Quench simulation and results for the MBXF magnet

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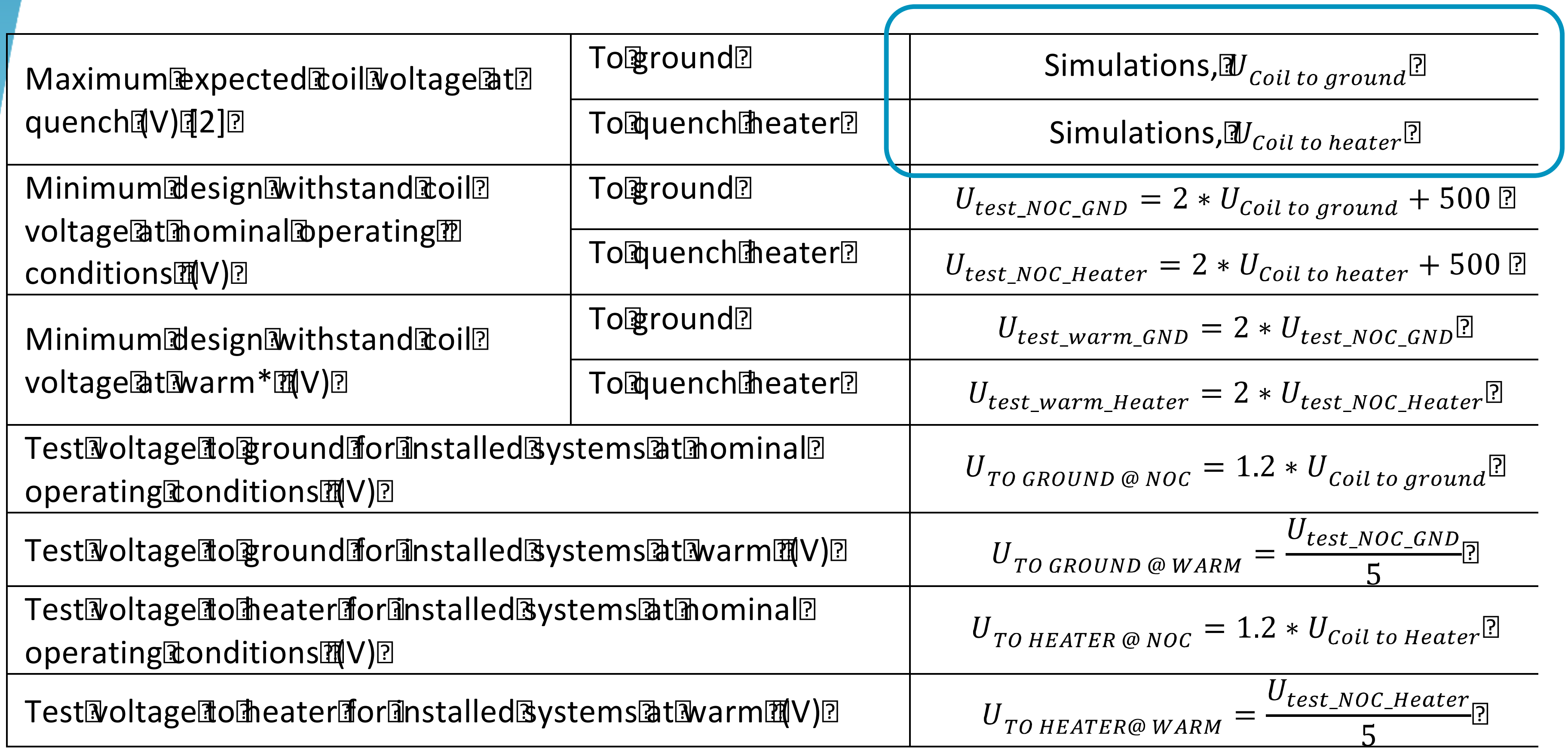
Introduction

- We have to understand the inspection or verification that is required for the electrical integrity of our magnet, MBXF, before the production stage
- Following the guideline described in EDMS1963398 (by Fernando and Felix), we have estimated the required test voltage as presented in this slide
- Please refer to the past slides (https://indico.cern.ch/event/693219/) for details of the simulation methodology

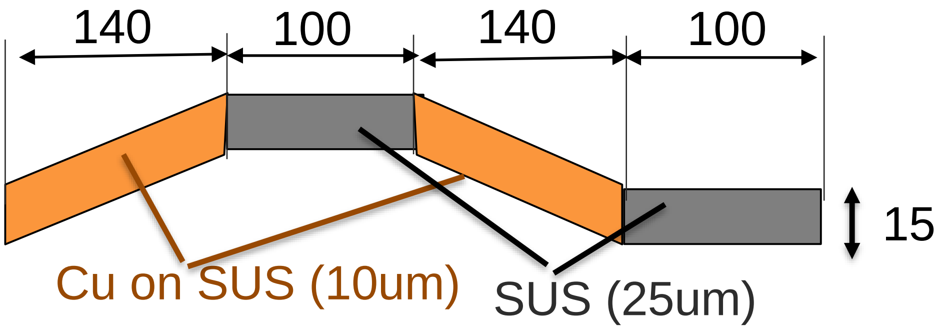
Test voltage
(Snapshot from EDMS1963398)



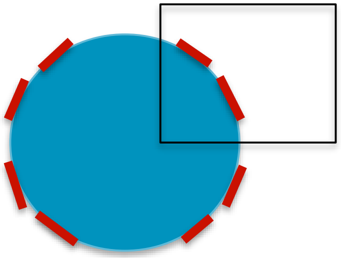
Maximum expected coil voltage at quench (V) [2]	To ground	Simulations, $U_{Coil\ to\ ground}$
	To quench heater	Simulations, $U_{Coil\ to\ heater}$
Minimum design withstand coil voltage at nominal operating conditions (V)	To ground	$U_{test\_NOC\_GND} = 2 * U_{Coil\ to\ ground} + 500$
	To quench heater	$U_{test\_NOC\_Heater} = 2 * U_{Coil\ to\ heater} + 500$
Minimum design withstand coil voltage at warm* (V)	To ground	$U_{test\_warm\_GND} = 2 * U_{test\_NOC\_GND}$
	To quench heater	$U_{test\_warm\_Heater} = 2 * U_{test\_NOC\_Heater}$
Test voltage to ground for installed systems at nominal operating conditions (V)		$U_{TO\ GROUND\ @\ NOC} = 1.2 * U_{Coil\ to\ ground}$
Test voltage to ground for installed systems at warm (V)		$U_{TO\ GROUND\ @\ WARM} = \frac{U_{test\_NOC\_GND}}{5}$
Test voltage to heater for installed systems at nominal operating conditions (V)		$U_{TO\ HEATER\ @\ NOC} = 1.2 * U_{Coil\ to\ Heater}$
Test voltage to heater for installed systems at warm (V)		$U_{TO\ HEATER@\ WARM} = \frac{U_{test\_NOC\_Heater}}{5}$

