Comparative analysis of proton and ion damages in Si detectors supplemented with SRIM simulations

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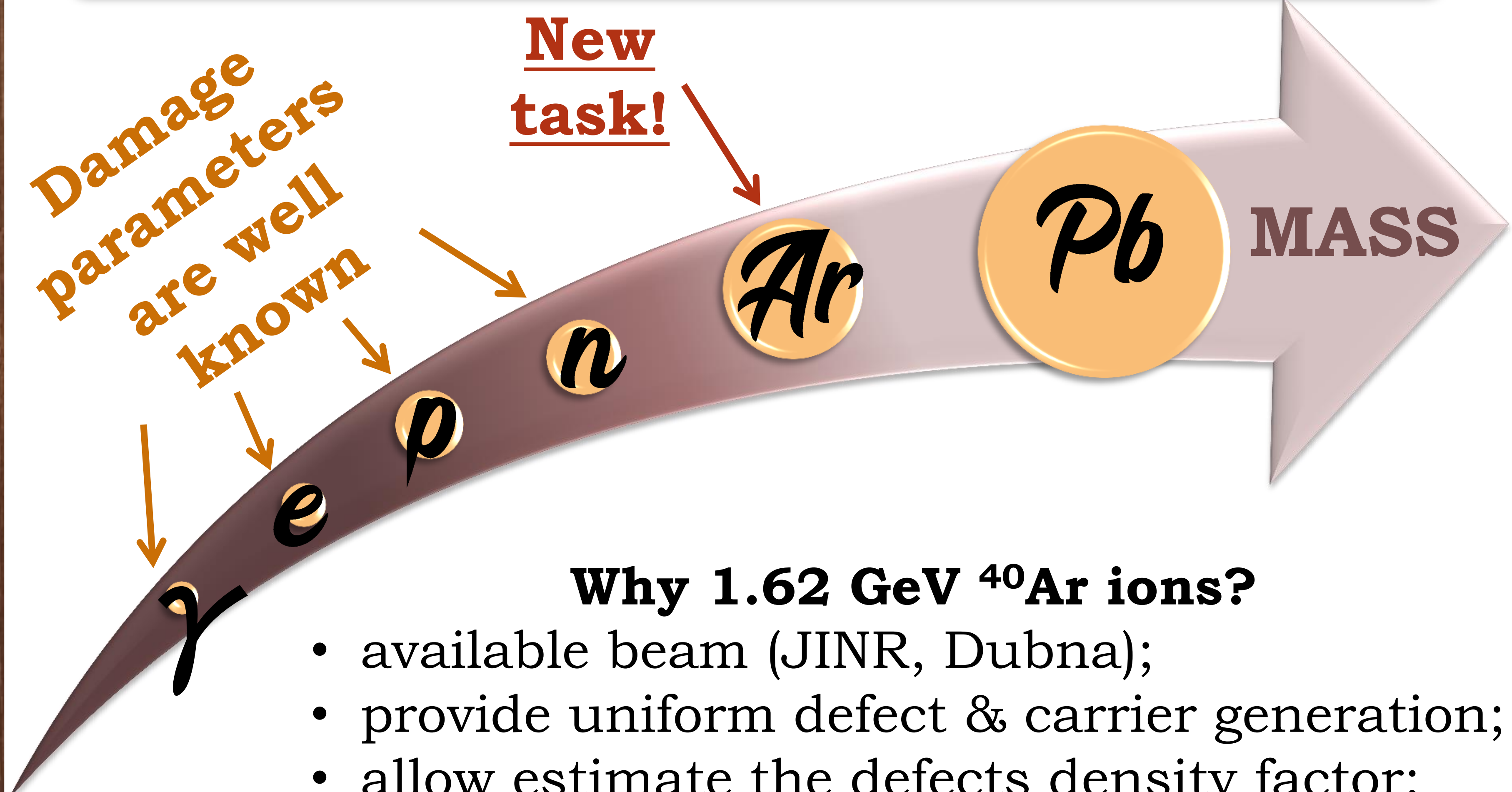
Motivation



Why 1.62 GeV ^{40}Ar ions?

