Study of Sensors Irradiated at CSNS

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01

Background

Upgrades to the HL-LHC

- The inner tracking system of the ATLAS detector is replaced by a fully silicon-based inner tracker (ITk)
- The ITk has a cylindrical structure with a ~1 m radius and a ~6 m long
- The inner region is composed of silicon pixel sensors while the outer region of silicon strip sensors
- The strip part (ITk Strips) consists of four layers on the barrel and six disks in both endcaps

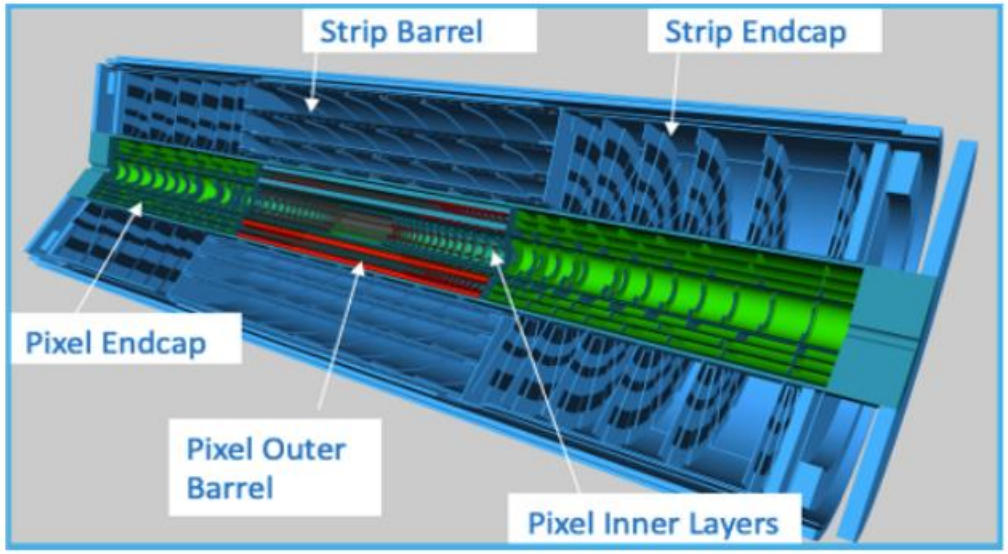


Figure 1: ATLAS Inner Detecor[1]

Sensor QA

- Quality Assurance (QA): aims at monitoring of radiation tolerance using dedicated QA test pieces on a sampling basis.
- In order to:
  - confirm key properties of the production sensors
  - establish a solid workflow of quality inspection
  - monitoring of the various sensor properties
- QA test pieces: include a $10 \times 10\,mm^2$ **mini sensor,** a simple $8 \times 8\,mm^2$ **MD8**

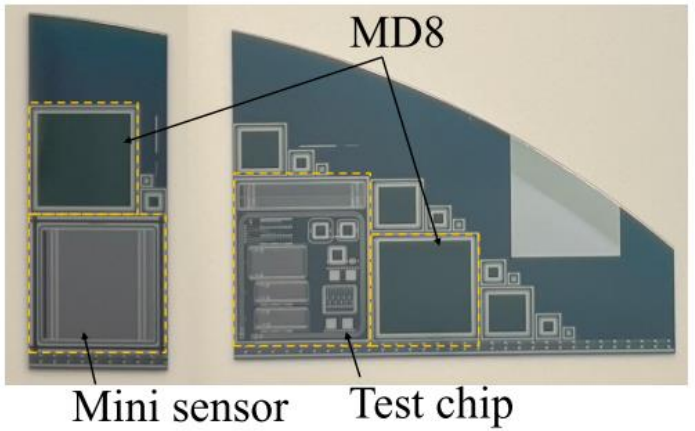


Fig. 1. Photos of the QA test pieces. The left structure holds a mini sensor and an MD8 while the right one a test chip and an MD8.

Flow Chart of QA

- All QA pieces were first delivered to CERN, and then distributed to each irradiation site
- After irradiation at the irradiation sites, all QA pieces were distributed to test sites
  - proton: KEK/Tsukuba, Birmingham
  - neutron: JSI, Ljubljana
  - γ-ray: Prague
- Our(China ATLAS ITk group) targets:
  - QA irradiation site--CSNS
  - QA test site--IHEP

