A study on the feasibility of CSNS becoming an ATLAS ITk sensor QA irradiation site

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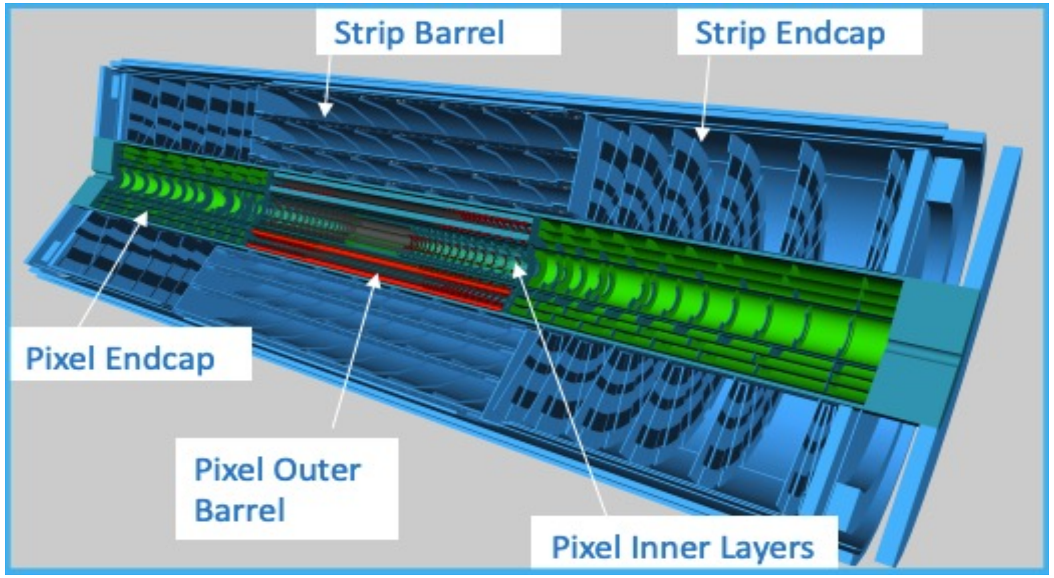
Introduction

- Nearly 22,000 large area silicon strip sensors will be produced by Hamamatsu Photonics K.K. (HPK) for HL-LHC upgrade

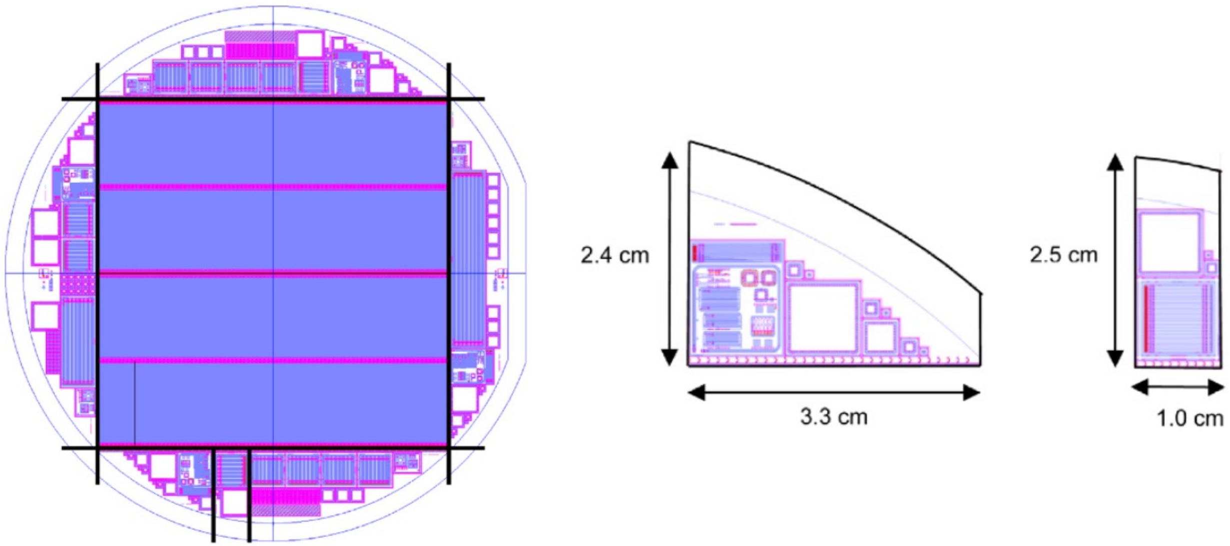
- In order to monitor these sensors production for the ATLAS Inner Tracker (ITk), a Quality Assurance (QA) strategy has been prepared

  - QA aims to flag the issues due to the fabrication process
  - A detailed irradiation and testing plan has been prepared by the ATLAS-ITk Collaboration



ITk Quality Assurance strategy

The main devices that are used for QA purposes are the miniature strip sensors with 1×1 cm^2 dimensions; the monitor diodes of 8×8 mm^2 size (MD8); and the ATLAS test chip.

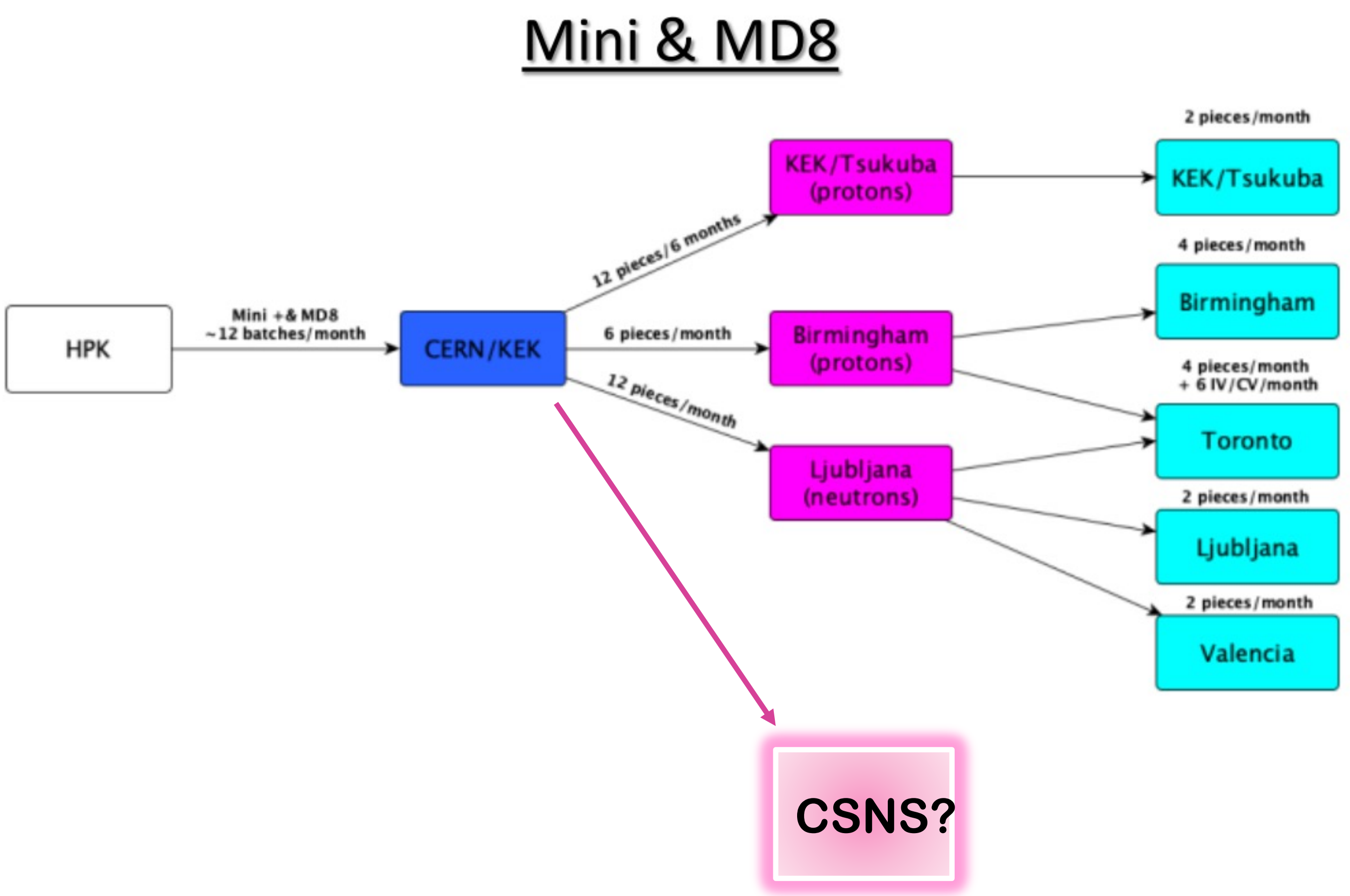


Dicing scheme for the wafers (left), Testchip & MD8 (center) and Mini & MD8 (right).

Test samples

- For Mini sensor, focus on CCE (charge collection efficiency) at $1.6\text{x}10^{15}$ neq/cm^2
- For MD8, focus on V_{FD}. MD8 is used for IV and CV measurements

ITk Quality Assurance strategy



The feasibility needs to be verified first!

