WP6 Thermal-Electric Model of Hi-Lumi SC Link

Yifeng Yang
University of Southampton

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Outline

Present Baselines

- ☐ Power layout at P1/P5
- ☐ HTS link layout

Static Thermal-Electric Model

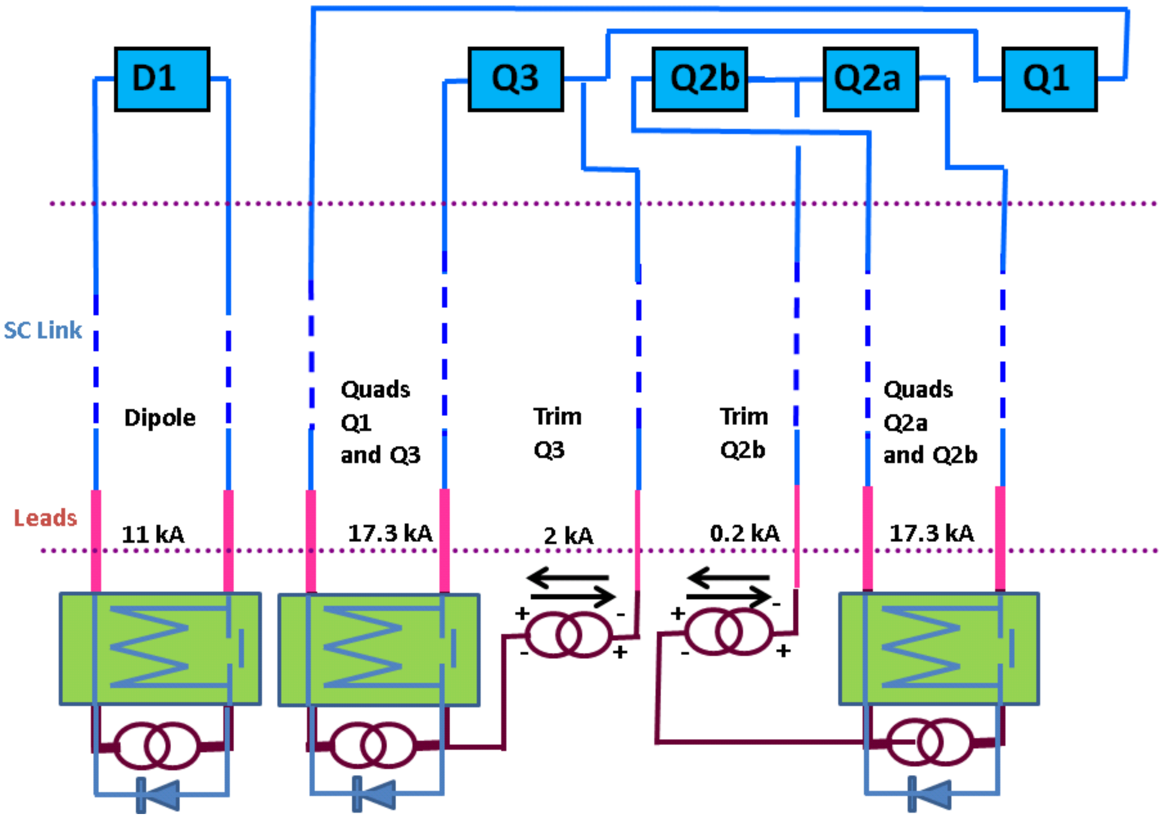
- ☐ Static magnetic field
- ☐ Thermal consideration

Quench Scenarios and Transient Thermal-Electric Model

- ☐ Quench of HTS Link
- ☐ Quench of Magnets

Conclusions and Further Studies

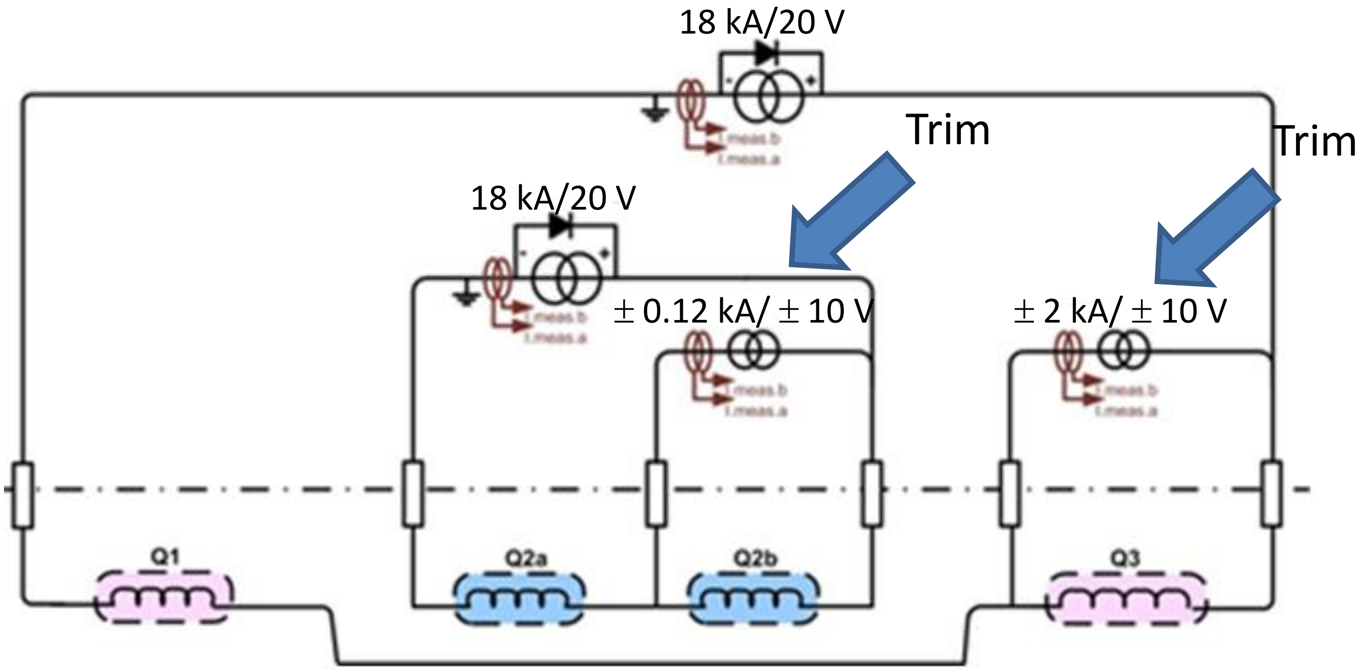
Old Powering Layout – Inner Triplet



- Baseline of two pairs of quadrupoles in series with trims to assure
- Full flexibility for the optics
- Reduced constraints for magnet protection
- Reasonable compromise for cold powering system and sc links (+ 2×17.3 kA)
- Preferred solution for the power converters
- Final location of 2 kA trim - Q3 or Q1 – to be defined at later stage

