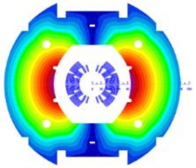


Experience with 11 T quench protection

G. Chlachidze and A. Zlobin for the 11T collaboration

QXF quench protection workshop at CERN
April 29, 2014

Introduction

Nb_3Sn based single-aperture 11T dipoles are developed at FNAL and CERN starting in 2011.

3 models were fabricated and tested at FNAL since then:

MBHSP01 with 2-m long coils #2 and #3 was tested in June 2012

- 0.7 mm diameter RRP 108/127 strand
- 12 mm thick SS welded skin

MBHSP02 with 1-m long coils #5 and #7 was tested in February 2013

- 0.7 mm diameter RRP 150/169 strand
- 12 mm thick bolted skin
- 0.025 mm thick and 11.5 mm wide stainless steel core in the conductor

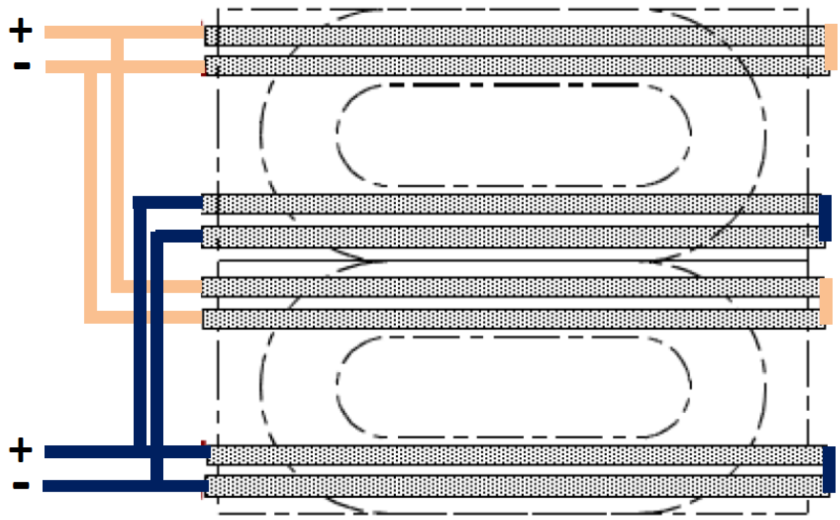
MBHSM01 mirror with coil #8 was tested in December 2013

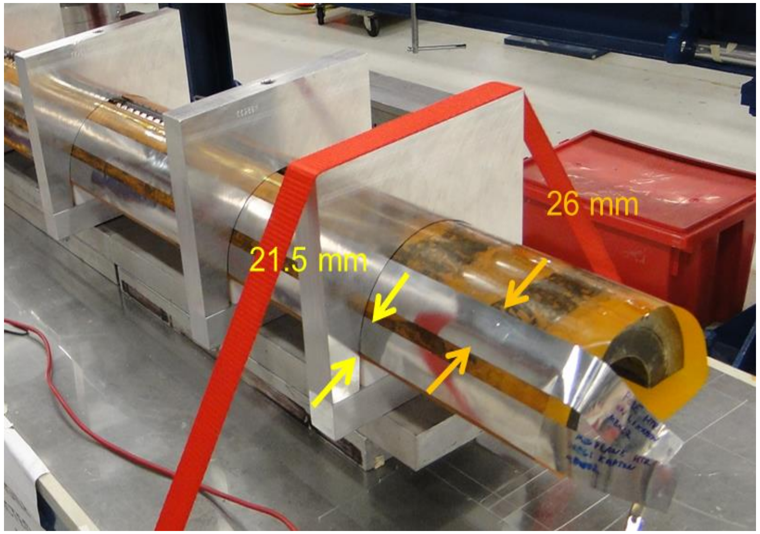
- Mix of 0.7 mm diameter RRP 108/127 and RRP 114/127 strands
- 12 mm thick bolted skin
- 0.025 mm thick and 11 mm wide stainless steel core in the conductor

Protection Strip Heaters

11T coils are equipped with 2 protection heaters on the outer coil surface

- Each heater consists of two 0.025 mm thick stainless steel (SS) strips
- SS strips are 21.5 mm wide in the mid-plane (LF) and 26 mm wide in pole area (HF)
- Heaters cover 31 turns per quadrant or about 56% of total coil surface





Due to difference in width of heater strips the peak power density dissipated in the LF is about 50% more than in the HF are

Heater to Coil Insulation

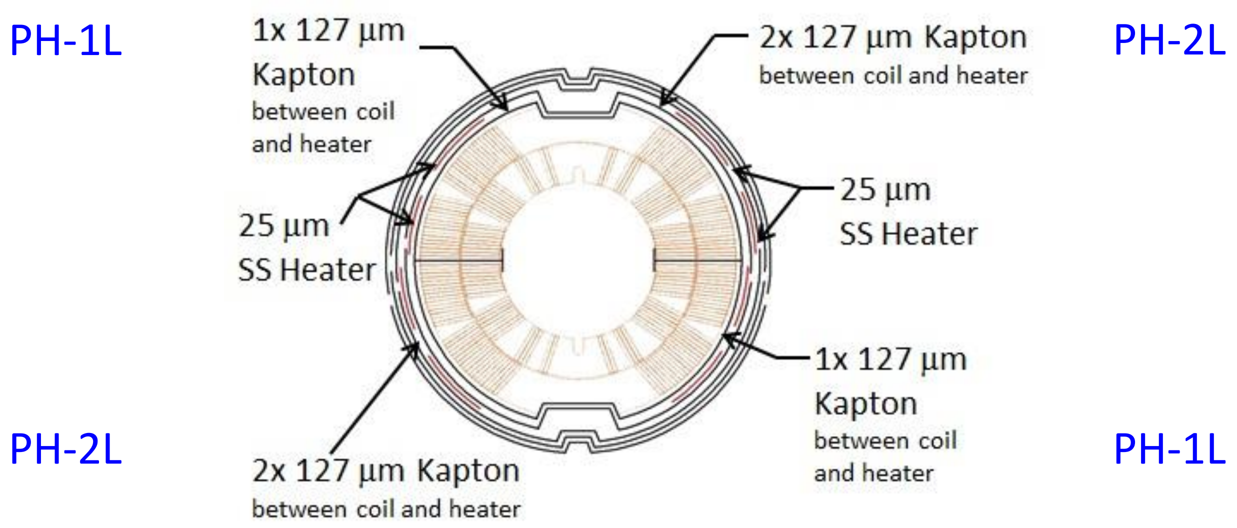
Heaters in 11T coils are placed between the ground insulation layers of *Kapton*

MBHSP01: two different heater-to-coil insulations were investigated

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

0.125 mm layer of glass on the outer coil surface was impregnated with all 11T coils

