Machine Protection Panel Meeting

Analysis of the LHCb VELO RF Foils Incident and First Actions

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On behalf of the **TE-VSC** Group

Outline

- **Context**
  - The VELO Vacuum System
  - Balancing Mode and Overpressure Safety System
  - Reading Pressure Switches
- **Incident Analysis**
  - Sequence of Events
  - Consequences
- **Incident Recovery**
  - Immediate Actions
  - Vacuum System Recovery (Summarized)
- **Safety System Redesign**

TE-VSC Team Involved

G. Bregliozzi
D. Calegari
N. Chatzigeorgiou
P. Chiggiato
R. Ferreira
C. Garion
M. Morrone
G. Pigny
J. Sestak

Context

VELO Vacuum System

The VELO Vacuum System was designed and built by Nikhef. The responsibility for the system was agreed and taken over by TE-VSC in 2011 (https://edms.cern.ch/document/681957/). We have since then experienced excellent cooperation between the TE-VSC and LHCb VELO Teams.

Electrical design of the VELO Vacuum System was left **essentially unchanged**

- Original layout of the controls rack, electronics, wiring, and overpressure safety system HW

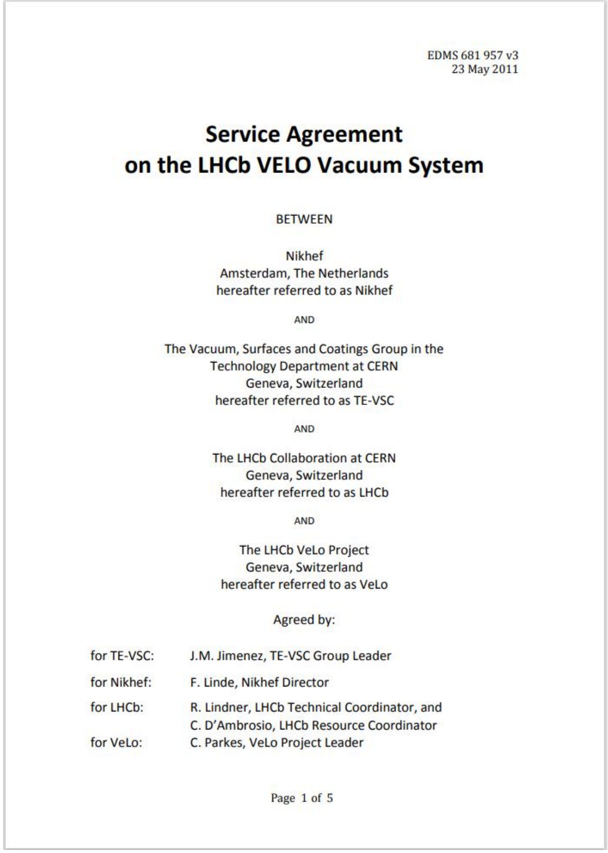
New Control System software (PLC/SCADA) was developed using our **Vacuum Framework** (deployed in LS2)

- Additionally, the PLC and all PLC modules were replaced with newer versions

Some **upgrades** and **improvements** were done by TE-VSC during LS2:

- Replacement of all pump controllers (turbo and ion) with newer versions
- Redundancy added to all main power supplies
- New hardware to provide data to the Detector Safety System

System successfully **recommissioned in October 2020.**


EDMS 681 957 v3
23 May 2011

Service Agreement
on the LHCb VELO Vacuum System

BETWEEN

Nikhef
Amsterdam, The Netherlands
hereafter referred to as Nikhef

AND

The Vacuum, Surfaces and Coatings Group in the
Technology Department at CERN
Geneva, Switzerland
hereafter referred to as TE-VSC

AND

The LHCb Collaboration at CERN
Geneva, Switzerland
hereafter referred to as LHCb

AND

The LHCb VeLo Project
Geneva, Switzerland
hereafter referred to as VeLo

Agreed by:

for TE-VSC:	J.M. Jimenez, TE-VSC Group Leader
for Nikhef:	F. Linde, Nikhef Director
for LHCb:	R. Lindner, LHCb Technical Coordinator, and C. D'Ambrosio, LHCb Resource Coordinator
for VeLo:	C. Parkes, VeLo Project Leader

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Balancing Mode and Safety System

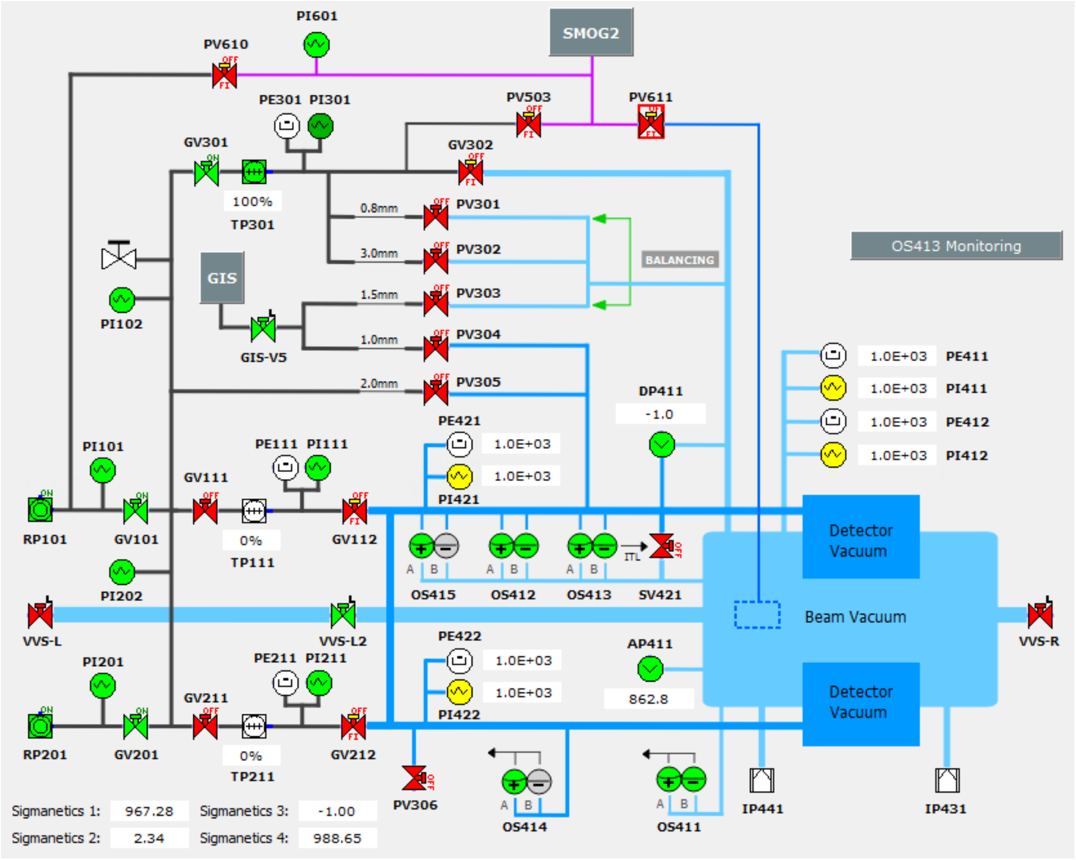
In order to protect the integrity of the RF foil, the Control System is designed to keep the pressure differential between Beam and Detector volumes within strict limits (+2/-5 mbar) at all times.

