Lawrence Berkeley National Laboratory

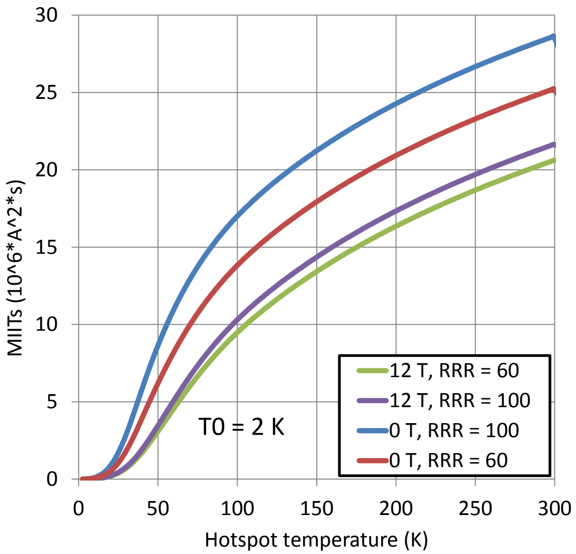
HQ
Summary of quench protection studies

2nd Joint HiLumi LHC – LARP Annual Meeting
INFN Frascati – November 14th to 16th 2012

LBNL: Helene Felice – Tiina Salmi – Ray Hafalia – Maxim Martchevsky
FNAL: Guram Chlachidze
CERN: Ezio Todesco – Hugo Bajas

Work partially supported by the U. S. Department of Energy, under Contract No. DE-AC02-05CH11231

MIITs curve and Time margin



- Well-known that material properties play an important role
- Example of HQ MIITS computation:

NIST+cryocomp /cryocomp /quenchpro
At 2K and 12 T RRR 60 = 20.6 / 21.6 / 19.5
At 2K and 0 T RRR 60 = 25.2/ 26.3 / 23.5

Average: 2 K, 12 T and RRR 60 = 20.6 +/- 1 MIITs

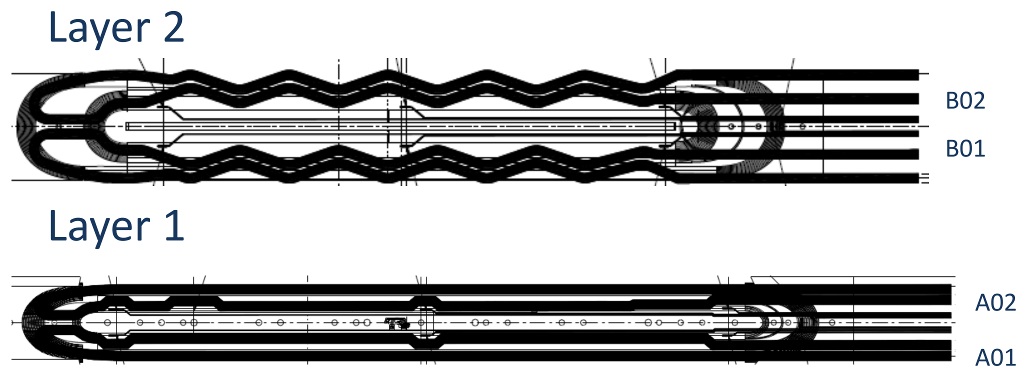
Figure of merit: the time margin (E. Todesco)

(MIITS budget – MIITS decay)/I^2 = time to quench

HQ time margin of the order of 27 ms

HQ protection scheme

Protection Heaters (PH)



- PH strip on both layers
- 2 strips per layer
- 4 strips per coil
- Strip R: ~ 4.5 Ω at 4.2 K

- Powering scheme
  - Typical: 4 circuits
    - all B02, all A02, all B01, all A01
  - PH hipot failure to coil can lead to replacement by a resistance
  - In some cases, enough power supplies to power a few strips individually

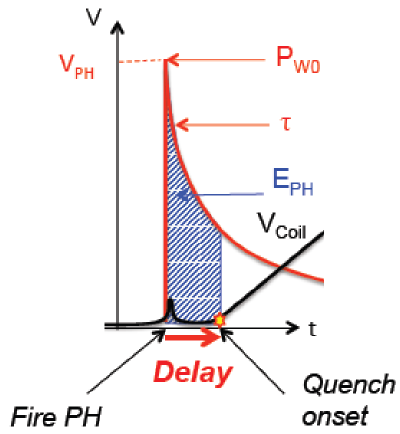
- Coverage of about 60 % (including propagation between station)

