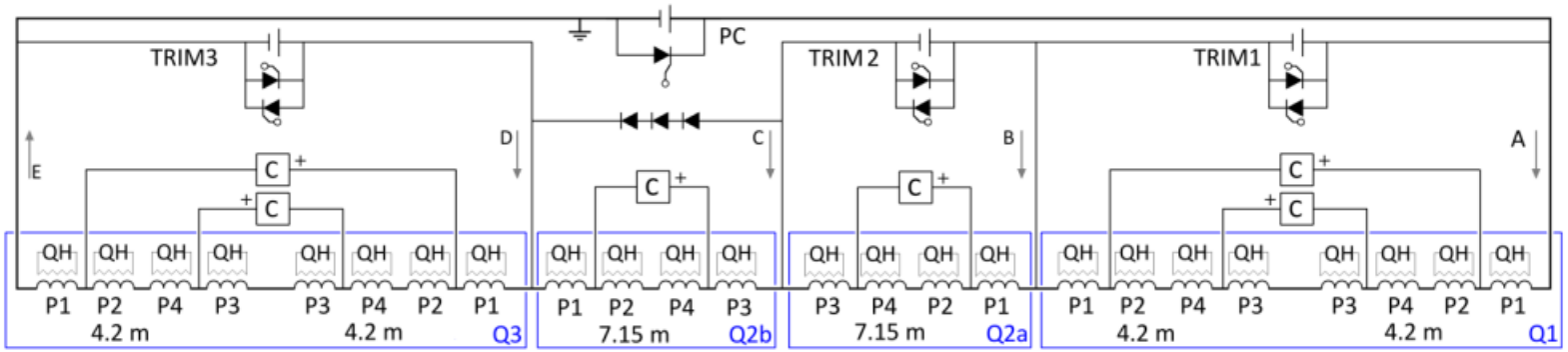
Transient Thermal Electromagnetic Behaviour of HL-LHC SC-Link

WP6a HL-LHC / WP4 UK-HL-LHC

6th HL-LHC Collaboration meeting, Paris, 14 - 16 Nov 2016

Background

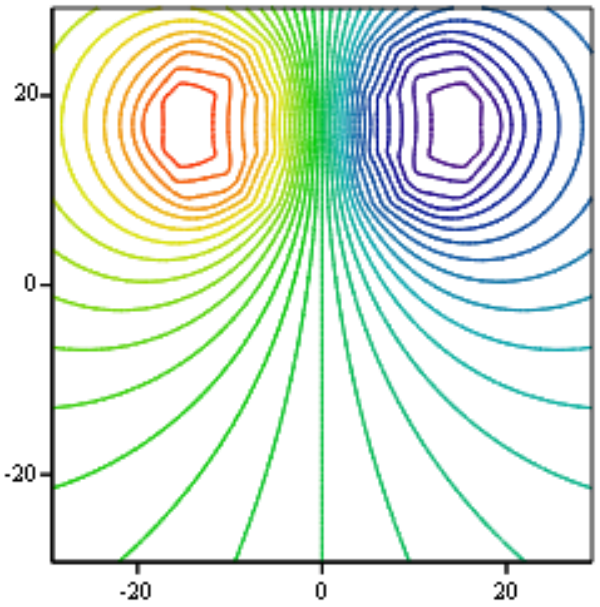
New power layout and quench protection/management

