Quench protection on the test benches

G. Willering

On behalf of the TF section,

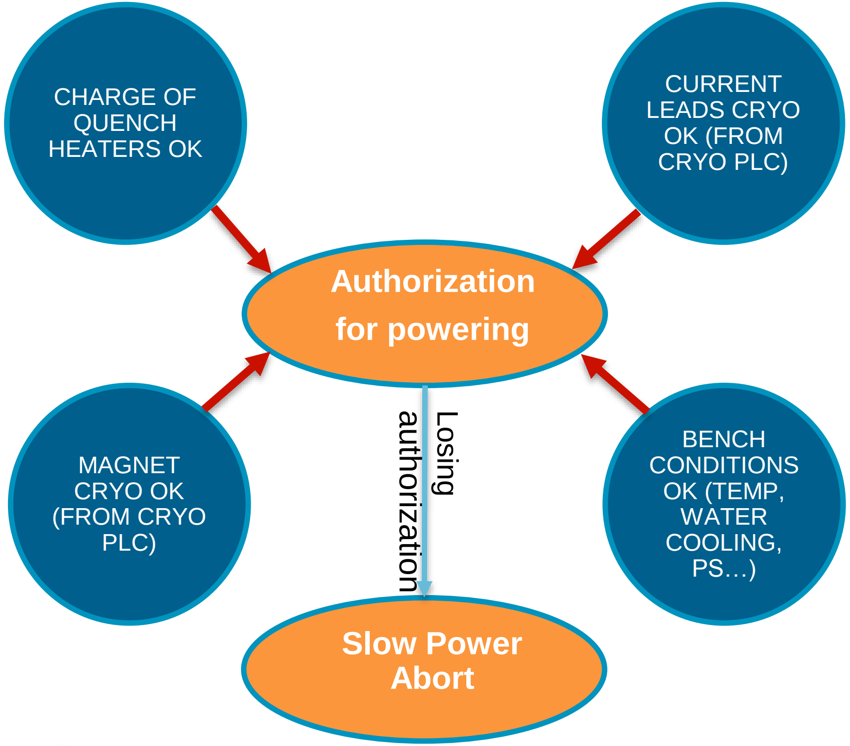
With special thanks for the slides to Max Chamiot-Clerc, Jerome Feuvrier, Maryline Charrondiere, Olivier Ditsch

Magnet test stand workshop, 13 June 2016

Events time line quench protection

- Powering interlocks with programmed logic controllers (PLC)
- Quench detection
  - "Classic" quench protection requirements with voltages (NbTi, Nb_3Sn)
  - Limitations due to flux jumps
  - Developments, mainly for HTS
- Security matrix
- Quench protection
  - Energy extraction
  - Quench heaters
  - CLIQ

Powering interlocks PLC



- PLC SAFETY MANAGEMENT
  - The PLC manage each conditions as a safety interlocks, to provide the authorization to perform a test.
  - In any case of interlocks, it needs a manual acknowledgement to release the interlock.
  - ***Needs to be a reliable programmable logic.***
  - Messages to operator by email/sms possible.

Example of a PLC

CERN experts on PLC present during the SM18 visit

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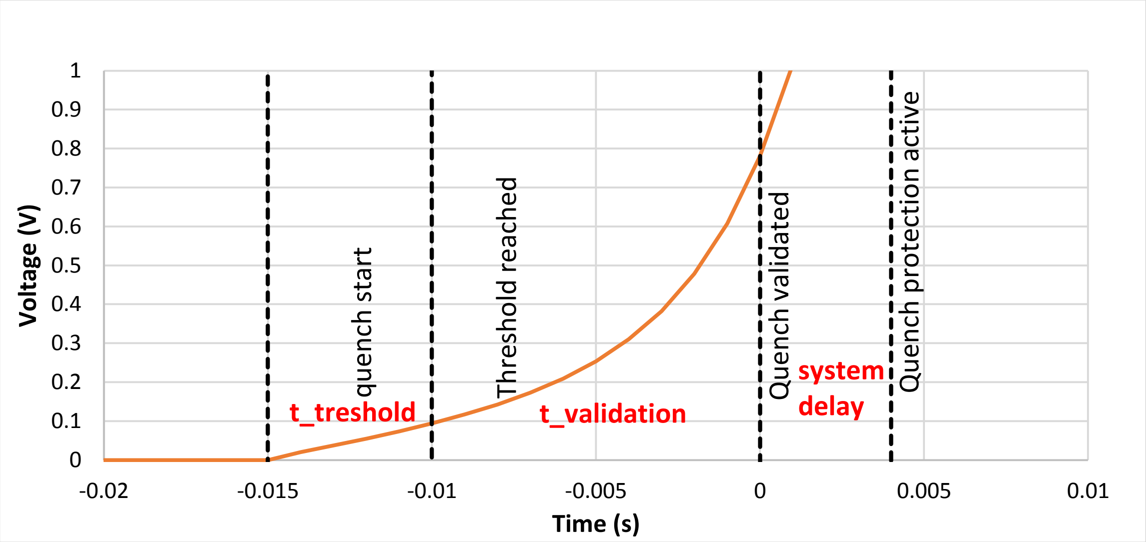
Characteristic times for detection and activitation