Dump resistor

- 30 to 40 mΩ

HQ
Protection studies overview

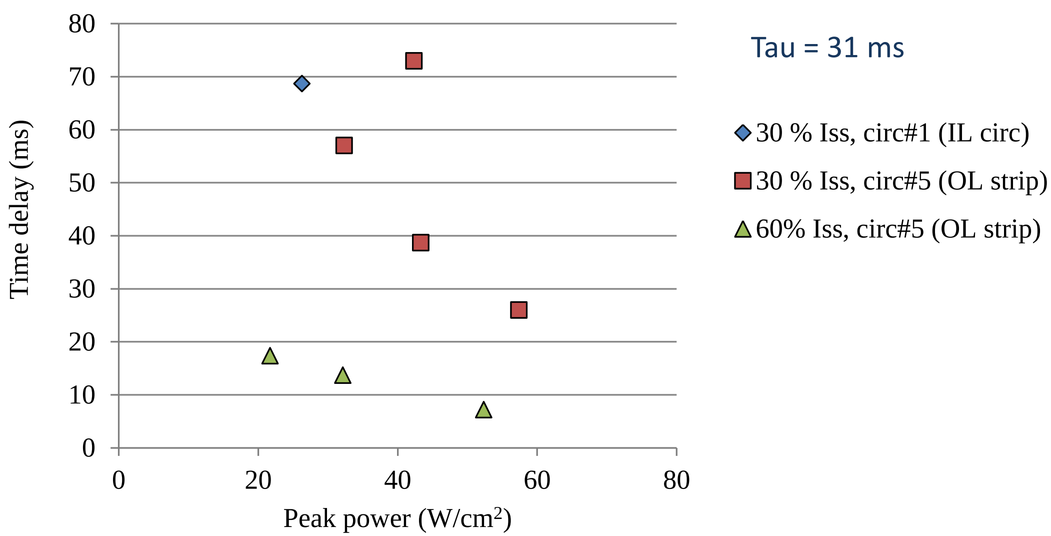
- **Several tests**
  - Magnets: HQ01a to e
  - Mirror: HQM01 and HQM04
- **Protection Heaters (PH) delay studies**
  - versus Heater peak power
  - versus magnet margin
  - versus Kapton thickness
- **Quench back**
- **MIITS limits**