MBHSP02, MBHSM01: both used only PH-1L heater insulation

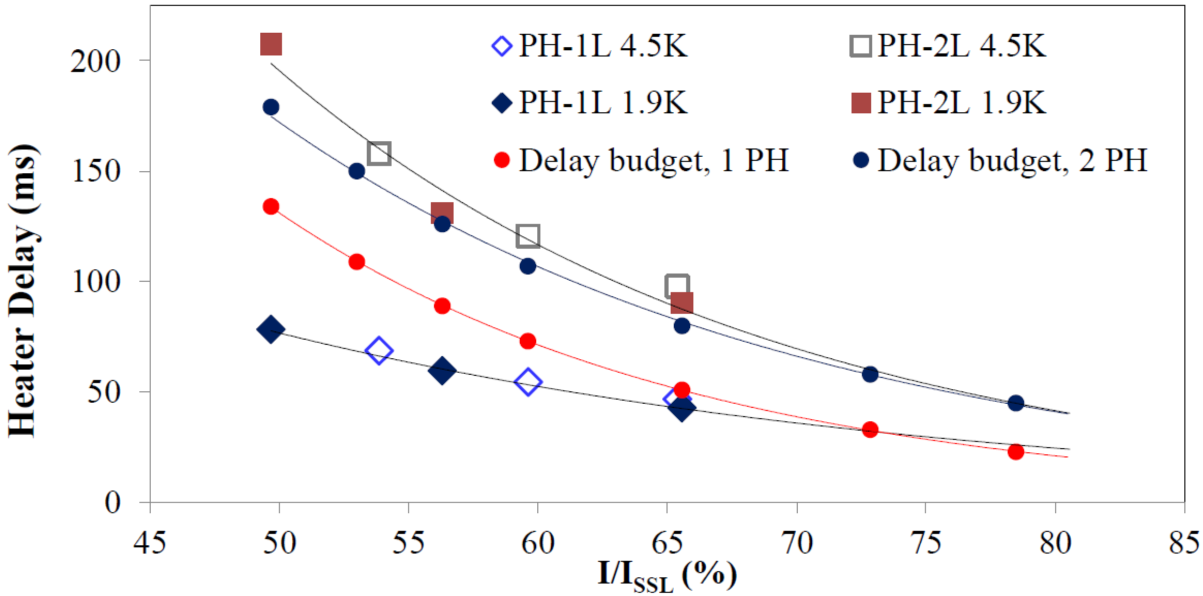


MBHSP01 Heater Tests

No available time margin was demonstrated when testing PH-2L heaters with 2 layers of the *Kapton* insulation.

Heater delay budget was estimated as (MIITs budget – decay MIITs)/I^2 for one or two PH per coil and coil T_{max} of 400 K

- (Delay budget – PH delay) = time for quench detection, validation, etc.



P = 25 W/cm^2
τ = 24 ms

Only one layer of *Kapton* insulation (0.114 mm) is used in all following 11T coils

Quench Protection Study

Comprehensive quench protection study was performed in different 11T models:

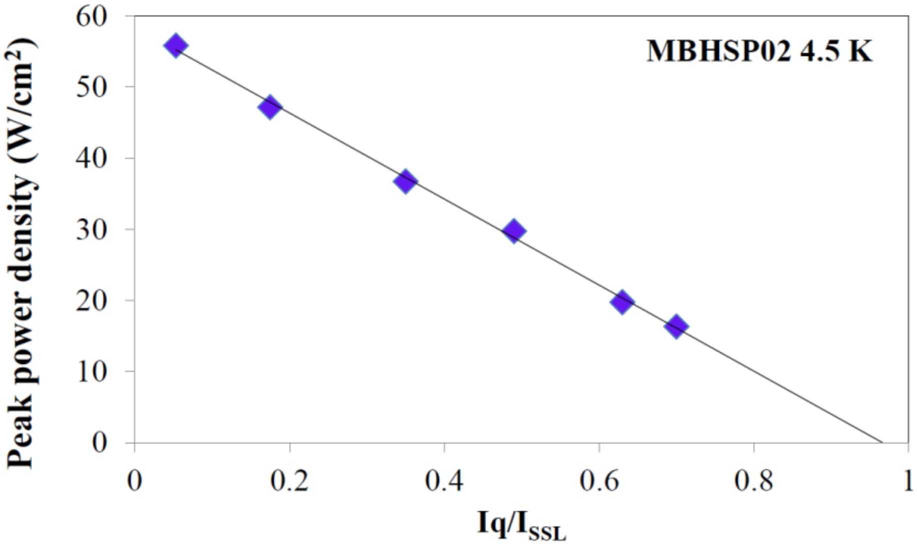
- Heater efficiency at different magnet currents
- Effect of heater insulation thickness
- Heater efficiency in low-field (LF) and high-field (HF) areas
- Radial quench propagation from the outer to the inner coil layer
- Quench integral study for different dump resistors
- Longitudinal quench propagation velocity
- Quench temperature measurements
- Fast extraction

To keep the cable temperature during a quench below 400 K, the quench integral has to be less than 19-21 MIITs (10^6 $A^2 \cdot s$). QI limit was set at 18 MIITs for quench protection study in 11T magnets.

PH efficiency studies

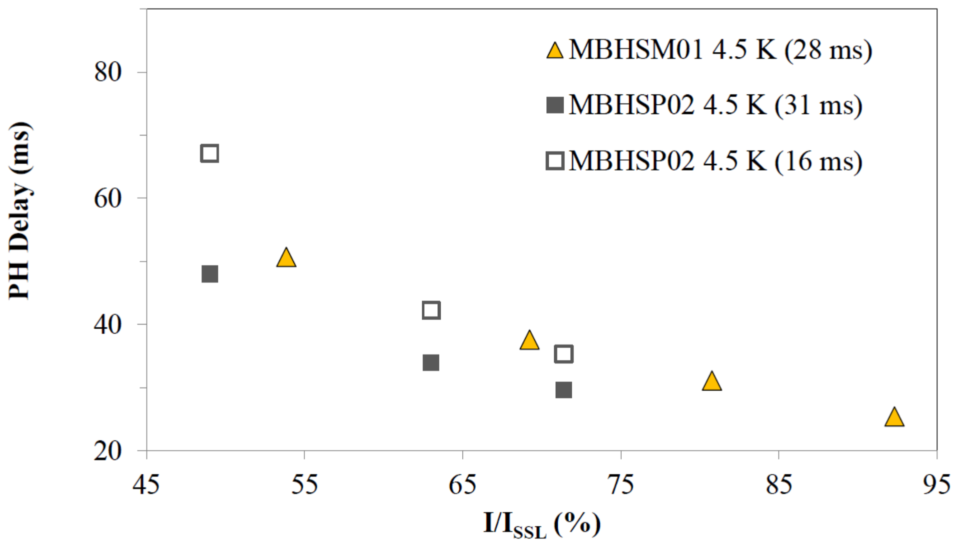
The minimum peak power density required to quench the magnet was estimated at different currents

