# SP109 High Voltage Tests Report

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# Overview of SP109 and Test Programme

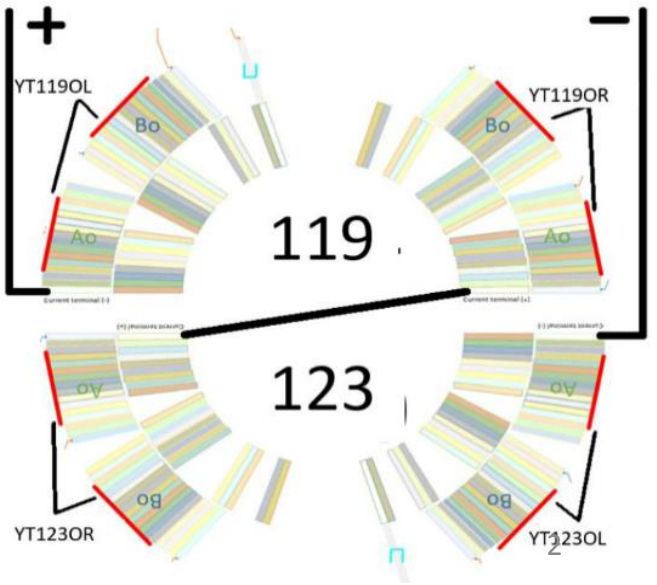
Previous HV test campaign on SP109 in Helium (superfluid and gas, 80 and 200 K) was in June 2019 (report from 11T Technical Meeting #18)

Summary:

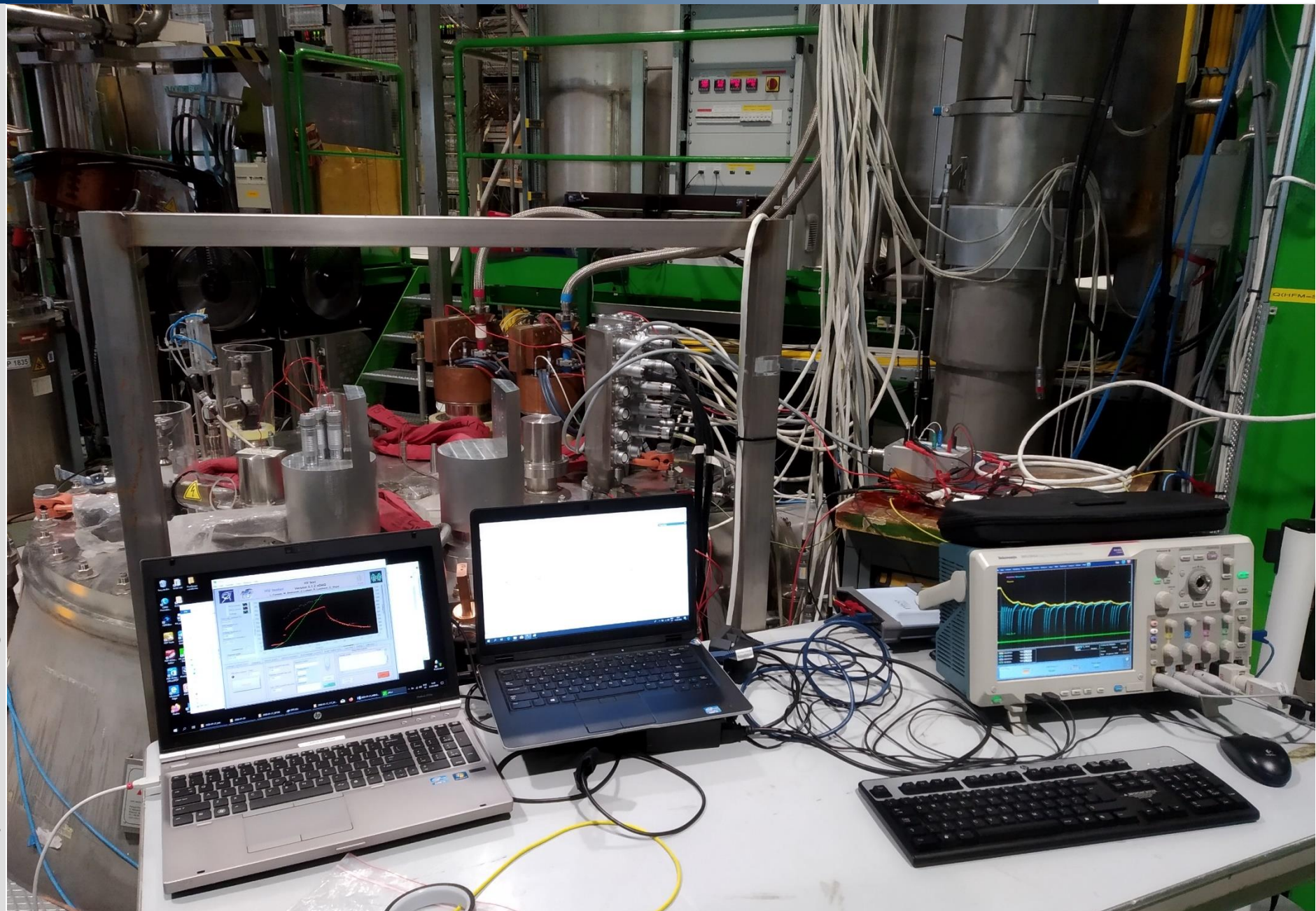
- QH 119R presented degradation after breakdown at 1291 V (200 K, 2.1 bar), while the other three circuits reached 1345 V
- Test programme stopped afterwards due to test station limitations at 200 K, 1.35 bar (1.1 to 1.3 kV)

**High voltage Test programme for January 2020 (link):**

1. In Superfluid Helium, 1.9 K, 1.1 bar:
   - HV tests at 1 kV (performed by SM18 team)
   - Provoked quench tests
   - HV insulation test at 3 kV
2. In gaseous Helium, 200 K, 3 bar:
   - HV 50x Endurance tests at 1 kV
   - HV insulation test at 1.3 kV and 1.6 kV



# Provoked Quench Tests



# Provoked Quench Tests - Description

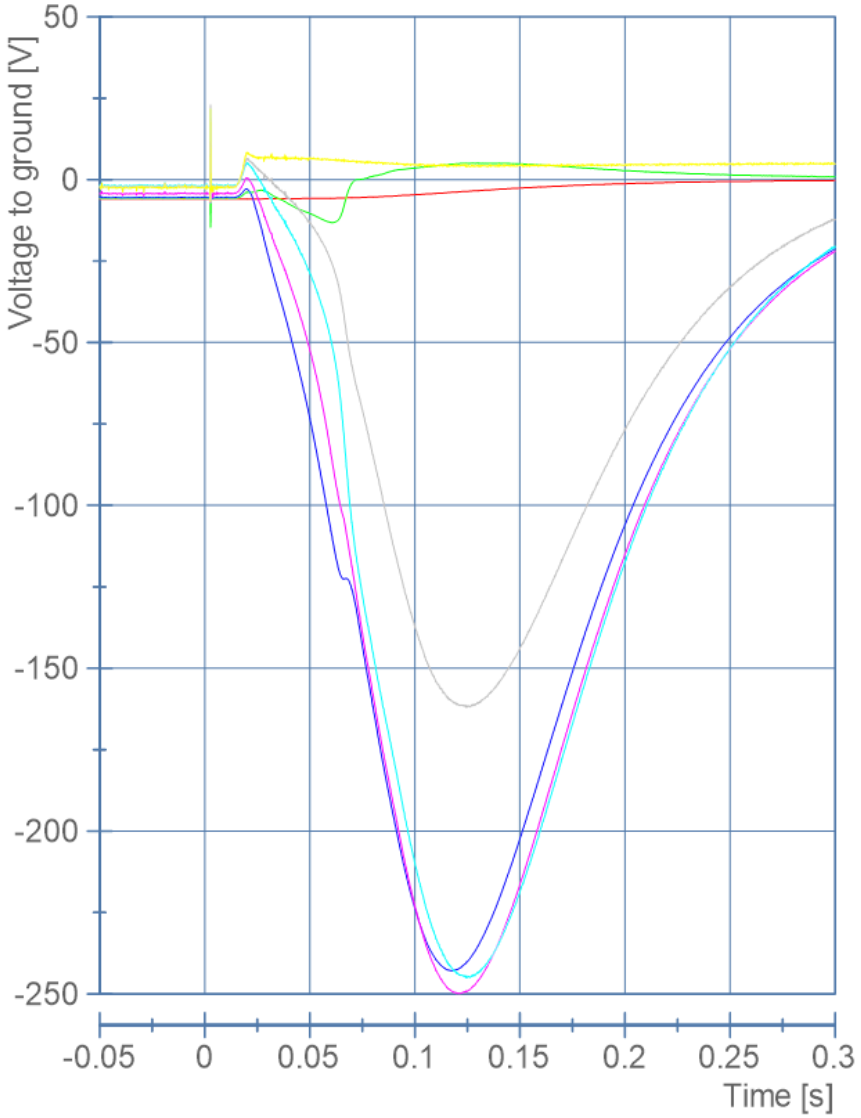
**Aim**: to test dielectric strength of QH-coil insulation during provoked quench.

