

First Results on PERLE Photocathodes

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On behalf of the PERLE Collaboration

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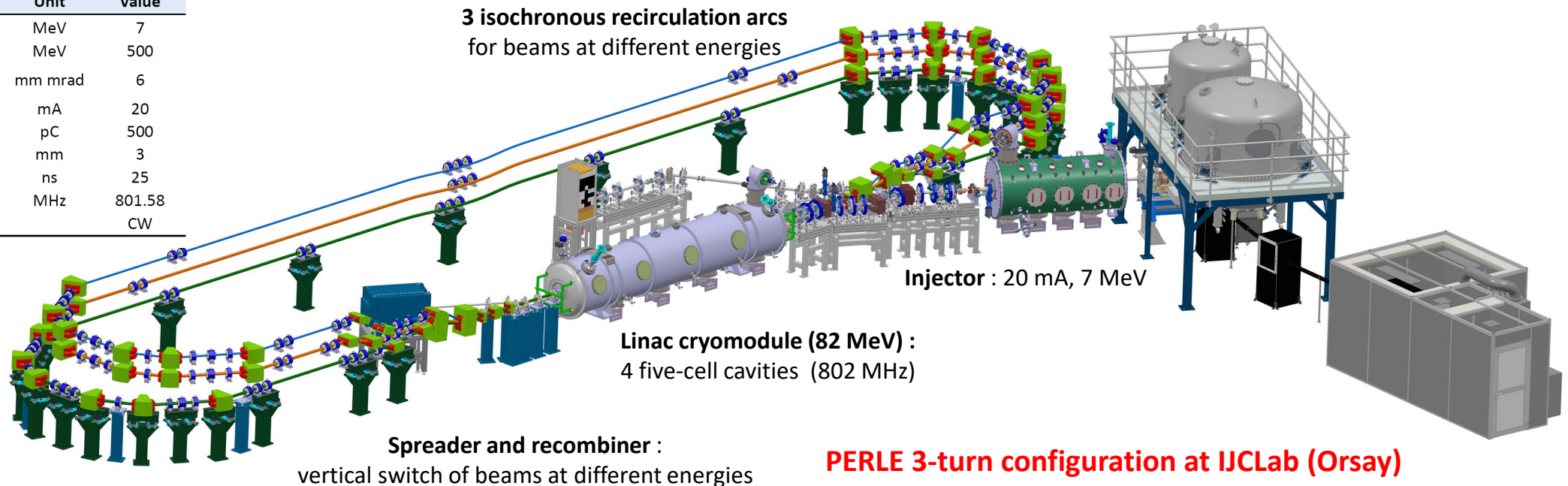
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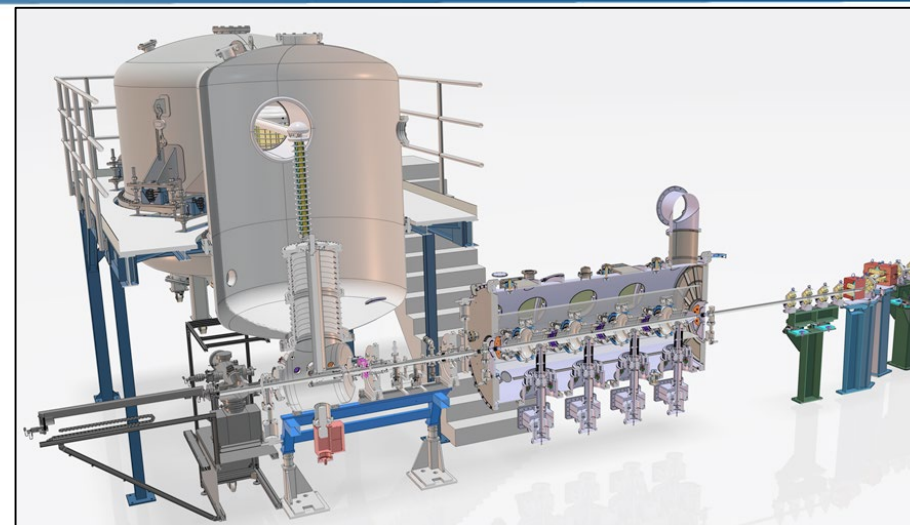


- **PERLE (Powerful Energy Recovery Linac for Experiment) : multi-turn ERL designed for multi-MW regime**
 - Aims to demonstrate energy-recovery at high power (20 mA, 250/500 MeV), under construction at IJCLab (Orsay, FR)
 - On the pathway towards LHeC, FCC-eh
 - Final step : 3-turn configuration
 - **Phase 1 (2030) : 1-recirculation loop (89 MeV) with high brightness injector**
- **International (Europe, USA) and national French collaboration (IJCLab, LPSC, IPHC, IP2I, GANIL)**

Target Parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	500
Normalised Emittance $\gamma\epsilon_{x,y}$	mm mrad	6
Average beam current	mA	20
Bunch charge	pC	500
Bunch length	mm	3
Bunch spacing	ns	25
RF frequency	MHz	801.58
Duty factor	CW	



- **PERLE phase 1 : 1 loop**
 - 1 recirculation (89 MeV)
 - Full injector (7 MeV)
- **Injector**
 - **DC photogun : 500 pC at 40 MHz ($I = 20$ mA)**
 - Bunching cavity at room temperature (802 MHz)
 - Booster cryomodule (7 MeV, 802 MHz)



Injector

HV system

*Funded by the national program
RI2 (CNRS)*

DC Photogun

Booster

Merger

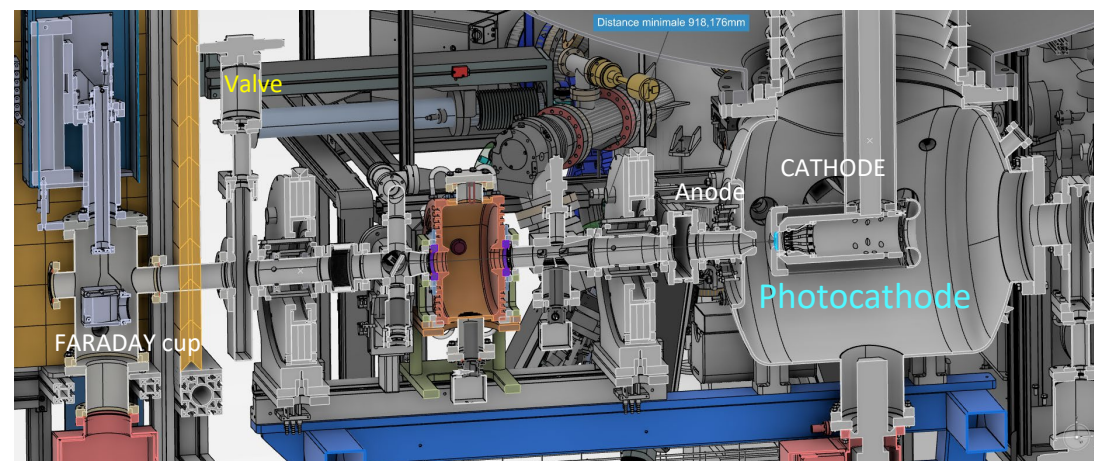
Buncher

Photocathode Preparation Facility (PPF)