While vented, VELO is set to **Balancing Mode**

- If Beam **Overpressure** > 2 mbar is detected, Beam Volume is **pumped** through PV301.
- If Beam **Underpressure** < 5 mbar is detected, ultrapure neon is **injected** in Beam Volume through PV303.

If the Balancing System fails or cannot cope, an independent **Overpressure Safety System** protects the foil:

- Electrical hardwired safety system, does not rely on PLC
- In case pressure differential reaches +/- 10 mbar SV421 is open, putting the volumes in contact and equalizing pressure
- This protects the integrity of the foil but can introduce gas contaminants in the Beam pipe.



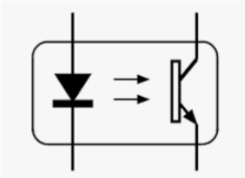
Pressure Switches

The Vacuum Control System and Overpressure Safety System use pressure switches to detect pressure differentials between Beam and Detector Volumes.

Control System (Balancing Mode)

	ΔP Threshold	OK State
OS412A	+2 mbar	Closed
OS412B	-5 mbar	Open

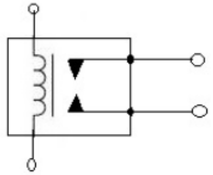
- Balancing Switches are read by the PLC using **optocouplers**

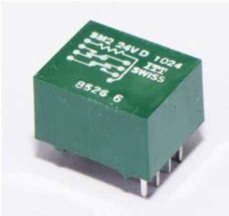


Safety System

	ΔP Threshold	OK State
OS413A	+10 mbar	Closed
OS413B	-10 mbar	Open

- Safety Switches are read by the PLC and Safety System using **mechanical relays**





Power Supply

- Pressure switches are electrically isolated from the rest of the system and are read using a **dedicated power supply**
- Power supply **failure is detected** using the same type of **mechanical relay** as the safety system
- If a **power supply failure** is detected, the PLC and Safety Systems know the status of the pressure switches cannot be trusted and **thus no equipment is actuated** (balancing stops, safety system does not trigger)

Incident Analysis

Sequence of Events

The following is a condensed sequence of the events that ultimately led to the over pressurization of the Detector Volume and subsequent deformation of the RF Foil. For a more detailed account you may consult the following EDMS document (https://edms.cern.ch/document/2820759/1).

Night of January 09-10, 2023

LHCb VELO Team – Warm up of the detector prior the AUG test (VELO is currently in Balancing Mode under ultra-pure neon). First time activity, detector warmup has never been tested in terms of gas balancing.

23h11 - Warm up of the detector starts

- Differential pressure on the detector side starts to increase (initial value -3.4mbar).

23h25 – Differential Pressure between Detector and Beam vacuum reaches -5mbar

- Detector volume is over pressurized compared to the Beam volume.
- Vacuum Control System correctly compensates with standard balancing cycle (+2/-5mbar), injecting neon into the beam volume.
- Pressure differential stays above 5 mbar, Balancing System keeps injecting neon.

Sequence of Events

23h41 – Differential pressure reaches -6.8mbar (exceeded limit of -5mbar)

- VELO team stops the warming cycle and contacts TE-VSC (**J. Sestak**).