A.Ballarino: Report from Task 6.1

Baseline Powering Layout: MQXF quadrupoles



18 kA/20 V

18 kA/20 V

Trim

Trim

± 0.12 kA/ ± 10 V

± 2 kA/ ± 10 V

All other circuits are individually powered

EE still in the present baseline - but convergence on no use of EE

Ramp down time with no EE (~ 1500 s) being optimized by power converters regulation (J. P. Burnet): current control + voltage control

Maximum Operating Current of Magnets and Powering Equipment*

Magnet type		Magnet current		Powering equipment current	
Quadrupoles	MQXF	17.3	kA	20	kA
Trim on Q3	Trim	± 2	kA	± 2.4	kA
Trim on Q2b	Trim	± 0.2	kA	± 0.24	kA
Dipole	D1	11	kA	13	kA
Non linear Correctors	MQSX	0.1	kA	0.12	kA
Dipole Correctors	MBCX	2.4	kA	3	kA

Powering layout 2 –proposed baseline

* Current Leads, HTS cables in SC link and power converters

Power Converters for Hi Lumi

Power converter	Current	
Type 1	18kA	Q1/Q3 – Q2a/Q2b
Type 2	13kA	D2, D1
Type 3	6kA	Q4, Q5, Q6
Type 4	±2kA	Orbit correctors Q3 and Q2, Trim on Q3
Type 5	±600A	Orbit correctors D2 and Q4 (2×MCBRD, 2×MCBYY)
Type 6	±200A	CP, Trim Q2
Type 7	±120A	Correctors Q5 , Trim on Q2b

Changes in baseline under study:

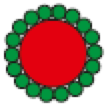
- powering of **all MQXF quadrupoles in series**

  → One main circuit plus two trims
- powering of **D2 in series with D1**

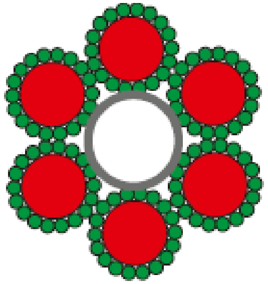
Layout of SC Link at LHC P1 and P5

● Cu

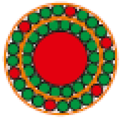
● MgB_2 , Φ = 0.85 mm



18 MgB_2 wires
Φ = 6.5 mm



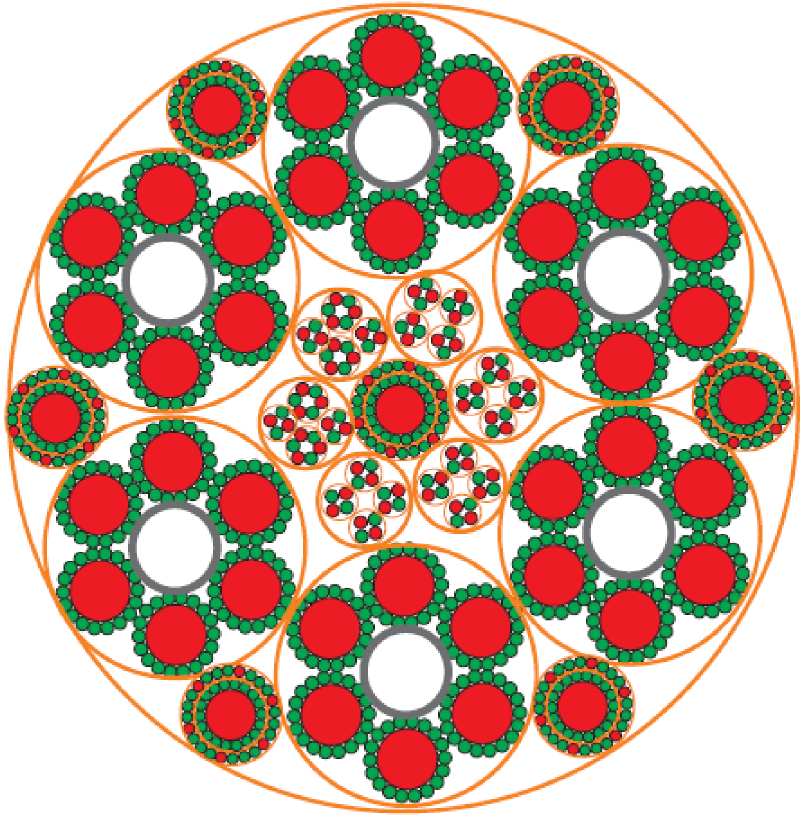
20 kA
Six cables, Φ = 19.5 mm



Concentric ± 3 kA
Seven cables, Φ = 8.4 mm

0.4 kA
Four cables

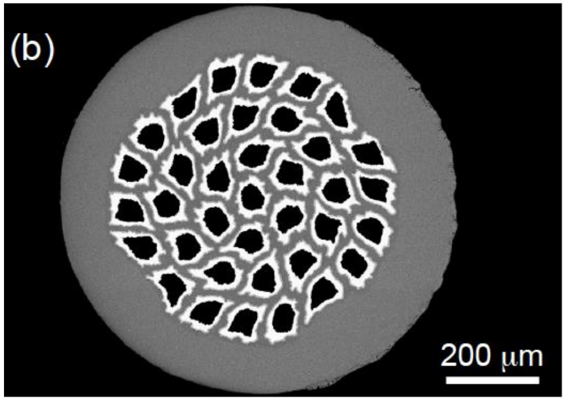
0.12 kA
Eighteen cables



Φext ~ 65 mm

Superconducting Material: State-of-the-art

Launched development of MgB_2 round wire



Φwire = 1 mm

37 MgB_2 filaments

Twisted filaments (LT=100 mm)

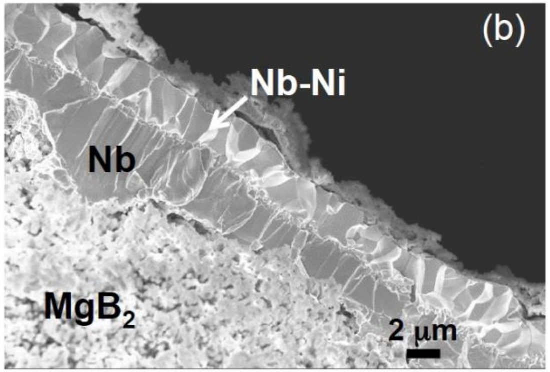
Φeq_MgB_2 = 56 μm

ACu ~ 5 % Awire (th=30 μm)

