Study of bulk damage of high gamma-irradiated n^+-in-p silicon diodes

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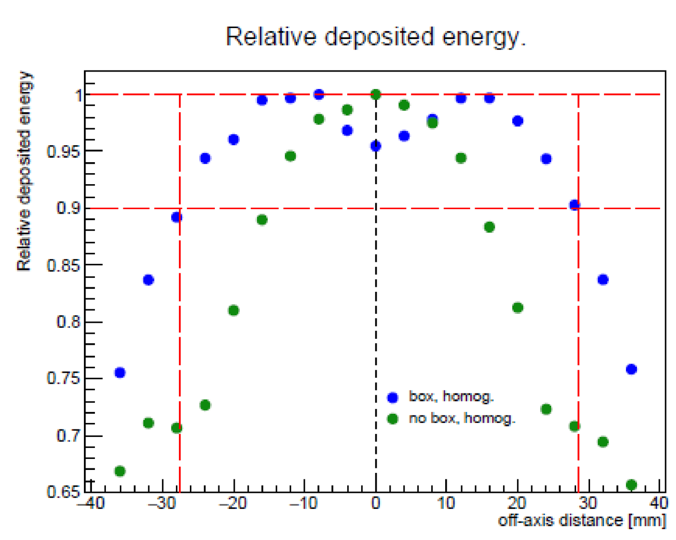
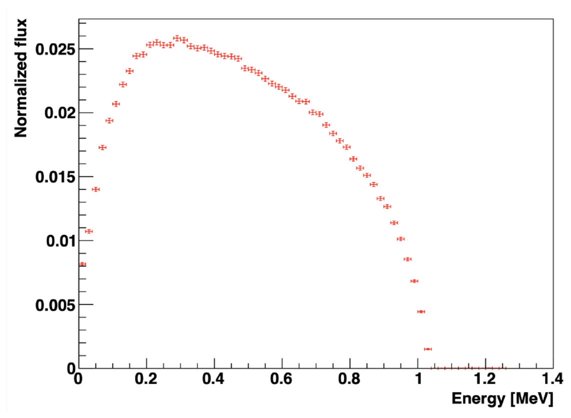
Introduction

- Presented study was performed to quantitatively evaluate bulk damage in Si n^+-in-p high resistivity sensors when exposed to γ- radiation reaching total ionizing doses (TID) up to 8.3 MGy.
- Main goal of study:
  - Characterization of γ-radiation induced displacement damage by measuring IV and CV, as well as evolution of full depletion voltage (V_{FD}) with TID,
  - Determination of relation between 1 MeV n_{eq}/cm^2 and TID delivered by γ-radiation,
  - Extraction of electric field distribution and verification of V_{FD} by Transient Current Technique [1].

Irradiation

- Diodes irradiated by ^{60}Co γ-source in CPE box according to ESA/SCC Basic Spec. No. 22900 [2]
  - CPE box minimizes dose enhancement from scattered low-energy particles and ensures uniform distribution of deposited energy
  - Dose rate 160-190 Gy/min in silicon (5% uncertainity)
- Displacement damage during ^{60}Co γ-irradiation is primarily caused by Compton electrons having a maximum energy of 1.2 MeV
- Cluster production not possible – min. electron energy needed for clusters ~8 MeV → damage exclusively due to point defects
- Max. recoil energy for primary knock-on Si-atom by Compton electron ≈ 140 eV
- Min. electron energy needed for single displacements for V-I (Frenkel pair) 260 keV