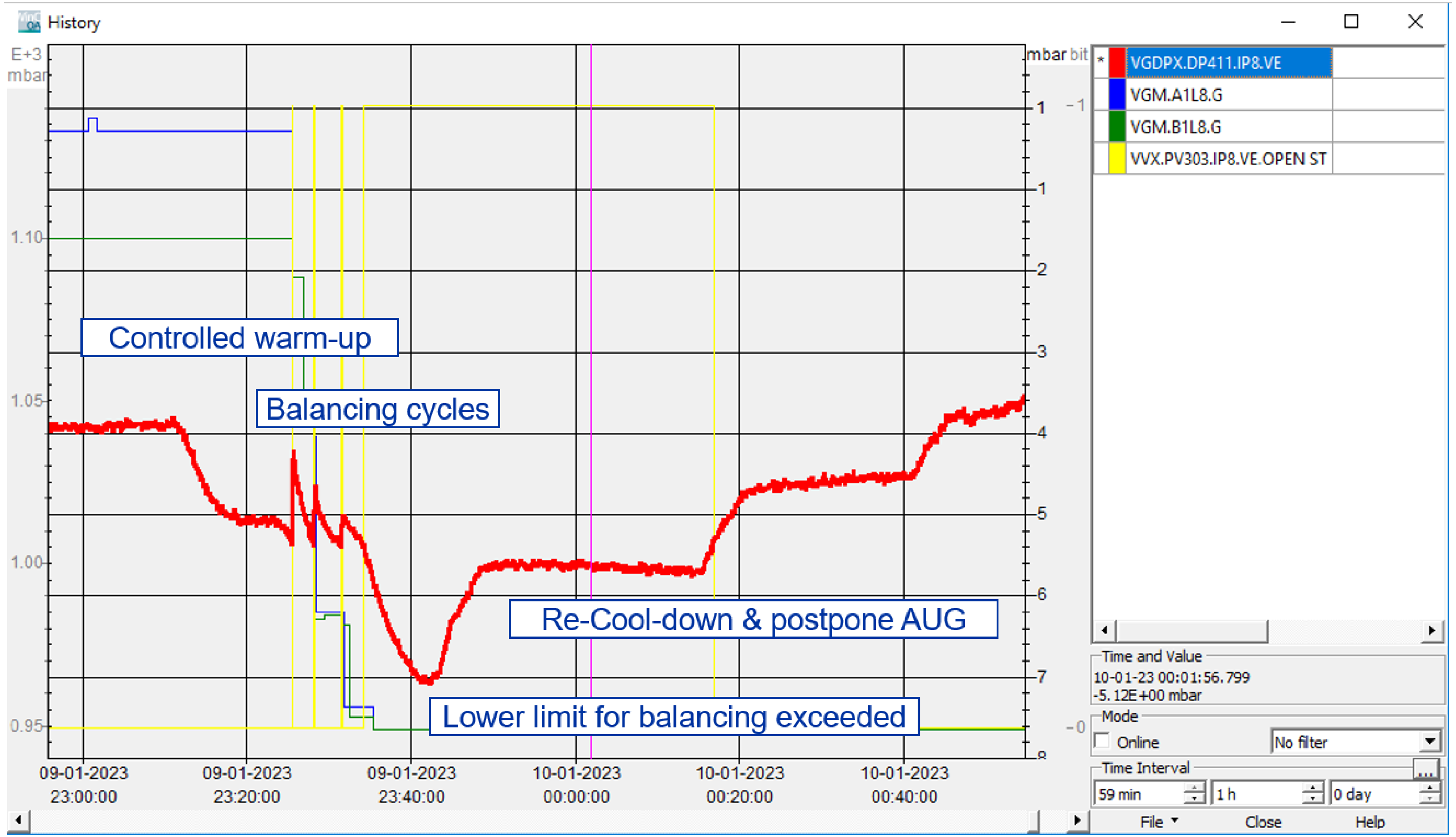
00h00 – TE-VSC performs remote diagnostic of the system and shares findings with LHCb

- It was verified that the warmup of the Detector Volume caused a pressure increase that the Balancing System cannot cope with (at the current pressure setting on the injection line)
- Quantity of gas needed to compensate DP on the Beam vacuum volume (injected by the balancing process) requires manual readjustment of the manometer setpoint on GIS neon bottle (which can only be done on-site by a VSC expert)
- TE-VSC requests to stop the warm-up, revert the temperature and wait for the morning.
- TE-VSC requests the postponing of AUG tests planned for the morning of 10/01/2023. LHCb VELO team agrees and will propagate the message towards the LHCb TC.

00h20 – LHCb VELO team reverts warm-up of the detector

- Detector is cooled back down to the original temperature
- Stable differential pressure of -2.4 mbar is achieved around 2 AM

Sequence of Events



Sequence of Events

Morning of January 10, 2023

6h22 – Dry air supply is stopped, and cooling stops as a result

- Dry air supply is stopped remotely by EN-CV as a preparatory action prior to the AUG test
- Loss of dry-air supply results in the shutdown of the cooling plant
- Detector starts warming up to ambient temperature in an uncontrolled way
- A fast differential pressure increase due to gas expansion is experienced in the Detector Volume

6h23 - DP between detector and beam vacuum volume reaches -5mbar

- Balancing system correctly starts to compensate the DP by neon injection
- Pressure keeps rising in the Detector volume, but the pressure of the injection system has not yet been increased, so the balancing system is unable to keep up
- The increase in differential pressure continues rapidly, at around 1 mbar/10s (with the Detector volume becoming more over pressurized)

Sequence of Events

6h24 – DP reaches -8.8 mbar and the Overpressure Safety System is triggered (start of the failure)

- Differential pressure hits the threshold of the pressure switch used in the Safety System (10 mbar by specification, but around 9 mbar in reality).
- At this point the Safety System should have opened the Overpressure Safety Valve. In reality, the relay used to read the pressure switch is faulty (a hidden failure, only detectable by proof testing) and short-circuits the power supply.
- The combined resistance of the wiring (around 5 Ohm) is high enough that the power supply does not totally shutdown but the voltage drops from **24V** to **9.8V**.
- Due to the failure of this relay the safety system fails to actuate the safety valve and equilibrate the pressure differential between the two volumes (the closed pressure switch status is never read).
- Additionally, the low voltage of the power supply causes a second problem in the control system.

