Experimental results from the 11 T DS Nb_3Sn dipole

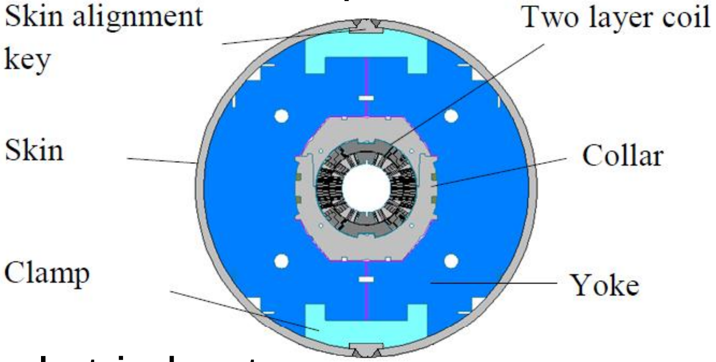
Guram Chlachidze
Fermilab

WAMSDO 2013
January 15-16, 2013 CERN

Introduction

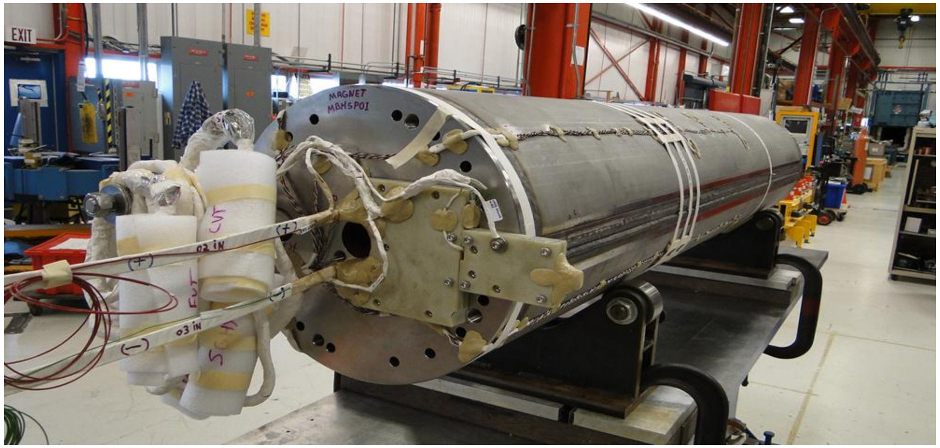
The first 2-m long single-aperture 11 T Nb_3Sn demonstrator dipole was tested at Fermilab in June-July 2012

- 40 strand Rutherford cable
- 0.7 mm diameter RRP 108/127 strand
- Two-layer 60 mm aperture coils
- 12 mm thick SS welded ski



Quench protection is provided by stainless steel strip heaters

- 60 mΩ dump resistor was used during the test at Fermilab



The magnet reached 10.4 T or 78% of SSL at 1.9 K

- Protection heater tests performed at currents up to 8500 A or 65% of SSL at 4.5 K

FERMILAB

Magnet Parameters

Parameter	Unit	Value
Magnet length (effective)	m	1.7
Number of turns per coil, N_{turn}/coil		56
Bare cable cross-section	mm^2	19.108
Cu:nonCu ratio		1.106
Cable packing factor	%	86.7
RRR		100
Insulation thickness	mm	0.1
Nominal current, I_{nom}	kA	11.85
Current density in copper stabilizer, J_{cu}	kA/mm^2	1.362
Inductance at I_{nom}	mH/m	6.04
Stored energy at I_{nom}, W_{nom}	kJ/m	424
Energy density, W/V_{coil}	MJ/m^3	85.9
Maximum quench field, B_{max}	T	13.4
Critical quench current current, I_{max}	kA	15.0
Maximum stored energy, W_{max}	kJ/m	680

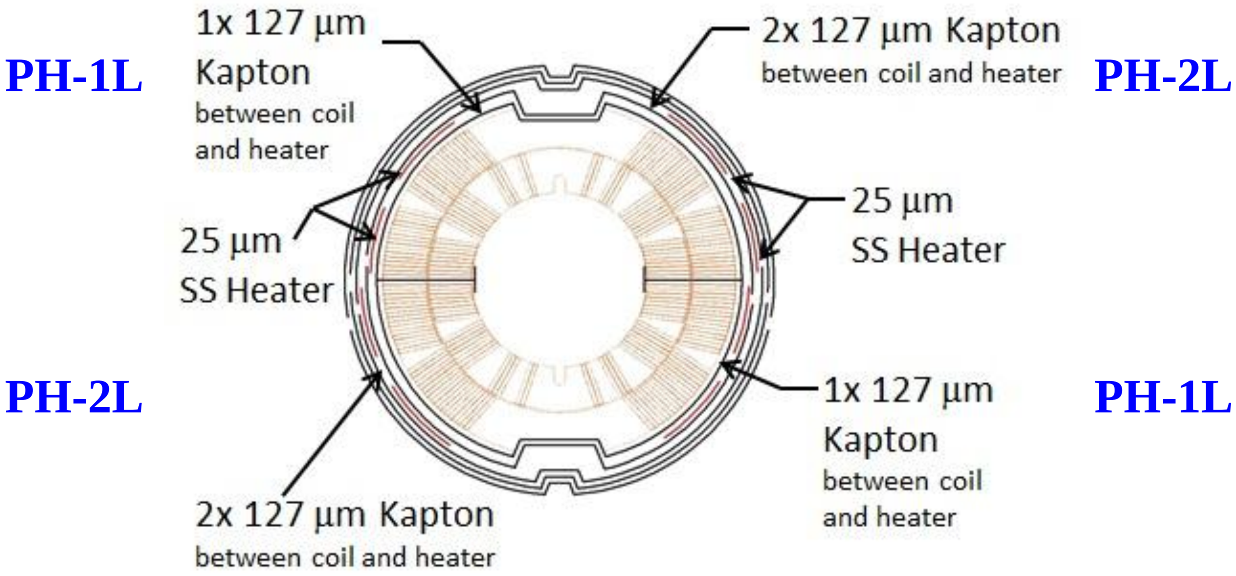
A. Zlobin « 11 T Nb_3Sn dipole - quench protection analysis »
FNAL-CERN meeting, 01/08/2013

