Silicon Pixel Detector Development for Director Measurement of Charm Baryon Dipole Moments at LHC

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On behalf of the TWOCRYST collaboration

3rd Italian Workshop on the Physics at High Intensity 13/11/2024

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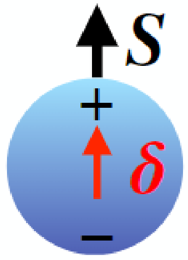
Outline

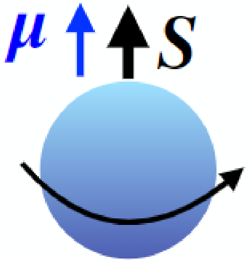
- Introduction and physics motivation
- Proposed experiment at LHC
- Detector layout and integration
- Summary

Electromagnetic dipole moments

- For spin $\frac{1}{2}$ particles we define:

EDM $\boldsymbol{\delta} = \frac{1}{2} d \mu_B \boldsymbol{P}$ MDM $\boldsymbol{\mu} = \frac{1}{2} g \mu_B \boldsymbol{P}$





with $\boldsymbol{P} = 2 < \boldsymbol{S} > / \hbar, \quad \mu_B = \frac{q\hbar}{2m}$

- Hamiltonian: $H = -\boldsymbol{\mu} \cdot \boldsymbol{B} - \boldsymbol{\delta} \cdot \boldsymbol{E} \xrightarrow{P,\,T} H = -\boldsymbol{\mu} \cdot \boldsymbol{B} + \boldsymbol{\delta} \cdot \boldsymbol{E}$

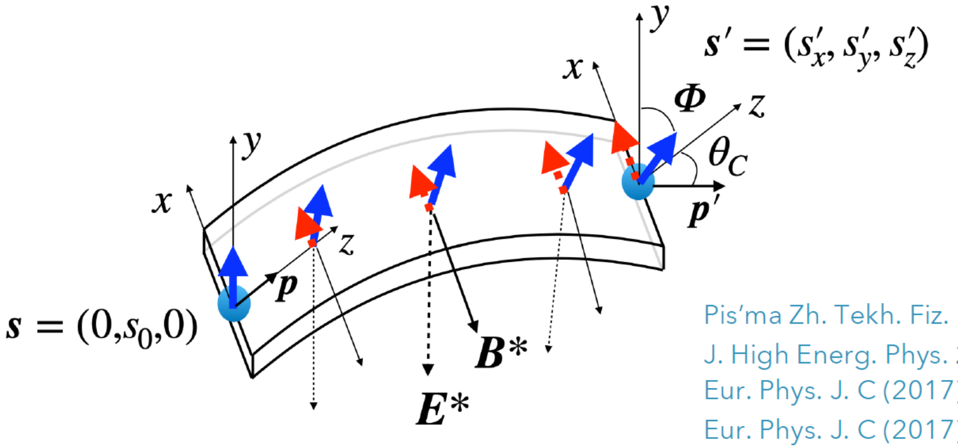
- The EDMs violate P,T → **CP violation beyond the Standard Model (BSM)**
  - Not yet measured for ***charm*** and ***beauty*** baryons and ***tau*** leptons

- The MDMs provide important information to QCD calculations

Measurement with bent crystals

- For short-lived particles ($\gamma c\tau \approx 5\text{cm}$), intense EM fields are needed to induce spin precession before the decay, not possible with magnets
- Exploit **channeling** in **bent crystals**:
  - Electric field between atomic planes $E \approx 1\text{GV/cm}$
  - Effective magnetic field $B \approx 500\text{T}$
  - Steer the trajectory of particles
  - Induce **spin precession**

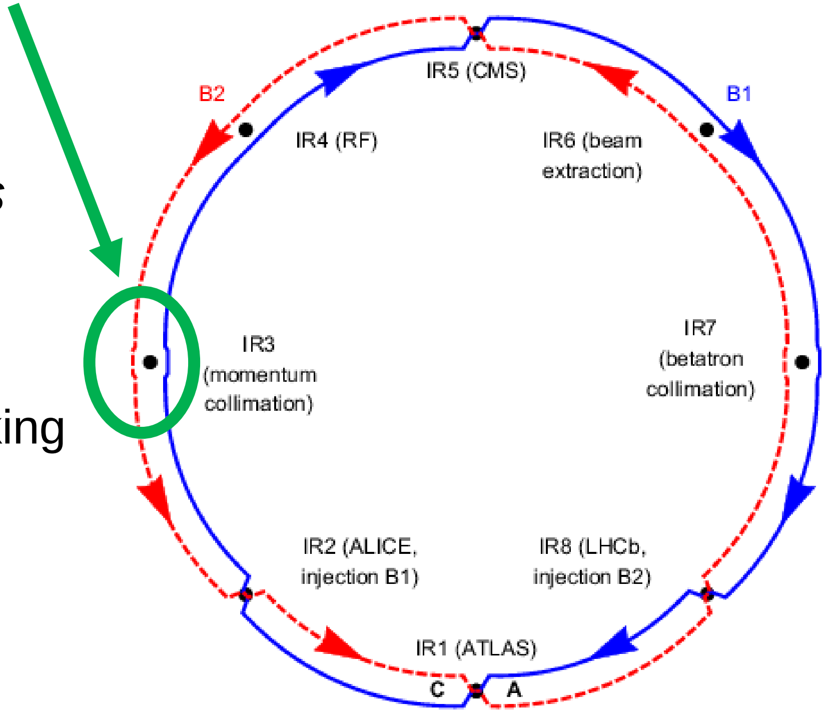
$$\Phi \approx \frac{g-2}{2}\gamma\theta_c \qquad s'_x \approx s_0 \frac{d}{g-2}$$

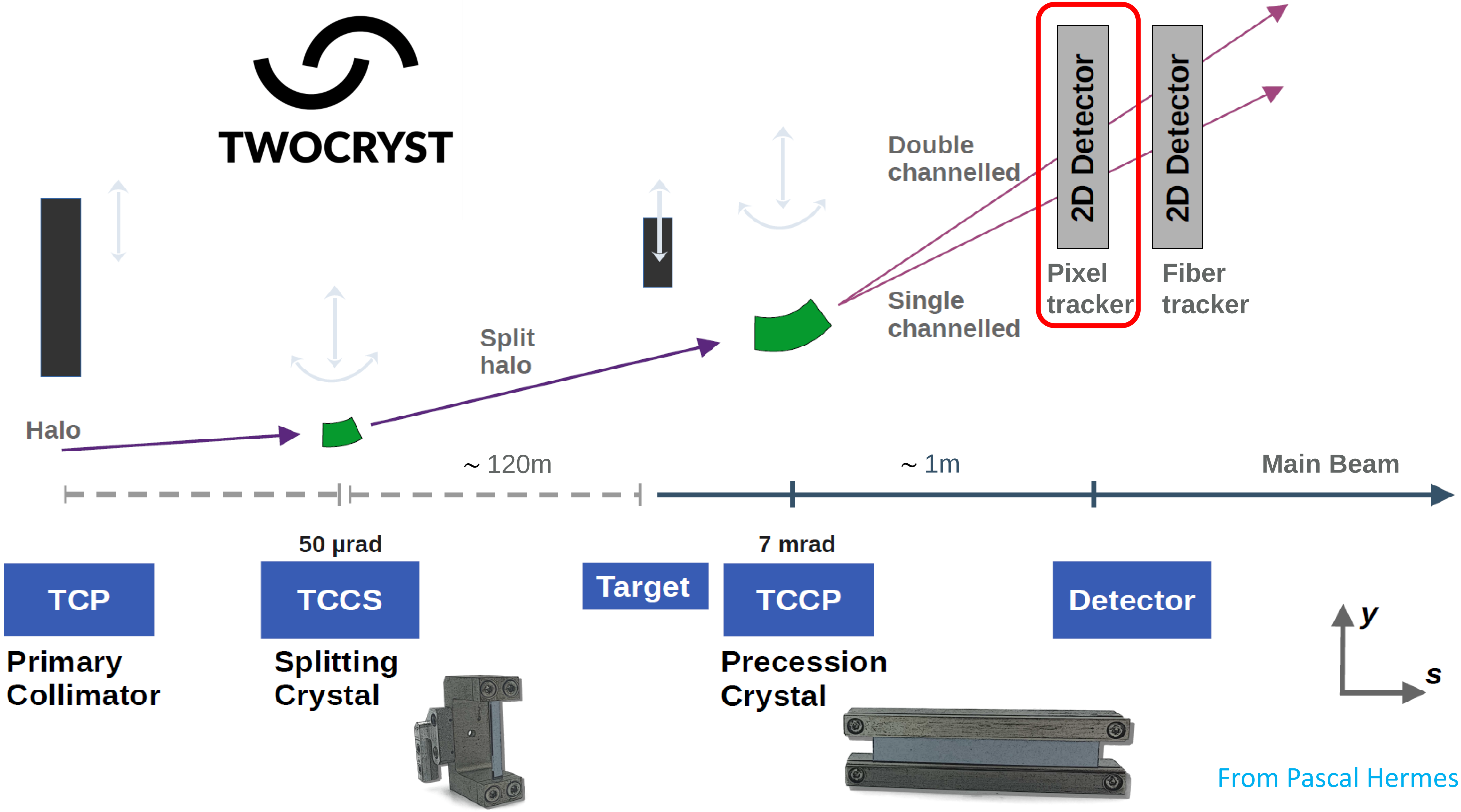


Pis'ma Zh. Tekh. Fiz. 5 (1979) 182
J. High Energ. Phys. 2017 (2017) 120
Eur. Phys. J. C (2017) 77:181
Eur. Phys. J. C (2017) 77:828

Proof of Principle (PoP) experiment

- The PoP test, called **TWOCRYST**, was approved for installation in **IR3** during 2025
- A Letter of Intent (LoI) was submitted to the LHCC for the proposed **ALADDIN** experiment (*A LHC Apparatus for Direct Dipole moments INvestigation*) [CERN LHCC-I-041]
- **Goals** of TWOCRYST:
  1. Demonstrate the operational feasibility of the double crystal and tracking detector setup at the LHC
  2. Confirm the estimated achievable rates of proton on target
  3. Measure channeling efficiency of long crystals at TeV energies
  4. Perform background studies
- **Timeline:**
  - Installation during EYETS 24/25
  - Data taking during MD shifts in 2025





From Pascal Hermes

Detector specifications

- Minimum 1 layer needed for background and efficiency studies
- Detect both channeled and unchanneled particles → active area ≥ 1x1cm^2
- High granularity < 100µm

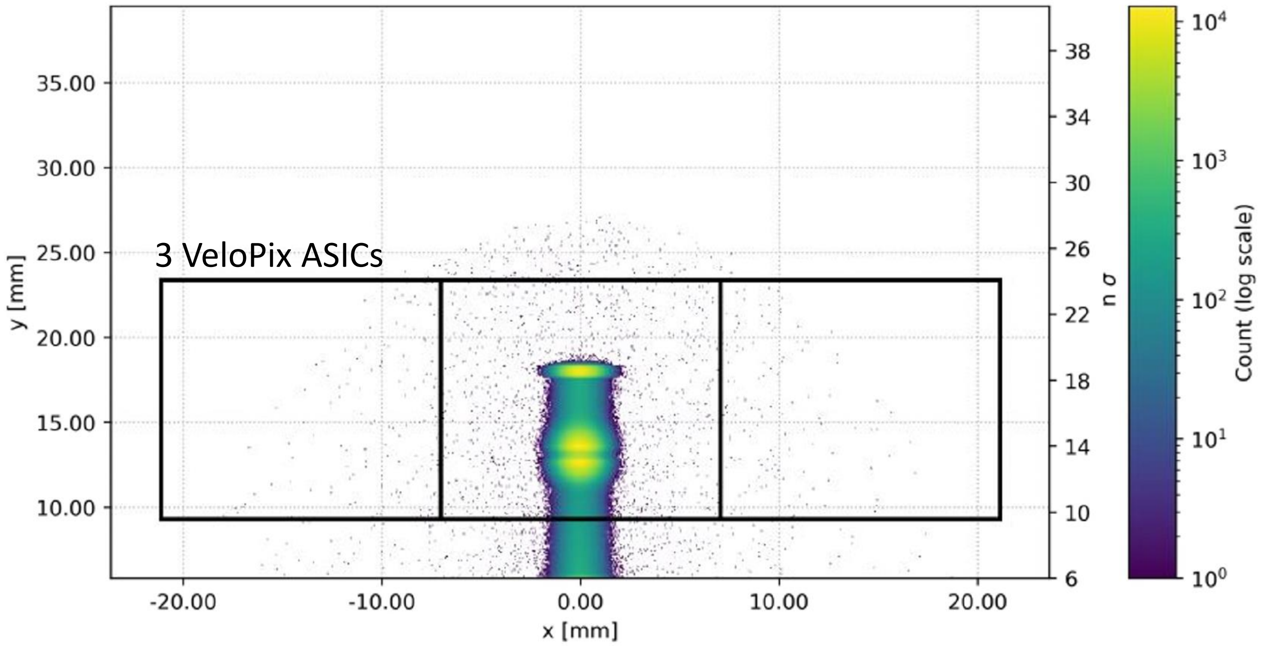
↓

Use LHCb Vertex Locator (**VELO**) pixel sensors and readout chain

- Active area: 42.57 x 14.08 mm^2, 200µm thick
- VeloPix ASIC: 256 x 256 pixels, 55µm pitch
- Sensor + 3 ASICs bump-bonded togheter

Technology	Silicon pixel sensors
N layers	≥ 1
Distance target-first layer	$70 \pm 5\ cm$
Transverse distance from the LHC beam	0.5-1 cm
Active area	$\geq$ 1×1 cm^2
Granularity	$< 100\ \mu m$
Radiation hardness	$\sim 10^{12}$ 1 $MeV\ n\ eq/cm^2$
Operational temperature	$< 20° C$