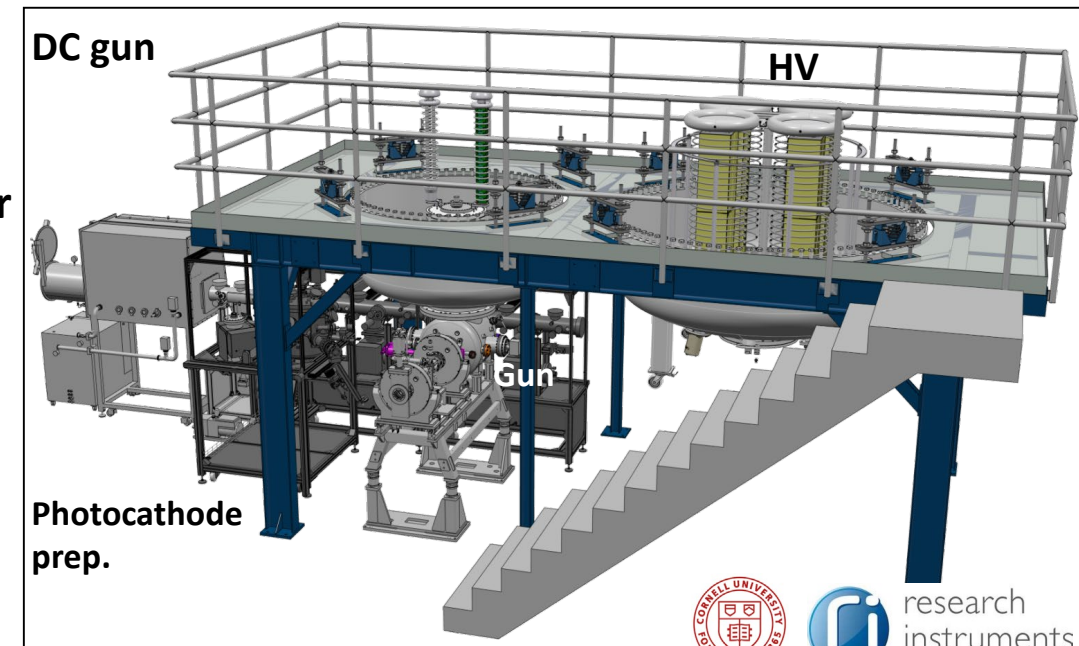
Diagnostics line

Temporary test configuration of the gun

- Simple Faraday cup in direct line of sight of the photocathode
- Will be modified with installation of the booster (2029)



- **DC photogun specifications**
 - High DC voltage to extract a high bunch charge : **350 kV**
 - Excellent vacuum for good operational lifetime : $\sim 10^{-11}$ mbar
 - Multi-alkali antimonide photocathode (**CsK₂Sb**)
 - Well suited for high current
 - Laser : 5 W of green light (500-550 nm)
- **Load-lock configuration**
 - Photocathode preparation facility (PPF) connected to the gun
 - Loading of photocathodes without gun bake for fast exchange



- **Collaboration agreement between IN2P3 and Research Instruments (RI) for photoinjector R&D since 2023**
 - Photogun based on the Cornell design [1]
 - Hardware of Lighthouse project [2] (terminated) transferred to IJCLab for PERLE (gun, HV system and PPF) in 2024

[1] Operational experience with nanocoulomb bunch charges in the Cornell photoinjector, A. Bartnik et al, Phys. Rev. ST Accel. Beams 18, 083401

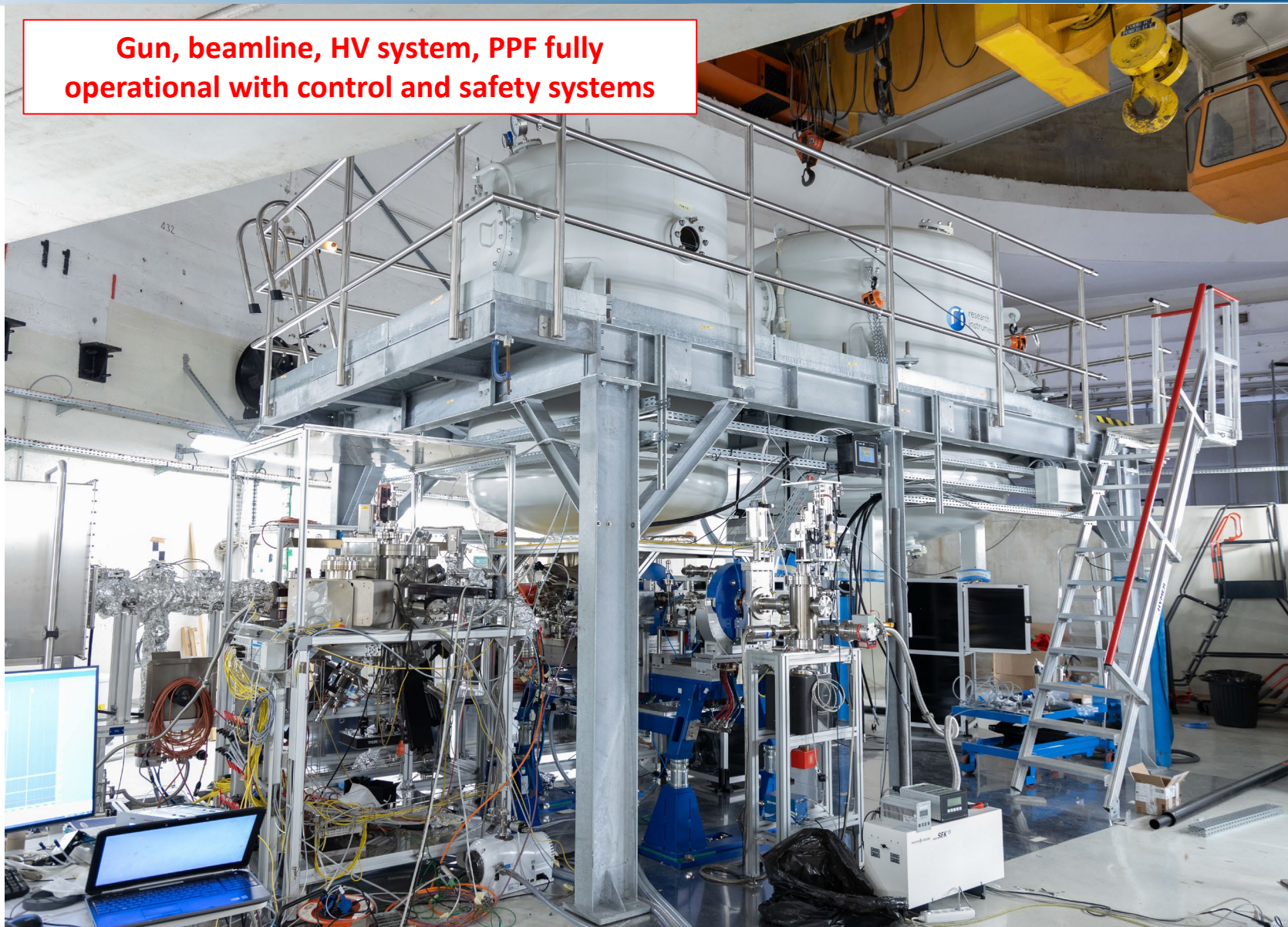
[2] Test of a DC-photogun Injector for the Lighthouse facility, G. Blokesch et al, doi: 10.18429/JACoW-IPAC2023-TUPA020