Cu plating

Sn coating of Cu surface

Ic(25 K, 0.9 T) > 186 A



Use of Nb barrier

Launched procurement of 80 km of wire

Unit lengths ≥ 500 m

20 km at CERN

60 km delivered before end 2015

Model Overview

Focused on 20kA cables

Static Model

- ☐ Global calculation for magnetic fields and inductances
- ☐ Cryostat thermal load not considered
- ☐ No significant concerns for thermal profiles

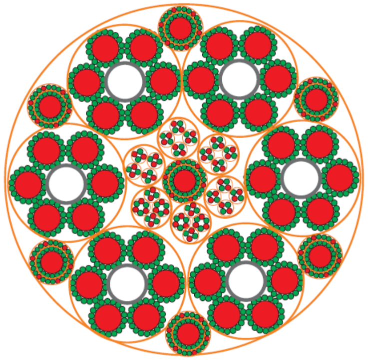
Transient Model

- ☐ Temperature gradient along the link considered
- ☐ Normal zone / MPZ initiation and detection not considered
- ☐ Cooling by helium gas ignored due to the short quench time constants
- ☐ Different current coupling loops considered but not no 3d EM modelling

Static Model: Magnetic Fields and Inductances

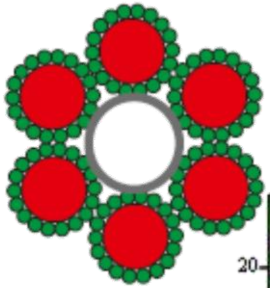
Cables/Link layout

6x20kA , 7x3kA,
4x0.4kA, 8x.12kA



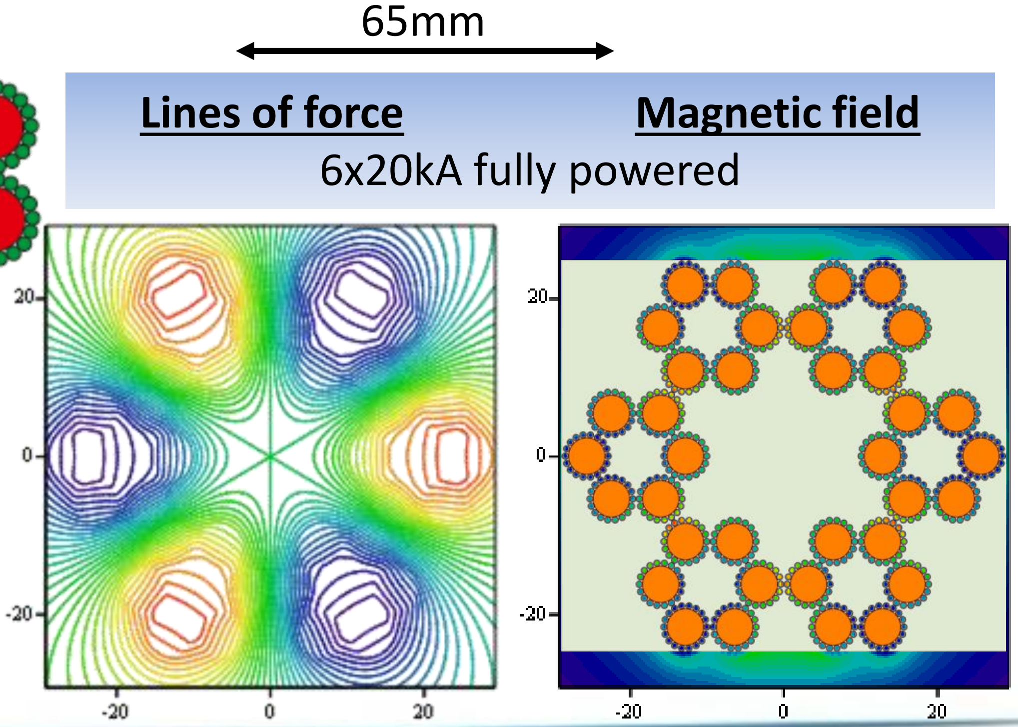
3kA coaxial cables have minimum impact on the overall field distribution within the link, hence not considered.

0.12/0.4kA cables not exposed to the 20kA fields , hence not considered.



Lines of force **Magnetic field**

6x20kA fully powered



Main Characteristics

Maximum Field:

1x20kA: $B_{max}=0.47$ T
(±)20kA: $B_{max}=0.90$ T
3x(±)20kA: $B_{max}=0.75$ T

Inductances

(±)20kA: $L = 0.19$ µH/m
3x(±)20kA: $L = 0.32$ µH/m
Insignificant compared to that of the quadrupoles

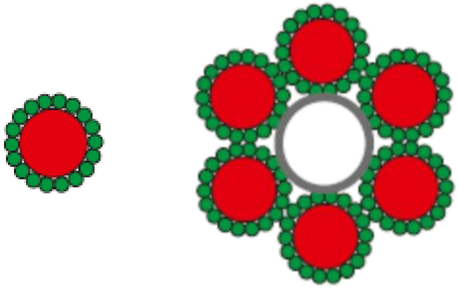
Transient Model: (Self) Quench of Cables

Heading dynamic upon the quench of a cable

- ☐ Assume that the normal zone has exceed the minimum propagation zone (MPZ) and longitudinal propagation has started.
- ☐ Neglect the retardation due to (a) heat diffusion to un-quenched section and (b) cooling by GHe.
- ☐ Assume a (sufficiently) small thermal/electrical contact resistance to the stabilizer.
- ☐ The relevant calculation is the quench load (QL):

$$(1-\lambda)^{-1}\int_{T_0}^{T}\frac{dc_v(T')}{\rho(T')}dT' = \int_0^t j_e^2(t')dt' = QL(T)$$

  - λ is the superconductor fill factor.
  - The stabilizer with a low resistivity ρ shares total current.
  - The specific heat c_v (Jkg^{-1}K^{-1}) and density d include both the superconducting wire and the stabilizer.