## Test programme description:

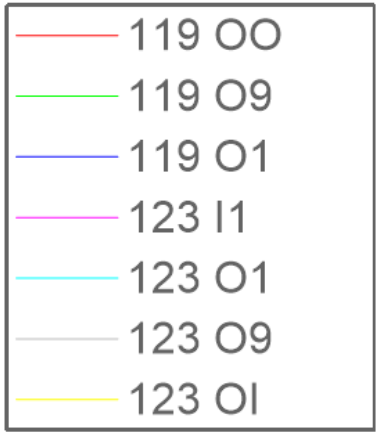
- Conditions: 1.9 K, 1.1 bar
- Current:
  - 3 kA, 6 kA, 11.85 kA
- Target heater-coil voltages:
  - 1 kV, 1.3 kV, 1.6 kV
- 1 QH circuit hi-potted during the test, while the other two circuits are used for protection.
- HV test level defined according to the target voltage heater-coil: ElQA voltage source defines a voltage heater-to-ground. A test at lower voltage was performed for each circuit to measure the voltage distribution in the coil:
  - Input voltage heater-to-ground = Target heater-coil voltage – unbalanced voltage (**on the outer layer Vtap closer to the hi-potted QH**)
- HV tests up to 1.6 kV were performed without power to verify insulation status.
- Energy Extraction was delayed to 1 second after QH fired.

| Step | Test procedure |
|---|---|
| 1 | Charge of 2 QH power supplies |
| 2 | Magnet powered up to target current |
| 3 | HV applied to tested heater |
| 4 | Stabilized conditions at HV plateau (~1 min) |
| 5 | QH manually fired |
| 6 | Energy Extraction delayed by 1s |
| 7 | HV continues being applied for ~2 min |

# Provoked Quench Tests – Voltage




| Channel | Max Abs Voltages | Voltage at 100ms |
|---|---|---|
| 119 OO | -5.91 | -4.61 |
| 119 O9 | -14.58 | 3.59 |
| 119 O1 | -242.92 | -223.37 |
| 123 I1 | -249.95 | -222.58 |
| 123 O1 | -245.10 | -209.52 |
| 123 O9 | -162.02 | -137.02 |
| 123 OI | -33.10 | 4.37 |

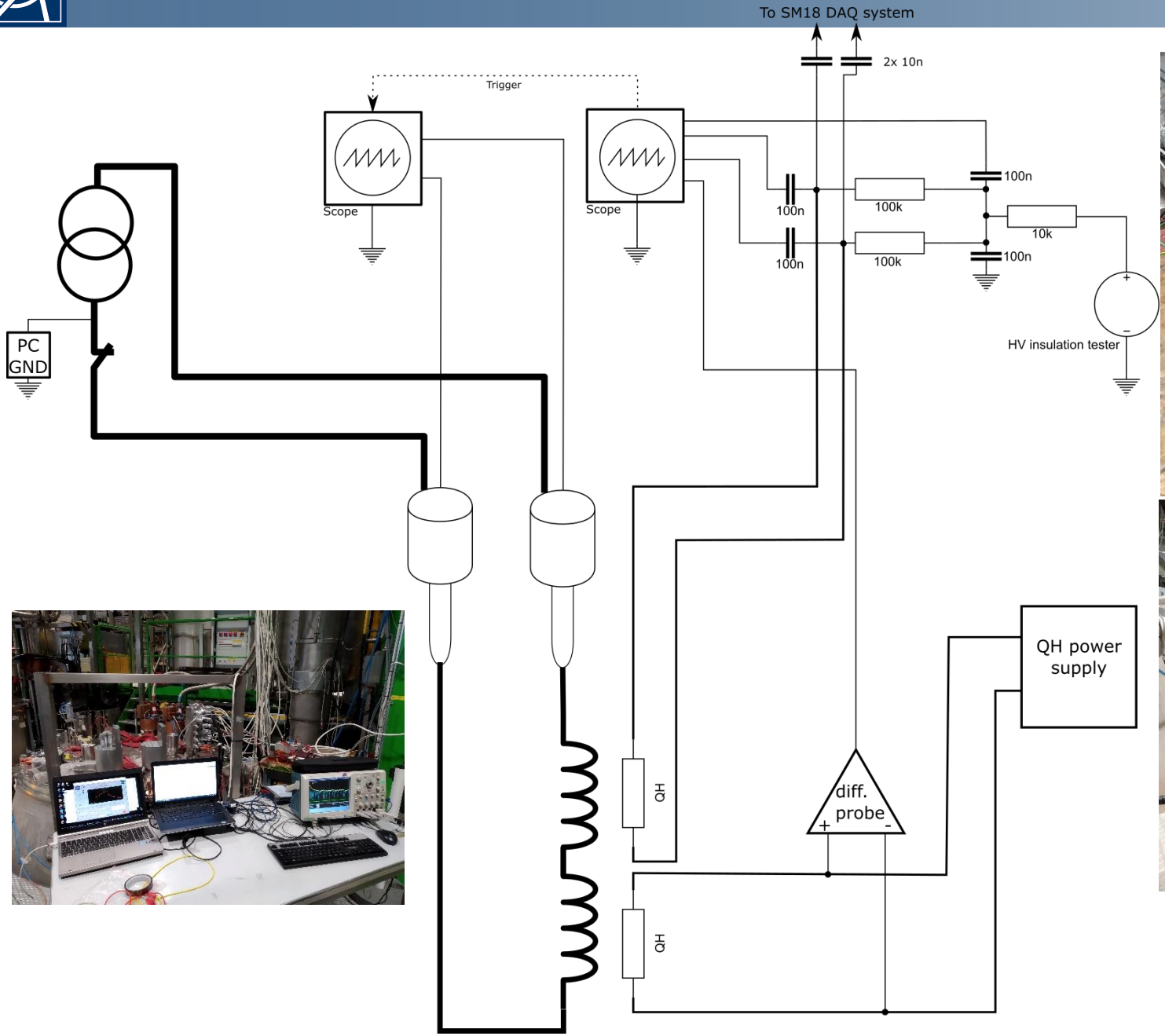



Measured coil-ground voltages at Inom

- QH123L: -66 V
- QH123R: -75 V
- QH119L: -250 V

Measured voltages on inner/outer layers of SP109, after provoked quench at 11.5 kA and HV on QH119L (*courtesy of Salvador Ferradas Troitino*)

# Provoked Quench Tests – Setup



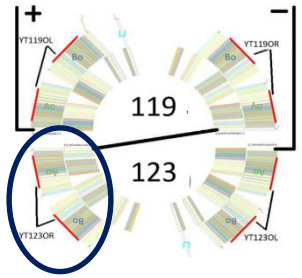



# Provoked Quench Tests – Results

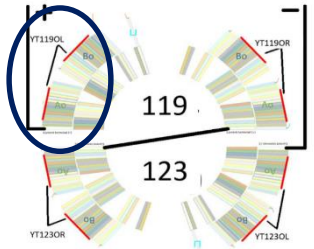
## QH123R

- 4 quenches provoked at 11.85 kA, target voltage heater-to-coil:
  - 0.5 kV
  - 1 kV
  - 1.3 kV
  - 1.6 kV

  } **all tests passed**




- Insulation was tested up to 1.6 kV without current before final provoked quench.




## QH119L

- Similar to QH123R: 4 quenches at 11.85 kA, same target voltages, **all tests passed**.
- Breakdown at **1590 V** without current, not to magnet circuit. Okay at 1.5 kV.
- This limitation did not influence the provoked quench test programme, as the unbalance on QH119L is -250 V, therefore the voltage heater-to-ground applied was **1350 V** (to reach 1.6 kV heater-coil).

# Provoked Quench Tests – Results



## QH123L

- Multiple breakdowns during quench tests:

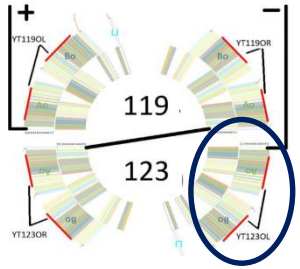
| | 1 kV | 1.3 kV | 1.6 kV |
|---|---|---|---|
| 0 kA (HV tests between firings) | 1 passed | 5 passed | 1 breakdown |
| 3 kA | 1 passed | 2 passed<br>3 breakdowns | 2 breakdowns |
| 6 kA | - | 1 breakdown | 2 breakdowns |
| 11.85 kA | 1 passed | 2 breakdowns | - |

| | 1.3 kV | 1.6 kV |
|---|---|---|
| 3 kA | 1st. Ok, with PD<br>2nd. Breakdown 8.65 s<br>3rd. Breakdown 3.3-6.2 s<br>4th. Ok<br>5th. Breakdown 4.5 s | 1st. Breakdown 18.5 s<br>2nd. Breakdown 4.5-6.7 s |
| 6 kA | Breakdown 13.4 s | 1st. Breakdown 2.3 s<br>2nd. Breakdown 3.1-4.8 s |
| 11.85 kA | 1st. Breakdown 7.2 s<br>2nd. Breakdown 8 s | - |

*Main objective:*

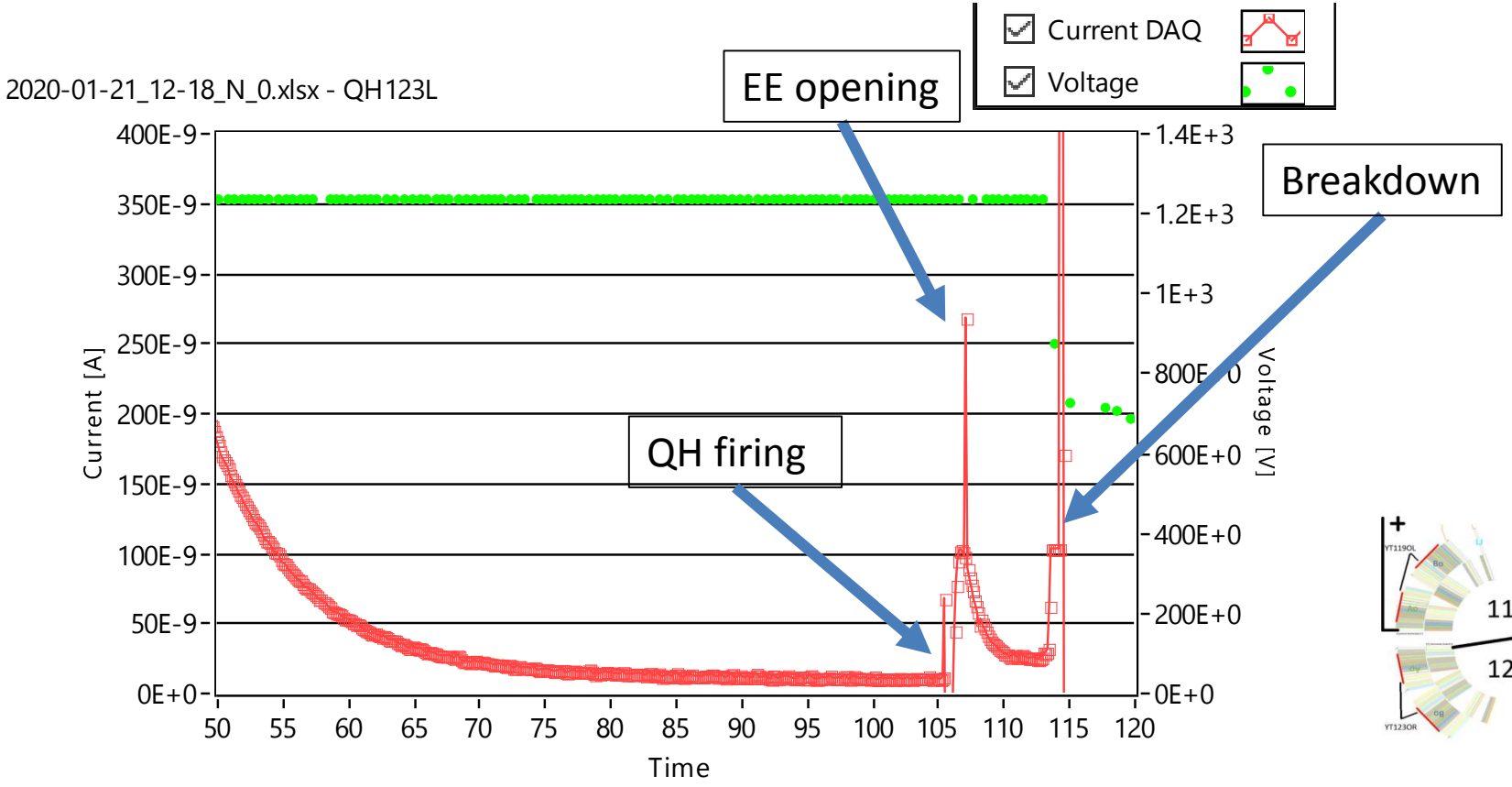
- *Test the maximum number of combinations of target heater-coil voltage and current.*
- *Check performance and pattern of time between heaters firing and breakdown.*