IGLOO bunker at IJCLab

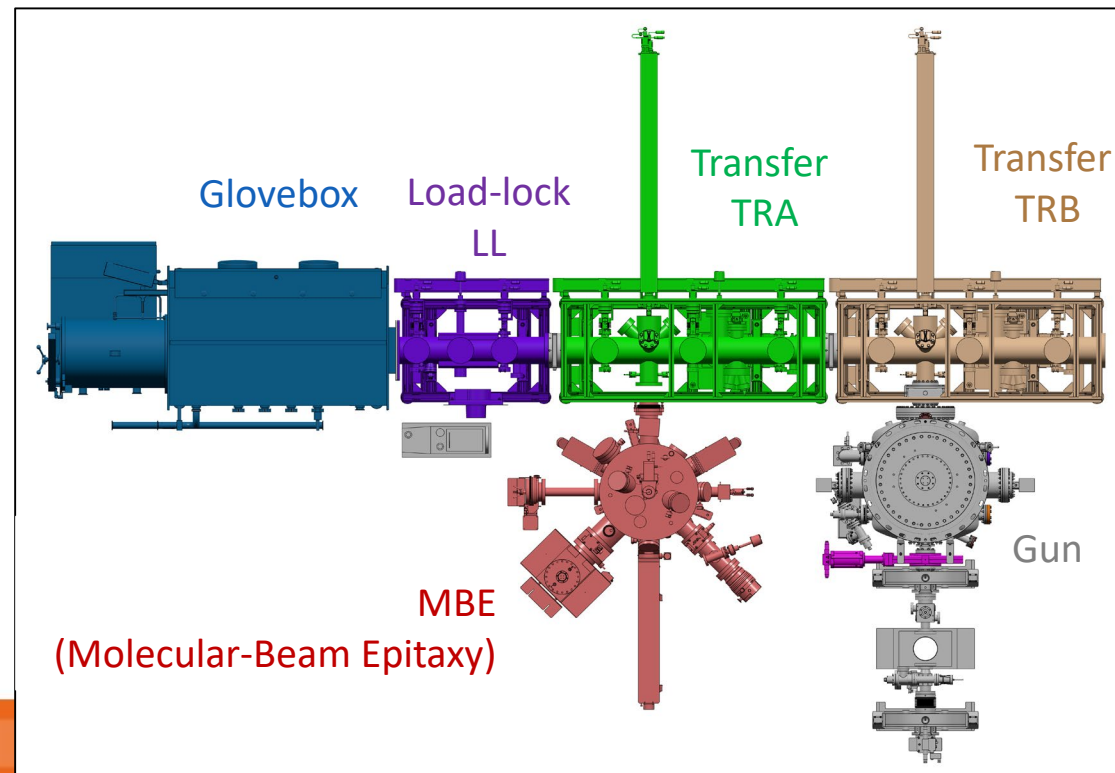


Gun, beamline, HV system, PPF fully operational with control and safety systems

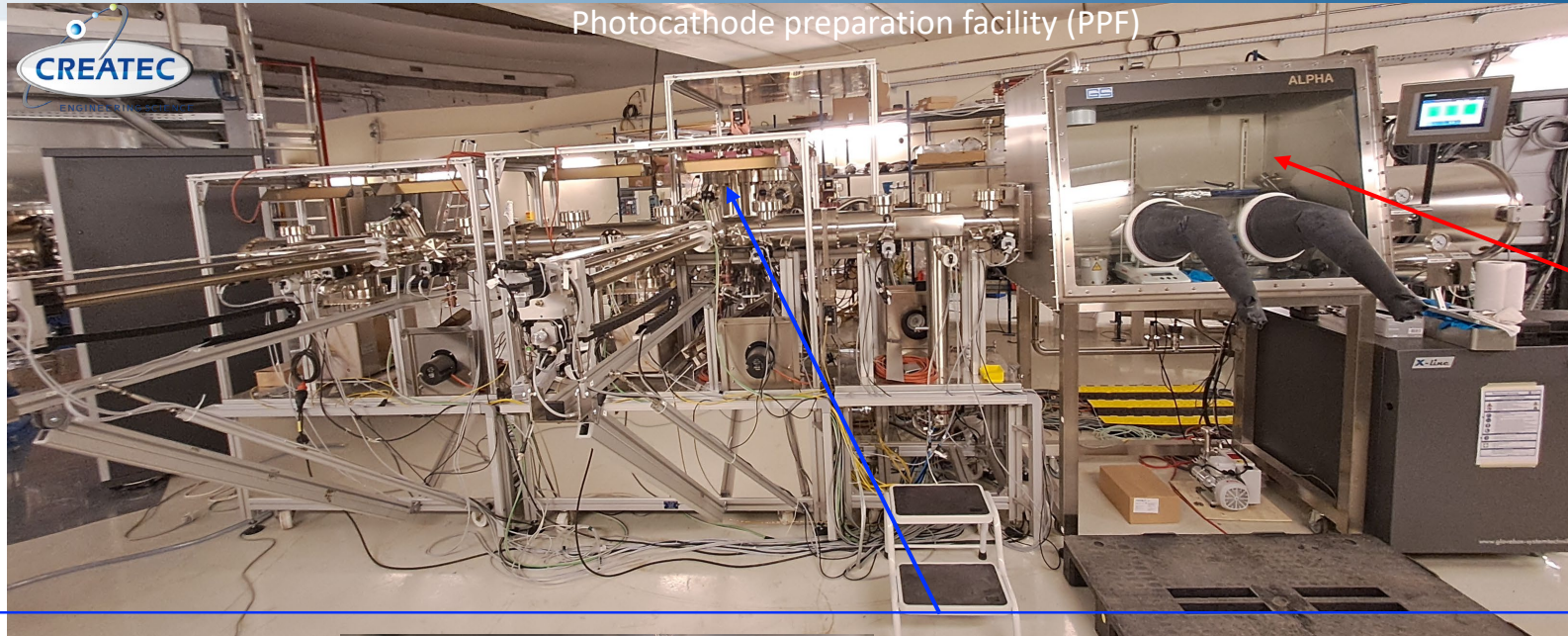


Photocathode preparation facility

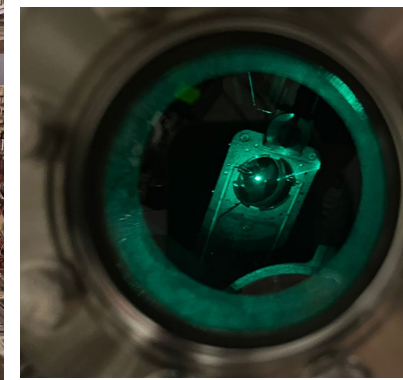
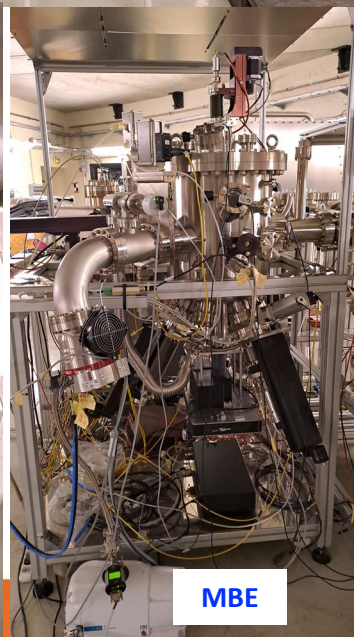
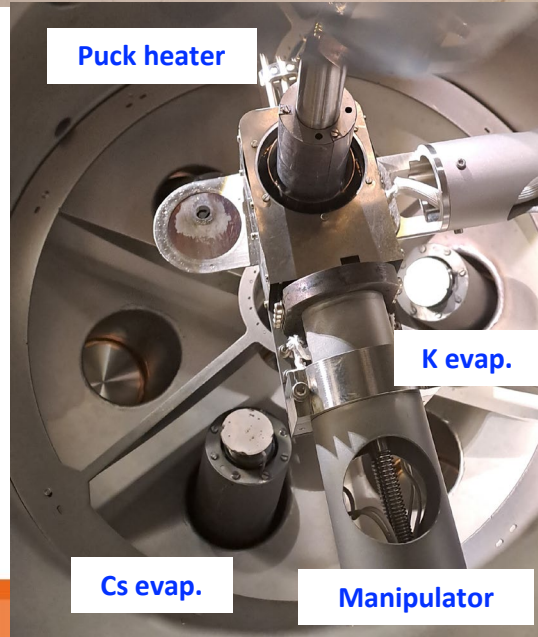
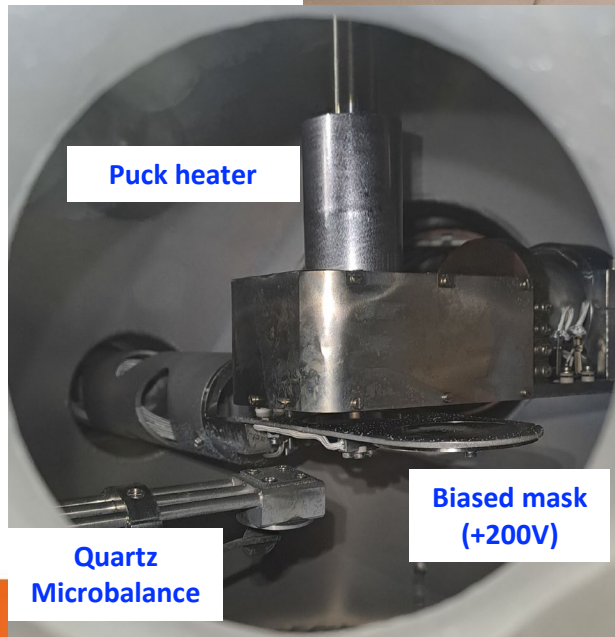
- Photocathode Preparation Facility (PPF) for deposition of CsK_2Sb : manufactured by CREATEC, concept by RI
- Equipment for photocathode preparation and transfer
 - Glovebox (precursor preparation) and load lock section
 - Trolley for 5 pucks (2" in diameter)
 - MBE chamber with 3 evaporators (Cs, K and Sb)
 - Small green laser (a few mW) for photocurrent measurement (at 532 nm)
- Hardware fully assembled and baked (June 2025)



