The 1MV MITICA power supply beyond the modern technologies limits: first experience during integration phase

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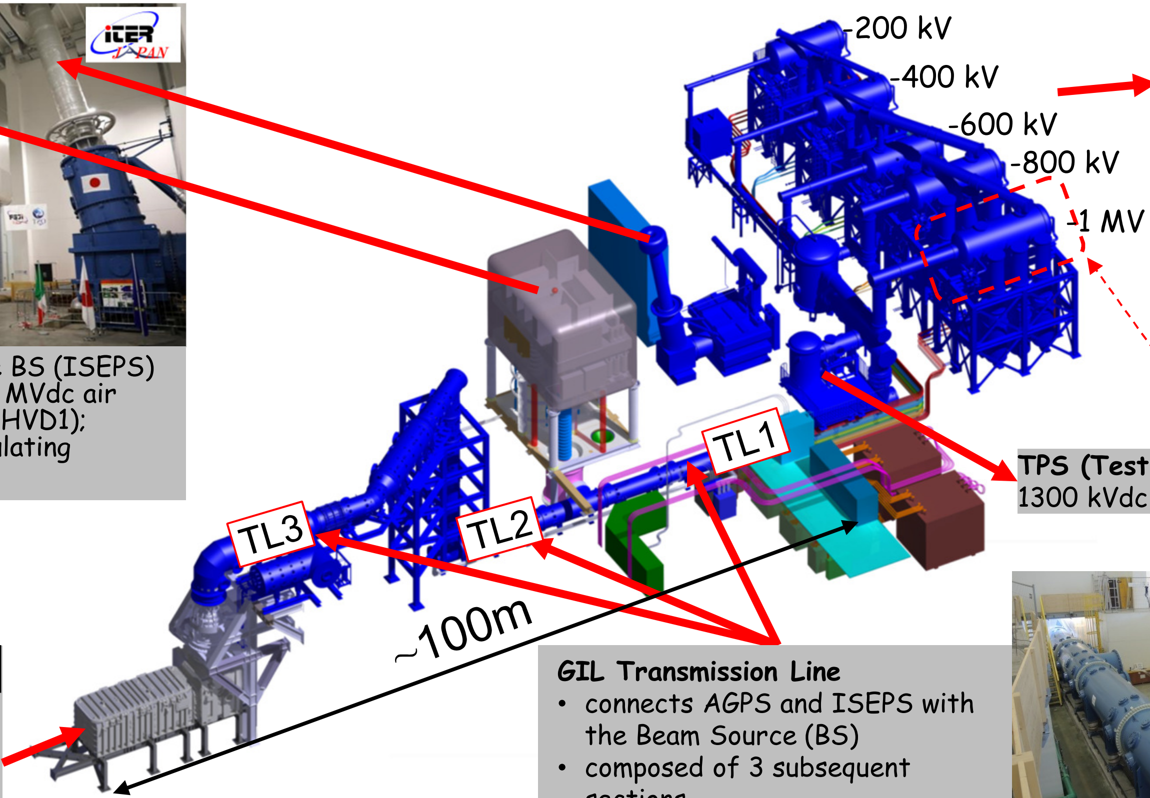
MITICA power supply overview

- MITICA PS is a very complex and big system (~100m long), composed of components beyond the modern technologies limit
- It is the first prototype at 1 MVdc, with such power rating, developed in the world. It is realized with the contributions of JA (JADA) and EU (F4E) domestic agencies

- PS & diagnostics for the BS (ISEPS) installed inside a large 1 MVdc air insulated Faraday cage (HVD1);
- ISEPS fed by 1 MV Insulating Transformer



AGPS (Acceleration Grid Power Supply)
5 200kV DC Generators, series connected to produce 1 MV;
Diodes bridge (SF_6 tank) rectifies AC to DC

TPS (Testing Power Supply)
1300 kVdc, 10 mA Generator

Vacuum vessel
- Will host the BS with accelerator
- Short Circuiting Device (SCD) presently installed inside for PS insulation and integrated tests

GIL Transmission Line
- connects AGPS and ISEPS with the Beam Source (BS)
- composed of 3 subsequent sections

Transmission Line 1 & 2

Project technical background

Design

- Carried out in collaboration between the EU (F4E and RFX) and JA teams under IO coordination
- Finalized in functional specifications, based as applicable on the international Codes and Standards (not covering DC applications for such high ratings)

Based on previous experience & specific R&D

- JT-60 (first NBI at 500kV acceleration voltage) was taken as reference input for DCGs design
- Specific R&D with realization of prototypes (a full size 1 MV insulating transformer, a 90% scale TL model, a HVD1 mock-up) to prove the proposed design reliability

Procurement strategy

- High voltage components have been procured by JADA and F4E (shared responsibility)
- Suppliers were selected to identify the ones skilled to manufacture UHV components, anyway the requested equipment was not in their standard production

Interface activities

- NBTF team took care of assuring interfaces with buildings (foundations, ancillaries plants) and among procurements (finalizing mechanical and electrical aspects)