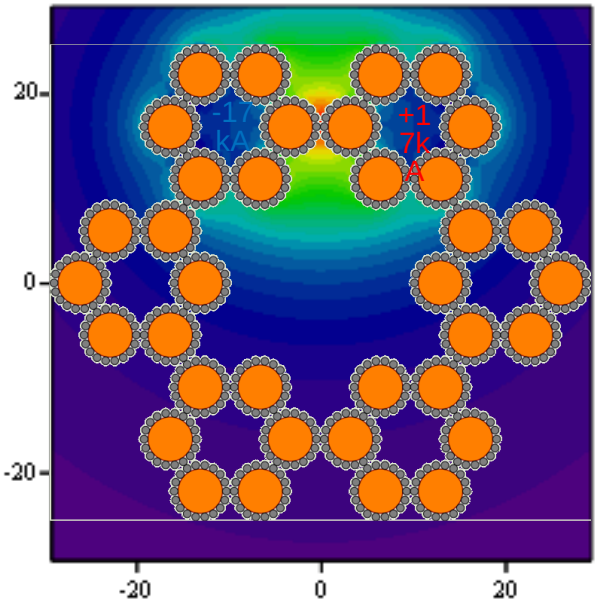


The maximum dI/dt on the main **18 kA leads** varies from a minimum of 106 kA/s (quench heaters on the magnets) to a maximum of 226 kA/s (protection via CLIQ - discharge of current).

Electromagnetic Transient: Field imposed by a circuit discharge

- The net field change ΔB within the link is the same as the field produced by the fast discharging cable.
- For a discharging current $I_0 e^{-t/\tau}$, the field change rate imposed on the link is $\dot{B} = \Delta B(I_0)\tau e^{-t/\tau}$, proportional to the field $\Delta B(I_0)$ produced at I_0.

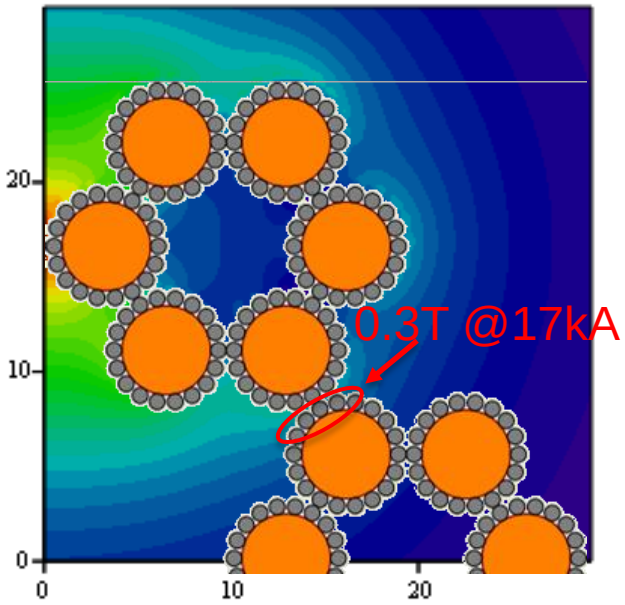


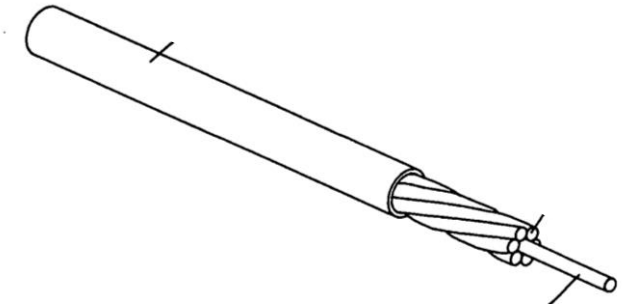


Electromagnetic Transient: Field imposed by a circuit discharge

Imposed $\dot{B}$, electrical field and induced current

- The maximum imposed field change is at immediate adjacent wires in the neighbouring cables.
- At 20kA, ΔB at these locations is about 0.4T, or 2T/s at $\tau = 0.2s$
- About 4-5 wires are exposed at any longitudinal location. The sub-cable twist pitch of 400mm means that each wire is exposed for about 90mm.

