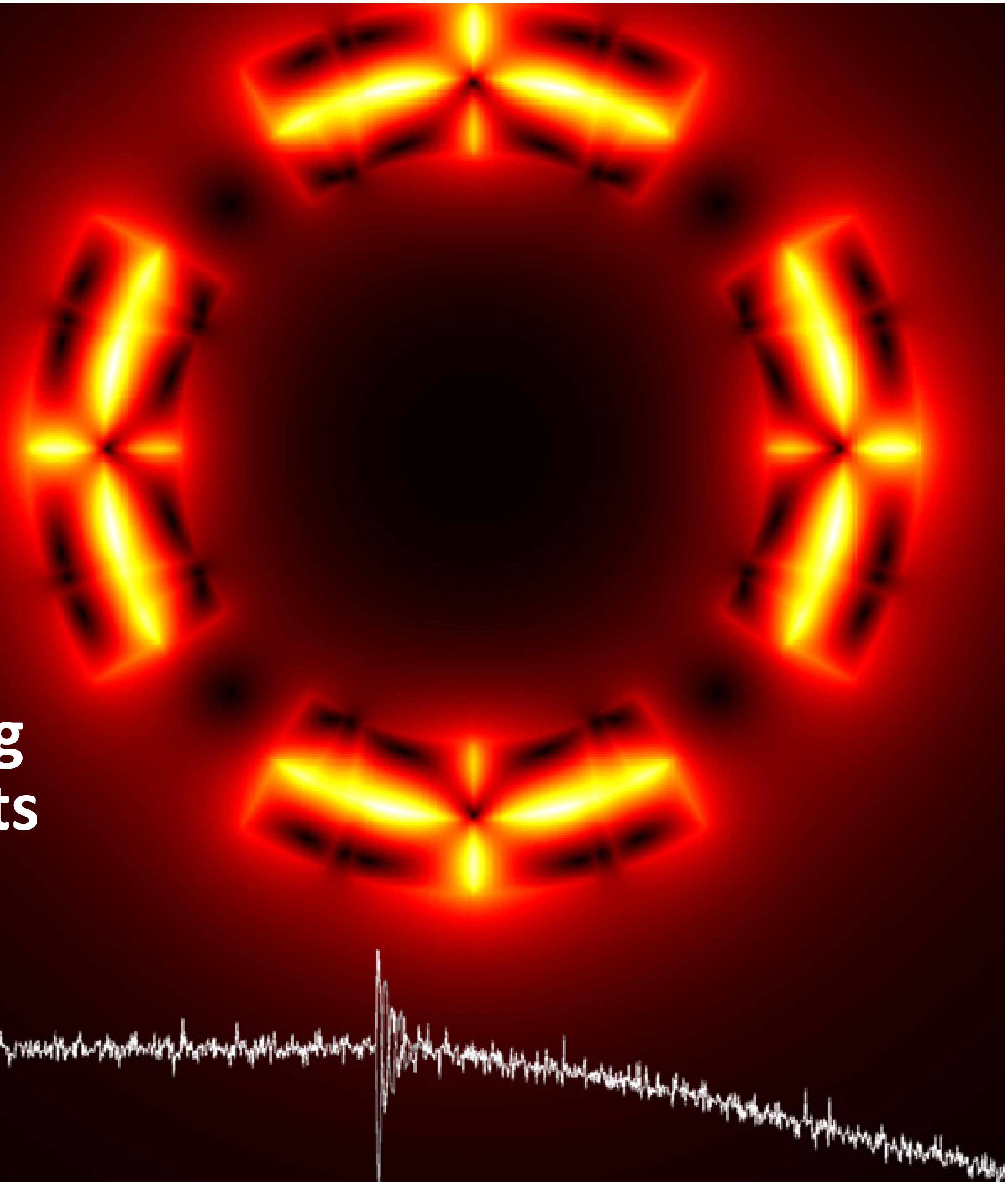
CLIQ:

a New Quench Protection Technology for Superconducting Accelerator Magnets

E. Ravaioli (LBNL)

12 October 2016



Outline

CLIQ – Coupling-Loss Induced Quench system

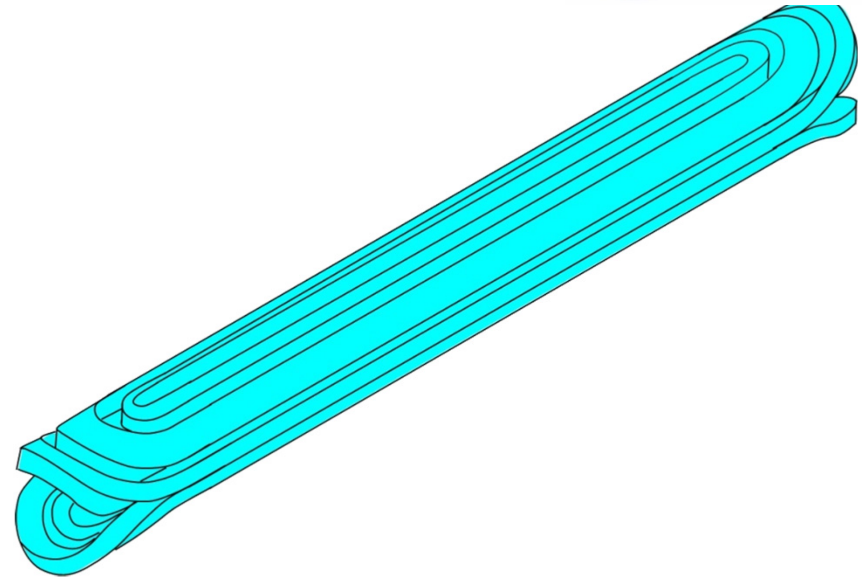
- **Magnet quench protection**
- **CLIQ technology**
- **CLIQ heating mechanism**

Implementation on existing accelerator magnets

Implementation on future accelerator magnets

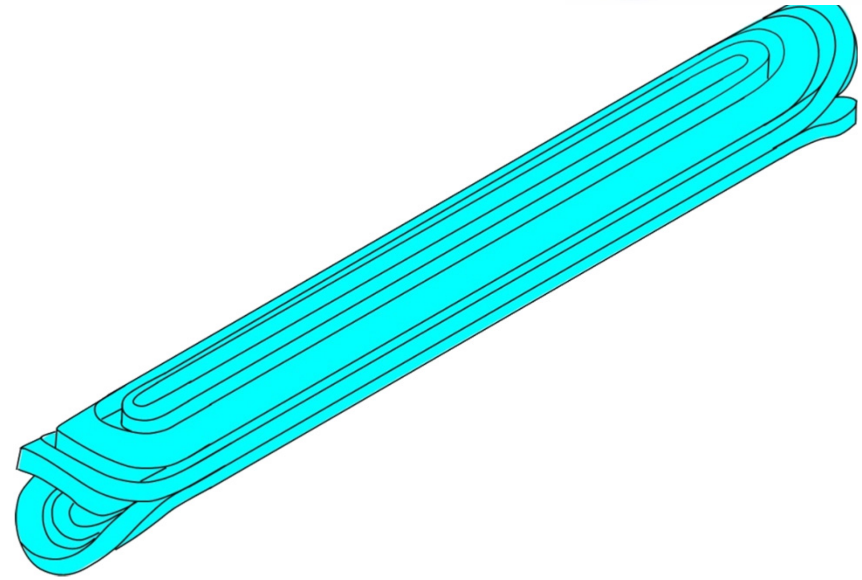
Outlook

Quench in a superconducting magnet



Quench in a superconducting magnet

High Current Density
$J \approx kA/cm^2$



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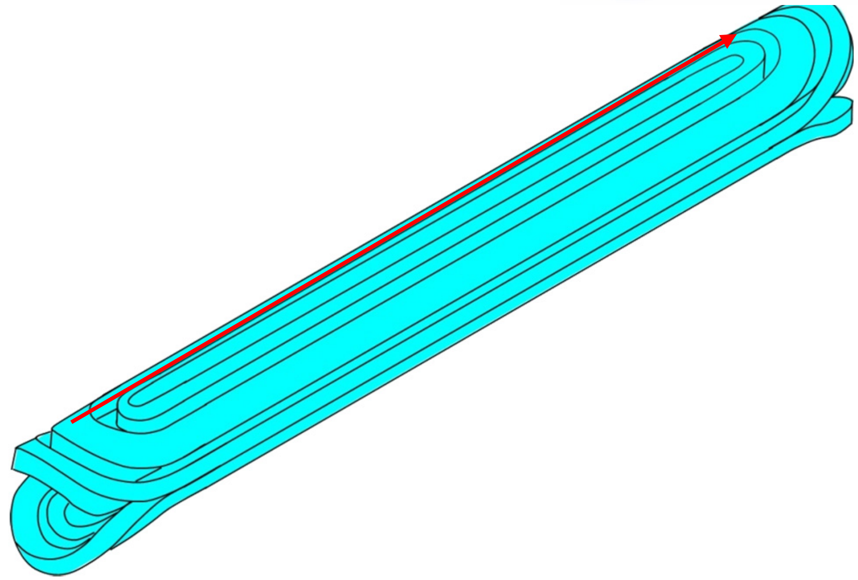

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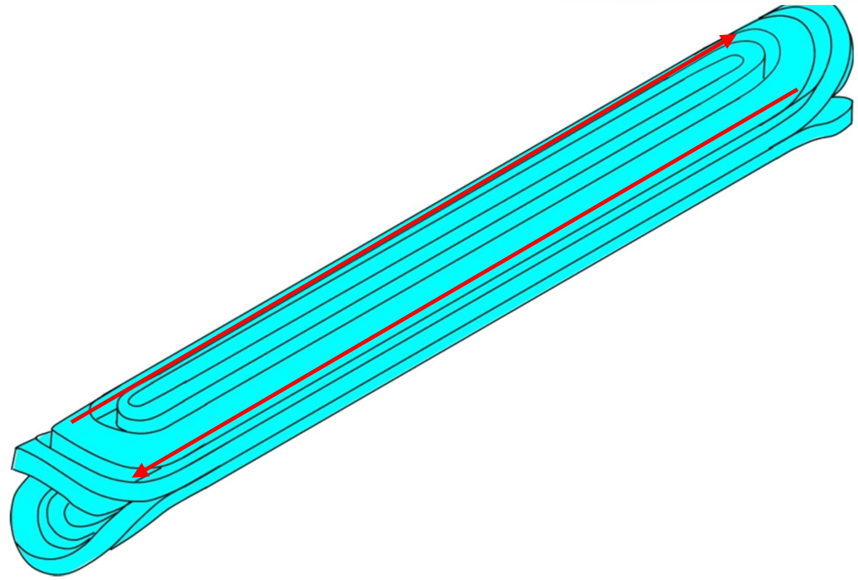

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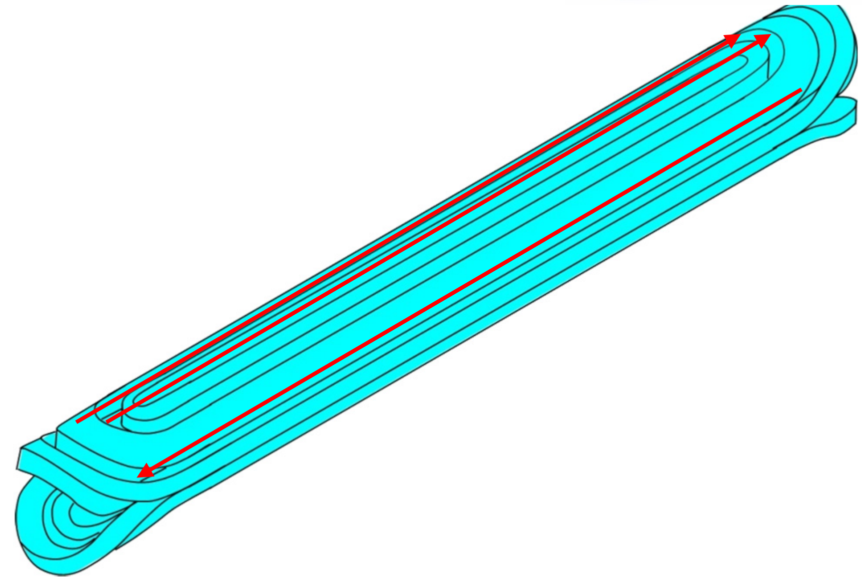

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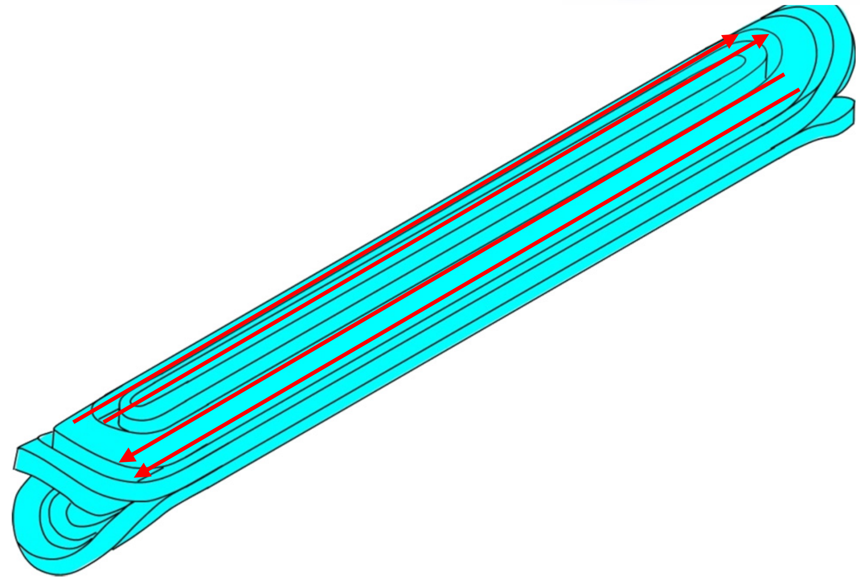

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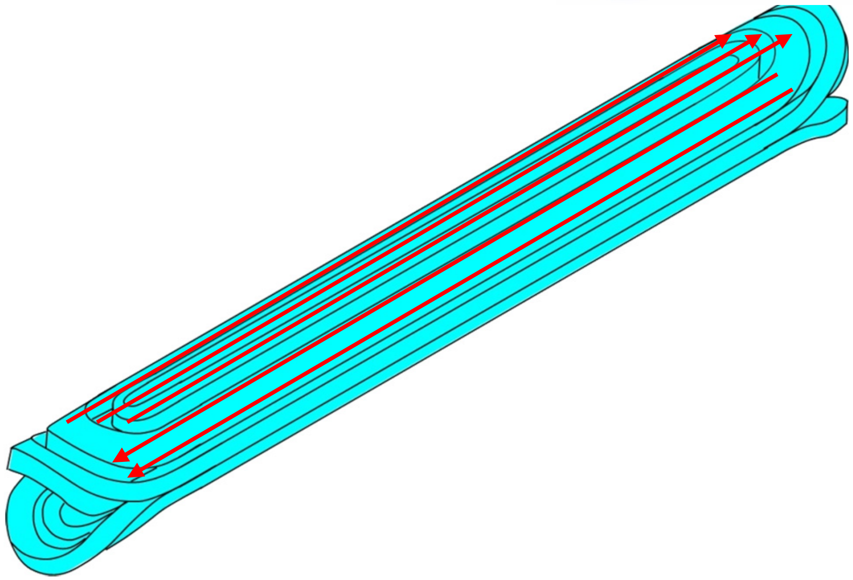

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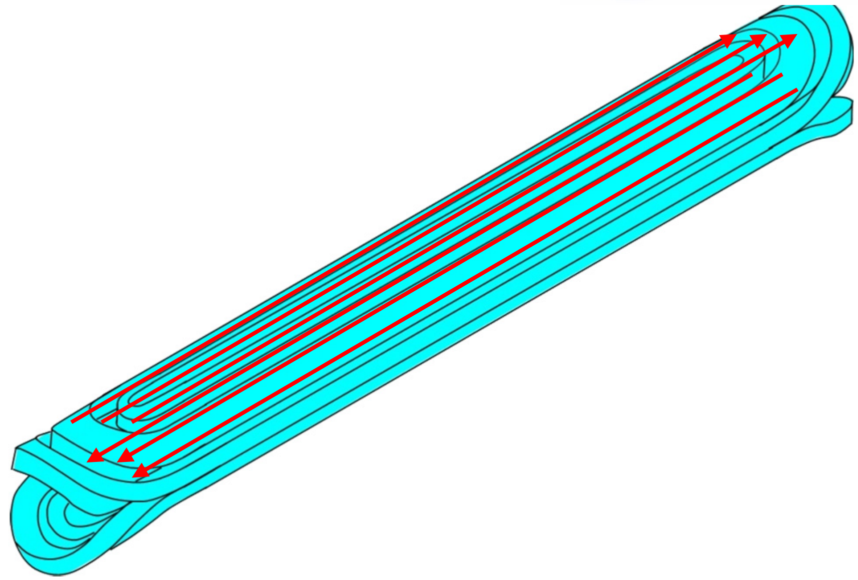

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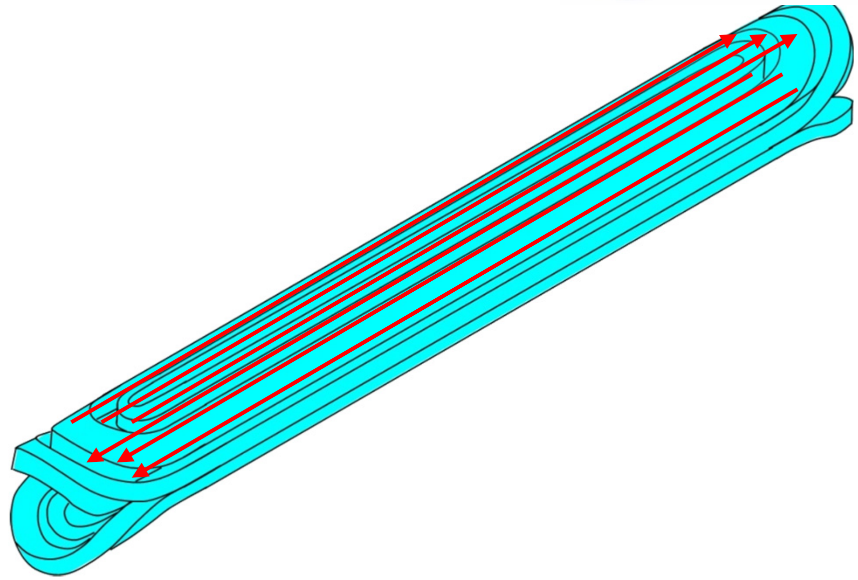

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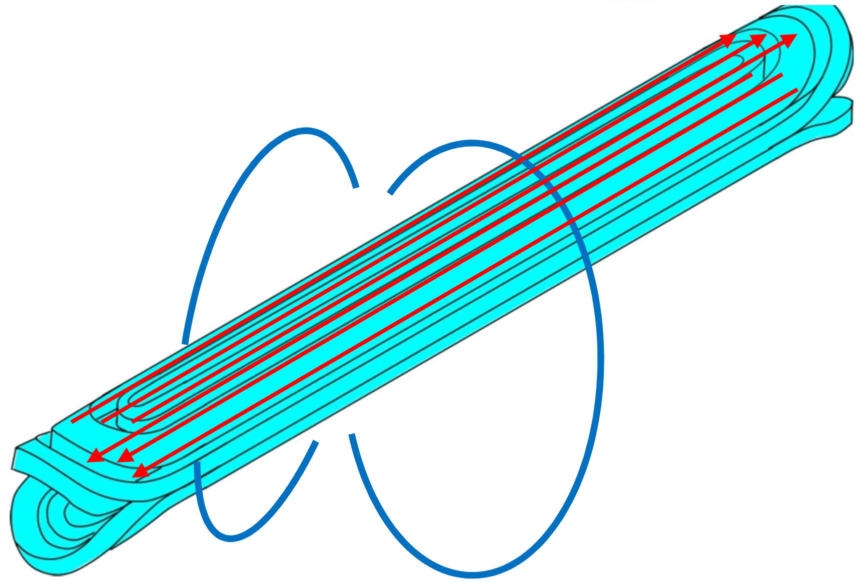

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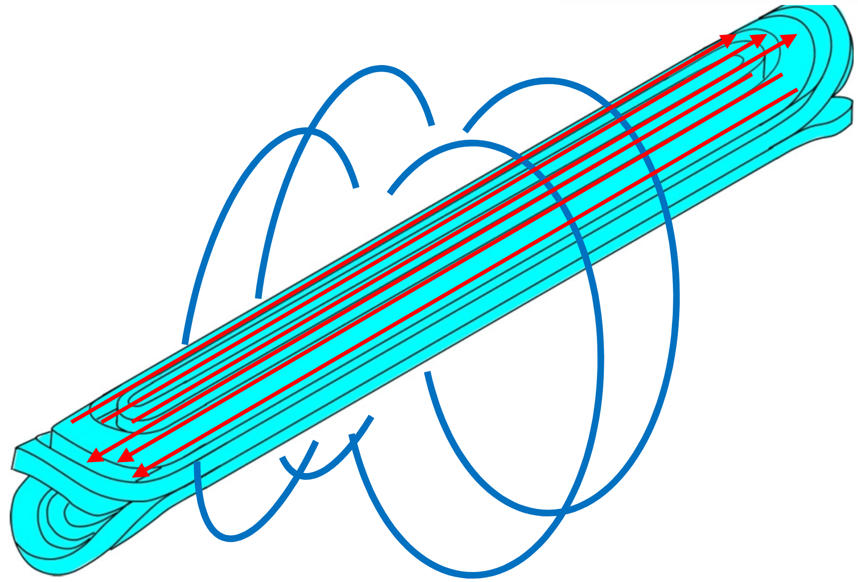

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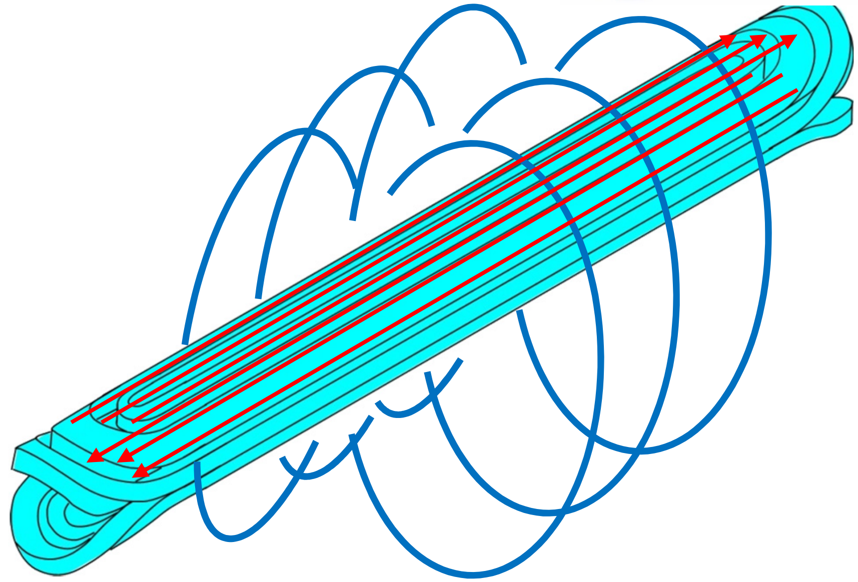

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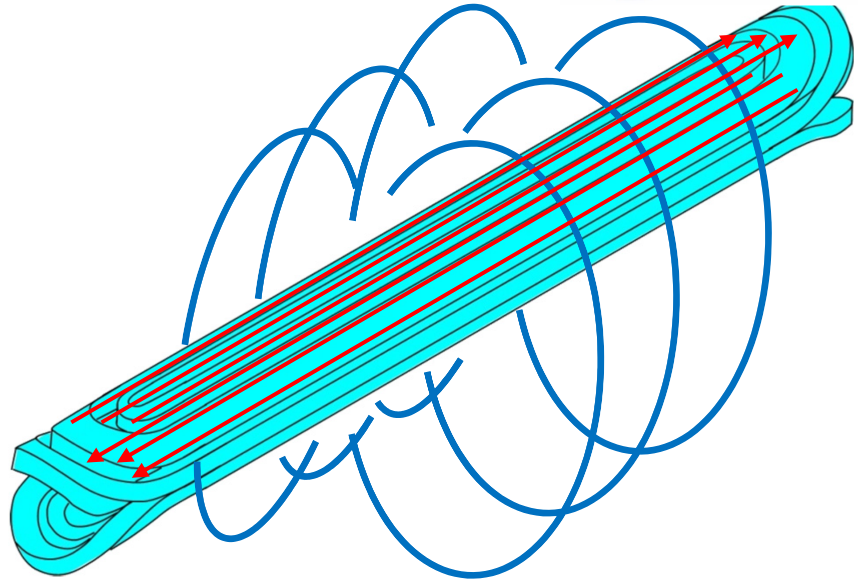

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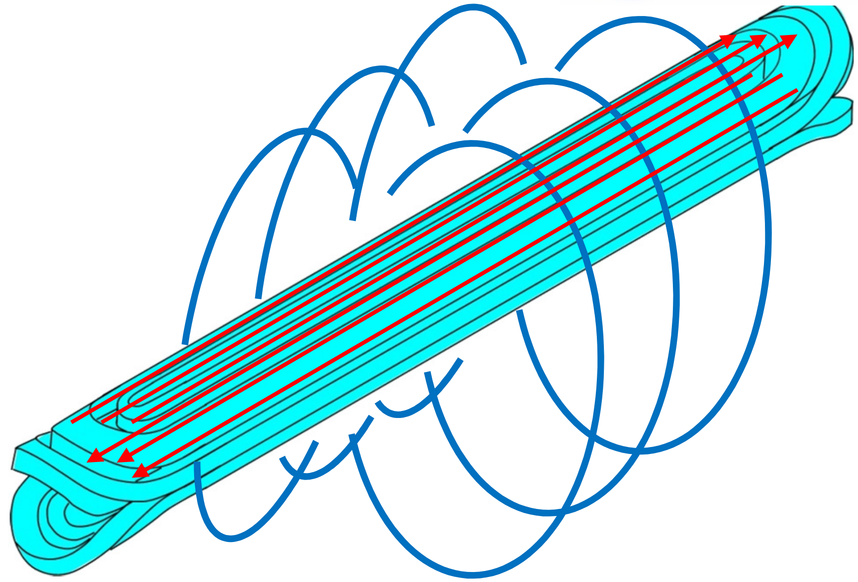

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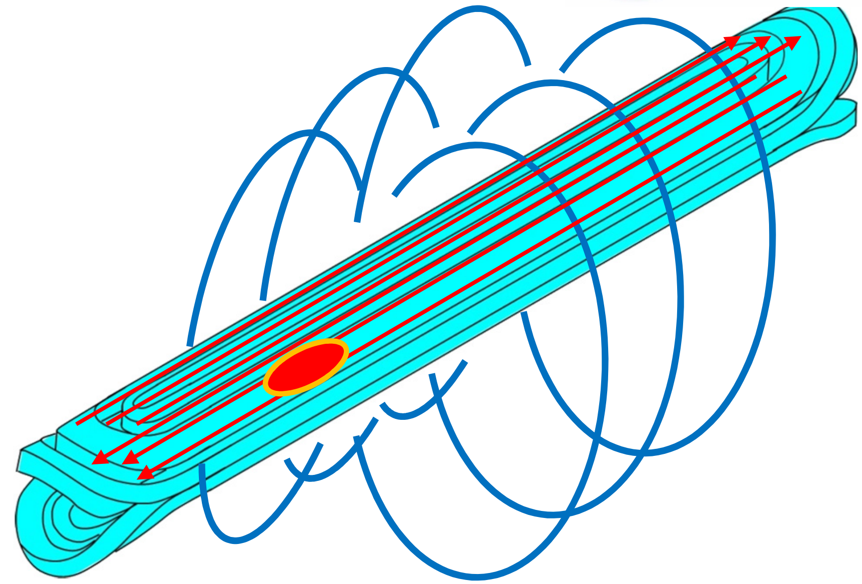

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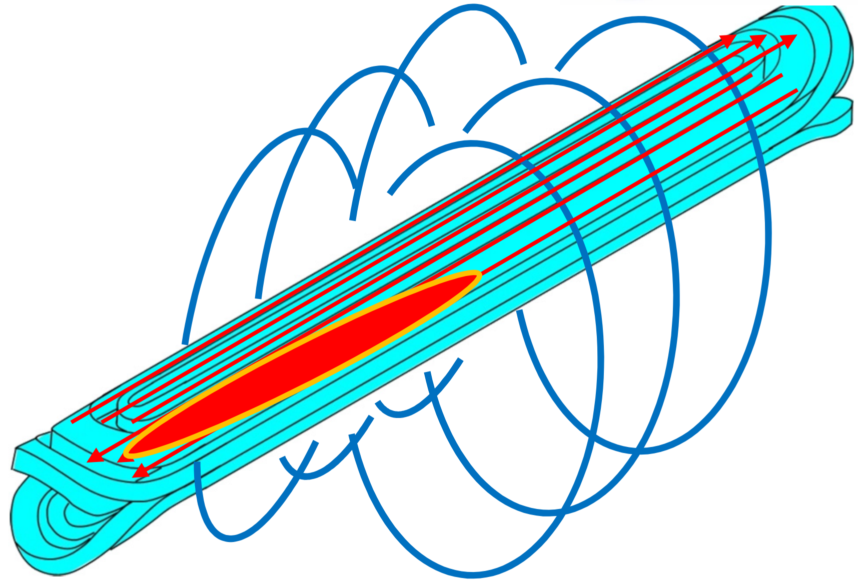

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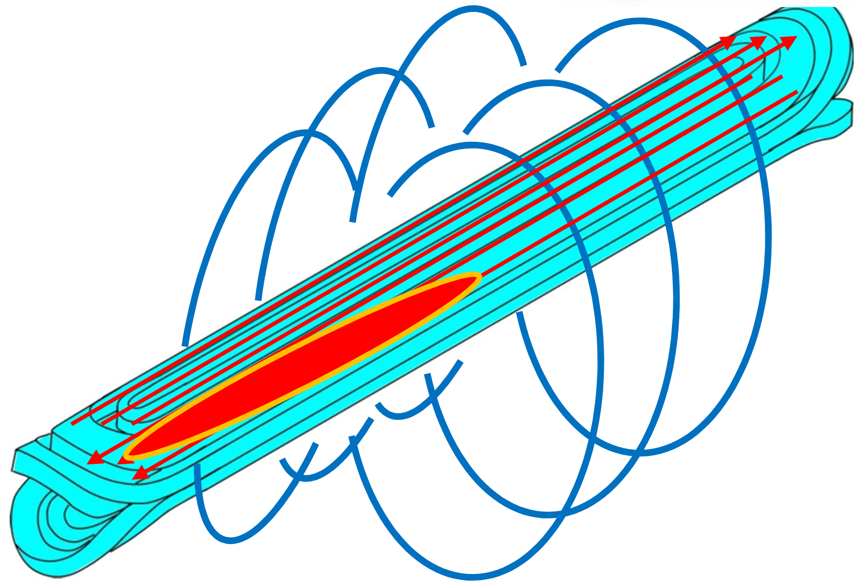

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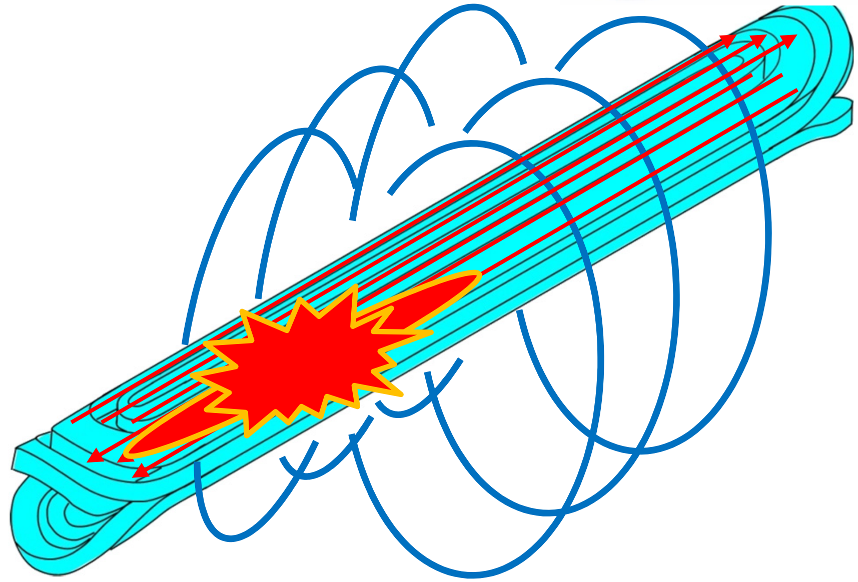

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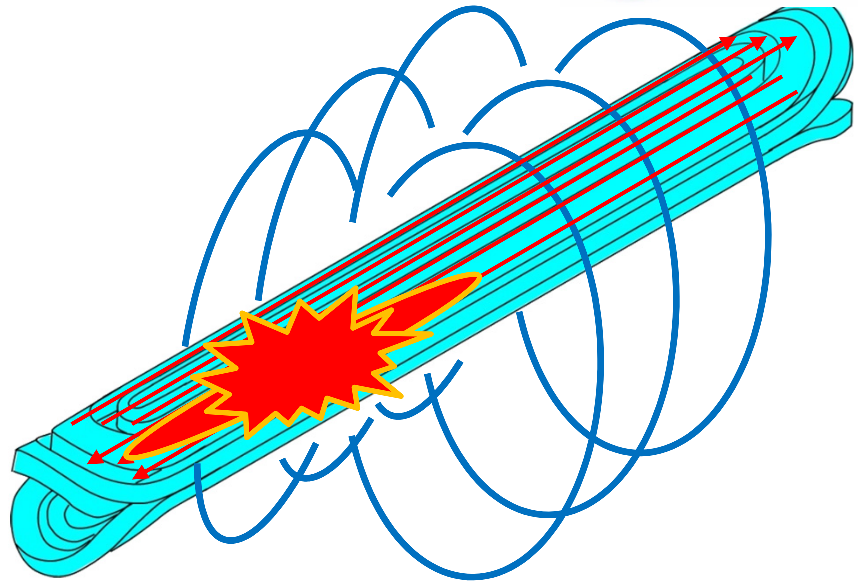

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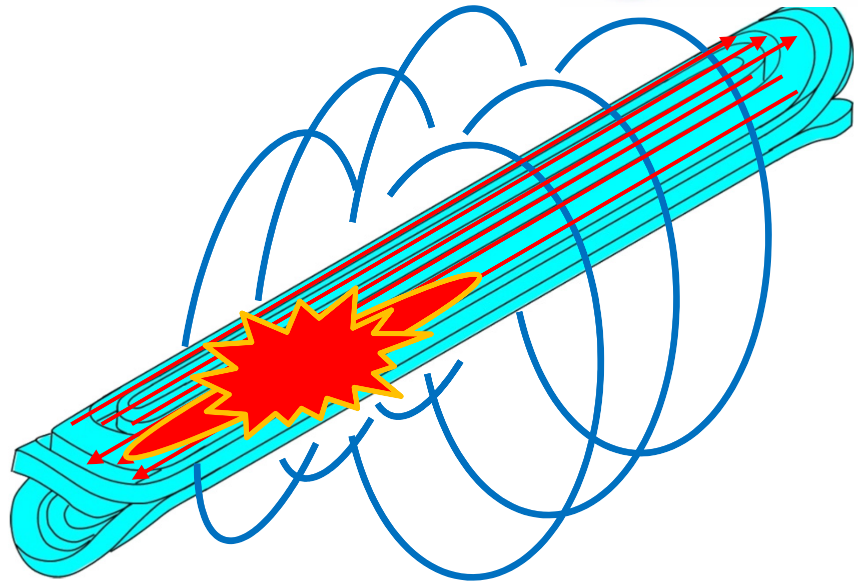

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Homogeneous
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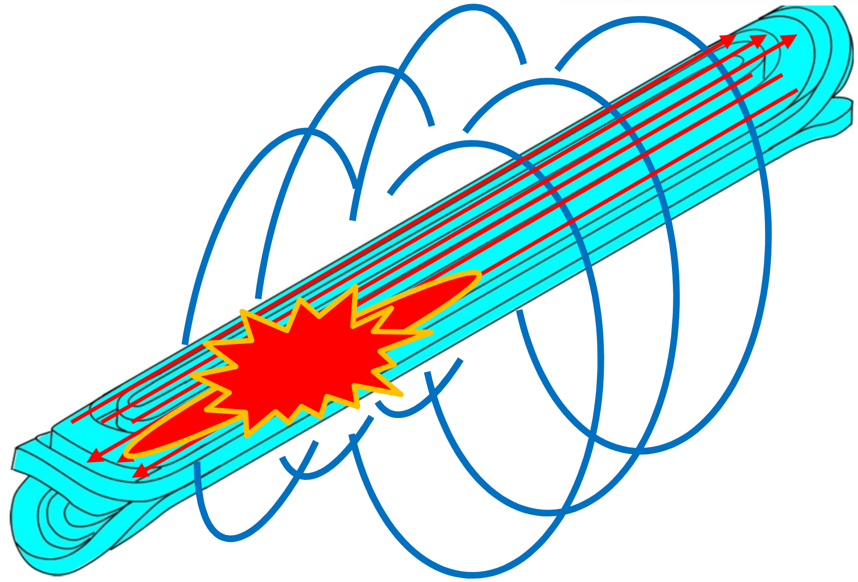

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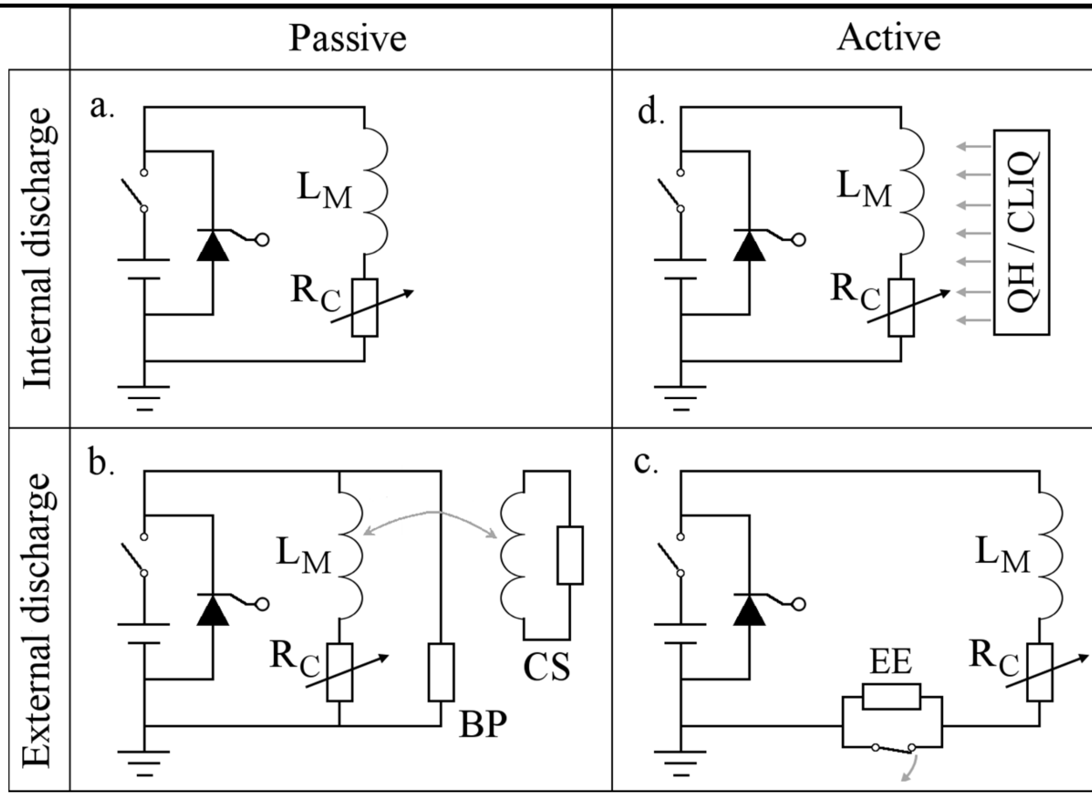
Homogeneous distribution of the quench energy