- To quench magnet at all operation currents P≥55 W/cm²



PH delays measured for the peak power density of ~ 50 W/cm²

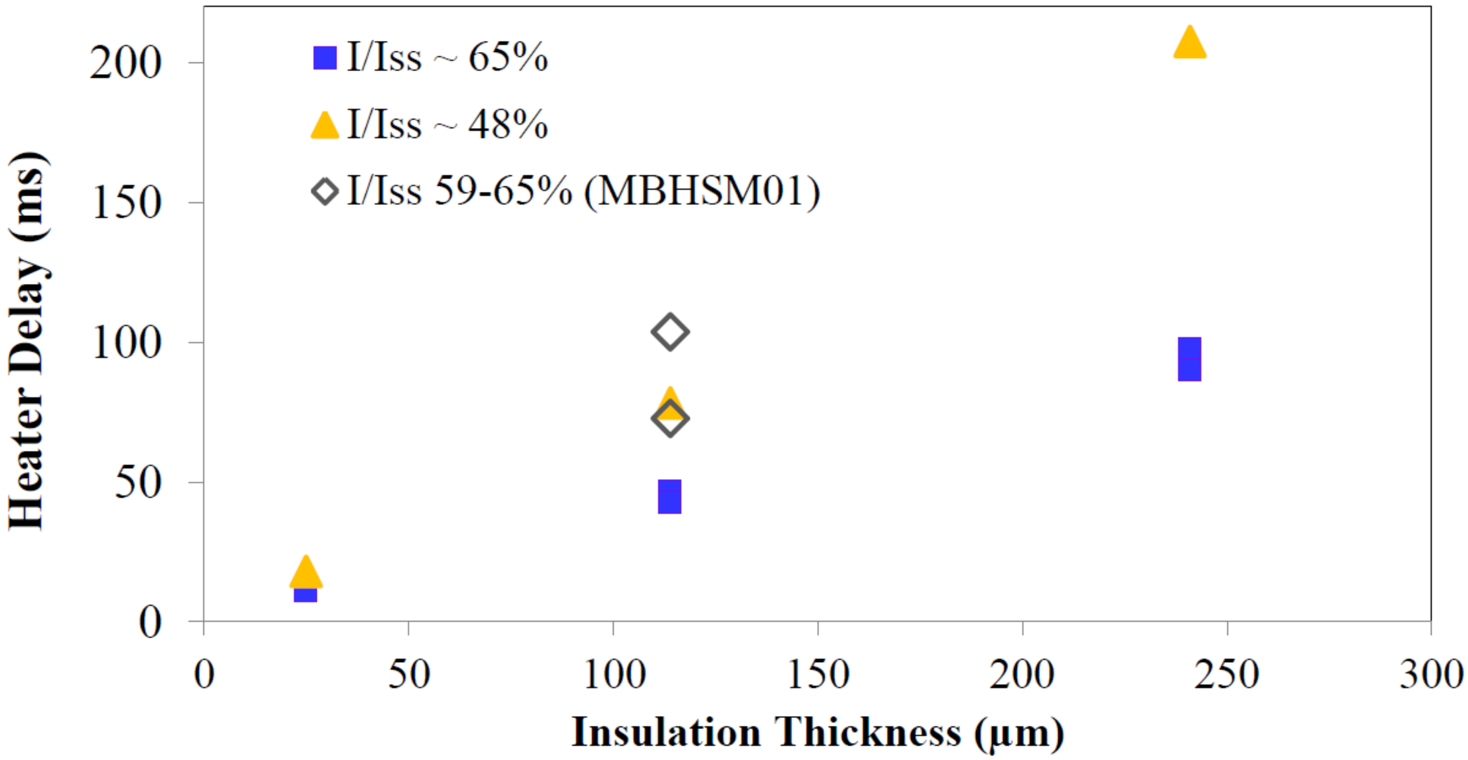
- PH delays consistent in different magnets



Effect of PH insulation

Peak power density of 15-20 W/cm^2 in MBHSM01 and 25 W/cm^2 for remaining data

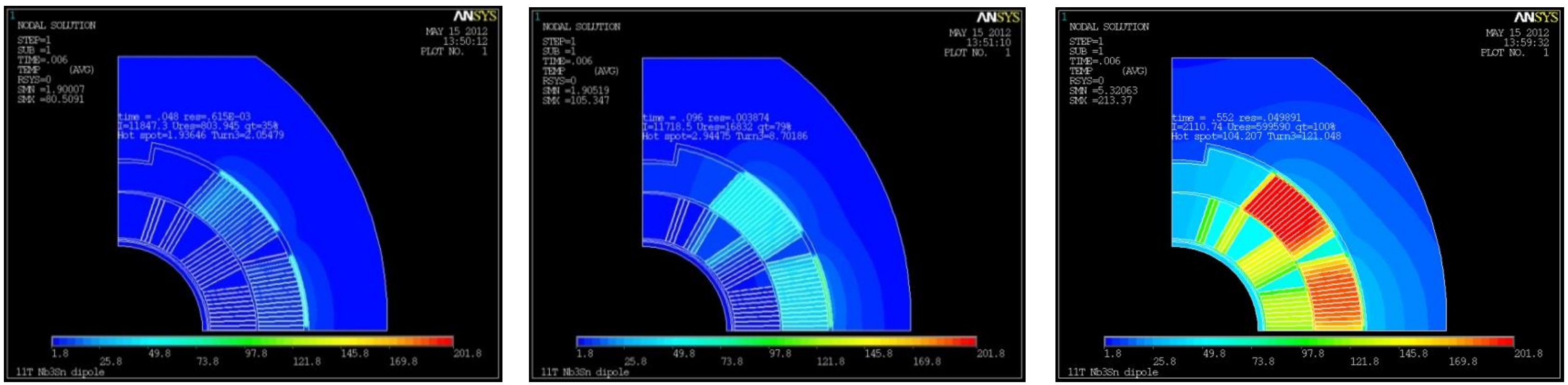
- PH delay is increasing proportionally to the insulation thickness



Radial & Azimuthal Quench Propagation

Heat transfer from the heater to the OL and then from the OL to the IL coil helps to spread and absorb the magnet stored energy

- Temperature profile in the magnet after 48 , 96 and 552 ms from the OL PH induced quench at a nominal current of 11.8 kA (ANSYS)



- 2D calculations - resistance in IL blocks #2 and #3

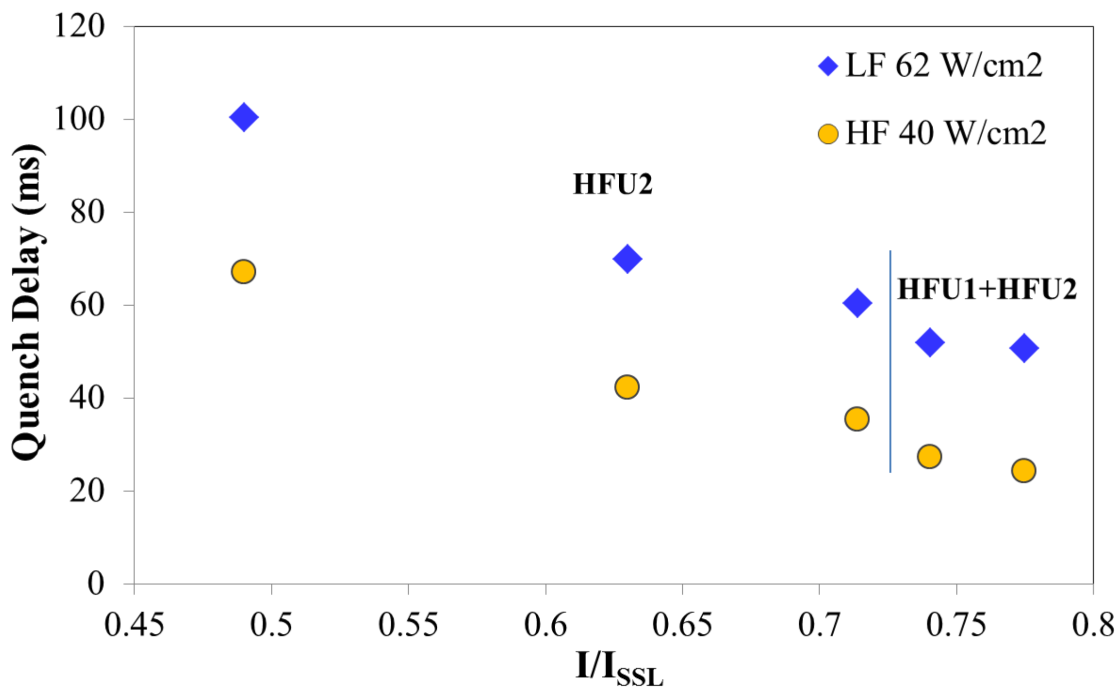
Radial quench propagation was measured in all 11T models

- Currently in the list of a standard 11T magnet measurements

PH delay in LF and HF areas

Due to different heater width the peak power density is also different in low-field (LF) and high-field (HF) blocks

$$P_{LF} = 1.24 \cdot P_{av}\,,\;\; P_{HF} = P_{av}/1.24 \;\; \text{where } P_{av} = I^2(R_{LF}+R_{HF})/(A_{LF}+A_{HF})$$