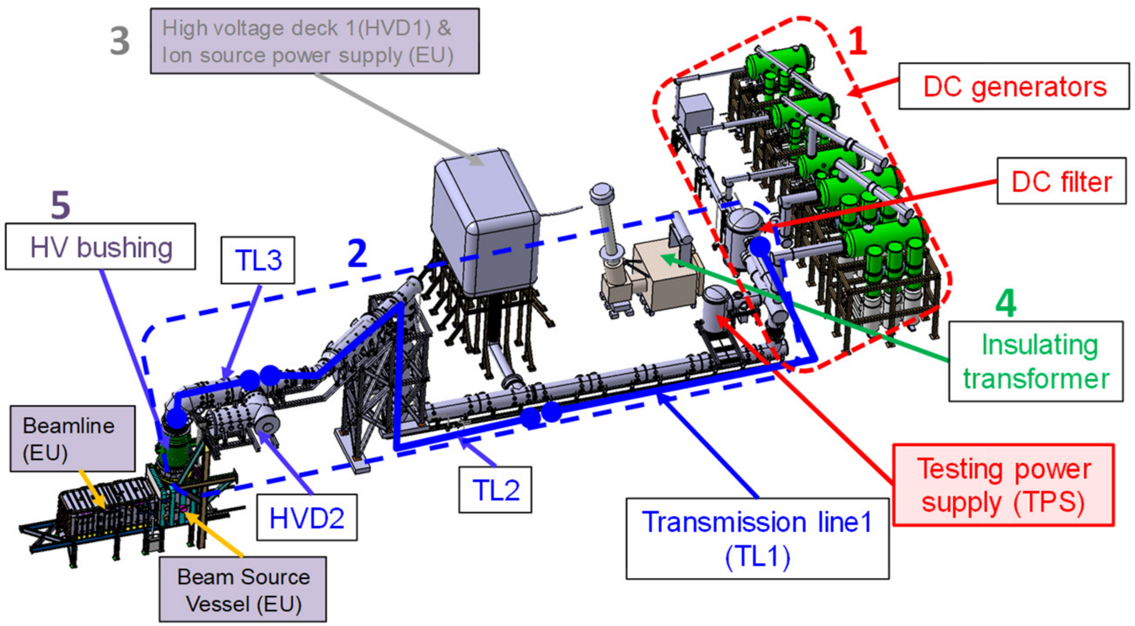
Integration

- Step by step site acceptance test of individual subsystems followed by integration tests
- Integrated test plan was discussed and agreed, taking into account the different responsibilities

Insulation tests

- MITICA PS installation started in December 2015, ended in 2019;
- Test sequence was agreed among parties *(there was no existing applicable DC standards or similar applications to be taken as reference)* and consisted in:
  a) 1.2 MV x 1 h: 20% margin with respect to the HNB rated voltage, nominal time duration;
  b) 1.06 MV x 5 h: long duration test to allow for voltage distribution transition from capacitive to resistive one;
  c) 5 peaks at 1.265 MV: 5 saw tooth ramp-up simulating the awaited overvoltage at accelerator breakdown.
- Insulation tests were performed in 5 subsequent phases, according to the installation progress after connecting equipment belonging to different procurements, by using the TPS:

1) DCGs;
2) TL1+TL2+TL3;
3) HVD1; to finally succeed, modifications on HVD1 cooling water pipes were needed and will be directly applied to IO HNB procurement;
4) HVD1+Insulating Transformer;
5) HV Bushing (tested at only 1 MV x 1 h to cope with HVB voltage withstanding capability)



AGPS integrated tests

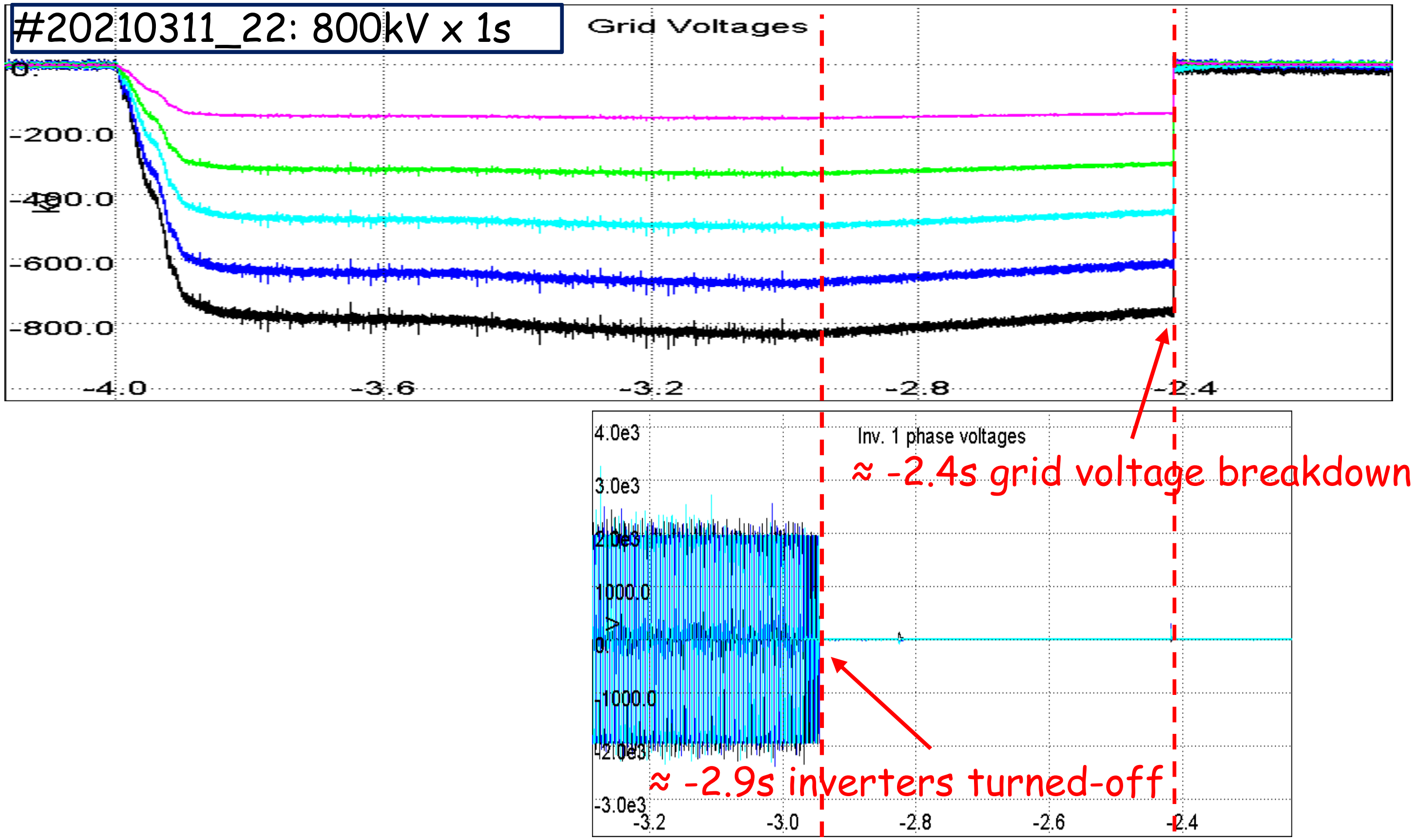
- During Covid19 pandemic (from beginning of 2020) slow down of activities, restarted on the second half of 2020; *QST colleagues followed-up operations via remote connections*

