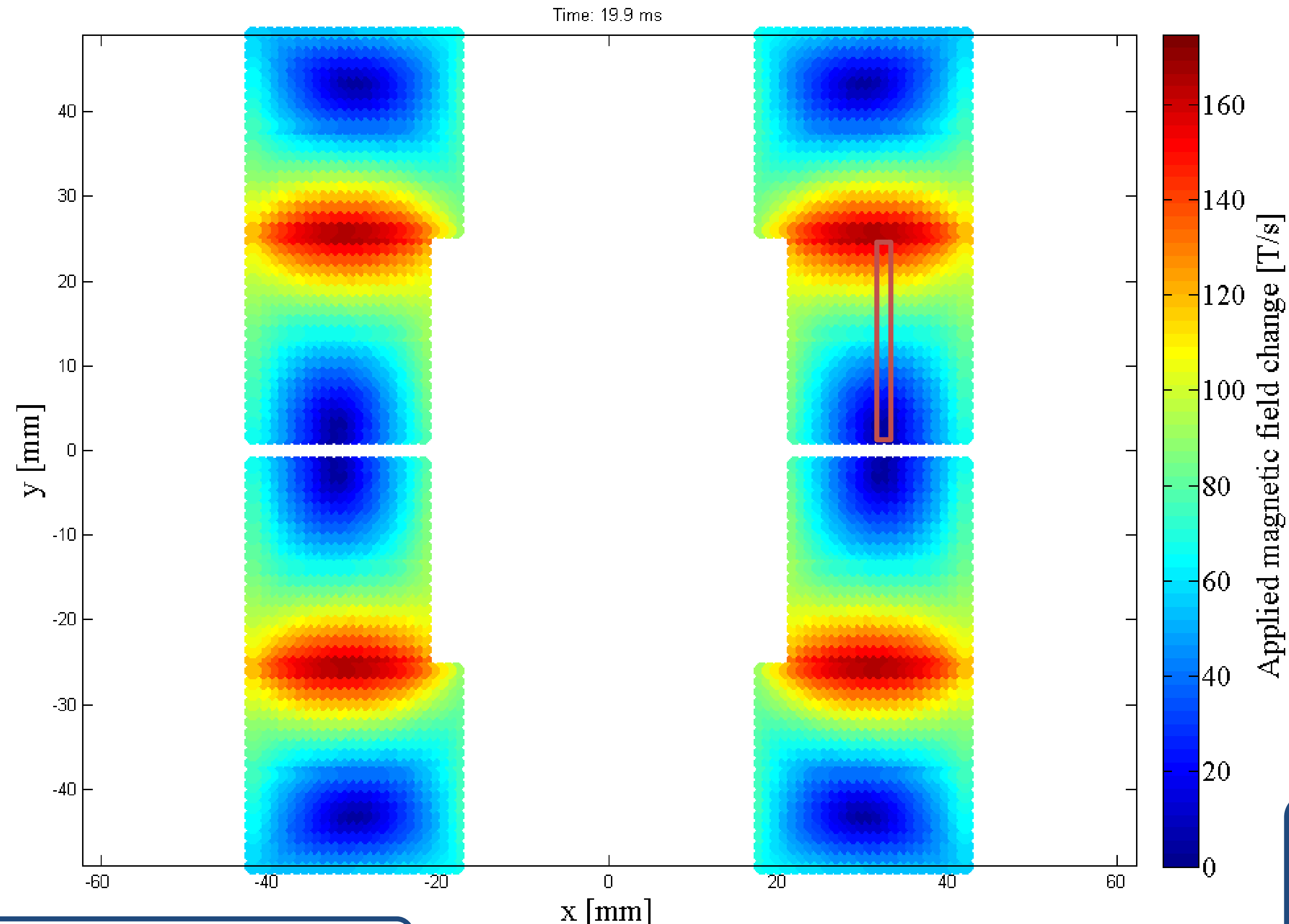
Magnetic-field changes introduced by CLIQ