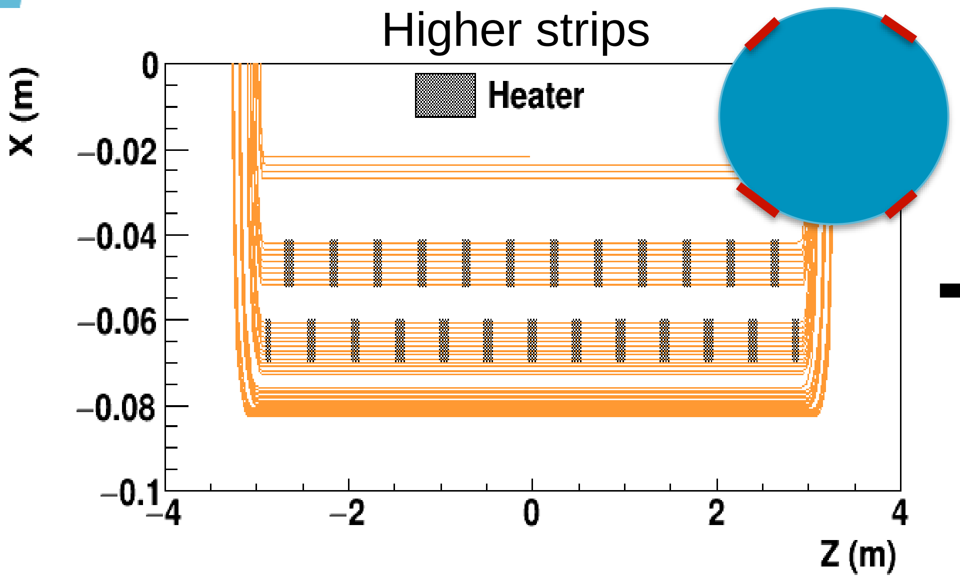
Design withstand and test voltages need to be estimated from the simulation level

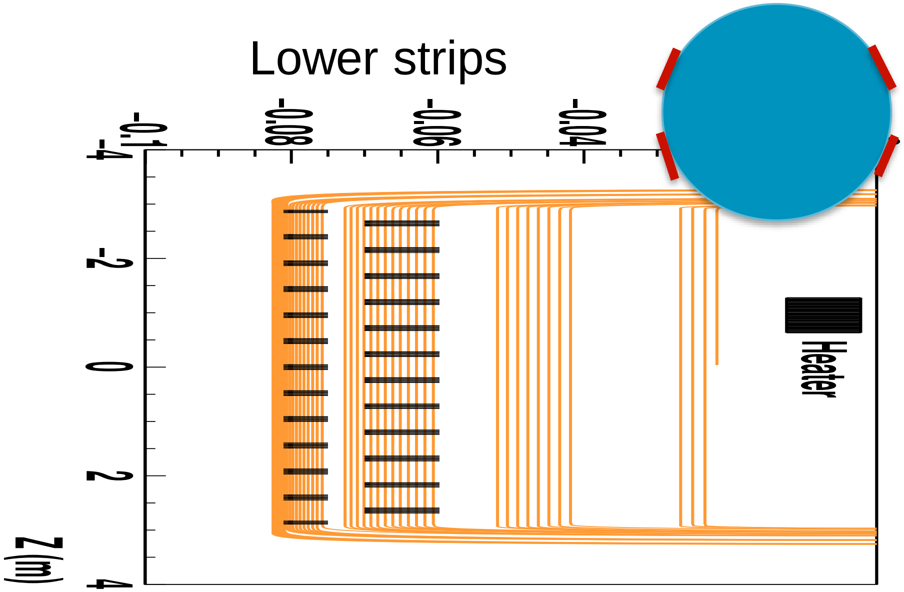
New QPH design



Two strips per qudrant







- Current scenario: the base material will be produced by CERN, and be patterned by Trackwise
- Composed of the two strips per quadrant, having a ‘zig-zag’ pattern for each
- Total resistance is adjusted by using copper bridges

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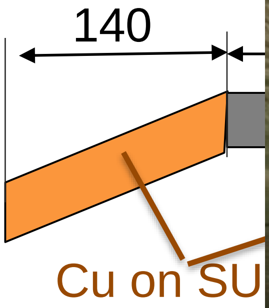
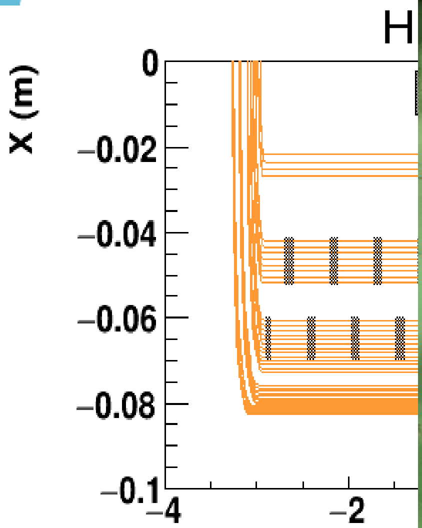
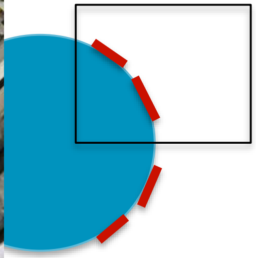
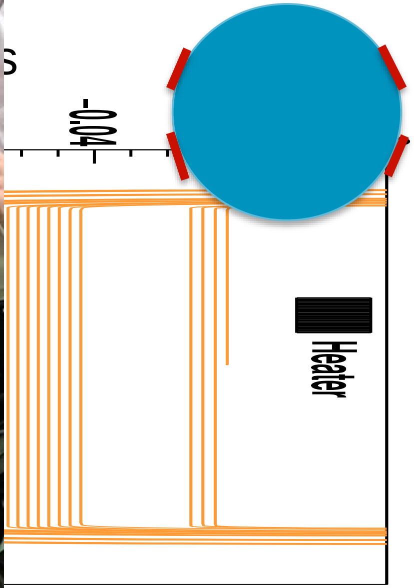
er qudrant





