



**High  
Luminosity  
LHC**

# **WP6 Thermal- Electric Model of Hi-Lumi SC Link**

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# Outline

## Present Baselines

- Power layout at P1/P5
- HTS link layout

## Static Thermal-Electric Model

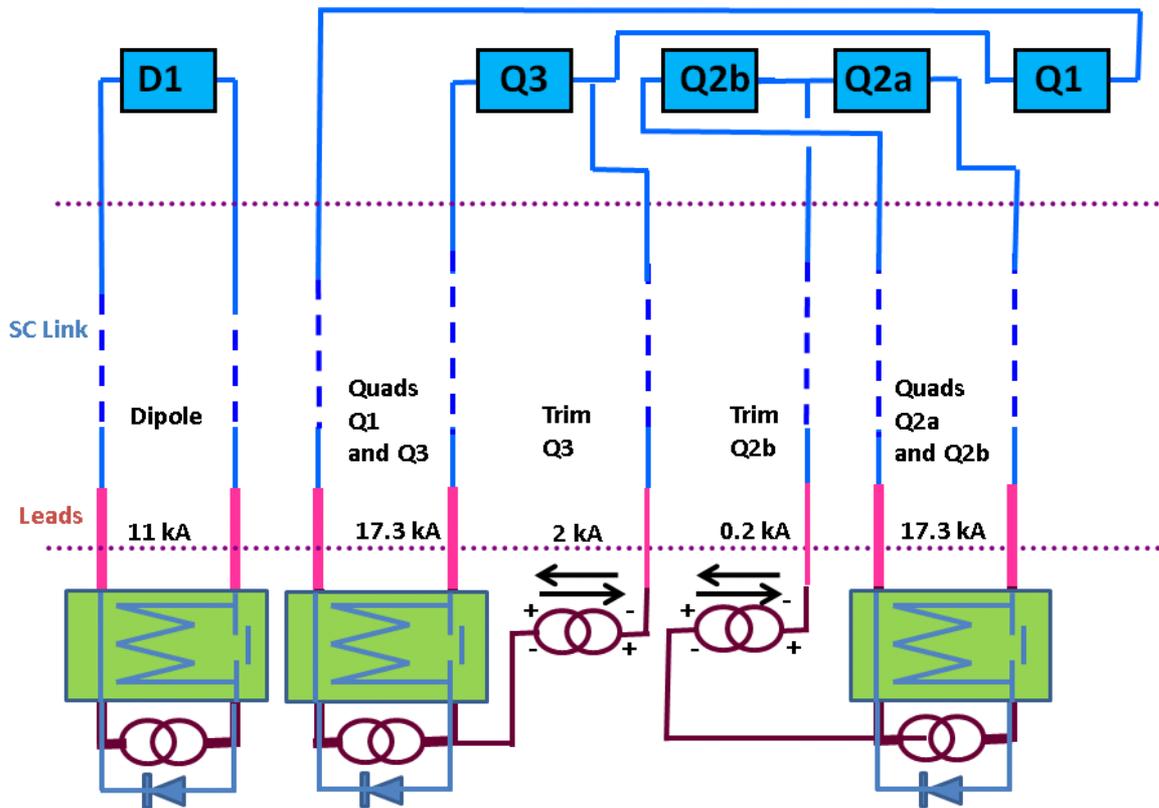
- Static magnetic field
- Thermal consideration