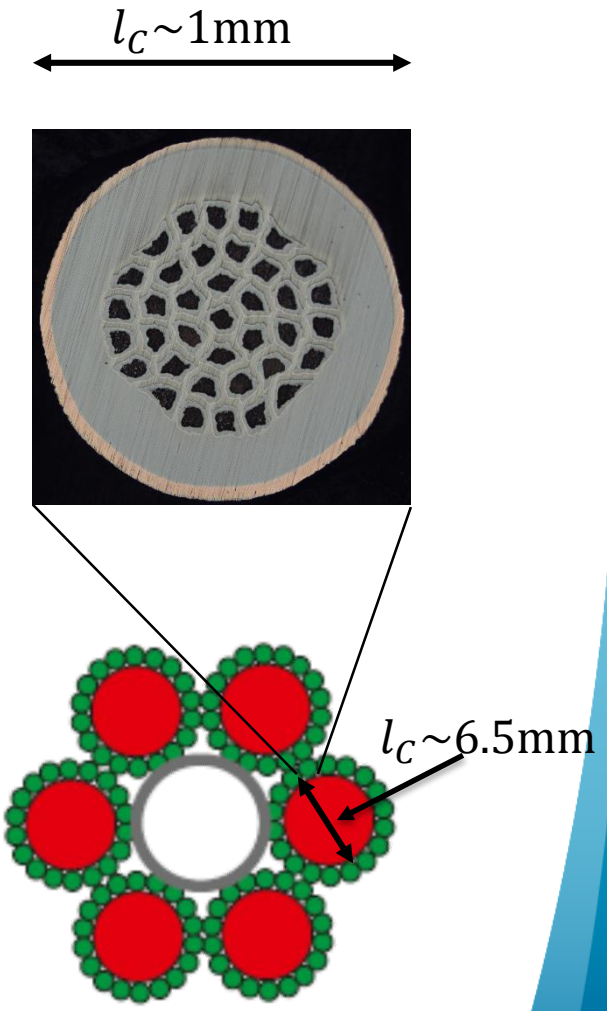




Electromagnetic Transient: Field imposed by a circuit discharge

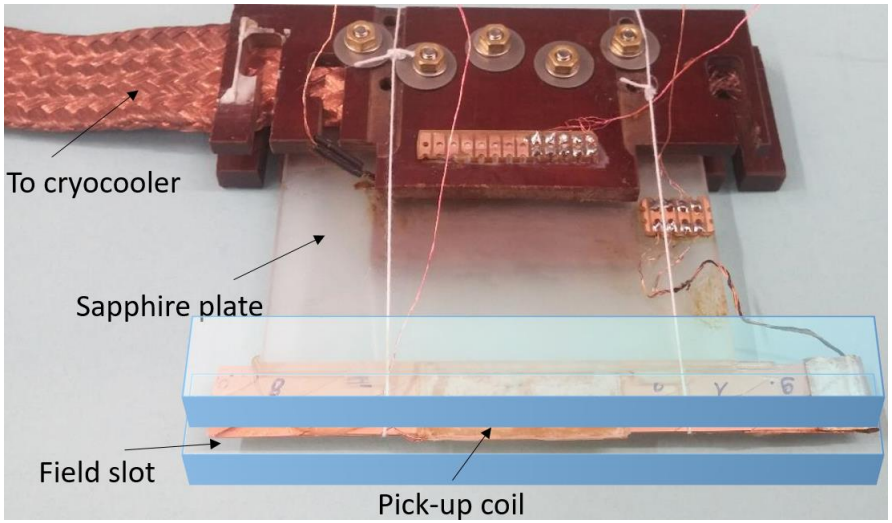
Coupling loops, induced current and dissipation

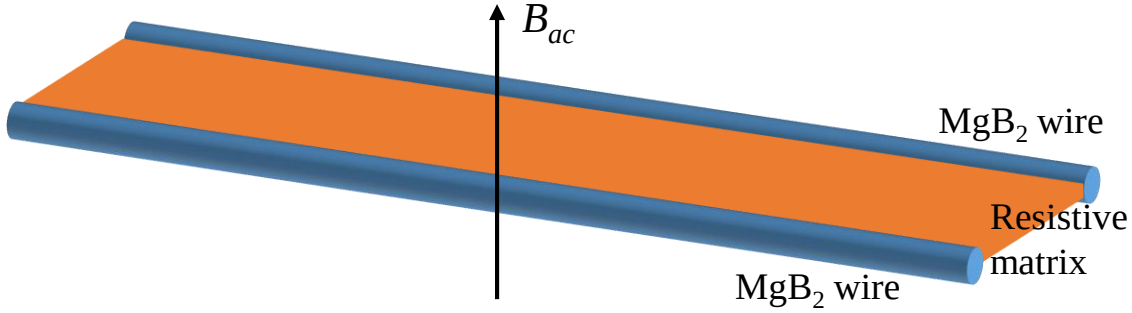
- **Two distinct coupling loops**
  - Intra-wire coupling among the filaments within individual wires
  - Inter-wire coupling among the wires within a sub-cable across the copper stabilizer
  - Coupling between the sub-cables unlikely
- **Intra-wire coupling** depends on twist pitch of the filaments and magnetic shielding.
- Inter-wire coupling is complex due to asymmetric $\dot{B}$ across the sub-cable, uncertainty in the contact resistance between the wires and stabiliser.
- The voltages for the induced current depend on the size of the coupling loop l_C, i.e. $E = \dot{B} \cdot l_C$.