18-wire sub-cable and 20kA cable are thermal/electrically equivalent: $\lambda\sim30\%$

The inner layer of the 3kA coaxial cable is equivalent to 18-wire sub-cable and the outer layer is under-stabilized

Transient Model: (Self) Quench of Cables

Specific heat is evaluated using:

$$c_v(T) = \gamma \cdot T + c_{v.ph}(T)$$

With the lattice specific heat calculated analytically with

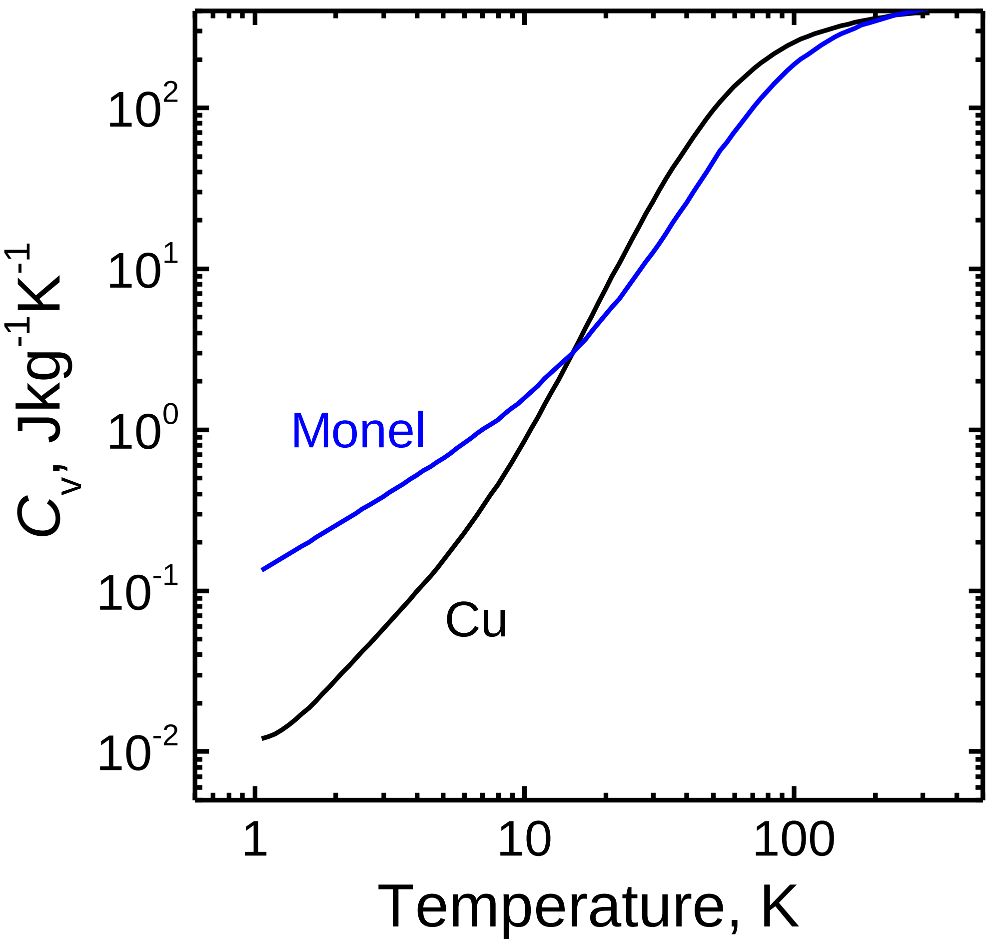
$$c_{v,ph}(T) = 9R \int_0^{\Theta_D/T} \frac{x^4 e^x}{(e^x - 1)^2}\,dx$$

The specific heat consists of two main components:

Ni-Cu alloy (monel) for the wire matrix

Copper as the stabilizer

The electronic heat capacity of monel is 10x that of copper. Although important for low temperatures, it is eventually offset by its large Debye temperature ($\Theta_D = 460$K)



Transient Model: (Self) Quench of Cables

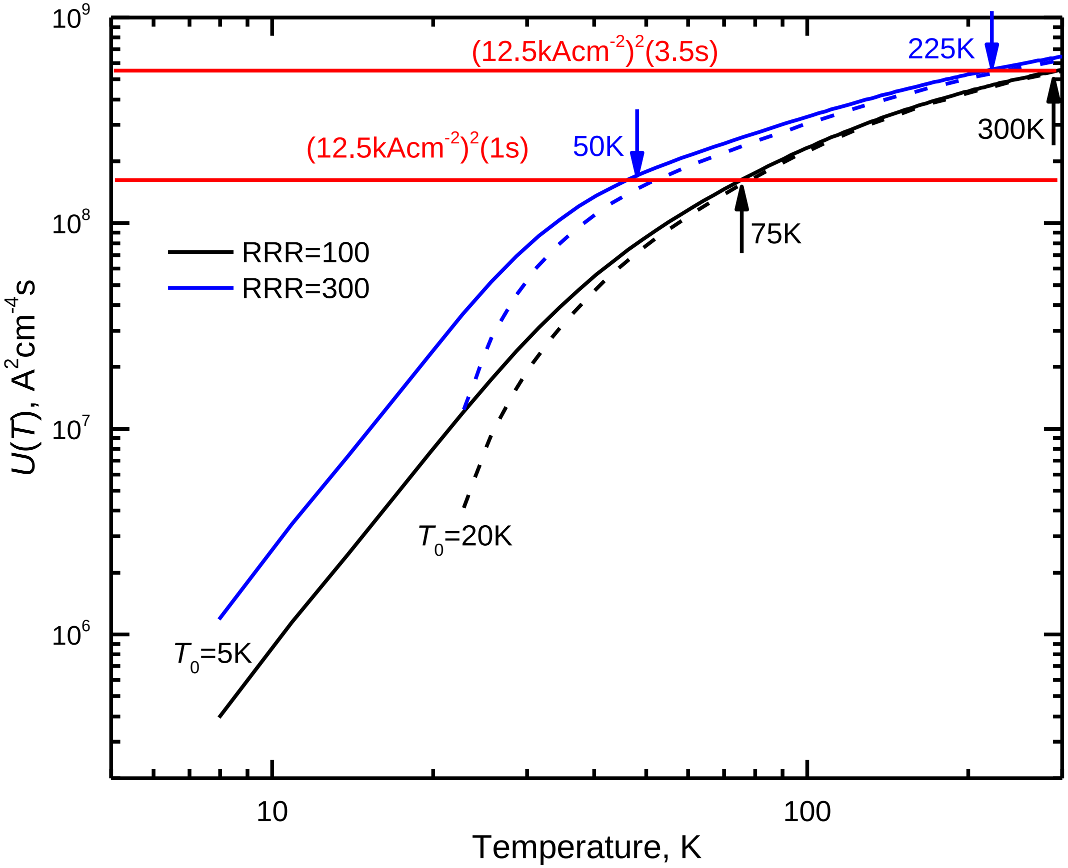
Quench load of 20kA cable

$$QL(T) = (1-\lambda)^{-1}\int_{T_0}^{T}\frac{dc_v(T')}{\rho(T')}dT'$$

With a nominal Cu RRR=100 for the stabiliser:

- The cable heats up to ~90K in 1 s at 17kA;
- Room temperature is reached in approximately 3.5 s.
- Little influence by the initial temperature and the contribution of monel.
- Stabilizer RRR has a significant impact at low/medium temperature (55K in 1s) and a moderate improvement at high temperature (230K in 3.5 s)
- When discharged at $I(t) = I_0 e^{-t/\tau}$ QL is matched by

$$I_0^2 t_{eff} = I_0^2\frac{\tau}{2}\left(1 - e^{-\frac{2t}{\tau}}\right)$$

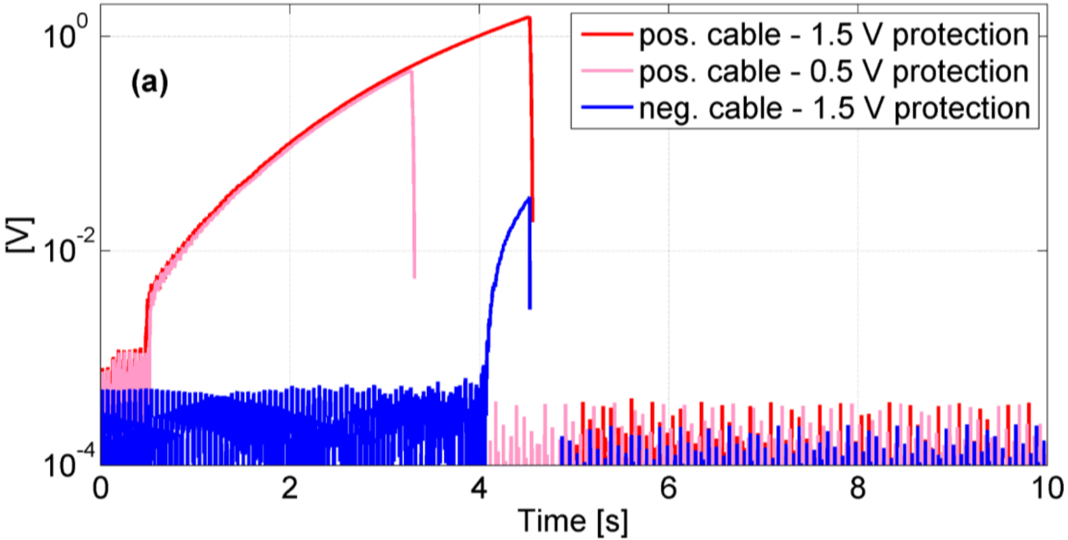


For magnet discharging time constant of $\tau = 7$s,

- $t_{eff} = 1$s to 90K at means $t = 1.17$s
- $t_{eff} = 3.5$s to room temperature at means $t = \infty$!, i.e. safely quench during magnet discharge

Recent results at CERN: consistent with QL calculation

Hot spot temperature lower than QL: not fully propagated



- Max hot-spot temperature reached T_{hs}~340 K with no degradation of cable performance
- 25 K, **3 kA**, **100 mV detection threshold** → 15 MIITS of "quench capital" before detection → final T_{max} ~ 150 K with **3 s time constant of the circuit**

Powering Layout and SC-Link Protection

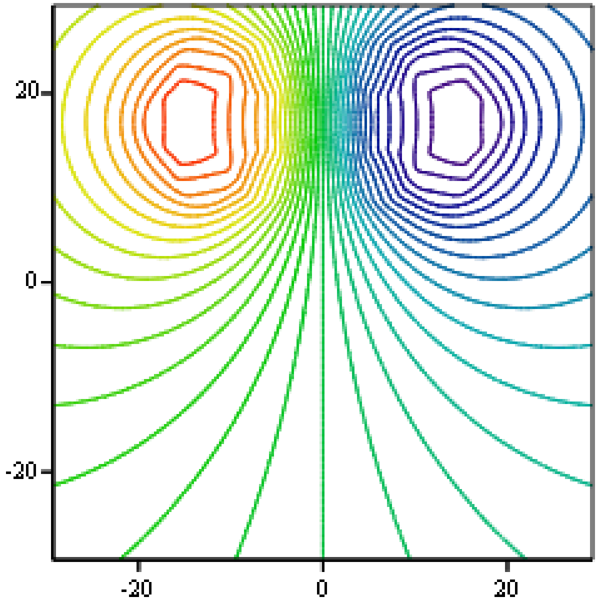
In the event of SC-Link Quench:

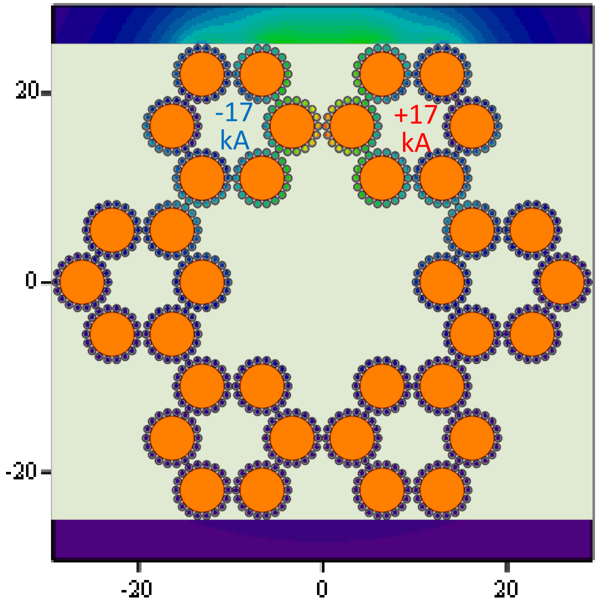
- With Energy Extraction (EE): the time constant of the circuit is ADDED to the time required for SC-quench detection. SC-Link must withstand the total period (as in 16kA HTS leads)
- Without EE, current in SC can be ramped sharply upon quench detection after triggering the quench of the magnets with QH and/or CLIQ through interlock

Transient Model: Electromagnetic Induced Quench of Cables

Response of neighbouring cables upon a fast discharge of a magnet circuit

- ☐ 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.