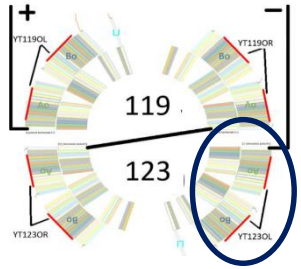
**No degradation observed**



# Provoked Quench Tests – Results of 123L

- No breakdowns were observed in the expected time range after quench (order of 100 ms – 300 ms)
- ~2 – 18 s after quench the conditions change sufficiently to reveal an insulation weakness between magnet circuit and quench heater

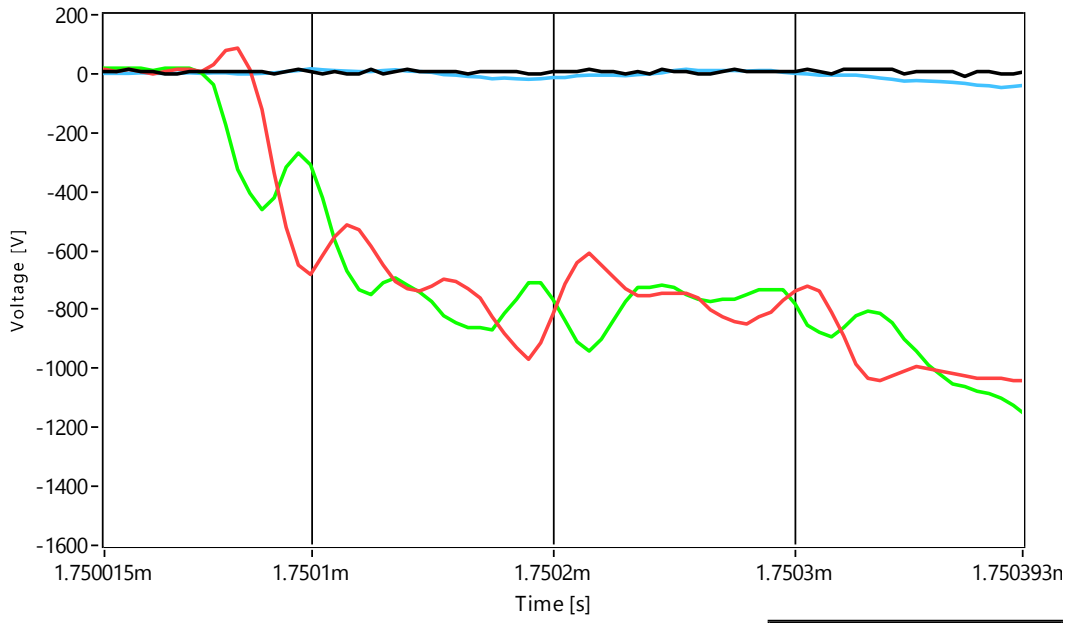


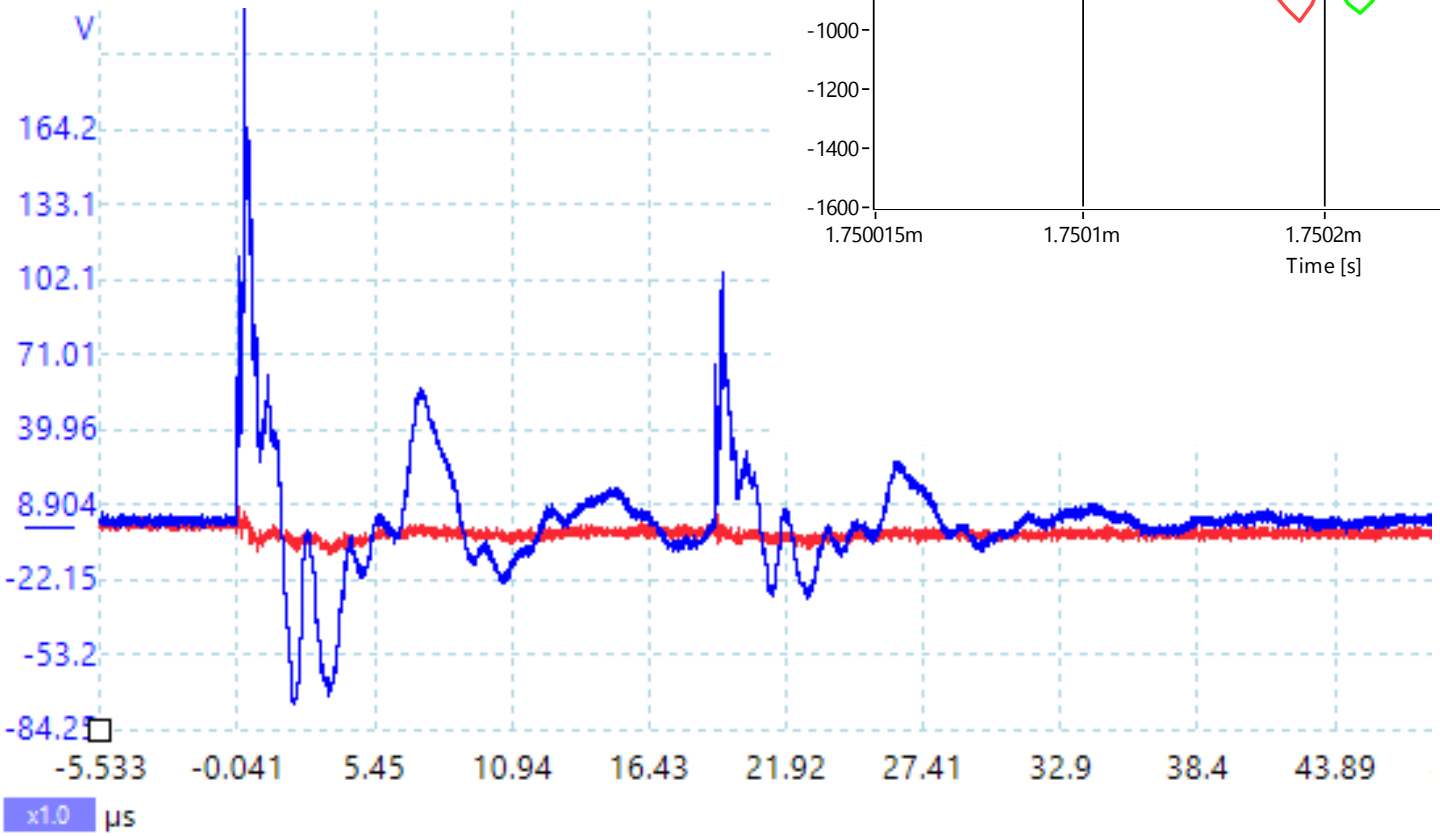



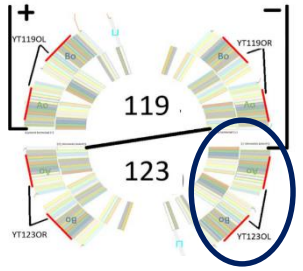
# Provoked Quench Tests – Results of 123L

- Voltage on magnet current leads shows that breakdown occurred between QH and magnet circuit