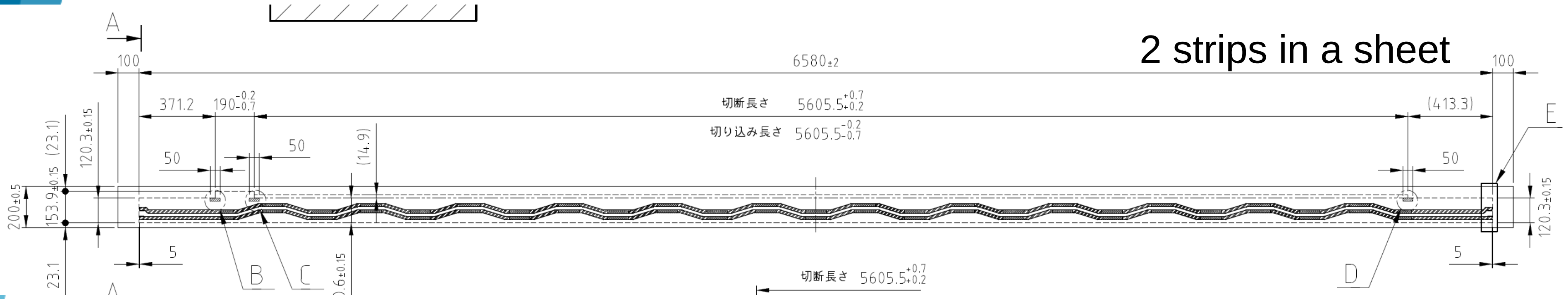

MBXFS2 (2m magnet)





- Current scen ERN, and be patterned by
- Composed o g' pattern for each
- Total resistar

QPH for the 7-m magnet, MBXF



2 strips in a sheet

*QPH Design parameter **

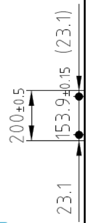
* (): t_{SUS} = 30um

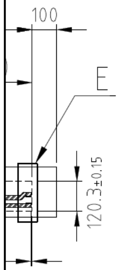
SUS regular patch length (mm)	100
SUS thickness (um)	25 (30)
SUS total length: L_{sus} (mm)	2430
Cu total length: L_{cu} (mm)	4220
L_{cu}/L_{sus}	1.74
SUS total resistance for each strip（Ω）	3.2 (2.7)
Peak temperature @ V_{charge}=900V (K)	920 (929)
Peak power density @ V_{charge}=900V (W/mm^2)	1.73 (2.07)
Peak current @ V_{charge}=900V (A)	141 (167)

<- Need to be checked

NOTE: In the simulation, we assume SUS thickness of 30 um

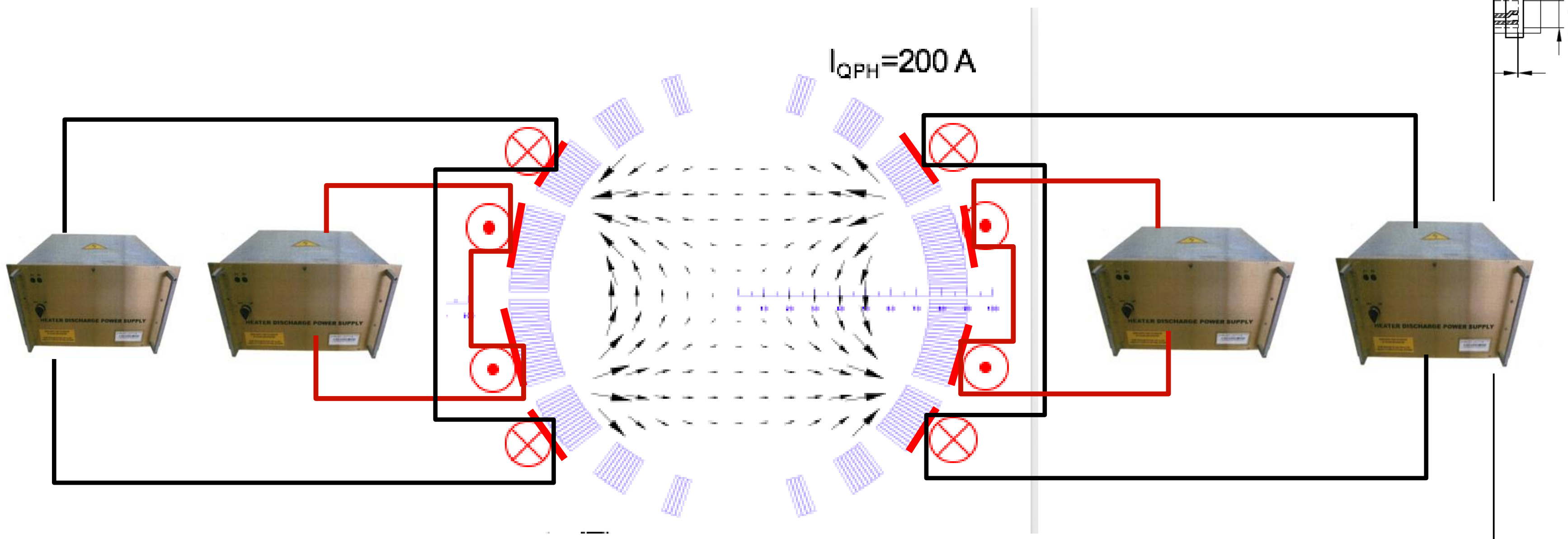
QPH for the 7-m magnet, MBXF





QPH connection
(one of the possibilities)

Total load is 6.4 Ω for each PS



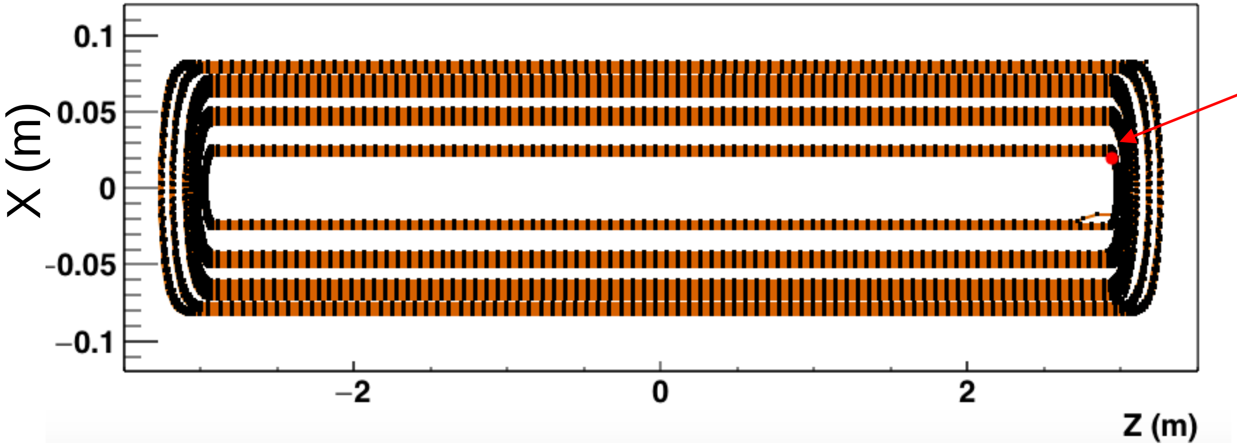
R$_{QPH}$ for each strip will be 3.2 Ω. It then increases to 6.4Ω if two strips are connected in series.

