REVIEW OF QUENCH DETECTION METHODS IN SUPERCONDUCTING MAGNETS

Felix RODRIGUEZ MATEOS
CERN, Geneva

3rd Workshop on Accelerator Magnets in HTS
(WAMHTS-3) , LYON (France) , Sept 11, 2015

OUTLINE

- Short recall on quench detection factors
- An overview on quench detection methods
- ITER and LHC: some relevant aspects from their quench detection systems
- Conclusions & Outlook

Short recall on quench detection factors

Factors playing a role in quench detection from an electronics designer point of view

- Detection level and Time (integration, validation, reaction)
- Sensitivity and accuracy, bandwidth
- Environmental conditions (magnetic induction, radiation)
- Perturbing signals – noise, e.m. coupling
- Rejection and compensation
- Appropriate signals – cabling, routing, compensation at source
- Voltage withstand, separation and common mode rejection
- Reproducibility
- Dependability
- And above all: simplicity
- And above all (2): have good diagnostics and remedy tools

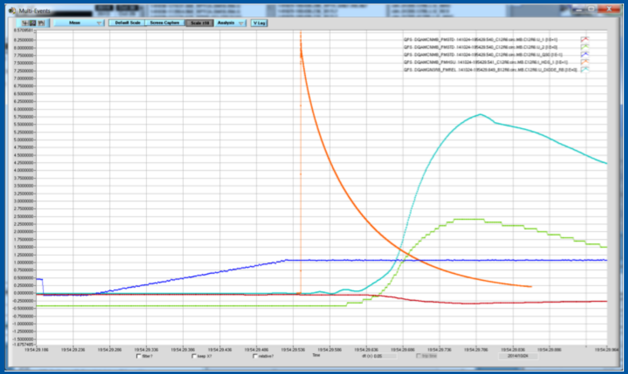
Factors playing a role in quench detection from a magnet designer point of view

- Volume and magnetic field, inductance and current
- Superconductor margins (*B, J, T*)
- Enthalpy at low temperature (stabilizer)
- T limit at quench for integrity (how good do we know the real limits of our magnets?)
- Voltage limits to ground and internal (idem)
- Frequency of quenches
- Thermal cycling
- Aging and fatigue
- How to instrument the coils and the bus bars and the leads in compatibility with design? (and with proper quench detection)?

And later, the role of a quench detector

- Trigger if needed
- Not trigger if not needed
- Don’t wait too long
- But make sure it’s a quench
- … And please send a clear picture of what happened

Bill Fontana, © CERN



Courtesy MP3, CERN

Listening to magnets sounds like fun!

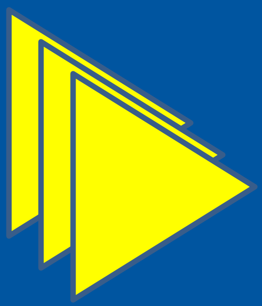
M. Marchevsky @ WAMSDO 2013

The building blocks for quench detection

Instrumentation

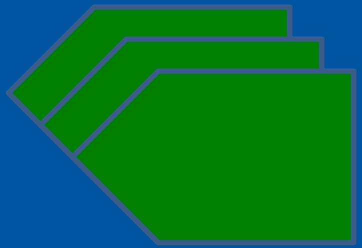
+

Analog inputs



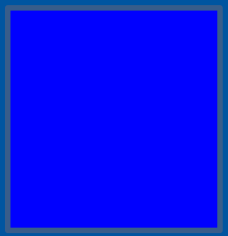
Analog front end, filter, attenuate/amplify/level/shift signal to fit ADC requirements.

ADC(s)



Analog to digital conversion. Resolution 16..24 bit. Key component in design.

Logic Device



Logic device. Performs quench detection algorithm:

- Filtering
- Inductive compensation
- quench detection

Includes interface to local crate controller.

Actuator(s)

Actuator reacts when quench is detected Usually current loops are cut. Different implementations with relay (slow) PhotoMOS (fast).

***Jens Steckert**, Reiner Denz (CERN), CAS Poster*

An overview on quench detection methods

A (non-exhaustive) list of methods

- Electromagnetic (the art of compensation)
  - Potential measurements (direct contact, taps)
    - Balanced bridge (quasi-cancellation)
    - Differential (*dI/dt* compensated)
    - Co-wound tape (self-compensated)
    - MIK (“fully” compensated)
  - Magnetic measurements (no direct contact)
    - Quench antenna
    - Hall sensors
  - Mixed methods (no direct contact)
    - Poynting’s vector
- Thermal (direct) and thermo-hydraulic (indirect)
  - Direct coil temperature (e.g. optical fibers)
  - Coolant temperature, pressure, flow
- Mechanical
  - Acoustic emission

(see talk by Dr. Kawagoe-san)

(see talk by Pr. Schwartz)

(see talk by Dr. Marchevsky)

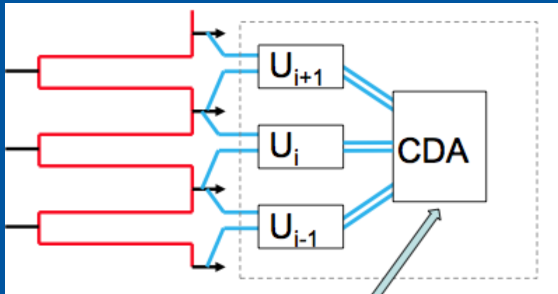
Basic Memento on QD voltage methods (1)

Balanced Bridge

$$U_{res} = U_1 - U_2$$

Differential, compensated

$$Ures = Umag + L * dI/dt$$



$$U_{CDA} = U_i + \frac{U_{i+1} + U_{i-1}}{2}$$

Central Difference Averaging

Principle of compensation

$$U_{measured-i} = L\frac{dI_i}{dt} + \sum_{k=1}^{k=nb\ magnets} M_{ik}\frac{dI_k}{dt} + I_i . R_{Quench}$$

$$U_{measured-i} = U_{inductive} + U_{resistive}$$

Quench : 0.5 V

Operation : 10 kV

MIK

M.A. Hilal et al., 1994 (see ref.)

Basic Memento on QD voltage methods (2)

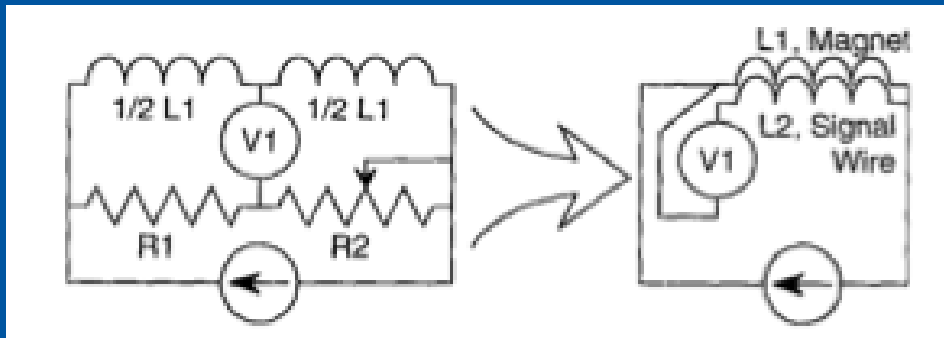
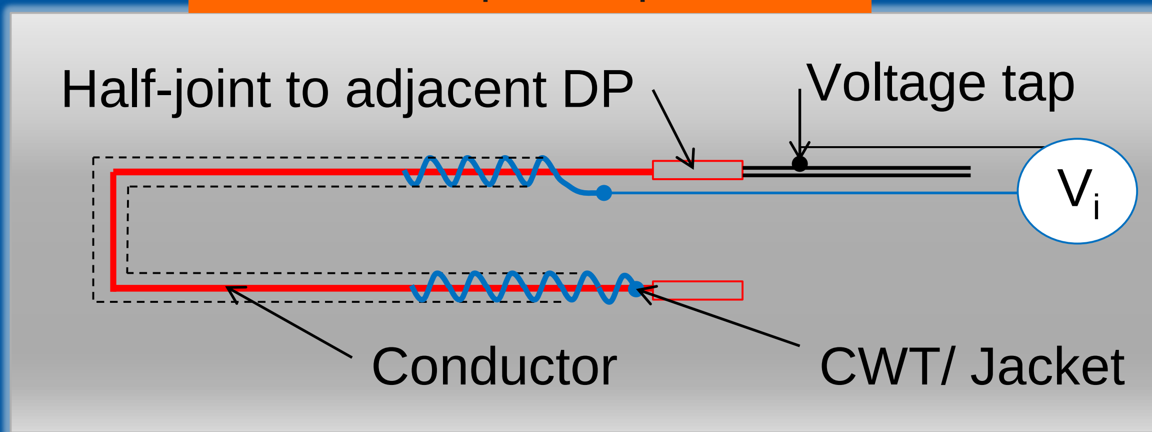