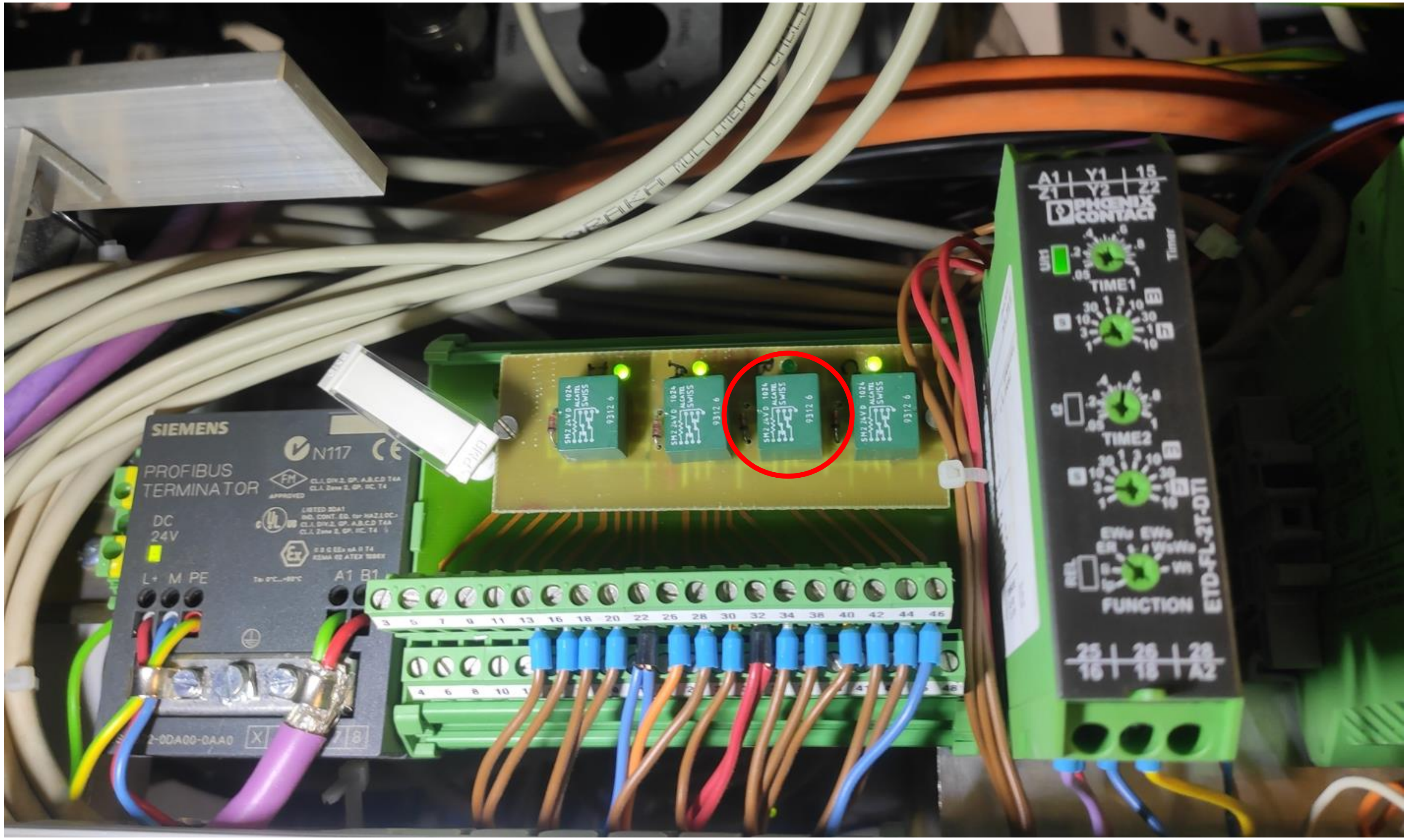
Sequence of Events

Optocouplers and mechanical relays have very different operational thresholds. Optocouplers typically require significantly higher turn-on and hold-on voltages compared to equally rated relays.

6h24 – Issue in the Balancing System

- The voltage of **9.8V** that is now being output by the pressure switch power supply is **not enough to actuate the optocouplers** used to read the Balancing Pressure Switches
  - All optocouplers open, meaning that the control system now **falsely** reads the **Beam Volume as over pressurized** (OS412A Open).
- The same **9.8V** are, however, **enough to keep the mechanical relays closed**.
  - The relay used to read the status of the pressure switch power supply remains closed, so the system **falsely** reads the **power supply status as being OK**.
- The software is designed to deal with a fault such as this. By design, the **PLC interlocks all balancing valves in case of a Power Supply failure** (i.e. nothing is actuated if the values of the pressure switches cannot be trusted). But because the supply status was still reported as OK, the Balancing system actuated as normal.

Sequence of Events



Safety System Relay Assembly (faulty relay marked in red)

Sequence of Events

While the pressure in the Detector continues to rise with the warm up, the PLC reads the following status:

- The status of the PSU is OK, so it can trust the pressure switch status (**false**)
- OS412B is Open, so the Beam volume is not underpressured anymore (**false**)
- OS412A is Open, which indicates a Beam Overpressure (**false**)

The balancing system acts according to what it sees: it proceeds to pump the beam volume in an effort to equalize a perceived differential Beam **overpressure** (while in reality it is the Detector volume that is **overpressurized** due to the uncontrolled warmup of the detector volume).