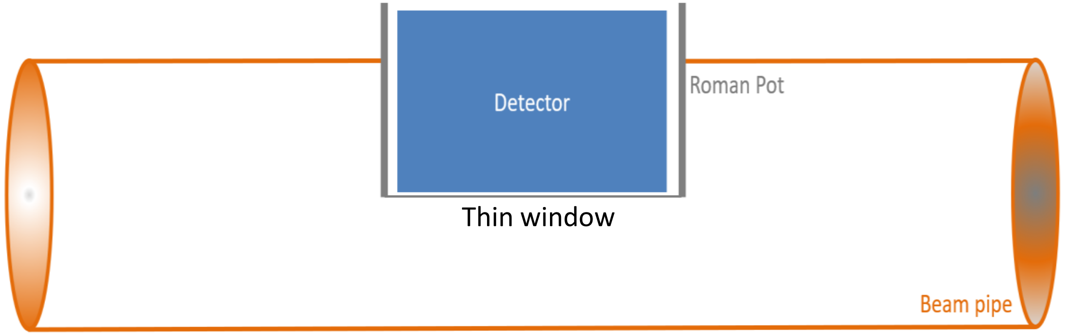
From Sara Cesare



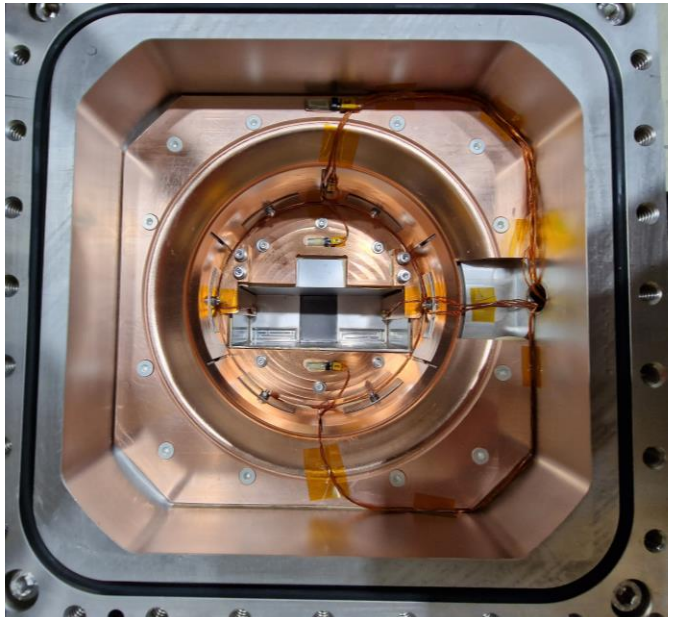
Simulations from Chiara Maccani

Roman pot station

- Distance between main beam and target < 1cm → detector must be **inside** the beam pipe
- Solution: **Roman Pot** station from ATLAS-ALFA
- To avoid bulging the *thin window*, the detector is kept under secondary **vacuum** (2mbar)

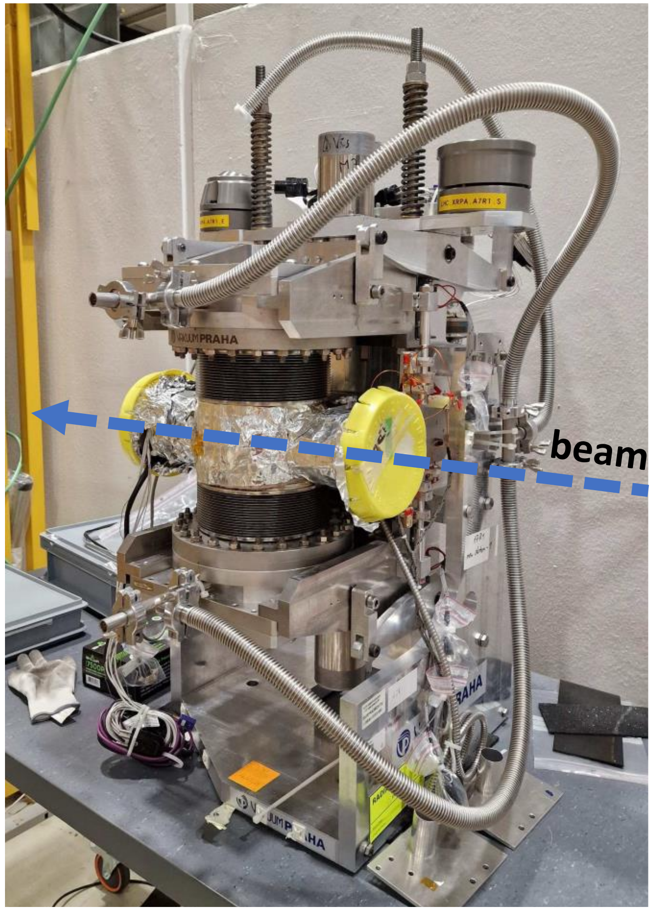


Need to re-adapt the VELO module to the Roman Pot geometry



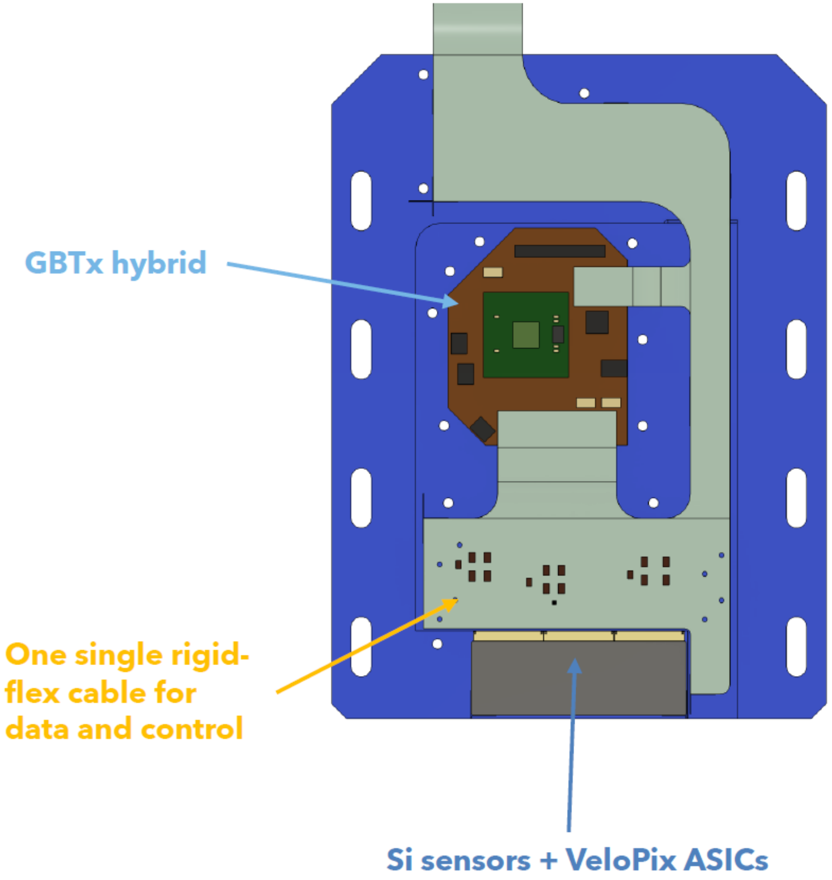
Top view of the Roman Pot

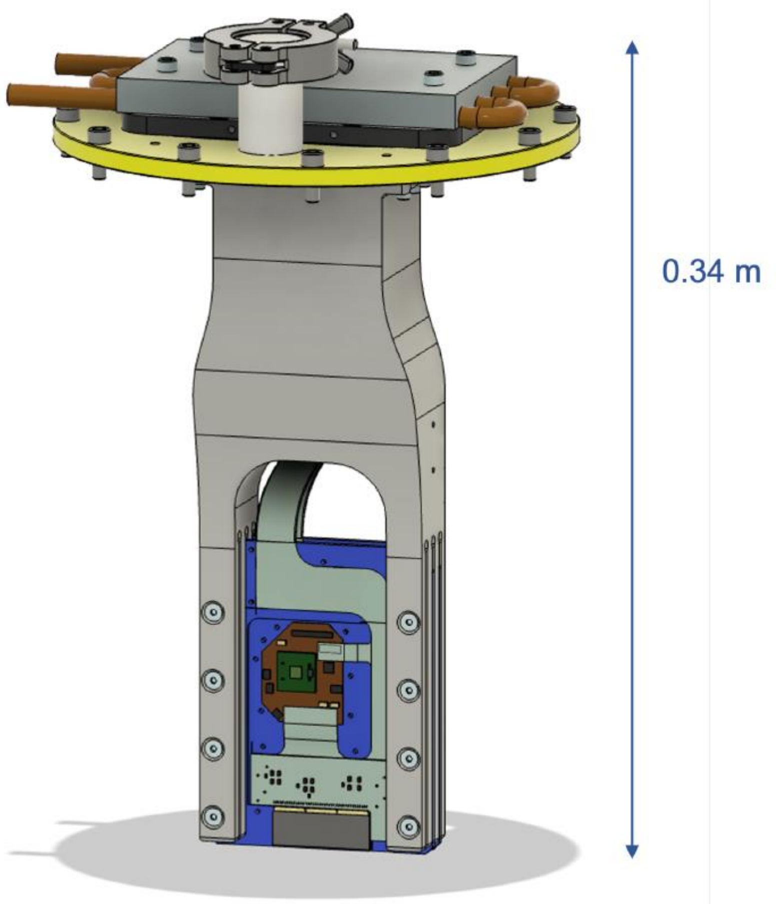
Credits: Sune Jakobsen

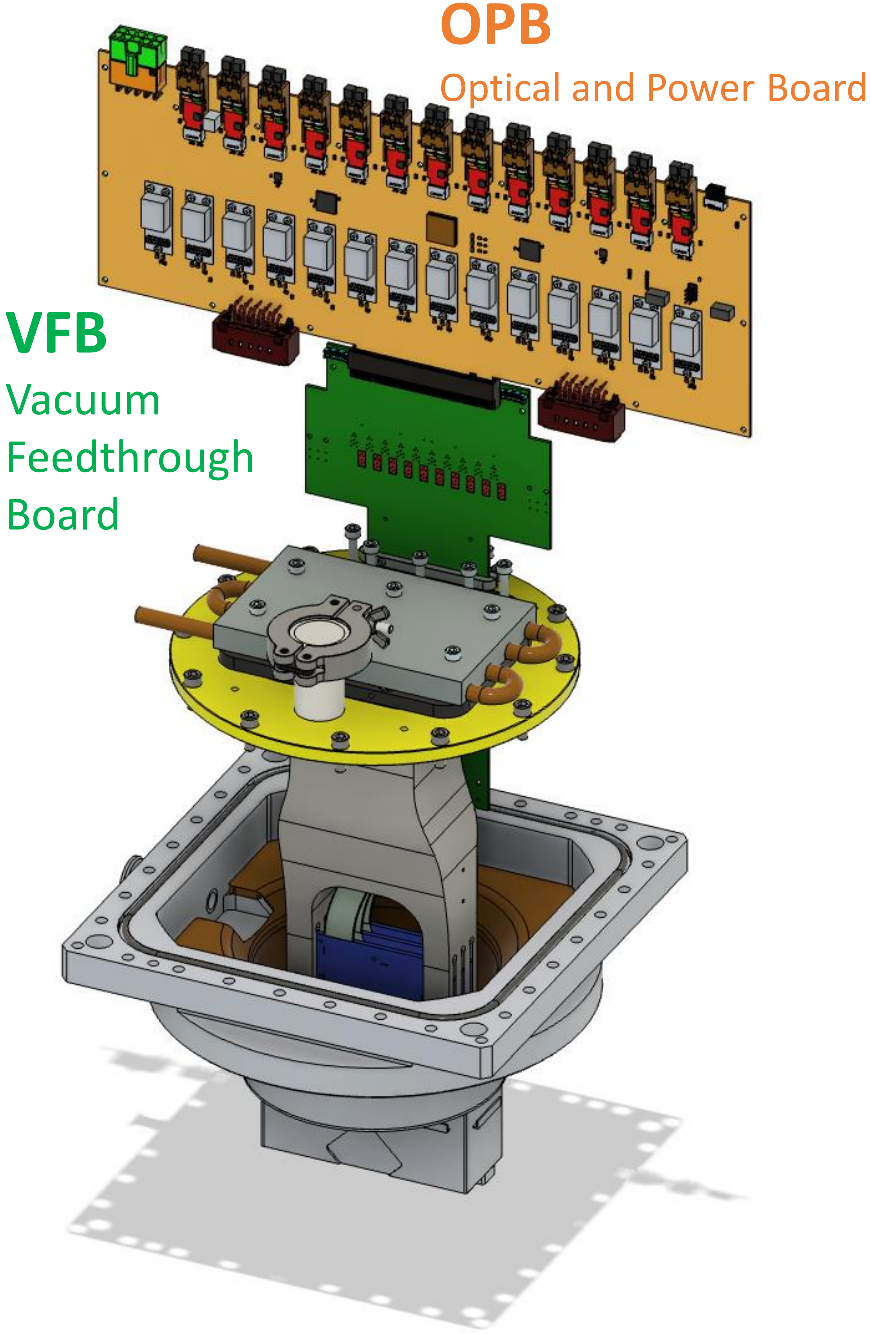


Roman pot station from ATLAS-ALFA

Pixel tracker



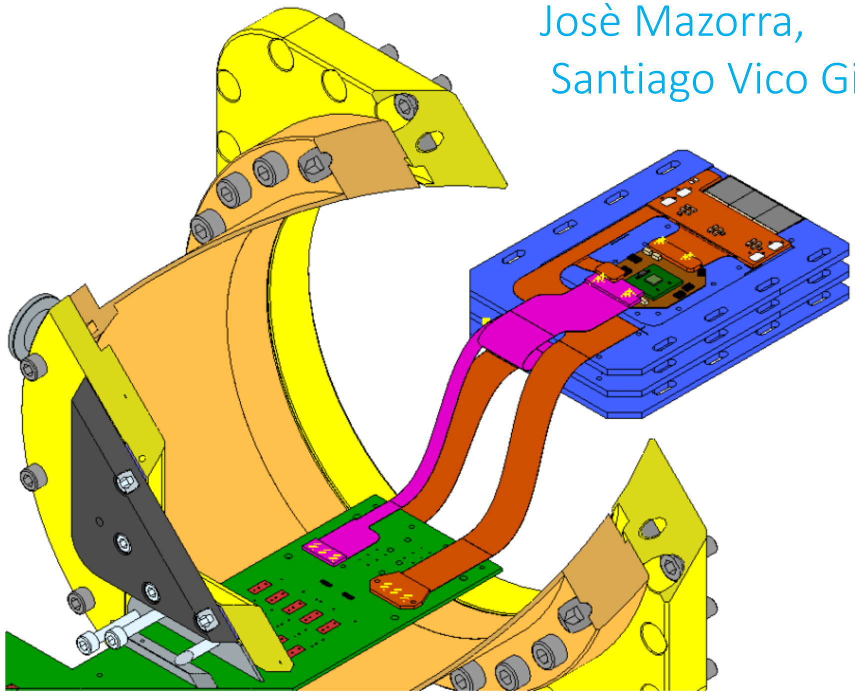




Credits: Massimo Benettoni, Nicola Turini

Detector electronics

Josè Mazorra,
Santiago Vico Gil



New flex cables:

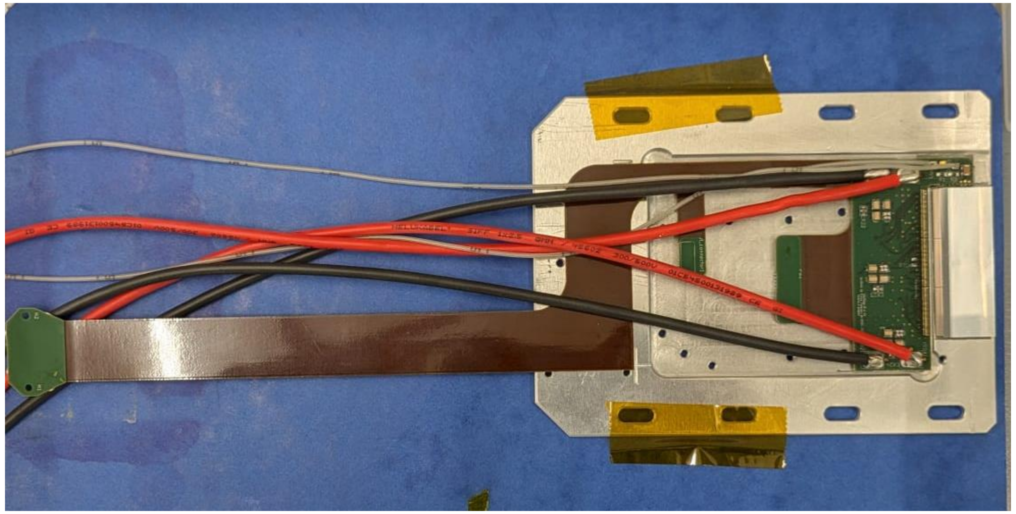
- Single circuit to integrate data and control signals and power
- Two different designs:
  - **Flex1**: GBTx on the same layer as tile (produced and tested)
  - **Flex2**: GBTx on different layer, longer arm (in production)

Vacuum feedthrough board (VFB):

- Passage of data, controls, LV and HV from air to vacuum
- Adapted design from VELO to fit in the vacuum flange

Optical and Power board (OPB): [CERN-LHCb-PUB-2021-012]

- DC/DC converters to manage LV power
- Optical data links (VTTx) and control links (VTRx)



Flex1 wire-bonded to the sensor

Credits: Florentina Manolescu

Josè Mazorra,
Santiago Vico Gil

Detector electronics

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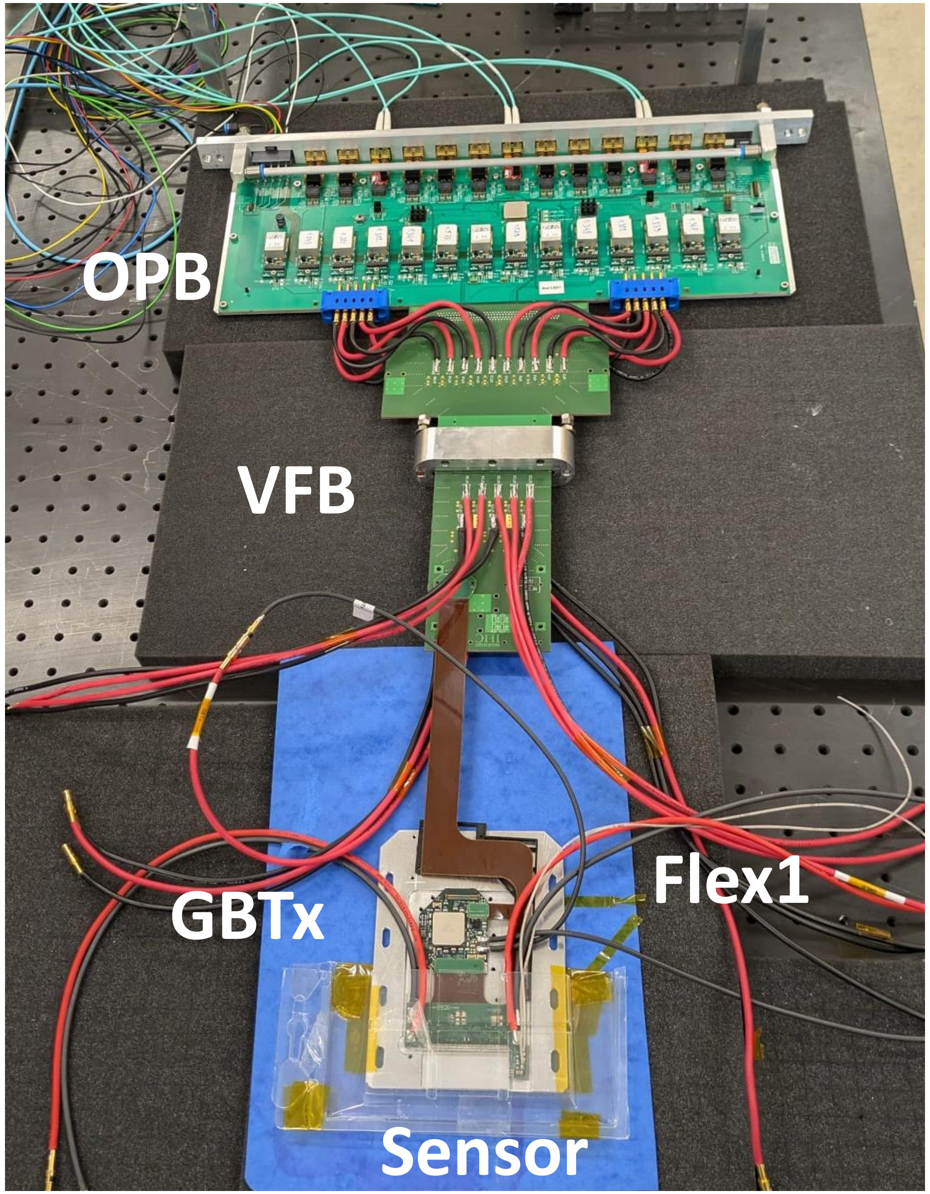


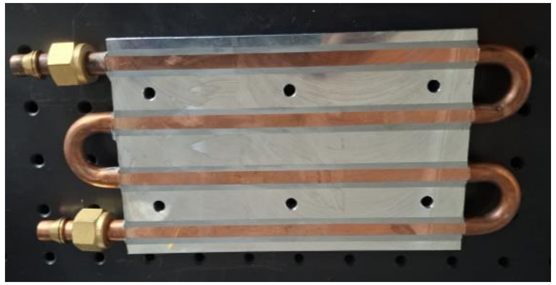
Cooling system

Requirements:

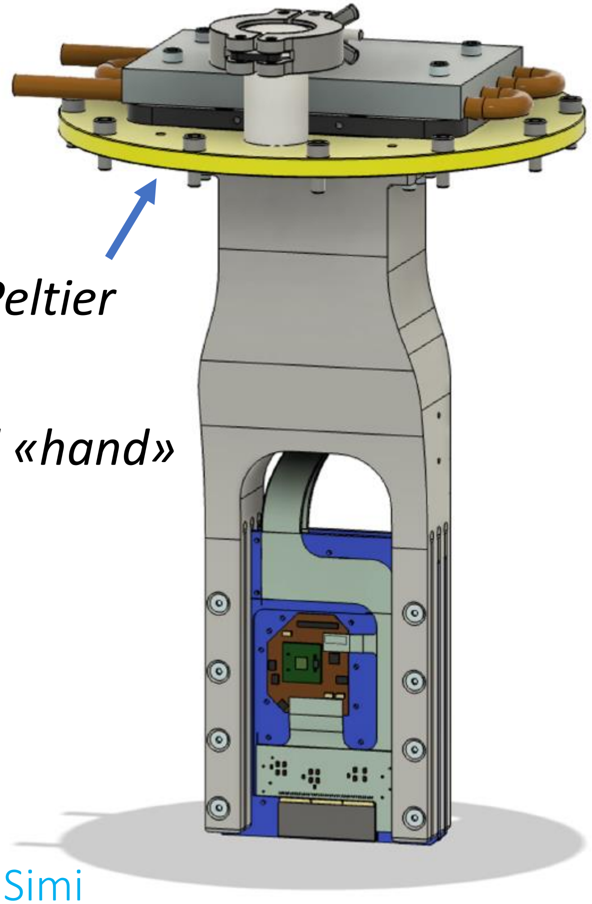
- Keep detector temperature below 30°C during operations
- Dissipate heat generated by electronics and beam induced currents
- **Total power budget ≈ 37W** (conservative estimate)

Solution:

- Thermo-electric cooling with **Peltier cell** (inside the vacuum)
- **Water**-based heat exchanger (outside vacuum, ≈ 140W)
- Water derivation from a nearby magnet (27°C, 20bar)
- Preliminary tests show that T ≈ 30°C on the sensor is achievable



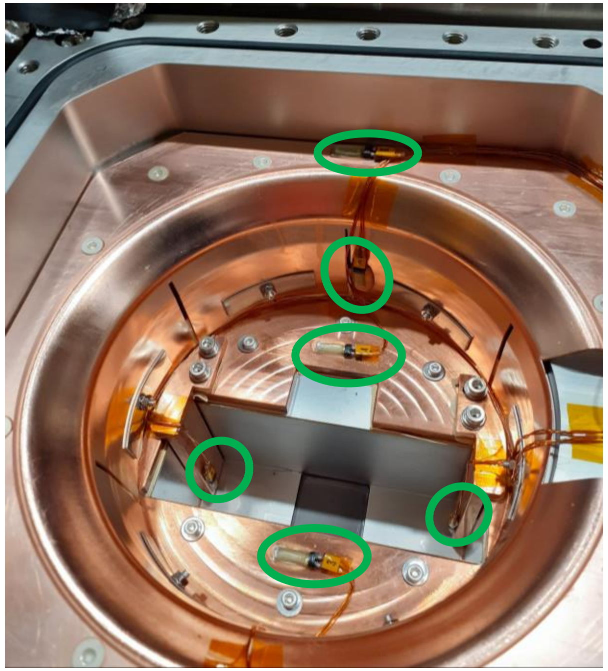
Water heat-exchanger

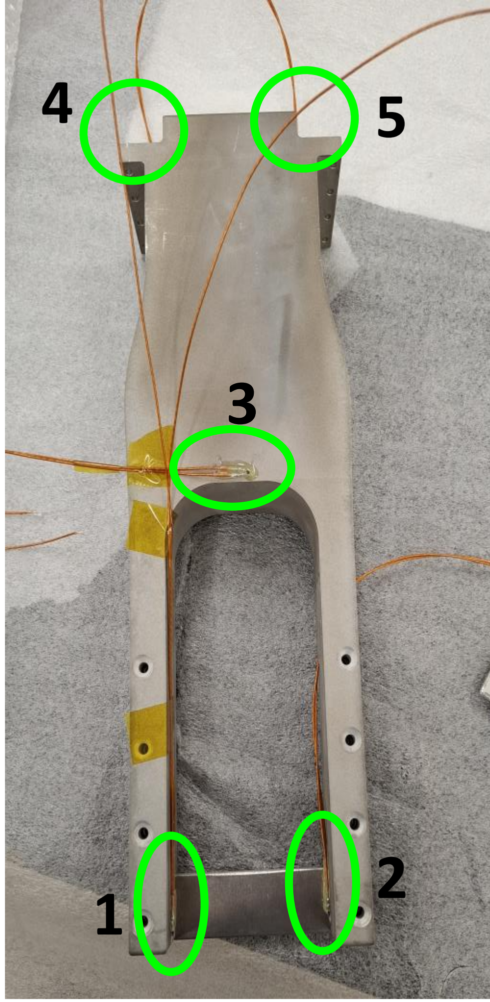


Credits: Massimo Benettoni, Gabriele Simi

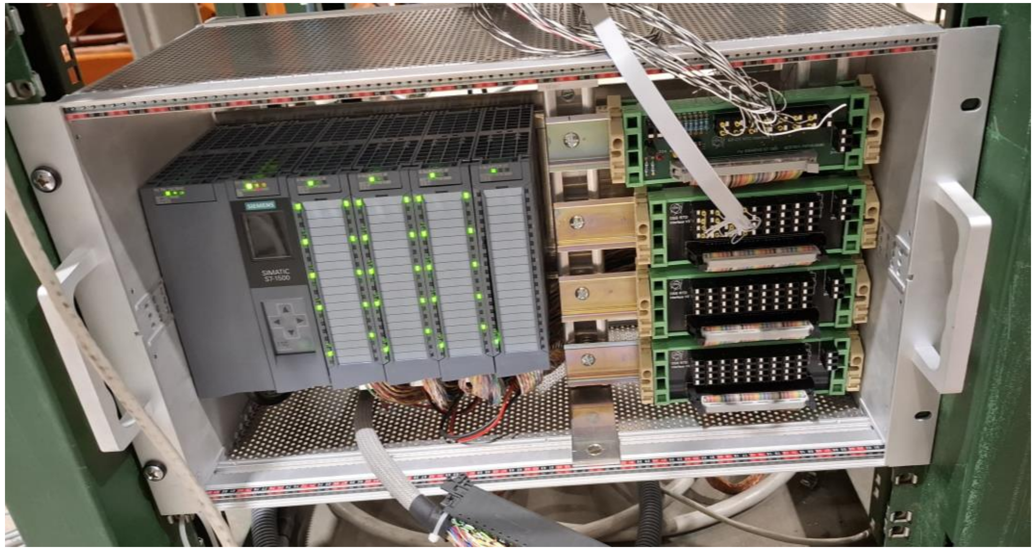
Monitoring system

- **Temperature** probes:
  - 12 Pt100 on Roman pot and "cold finger"
  - 7 NTC (3 Flex, 2 GBTx, 2 on OPB)
- Alarm signal from **vacuum** system
- **Flow** switch (water cooling system)