Photocathode preparation facility



Trolley of pucks



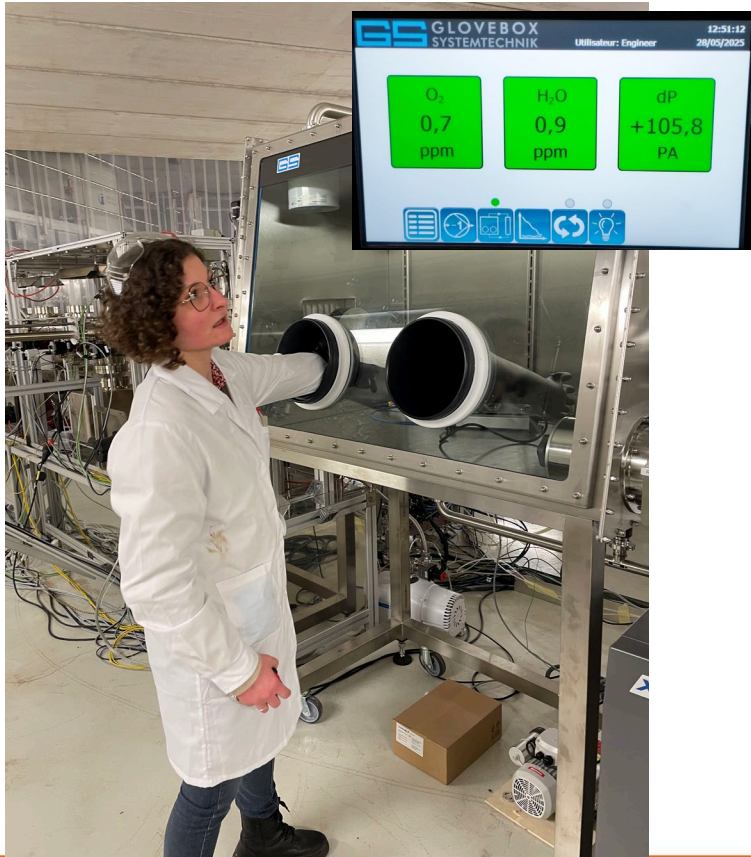
Laser (532 nm) focused on the photocathode in the MBE



Puck

Photocathode preparation

- Preparation of Sb, Cs and K evaporators
 - Cs and K are not stable in air
 - Preparation of air-stable alloys of Cs and K with indium
- ➔ A glove box with an inert atmosphere is required to prepare the precursors : O_2 and $H_2O < 1$ ppm
- Evaporators mounted on the MBE chamber and baked



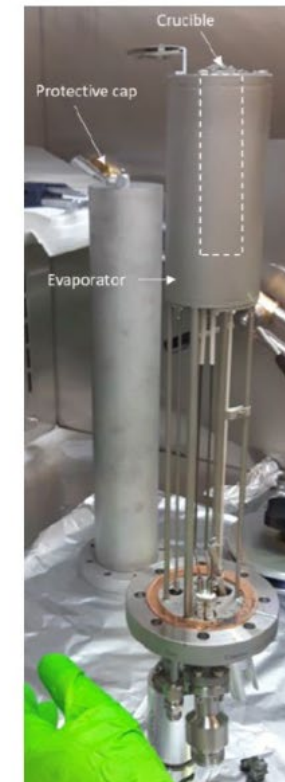
Weighing Sb in glove box



Crucible for Sb

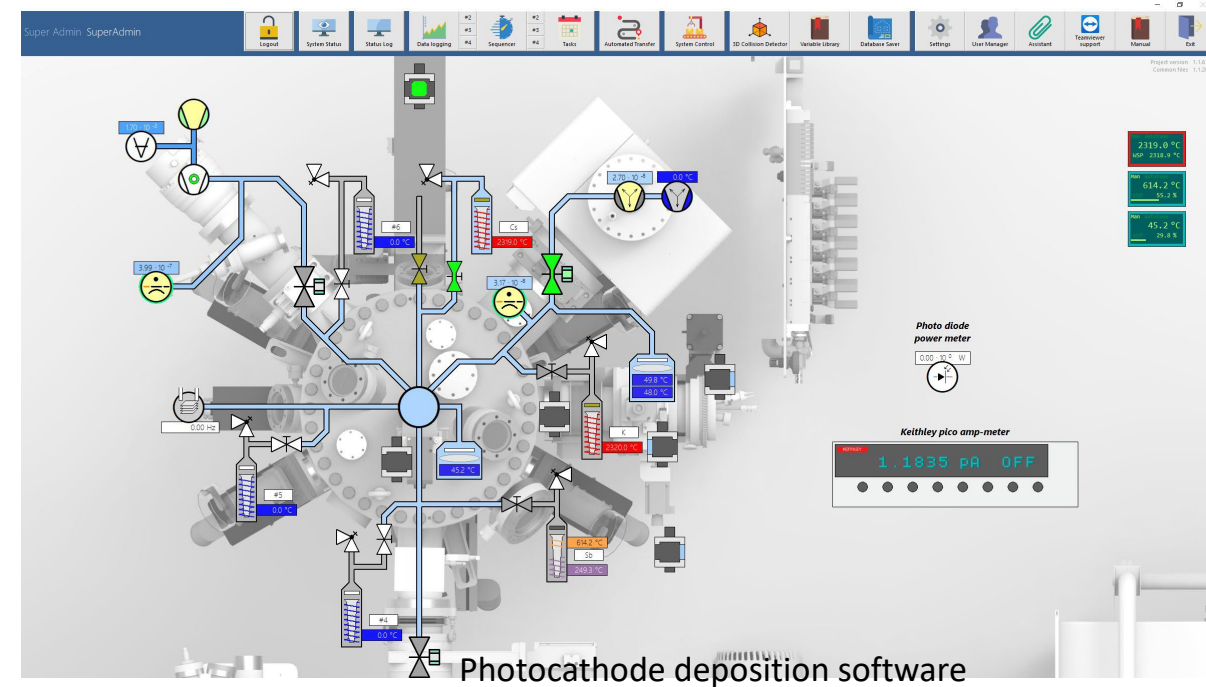


Evaporator



CsK₂Sb photocathode deposition procedure

- **Prerequisites**
 - Puck pre heated at 500 °C/8h
 - The 3 evaporators are heated in the MBE
 - Photocathode puck biased (200 V), laser on
- **Automatic (or manual) procedure for the sequential deposition of each element (Sb, K, Cs)**
 - Puck temperature maintained at 100 °C during the deposition (except during Cs deposition)
 - Photocurrent measurement during deposition
 - Thickness measurement during deposition (quartz microbalance)
 - Sb thickness ≈ 20 nm



Summary of photocathode production and characteristics

- 5 photocathodes produced in the PPF over 10 months
 - Characterization in terms of QE and lifetime

- Photocathode lifetime can be expressed as :

$$QE = QE_0 \times \exp\left(-\frac{t}{\tau}\right) \times \exp\left(-\frac{\rho}{D}\right)$$