- available beam (JINR, Dubna);
- provide uniform defect & carrier generation;
- allow estimate the defects density factor;
- higher defect density

Goal

- To find macroscopic parameters (from I-V, I-T, TCT)
- To find microscopic parameters (from DLTS)
- To compare obtained damage parameters with parameters for proton irradiation
- To add SRIM as a tool for microscopic damage study

Results partially published in:
V. Eremin, D. Mitina, et al., A comparative study of silicon detector degradation under irradiation by heavy ions and relativistic protons, 2018 *JINST* **13** P01019

Detectors

Structure:

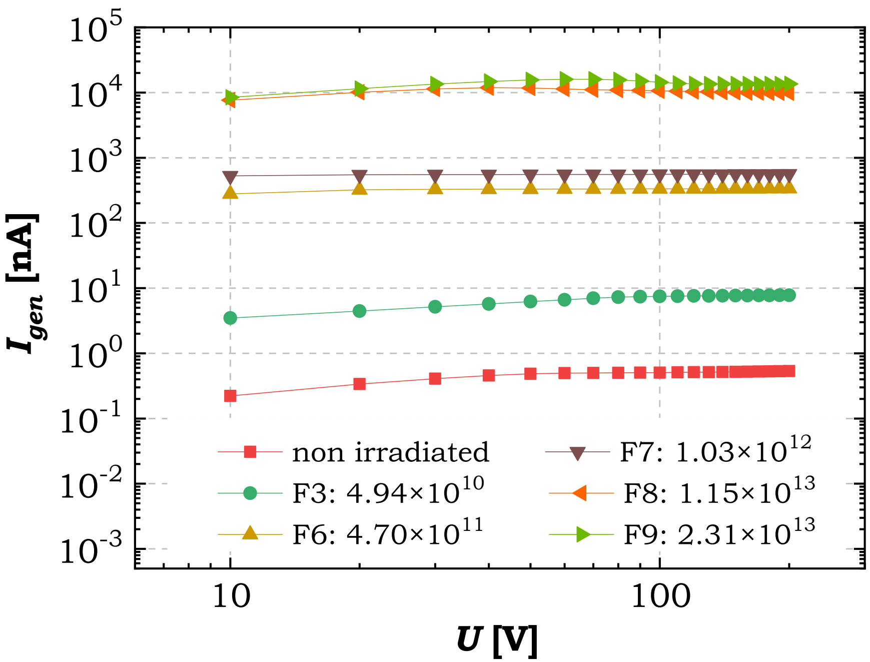
- *p*-on-*n* pad FZ detectors; *p*-*n* junction area: 25 mm^2
- thickness: 300 μm
- resistivity: 10 kΩcm and 50 Ωcm

Irradiation:

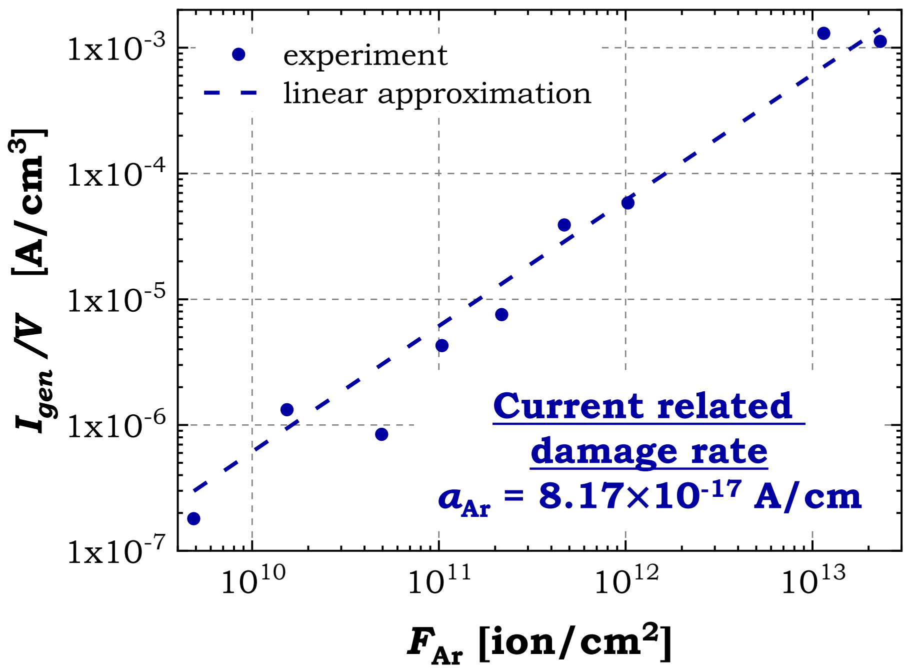
- JINR, Dubna, Russia
- 1.62 GeV ^{40}Ar ions (40.5 MeV/u)
- Beam intensity: 10^8 to 10^{10} ion/cm^2 per second
- Fluence: 5×10^{10}–2.3×10^{13} ion/cm^2

Bulk Generation Current

I-V characterization for high-resistivity detectors irradiated by ^{40}Ar ions



Fluence dependence of generation current



Temperature Dependences of I_{gen}

According to the **Shockley-Read-Hall** theory:

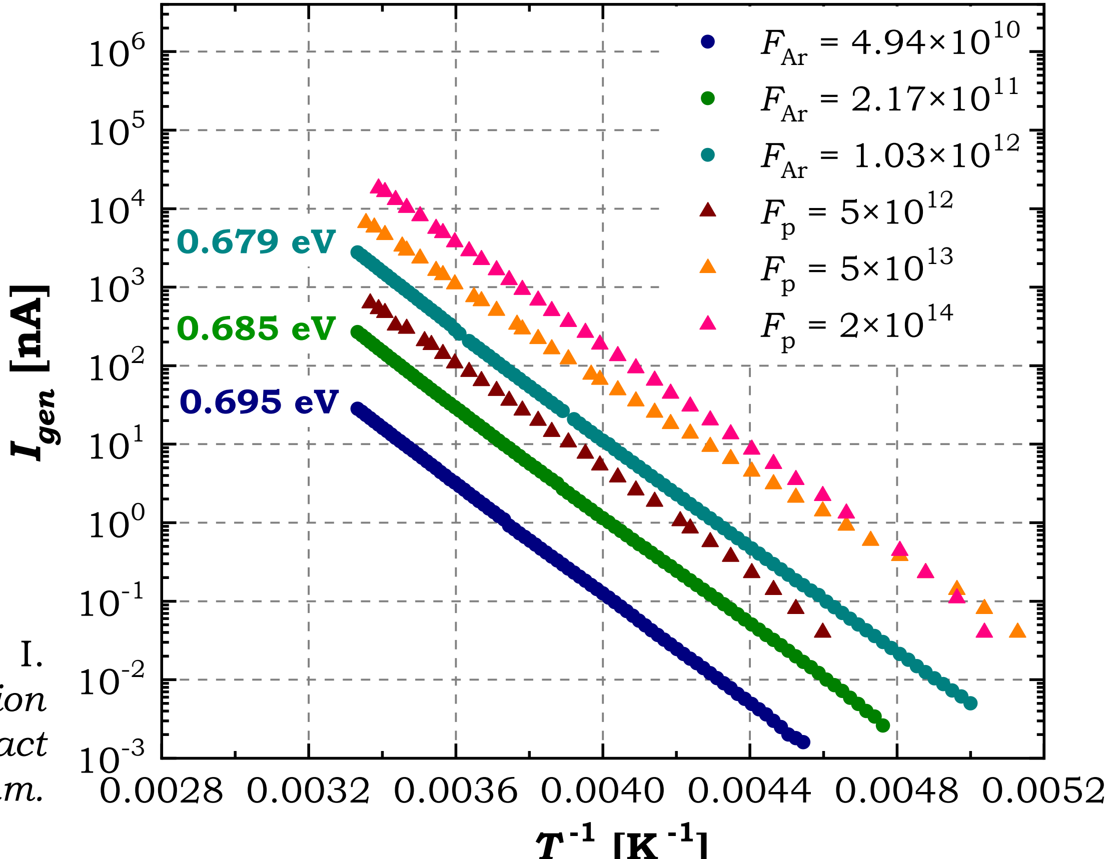
$$I_{gen} \approx \frac{\sigma_e \sigma_h N_t}{\sigma_e exp\left(-\frac{E_g - E_t}{k_B T}\right) + \sigma_h exp\left(-\frac{E_t}{k_B T}\right)}$$

Approximation was performed assuming that

$\sigma_e = \sigma_p = 8\times10^{-14}\ \mathrm{cm}^2$

Activation energies:

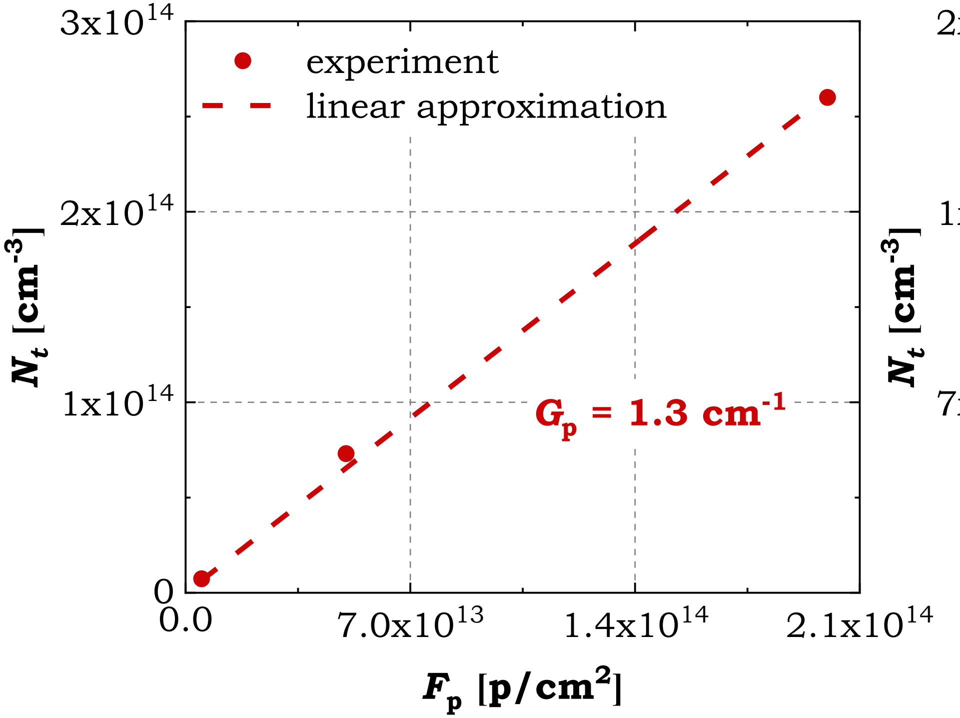
protons	^{40}Ar ions
0.65 eV	0.68 eV



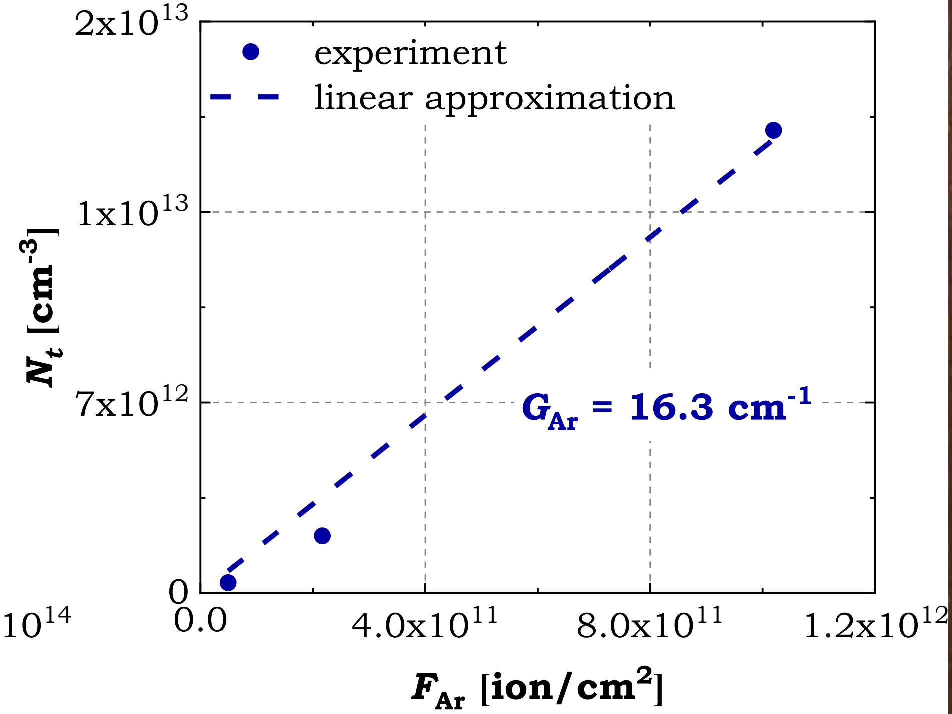
E. Verbitskaya, V. Eremin, I. Ilyashenko and Z. Li, *Carrier generation in irradiated Si detectors and its impact on the electric field profile*, *Nucl. Instrum. Meth.* **A 754** (2014) 63

Introduction Rates

protons



^{40}Ar ions



E. Verbitskaya, V. Eremin, I. Ilyashenko and Z. Li, *Carrier generation in irradiated Si detectors and its impact on the electric field profile*, *Nucl. Instrum. Meth.* **A 754** (2014) 63