## Quench Scenarios and Transient Thermal-Electric Model

- Quench of HTS Link
- Quench of Magnets

## Conclusions and Further Studies

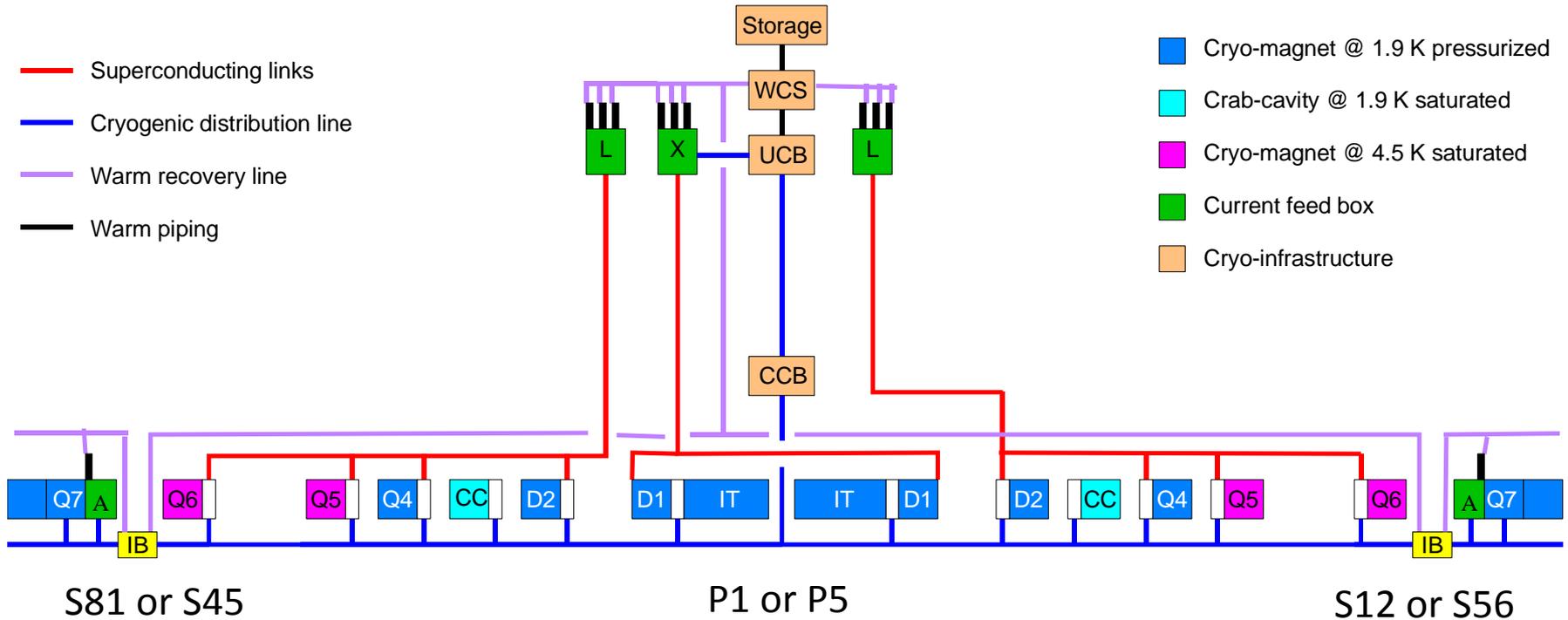
# Powering Layout – Inner Triplet



- 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 (+  $2 \times 17.3$  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

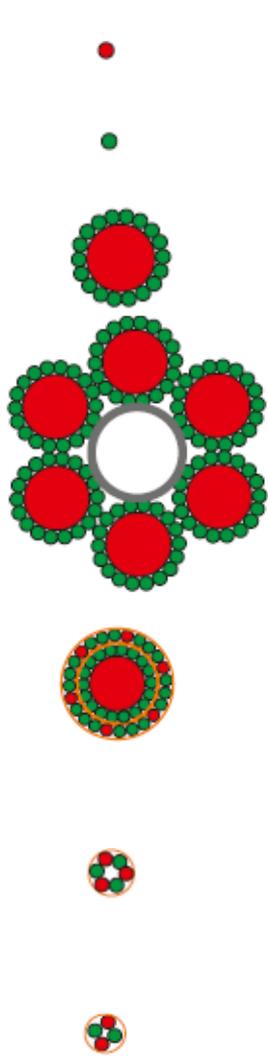
# Baseline for P1 & P5 layout: Matching section cooled with inner triplet cryoplants



- Q5, Q6 at 4.5 K,
- DFBA remains in tunnel, # of superconducting links and surface DFB-boxes to be optimized,
- level of cryogenic redundancy (IB) to be detailed
- Space requirements for CCB and shaft-piping

R.Van Weelderen: Cooling configuration in IR1&5

# Layout of SC Link at LHC P1 and P5



Cu

MgB<sub>2</sub>,  $\Phi = 0.85$  mm

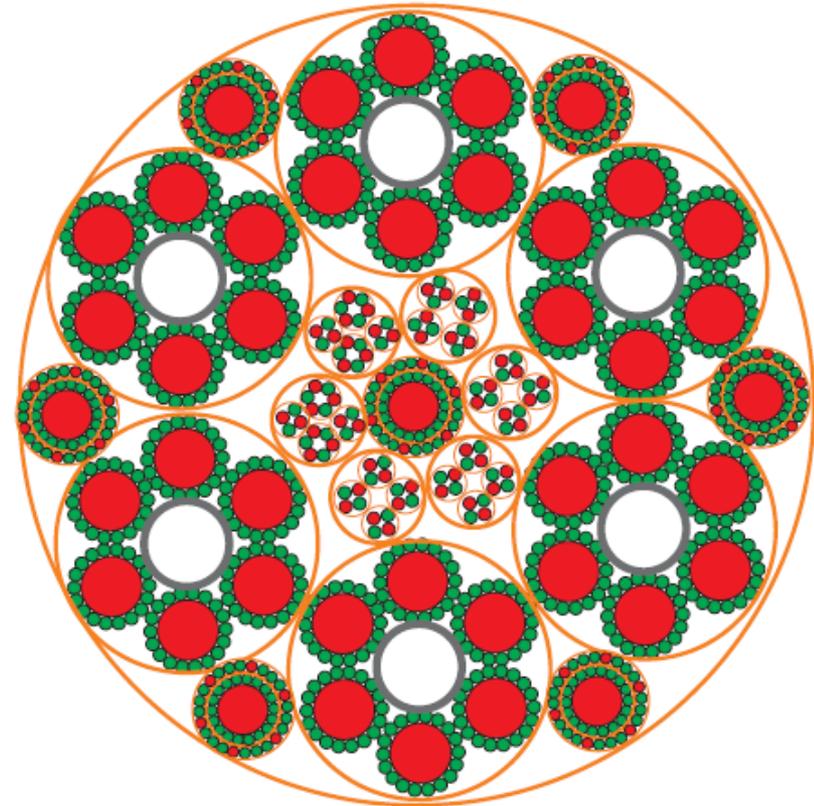
18 MgB<sub>2</sub> wires  
 $\Phi = 6.5$  mm

20 kA  
Six cables,  $\Phi = 19.5$  mm

Concentric  $\pm 3$  kA  
Seven cables,  $\Phi = 8.4$  mm

0.4 kA  
Four cables

0.12 kA  
Eighteen cables



$\Phi_{\text{ext}} \sim 65$  mm

# 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	$\pm 2$	kA	$\pm 2.4$	kA
Trim on Q2b	Trim	$\pm 0.2$	kA	$\pm 0.24$	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