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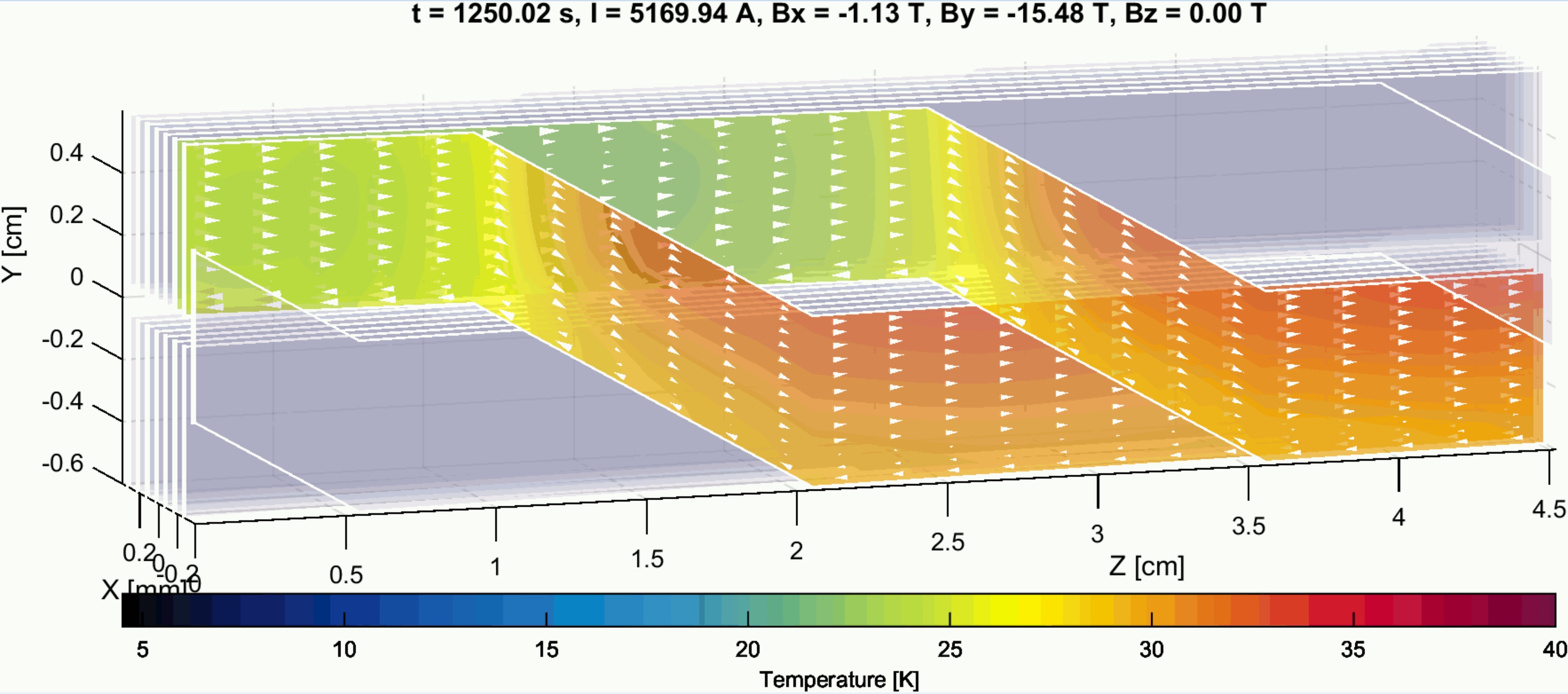
1 CLIQ unit
U_0=1 kV
C=10 mF