*The breakdown signatures are perfectly reproducible*



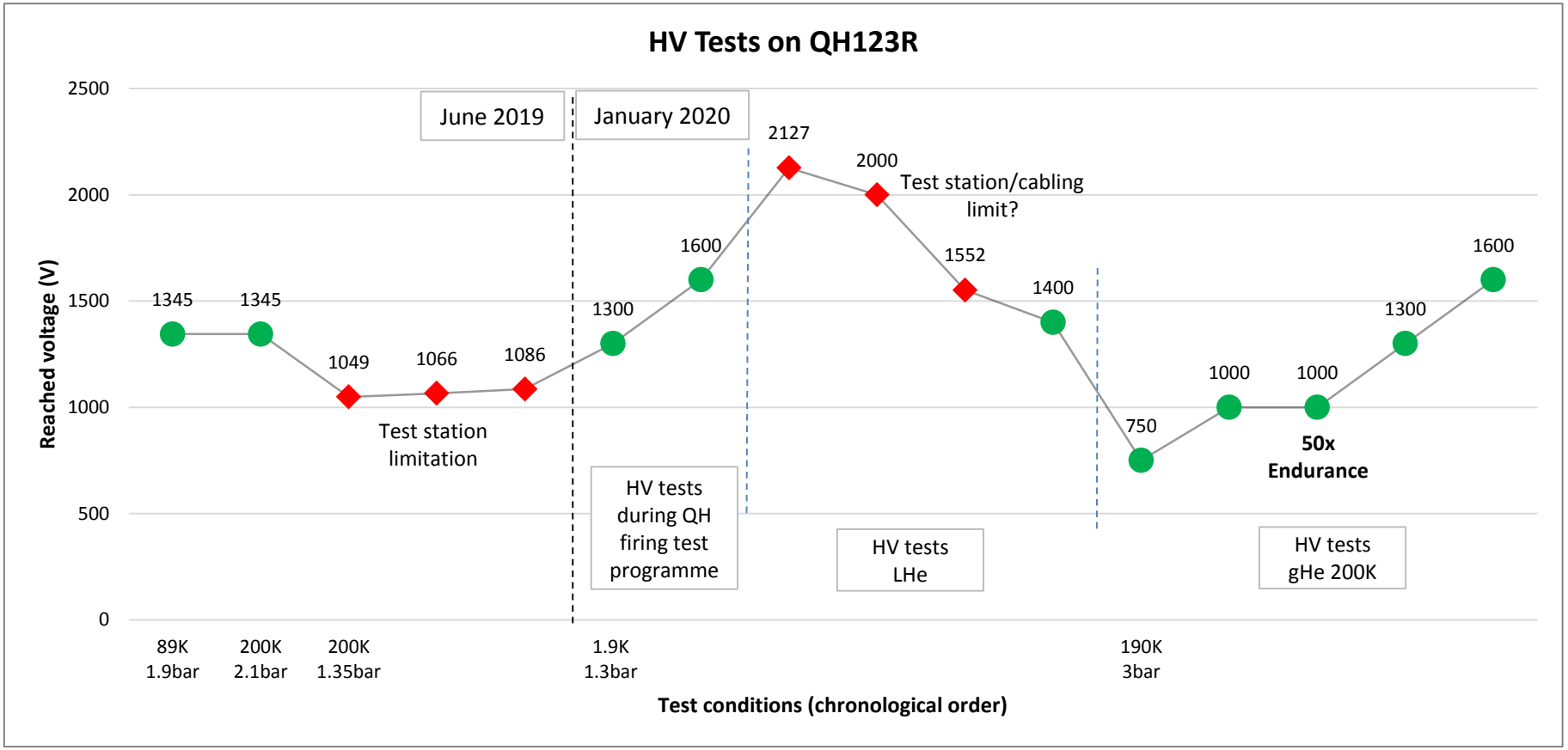
# HV Insulation tests in LHe and GHe

# HV Insulation tests in LHe and GHe

- HV tests were performed in all quench heater circuits to coil and ground
  - QH119R (not tested up to this moment) was also included
  - Non-tested QH circuits grounded
  - Measurement system unchanged

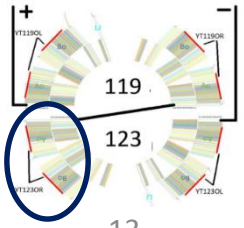
- Tests in Superfluid Helium, 1.9 K, 1.1 bar:
  - HV insulation test at 3 kV
- Tests in gaseous Helium, 200 K, 3 bar:
  - 50x endurance tests at 1 kV
  - HV insulation test to 1.6 kV

# HV Tests – Summary of QH123R



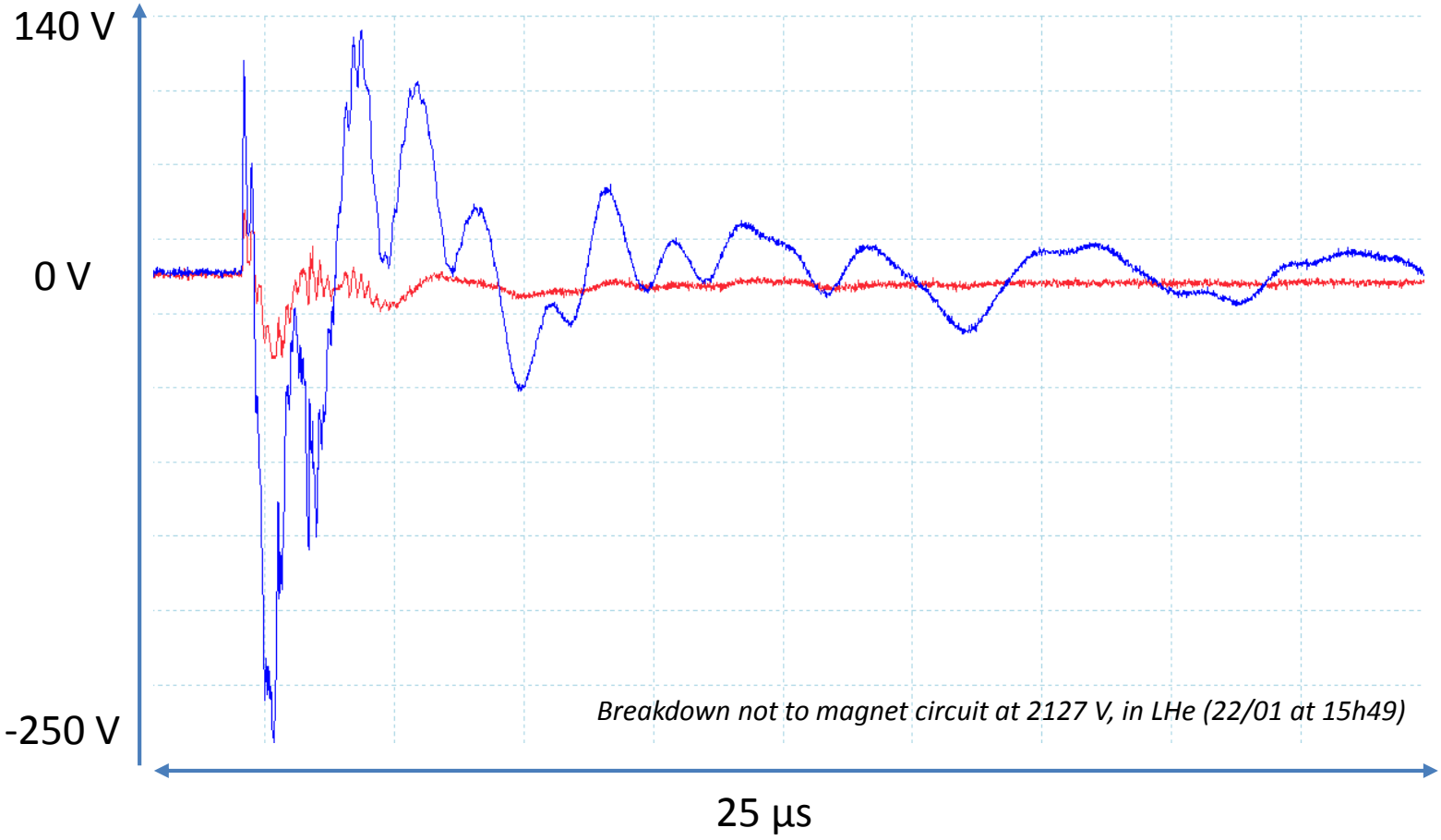

- Breakdowns in LHe **not** to the magnet circuit (see next slide). However some degradation on the fault location was observed.

- At 200 K, 3 bar, the circuit withstood the endurance test and a HV test up to 1.6 kV.



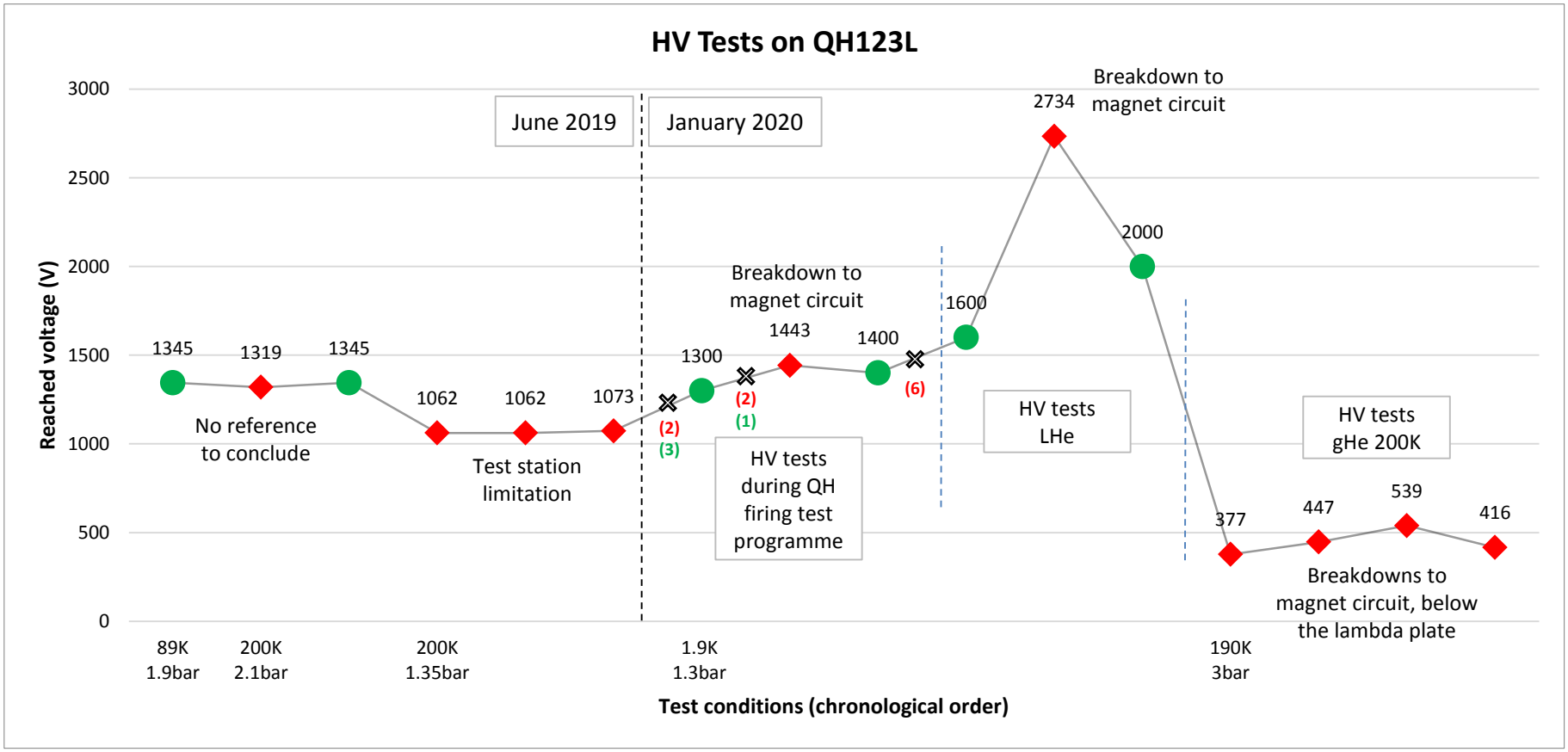
# HV Tests – QH123R Breakdown Analysis

- Breakdown at 2127 V in LHe. Resulting voltages on magnet leads show a peak negative voltage – breakdown **not** to magnet circuit.
- Following breakdowns in LHe on the same circuit presented similar results.