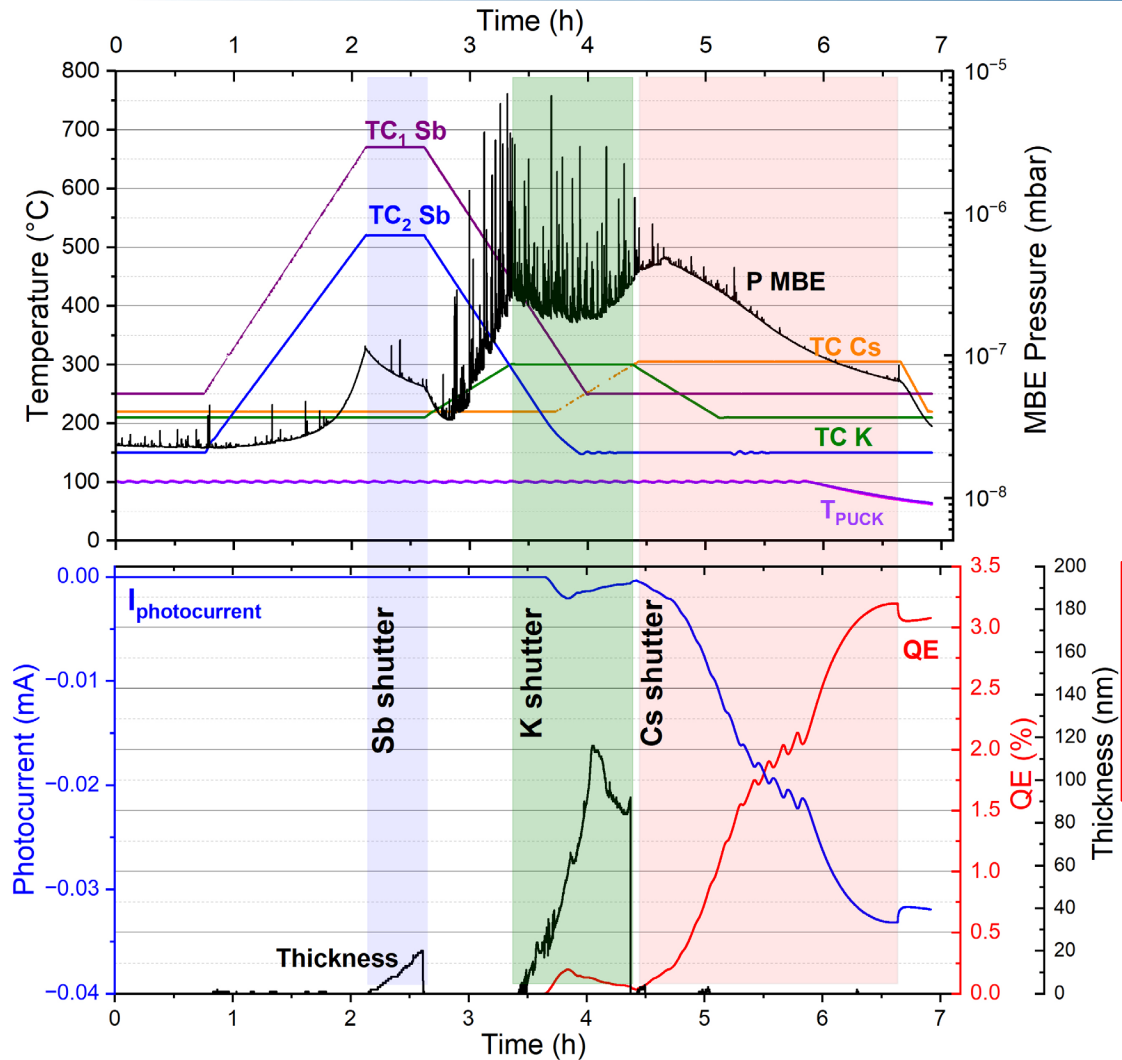
Diagram illustrating the equation for photocathode lifetime:

- τ is labeled as dark lifetime (hours).
- ρ is labeled as charge density.
- D is labeled as charge lifetime (C/mm²).

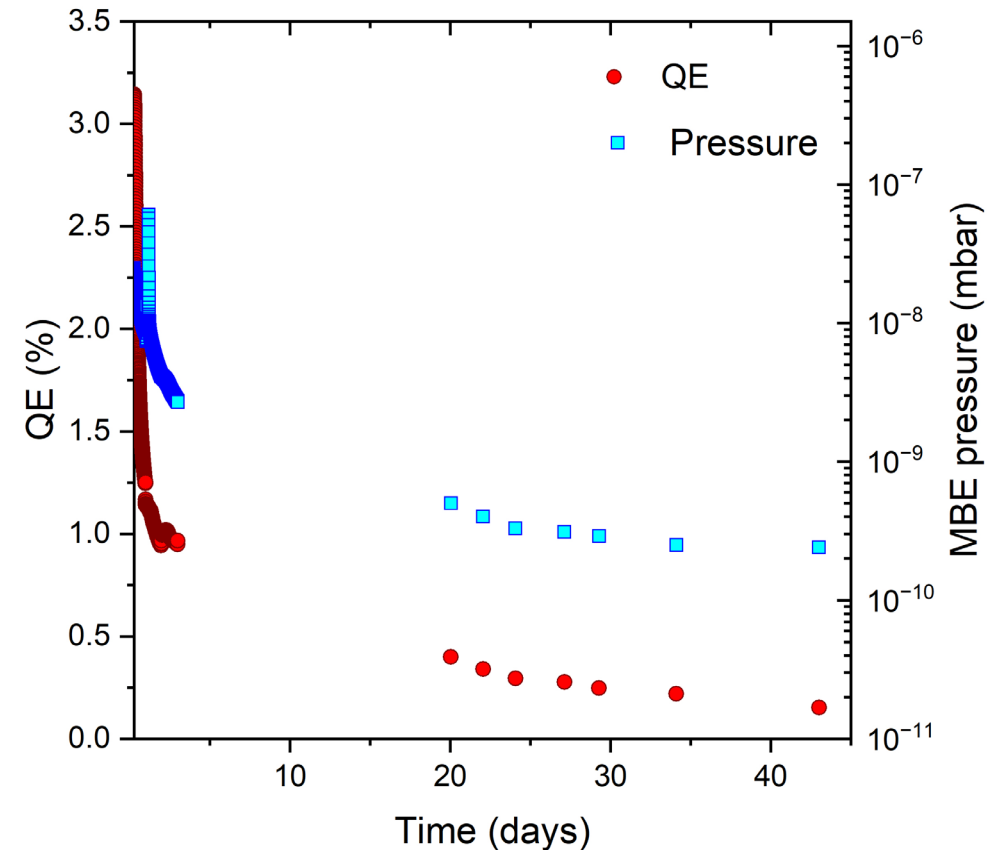
- Dark lifetime: measured in the MBE deposition chamber
→ pressure higher than in the gun (few 10⁻⁸ right after deposition to few 10⁻¹⁰ mbar)
- Charge lifetime: measured in the gun during initial conditioning, some HV tests, debugs

→ preliminary results show trends rather than precise values

The first photocathode



**QE=3% on
the first
attempt**



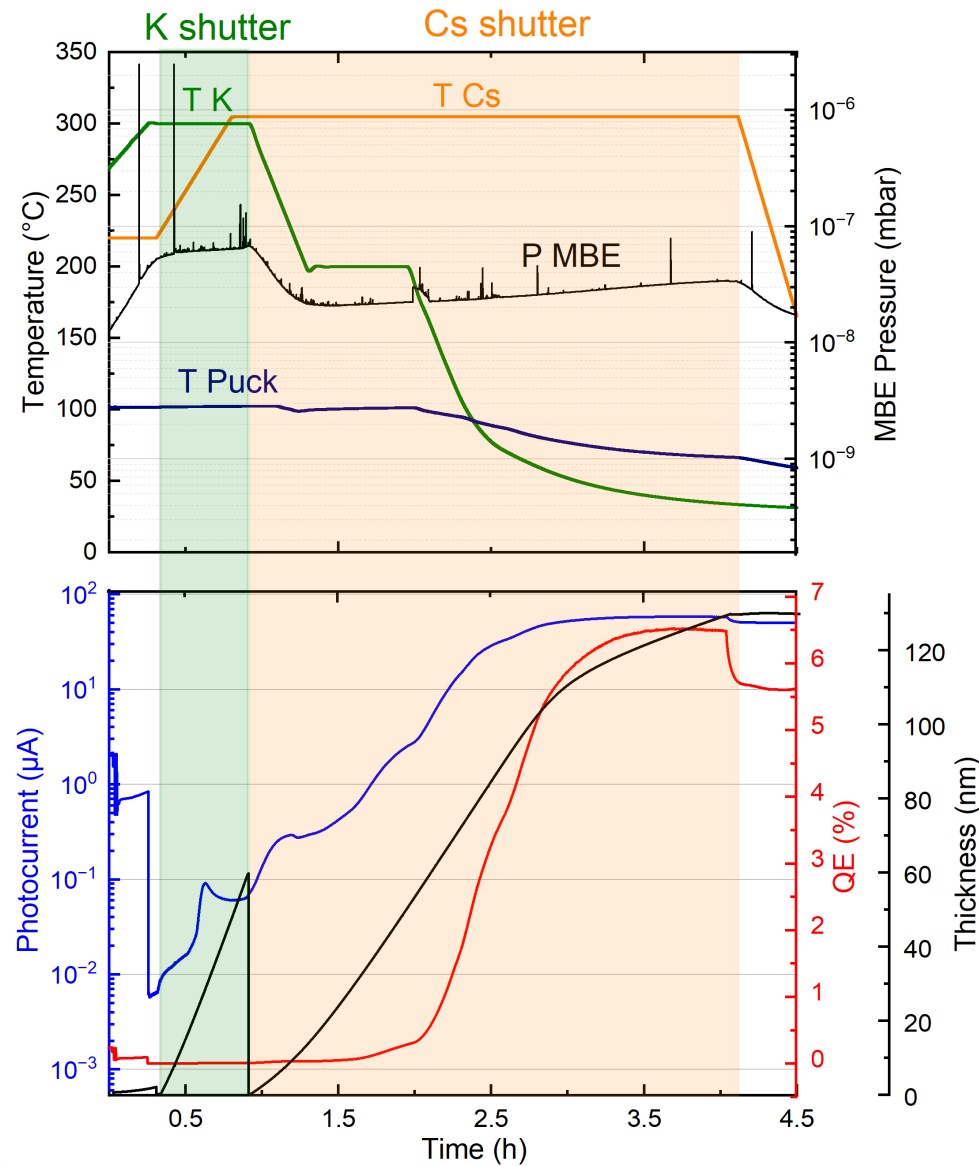
After deposition the photocathode is stored in the MBE chamber :

