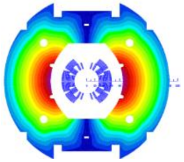


11T Magnet Protection

G. Chlachidze, A. Zlobin

CERN-FNAL Collaboration Meeting on DS 11T Dipole Grounds

September 21-23, 2015 @ FNAL

Introduction

11T magnet protection study at FNAL was focused on coil overheating and related issues

- Quench Protection system should provide a reliable protection for all possible quenching scenarios

Quench protection in 11T magnets is provided by protection heaters on the outer coil surface

- Traditional PH position in accelerator magnets, good thermal contact with coils and good ground insulation
- Other heater locations previously tested: Inner layer heaters in LARP LQS and HQ models; Interlayer heaters in first Nb_3Sn models at FNAL (HFDA), as well as in short MQXB models (HGQ)

11T protection study results were presented at various conferences and workshops

- ASC 2012 (Portland, USA), IPAC 2012 (New Orleans, USA), WAMSDO 2013 (CERN), IPAC 2014 (Dresden, Germany), ASC 2014 (Charlotte, USA), QXF Quench Protection Workshop in 2014 (CERN) and other conferences and collaboration meetings

Protection Study Objectives

Comprehensive protection study was done in a single aperture 11T models:

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

Only few tests were performed in dual aperture magnet MBHDP01

External energy extraction was part of this study

- Low dump resistors 2.5 mΩ, 5 mΩ and 10 mΩ were implemented at VMTF
- No dump condition was simulated by delaying the dump firing for 1000 ms

11T protection tests at FNAL

Protection test data are available for the following magnets:

MBHSP01 demonstrator with 2-m long coils #2 and #3 - 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 - February 2013

- 0.7 mm diameter RRP 150/169 strand
- 12 mm thick bolted skin
- 0.025 mm thick and 11 mm wide stainless steel core in the conductor

MBHSM01 mirror with coil #8 – December 2013

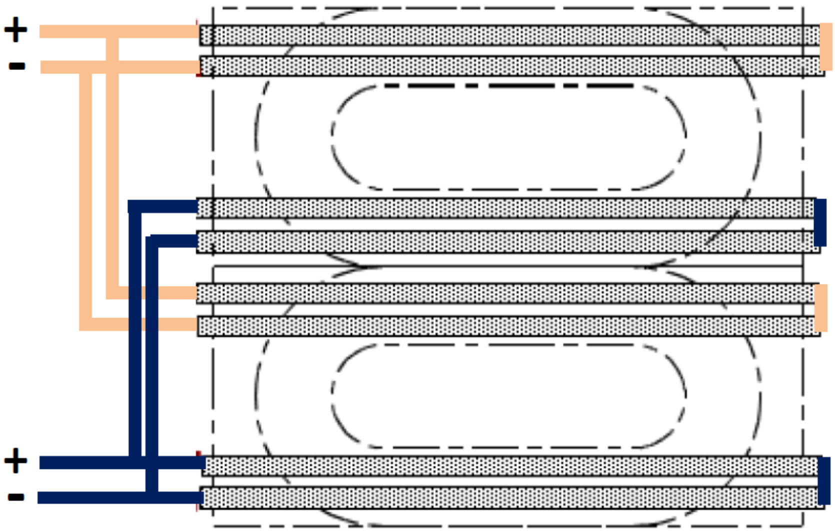
- Mix of 0.7 mm diameter RRP 108/127 and RRP 114/127 strands
- 12 mm thick bolted skin
- 0.025 mm thick and 11 mm wide stainless steel core in the conductor

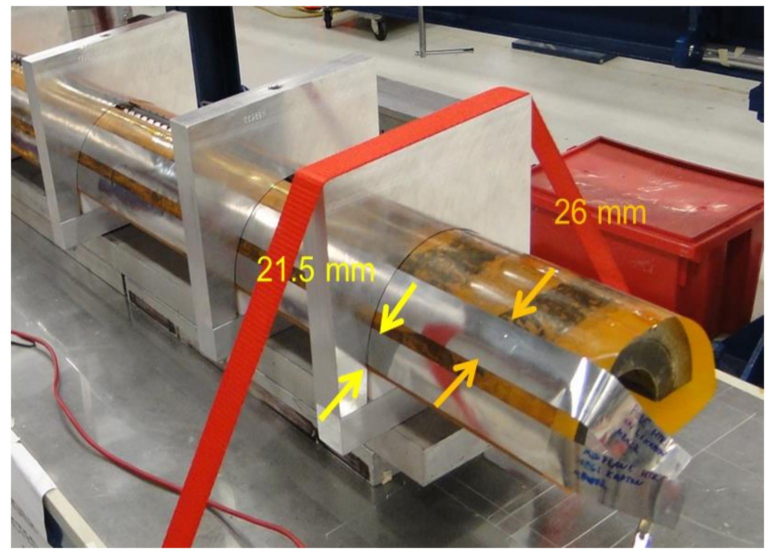
MBHDP01 dual aperture magnet with coils #5 and #7 from MBHSP02 and coils #9 and #10 from MBHSP03

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 area

Heater to Coil Insulation

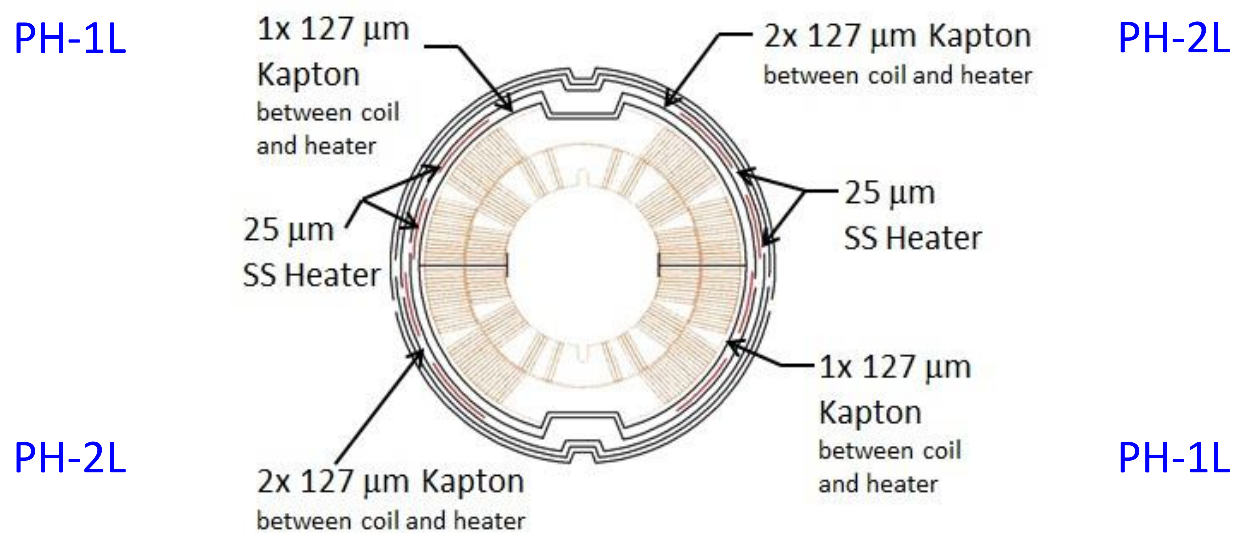
Strip Heaters are placed between the ground insulation layers of *Kapton*

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, MBHDP01: only PH-1L heaters were used



