Flux Jump characteristics in MBH coils

and a possible link to ‘spikes’ in MBHA-001

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- What are Flux Jumps?
- When do they happen?
- Characteristics of “Local” flux jumps
- Characteristics of “Propagating” flux jumps
- Comparison flux jumps and spikes in MBHA-001

Flux Jumps in Magnets

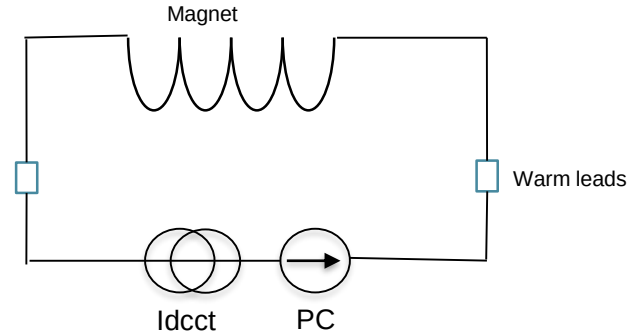
Flux Jump:
- Large motion of flux lines in the superconductor

Effect of Flux Jump:
- Causes a change in field
- Gives losses in the conductor and locally increases temperature.
- Could locally turn the conductor normal conducting.
  -> Could lead to a full magnet quench
  (There are no cases in 11T magnets where FJ leads to quench (not looking at self-field instability at high current))

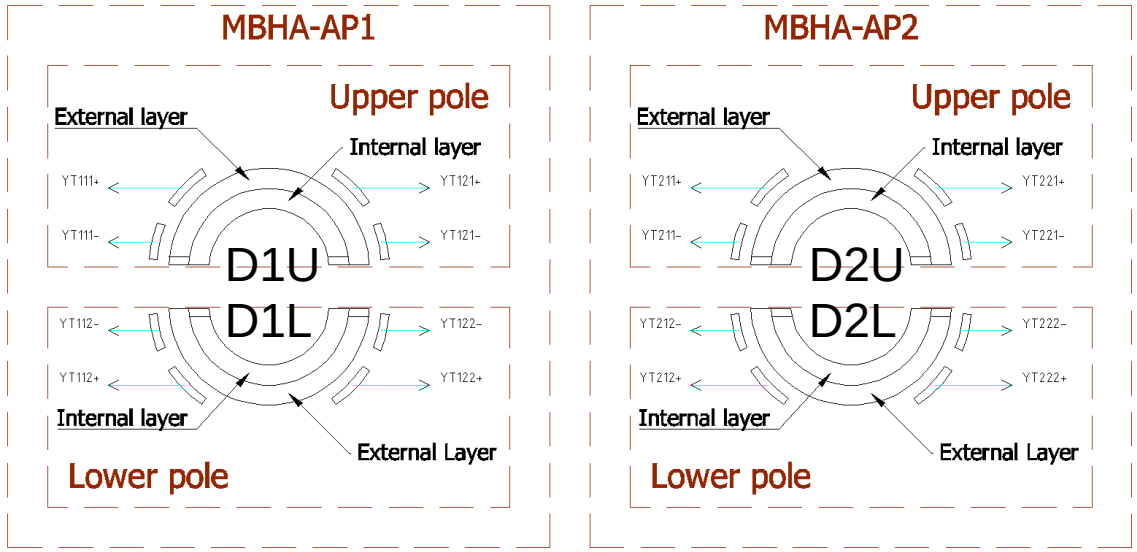
Secondary effect:
- Drop of current, sometimes mesurable

Following law of conservation of energy the loss generated by the flux jump will create a drop in current.
The PC will compensate this later (regulation time >> flux jump duration)

$$\int_{t_1}^{t_2} VIdt = \int_{I_1}^{I_2} 0.5\, LI^2 dI$$



Nomenclature



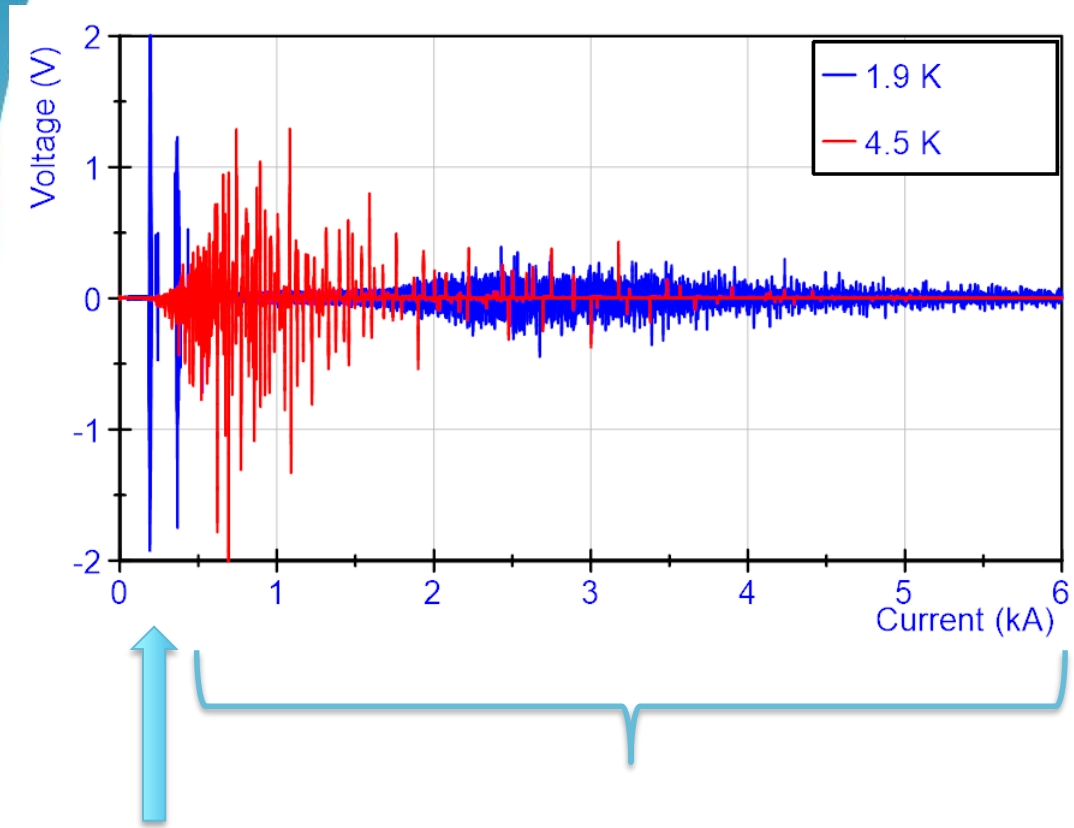
Our typical voltage measurement is “differential”

If we note: D1-D2 we have the voltage of Aperture 1 minus voltage of Aperture 1.

D1L-D1U = Lower coil aperture 1 minus Upper coil Aperture 1

D2U-D2L = Upper coil aperture 2 minus Lower coil Aperture 2

Occurence of Flux jumps in MBHB-002



"Local" flux jumps 1.9 K

"Traveling" flux jumps 1.9 K and 4.5 K

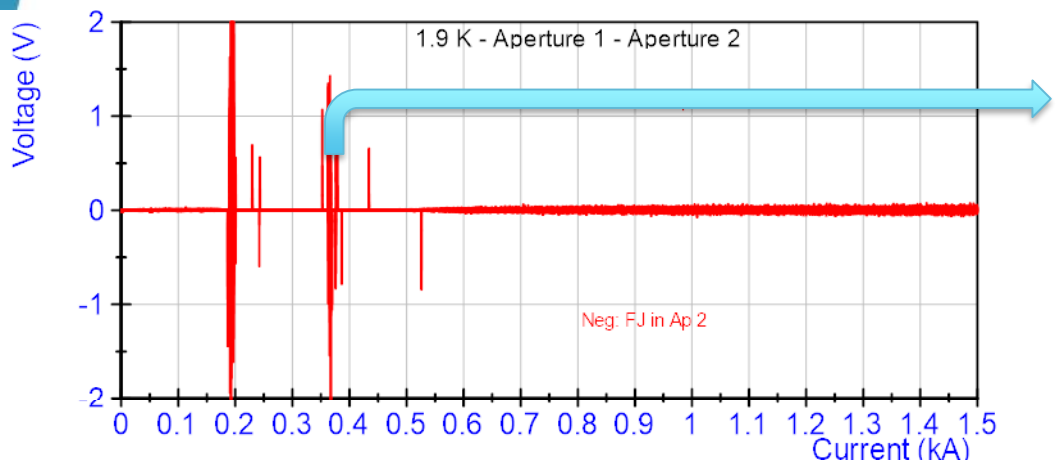
Large study in MBHB-002, mainly towards QPS thresholds and validation time strategy. See E. Karentzos, EDMS 2243504

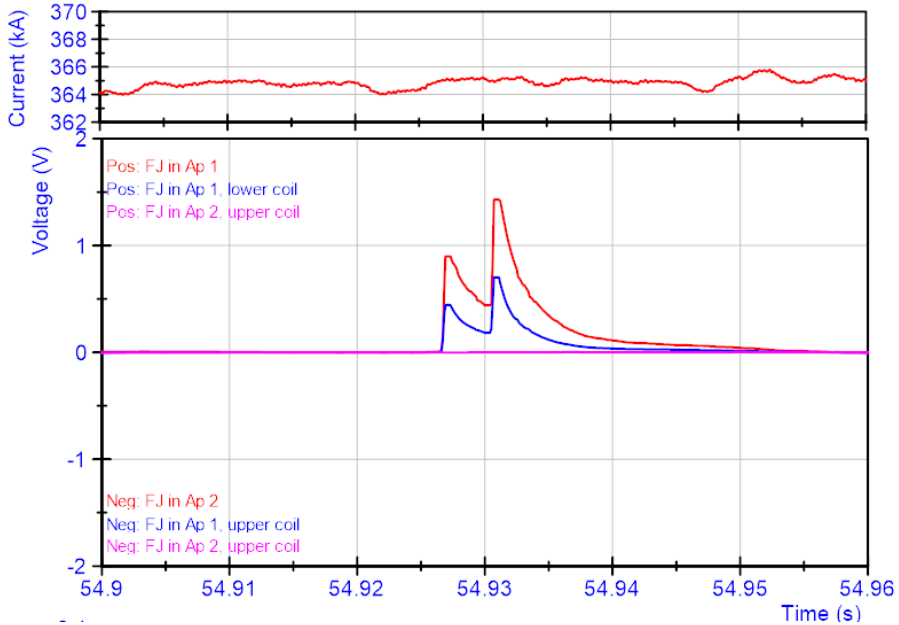
1.9 K:
- Very distinct and large flux jumps between 150 and 550 A
- Another flux jump type between 2 and 4 kA

