Progress in the Development of a Penning Ionization Gauge Against Vacuum Degradation in Tokamak Cryostats

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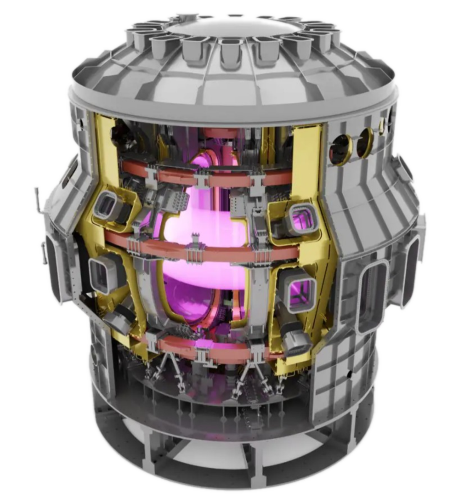
Paschen Discharges in Tokamak Cryostat – JT-60SA Case



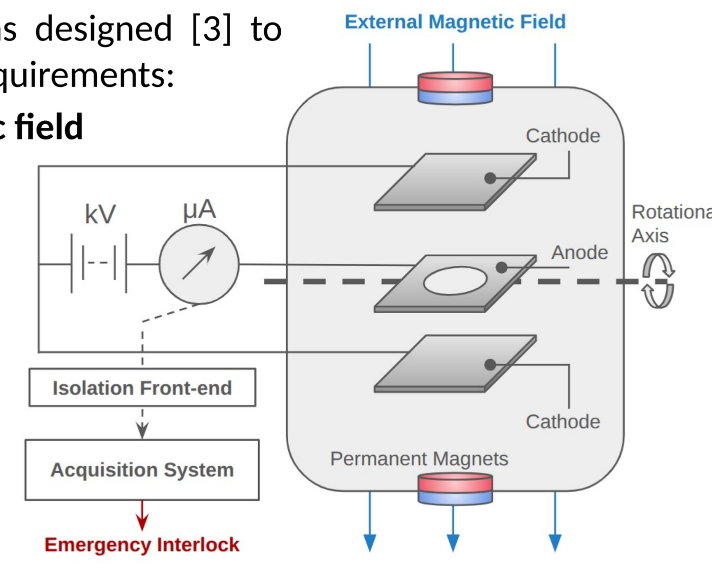
- During quench events, superconducting magnets rapidly discharge, producing **High Voltage Spikes**
- In nominal conditions the cryostat vacuum (<10-5 Pa) acts as insulator
- Vacuum deterioration and thermal cracks in coil insulation may produce a **Paschen Discharges**
- A **Vacuum Monitoring System** can promptly identify vacuum degradation and trigger machine protection before reaching dangerous conditions

9 March 2021 [1]
JT-60SA coil EF1 experienced a disruptive fault to ground, leading to long and extensive repair and a **2-year delay.**

Roll-out strategy [2]:
- ✔Reinforced Insulation → Done
- ✔Global Paschen Tests → Done
- ✔**Vacuum Monitoring System** → Ongoing

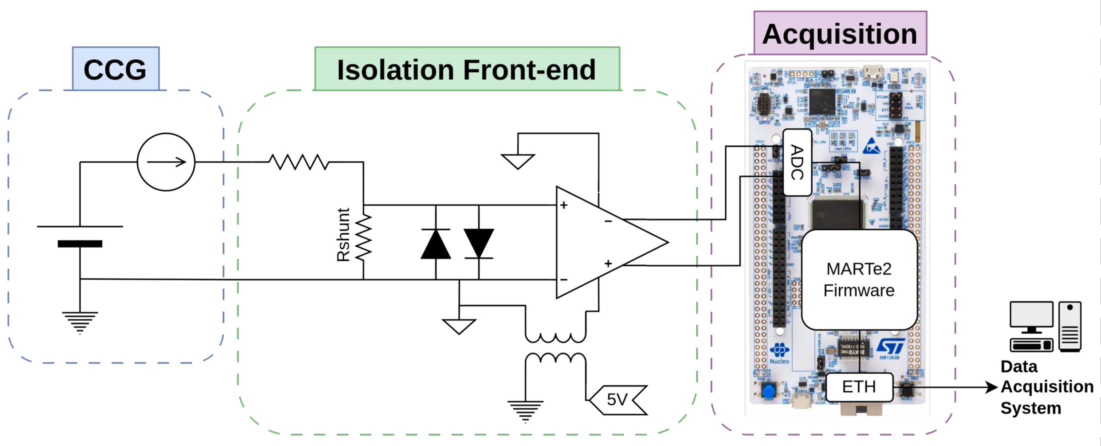
Cold Cathode Gauge (CCG)

