Electromagnetic compatibility and losses in SC cables

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WP6a partner through UK-HL-LHC collaboration

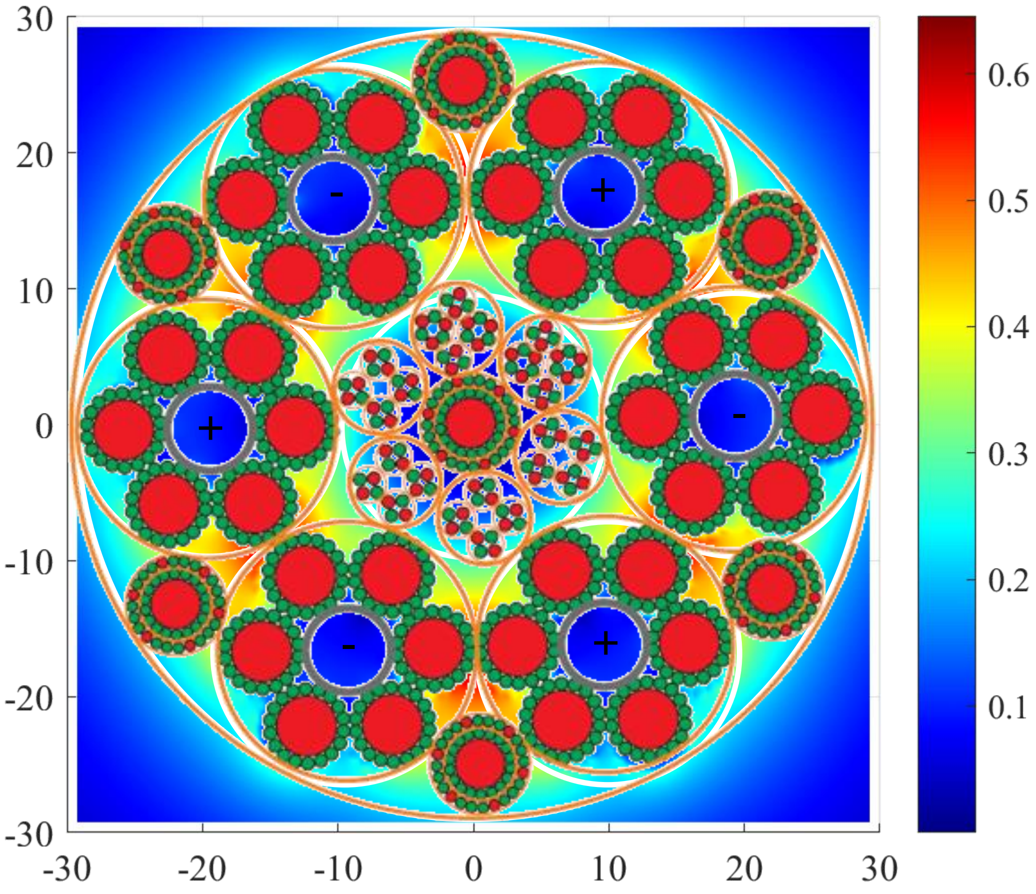
International Review of the Conceptual Design of the Cold Powering System
for the HL-LHC Superconducting Magnets Geneva, CERN 3-4 July 2017

Outline

1. Scope: The magnetic/inductive coupling aspect of *electromagnetic compatibility*
2. Static field distribution
3. Field changes for different quench scenarios
4. AC losses in wires and wire assemblies
5. Estimation of losses and heating for different quench scenarios

Previous Baseline

- Baseline until May 2017consists of 6x18kA cables
  - Inner triplets: 2x18kA
  - D1: 2x12kA
  - Backup: 2x18kA
  - 7x(2kA) coaxial cable
- Symmetric layout
  - Evenly distributed B_{max}
  - Lowest self-induction



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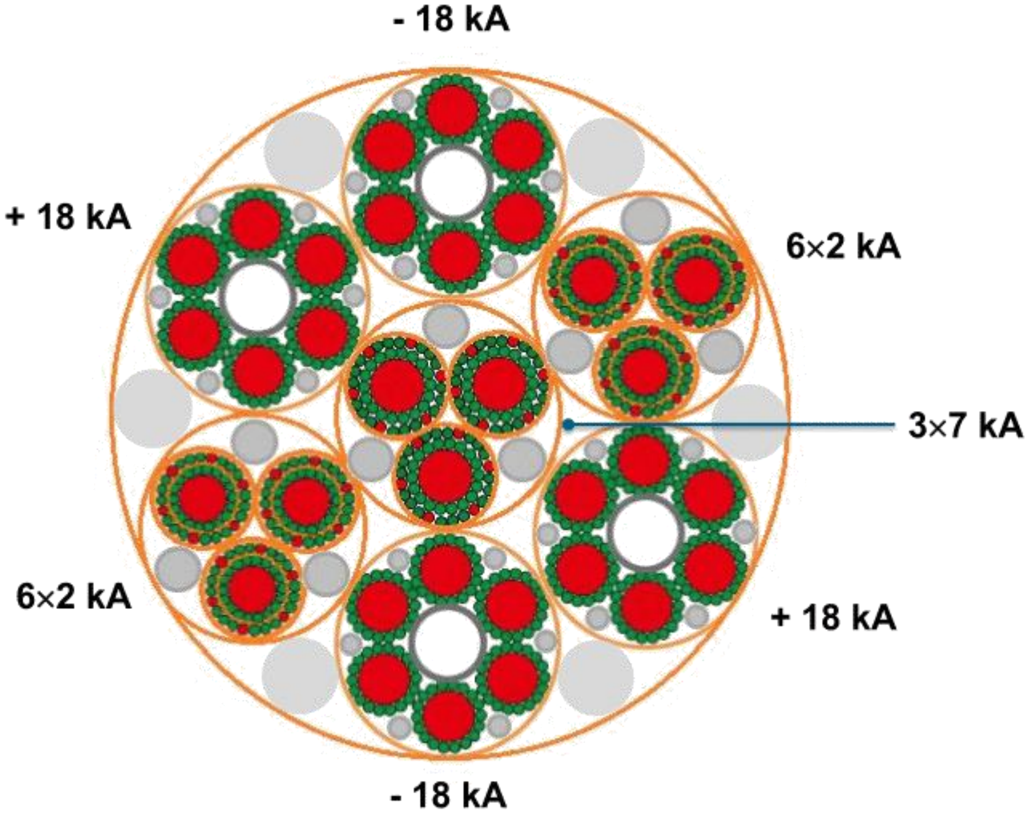
Updated Baseline and Nominal Conditions (2)