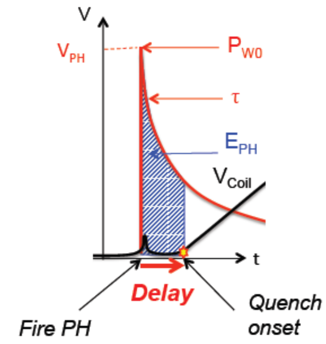


Protection Heater (PH)
Delay time versus peak power

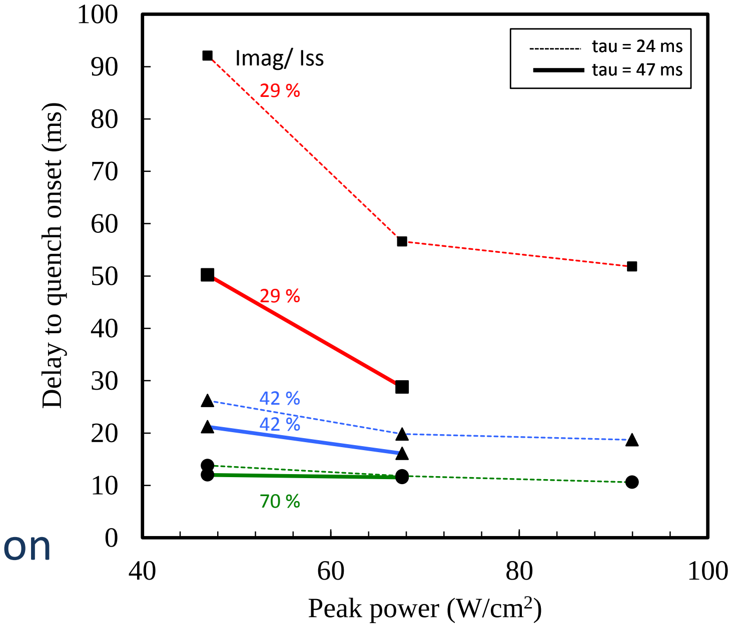
Lawrence Berkeley National Laboratory

HQ01d



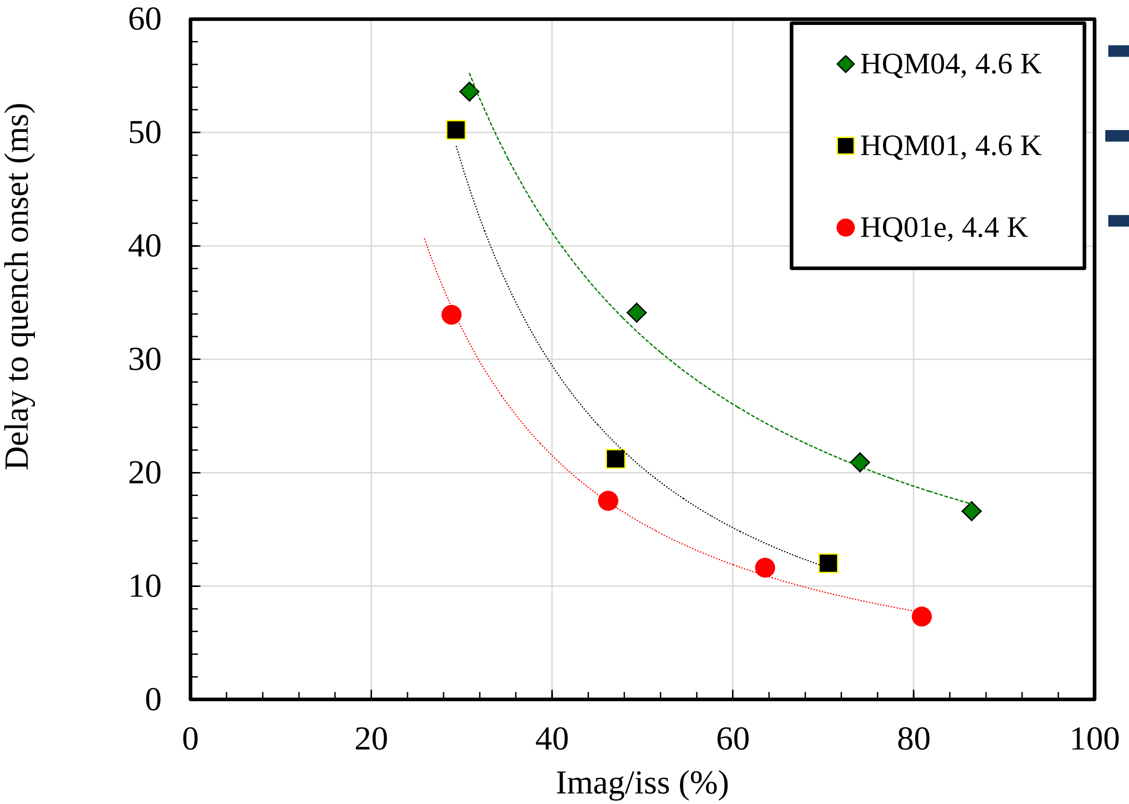


HQM01



- Some saturation of the delay at high peak power
- Tau => total energy impacts the delay time
  - Strongly at low fraction of I_{ss}
  - Marginally at higher fraction of I_{ss}
  - Some studies on optimization of energy deposition

Impact of Kapton thickness on PH delay



Kapton thickness

➡ 75 μm

➡ 50 μm

➡ 25 μm

- Large increase of PH delay with Kapton thickness
- From 60 to 150 % from HQ01e to HQM04
- 75 μm: choice made for HQ02 to ensure electrical integrity

H. Bajas et al., "Test Results of the LARP HQ01 Nb_3Sn quadrupole magnet at 1.9 K", presented at ASC2012

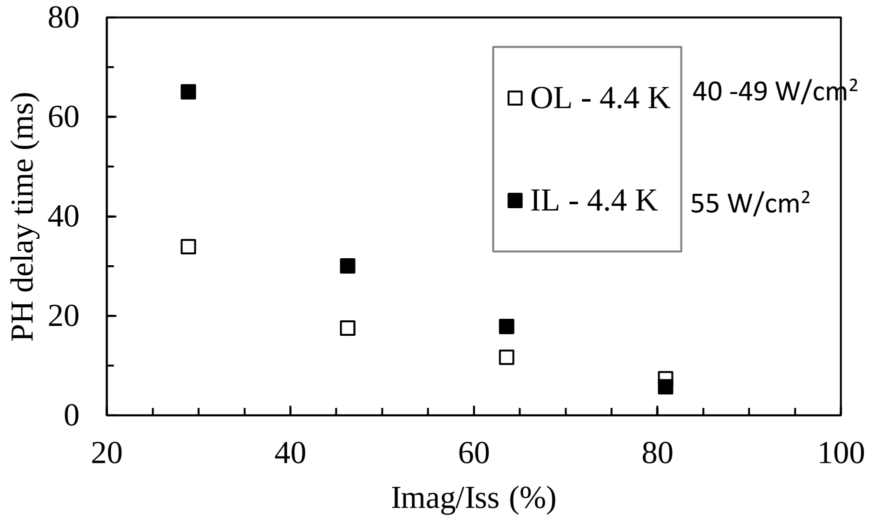
T. Salmi et al.: "Quench protection challenges in long Nb_3Sn accelerator magnets", AIP Conf. Proc. 1434, 656 (2012)