# 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

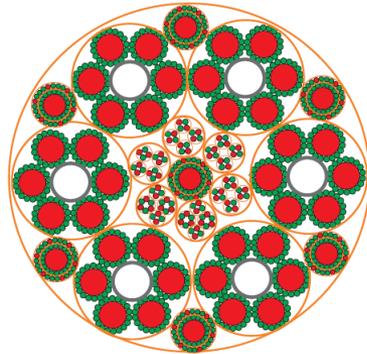
- Temperature gradient along the link considered
- Normal zone / MPZ initiation and detection not considered
- Cooling by helium gas ignored due to the short quench time constants
- Different current coupling loops considered but not no 3d EM modelling

# 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.

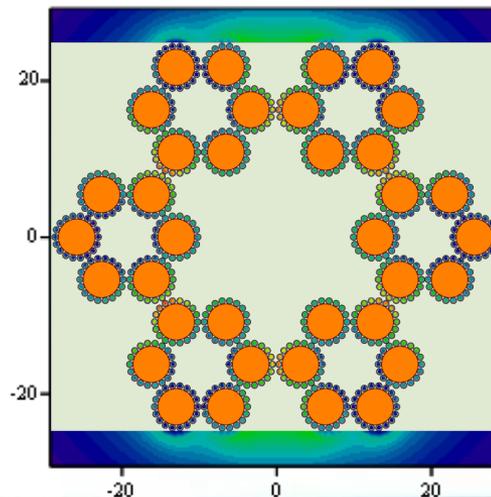
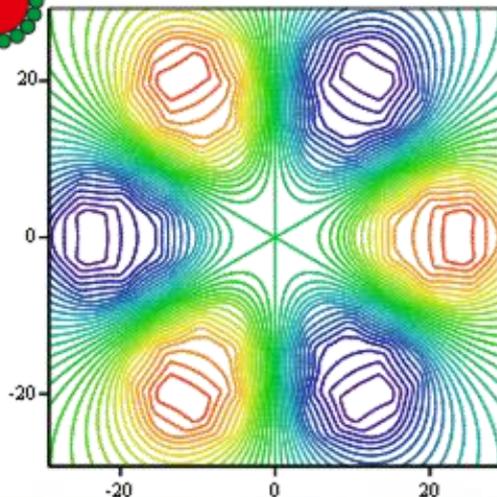
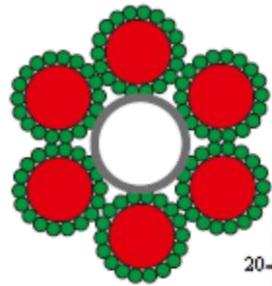
65mm



### Lines of force

### Magnetic field

6x20kA fully powered



### Main Characteristics

#### Maximum Field:

1x20kA:  $B_{\max} = 0.47 \text{ T}$

( $\pm$ )20kA:  $B_{\max} = 0.90 \text{ T}$

3x( $\pm$ )20kA:  $B_{\max} = 0.75 \text{ T}$

#### Inductances

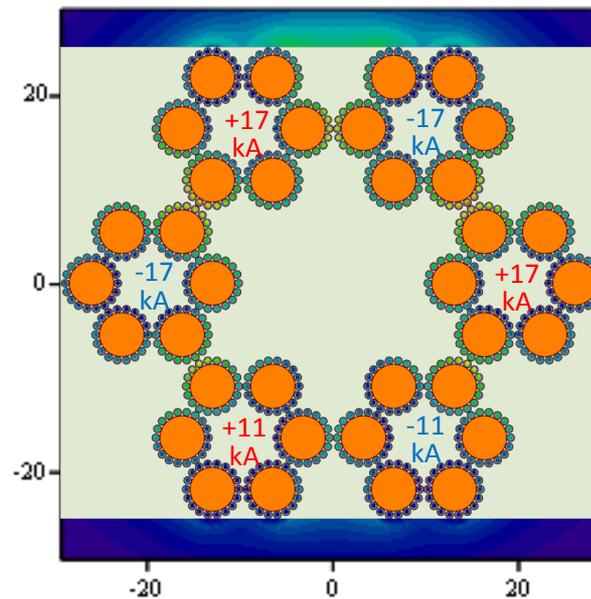
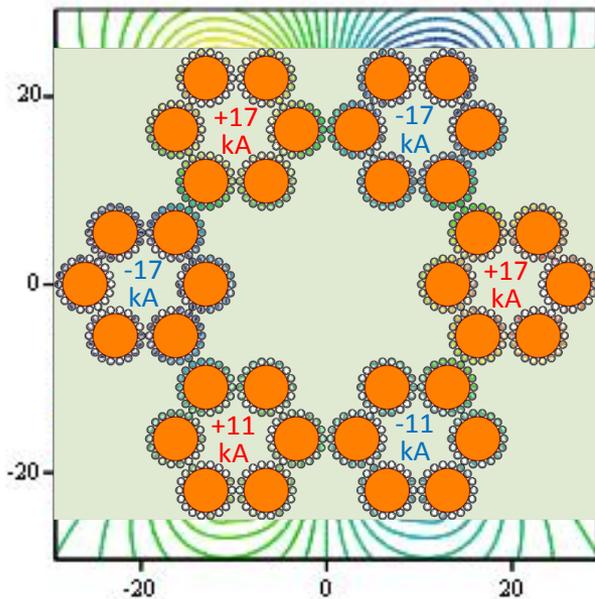
( $\pm$ )20kA:  $L = 0.19 \mu\text{H/m}$

3x( $\pm$ )20kA:  $L = 0.32 \mu\text{H/m}$

Insignificant compared to that of the quadrupoles

# Static Model: Magnetic Fields and Inductances

## 6x20kA cables powered to nominal currents



Asymmetric field distribution with a moderate change in maximum field.