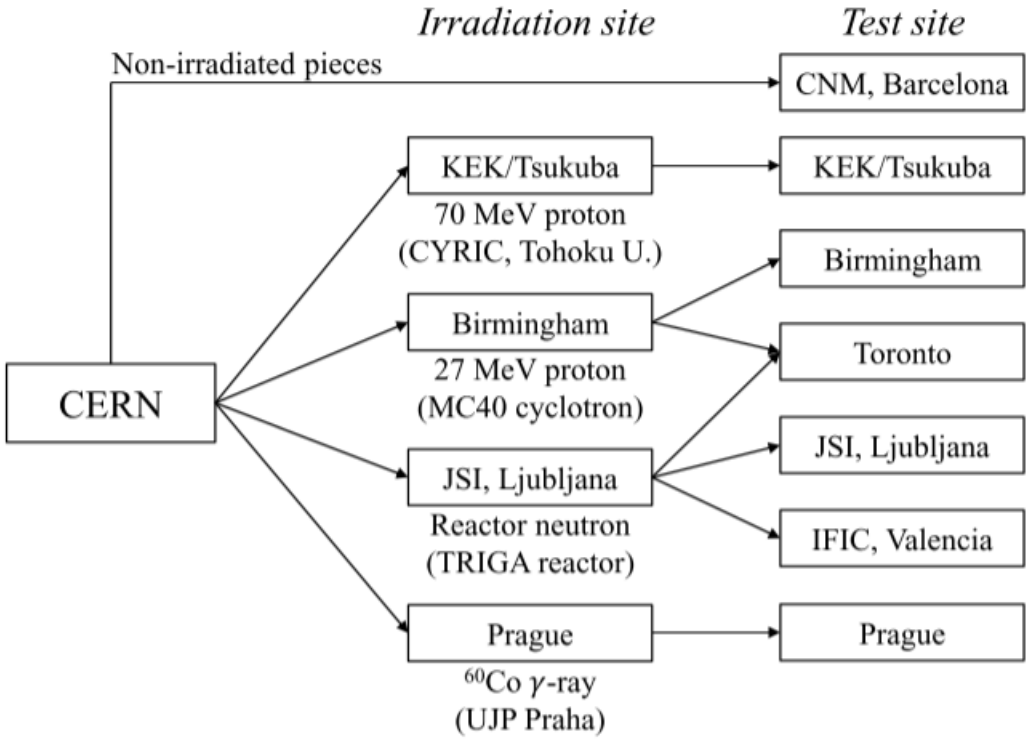


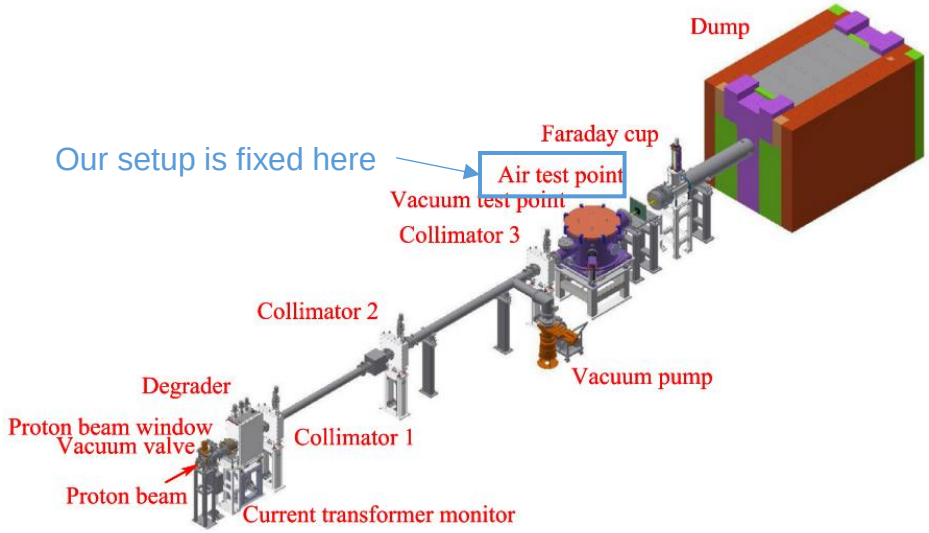
Fig. 2. Flow chart of the strip sensor QA test pieces for the pre-production QA.

02

Experimental Setups

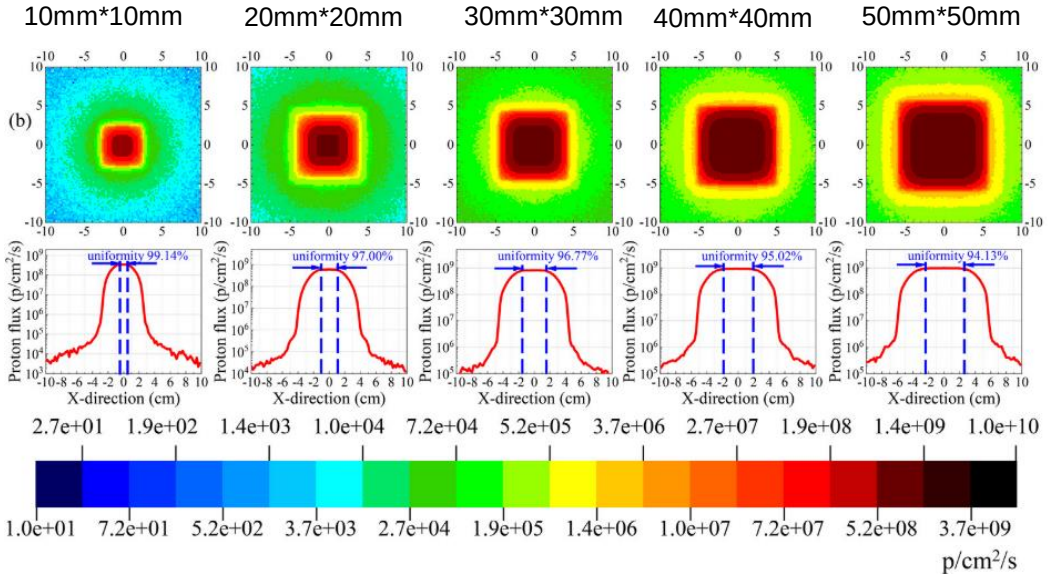
Introduction of Proton Beam at CSNS

- Irradiation at APEP(Associated Proton Experiment Platform) of CSNS(China Spallation Neutron Source)
- Testing at IHEP(Institute of High Energy Physics)
- Beam Energy range: $10 - 80MeV$
- Beam spot size: $10 \times 10mm^2 - 50 \times 50mm^2$
- Beam parameters of our experiment: $80\ MeV, 20 \times 20\ mm^2$
- Beam spot uniformity: >90%
- Fluence Rate: $1.25 \times 10^{12} p/s\ (80MeV)$



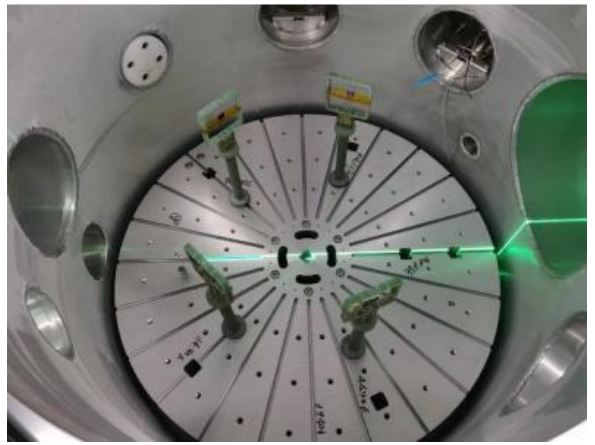
The main composition of the Associated Proton Experiment Platform [1]

[1] Physical design of the APEP beam line at CSNS



Beam spot distributions and the corresponding profile curves for an energy of 70 MeV at the air test point

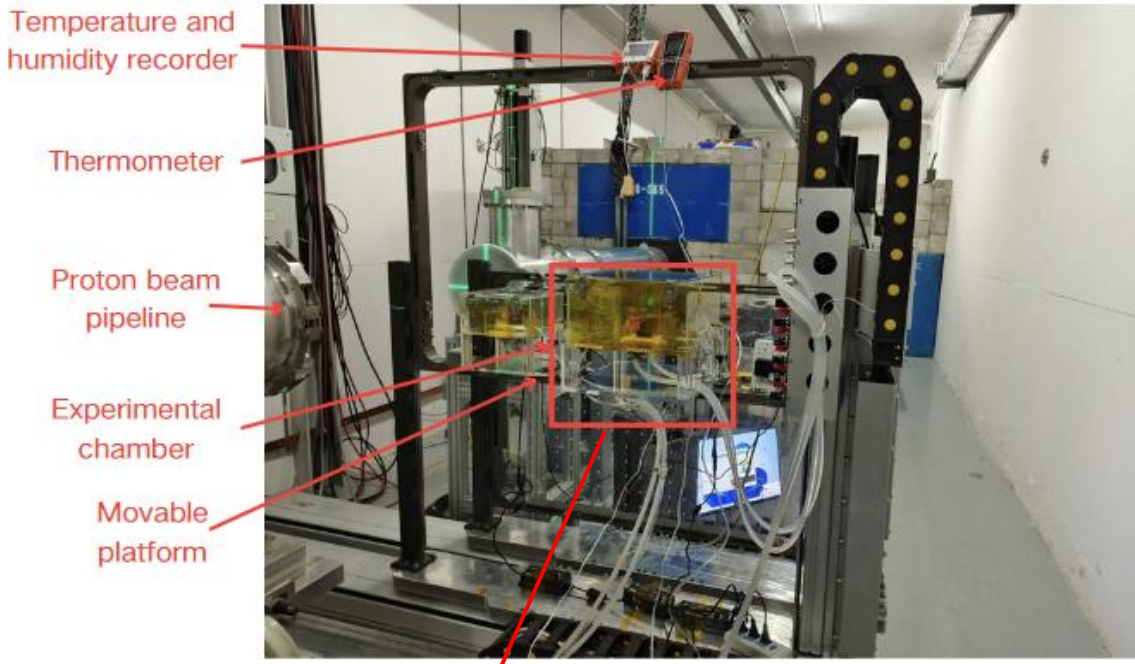
Air Test Point (our setup placed here)