Discharge of the magnet current with coil resistance

Magnet quench protection

After a **quench** in a superconducting coil, the magnet has to be **discharged** to avoid damage due to overheating and overvoltages



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Too slow

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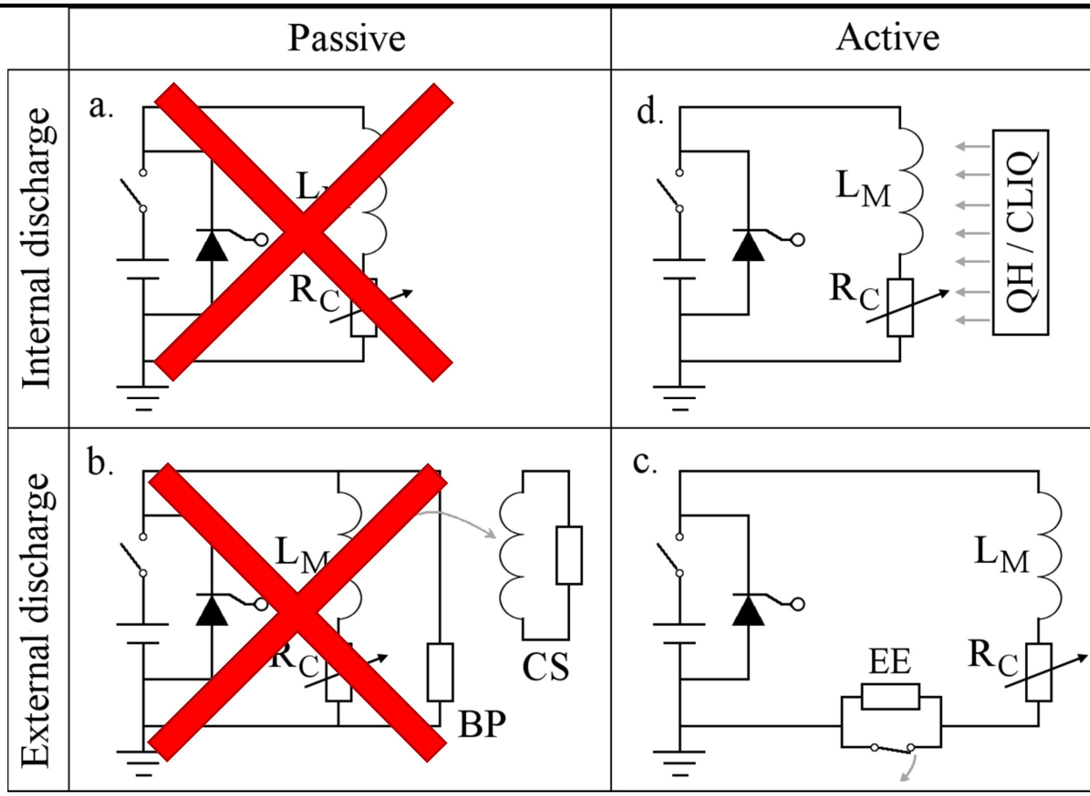

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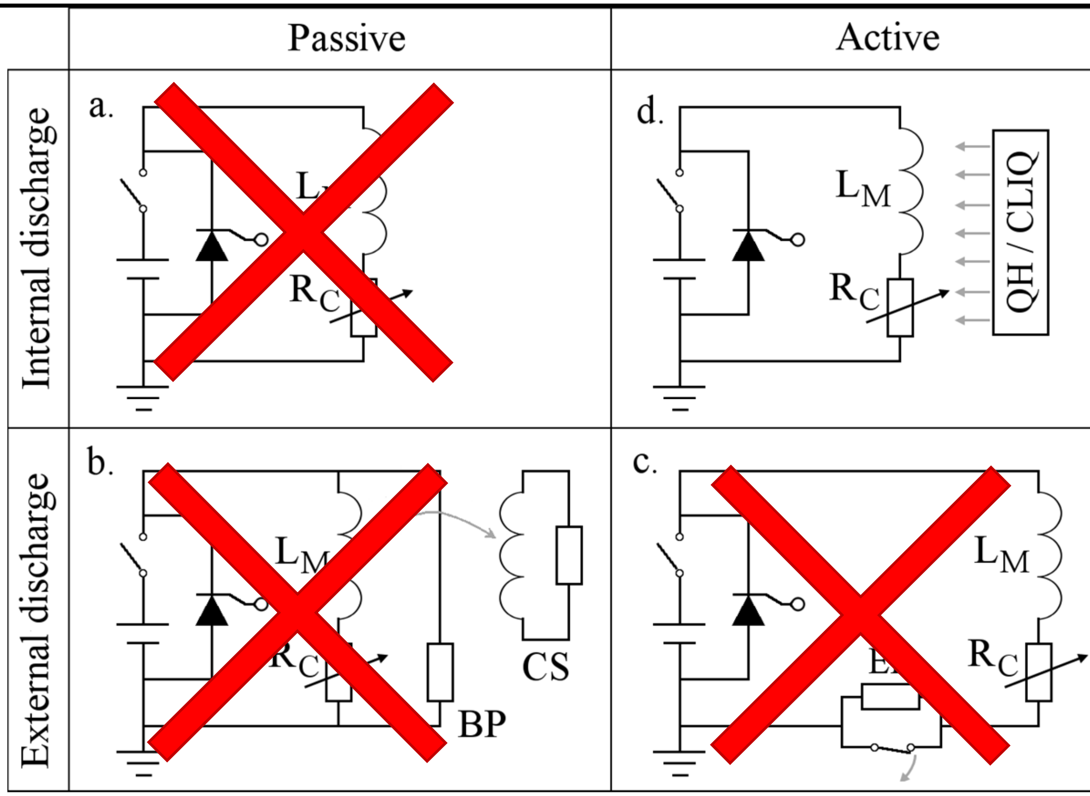

Expensive, large, not sufficient for magnet chains

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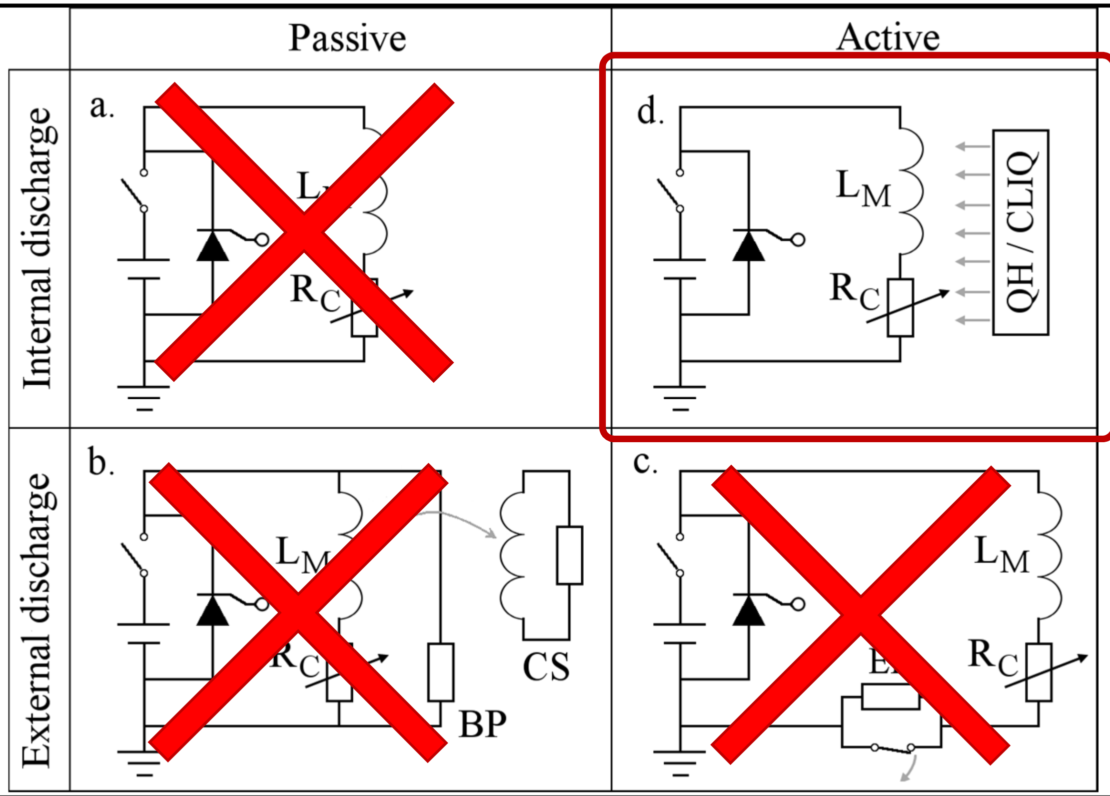
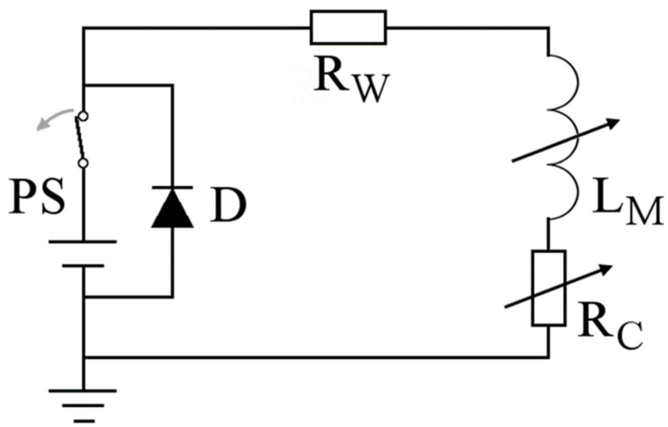


Expensive, large, not sufficient for magnet chains

Today's focus: Active protection systems relying on an **internal discharge**, required for **high energy density** magnets

Traditional approach: Quench heaters



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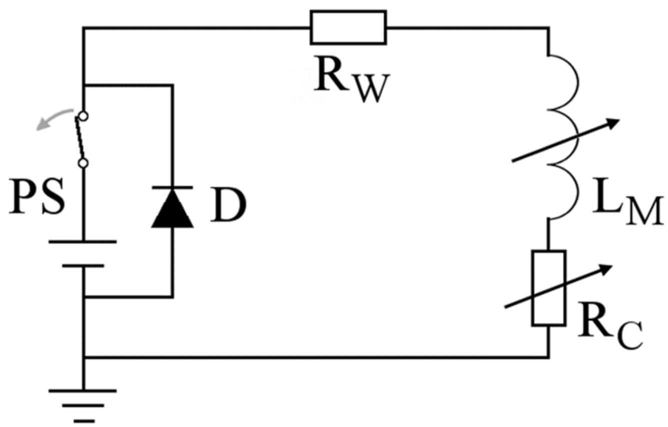
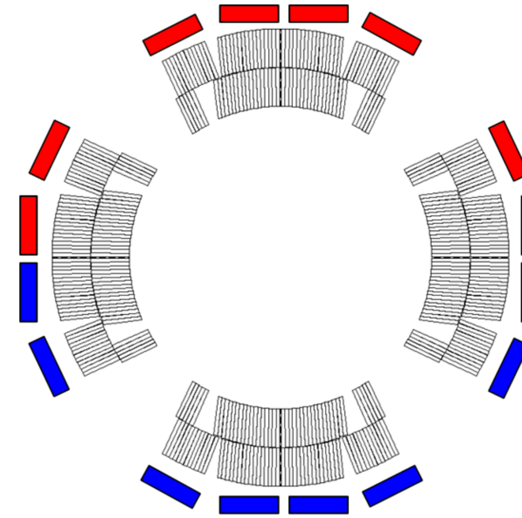
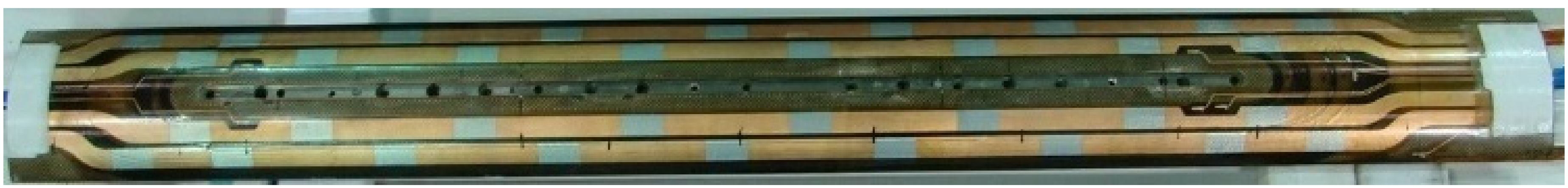


Quench heaters are μm-thin strips glued to the coil, which heat the turns by **thermal diffusion**

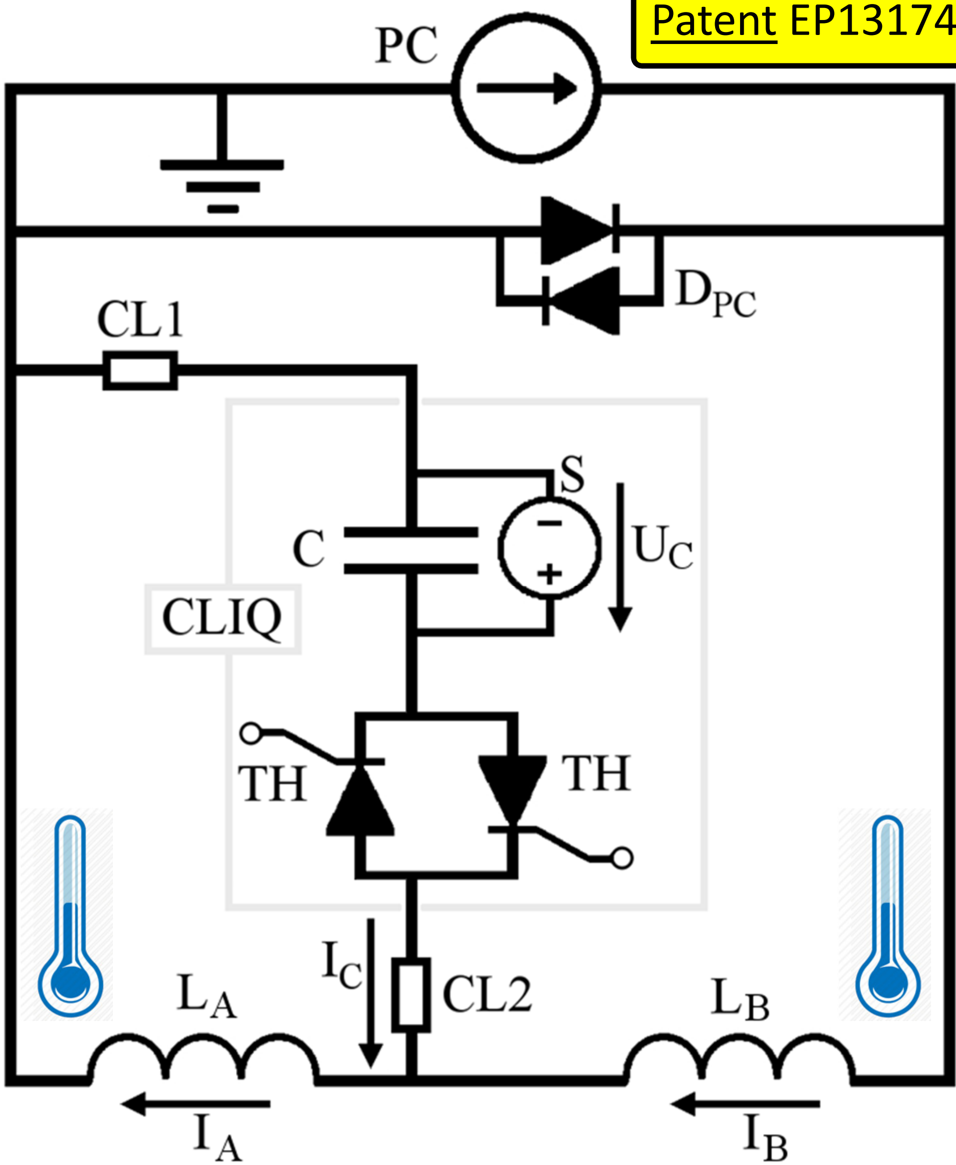


Example:
HL-LHC 12 T Nb_3Sn quadrupole model magnet (MQXFS1, 1.2 m)



CLIQ – Coupling-Loss Induced Quench

Patent EP13174323.9



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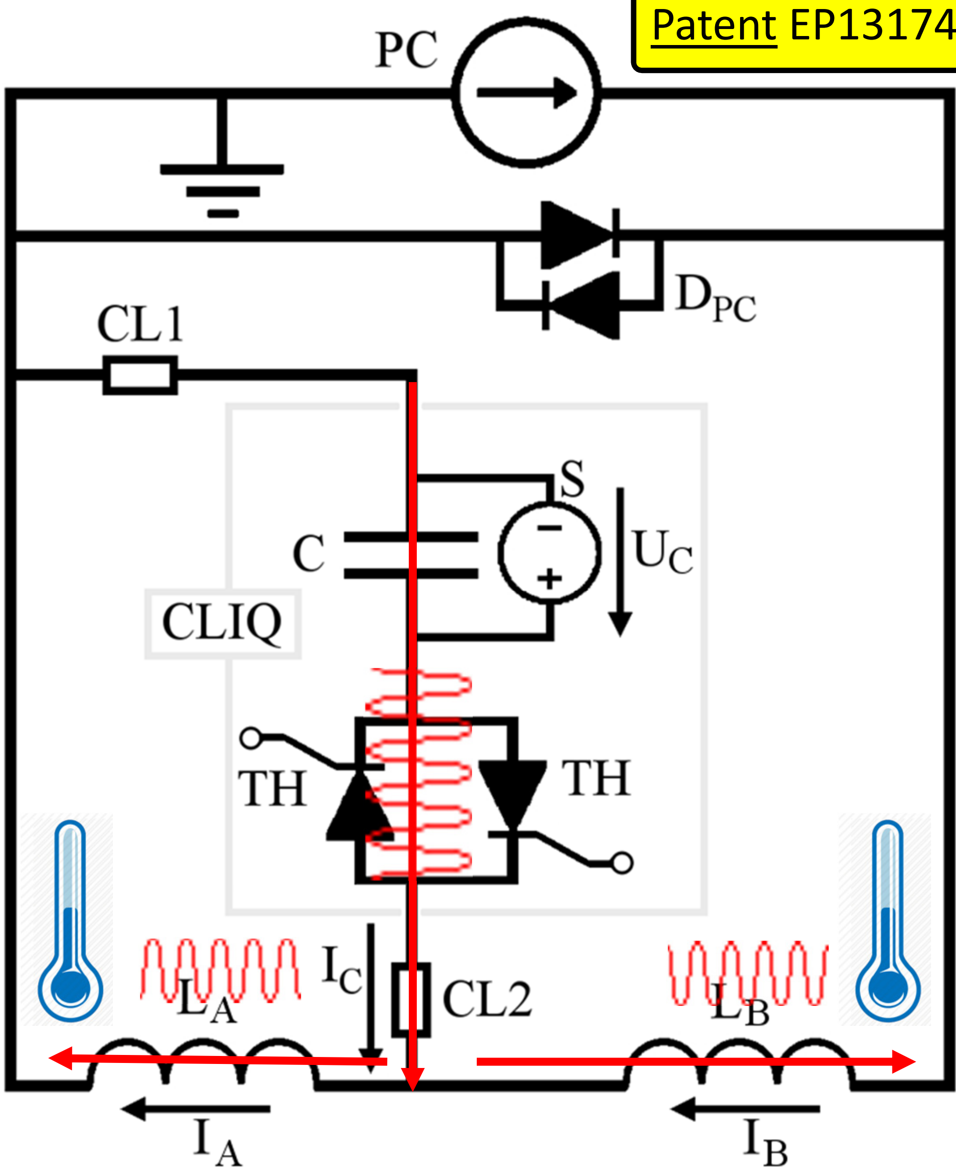

Current change

CLIQ – Coupling-Loss Induced Quench

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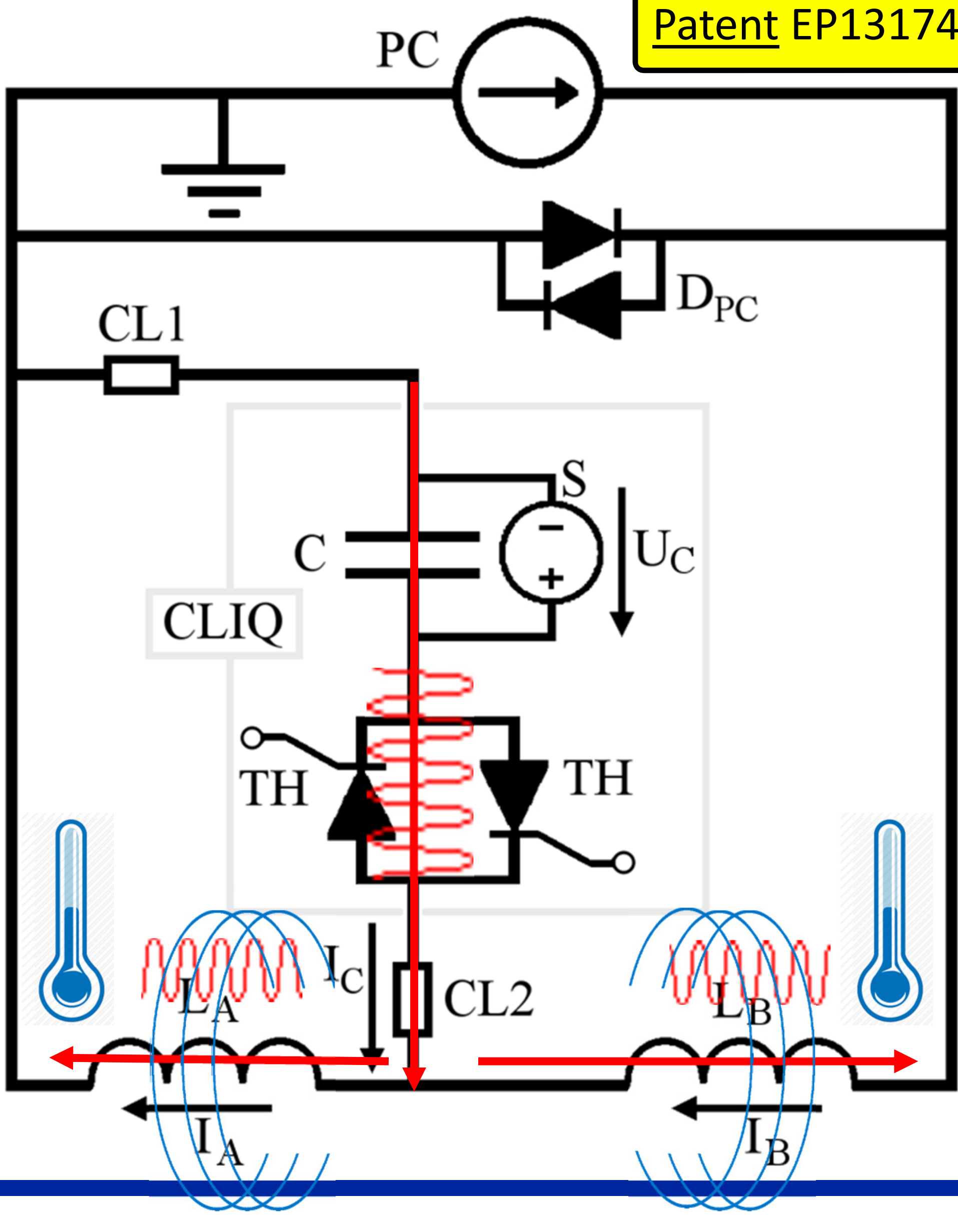

Current change

Magnetic field change

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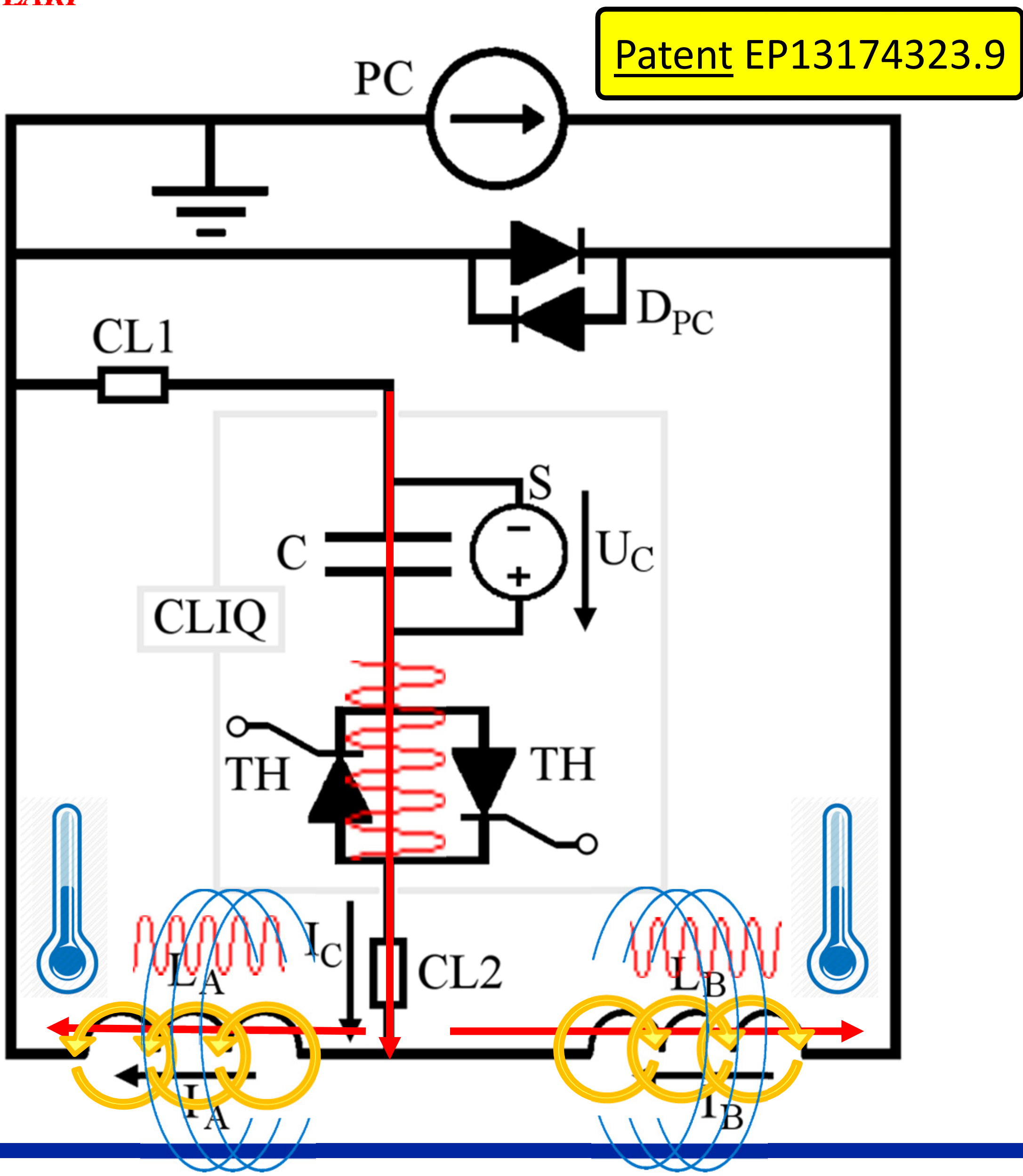

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Magnetic field change

Coupling losses (Heat)

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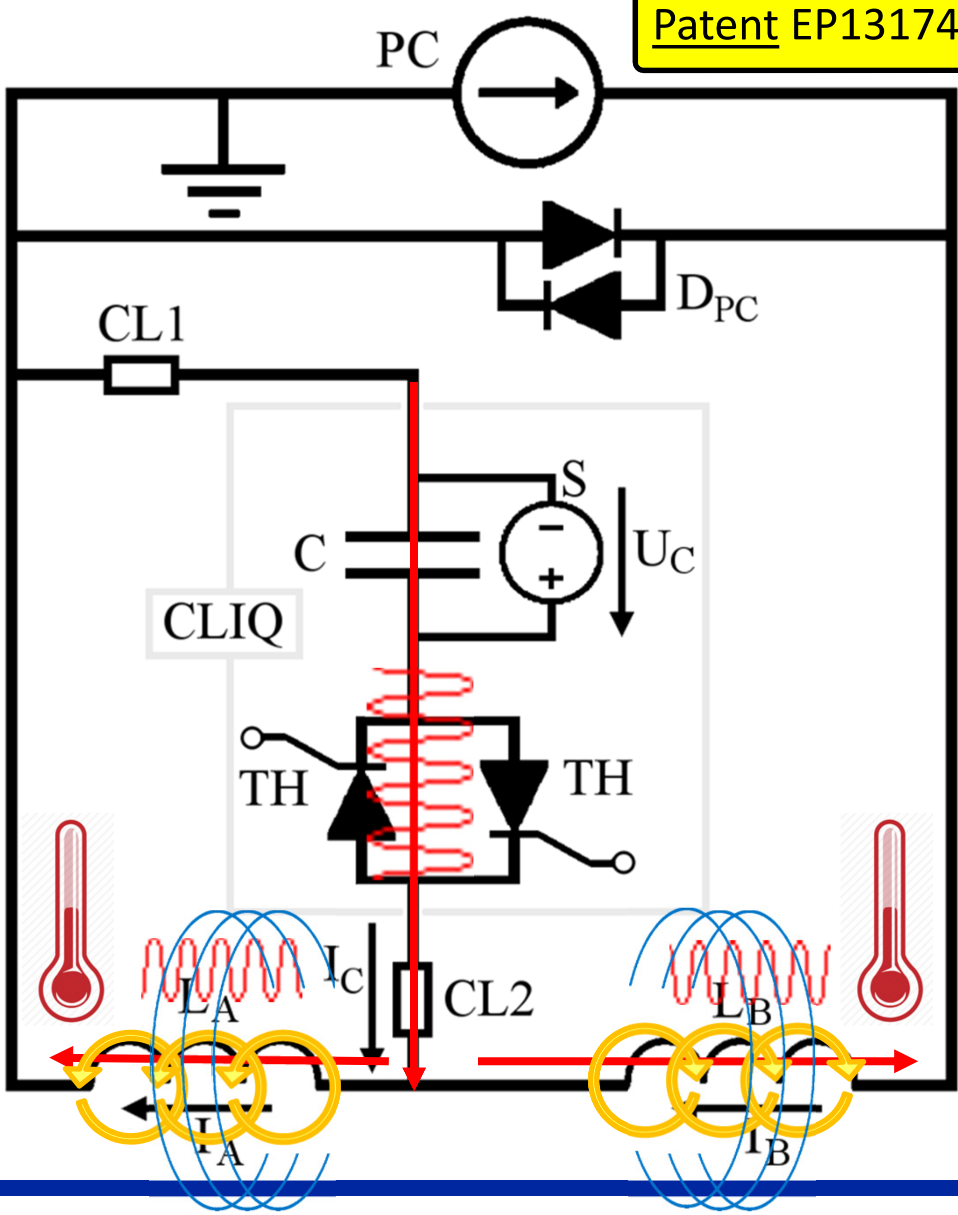


Current change

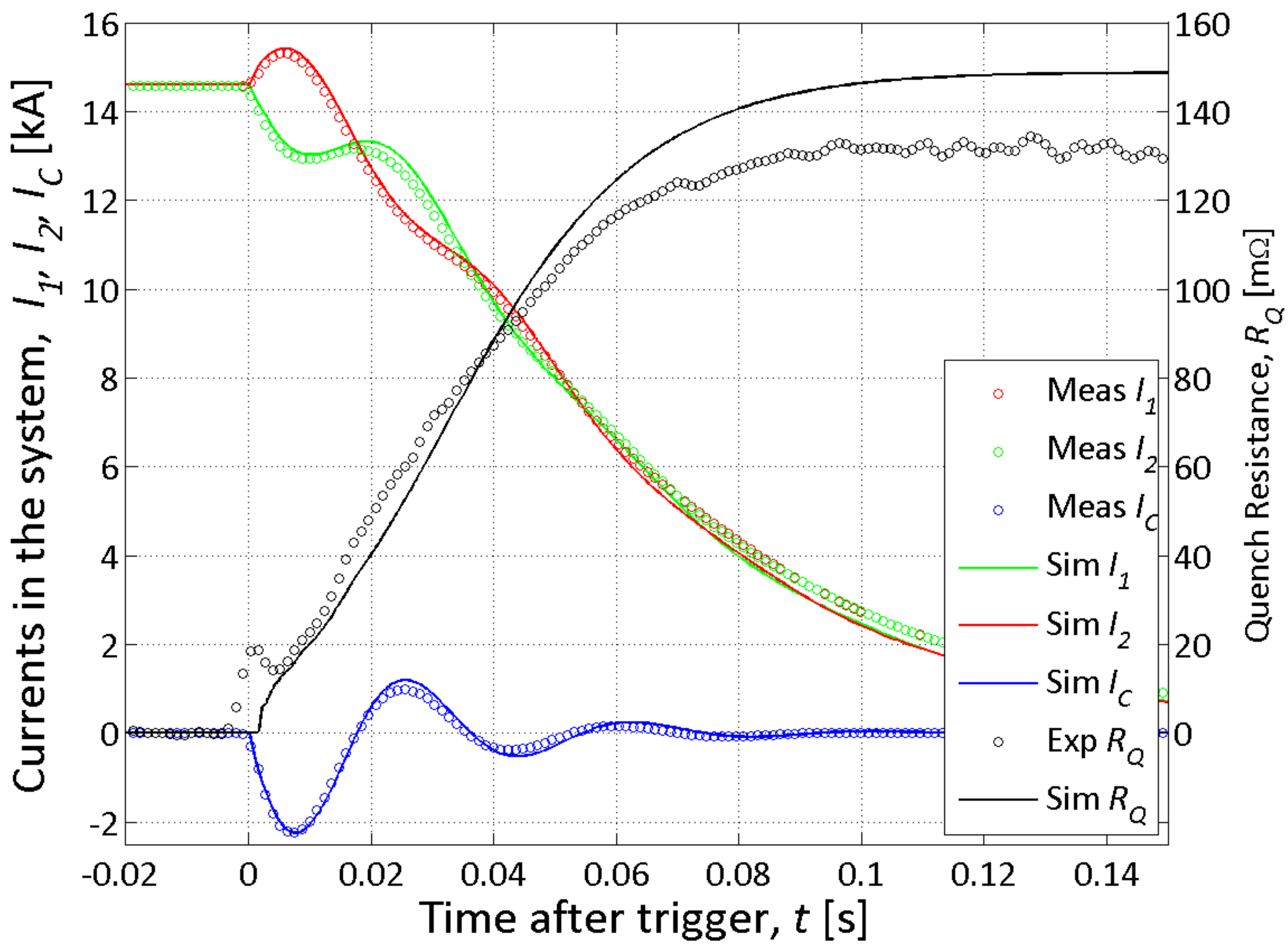
Magnetic field change

Coupling losses (Heat)

Temperature rise

QUENCH

Example of CLIQ discharge



CLIQ main advantages & disadvantages

- More **effective** energy deposition
- **Faster** and more **homogeneous** quench initiation

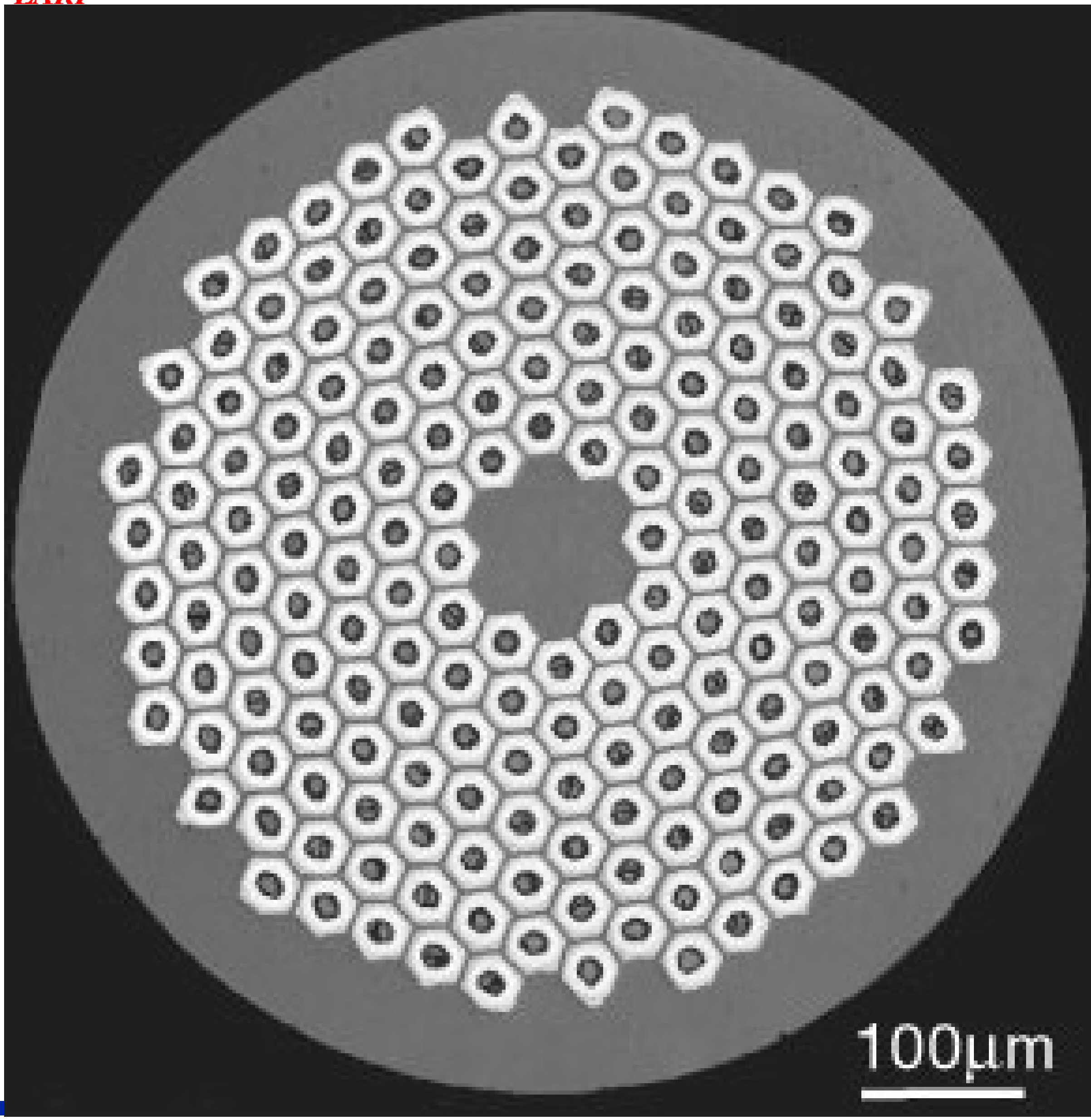
- **More robust** electrical design
- **Easier** to implement and repair
- Lower expected **failure rate**