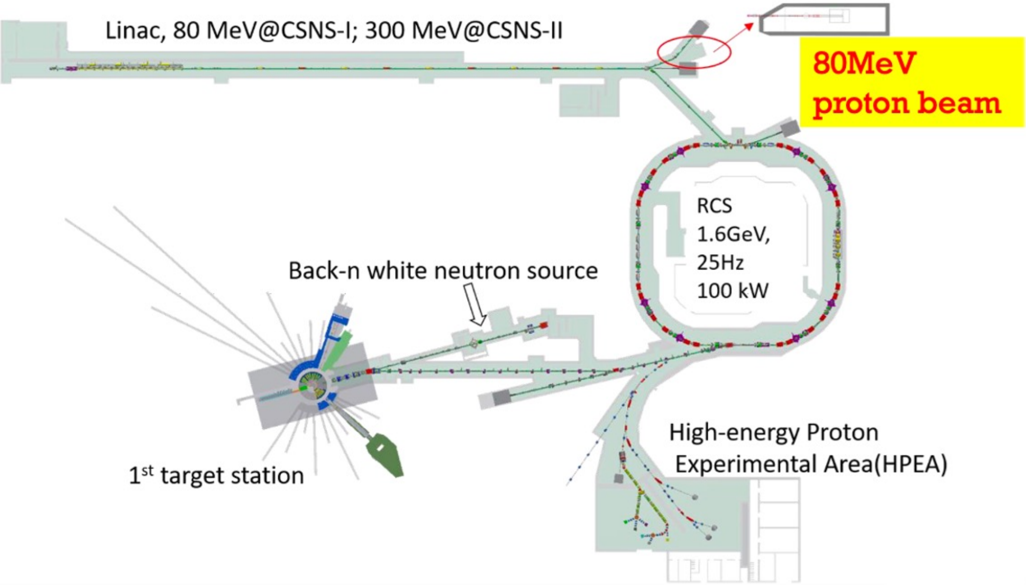
Planned irradiation

- All QA pieces are first delivered to CERN and then distributed to each irradiation site
- The ITk strip sensors need to endure a high level of radiation. They're designed to handle around a neutron-equivalent fluence of 1.6×10^{15} neq/cm^2
- After irradiation, the QA pieces are sent to test sites for measurements

China Spallation Neutron Source

CSNS

- Located in Dongguan city
- It is the first pulsed neutron source facility in China.
- It now includes:
  - a powerful linear accelerator and a rapid circling synchrotron
  - a target station and three Phase I neutron instruments
- We use the Associated Proton Experiment Platform (APEP) in CSNS to irradiate the test samples. APEP locates at the end of the CSNS linear accelerator



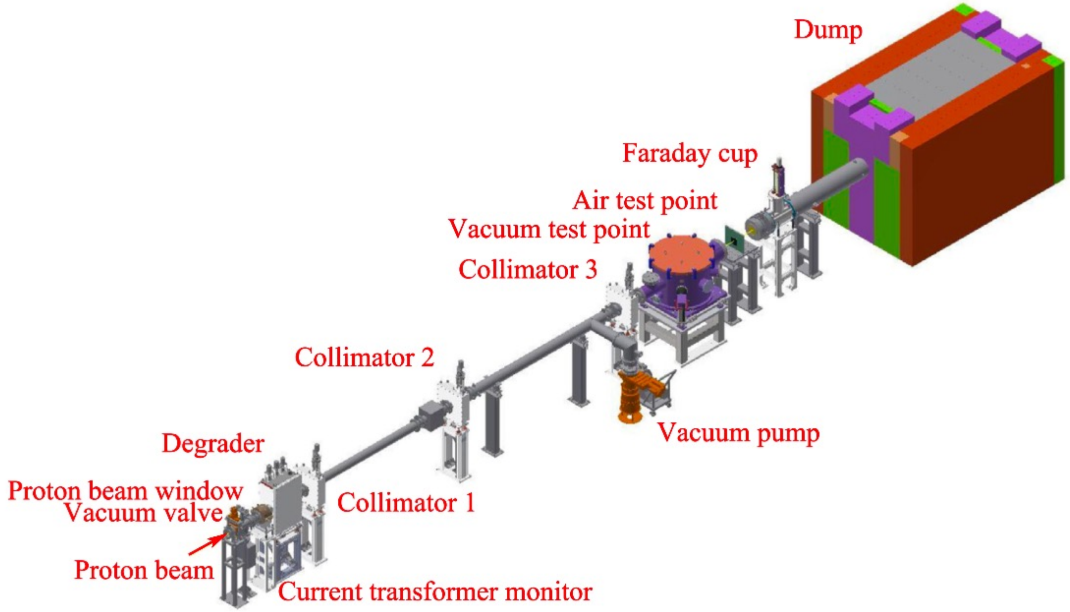
Associated Proton Experiment Platform

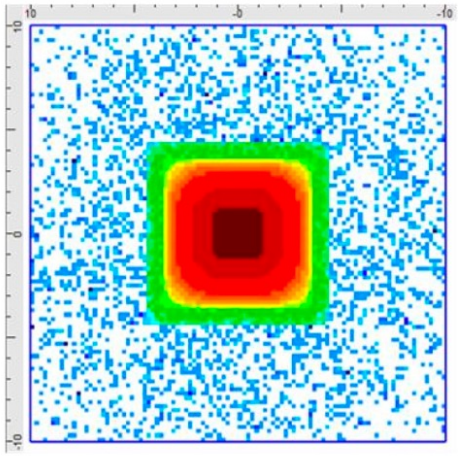
APEP

- Energy range: 10-80 MeV
  - We use the 80 MeV proton beam energy.

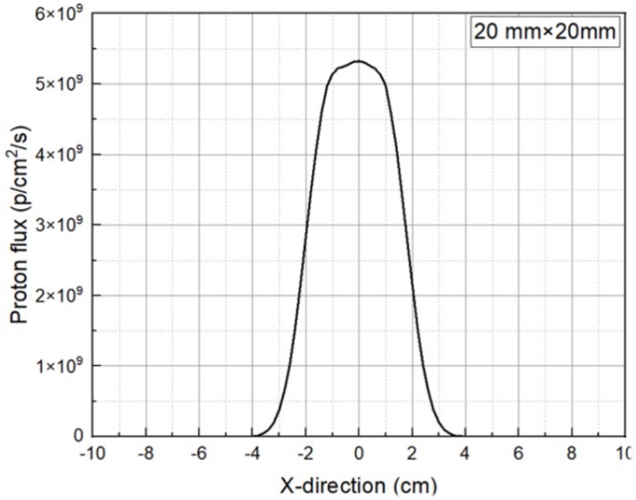
- Beam size: 10mm x 10mm ~ 50mm x 50mm
  - We use a 20 mm × 20 mm (flat top of flux) beam spot.

- The flux intensity at the sample location for a beam spot of this size is about 3.04×10^{9} p/cm²/s
- It would take around 102.3 hours to reach 1.6×10^{15} neq/cm²





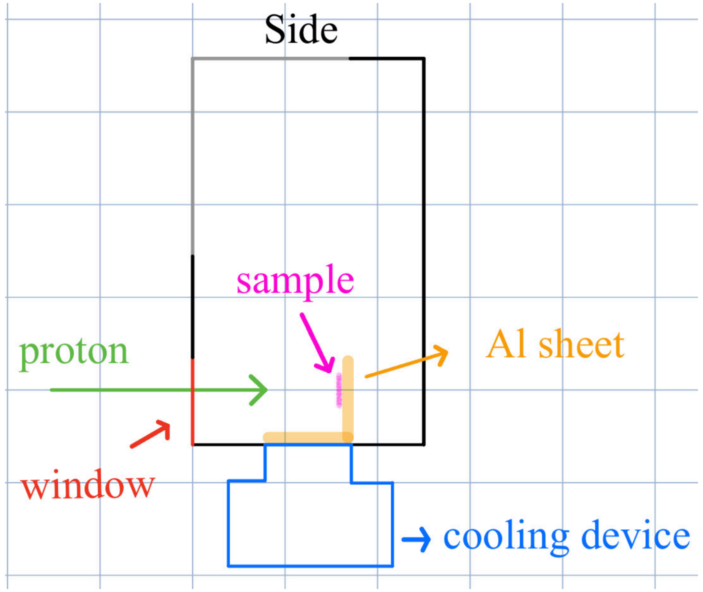
20mm×20mm

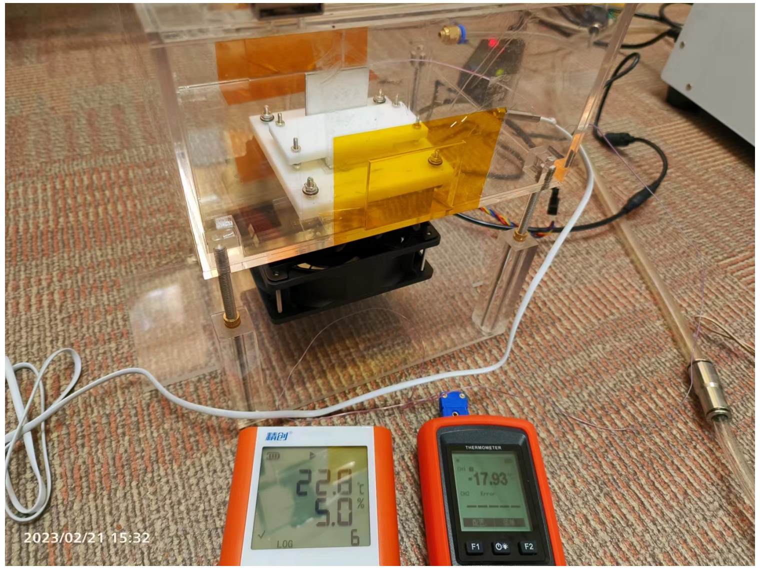


Low temperature irradiation setup

QA irradiation should be conducted at less than -15°C to avoid the sample annealing.
To meet this requirement:

- ✓ **Temperature (T ~ -15 ℃) control:**
  Semiconductor refrigeration sheet + aluminum sheet
- ✓ **Humidity (RH ~ 5%) control:**
  Air compressor + dryer
- ✓ **Temperature monitoring:**
  Thermocouple + Thermometer
- ✓ **Humidity monitoring:**
  Electronic hygrometer

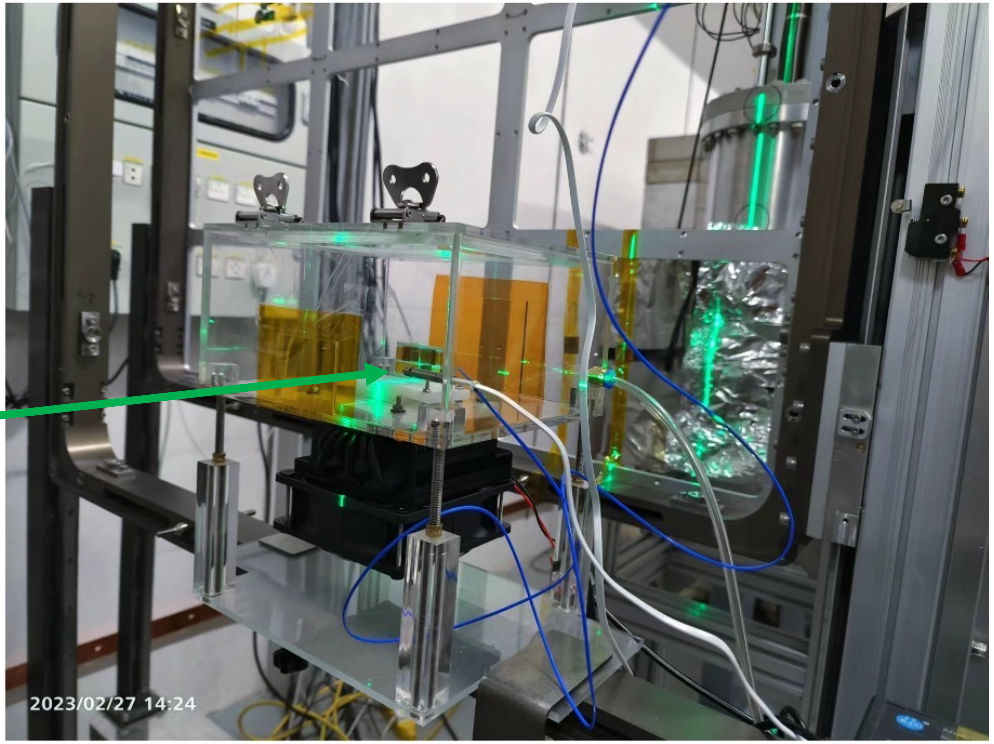


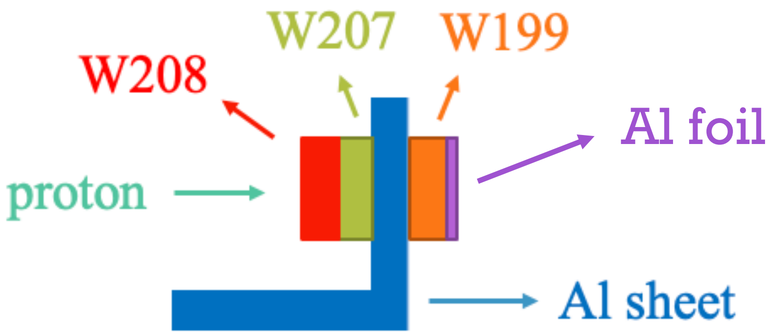


CSNS irradiation

	beam energy [MeV]	proton fluence [p/cm^2/s](10mA)	Conversion factor	total proton fluence[p/cm^2]	neutron fluence[neq/cm^2]	run time[h]
Target	80	3.04E+09	1.427	1.12E+15	1.60E+15	102.3

The neutron equivalent fluence measured from Al foil behind W199 is 1.64E+15 neq/cm^2, calculated by beam simulated parameters is 1.47E+15 neq/cm^2.





The temperature of the Al sheet is -15.4 ℃
The humidity of the cold box ~ 5%

IV test

- ✓ For unirradiated diodes, the current should not exceed 0.1 μA/cm² at 500 V (RH < 20%)
- ✓ The diodes should show a leakage current of less than 0.1 mA/cm² at 500 V (-20 ℃) after irradiation to 1.6×10^{15} neq/cm²
- ✓ Onset of micro-discharge should be at V_{MD}>500 V for both unirradiated and irradiated diodes

$$\frac{\Delta I}{V} = \alpha\Phi_{eq}$$

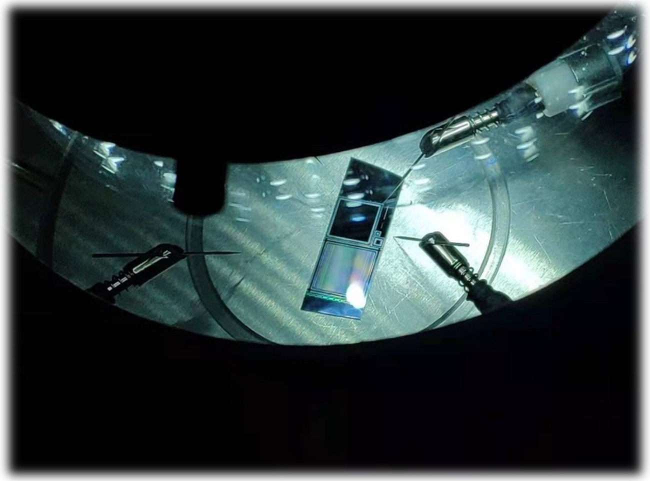
ΔI in this formula is corresponded to 20 ℃

Temperature affects current

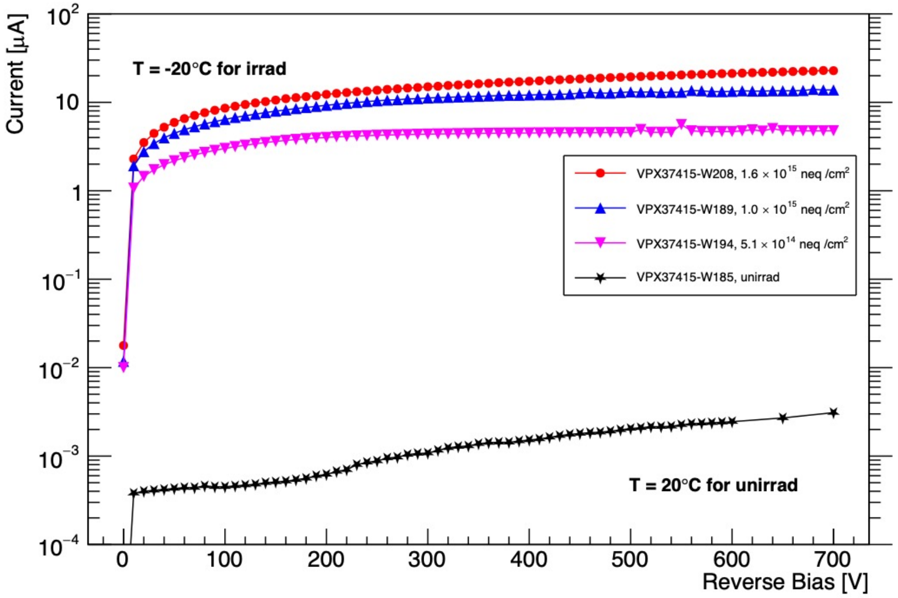
$\Phi_{eq} = 1.6\times10^{15}$, $\alpha = 4\times10^{-17}$, V = 0.0165 cm³

when T = -20 ℃, ΔI ~ 21 uA

The result looks reasonable



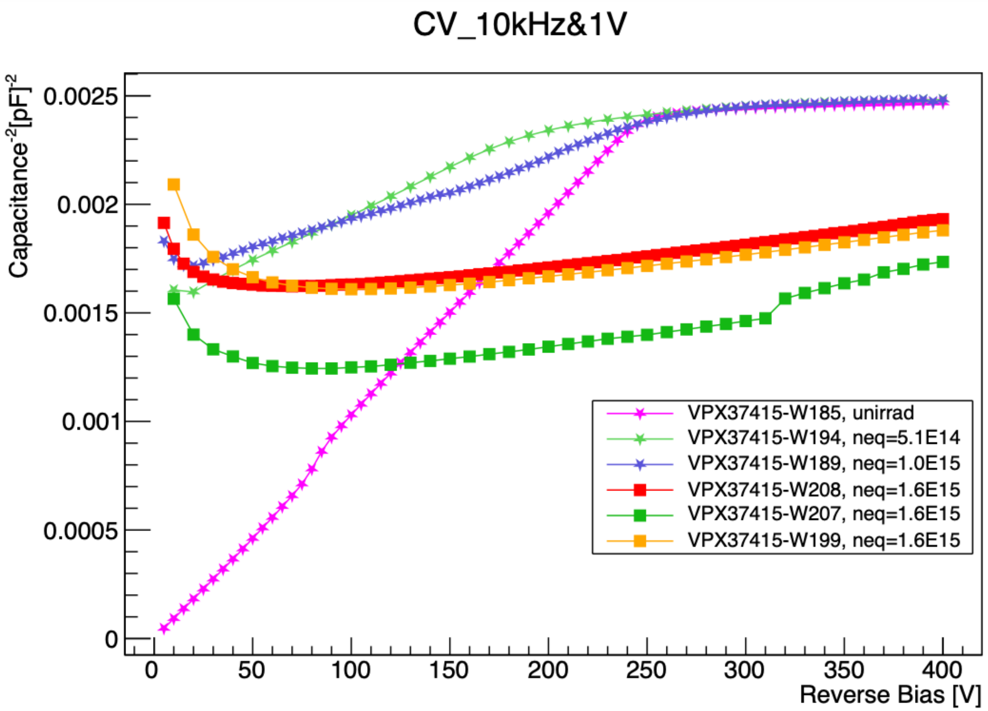
IV for irrad and unirrad



CV test

An LCR meter (Keysight E4980A) is used for CV test.