Electromagnetic Transients: AC Loss Measurements

- **Applied sinusoidal field**
  - $B_0 \leq 0.2$ T
  - $5\text{Hz} \leq f \leq 2\text{kHz}$
- **Measurements**
  - $3\text{K} \leq T \leq 100\text{K}$
  - Single-turn saddle pick-up coil
  - Sample length $L \leq 100\text{mm}$

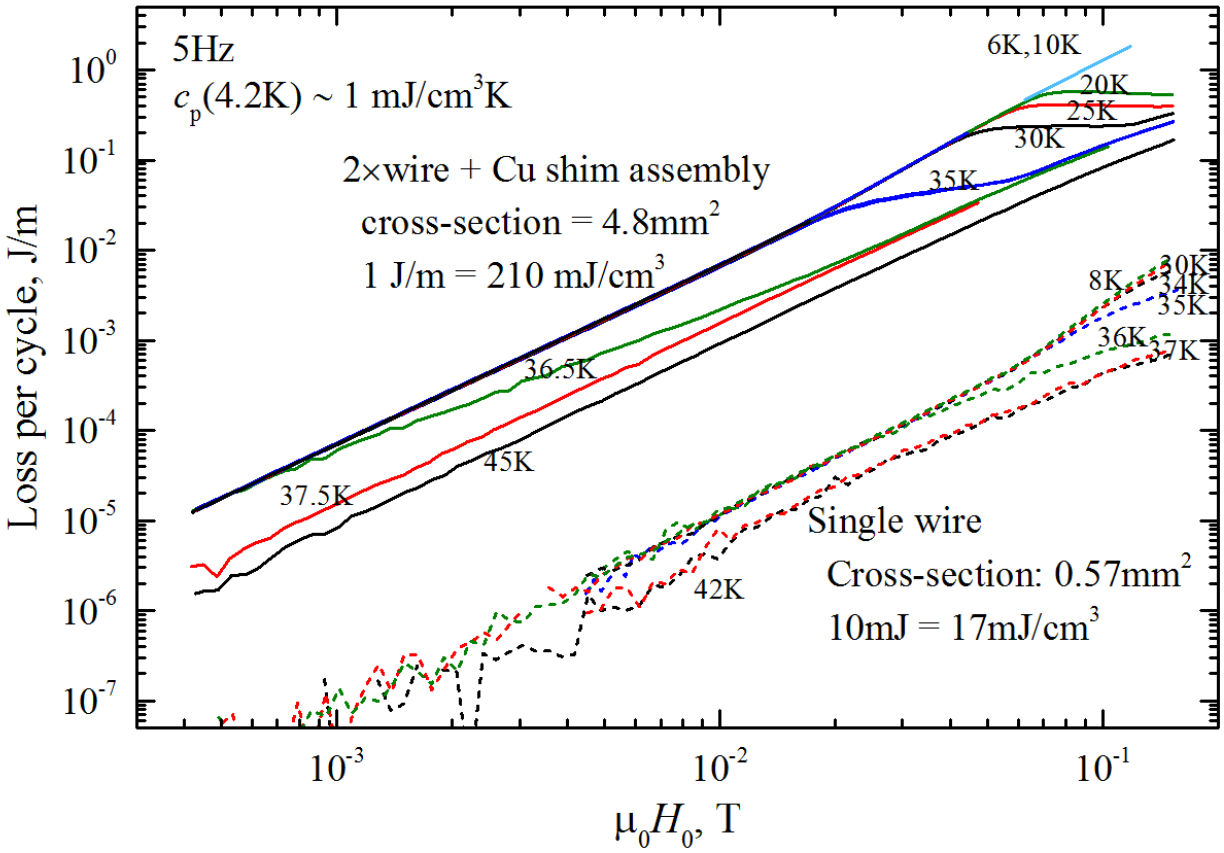




- Focus on the coupling among the wires in a sub-cable