- **Integration** in the magnet circuit to be studied

- Internal **voltage distribution** to be carefully analyzed

- **Redundancy** of the system

Inter-filament coupling loss



"Fast" loss:
Characteristic time constant in the order of **ms** or **tens of ms**

Deposited **power** density roughly proportional to $\dot{B}^2$

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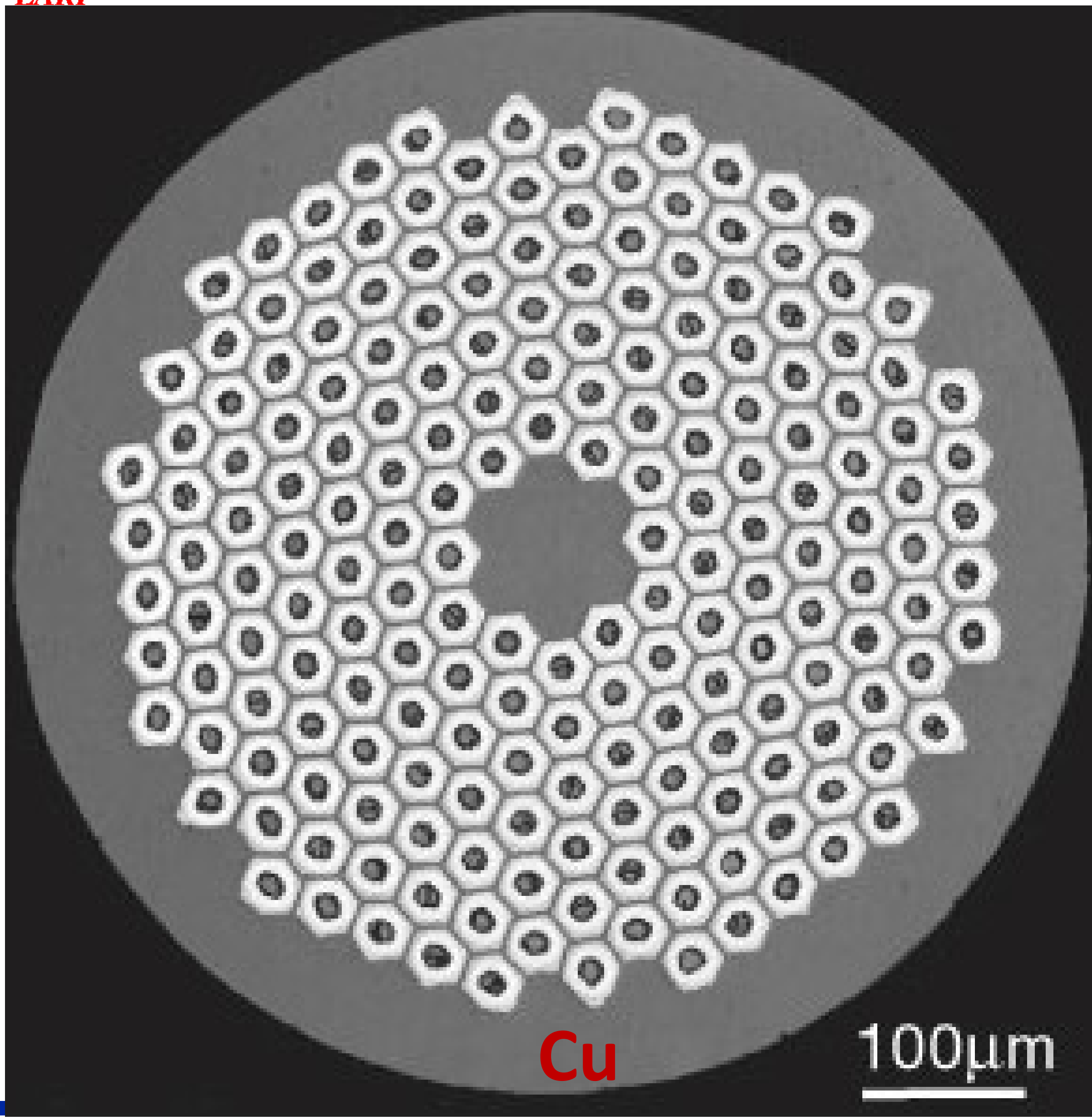

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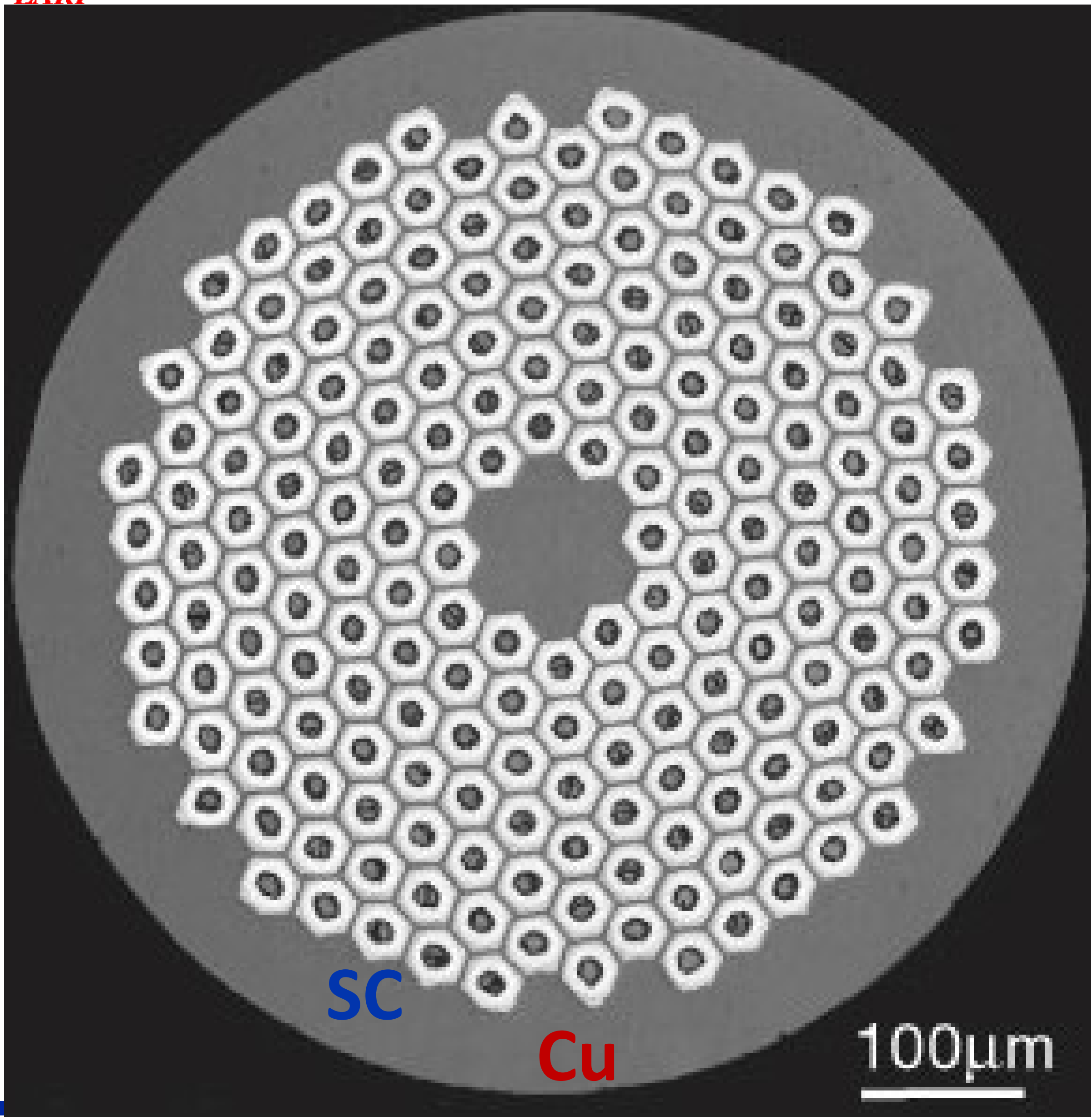

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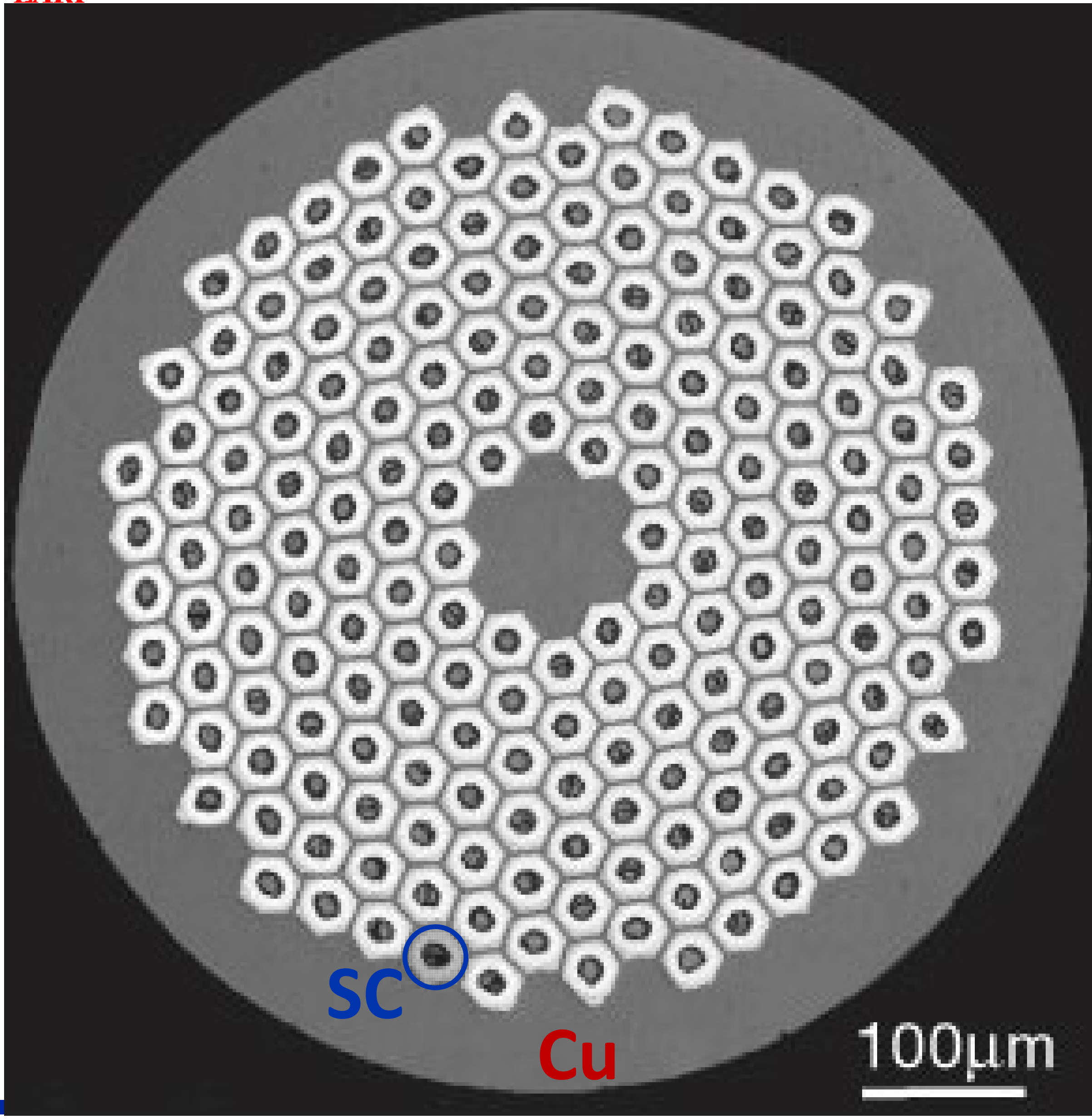

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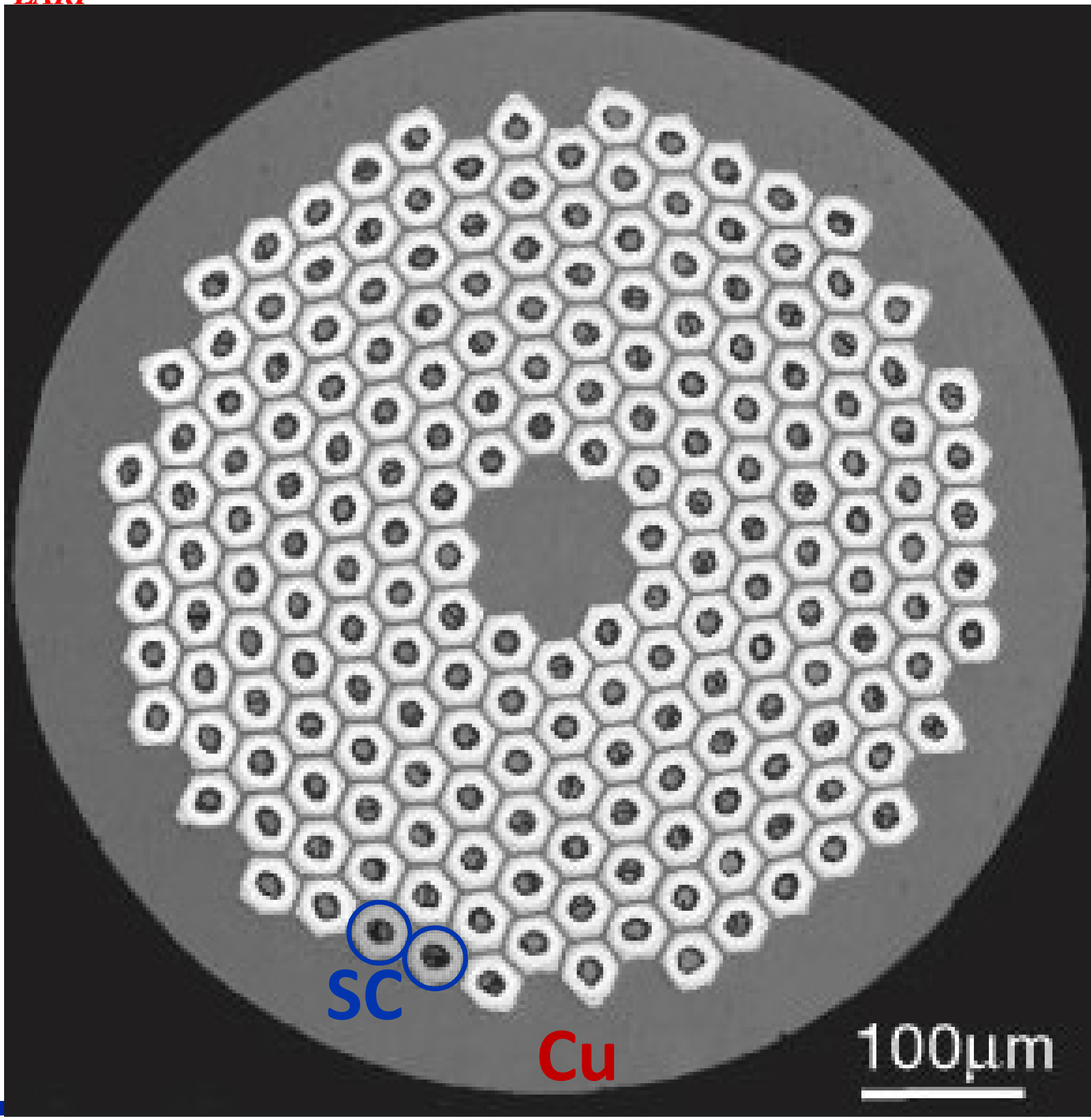

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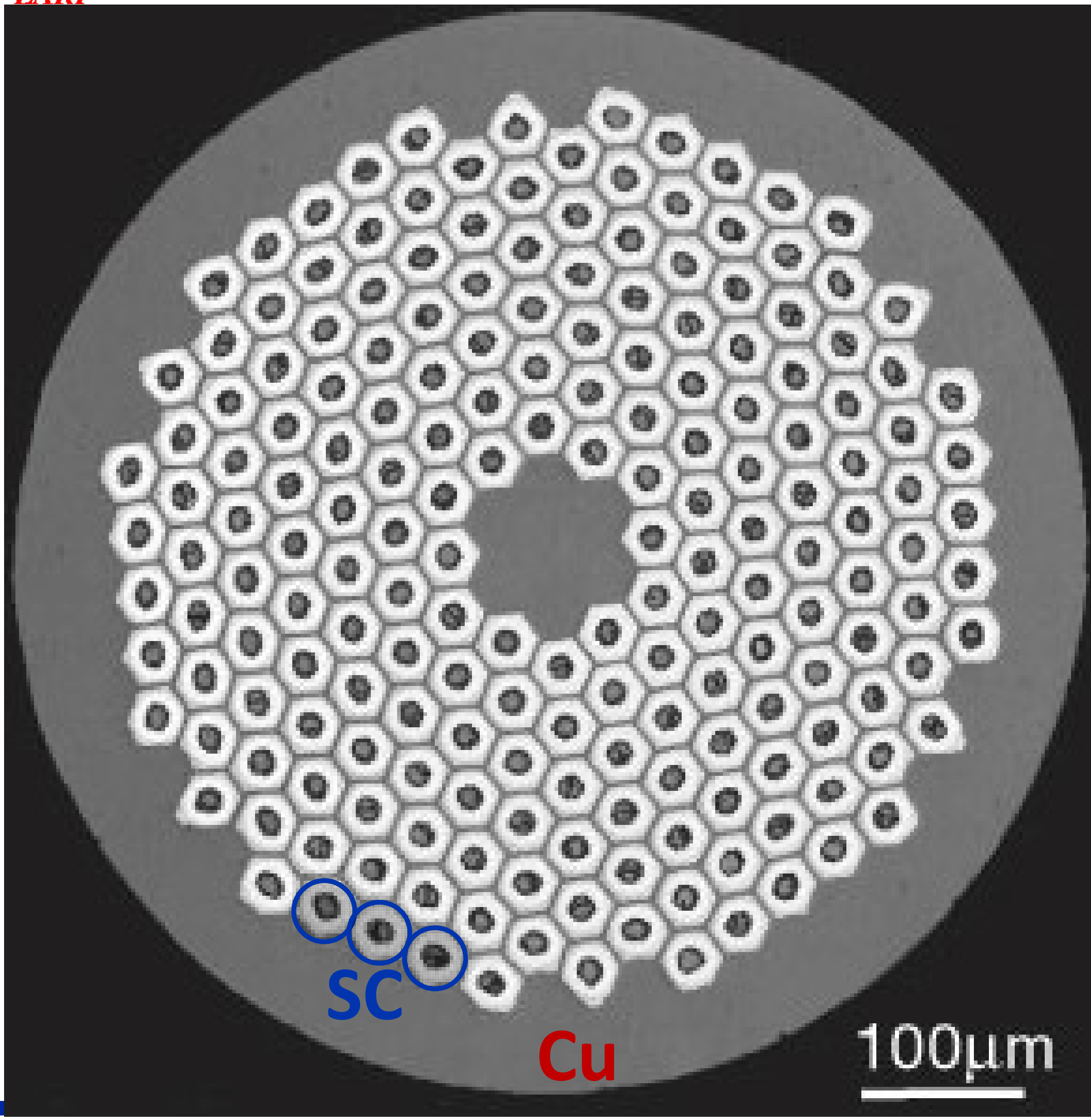

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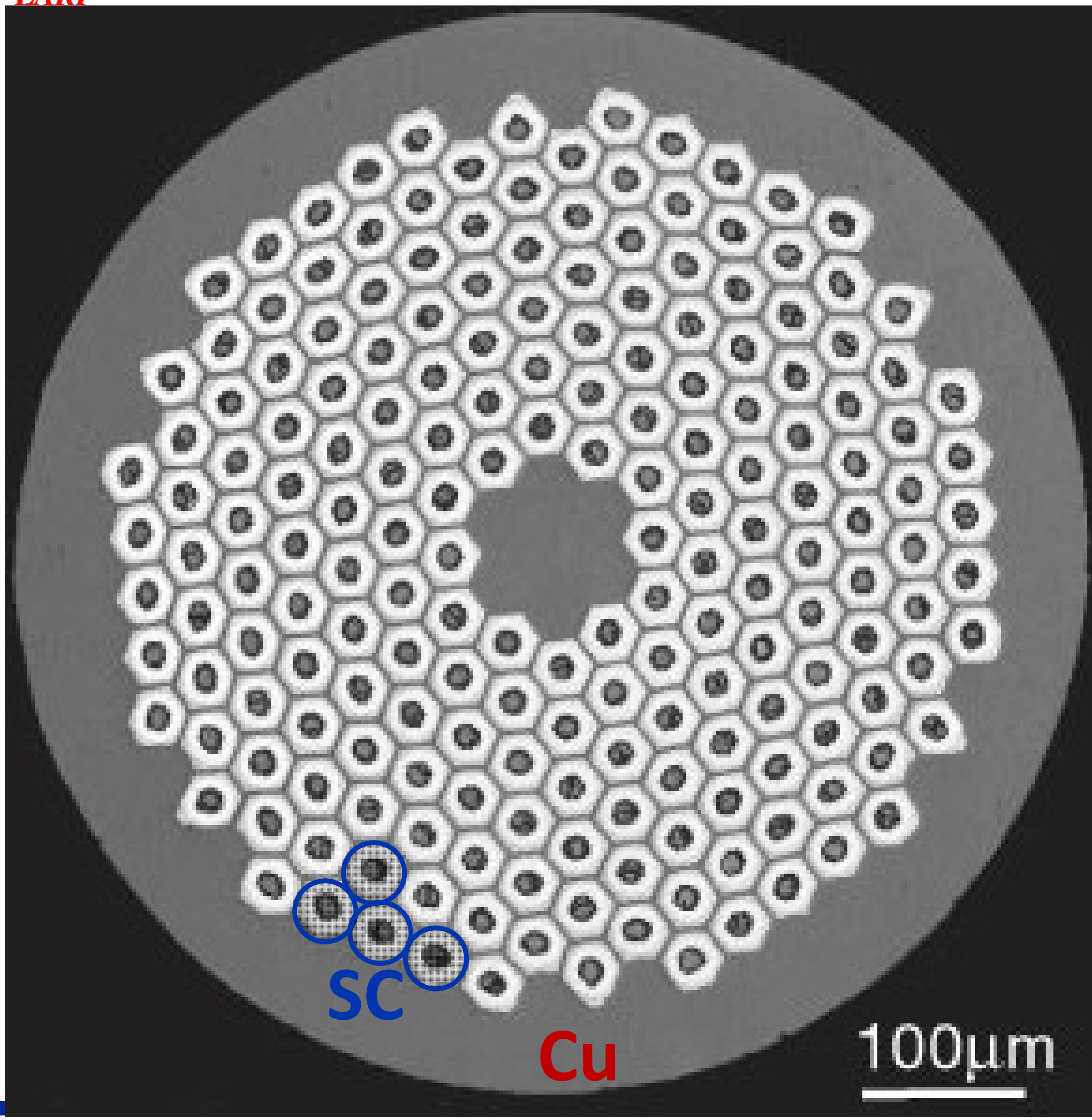

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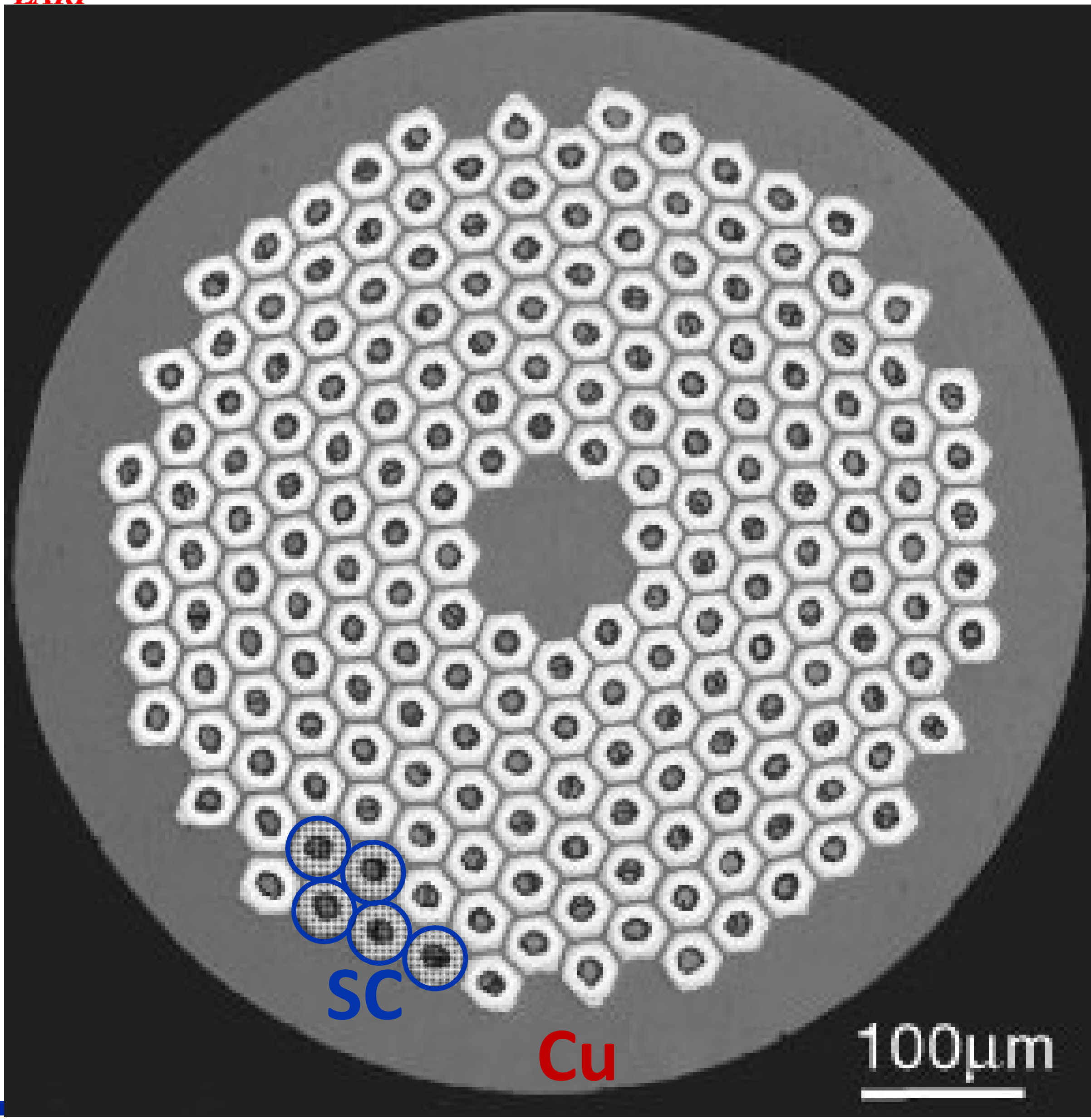

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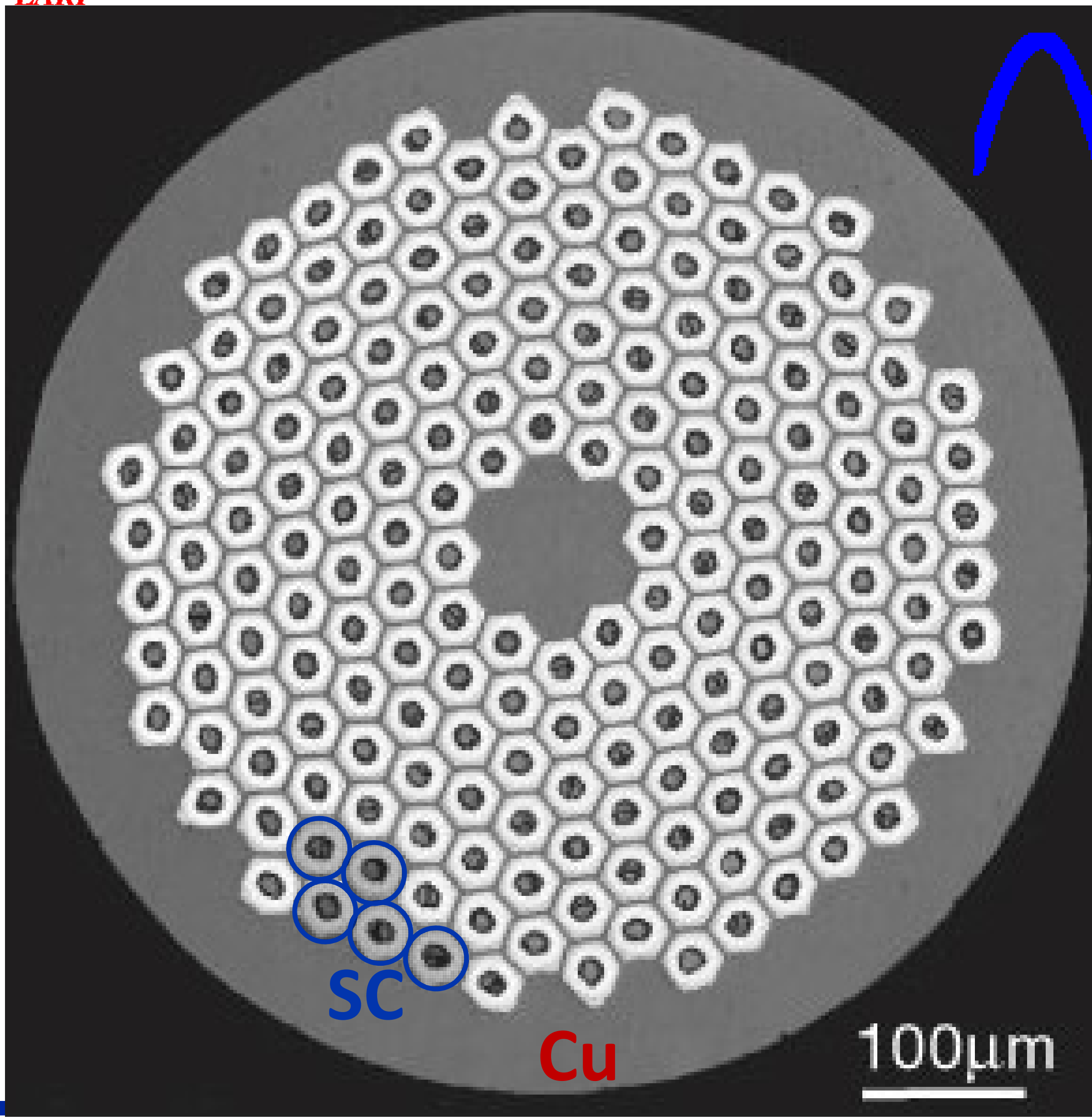

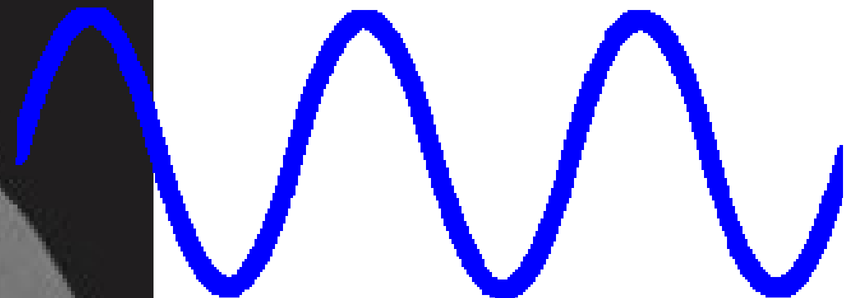

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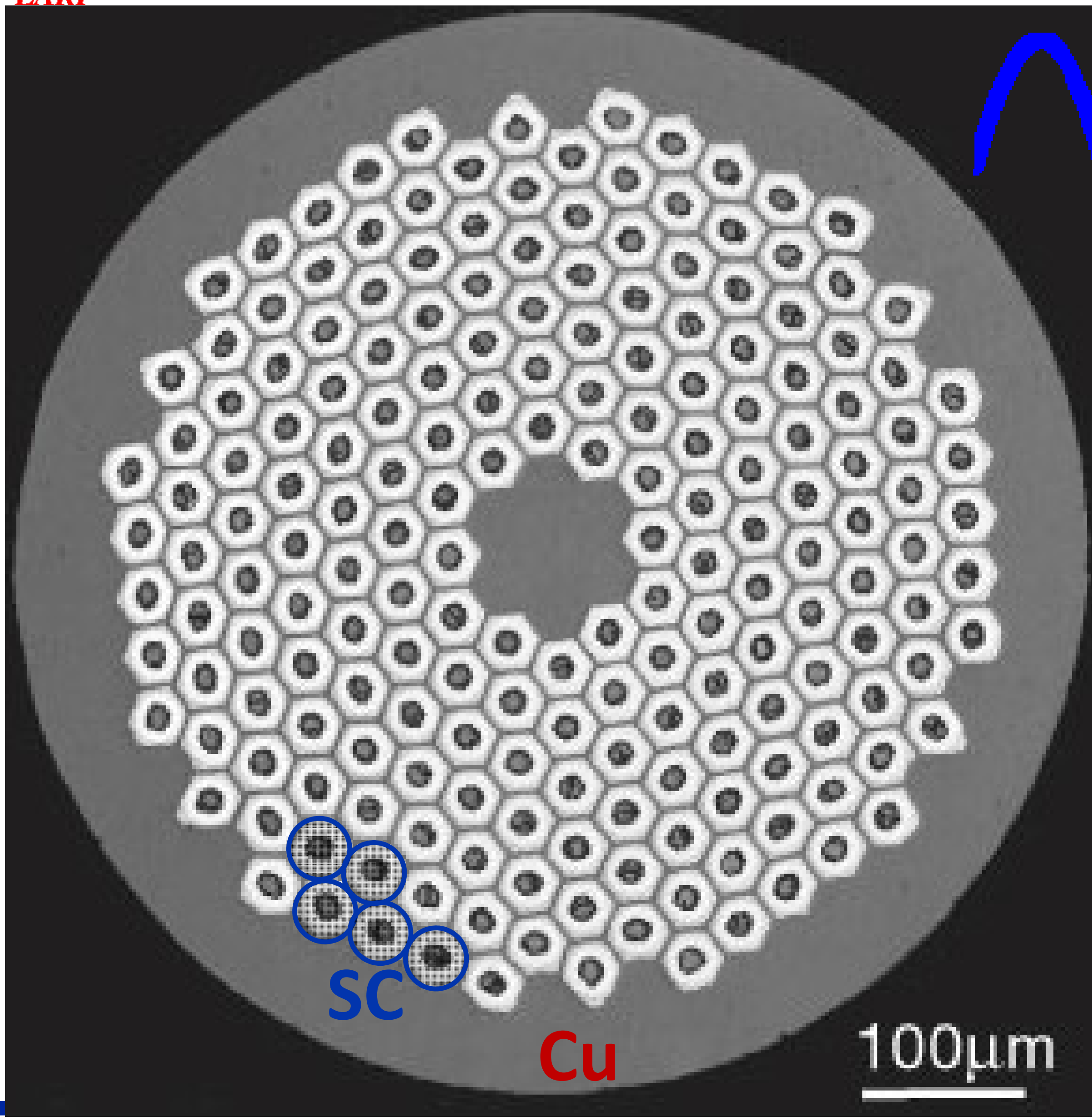

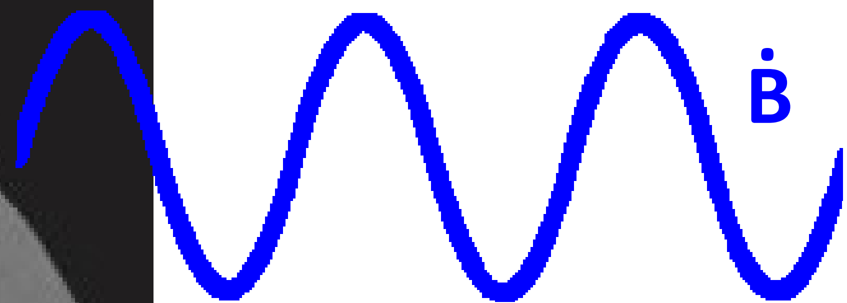

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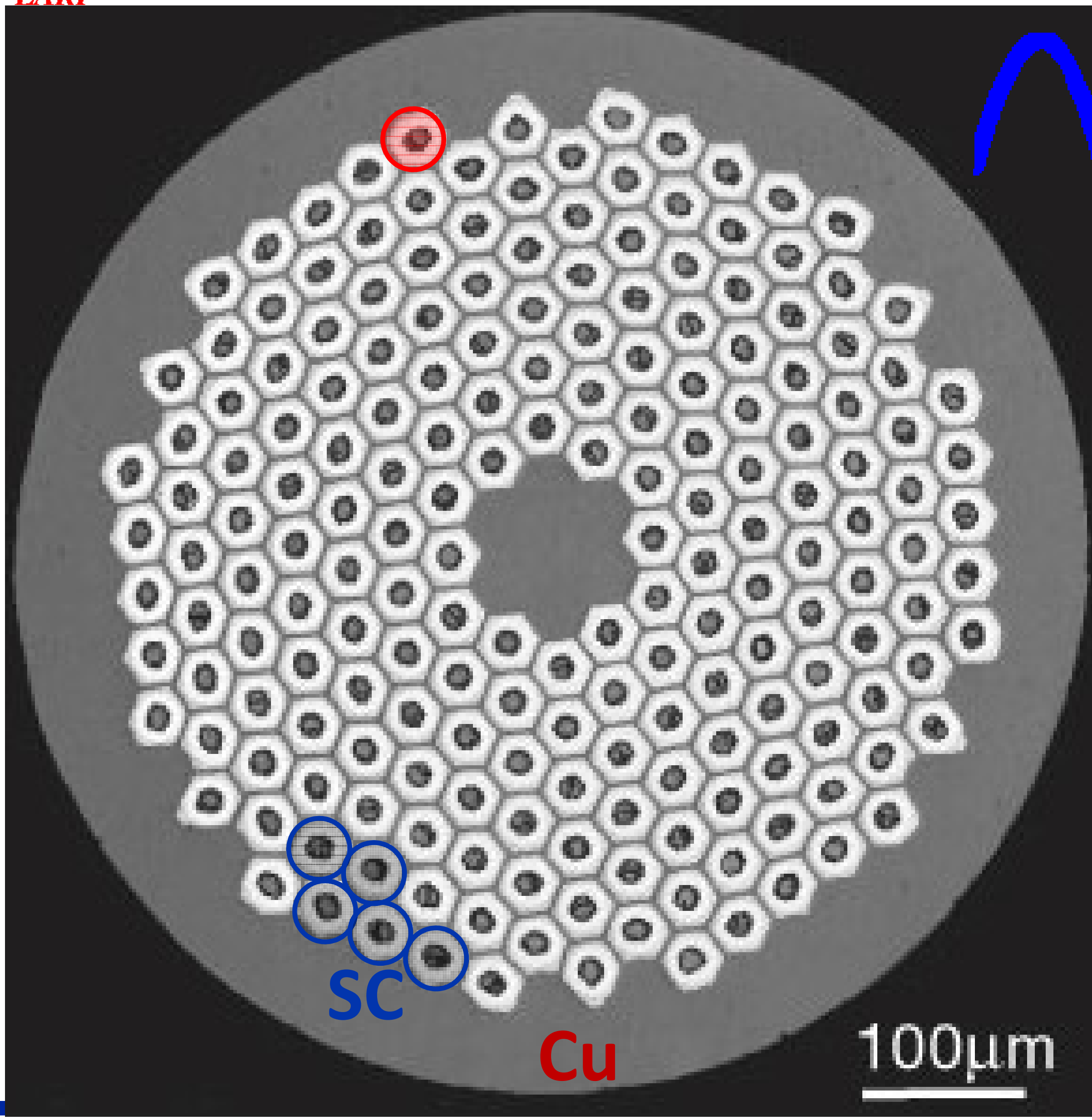