From the experience in the 1st model cold test, we want not to exceed the total load of ~6.0Ω per PS.

Accordingly, we need 4 PSs in total for the 7-m magnet

Quench simulation w/ new QPHs

- Magnet: 7m-long magnet (MBXFS2-end)
- Operation current : **12047A (Nominal current)**
- No dump resistor is used in the circuit
  - Only magnet : Series of L_{coil} (M_{coil}) and R_{coil}
    - The terminal voltage is fixed to **zero** throughout the energy dump
- **4 PSs scenario: two strips are connected in series**
- Provoke the quench at the higher field region (B=5.2T) in the bottom coil, followed by the current dump and the QPH fire
  - Condition of the quench detection: ΔV_{bal}=0.1V w/ validation time=10ms

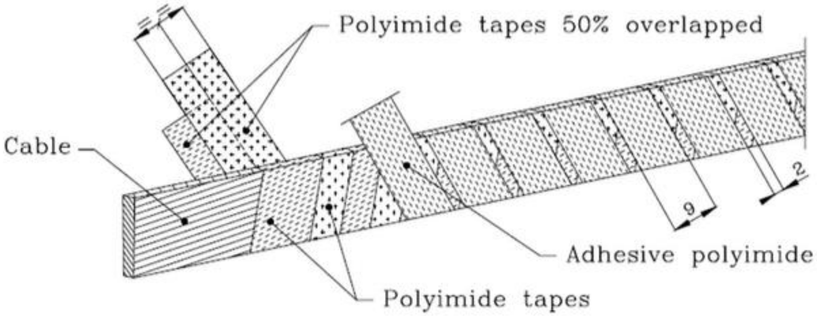


Quench location

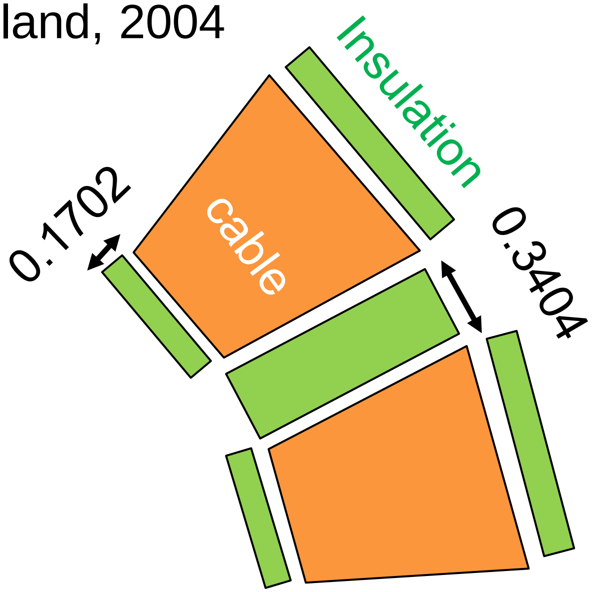
Conductor parameter in simulation

Cable	Parameter
Copper to SC ratio	1.9
Strand Φ (mm)	0.825
# of strands	36
RRR	150
Thin edge (mm)	1.362
Thick edge (mm)	1.598
Cable width (mm)	15.1

Insulation	Parameter
1st & 2nd layer thickness (mm)	0.0508
3rd layer thickness (mm)	0.0686
Total thickness (mm)	0.1702

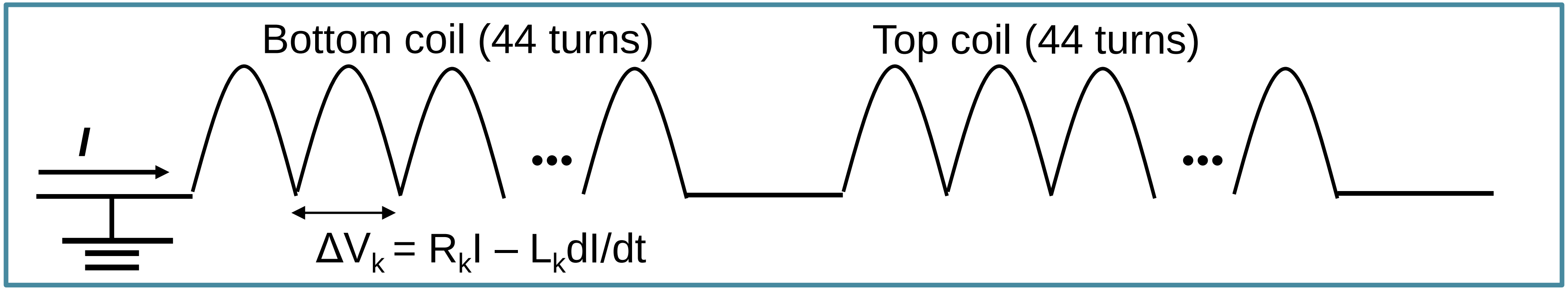


O. S. Bruning et al.,
LHC design report vol. 1 CERN, Geneva, Switzerland, 2004



Estimation of the maximum voltage to ground for the 7m-long magnet

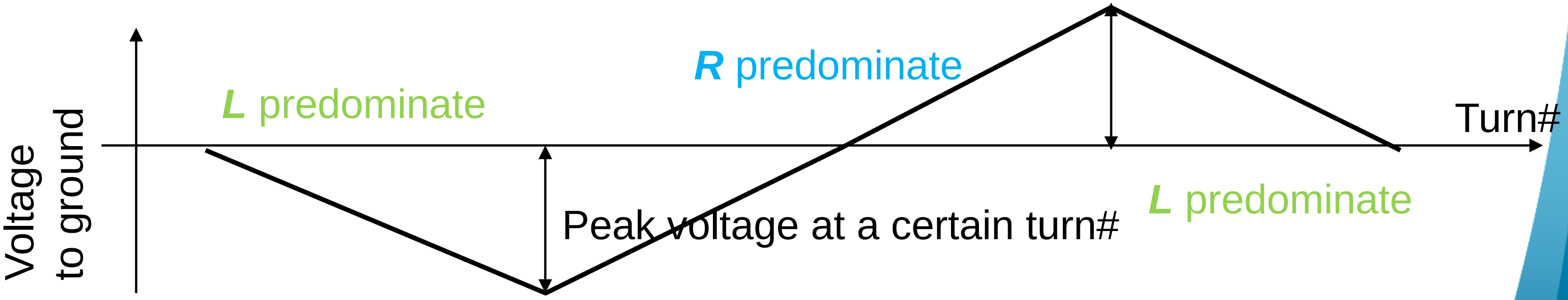
Resistance and mutual inductance are computed for each turn (R_k, L_k: k=turn#, 88 turns in total)