Protection strip heaters

4 SS strips were placed between the ground insulation layers on the outer coil surface

- 0.025 mm thick 2100 mm long stainless steel strips
- 26 mm wide in high field and 21 mm wide in low field blocks
- Heaters cover 31 (out of 34) turns per quadrant or about 56% of total coil surface

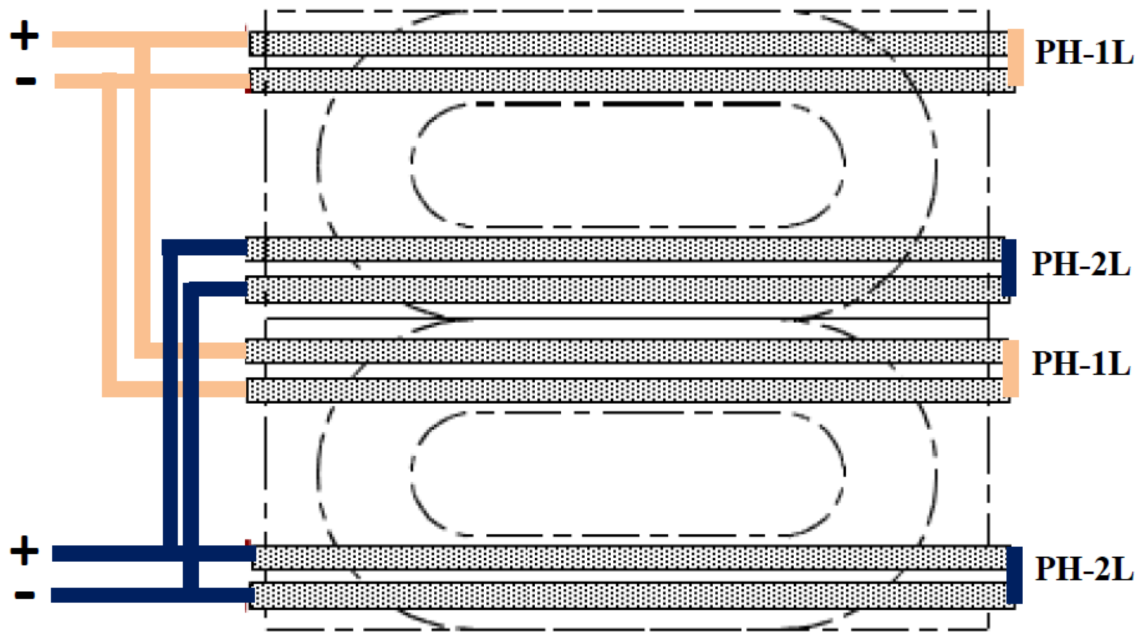
One pair of strips is placed between the 1st and 2nd Kapton layers (PH-1L) and another pair – between the 2nd and 3rd Kapton layers (PH-2L)



Strip heater wiring

2 SS strips on each side of the coil are connected in series at the return end and form a single protection heater (PH)

- 2 PH per coil, 4 PH in total
- PH resistance was ~ 5.9 Ω at room temperature and ~ 4.3 Ω at 4.5 K



PH-1L and PH-2L heaters from both coils are connected in parallel to a separate Heater Firing Unit (HFU)

Protection system parameters

HFU provides a maximum heater voltage up to 450 V and DC current up to 200 A

- Maximum HFU voltage during the test was 400 V corresponding to a peak heater power density of 25 W/cm^2
- The highest achievable peak power density is ~ 30 W/cm^2
- For more power density we need to change PH design or modify HFUs

Adjustable HFU bank capacitance varies from 4.8 mF to 19.2 mF

- Available range of PH decay time constant was 12 - 50 ms, most tests performed with τ = 24 ms

Dump delay for all heater tests was set to 1 ms and PH delay was set to 0 ms

- Dump was delayed only for quench propagation studies from outer to inner coil layer

In all tests we measure PH delay - a time interval between the heater discharge and the first quench development in the magnet