A decreasing of QE in one month from 3% to 0.1 % even if the pressure decreases from a few 10^{-8} to 2.5×10^{-10} mbar

Poor dark lifetime probably due to poor vacuum conditions before and during the deposition process

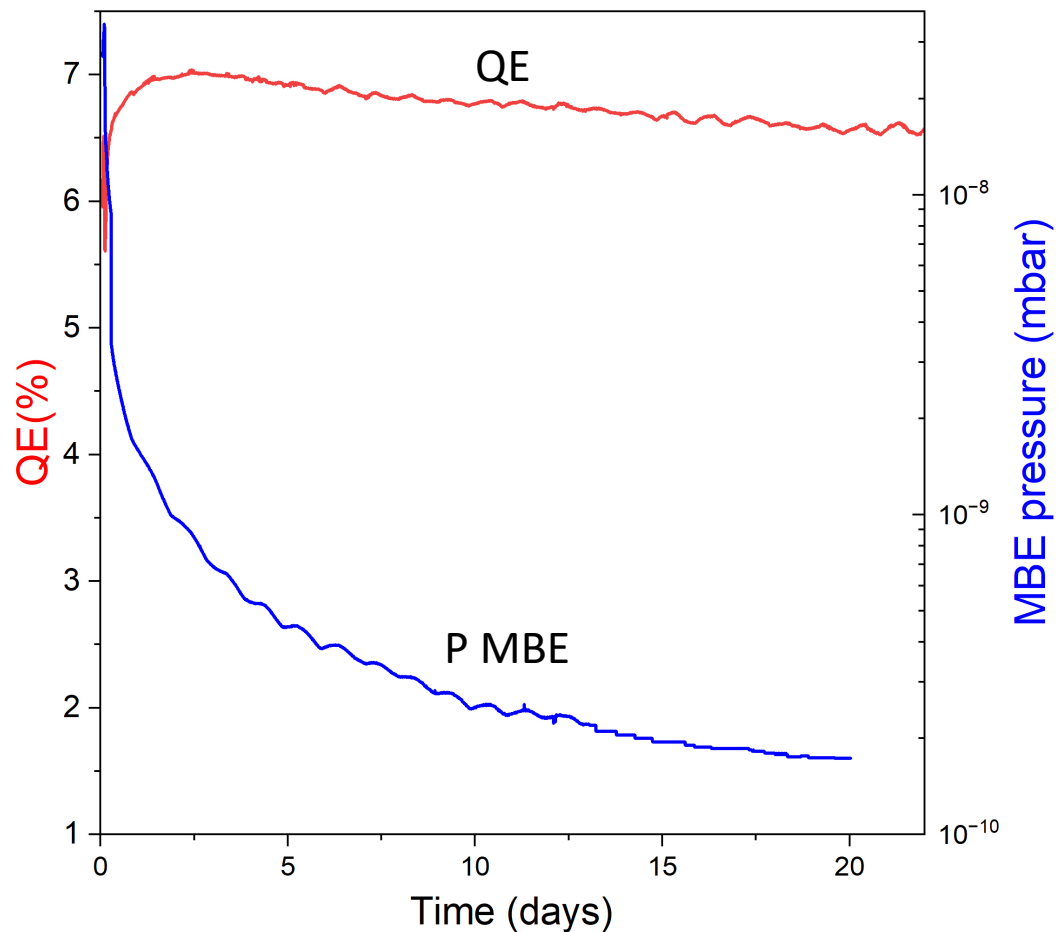
Puck already deposited, re-heated

Deposition rate :
 Sb $\approx$ 30 nm/h
 K $\approx$ 80 nm/h
 Cs $\approx$ 40 nm/h