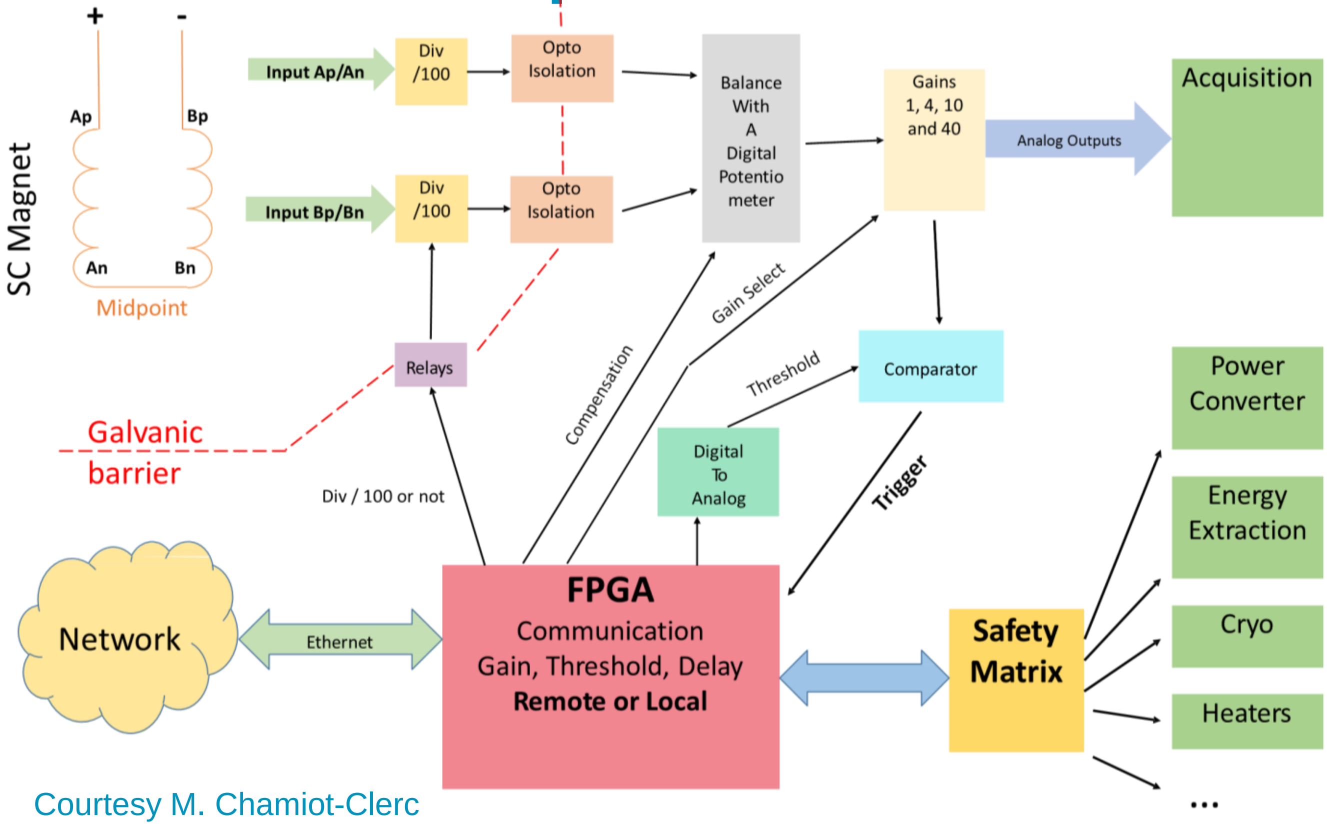
$t_{threshold}$	Conductor related quench propagation and heating effect, field depend, etc.
$t_{validation}$	Noise and fluxjump related, electronics related
$t_{systemdelay}$	Electronics related

Detection: Electronics for quench detection

- From reaching threshold to giving a trigger, the detection cards need 100 % reliability and preferably 0 % false triggers.
- In the CERN test stations the PotAim cards are being used
  - PotAim (Potential Aimant)
  - New developments of PotAim crates is ongoing within the TF section