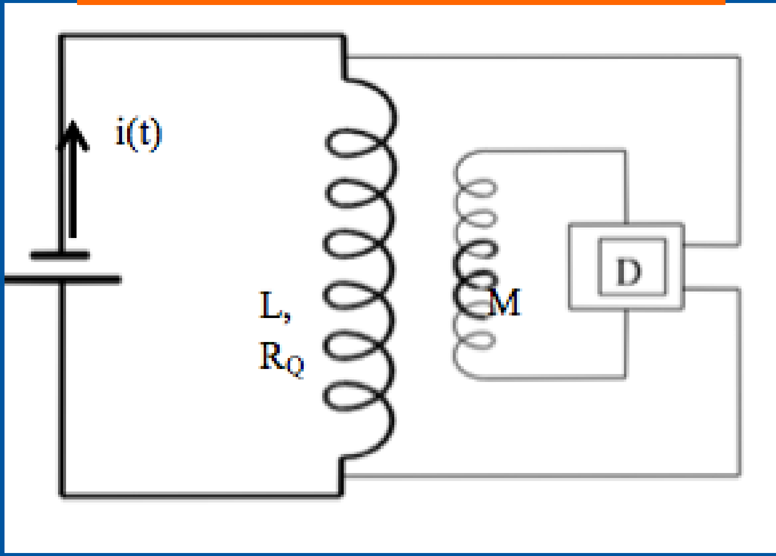
Fig. 1. Balanced-Bridge & Co-Wound Sensor Quench Detection

Co-wound tape compensation



Basic Memento on QD voltage methods (3)

Pick-up coil/quench antenna

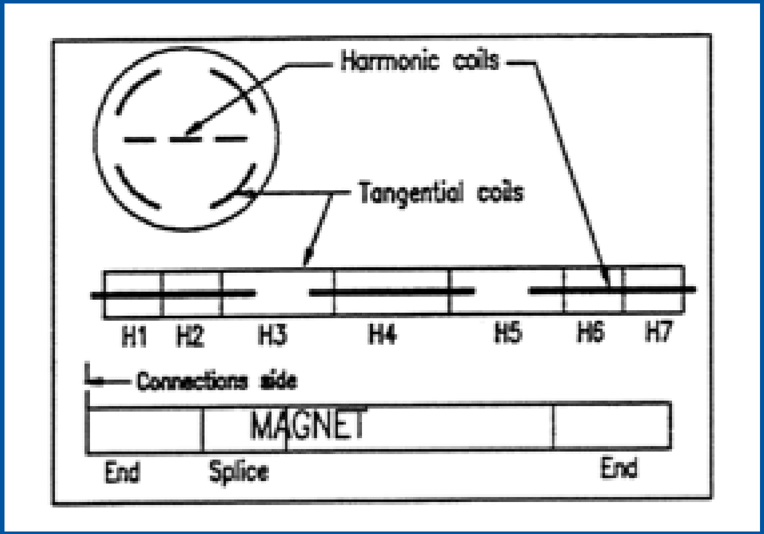


$$V = L * \frac{di}{dt} + I * R_Q - M * \frac{di}{dt}$$

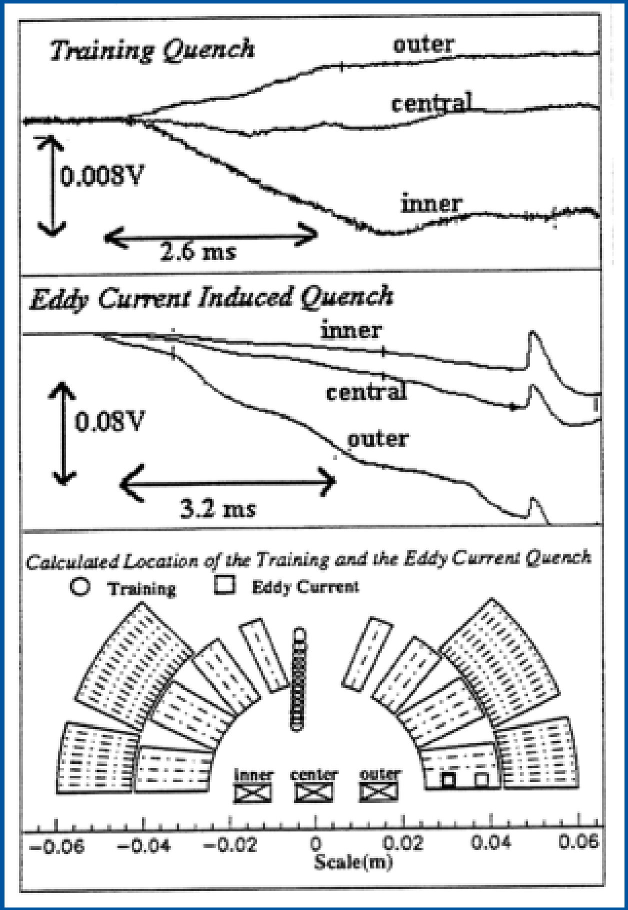
1. When L=M, the voltage is not a function of di/dt anymore
2. It is equivalent to the CWT when the pitch is adapted to cancel out the difference of radius

Basic Memento on QD voltage methods (3bis)

Pick-up coil / quench antenna



Pick-up coils within the coil bore

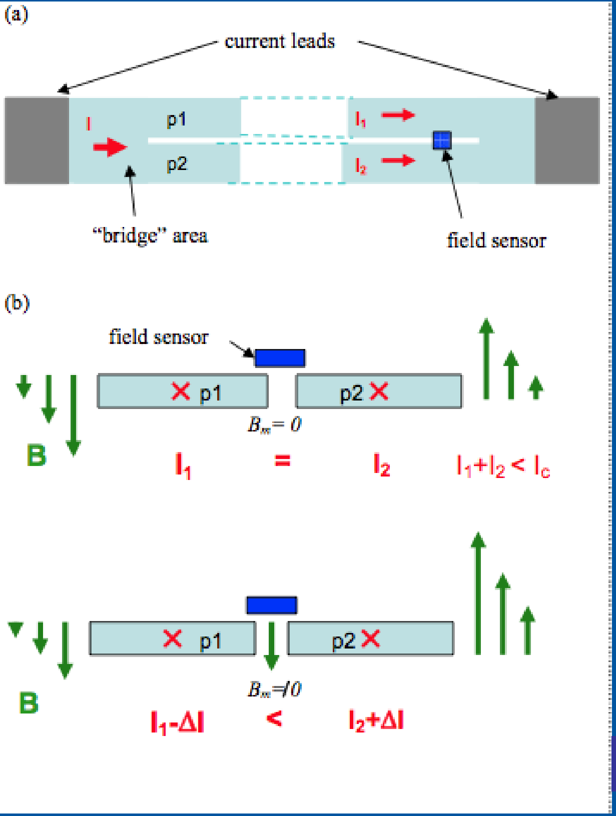


Sensitivity / timing performance

D. Leroy et al. (see ref.)

Basic Memento on QD voltage methods (4)