- A simpler arrangement: two wires soldered to the long edges of a metal shim of 6mm wide and 0.5mm thick
- Cu, Cu braids and brass shims were used

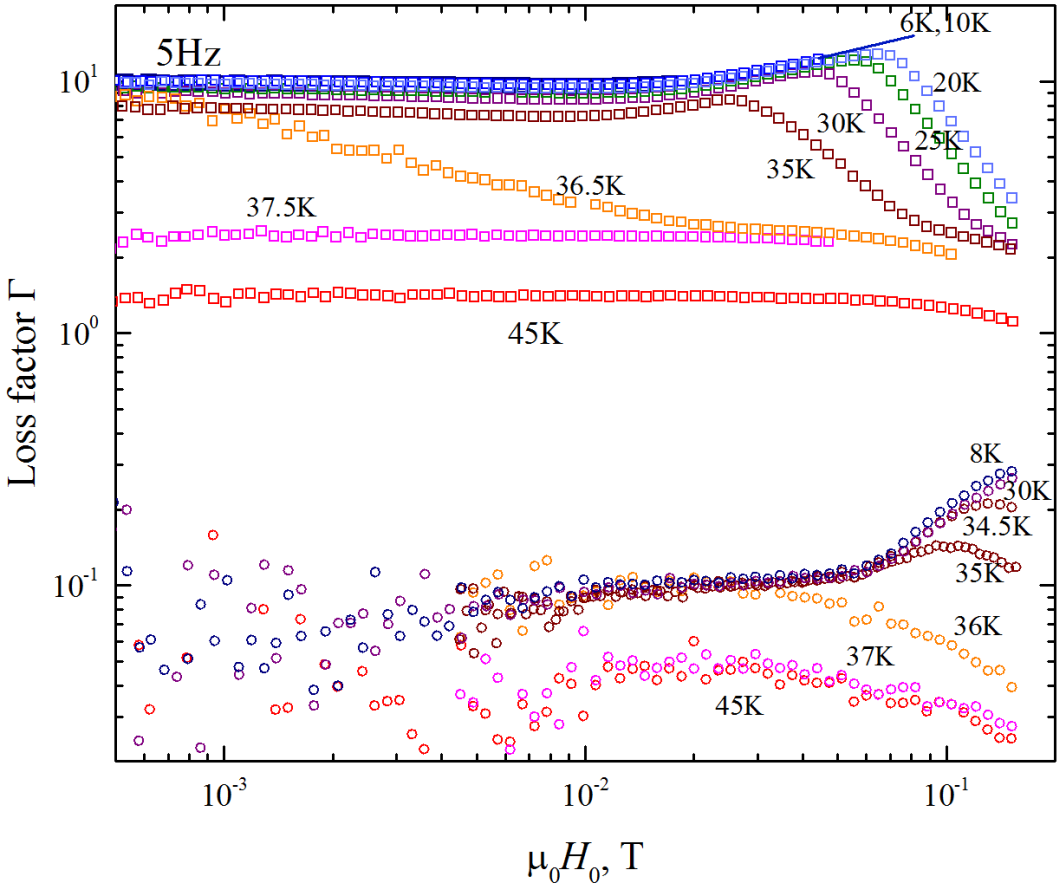
Electromagnetic Transients: AC Loss Measurements

Losses in the assembly is 1000x of a single wire;
Losses in superconducting state is 10x of normal state;