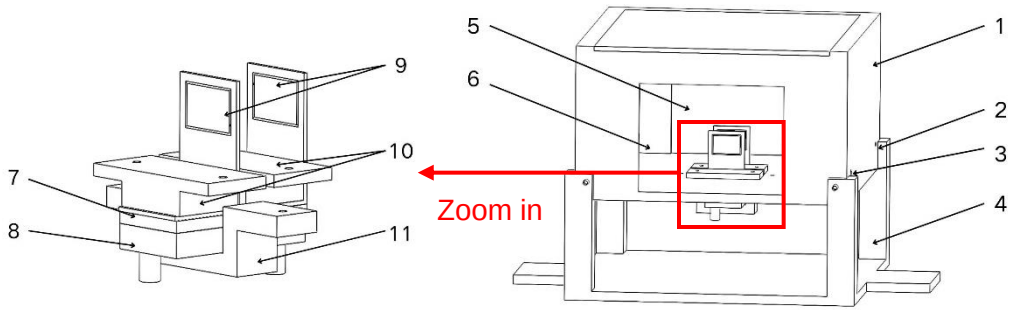
Vacuum Test Point

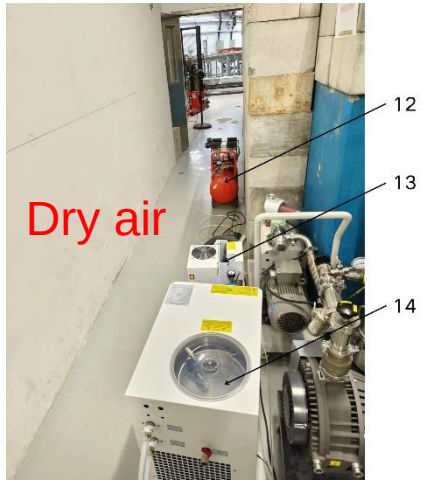
Experimental Setup for Irradiation

- QA requirements: -20℃, <10%RH
- **Samples attachment:** graphite sheet with Kapton tape
- **Cooling:** Peltier + water cooling → Temperature: -20℃
- **Humidity control:** air compressor + air dryer → ~5%RH
- An experimental chamber can irradiate up to 8 samples simultaneously
- Up to 16 samples in two chambers can be irradiated in one week
  - ➢ A movable platform allows the move of the chamber
- This irradiation experimental setup has been improved based on previous work [2]



Air Temperature: 20℃
Relative Humidity: 5%
Dew Point Temperature: -20.8℃ (lower than -20℃)



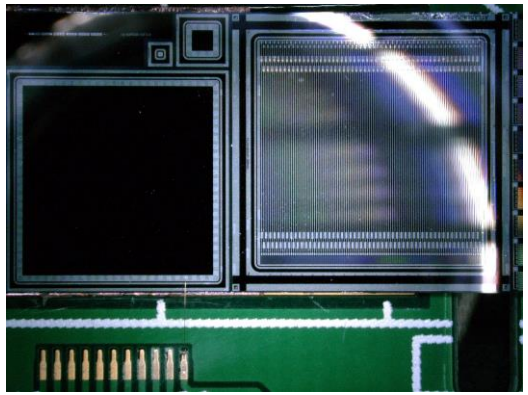


1.Experimental chamber; 2.Air inlet; 3.Probe inlet;
4.Bracket; 5.Front window; 6.Rear window;
7. semiconductor cooling chip; 8. water block;
9.L-shaped graphite sheet; 10.Press block;
11.Clamp;12.Air compressor; 13. air dryer; 14. chiller

[2] Feasibility study of CSNS as an ATLAS ITk sensor QA irradiation site

Experimental Setup for IV and CV Measurement

- **Temperature requirement:20℃(unirradiated), -20℃(irradiated), controlled by the chamber**
- Introduce dry air into the chamber to reduce humidity **(Minimum humidity: 5%RH at -20˚C)**
- **Endoscope:** Used to check if ice has formed on the sample surface after cooling



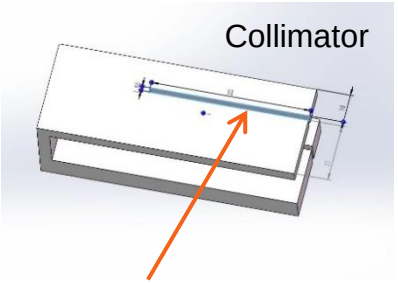
The MD8 is mounted on the PCB for IV and CV measurements

Interior of the temperature and humidity chamber

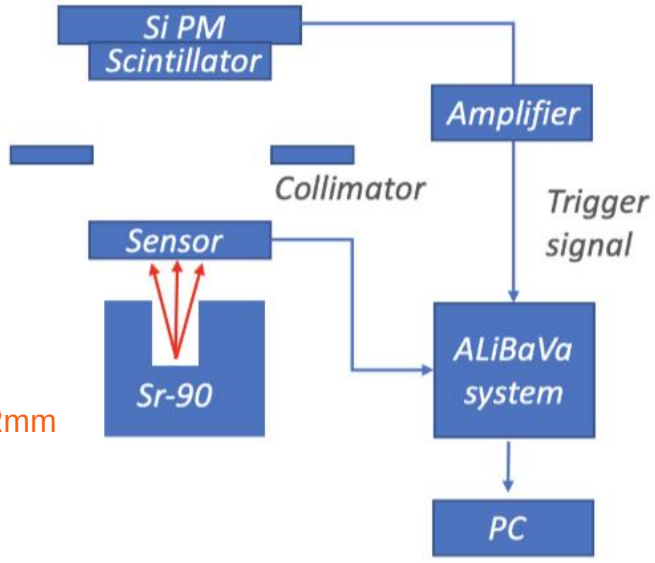
IV measurement experimental setup in the cleanroom