Cable Maximum Temperature

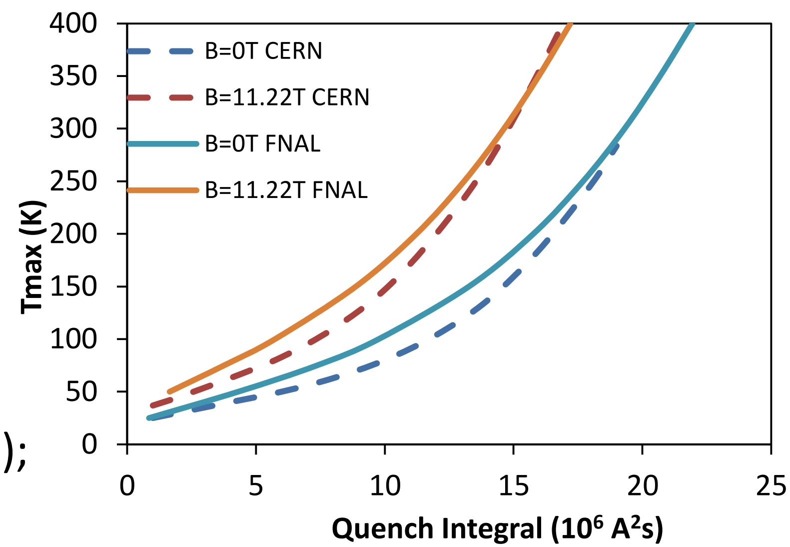
In adiabatic conditions

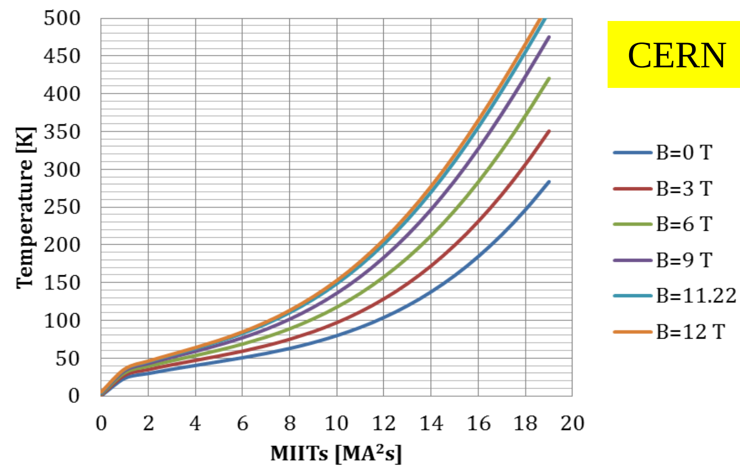
$$\int_0^\infty I(t)^2 dt = \lambda \cdot S^2 \cdot \int_{T_q}^{T_{max}} C(T)/\rho(B,T)\, dT$$

where

- I(t) is the current decay after a quench (A)
- Tq is the conductor quench temp. (K);
- S is the cross-section of insulated cable (m^2);
- λ is fraction of Cu in insulated cable cross-section;
- C(T) is the average specific heat of insulated cable ($J/K/m^3$);
- ρ(B,T) is the cable resistivity (Ω·m).

FNAL-CERN calculations are consistent

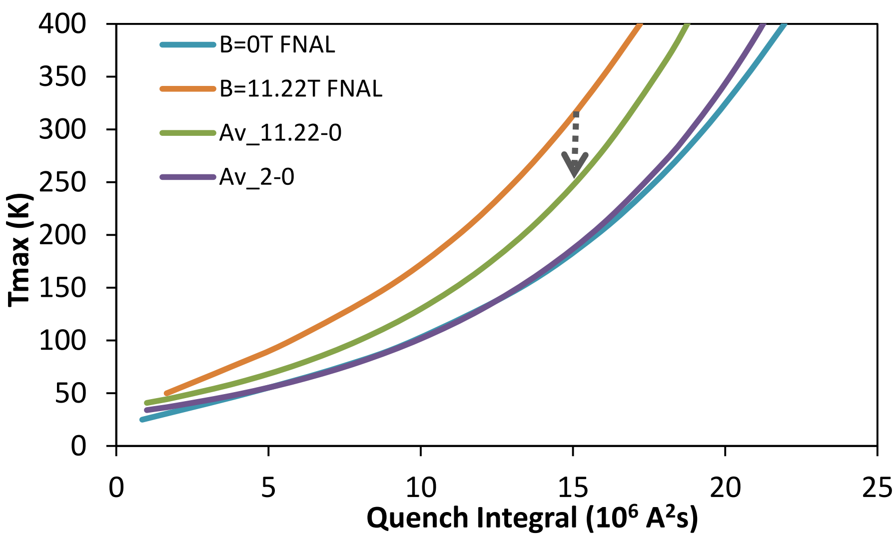


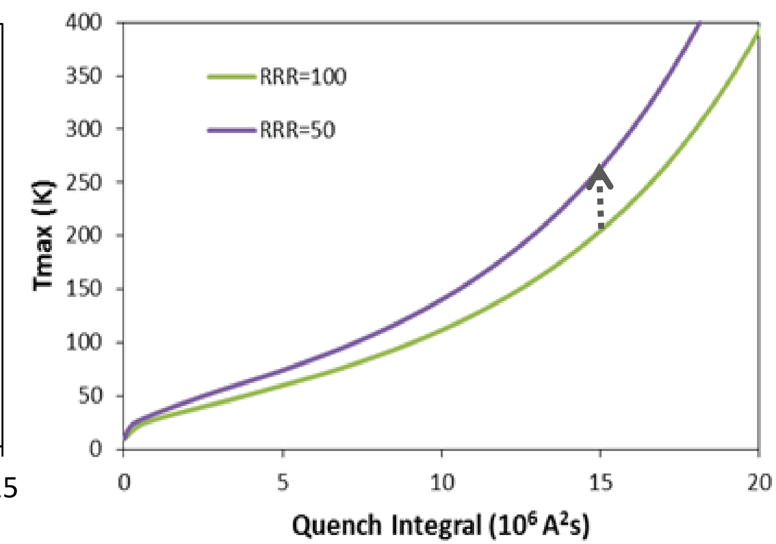


Quench Integral Limit

Additional corrections are required due to field change during current decay after quench and strand RRR:

- Average temperature between B_{max} and B=0 (left)
- Curves for RRR=100 and RRR=50 fit well (right)





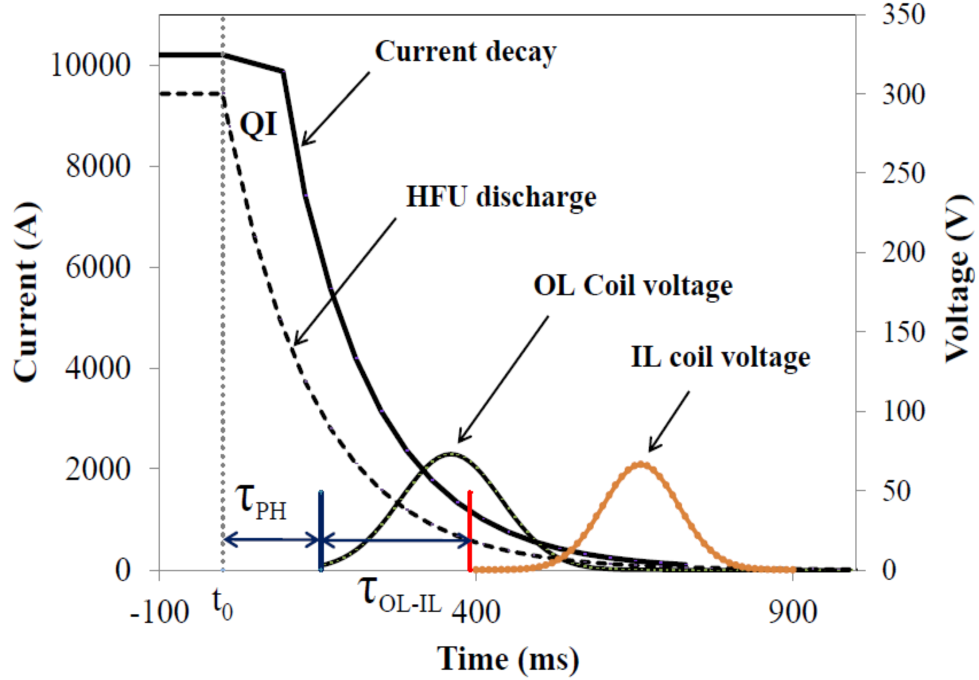
To keep T_{max} below 400 K - a safe limit for Nb_3Sn accelerator magnets – QI should be less than (19-21)*10^6 A^2s (MIITs) for the HF and LF coil blocks

PH Test Procedure/Definitions

Manual trip at $t_0=0$: No dump (1000 ms delay), OL heaters fired, magnet current decay starts

τ_{PH} Heater delay - delay between the heater firing and the quench start

$\tau_{OL\text{-}IL}$ - Quench propagation time between the OL and IL coils



Peak heater power density is defined as $P_{PH} = I_{PH}^2 \cdot R_{PH}/A$, where

- I_{PH} is the maximum heater current (A),
- R_{PH} is the heater resistance (Ω)
- A is the heater area (cm^2)