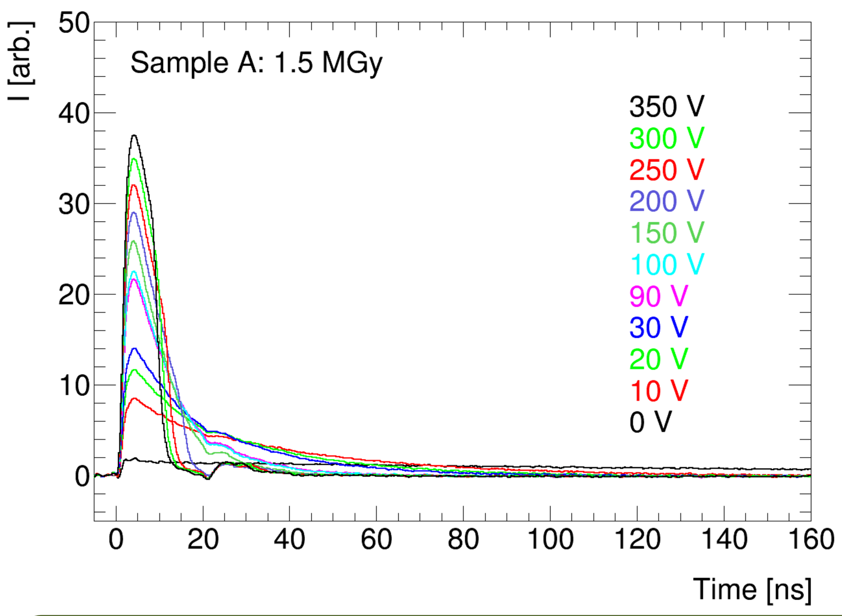
Spectrum of secondary electrons created by ^{60}Co fotons in CPE box

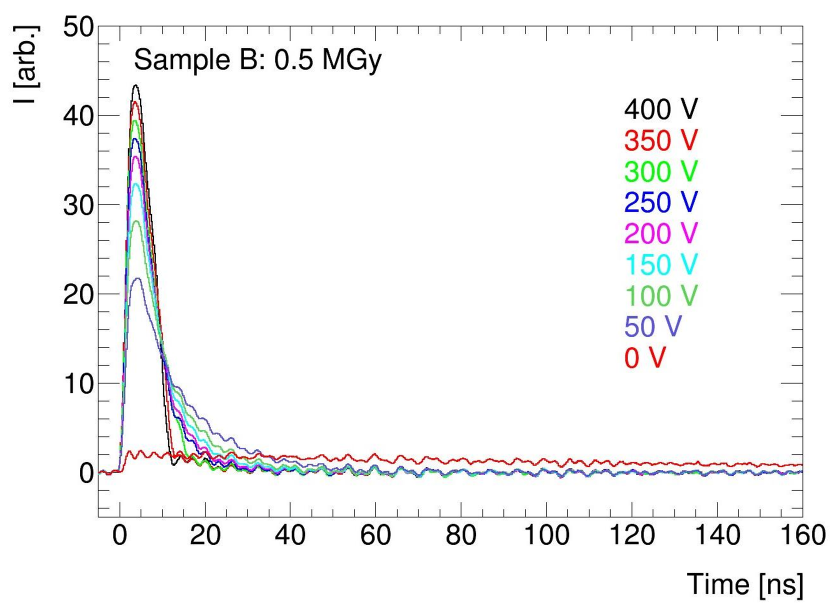
SIMS

- **S**econdary **I**on **M**ass **S**pectrometry technique was used to determine relative concentration of oxygen in individual samples to a maximum depth of 14 μm. Cs ions with energy of 7 keV were employed as primary source.
- **Results:**
  - Concentration of oxygen decreases with increasing depth of diode.
  - Decrease in oxygen concentration is least pronounced in sample C and most significant in sample A.
  - At depth of 14 μm, sample C has the highest oxygen concentration, while sample A has the lowest.