Experimental Setup for CCE Measurement

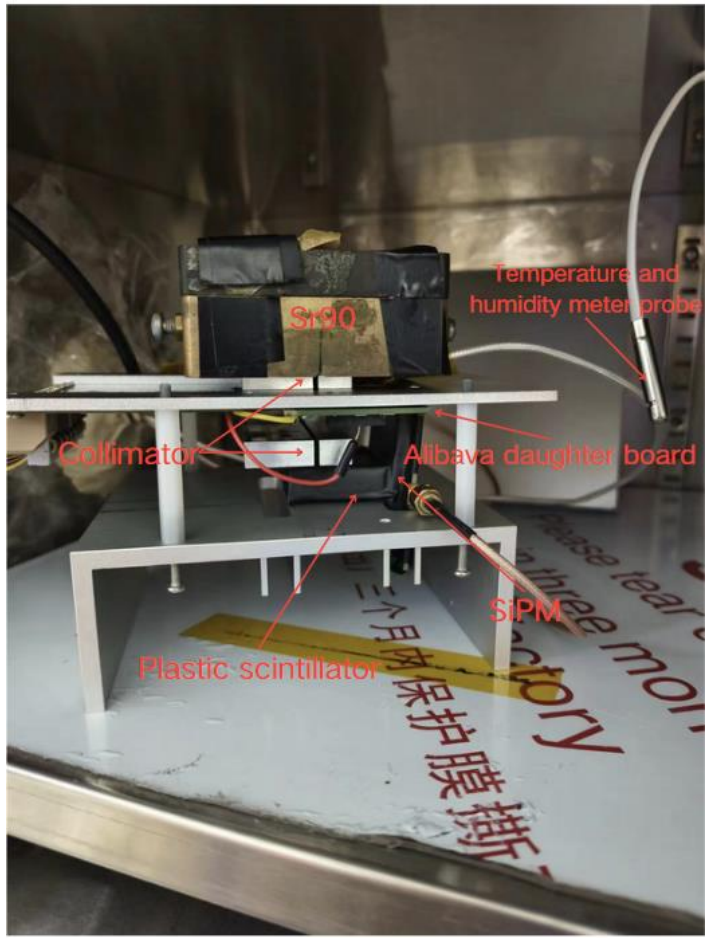
- Requirements:
  - Temperature: 20C (irradiated), -20C(unirradiated)
  - Humidity: <10%RH
- Setup placed in fridge
- Dry air introduced into the fridge to reduce humidity
  - Humidity from 54% to 3%: 45min
  - Stable in the range of **5%~7%RH** when the temperature inside the fridge is **-23°C ~ -26°C**
- Unirradiated samples are measured at -20 °C (because of temperature range of fridge: -15~-45 °C)



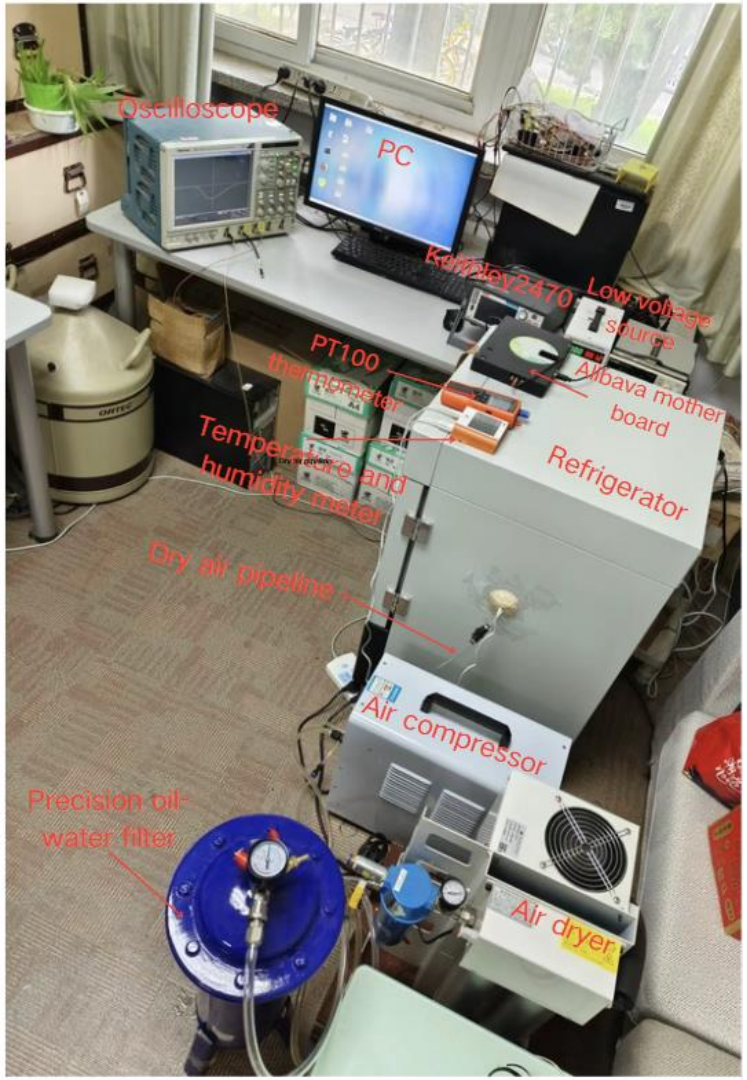
Gap of collimator: 1.5mm*52mm



Air Temperature: -26℃
Relative Humidity: 7%
Dew Point Temperature: -51.5℃ (lower than -20℃)