CERN experts on electronics present during the SM18 visit

Future quench detection in SM18

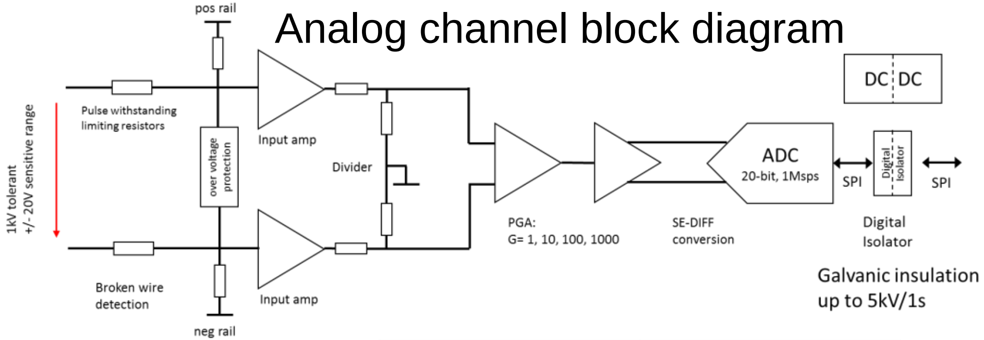


Courtesy M. Chamiot-Clerc

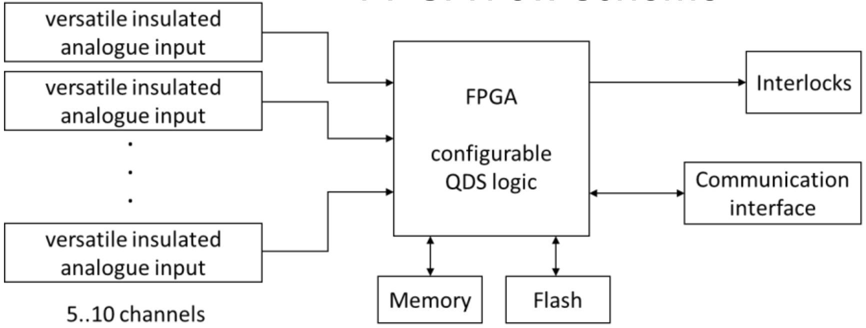
Detection: Electronics for quench detection

- FPGA (Field Programmable Gate Array) is used for the LHC nQPS and in other test stations.
- uQPS in development, can be used for current dependent threshold.

Analog channel block diagram



FPGA flow scheme



Parameter	Value
Sensitive input voltage range	G=1: +/-20V G=10: +/-2V G=100: +/-200mV G=1000: +/-20mV
Max. input voltage	1kV/10s
Resolution	20bit → 40uV/LSB @ G=1
Sampling speed	1MHz
Cut-off frequency	100kHz
ADC latency	1 t_{sample} = 1us
Trigger latency	~1ms
Galvanic insulation	5kV/1s channel/channel/ground
Galvanic insulation method	Isolated DC-DC & digital isolator

Courtesy J. Steckert

CERN experts on electronics present during the SM18 visit

Detection: From NbTi to Nb_3Sn magnets

- Same principles for 11T magnets and MQXF magnets as for the LHC NbTi magnets, ***but***:

- More critical in time budget
- Higher critical current density
- Higher stored energy
- Larger filaments: Stronger flux jumps making Quench Detection more difficult

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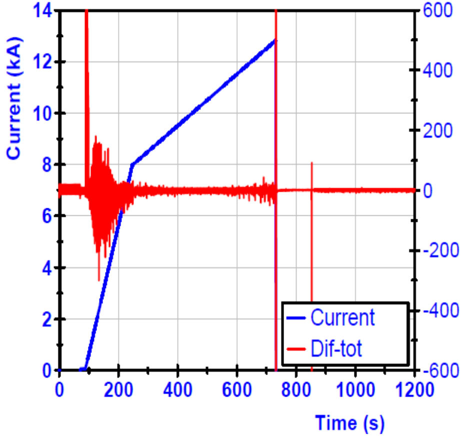
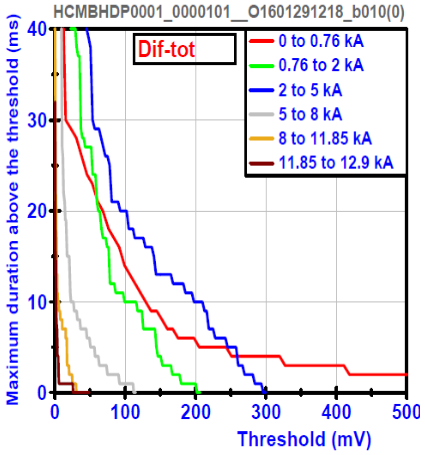
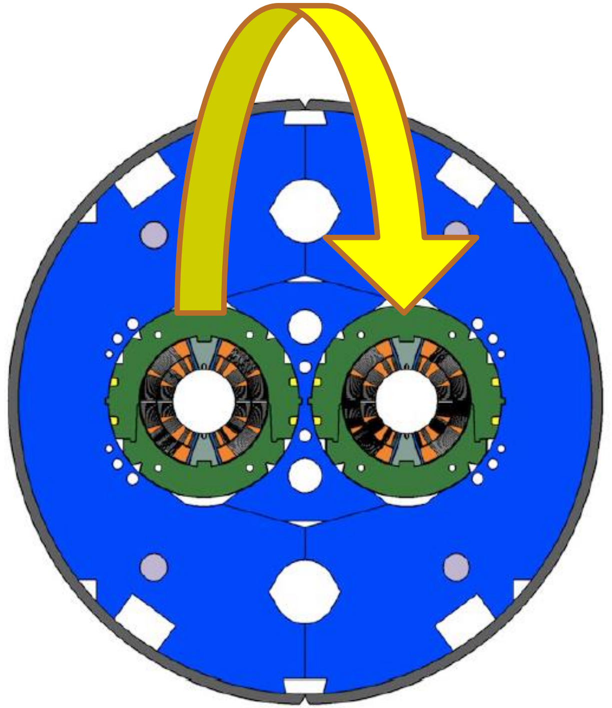
Detection: Validation time and flux jumps