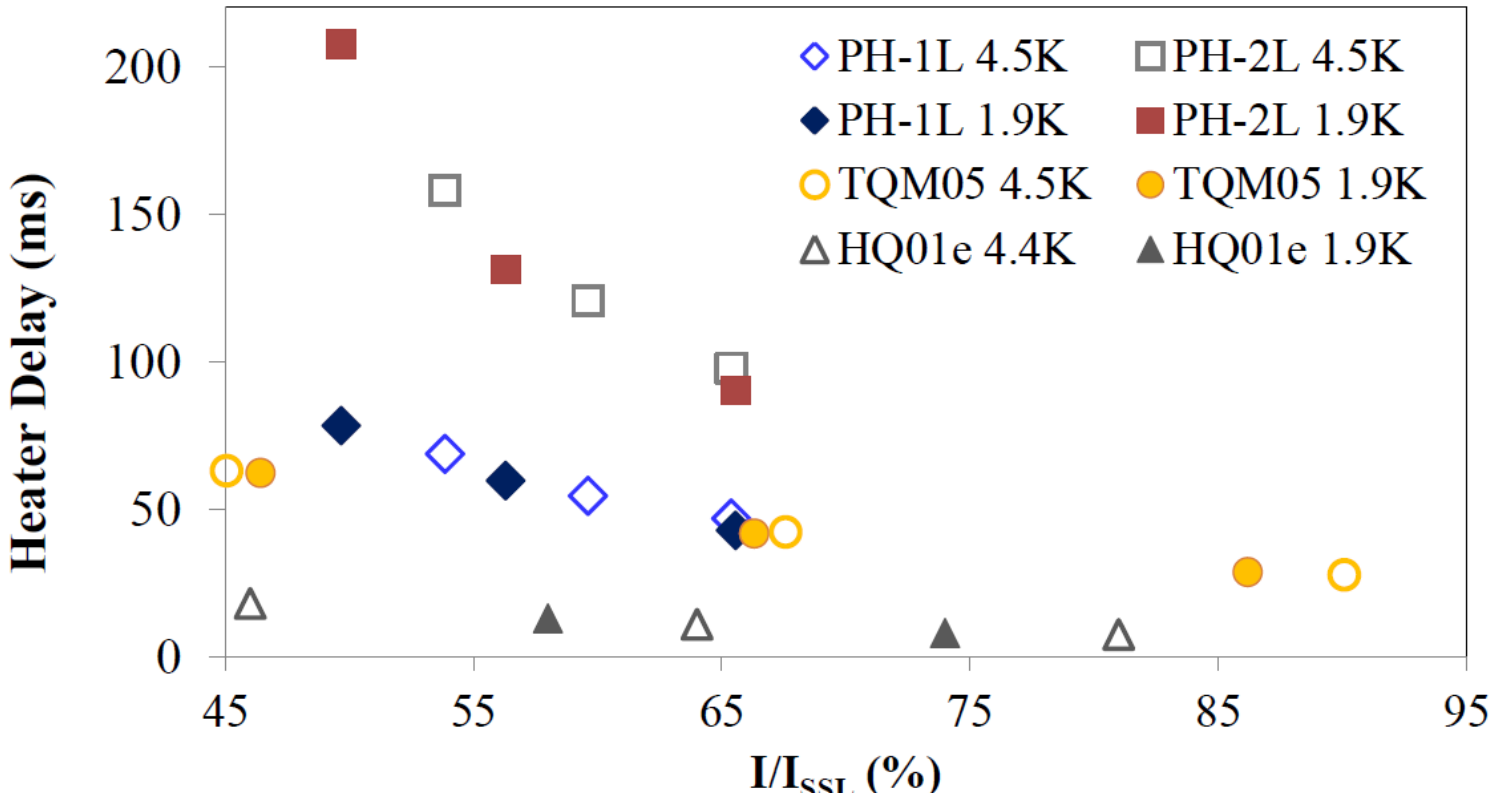
Quench propagation speed was estimated as 27 m/s in only one quench at 72% of SSL

- Most quenches developed in the mid-plane block

Protection Heater Tests

Heater tests were performed both at 4.5 K and 1.9 K

- Various magnets with different heater design and insulation show similar delay times at 4.5 K and 1.9 K



***H. Felice et al., "Summary of HQ quench protection studies"*, 2nd HiLumi LHC-LARP meeting, Frascati 2012**

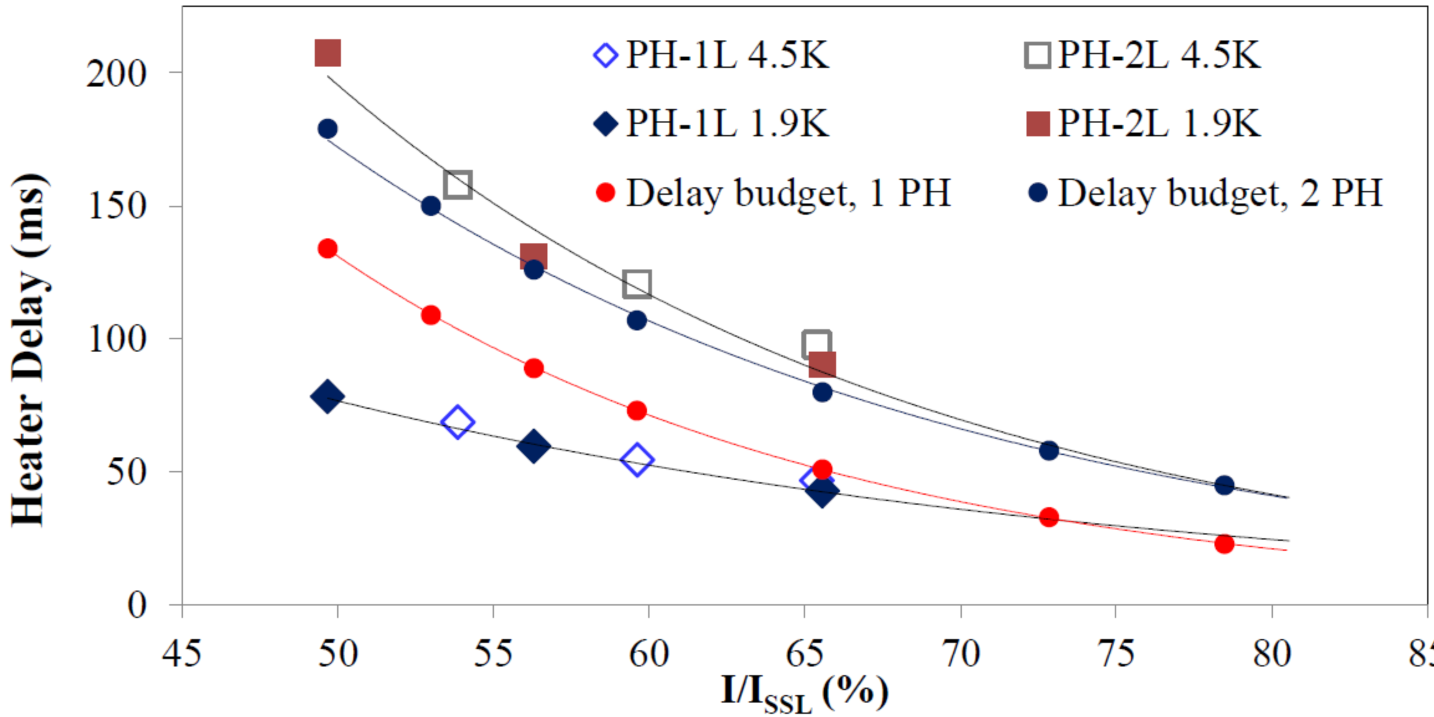
Protection Heater Tests (cont'd)