- **PLC**: readout and hardware **interlocks** on the power supply for **detector safety**

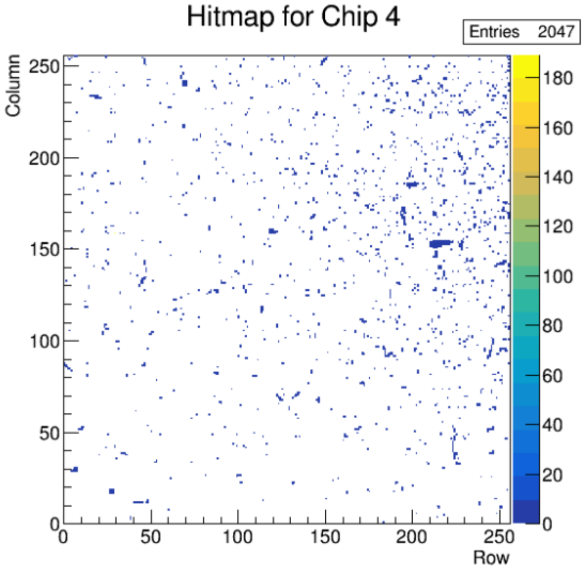


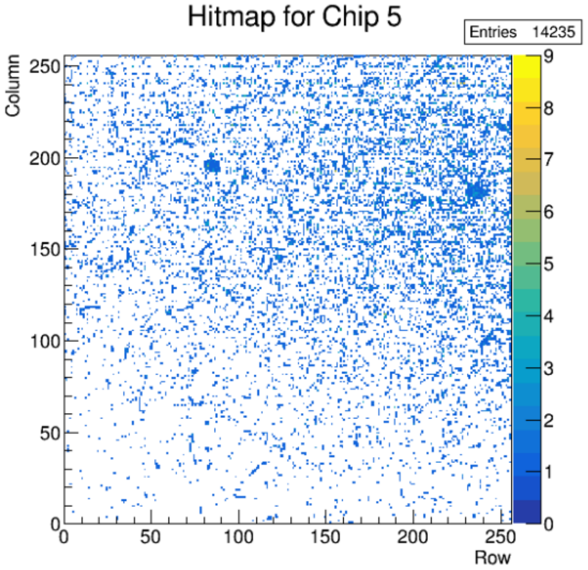
Thanks to Giulio Malaguti, Maciej Ostrega, Xavier Pons

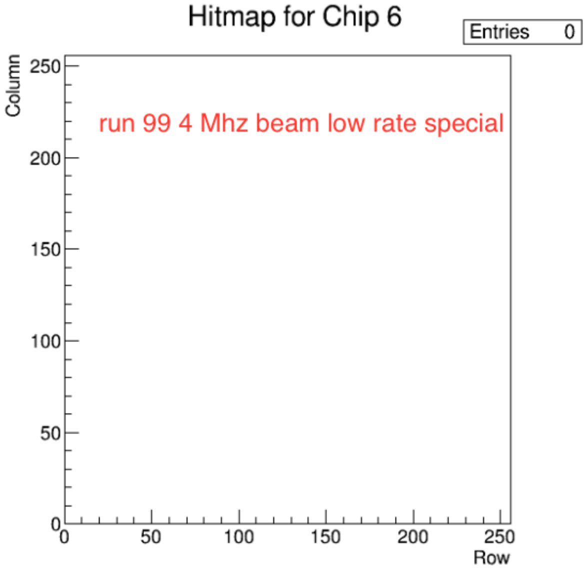
Testbeam

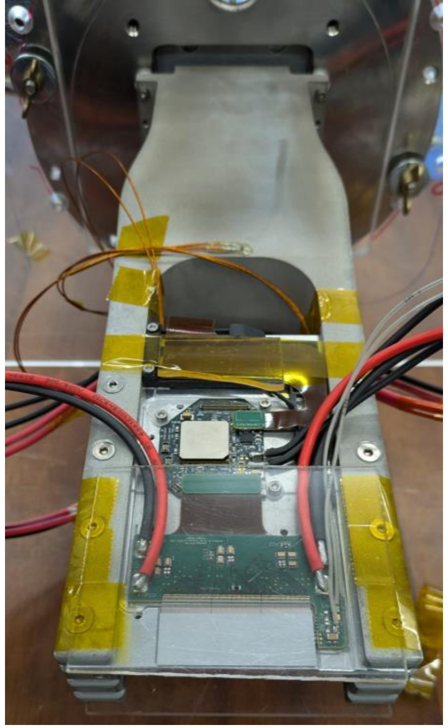
Testbeam campaign at **SPS H8** line:

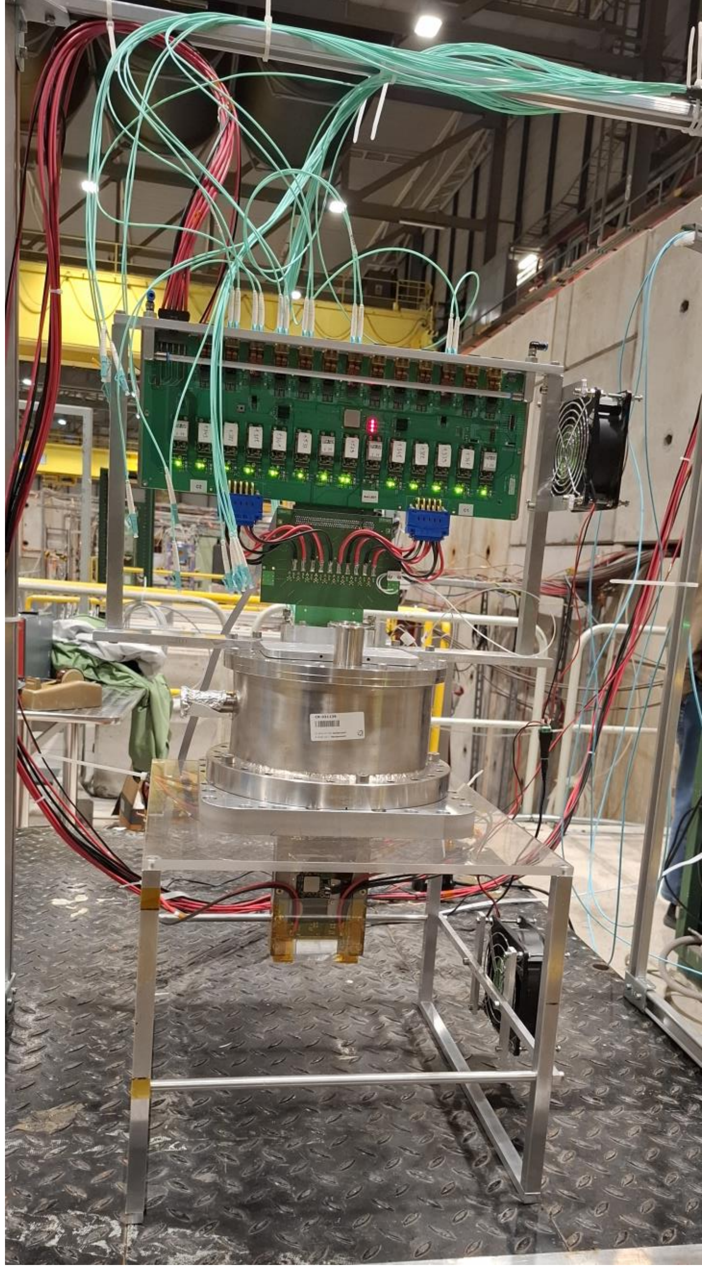
- First assembly of one module + full readout chain
- Configuration of the chips
- Test of the DAQ system
- Equalisation of the thresholds
- *Recorded first particles hits*









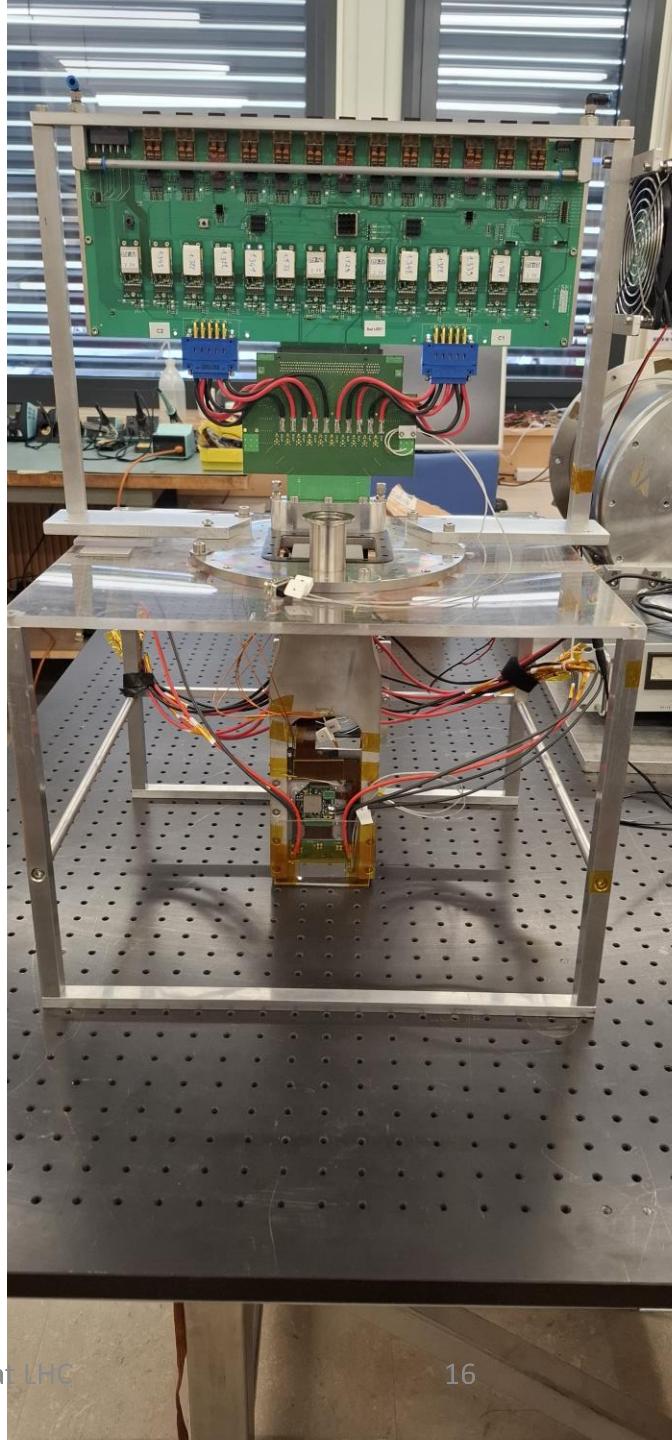


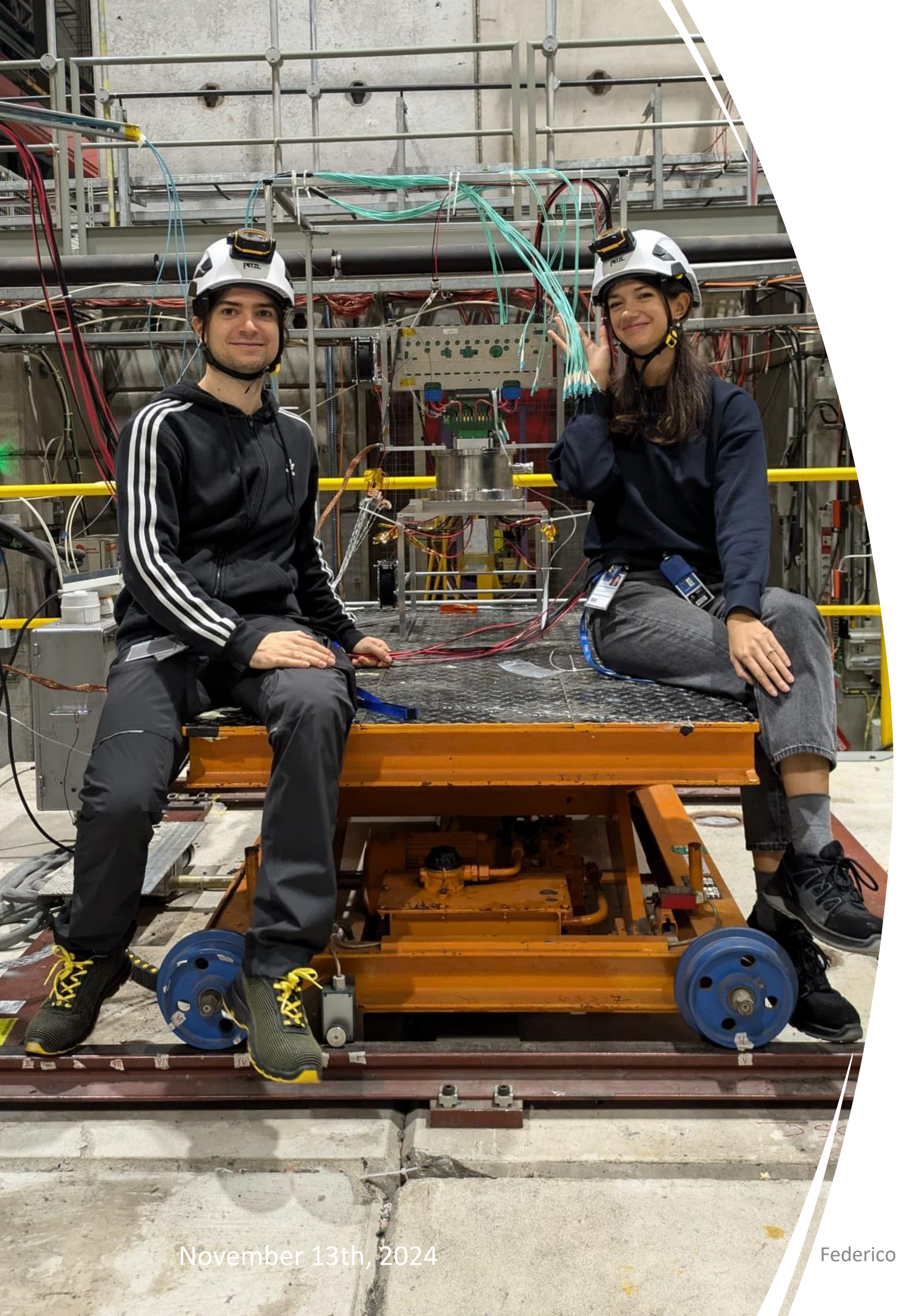
Detector package installed at SPS H8

Credits: Sara Cesare, Santiago Vico Gil, Gianluca Lamanna, Josè Mazorra, Marco Sozzi, Federico Zangari