Hall Sensor



Current balance detector applied to 2G HTS wires
Hall sensor sensitivity is $7 \cdot 10^{-5}$ V/Gauss

M. Marchevsky et al. (see ref.)

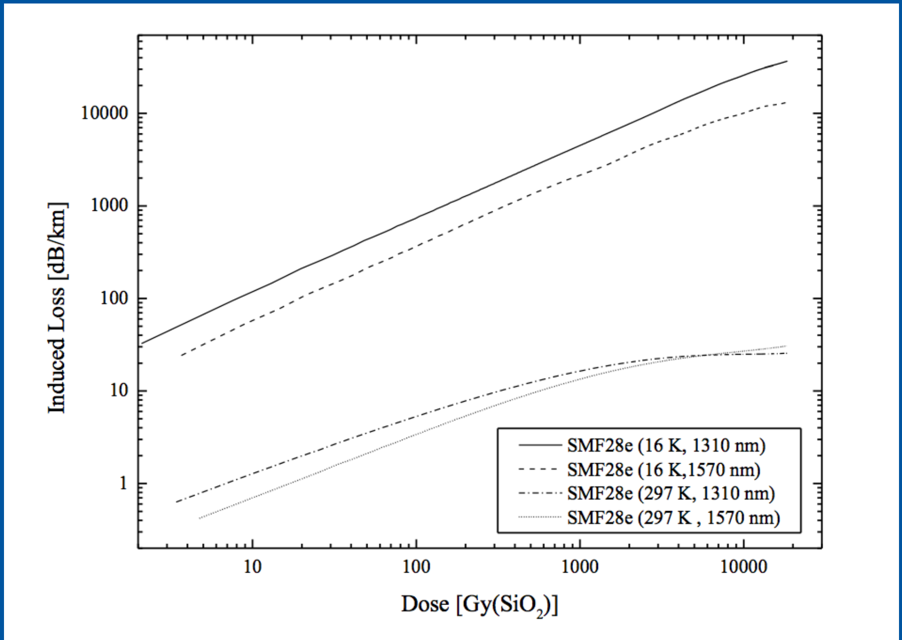
1. Signal to noise ratio improved by factor of 100 compared to voltage measurements
2. Detection works also for pre-quench conditions (thermal degradation of the critical current by application of heat pulses)

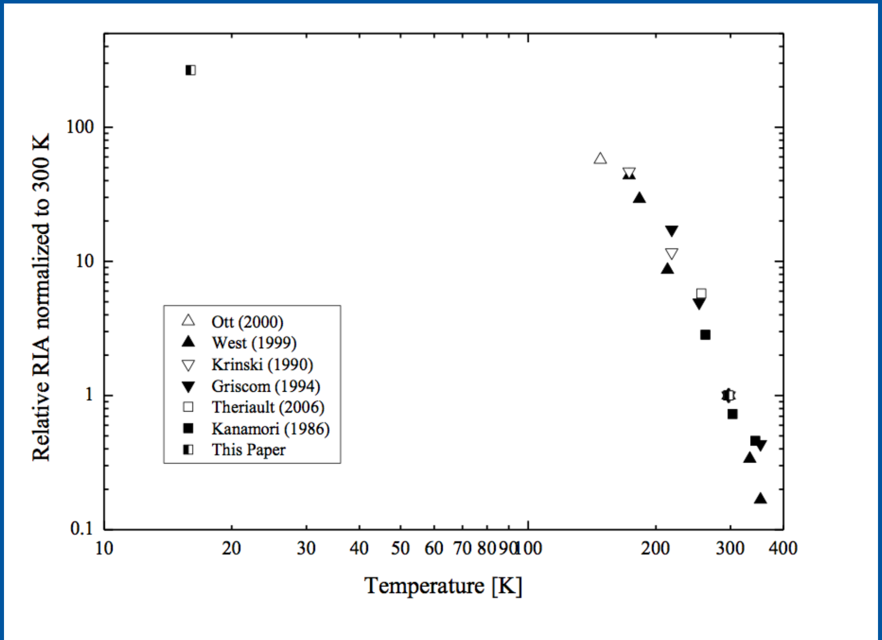
Optical fibres and acoustic emission

Very briefly, two talks on these subjects by world experts!

Radiation aspects in optical fibres

J. Kuhnhenn et al., see references



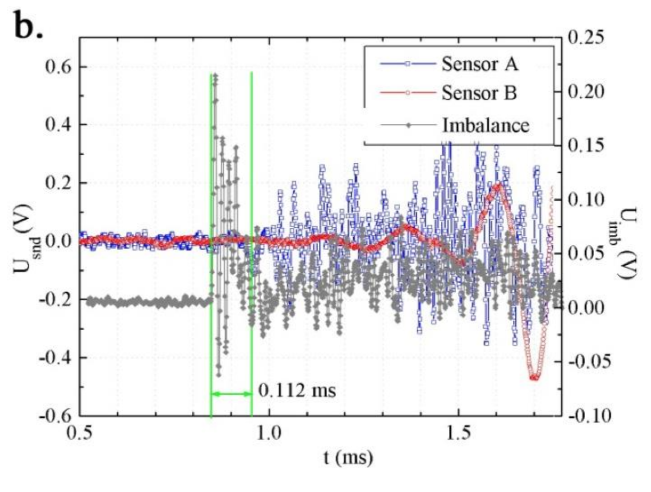


- Irradiations done at the TK1000A Co-60 gamma facility at Fraunhofer Institute (Germany)
- Tests on Ge-doped fibres at 1312 nm and 1570 nm
- For 1312 nm, loss was 2.6dB (100m) at room temperature while 36.6 dB (1 m) at 16K. Even for small lengths of fiber the attenuation is dramatic
- First time results of irradiation done at T down to 16 K have been presented

Acoustic emission

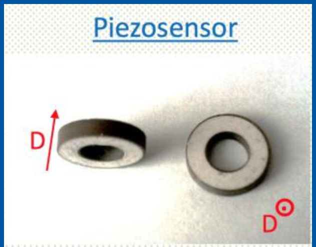
Slide with inputs from M. Marchevsky, WAMSDO, CERN, 2013 and M. Marchevsky et al., see references

I=10036 Ain LARP HQ01



Advantages of sensing sounds for magnet diagnostics:

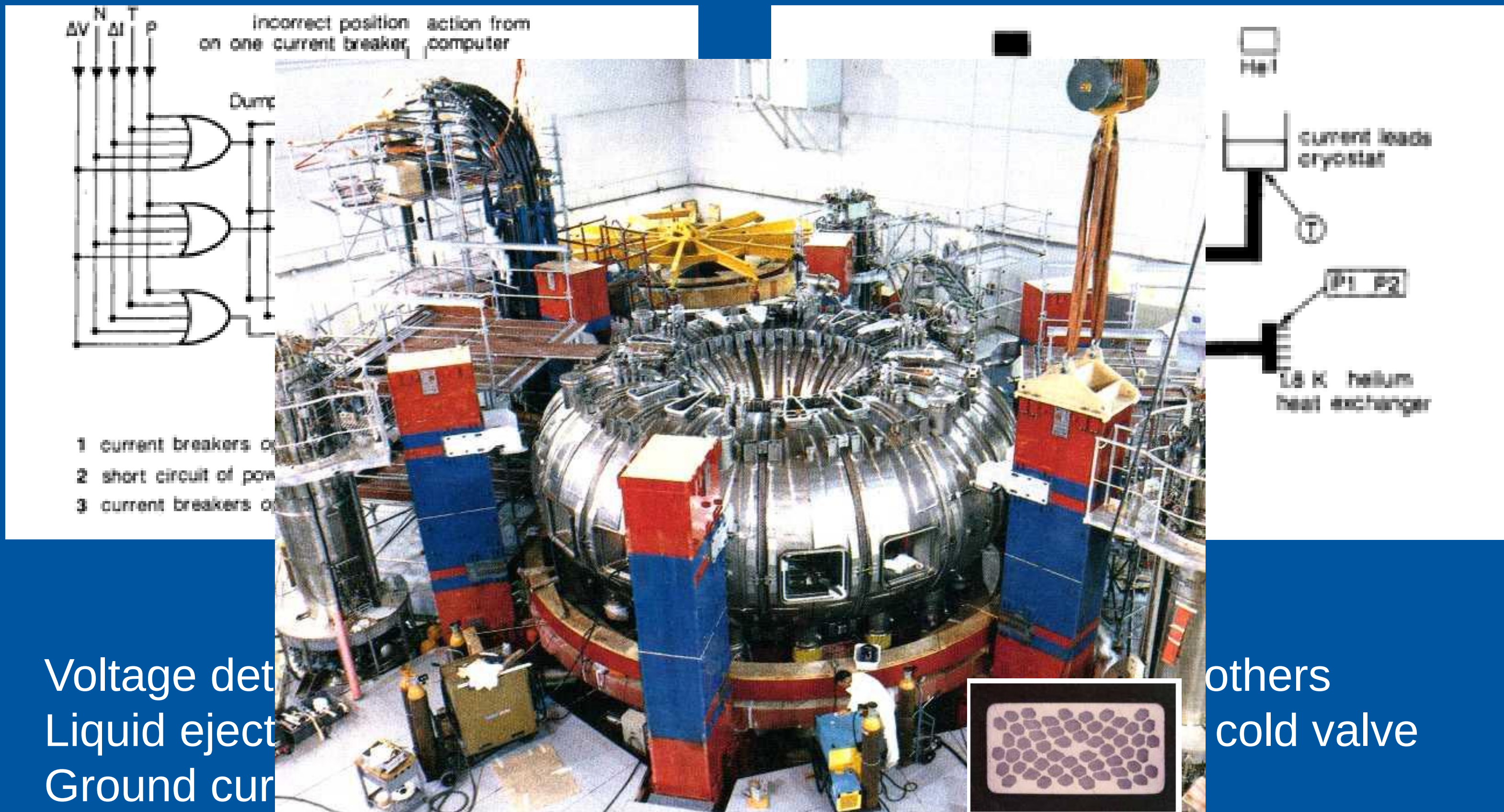
- Propagation velocity is large (several km/s), so that detection can be accomplished on a time scale that is comparable (or faster) to other techniques
- Using sensor arrays, sound sources can be localized with a few cm accuracy through triangulation
- Selectivity for different kinds of events, through frequency and phase analysis
- Outer surfaces sensor mounting for non-intrusive detection
- Immunity to magnetic fields
- Sensors and acquisition hardware are relatively inexpensive, portable and easily adaptable to various magnet configurations



"Further development of the acoustic technique is needed, focusing on improving sensitivity and selectivity to small signals, developing instrumentation and software for precise localization of the sound sources and quantifying energy release in the detected acoustical events"

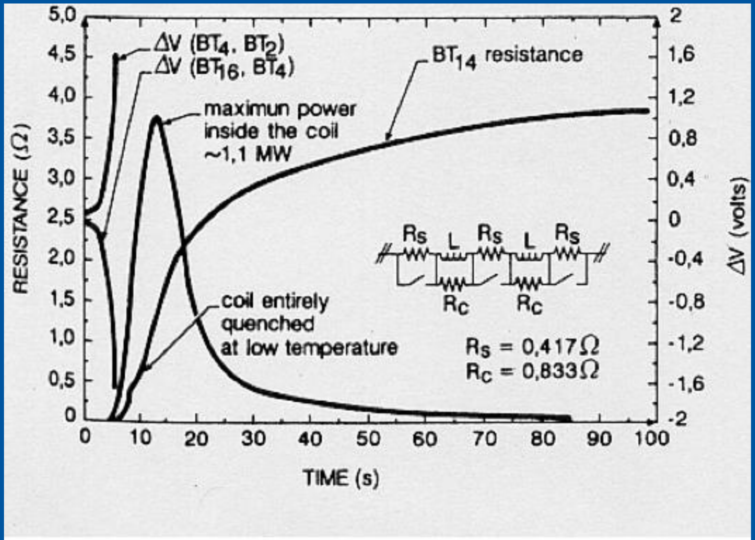
Thermo-hydraulic quench detection

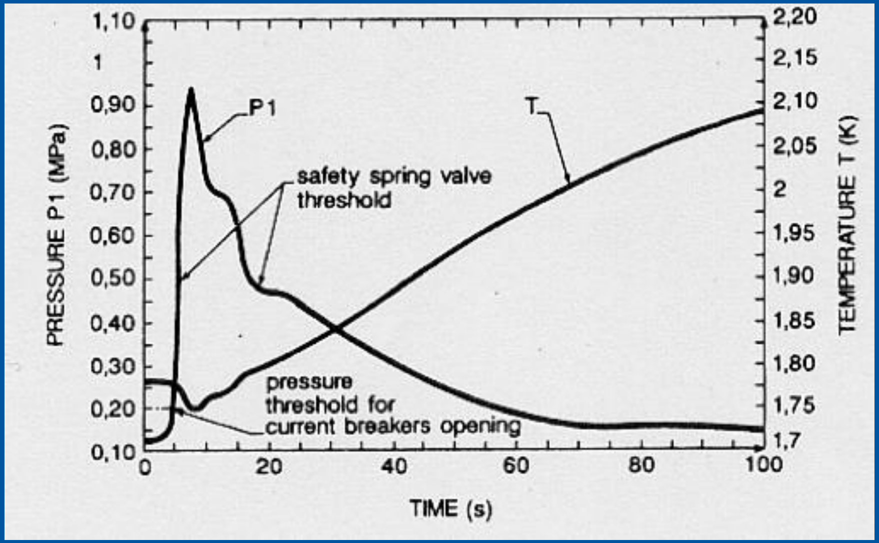
The case of Tore-Supra



Voltage det… others
Liquid eject… cold valve
Ground cur…
Temperature (T)
Over-pressure detection (p) Two p sensors in 1.8K ensure fast detection

A quench in coil BT4 . . .