- *AGPS* integrated test program (TPS disconnected, power supply provided by the *AGPS* up to -1 MV) consisted in:
  - No load tests with High voltage generation;
  - Dummy load tests, with *AGPS* rated current generation;
  - Short circuit tests, intentionally generated with the SCD.

- Integrated tests began in March 2021

Event in March 2021

- No load tests, *reaching smoothly 700 kV x 1000 s at a first attempt in such large NBI, an important result in view of ITER/DEMO*
- during pulse 800 kV x 1 s, a grid voltage BD occurred at ≈ -2.4s, 0.5 s after inverters switch-off (≈ -2.9s).



Event in March 2021

Actions carried out:

- Gas and air insulated components were inspected to assess damages and possibly find the BD location
- Fast transient model was developed to explain the failure dynamic

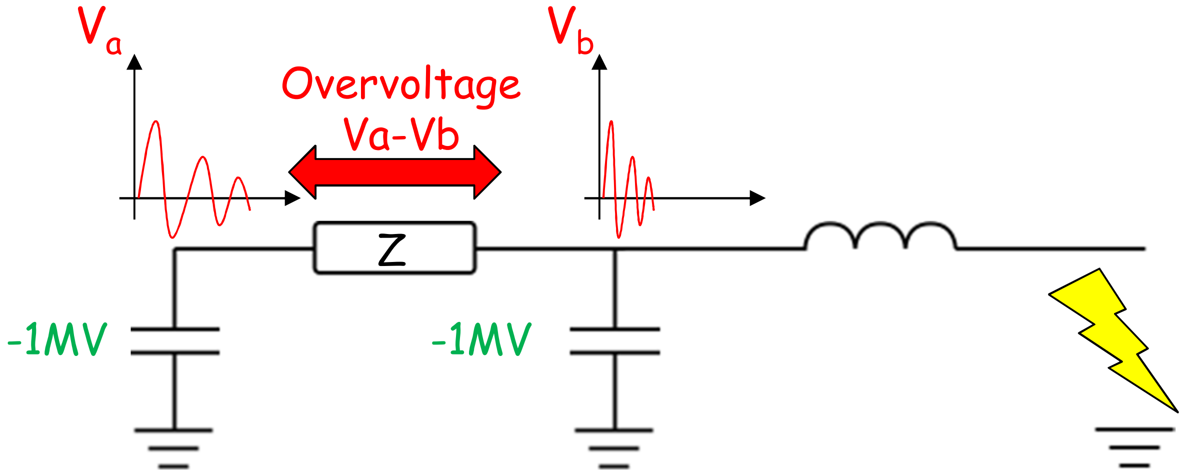
Inspection results:

- In DCG1 (-800/-1000 kV) a diode arm was found damaged
- the location of the BD was not identified

Decisions:

- Thanks to the fast transient model, the dynamic of the failure was explained, demonstrating the need of an additional DCG diodes protection
- The realization of such protections has to be implemented together with the replacement of the diodes (JADA/Hitachi)
- Carry out an insulation test campaign to identify the possible weak insulation point originating the BD

Overvoltages are generated by different LC transients:
MITICA HV system is characterized by physical and stray capacitances charged at -1 MV.
When a breakdown occurs in the accelerator or in another upstream place (short-circuit between 1MV and ground) these capacitances discharge with different oscillation frequencies, causing overvoltage on the connecting impedance Z.