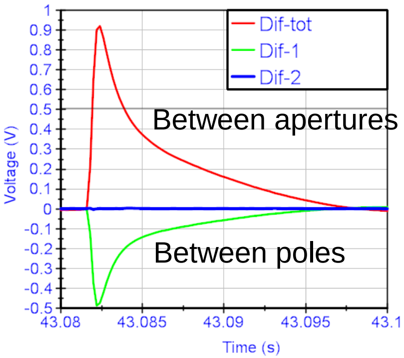
- Typical validation time of 10 ms weighs heavy on time budget and Quench Integral budgets.
- Example DS11T magnet
- Differential voltage signal between apertures (dif-tot)

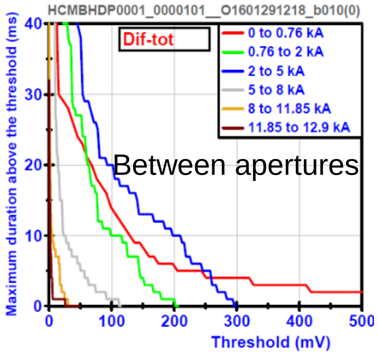


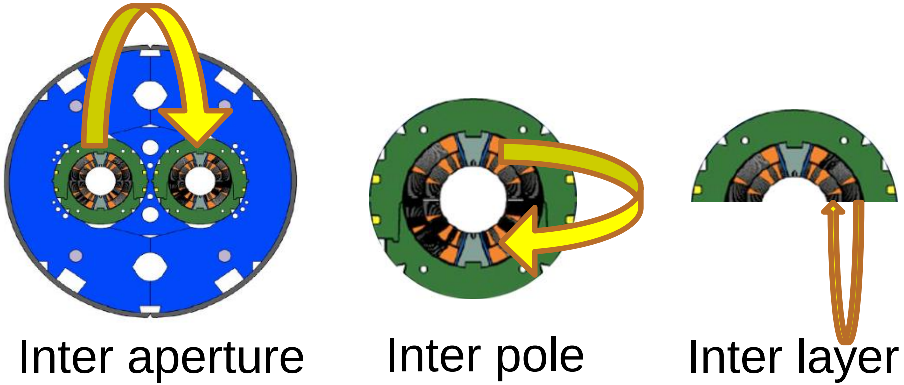


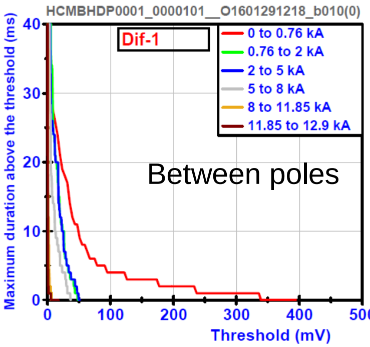


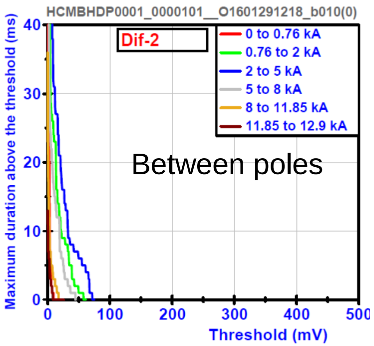
Detection: Fluxjump coupling in 2 meter 11T model









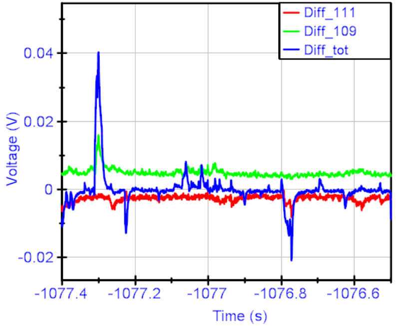


In the MBHDP101 magnet the largest and longest flux jumps measured between apertures and requires current dependent thresholds for 100 mV, 10 ms.

Flux jumps between poles about half the size
Flux jumps between the inner and outer layer again smaller.

Clear coupling of flux jumps throughout the coil.

Important for protectability of the magnets.