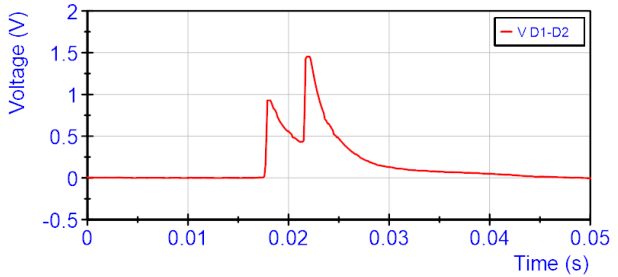
4.5 K:
- No large flux jumps at very low current
- Most and largest flux jumps between 0.5 and 2 kA
- Still some flux jumps towards 4 kA.

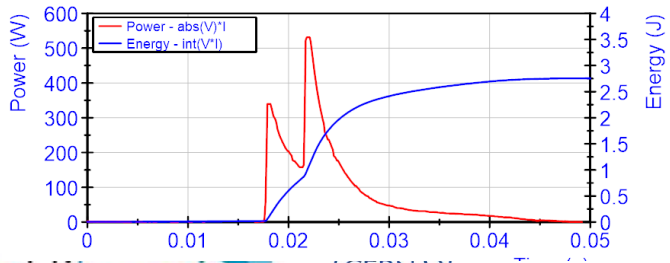
Characteristics of ‘Local’ Flux Jumps

“Local” Flux Jumps : Appearing at 150 A to 550 A









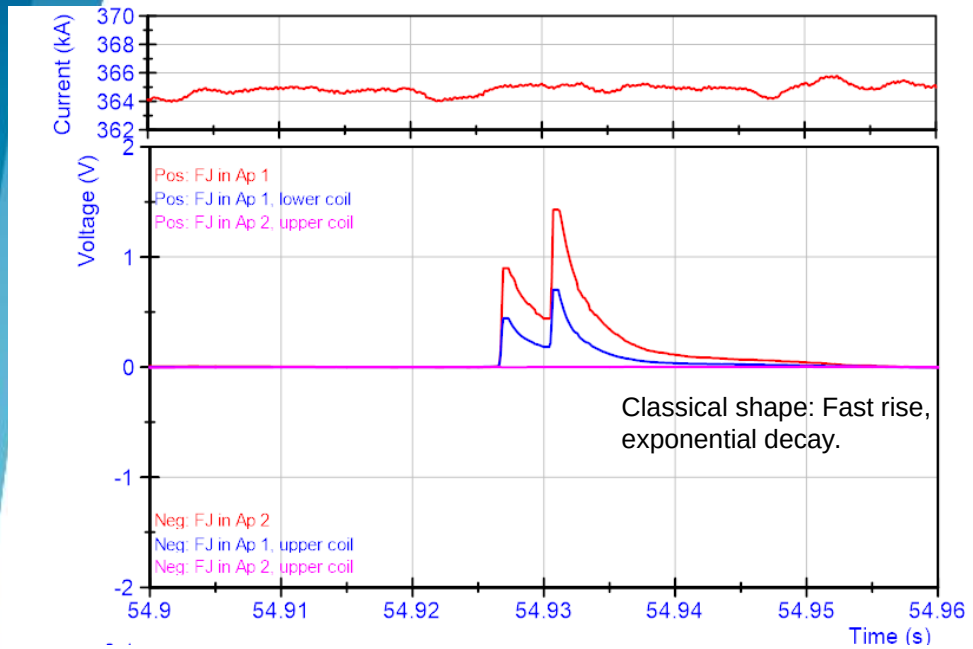
Power (V*I) in a flux jump > 500 W

Energy for the largest event is 1 to 2 J

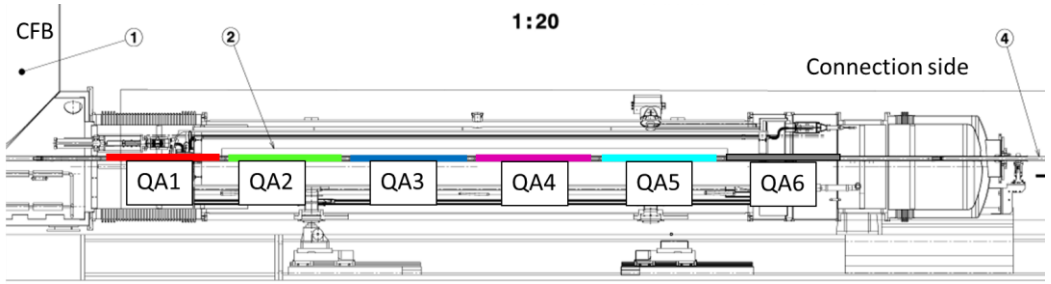
Classical shape: Fast rise, exponential decay.

Limited to a single aperture
(Note: Flux jump voltage is a loss, and therefore always gives a positive voltage when measured in a direct signal.)

“Local” Flux Jump

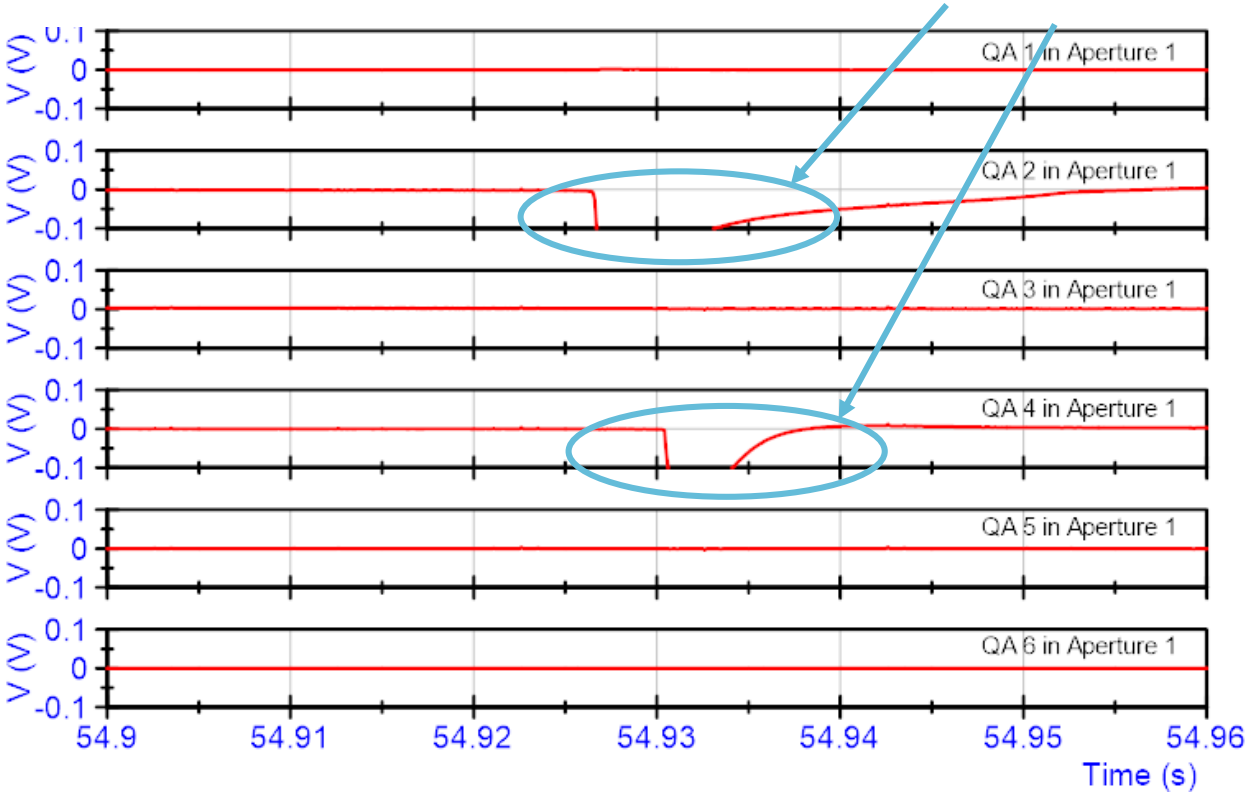


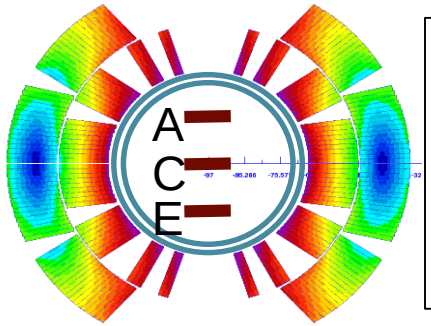
Classical shape: Fast rise, exponential decay.



6 quench antenna per aperture, each covering a length of 1.25 m

Quench antenna show that the two events are separated longitudinally by at least 1.5 meter.
Lack in signal in QA 3 suggest these 2 seperate events.
We can call it “Localized”, at least longitudinally.