HQ01e at CERN: Pw0 = 50 W/cm², tau 40 ms: Iss = 17.3 kA @ 4.4 K; 19.1 kA @ 1.9 K
HQM04 at FNAL: Pw0 = 45 W/cm², tau 46 ms: Iss = 16.2 kA @ 4.6 K; 18.2 kA @ 2.2 K
HQM01 at FNAL: Pw0 = 47 W/cm², tau 46 ms: Iss = 17.0 kA @ 4.6 K

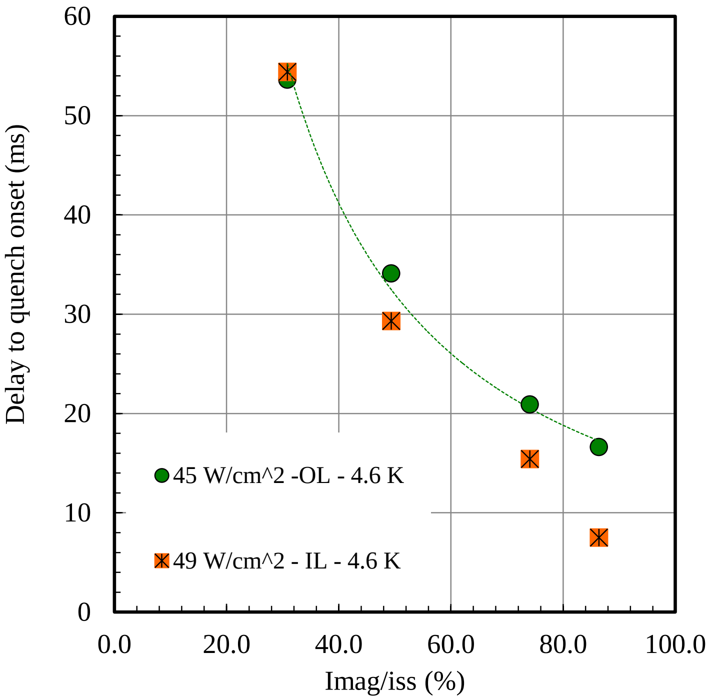
Il versus OL

Lawrence Berkeley National Laboratory

HQ01e at CERN – coil 9 tested
(25 μm Kapton)



HQM04 at FNAL (75 μm kapton)