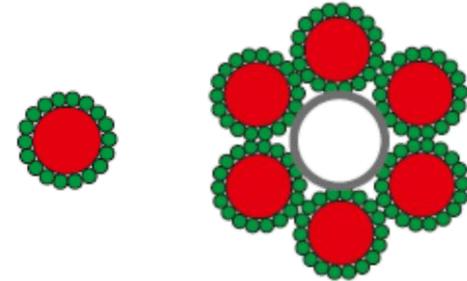
# Transient Model: (Self) Quench of Cables

## Heating dynamic upon the quench of a cable

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

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

- $A$  is the cable overall cross-section and  $\lambda$  is the superconductor fill factor.
- The stabilizer with a low resistivity  $\rho$  shares total current.
- The specific heat  $c_v$  ( $\text{Jkg}^{-1}\text{K}^{-1}$ ) and density  $d$  include both the superconducting wire and the stabilizer.



18-wire sub-cable and 20kA cable are thermal/electrically equivalent:  $\lambda \sim 30\%$



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:

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

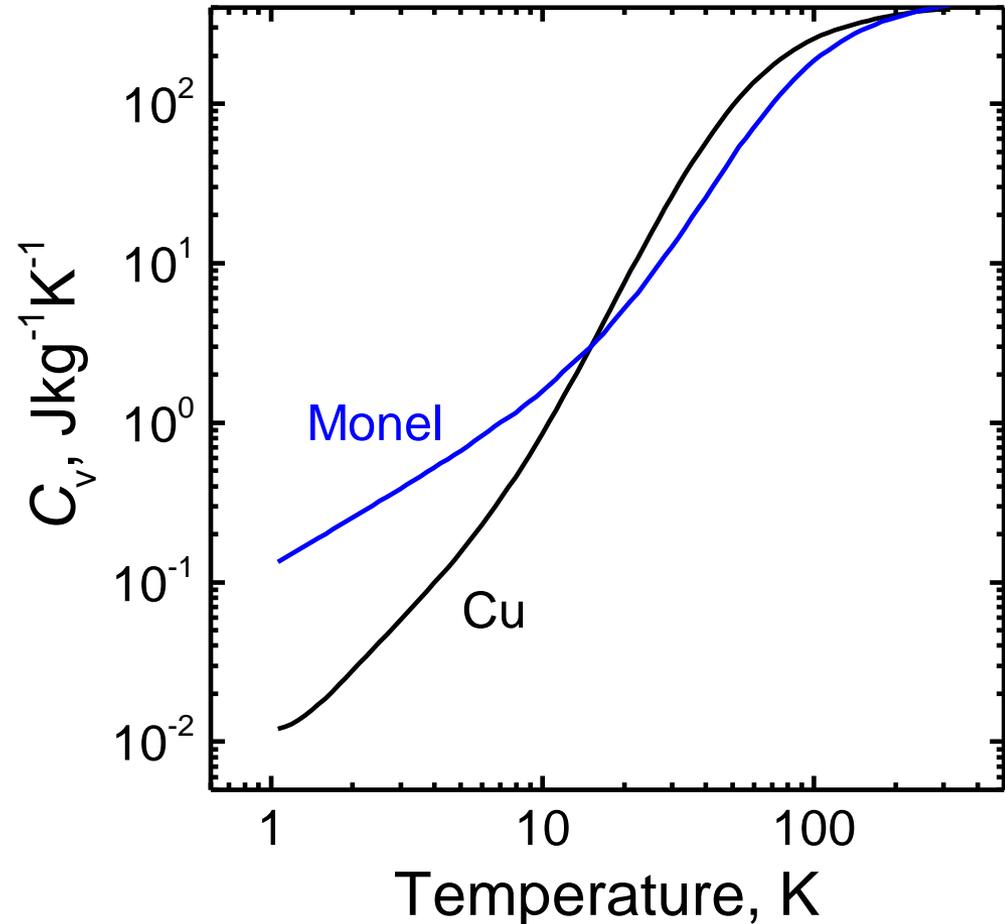
With the lattice specific heat calculated analytically with

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

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 ( $\Theta_D = 460\text{K}$ )