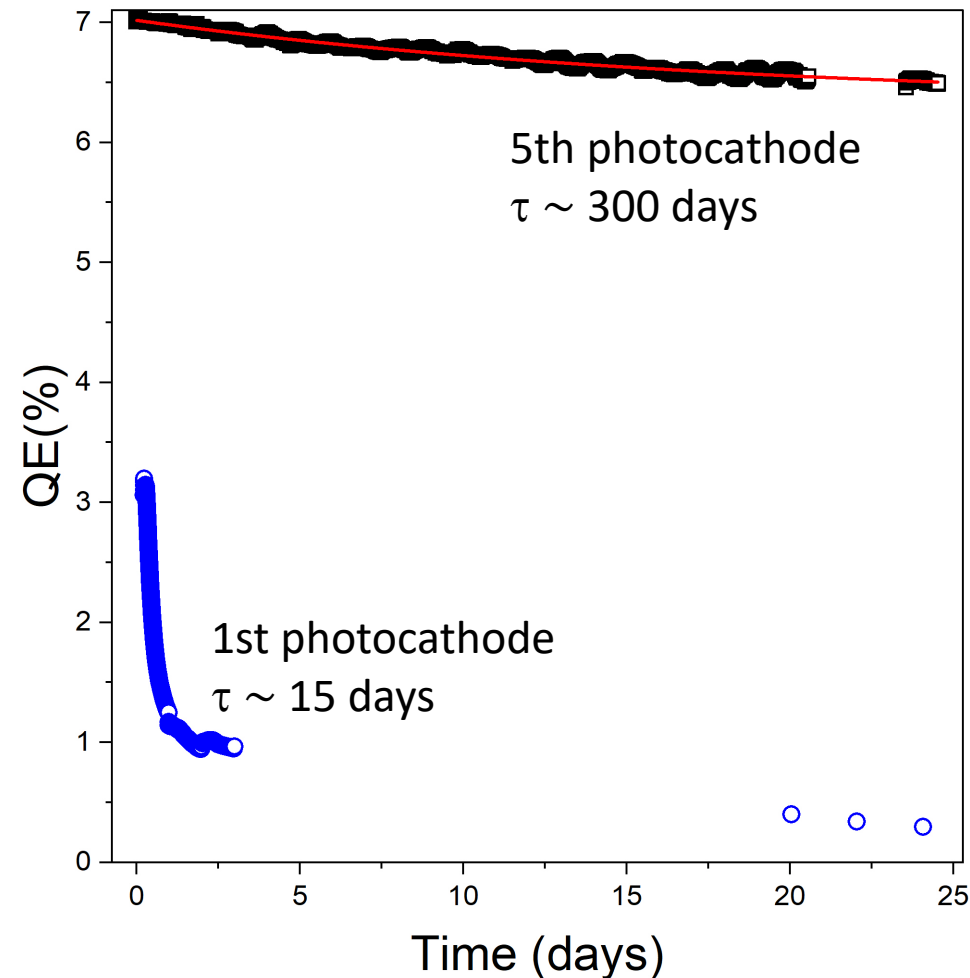


**Fifth photocathode :
 Final QE $\approx$ 5.6 %**

QE and dark lifetime



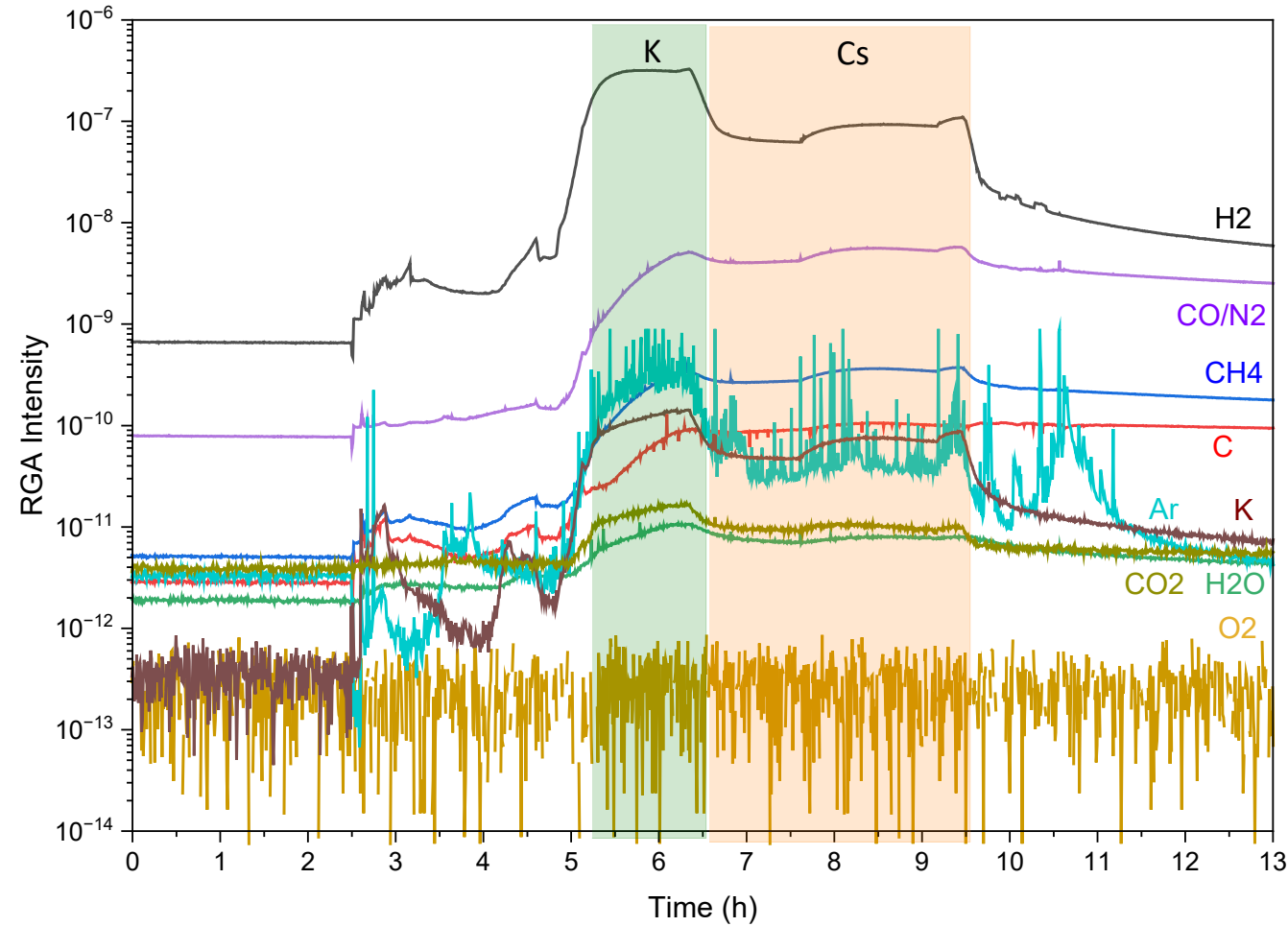
Surprisingly, during storage in the MBE chamber, the QE increased and then decreased only very slowly for the 5th photocathode



The dark lifetime is significantly better than that of the first photocathode, likely due to the improved vacuum quality

RGA measurements during deposition

The evolution of the residual gas composition was measured during deposition.



Main gas detected : H_2

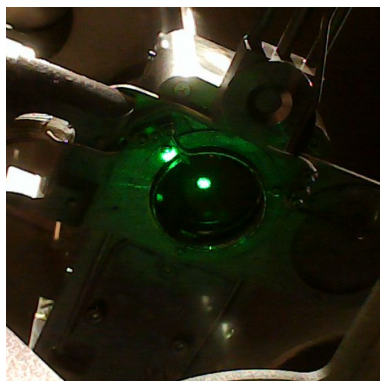
O_2 and H_2O remain at very low levels, Ar desorption comes from the precursors

QE measurements at different positions

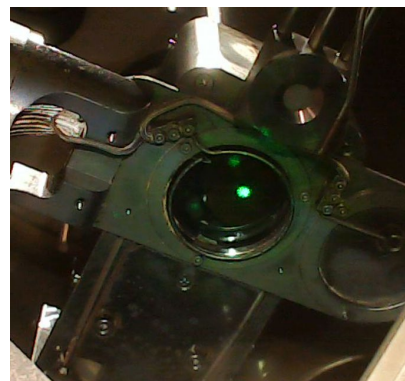
The QE was measured at different laser positions to assess the spatial homogeneity of the photocathode.