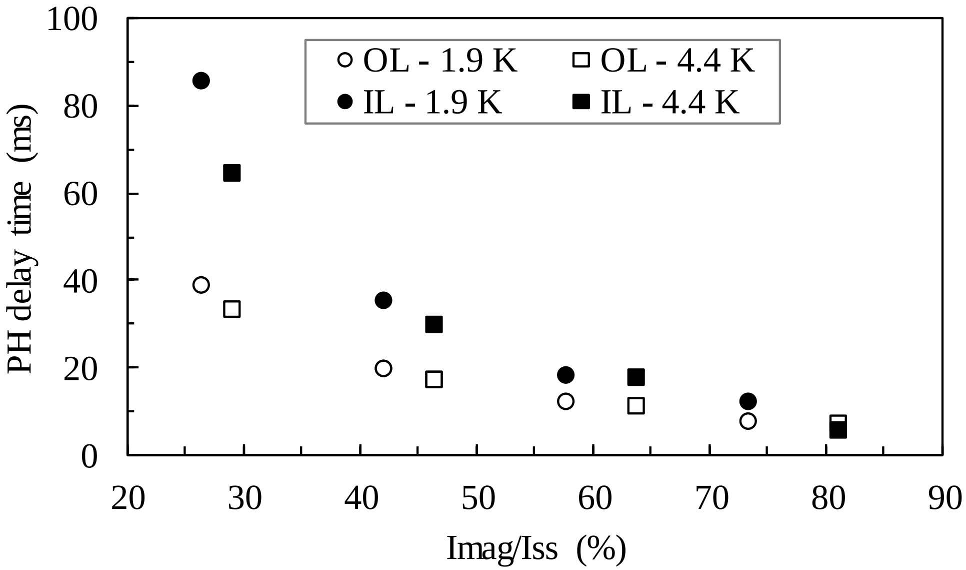


- In HQ01e: OL PH delay shorter than IL
- In HQM04: IL PH delay shorter than OL
- Possible differences between HQ01e and HQM04
  - => Cooling of the bore?
  - => high compression due to mechanical preload in HQ01e: better thermal contact?

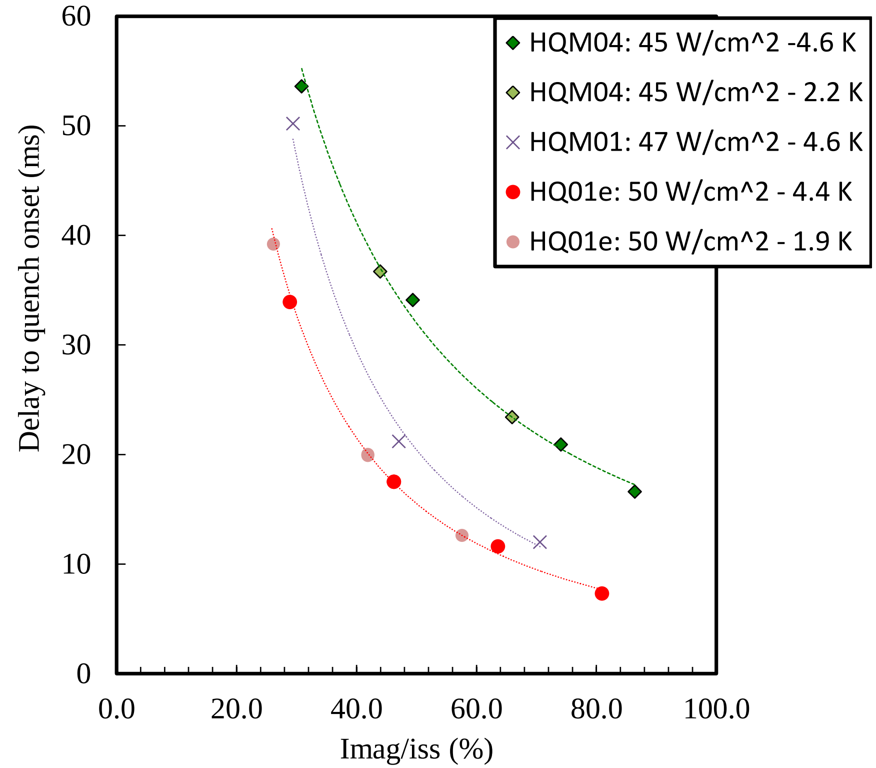
Bath Temperature

Lawrence Berkeley National Laboratory

HQ01e at CERN



HQ01e at CERN – HQM04 at FNAL

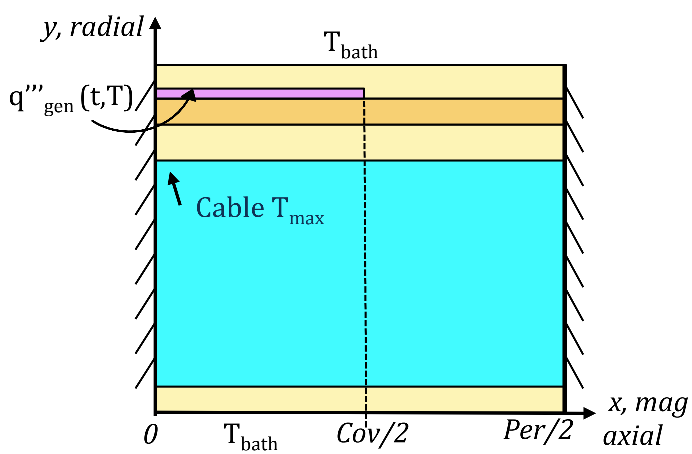


- From HQ01e and HQM04:
  No effect of the bath temperature observed on the PH delay