- New baseline (June 2017) consists of 2x18kA
  - Inner triplets: 2x18kA
  - D1: 2x12kA
  - 2x[3x(2kA coaxial pair)]
  - 3x7kA for trim transients
- Reduced symmetry
  - Negligible exterior field from paired coaxial cable (CC)
  - 7kA trim coaxial cables at nominal 2kA further breaks the sextupole symmetry



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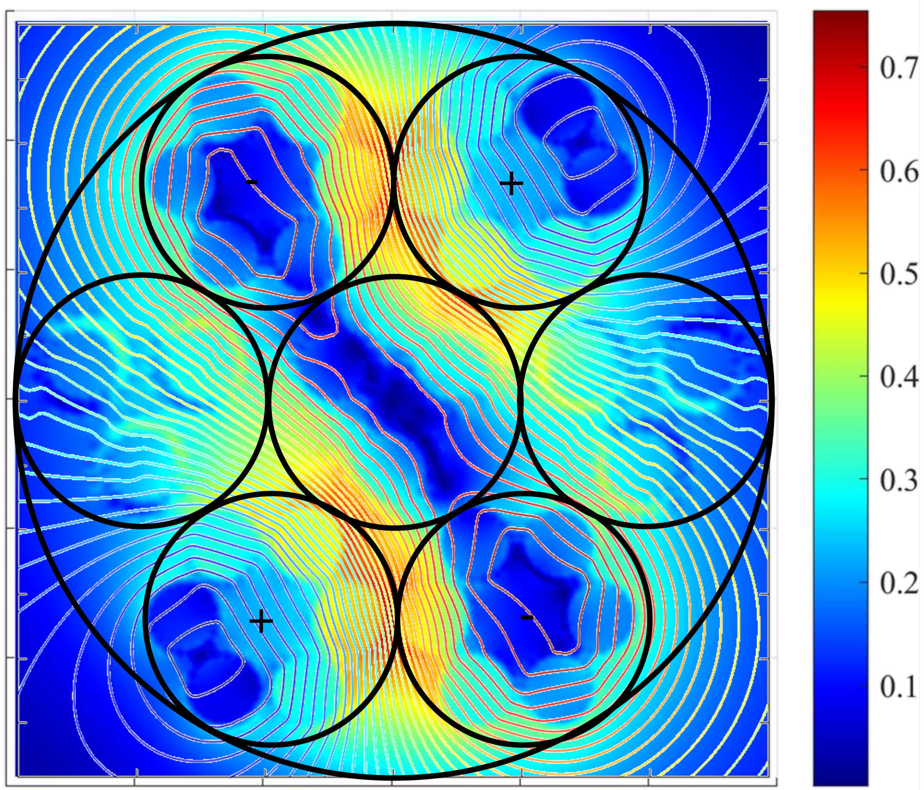
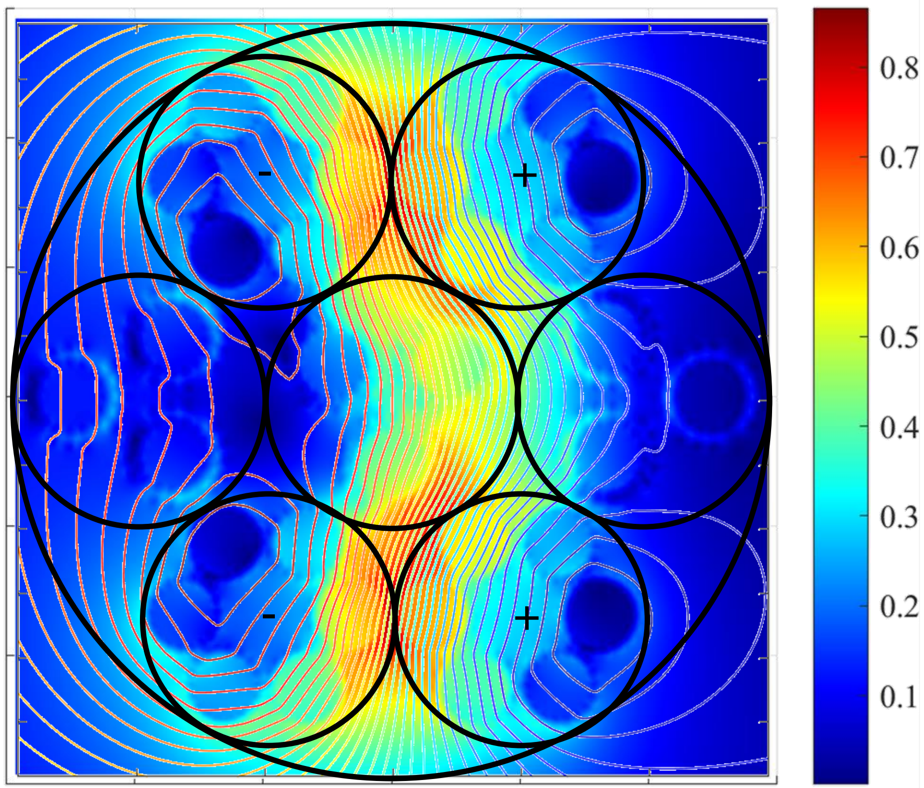
Updated Baseline and Nominal Conditions (2)