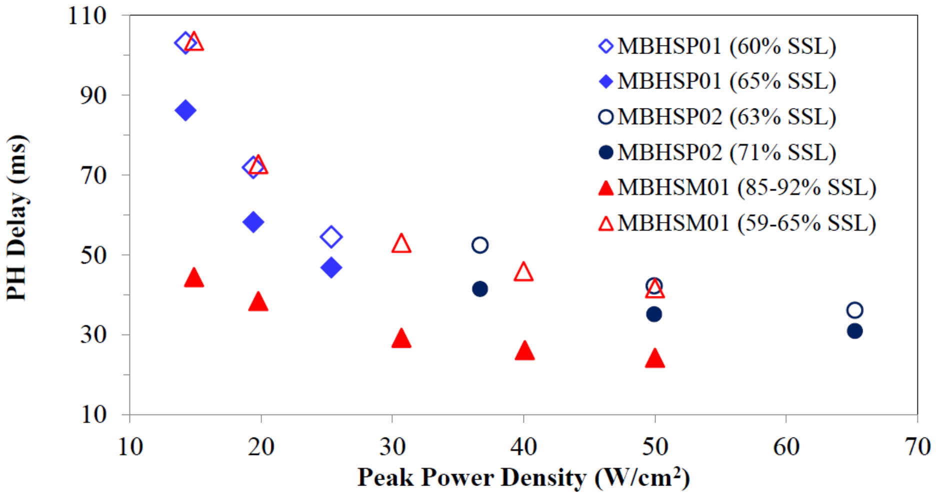


The difference in quench time between LF and HF blocks is ~30 ms

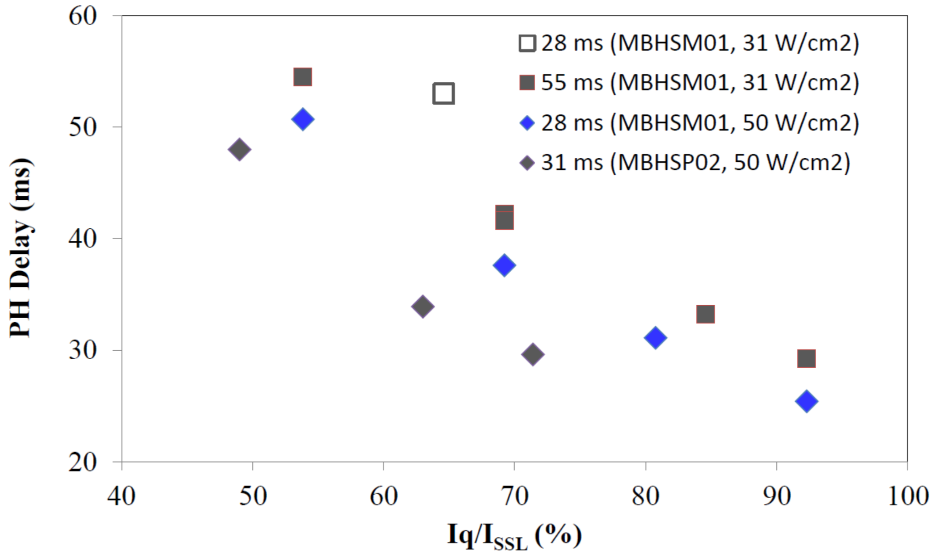
PH efficiency (cont'd)

PH delay measured at different peak power density. Time constant (RC) of the PH circuit was:

- ~25 ms in MBHSP01,
- ~16 ms in MBHSP02,
- ~55 ms in MBHSM01



PH Delay measured for different time constant (RC)

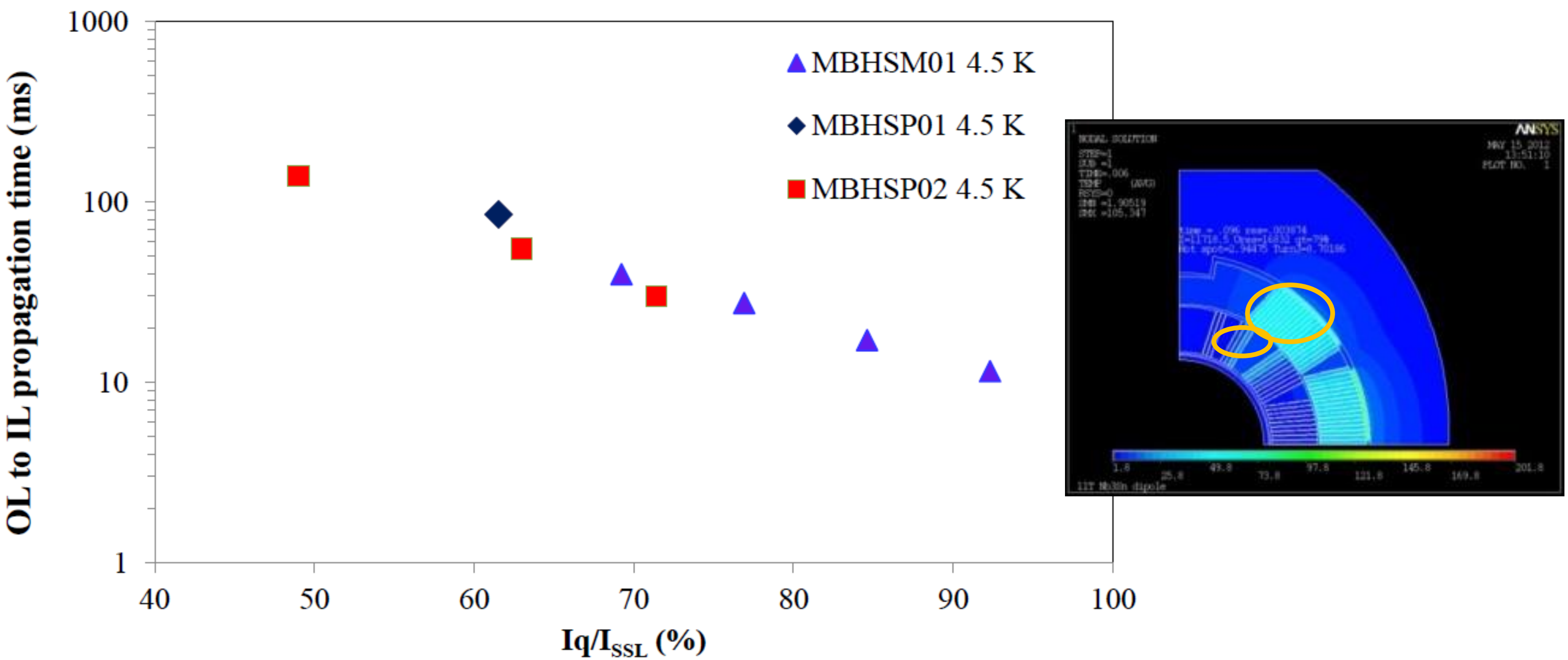


PH delay can be reduced by adjusting the PH peak power or decay constant

Radial Quench Propagation

OL to IL quench propagation time was measured in quenches with dump delay of 1000 ms. Average peak power density was ~50 W/cm^2