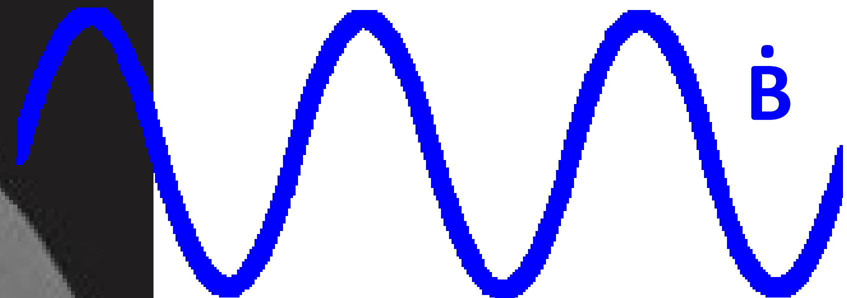

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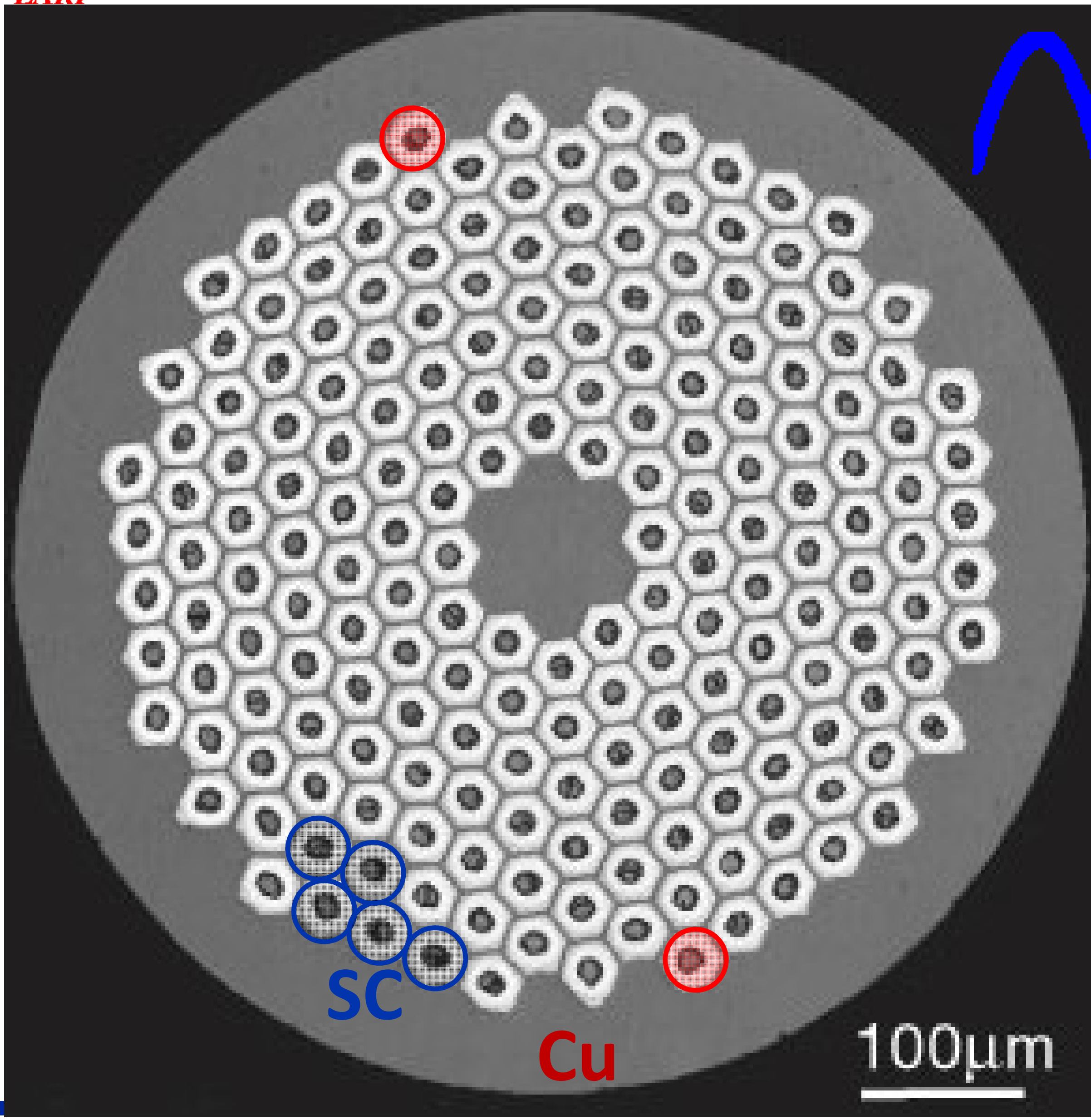

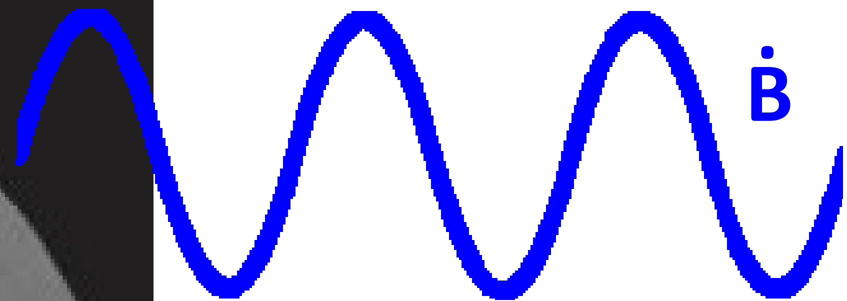

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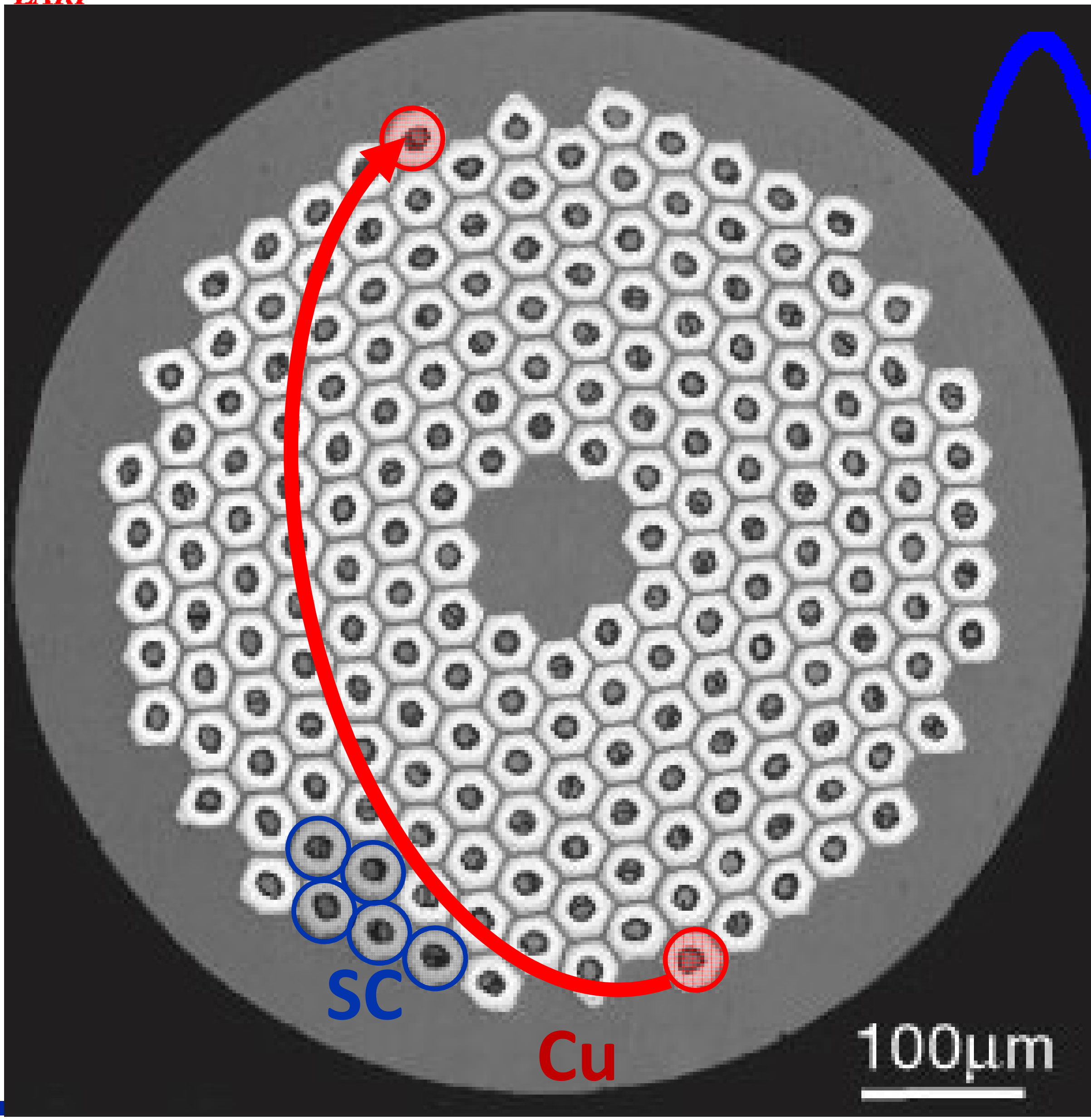

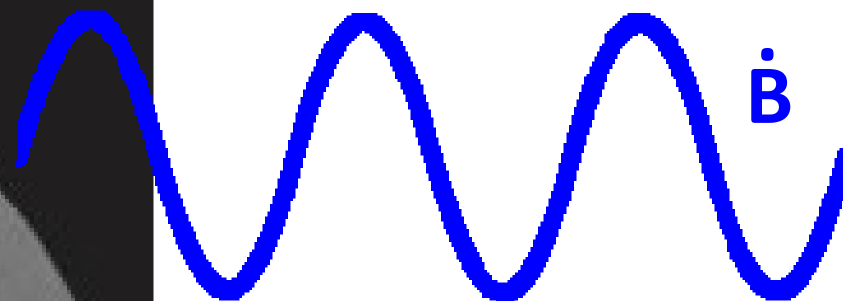

"Fast" loss:
Characteristic time constant in the order of **ms** or **tens of ms**

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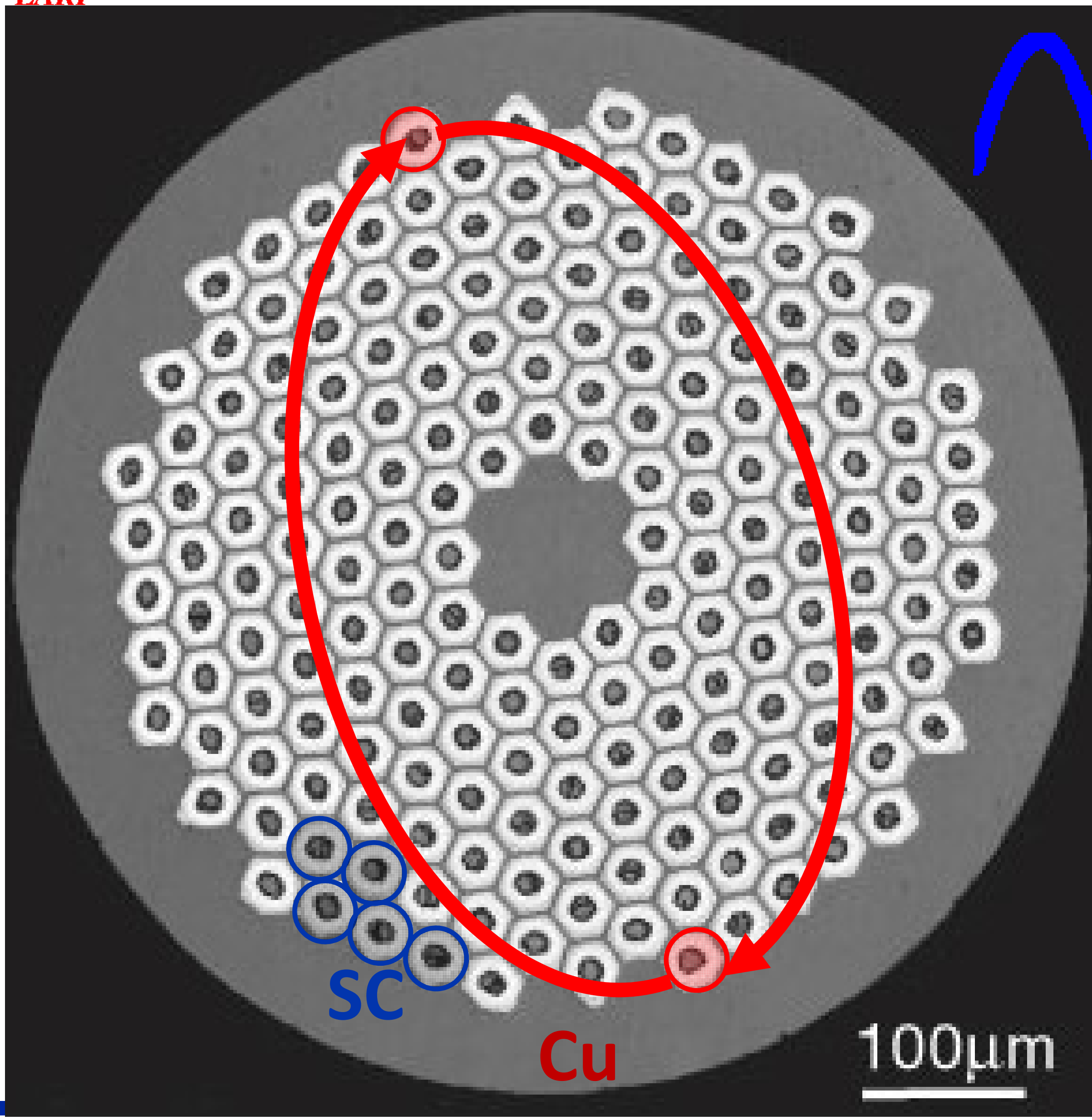

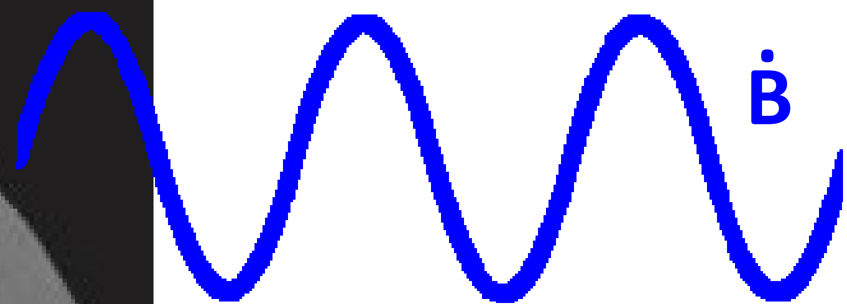

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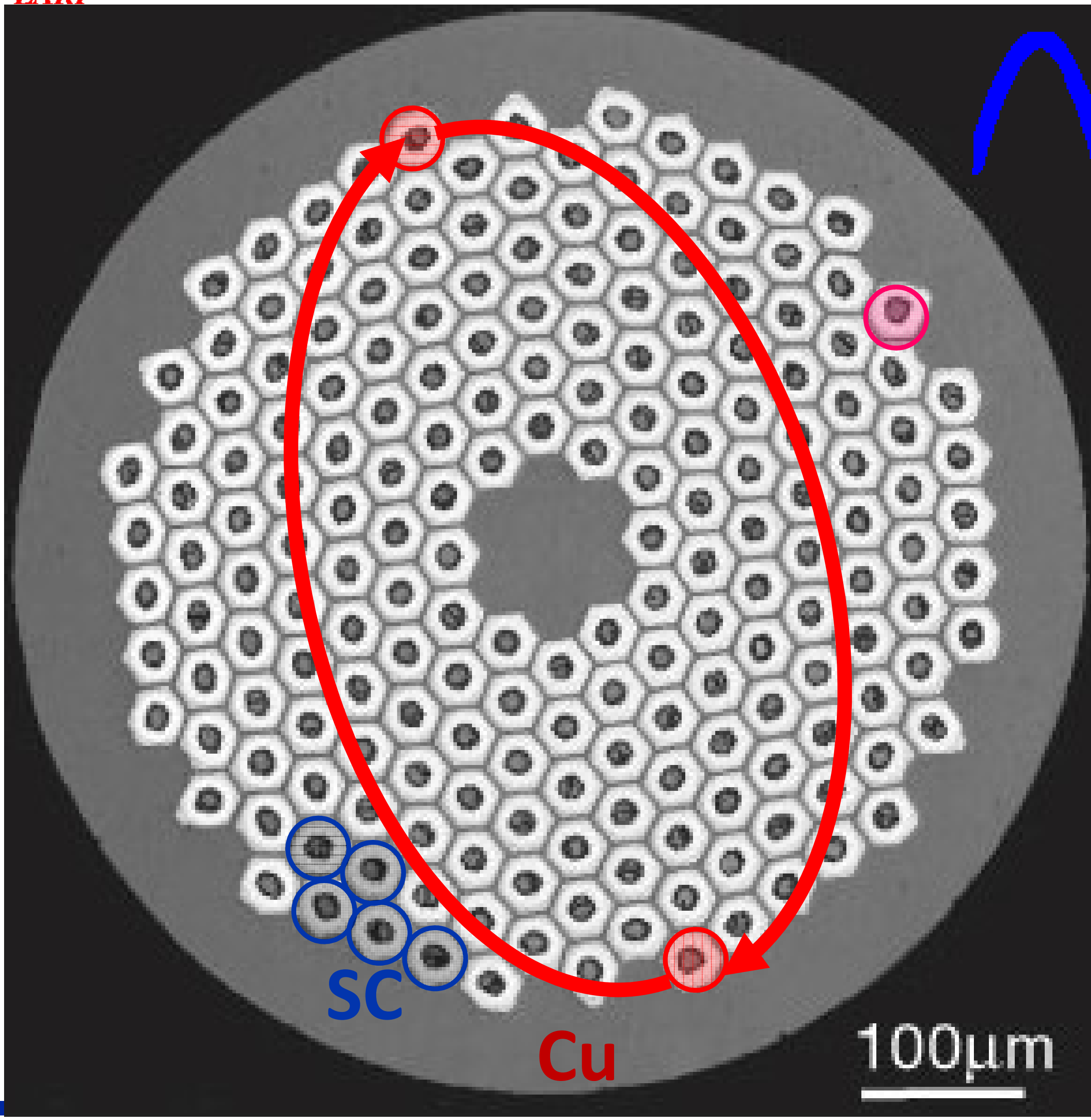

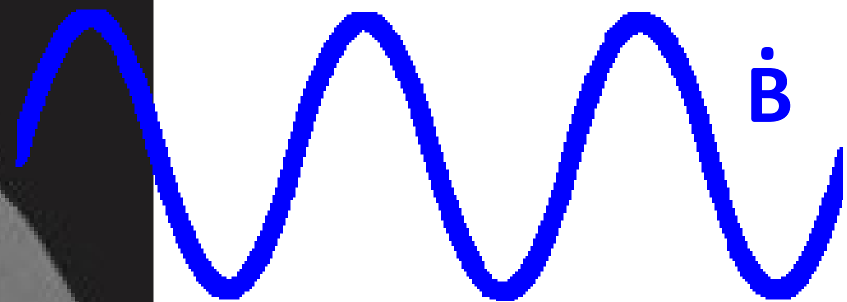

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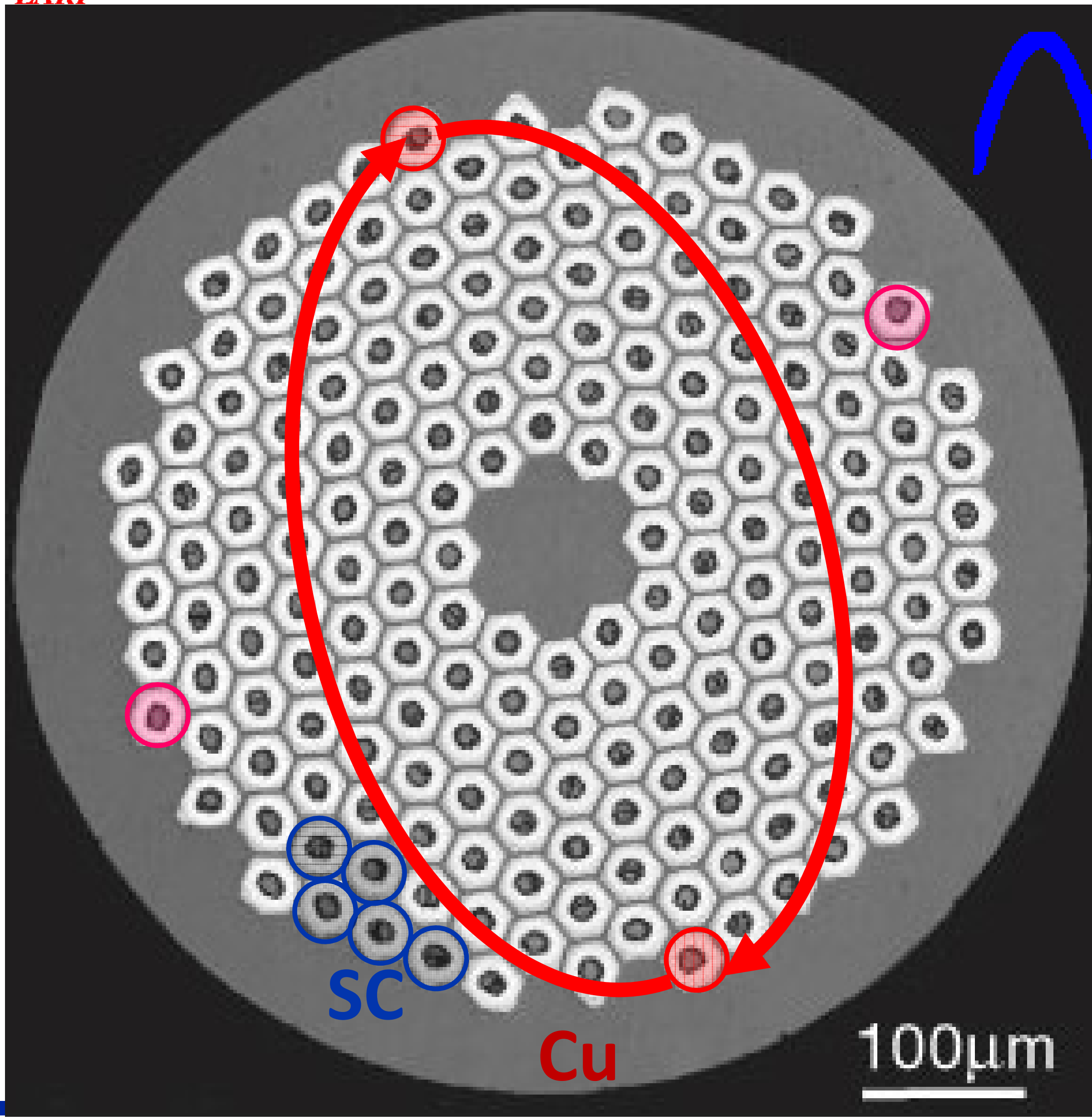

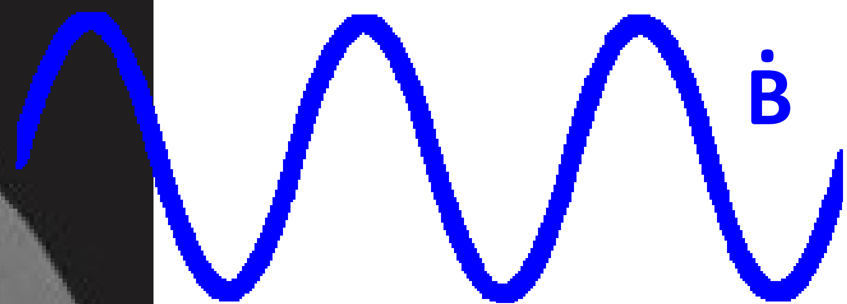

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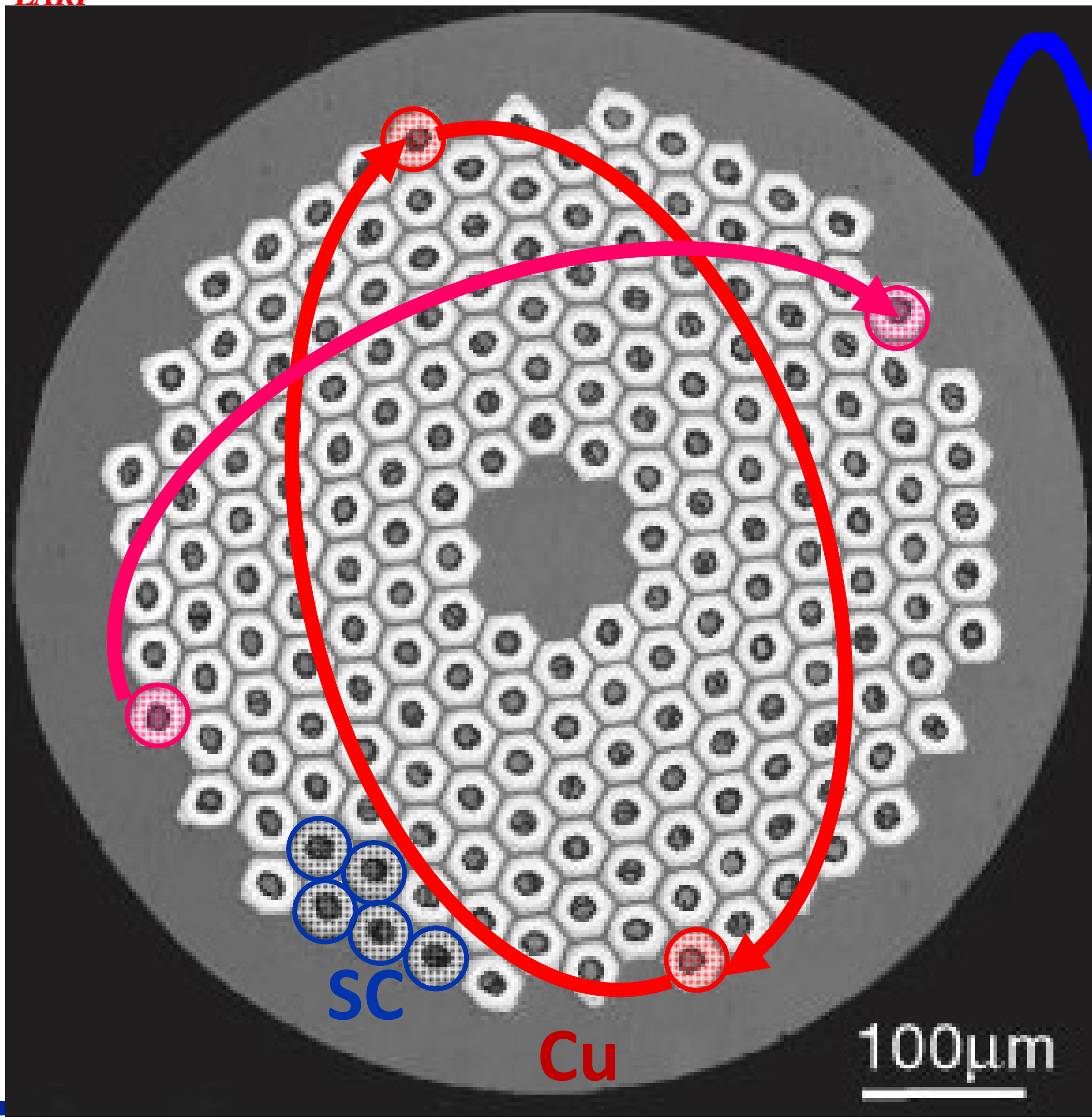

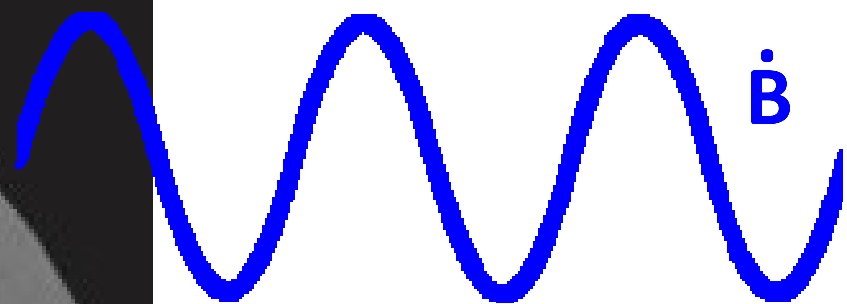

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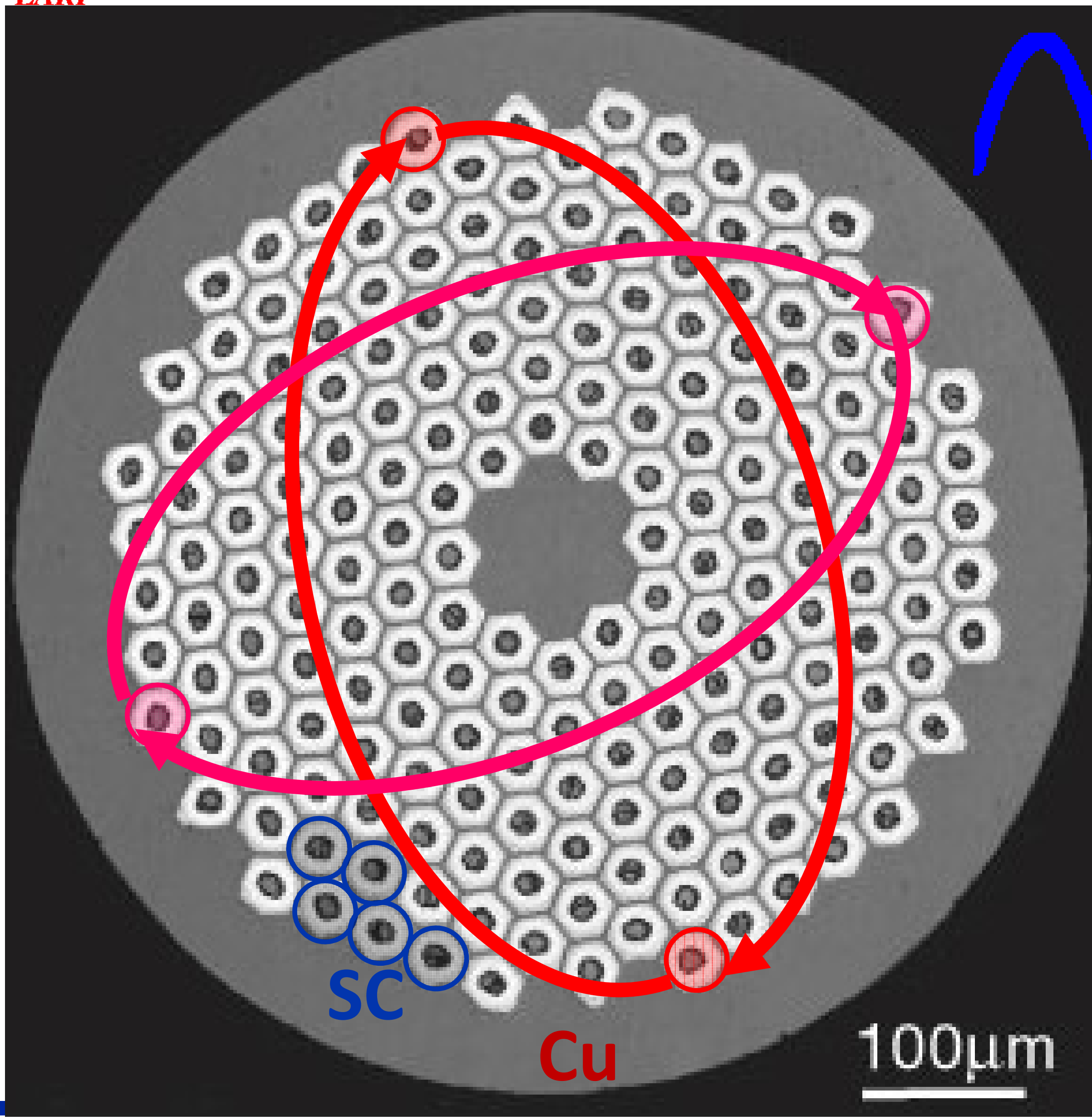

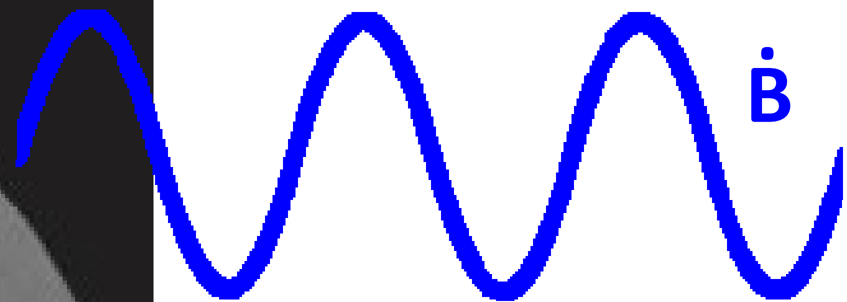

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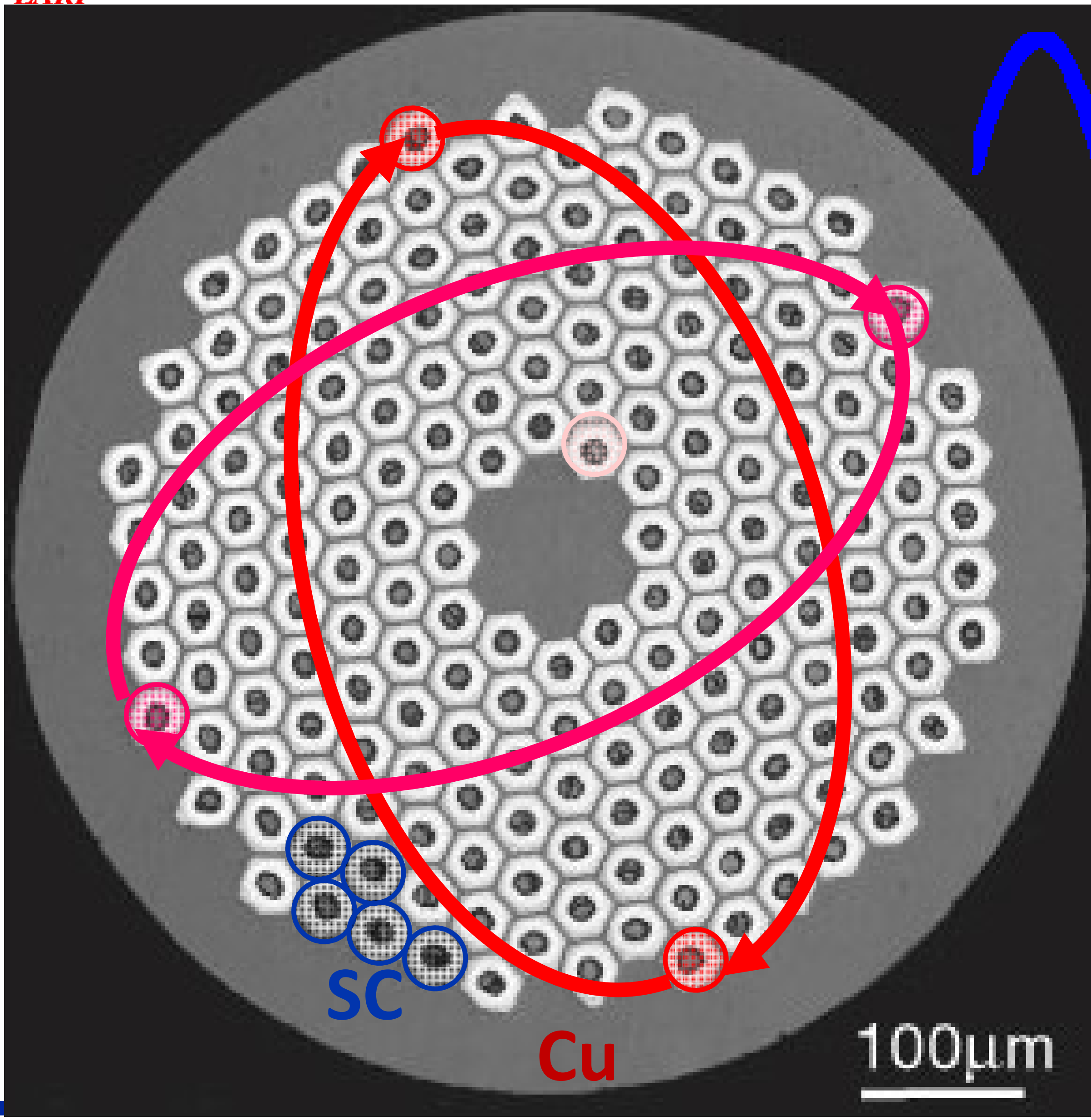

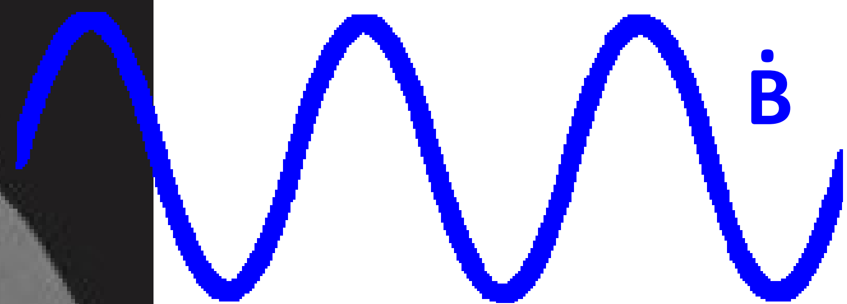

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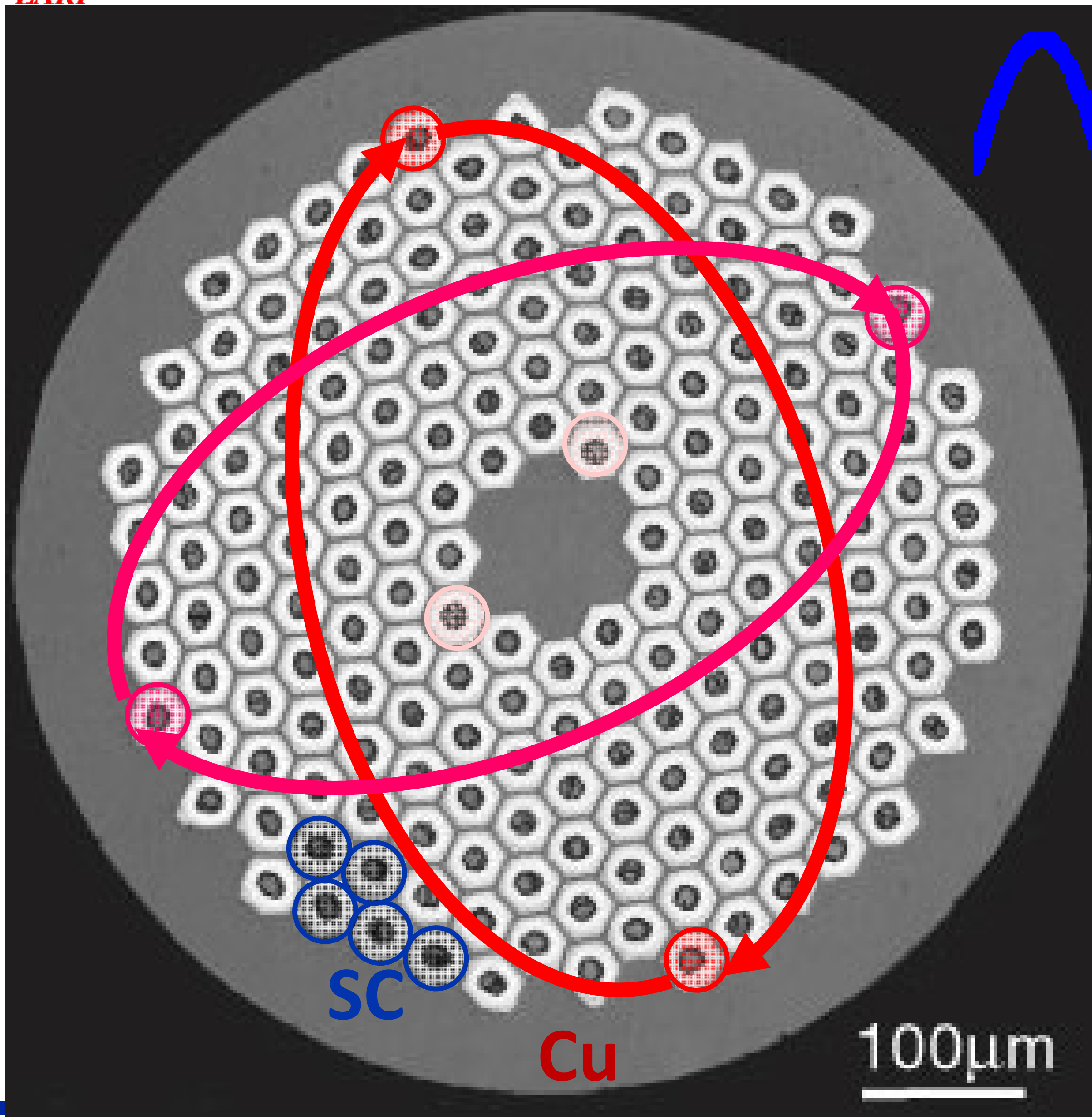