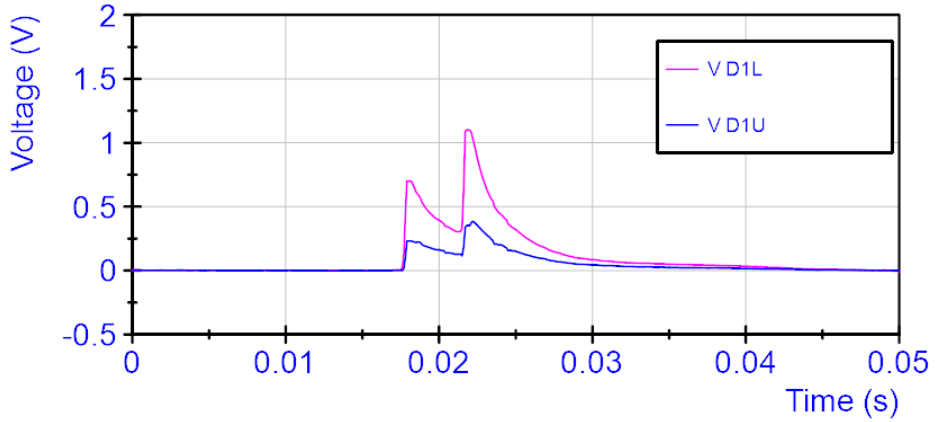




Note: Also the Quench Antenna are measured differentially. Here we show segment A minus E.
This means that any global current change is canceled by the way of measuring.

Also midplane flux jumps will be less visible as we would expect symmetry between A and E.

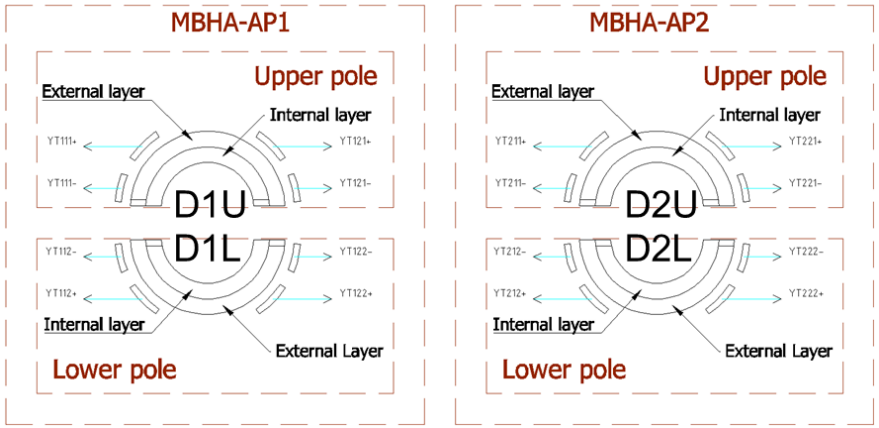
Symmetry?



Reconstructed voltage from measurement D1-D2 and D1L-D1U (assuming 0 V in D2).

The voltage in D2U and D2L remains 0.

Note: LdI/dt is canceled by the differential measurement

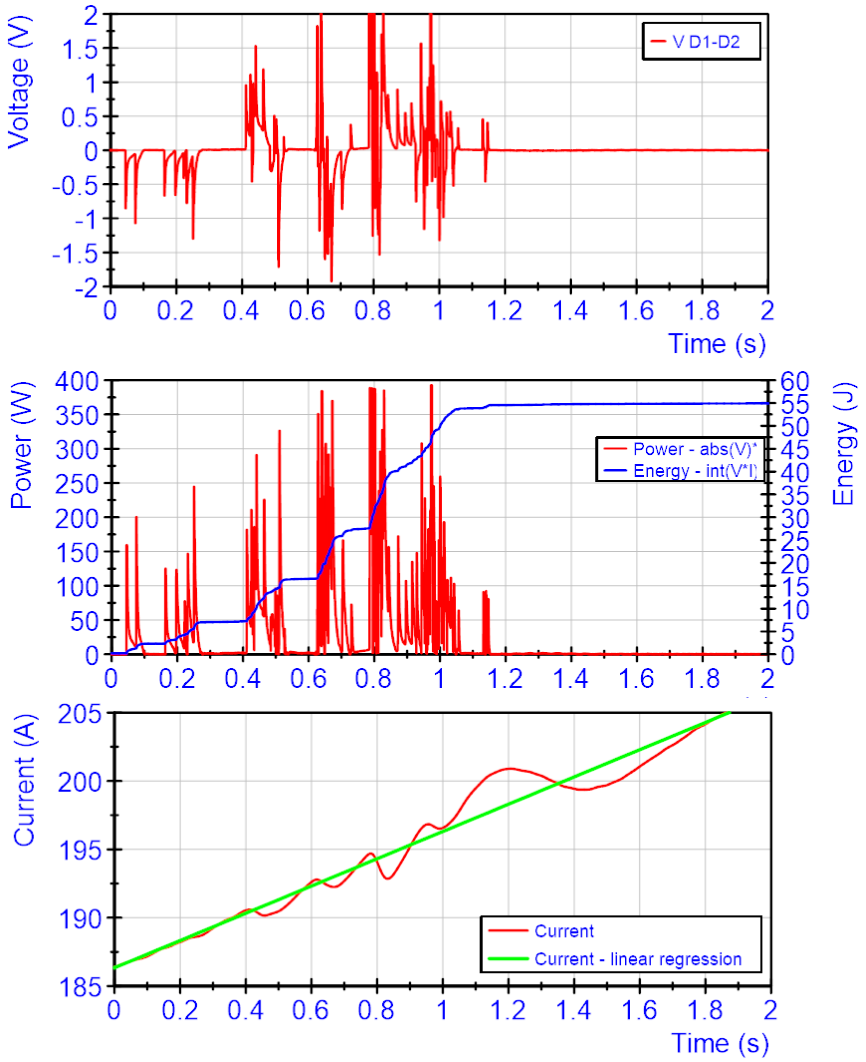


Observation

- **No** symmetry.
- Either flux jump in a single coil with mutual coupling into the neighboring coil,
- Or flux jump occurs in both coils simultaneously.

Note2: There is always a signal in both opposing coils: we use this knowledge already for improved QPS settings.
This suggests that the mutual coupling plays a role.

Can we measure a current drop?



Example of a train of flux jumps

Flux jumps, in both aperture 1 (positive voltage) and aperture 2 (negative voltage)

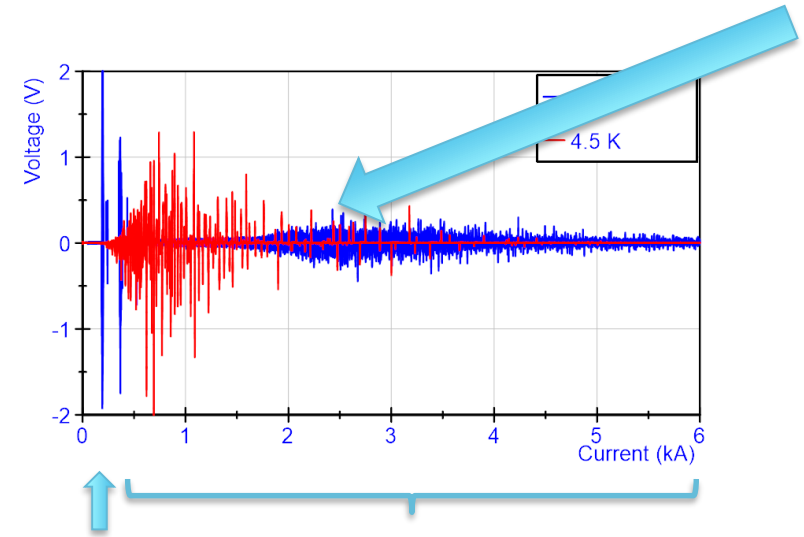
Simple power and energy dissipation calculation.
Largest single events deposit about 3 J in this current range.

10 J corresponds to about ΔI of 0.5 A (if L = 100? mH, at 195 A)

$$\int_{t_1}^{t_2} VIdt = \int_{I_1}^{I_2} 0.5\, LI^2 dI$$

Leads to current drops.
PC compensates.
Overshoot between 1 and 1.4 seconds.