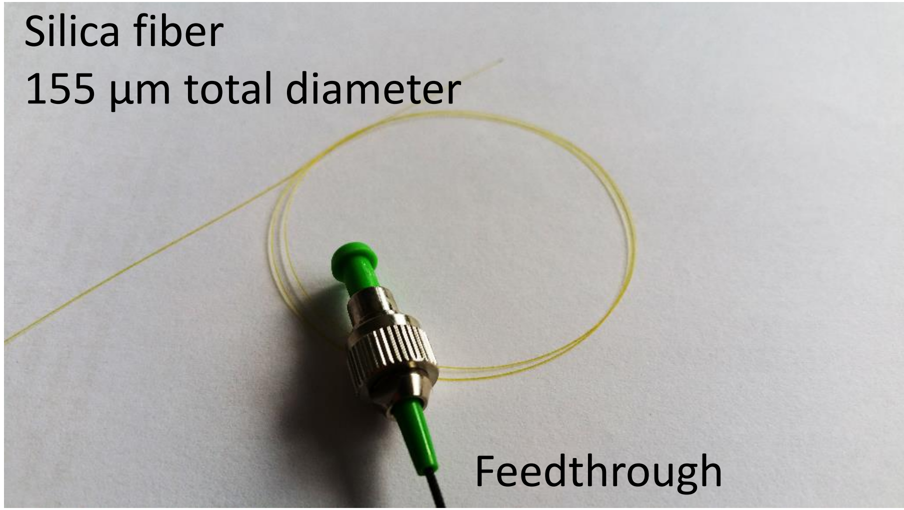


Future quench detection systems

- Classic quench detection with voltage taps is more difficult in HTS due to much slower quench propagation.

- Example: Fiber Optic Sensors under development at CERN

- Distributed sensors for quench detection in SC link and in SC magnets.



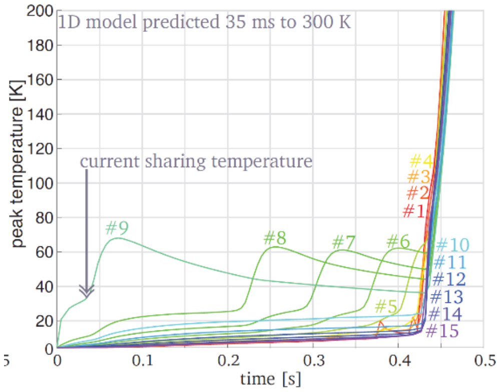
Courtesy A. Chiuchiolo

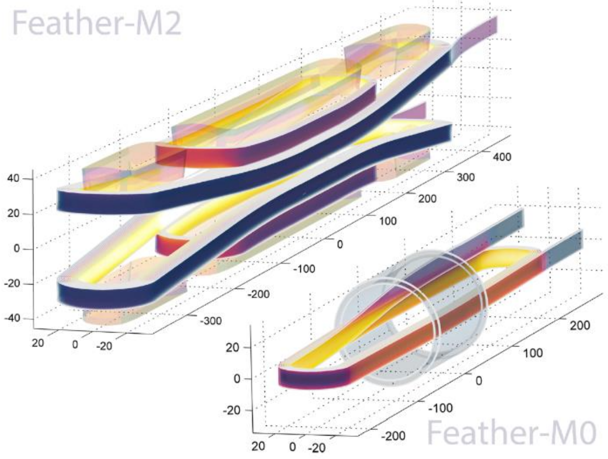
CERN experts on Fiber Optics present during the SM18 visit

Future quench detection systems

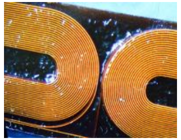
Classical protection:
Max 0.8 mV voltage buildup in the HTS coil, difficult to pick up.

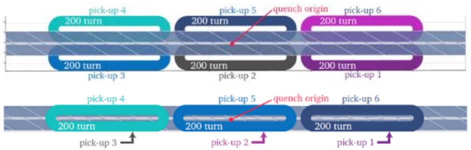
Distributed (parallel) temperature probes on the conductor





Pickup coils on roebel cable.

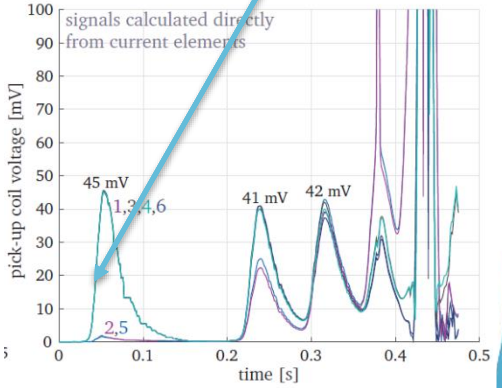




EuCARD2 WP 10 project
Courtesy G. Kirby and J. van Nugteren

5 Tesla stand alone, (18 T in 13 T background)
Roebel type ReBCO cable
40 mm aperture
10 kA class cable
Accelerator Field quality
@ 4.5K