A custom Penning CCG was designed [3] to satisfy the stringent VMS requirements:
- Perates at **1 T magnetic field**
- No effect of magnetic configuration (self-orienting structure)
- Operates at cryogenic temperatures **4 K**
- Can measure pressures down to **10^{-6} Pa**



Design of a Custom CCG for JT-60SA Cryostat

Acquisition Front-End



Penning discharge current follows a power law dependence on pressure $I = k\,P^n$ At very low pressures **nA plasma currents** are to be measured on a **kV circuit**. A custom front-end was developed to:

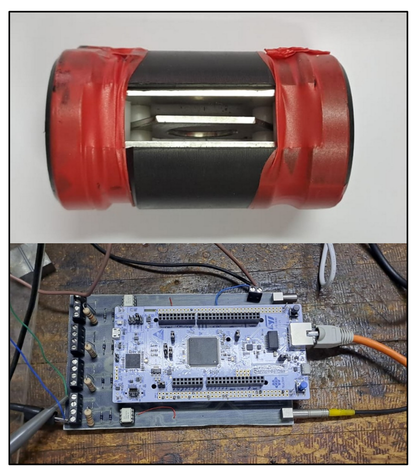
1. Protect acquisition system from high voltage spikes
2. Converts a nA current into an easily measurable 0-3.3 V signal

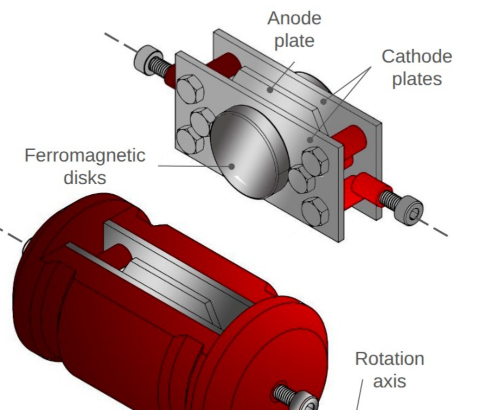
Custom PCB was designed and printed housing a high value **Shunt Resistor**, a voltage-isolated barrier rated for 5.2 kV and an isolated amplification stage.

- **Amplification** stage rejects high-frequency noise and improves minimum detectable pressures
- Current PCB design enables up to **4 channels** isolated acquisition per module
- **Inexpensive!** Compared to general-purpose isolated acquisitions systems

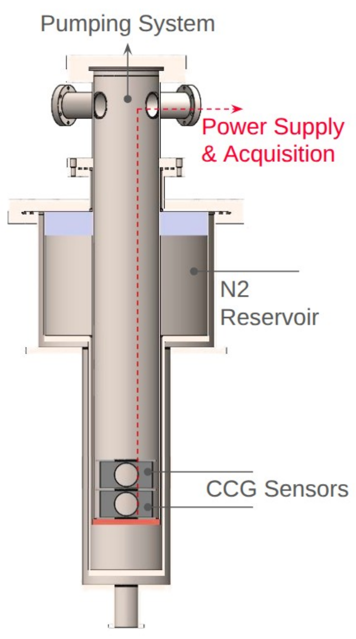
Sensor Assembly

Two prototype sensor have been built in-house using additive manufacturing for the casing and **Aluminum** or **Stainless Steel** (AISI316) for the electrodes.