Characteristics of “Propagating” Flux Jumps

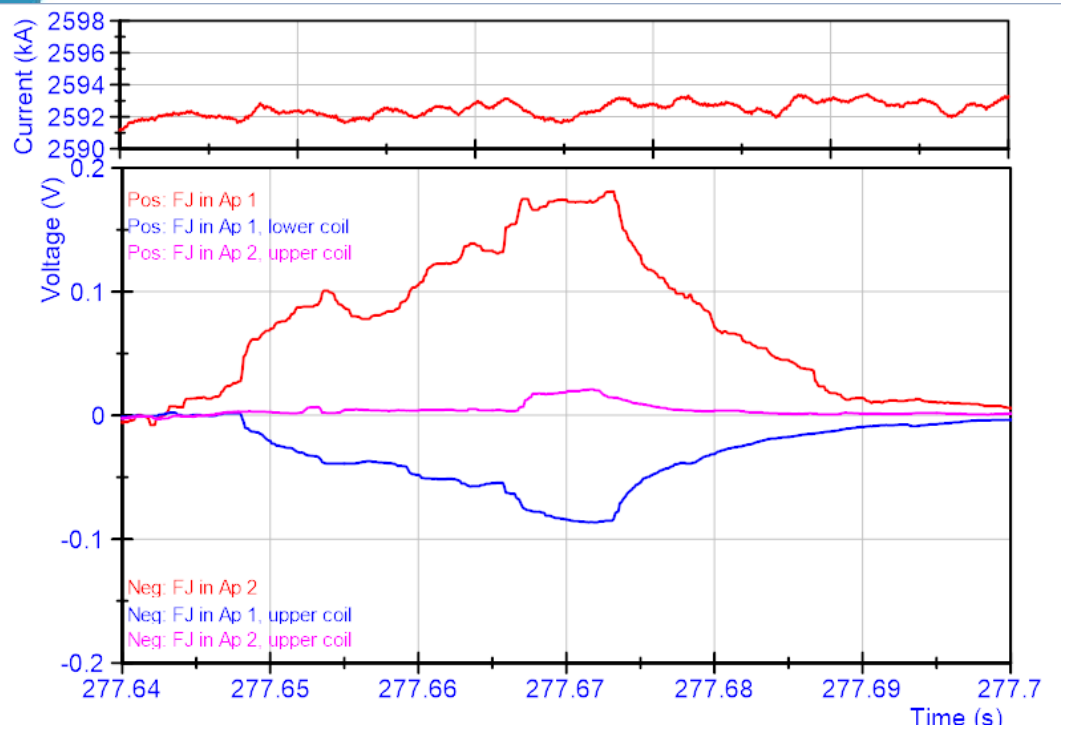


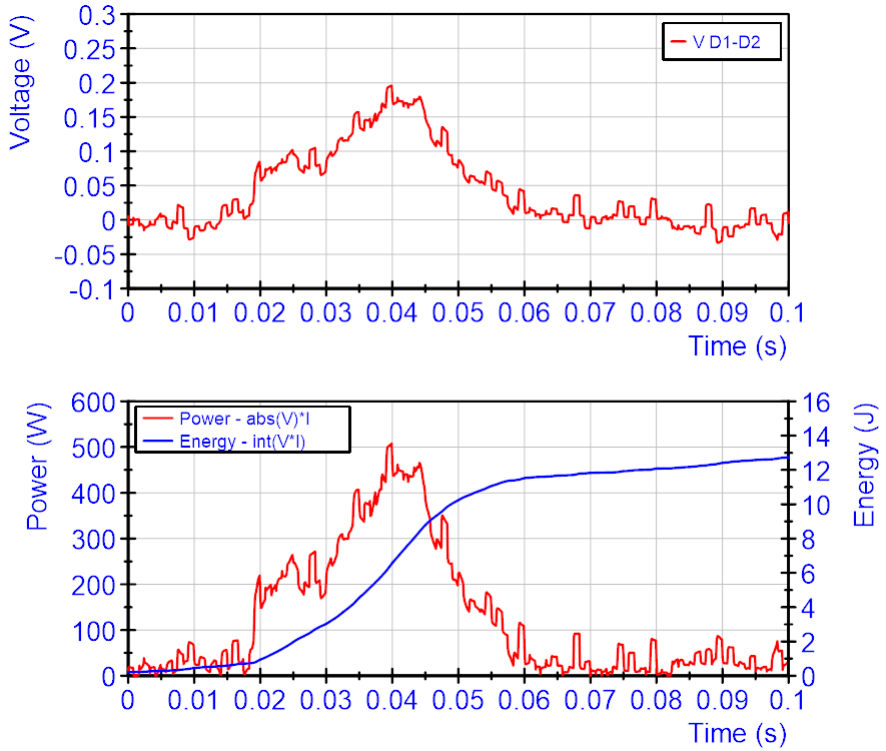
“Local” flux jumps 1.9 K

“Traveling” flux jumps 1.9 K and 4.5 K

In the next slides we look at an event at 2590 A.

“Propagating” Flux Jumps - Example of one typical event.



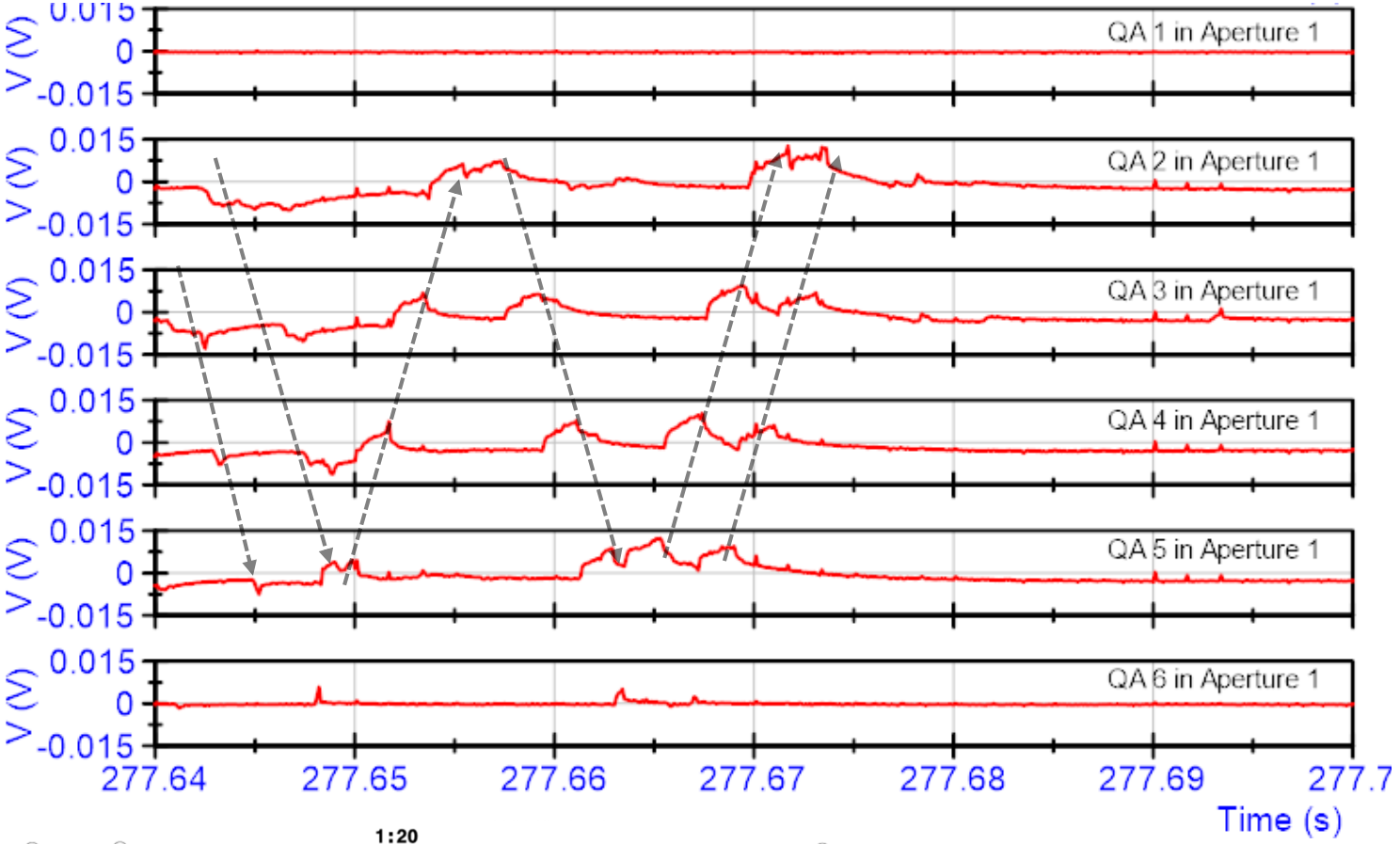


Very different voltage signature then “Local” flux jump.

Voltage build-up and decay much less regular.

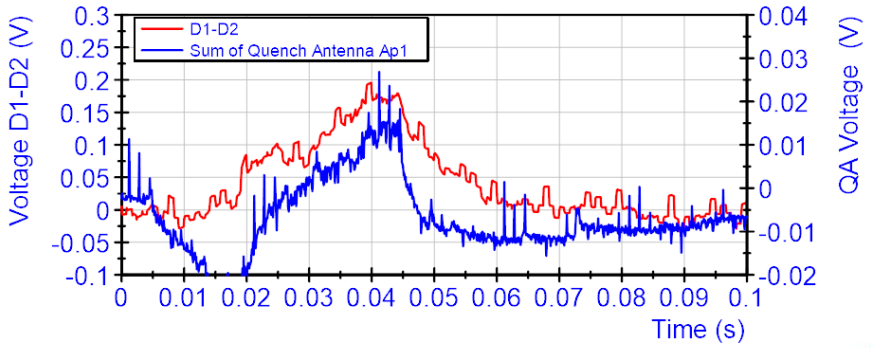
Energy dissipated, or $\int VI\,dt$ ~ 10 J for this event.

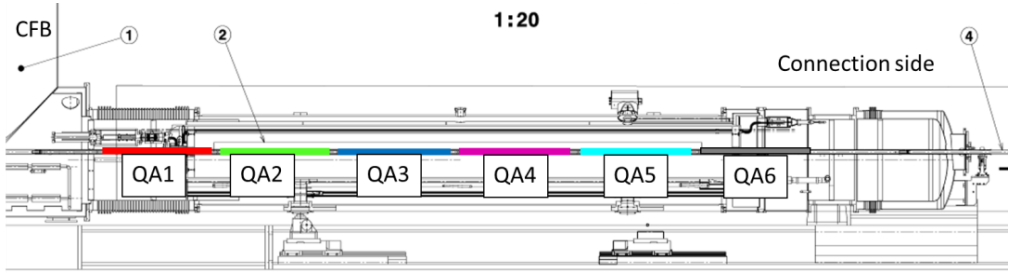
“Propagating” Flux Jumps - Quench Antenna



In the Quench Antennas of aperture 1 we can see a moving pattern appearing back and forth at about 700 m/s.

When adding all 6 signals of aperture 1, we can find a signal shape more or less corresponding with the voltage signal.