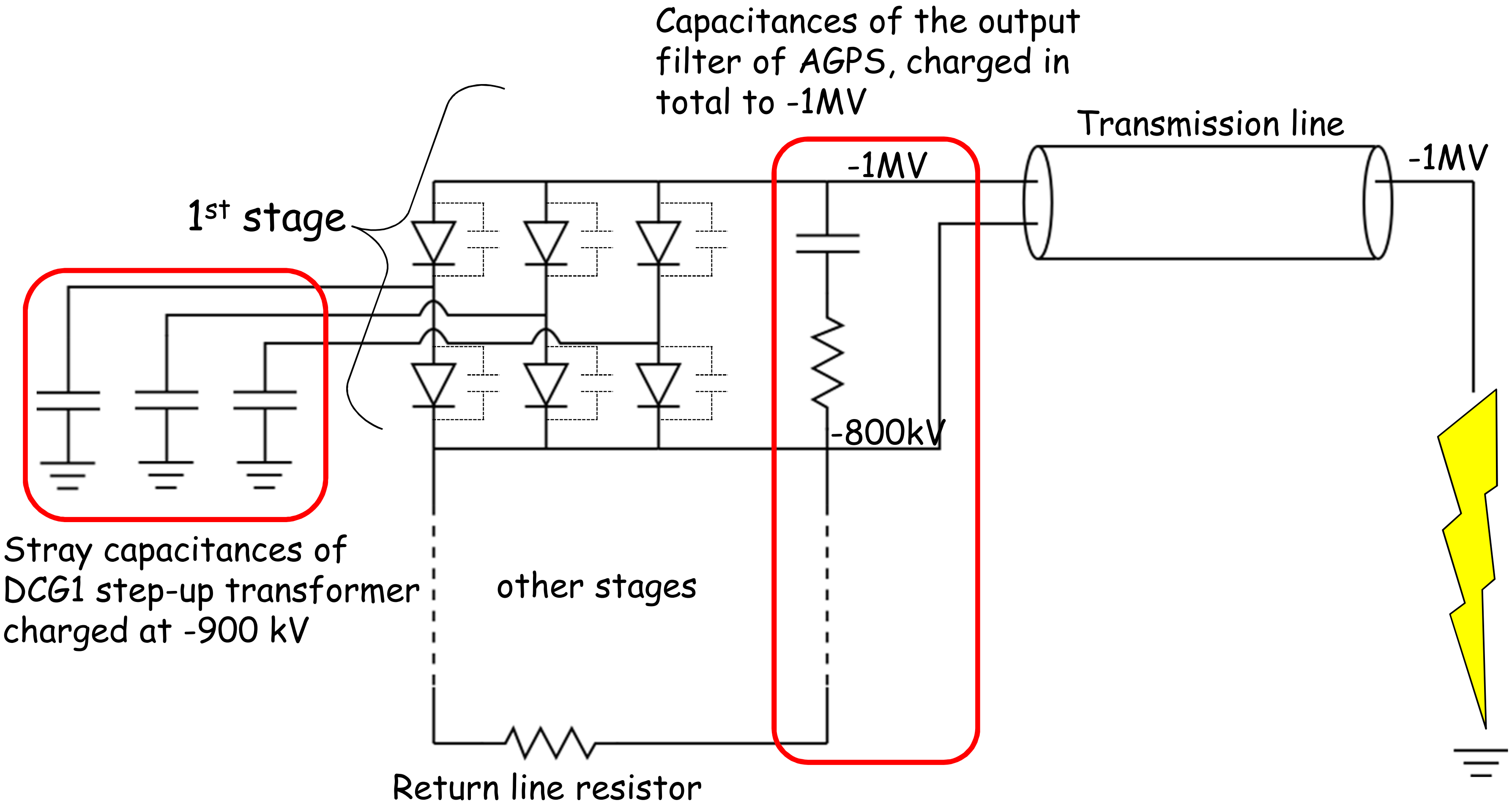


In steady state
In transient

This phenomenon has created unexpected voltage peaks on some components, beyond their design ratings