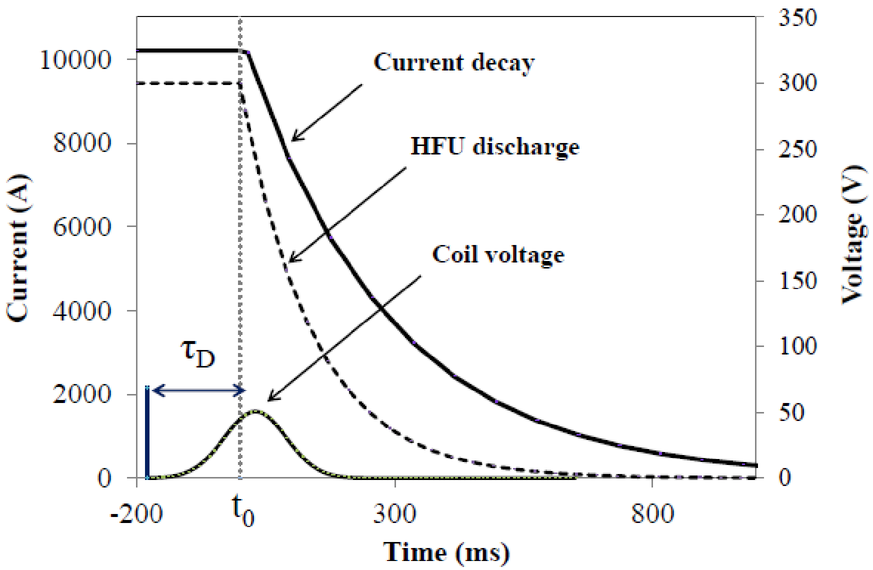
Budget Estimates

MIITs budget in a spontaneous quench is estimated as

$$\int_0^{\infty} I(t)^2 dt = I_0^2 \cdot \tau_D + \int_{\tau_D}^{\infty} I^2(t) dt$$

where

- I_o is the magnet quench current
- τ_D is the total delay time including the quench detection, protection switch operation, heater delay time
- *I(t)* is the current decay after quench detection



Delay budget is estimated as

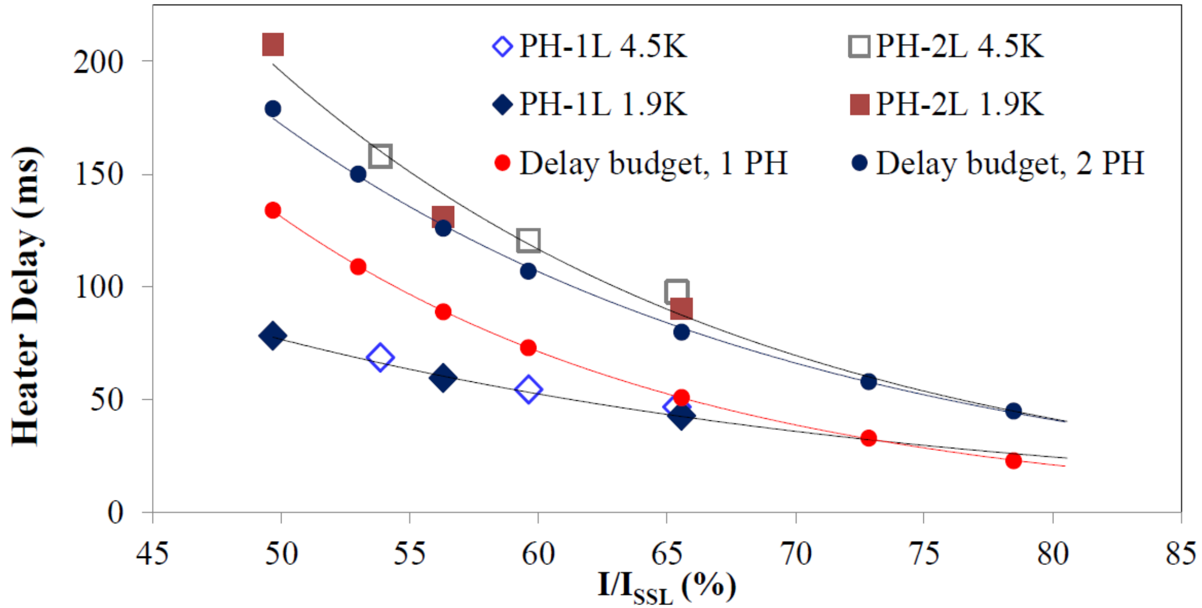
$$I_0^2 \cdot \tau_D = \int_0^{\infty} I(t)^2 dt - \int_{\tau_D}^{\infty} I^2(t) dt$$

Heater Delay Budgets

Heater delay budgets estimated for the 1 PH or 2 PH operations in MBHSP01

- Coil T_{max} is 400 K
- Average quench detection time 10 ms
- Protection switch operation time 5 ms

H-2L heaters with 2 layers of the *Kapton* insulation demonstrated large delays, providing no delay margin both for 1 PH or 2 PH operations

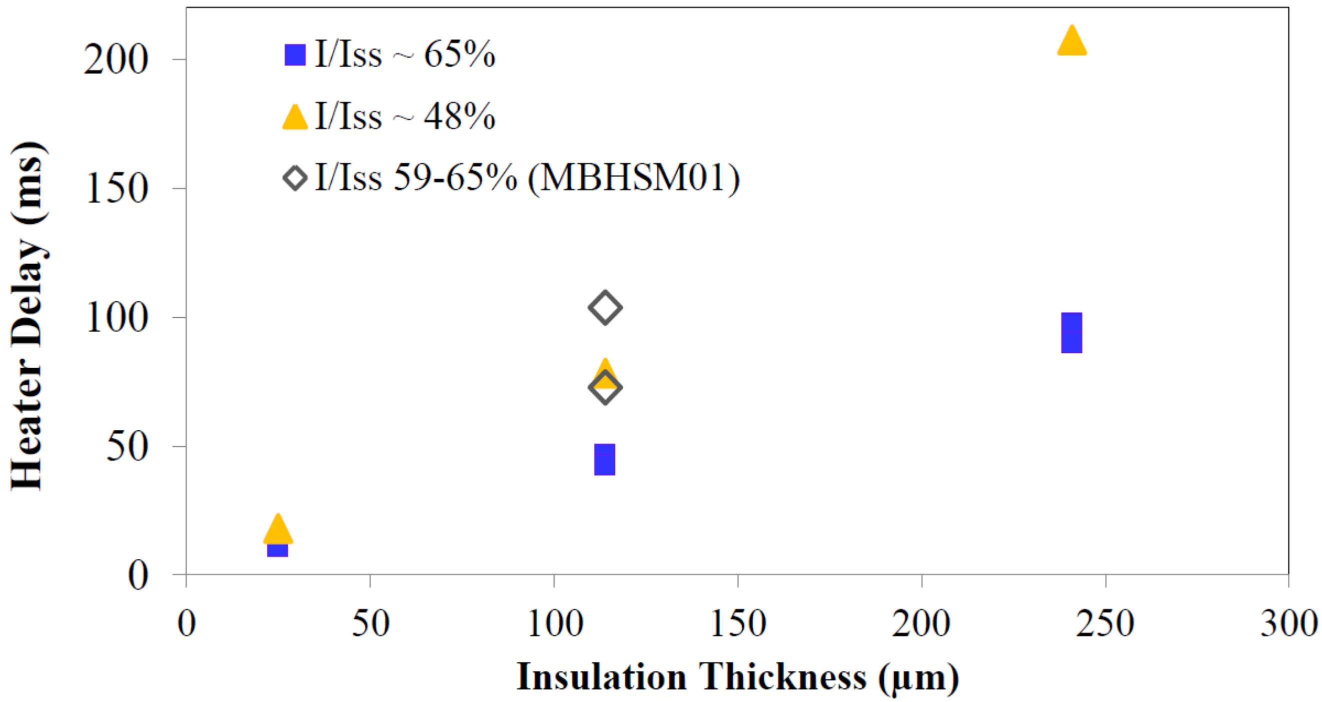


P_{PH} = 25 W/cm^2
τ (RC) = 24 ms

Effect of PH insulation

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

- PH delay is increasing proportionally to the insulation thickness

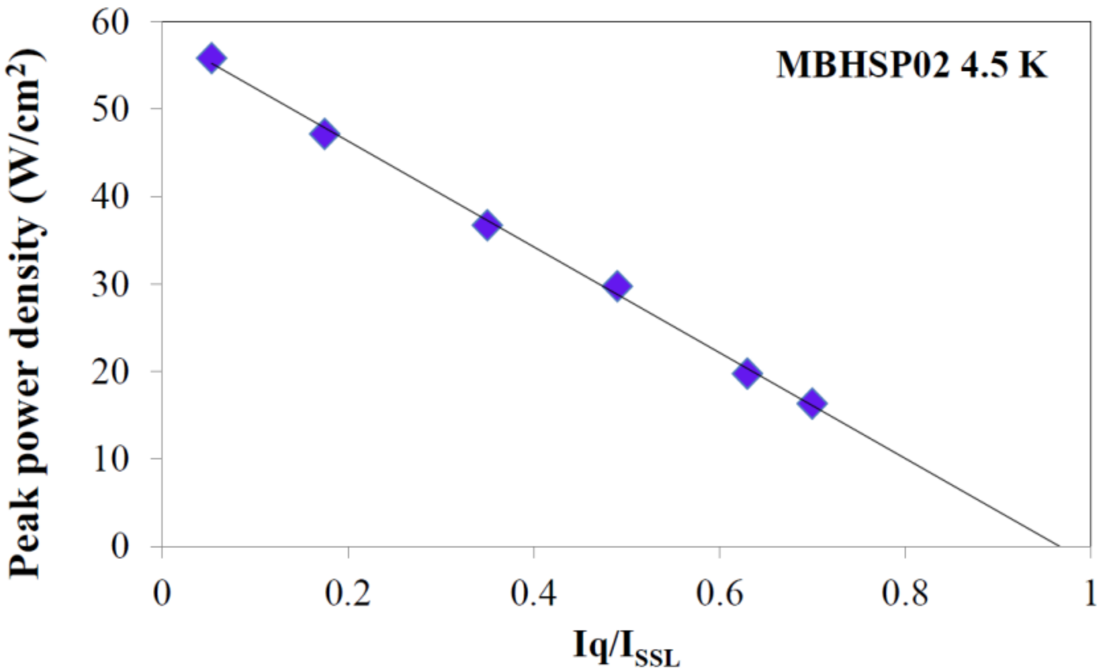


Insulation thickness could be reduced until it provides good electrical isolation between the coil and heaters