# Transient Model: (Self) Quench of Cables

## Quench load of 20kA cable

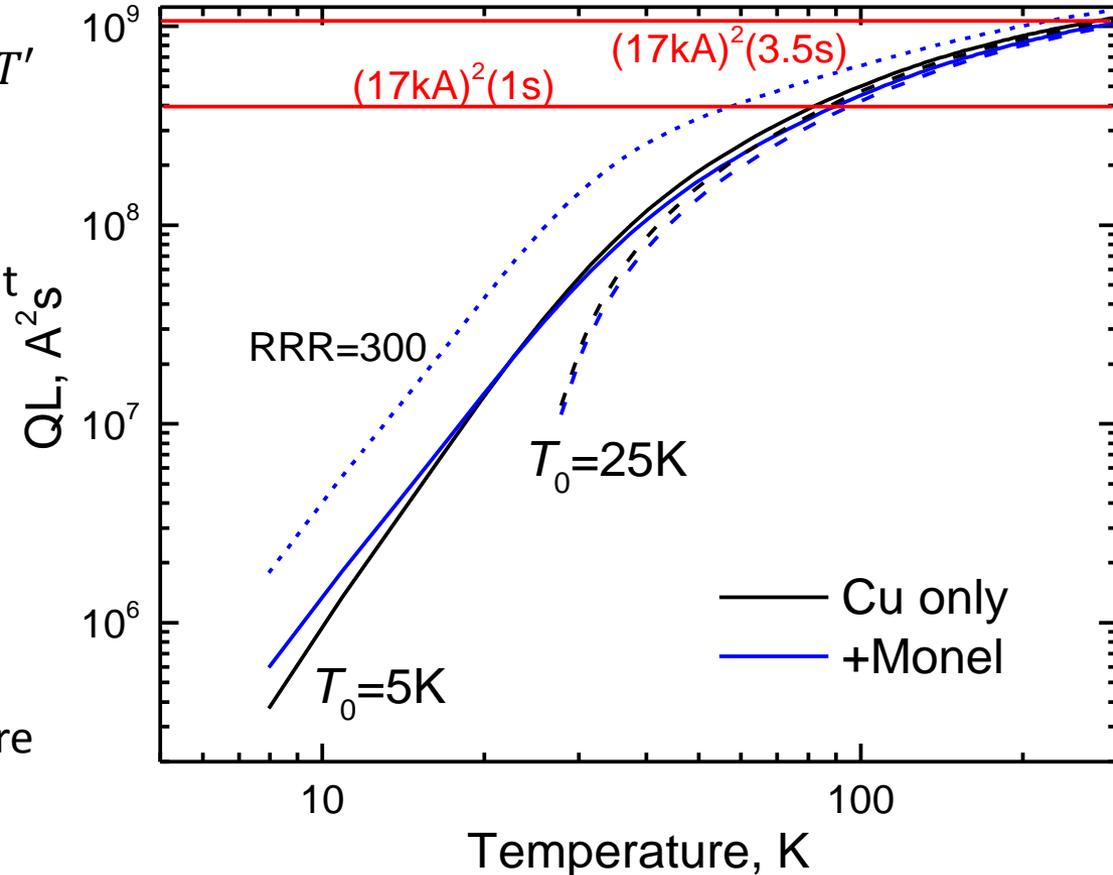
$$QL(T) = (1 - \lambda)^{-1} A^2 \int_{T_0}^T \frac{dc_v(T')}{\rho(T')} dT'$$

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

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



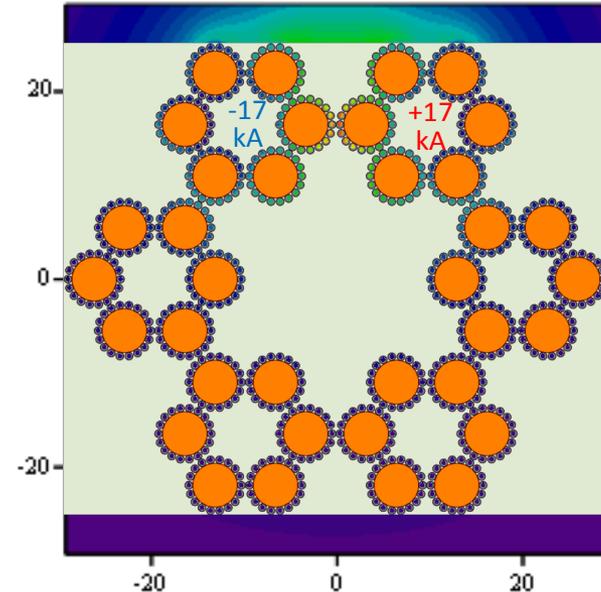
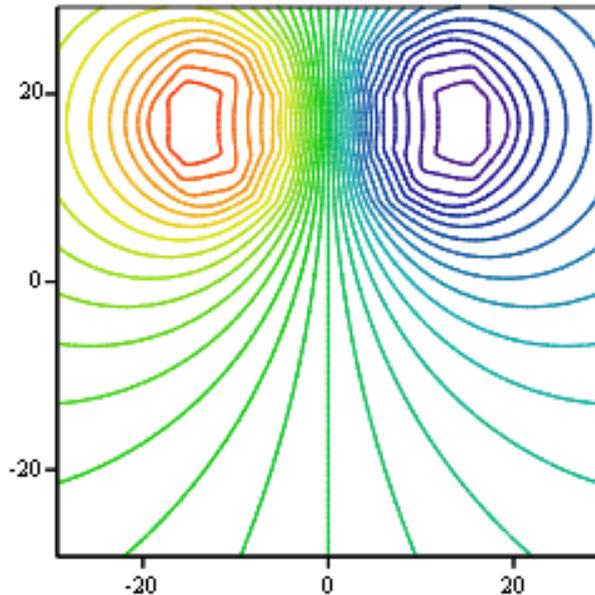
For magnet discharging time constant of  $\tau = 7s$ ,