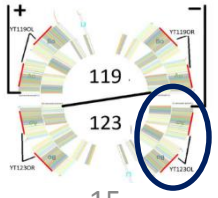



*Breakdown not to magnet circuit at 2127 V, in LHe (22/01 at 15h49)*

# HV Tests – Summary of QH123L

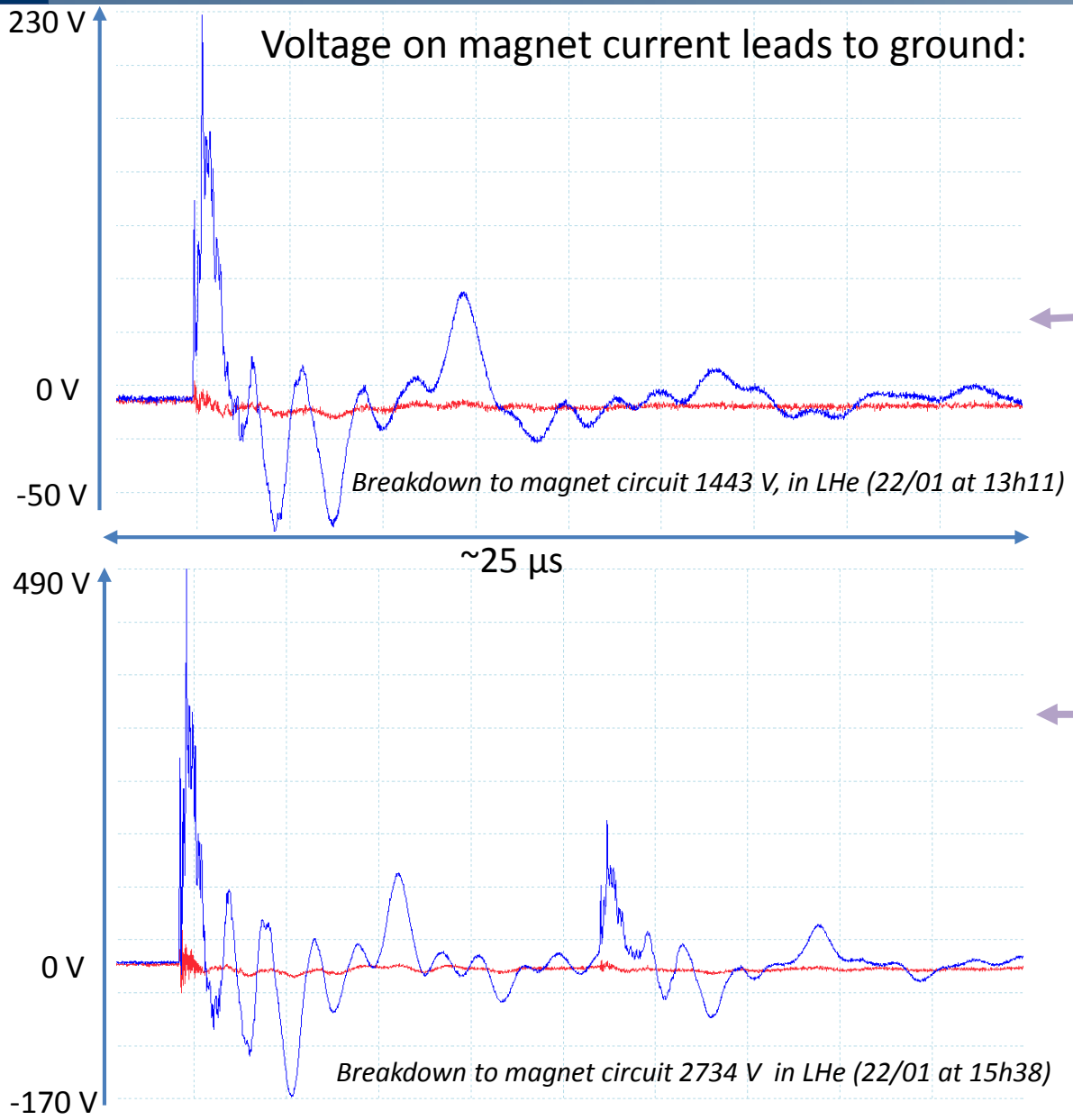


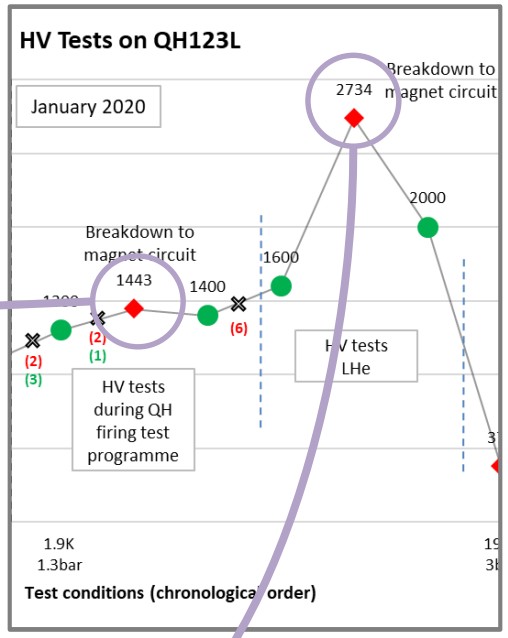

- Quench heater with the breakdowns during provoked quenches.
- Breakdowns in LHe at 1443 V and 2734 V were **to magnet circuit** and showed similar behaviour.
- At 200 K, 3 bar, the circuit failed at ~400 V
- There is an insulation weakness between this quench heater and magnet circuit
- *In addition, during previous breakdowns, the insulation might have degraded*



# HV Tests – QH123L Breakdown Analysis





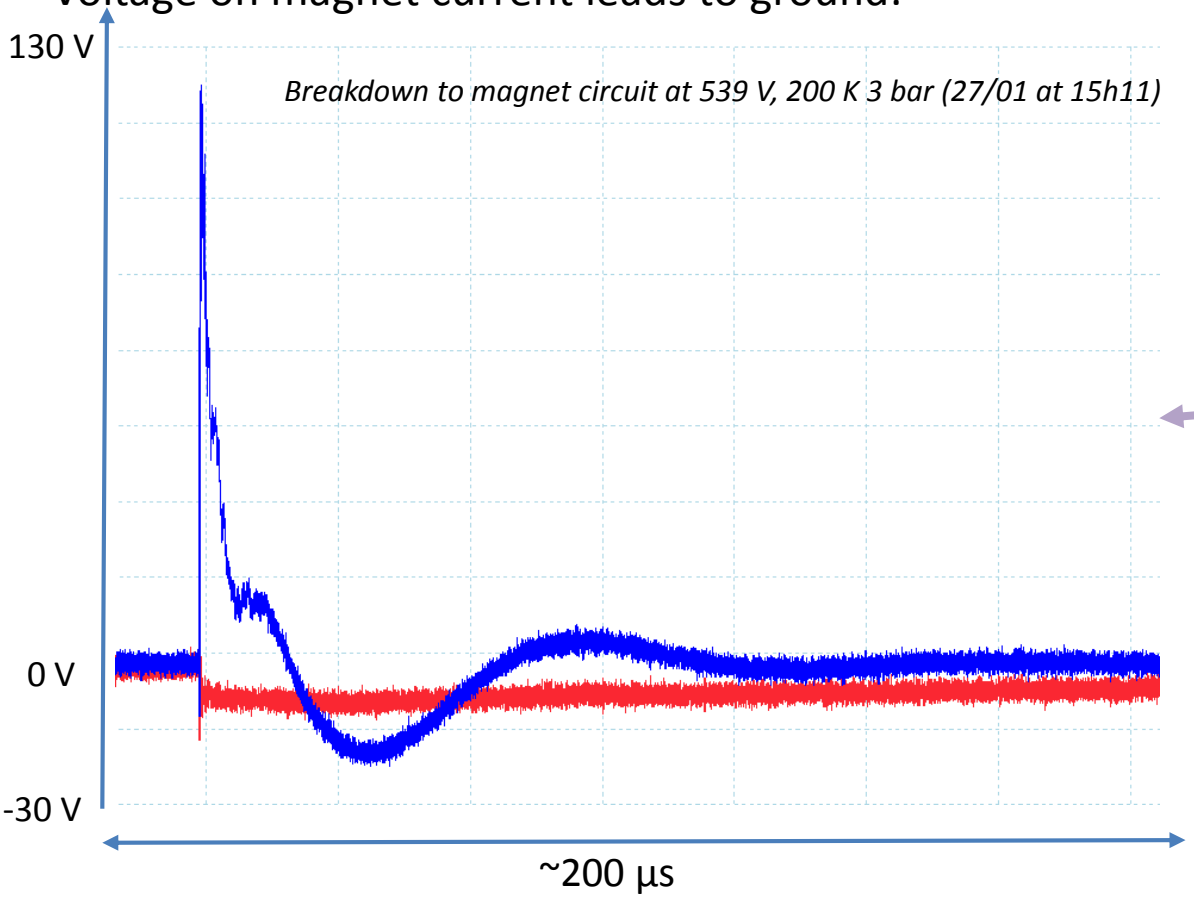



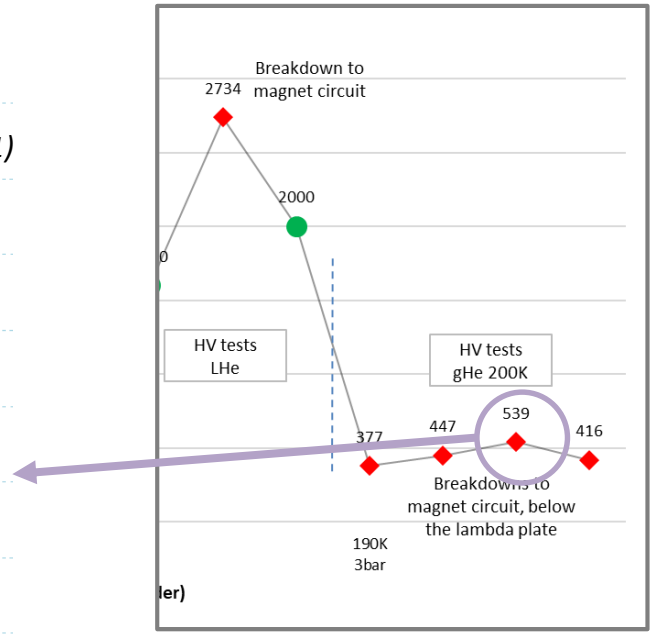

- Breakdowns in LHe
- The breakdown signatures are very similar: they are located at the same spot