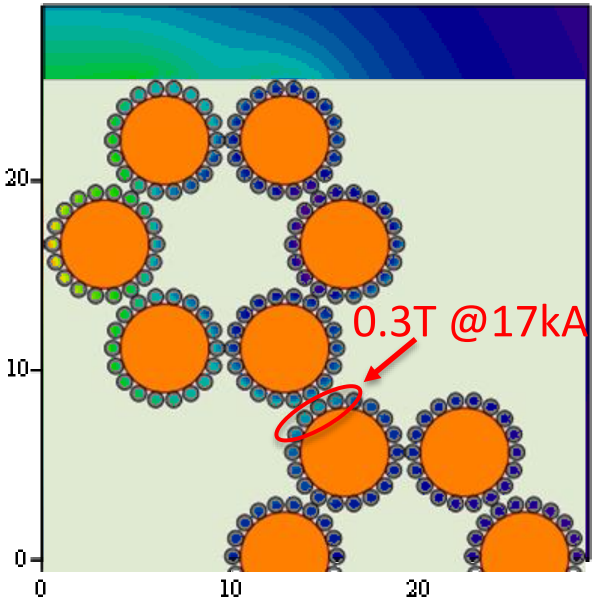




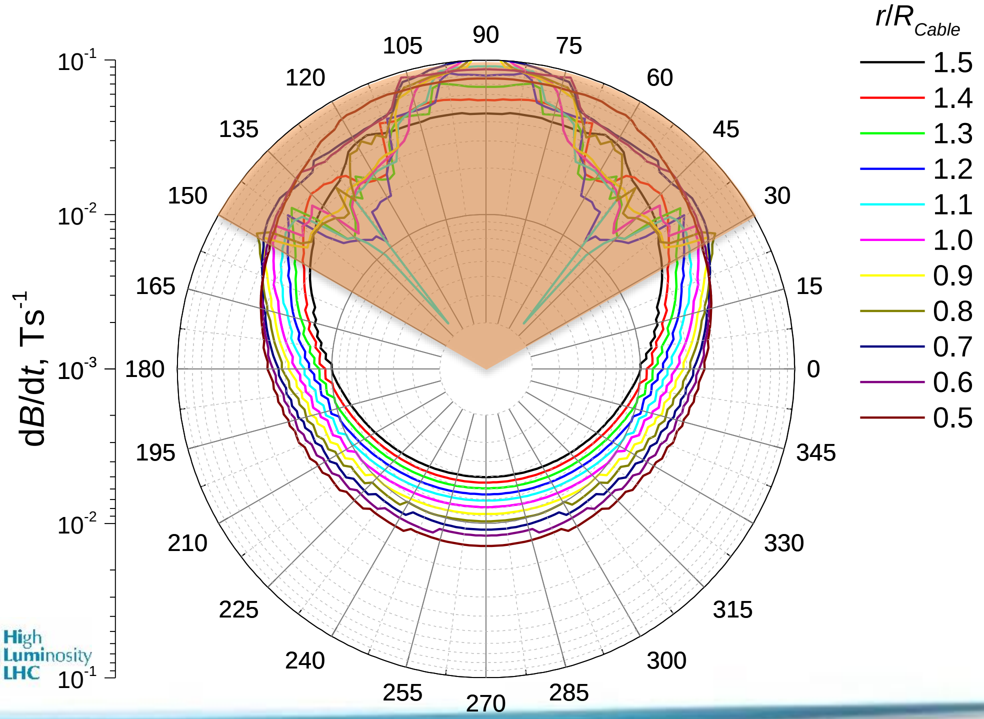
Transient Model:
Electromagnetic induced Quench of Cables

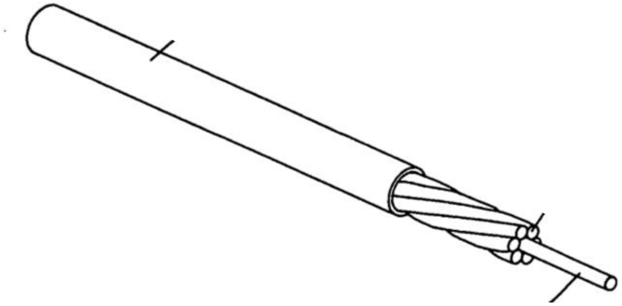
Imposed $\dot{B}$, electrical field and induced current

- ☐ The maximum imposed field change is at immediate adjacent wires (30° and 150°) in the neighbouring cables.
- ☐ At 20kA, ΔB at these locations is about 0.3T, or 40mT/s at $\tau = 7s$.
- ☐ About 4 wires are exposed at any longitudinal location. The present wire twist pitch of 400mm means that each wire is exposed for about 90mm.



0.3T @17kA



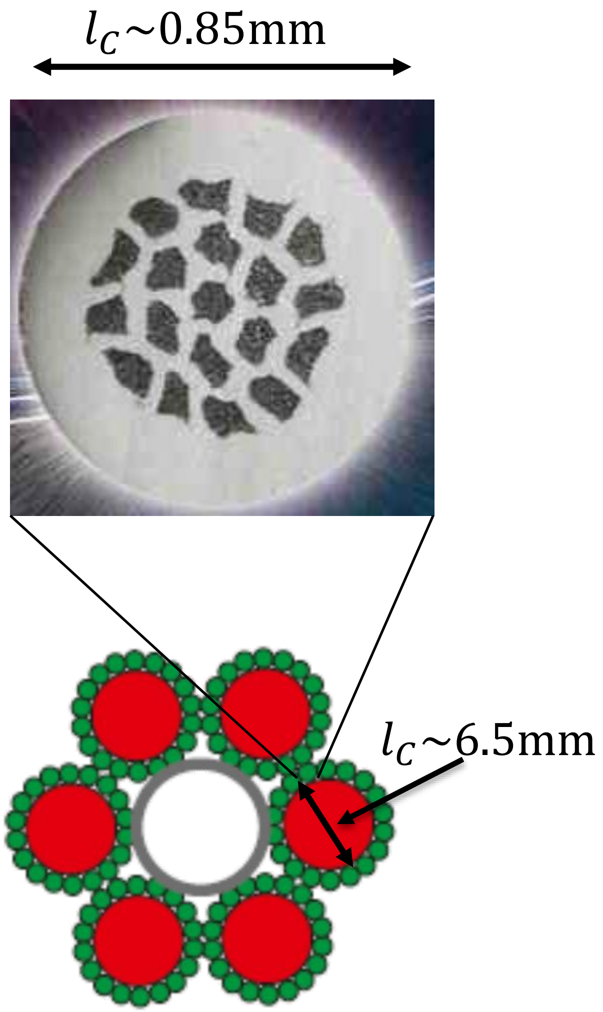


Transient Model: Electromagnetic induced Quench of Cables

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 an.
- 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. $E = \dot{B} \cdot l_C$.
- Intra-wire: $l_C \sim \phi_w = 0.85\text{mm}$, $E \sim 0.4\mu\text{Vcm}^{-1}$ at $\tau = 7\text{s}$
- Inter-wire: $l_C \leq \phi_{sc} = 6.5\text{mm}$, $E \sim 3\mu\text{Vcm}^{-1}$ at $\tau = 7\text{s}$
- The voltage is sufficiently high that the induced current will reach critical current $J_c(T)$ and give a dissipation at