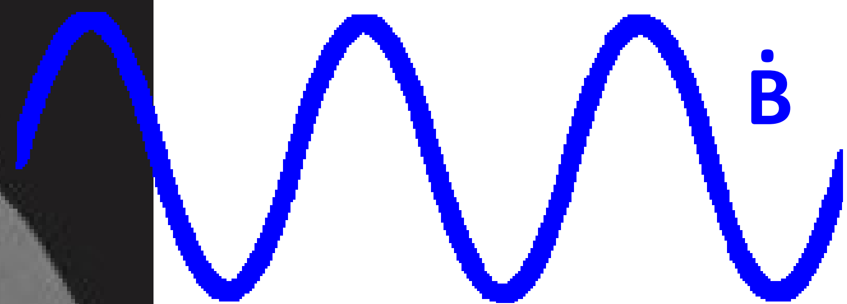

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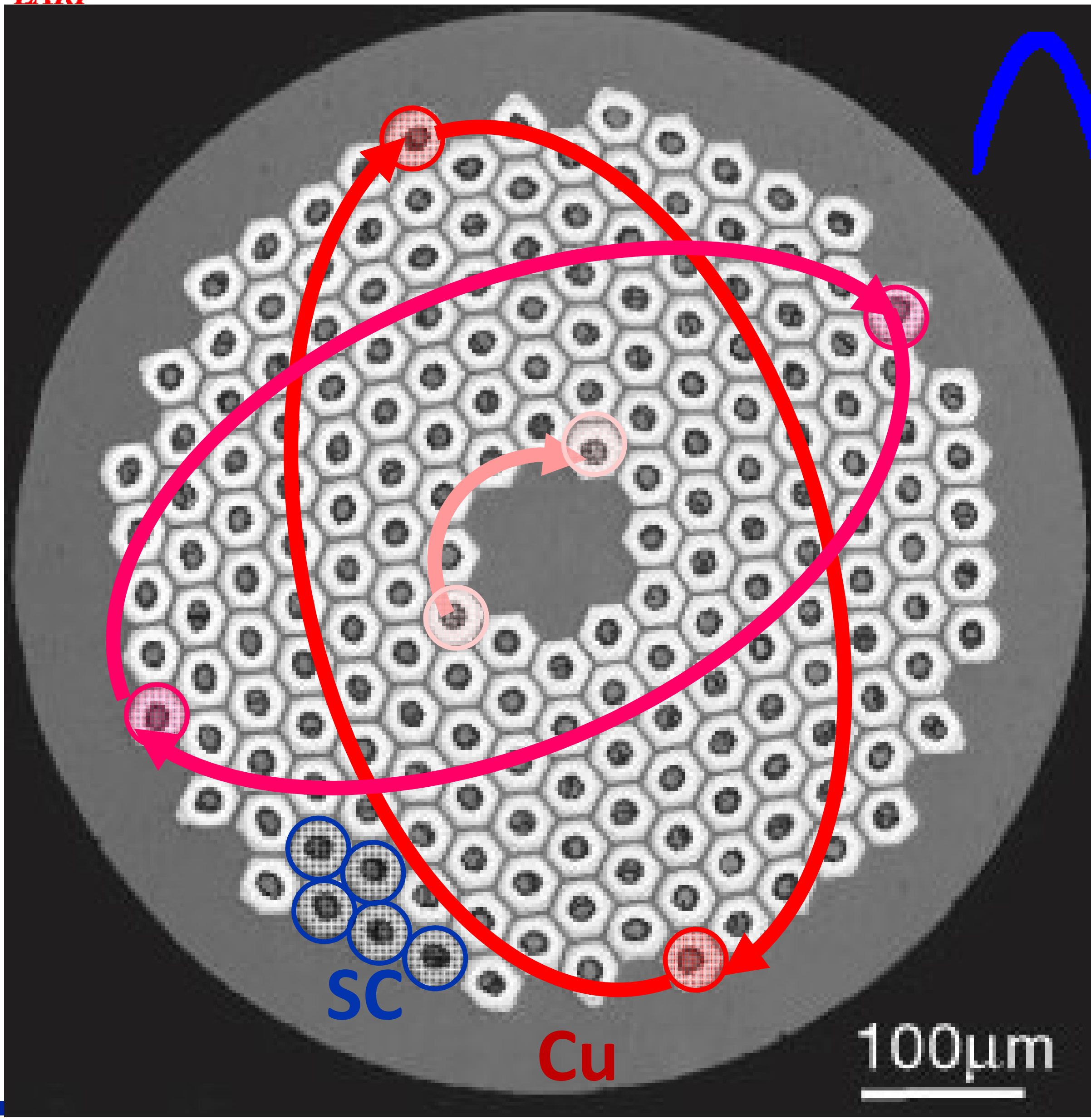

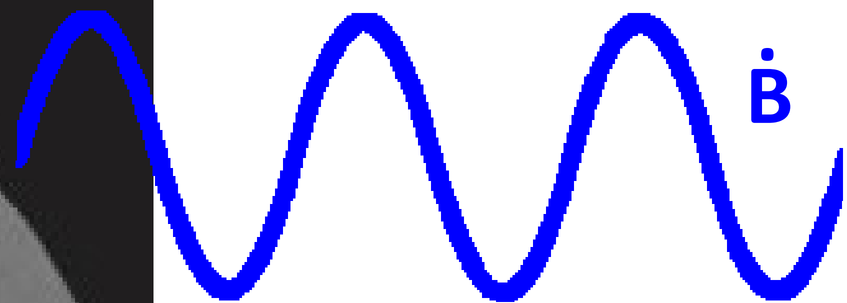

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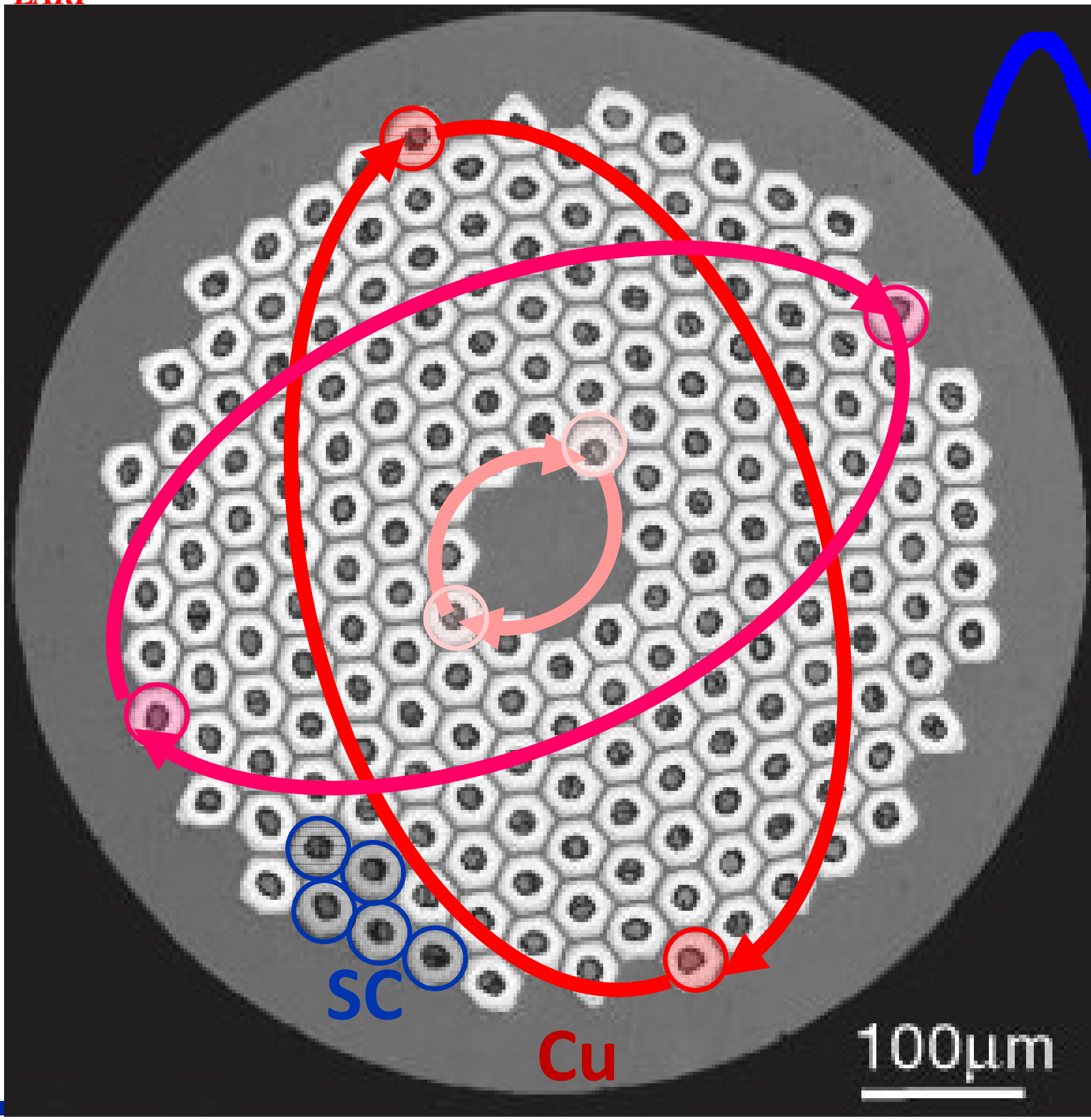

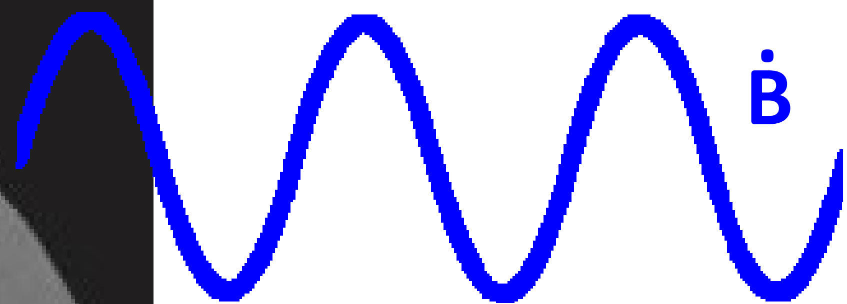

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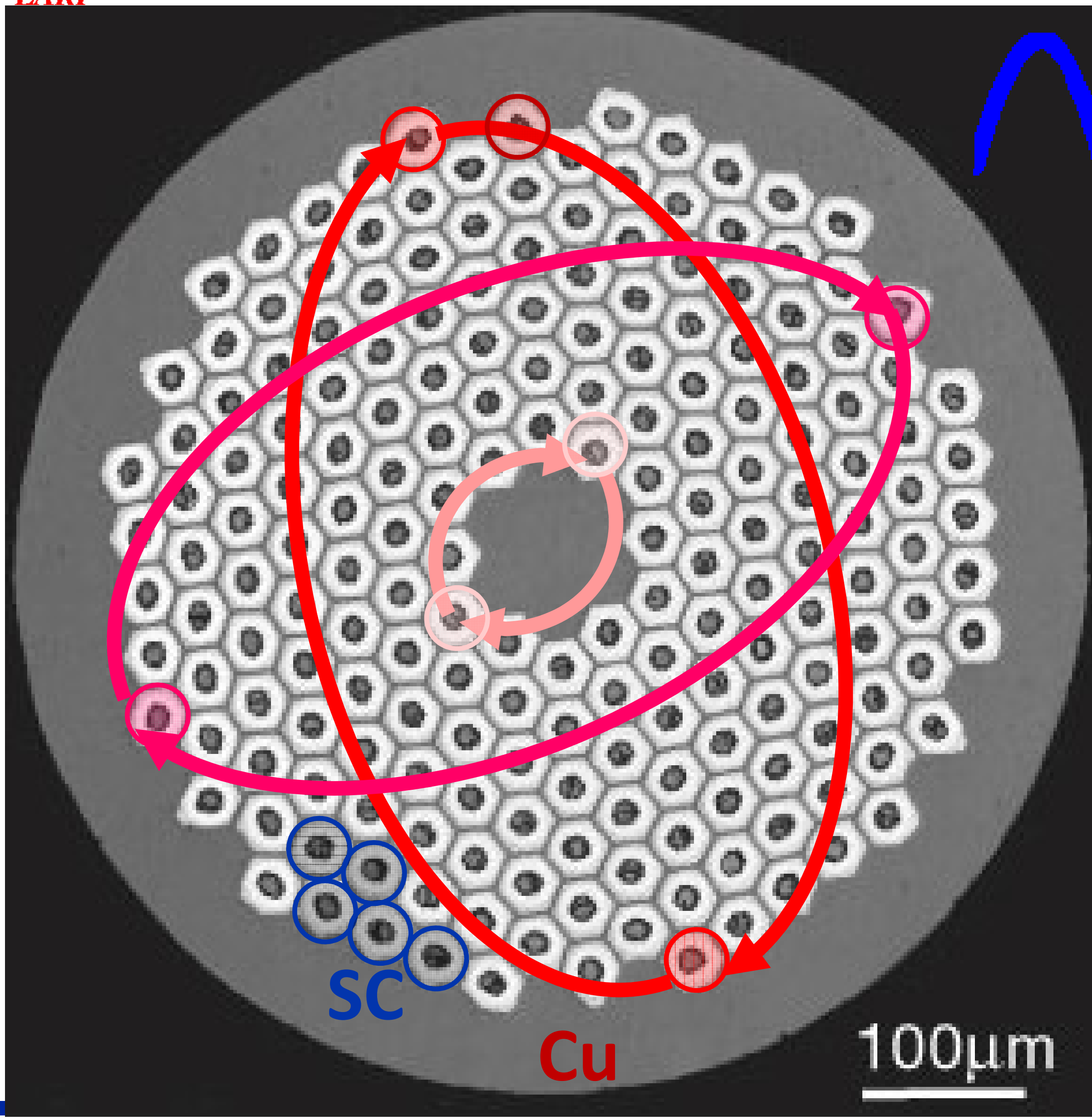

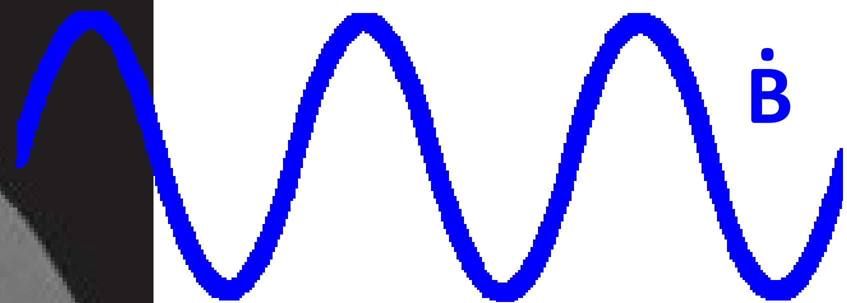

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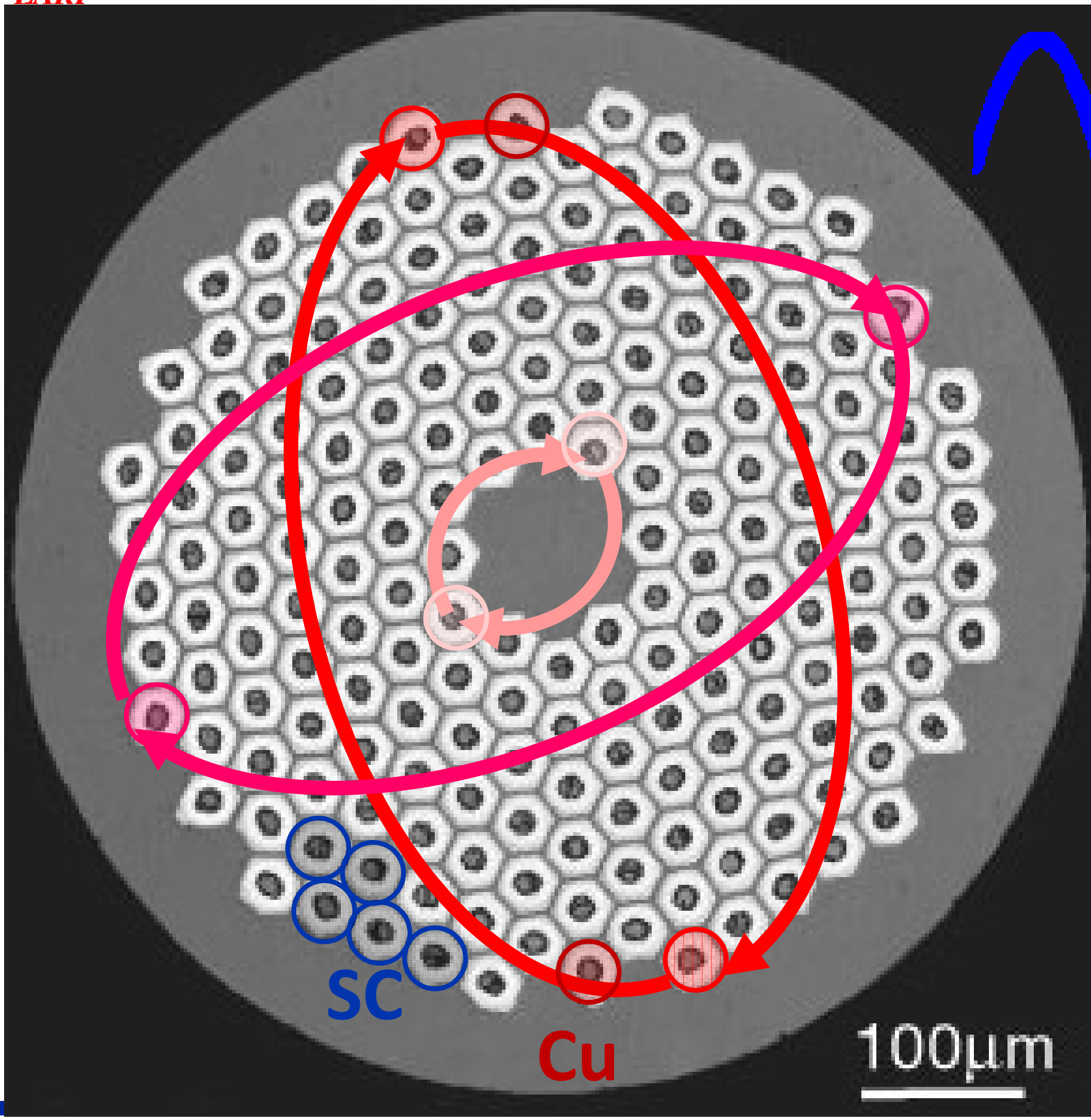

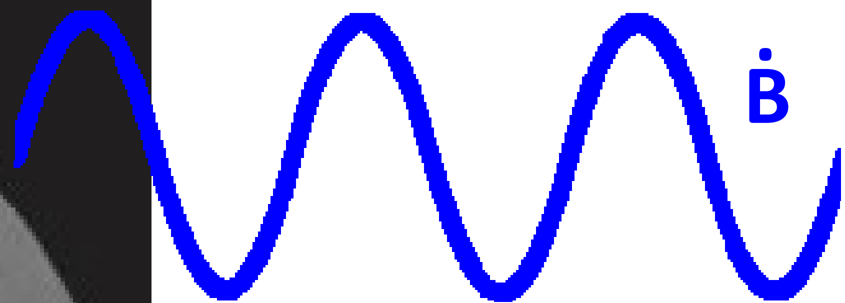

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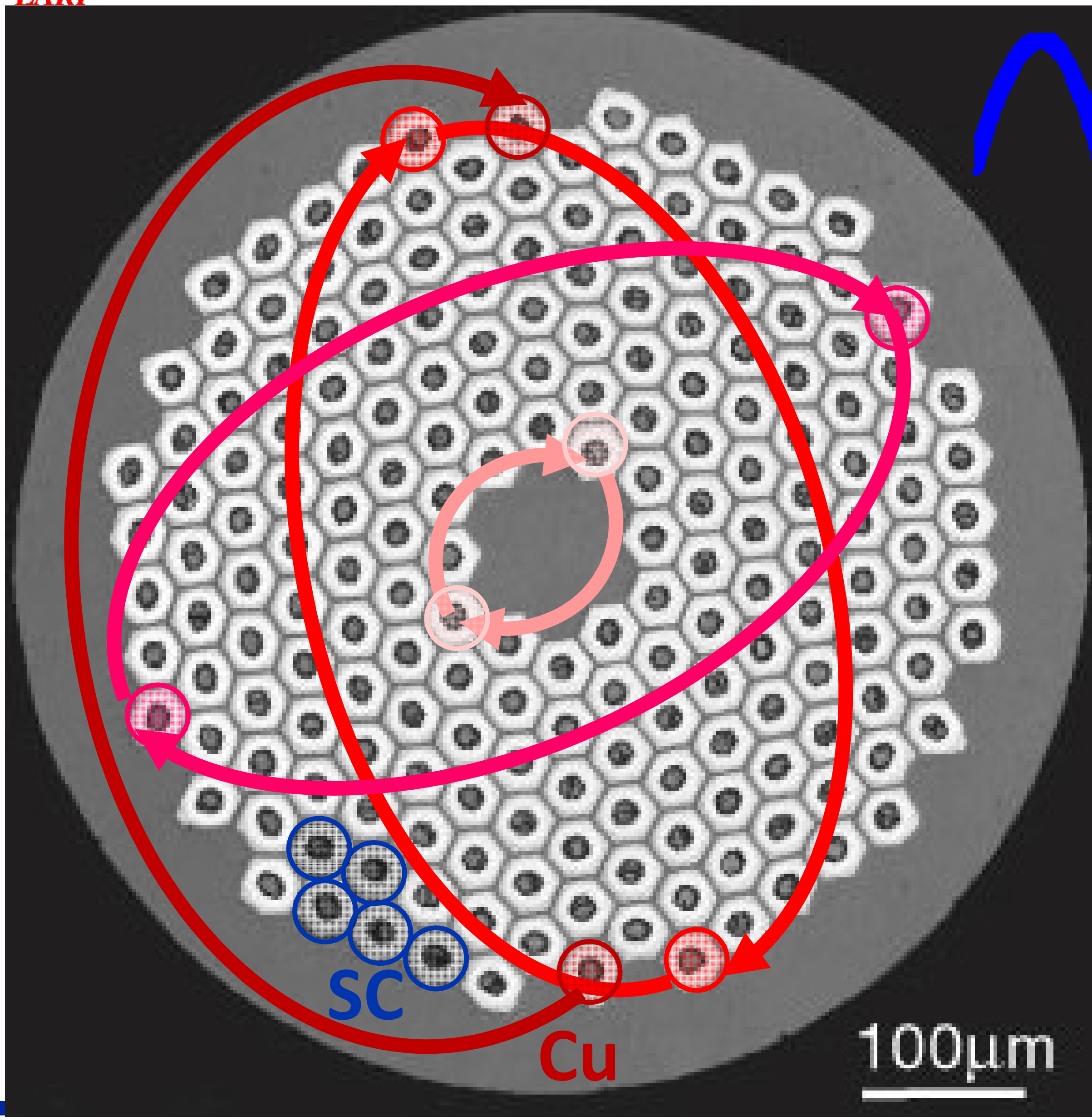

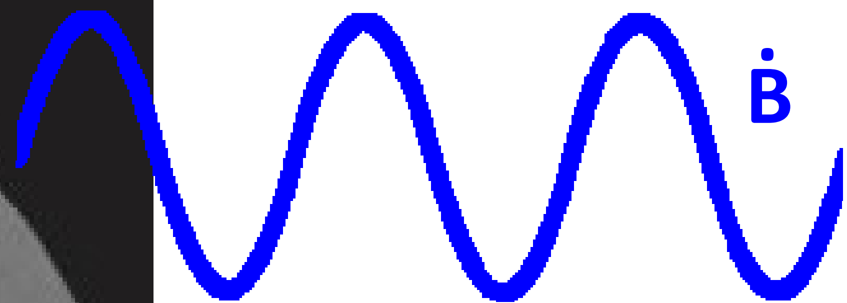

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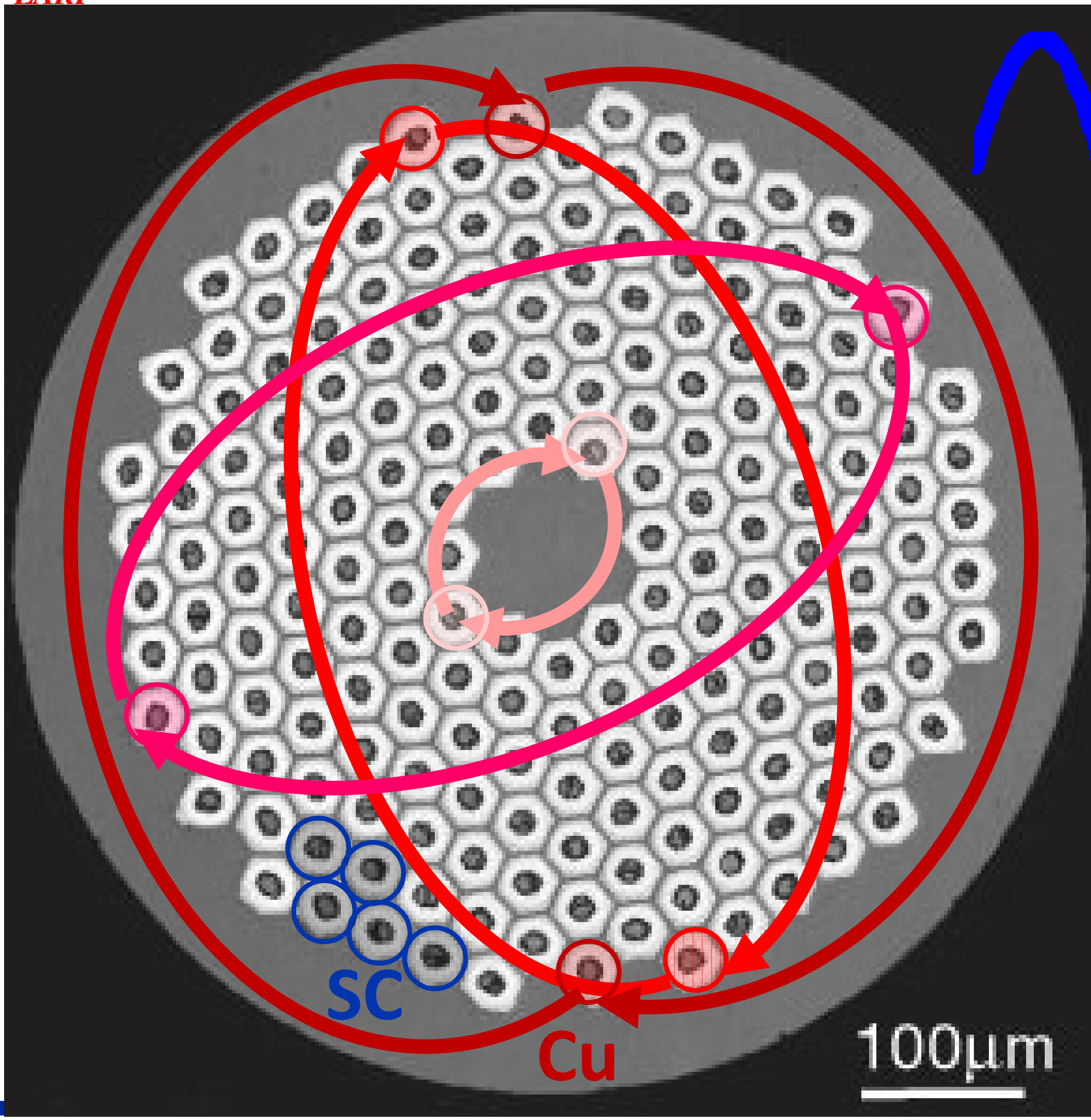

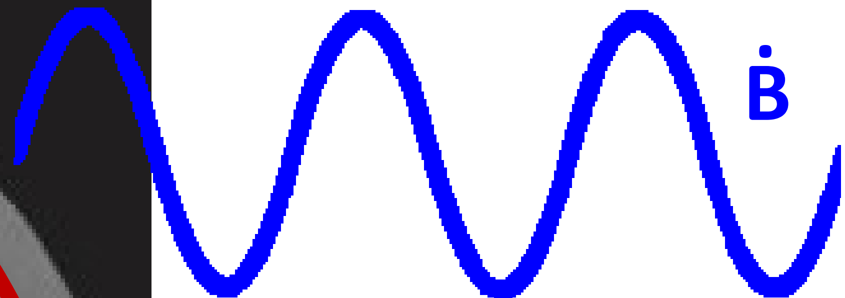

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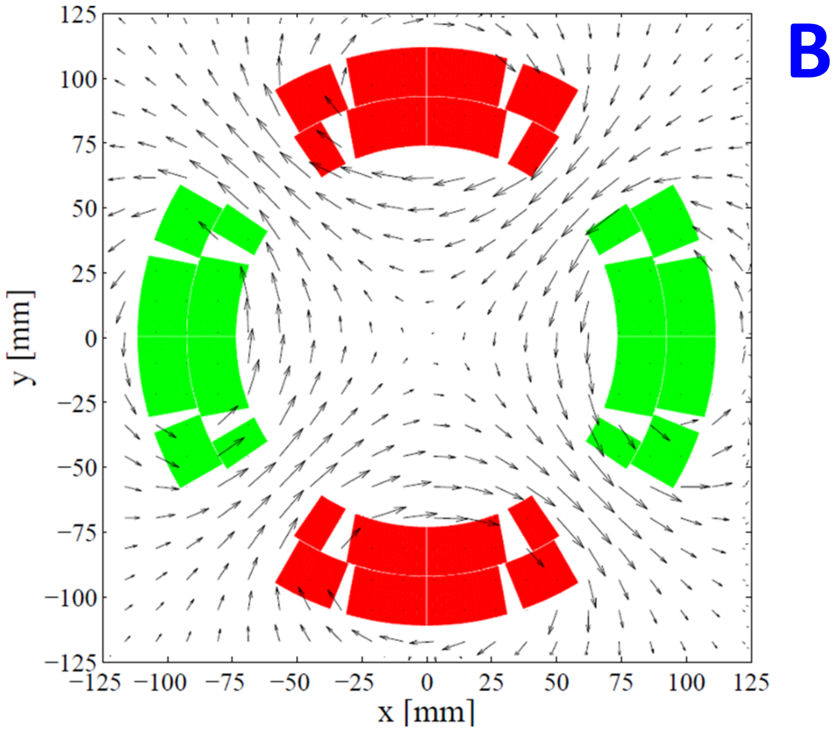
CLIQ magnetic-field change

Quasi-static field during operation



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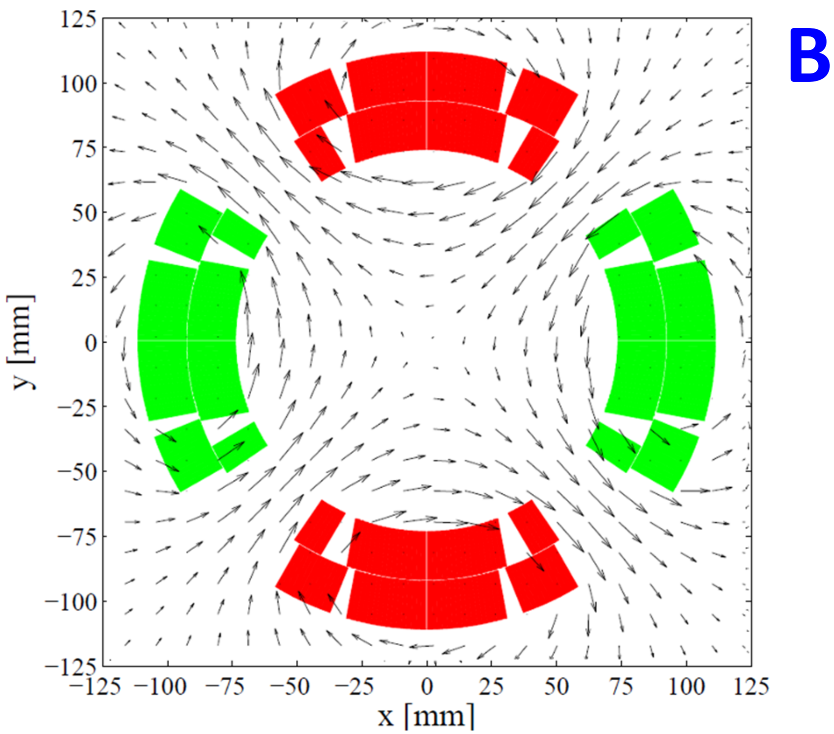
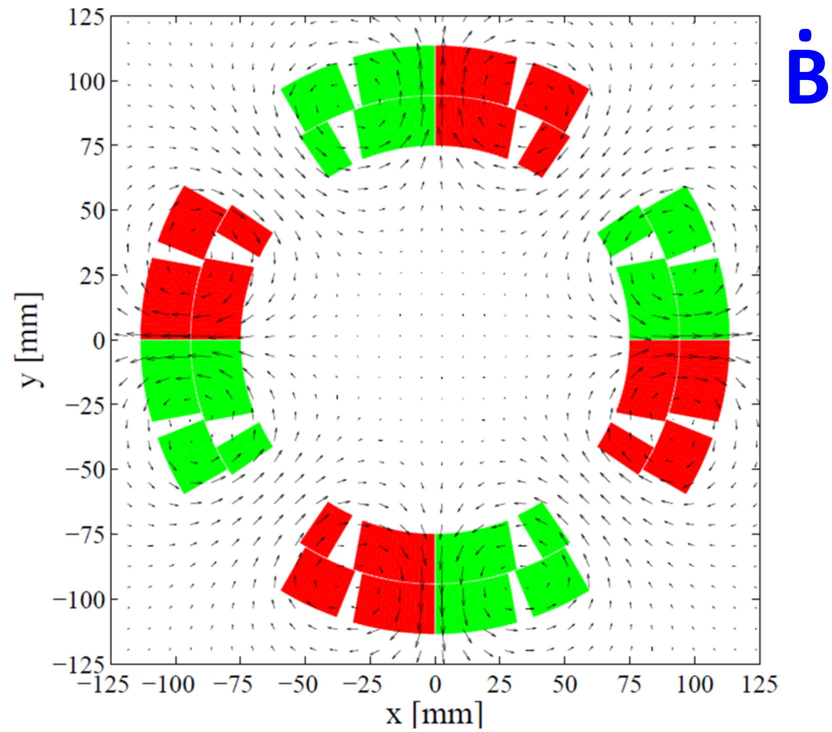
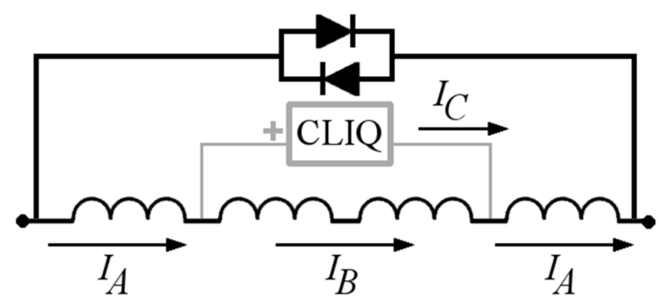


Oscillating field at CLIQ discharge



The **oscillating current** introduced by CLIQ rapidly change the **local magnetic field**



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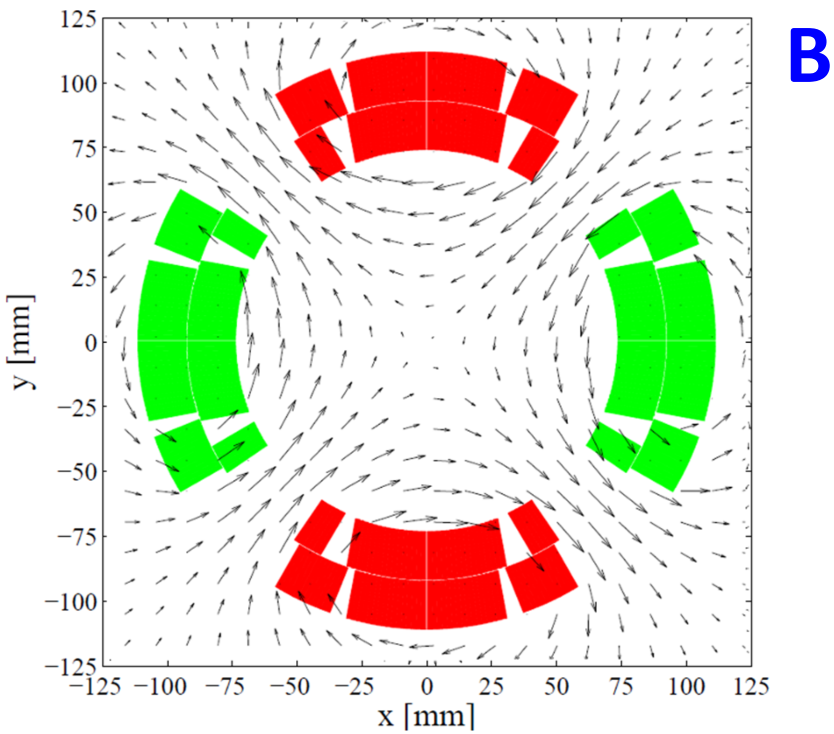

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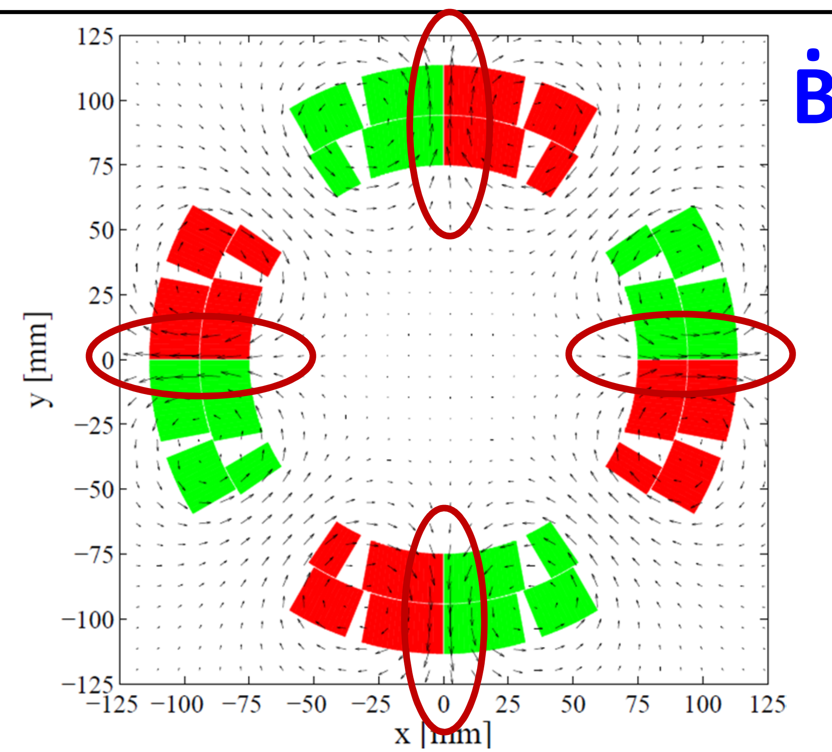

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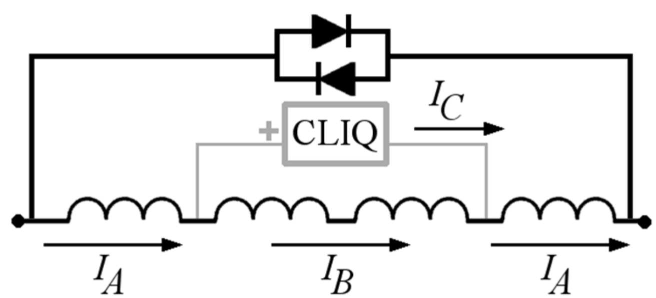

Scaling CLIQ performance

$$\frac{P_{IF}}{vol} \propto \psi_1^{\,2}\left(N_C \frac{U_0}{l_m}\right)^2$$

$$\boxed{\frac{U_0}{l_m}}$$

At high current
- Low energy needed to start the quench
- High energy density, needs to be quick!