PH delay budget was estimated as (MIITs budget – decay MIITs)/I^2

- One or two heater per coil, coil T_{max} = 400 K

Delay budget – PH delay = time for quench detection, validation, switch etc.

- No available time margin in case of PH-2L
- PH-1L provides time margin only in case of two-heater protection



$P = 25\ W/cm^2$

$\tau = 24\ ms$

***A. Zlobin*, FNAL-CERN meeting , 01/08/2013**

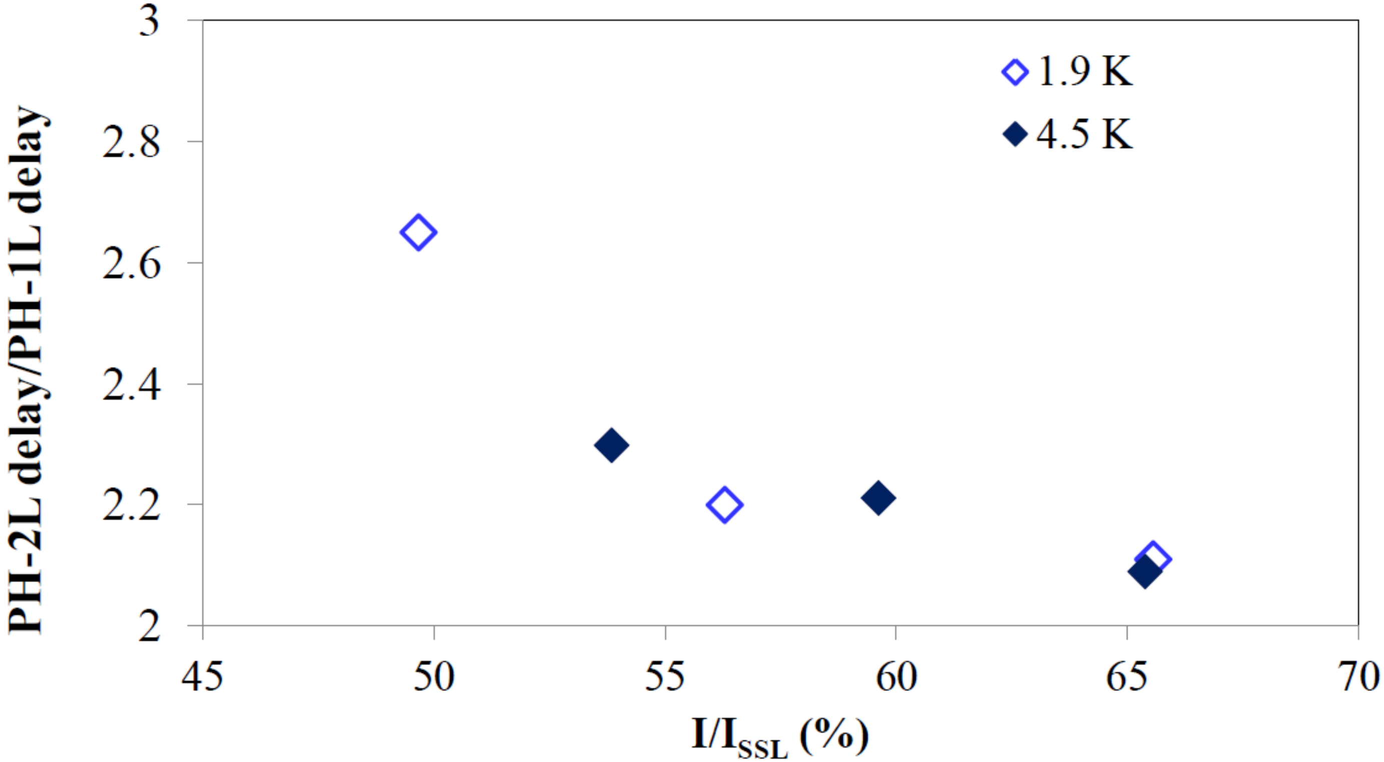
PH delay margin

Not enough time margin is provided in case of one-heater protection

- Any heater failure during the test will be critical

Can we get more margin for PH delay time ?