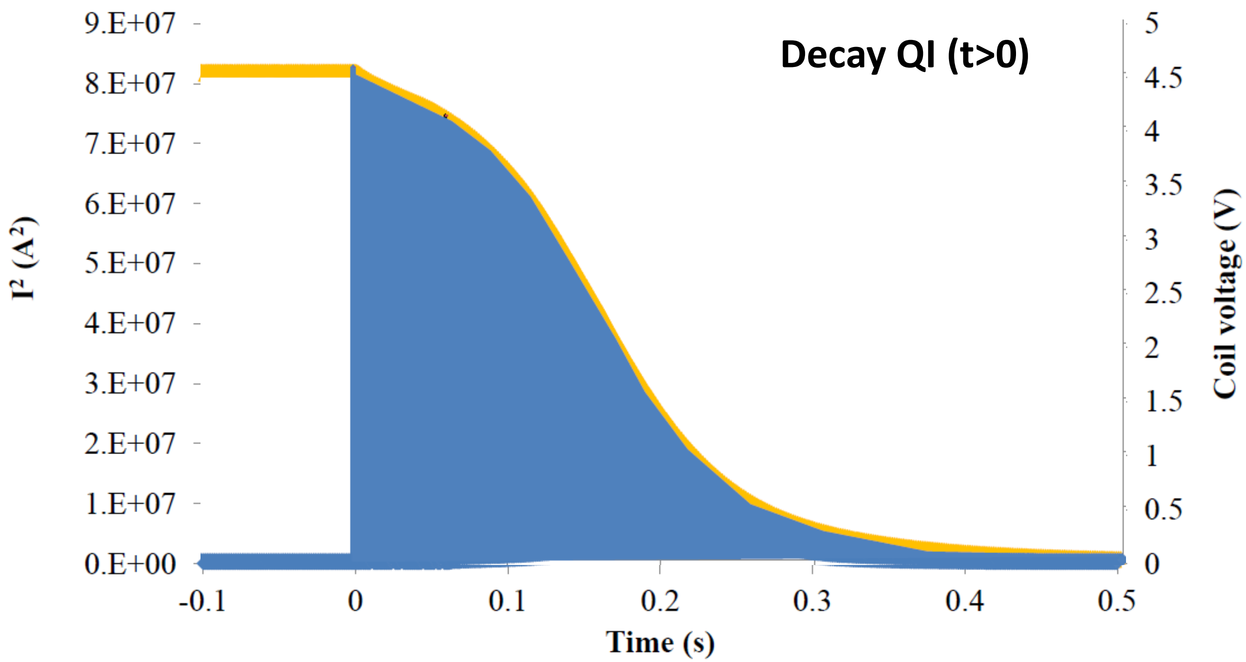
- $\Delta t(I_{nom})$~25 ms, reproducible, OL pole block and IL 2nd block quenching first



Quench Integral Study

The Quench Detection system was manually tripped; the outer layer heaters included in the magnet protection system

- Decay QI was calculated for the whole current decay, including the heater delay
- Decay QI can be used to estimate expected QI in a spontaneous quench by adding MIIts corresponding to the quench detection time



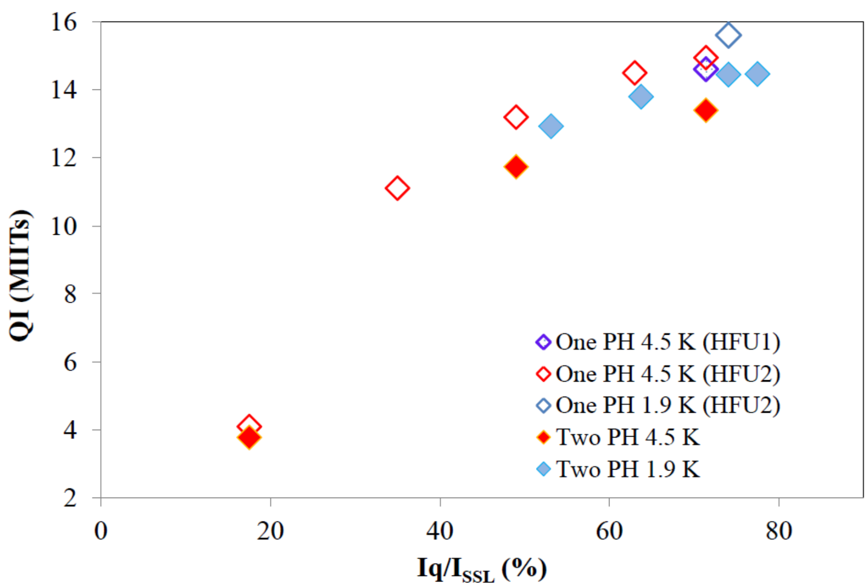
QI Study in 11T magnets

QI was measured in MBHSP01-02 with the external dump delayed for 1000 ms ("no dump")

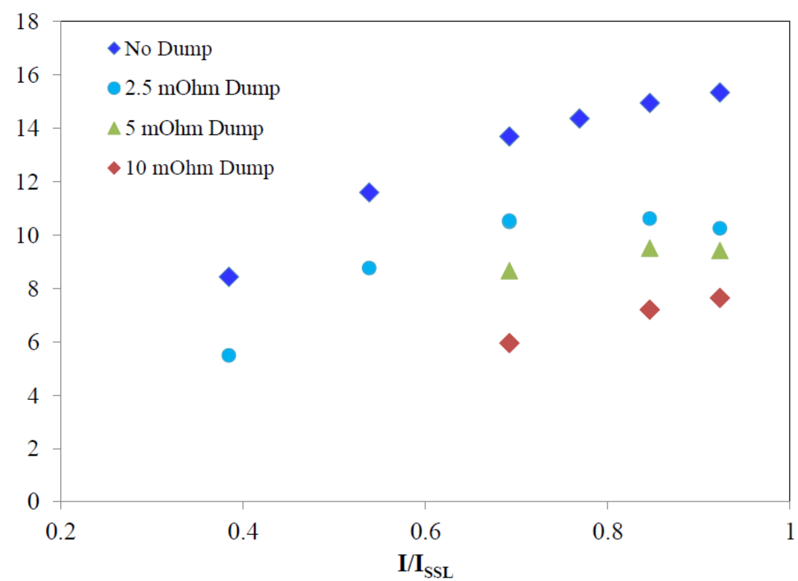
In MBHSM01 QI was estimated for "no dump", as well as for 2.5 mΩ, 5 mΩ and 10 mΩ dump resistors

- $QI(I_{nom})$~16 MIITs, QI_{max}=19/21 MIITs (HF/LF) - estimated time budget for Quench Detection seems reasonable: ~20 ms in HF and ~35 ms in LF

MBHSP01-02 Decay QI, "no dump"



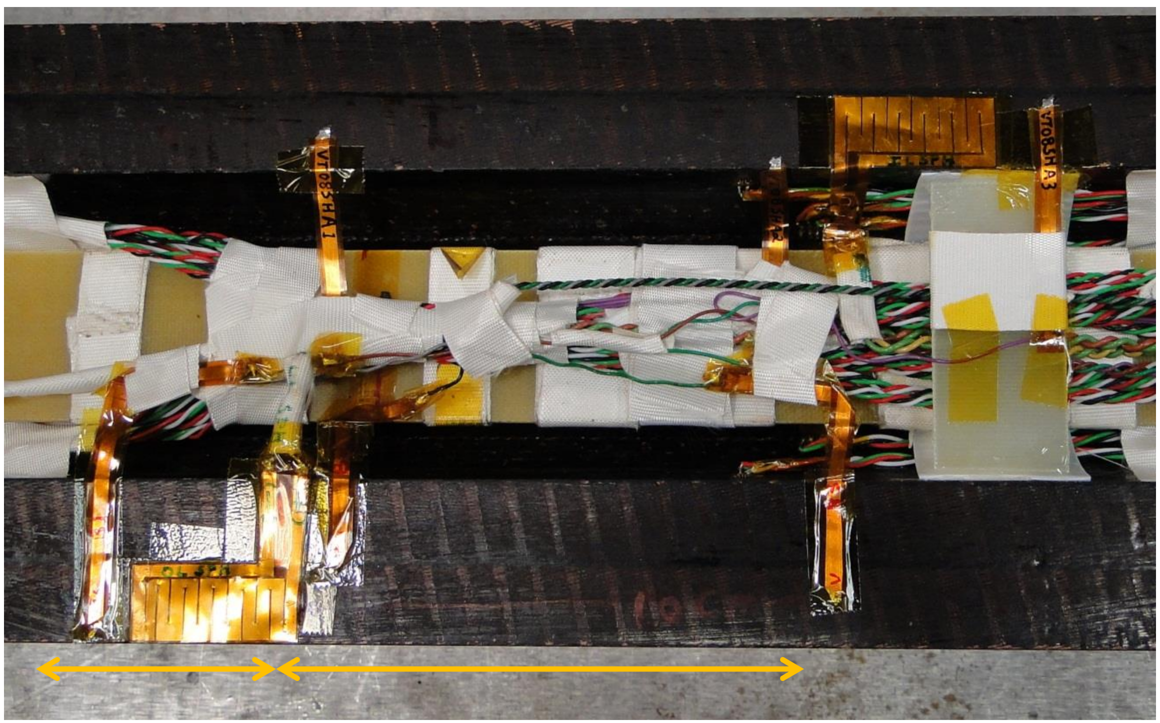
MBHSM01 Decay QI



Spot Heaters in MBHSM01

Spot heaters (SH) installed for estimation of the quench temperature and longitudinal propagation velocity