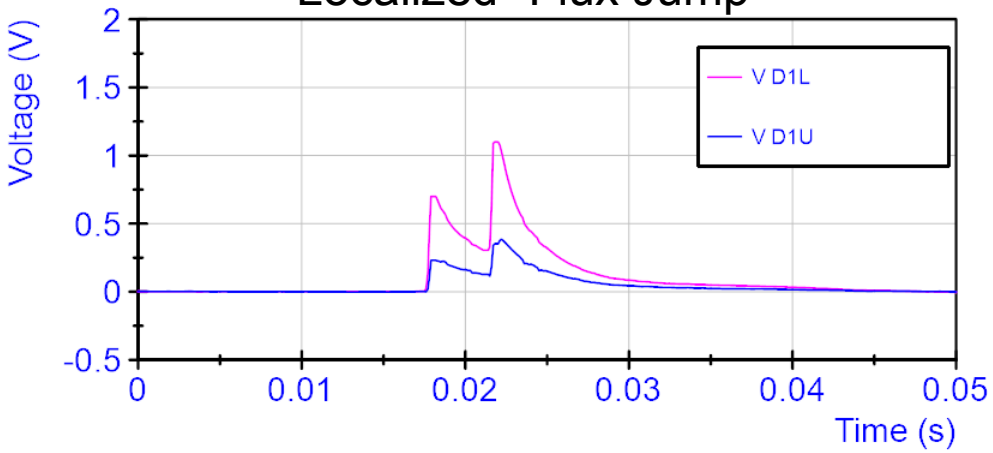


Interpretation:

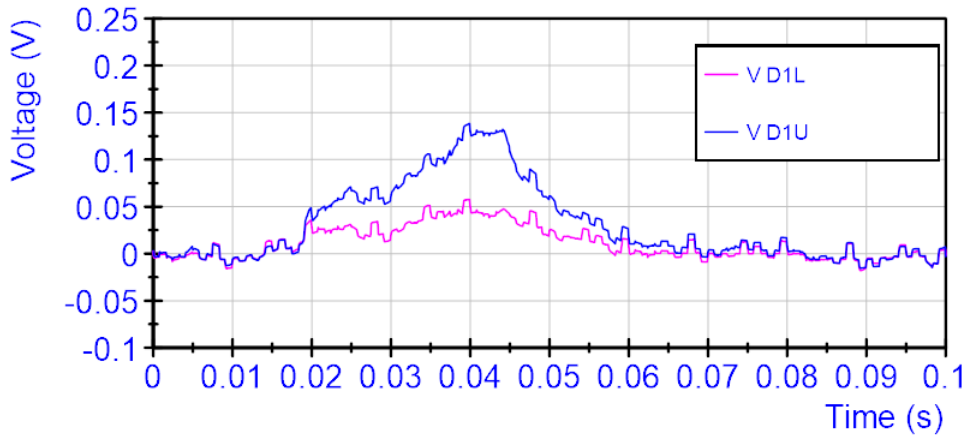
- This flux jump event is located in one aperture, likely in one coil.
- It is not localized to a single longitudinal spot.
- It is a propagating event: One could speculate that it occurs in one strand, one cable turn or multiple turns.

Symmetry comparison?

“Localized” Flux Jump



“Propagating” Flux Jump



Reconstructed voltage from measurement D1-D2 and D1L-D1U (assuming 0 V in D2).

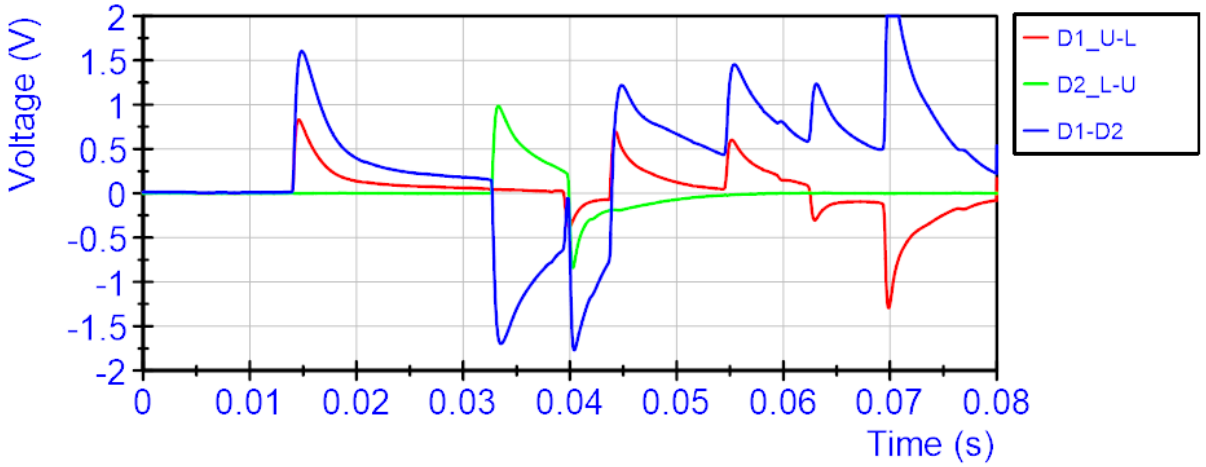
The voltage in D2U and D2L remains 0.

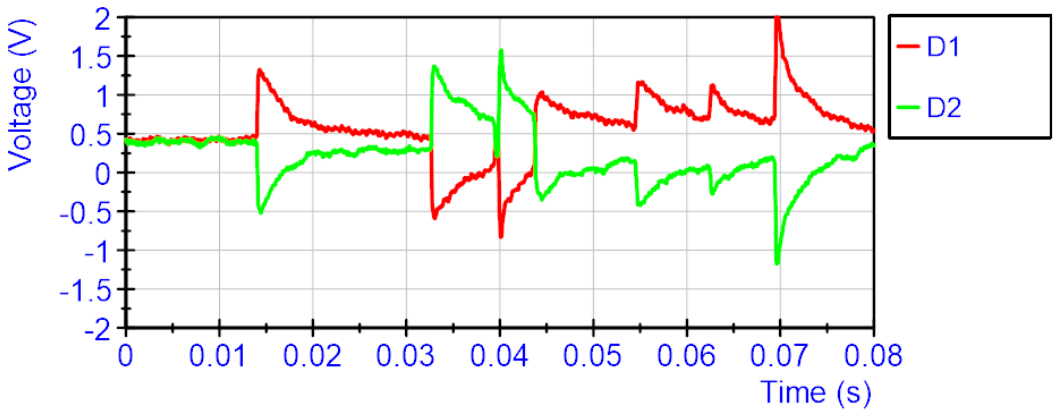
Observation:

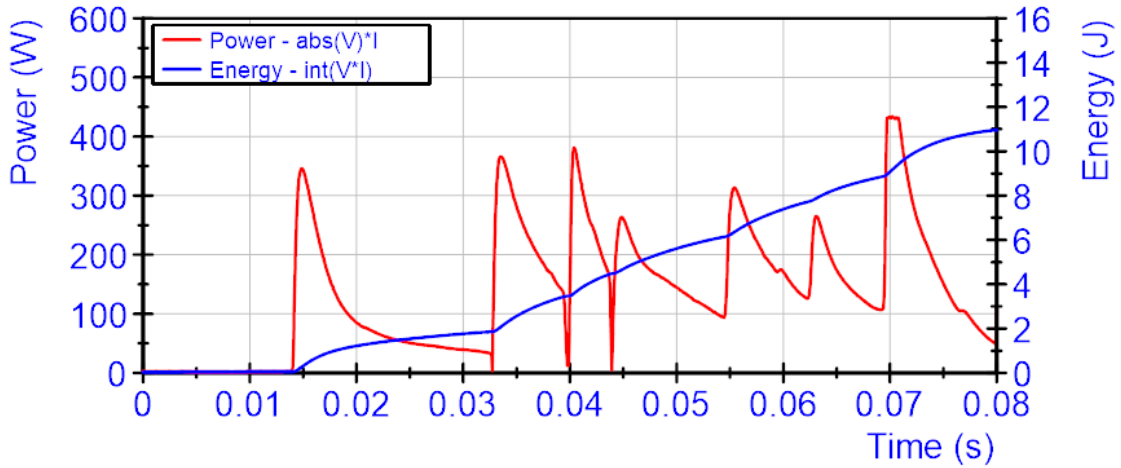
- **No** symmetry.
- All flux jumps we observed so far show:
  - Voltage in one coil always accompanied by smaller voltage in the other coil in the same aperture (about a quarter to half the amplitude) of the same sign.
  - Voltage in one aperture shows no voltage in other aperture. (excluding main inductive component)

For one MBHB002 flux jump trip at 216 A we recorded all data

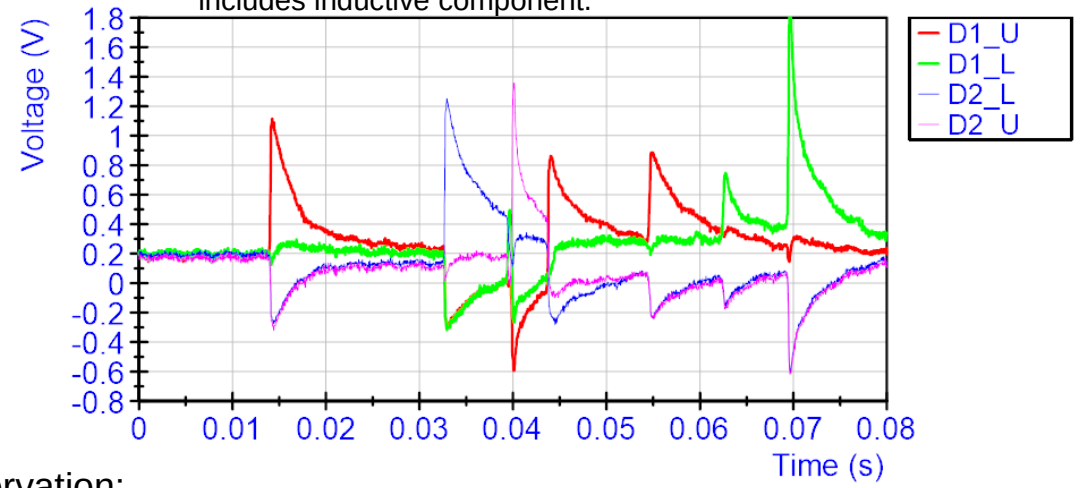
For one event (MBHB002 flux jump trip at 216 A) we recorded all data:







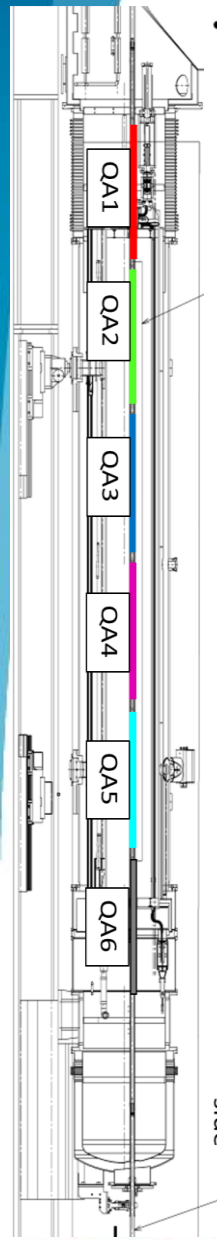
Note: the direct voltage measurement shown here includes inductive component.