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

# Transient Model: Electromagnetic Induced Quench of Cables

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

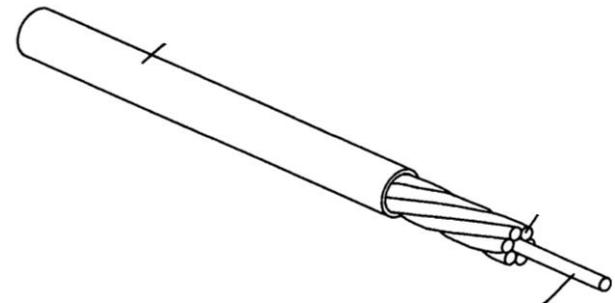
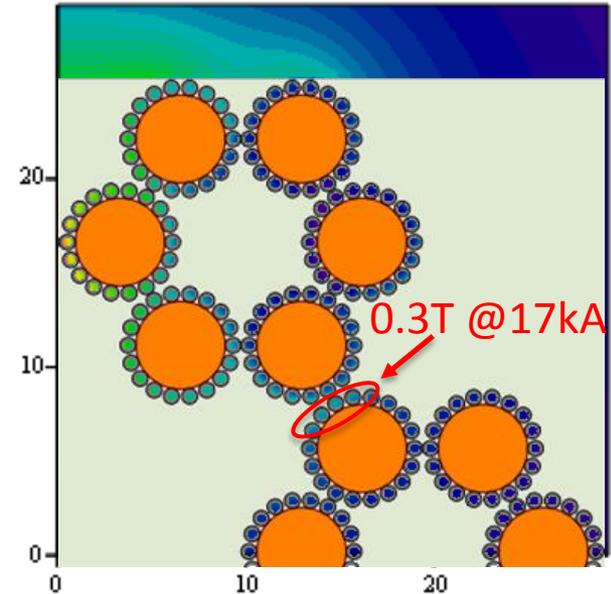
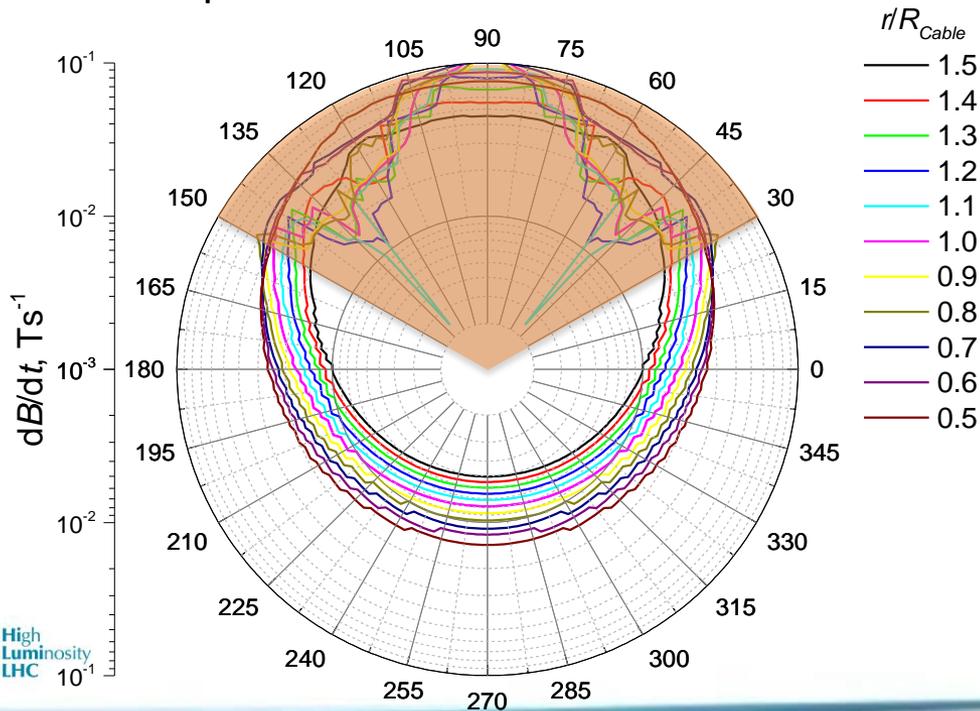
- ❑ The net field change  $\Delta B$  within the link is the same as the field produced by the fast discharging cable.
- ❑ For a discharging current  $I_0 e^{-t/\tau}$ , the field change rate imposed on the link is  $\dot{B} = \Delta B(I_0) \tau e^{-t/\tau}$ , proportional to the field  $\Delta B(I_0)$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



## Electromagnetic induced Quench of Cables

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

- ❑ The maximum imposed field change is at immediate adjacent wires ( $30^\circ$  and  $150^\circ$ ) in the neighbouring cables.
- ❑ At 20kA,  $\Delta B$  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.

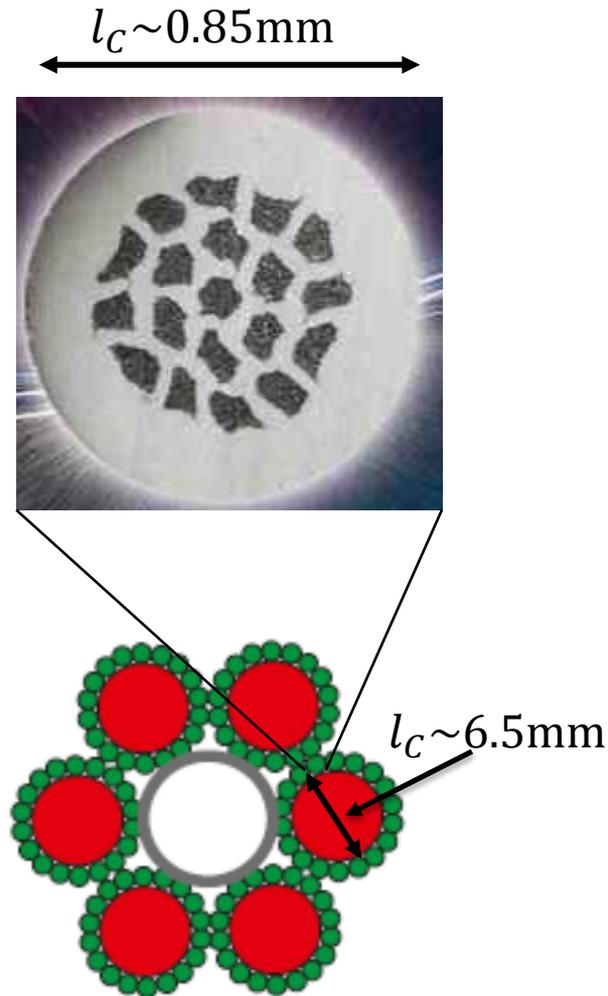


# Transient Model: Electromagnetic induced Quench of Cables

## 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 is almost certain: the twist pitch of the filaments will be longer than the exposed length of 90mm.
- ❑ 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