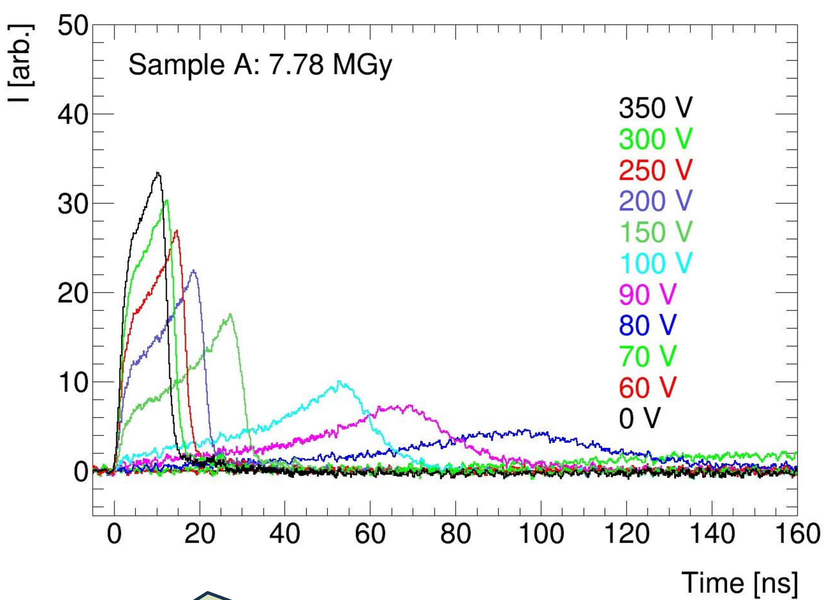
TCT

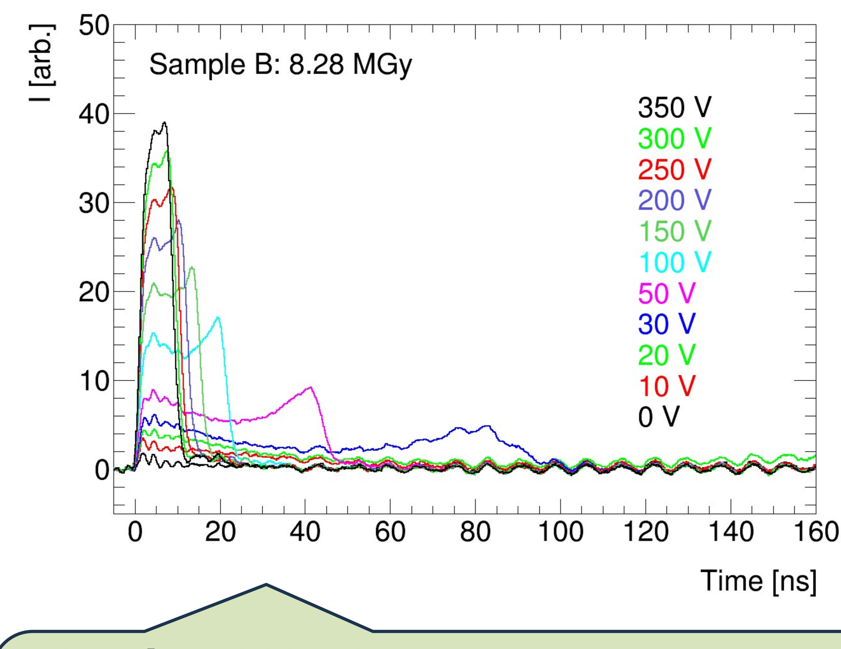
- Transient Current Technique (TCT) [1] was used to verify V_{FD} values obtained from CV, and to extract electric field distribution and the sign of space charge N_{eff} of silicon diodes irradiated to the lowest and the highest TID
- Diodes were illuminated from n+ side by red laser (660 nm)





Samples A (1.5 Mgy) and B (0.5 Mgy)
- High E-field on n^+ side, falling towards p^+ side ➔ diodes n^+-in-p type after low TIDs
- V_{FD} : 250 V – 300 V





Sample A: 7.78 MGy
- Gamma inverted bulk from p-type to n-type
- p-n junction is on the back side
- No signal to 60 V => V_{FD} ~ 70 V

Sample B: 8.28 MGy
- Shape of the pulses indicates the double junction with high field regions on both diode sides
- n-type but space charge concentration low
- V_{FD} between 30 V – 40 V

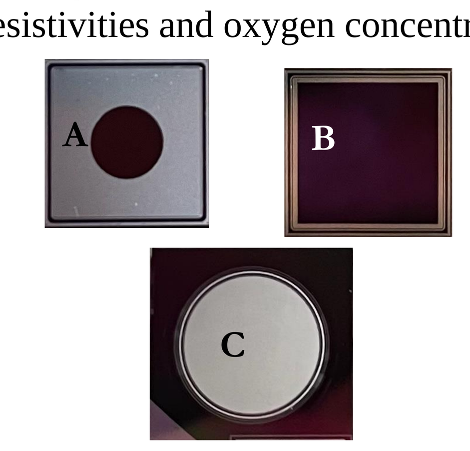
Conclusions

- Bulk current of gamma irradiated high resistivity p-type silicon diodes increases linearly with TID, and damage coefficient depends on initial resistivity and/or oxygen concentration of silicon diode.
- Effective doping concentration, and therefore also V_{FD}, significantly decreases with increasing TID, before it starts to increase again at a specific TID. Observed behavior indicates silicon bulk type inversion.
- Diode with higher initial resistivity, i.e. with lower or compensated boron doping, reaches minimum value of V_{FD} at lower TID.
- We assume that initial decrease of effective doping concentration is caused by effect of acceptor removal.
- TCT measurements confirmed type inversion in both measured diodes irradiated to high TIDs.
- IV and CV measurements of gamma irradiated diodes did not reveal any annealing effect.