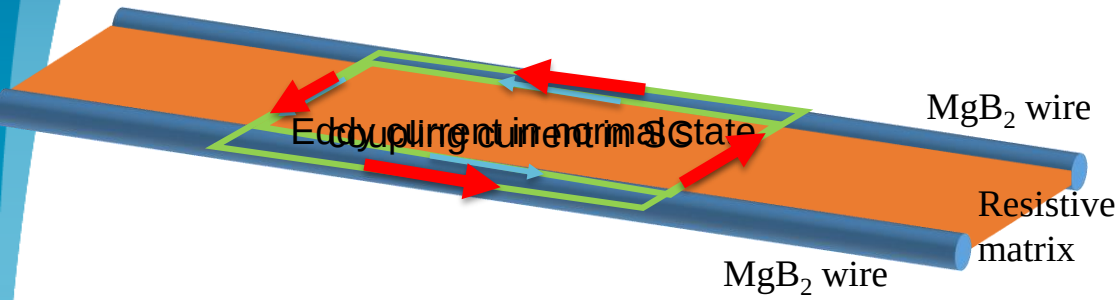


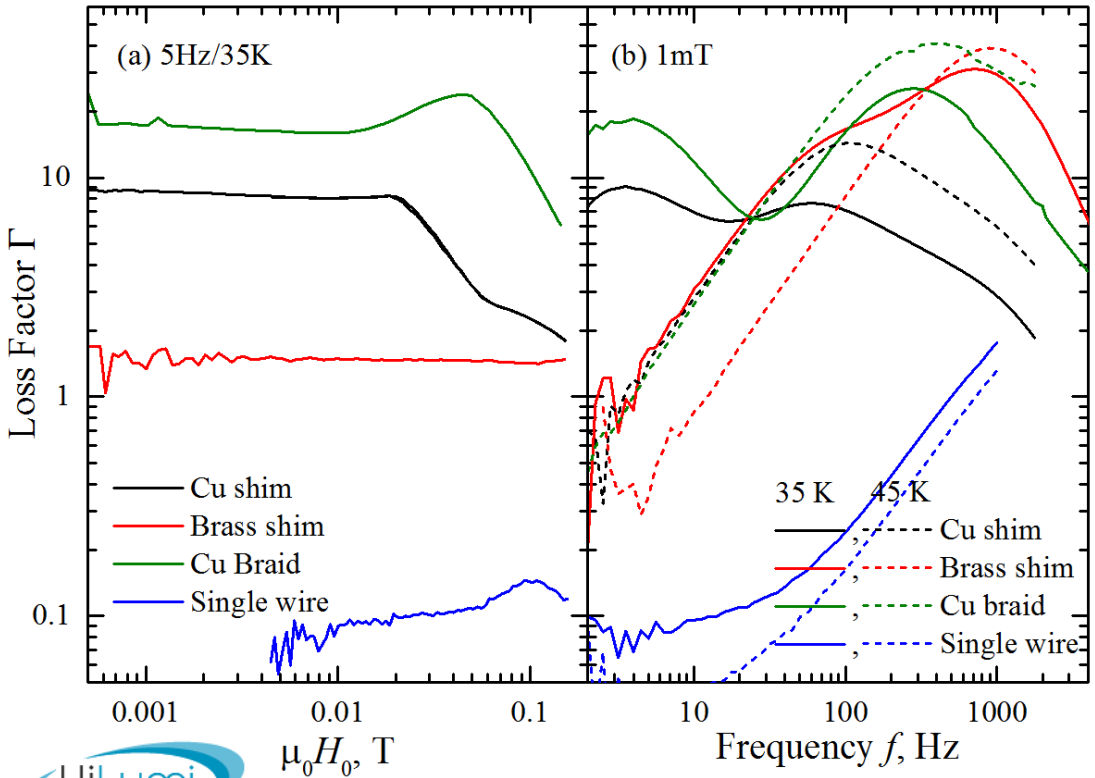
Electromagnetic Transients: AC Loss Measurements

Losses are eddy current like ($Q \sim B^2$ and $\Gamma \sim$ constant) until saturation of coupling current