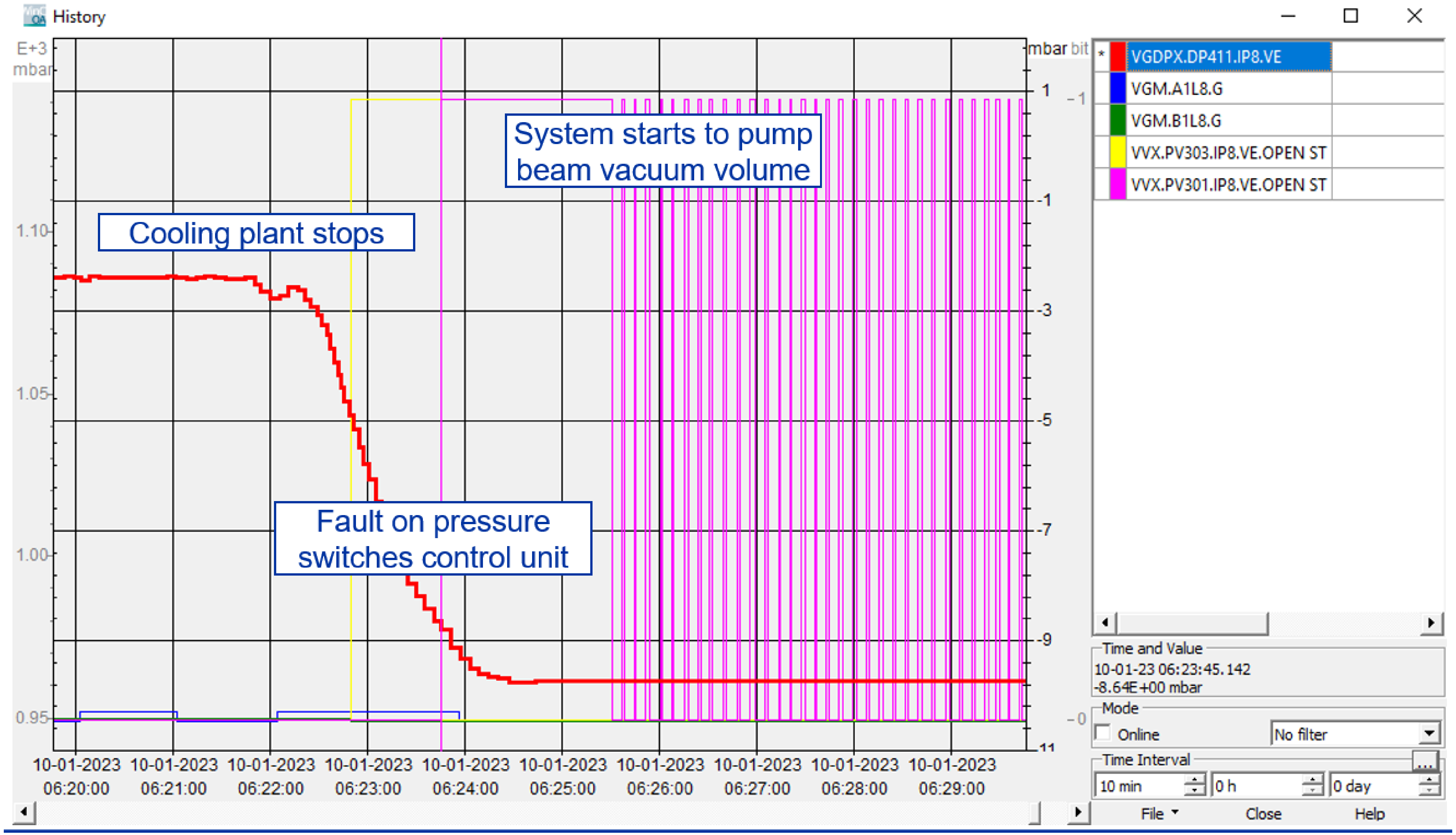
6h25 – DP between detector and beam vacuum volume reaches -9.8 mbar

- Differential Gauge reading freezes (for an unknown reason, given that the differential pressure continued to increase and the gauge is rated at -133/133 mbar)

6h36 – LHCb VELO team contacts VSC piquet (as the expert is unavailable)

- Situation is unclear, so it is decided to meet at CERN to analyse the situation

Sequence of Events



Sequence of Events

7h05 – TE-VSC analyses the system status on the SCADA and tries to make sense of it

- The instrumentation shows entirely inconsistent information (and thus cannot be trusted):
  - OS414 and OS411 indicate that **both volumes are over pressurized** in relation to atmosphere
  - Absolute pressure measurement gauges indicate we are **around 650 mbar** in the Beam
  - Pressure switch OS412A indicates a Beam **overpressure > +2 mbar**
  - Differential pressure measurement reads -**9.8 mbar of Beam under pressure**
  - Safety pressure switches indicate that we are **within the -10/+10 mbar range**
- **SV421 is closed** and the safety system did not trigger
- **Beam Vacuum is being pumped via PV301 by the Balancing System**
- The **power supply** for the **pressure switches** is **working properly**

9h43 – TE-VSC stops automatic Balancing

- After considerable internal discussion, TE-VSC stops automatic balancing process
- Pumping of the Beam Volume through PV301 is stopped
- Ongoing discussions between the LHCb VELO team and VSC experts

Final Status

12h00 – **TE-VSC inspects VELO and VELO control racks**

- VELO elliptical head zone is inspected (rupture discs control, safety valve physical status)
- VELO control racks are inspected and the issue with the power supply is identified

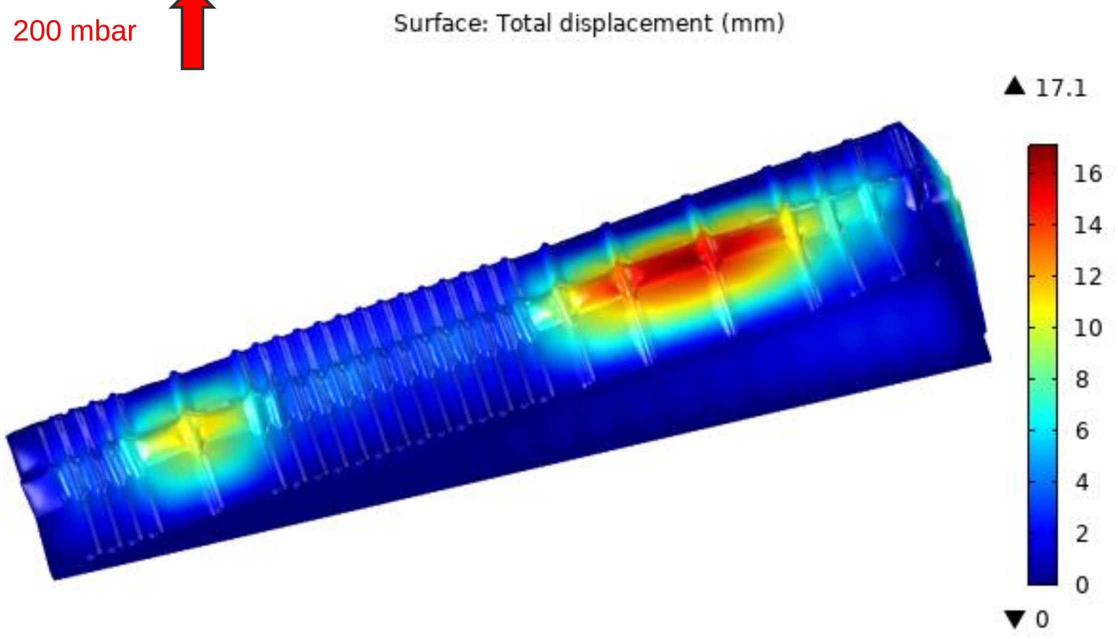
16h30 – TE-VSC performs measurement using Gas Injection System line