Samples

- Study was carried out on three types of n^+-in-p standard float zone diodes produced by three different manufacturers
- Diodes with comparable active areas and thicknesses but different silicon bulk resistivities and oxygen concentrations

	A	B	C
Active Thickness d [μm]	285	290	285
Active area A [mm²]	49.95	51.55	50.17
Active Volume V [cm³]	0.0142	0.0149	0.0143
Bulk Capacitance C_{bulk} [pF]	18.79	19.48	19.88
Full Depletion Voltage V_{FD} [V]	283.6 ± 12.0	273.4 ± 10.7	36.9 ± 8.3
Bulk Resistivity ρ [kΩ.cm]	3.1 ± 0.1	3.3 ± 0.1	24.0 ± 4.0
Wafer Oxygen Concentration	1.5×10^{16} - 6.5×10^{17}		NA

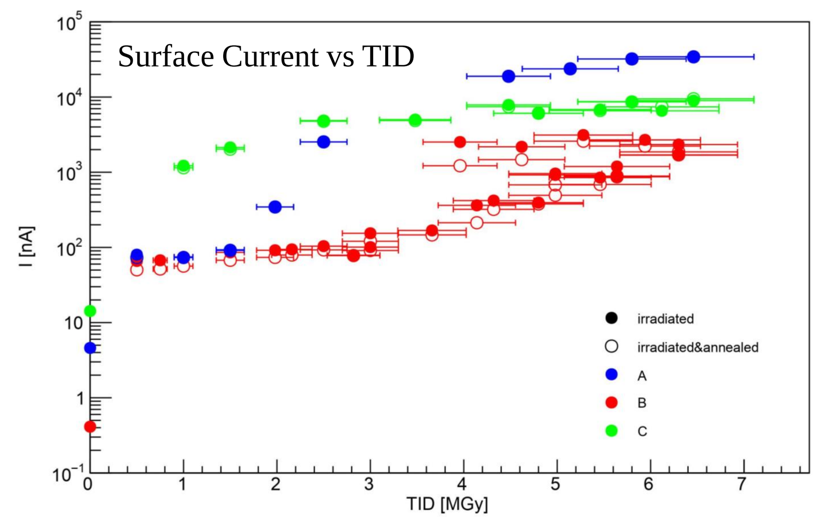


Leakage Current after Gamma Irradiation

- Great care taken to properly determine leakage current contributing only to active volume of diode (I_{bulk}) by subtracting parasitic currents contributed by diode surface (I_{sur}):

$$I_{tot} = I_{bulk} + I_{sur}$$

Sample	α_γ [A·cm^{-3} MGy^{-1}]	ρ [kΩ·cm]
A	$(6.33 \pm 0.08)\cdot 10^{-6}$	3.1 ± 0.1
B	$(6.49 \pm 0.09)\cdot 10^{-6}$	3.3 ± 0.1
C	$(10.20 \pm 0.30)\cdot 10^{-6}$	24.0 ± 4.0