Temperature profile in two adjacent tapes



Study jointly performed by
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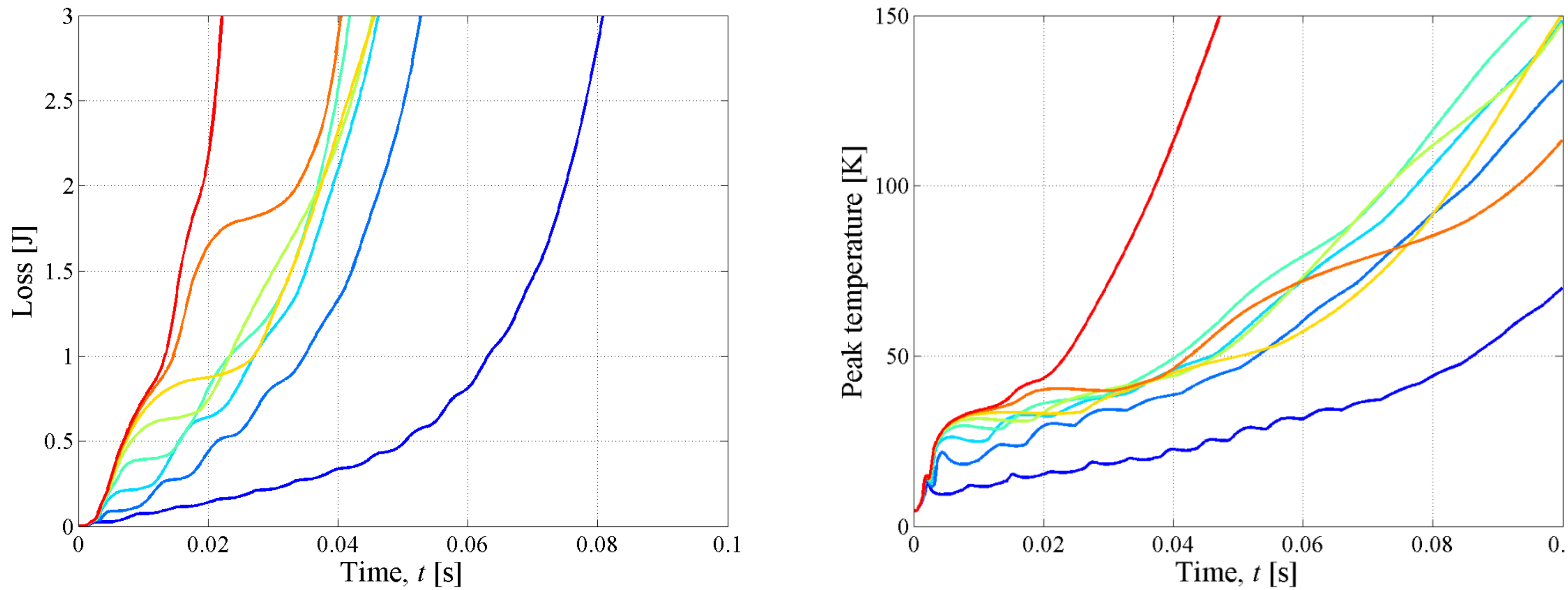
1 CLIQ unit
U_0=1 kV
C=10 mF

Deposited loss (Hysteresis+Ohmic) and Temperature



U_0=1 kV (±500 V to ground)
C between 1 and 128 mF

Study jointly performed by
E. Ravaioli and J. Van Nugteren

With reasonable charging voltage and capacitance, this HTS coil can be effectively quenched by CLIQ **<u>in <20 ms</u>**

...with only
1 CLIQ unit and
2 CLIQ terminals!

Next steps to conclude the analysis

Study the interaction between stacked cables

Run similar simulations for tapes in different locations of the coil

Complete electro-thermal simulation

(Loss → Temperature → Quench → Resistance → Magnet discharge)

Study the effect of losses on the differential inductance

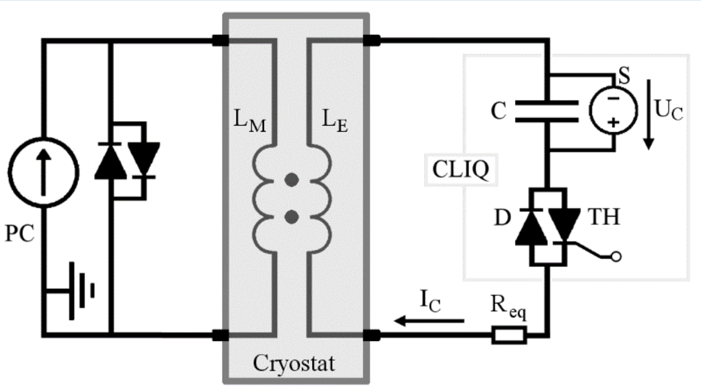
For LTS, all steps done and model validated