→ **POWER** density is the key parameter

- (Number of CLIQ units)^2
- (Charging voltage)^2
- (magnetic length)^-2 (fixed by design)

Scaling CLIQ performance

LARP

High Luminosity LHC

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$$\frac{E_{CLIQ}}{vol} \propto \frac{N_C C U_0^{\,2}}{l_m}$$

$$\boxed{\frac{C U_0^{\,2}}{l_m}}$$

At low current
- High energy needed to start the quench
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→ **ENERGY** density is the key parameter

- Number of CLIQ units
- (Charging voltage)^2
- Capacitance of each unit
- (magnetic length)^-1

Scaling CLIQ performance

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$$f \propto \sqrt{\frac{N_C}{l_m C}}$$

- Magnetic length
- # of CLIQ units
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CLIQ effectiveness

→ Coil geometry

→ Position of CLIQ connections

→ Electrical order of the poles

→ etc…

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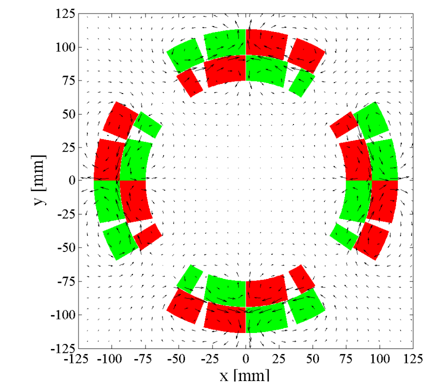
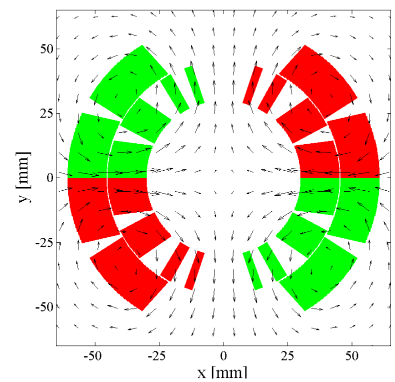
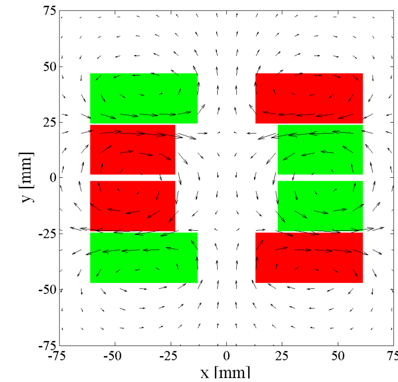
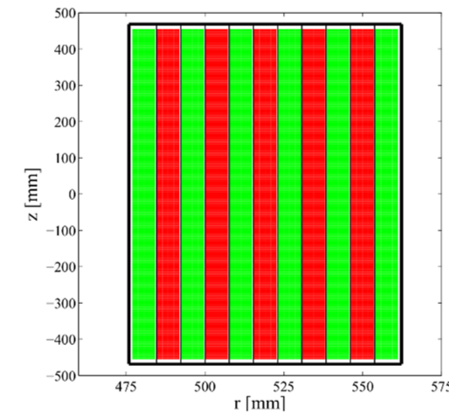
- Magnetic length
- # of CLIQ units
- Capacitance

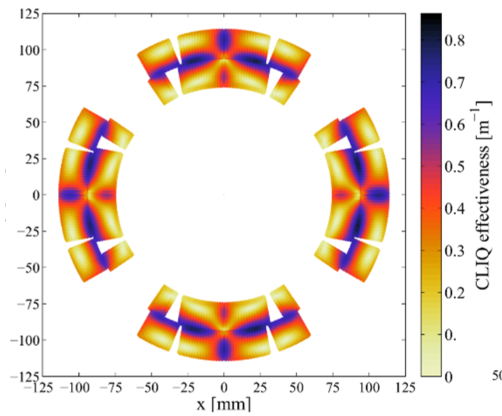
CLIQ effectiveness, Ψ_1
How much dB/dt for given N_C U_0 and I_m ?





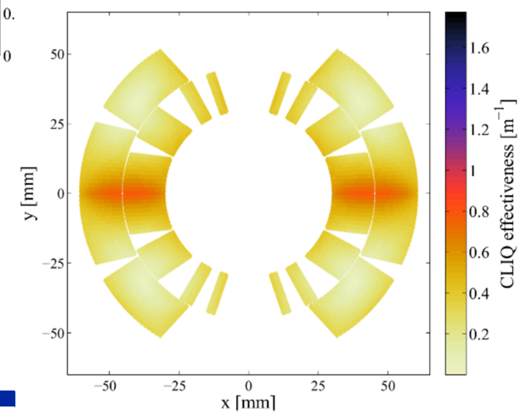


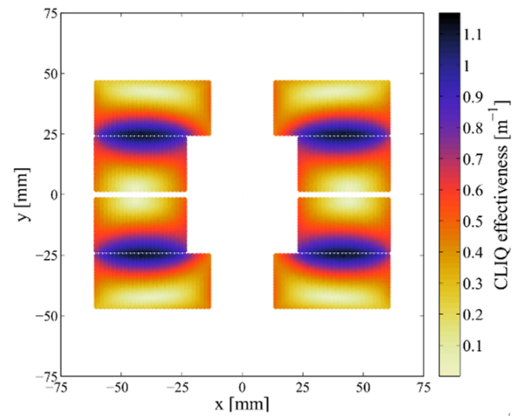




Quadrupole

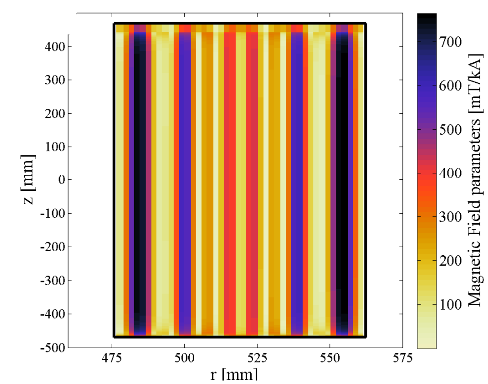
Cos-θ dipole





Block-coil dipole

Solenoid



Outline

CLIQ – Coupling-Loss Induced Quench system

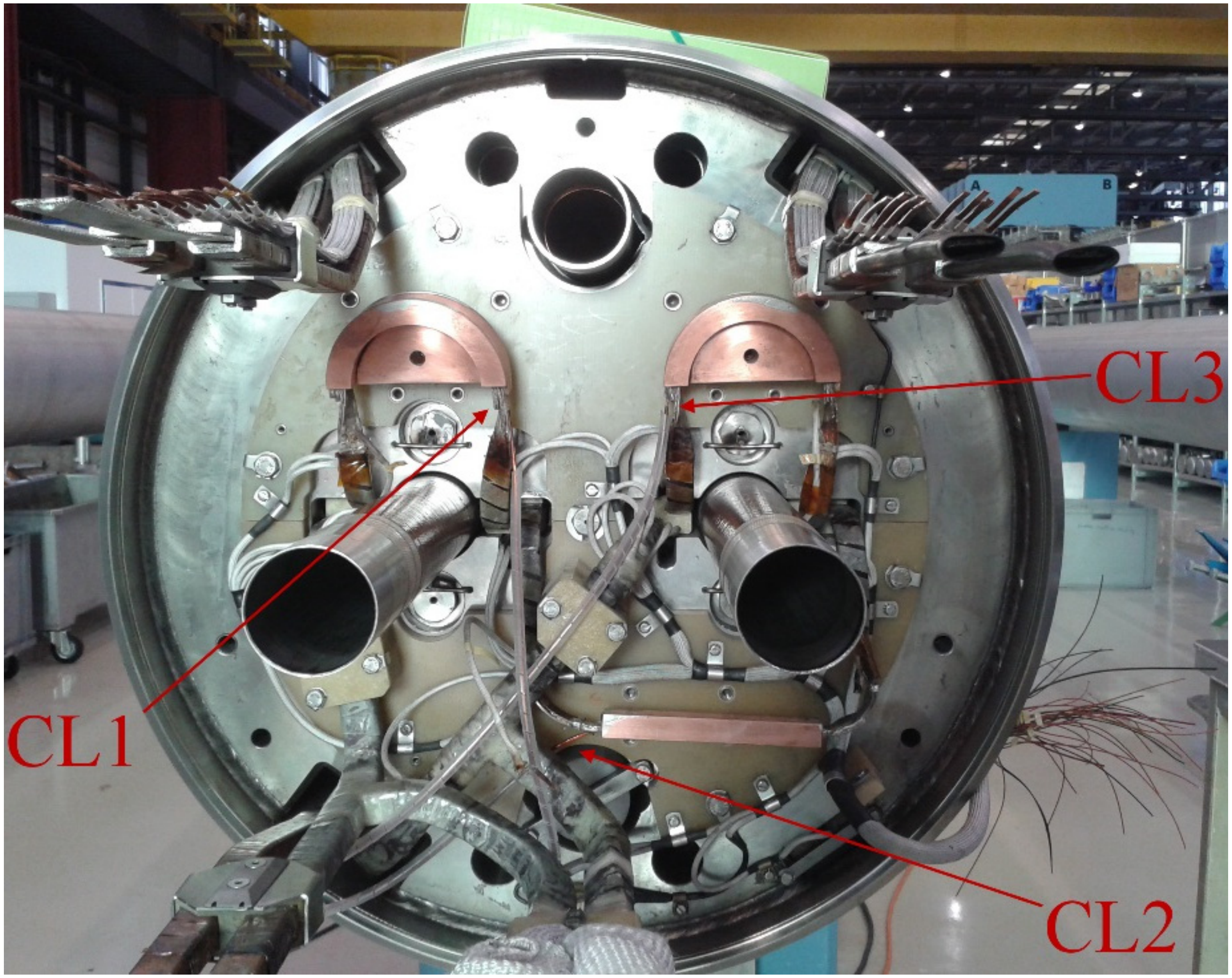
Implementation on existing accelerator magnets

LHC main dipole magnet (*full-scale*)

Implementation on future accelerator magnets

Outlook

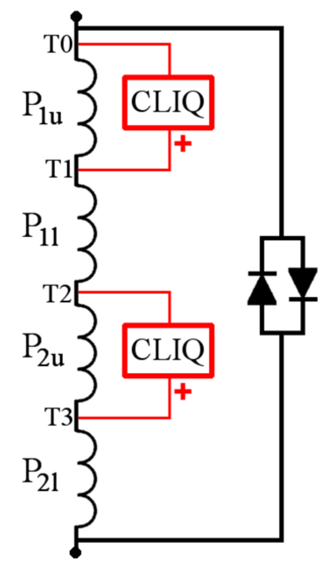
CLIQ on a full-size 14 m LHC main dipole



LHC main dipole magnet	
Twin aperture magnet	
Magnetic Length	14.3 m
Self-inductance	100 mH
Nominal current	11.8 kA
Peak magnetic field	8.3 T
Superconductor	Nb-Ti

2 CLIQ Units

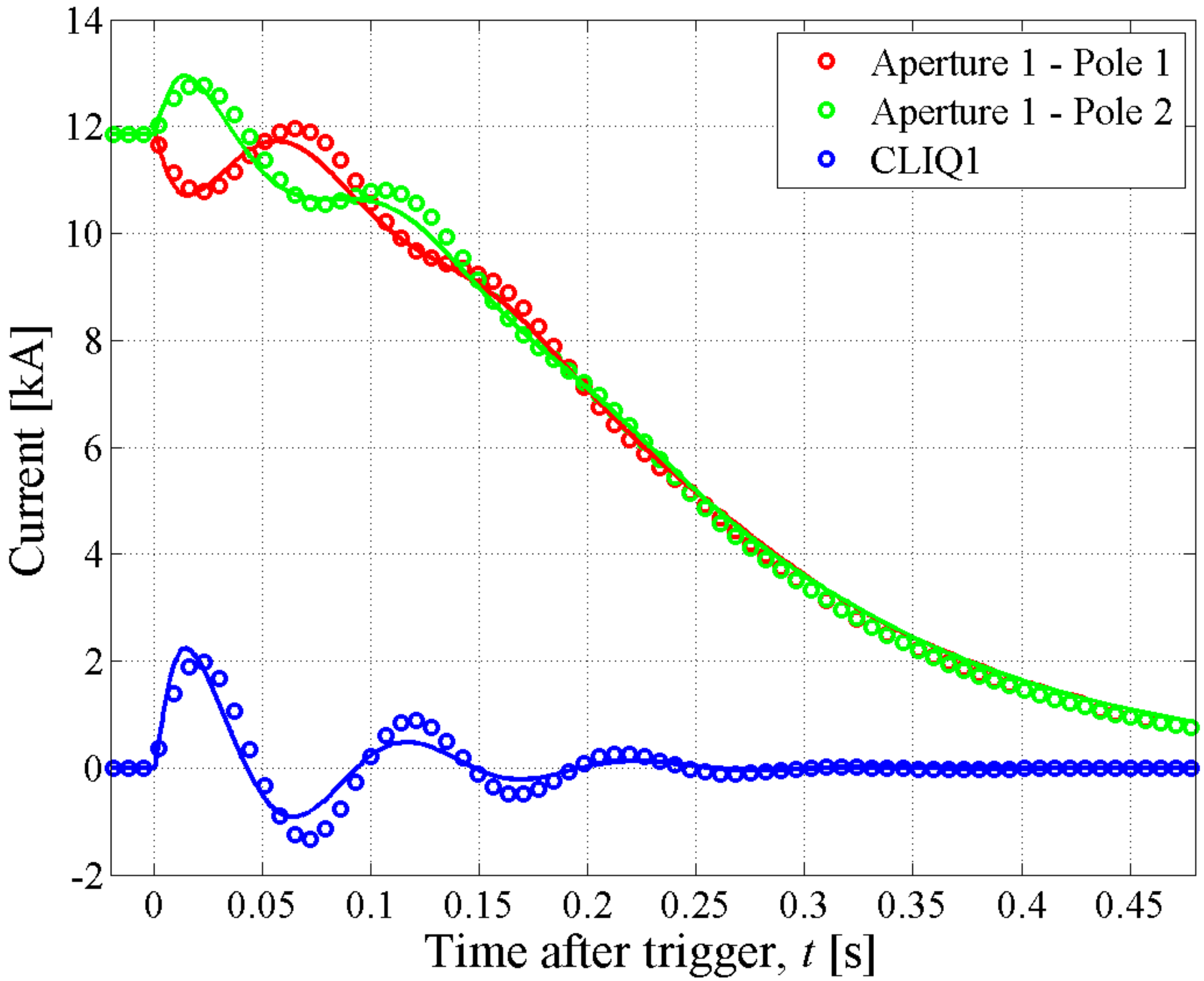
U0=500 V C=80 mF



CLIQ on a full-size 14 m LHC main dipole

LARP

High Luminosity LHC



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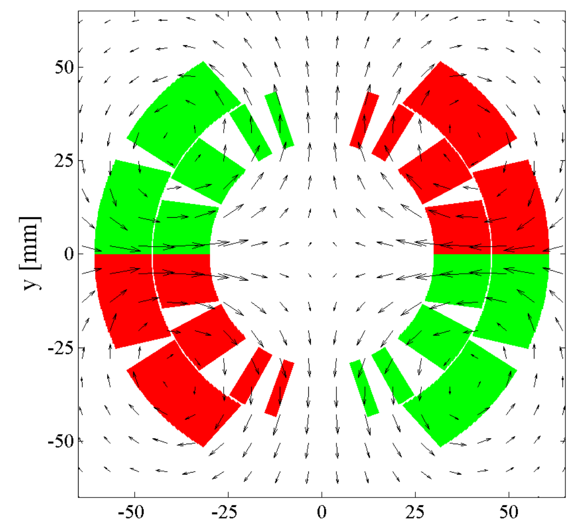
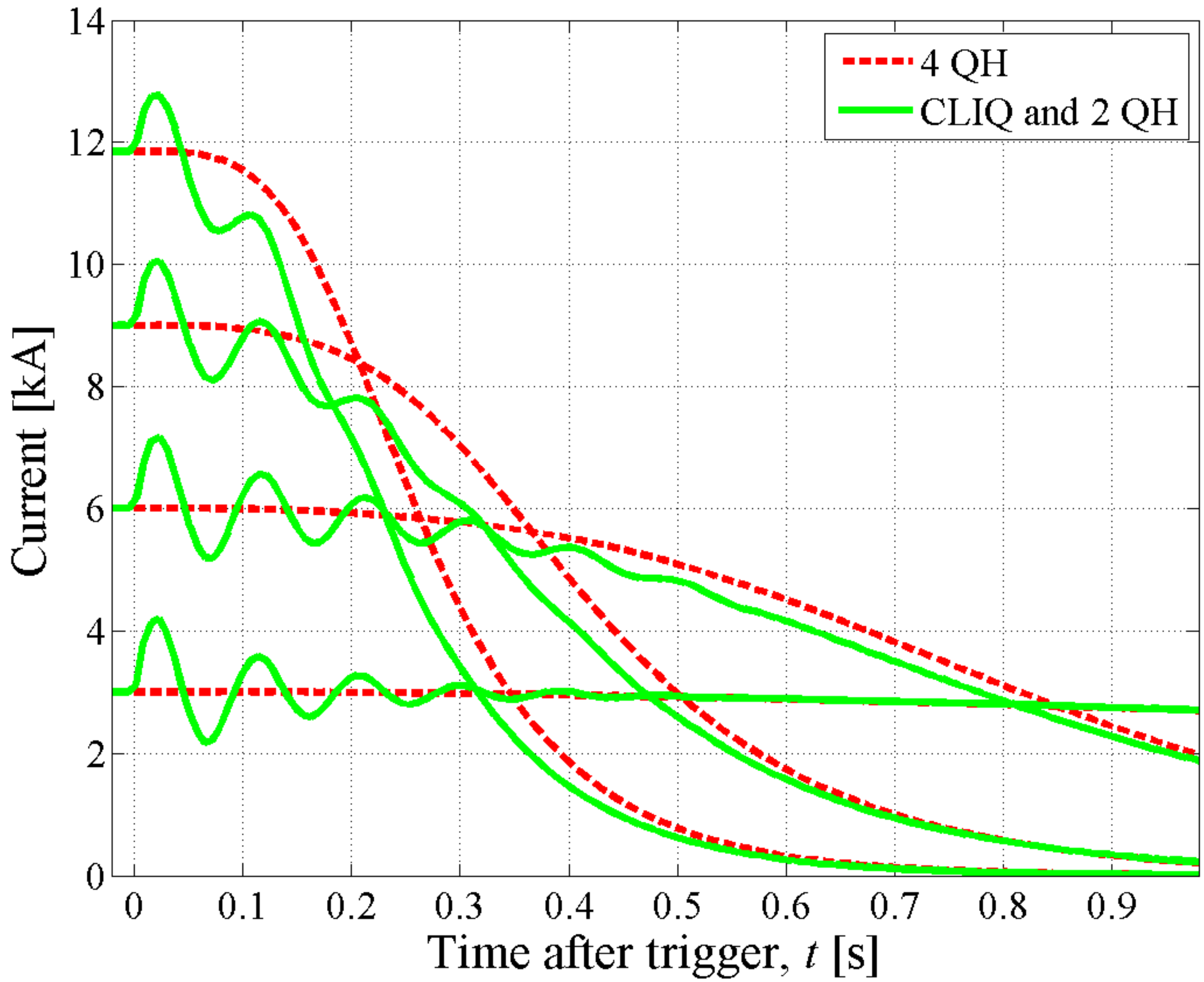
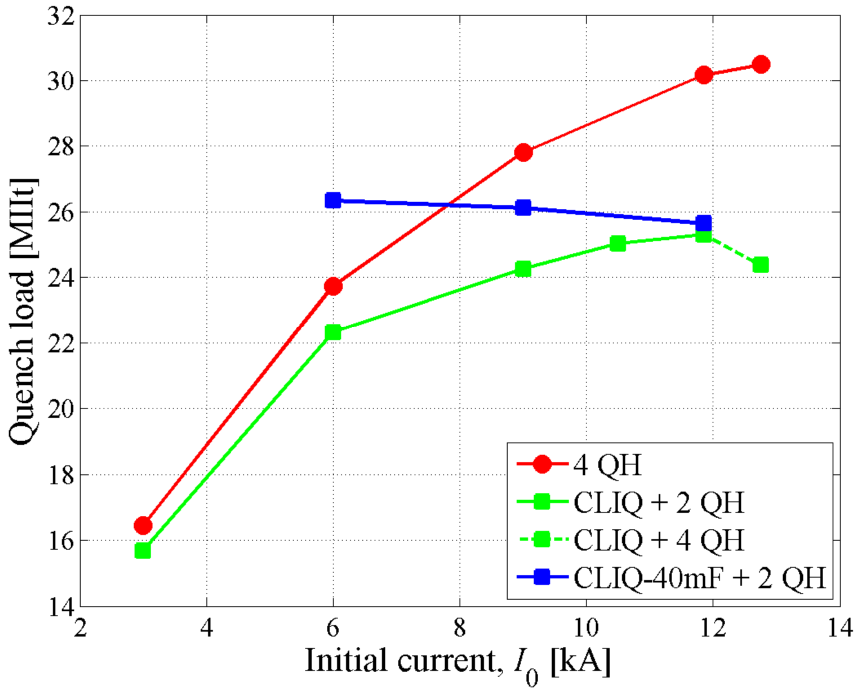


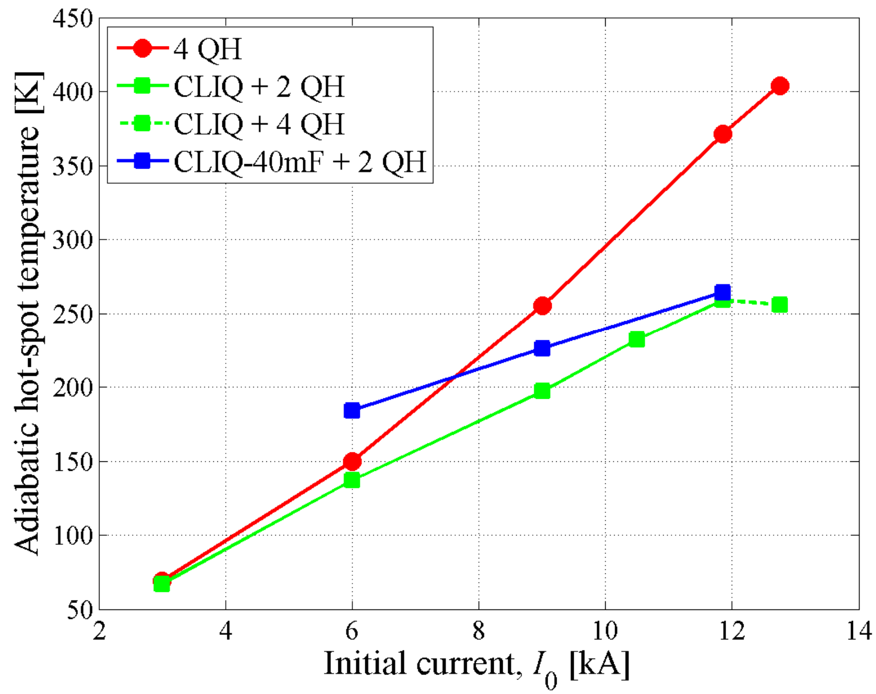
CLIQ technology proved on full-size magnets

Comparison with conventional QH's



Comparison with conventional QH's

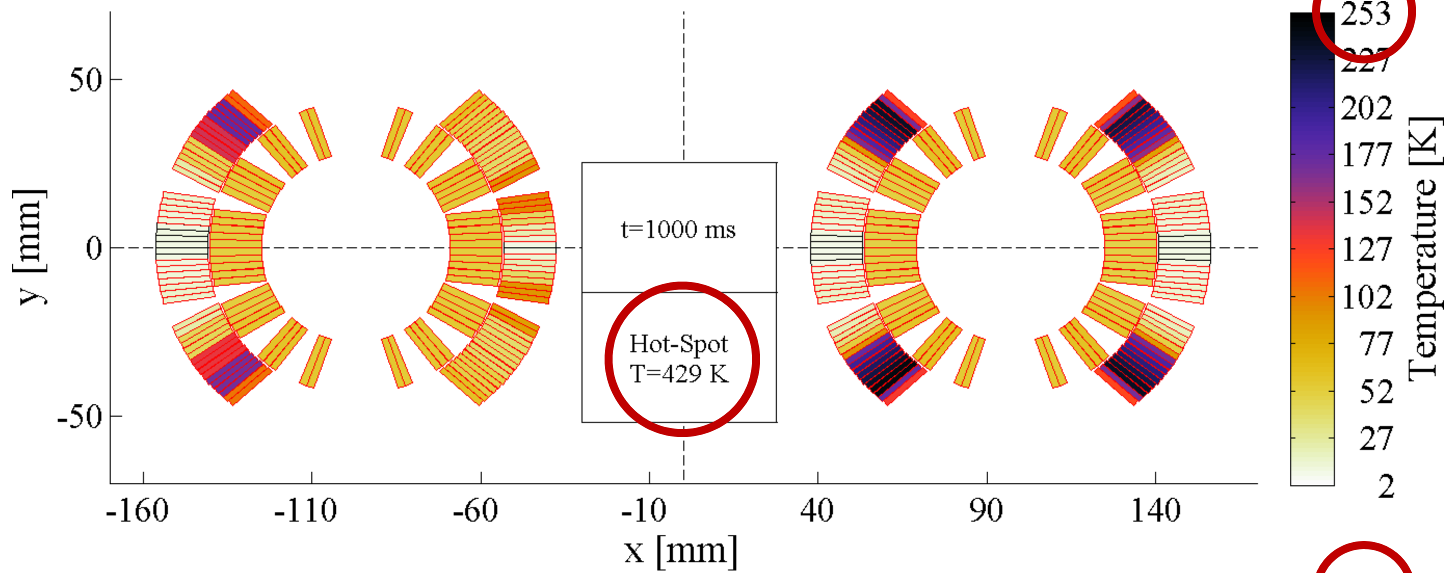




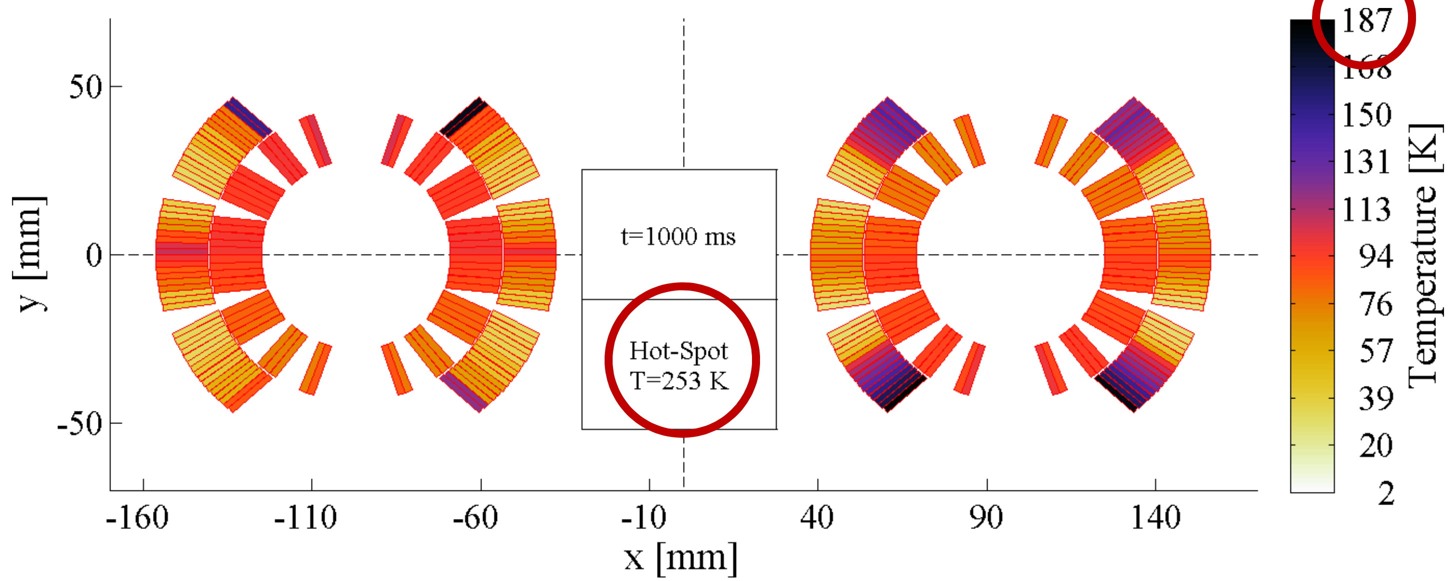
CLIQ technology achieved a significant **reduction** of the **hot-spot temperature**

Simulated temperature profiles

QH



CLIQ



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CLIQ – Coupling-Loss Induced Quench system

Implementation on existing accelerator magnets

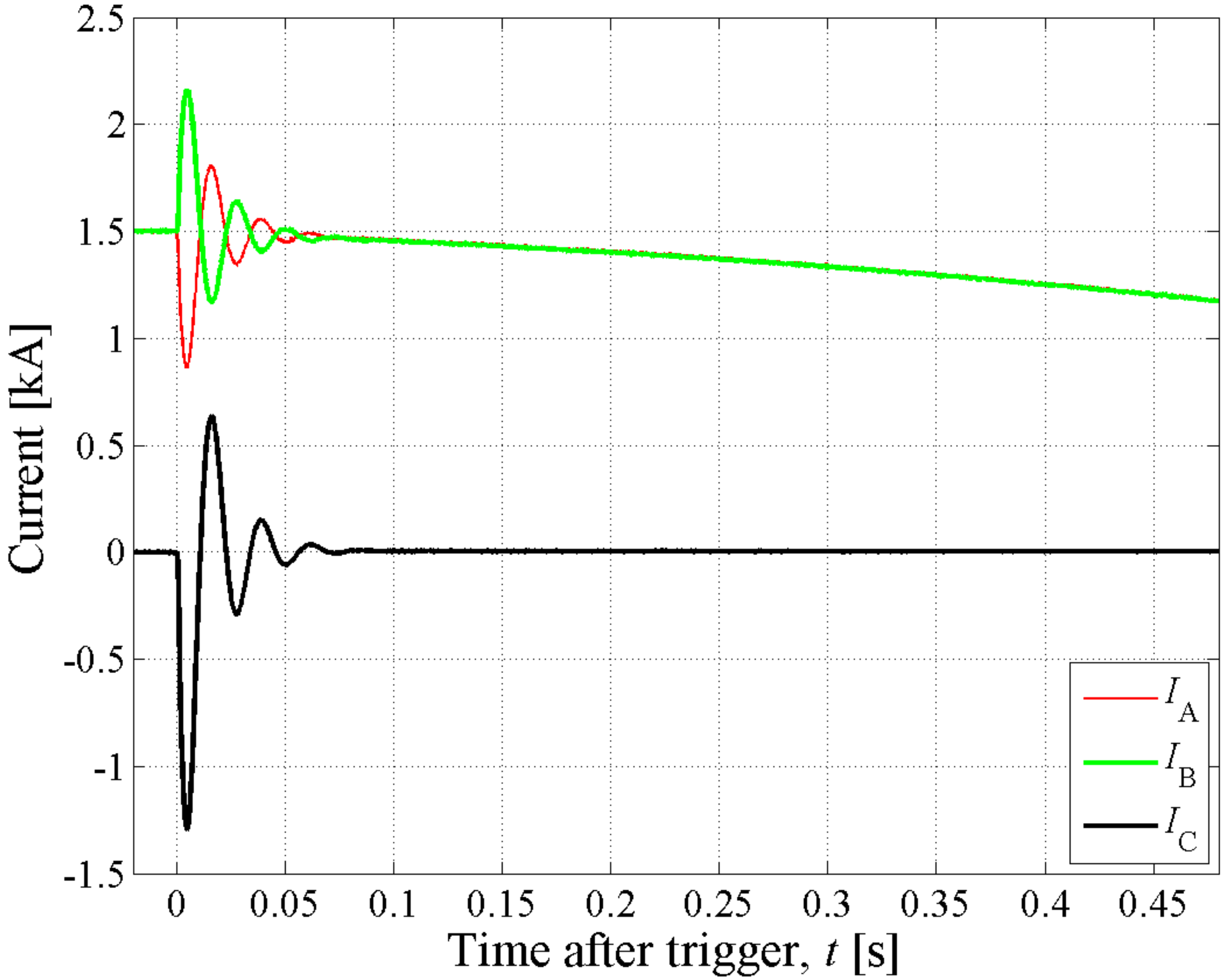
LHC main dipole magnet (*full-scale*)

LHC matching quadrupole magnet (*full-scale*)

Implementation on future accelerator magnets

Outlook

CLIQ on full-scale LHC quadrupole

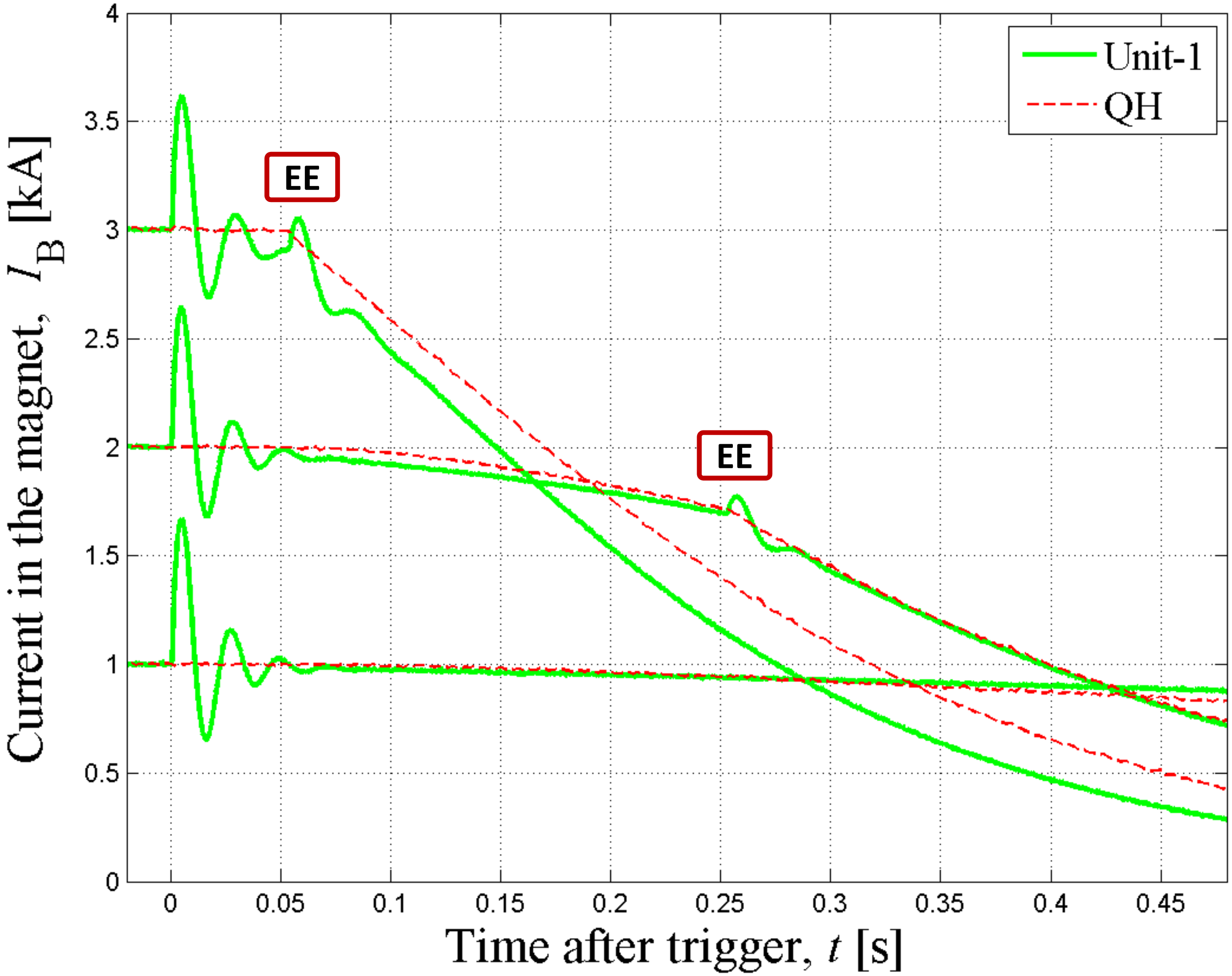


<u>LHC matching quadrupole</u>
(1 aperture)

Magnetic Length	3.4 m
Self-inductance	72 mH
Nominal current	3.6 kA
Superconductor	Nb-Ti