Inside the refrigerator

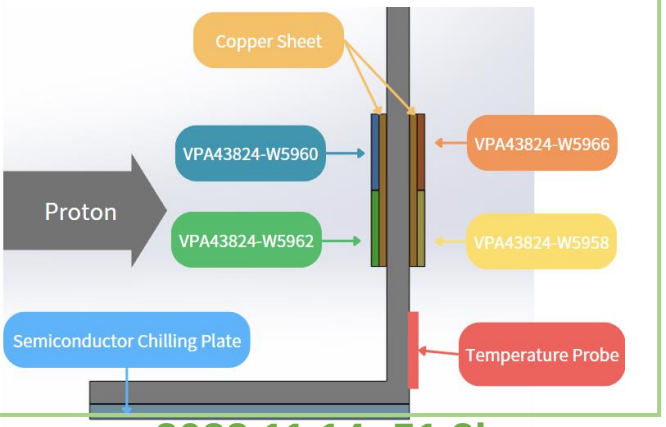


03

Results of Irradiation: IV, CV, CCE

Irradiation

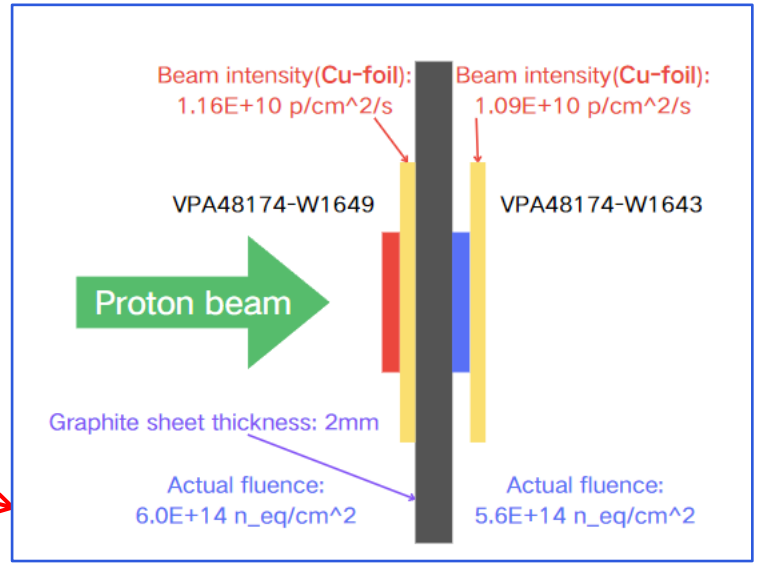
Beam intensity:$9.53 \times 10^9\ p/cm^2/s$
Actual fluence: $2.6 \times\ 10^{15}\ n_{eq}/cm^2$

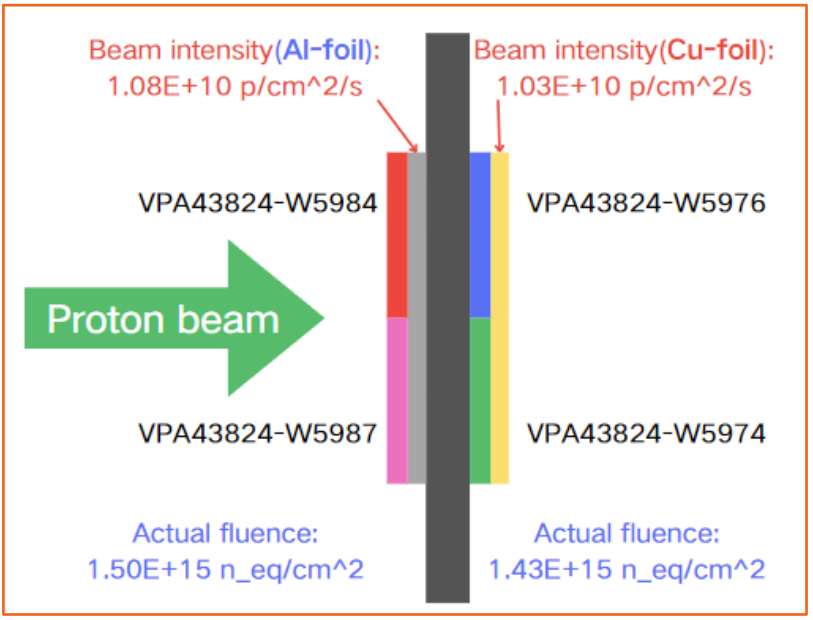


2023.11.14: 51.3h

- Three irradiation were carried out
- Al-foil and Cu-foil attached to the samples measure the irradiation fluence using foil activation technique [3]
- Al-foil and Cu-foil provide consistent results of fluence