From Eddy Current to Coupling-current



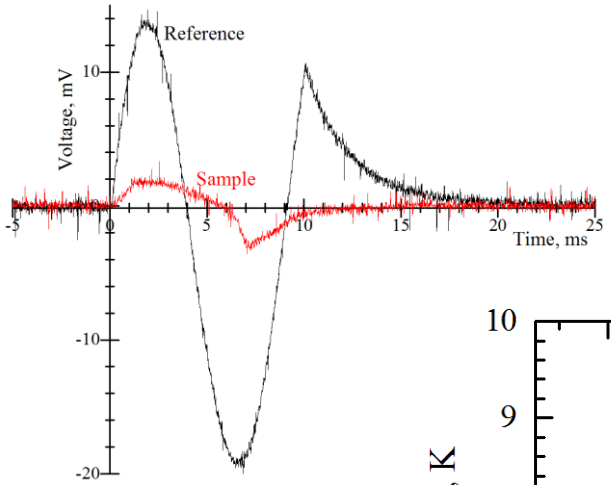


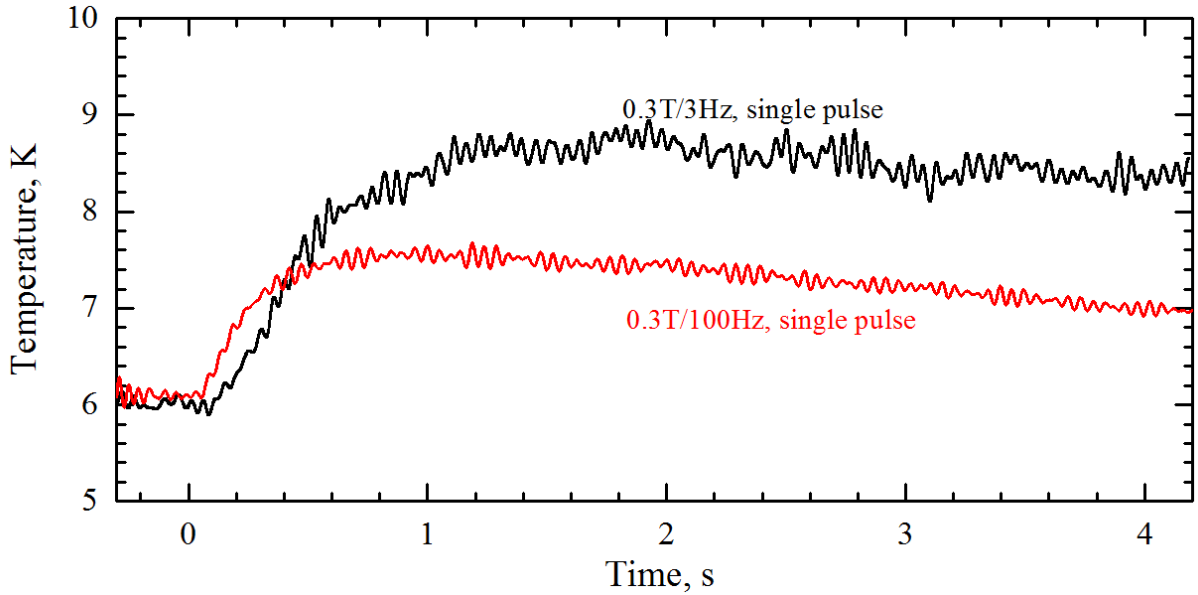
- Eddy currents in normal state vary with matrix resistivity as expected: reduced coupling and shorter time constant at higher ρ;
- Coupling superconducting state, the wires provide longitudinal super-current, reducing the effective resistivity and increasing time constant.
- Coupling current loss peaks around 3-5Hz for Cu /Cu-braids.

Thermal Effects

Single pulse measurement for losses due to circuit discharge.

Simultaneous electrical and thermal measurements





Conclusions

- Significant ac loss in a simple wire assembly observed experimentally
- Losses are due to coupling at the size of the sub-cables
- Decouple by high resistive matrix effective
- Must be compromised with thermal stability requirements
- Need to move onto sub-cables to account for multi-wire coupling.
- Contact resistance between the matrix and conductors in sub-cables should be studied.
- Current margins at low temperature and increased c_p at high temperatures maybe sufficient to mitigate the issue.

Thank you for your attention