Early quench detection



For now these are calculations, but may well become reality in the future

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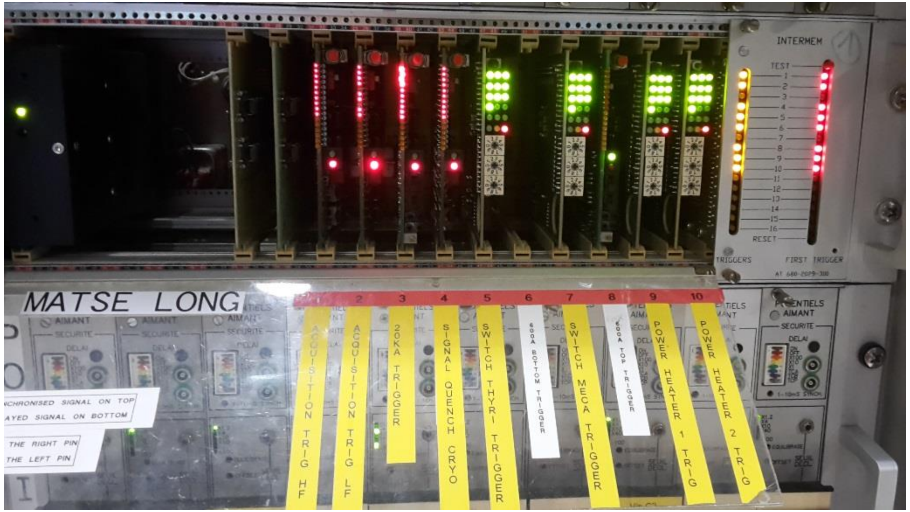
Security matrix

- All triggered PotAim cards are connected through the Security matrix that will activate the protection units.
- One of the recent upgrades in the security matrix is easier setting of delays for protection studies.
- Redundancy in triggers is important.



CERN experts on electronics present during the SM18 visit

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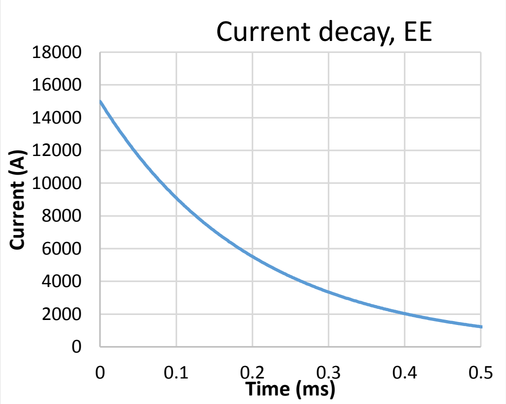
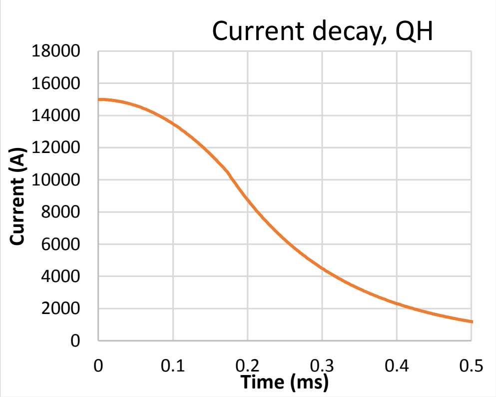
Protection: Overview CERN test benches

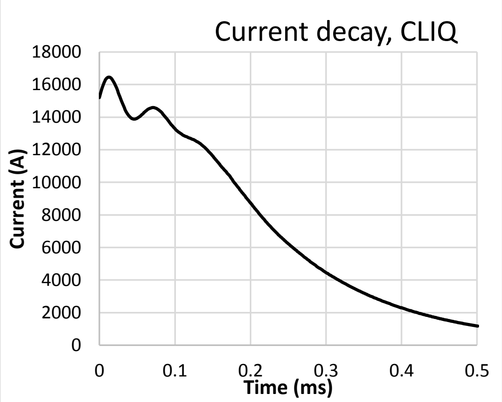
		Active protection		
	Detection	**Energy Extraction**	**Quench Heater discharge**	**CLIQ**
Horizontal benches, A, B, C, E I_max = 15 kA	PotAim	None	Available	Used, but not standard
Vertical bench Cluster G, I_max = 20 kA	PotAim	Thyristor	Available	Used, but not standard
Vertical bench Cluster D, I_max = 30 kA	PotAim	IGBT	Available	Equipped

Quench protection: de-energize magnet

- Switch off power converter (possibly with a crowbar)
- Activate the Energy Extraction (EE) switch
- Discharge capacitive charge in Quench Heaters (QH)
- Discharge capacitive charge in coils (CLIQ)
- *A combination of the above actions is quite common.*