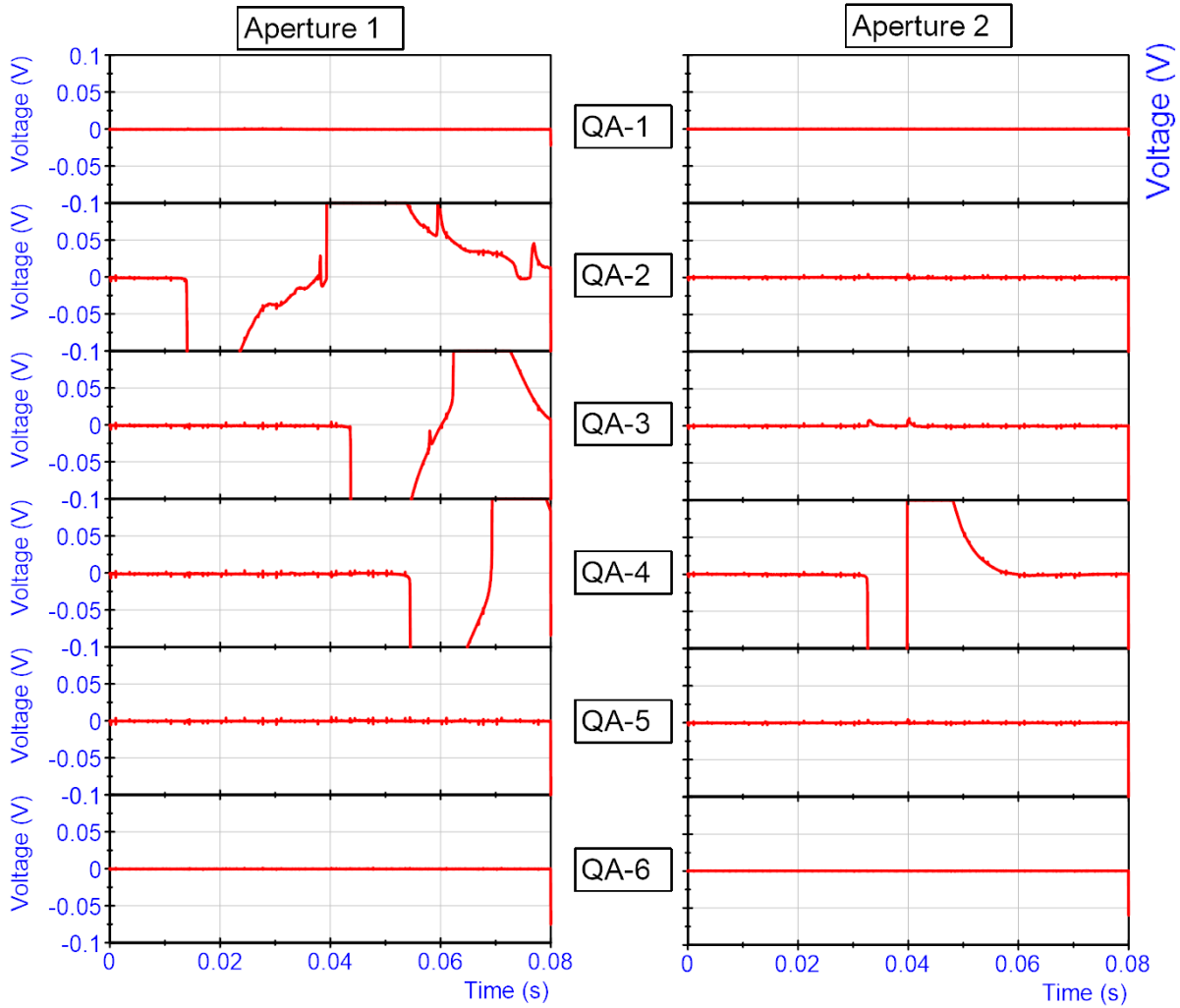


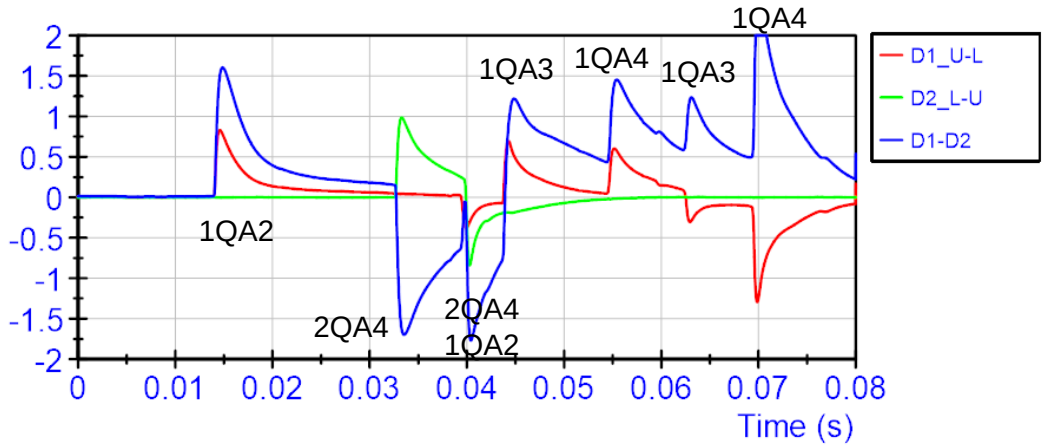
Observation:

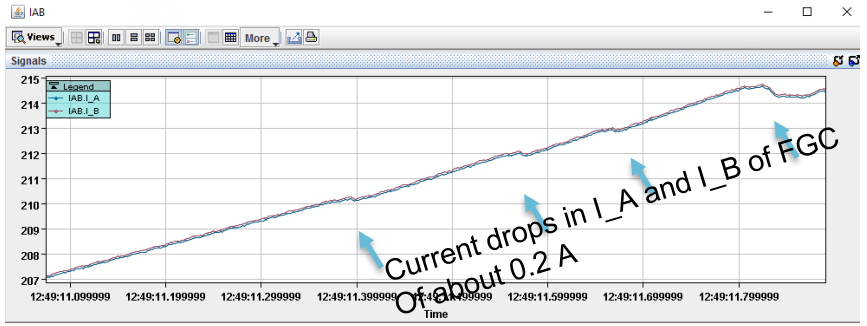
- D1 and D2 are not zero. Positive (FJ) voltage **MUST** always balanced by inductive voltage in the other coil. V_D1+V_D2 is imposed by $V_{res,warm\ leads}$+ V_PC or V_freewheel diode.
- Example: If D1U has a spike, D2L and D2U show a negative voltage and D1L has a voltage in between.

For one event (MBHB002 flux jump trip at 216 A) we recorded all data:



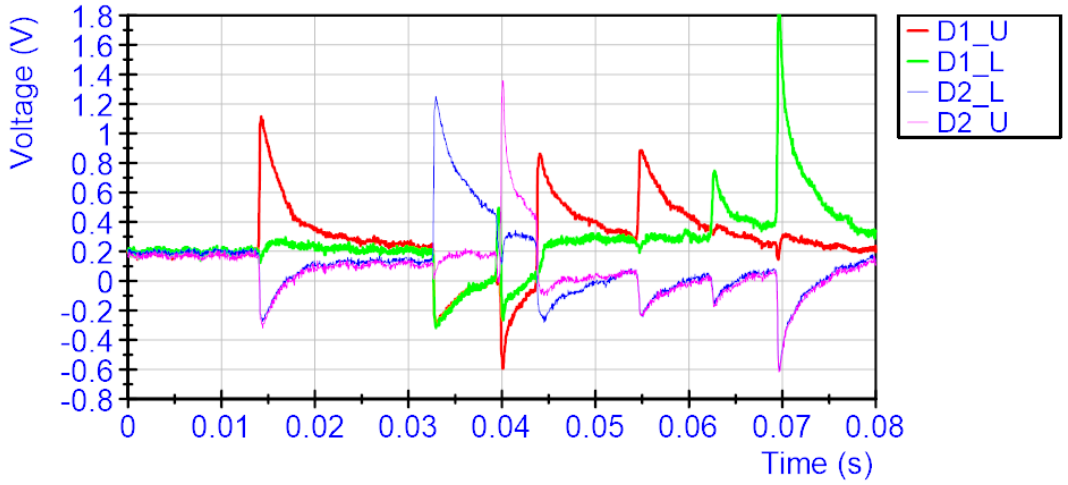


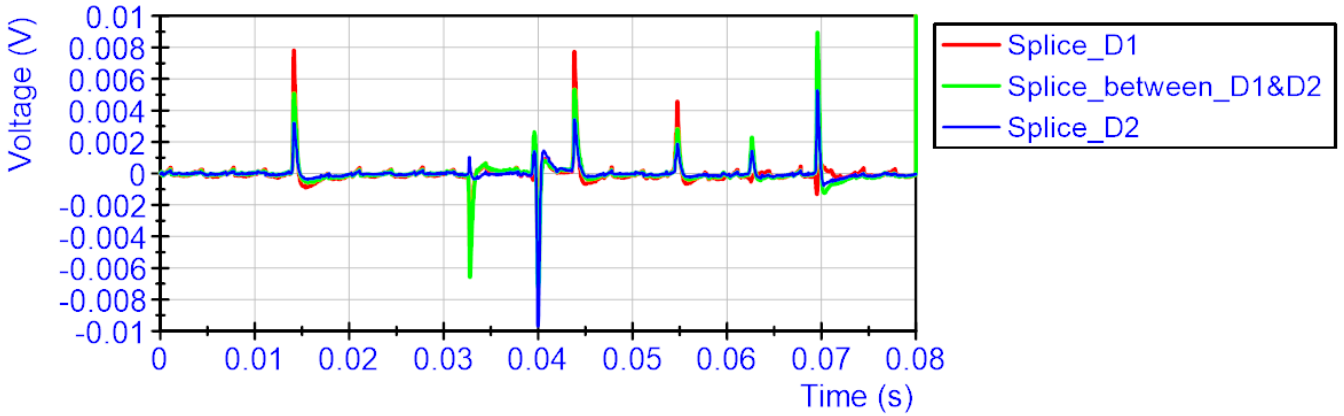




The flux jump events occur in both apertures, in multiple segments.