PH efficiency studies

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

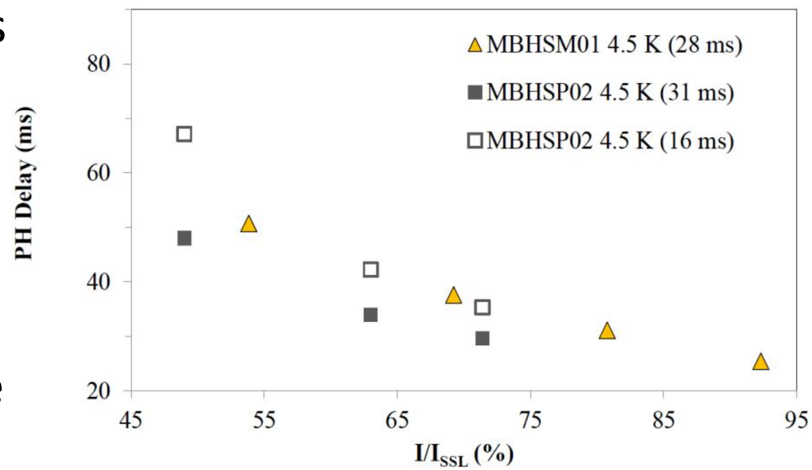
- 2 OL heaters in protection, time constant of ~ 25 ms
- Heater power density increased gradually until quench occurs
- For P_{PH}≈55 W/cm^2 magnet is protected at all operation currents



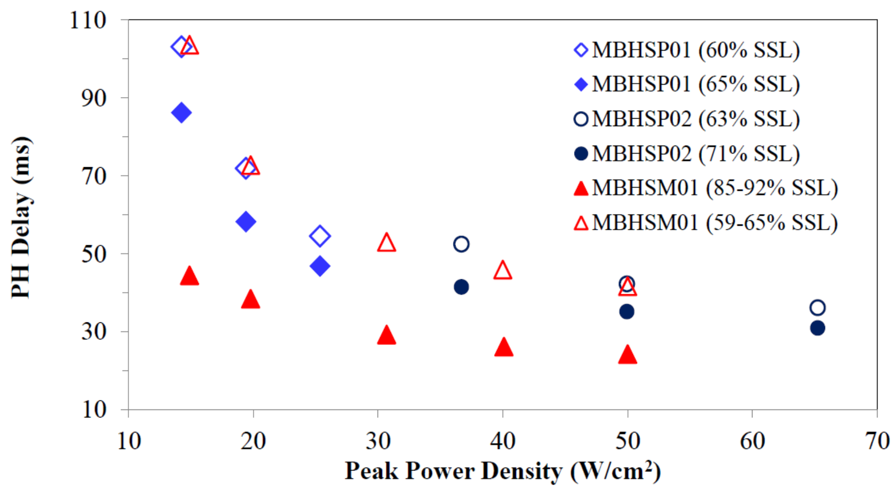
PH efficiency studies

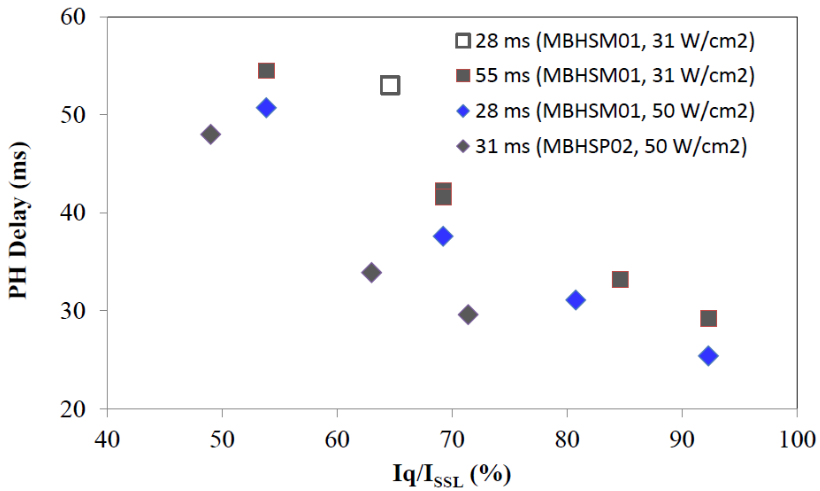
PH delays consistent in different magnets