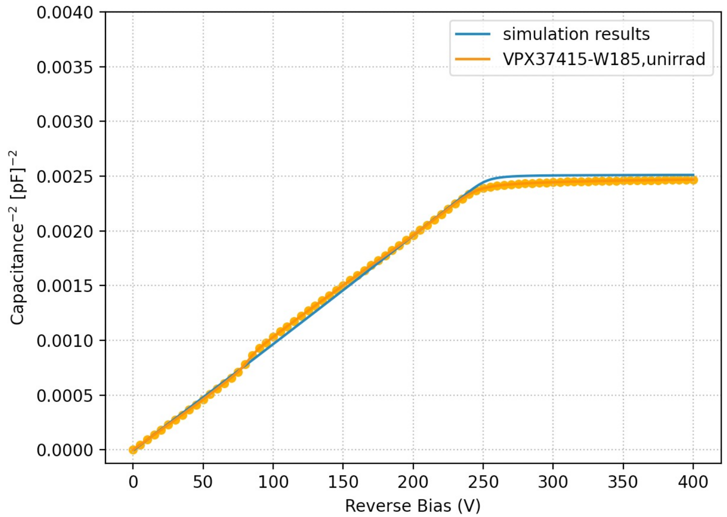
✓ For unirradiated diodes, the depletion voltage (V_{FD}) should be less than 350 V



Simulation

RASER (**RA**diation **SE**miconducto**R**): Device and Detector simulation
https://raser.team/about

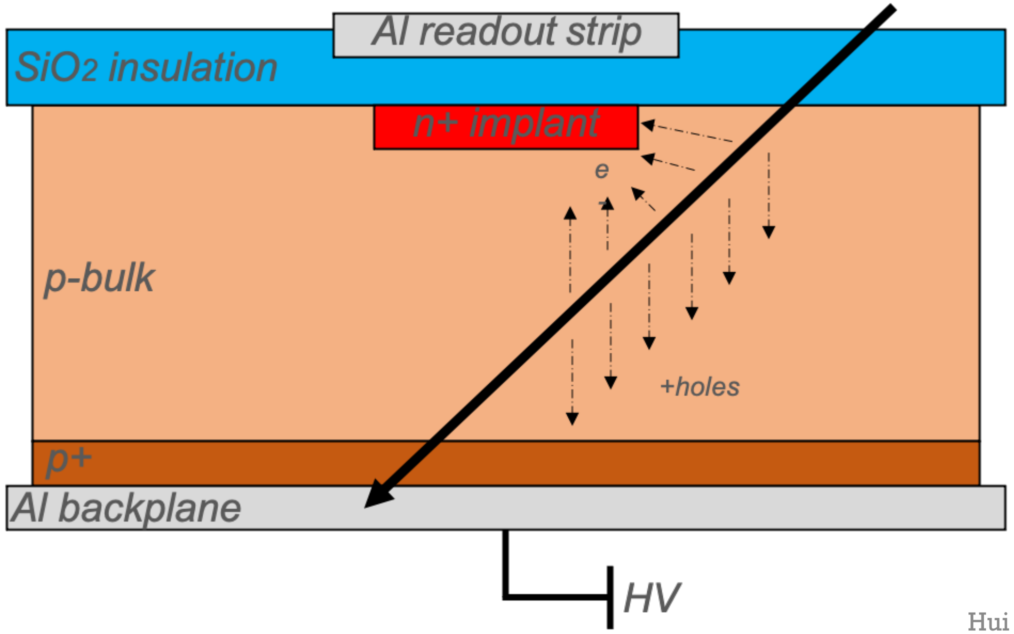
- Active area of MD8: 0.74×0.74 cm^2
- Sample active thickness: 300 μm
- n^+ implants in p-type bulk
- Bulk doping concentration: 4.0×10^{12} cm^{-3}

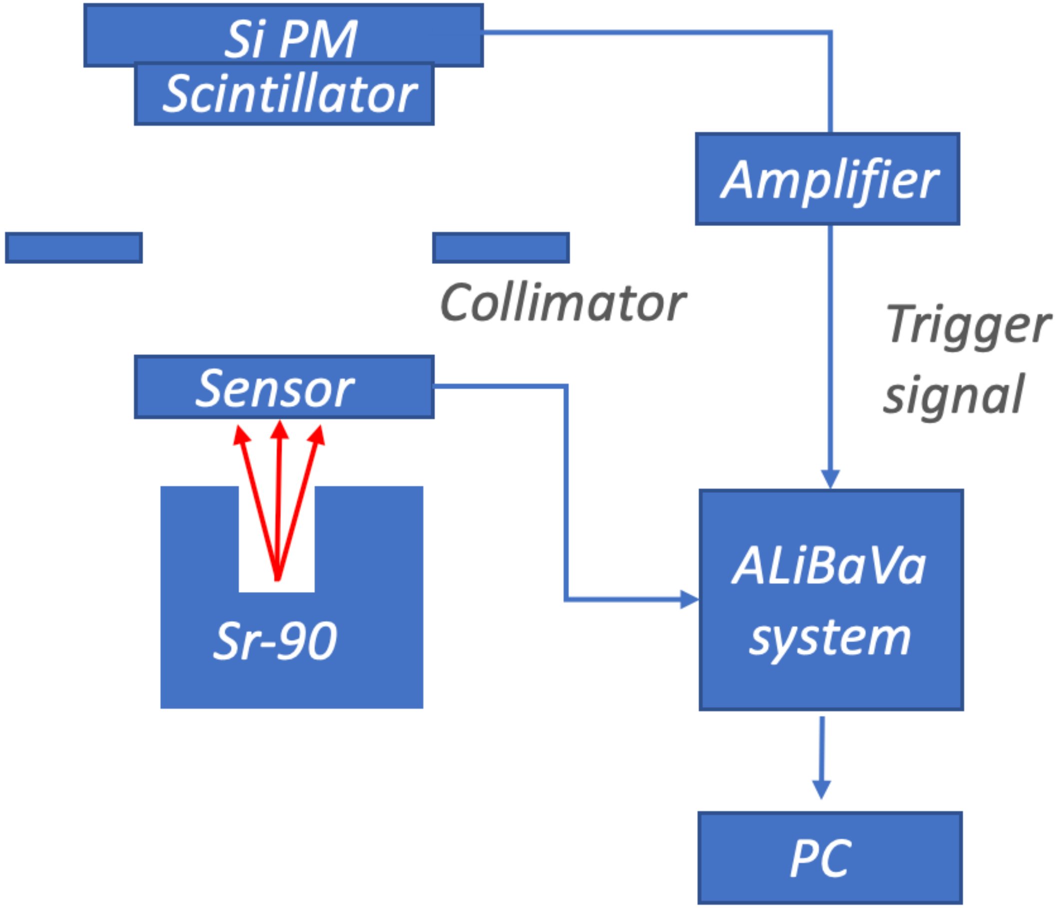


CCE test

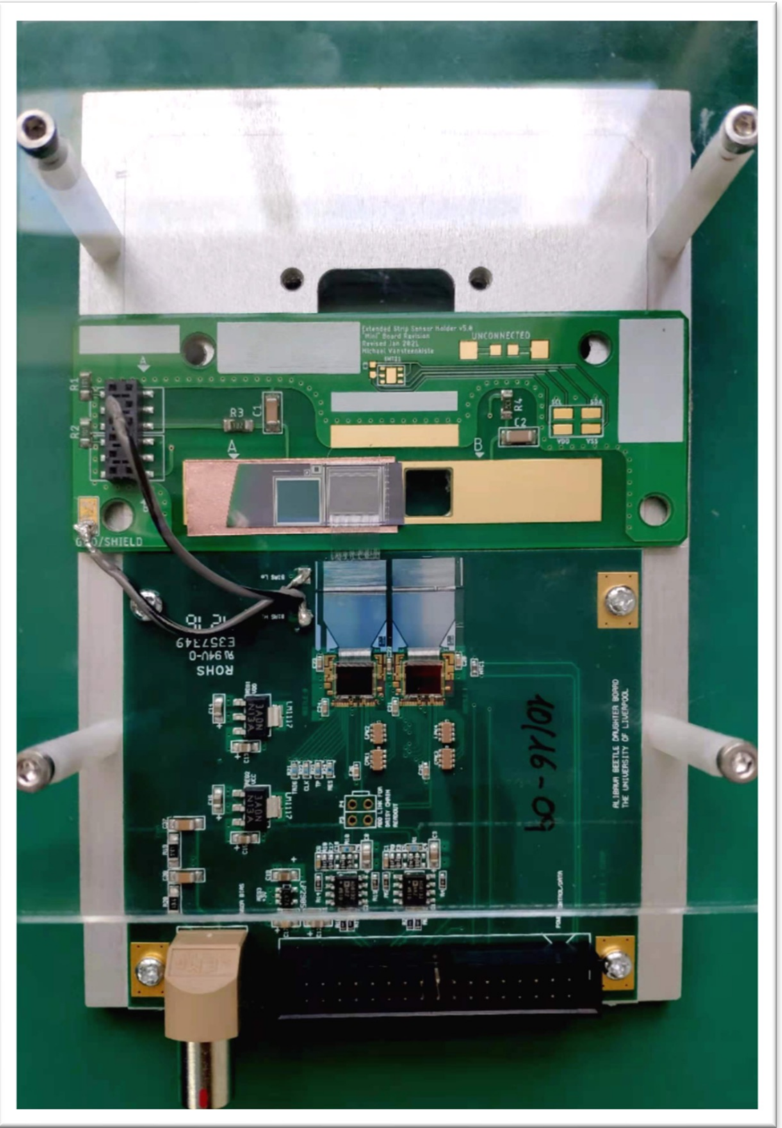
Charge collection

- **Radioactive source:** Sr-90
- **Trigger:** scintillator and silicon photomultiplier
- **Sensor to be tested:** ATLAS18LS miniature sensor
- **Read out system:** ALiBaVa system