Detection thresholds

	V Voltage (V)	P Cold pressure (Pa)	N Cold Liquid In cold valve region (K)	T Temperature near Current lead cryostat (K)	I Ground current (A)
Thereshold level	<2.	<2. 10^5	>1.95	<2.05	50.
Time delay (s)	1.	0.5	2	2.	0.5

channel	V	P	N	T	I
Detection time [s]	1.	0.	0.8	81.6	16.9

Chronology of detection

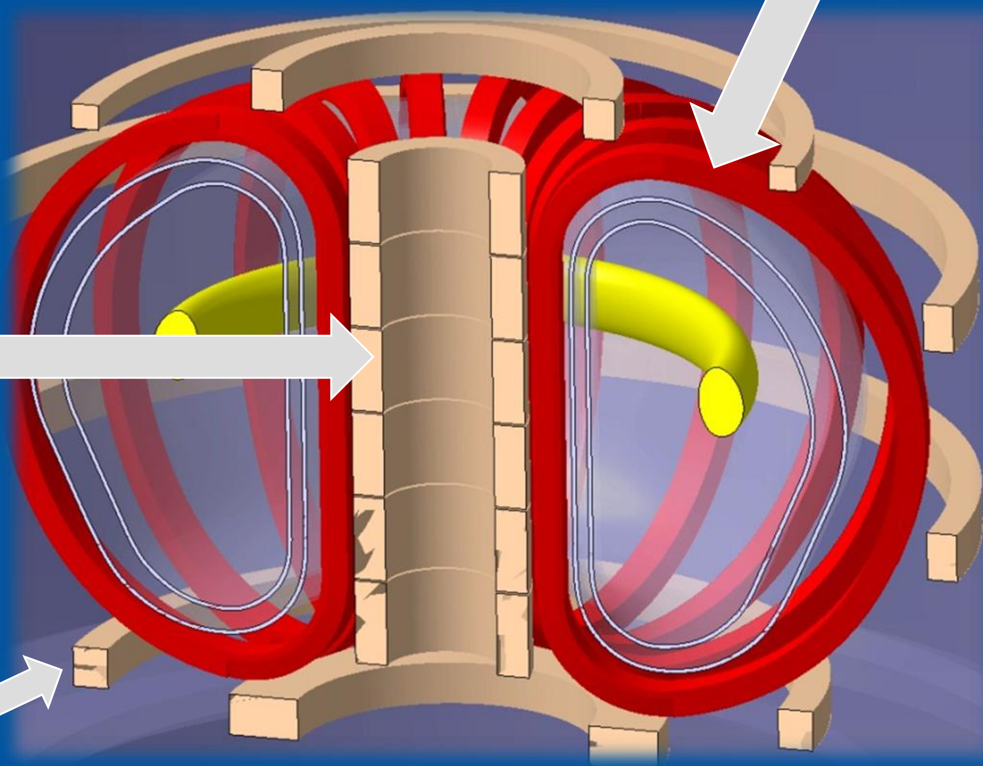
J.L. Duchateau et al., see references

Quench detection in ITER

Methods case study : the ITER QDS

MAIN MAGNETIC SYSTEMS OF THE **ITER** MACHINE

TF



CS

PF

Perturbations inherent to a tokamak like ITER

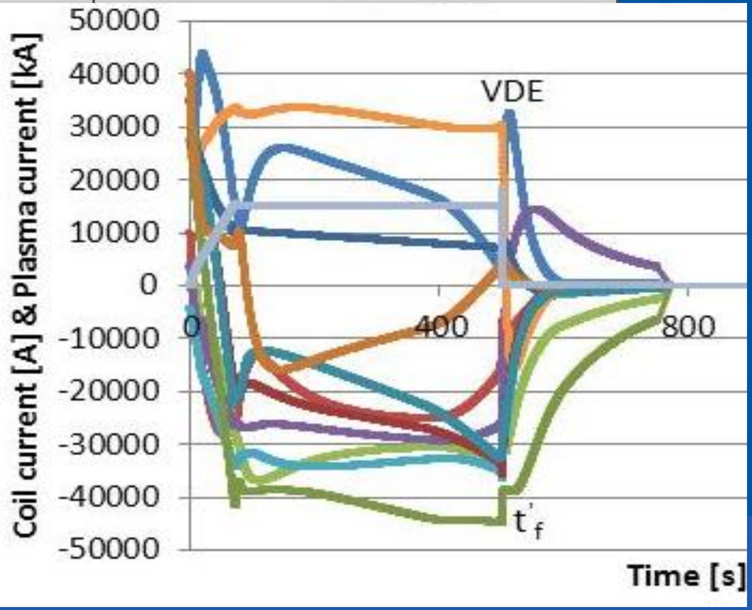
- The plasma is shaped and confined by magnetic fields
- Strong coupling between a) pulsed magnet systems, b) plasma and magnets, and c) structures and magnets

CS Module	11 kV	Normal operation	Induced/applied
TF coil	4.0 kV	In fast discharge	Induced/applied
PF coil	9 kV	During plasma event	Induced/applied
Quench	0.5 V	Typically	**Resistive**

The quench voltage must be distinguished among the time-dependent outweighing inductive signals:

holding time τ_h **> perturbation time**

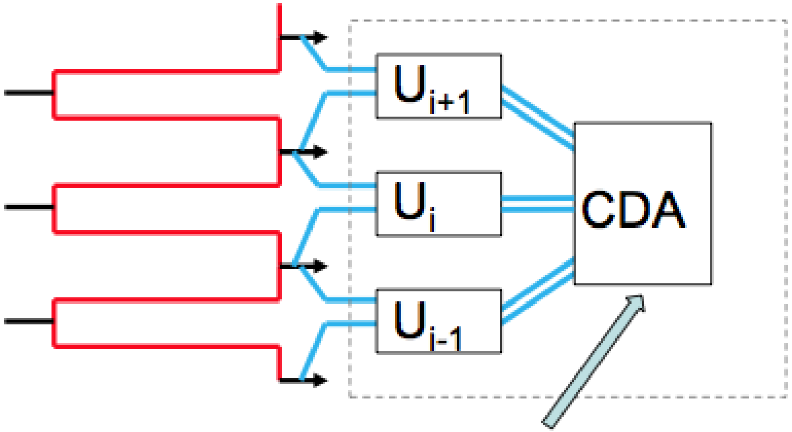
Quench detectors trigger a Fast Discharge in all three systems (TF, PF and CS)



CERN

QD principles applied for ITER's CS

Measurements on CS :



$$U_{CDA} = U_i + \frac{U_{i+1} + U_{i-1}}{2}$$

Central Difference Averaging

Measurements on power supplies :

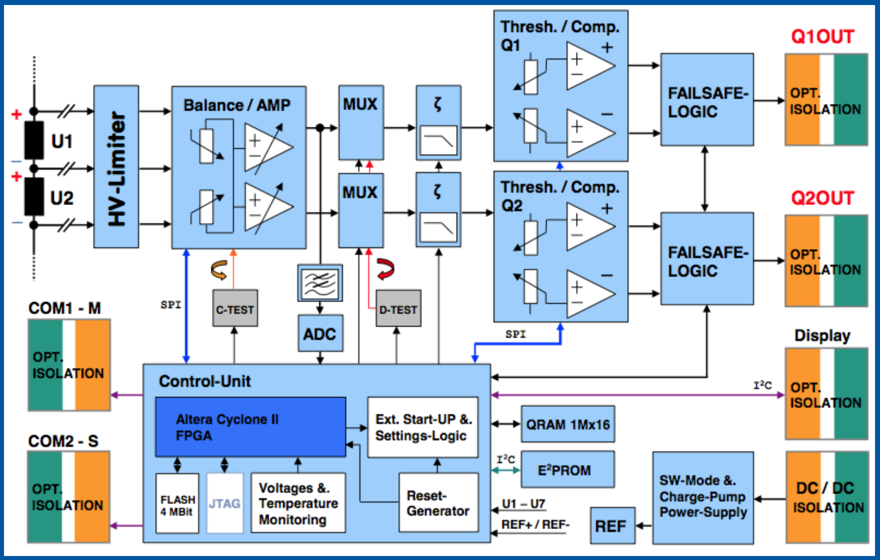
Each of the 12 CS/PF coils: $\frac{di(t)}{dt}$