- Neither the Absolute nor the Differential Baratron gauges can be trusted at this point
- Pressure gauge on the GIS line is used to measure Beam volume pressure, confirming the drop to be around 180 mbar.
- Gauges on the VELO Detector vacuum volume indicate a pressure increase of approximately 40 mbar compared to before the event
- **This means the differential pressure between Beam Vacuum volume and Detector Vacuum volume would be in the range ≈ 200 – 220mbar.**

Final Status: Estimated VELO deformations by FEM analyses

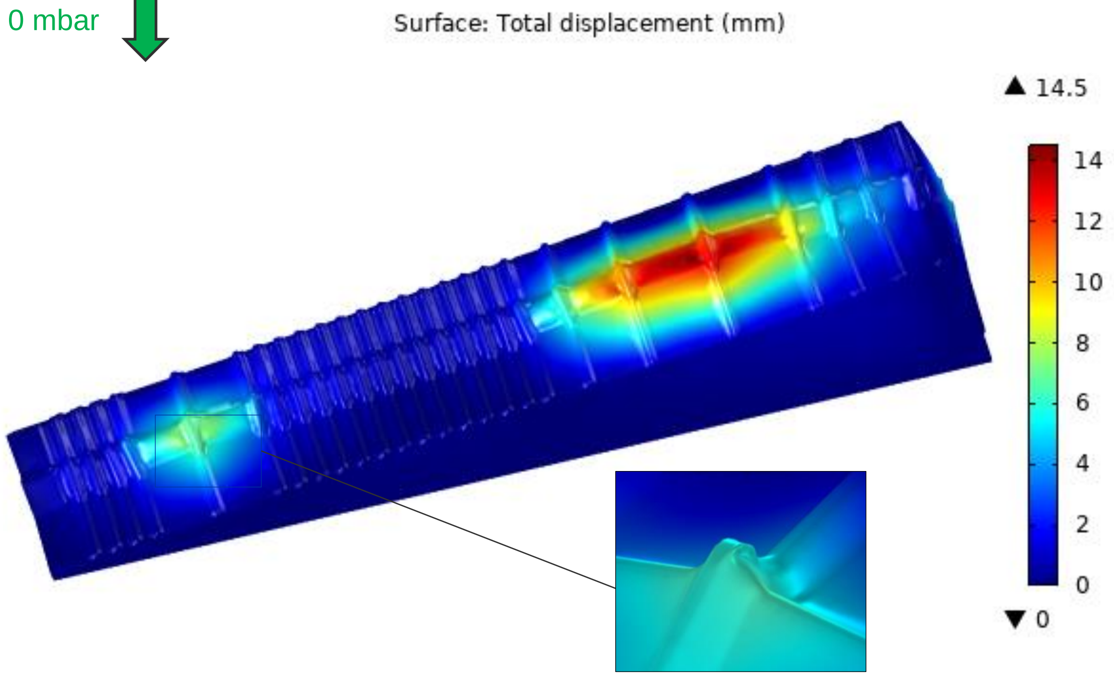
- The deformation was estimated by highly non-linear, elasto-plastic FEM simulations (for more details see EDMS 2820818)
- The simulations are in good agreement with specific tests performed at Nikhef labs on a short RF foil up to 200 mbar
- The 200 mbar pressurisation led the VELO RF foil to ‘inflate’

200 mbar



A maximum total deformation of around 17 mm is expected in the most flexible area (less ribs) at 200 mbar.

0 mbar



A residual total deformation of around 14 mm is expected in the same area when the pressure returns to 0 mbar. Local instabilities are present in the ribs (verified by experiments).

Incident Recovery

For a more detailed account check the **LHCb VELO Update** presentation on the **LMC #457** (J. Sestak)

https://indico.cern.ch/event/1256438/

Immediate Recovery (11/01/2023)

Several actions were taken in the immediate aftermath of the event

Instrumentation

Most immediate concern was to understand the real state of VELO (SCADA cannot be trusted) and recover the instrumentation chain.

Intervention in UX85 control racks:

- Measuring of line voltages and inspection of mechanical and opto-relays – **Power Supply issue identified**.
- Disconnection of all pressure switch cables – **Root cause of failure identified as OS413B relay short circuit**.

OS413B cable kept disconnected, which allowed us to **recover the remaining instrumentation.**

Vacuum

RF foil did not seem to have ruptured, but pressure differential had to be reduced to a safer value.

Manual neon injections through the GIS system:

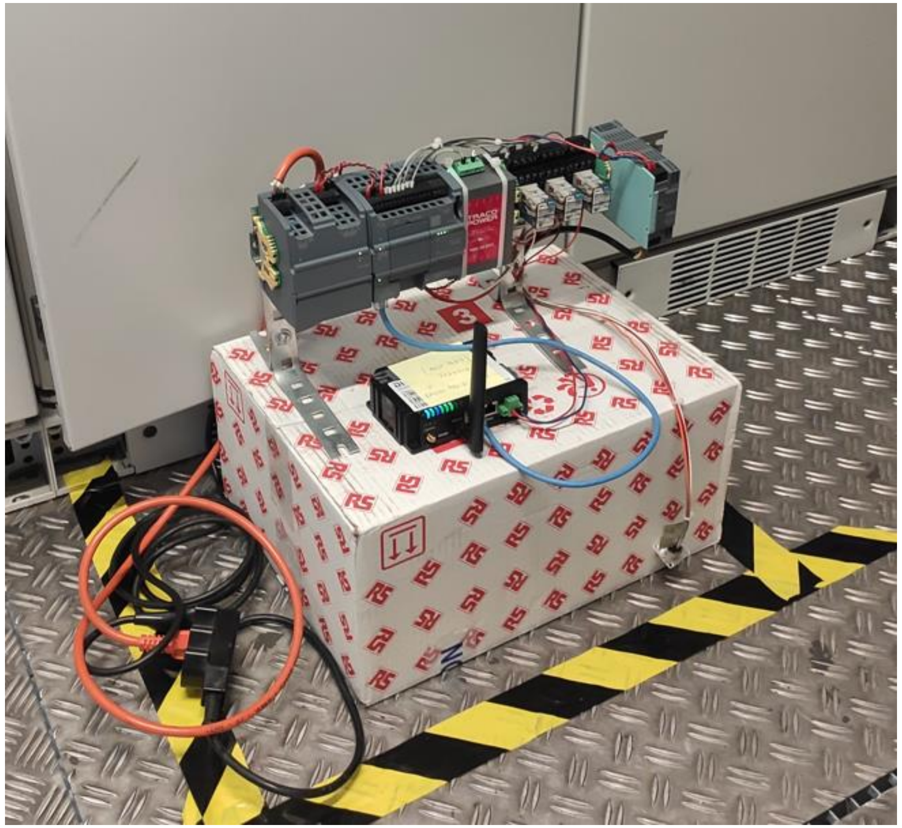
14h00 to 16h00
1st Compensating neon injection
(Beam pressure increased by 50 mbar)