## Heating by induced current

- ❑ The temperature rise by induced current heating can be calculated with

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

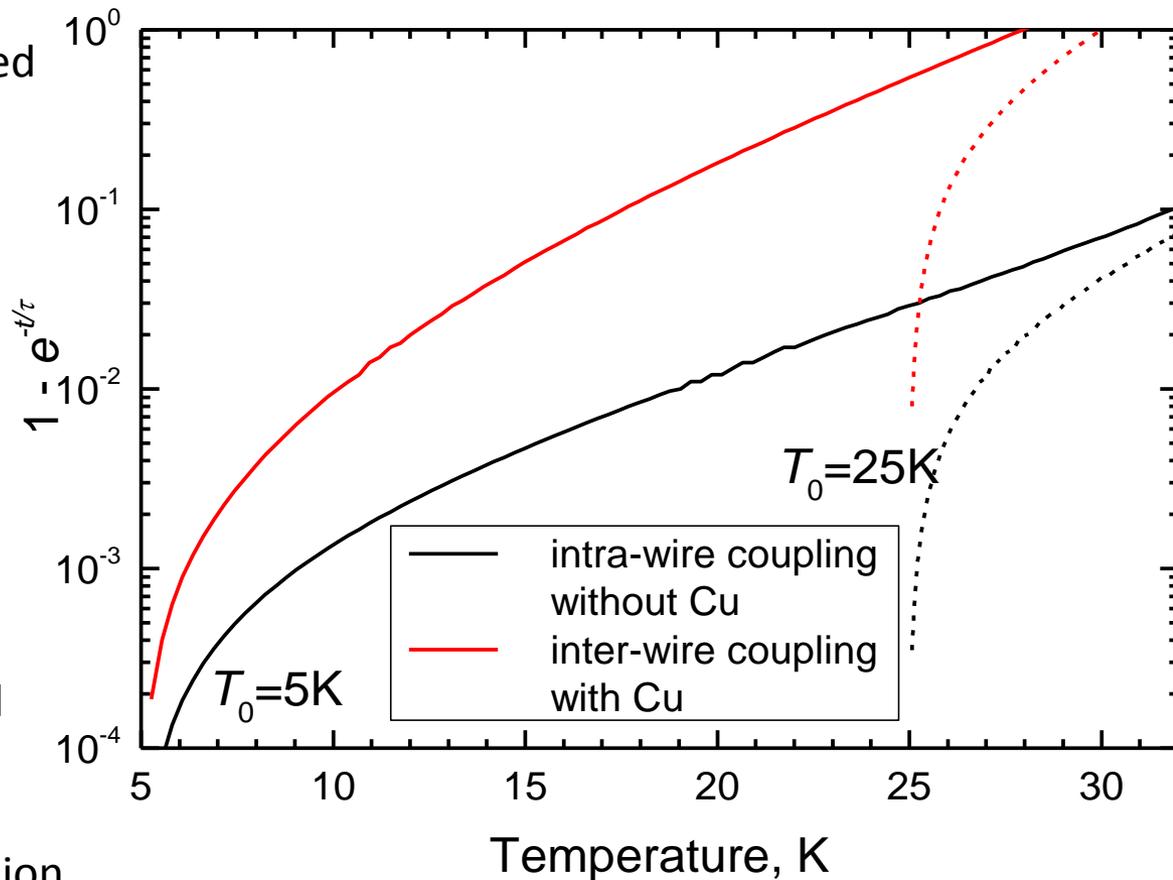
$A_h$  is the heated area including thermal diffusion outside the coupling loop.