Summary

- TWOCRYST is approved for installation during 2025
- A new pixel detector is being developed, based on the LHCb Vertex Locator
- The first module was assembled and successfully tested with beam at SPS
- New modules are currently in production
- The detector is getting ready for installation in the LHC tunnel during the EYETS 24/25
- *Special thanks to the VELO experts for their outstanding support!*
(in particular Jan Buytaert, Edgar Lemos Cid, Victor Coco, Raphael Dumps, Karol Hennessy, Massimiliano Ferro-Luzzi)





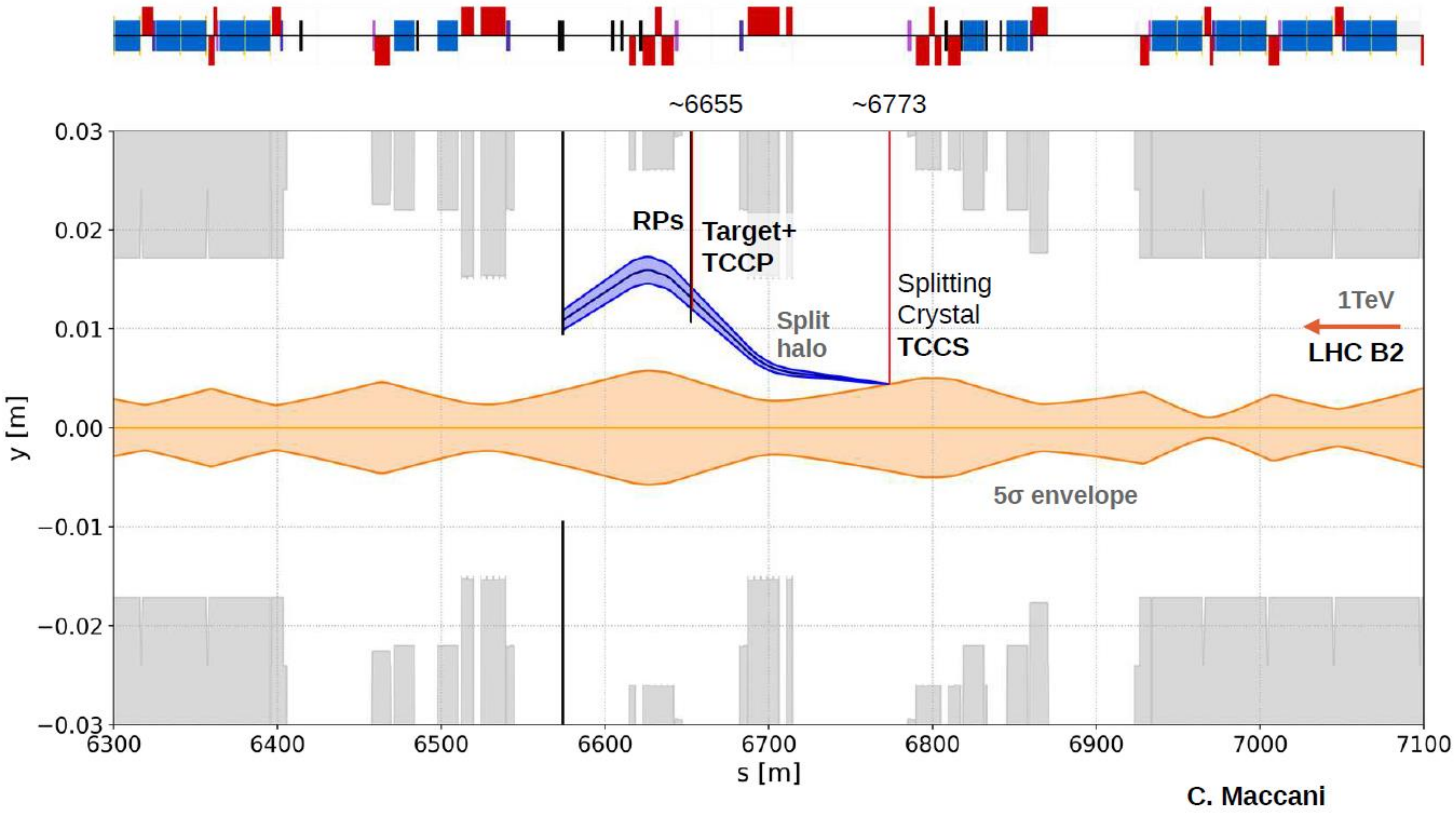
Thanks for the attention!

Acknowledgments for financial & hardware support

- **ERC** Consolidator Grants SELDOM G. A. 771642
- **PRIN 2022**, Italian Ministry of University and Research (MUR), 202277EWLW
- **Physics Beyond Colliders** study group
- **ATLAS ALFA experiment**

Backup

TWOCRYST layout

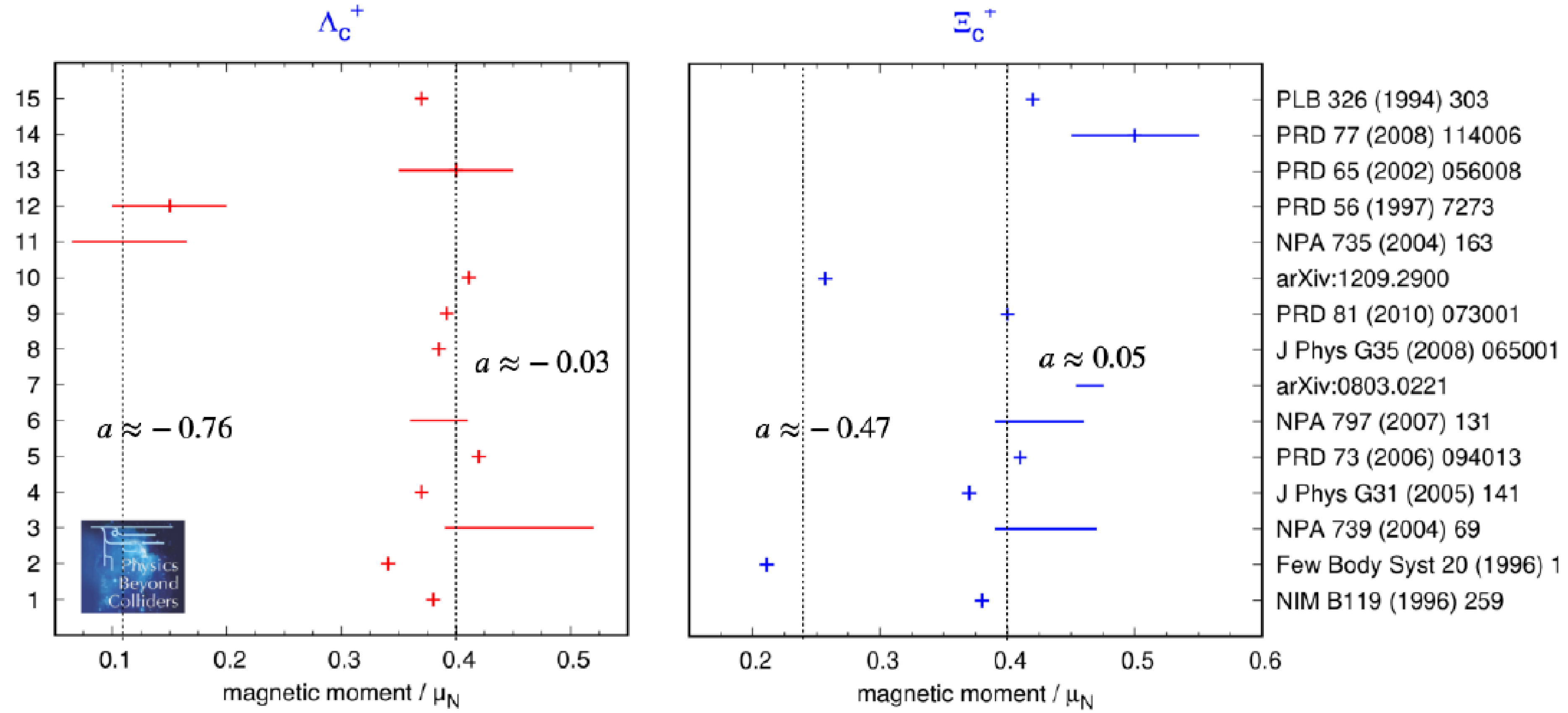


Magnetic dipole moments of charm baryons

From Sara Cesare

Naive quark model MDM $\mu_{\Lambda_c^+} = \mu_c, \quad \mu_{\Xi_c^+} = \mu_c$

No measurements to date for short-lived **charm** baryons - will provide important anchor points for QCD calculations.



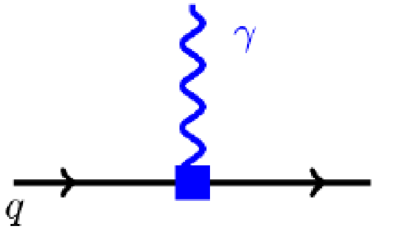
CERN-PBC-REPORT-2018-008

Electric dipole moments of charm baryons

From Sara Cesare

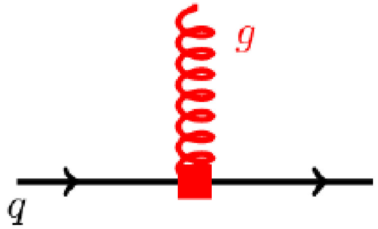
charm EDM

$$d_q\, \bar{q} i \sigma^{\mu\nu} \gamma_5 q\, F_{\mu\nu}$$



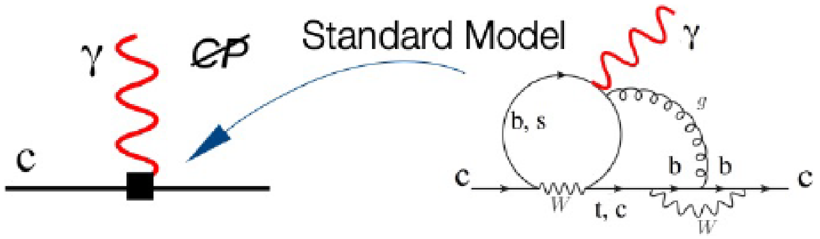
charm chromo-EDM

$$\tilde{d}_q\, \bar{q} i \sigma^{\mu\nu} \gamma_5 t_a q\, G^a_{\mu\nu}$$



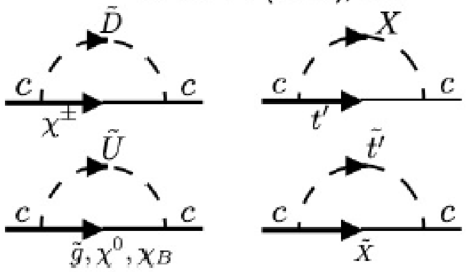
Charm EDM in SM-CKM ~10^{-32} e cm

Khriplovich, Lamoreaux (1997)