- PH delays measured for the peak power density of ~ 50 W/cm^2



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

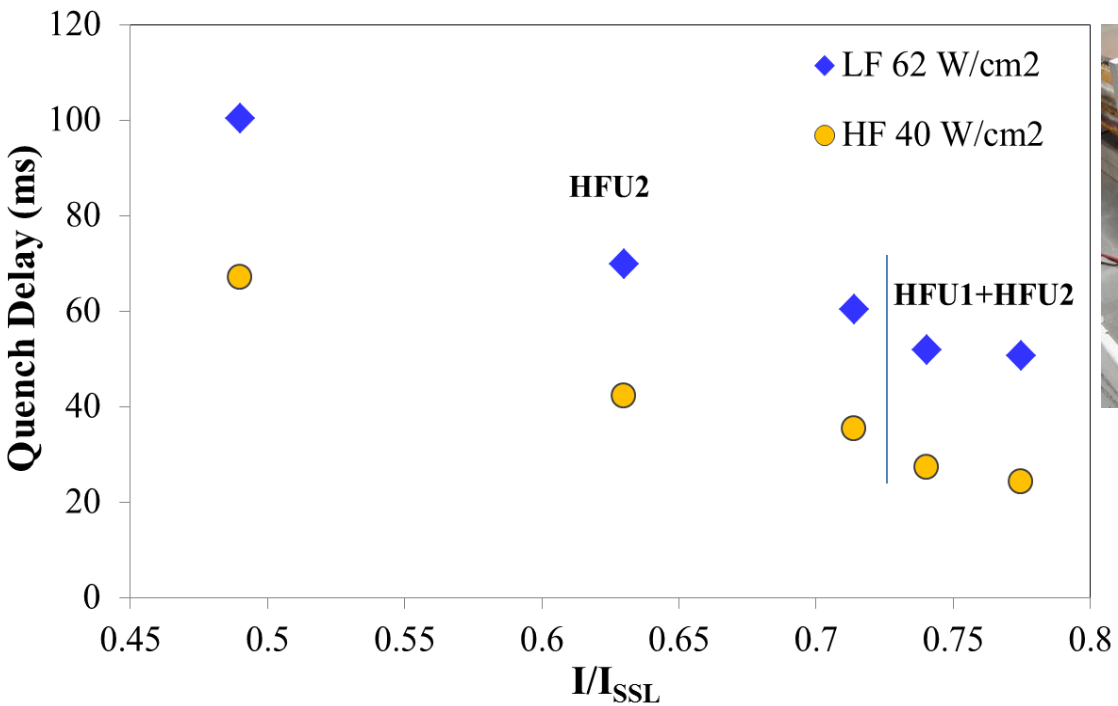


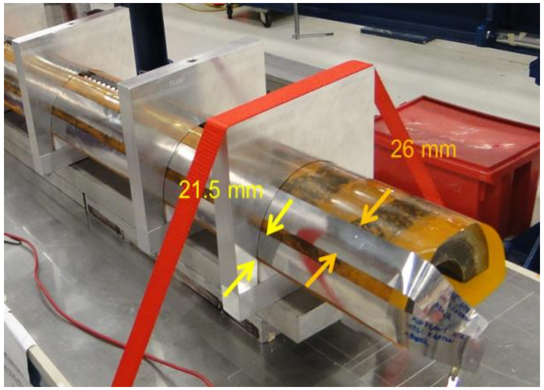


PH delay in LF and HF areas

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

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



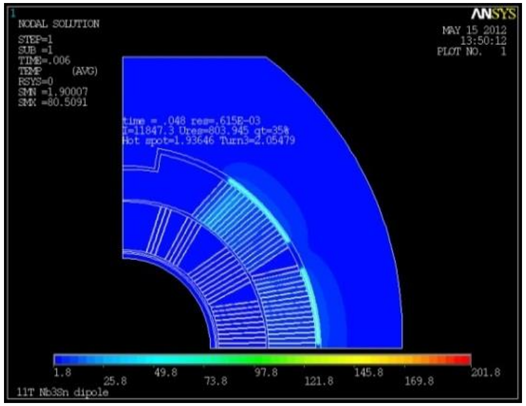


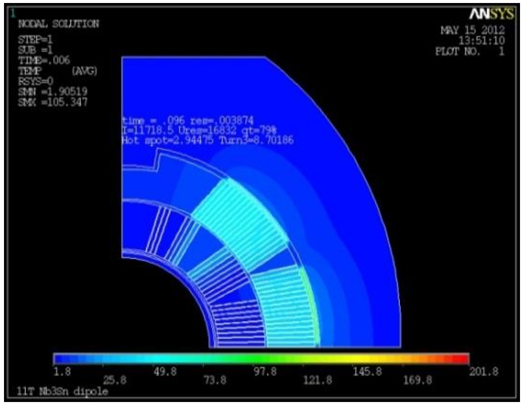
The difference in quench time between LF and HF blocks is ~ 30 ms

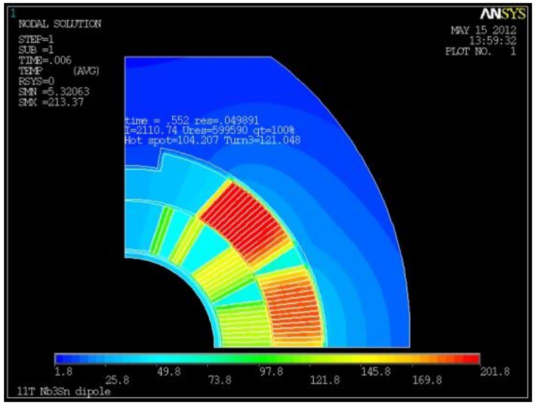
Radial & Azimuthal Quench Propagation

Heat transfer from the PH 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

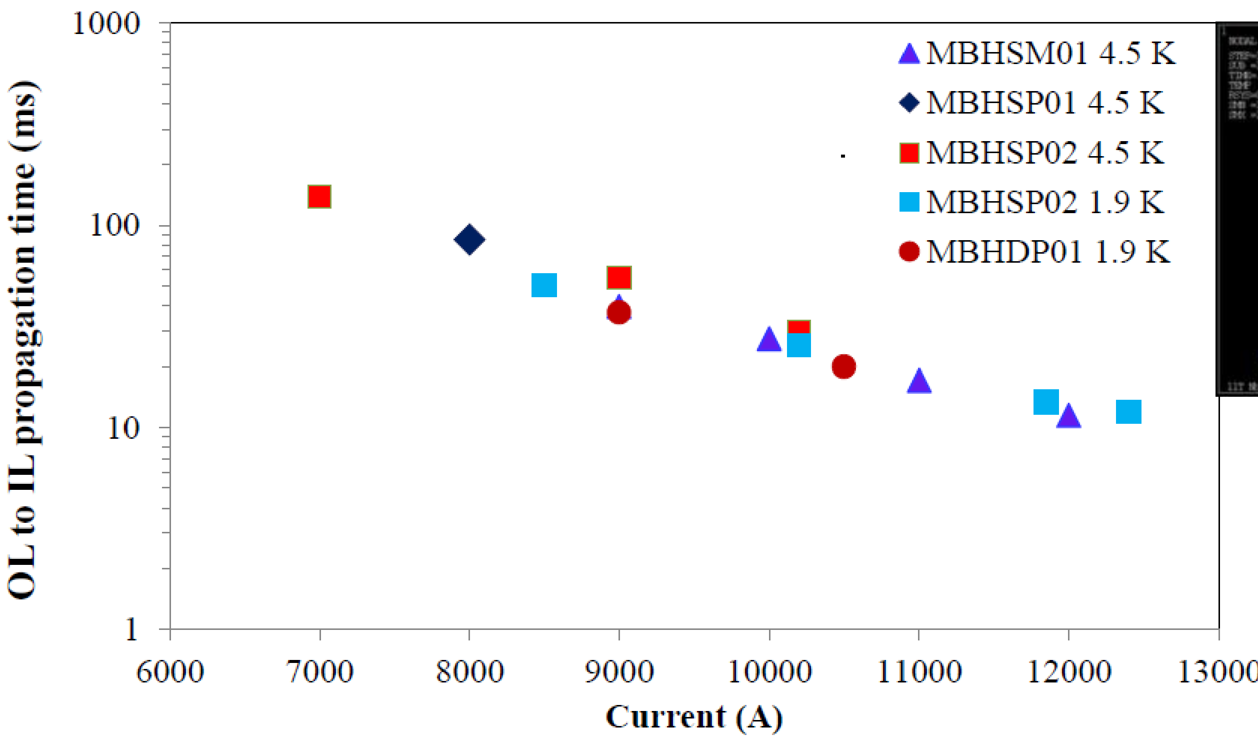
Radial quench propagation was measured in all 11T models

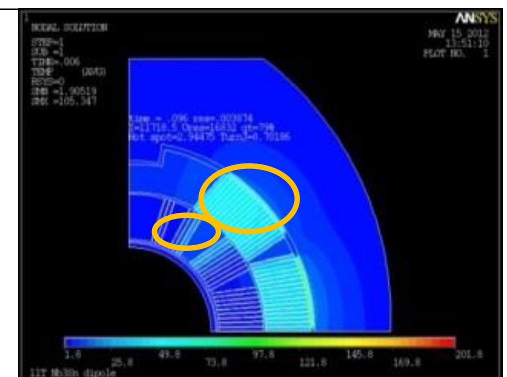
- Currently standard measurement for all Nb3Sn magnets

Radial Quench Propagation

OL to IL quench propagation time was measured in quenches with dump delayed for 1000 ms (No Dump)

- 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

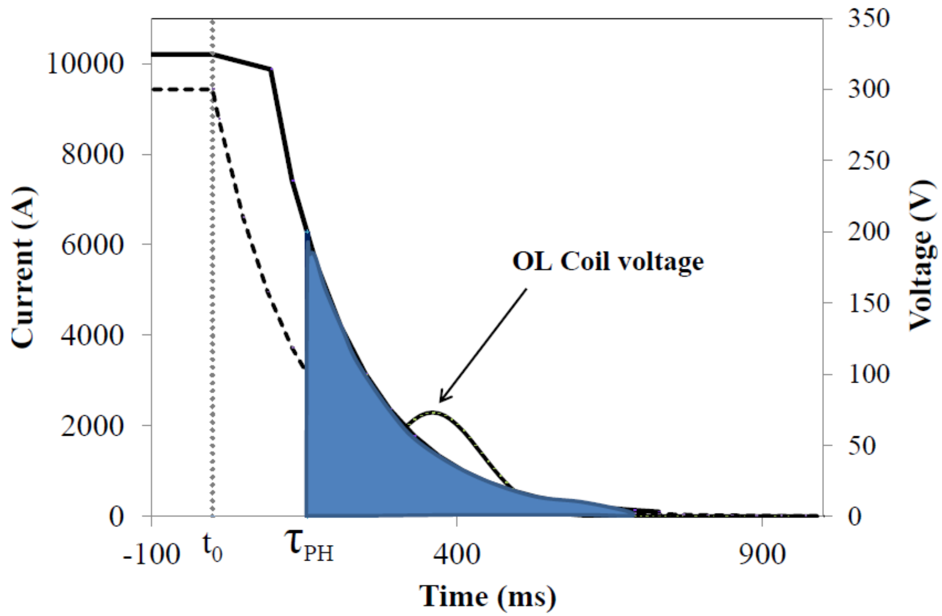




Quench Integral Study

The Quench Detection system was manually tripped at t_0; the OL heater induced quench will start after τ_{PH}

- Decay QI was calculated for the whole current decay (t_0,∞), 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