Then sum the voltage drops (ΔV_k) until X turns :

$$V_{\text{to ground}}(X) = \sum_{k=1}^{k=X} \Delta V_k$$

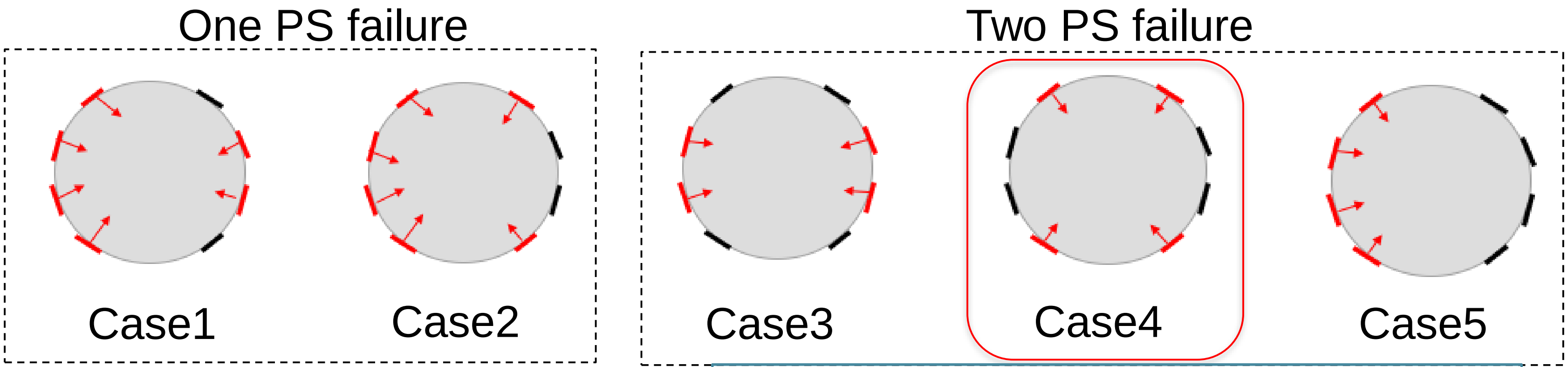
index ***k :*** turn# (1-88)



We can seek the maximum V by sweeping X for each time step

We define the highest $V_{\text{to ground (X)}}$ as the maximum voltage to ground at quench

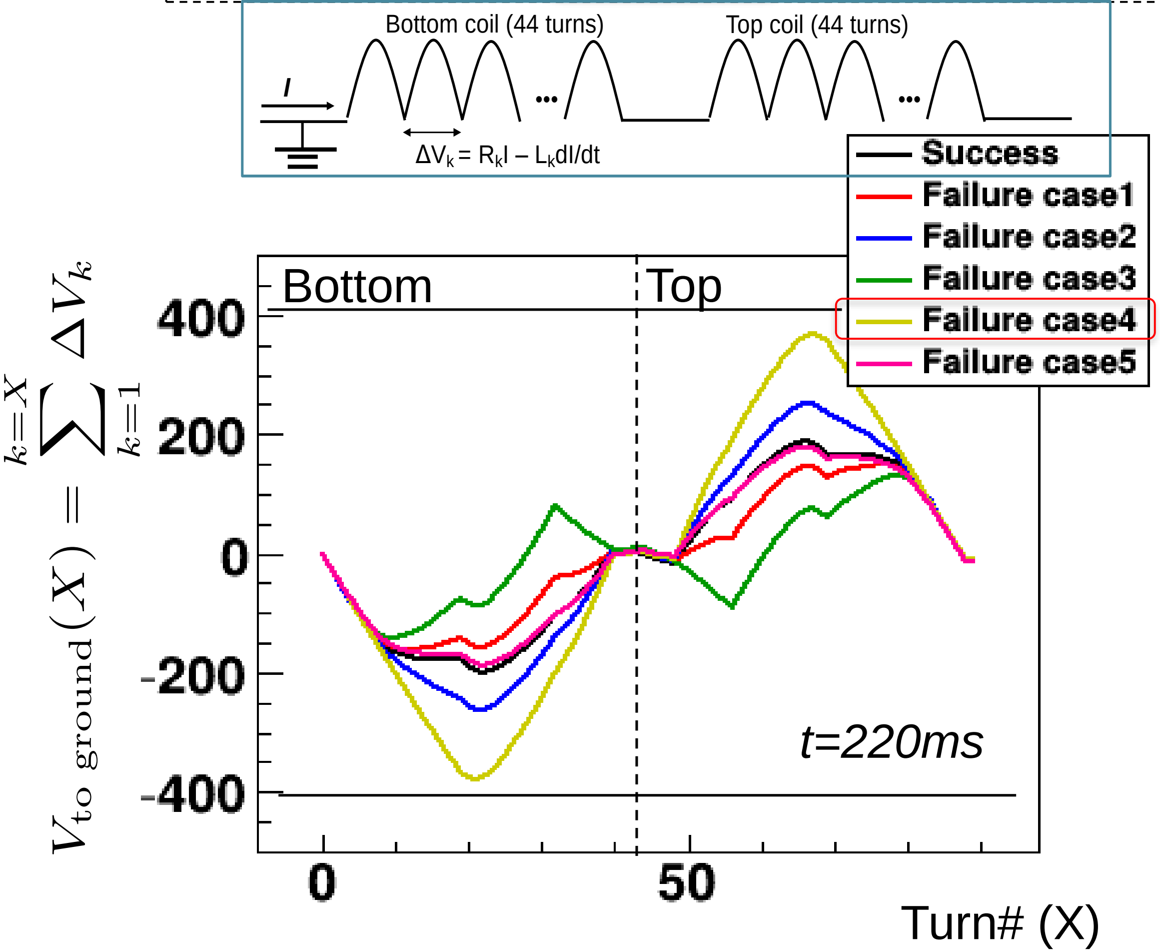
Quench voltage results



Quench voltage reaches its peak at ***t***=220 ms (***t***=0 : quench provocation)

The worst scenario is '**case 4**' where the voltage reaches **~400 V** at maximum