- VT installed in close proximity to the SH

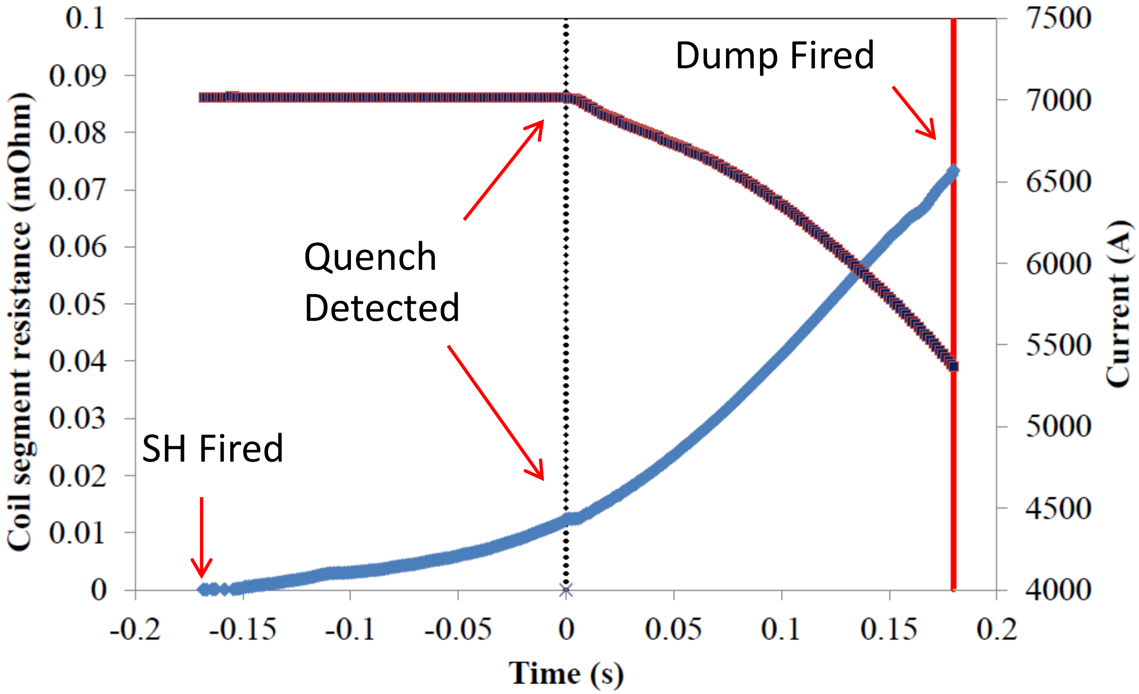


5 cm 10 cm

Spot Heater Tests at 4.5 K

Only OL spot heater was available for testing:

- Peak power density of ~26 W/cm^2 was deposited at different currents
- Dump was delayed for 70-250 ms to increase accumulated QI
- Coil temperature was measured during the warm-up from 4.5 K to 200 K to calibrate the coil resistance change during the quench

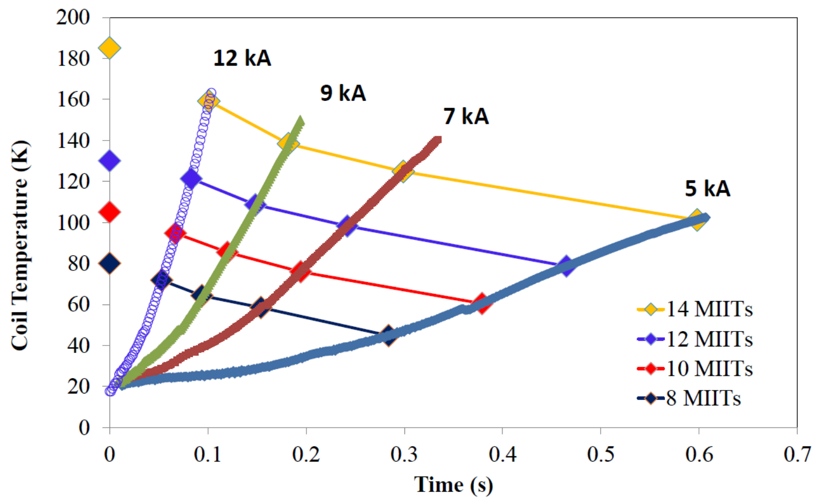


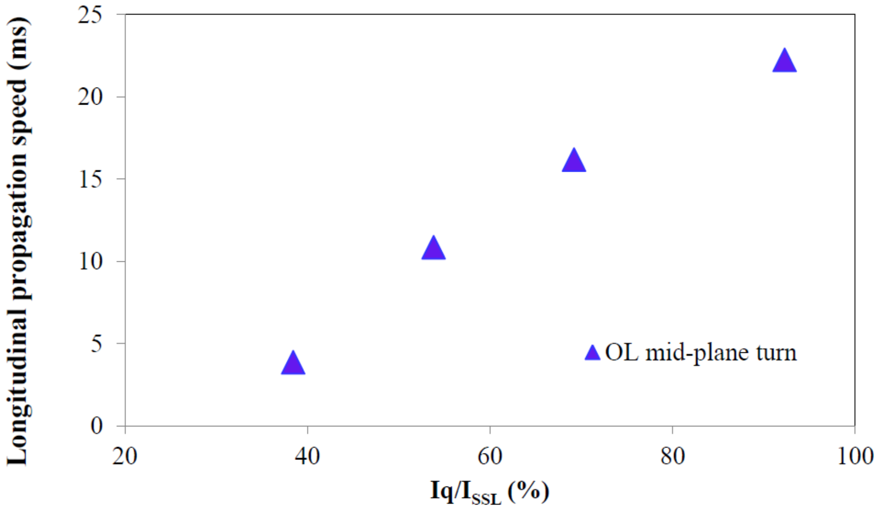
Spot Heater Tests at 4.5 K

Coil temperature as a function of time was estimated in the OL mid-plane turn at different currents. Data point with the same QI are also shown in the plot

Adiabatic coil temperature estimations for different QI are shown at t=0

- Cable insulation, epoxy inside the cable and bronze inside sub-elements were included in calculations
- Current decays almost fully in 0.1-0.2 s, i.e. measured T_{max}= ~ $0.8T_{calc}$





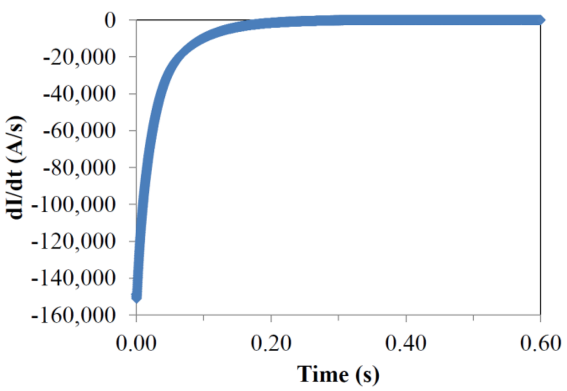
Longitudinal quench propagation velocity estimated only in the OL mid-plane turn

Fast extraction tests

The extraction dump is initiated at different currents w/o protection heaters.