- Possible connection arrangements for 2x18kA
- Non-negligible effect on B_{max}





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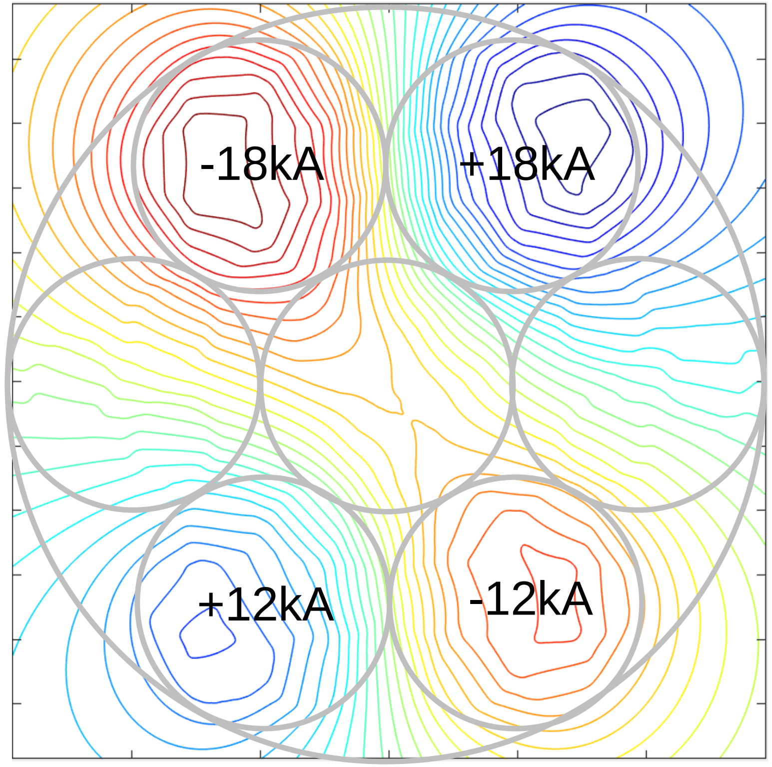
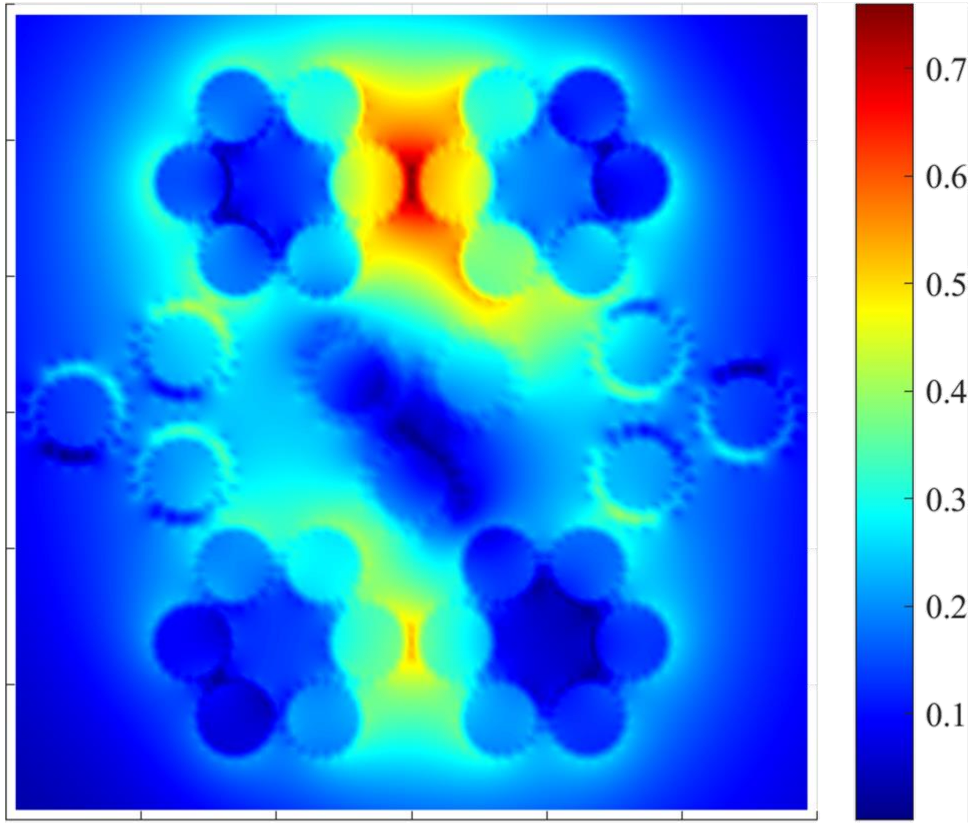
Updated Baseline and Nominal Conditions (3)

- Reference configuration: 2x18kA and 2x12kA
- B_{max}=0.76T between 2x18kA





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Electromagnetic Compatibility of Magnetic Inductance upon Quench Transients