So, we use 400 V for the input to the test voltage

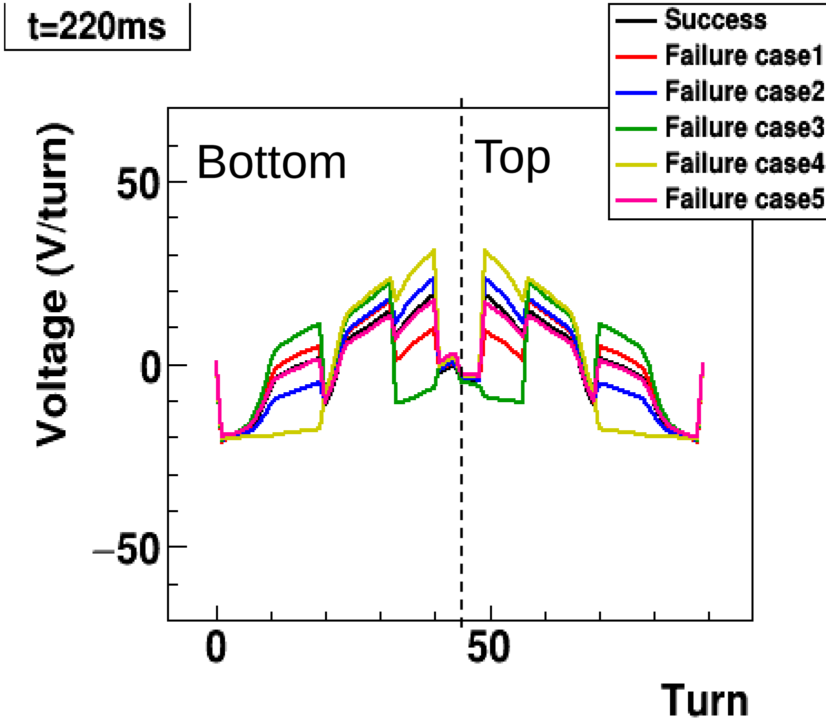


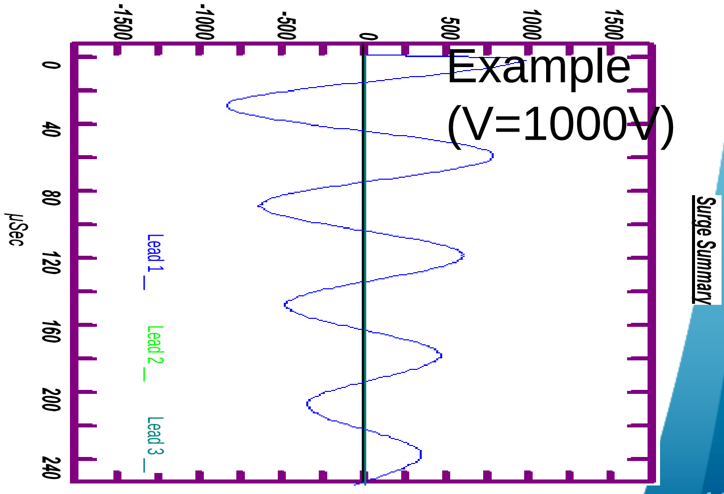
Test voltages for MBXF

Maximum expected coil voltage at quench (V)	To ground	**400**
	To heater	900
Maximum design withstand coil voltage at nominal operating conditions (V)	To ground	1300
	To heater	2300
Minimum design withstand coil voltage at warm (V)	To ground	2600
	To heater	4600
Test voltage to ground for installed system at nominal operating conditions (V)		480
Test voltage to ground for installed system at warm (V)		260
Test voltage to heater for installed systems at nominal operating conditions (V)		1080
Test voltage to heater for installed systems at warm (V)		460
Maximum leakage current (uA)		10
Test voltage duration (s)		30

Comment: Ringing voltage

- Another input to the integrity check is ‘ringing test voltage’,
- In order to estimate the required ringing voltage, we’ve estimated the ‘maximum inter-turn voltage’ using our simulation, which showed **30 V/turn** is expected at worst
- So, our present plan is to set 30x44 turns=1.3 kV as the ringing test voltage