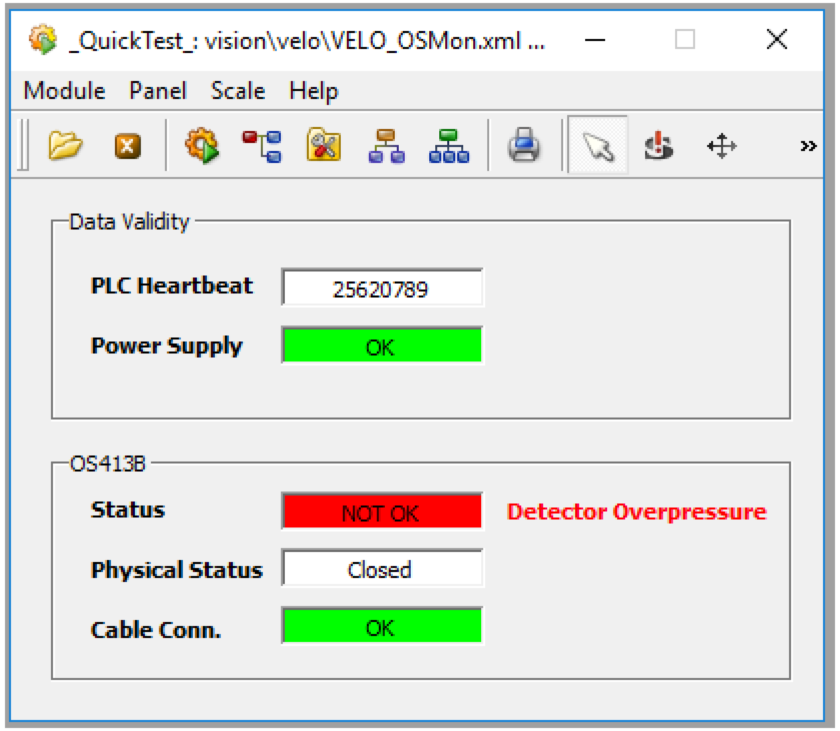
17h15 to 18h30
2nd Compensating neon injection
(Beam pressure increased by 50 mbar)

Differential pressure between Detector volume and Beam volume was reduced, but still expected to be still around **120-100 mbar**.

Recovery of Instrumentation (13/01/2023)

A PLC-based **external measurement system** was designed and temporarily installed next to the racks in order to be able to read the status of OS413B. The data was integrated in the SCADA, restoring the monitoring of all pressure switches.





Continued Recovery (16/01/2023 to 20/02/2023)

Incident

15/01/2023

Start of the design of the new (temporary) safety system

- More about this later

16/01/2023

Update of GIS table for precise pressure measurement

- GIS table modified with new gauge assembly for on-site, accurate pressure measurement.
- Pressure differential confirmed to be at **103 mbar**

20/01/2023

Further manual pressure equalization

- Third neon injection, now with accurate pressure measurement. Pressure differential **reduced to 24 mbar**.

27/01/2023

New safety system electronics completed and extensively tested in the lab

- System design, test results, and installation / commissioning plan presented to and validated by LHCb team.

01/02/2023 and 02/02/2023

New safety system electronics installed and commissioned.

- Instrumentation chain fully recovered. Main faults of the existing safe system have been addressed.
- New safety system electronics fully tested and validated

Each step and procedure was **carefully planned**, presented to the **LHCb VELO** teams, and **approved** beforehand.

Continued Recovery (16/01/2023 to 20/02/2023)

02/02/2023

Manual Balancing of VELO Vacuum System

- Pressure in Beam Vacuum progressively increased by controlled neon Injection (< 0.5 mbar / min)
- **All pressure switches tested** (except two) and found to be **working properly**

03/02/2023

Control System Nominal operation is reinstated

- DP is manually reduced to -1 mbar
- Automatic Balancing Mode is reactivated
- SV421 Safety Valve is reconnected, reactivating the Overpressure Safety System

14/02/2023

VELO Pumpdown to operational levels (without Ion Pumps)

- Control and Vacuum systems found to be working properly
- No leaks found in RF foil
- SV421 test opening

LHCb performs tests on the detector (motion, cooling, HV, etc)

20/02/2023

VELO Venting to normal Technical Stop pressure (~800 mbar)

- Standard neon Venting process also confirmed to be working properly

Now

Safety System Redesign

Safety System Redesign

Going back to automatic operation with the same safety system design was **not acceptable**. The root cause of the failure, at least, had to be addressed.

Circumstances did not allow extensive re-engineering, installation and recommissioning of a new safety system.

Intermediate solution was proposed by TE-VSC: design a new **system that keeps the same exact logic as the original** but **re-implements the electronics in order to address some of the identified shortcomings:**

1. **Add redundant power supplies** and a redundancy module that allows pre-emptive detection of individual equipment failures.