For HTS, some work is still needed…

CLIQ with external excitation coils

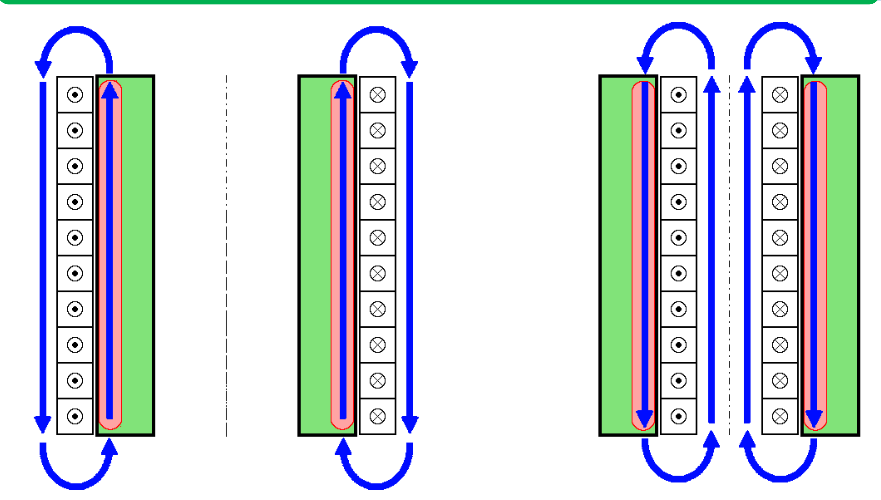
What is CLIQ	AC loss in HTS	CLIQ optimization (valid for any magnet)	Possible game changers	First study case of CLIQ on HTS (Ravaioli & Van Nugteren)	**CLIQ with external excitation coils**

CLIQ with external excitation coils



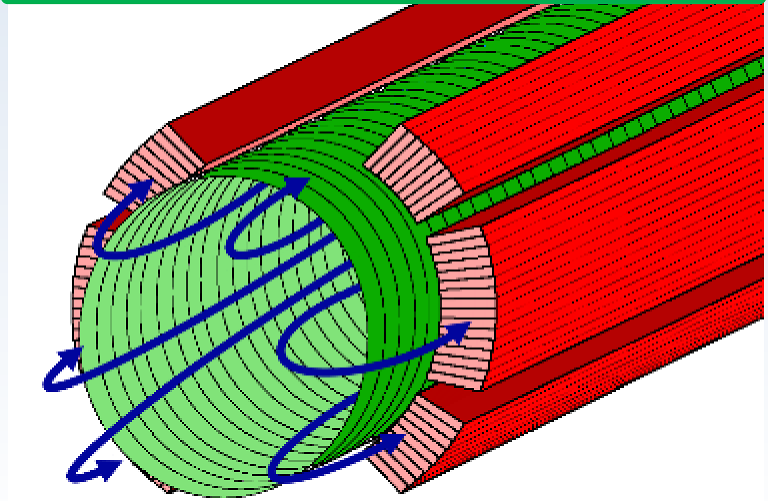
Tested in 2013 on LTS

External or internal to the coil, or between layers

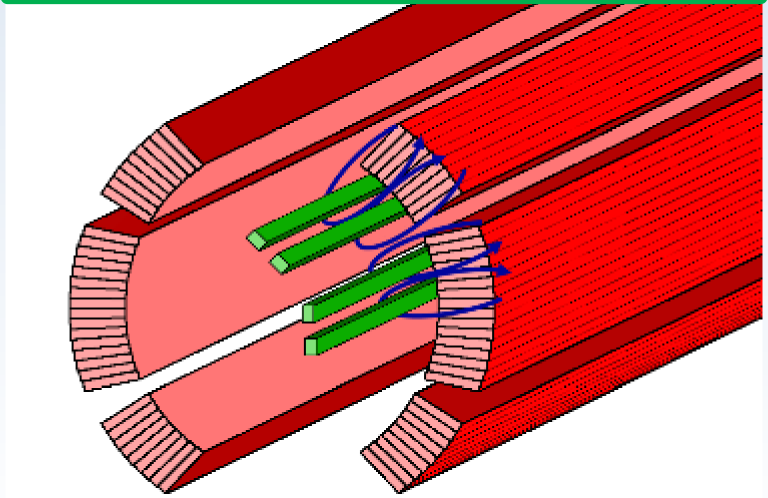


Advantages: Galvanically separated from the coil, High voltages can be introduced