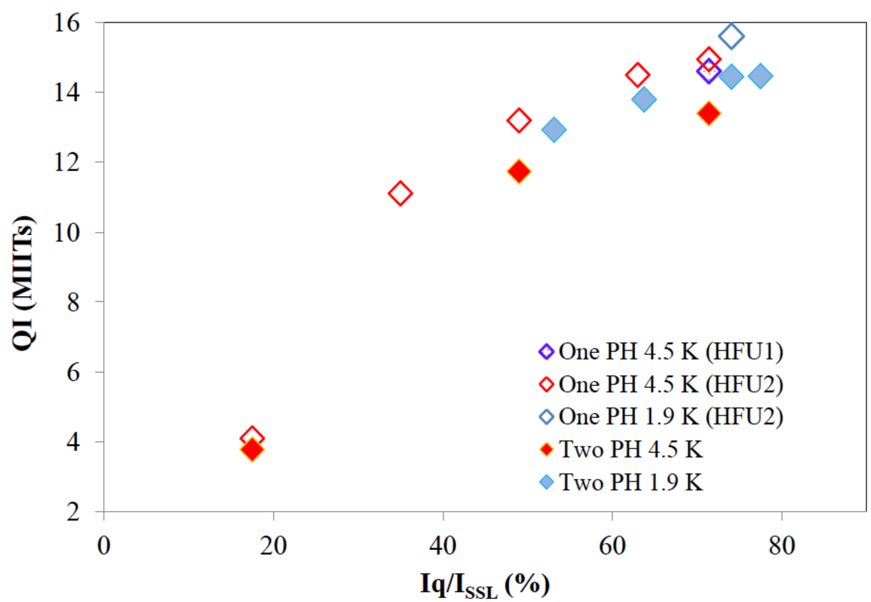
Safe for magnet

QI Study in 11T magnets

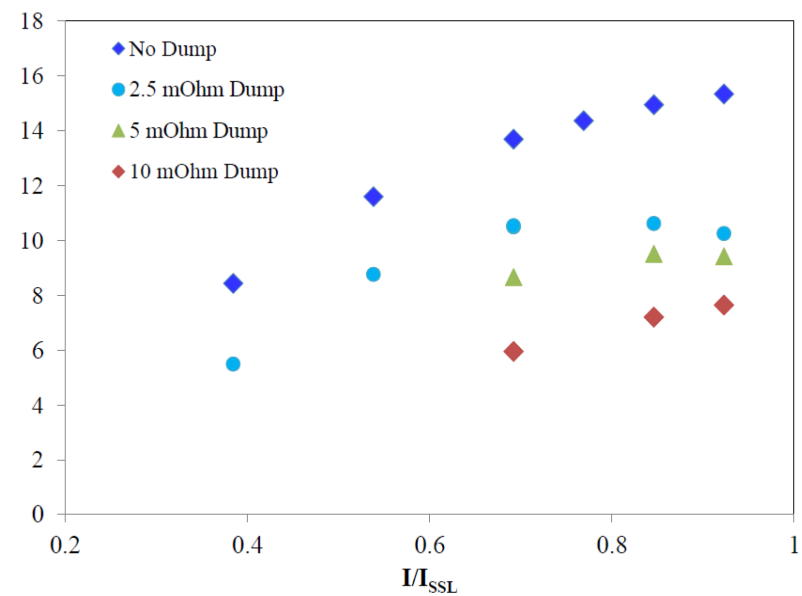
Decay QI for No Dump case (dump delayed for 1000ms) were estimated in MBHSP01/02 and MBHSM01 magnets

- In MBHSM01 QI was estimated also for low dump resistors 2.5 mΩ, 5 mΩ and 10 mΩ
- Decay QI(I_{nom}) is ~15 MIITs, therefore estimated QI budget of 19/21 MIITs (HF/LF) provides reasonable budget for quench detection time: ~28 ms in HF and ~42 ms in LF coil blocks

MBHSP01-02 Decay QI, "no dump"



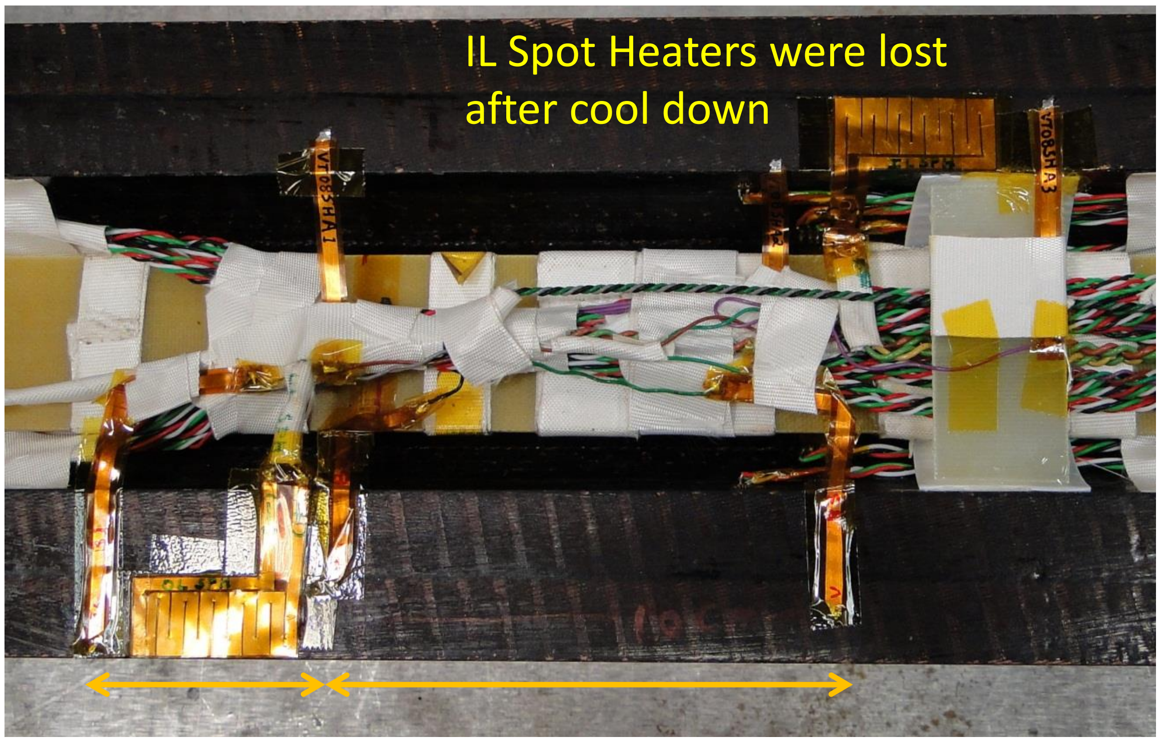
MBHSM01 Decay QI



Spot Heater Tests

Spot heaters (SH) installed in MBHSM01 for estimation of the quench temperature and longitudinal propagation velocity

- VT installed in close proximity to the SH

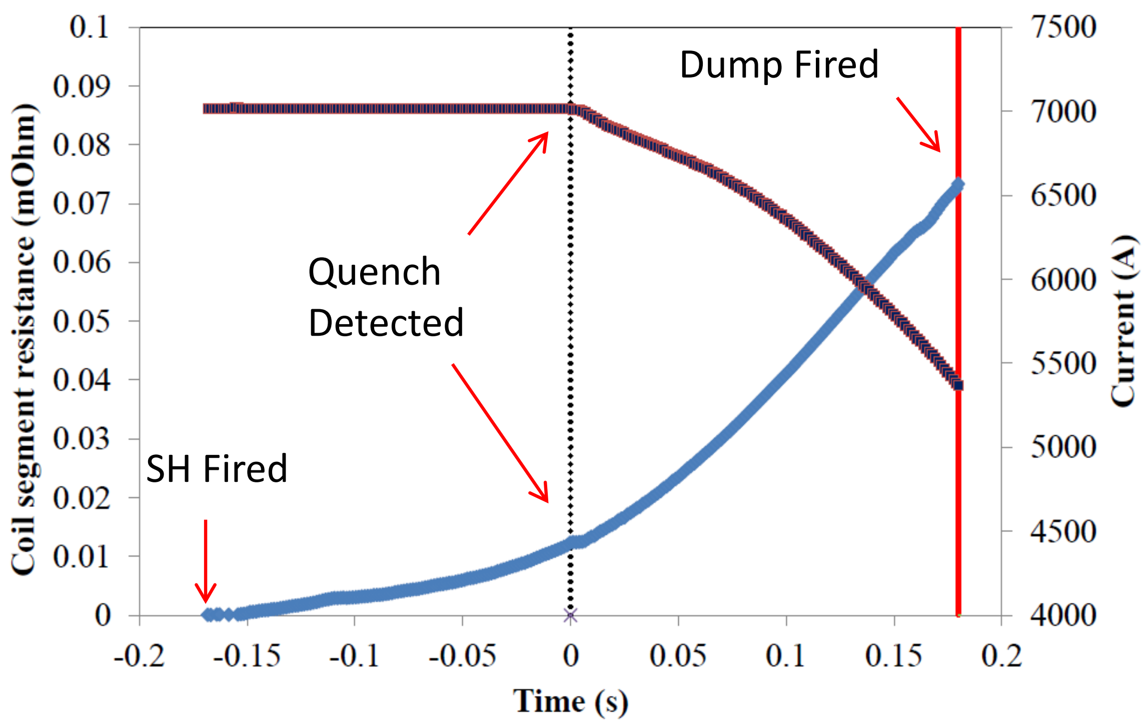


5 cm 10 cm

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 and reach higher temperatures