(Rogowski coils)

$$U_{MIK} = \begin{bmatrix} inductance \\ matrix \end{bmatrix} \begin{pmatrix} di_{PF1}/dt \\ di_{PF2}/dt \\ \vdots \\ di_{CS2L}/dt \\ di_{CS3L}/dt \end{pmatrix}$$

$$\Delta U_Q = U_{CDA} - U_{MIK}$$

Potential separation to ground: an example



KIT- Quench Detector UNIQD Type 3420 (sealed / unsealed)

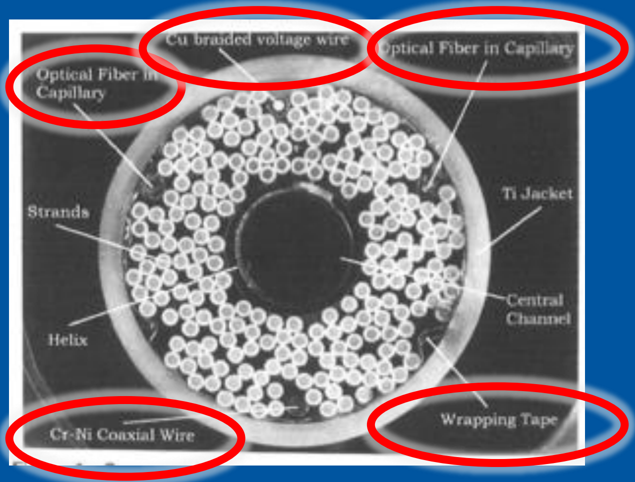
- Integrated FPGA design
- Fully floating, separation given by the DC/DC converter
- Remote interface control
- High flexibility (parameterization, calibration, diagnostics)
- All-in-one Windows®
- Interface for remote control by host

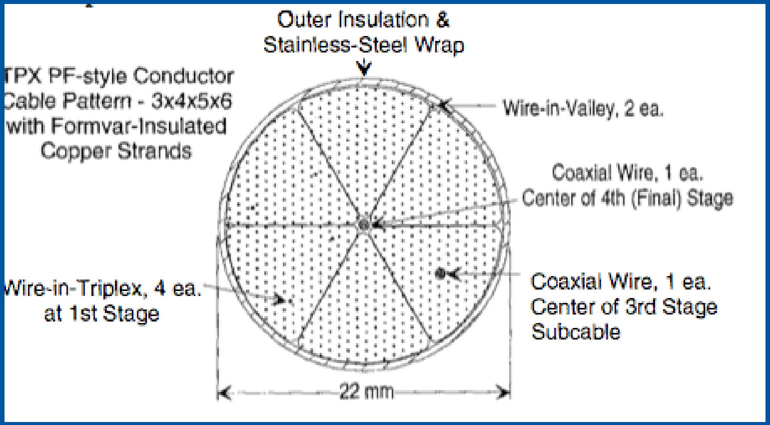
Potential separation to GND up to 30 kV
Maximum differential input 500 V
Threshold down to 5 mV

Courtesy K. Petry (KIT)

Patented in EU by KIT

More on noise rejection





QUELL @ CRPP, CH

- CWT has the higher rating as a quench detector in CICC (400 times better NR than standard taps)
- Internal T detection by optical fibres provides a reliable method
- Extraction of sensors was not problematic
- Thermo-hydraulic detection are not recommended in CICC applications

S. Pourrahimi et al., see references

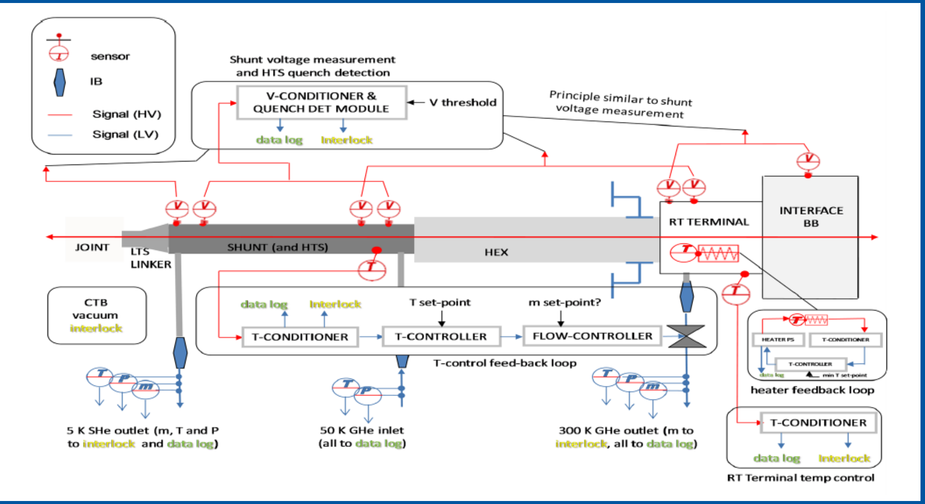
NRE @ LLNL, USA

- NR factors better than 10^4 for transverse fields were obtained, depending on positions of the CWT and pattern of fields
- Final recommendation was to use a CWT at the center of the first stage of the cable (triplex)

N. Martovetsky et al., see references

HTS quench detectors in ITER (CL tests)

- A system was designed by a team in ITER for the current leads test bench in ASIPP, Hefei, China based on industrial, commercially available solutions
- The quench detector part was implemented using NI-cRIO controllers which directly interface the power supply
- There was no HV issue and 300V galvanic separation was provided by the NI chassis
- Recent tests of the first leads have been successful
- This solution can't be envisaged for the final ITER machine but has given satisfactory results so far at the ASIPP test station