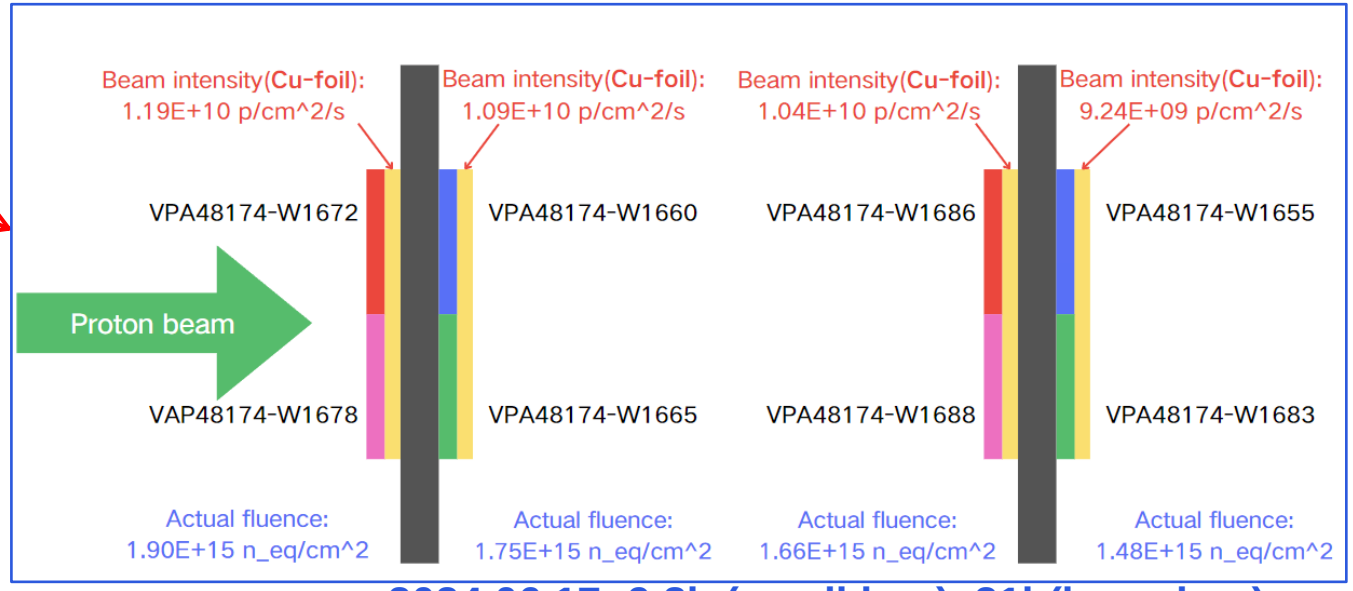
Small box





2024.04.15: 26.711h

Large box



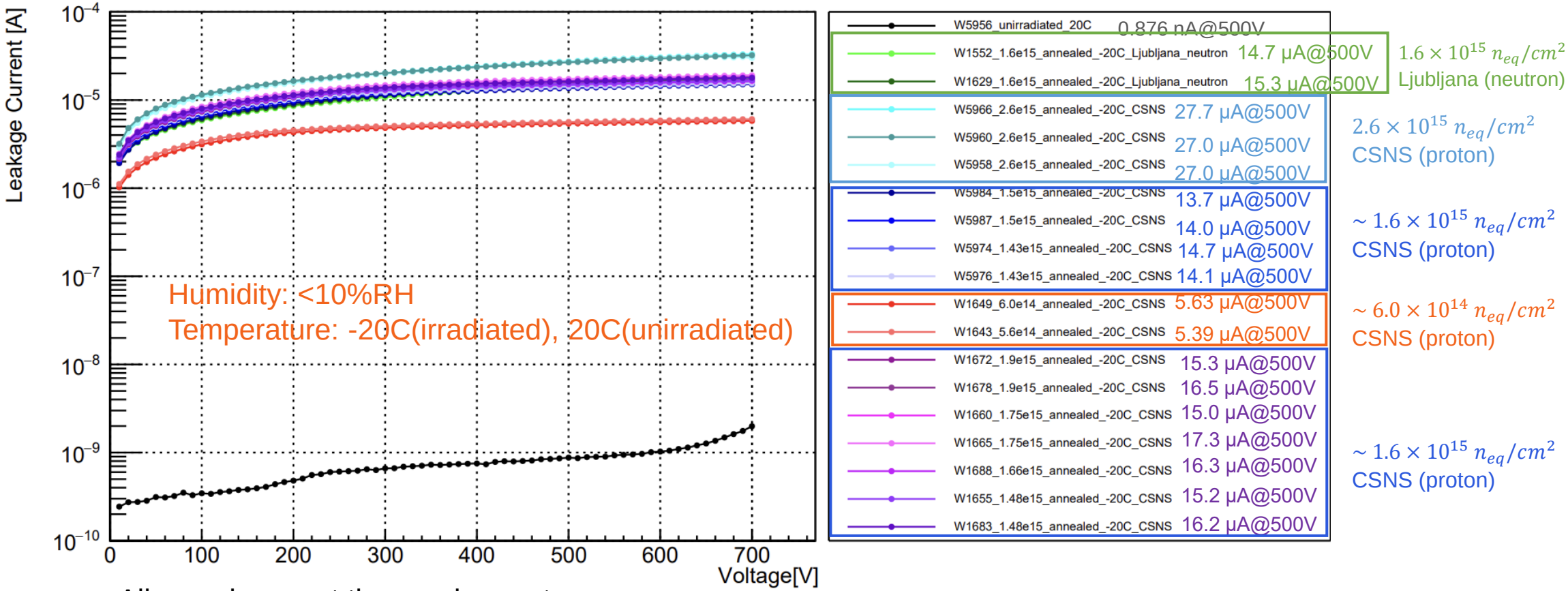
2024.06.17: 9.8h (small box), 31h(large box)

[3] Measurements of proton beam flux and energy of APEP using foil activation technique

Time	Sample ID	Irradiation	fluence [n_{eq}/cm^2]	IV+CV (MD8)	CCE (Mini)	Comment
2024.04.15 Shipped from Ljubljana	VPA48176-W1552	neutron	1.6×10^{15}	√	√	
	VPA48203-W1629		1.6×10^{15}	√	√	
2024.04.29 Shipped from Birmingham	VPA48170-W1388	proton	1.8×10^{15}	none	√	
	VPA48194-W1659		1.8×10^{15}	none	√	
	VPA48174-W1677		1.5×10^{15}	none	√	
2023.11.14 Irradiated at CSNS	VPA43824-W5966	proton	2.6×10^{15}	√	√	
	VPA43824-W5962		2.6×10^{15}	none	none	broken due to operational error
	VPA43824-W5960		2.6×10^{15}	×	√	breakdown @180V, No breakdown during remeasurement
	VAP43824-W5958		2.6×10^{15}	√	√	
2024.04.15 Irradiated at CSNS	VPA43824-W5984	proton	1.50×10^{15}	√	×	humidity(~27%) was too high → CCE breakdown at 680V
	VPA43824-W5987		1.50×10^{15}	√	√	
	VPA43824-W5976		1.43×10^{15}	√	√	CCE: unannealed + annealed
	VPA43824-W5974		1.43×10^{15}	√	√	CCE: unannealed + annealed
2024.06.17 Irradiated at CSNS	VPA48174-W1649	proton	6.0×10^{14}	√	√	
	VPA48174-W1643		5.6×10^{14}	√	√	
	VPA48174-W1672	proton	1.90×10^{15}	√	√	
	VPA48174-W1678		1.90×10^{15}	√	√	
	VPA48174-W1660		1.75×10^{15}	√	√	
	VPA48174-W1665		1.75×10^{15}	√	√	
	VPA48174-W1686		1.66×10^{15}	√	×	CCE: unannealed + **annealed (breakdown at 480V)**
	VPA48174-W1688		1.66×10^{15}	√	√	CCE: unannealed + annealed
	VPA48174-W1655		1.48×10^{15}	√	√	
	VPA48174-W1683		1.48×10^{15}	√	√	

All samples are in the annealed status by default unless otherwise specified.