# HV Tests – QH123L Breakdown Analysis



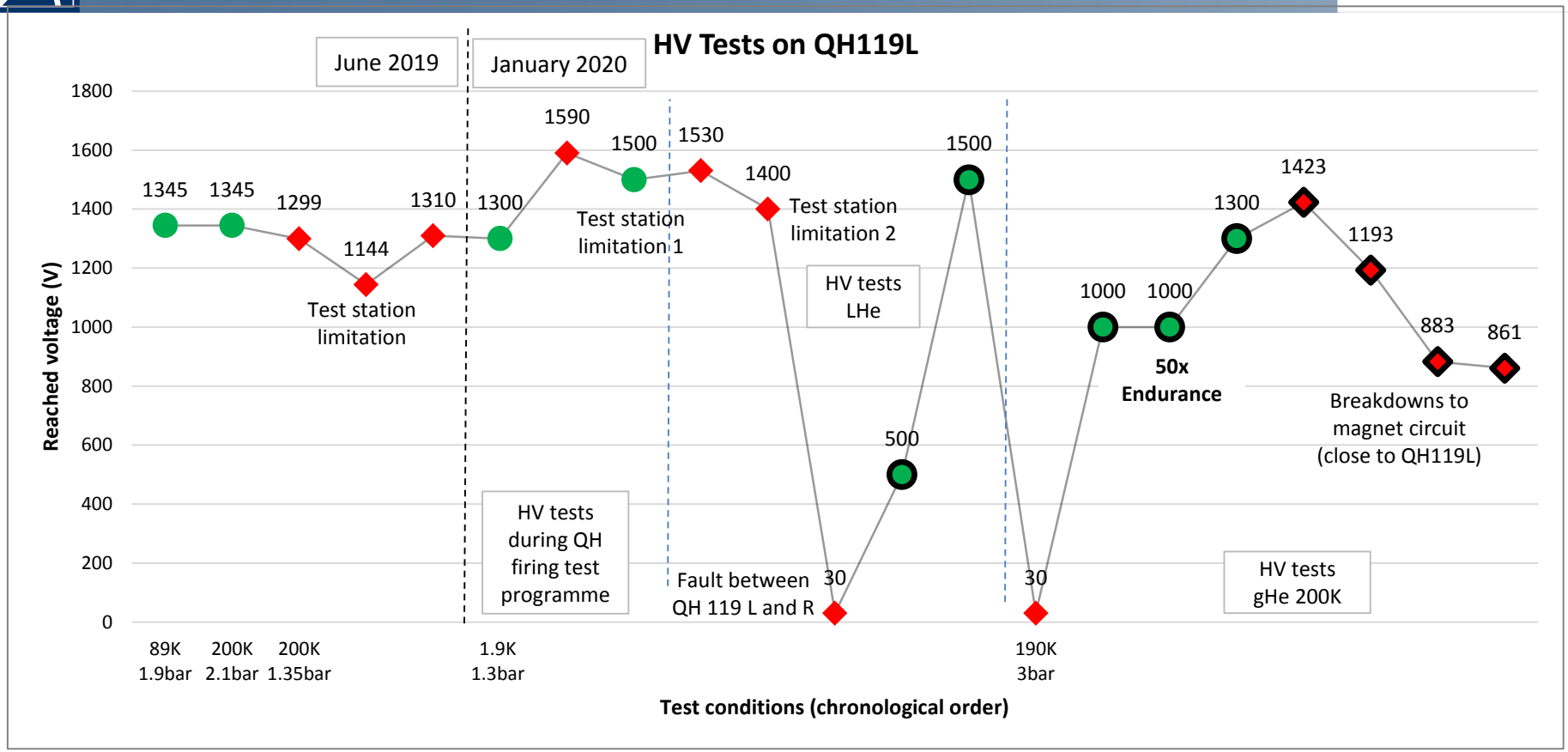
Voltage on magnet current leads to ground:



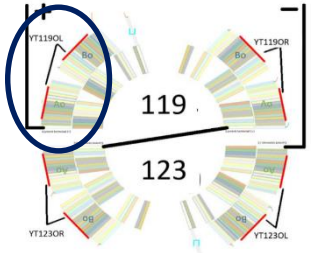




- DC cables disconnected
- Test set-up modified
- Breakdown signatures not comparable

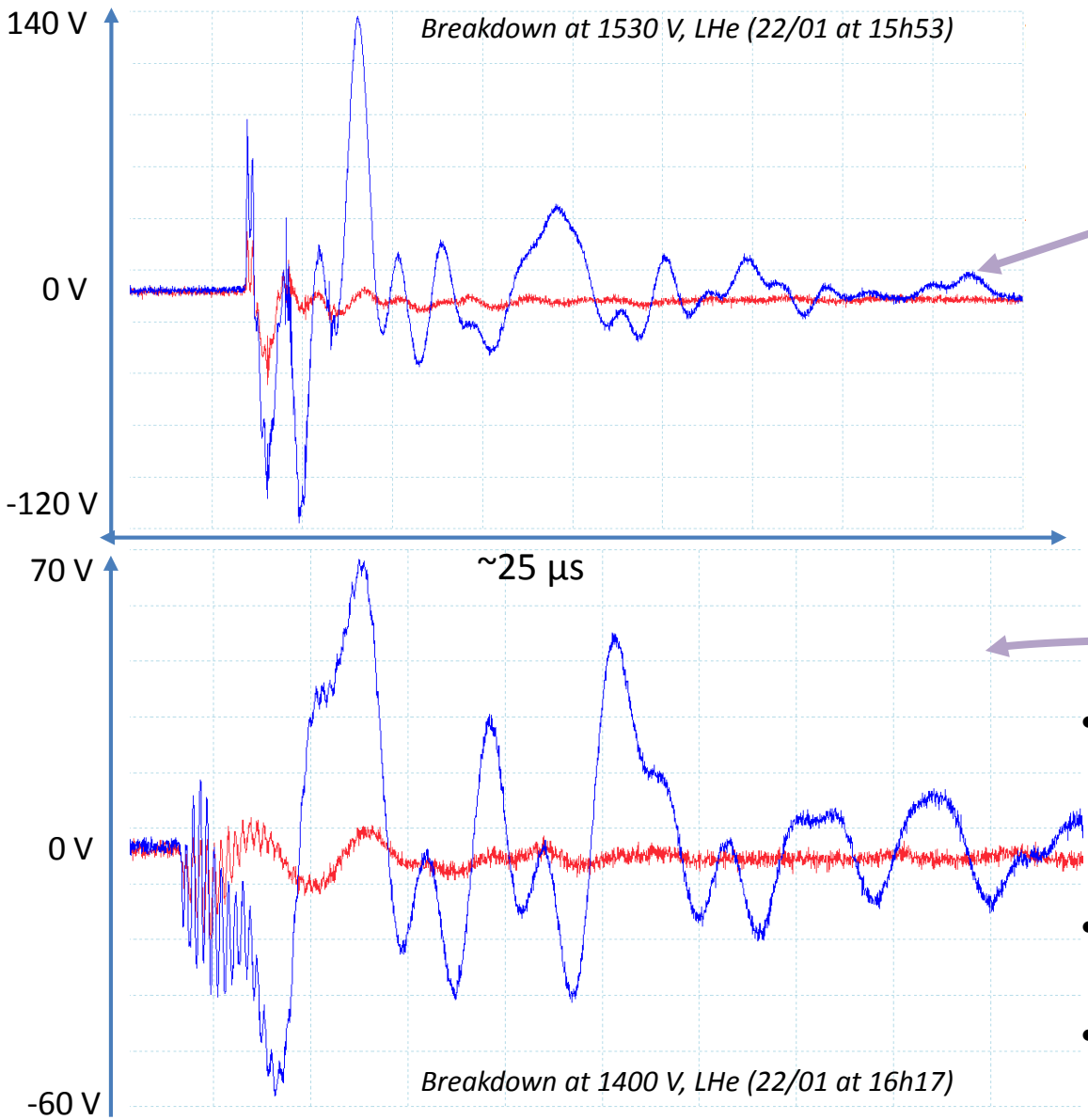
# HV Tests – Summary of QH119L

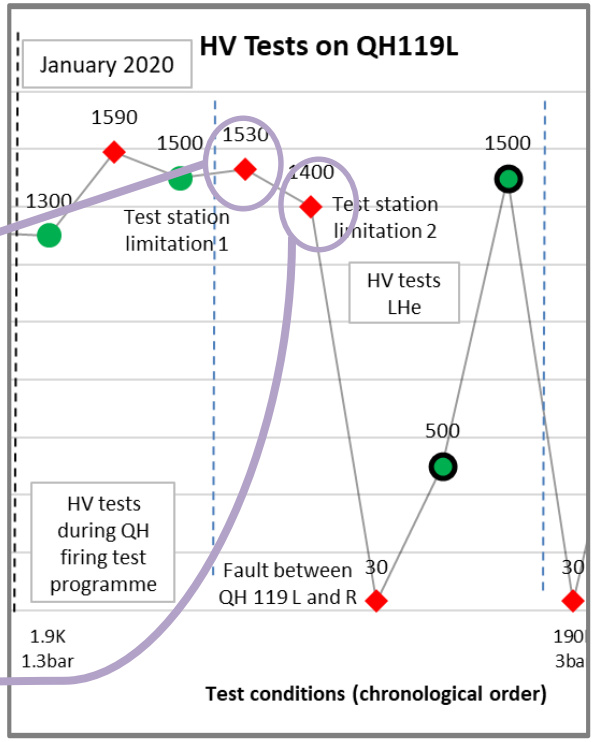



- In LHe two distinct fault types were detected, both related to the test station
  - Second one is between QH119L and QH119R
- QH119L and QH119R tested together:
  - 1500 V in LHe -> **Test OK**
  - 1000 V endurance test (50x) -> **Test OK**
  - 1300 V at 200 K, 3 bar -> **Test OK**
  - 1400 V at 200 K, 3 bar -> **Breakdown to magnet circuit and degradation**