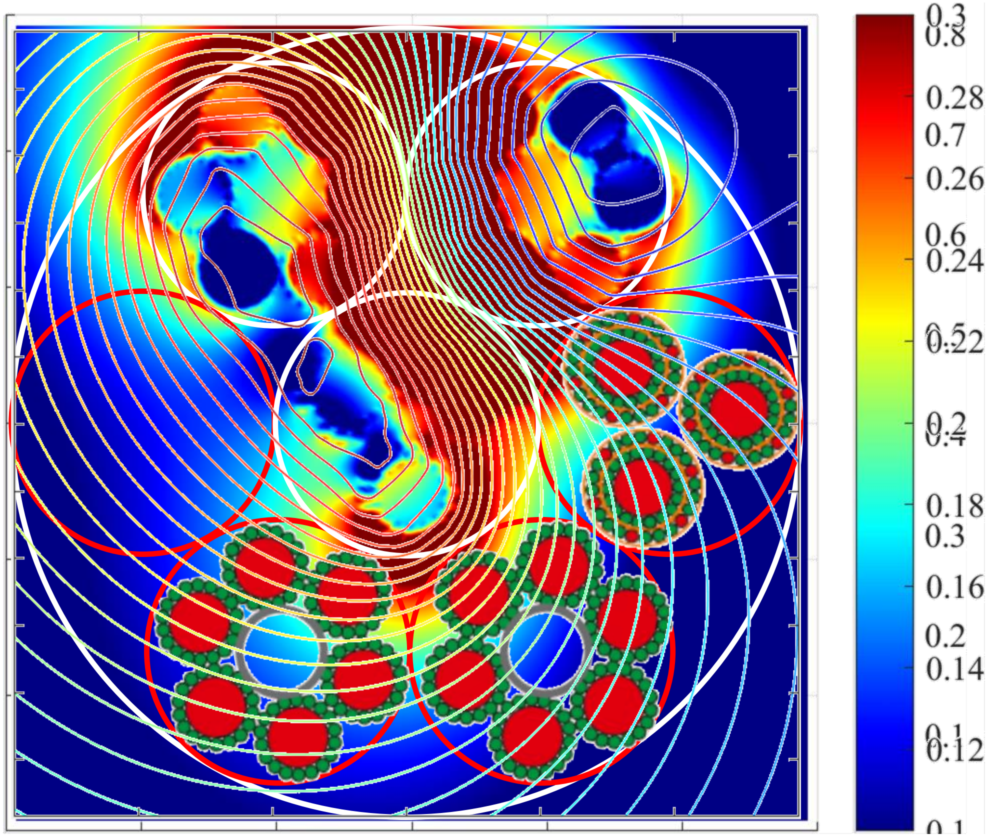
- Detailed process very complicated involving multiple induction loops of different sizes and impedances
- Challenging even by modelling
- A simplified approach:
  - Identify the distribution/orientation of ΔB due to the disappearing current of the quenched circuit
  - Identify the dominant induction loops and their sizes
  - Experimental study of losses in typical loops
  - Estimation of losses

Transient Scenarios

- Inner triplet circuit quench:
  - Field change due18kA disappearing
  - Field change due to the transient currents in the trims
- D1 circuit quench
  - Field change duo to 12kA disappearing
- Coaxial cables (CC) quench
  - Non-significant impact on their exterior field
  - Ignored

Transient Scenario: Inner Triplet Circuit Quench

- Net current change
  - Main triplet 18kA cable
    $\Delta I = \pm 18\text{kA}$
  - Trims B/C/D:
    $\Delta I_B = 0.4\text{kA}$
    $\Delta I_C = 0.8\text{kA}$
    $\Delta I_D = 3.6\text{kA}$
- Field change
  - $\Delta B_{CC} \lesssim 0.45\text{T}$
    - Scattered Cu in outer layer
    - Inner $\Delta B_{CC} \lesssim 0.3\text{T}$
    - “Uniform” field across the induction loops
  - $\Delta B_{D1} \lesssim 0.3\text{T}$
    - Modest field gradient across the induction loops



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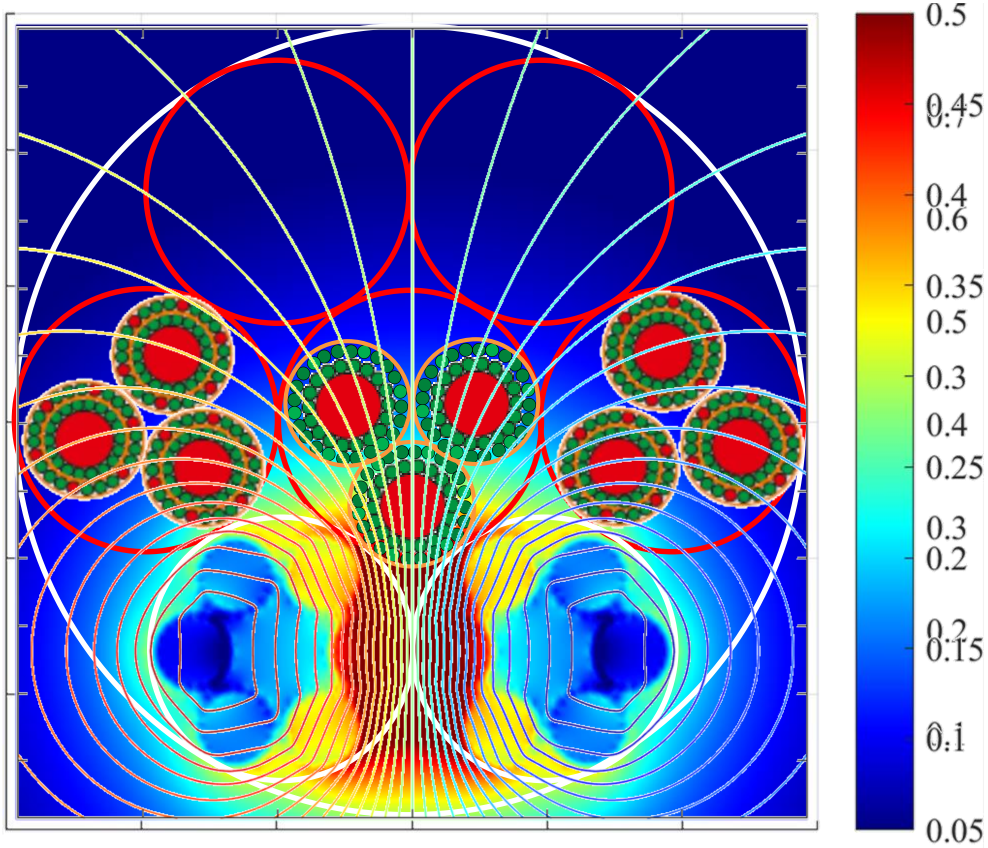
Transient Scenario: D1 Circuit Quench

- Net current change
  - D1 12kA cable
    $\Delta \mathrm{I} = \pm 12\mathrm{kA}$
- Field change
  - $\Delta \mathrm{B}_{\mathrm{Trim}} \leq 0.45\mathrm{T}$
    - Scattered Cu in outer layer
    - Inner $\Delta \mathrm{B}_{\mathrm{Trim}} \leq 0.4\mathrm{T}$
    - Widest loop: $\Delta \mathrm{B}_{\mathrm{CC}} \leq 0.33\mathrm{T}$
    - “Uniform” field across the induction loops
  - $\Delta \mathrm{B}_{\mathrm{CC}} \leq 0.27\mathrm{T}$
    - Scattered Cu in outer layer
    - Inner $\Delta \mathrm{B}_{\mathrm{CC}} \leq 0.23\mathrm{T}$
    - Widest inner loop: $\Delta \mathrm{B}_{\mathrm{CC}} \leq 0.17\mathrm{T}$
    - Modest gradient across the induction loops