<u>1 CLIQ unit</u>
U0=650 V C=8.8 mF

Comparison with conventional QH's



Outline

CLIQ – Coupling-Loss Induced Quench system

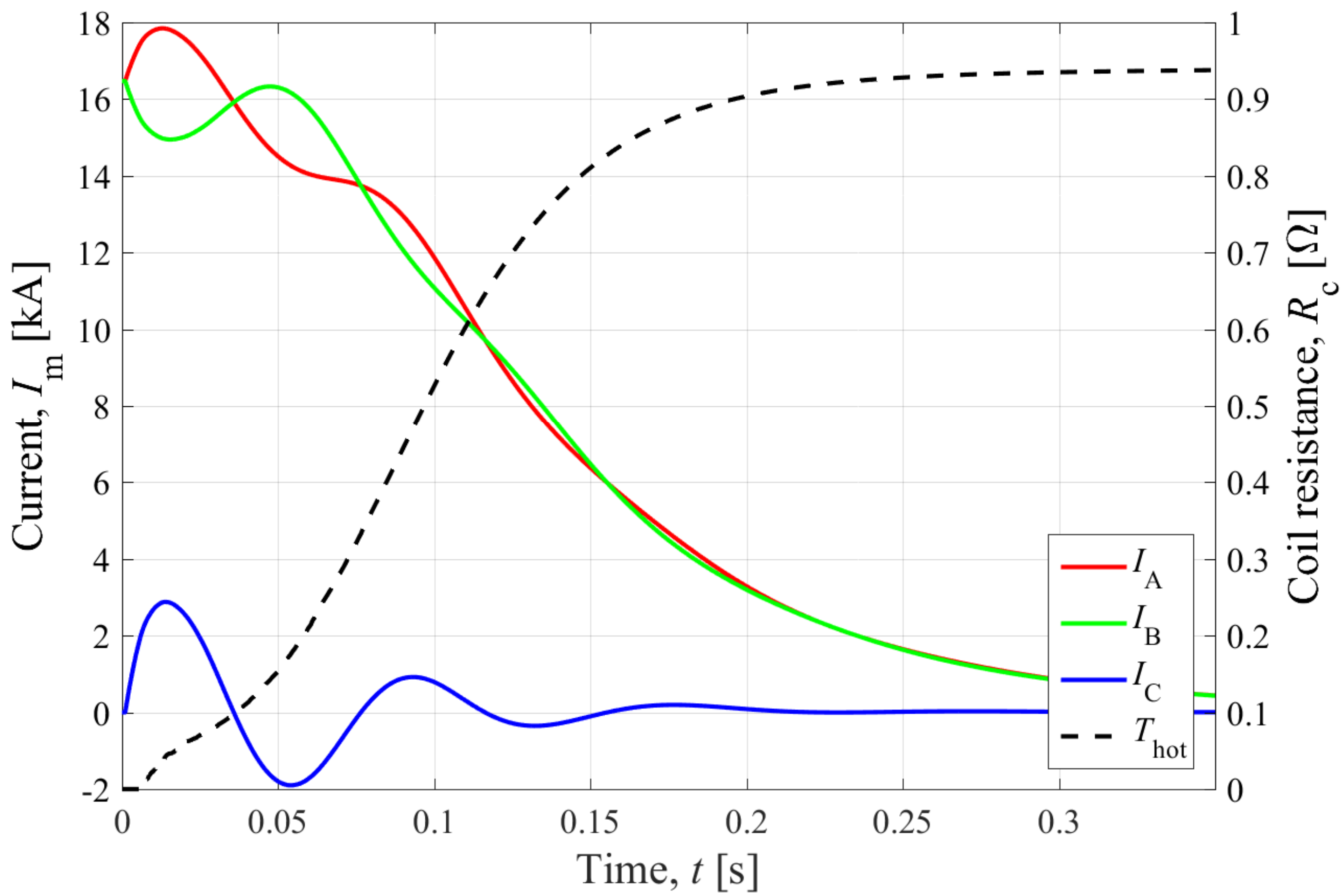
Implementation on existing accelerator magnets

Implementation on future accelerator magnets

High-Lumi LHC inner triplet quadrupoles

Outlook

CLIQ on full-scale Nb_3Sn low-β quad



<u>HL-LHC inner triplet quad</u>

Magnetic Length	7.15 m
Self-inductance	68 mH
Nominal current	16.5 kA
Peak magnetic field	12.1 T
Superconductor	Nb_3Sn

<u>1 CLIQ Unit</u>

U0=1 kV C=40 mF

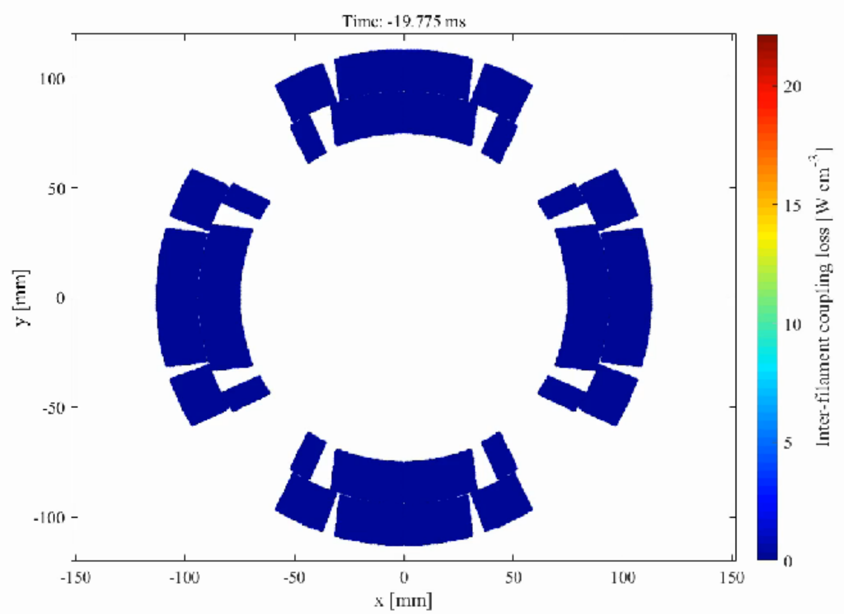
CLIQ in the baseline: **first application** in an accelerator

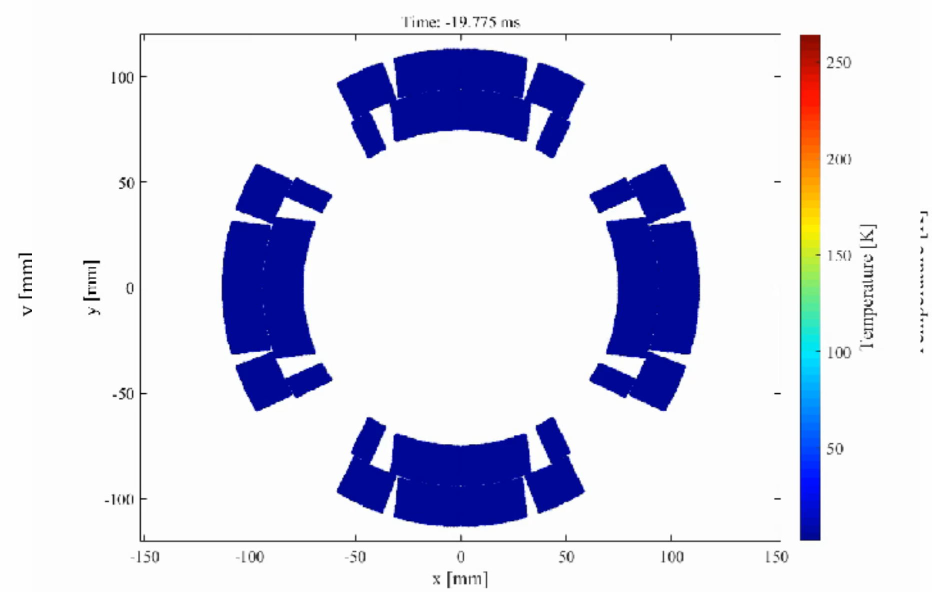
All simulations performed with the software LEDET

Simulated CLIQ discharge

Inter-filament coupling loss

Temperature

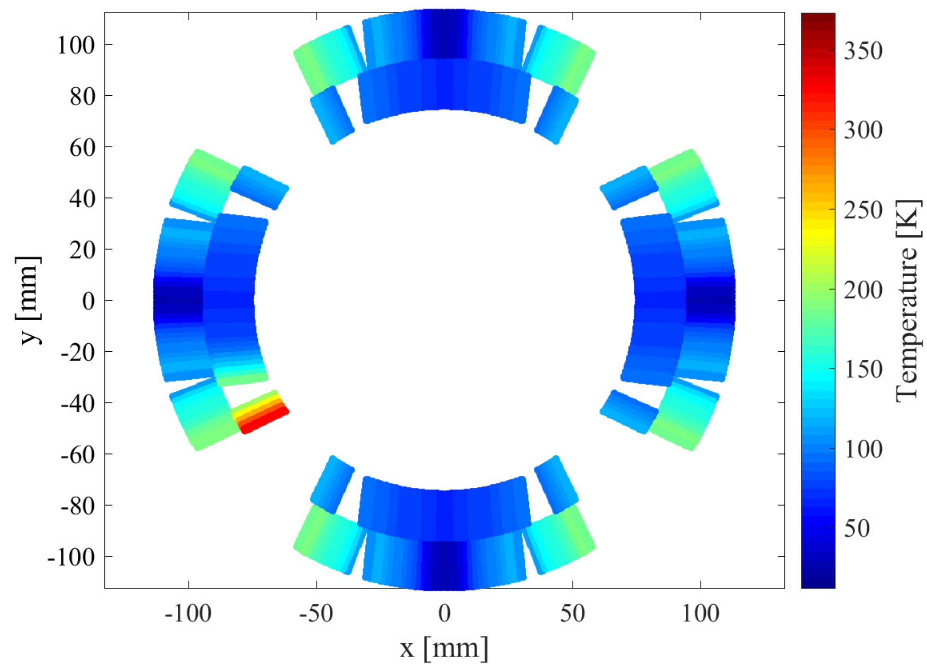




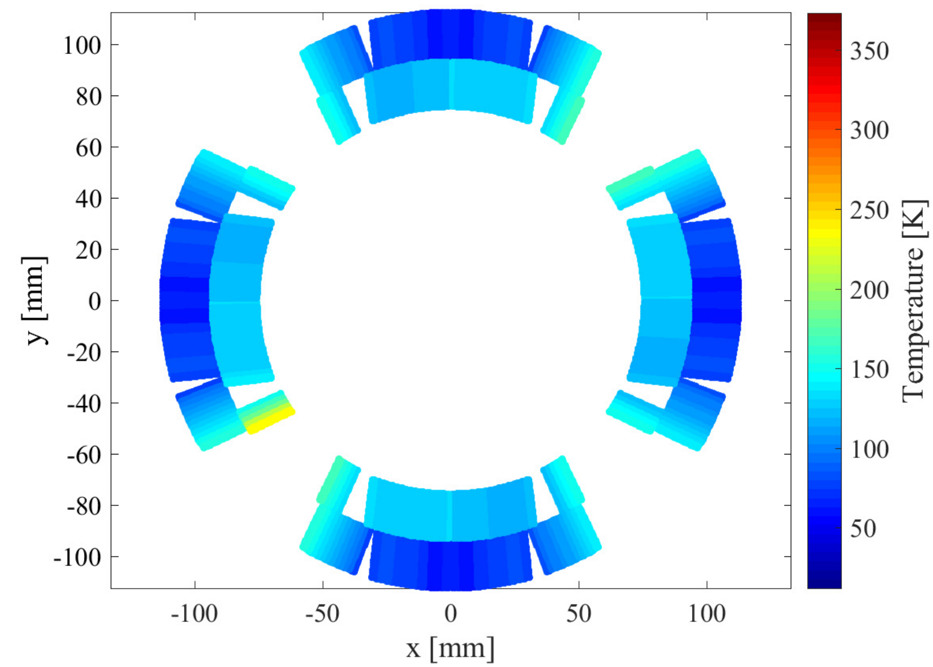
All simulations performed with the software LEDET

Simulated temperature distribution

With outer quench heaters

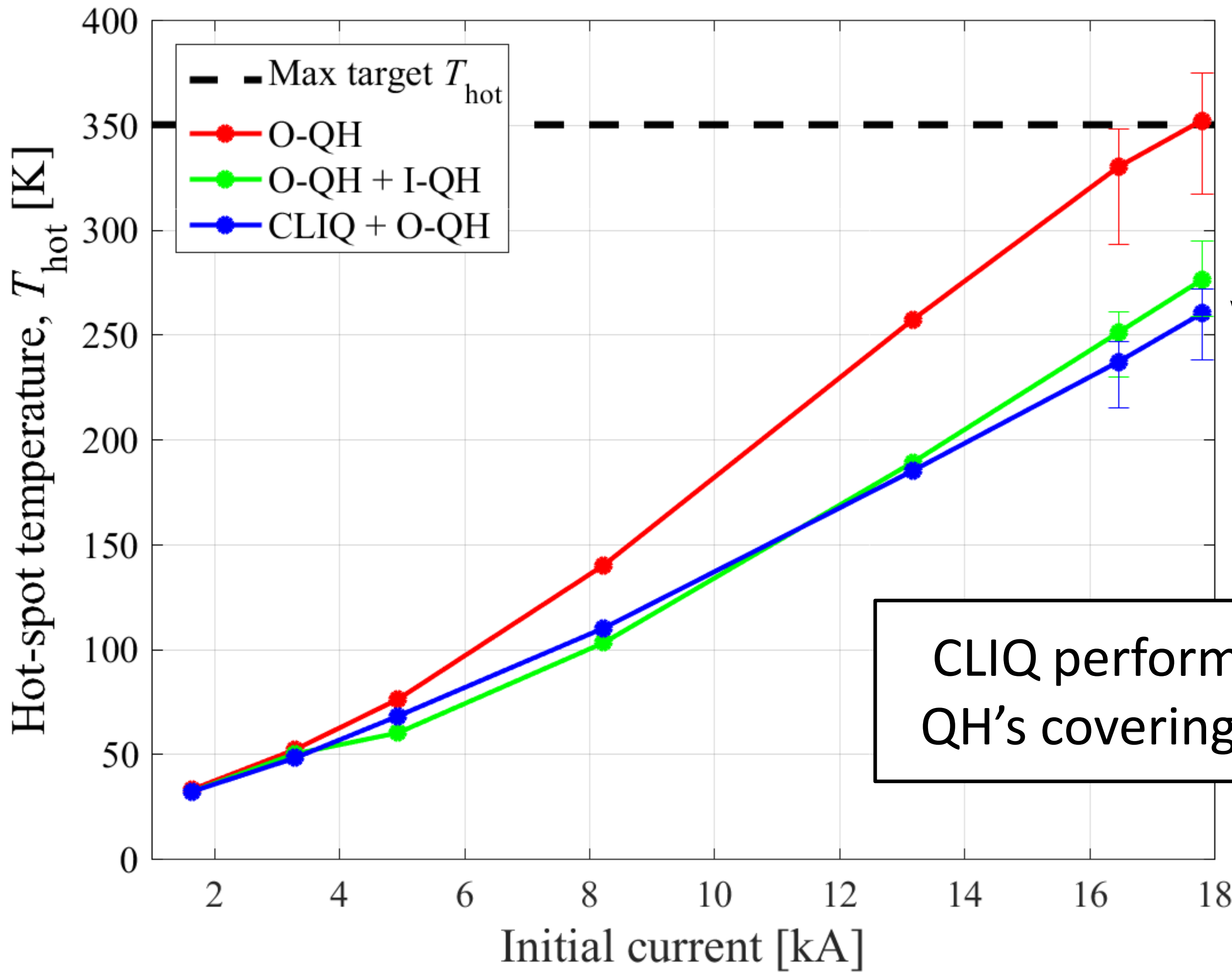


With CLIQ



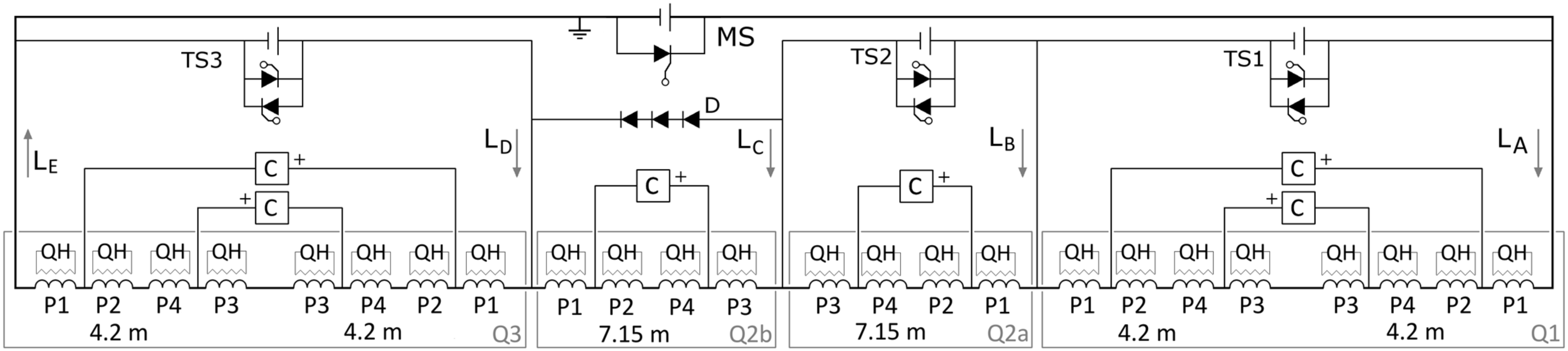
Due to CLIQ's **faster** quench initiation, **lower hot-spot temperature** and **more homogeneous** temperature distribution

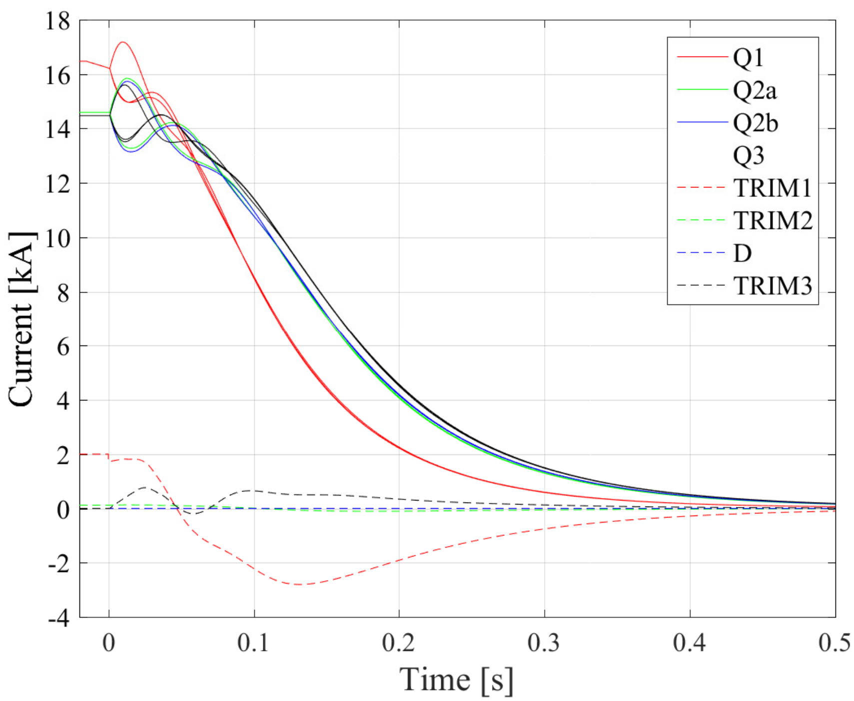
Simulated protection performance

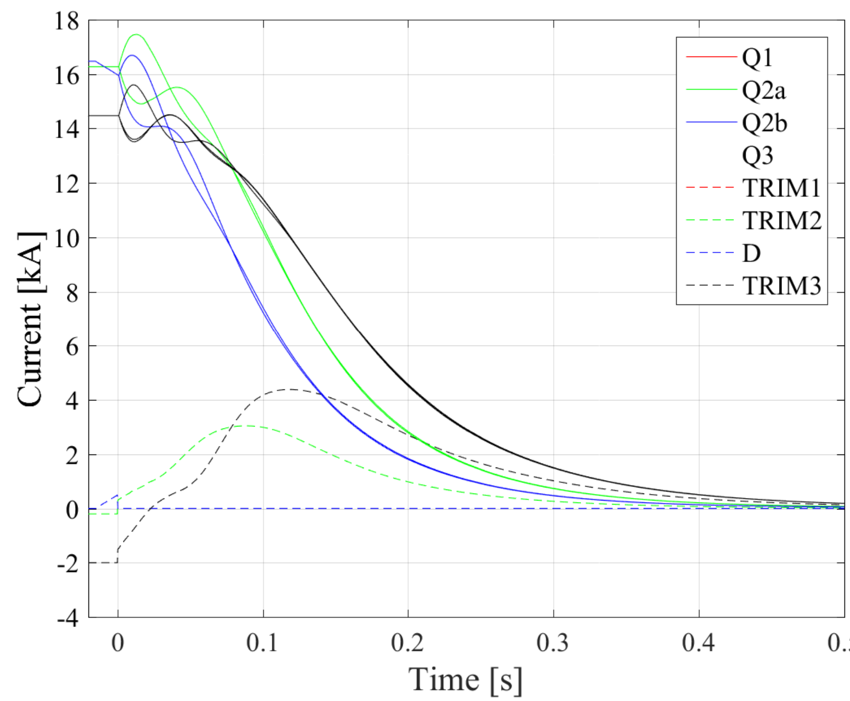


CLIQ performance similar to QH's covering most coil turns

CLIQ integrated in the MQXF circuit







Outline

CLIQ – Coupling-Loss Induced Quench system

Implementation on existing accelerator magnets

Implementation on future accelerator magnets

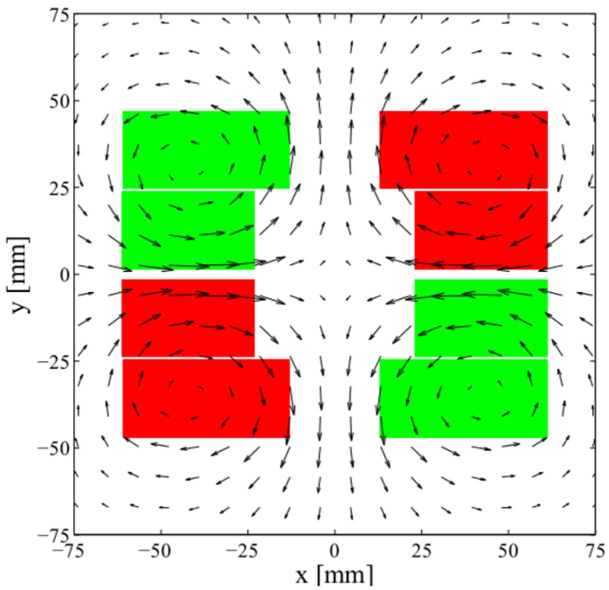
High-Lumi LHC inner triplet quadrupoles

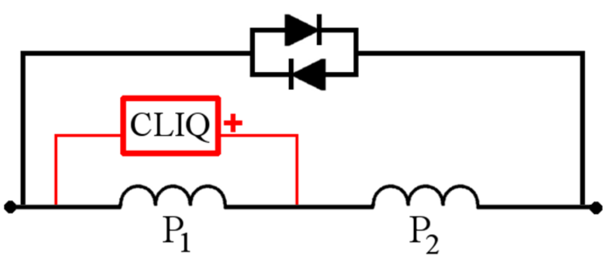
FCC 16 T block-coil magnet

Outlook

CLIQ on 16 T block-coil magnet

Pole-Pole





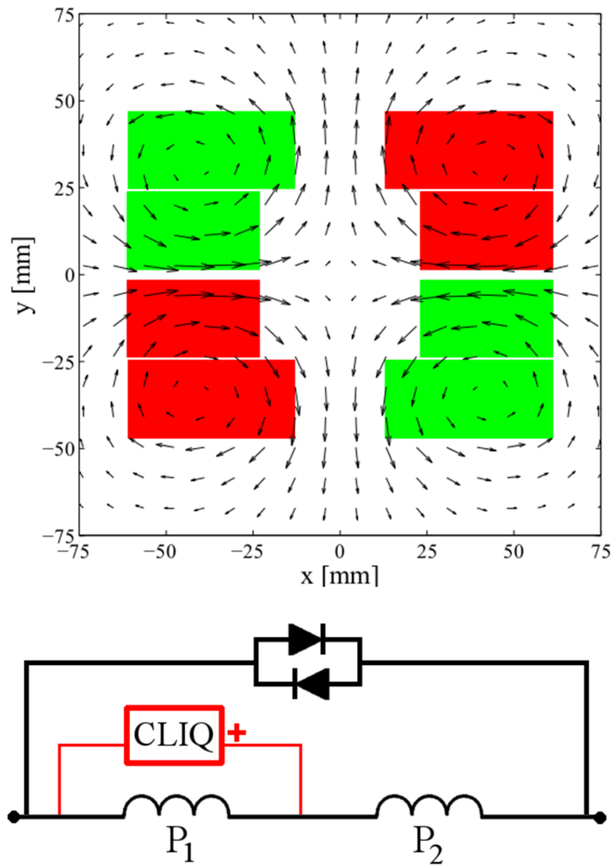
Requiring 1 **intra-pole** CLIQ terminal

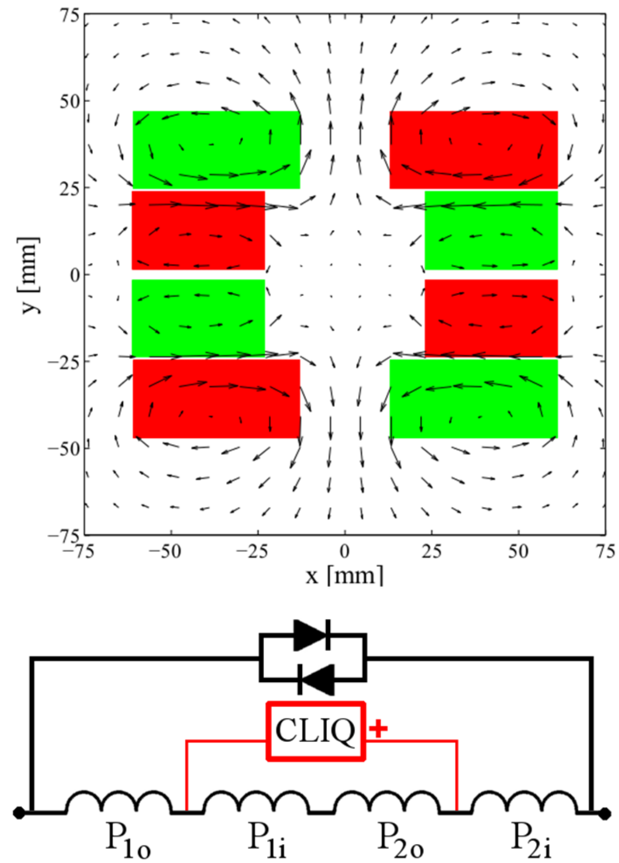
J. Blomber Ghini, thesis, 2015

CLIQ on 16 T block-coil magnet

Pole-Pole

Crossed-Layer



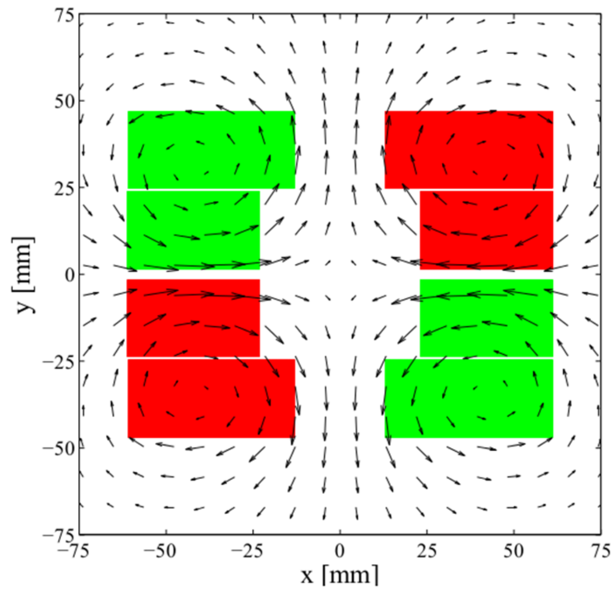


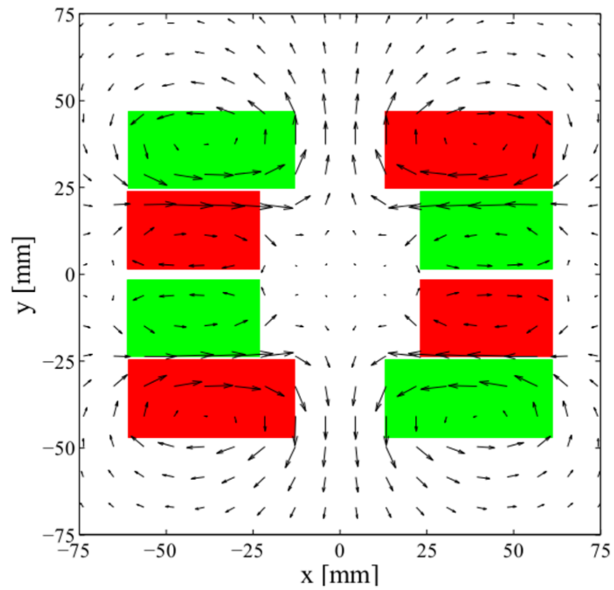
Requiring 1 **intra-pole** CLIQ terminal

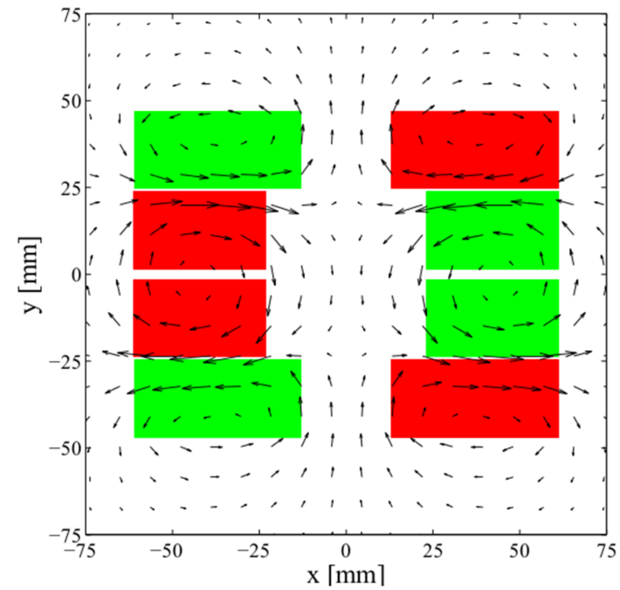
J. Blomber Ghini, thesis, 2015

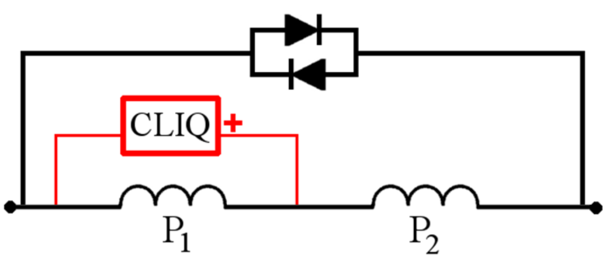
CLIQ on 16 T block-coil magnet

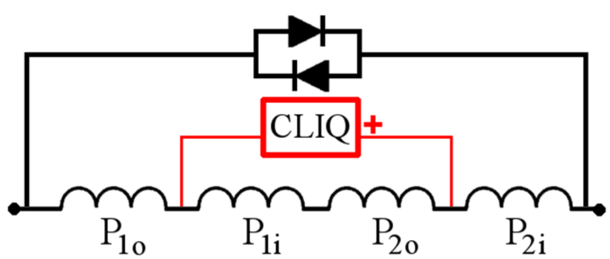
Pole-Pole	Crossed-Layer	Layer-Layer

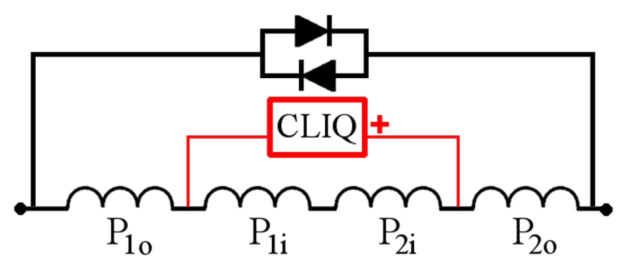












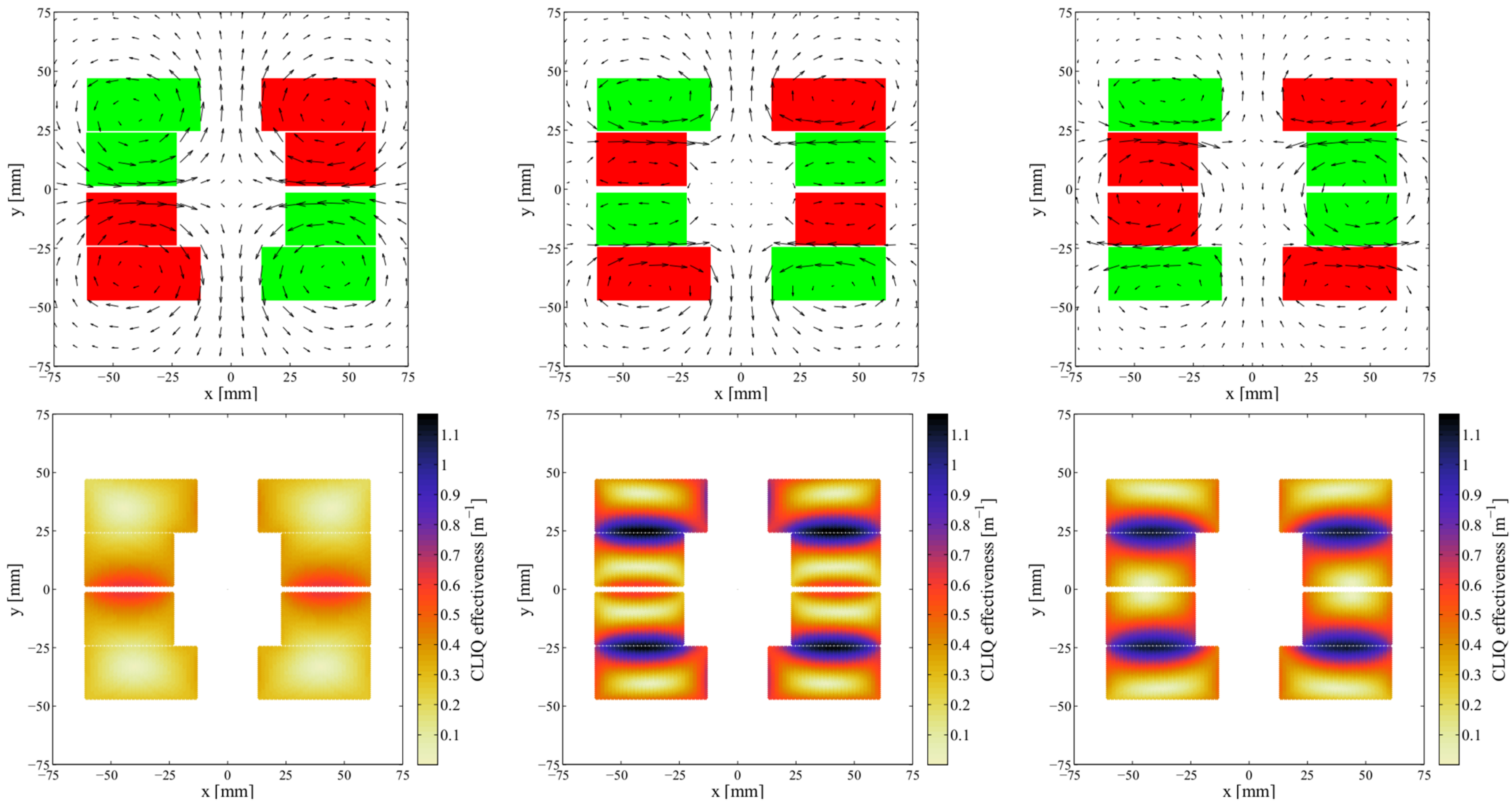
Requiring 1 **intra-pole** CLIQ terminal