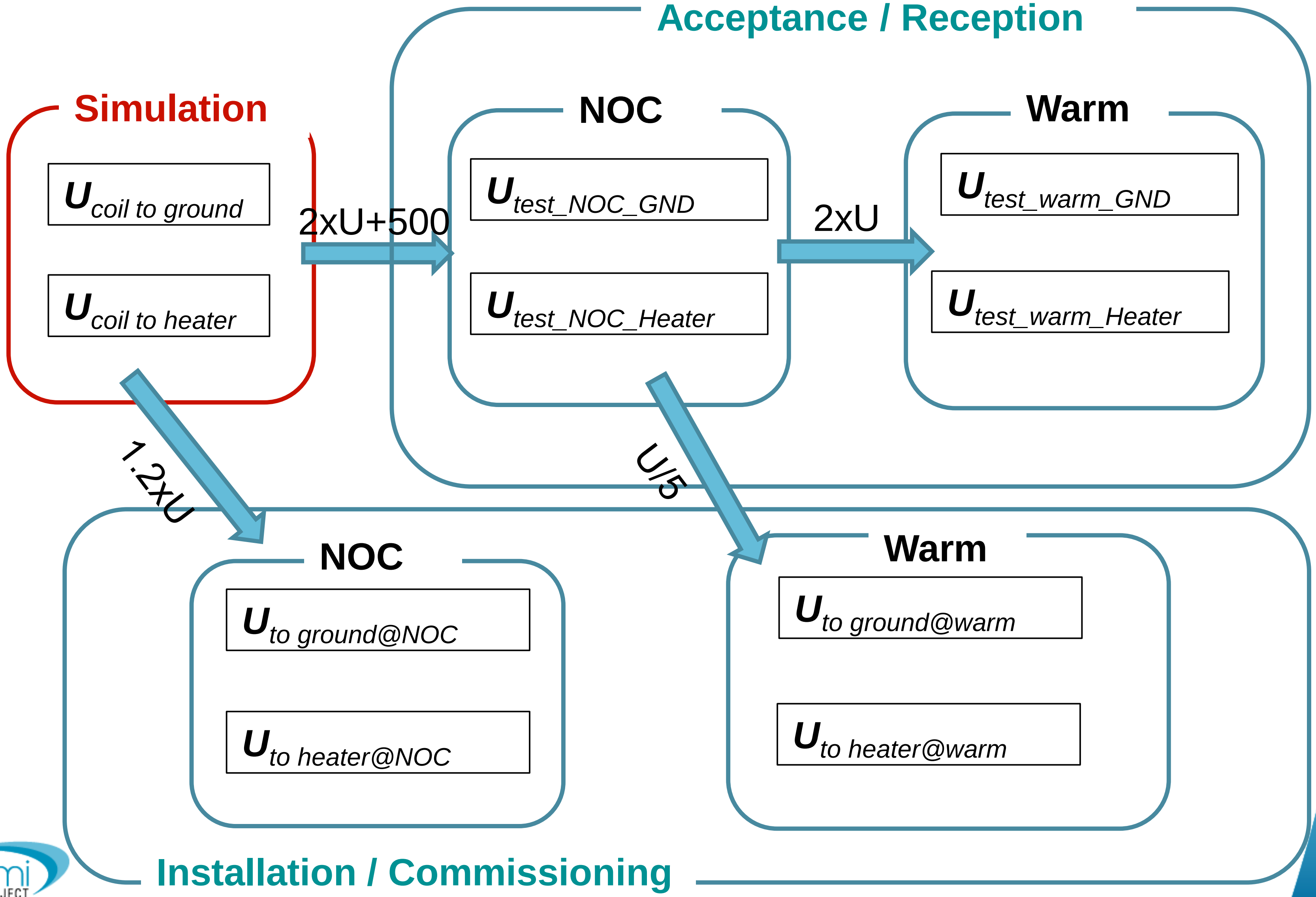

Example (V=1000V)

Summary

- Maximum voltage-to-ground is calculated for the new QPH pattern and for the 7m-long magnet, MBXF
- The worst scenario is ‘case 4 ’ where the voltage reaches **400 V** at maximum, which is then inputted to the integrity check list of our magnet
- Ringing voltage is also estimated on the simulation basis, which is set to **1.3 kV**

Supplement

Test voltage diagram (in our understandings)



Acceptance / Reception

Simulation

$U_{\text{coil to ground}}$

$U_{\text{coil to heater}}$

2xU+500

NOC

$U_{\text{test\_NOC\_GND}}$

$U_{\text{test\_NOC\_Heater}}$

2xU

Warm

$U_{\text{test\_warm\_GND}}$

$U_{\text{test\_warm\_Heater}}$

1.2xU

U/5

NOC

$U_{\text{to ground@NOC}}$

$U_{\text{to heater@NOC}}$

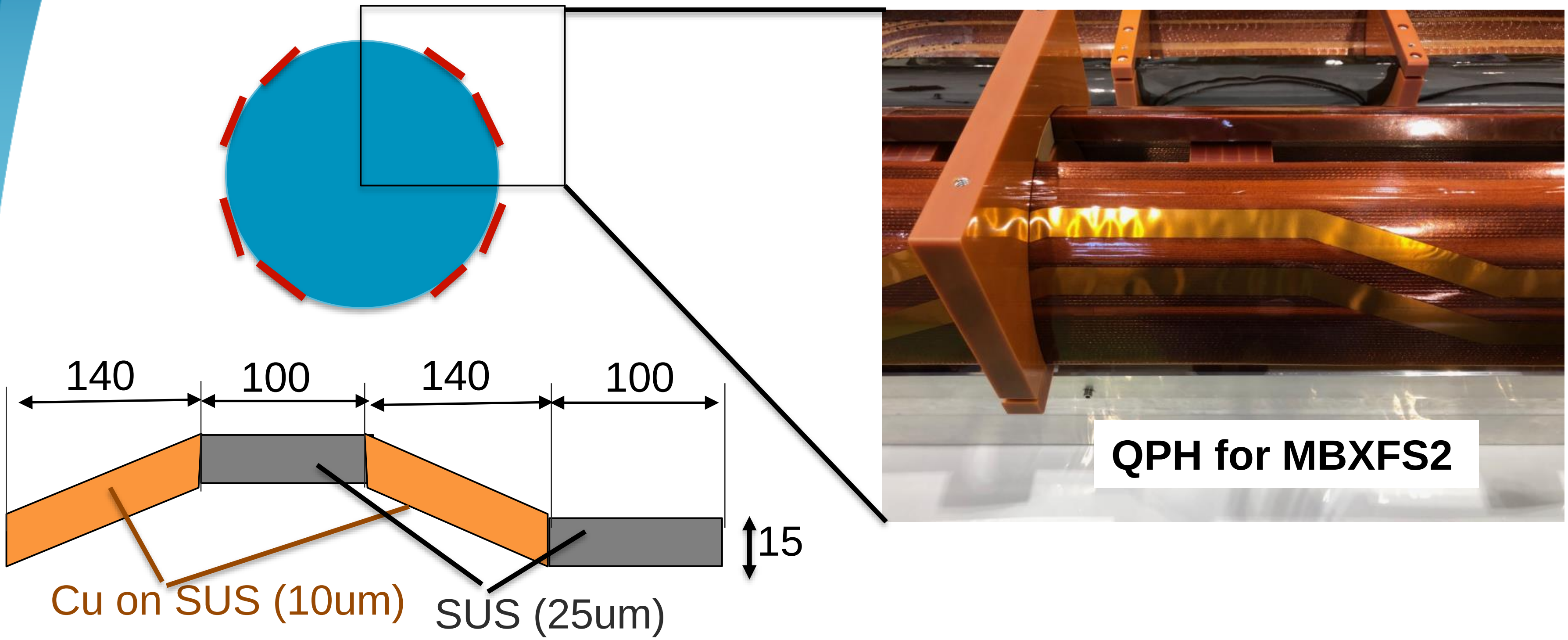
Warm

$U_{\text{to ground@warm}}$

$U_{\text{to heater@warm}}$

Installation / Commissioning

New QPH design



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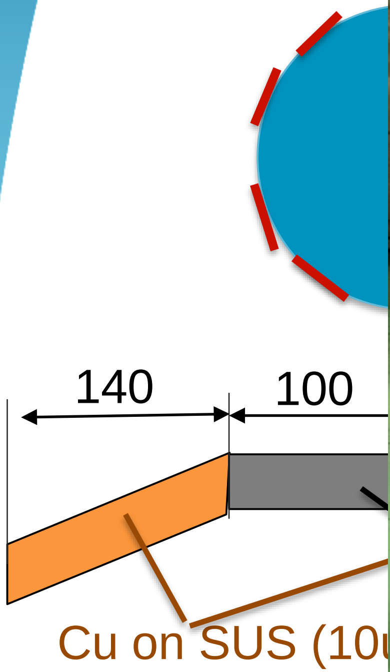

- Current s
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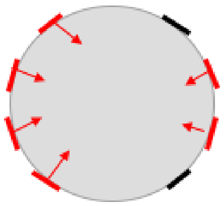
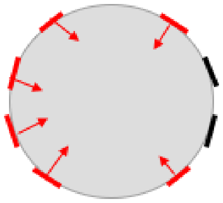
  CERN, a
- Compose
  g a ‘zig-zag’
  pattern fo
- Total resi
  dges