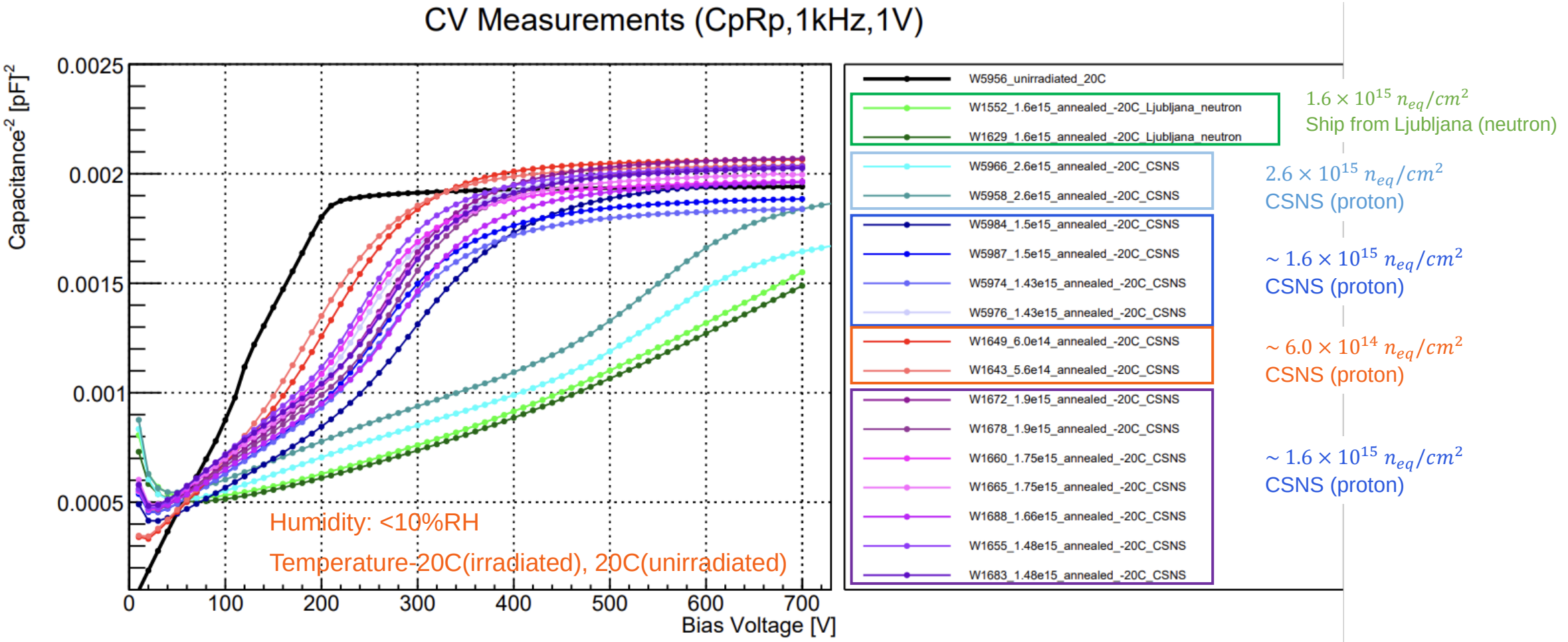
IV



- All samples meet the requirements:
  - Unirradiated: not exceed 0.1μA/cm^2(at 500V, RH<20%)
  - Fluence=$1.6 \times 10^{15}\ n_{eq}/cm^2$ ($5 \times 10^{14}\ n_{eq}/cm^2$): not exceed 0.1mA/cm^2 (no more than 20μA) at 500V [4]
- Samples irradiated with the same fluence have the same behavior
- The higher the fluence, the greater the leakage current

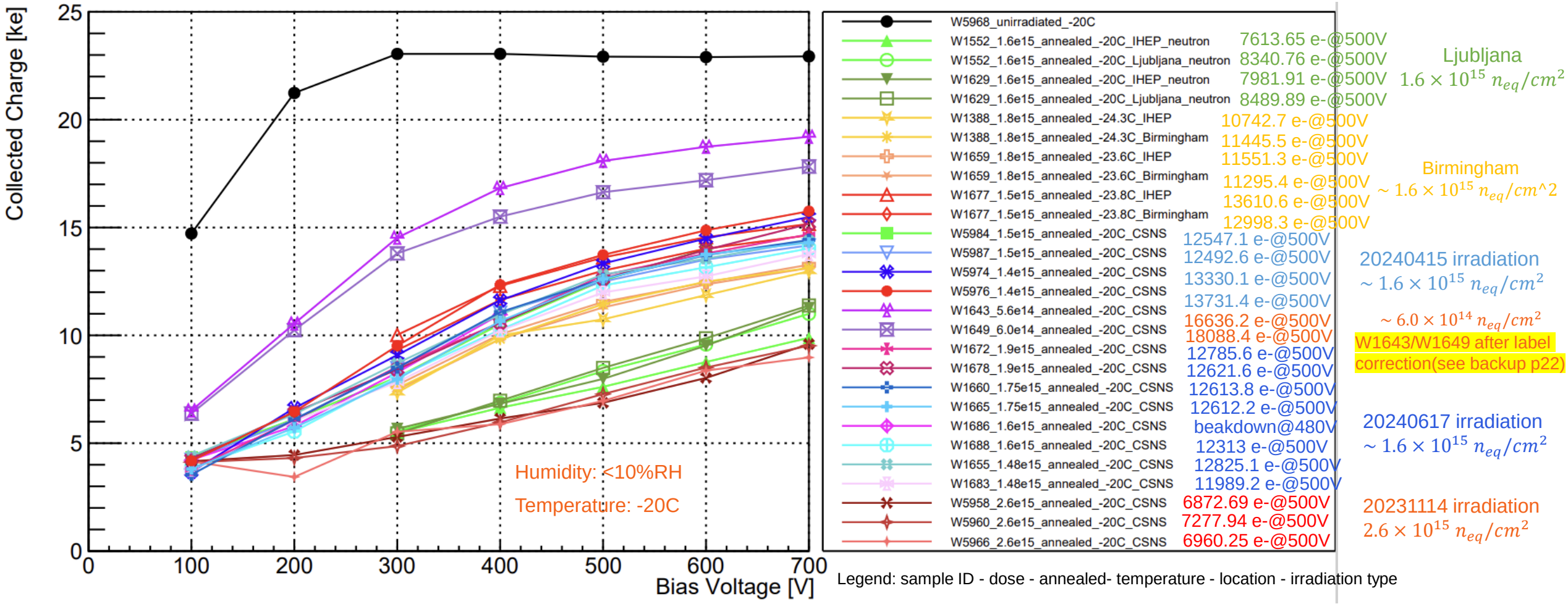
[4] Specifications and pre-production of n+-in-p large-format strip sensors fabricated in 6-inch silicon wafers, ATLAS18, for the Inner Tracker of the ATLAS Detector for High-Luminosity Large Hadron Collider

CV



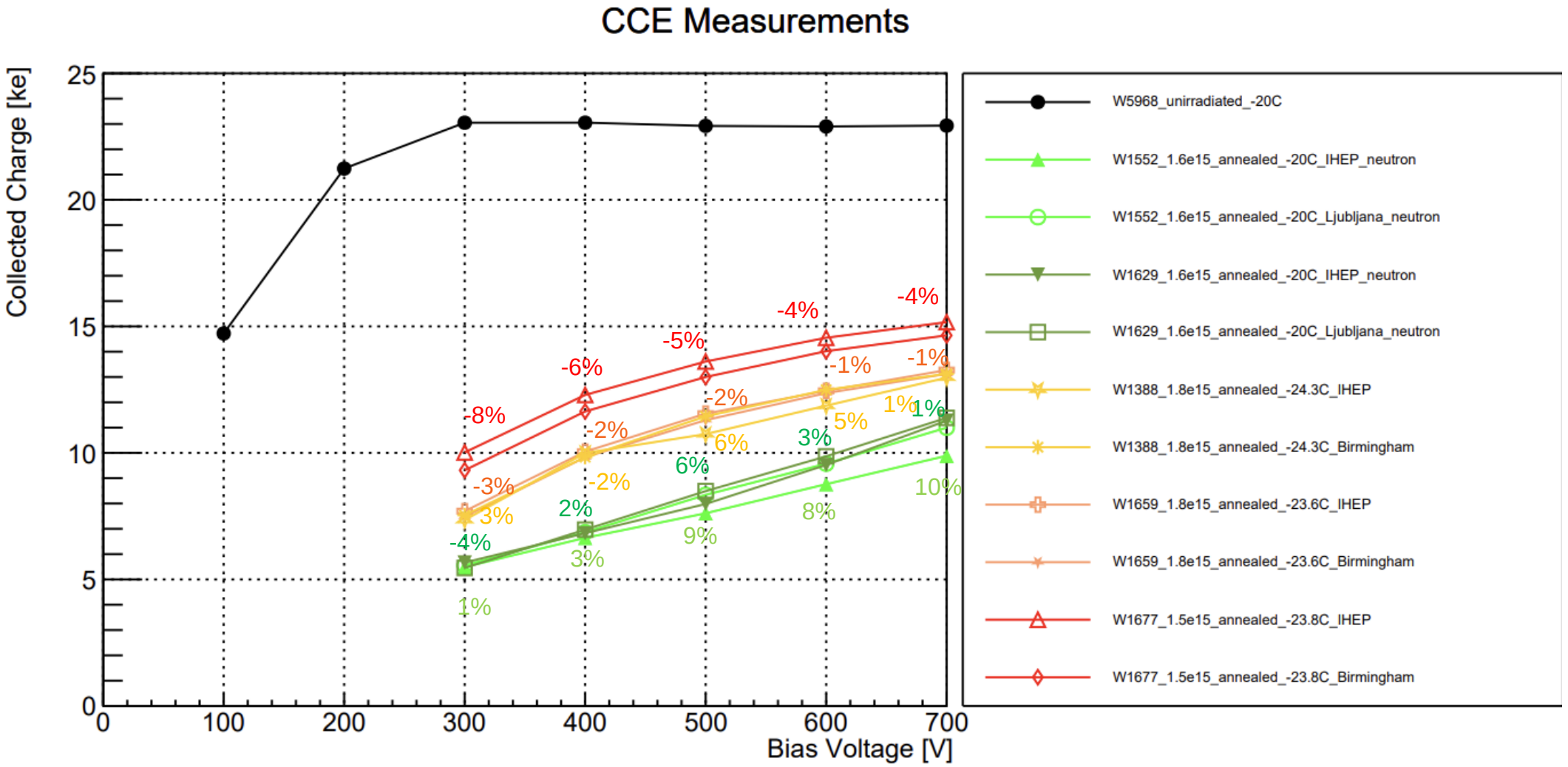
- V_{FD}: no more than 350V for unirradiated sample
- Samples with similar fluence have close full depletion voltages
- The higher the fluence, the larger the full depletion voltage