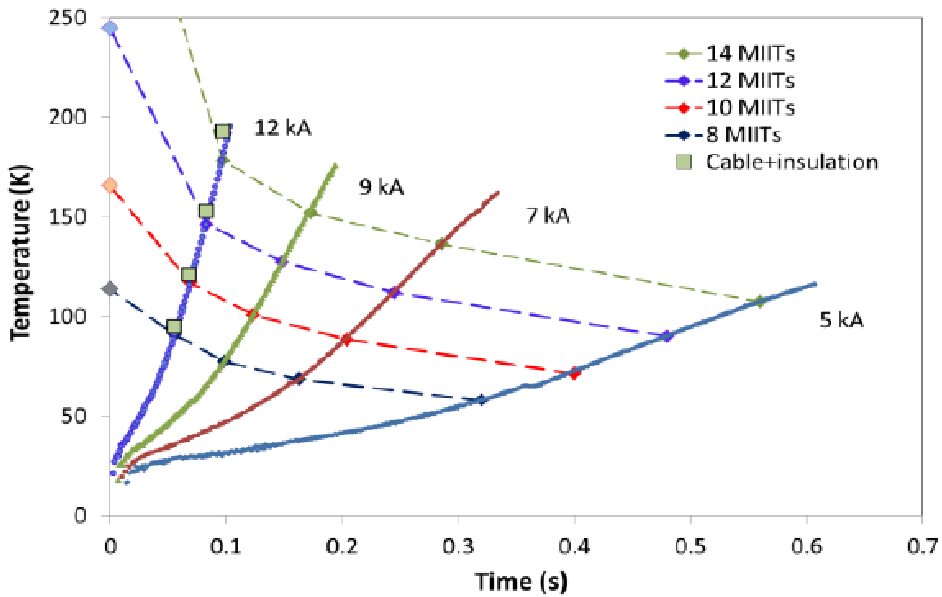
Quench Temperature measurements

Coil temperature as a function of time was estimated in the OL mid-plane turn at different currents

- Dashed lines connect points with the same QI
- Coil temperature estimated from the equation $V(t) = \frac{I \cdot \rho_{Cu}(B, T(t)) \cdot L}{S_{Cu}}$
- Coil temperature was measured during the warm-up from 4.5 K to 200 K to calibrate the coil resistance change during the quench

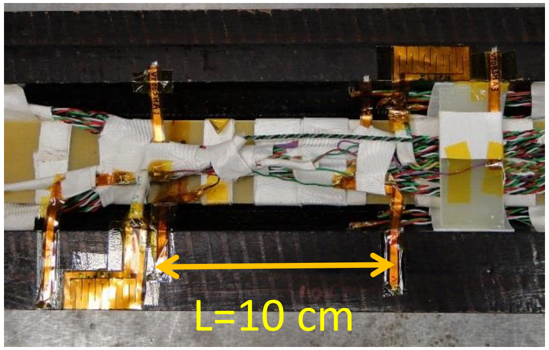
Strong cooling effect in the coil

- Heat transfer from the cable



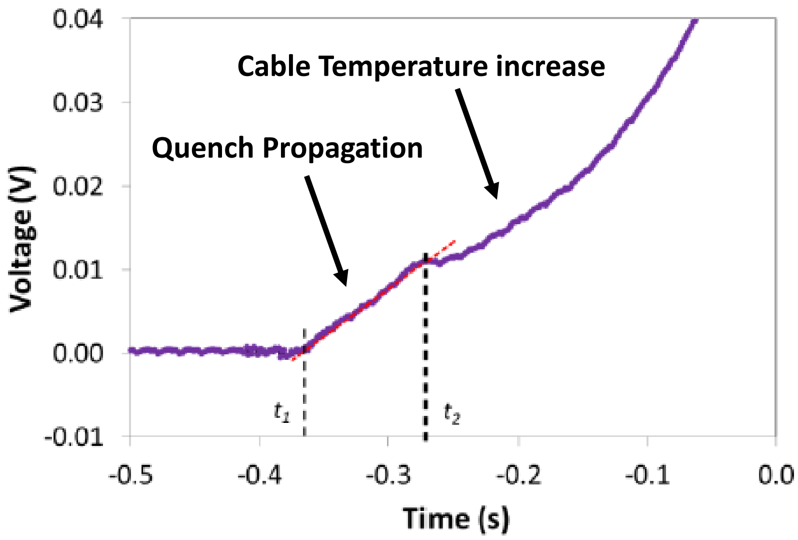
Longitudinal Quench Propagation

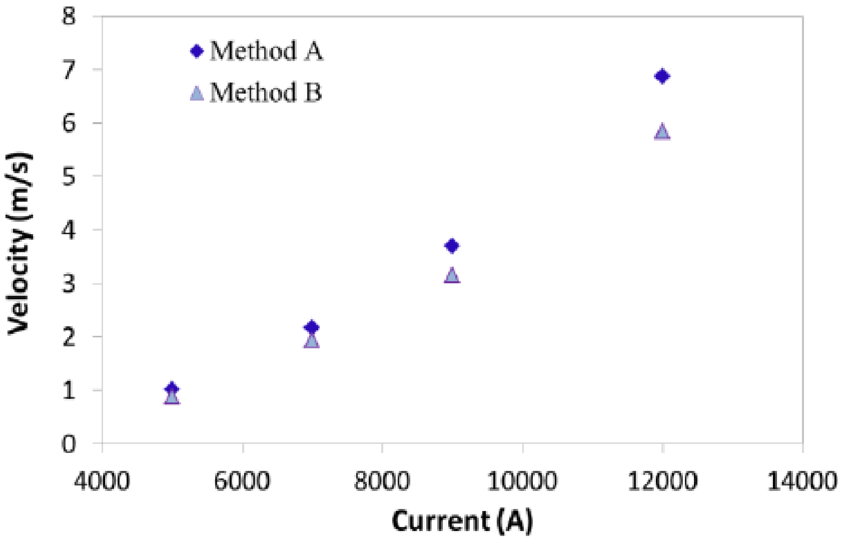
The OL spot heater quenches in MBHSM01 used to estimate the longitudinal quench propagation velocity



Voltage growth with time in the L=10 cm long segment next to the SH

Method A: $v = \frac{dV}{dt}\frac{S_{Cu}}{\rho_{Cu}(B) \cdot I}$ B: ~ $L/(t_2-t_1)$



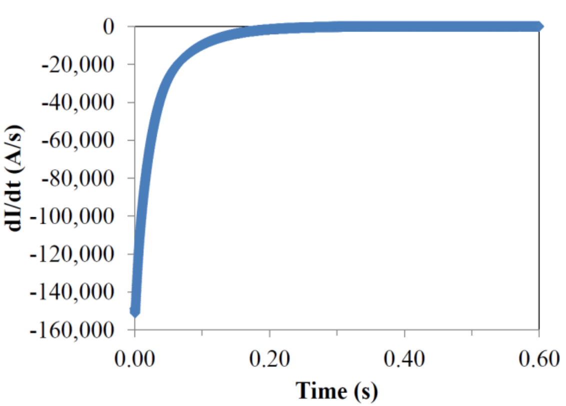


Fast extraction tests

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

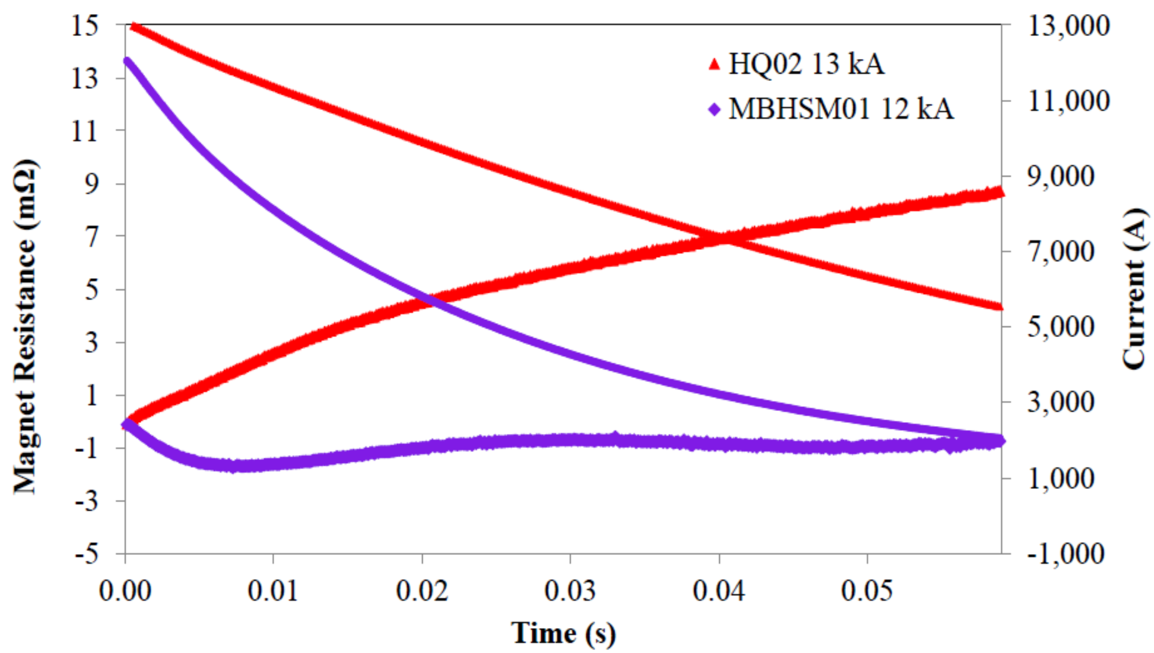
No resistance increase was observed in the coil for the fast extraction at 12 kA