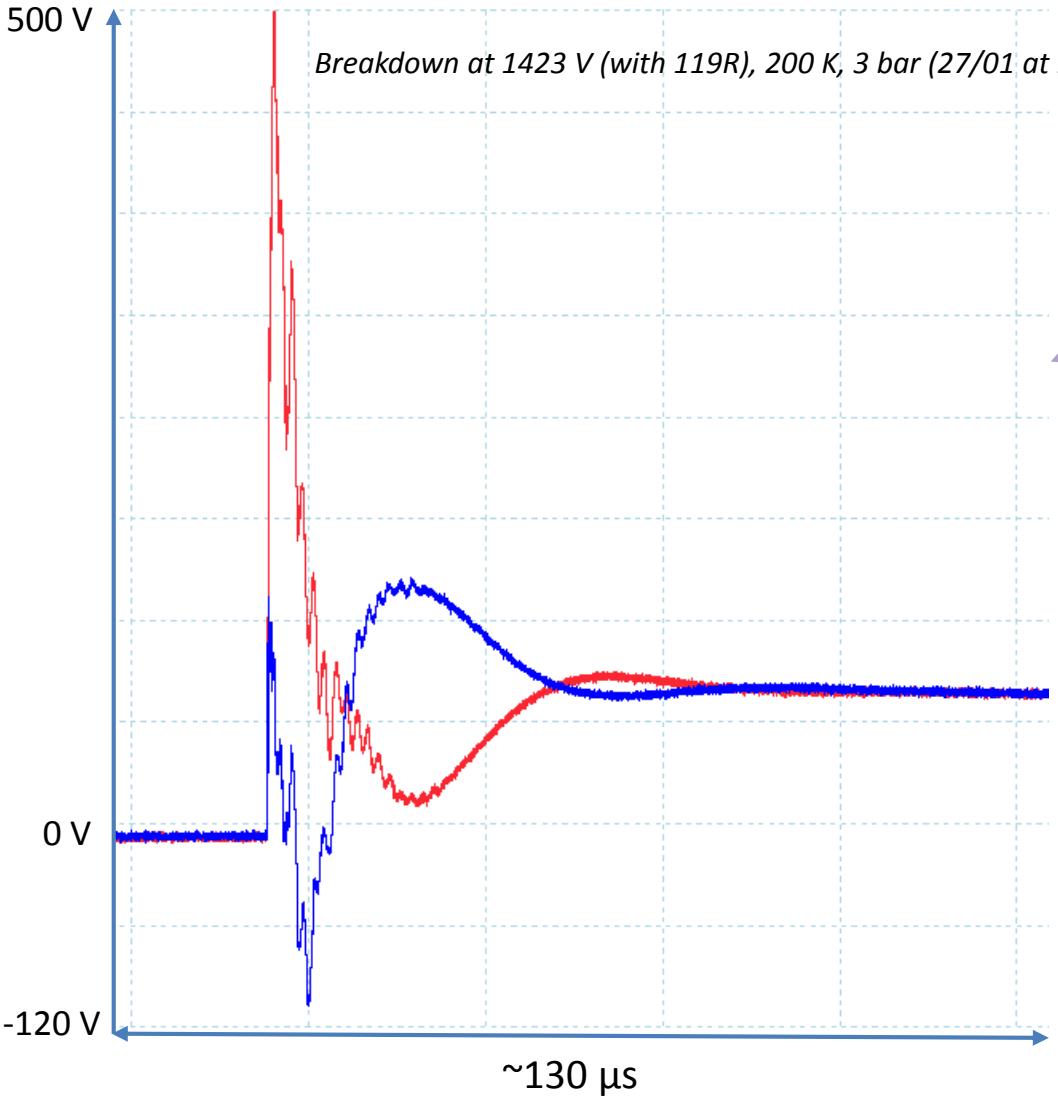
# HV Tests – QH119L Breakdown Analysis

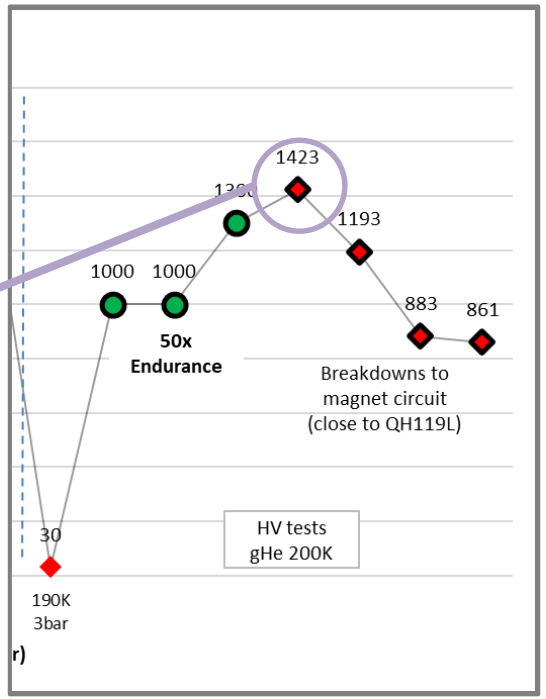



- Both breakdowns are **not** to the magnet circuit
  - Most likely test station limitation – to be checked
- Different signature – two different fault origins
- QH119R was tested in the mean-time and had a breakdown

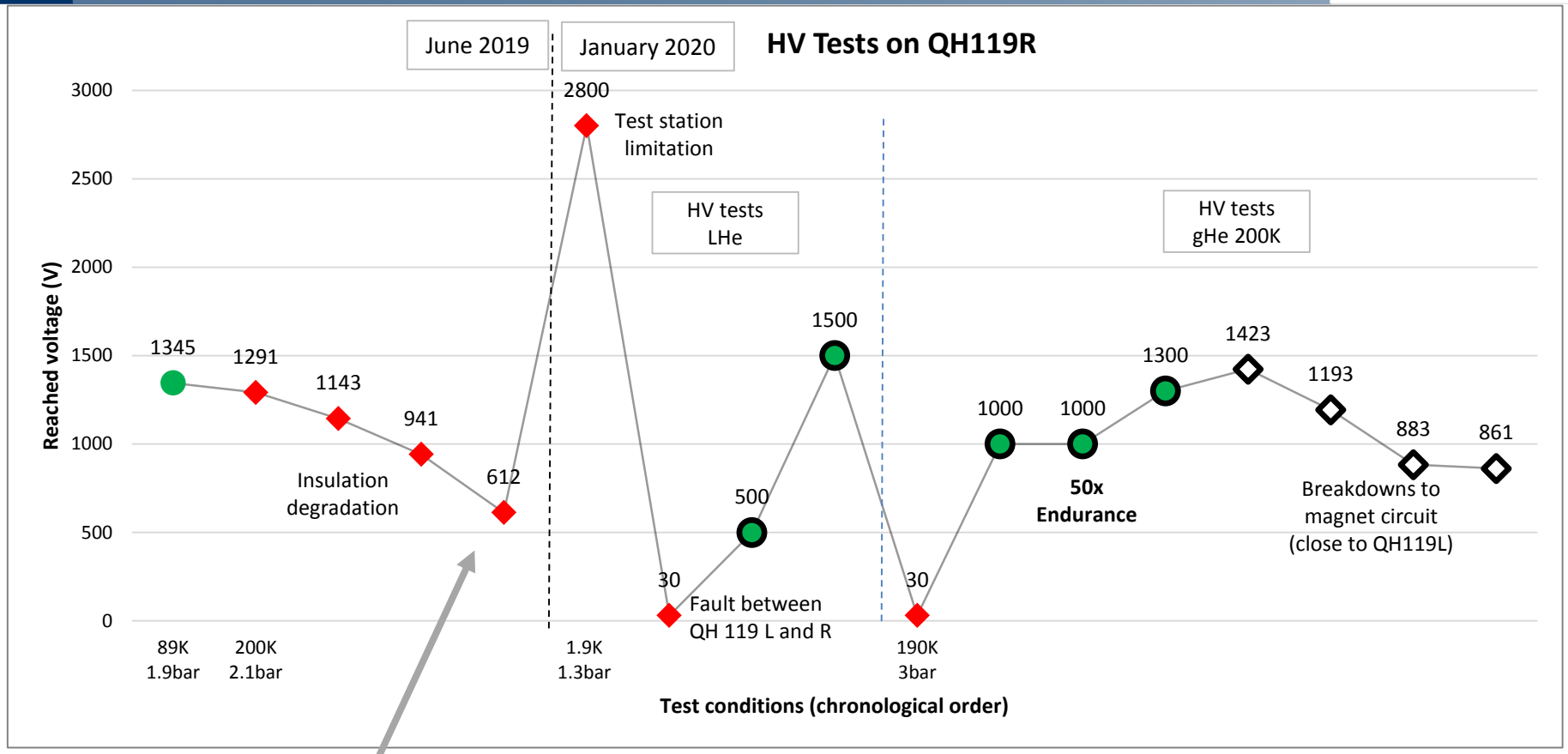
# HV Tests – QH119L Breakdown Analysis



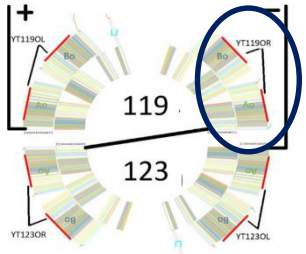




- Breakdown to the magnet circuit
- Third fault on this QH
- In GHe the breakdown voltage is lower, below the test station limitation level