CCE test

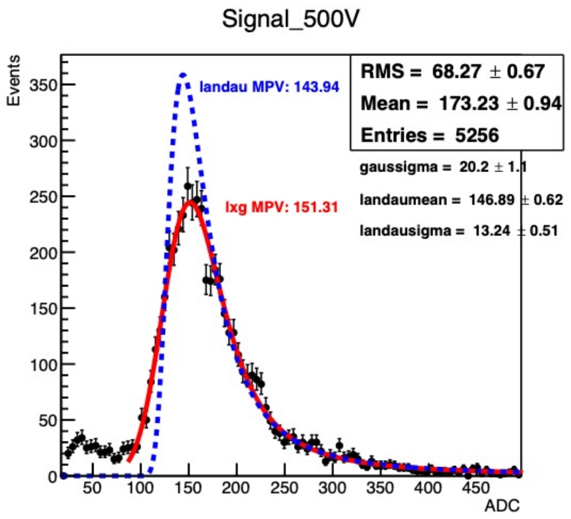


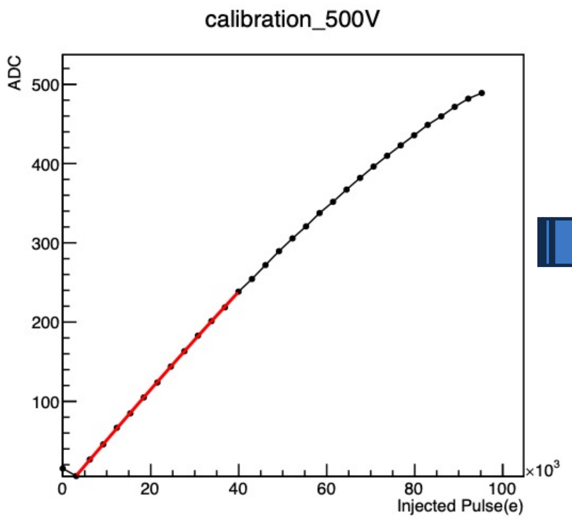
ALiBaVa daughter board,
wire bonding with mini sensor

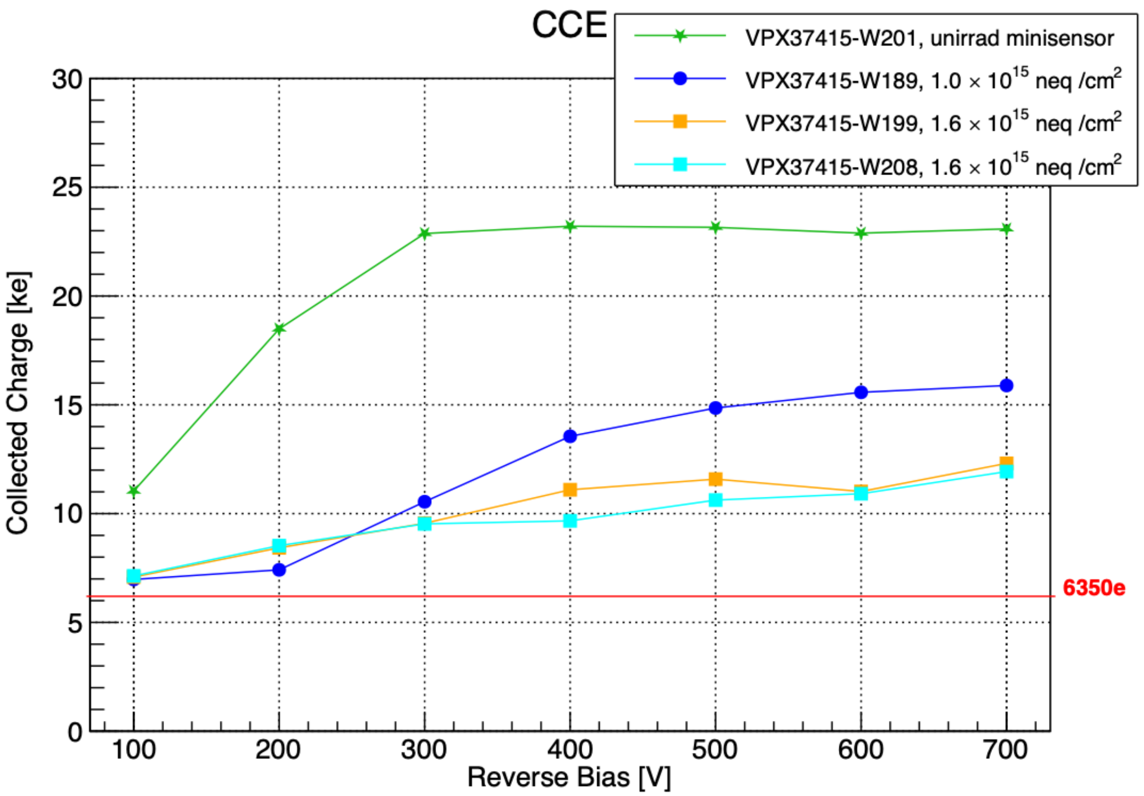
ALiBaVa system

CCE test

- Landau convolutional Gaussian distribution of signal spectrum
- Obtain the ADC value of the Landau peak
- Combined with the calibration to get the collected charge







For Sr90 source, the maximum possible value of charge collection for a fully depleted unirradiated Mini is 23180 e.

✓ At 500 V, the CCE of data points for unirradiated mini sensor ~23 ke, for 1.0×10^{15} neq/cm^2 ~15 ke, for 1.6×10^{15} neq/cm^2 ~11 ke. The collaboration has established a minimum threshold of 6.35 ke

Conclusion

- Several proton irradiations have been performed at the Associated Proton Experiment Platform (APEP) in China Spallation Neutron Source (CSNS).
- We tested ITk strip Mini and MD8 sensors with controlled temperature (-15.4 ℃) and humidity (5%) during irradiation.
- The fluence points used are from 5.1×10^{14}, 1.0×10^{15}, and 1.6×10^{15} neq/cm^2.
- The post-irradiation measurements (IV, CV, and CCE) are done, under the cold temperature (-8° C), after annealing for 80 minutes at 60° C.
- Test results are consistent with other sites, which means CSNS could be a proton irradiation site for ATLAS ITk sensor QA, after formal site qualification.

☺

Thank you!

Back up (Radiation)

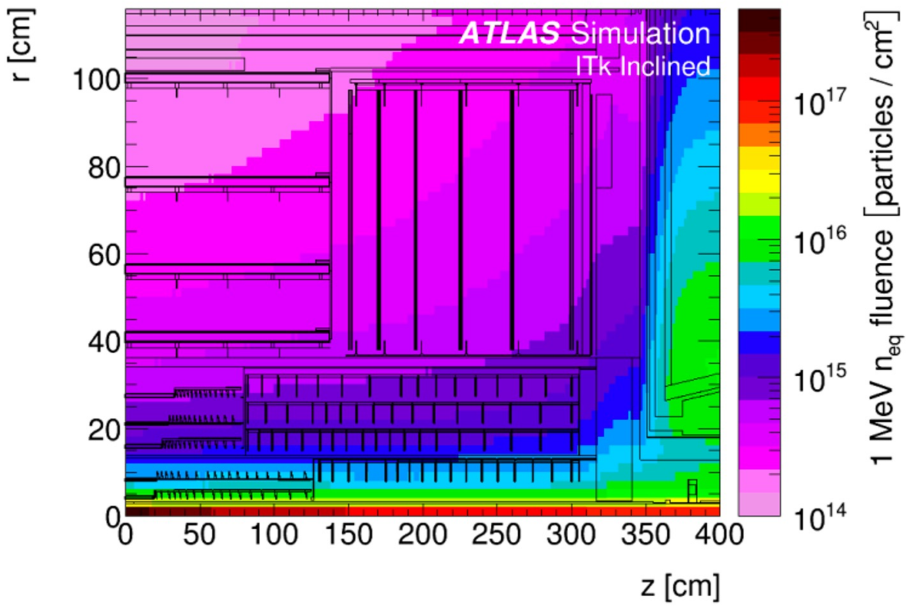


Fig1: The fluence and dose distributions for the ITk layout, use the 1 MeV neutron equivalent flux.