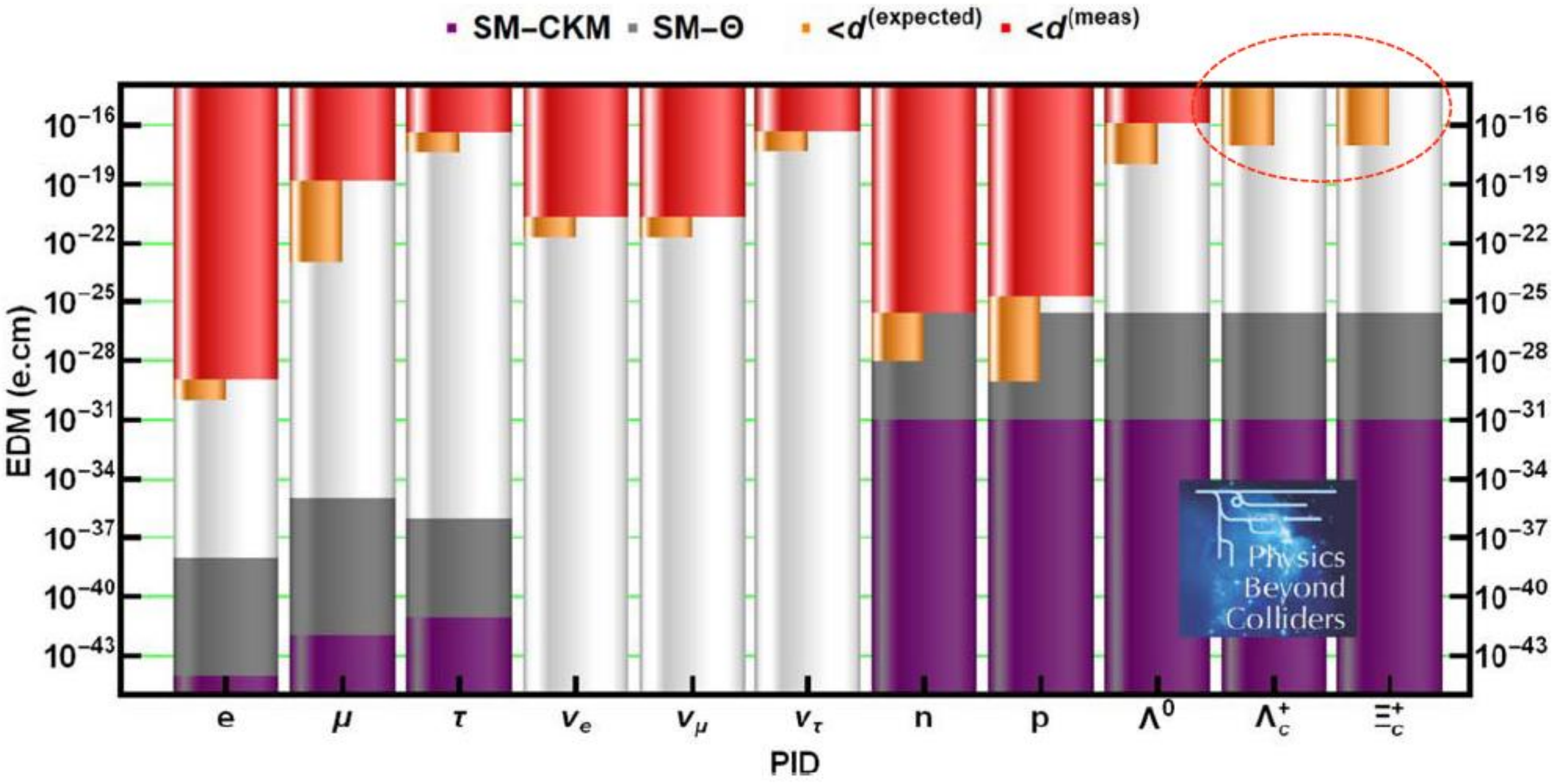


Charm EDM with new physics ~$5 \cdot 10^{-17}$ e cm

EPJC 77 (2017), 102



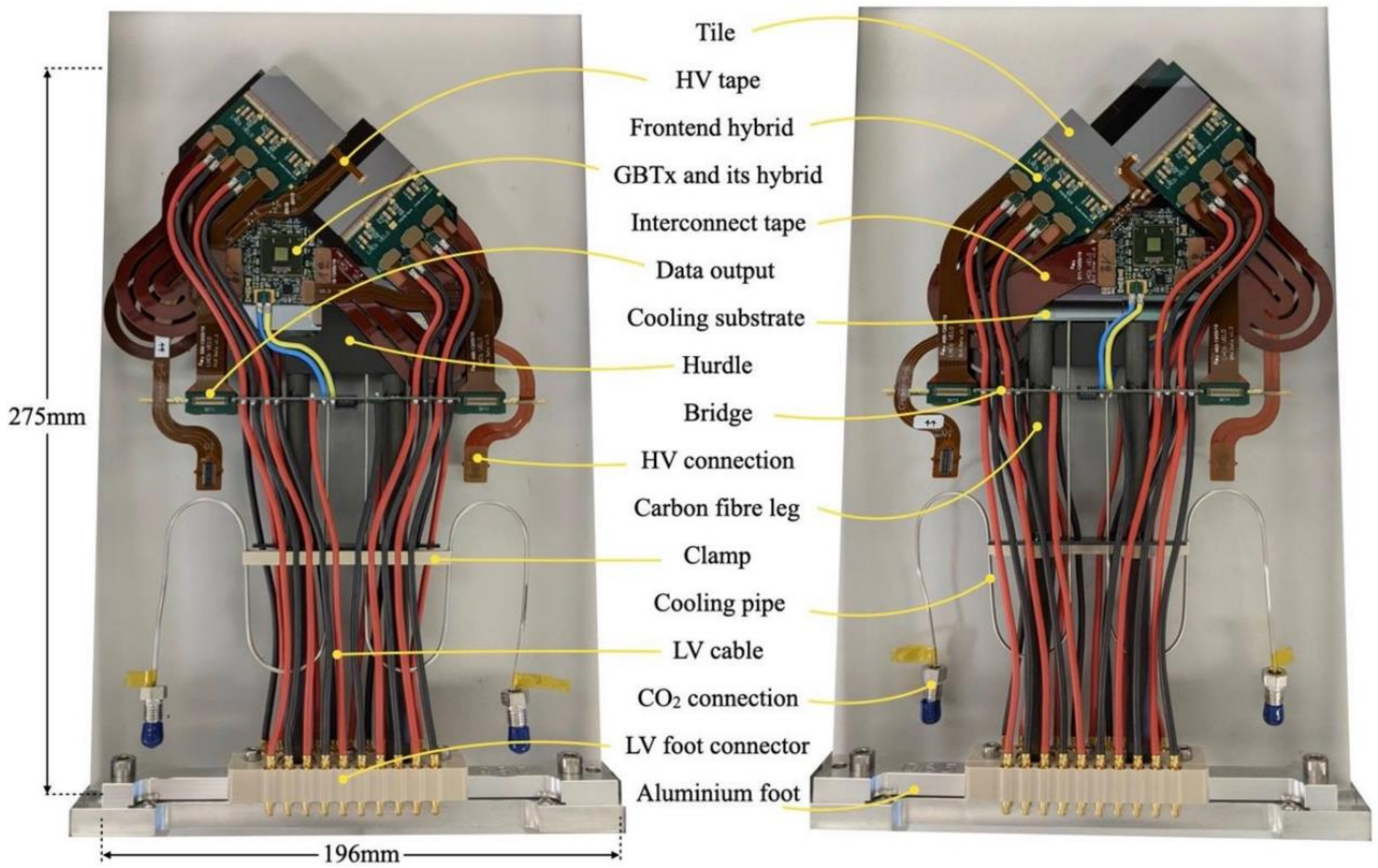
Electric dipole moments of charm baryons

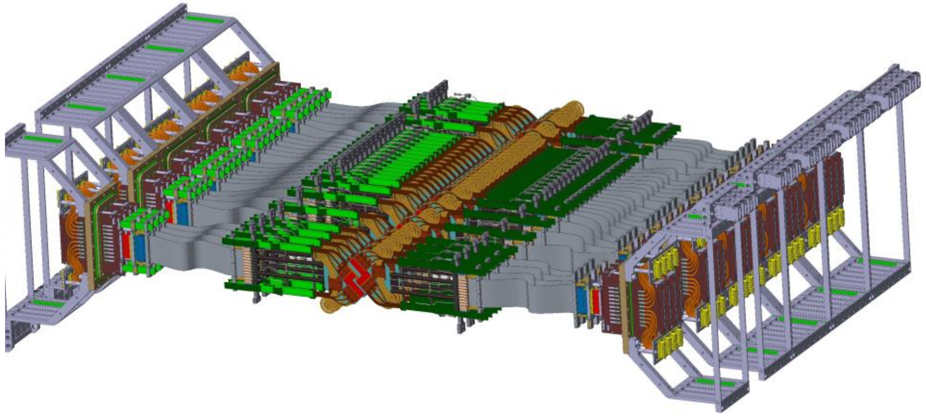


J. Phys. G: Nucl. Part. Phys. 47 (2020) 010501

The Vertex Locator

https://doi.org/10.1016/j.nima.2022.167804

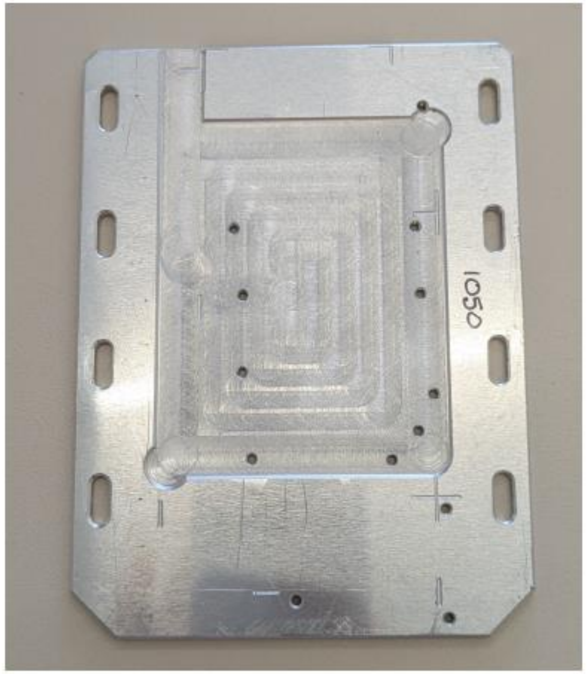




From Sara Cesare

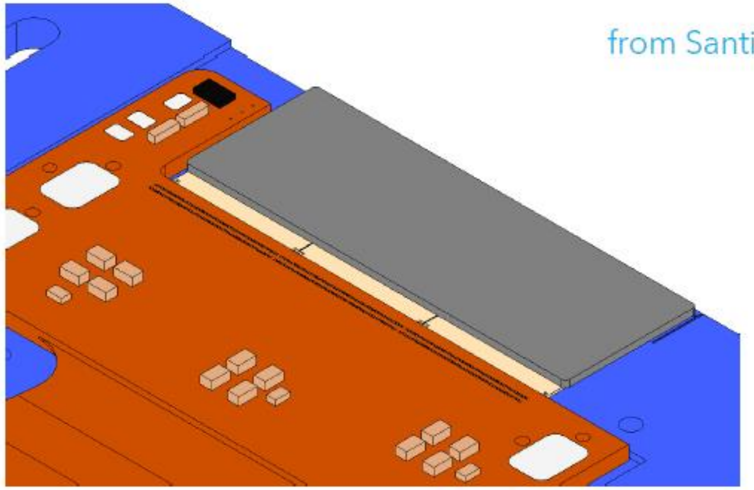
Gluing

- The VELO tile and the rigid part of the flex cable will be glued in the next few weeks at the wire bonding lab at CERN using STAYSTIK 672 thermoplastic film
  - The film is resistant to radiation up to 10^15 1 MeV neq/m



Wire bonding

- ASIC: There are two rows of pads in the ASICs and two in the FE flex cable. The dimensions of the pads are 100x200 µm^2. The distance between the nearest row of pads and the edge of the sensor is 2.31 mm.
- HV wire bond from the rigid-flex to the sensor



from Santiago Vico Gil

Tiles Quality Assurance

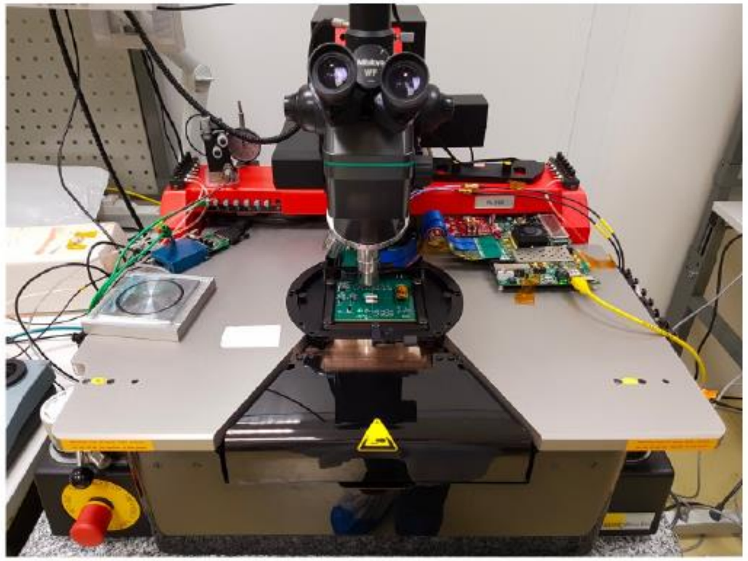
From Sara Cesare

BUMP-BONDING QA (ADVAFAB)

- Visual inspection of the wafer ASIC and bump quality
- IV measurements
- Delivered in gel-packs

Tiles

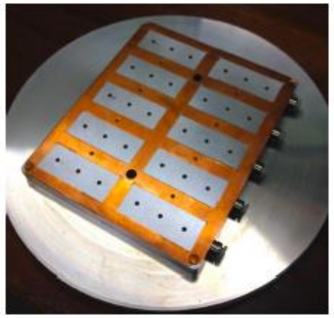
Probe station



TILES QA (VELO PROCEDURE)

Setup for functional test

- Designed dedicated holder
- Karl Suss PA200 semiautomatic probe- station (PS).
- SPIDR readout board
- Bias the sensors with HV needle