$$P = J_c(T)E = J_c(T)\dot{B}l_C$$



Transient Model:
Electromagnetic induced Quench of Cables

Heading by induced current

- ☐ The temperature rise by iduced current heating can be calculated with

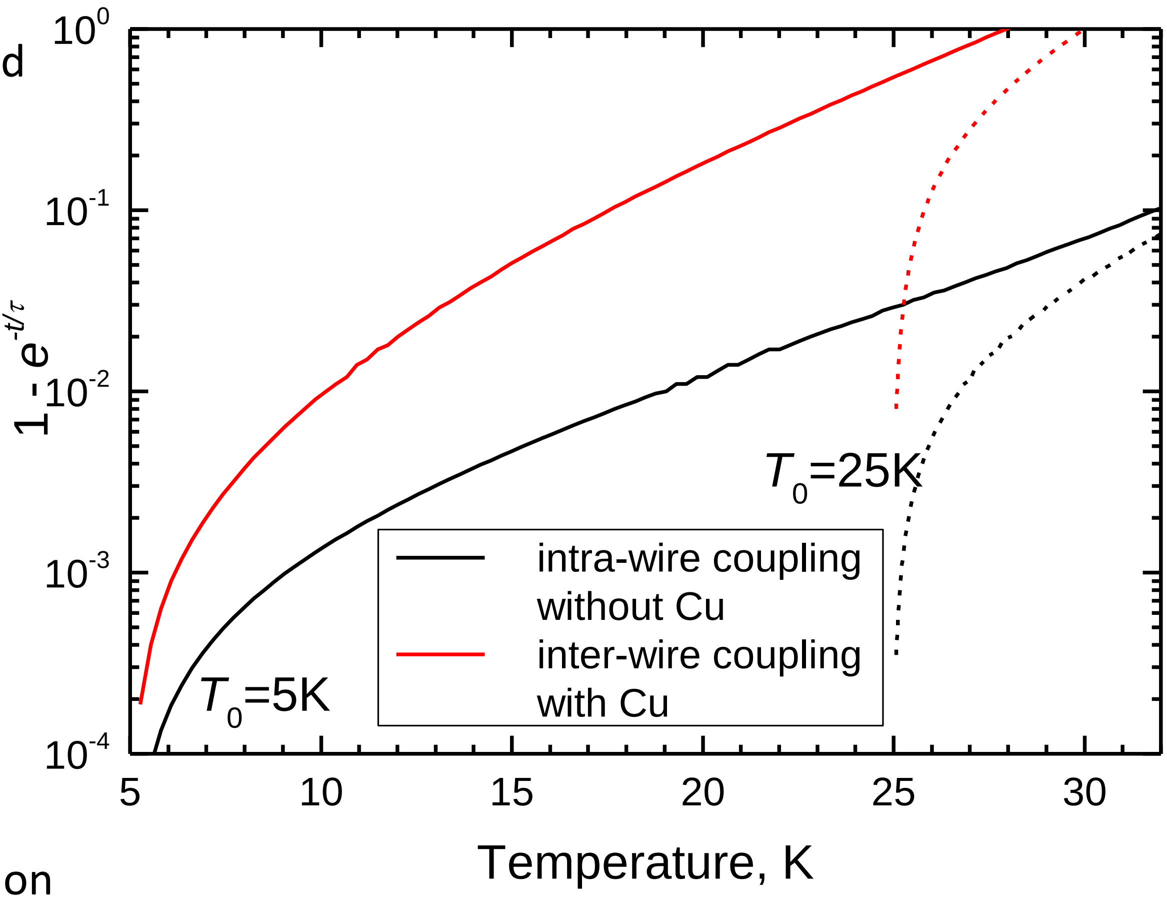
$$\mathrm{A_h}\rho_d c_v(T)\frac{dT}{dt} = I_c(T)\dot{B}\,l_C$$

A_h is the heated area including thermal diffusion outside the coupling loop.