TCT Data

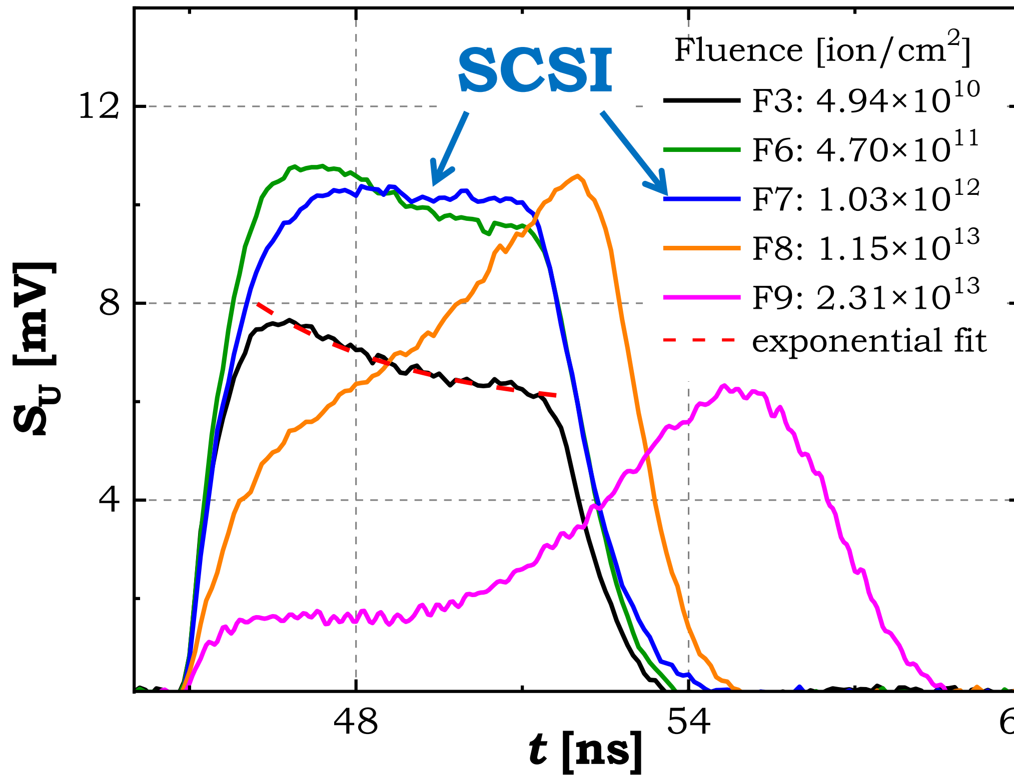
Current response, generated by electrons:

$$i(t,T) = \frac{Q_0}{d}\mu(T)E_0\,exp\left(-\frac{t}{\tau_{dr}}\right)$$

$$\tau_{dr} = \frac{\varepsilon\varepsilon_0}{\varepsilon\mu(T)N_{eff}}$$

Last equation allows one to calculate N_{eff} at a fixed mobility via approximation of the experimental current pulse top by an exponential function.

Pulse shapes of detectors irradiated by ^{40}Ar ions



Effective Concentration

Hamburg model:

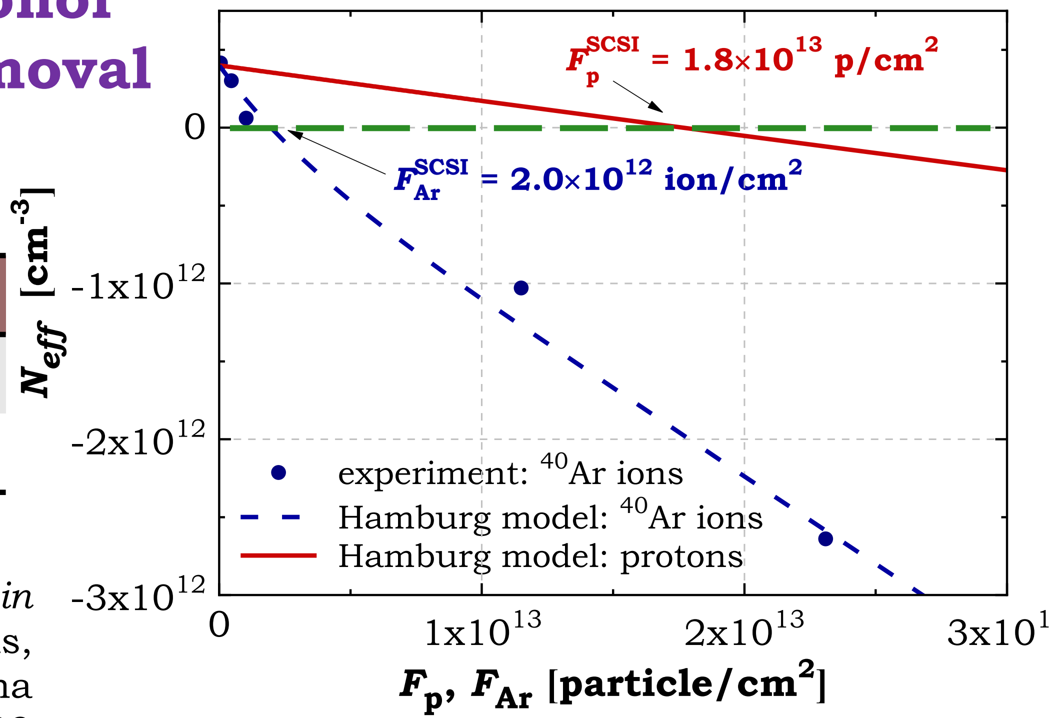
$$N_{eff}(F) = N_0 e^{-cF} - \beta F$$

acceptor introduction — **donor removal**

Approximation results:

	^{40}Ar	p
c [cm^2]	3×10^{-13}	1×10^{-14}
β [cm^{-1}]	0.11	0.019

Effective concentration dependences on fluence



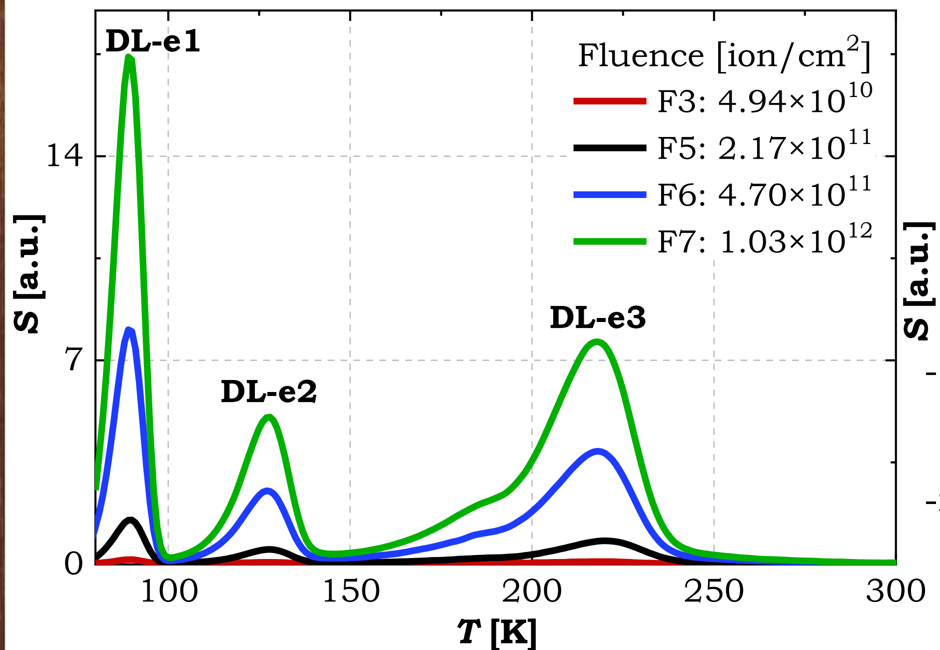
G. Kramberger, *Signal development in irradiated silicon detectors*, Ph.D. Thesis, University of Ljubljana, Ljubljana Slovenia (2001), CERN-THESIS-2001-038