Failure dynamic in March 2021

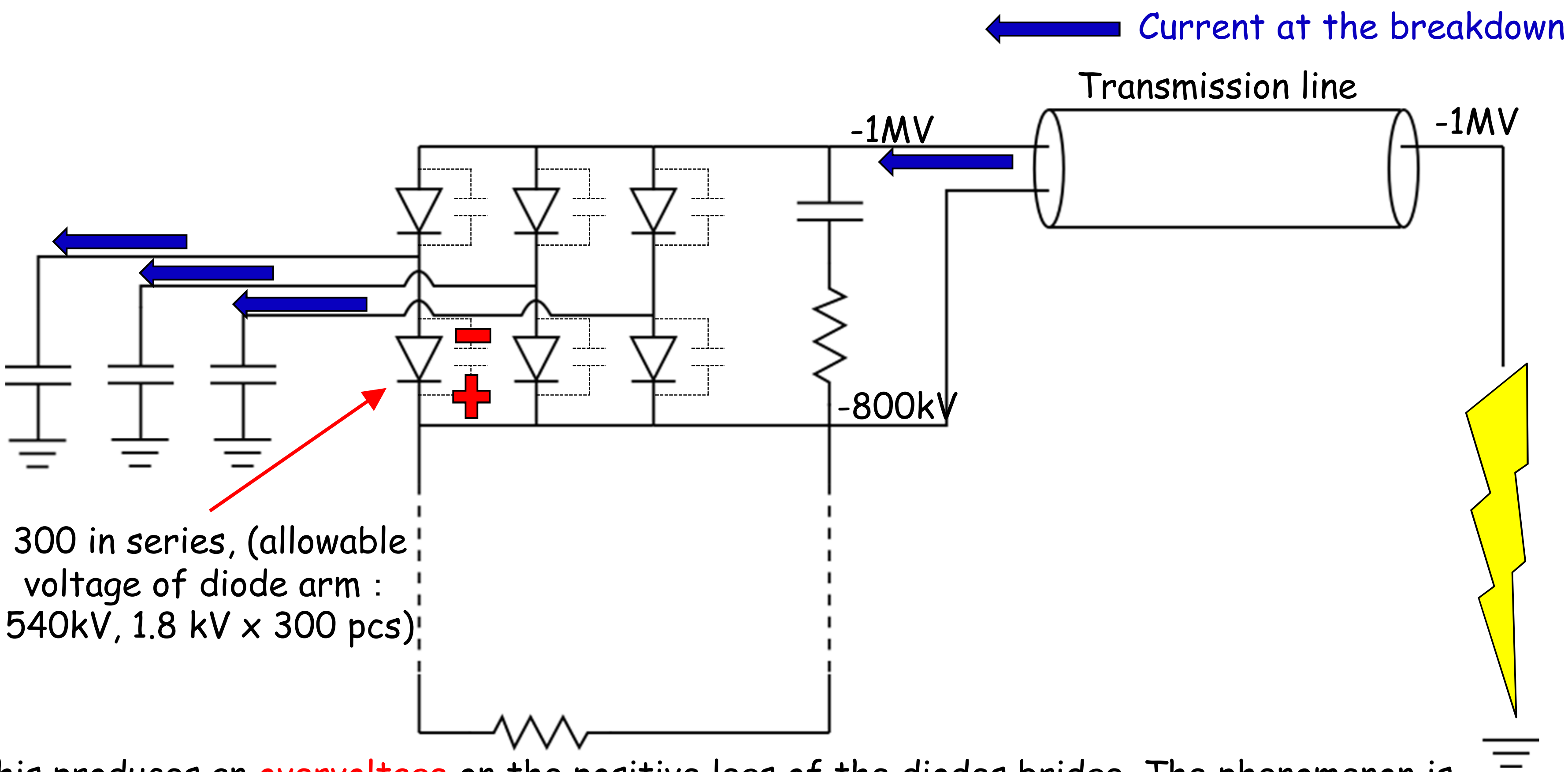
Schematic of the system for the analysis of the diodes fault



The capacitances, charged at high voltage, discharge via the transmission line towards the BD.