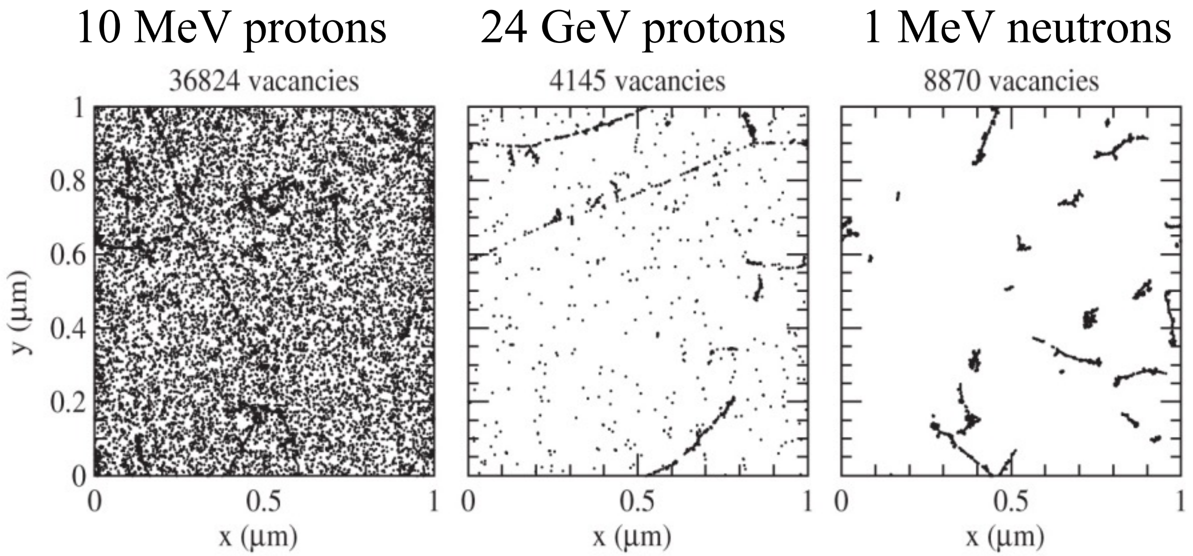


Fig2: Initial distribution of vacancies. The plots are projections over 1 μm of depth z and correspond to a fluence of 10^{14} cm^2

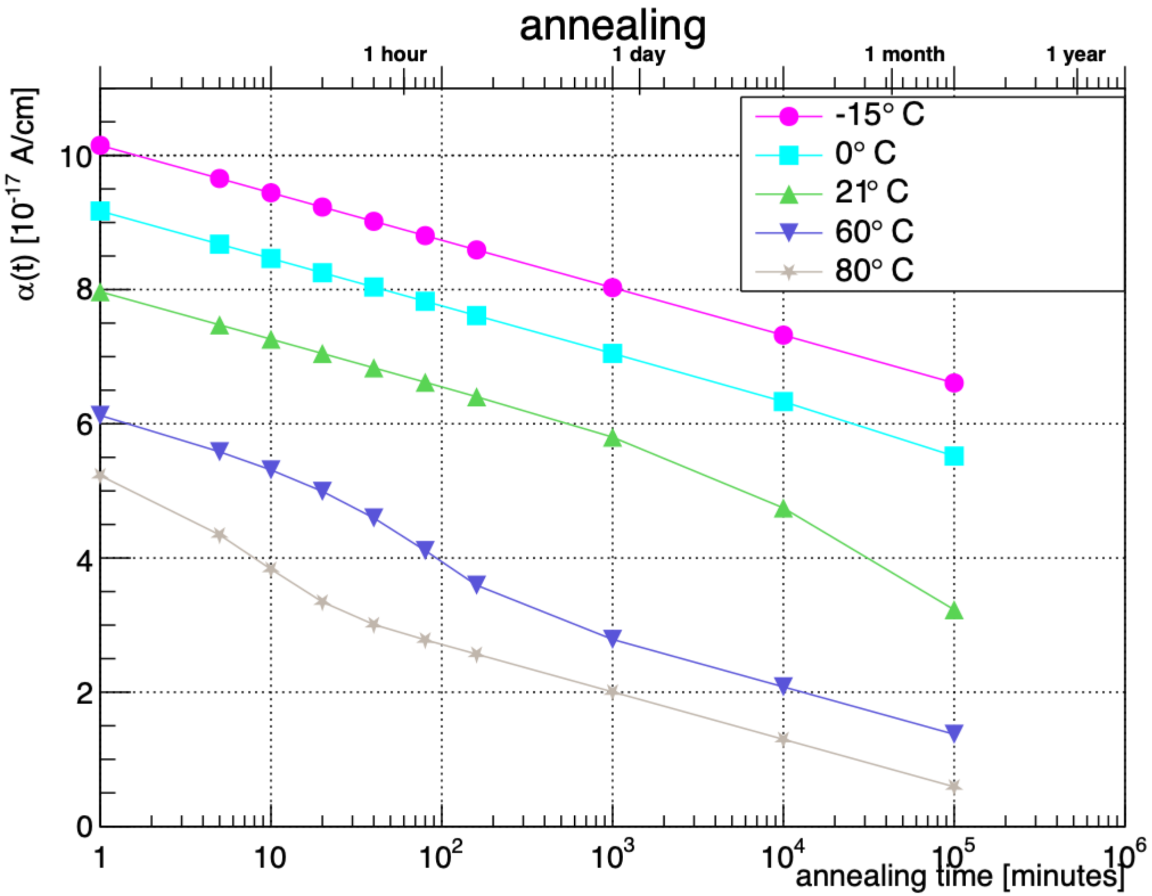
Layer	Radius [mm]	Maximal Fluence [n_{eq}/cm^2]	Maximal Dose [MRad]
Strips			
Long Strips	762	3.8×10^{14}	9.8
Short Strips	405	7.2×10^{14}	32.5
End-cap	385	1.2×10^{15}	50.4

Table: Overview on maximal fluences and doses. The values including a safety factor of 1.5.

Back up (Annealing)

Annealing

- At high temperatures, the diffusion of defects will happen. This process is called annealing.
- $\frac{\Delta I}{V} = \alpha \Phi_{eq}$
- α is the current-related damage rate.
- The average α after a standard annealing scenario of 80 minutes at 60° C is 4×10^{-17} A/cm.
- The collaboration uses the parameter above for annealing, to get to the minimum of the non ionizing energy loss (NIEL) damage in the bulk.



Back up (Annealing)

$$\frac{\Delta I}{V} = \alpha\Phi_{eq}$$

ΔI: leakage current saturation value
Φeq: 1MeV neutron equivalent fluence
V: normalizes for a given volume
α is called the current-related damage rate

$$\alpha = \alpha_0 + \alpha_I e^{-\frac{t}{\tau_I}} - \beta \cdot ln\frac{t}{t_0} \qquad \alpha_0 = -(8.9 \pm 1.3)\cdot 10^{-17}\ \mathrm{A/cm} + (4.6 \pm 0.4)\cdot 10^{-14}\ \mathrm{AK/cm}\cdot \frac{1}{T_\alpha}$$

$$\alpha_I \sim 1.25\cdot 10^{-17}\ \mathrm{A/cm},\ \ \beta \sim 3\cdot 10^{-18}\ \mathrm{A/cm} \qquad t_0 = 1\ \mathrm{min}$$

[1]

$$\frac{1}{\tau_I} = k_{0I} \times \exp\left(-\frac{E_I}{k_B T_a}\right) \quad \text{with} \quad k_{0I} = 1.2^{+5.3}_{-1.0} \times 10^{13}\,\mathrm{s}^{-1},\ \ E_I = (1.11 \pm 0.05)\ \mathrm{eV}.$$