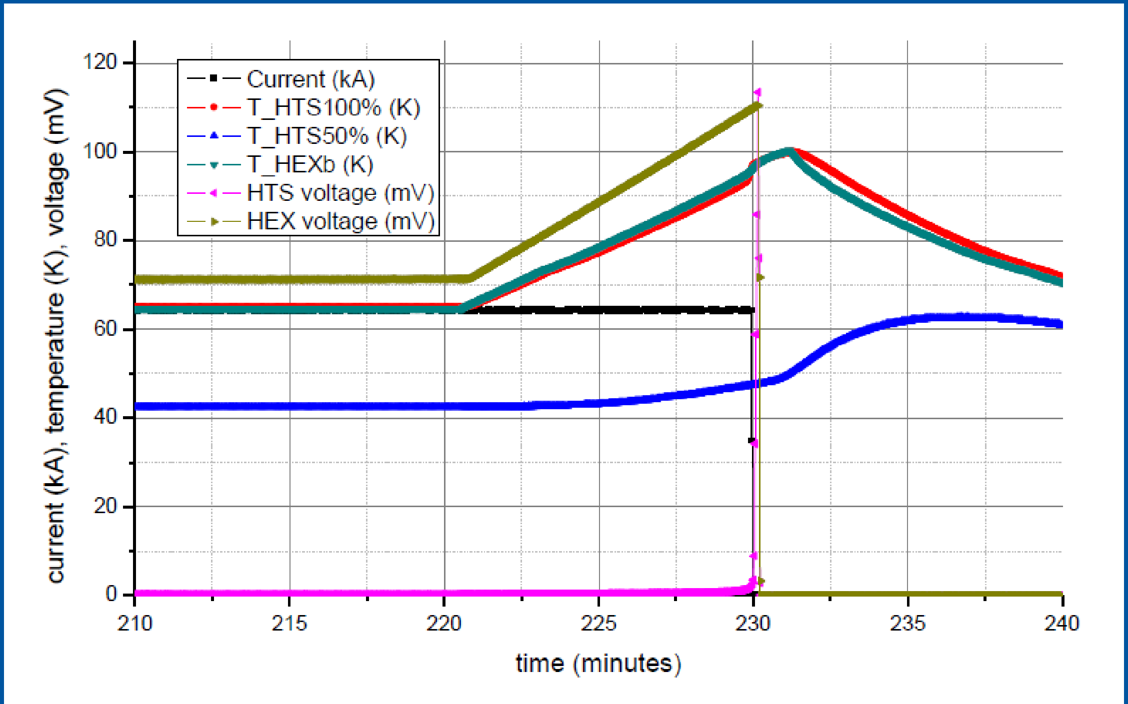
First results

Slide courtesy P. Bauer (ITER) and Dr Ding (ASIPP)

ITER TF HTS Prototype Test Results from ASIPP/China

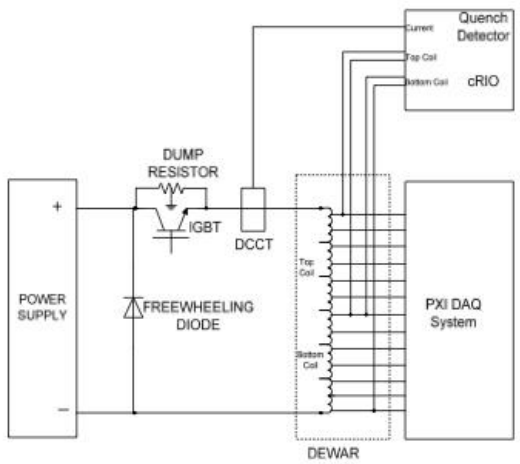
- QDS threshold set to 3 mV during TF prototype test;
- Quench event at 64 kA during LOFA test: voltage allowed to rise further to 100 mV to measure so called overheating time (=time at full current until temperature reaches 150 K in the HTS)

Top: Test cryostat and cubicles
Bottom: Leads inside CTB



Quench in the HTS following a LOFA test . Temperature at warm end of HTS and HTS voltage.

Similar QD system developed at BNL



Quench Detection System for Superconducting Magnets
US 20130293987 A1

Patented!

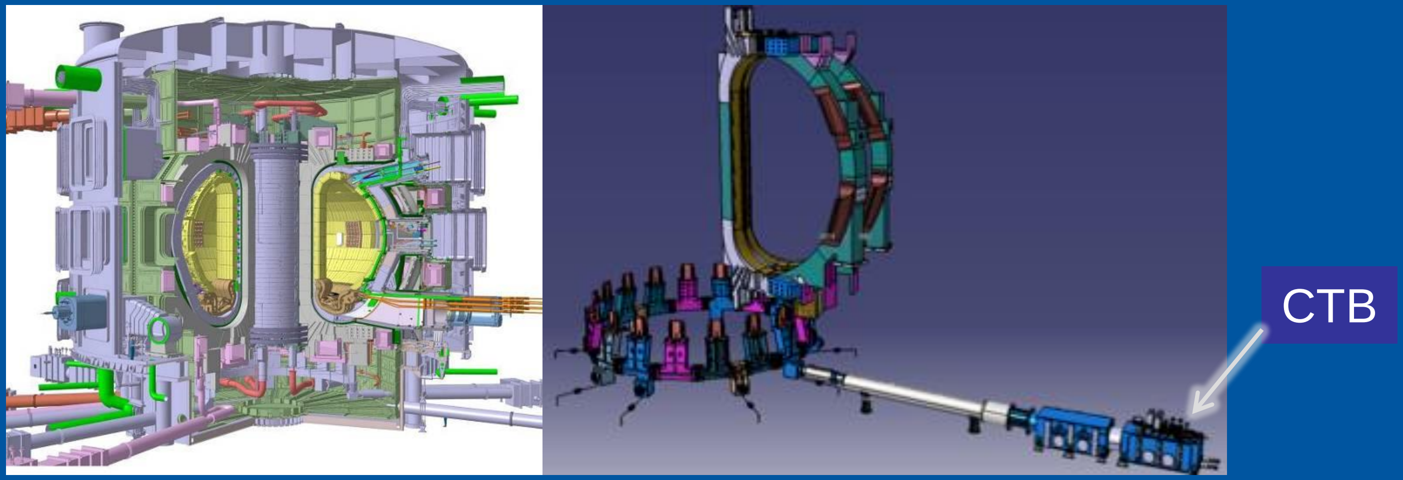
- Bridge QD
- L*dI/dt compensation
- 50 µs to 100 µs FPGA loop time for discrete filtering
- Filter response time 250-500 µs

- NI CRIO backplane powered by reconfigurable Field Programmable Gate Array (FPGA) technology
- Real time controller
- DAQ module with 4 channel
- 50KS/s simultaneous sampling
- 16 bit A/D
- 16 channel fast digital IO module
- 300V channel to channel isolation and 300V channel to ground isolation

Threshold : 1 mV (0.1 µV/cm)
Detection time : 2 - 3 ms

“Novel Quench Detection Method for HTS coils”; P. Joshi, S. Dimaiuta, G. Ganetis, R. Gupta, et al.; Proceedings of 2011 PAC, NY, USA

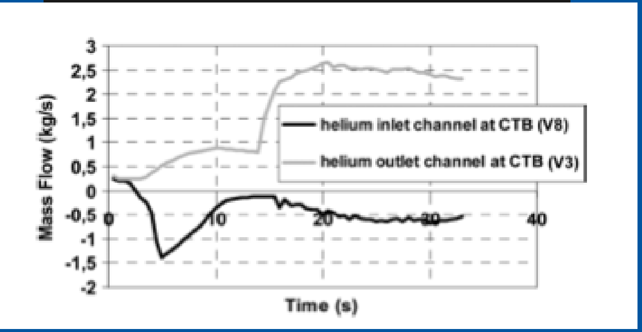
Secondary (Safety) QD in ITER's TF coils



- Cryogenic instrumentation (all flow-meters and pressure sensors and most of the temperature sensors are located at the extremity of the cryostat extensions, within the so-called Coil Terminal Boxes)
- Variations in pressure and in flow during quenching inside of the coils are measured and monitored at the CTB's instrumentation
- This can constitute a second line detection method, the so-called Safety QD which does not protect the coils against overheating, but avoids rupture of the plasma containment walls in case a quench goes undetected by the primary, electromagnetic method(s)

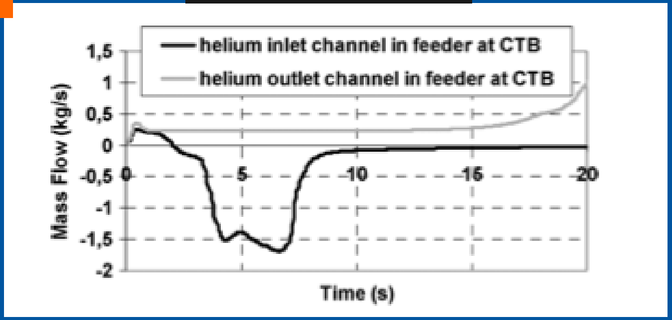
How to detect a quench not seen by the e.m. QD?