Deep Level Transient Spectroscopy

DLTS spectra for 50 Ωcm irradiated detectors

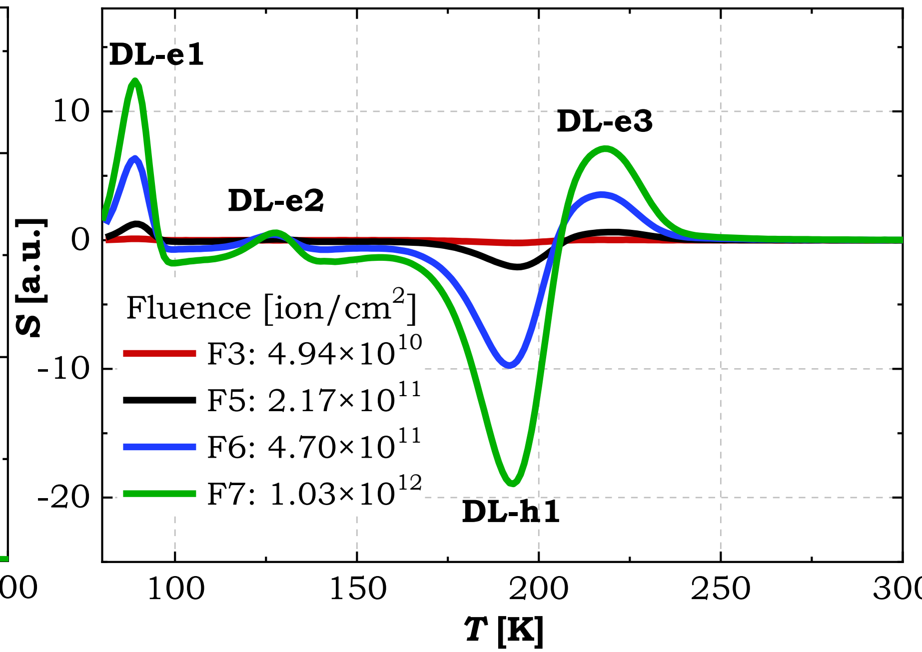
Neutrality + Emission

U_e = 20 V t_e = 50 ms
U_f = 0 t_p = 5 ms



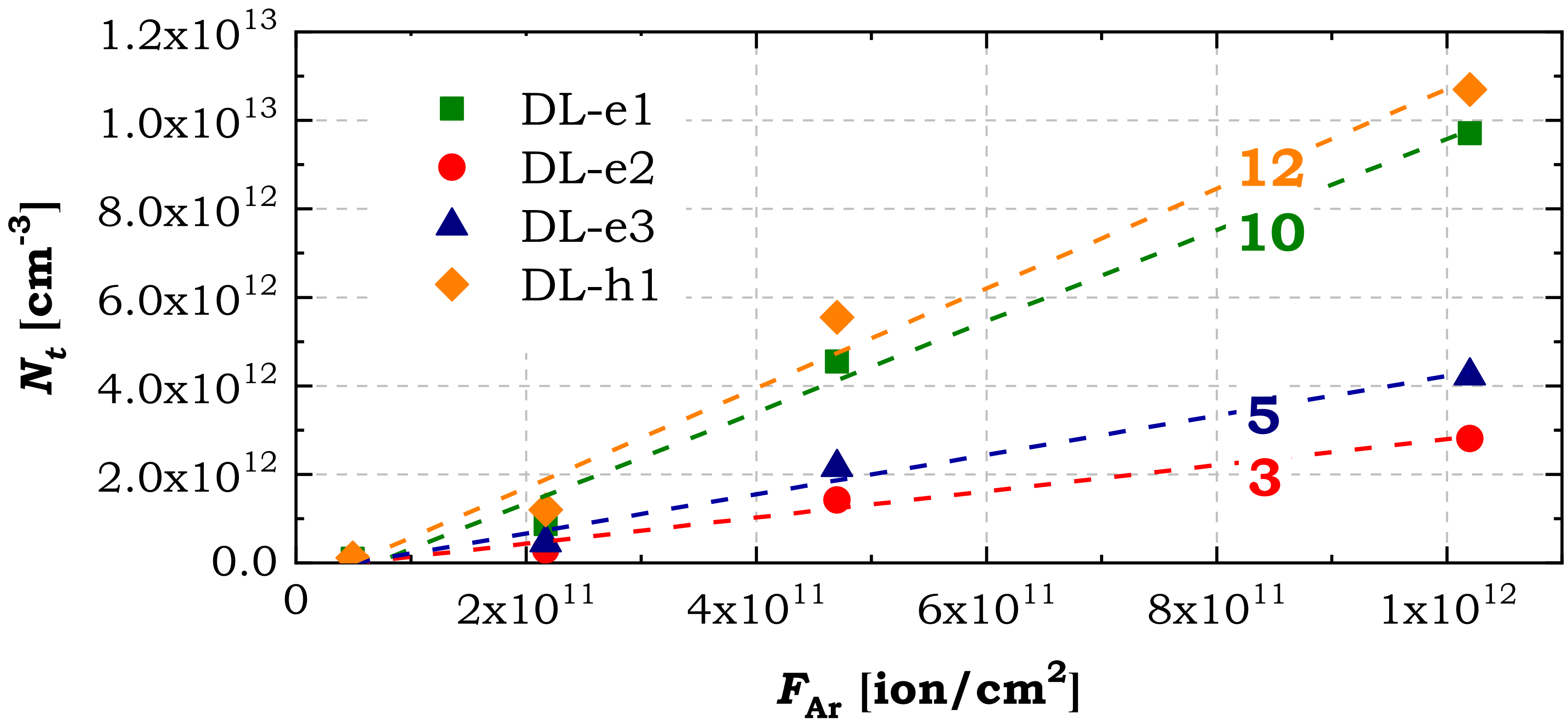
Injection + Emission

U_e = 20 V t_e = 50 ms
U_f = -10 V t_p = 5 ms



Trap Parameters

	DL-e1	DL-e2	DL-e3	DL-h1
E_t [eV]	0.168	0.240	0.415	0.366
σ_t [cm^2]	4.28×10^{-15}	3.31×10^{-15}	1.74×10^{-15}	1.18×10^{-15}