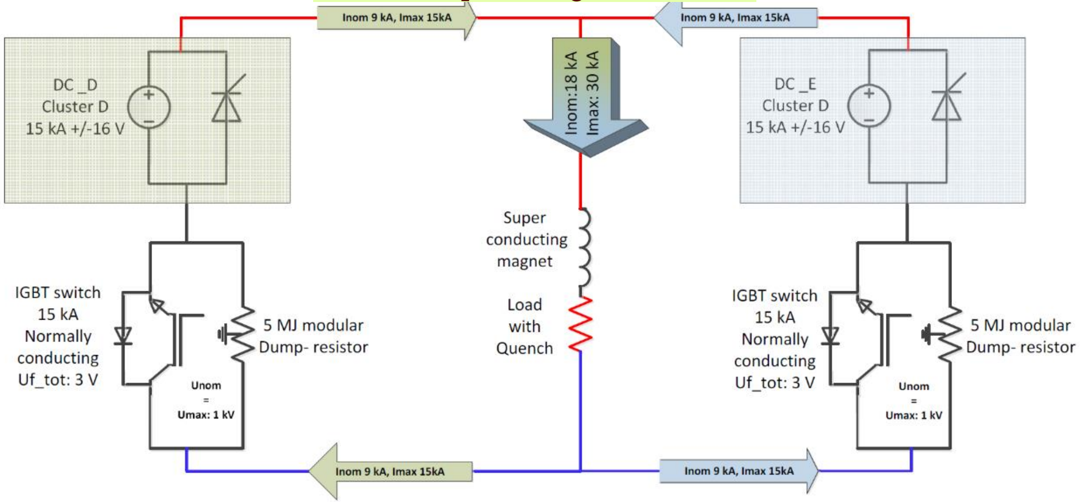
Protection: Energy extraction

- Thyristor switch with modular dump resistance (5 to 120 mOhm) operational since a long time on the vertical benches at 20 kA.

- New technology foreseen for cluster D with 2 times I_{max} = 15 kA.
- IGBT switch is already succesfully applied at BNL.

- In general the limitation for the energy extraction is the maximum voltage over the switch. 1 kV for Thyristor and IGBT switch.

Cluster D powering schematics



Courtesy GJ Coelingh

CERN expert on Energy Extraction present during the SM18 visit

Protection: Quench heater

- On all SM18 benches four 900 V (± 450 V, 2*14 mF in series) heater discharge power supplies are present, type HCDQHDS type.
- In recent years the QH interface has been upgraded for better discharge current reading up to 150 A.
- Electronics delay between trigger and heater firing is about 4 ms. This is due to be reduced in view of the coming Nb_3Sn magnets.

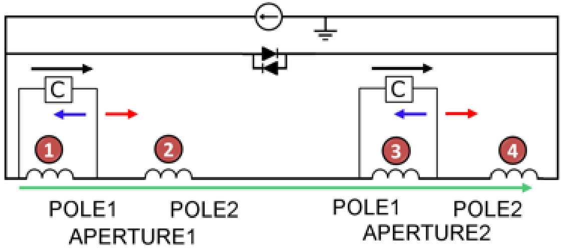
QH interface crate, by M. Chamiot-Clerc

Heater discharge power supplies

CERN experts present during the SM18 visit

Protection: CLIQ in the test station

Experience gained with early prototypes of CLIQ in the vertical test facility on several magnets
- MQXC, MQY, HQ



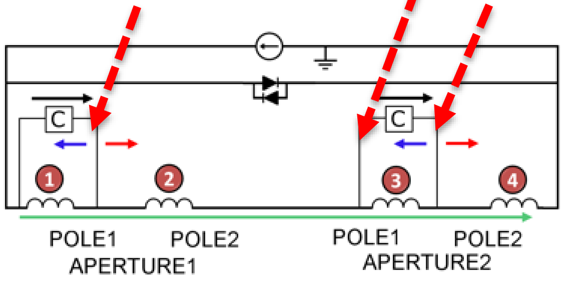
Adaptations to the test facility are quickly done.

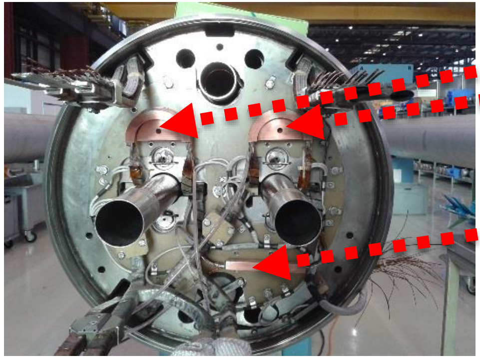
- place a string of diodes across the power converter in inverse direction. (V_{fw} about 20 V)
- Only a few small current feed-through are needed (~10 mm^2 Cu)
- Trigger signals should arrive in CLIQ box
- Connect CLIQ to Interlock

In 2015 a spare LHC main dipole was tested with CLIQ protection only!!

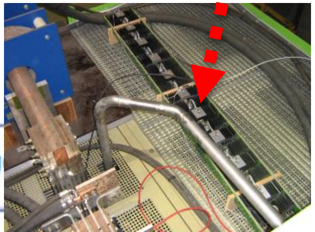
Protection: Validation of CLIQ on an LHC main dipole

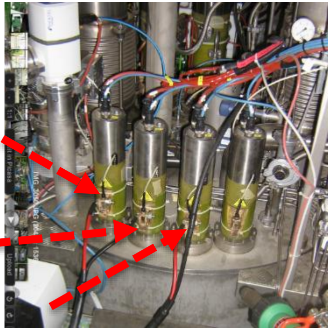
With Emmanuele Ravaioli, Alejandro Fernandez Navarro





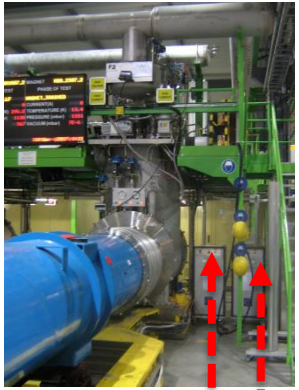
Diode string





Inside the magnet 3 CLIQ leads are connected by the spool pieces, making an easy connection to the 600 A leads on the test station.