n-3.MGy-
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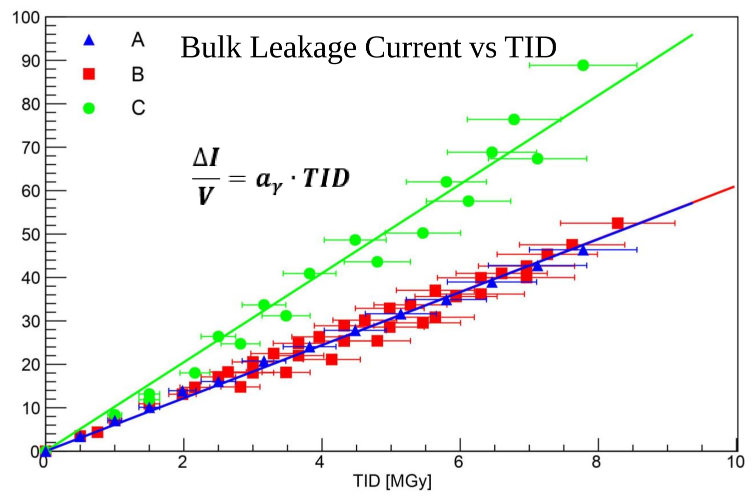
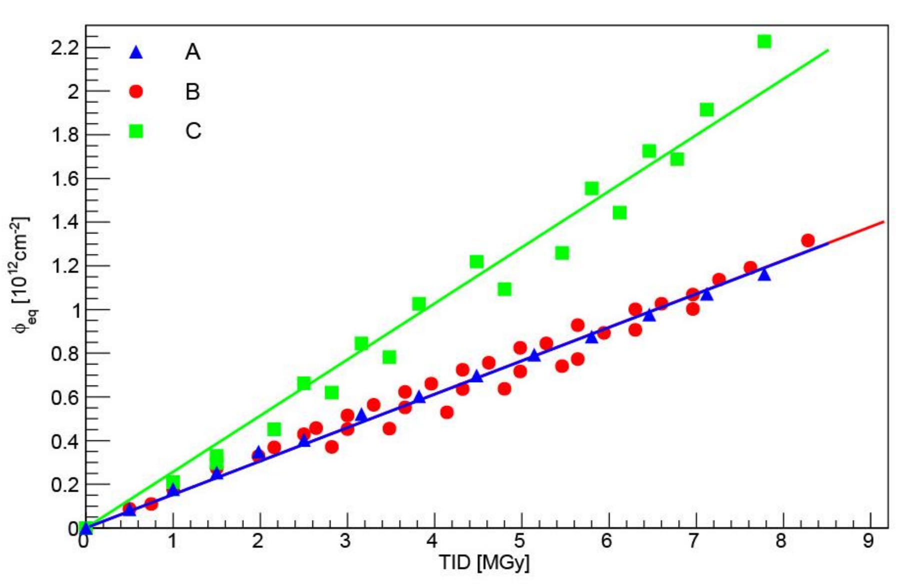


- Surface current of all diodes increases rapidly already for initial TID, after which it rises only gradually [4]
- Bulk current at V_{FD} normalized to active volume of diode increases linearly with increasing TID
- Diodes with similar ρ and V_{FD} show equivalent radiation damage

Relation between 1 MeV n_{eq}/cm^2 and TID Delivered by Gamma Irradiation

Assuming linear increase of the radiation-induced leakage current with TID is caused by a displacement damage, conversion factor k between TID [MGy] and delivered fluence ϕ_{eq} [n_{eq}/cm^2] can be estimated as:



$$TID\,[MGy] = k \cdot \phi_{eq}[n_{eq}/cm^2]$$

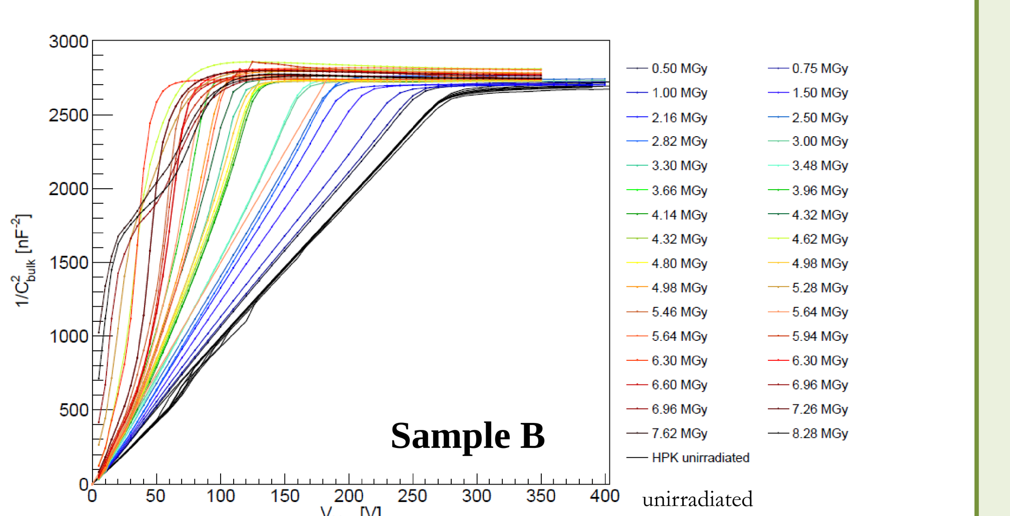
$$\phi_{eq} = \frac{\Delta I}{V}\frac{1}{\alpha}$$

with $\alpha = 3.99 \times 10^{-17}$ A/cm [5], V is active volume of diode.