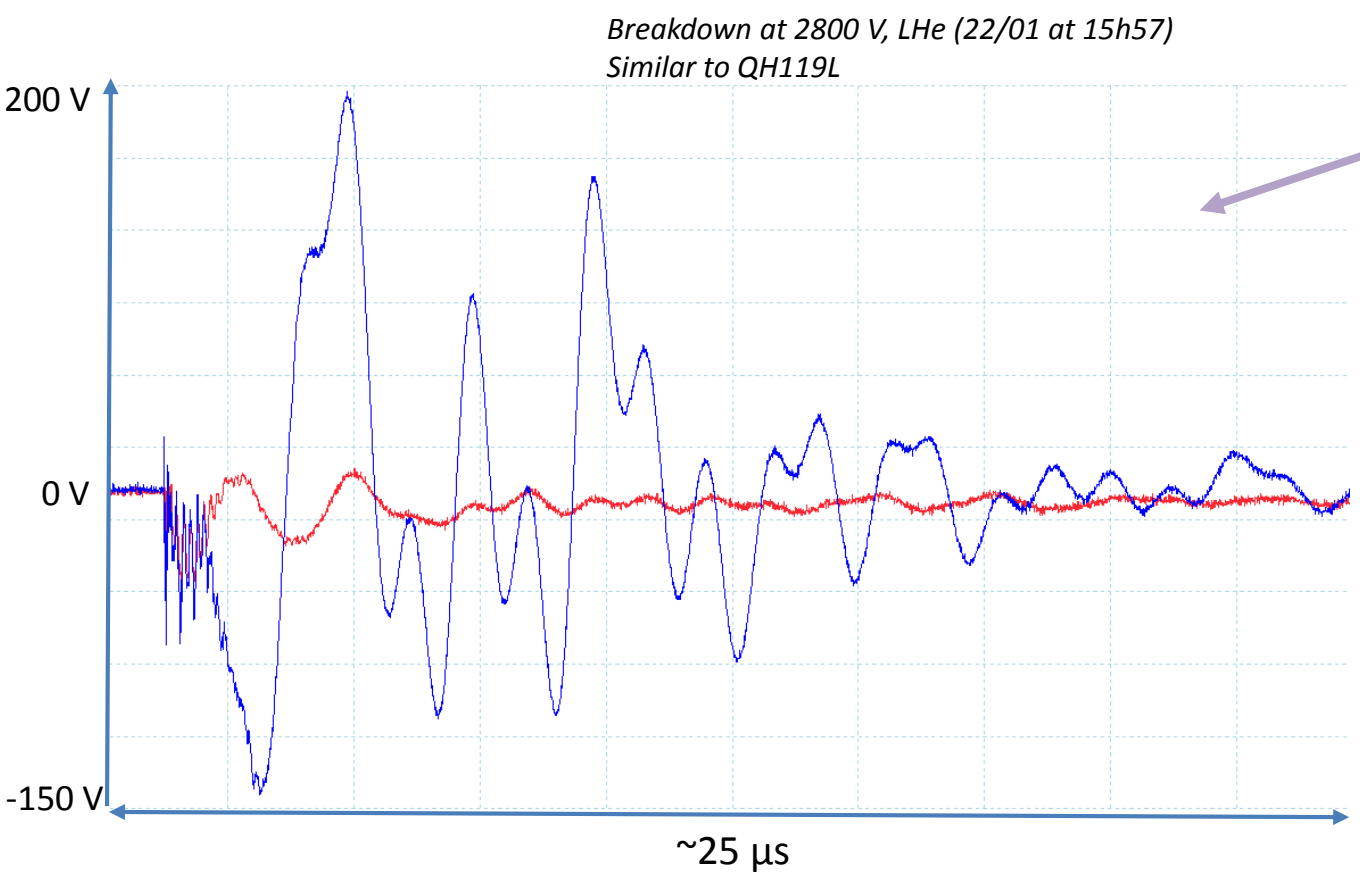
# HV Tests – Summary of QH119R

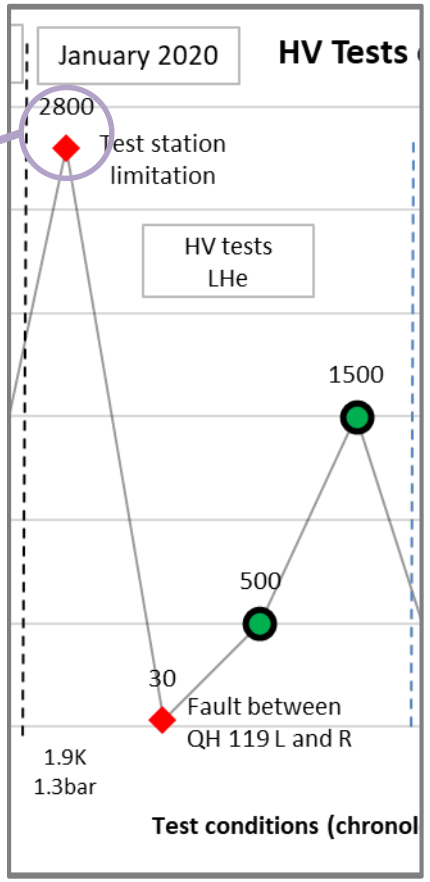



- Based on the June test campaign this QH was considered 'broken'
- In LHe the breakdown occurred at 2800 V, most likely it was the test station limitation (path towards QH119L)
  - In LHe the breakdown voltage of the QH to magnet circuit was not reached
- QH119L and QH119R tested together
- In GHe this QH withstood 1400 V, and couldn't be tested higher because of the limitation in QH119L



# HV Tests – QH119R Breakdown Analysis




- In LHe the breakdown occurred at 2800 V, most likely it was the test station limitation (path towards QH119L)

# Summary Table of SP109 HV Tests

| | LHe, 1.9 K, 1.1 bar | | | | GHe, 200 K, 3 bar | | |
|---|---|---|---|---|---|---|---|
| | **HV to 1 kV (by SM18)** | **Provoked Quenches** | **HV to 3 kV** | | **HV to 1 kV** | **50x 1 kV (Endurance)** | **HV to 1.6 kV** |
| **QH123L** | **Ok** | **Breakdowns** 1.4kV and during QH firing (at 3, 6 and 11.85 kA) | **Breakdown** at 2.7kV to magnet circuit. **Ok** at 2 kV | | **Breakdown** to magnet circuit at 337-539 V | - | - |
| **QH123R** | **Ok** | **Ok** | Test station limitations. **Ok** at 1.4 kV | | **Ok** | **Ok** | **Ok** |
| **QH119L** | **Ok** | **Ok** (HV test station limitation at 1.6 kV) | **Fault** to QH119R | **Ok** at 1.5 kV | **Ok** | **Ok** | **Breakdown** to magnet circuit at 1.4 kV, then degradation (close to QH119L) |
| **QH119R** | - | - | Test station limitation at 2.8 kV. **Fault** to QH119L. | | | | |

Summary of all HV tests performed (in chronological order), per circuit configuration.

# Conclusions (1/2)

## Tests in LHe, 1.9 K, 1.1 bar

- First of a kind HV tests of quench heaters during quench heater provoked quench at high current.

- Immediately after quench, when the voltage QH-coil reaches the highest level, no breakdown was observed.

- 2 QH were not susceptible to the changes in cryogenic conditions following quench, one QH was:
  - A weakness between magnet circuit and QH exists in liquid helium bath, ~2-18 s after quench the conditions change sufficiently to lead to a breakdown.
  - No degradation observed during these tests.

# Conclusions (2/2)

## Tests in gaseous He 200 K, 3 bar

- In some cases there is a visible test station limitation, likely at the level of warm side connectors:
  - The level of insulation on the test station was significantly improved since the last series of tests (in June).
  - Short between QH119L and R was localised in the fisher connector after the magnet was removed from the cryostat.

- After breakdowns, insulation degradation was often observed, especially in cases where the breakdown is suspected to occur between the quench heater and coil.

- Endurance test did not induce any trace of degradation:
  - If there are faults, HV tests can make them more visible.

# Backup slides

# Provoked Quench Tests – Results of 123L

| Date | Time | Test Type | Current [kA] | Voltage QH-ground | Target V_QH-coil | Measured V_QH-coil | Comments |
|---|---|---|---|---|---|---|---|
| 20/01 | 09h51 | HV | - | 1000 V | - | - | Ok. Check of insulation |
| | 10h01 | QH firing (2a) | 3 | 1000 V | - | - | Ok. |
| | 10h18 | QH firing (2) | 11.85 | 925 V | 1000 V | 991 V | Ok. |
| | 17h23 | HV | - | 1300 V | - | - | Ok. Check of insulation |
| | 17h30 | QH firing (5a) | 3 | 1234 V | - | - | Ok. Very strange signal in all channels. Increase of current for 30 s. |
| | 17h47 | QH firing (5) | 11.85 | 1234 V | 1300 V | 1311 V | Breakdown, 7.2 s after the quench. |
| | 18h21 | HV | - | 1300 V | - | - | Ok, with small partial discharge. |
| 21/01 | 10h05 | HV | - | 1300 V | - | - | Ok. |
| | 10h19 | QH firing (5a-rep) | 3 | 1234 V | - | - | (Change of triggering to falling voltage on tested QH instead of differential on active QH). Breakdown after 8.65 s. |
| | 11h18 | HV | - | 1300 V | - | - | Ok. |
| | 11h35 | HV + firing | 0 | 1300 V | - | - | Ok. Special test. |
| | 11h44 | QH firing (5a-rep 2) | 3 | 1234 V | - | - | Repeated: Breakdown. One spike at 3.28 s and a second spike at 6.2 s (Much narrower than the other breakdowns). |
| | 12h02 | QH firing (5a-rep 3) | 3 | 1234 V | - | - | Ok. Repetition of last test. |
| | 12h18 | QH firing (5-rep) | 11.85 | 1234 V | 1300 V | 1311 V | Breakdown after 8s. |
| 22/01 | 13h11 | HV (8aa) | - | 1600 V | - | - | Breakdown at 1443 V, to magnet circuit. |
| | 13h21 | HV (8ab) | - | 1400 V | - | - | Ok. (Test to check insulation at lower voltage and define test level). |
| | 13h28 | QH firing (8a) | 3 | 1400 V | - | - | Breakdown after 18.5 s. |
| | 13h45 | QH firing (8b) | 6 | 1400 V | - | - | Breakdown after 2.3 s. |
| | 14h05 | QH firing (8c) | 6 | 1234 V | - | - | Breakdown after 13.4 s. |
| | 14h31 | QH firing (8d) | 3 | 1234 V | - | - | Breakdown. Two narrow spikes. One at 4.44 and second at 4.485s. |
| | 14h46 | QH firing (8e) | 3 | 1400 V | - | - | Breakdown. Discharge after 4.5 s and then again at 6.7 s. |
| | 15h05 | QH firing (8f) | 6 | 1400 V | - | - | Breakdown. Discharge after 3.05 s (narrow and 10 V peak) , 3.35s (narrow and 20 V peak) and again at 4.75s. Repetition of test 8b to check time to breakdown. |