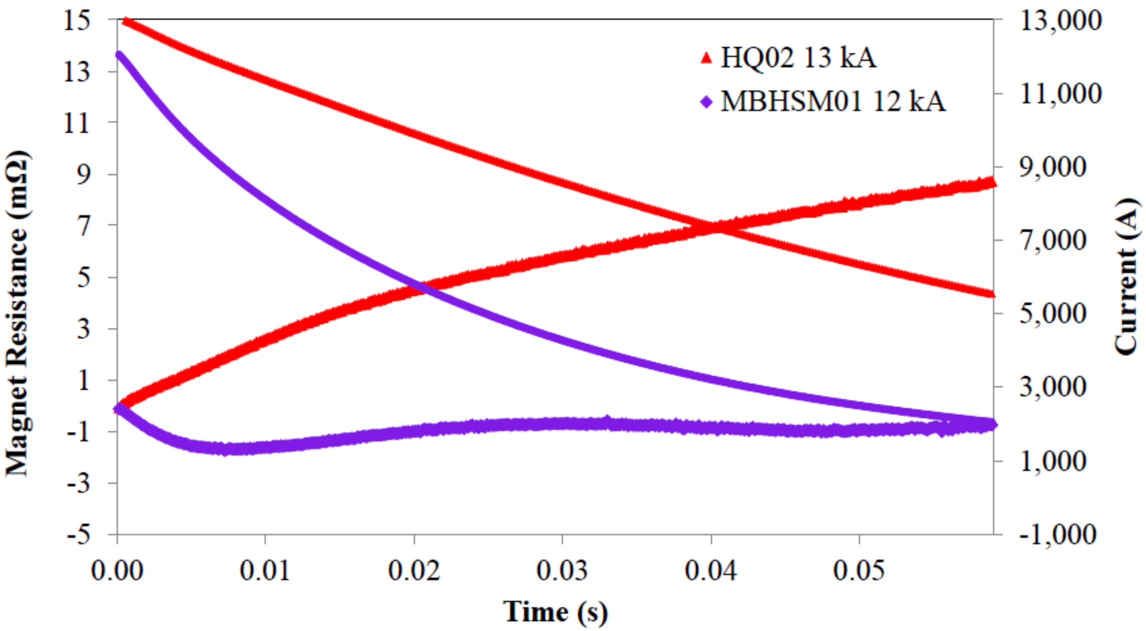
No resistance increase was observed in the coil for the fast extraction at 12 kA

- Effect of cored cable and small filament size



Ramp rate for the fast extraction test

Whole coil resistance change in HQ02 and MBHSM01 magnets



Summary

Quench protection study was performed at currents up to 92% of SSL and for different external dump resistors in 2 dipole and 1 mirror models

Minimum peak power density of ~55 W/cm^2 is required to quench magnet at currents $I_{inj} < I < I_{nom}$

Azimuthal and Radial quench propagation was measured at different currents and temperatures

- Quite small quench delay helps to spread energy in the coil

Longitudinal quench propagation velocity was estimated in the mid-plane turn at different currents

- Quite large velocity helps to spread energy in the long magnet coils

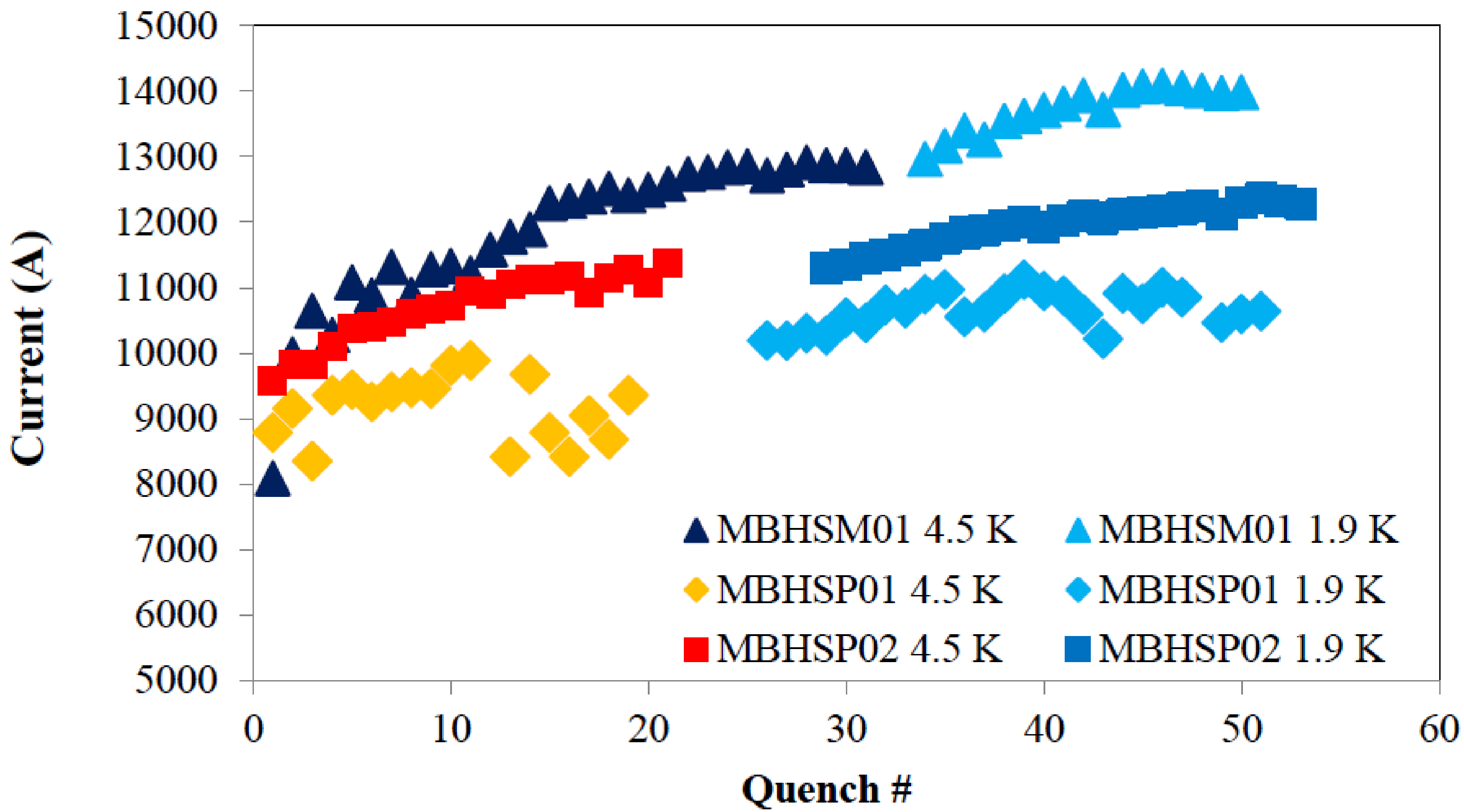
Coil temperature increase as a function of time was studied at different currents

- T_{max} measured is ~20% lower than the calculated one due to the cable cooling