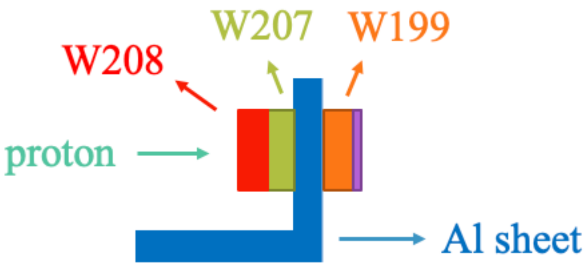
This equation is very sensitive to E

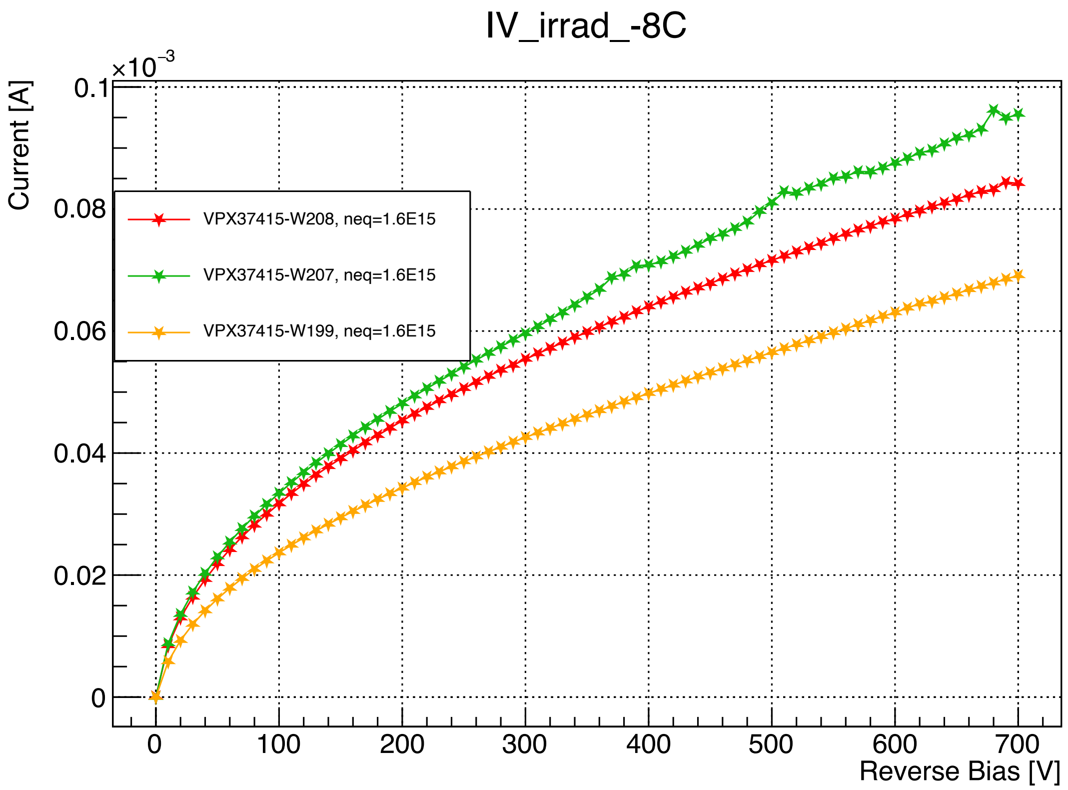
annealing temperature T_α K_B=1.38e-23 J/K

e.g. $\tau_I \approx 10$ days at room temperature.

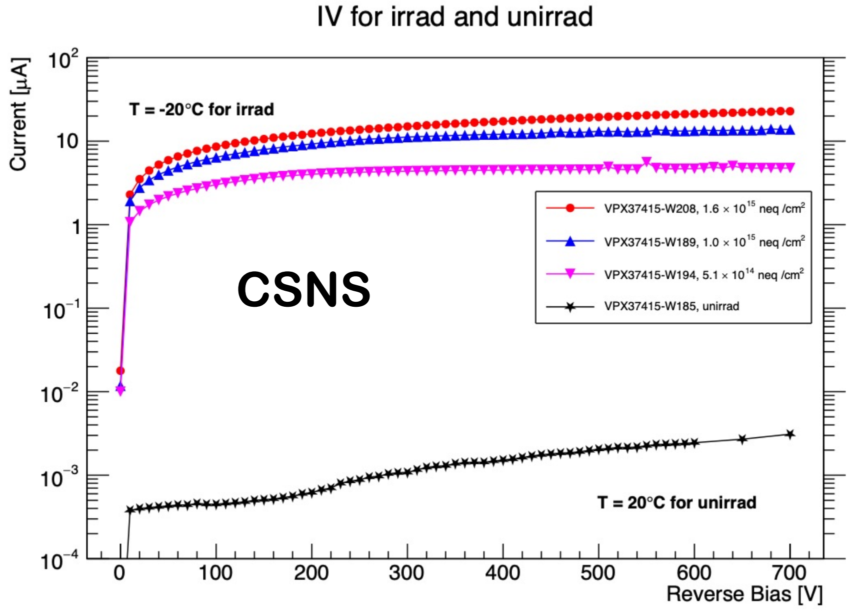
[1] Moll M . Radiation damage in silicon particle detectors: microscopic defects and macroscopic properties[J]. Dec, 1999.

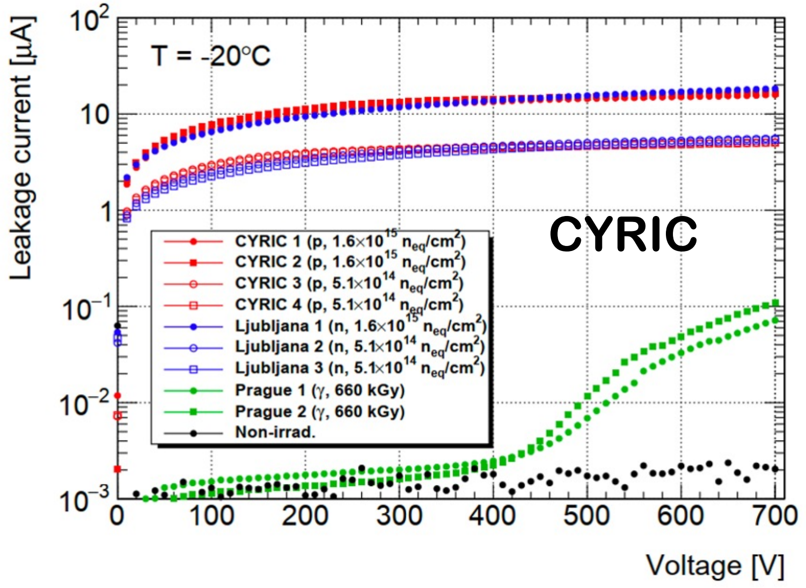
Back up (IV test)



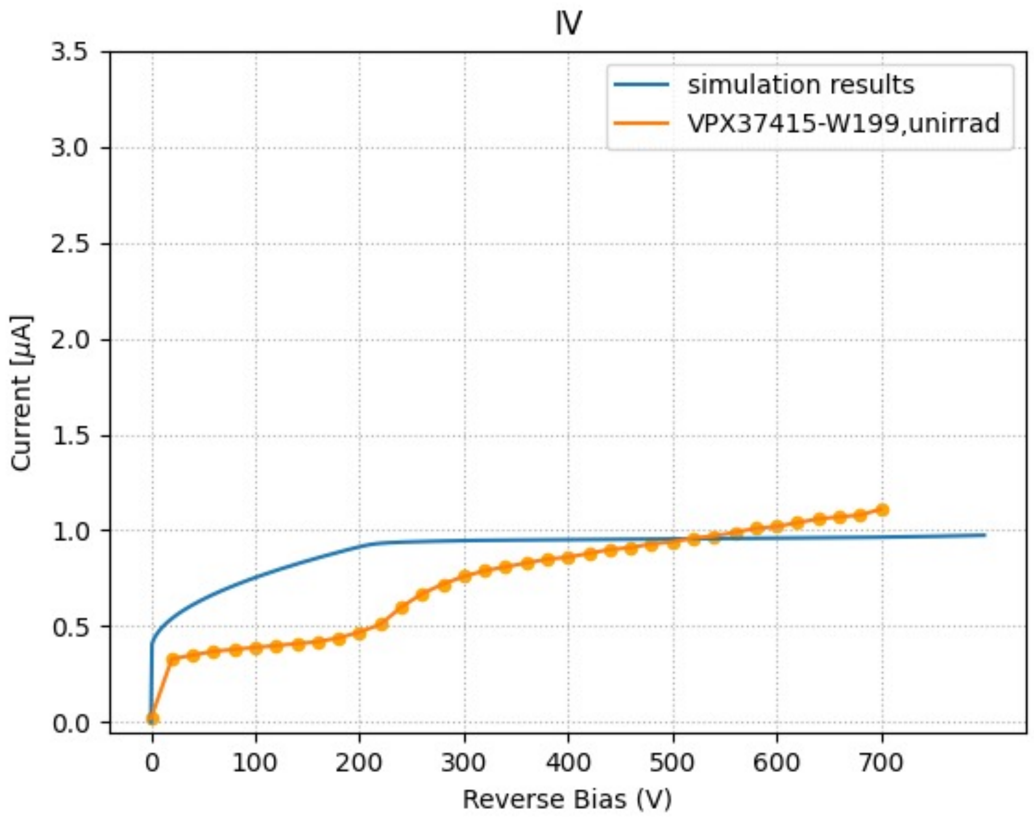


IV for MD8 after annealing, 1.6×10^{15} neq/cm^2.





Back up (IV test)



$$I_{DIFF} = I_0(e^{qV_A/kT} - 1)$$ → Shockley equation

$$I_0 = qA(\frac{D_N}{L_N}\frac{n_i^2}{N_A} + \frac{D_P}{L_P}\frac{n_i^2}{N_D})$$

$$D_N = \mu_n\frac{kT}{q}, D_P = \mu_p\frac{kT}{q}$$

$$L_N = \sqrt{D_N\tau_n}, L_P = \sqrt{D_P\tau_p}$$

$$I_{R-G} = -\frac{qAn_i}{2\tau_0}W$$ → Recombination-Generation current

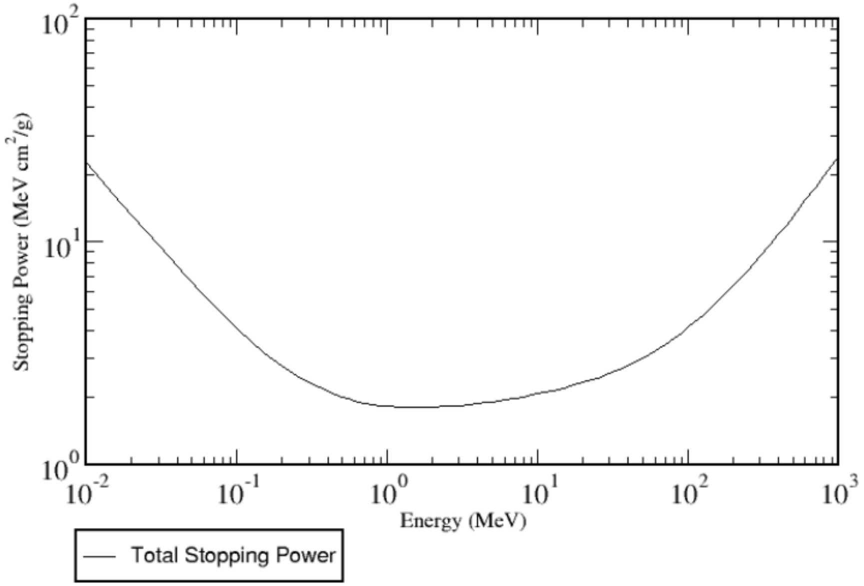
$$\tau_0 = \frac{1}{2}(\tau_p\frac{n_1}{n_i} + \tau_n\frac{p_1}{n_i})$$