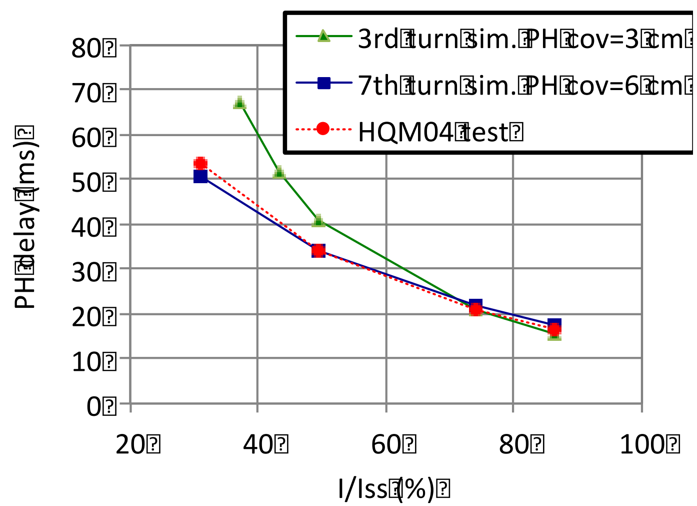
Next steps on PH studies

- Development of a 2D thermal model (Tiina Salmi, LBNL)
  - Simulation of heat transfer from PH to coil for design optimization
    - Heater longitudinal layout
    - PH to coil insulation layout
    - PH powering
      - Optimization of energy deposition: Square pulse, Truncated capacitance discharge
      - Minimizing PH Temperature and Voltage
  - Comparison with experimental data showing good agreement

Thermal system: half PH period



HQM04 simulation



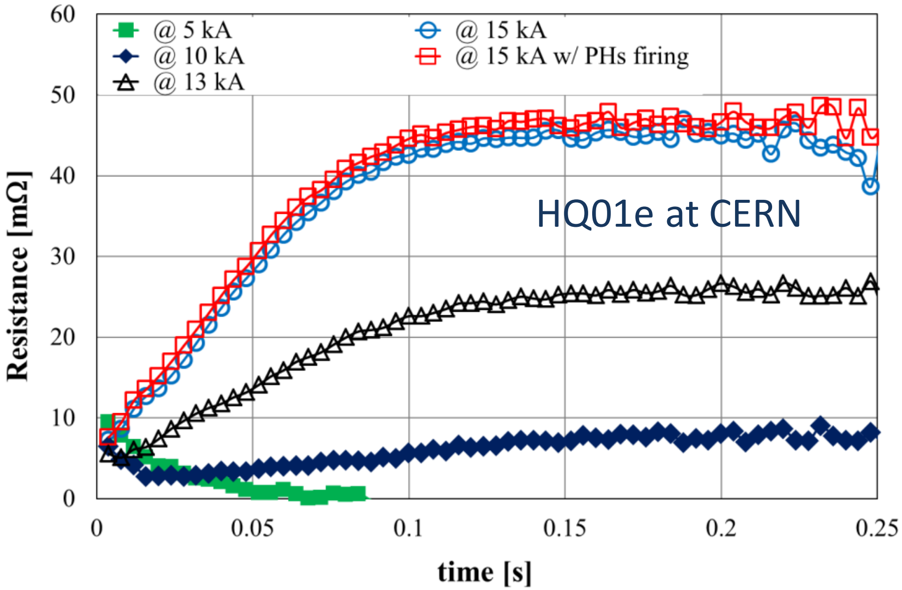
HQ01e – Quench-Back

- Magnet sitting at a constant current: from 5 to 13 kA – (NO quench)
- Discharge in the 40 mΩ dump resistor without PH

- Does the magnet quench from eddy current generation in the cable (form of quench-back)?
- From the current decay:

$$I(t) = I_0 e^{\frac{-R\,t}{L}}$$

$$R_{mag}(t) = -L\frac{d}{dt}\ln\left(\frac{I(t)}{I0}\right) - R_{dump}$$

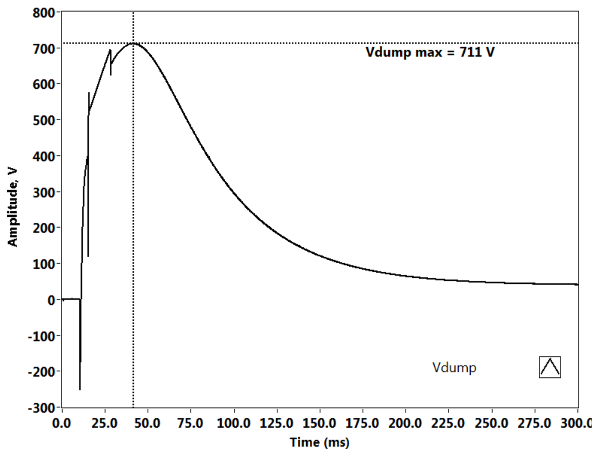


H. Bajas et al., "Test Results of the LARP HQ01 Nb_3Sn quadrupole magnet at 1.9 K", presented at ASC2012

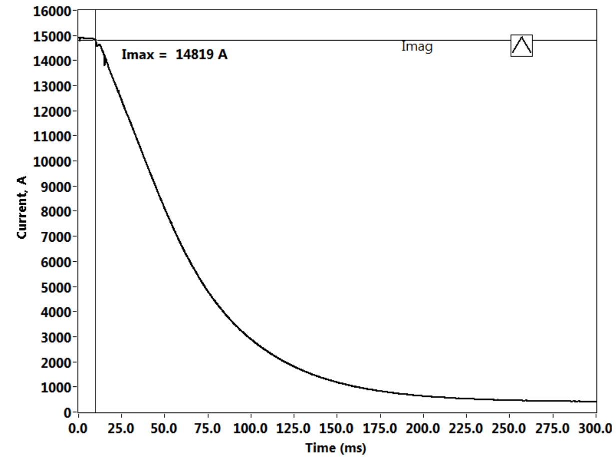
- At 5 and 10 kA: no sign of quench
- A 13 kA: signs of quench
- At 15 kA: fraction of the magnet is quenching
- Last 15 kA test with PH: no clear impact

Estimate of HQ01 resistance during extraction

1) Find energy dissipated in the dump resistor



X



A36

$$E_{dump} = \int_{10\ ms}^{300\ ms} I(t) * V_{dump}(t)\, dt = \mathbf{0.425\ MJ}$$

2) Find total energy in the magnet:

Magnet inductance is L=7.5 mH; Then, at I = 14819 A, $E_{mag} = LI^2/2 =$ **0.823 MJ**

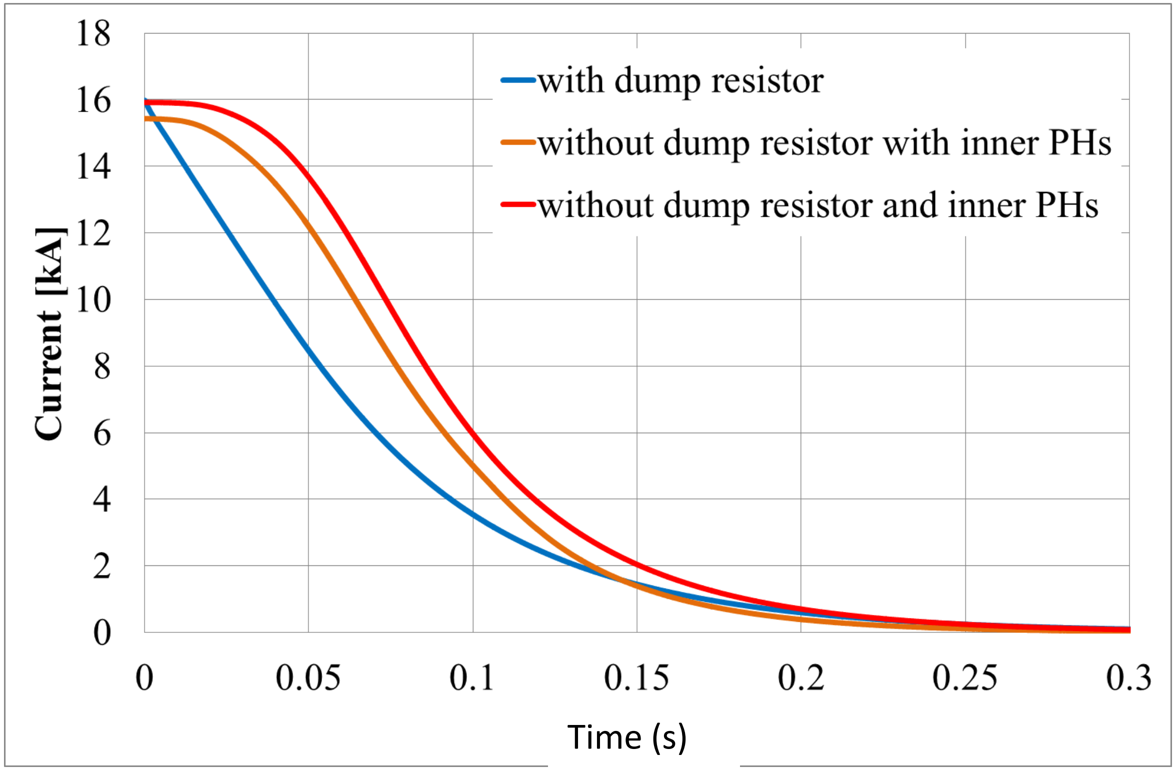
3) Find energy dissipated in the cryostat: E_{cryo} = 0.823-0.425 = **0.398 MJ**