- ❑ With an exponential discharge,

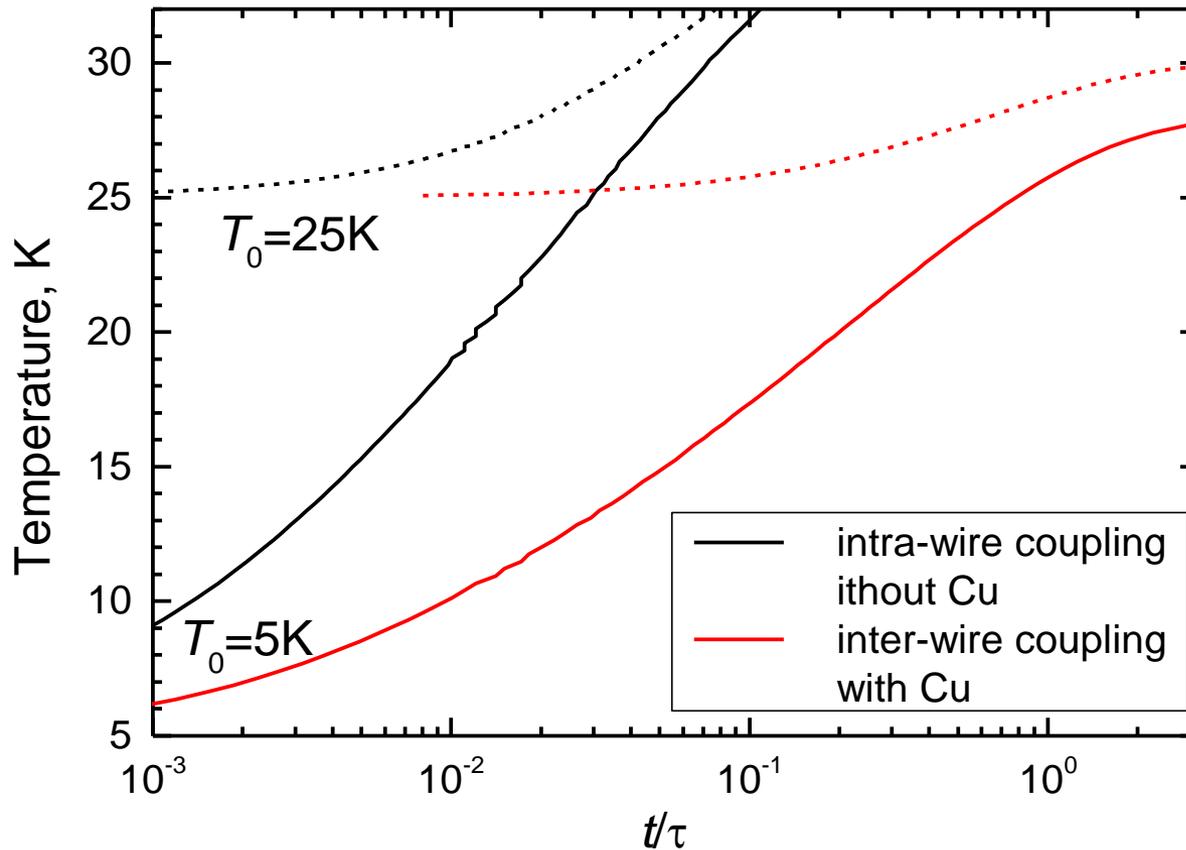
$$\int_0^T \frac{A_h \rho_d c_v(T)}{I_c(T) \Delta B(I_0) l_C} = 1 - e^{-\frac{t}{\tau}}$$

- ❑ Two limiting cases:

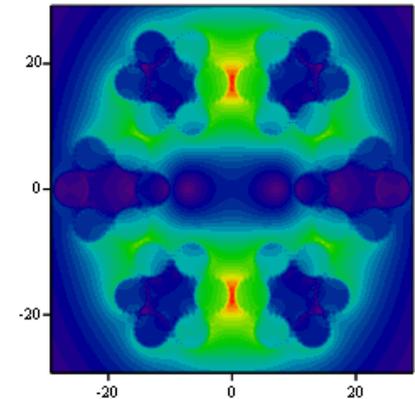
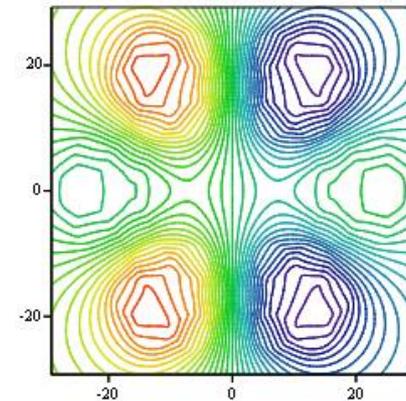
- Intra-wire without thermal diffusion,  $A_h = A_w$
- Inter-wire coupling with partial (1/3) thermal diffusion



# Transient Model: Electromagnetic induced Quench of Cables



Field in the cable can be reconfigured for better stability



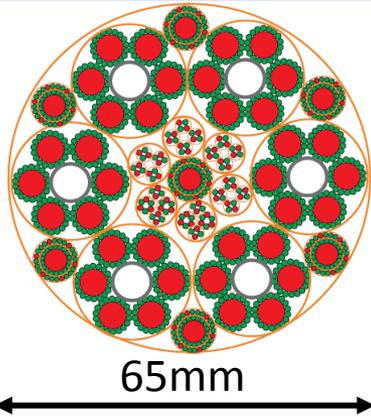
# Conclusions and future work

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

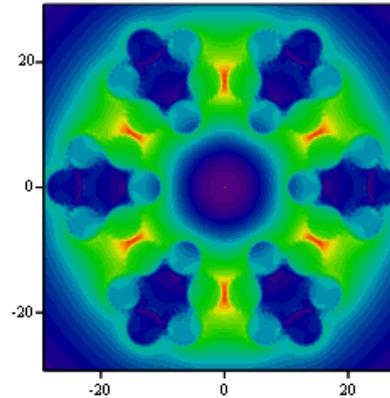
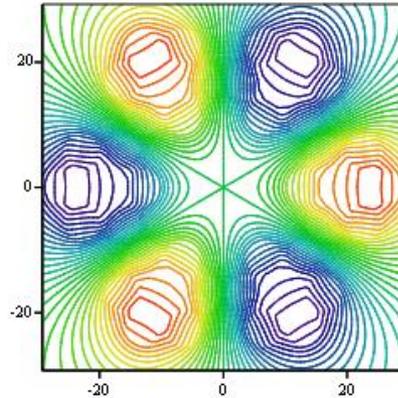
6x20kA , 7x3kA,  
4x0.4kA, 8x.12kA



## Lines of force

## Magnetic field

6x20kA fully powered



## 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

## 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  $B_0 e^{-t/\tau}$ ;
- $E \sim 0.4\mu\text{Vcm}^{-1}$ : coupling within single wire
- $E \sim 3\mu\text{Vcm}^{-1}$ : 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