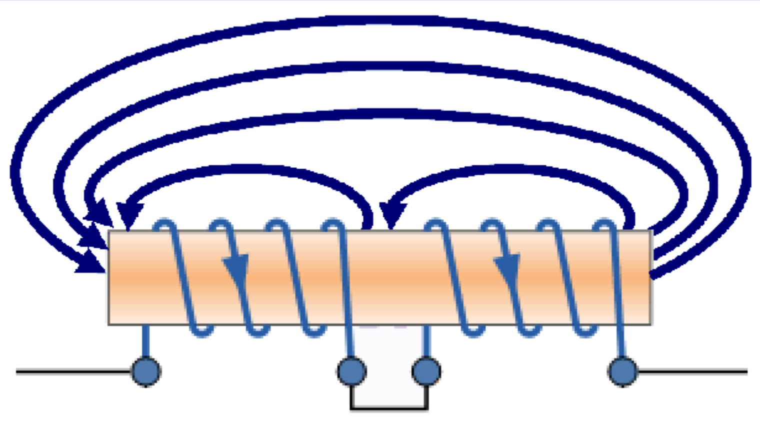
Solenoid coil

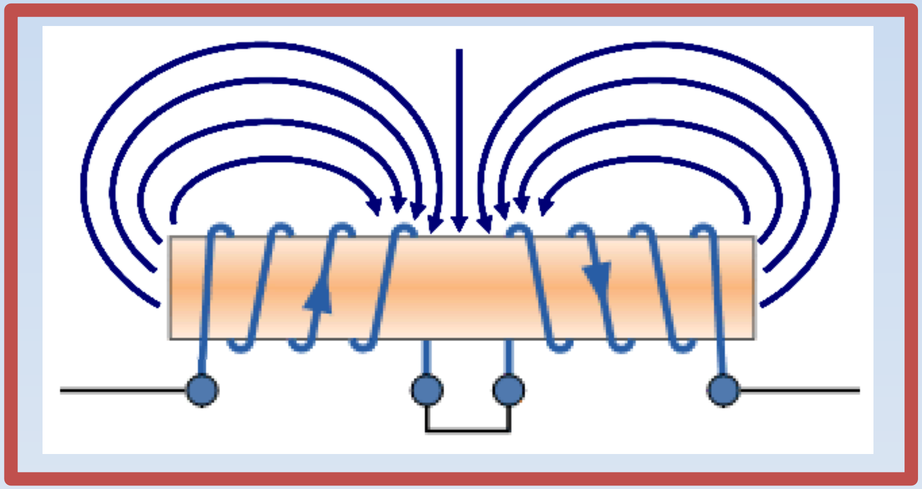


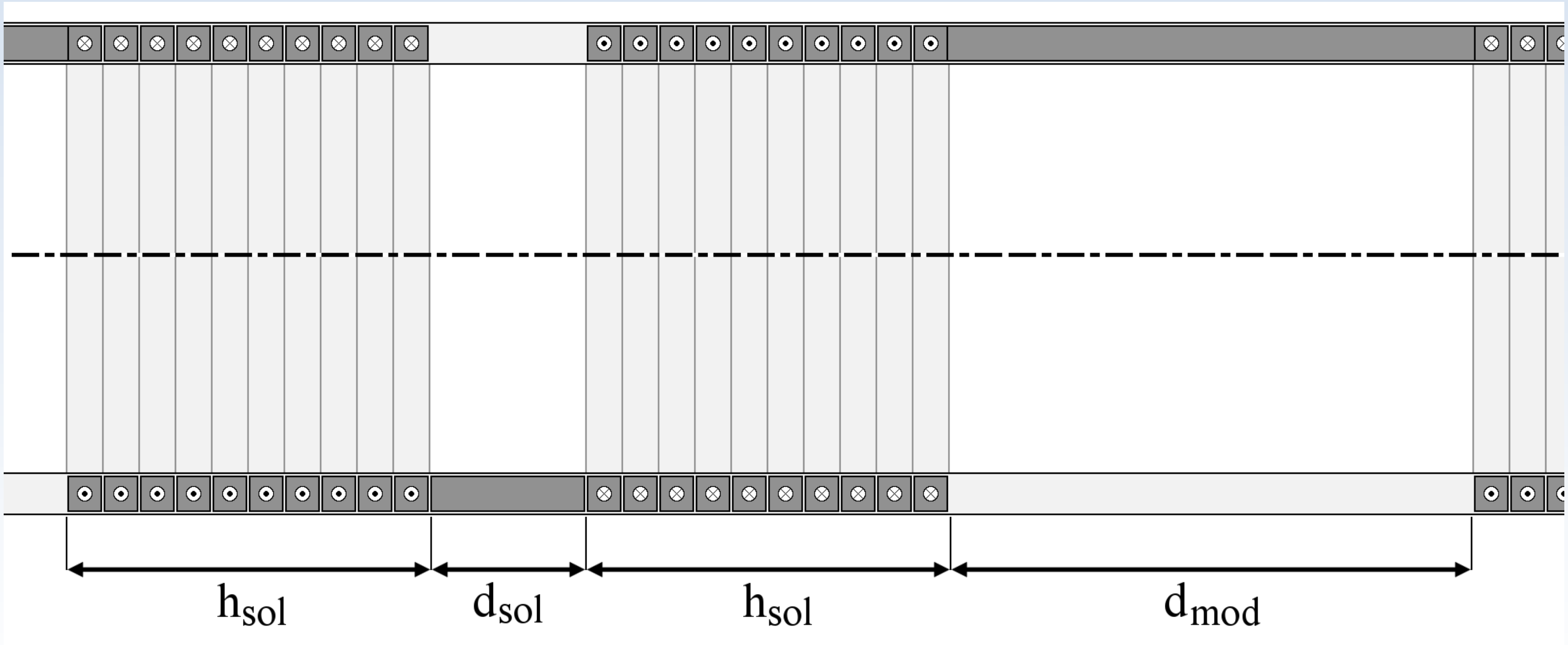
Multipole coil



CLIQ with external excitation coils – Multi-Solenoid

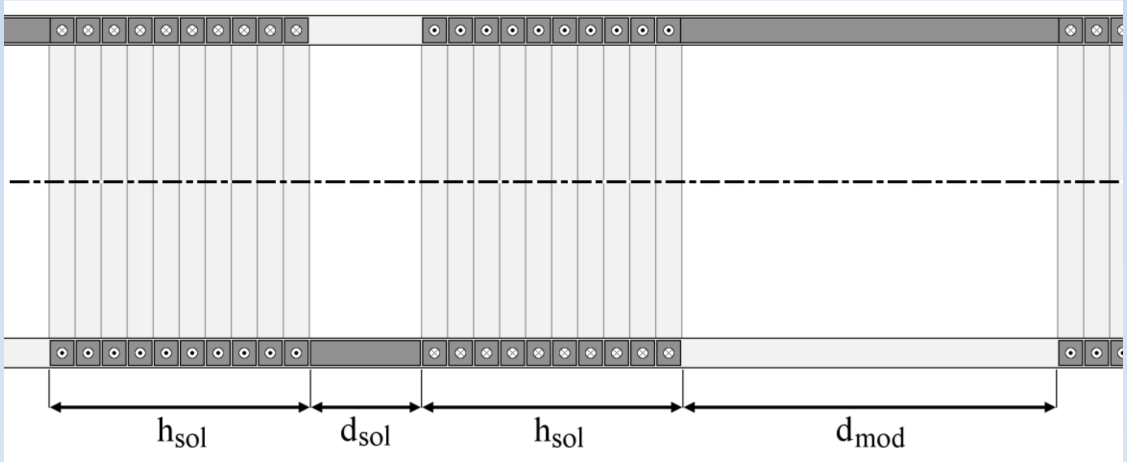




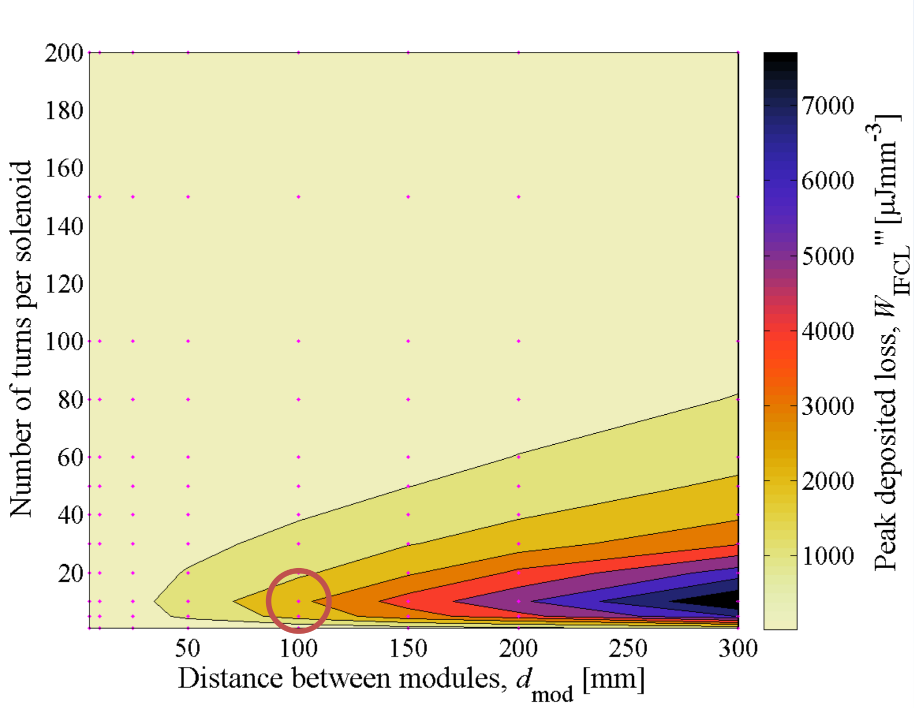


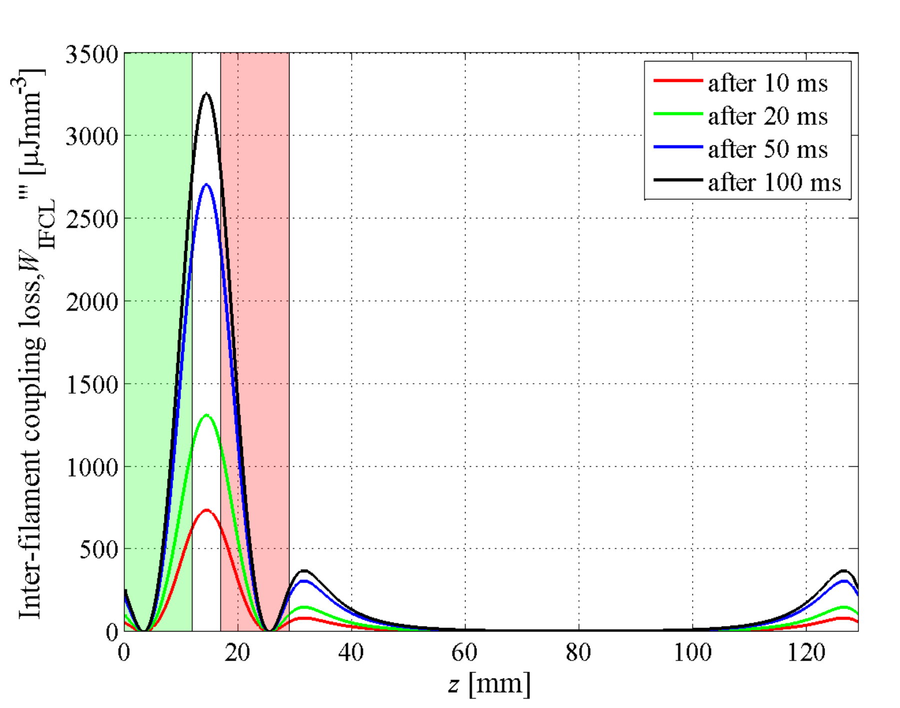
CLIQ with Multi-Solenoid excitation coil

In my humble opinion, this seems a subject for a very interesting PhD..



Very high energy deposition achieved in effective "inductive heating stations"
(~J/cm^3 in <20 ms)





Conclusion and outlook

Very promising!

CLIQ: **Mature technology** for LTS magnets

Optimization methods presented (U_0, N_{CLIQ}, terminal positioning, C, excitation coils)

With inter-filament coupling loss, increasing the **CLIQ power deposition** by **100+ times** with respect to present systems are **within reach**

Different loss mechanisms (particularly in cables) could be game changers (either way..)

Way to go: Collaborations between experts of CLIQ protection and AC losses in HTS (loss measurements, modeling, CLIQ optimization, circuit simulations,…)

QUESTIONS?