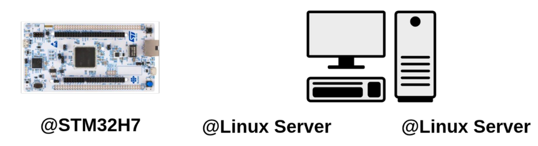
- Sensors were placed in a cylindrical cryostat to perform vacuum and cryogenic tests
- Vacuum was optimize using all-metal vacuum seals, reaching down to 1·10^{-5} Pa at RT
- Commercial CCG (Pfeiffer) used for reference pressure reading and cross-calibration



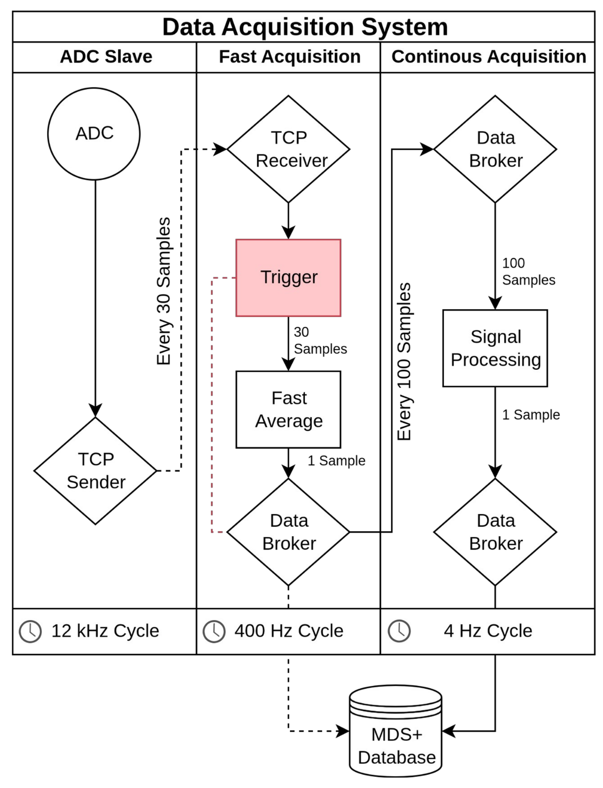
Software Integration

Sensors acquisition system was designed for **integration in a Tokamak environment** and safety control system.

- Real-time control framework **MARTe2** developed for Tokamak control (JET) and foreseen for ITER
- Multi-thread and multi-device operation allows for a **Slave-Master Architecture**: an STM32H7 micro-controller is used for fast ADC acquisition while a Linux server receives and process data



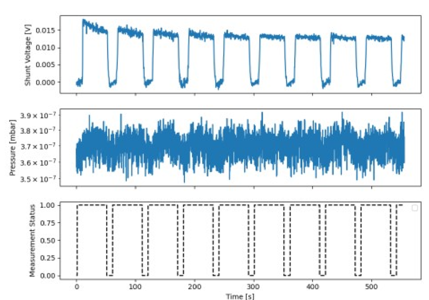
- Slow 4 Hz acquisition produces continuous data for a **Plant Monitoring Data Base (PMDB)**
- When a triggering signal (sensor current) overcomes a set threshold a **Trigger** is produced a fast 400 Hz data is produced to diagnose a potential vacuum degradation

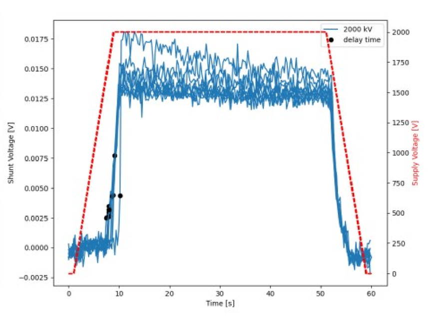


CCG Delay Start Measurement

A CCG does not immediately start when power is applied but requires triggering by cosmic ray or energetic particle [4]:

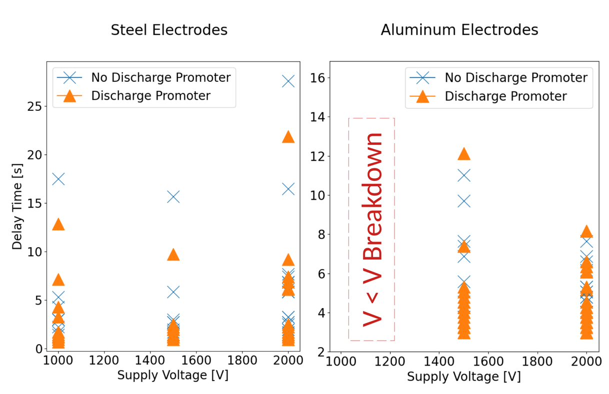
- A mild α-emitter, in the form of a W-Th rod was embedded in the sensor as **discharge promoter**
- Sensors were powered repeatedly under various supply voltages from 1kV to 2kV measuring start delay times





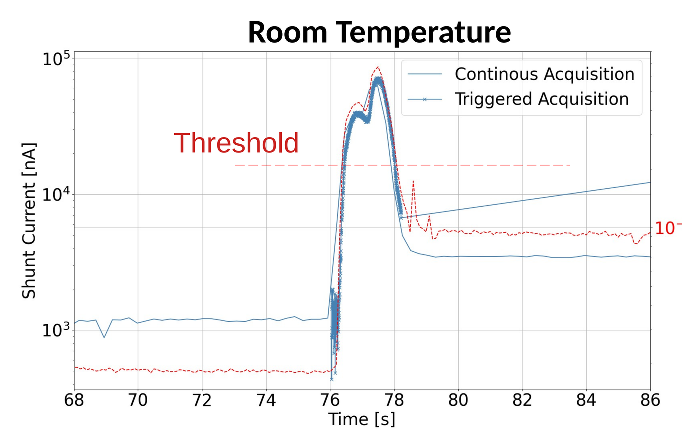
A higher reproducibility of breakdown onset is observed.

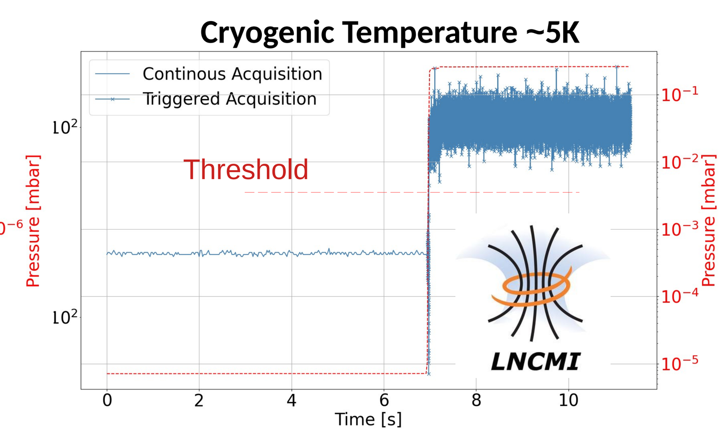
- No reduction in total delay time observed at RT. A measurable improvement is expected when operating at lower pressures (cryogenic effect)