Tiles holder

SPIDR board

Test setup at CERN DSF clean room

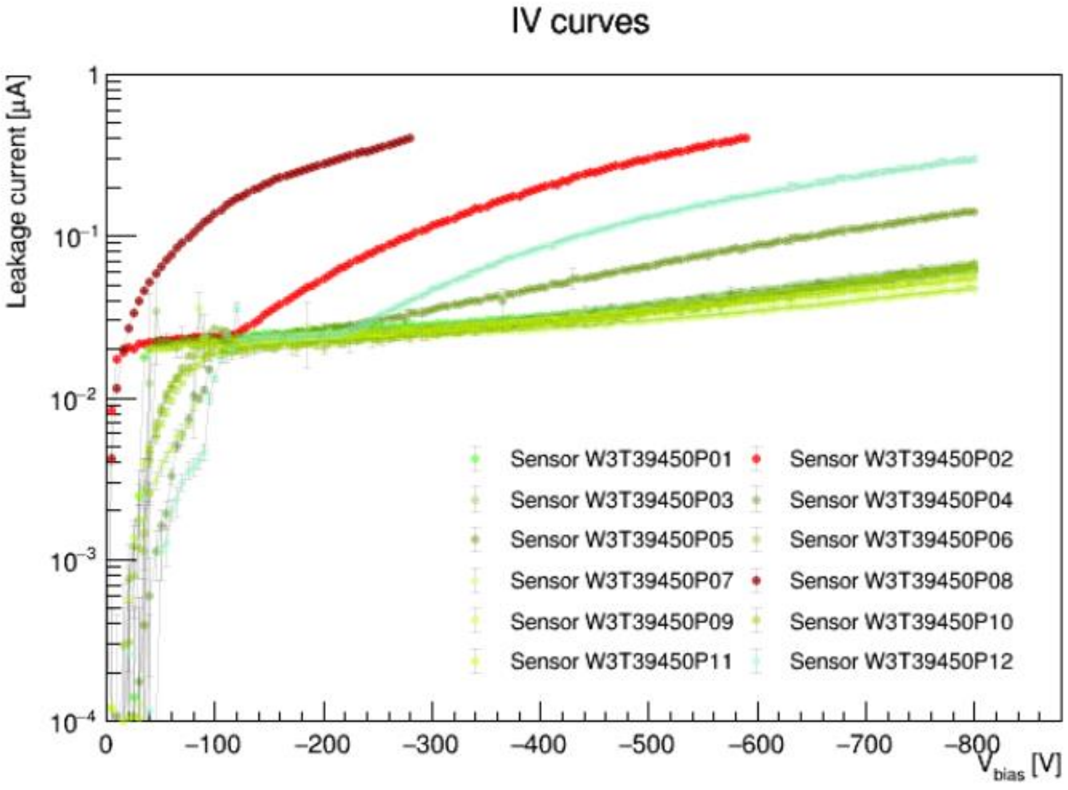
Special thanks to Victor Coco from the VELO group

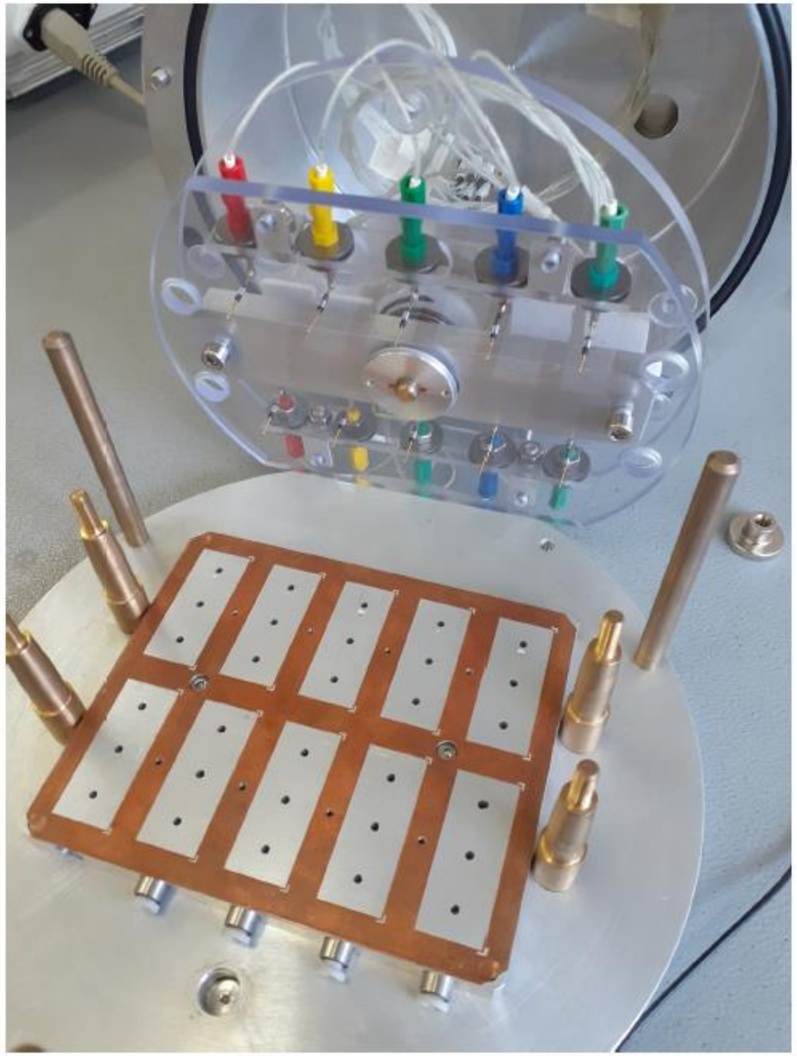
IV scans

From Sara Cesare

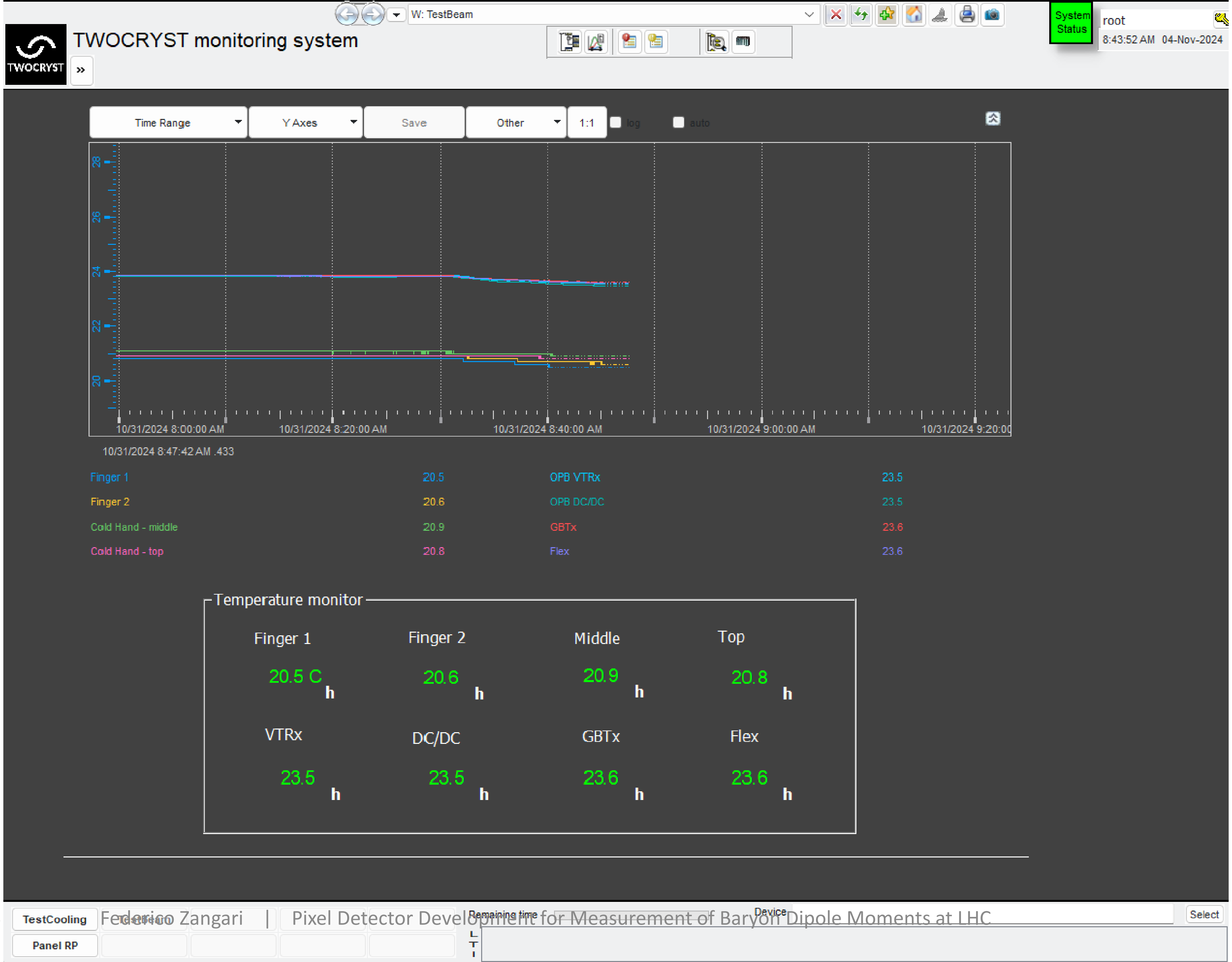
Test setup at CERN in the VELO lab

Sensors have been tested up to V=-800 V

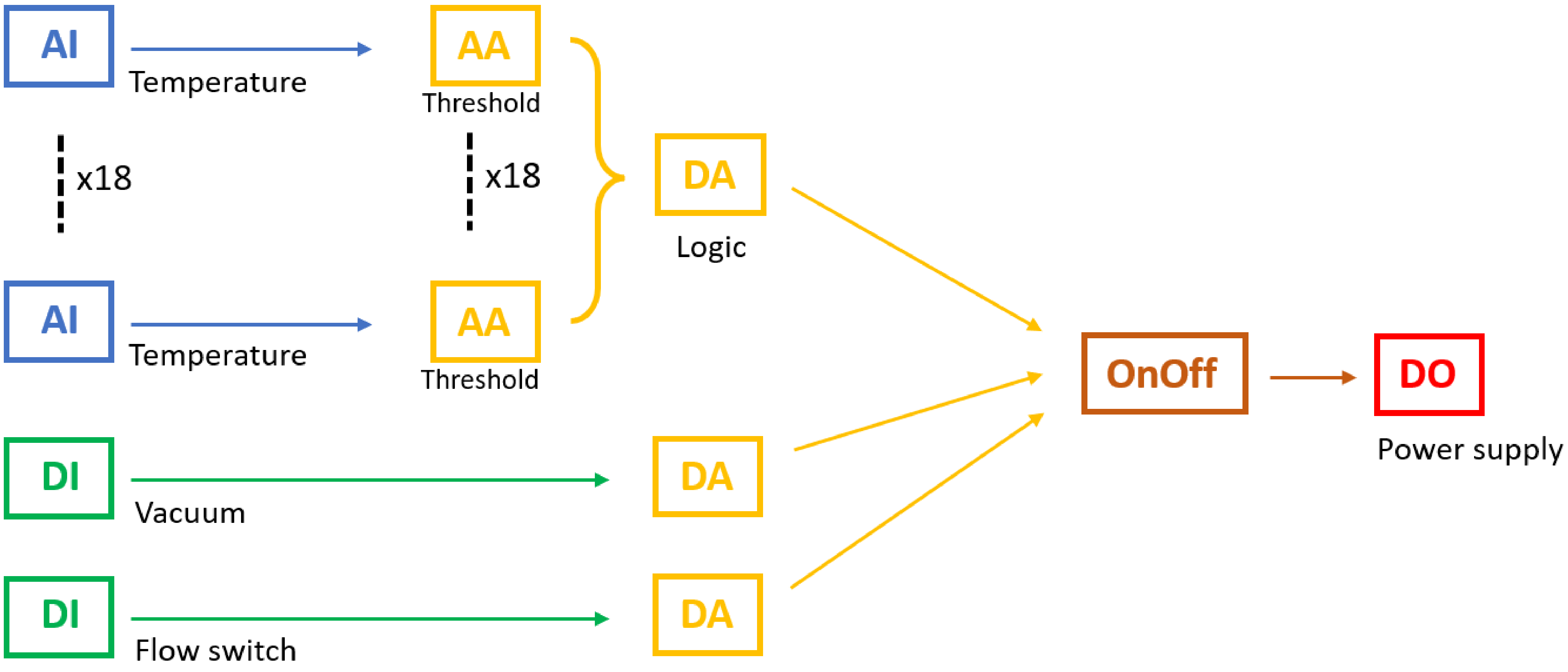




WinCC panels



Interlock logic (UNICOS framework)



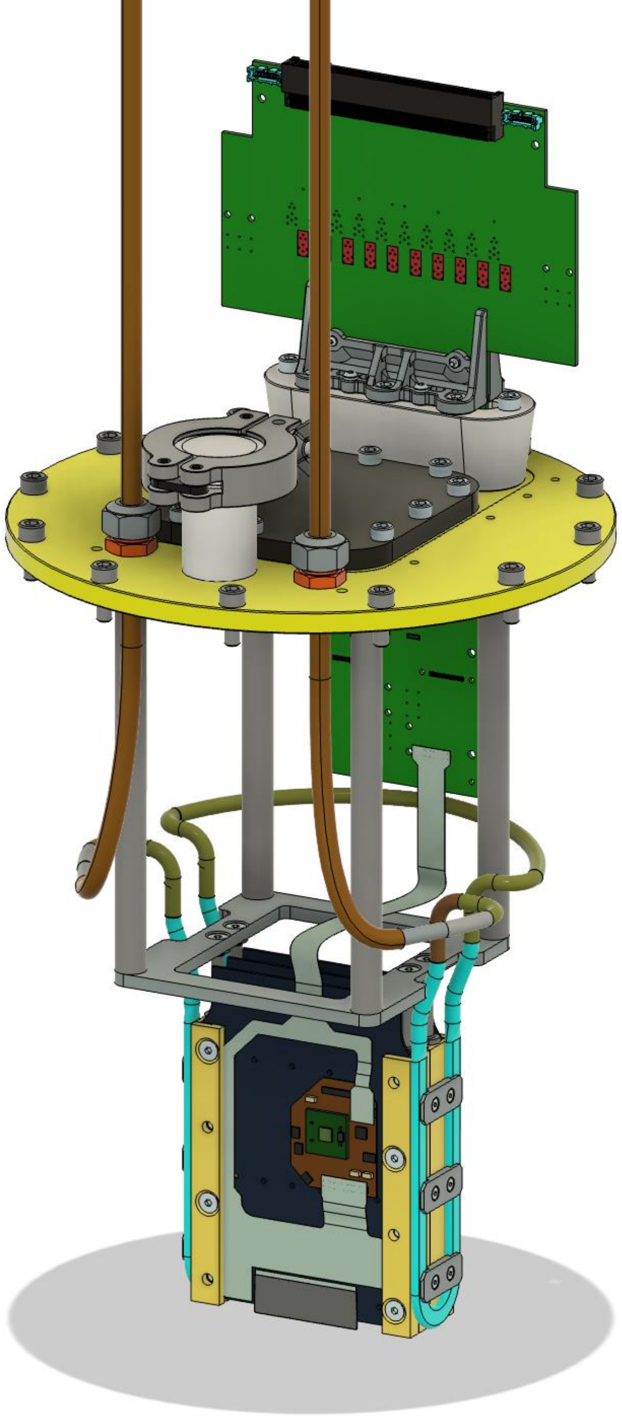
AI = Analog input
DI = Digital Input
AA = Analog Alarm
DA = Digital Alarm
DO = Digital Output