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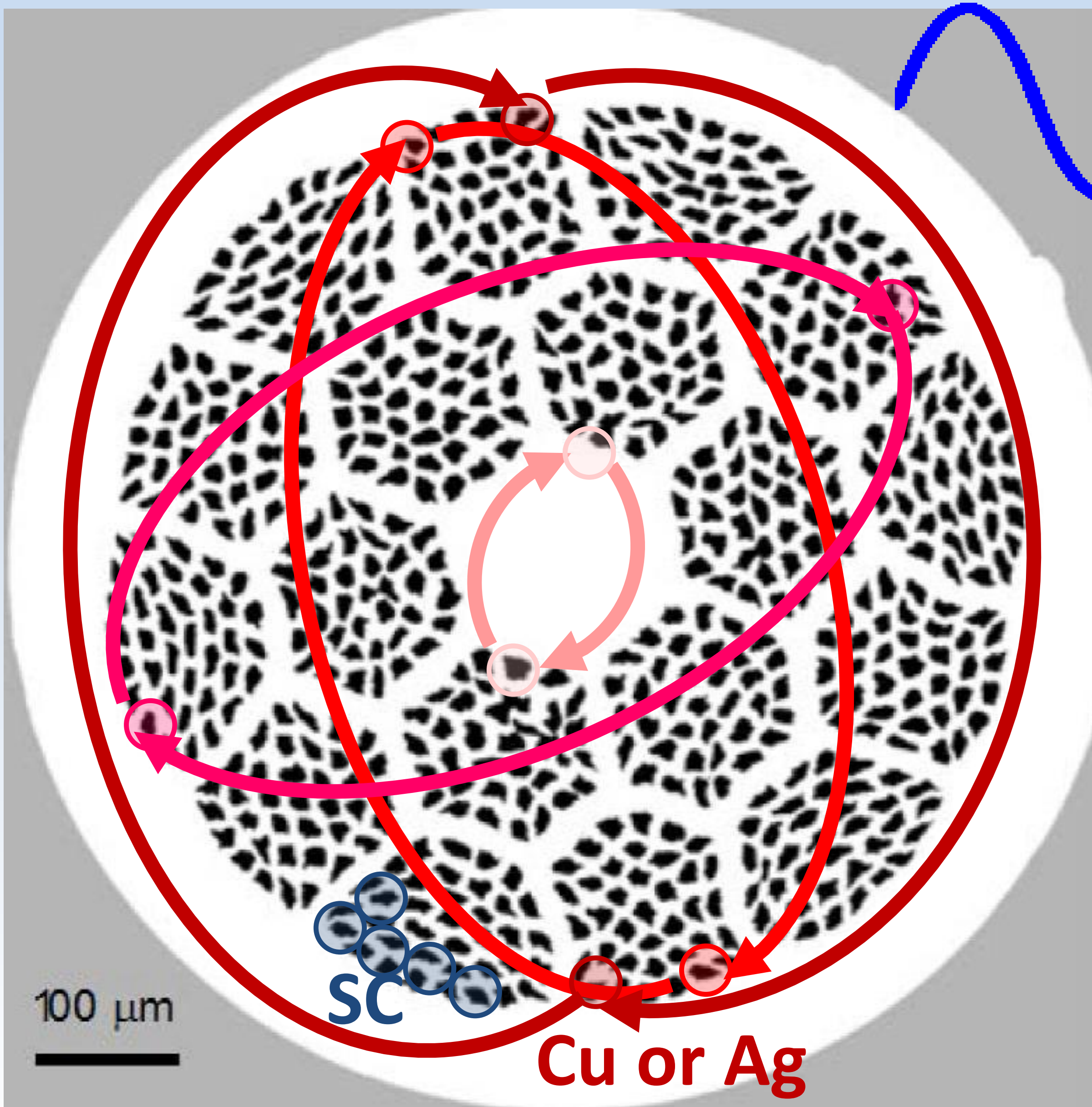
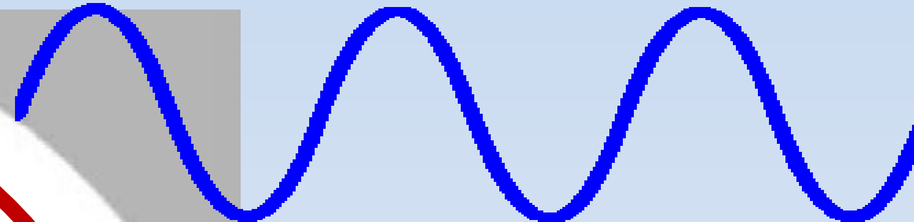
Multi-filamentary wires/strand: inter-filament coupling loss





Same physics as inter-filament coupling loss in LTS, but different material properties

$$\frac{P_{IF}}{vol} = \left(\frac{l_p}{2\pi}\right)^2 \frac{1}{\rho_{eff}(B)} \left(\frac{dB}{dt}\right)^2$$

$$\tau_{IF} = \frac{\mu_0}{2} \left(\frac{l_p}{2\pi}\right)^2 \frac{1}{\rho_{eff}(B)}$$

Filament twist-pitch and effective **transverse resistivity of the matrix** are the key parameters

Hysteresis loss