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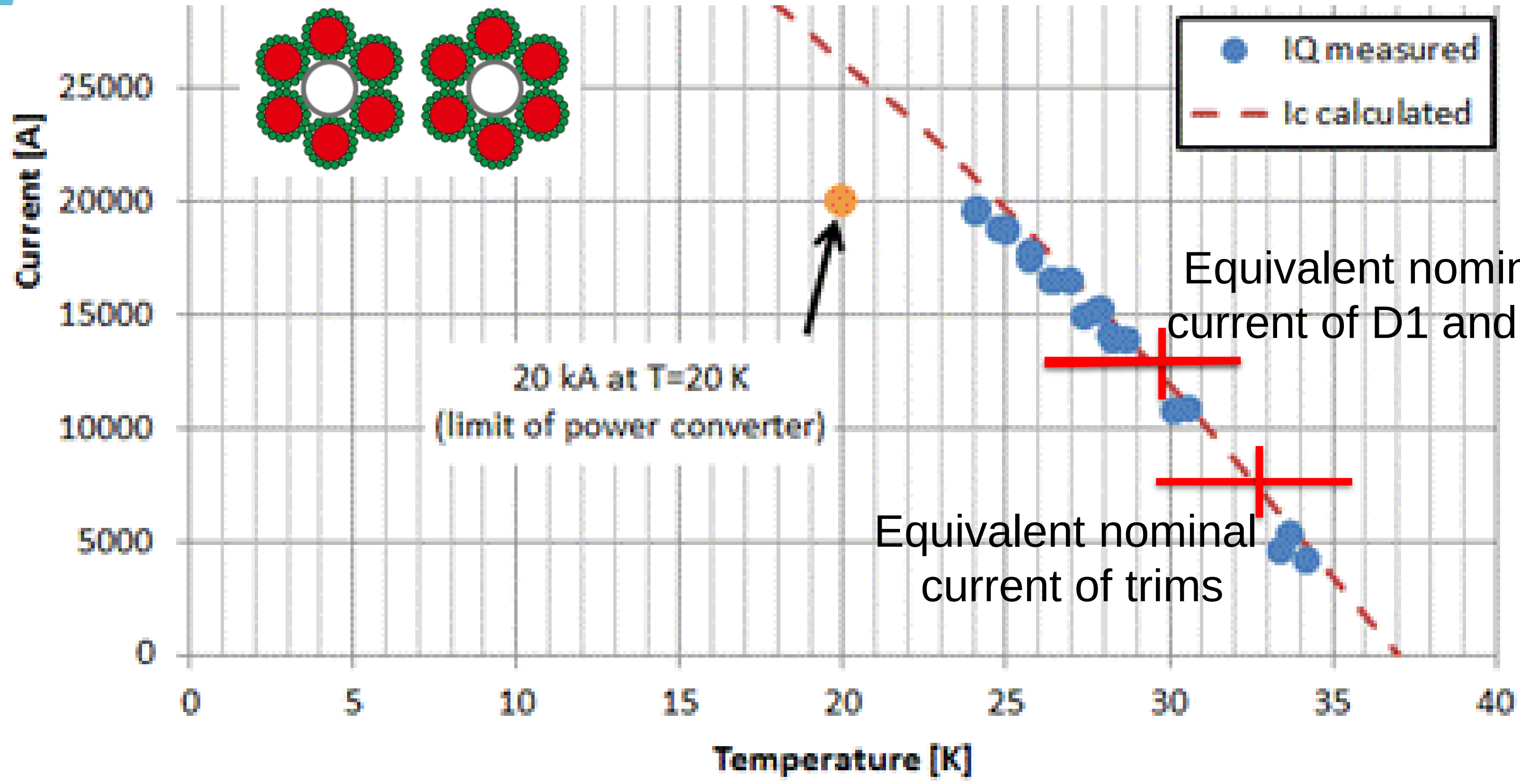
Critical Current and Temperature Margins

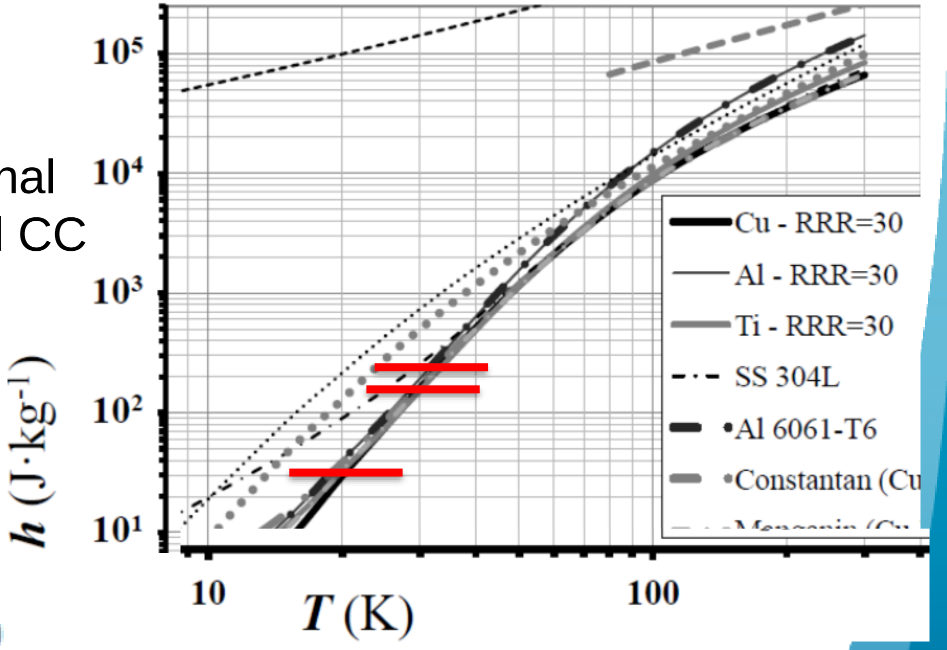
- 18kA cables of the inner triplet do not experience significant transient effects
- D1 and CC at (equivalent) 12kA: current sharing T_{cs} = 30K
- Trim cables nominal current at equivalent 6kA, T_{cs} = 33K