6.7%



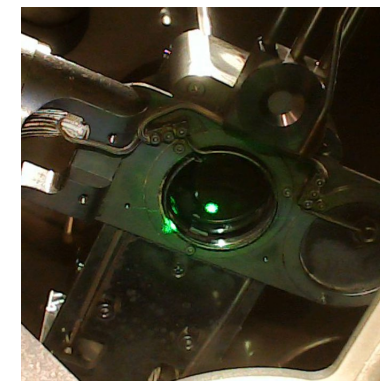
6.3%



6.3%



5.7%



6.6%

Relatively good QE homogeneity over the photocathode surface

QE = 5.7–6.7 %

Slight decrease observed at one position

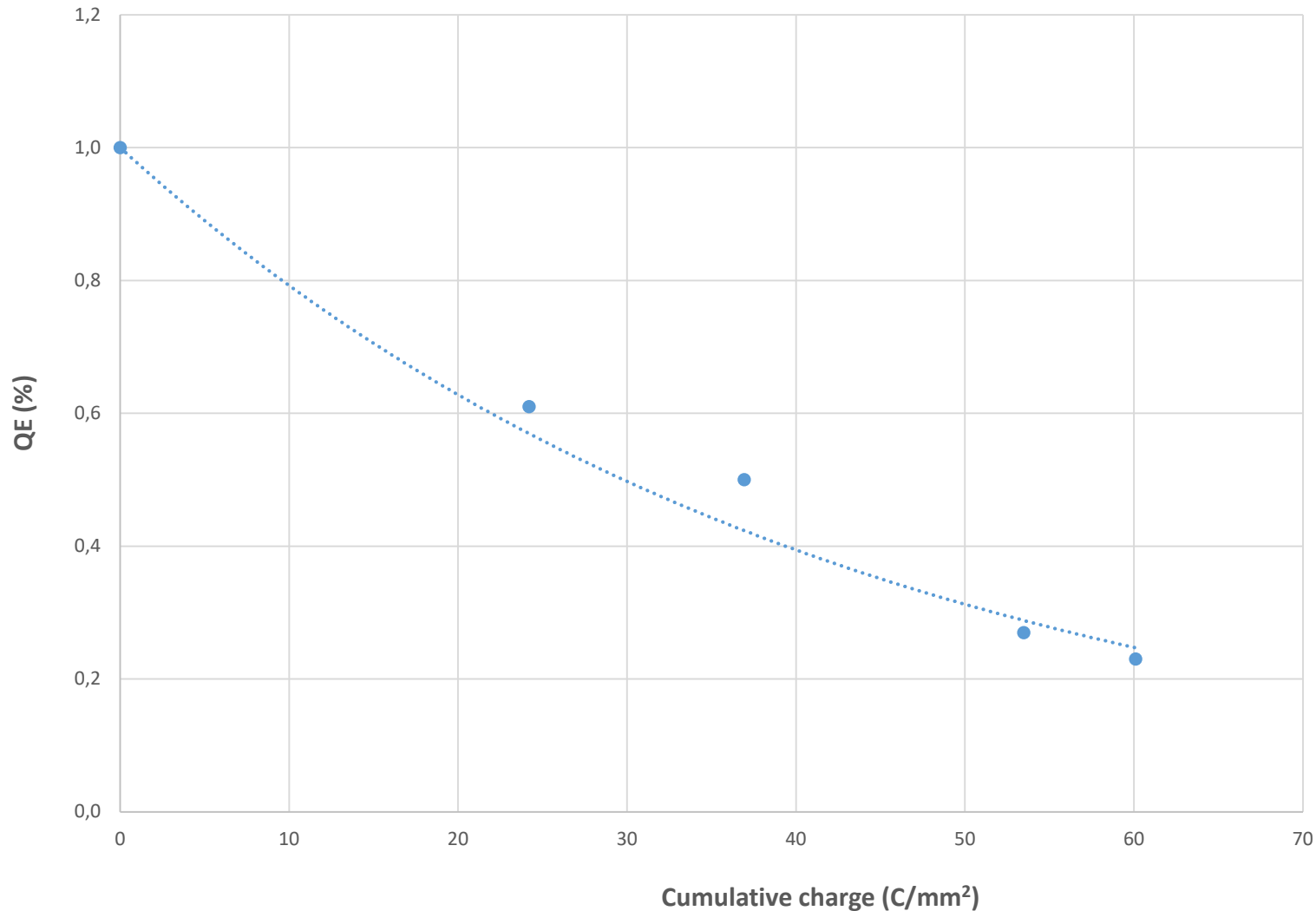
QE and dark lifetime: a summary

N°	Name	Substrate	QE (%)	$\tau_{\text{dark MBE}}$ (days)	Comments
PC#1	131088, ASM-0023	St St	3	~ 15	Poor vacuum : up to $\sim 5.10^{-7}$ mbar Never transferred to the gun
PC#2	131088, MBS-005	St St	7.5	~ 100	From 5.10^{-8} to 3.10^{-10} mbar over the measurement (25.5 days) <u>Used in the gun</u>
PC#3	11760	Mo	1	~ 5	From 5.10^{-8} to 10^{-9} mbar over the measurement (3 days) <u>Used in the gun</u>
PC#4	11760	Mo	0.5	~ 9	From 7.10^{-8} to 3.10^{-10} mbar over the measurement (6 days) Poor QE, never transferred to the gun
PC#5	131088, MBS-005	St St	6.5	~ 300	From 2.10^{-8} to 2.10^{-10} mbar over the measurement (27 days) Puck already deposited, re-heated, <u>used in the gun</u>

- **QE :**
 - max QE of 6-7% can be achieved when the process is well controlled (comparable to [1])
 - counterintuitive results with St St and Mo substrates probably due to puck preparation
 - Lack of ultra-sonic bath for the pucks before insertion in the PPF: different oxydes on Mo and SS ?
 - Slight changes in evaporator temperature during deposition ?
- **Dark lifetime**
 - depends on the vacuum level in the MBE during deposition (H_2O , O_2)
 - « good » values are comparable to the state of the art (e.g. [2])

Estimation of the charge lifetime PC#3

Cumulative charge per unit area vs QE



DC gun at 200 kV
Laser RMS= 1 mm
Anode biased at 200 V

PC#3
47 C extracted

Charge lifetime $\approx 45 \text{ C/mm}^2$

Beam delivered mainly over 4 days mostly
(between July 15 and 27)

QE and charge lifetime: a summary

	Name	Substrate	QE (%)	$\tau_{\text{dark MBE}}$ (days)	τ_{charge} (C/mm ²)	Q _{total} (C)	Comments
PC#1	131088, ASM-0023	StSt	3	~ 15	-	-	Poor vacuum (up to $\sim 5 \cdot 10^{-7}$ mbar) <i>Never transferred to the gun</i>
PC#2	131088, MBS-005	StSt	7.5	~ 100	~ 10	28	Initial commissioning current, beam up to 2.5 mA Vacuum incident (10^{-8} mbar) due to YAG screen overexposure
PC#3	11760	Mo	1	~ 5	~ 45	47	Biased anode (+200 V)
PC#4	11760	Mo	0.5	-	-	-	Poor QE, <i>never transferred to the gun</i>
PC#5	131088, MBS-005	StSt	6.5	~ 300			Puck already deposited, re-heated, re-used in the gun : 5 mA

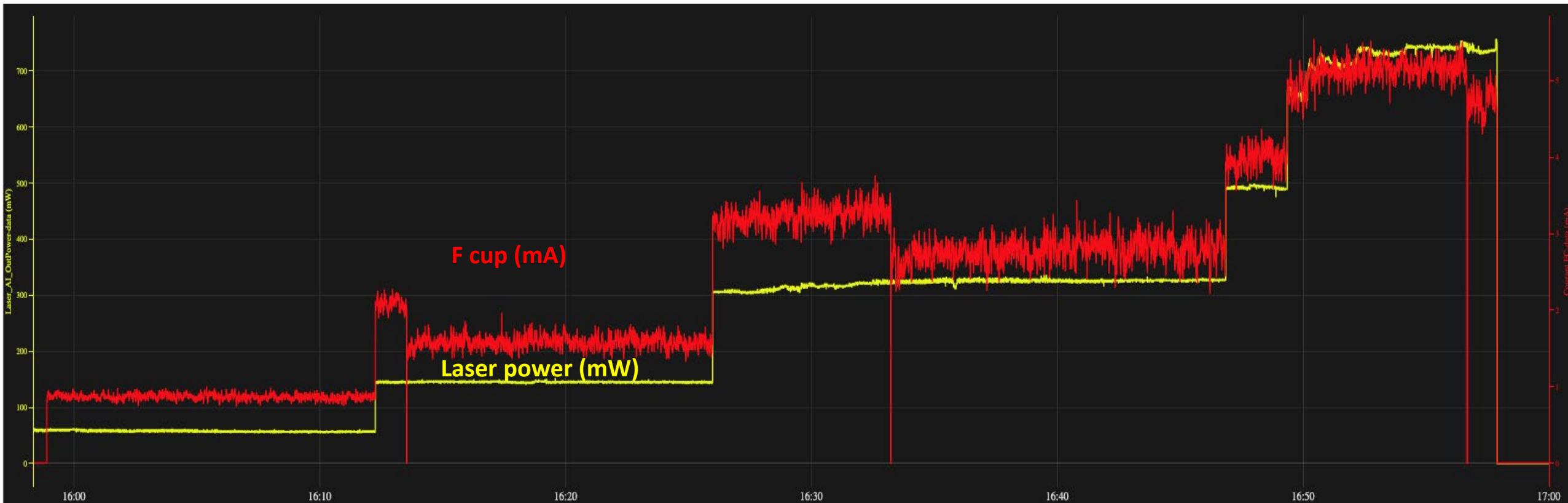
- **Charge lifetime**
 - **Limitations**
 - Faraday cup in direct line of sight of the photocathode, distance ≈ 1.5 m, in temporary configuration
→ Electron-induced desorption could contribute to photocathode degradation
 - Laser spot relatively small
→ the extracted charge is concentrated over a small area of the photocathode
 - **Some improvement from PC#2 to PC#3:**
 - Progressive conditioning of the Faraday cup by the beam, leading to better vacuum conditions?
 - Biased anode

High current beam test at 250 kV (PC#5)

August 2026

- High current beam test (250 kV) with increasing laser power
 - Beam current of 5.1 mA measured in the Faraday cup
 - Some electrical discharges leading to QE degradation (QE reduction)

5.1 mA (250 kV)



See the poster presented by Maud for more details

➤ PERLE photoinjector

- **Gun, beamline, HV system and PPF fully operational for 9 months**, including control and safety systems
- **5 photocathodes produced at IJCLab**, with QE reaching **5–7%** when the deposition process is well controlled
- **Beam currents up to 5 mA delivered by the gun**

➤ Main challenge

- Maintaining a high beam current over long periods remains challenging
- Study of **laser spot movement on the photocathode** to compensate for the decrease in QE due to charge extraction

➤ Next steps

- **Replacement** of the current precursors by commercial pills for safer handling
- QE measurements at **different wavelengths**
- **Reflectometry measurements**
- Perform QE scans across the photocathode to check the **homogeneity**
- Development of a **UHV suitcase** for photocathode transfer to XPS for surface analysis



M. Baylac, V. Kuemper (RI), G. Sattonnay, T. Gérardin, M. De Vos, O. Frossard, S. Brault, D. Reynet, B. Mercier

Thank you for your attention