Requiring 2 **intra-layer** CLIQ terminals

J. Blomber Ghini, thesis, 2015

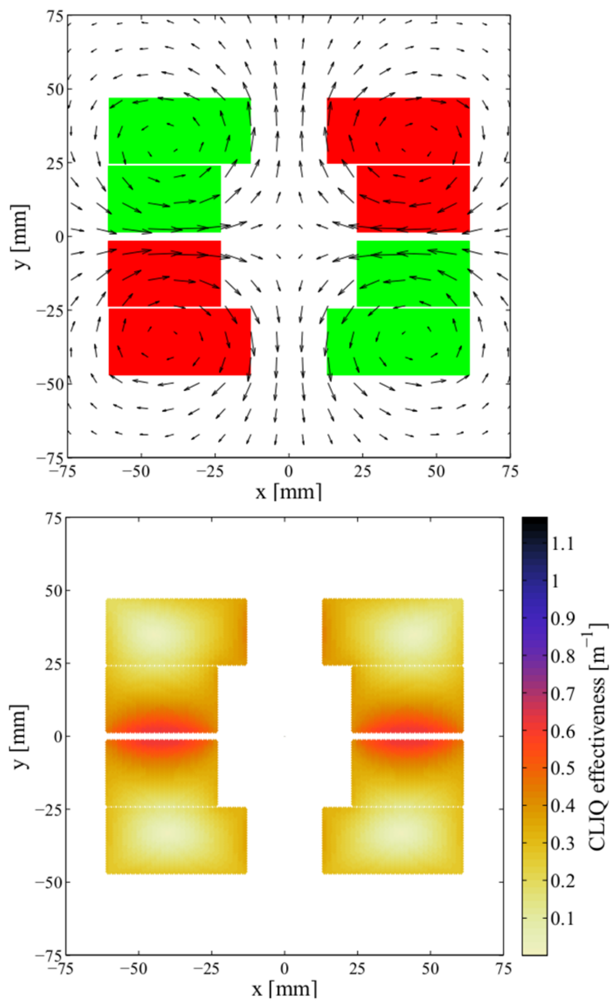
CLIQ on 16 T block-coil magnet

Pole-Pole | Crossed-Layer | Layer-Layer

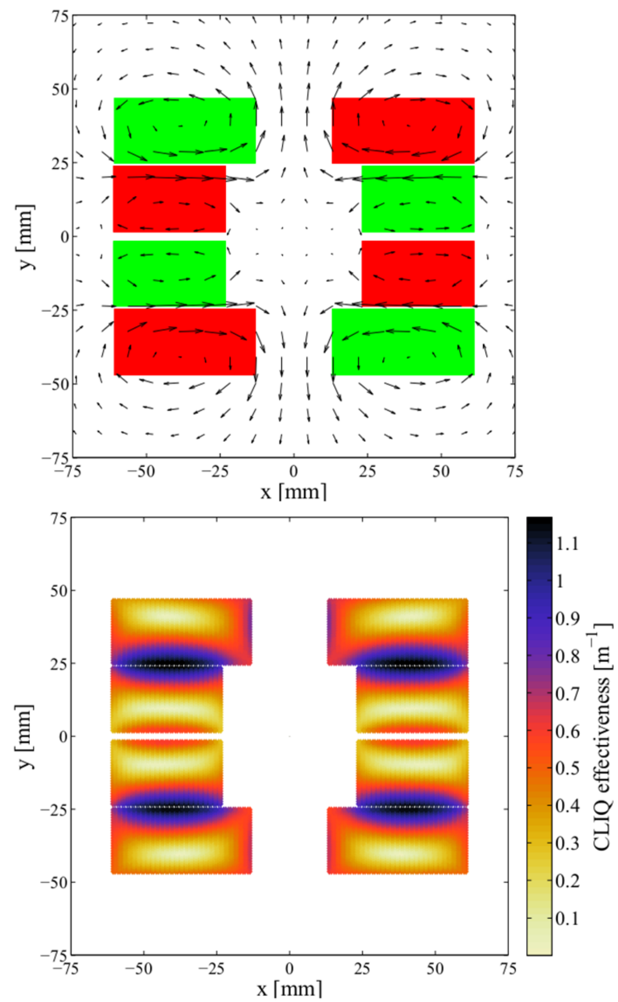


CLIQ on 16 T block-coil magnet

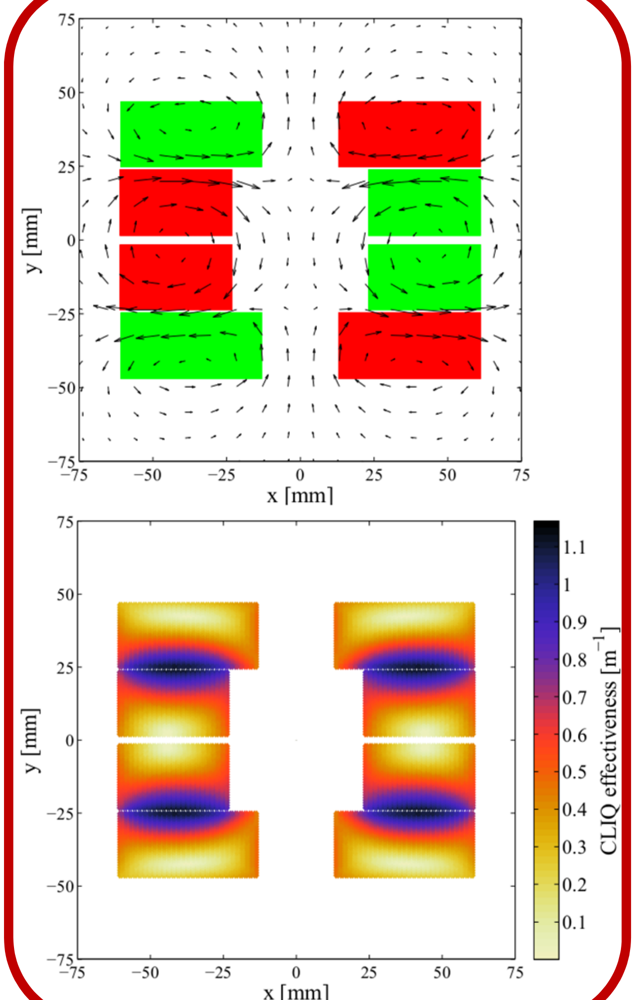
Pole-Pole



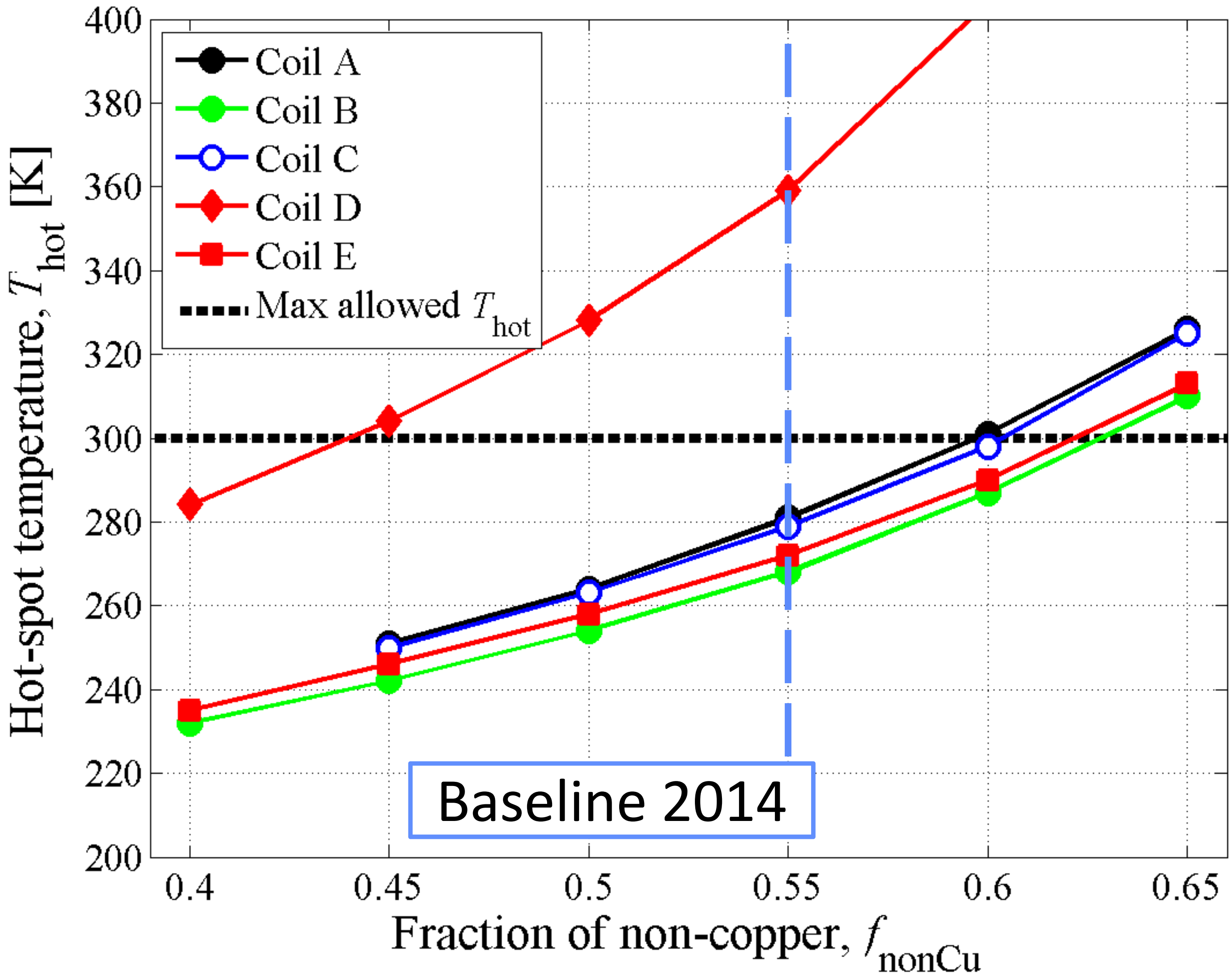
Crossed-Layer

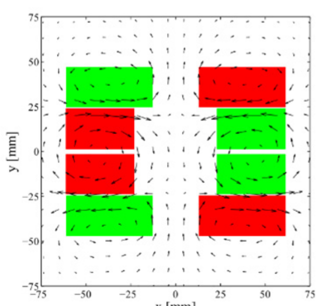


Layer-Layer

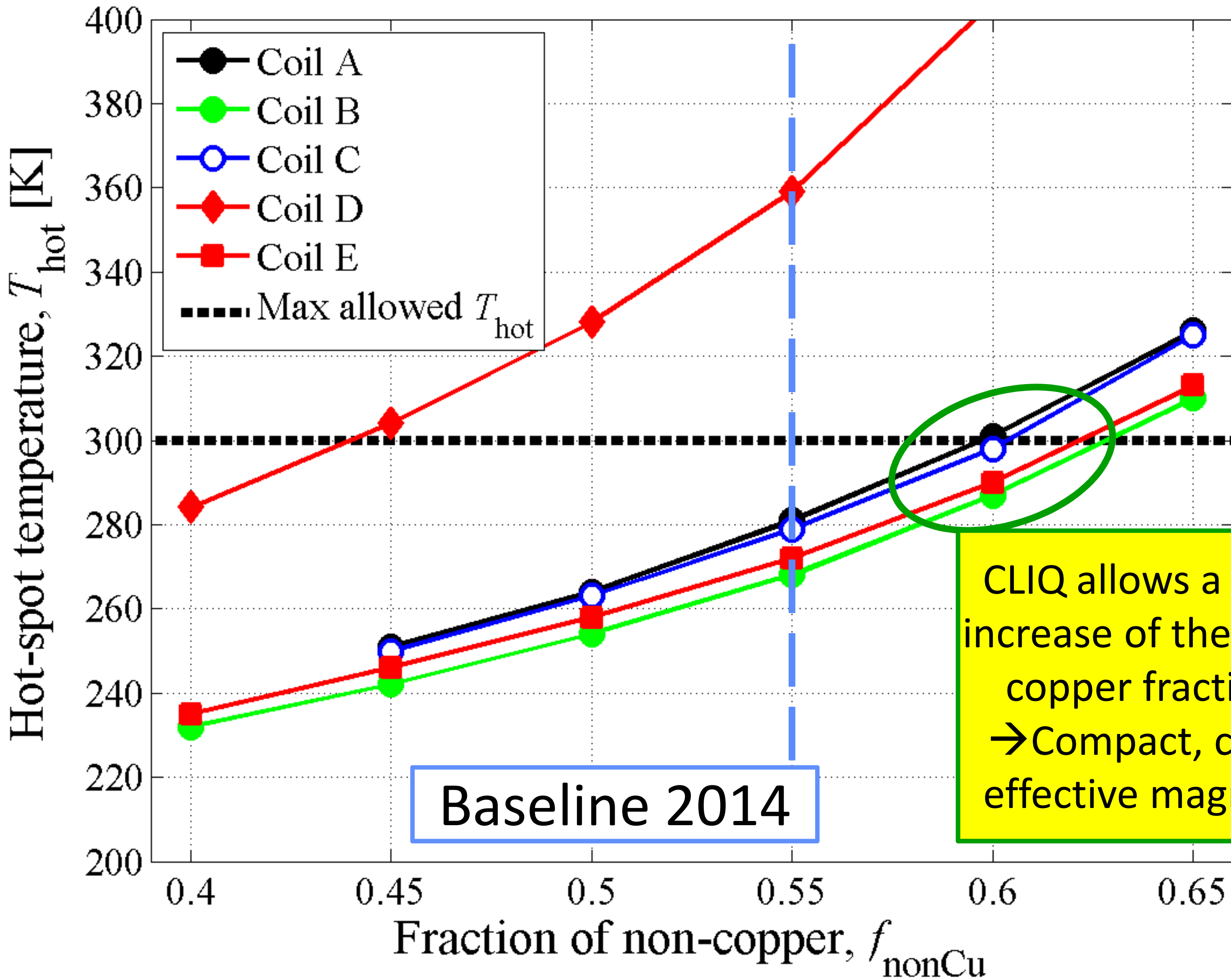


CLIQ on 16 T block-coil magnet

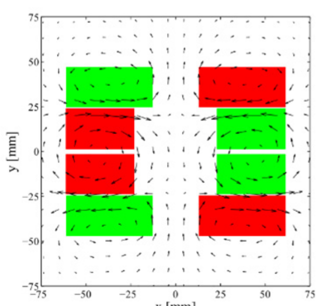




CLIQ on 16 T block-coil magnet



CLIQ allows a safe increase of the non-copper fraction →Compact, cost-effective magnets



Outline

CLIQ – Coupling-Loss Induced Quench system

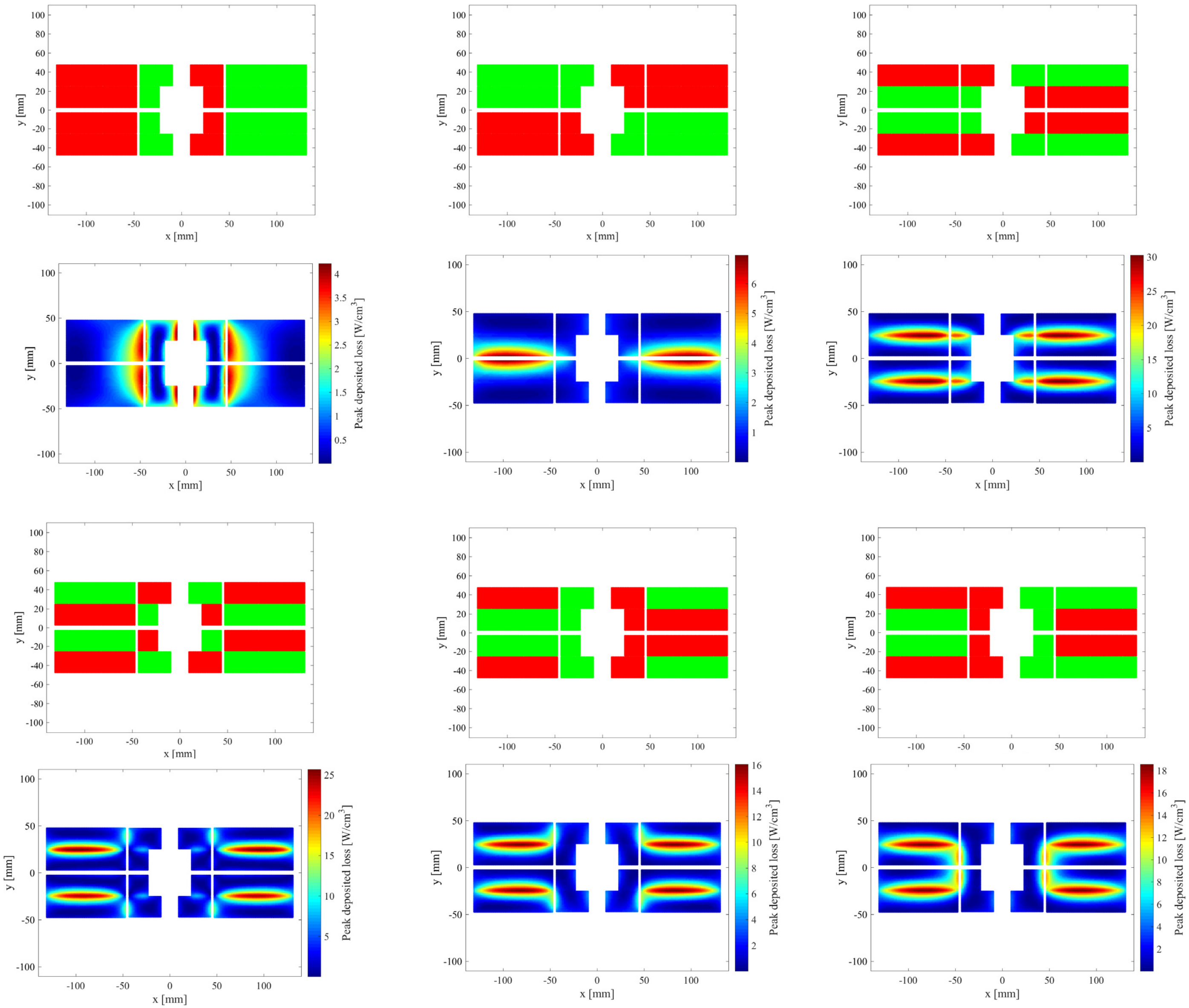
Implementation on existing accelerator magnets

Implementation on future accelerator magnets

- High-Lumi LHC inner triplet quadrupoles
- FCC 16 T block-coil magnet
- **FCC 20 T block-coil magnet with HTS insert**

Outlook

CLIQ on 20 T LTS/HTS block-coil magnet



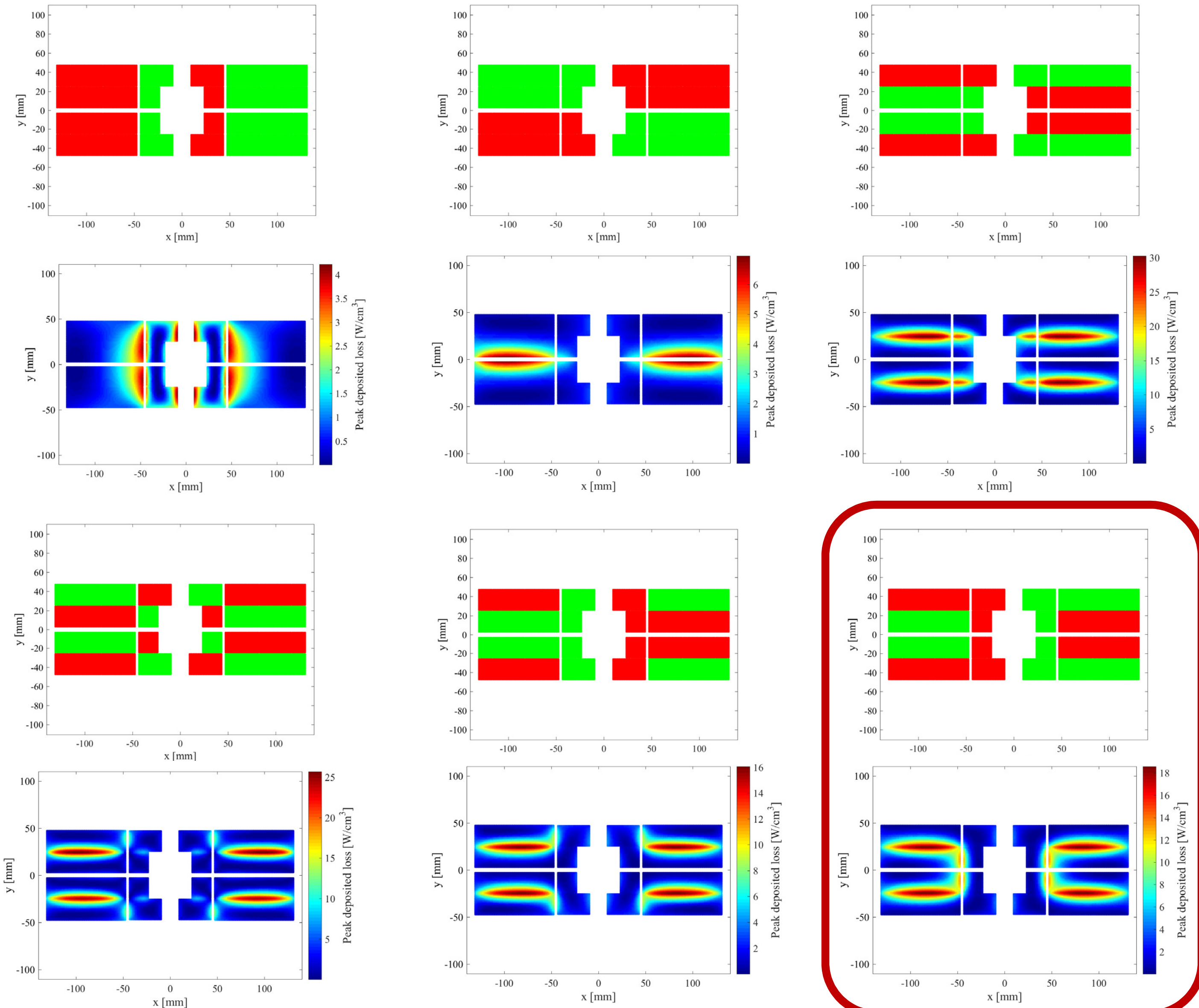
Nb$_3$Sn 15 T
Outsert
in series to
Bi-2212 5 T
Insert

<u>1 CLIQ Unit</u>
U0=1 kV C=150 mF

CLIQ on 20 T LTS/HTS block-coil magnet

LARP

High Luminosity LHC

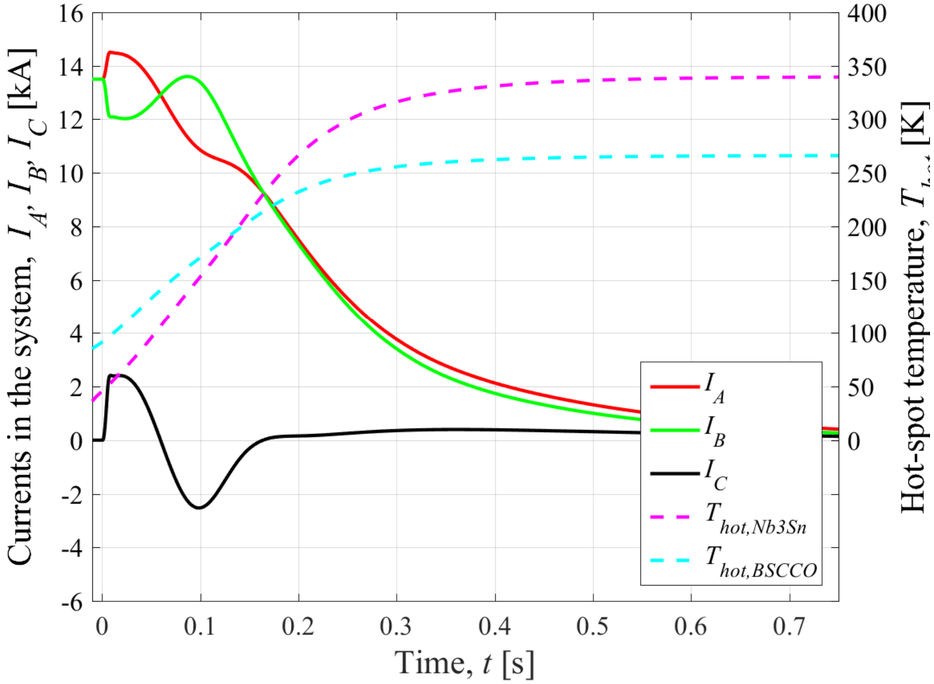


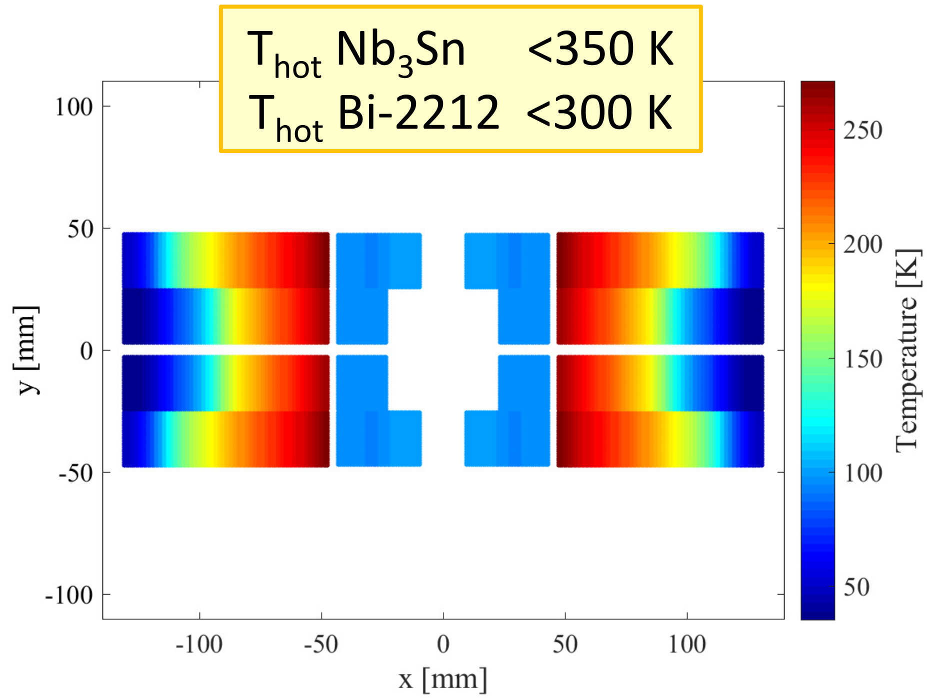
Nb_3Sn 15 T Outsert
in series to
Bi-2212 5 T Insert

1 CLIQ Unit
U0=1 kV C=150 mF

Optimum CLIQ configuration

CLIQ on 20 T LTS/HTS block-coil magnet





LTS+HTS protection with CLIQ: **HTS insert** is safely discharged by the resistance developed in the **LTS outsert** connected in series

Outline

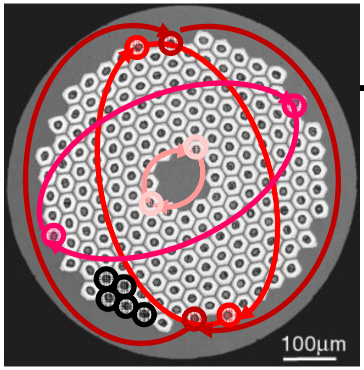
CLIQ – Coupling-Loss Induced Quench system

Implementation on existing accelerator magnets

Implementation on future accelerator magnets

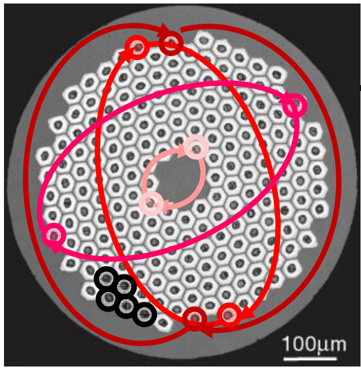
Outlook

Outlook



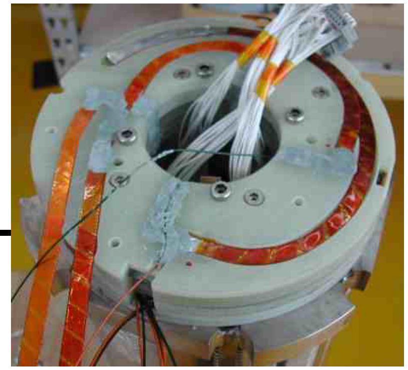
CLIQ: **Faster** and **more effective** energy deposition mechanism

Outlook

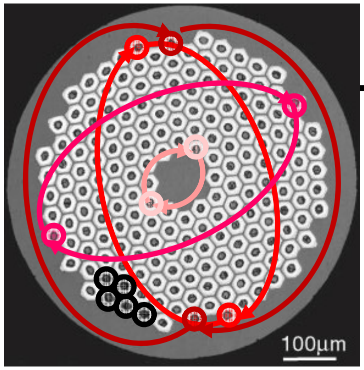


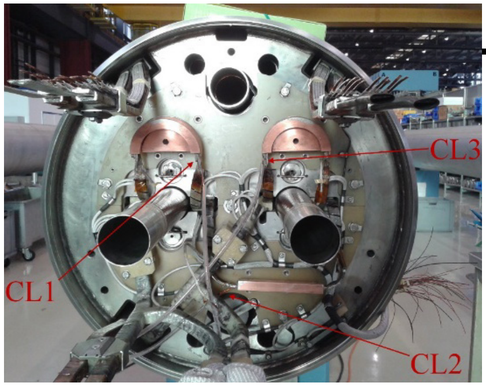
CLIQ: **Faster** and **more effective** energy deposition mechanism

CLIQ: **More robust** electrical design



Outlook

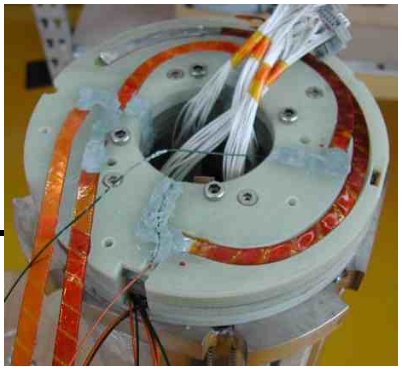




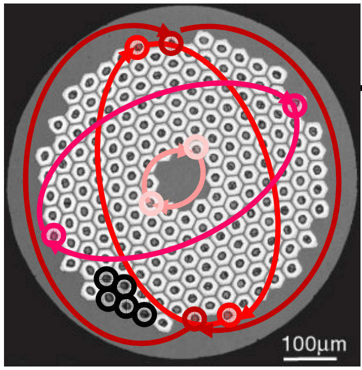
CLIQ: **Faster** and **more effective** energy deposition mechanism

CLIQ: **More robust** electrical design

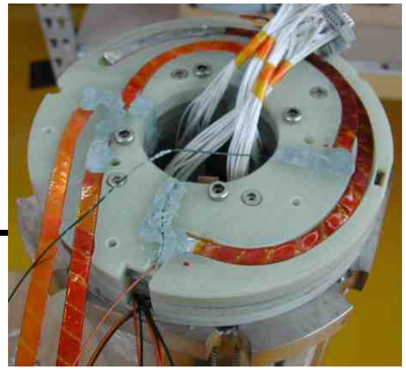
Tested on **full-size** accelerator dipole & quadrupole magnets



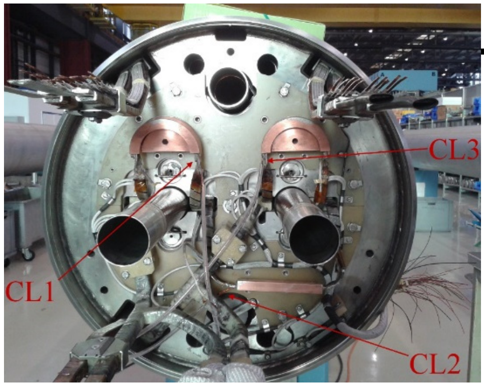
Outlook



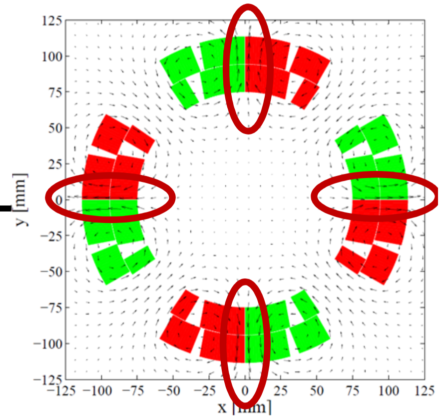
CLIQ: **Faster** and **more effective** energy deposition mechanism



CLIQ: **More robust** electrical design

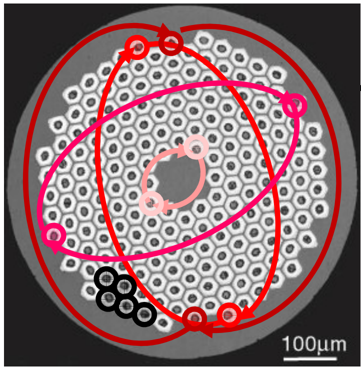


Tested on **full-size** accelerator dipole & quadrupole magnets



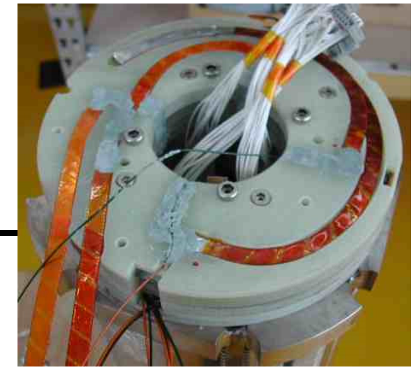
In the baseline for the **protection** of **HL-LHC** Nb_3Sn inner triplets

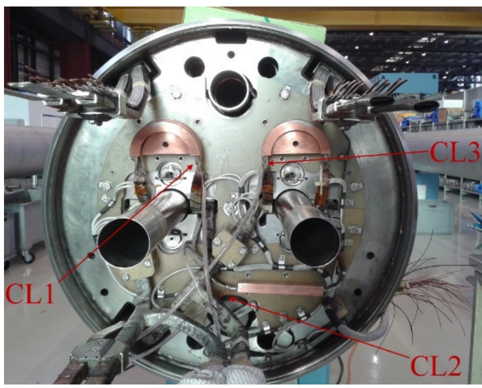
Outlook



CLIQ: **Faster** and **more effective** energy deposition mechanism

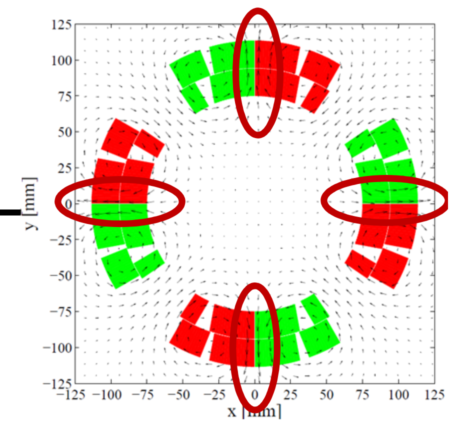
CLIQ: **More robust** electrical design

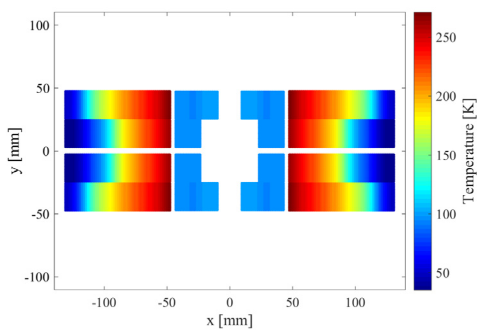




Tested on **full-size** accelerator dipole & quadrupole magnets

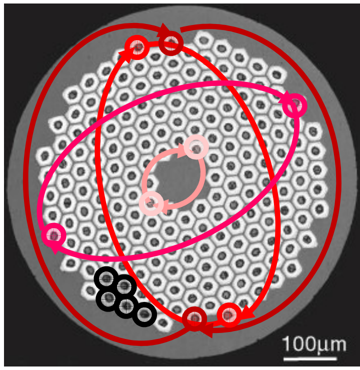
In the baseline for the **protection** of **HL-LHC** Nb_3Sn inner triplets



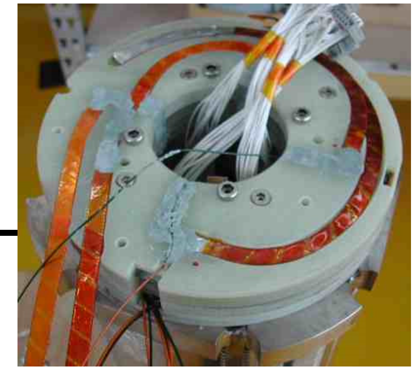


Protection of future magnets (**Future Circular Collider**, HTS)

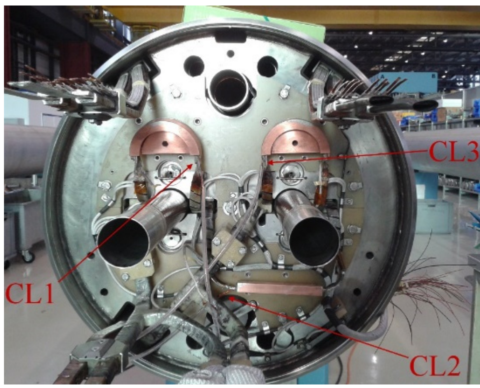
Outlook



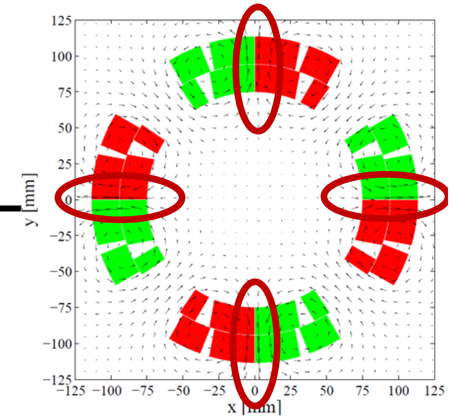
CLIQ: **Faster** and **more effective** energy deposition mechanism



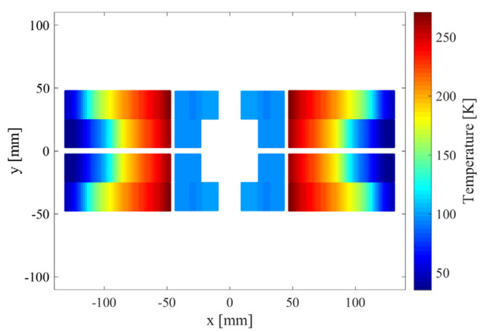
CLIQ: **More robust** electrical design



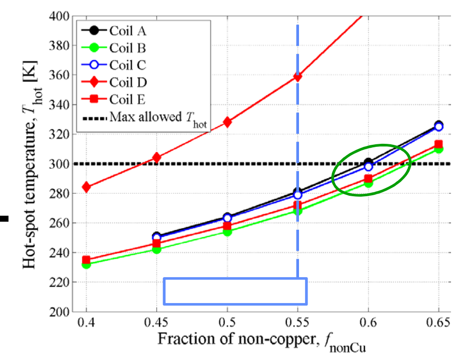
Tested on **full-size** accelerator dipole & quadrupole magnets



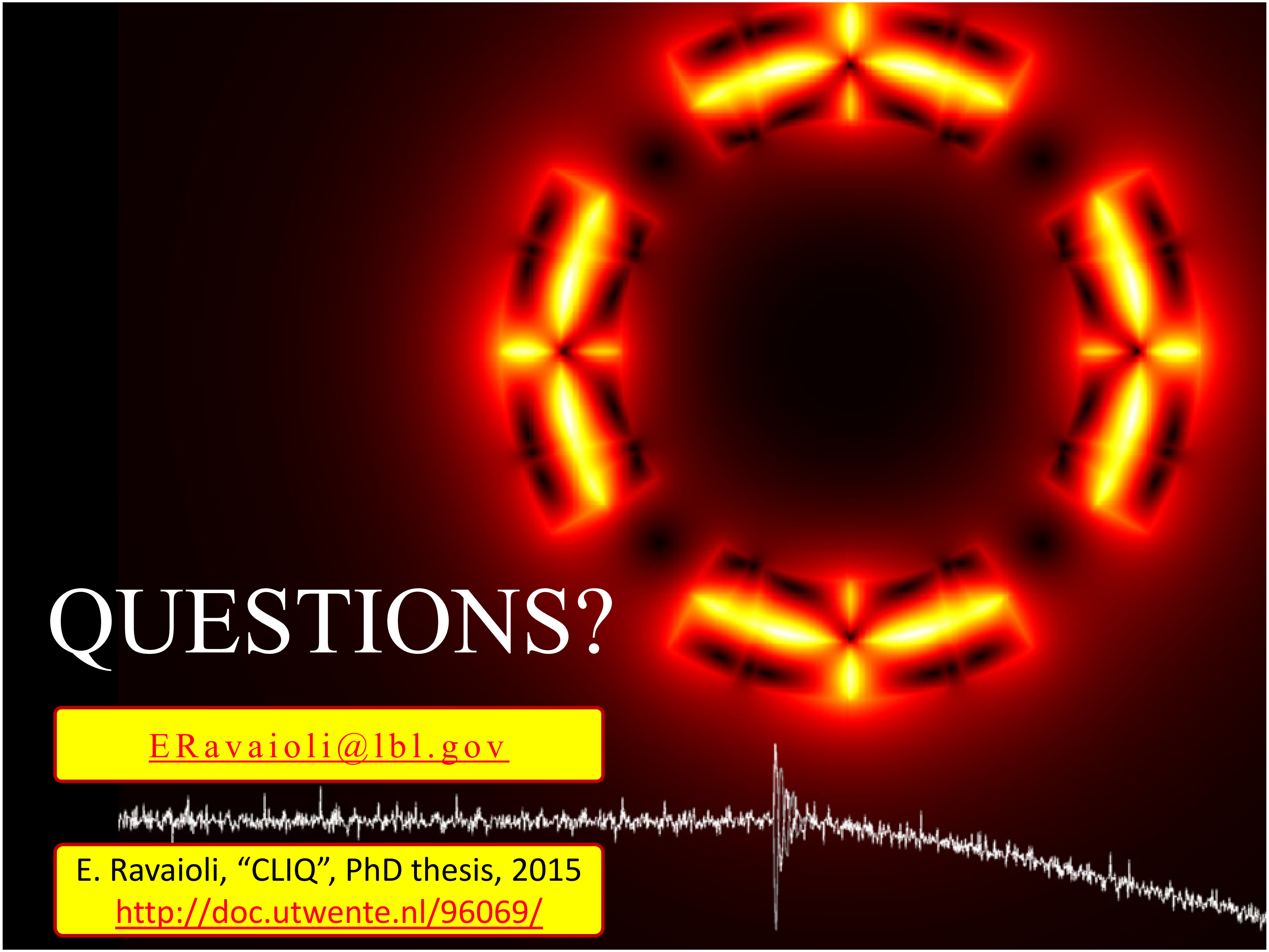
In the baseline for the **protection** of **HL-LHC** Nb_3Sn inner triplets



Protection of future magnets (**Future Circular Collider**, HTS)



Will CLIQ technology influence the **design** of future accelerator magnets? (less Cu, **more compact**)


QUESTIONS?
ERavaioli@lbl.gov
E. Ravaioli, "CLIQ", PhD thesis, 2015
http://doc.utwente.nl/96069/