Failure dynamic in March 2021

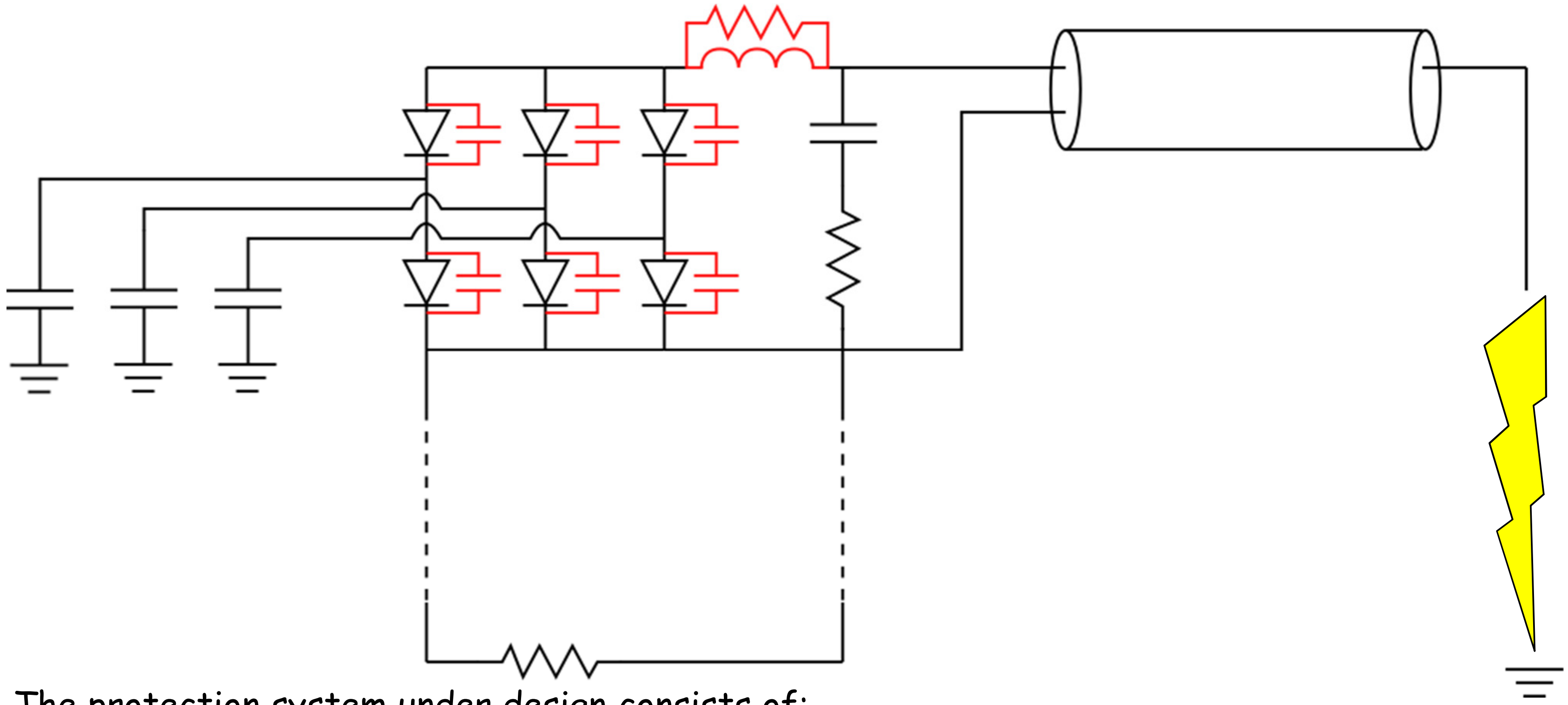
Overvoltage on the diodes



This produces an overvoltage on the positive legs of the diodes bridge. The phenomenon is more complex: the dangerous overvoltage causing the fault derives from the uneven distribution of the transient voltage on the diode elements composing the leg (300 in series) determined by the diodes stray capacitances versus the tank where they are installed, overcoming the even huge design margin and leading to the arm fault per cascade effect.

Failure dynamic in March 2021

Protection system under design



The protection system under design consists of:

- capacitances, to be added in parallel to the original diode snubbers, to limit the overvoltages on the counter-polarized elements;
- output reactor to concentrate the overvoltage on a specific component (L) and damp the transient (R); this reactor has to be designed to withstand very high voltage peaks.

Event in June 2021

To identify the locations of possible weak insulation points, an insulation test campaign was performed:

- using TPS, after disconnecting the AGPS;
- with 1 MV insulating transformer energized to operate the core snubbers bias circuits

Event: once reached 1 MV, after about 1 s, an arc was observed on the top of the bushing, lasting in total for about 2 s (the fault was interrupted by the intervention of the Buchholtz protection of the transformer)

Inspection results

- Complete inspection of other components, both in air and in gas: no evidences of BD
- Damages were found on the insulating transformer bushing (melted materials), both in air and SF_6 side, while the transformer itself was only polluted (soot/dust)