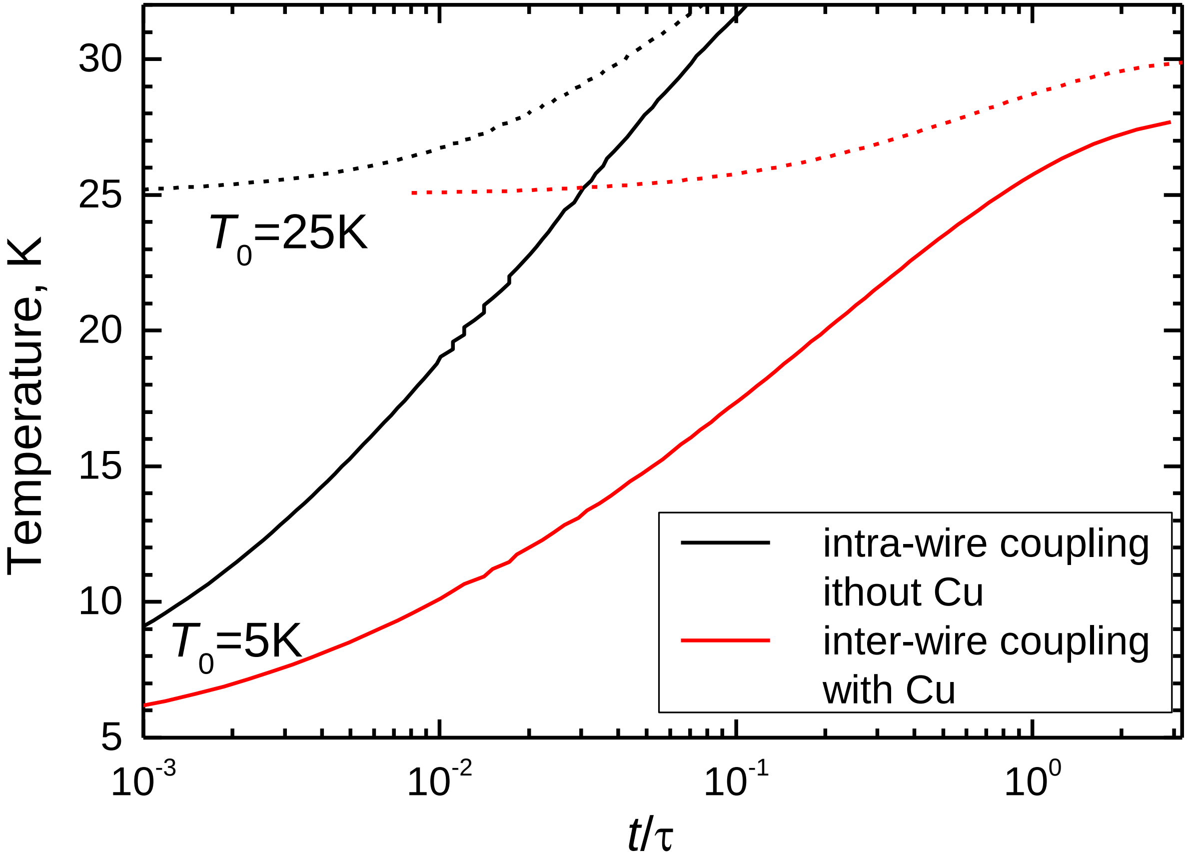
- ☐ With an exponential discharge,

$$\int_0^T \frac{\mathrm{A_h}\rho_d c_v(T)}{I_{c(T)}\Delta B(I_0)\,l_C} = 1 - e^{-\frac{t}{\tau}}$$

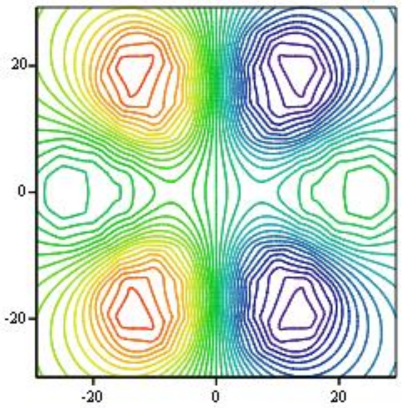
- ☐ Two limiting cases:
  - Intra-wire without thermal diffusion, $A_h = A_w$
  - Inter-wire coupling with partial (1/3) thermal diffusion

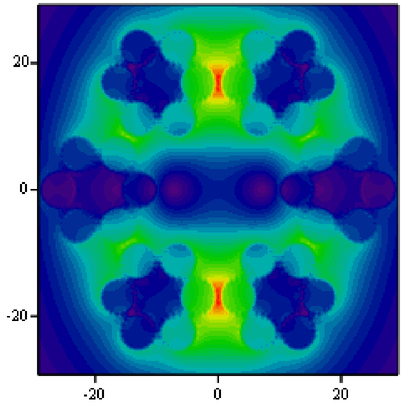


Transient Model:
Electromagnetic induced Quench of Cables



Field in the cable can be reconfigured for better stability





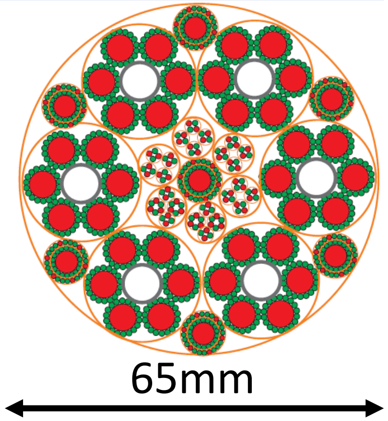
Conclusions and future work

1. Self-quench time constant for cables is the comparable to that of the magnets
2. Thermal/electrical contact resistances is crucial, but with competing considerations.
3. Sub-cable coupling is acceptable and an induced quench time constant comparable to that of the magnets
4. Detailed response of the cables to fast field changed should be in the further study.
5. Further optimisation of contact resistance is essential.

Task 6.3 Thermal-Electrical Model for Hi-Lumi SC Link

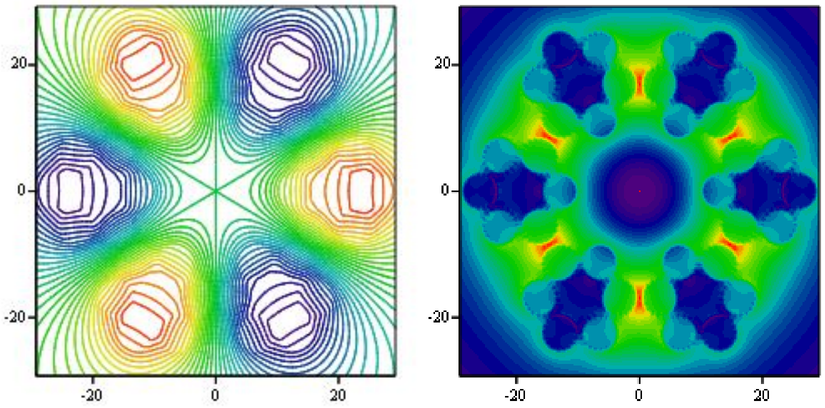
Cable layout

6x20kA , 7x3kA,
4x0.4kA, 8x.12kA



Lines of force   Magnetic field

6x20kA fully powered



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3x(±)20kA: B_{max}=0.75 T

Inductances

(±)20kA: L = 0.19 µH/m
3x(±)20kA: L = 0.32 µH/m

Link/Cable Stability upon Quench of a Magnet

- $\dot{B} \sim 0.3\tau^{-1}$ T/s imposed on 20kA/3kA cables upon quadrupole discharge at $B_0 e^{-t/\tau}$;
- $E \sim 0.4\mu\mathrm{V cm}^{-1}$: coupling within single wire
- $E \sim 3\mu\mathrm{V cm}^{-1}$: coupled across sub-cable
- $J_c(T)$ will be induced, significant dissipation.
- Heat diffusion to Cu stabilizer essential, as time to reach 25K:
  - $< 0.03\tau$ without copper
  - $\sim (0.5 - 1.0)\tau$ with copper

Quench Load of Link/Cable

- With full current share by copper, the time constant of heating to room temperature for a quenched link is 2-4s, according to $\int_0^{\tau} I^2(t)dt = (1-\lambda)^{-1} A^2 \int_{T_0}^{T} \gamma c_v(T)/\rho(T)\, dT$
- Implying magnet discharge at nominal rate

Next

- Further ac loss study
- Further optimisation of contact to copper