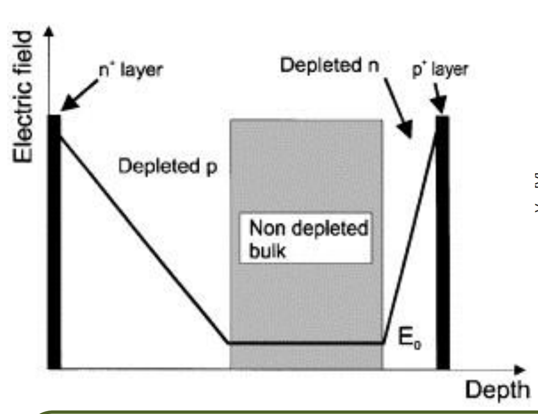
Determined relation between TID of 1 MGy and 1 MeV equivalent fluence ϕ_{eq} is :
- 1 MGy = 2.6×10^{11} 1 MeV n_{eq}/cm^2 for diode C (ρ ≈ 24 kΩ・cm)
- 1 MGy = 1.6×10^{11} 1 MeV n_{eq}/cm^2 for diodes A and B (ρ ≈ 3 kΩ・cm)

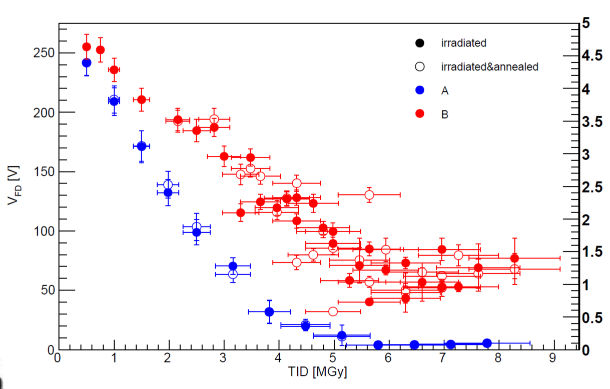
CV Characteristics and Full Depletion Voltage

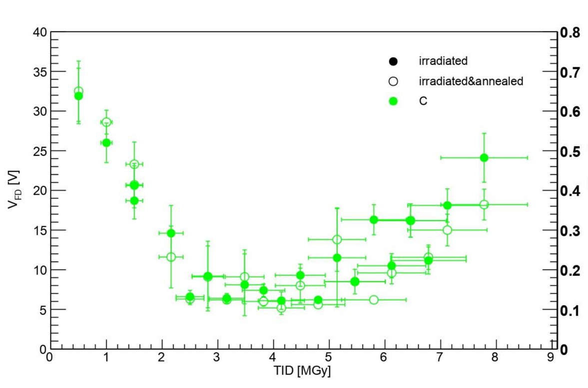
- CV characteristics at different TIDs (unirradiated in black) [6]
- V_{FD} decreases significantly with increasing TID
- V_{FD} (@ 0.5MGy) = 255 V (in agreement with TCT results)
- V_{FD} (@ 8.28MGy) = 25 V or 70 V (determination of VFD is complicated by presence of two bumps in CV characteristics - presence of double junction)



V_{FD} estimated from CV [1]







Qualitative electric field distribution in an irradiated silicon with double junction [7].

Effective doping concentration significantly decreases with increasing TID, before it starts increasing at a specific TID value.

References

[1] G. Kramberger et al., NIM A476 (2002) 645
[2] European Space Agency, ESCC Basic Specification No. 22900 (2003)
[3] UJP PRAHA a.s. , https://ujp.cz/en/
[4] M. Mikestikova et al., NIMA, In Press doi.org/10.1016/j.nima.2024.169432
[5] Moll M., IEEE Trans. Nucl. Sci. Vol. 65, N. 8 (2018) 1561-1582
[6] I. Zatocilova et al., JINST 19 (2024) 02, C02039
[7] Z. Li, H.W. Kraner, IEEE Trans. Nucl. Sci. Vol. 39 (1992) 577

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