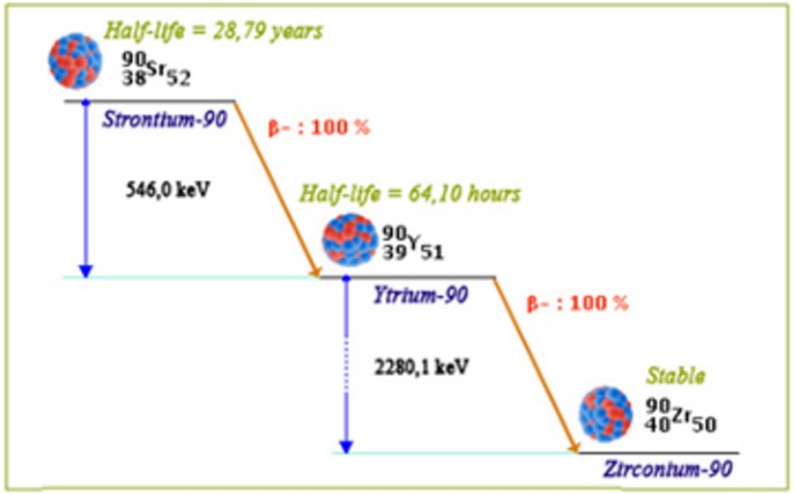
$$W = [\frac{2K_s\varepsilon_0}{q}(\frac{N_A + N_D}{N_AN_D})(V_{bi} - V_A)]^{\frac{1}{2}}$$

$$V_{bi} = \frac{kT}{q}ln(\frac{N_AN_D}{n_i^2})$$

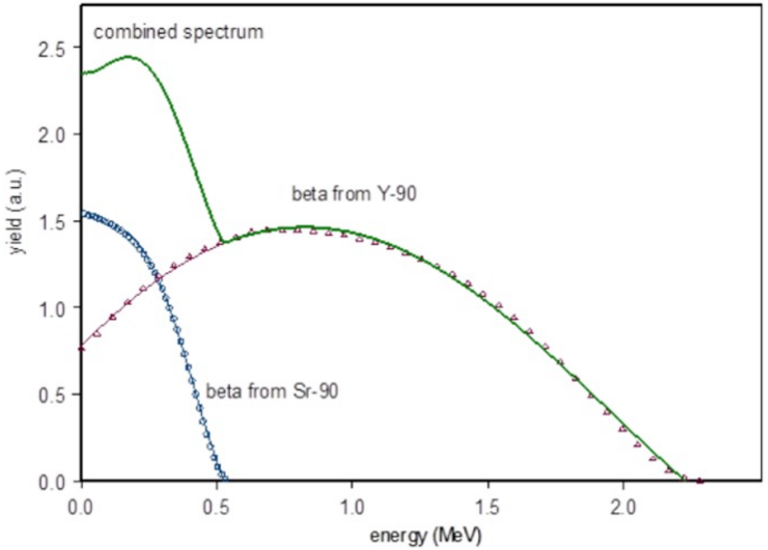
$$I = I_{DIFF} + I_{R-G}$$ → Theory total current

Back up (CCE test)



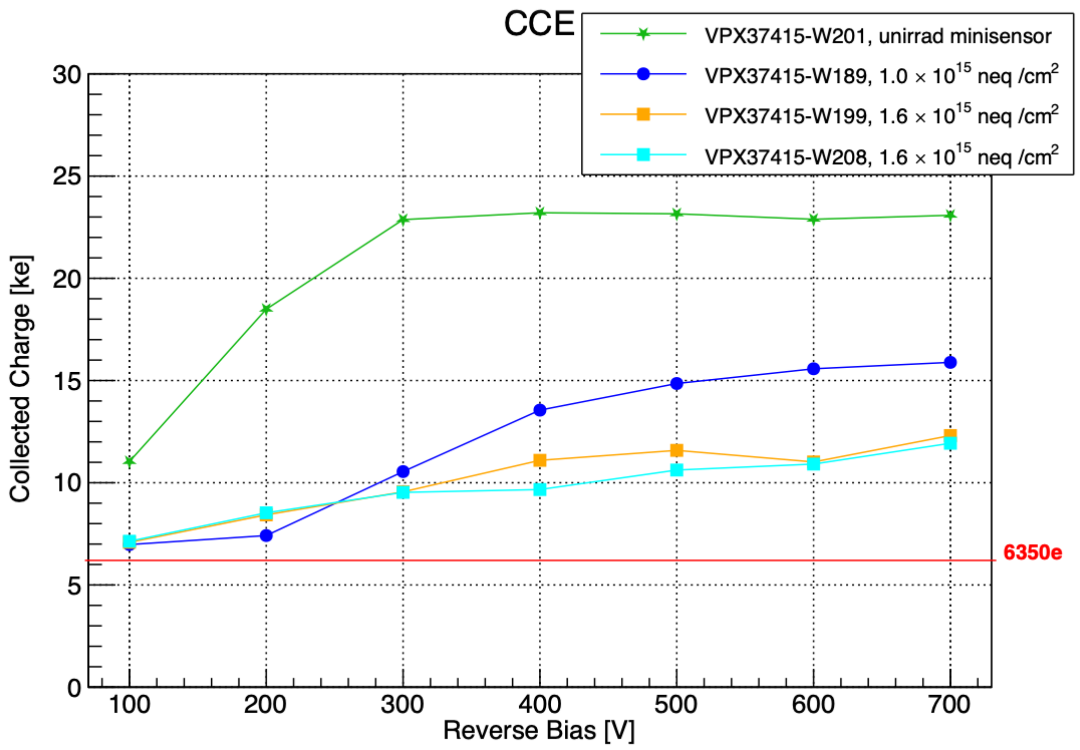


If a particle has βγ around 4, its ionization energy loss in the material (dE/dx) is minimal, we call it a minimum ionization particle (MIP). Generally, particles with βγ between 1 and 10 are considered to be MIPs.

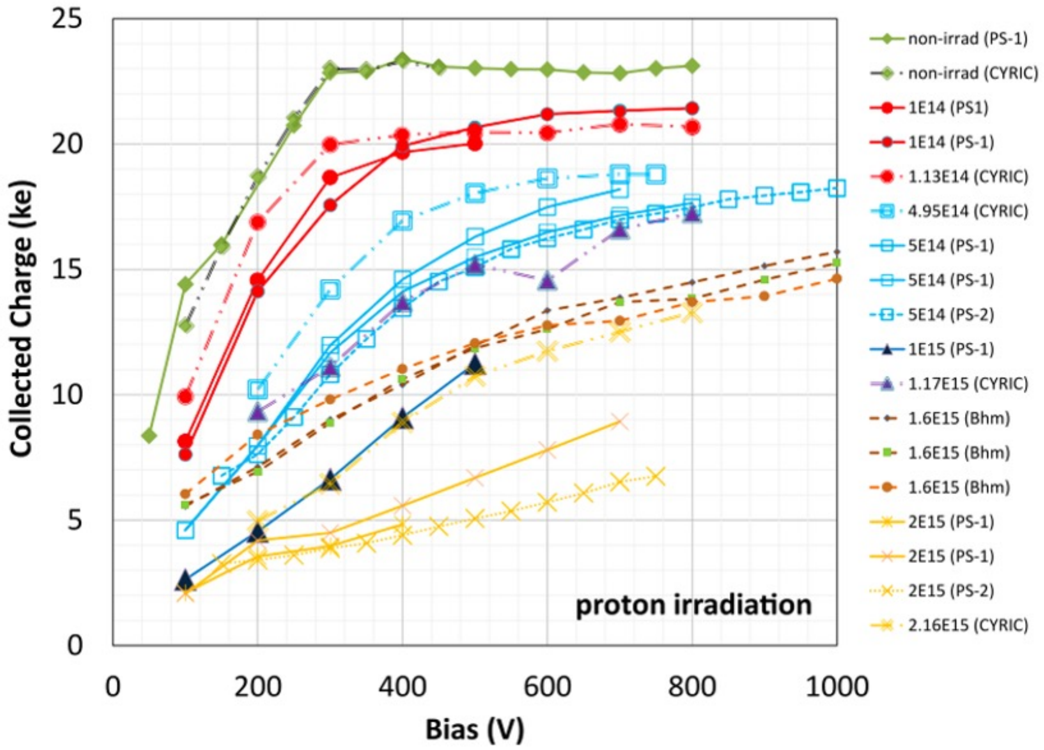


The average energy of the electrons emitted by 90Sr and the daughter nucleus 90Y is about 0.7 MeV, corresponding to βγ ~ 2.15.

Back up (CCE test)



CSNS with 80 MeV proton beam



compare with other sites,
Birmingham (MC40 27MeV-37MeV),
CYRIC with 70MeV proton beam