For one event (MBHB002 flux jump trip at 216 A) we recorded all data:





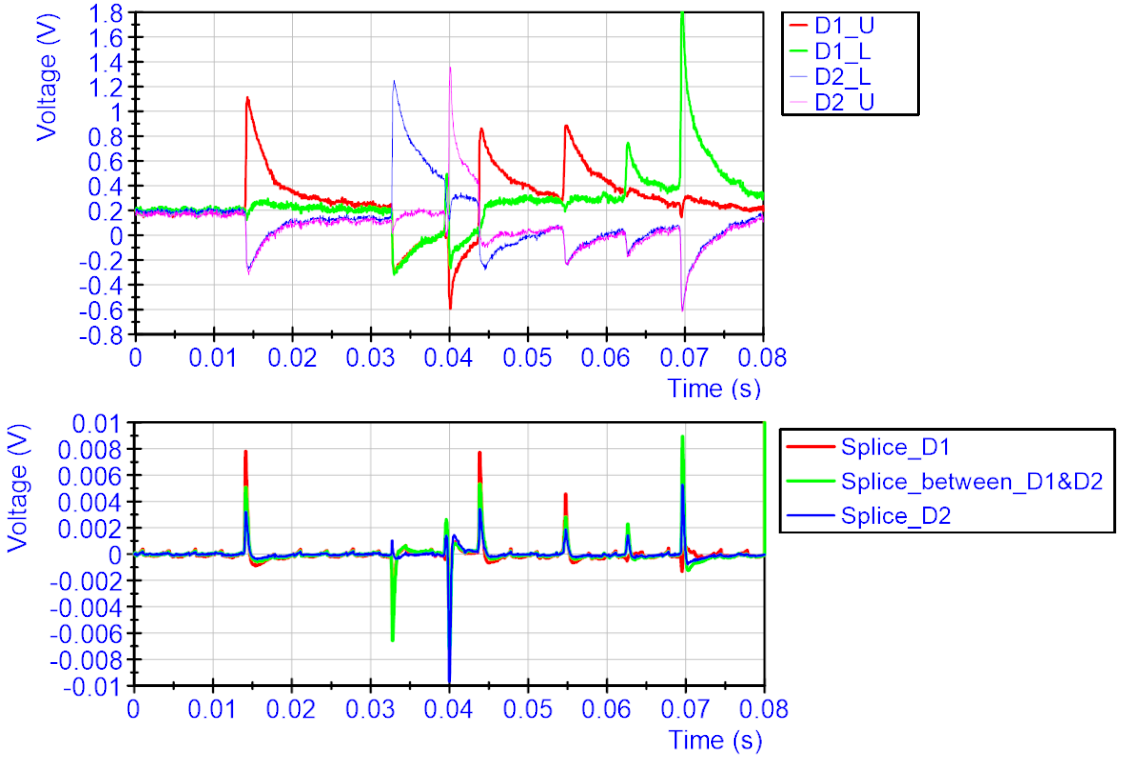
Also the splice data was recorded. Interestingly, there are spikes in the signals, but with a much faster decay than in coil voltage measurements. Why??

Same “short” spikes seen in MBHA-001 splices? See slides Franco.

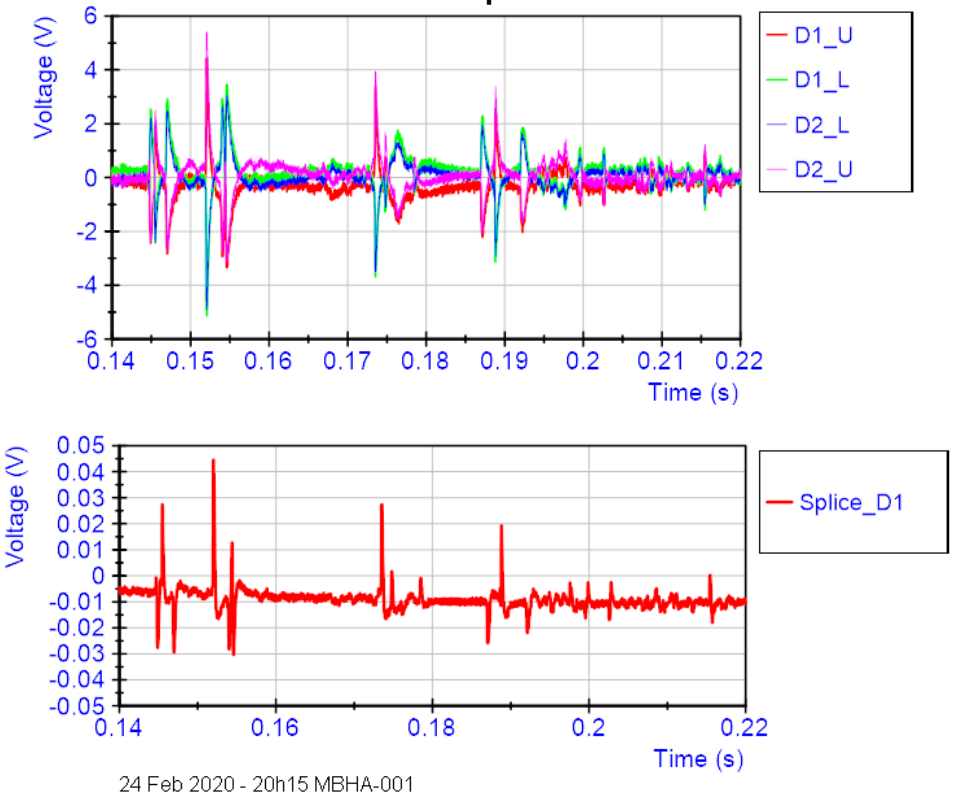
Comparison “normal flux jump” observation and MBHA-001 spikes

Signal Comparison “normal” flux jump and MBHA-001 spikes

MBHB-002 flux jumps



MBHA-001 spikes



Main difference is in the symmetry:
‘normal’ flux jumps are **always** strongest in one coil.
Spikes are **always** similar in all coils (with equal in sign in D1L and D2L.

On time constants: Difficult to conclude, since we look at 200 A, 10 A/s events compared to 6 kA events with 40 kA/s.

Quench antenna comparison

Unfortunately no QA data on the spikes, since they were all saturated. Needs specific recording strategy to measure them in the next MBHA-001 run.

Summary

Normally we can distinguish **2 types of flux jumps**

- “Local” flux jumps, occurring at very low currents (150 – 550 A) at 1.9 K.
- Propagating flux jumps, mostly active from 2 to 4 kA at 1.9 K an also from 0.5 to 2 kA at 4.5 K.

Flux Jump characteristics:

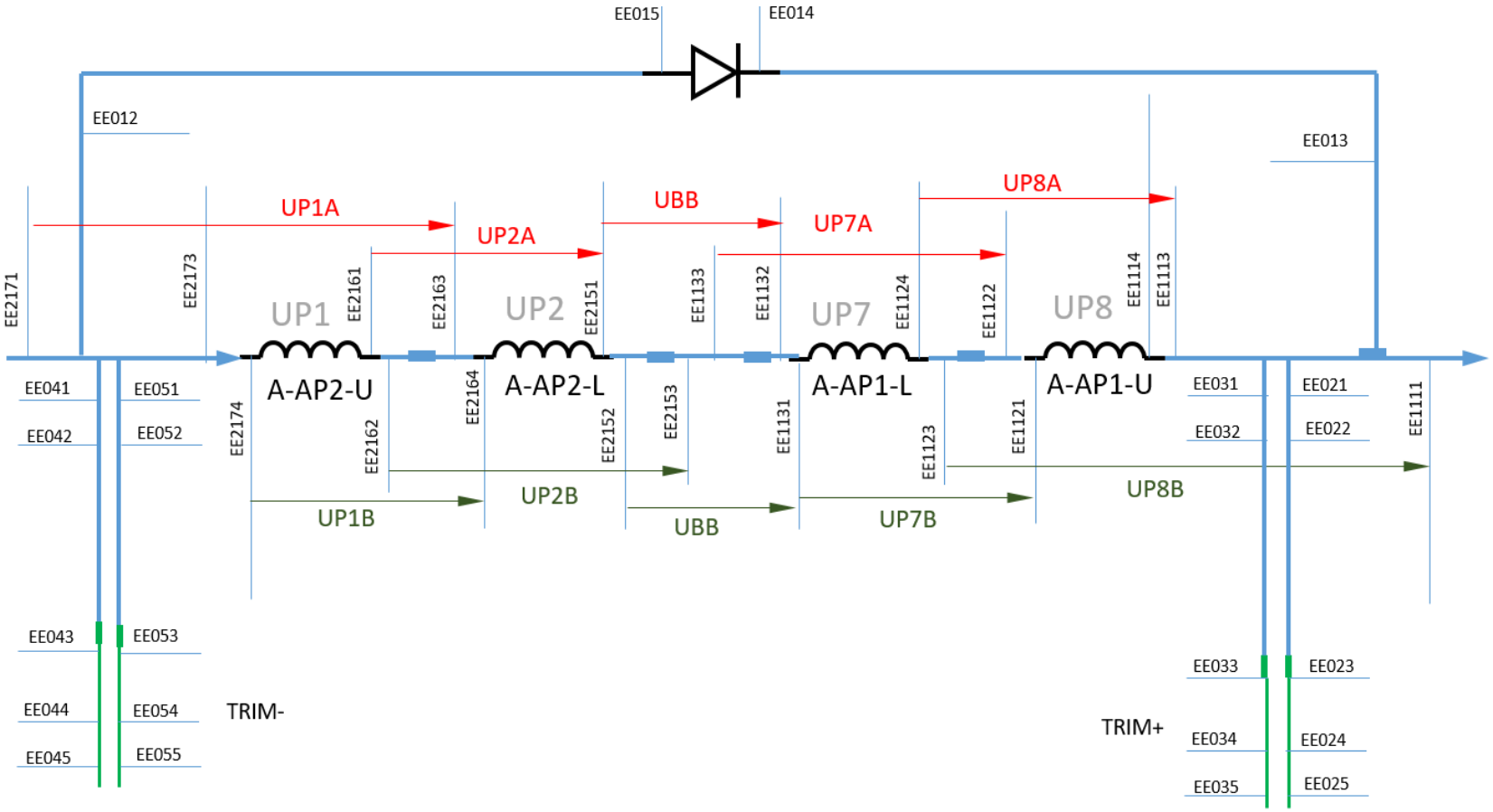
- Flux jumps are confined within an aperture.
- During flux jump there is ALWAYS some (mutual?) coupling between the affected coil and the neighboring coil in the same aperture. (we use this for enhanced QPS settings).
- The voltage D1+D2 is imposed by the warm part of the circuit (warm leads+PC or warm leads+freewheeling diode).