CCE



- Fluence=$1.6 \times 10^{15}\ n_{eq}/cm^2$: more than 6350 e- at 500V
- All samples meet the requirement.
- The larger the fluence, the fewer the collected charges

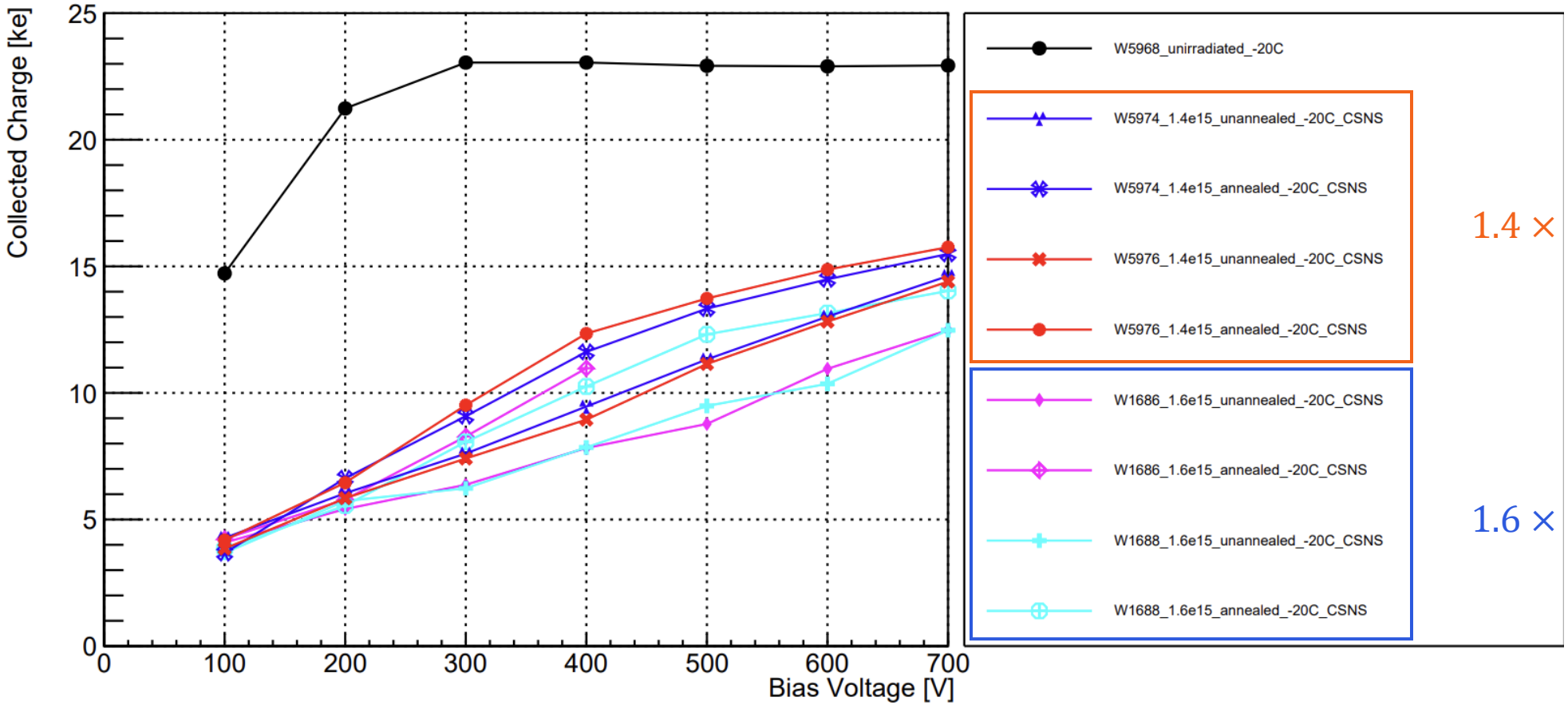
CCE: Cross Check



Cross check: (The specific values are in the backup.)

- W1552 and W1629 were shipped from Ljubljana; W1388, W1659 and W1677 were shipped from Birmingham
- the differences are less than 10%

CCE Measurements: annealed vs. unannealed



$1.4 \times 10^{15}\ n_{eq}/cm^2$

$1.6 \times 10^{15}\ n_{eq}/cm^2$

- Four samples were tested for both annealed and unannealed states. **(annealed: 60℃, 80min)**
- The annealed samples have better charge collection capability than the unannealed samples as expected.
- The CCE of **unannealed** W1686 can be measured normally, but breakdown at 480V for **annealed** W1686 . We are trying to understand the reason.

Summary

- 18 samples have been irradiated with proton beam at CSNS
- 5 irradiated samples from Ljubljana and Birmingham
- CCE results we measured are in good agreement with those from Ljubljana and Birmingham
- Our setup and measurements are valid
- CSNS could be a QA irradiation site, and IHEP could be a QA testing site for sensors
- Further investigation is needed to understand the mentioned issues

THANKS