BACKUP SLIDES

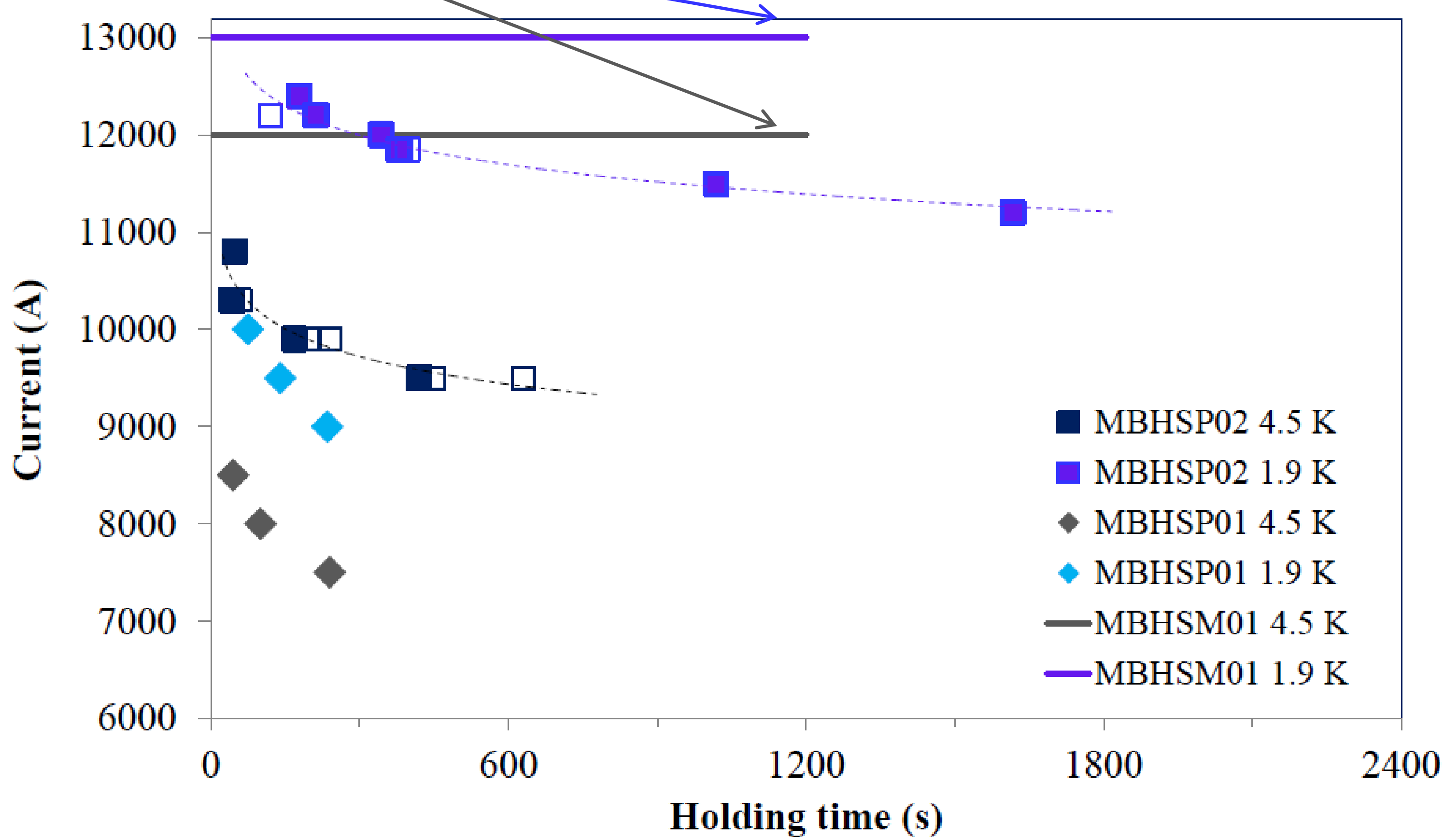
MBHSM01 vs. MBHSP01/02

Quench training in all 11 T magnets



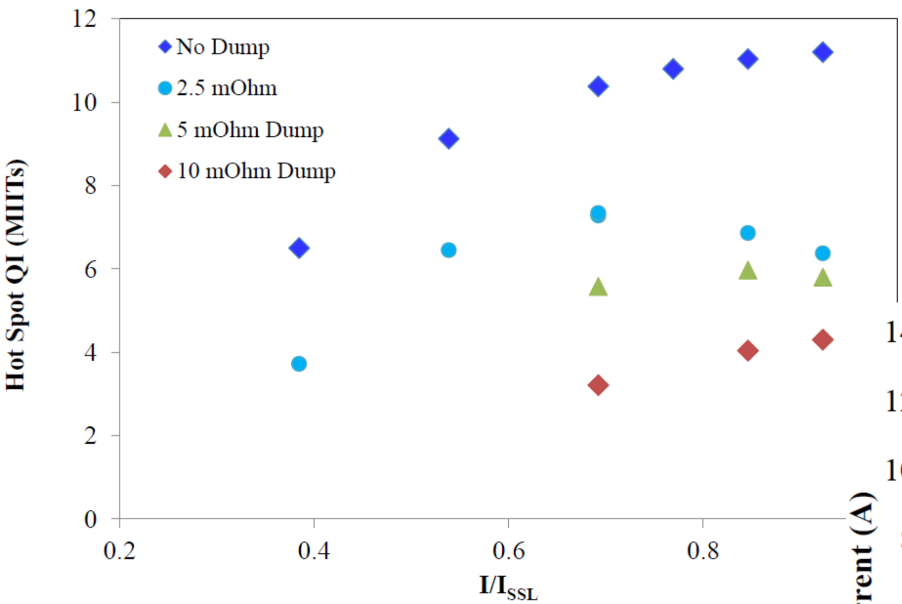
“Holding quenches”

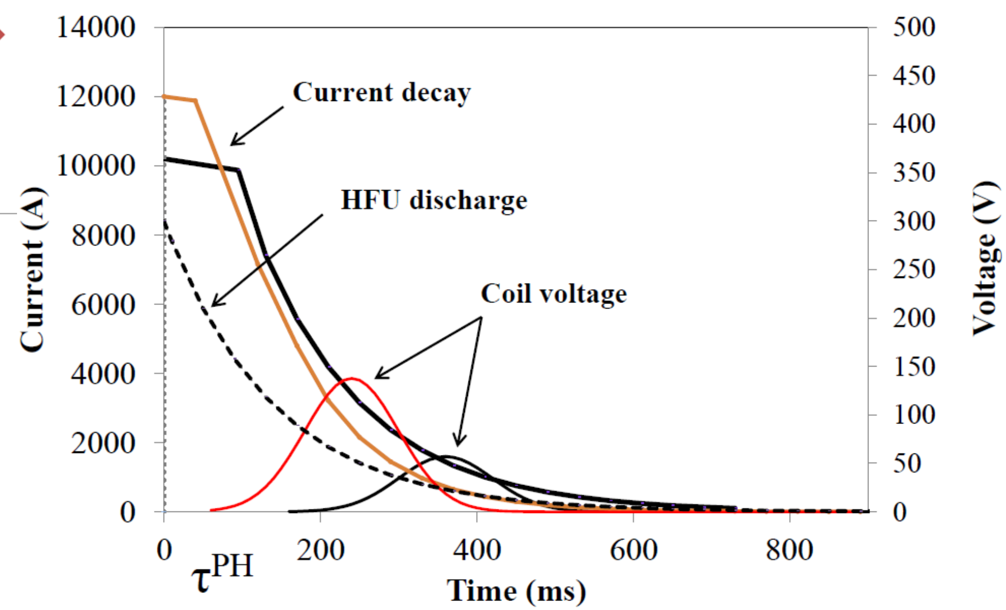
No quenches in MBHSM01 after “holding” 13 kA at 1.9 K and 12 kA at 4.5 K for ~22 min



QI Study in 11T magnets

QI (t>tq) exhibited similar current dependence in MBHSM01





QP tests at 10 kA and 12 kA

RRR Measurements

Average RRR in MBHSM01: ~220

- All segments shown for MBHSM01