- Effect of cored cable and small filament size



Ramp rate for the fast extraction test

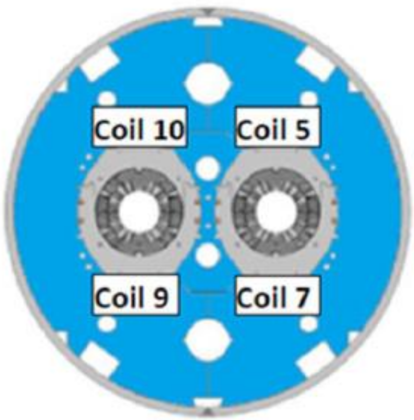
Whole coil resistance change in HQ02 and MBHSM01 magnets



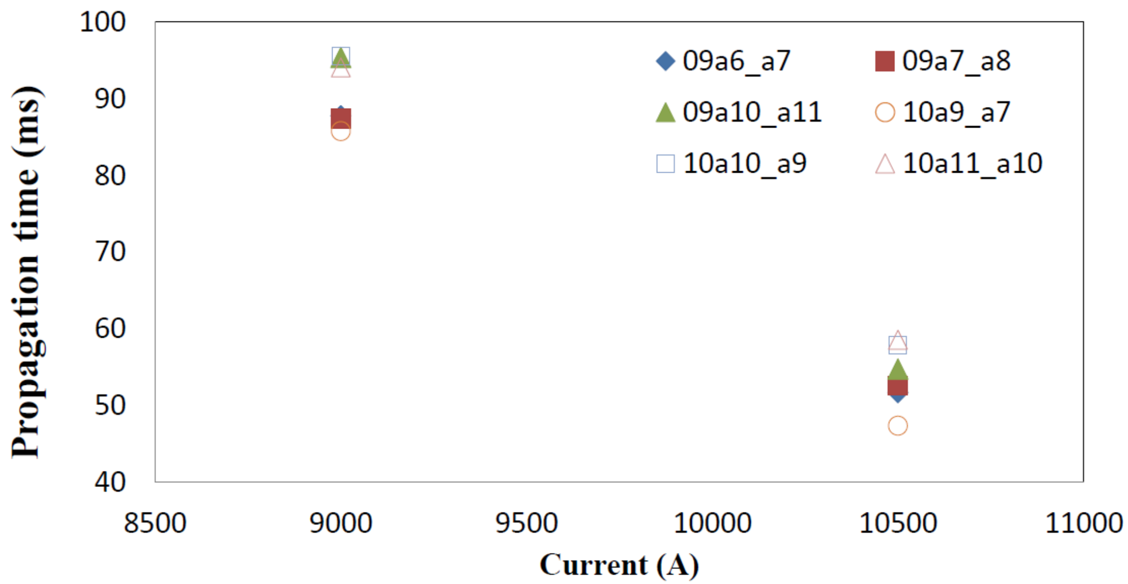
MBHDP01 Tests

Quench propagates between the magnet apertures

- PH induced quenches in coils #5 and #7
- Dump and heaters in the 2nd aperture delayed to see quench development in coils #9 and #10



More tests will be done in TC2



Summary

Quench protection study was performed at currents up to 92% of SSL and for different external dump resistors in different 11T models

Operation with at least 2 OL protection heaters is required for adequate protection of 11T magnets

Reduced heater to coil insulation helps to increase the heater efficiency, but sufficient electrical insulation has to be provided

Estimated QI budget of 19-21 MIITs provides reasonable quench detection time budget of ~ 28 ms in the high field coil block

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

Summary (cont'd)

Radial quench propagation was measured at different currents and temperatures

- Quite small delay at high currents helps to spread energy in the coil

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

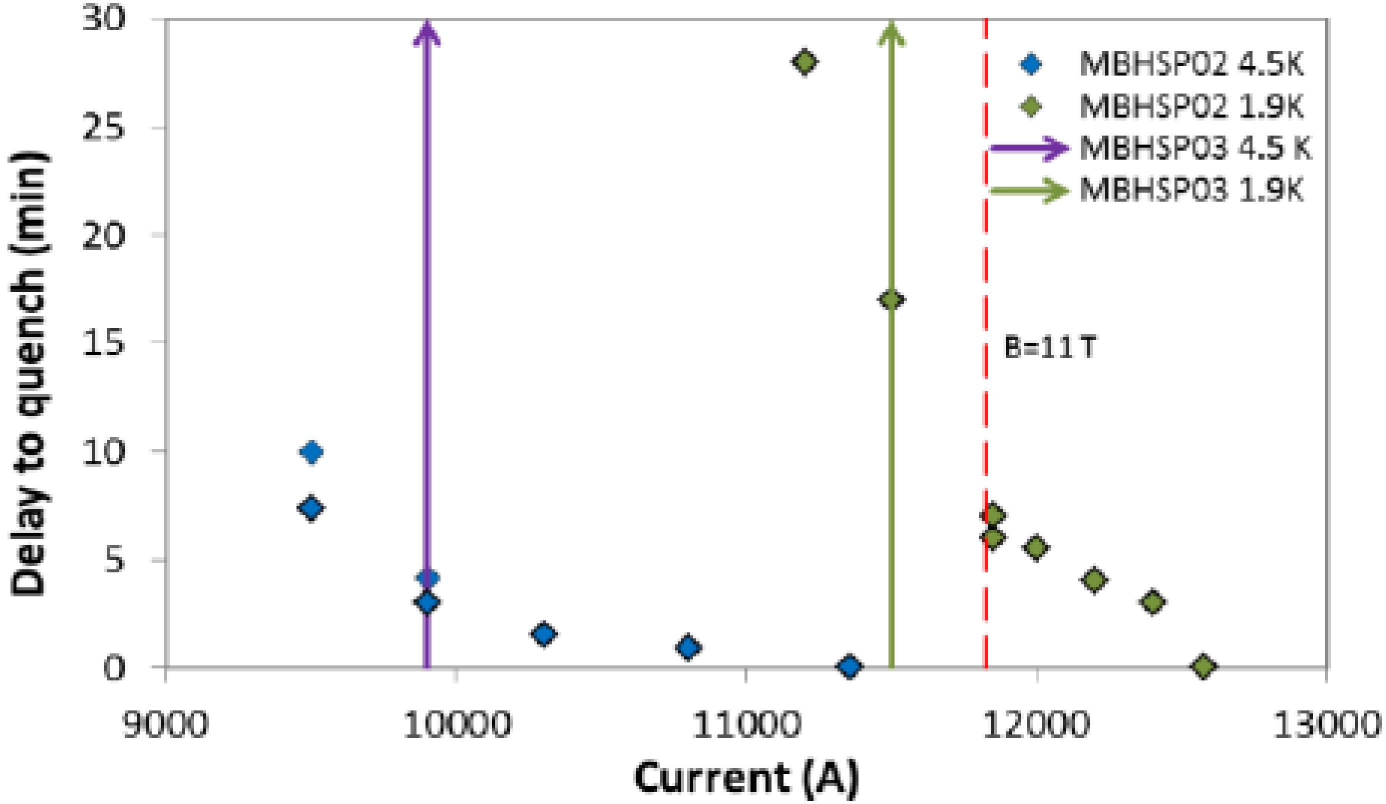
Coil temperature increase with time after quench was studied at different currents

Fast extraction tests did not exhibit noticeable increase of the coil resistance

BACKUP SLIDES

"Holding quenches"

No quenches in MBHSM01 (coil #8) after "holding" 13 kA at 1.9 K and 12 kA at 4.5 K for ~22 min



Quench training of 11T magnets