Spikes in MBHA-001 **do not look like** “normal” flux jumps:

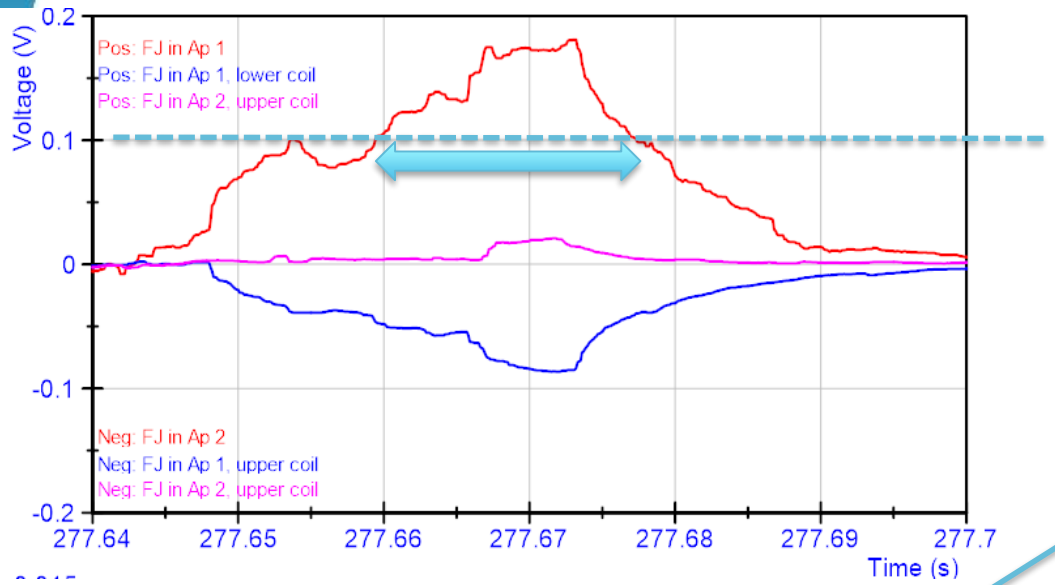
- Symmetry is very different.
- Time constants are somewhat different

Backup slides

Voltage taps and signals.

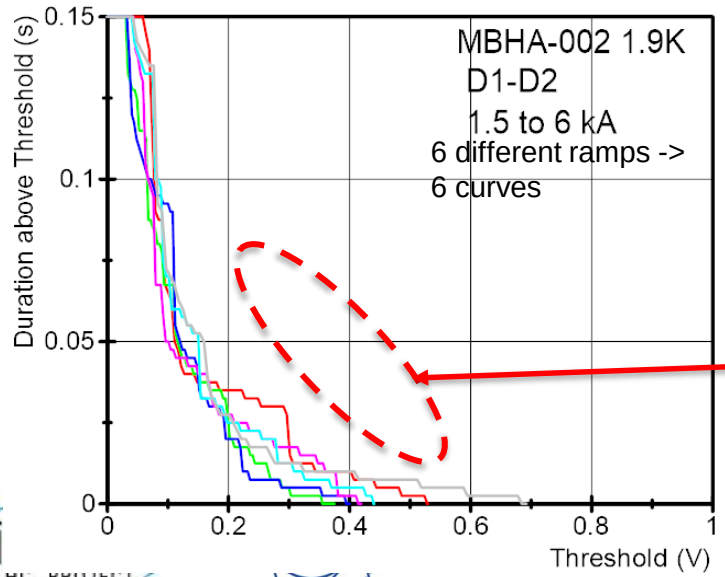


Flux Jump characterization for QPS threshold



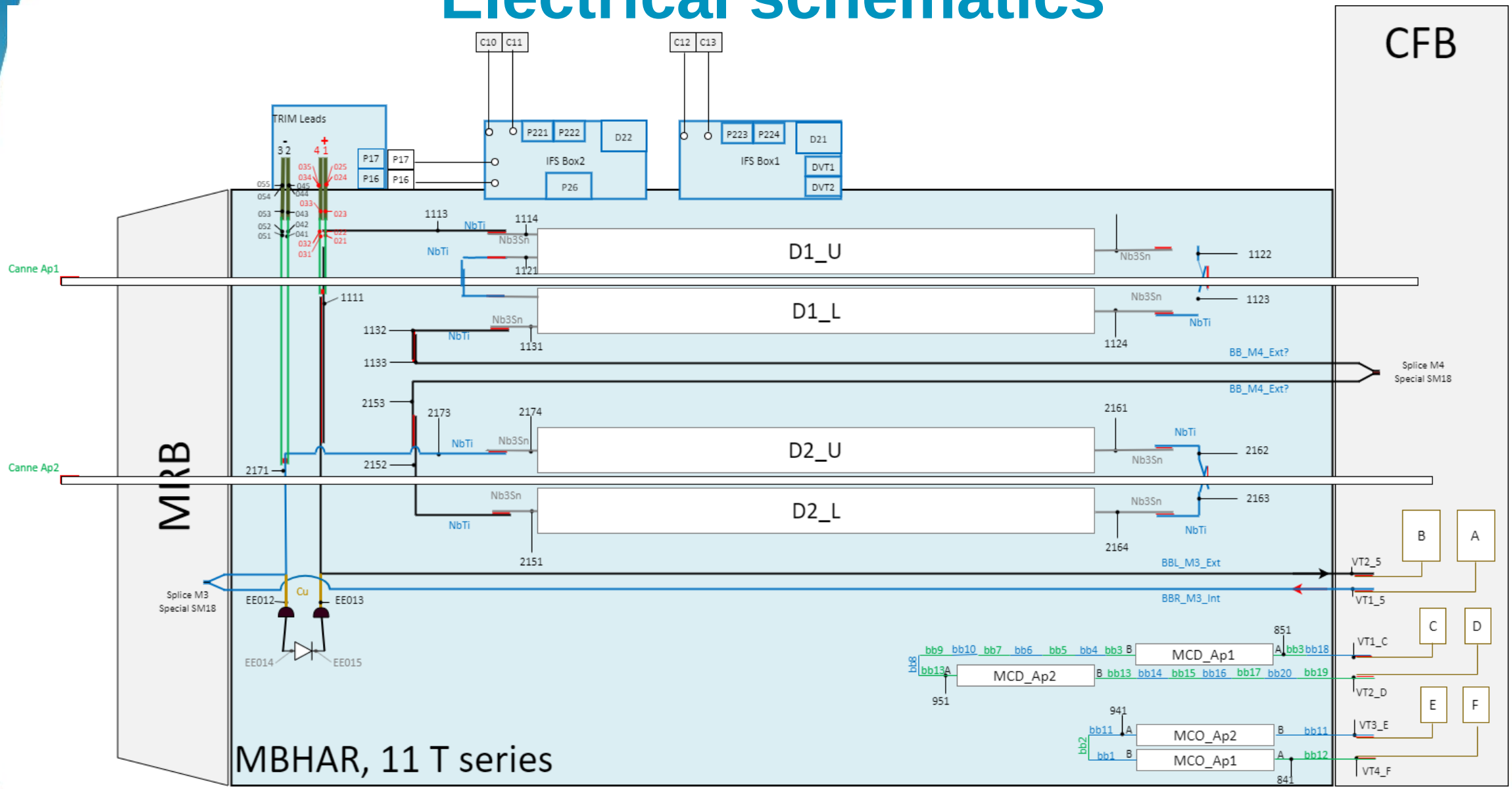
Possible threshold
Duration above threshold.

Method of characterizing flux jumps:
Scan for each possible threshold voltage the maximum duration over that voltage.
Scan each ramp (use the current ranges as specified for QPS, for example 1.5 kA to 6 kA, 6 to 9 kA, etc…).



Typical region of choice for threshold/validation time

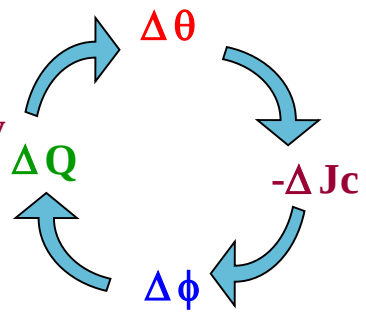
Electrical schematics



Flux Jumps in Magnets

a magnetic thermal feedback instability

- **screening currents**
- **temperature rise**
- **reduced critical current density**
- **flux motion**
- **energy dissipation**
- **temperature rise**



Courtesy M. Wilson

https://indico.cern.ch/event/471931/contributions/1149849/attachments/1222205/1787373/JUAS_16_lect_3_mags_training_stability.pptx