Quench and disruption

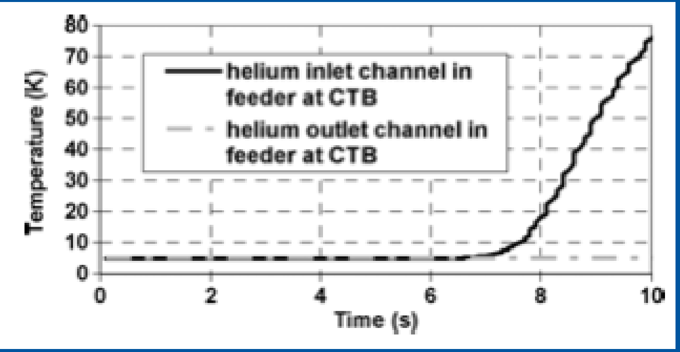


Mass flows at CTB

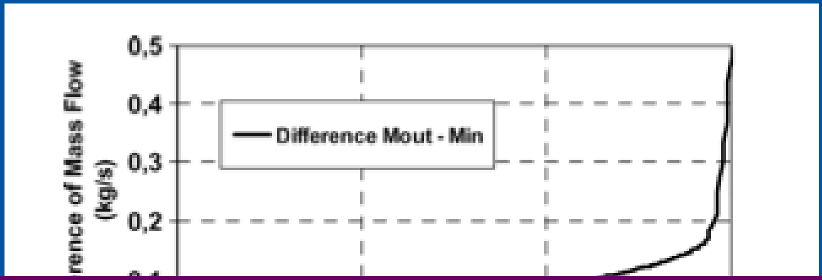
Undetected



Temperatures at CTB



Differential mass flow at CTB



For a threshold of Δm= 0.1 kg/s detection is feasible within 10 s from the quench initiation (ultimate limit is set to 25 s)

S. Nicollet et al., see references

Quench detection in LHC

Please see :

“State-of-the-art and future challenges for the quench detection and protection of accelerator superconducting magnet circuits” by A. Siemko, at the 2014 Kyoto Workshop on HTS Magnet Technology for High Energy Physics – WAMHTS-2

HTS quench detectors in LHC

- Based on ADuC834™ microcontroller with integrated 24 Bit ∑Δ analog to digital converter ADC
  - High resolution < 15 nV @ +/-12.5mV
  - Minimum reaction time t_{EVAL} = 100 ms
- Originally developed for the protection of hybrid HTS current leads, these detection systems are meanwhile also in use for the protection of the bus-bar splices in the LHC main circuits (3266 redundant systems installed in total)
- Reliable operation with detection thresholds as low as 500 μV
- Measurement of bus-bar splice resistance with ΔR ≤ 1 nΩ
- Programmable gain based version used for circuit protection and diagnostics during the Copper Stabilizer Continuity Measurement (CSCM) campaigns

Courtesy Denz/Siemko/Steckert, CERN

Conclusions & Outlook

- Future developments in fast and high resolution digital electronics will bring increasing capabilities for fast detection at every time lower levels
- Coil / bus bar / current lead's sensors are an integral part of a quench detection system, so the design has to be done by putting together from the beginning the magnet engineer, the electronics engineer and the future operators/analysts
- Never forget that magnets are always part of circuits and electrodynamics of quench protection can be tricky when going to the circuit level (power supplies, by-passes, environmental constrains, couplings, noise, transmission line effects, etc)
- Radiation has to be limited to systems which become the more and more complex
- Contacts across disciplines is fundamental to keep innovation and inventiveness alive!
- New methods for the future are going to be hybrid and with adaptive threshold filters
- When will we see the breakthrough of a new detection method ?

References:

- “Engineering Superconductivity”; edited by Peter J. Lee, May 2001, Wiley-IEEE Press
- “Superconducting Accelerator Magnets”; KH. Mess, P. Schmüser, S. Wolff, World Scientific, 1996
- “Quench Observation in LHC Superconducting One Meter Long Dipole Models by Field Perturbation Measurements”, D. Leroy et al., IEEE Transactions in Applied Superconductivity, Vol. 3 (1993)
- “Electromagnetic Quench Detection in ITER Superconducting Magnet Systems”, F. Rodriguez Mateos et al., ASC 2014, Charlotte, USA
- “Detection of the Normal Zone with Cowound Sensors in Cable-in Conduit Conductors”, N. N. Martovetsky and M. R. Chaplin, 1997, IEEE Transactions in Applied Superconductivity, pages 451-454
- “Quench Detection System for the ITER HTS Current Lead Test”; P. Bauer, C.Y. Gung, S. Lee, D. Carrillo, A. Vergara and F. Rodriguez Mateos, Technical Specification,
- “Monitoring and Controlling Tore Supra Toroidal Field System: Status after a year of operation experience at nominal current”; J.L. Duchateau et al., IEEE Transactions on Magnetics, Vol 27, No. 2 , March 1991
- “Contribution à l’Etude des aimants supraconducteurs utilisant des matériaux supraconducteurs à haute température de transition”; PhD Thesis of Thibault Lecrevisse, Université de Grenoble/CEA/IRFU, December 2012
- “Lectures on Applied Superconductivity Beyond Nb-Ti”; Martin Wilson
- “Novel Quench Detection Method for HTS coils”; P. Joshi, S. Dimaiuta, G. Ganetis, R. Gupta, et al.; Proceedings of 2011 PAC, NY, USA

References (cont'd):

- "Thermal Behavior and Quench of the ITER TF System During a Fast Discharge and Possibility of a Secondary Quench Detection"; S. Nicollet et al., IEEE Transactions on Applied Superconductivity, June 2012
- "Development of the TF Safety Quench Detection System at ITER"; Y. Chu et al., ITER Org. Internal Report BHS3DB, January 2013
- "State-of-the-art and future challenges for the quench detection and protection of accelerator superconducting magnet circuits"; A. Siemko, Workshop on HTS Magnet Technology for High Energy Physics – WAMHTS-2, Kyoto (Japan), 2014
- "Acoustic Detection In Superconducting Magnets For Performance Characterization And Diagnostics", M. Marchevsky at al.,
- "Detecting mechanical vibrations in superconducting magnets for quench detection and diagnostics", M. Marchevsky , WAMSDO, CERN 2013
- "Quench Detection of Multiple Magnet System"; M.A. Hilal et al., IEEE Transactions on Applied Superconductivity, Vol. 4, September 1994
- "Quench detection method for 2G HTS wire"; M. Marchevsky et al., EUCAS 2009
- "The ITER –QUELL experiment, a quench propagation experiment on long length CICC with central channel"; A. Anghel et al.
- "Performance of the US Quench Detection Systems in the QUELL Experiments"; S. Pourrahimi et al., IEEE Transactions in Applied Superconductivity, Vol. 7, June 1997
- "Irradiation tests on Optical Fibers Below 20 K"; J. Kuhnhenn et al., International Conference on Space Optics, Tenerife (Spain), Oct 2014
- "Multipurpose Fiber Optic Sensors for High Temperature Superconducting Magnets"; M. Turenne et al.,

Acknowledgment

Sources of information, advice and discussions:

- Amalia Ballarino (CERN)
- Pierre Bauer (ITER)
- Luca Bottura (CERN)
- Marc Coatanea-Gouachet (ITER)
- Reiner Denz (CERN)
- Glyn Kirby (CERN)
- César Luongo (Jefferson Lab)
- Klaus Petry (KIT)
- Andrzej Siemko (CERN)
- Jens Steckert (CERN)
- Antonio Vergara (ITER)

Many thanks for your attention …