Trap Structure

A comparison of the introduction rates and activation energies for protons and ^{40}Ar ions

	protons		**^{40}Ar ions**	
	g [cm^{-1}]	**$\langle E_t \rangle$ [eV]**	**g [cm^{-1}]**	**$\langle E_t \rangle$ [eV]**
DL-e1: *V-O*	0.73	0.176	10	0.168
DL-e2: VV^{--}	0.37	0.241	3	0.240
DL-e3: VV^{-}	0.37	0.410	5	0.415
DL-h1: C_i-O_i	1.30	0.320	12	0.366

I. Pintilie, *Investigation of radiation defects*, in proceedings of the *3rd MC-PAD Network Training Event on Radiation Hardness and Silicon processing and the Project Midterm Review*, Ljubljana, Slovenia, 26–30 September 2010.

Comparison

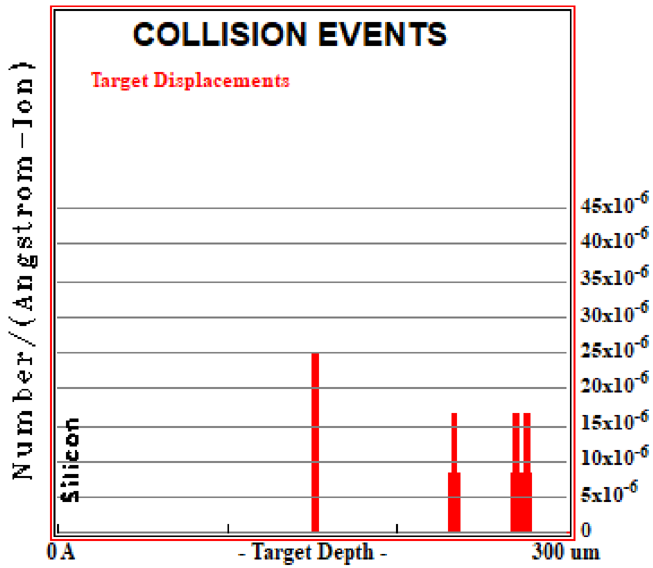
		protons	^{40}Ar ions	ratio
a [A/cm]		0.83×10^{-17}	8.17×10^{-17}	9.81
G [cm^{-1}]		1.3	16.3	12.5
F^{SCSI} [particle/cm^2]		1.8×10^{13}	2.0×10^{12}	9
g [cm^{-1}]	V-O	0.73	10	13.7
	VV^{--}	0.37	3	8.11
	VV^{-}	0.37	5	13.5
	C_i-O_i	1.30	12	9.23

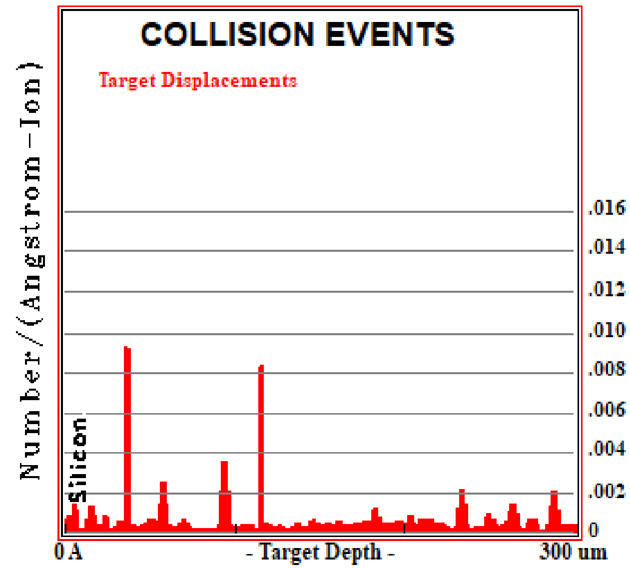
Scaling Coefficient ~ 11

SRIM simulation

	50 MeV protons	1.62 GeV ^{40}Ar ions
collisions	8	132
displacements	8	1725
vacancies	1	1594

collision events for 3 incident particles





Summary

- The activation energy of the bulk generation current in ^{40}Ar irradiated detectors is only 5% higher than the corresponding energy in the case of proton irradiation;
- The increase of ion fluence led to space charge sign inversion at $F \sim 1\times10^{12}$ ion/cm^2;
- DLTS-spectra demonstrated a set of deep levels which are typical of proton irradiation;
- The difference in effects on silicon detectors of hadrons and heavy ions can be scaled by the Scaling Coefficient parameter;
- SRIM simulation demonstrated that the divacancy production rate is significantly lower for ^{40}Ar irradiation than for protons.


Thank you
for attention!