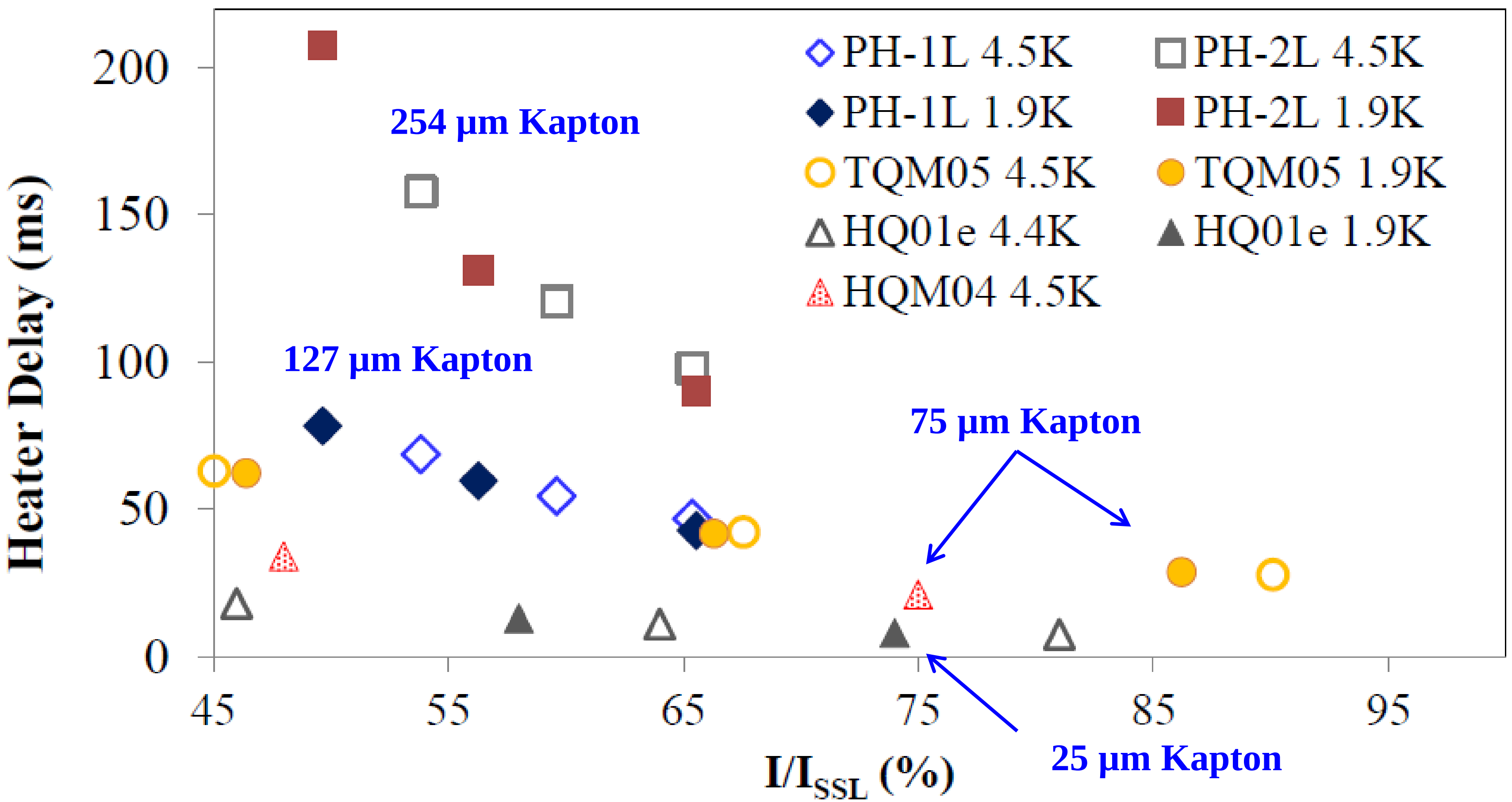
- Reduce heater-to-coil insulation if possible



PH delay margin (cont'd)

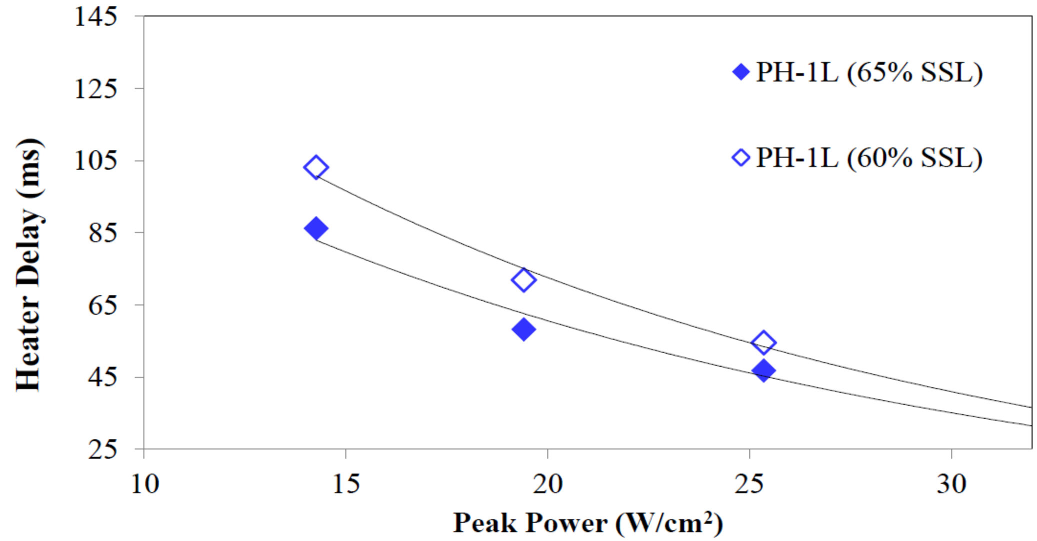
- Reduce heater-to-coil insulation if possible