$$h(20\mathrm{K}) = 30\mathrm{mJg}^{-1} = 0.264\mathrm{mJmm}^{-3}$$
$$h(30\mathrm{K}) = 150\mathrm{mJg}^{-1} = 1.320\mathrm{mJmm}^{-3}$$
$$h(33\mathrm{K}) = 200\mathrm{mJg}^{-1} = 1.760\mathrm{mJmm}^{-3}$$
$$\Delta h_{D1/CC} \sim 1.0\mathrm{mJmm}^{-3}$$
$$\Delta h_{Trim} \sim 1.5\mathrm{mJmm}^{-3}$$



Equivalent nominal current of D1 and CC

Equivalent nominal current of trims



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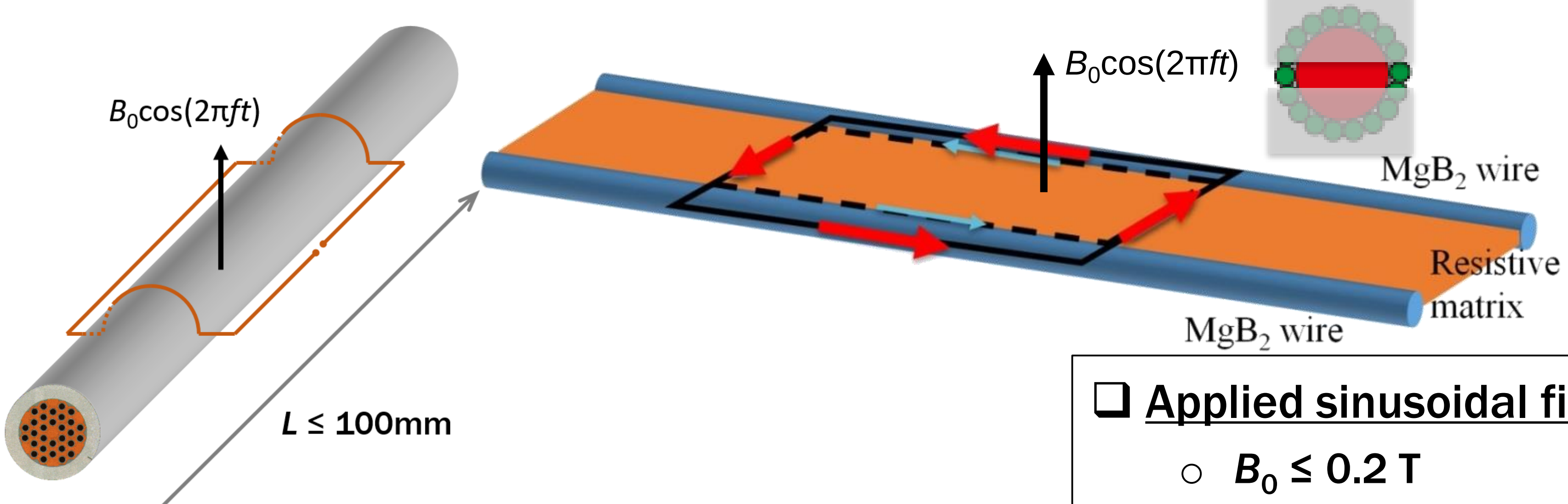
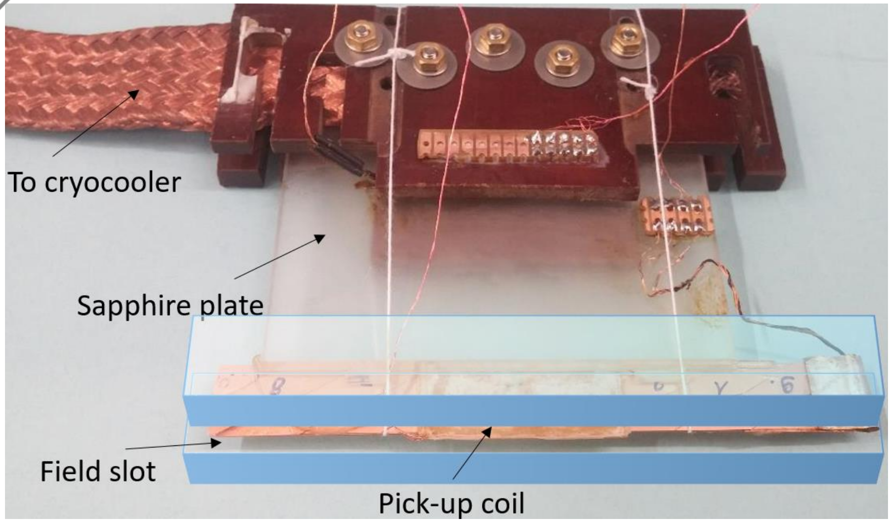
AC Loss Measurements (1)

- Direct measurements of ac losses in MgB_2 strands
- Direct measurement of 2x MgB_2 strands coupled via a norm matrix



Sample length ~ a half of sub-cable twist pitch



❑ **Applied sinusoidal field**

- **$B_0 \leq 0.2$ T**
- **5Hz ≤ f ≤ 2kHz**

❑ **Measurements**

- **3K ≤ T ≤ 100K**
- **Single-turn saddle pick-up coil**
- **Sample length $L \leq$ 100mm**
- **Sample diameter < 3mm**