4) Find magnet resistance: $A = \int_{10\ ms}^{300\ ms} I^2(t)\, dt = 7.13\ 10^6$ =>

=> $R_{av} = E_{cryo}/A$ = **0.055 Ω** – average magnet resistance during extraction (10-300 ms)

HQ01e MIITS limit

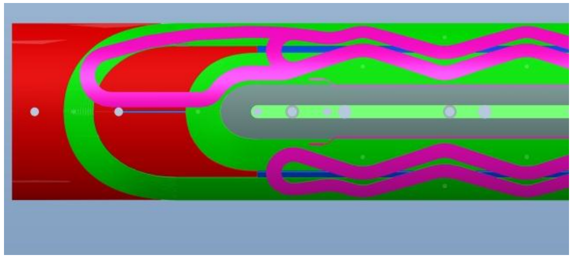
H. Bajas et al., "Test Results of the LARP HQ01 Nb_3Sn quadrupole magnet at 1.9 K", presented at ASC2012



- Explored high MIITS by removing the dump resistor and inner layer PH (spontaneous quenches)
- HQ01e-3 at LBL will perform validation quench to check for degradation

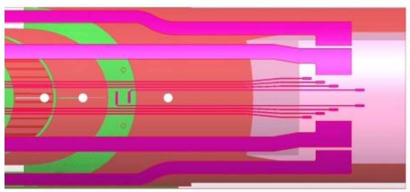
PH and Trace revision

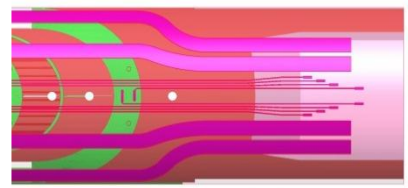
- Avoid overlapping PH strip with metallic end parts: Rev C

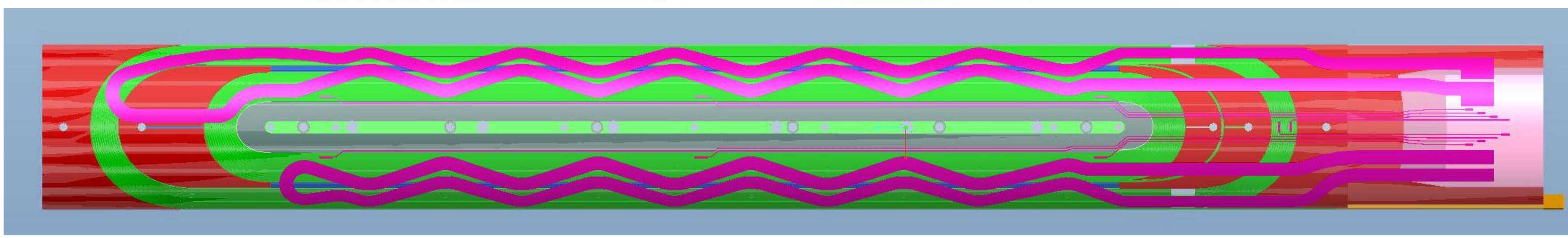


- first implemented in HQ16

- Fit the "LHQ style" extension (Rev D): will be first implemented in HQ20







HQ02: - coil 15 OL: rev B - coil 17 OL: rev C -IL unchanged
- coil 16 OL: rev C - coil 20 OL: rev D

HQ02 coils will have 75 microns kapton between PH strips and coil

Summary

- **Protection heaters:**
  - A wide mapping of the PH delay has been performed with the HQ01 series and the mirrors
    - Good start to benchmark models
  - From HQ01e: OL PH seem more efficient than IL PH
  - PH efficiency seems to be independent of temperature
- HQ01e test at CERN explored **High MIITs regime**
  - The dump resistor as well as the IL PH were deactivated
- HQ01e test at CERN exposed **quench-back in the cable** for current above 13 kA
  - HQ01e coils do not have a core
- Necessity to reproduce these tests with HQ02
  - cored cable
  - 75 microns Kapton between coil and PH strip