Cooling and mechanics

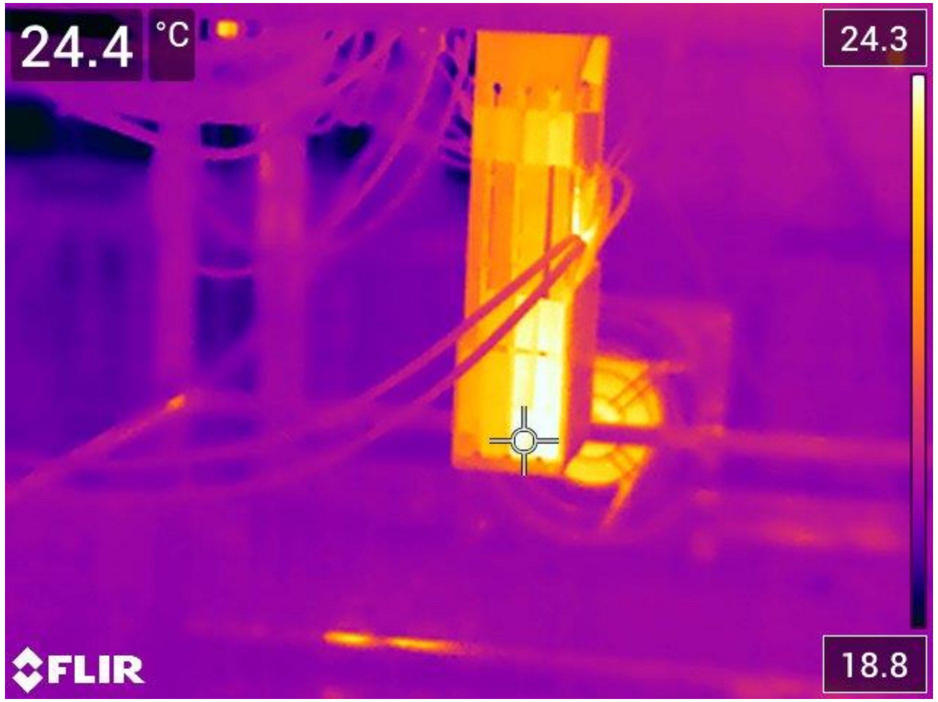
- First version, **water-based cooling** inside roman pot
- Problems:
  - Need of a radiation-hard chiller (placed close to the roman pot)
  - OR very long water pipes ≈ 300m, high costs (chiller placed in UJ33)
  - If water from the LHC (magnets, collimators) is used, it has high pressure 20bar → risk of water leaks in the LHC beam pipe

↓

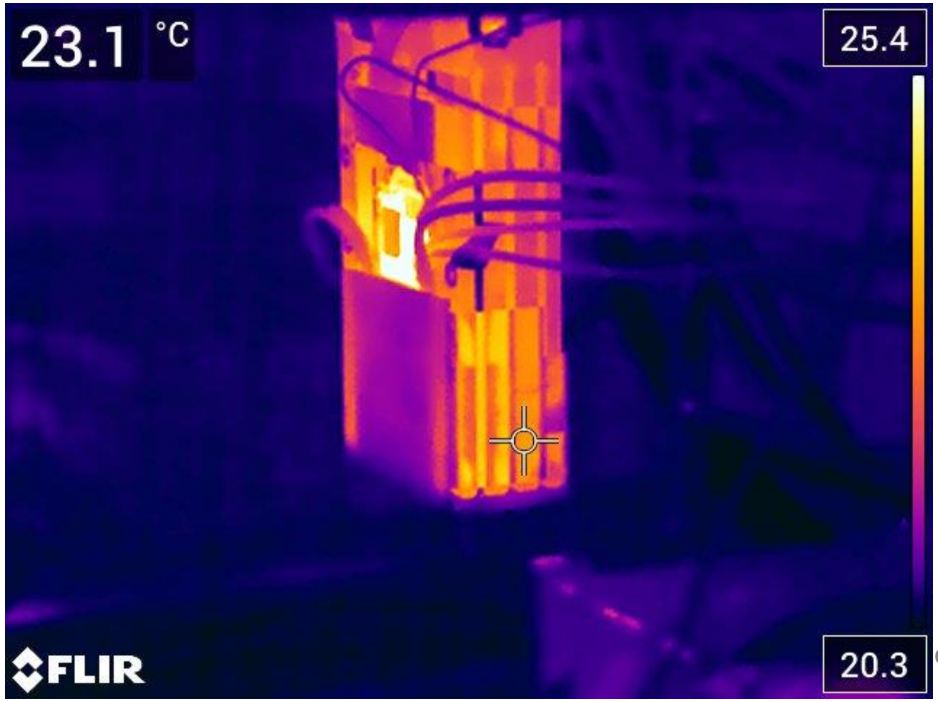
Switched to **Peltier** only inside the vacuum



1

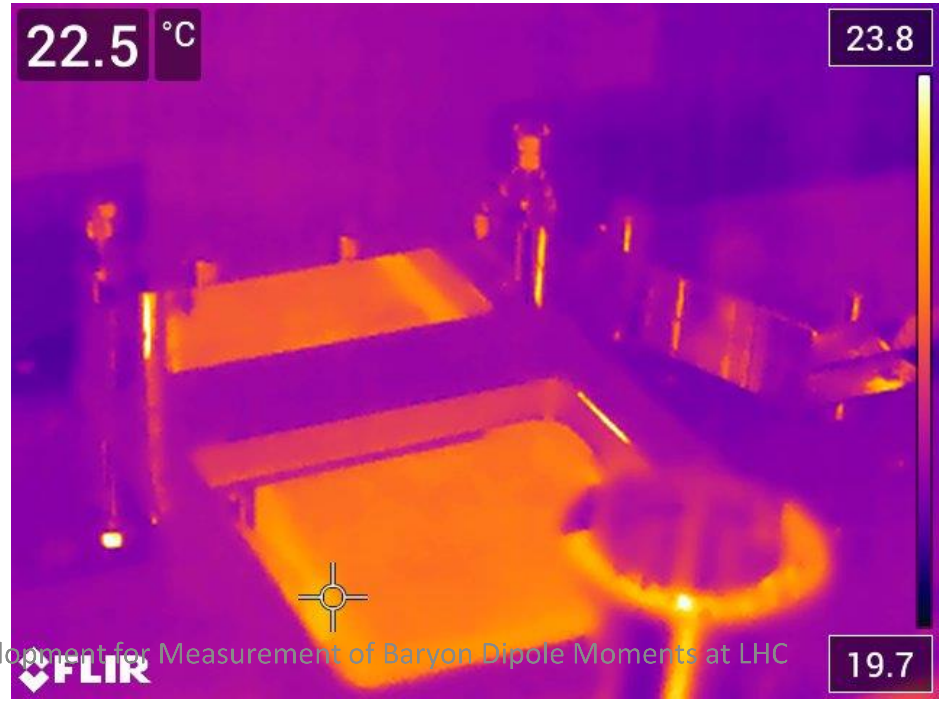


2



3

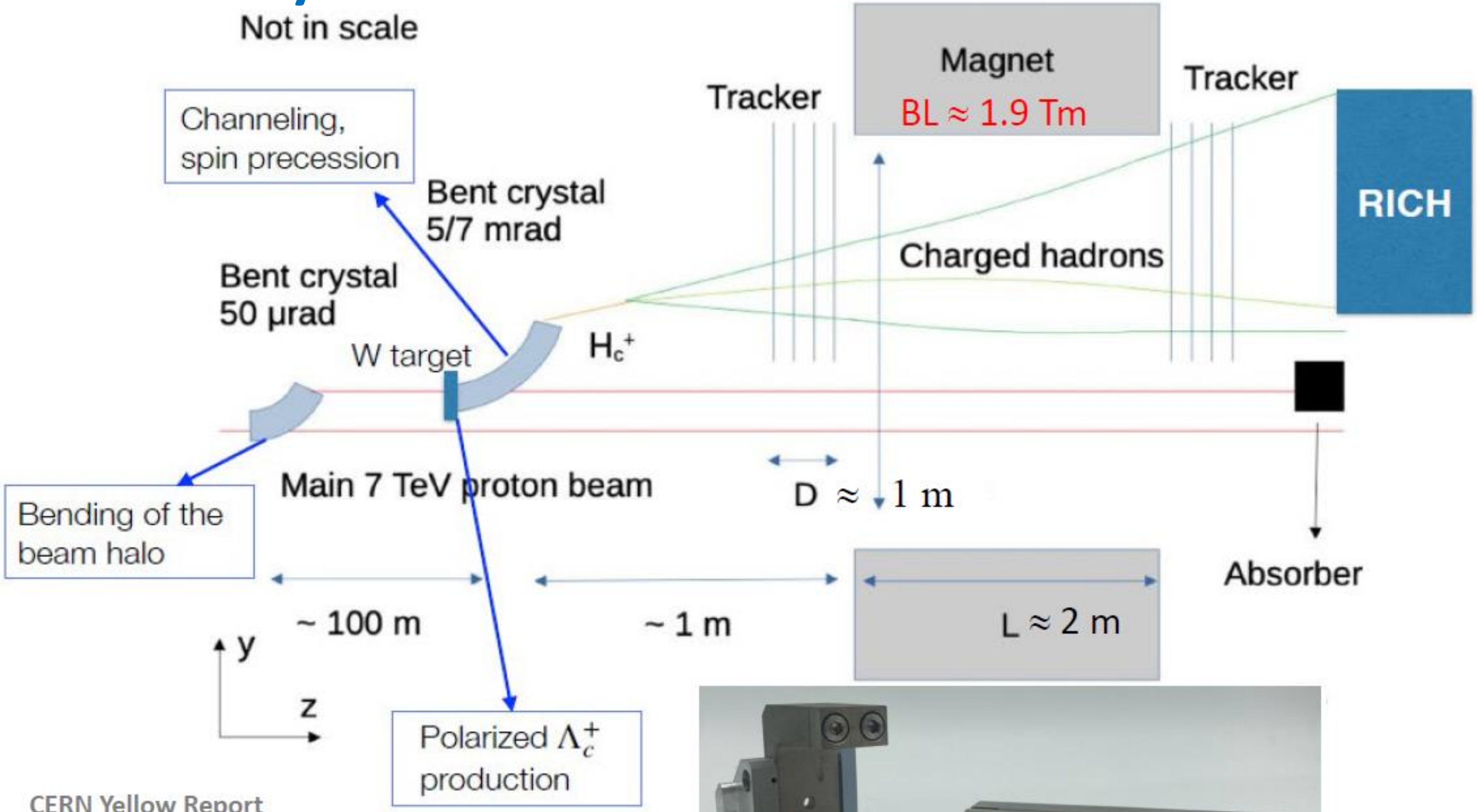
4



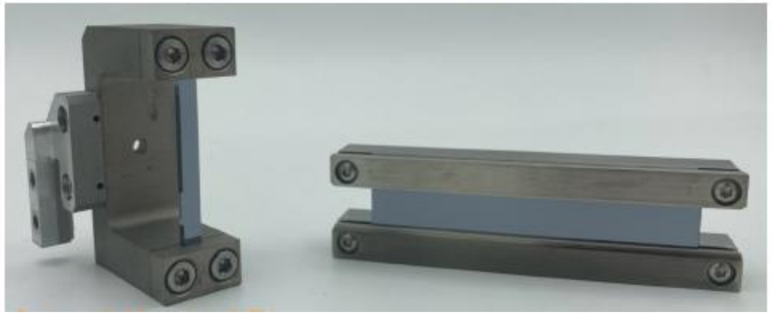
Thermal camera used to **calibrate** PT100 readout

Resistance on the VFB (≈3Ω) not negligible: Offset 11°C compensated ✓

ALADDIN layout



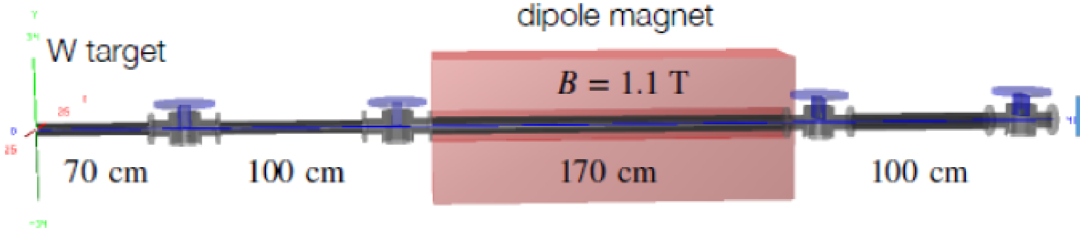
CERN Yellow Report
CERN-2020-004

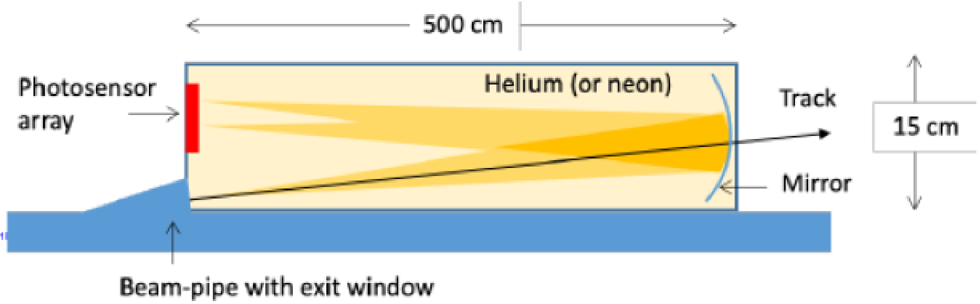


ALADDIN layout

Spectrometer: 440 cm length

RICH: 500 cm length





Si detectors in 4 Roman Pot stations

Helium radiator gas with SiPM array