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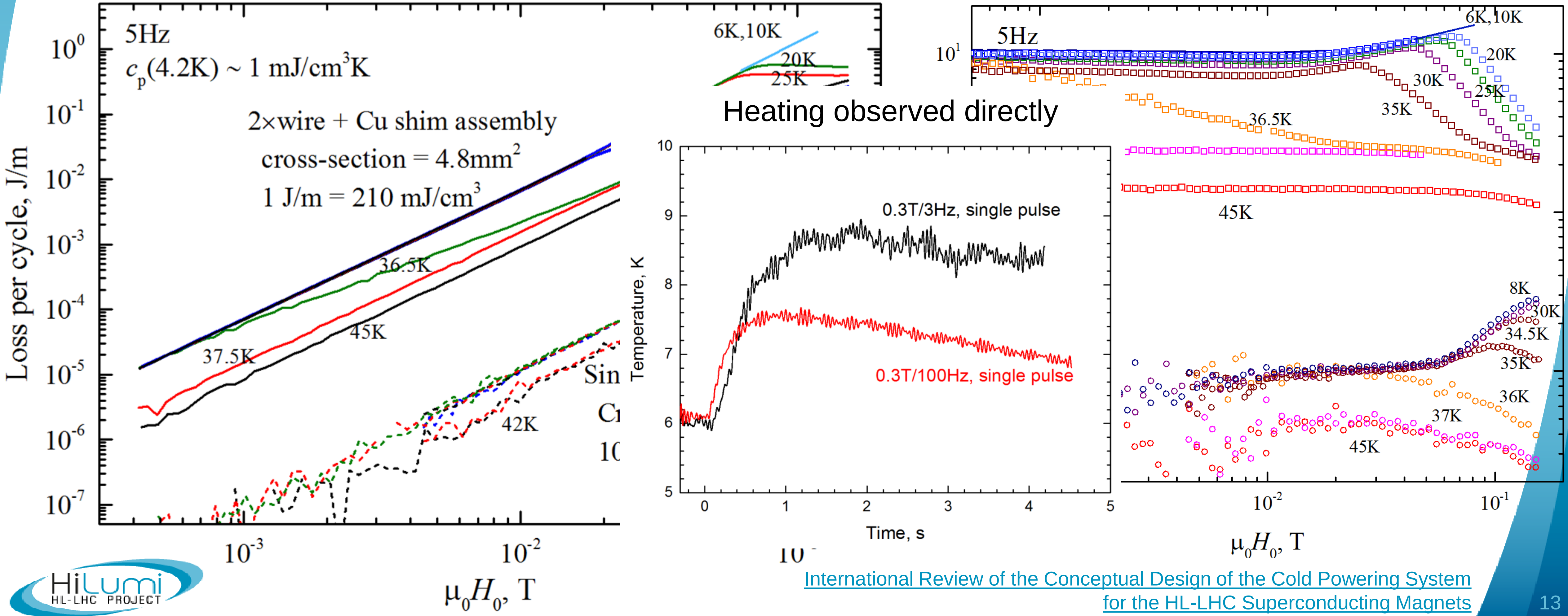
AC Loss Measurements (2)

- Wire losses 1/1000th of the coupled wires
- Losses dominated by coupling current (~B_0^2)



Heating observed directly

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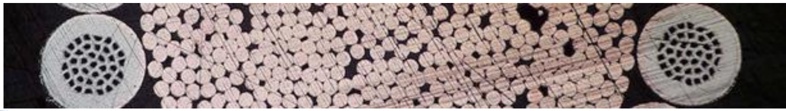
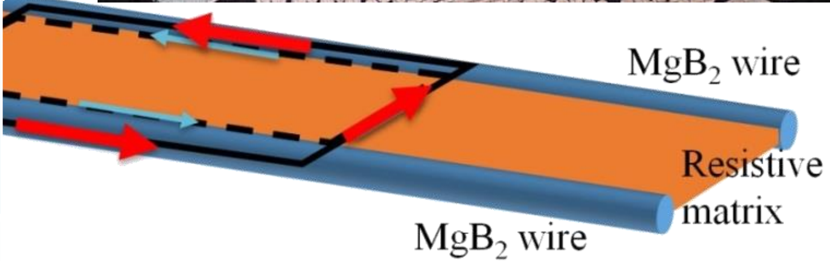
AC Loss Measurements (3)