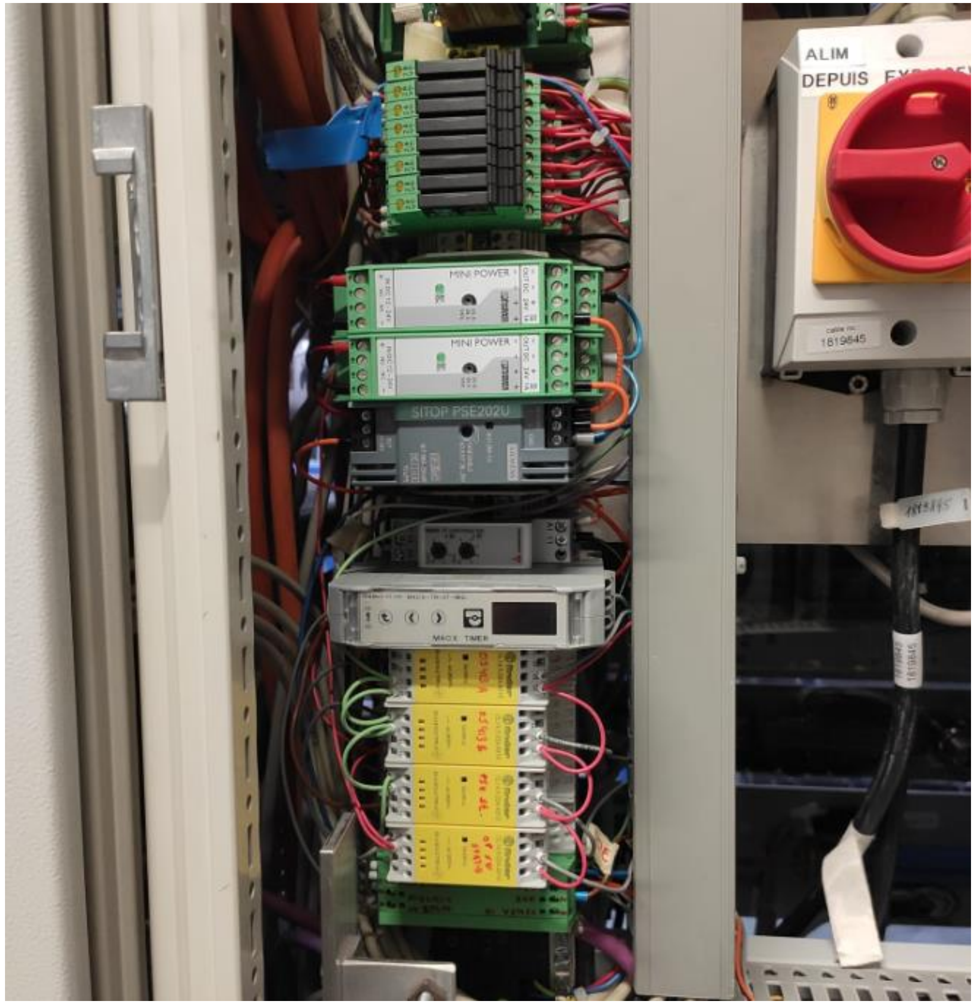
2. **Introduce a precise, reliable way to detect power supply failure** by adding a line voltage monitoring relay with a configurable threshold (rather than simply actuating a relay with an arbitrary operating voltage).

3. **Re-implement safety system logic** using SIL3 rated **Safety Relays** (rather than the existing homemade solution with signal relays and hand-soldered wires).

4. **Replace existing time-relay** (discontinued) with a modern version for which spare parts can be acquired.

Safety System Redesign

Original Safety System Electronics



Redesigned Safety System Electronics

Safety Considerations

The **new safety system** addresses the root cause of the failure that led to the incident but should nonetheless be considered a **temporary solution**. Before replacement of the RF Foils, a new system that adheres closely to **Functional Safety** principles will be designed and installed (in collaboration with other groups at CERN).

An important limitation of the original mechanical design of the VELO Vacuum System is that it **does not allow a complete test of the Safety System chain ***

- There is no way to test the pressure switches without inducing pressure differentials directly on the Beam and Detector Volumes.
- There is no way to test the opening of SV421 without putting the Beam and Detector volumes in contact. This results in probable contamination of the Beam Vacuum and the need to re-bake the whole IP8.

If feasible, addressing these limitations to allow regular testing of the Safety System would bring considerable improvement to the reliability. This will also be evaluated.

* According to the **IEC 61511 Functional Safety Standard** it is a fundamental tenet that any low demand Safety Instrumented System must be regularly Proof Tested and that a Proof Test Interval must be defined and followed. This is the only way to identify Dangerous Hidden Failures and an important part of bringing the risk of incident down to an acceptable level.

Spare Slides

Safety System Redesign

- The solution was presented at the VELO follow-up meetings on **31/01/2023** and is described in detail in the following technical note (https://edms.cern.ch/document/2818067/1).

- The system design, along with all related documentation, was reviewed and accepted by *P. Collins* (EP-LBD), *J. Buytaert* (EP-ESE), *S. Ravat* (EP-DT) and *V. Coco* (EP-LDB).
    - **Validation Tests** (https://edms.cern.ch/file/2816519/1/VELO_Safety_System_-_Lab_Test_Results_-_20230124.xlsx)
    - **Commissioning Plan** (https://edms.cern.ch/file/2816519/1/VELO_Safety_System_-_Commissioning_Plan.xlsx)
    - **Schematics** (https://edms.cern.ch/file/2816519/1/VED_xxxx_VELO_OverpressureSafetySystem_v1.1.pdf)

- New electronics installed and commissioned between **1/02/2023** and **2/02/2023** after green light from LHCb.
    - **Commissioning Report** (https://edms.cern.ch/file/2816519/1/VELO_Safety_System_-_Commissioning_Report_-_20230202.xlsx)
    - **Point-to-point Testing** (https://edms.cern.ch/file/2816519/1/Point_to_Point_Testing_-_20230202.pdf)

Thank You

(From the TE-VSC Team)