The 4th warm CLIQ lead is connected to the main 13 kA current lead.



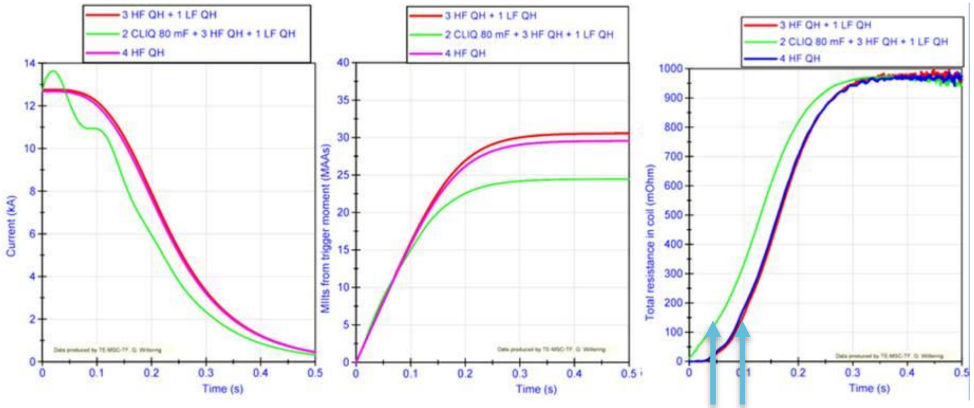
Two first industrial quality CLIQ units tested before shipment to FNAL

About 10-15 m long cables connected to the 600 A current leads

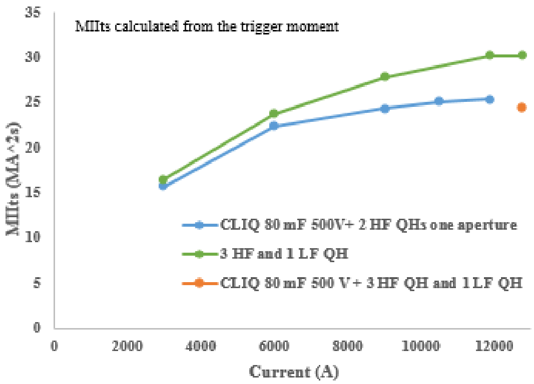
2 CLIQ units of 80 mF, 500 V

Protection: Validation of CLIQ on an LHC main dipole

- With CLIQ added at high current the current decay was much faster.
- An LHC spare dipole only protected by a 2-CLIQ system,
- Non-optimized CLIQ unit, therefore no reduncancy in case of failure of one of the two.
- The CLIQ units were tested before shipment to FNAL.



Shift in magnet resistance buildup of about 35 ms in favor of CLIQ compared to QH



CERN experts on CLIQ present during the SM18 visit

Protection of leads

Detection settings in the magnet:

100 mV, 10 ms for the magnet

8 mV, 10 ms for leads (Low Field, slow propagation, well cooled)

What can possibly go wrong??

Just an example of issues in the last years

1. Too high resistance of a clamped connection resulting in quench.
   Protected at 8 mV, 10 ms detection, but it limited the test of the magnet.
2. Too small NbTi current lead interconnecting coils in Nb_3Sn magnet
   Results in melted current lead.
3. Loss of helium level – lack of slow power abort interlock – detection failure:
   Resulted in a melted current lead

logo area

Thank you

SM18 Visit program Tuesday afternoon

13:40 – 14:20 A general tour through the magnet test facility will be given, giving an overview of the test facilities.

14:20 – 15:40 The workshop participants can walk freely in a part of the test facility and experts from CERN will be present on many locations in the hall. In some cases they will be able to show equipment and in other cases posters. Excursions into the test zones are possible to see the test station from close by.

There will be many experts and topics like

PLC/hardware security	Horizontal test bench operation	Power converters
high-current switches	Cluster D integration	Cryostat cluster D and HFM Inserts
Analysis and control	Feedbox for Sclink	Cryogenic infrastructure
Optic fibers	Electronics for protection,	Cryogenic design of inserts and CFBs
Mechanical measurements	LN_2test station	Data acquisition
Magnetic measurements/shafts		

We hope this part will give a lively and detailed discussion between experts in the field from the various test facilities.

15:40-16:40 In the upstairs meeting room **coffee** is available and there is place available for further discussions.

16:40 the workshop will close out with the preparation of the action list and a close-out session.

Visit program Tuesday afternoon