Event in June 2021

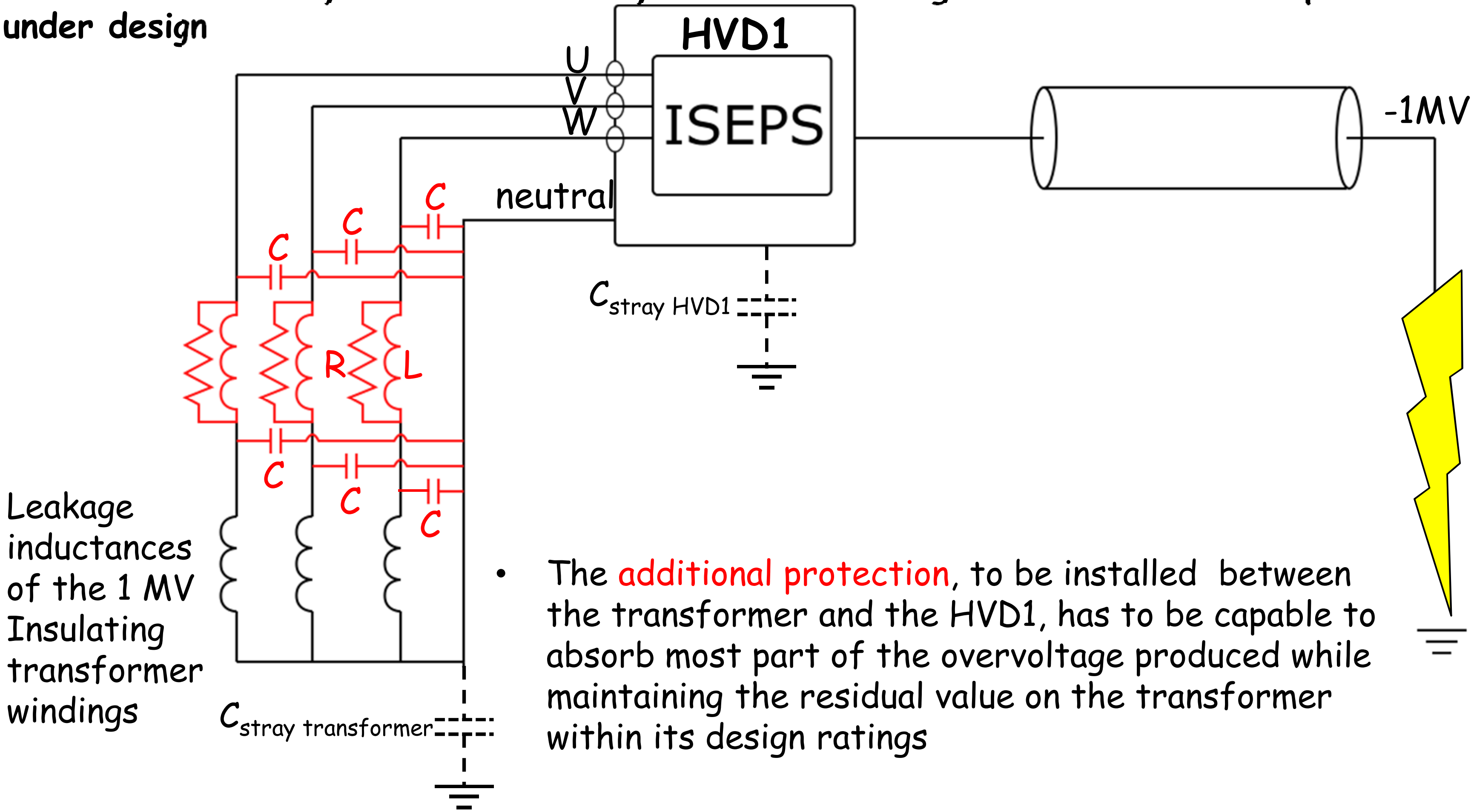
Fault dynamic explanation

- a BD generated in an unknown location produced an impulse overvoltage (hundreds of kV in tens of μs) towards the transformer and was hence applied between phases and neutral
- The transformer, according to standards, is a D/Yn 22/6.6 kV with 170 kV Lightning Impulse (BIL) insulation level (with possible additional margin added by the Supplier)
- This surge triggered sparks both on the top and also inside the bushing

- Fast transient model was developed to explain the failure dynamic, *generated by different LC transients as in the previous case*

Failure dynamic in June 2021

Schematic of the system for the analysis of the bushing fault and additional protection under design



- The additional protection, to be installed between the transformer and the HVD1, has to be capable to absorb most part of the overvoltage produced while maintaining the residual value on the transformer within its design ratings

The protection is a snubber consisting of:

- Damping capacitors "C" to limit overvoltages between phases and neutral at Bushing and HVD1;
- Output reactor for concentrating the overvoltage on a specific component "L" and dumping the transient "R"; this reactor has to withstand very high voltage peaks

Insulation test in July 2022

After benchmarking tests using external dc voltage generator up to 150 kV (December 2021) to identify at reduced voltage the patterns of I&V measurements, installed along the plant, associated to different breakdown locations intentionally induced with an external spark gap **new insulation tests (with DCGs and Insulating Transformer disconnected) were performed to identify the breakdown area.**

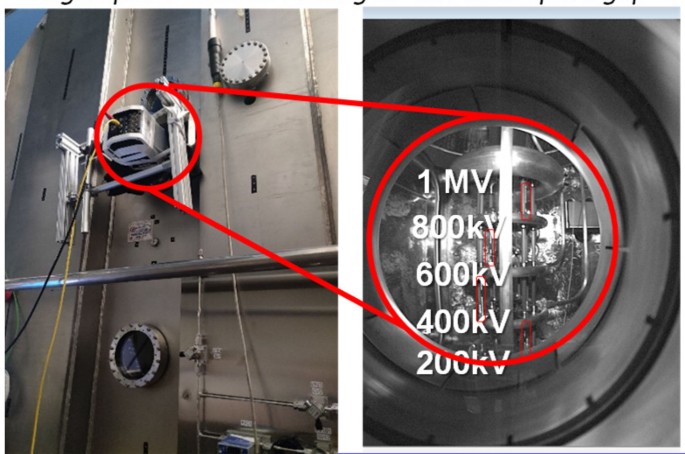
Test setup:

- SCD fixed spark gaps distance increased (previously it was very close to -1 MV voltage limit)
- introduced Partial Discharge instrumentation *(in collaboration with HV experts)* to identify possible PD occurrence *(precursors of BD)* in air insulated equipment

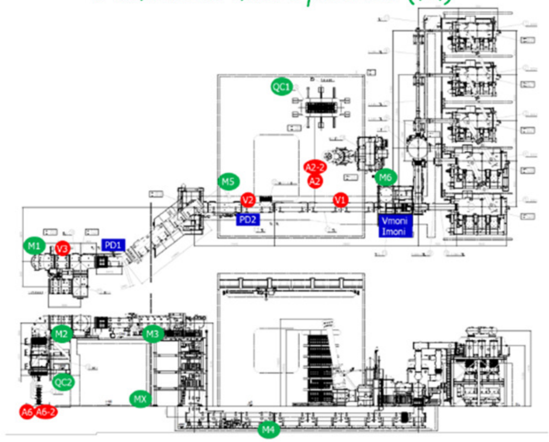
The diagnostic system was further improved adding:

- one camera with microphone inside the HVD1; a microphone installed nearby the vessel; high speed camera looking at the SCD fixed spark gaps, 6 ambient microphones installed along the plant to identify the sound occurrence associated to a BD event and its propagation along the plant

high speed camera looking at the SCD spark gap



6 ambient microphones (M)



Insulation test in July 2022

Sequence of the event:

- test voltage was gradually increased up to 900 kV and applied for 23 min, *the longest possible time before TPS high current threshold intervention*
- Once recovered HVD1 insulating breaks lower water conductivity, the voltage was newly increased but after 2 s at 850 kV collapsed because of a breakdown

Analysis of information acquired during the BD:

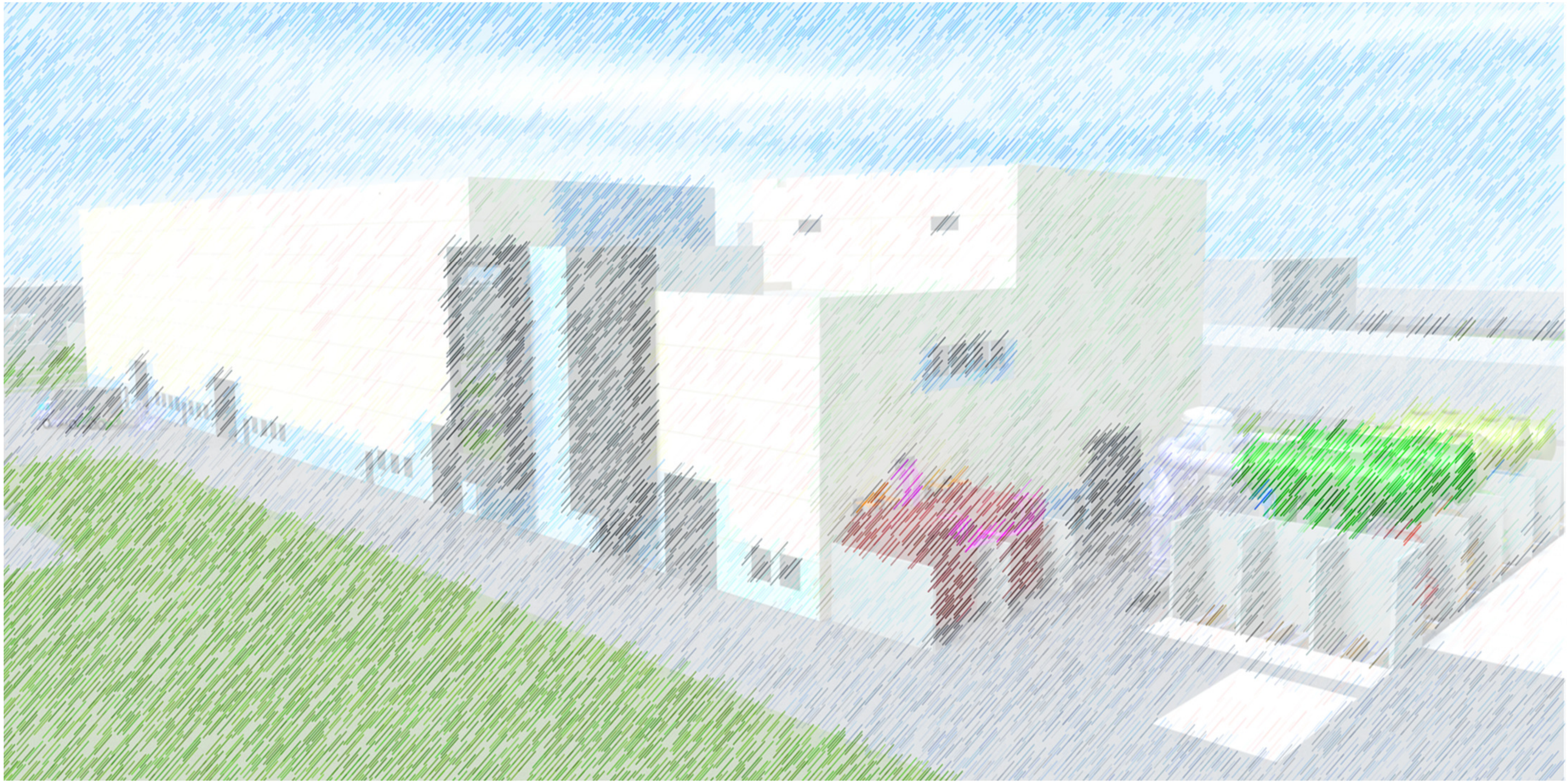
Data analysis didn't allow for unambiguous interpretation, because:

1. no precursors of the BD on air insulated equipment were detected;
2. images acquired by the camera looking inside the vessel confirmed that an arc occurred between the SCD electrodes (but only visible on the 2 higher voltage stages);
3. a strong sound was registered inside the HVH (but not originated inside the HVD1) as well as nearby the SCD vessel; the sound was captured by the 6 ambient microphones but at the same starting time and all the microphones saturated, making therefore impossible to discriminate the source position;
4. additional electric measurements patterns were compatible with a discharge *between the high voltage conductor(s) and the return line, hence* likely occurring in the SF6 insulation.

All these findings didn't allow to understand whether the SCD arc was the main event or if it was consequent to a BD happened elsewhere. Nonetheless, based on PD diagnostics measurements and HVH cameras registration, it can be excluded that the BD occurred on air insulation.

Summary and next steps

- During MITICA integrated tests, two breakdowns occurred somewhere *in the HV plant*
- Dedicated fast transient models were used to explain failures *and verify the additional protections effectiveness*
- The detection system has been enhanced *(by adding I&V sensors, instruments for DC partial discharge on air-insulated equipment and a number of cameras and microphones)*
- Information gathered during 2022 test campaigns resulted not conclusive but, *based on PD diagnostics measurements*, it is very unlikely BD occurrence in air insulated equipment
- Further test campaigns are scheduled in MITICA begin 2023, after TPS modification to make its operation compatible with BD occurrence
- *It will be optimized the definitive installation (in MITICA as well as in future ITER HNBs) of the identified PD instrumentation for detection and protection against system BD*
- The implementation of a non-invasive PD detection on SF6 insulated components *(sensors to be applied on the equipment tanks)* will be investigated *in preparation of the incoming test campaigns*
- Unavoidable schedule delays have been introduced but MITICA is demonstrating its mission to identify and address unpredictable problems deriving from the integration of high voltage non-standard components, *allowing the definition of corrective actions and testing their effectiveness in due time for ITER HNBs installations.*



Thank you for your attention