Matrimid impregnated coil tested in TQM05

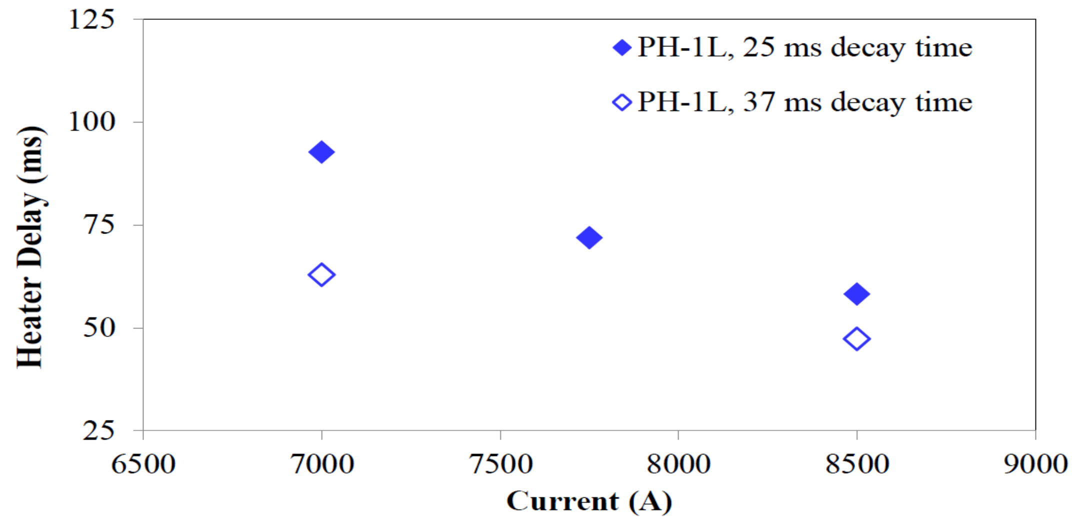


PH delay margin (cont'd)

- Increase peak power density of PH



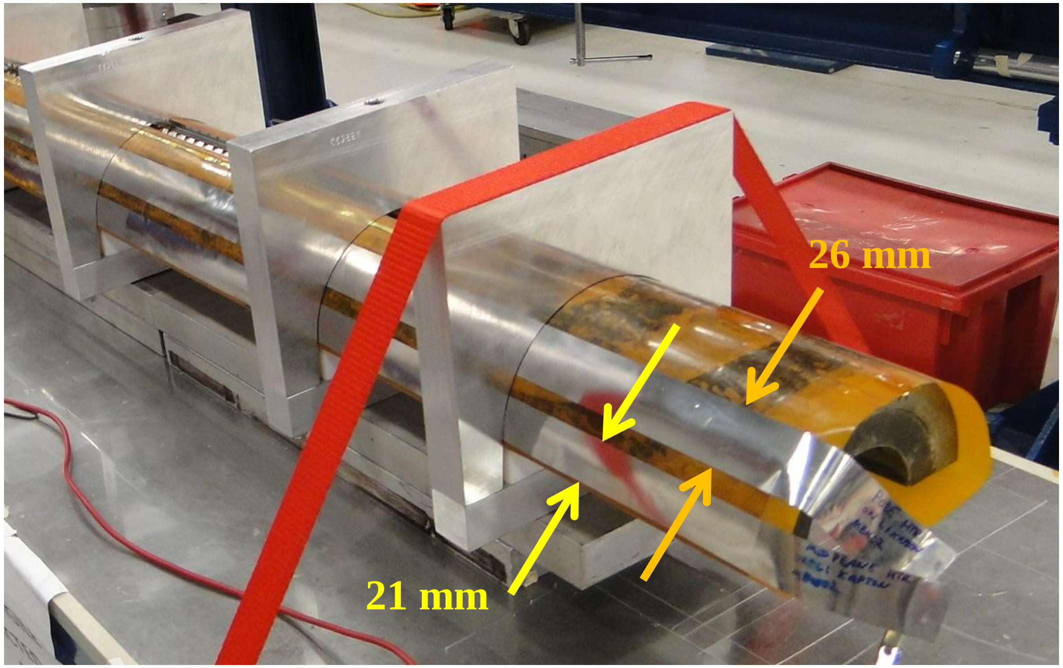
- Increase heater decay time constant

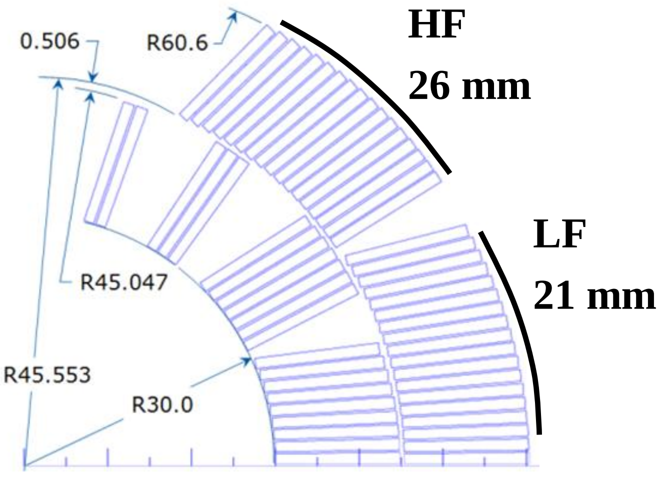


PH in low and high field blocks

Heater strips in the low and high field (LF and HF) coil blocks have different width, as a consequence dissipated peak heater power density also is different:

$P_{LF} = P_{PH} * 1.24$ and $P_{HF} = P_{PH} / 1.24$, where $P_{PH}=I^2(R_{LF}+R_{HF})/(A_{LF}+A_{HF})$