Quench Time Constants Equivalent to 2-5Hz, 10Hz max

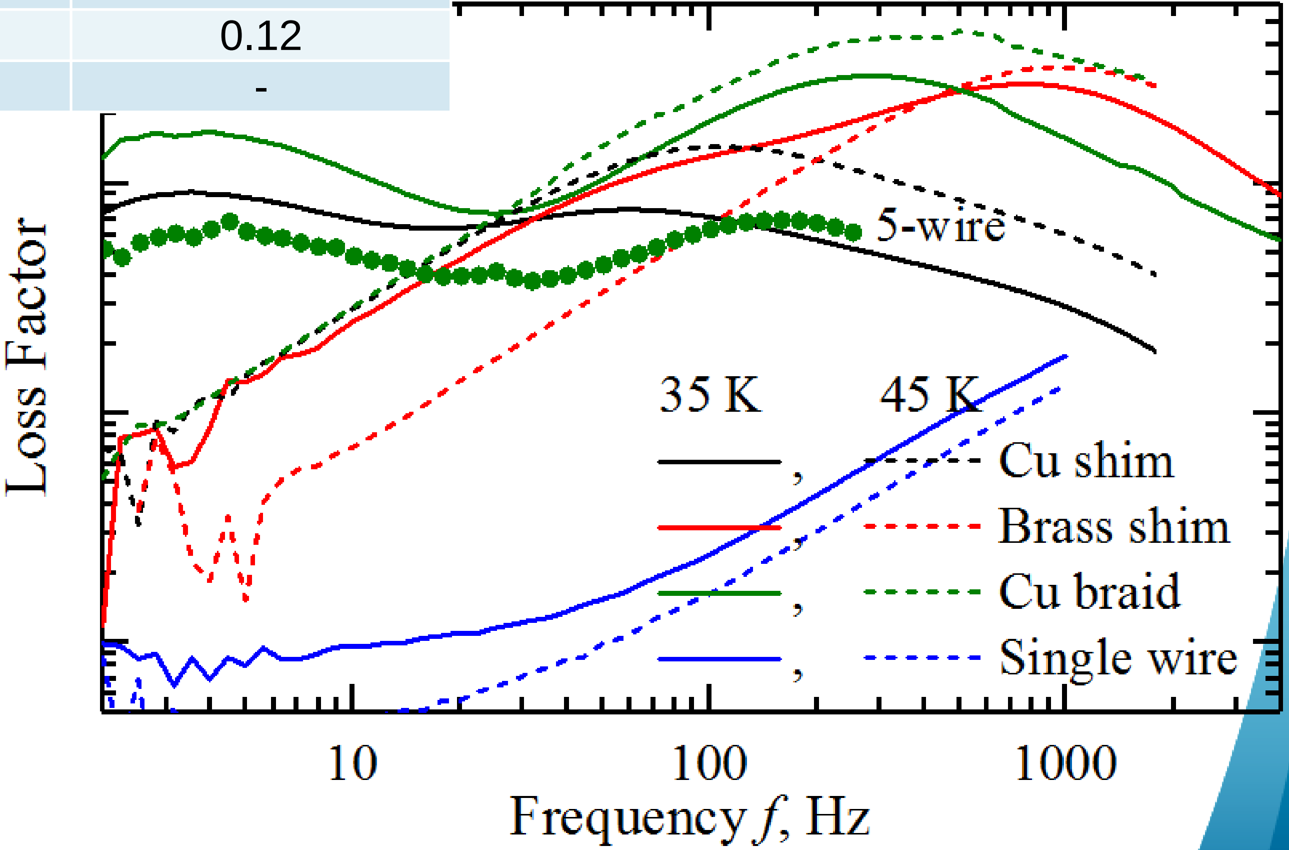
Rating (kA)	MIITs ($kA^2 \cdot s$)	dI/dt (kA/s)	τ_n (no quench of magnets) (s)	τ_Q (quench of magnets) (s)	Equivalent time (s)
18 (*)	32	250	130	0.2	0.1
7	5	250	130	0.2	0.12
2 (**)	1	20	20	0.5	-





copper/copper braid where the loss factor $\Gamma =$ $Q/(2\mu_0\Delta B^2)$ peaks.

4. The coupling current is weakly dependent on temperature below 40K, as the resistivity quickly settles to the residual levels.
5. Due to the larger demagnetizing effect of its higher aspect ratio, the 2-wire model is expected to have higher loss than a round sub-cable. The peak $\Gamma \sim 15$ of 2-wires with dense braid is reduced to $\Gamma \sim 5$ for 5-wires.
6. $\Gamma \sim 5$ is a conservative estimation for the sub-cables



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Loss Estimation for Inner Triplet Circuit Quench

- Inner Triplet Quench
  - $\Delta \mathrm{B_{CC}} \lesssim 0.45\mathrm{T}$
    - Scattered Cu in outer layer
    - Inner $\Delta \mathrm{B_{CC}} \lesssim 0.3\mathrm{T}$
    - "Uniform" field across the induction loops
    - $T_{CS} = 30\mathrm{K}$
  - $\Delta \mathrm{B_{D1}} \lesssim 0.3\mathrm{T}$
    - Modest field gradient across the induction loops
    - $T_{CS} = 30\mathrm{K}$

$$\Gamma = \frac{Q}{2\mu_0^{-1}\Delta B^2} \lesssim 5$$

$$\Delta B \lesssim 0.3\mathrm{T}$$

$$Q \lesssim 10\mu_0^{-1}\Delta B^2 = 0.72\mathrm{mJmm^{-3}}$$

The enthalpy for reaching $T_{cs} = 30\mathrm{K}$ of 12kA is

$$\Delta h_{D1/CC} = 1.0\mathrm{mJmm^{-3}} > Q$$

Hence heating by coupling current will not result in the quench of D1 and CC cables

Loss Estimation for D1 Circuit Quench

- Field change
  - $\Delta \mathrm{B}_{\mathrm{Trim}} \leq 0.45\mathrm{T}$
    - Scattered Cu in outer layer
    - Inner $\Delta \mathrm{B}_{\mathrm{Trim}} \leq 0.4\mathrm{T}$
    - Widest loop: $\Delta \mathrm{B}_{\mathrm{CC}} \leq 0.33\mathrm{T}$
    - "Uniform" field across the induction loops
    - $T_{CS} = 33\mathrm{K}$
  - $\Delta \mathrm{B}_{\mathrm{CC}} \leq 0.27\mathrm{T}$
    - Scattered Cu in outer layer
    - Inner $\Delta \mathrm{B}_{\mathrm{CC}} \leq 0.23\mathrm{T}$
    - Widest inner loop: $\Delta \mathrm{B}_{\mathrm{CC}} \leq 0.17\mathrm{T}$
    - Modest gradient across the induction loops
    - $T_{CS} = 30\mathrm{K}$

For the trim cables

$$\Gamma = \frac{Q}{2\mu_0^{-1}\Delta B^2} \leq 5$$

$$\Delta B \leq 0.4\mathrm{T}$$

$$Q \leq 10\mu_0^{-1}\Delta B^2 = 1.24\mathrm{mJmm}^{-3}$$

The enthalpy for reaching $T_{cs} = 33\mathrm{K}$ of 6kA is

$$\Delta h_{Trim} = 1.5\mathrm{mJmm}^{-3} > Q$$

Hence heating by coupling current will not result in the quench of the trim cables

Conclusions

- Transient fields imposed by different quench scenarios are analysed.
- Significant induction loops for different quench scenarios are identified
- AC loss measurements (1) show loss dominated by coupling current between wires via the normal matrix and (2) set the upper limit of the coupling current loss
- Single wire losses can be ignored
- Coupling current losses and the corresponding temperature rise for different quench scenarios estimated
- Neighbouring circuits will not quench due the transient of a quenched circuit
- Safety margin likely greater due to: partial heating in subunit cables, longer coupling current time constant for a longer twist pitch, and transient cooling by helium gas

Thanks for your attention!