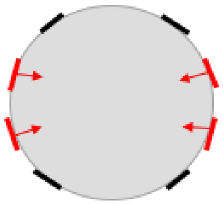
Expected MIITs at I=13000A for the 7m magnet



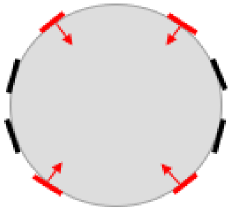
Case1



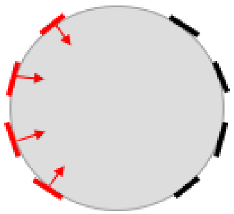
Case2



Case3



Case4



Case5

	Quench integral $\int_{t=t_{valid}}^{t=\infty} I^2 dt$	**Expected total *MIITs* (incl. simulation uncertainty)**	
		HF quench (**limit: 32.8**)	LF quench (**limit: 38.4**)
Success	23.9	30.0	35.4
Failure case1	25.0	31.1	36.5
Failure case2	25.0	31.1	36.5
Failure case3	26.6	32.7	38.1
Failure case4	26.7	32.8	38.2
Failure case5	27.8	33.4	39.3

Quench simulation:
Heat balance equation among ‘nodes’

$$\begin{aligned}S^p_{i,j,k}\Delta V_{i,j,k}\frac{T^{p+1}_{i,j,k}-T^p_{i,j,k}}{\Delta t} = q^{\mathrm{joule},p}_{i,j,k}+q^{\mathrm{qph},p}_{i,j,k}+&\left[\left(\frac{T^p_{i-1,j,k}-T^p_{i,j,k}}{R^p_{i-1\to i}}\frac{T^p_{i+1,j,k}-T^p_{i,j,k}}{R^p_{i+1\to i}}\right)\right.\\ &+\left(\frac{T^p_{i,j-1,k}-T^p_{i,j,k}}{R^p_{j-1\to j}}+\frac{T^p_{i,j+1,k}-T^p_{i,j,k}}{R^p_{j+1\to j}}\right)\\ &\left.+\left(\frac{T^p_{i,j,k-1}-T^p_{i,j,k}}{R^p_{k-1\to k}}+\frac{T^p_{i,j,k+1}-T^p_{i,j,k}}{R^p_{k+1\to k}}\right)\right]\end{aligned}$$

$S_{i,j,k}$: Volumetric specific heat (J/m^3/K)

$\Delta V_{i,j,k}$: Volume (m^3)

$q^{joule}_{i,j,k}$: Joule heat (J)

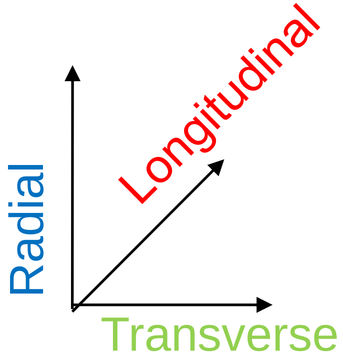
$q^{qph}_{i,j,k}$: Heat input from QPH (J)

R: Thermal resistance (m/W)

Index *p*: time evolution

In case of D1 magnet:

- i-1 (i+1) → i : Longitudinal direction (**current direction**)
- j-1 (j+1) → j : Transverse direction (**turn-to-turn propagation**)
- k-1 (k+1) → k : Radial direction (**layer-to-layer propagation**)

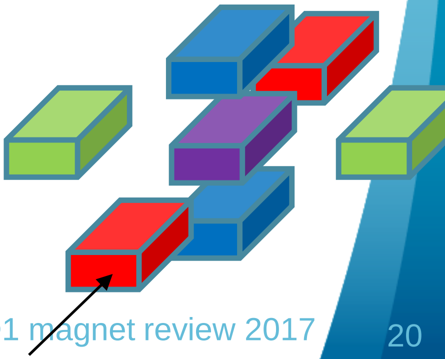


Strategy on the simulation: as realistic as possible

— Geometry : position, contact material

— Magnetic field

— Coil inductance etc.



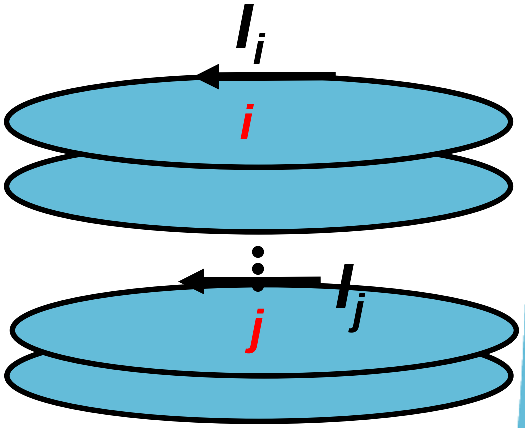
Concept of ‘turn’ inductance

Mutual Inductance of Loop ‘*i’ and ‘j’*

The stored energy ***W*** :

$$W = \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n} L_{ij} I_i I_j \quad ①$$

Inductance of Loop ‘*i*’ (turn inductance)



W can also be expressed with ‘flux’:

$$W = \frac{1}{2}\sum_{i=1}^{n} \Phi_i I_i \quad ②$$

Combining ① and ②, a relation of flux $\boldsymbol{\Phi_i}$ and the mutual inductance $\boldsymbol{L_{ij}}$ is :

$$\Phi_i = \sum_{j=1}^{n} L_{ij} I_j$$

If $\boldsymbol{I_i = I_j = I}$ (loops are connected in series)**:**

$$\Phi_i = \sum_{j=1}^{n} L_{ij} I \equiv L_i I$$

Thus, inductance of loop ‘i’ (=$\boldsymbol{L_i}$: Turn inductance) can be calculated as $\boldsymbol{\Phi_i / I}$

Inductance calculation

- According to the 2D field calculation, most of the flux distributions (B_y at z=0) approximately look flat along the x direction, and have similar strengths
- The total inductance at turn ***i*** (=L_i) can approximately be calculated by

$$L_i = \frac{\Phi_i}{I} = \frac{1}{I}\int_i \vec{B}\cdot d\vec{S} \simeq \frac{B}{I}\int_i \vec{n}\cdot d\vec{S} = \frac{BS_i}{I}$$

- Once the total inductance is obtained, L_i can be calculated by:

$$\frac{L_i}{L_\text{total}} \simeq \frac{S_i}{\sum_i S_i} \leftrightarrow \boxed{L_i \simeq L_\text{total}\frac{S_i}{\sum_i S_i}}$$