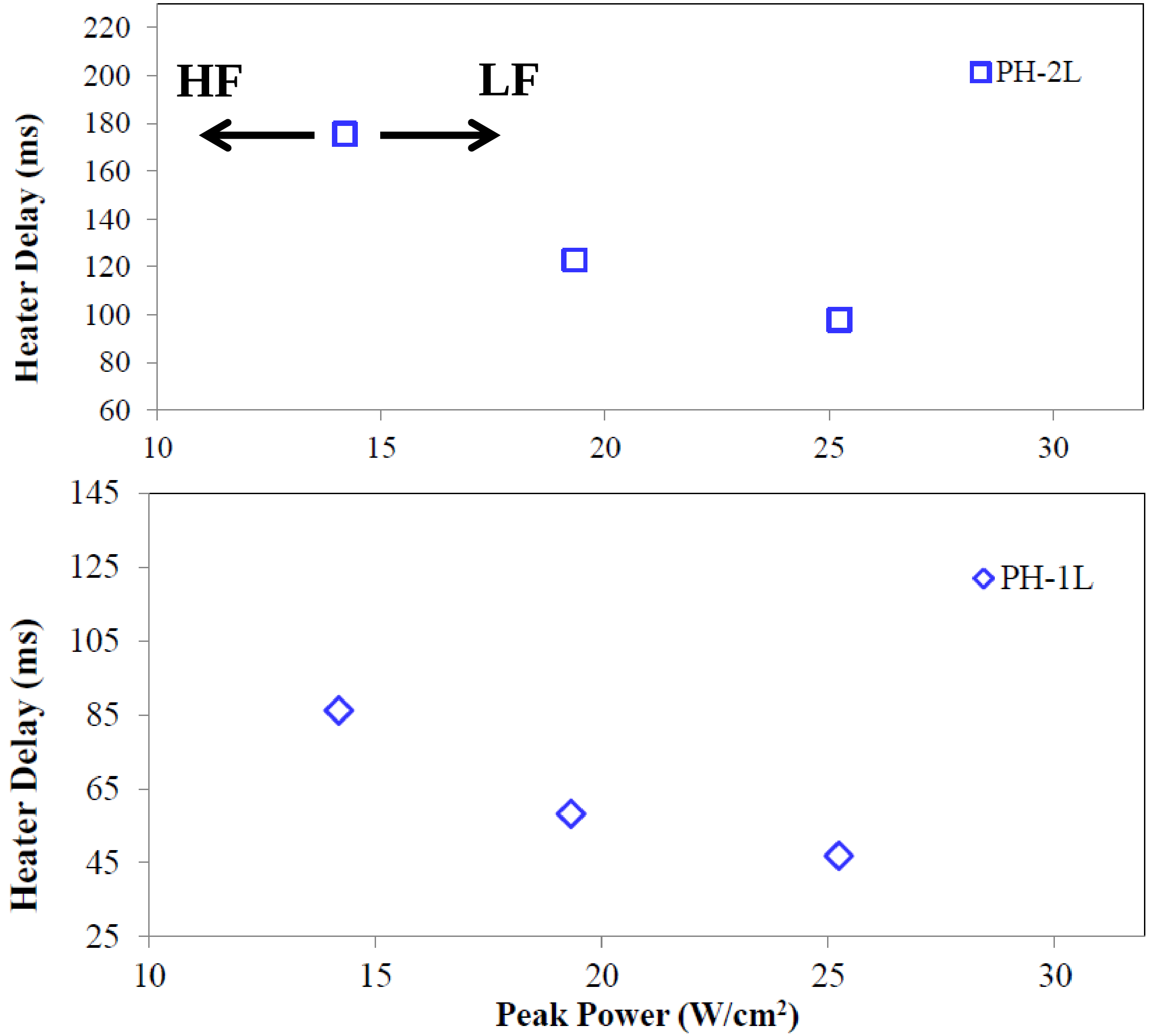




PH delay in LF/HF coil blocks

I_q/I_{SSLq} = 65%

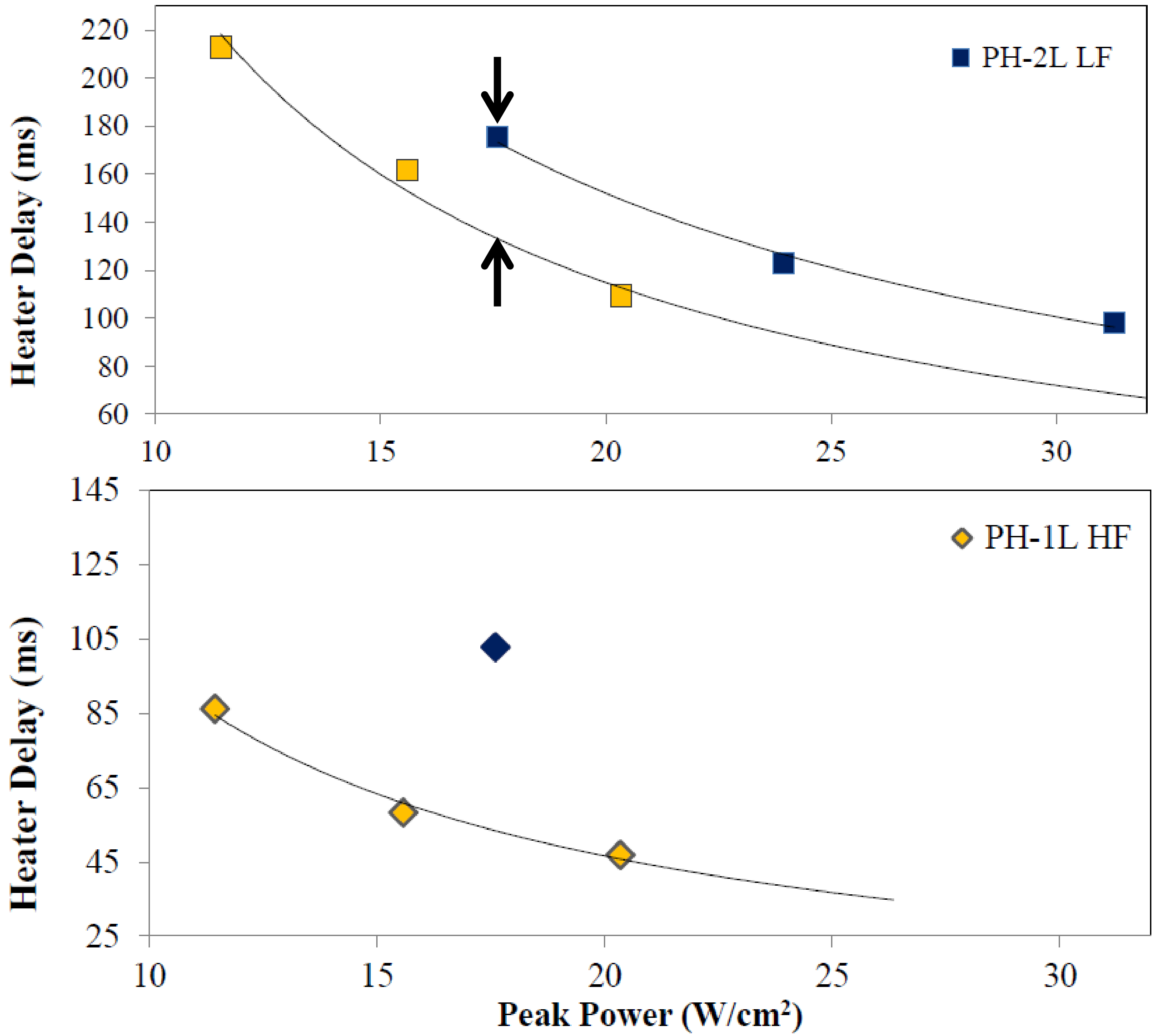
τ_{PH} = 24 ms



PH delay in LF/HF coil blocks

I_q/I_{SSLq} = 65%

τ_{PH} = 24 ms

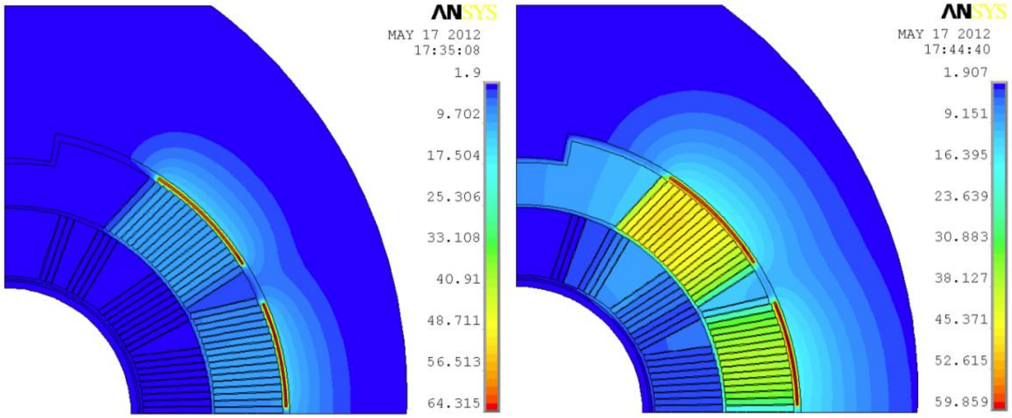


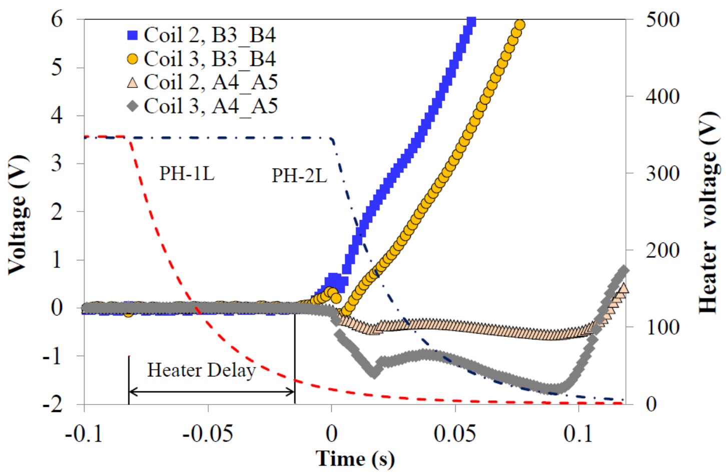
More PH tests

Heat transfer from the PH to the outer coil layer (OL) and then from the OL to the inner-layer coil (IL) helps to spread and absorb the magnet stored energy

Temperature profile after ~50 ms (left) and ~100 ms (right) from the heater discharge

2D quench simulation based on ANSYS by R. Yamada et al.





OL to IL quench propagation experimentally was observed in PH-1L induced quench with a dump delay of 120 ms

- Quench propagates from OL to IL in ~ 80 ms at 62 % of SSL

Summary and Plans

FERMILAB

Protection heaters with different insulation thickness (254 µm and 127 µm) evaluated for the first single-aperture 11 T Nb_3Sn demonstrator dipole

Quench protection tests were performed at 4.5 K and 1.9 K temperatures

Due to limited magnet performance PH tests were performed at currents up to 65% of SSL

PH delay budget estimated for the maximum coil temperature of 400 K

Quench protection study showed that

- Heaters with 254 µm Kapton insulation does not provide enough protection
- Heaters with 127 µm Kapton insulation provide some margin for the delay time only if two heaters are used in each coil
- Heater delay time could be further decreased by reducing heater to coil insulation or by increasing peak heater power density

Summary and Plans (cont'd)

Quench protection simulation in progress both at CERN and Fermilab

- Results will be discussed at a regular CERN-FNAL meetings

Quench protection study will continue with the next 11 T dipole model

- 1 m long single-aperture magnet with RRP 150/169 strand design and SS core in the conductor will be tested at Fermilab
- 127 μm Kapton insulation between heaters and coil

Heater tests will be performed at 1.9 K and 4.5 K

- Tests at each temperature will be specified in advance

More PH tests will be performed with delayed dump