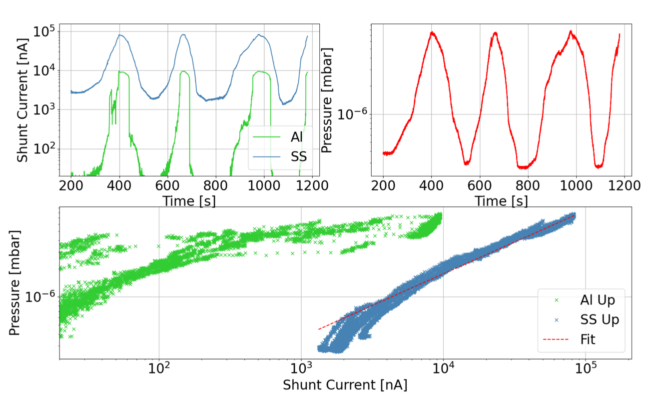
CCG Response to Gas Injection

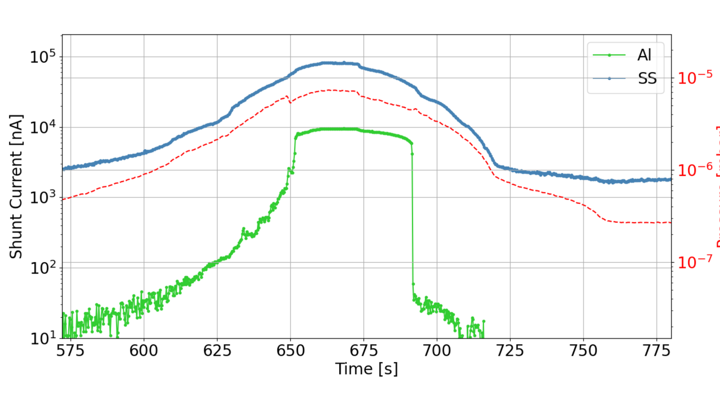
CCG Triggered Response:
- Sudden injection of gas (Air or N_2) triggering the fast acquisition regime
- Improved temporal resolution provides machine protection with additional data
- Threshold adjusted for environment: lower signal at cryogenic conditions





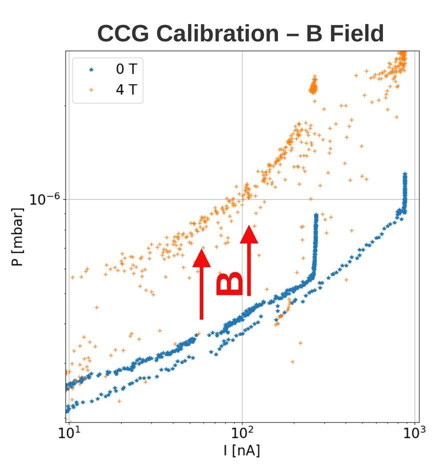
CCG PvI Characteristic:
- Air injection through adjustable needle valve to acquire the **Pressure- Current** curve
- AISI312 sensor demonstrated good linearity and small hysteresis drift
- Al showed abrupt changes from **low-current** to **high-current** regime. Effect of surface Al_2O_3 was excluded by fluxing in pure N2

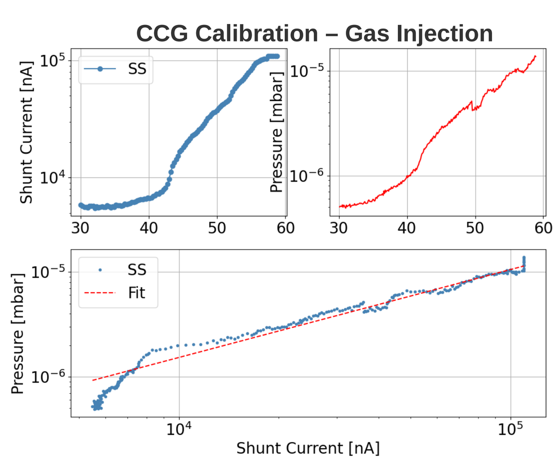




Conclusions

- Two **prototype Penning CCG sensors** were assembled. Suitable front-end acquisition electronic and software were developed
- Sensors were characterized in terms of **PvI characteristic, delay start time** and response to **fast injection of Air and N_2**
- Comparative performances of steel and aluminum as electrode materials. **Steel proved superior** in terms of reliability, discharge stability, and signal
- The RT sensor characteristic and the effect of magnetic field were assessed





Perspectives

- *Sensor characterization and gas injection response at* ***cryogenic temperature***
- *Optimize acquisition system from system-level design towards full-scale production*
- *Validate system on the upcoming* ***JT-60SA experimental campaign***

References

[1] K. Hamada et al 2023, IEEE Transaction on applied superconductivity

[2] H. Shirai et al 2024, Nucl. Fusion

[3] K. Fukui et al 2025, IEEE Transaction on applied superconductivity

[4] B.R.F. Kendall, E. Drubetsky 1995, Journal of Vacuum Science & Technology

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