Single Event Effects Hardness Assurance of Electronic Devices Using New and Existing Testing Facilities

Anatoly Smolin, Dmitry Bobrovsky, Sergei Soloviev, Anna Boruzdina and Alexander Chumakov

National Research Nuclear University MEPhI
(Moscow Engineering Physics Institute)

JSC “SPELS”

Outline

1. Qualification requirements for space applications
2. Single-Event Effects (SEE) testing using heavy ion accelerators
3. Combined use of heavy ion accelerators and lasers
4. New test facilities based on NICA accelerator complex
6. Conclusion

Single Event Effects

SEE (Single Event Effects) - destructive or non-destructive events in electronic devices caused by interaction of a single energetic particle with a sensitive region of the device.

Several types of particles can cause SEEs:

- <u>heavy ions</u> (GCR, SEP, α-particles from devices' materials)

- <u>protons</u> (GCR, SEP, Van-Allen belts)

- <u>neutrons</u> (secondary particles produced by cosmic rays)

Other particles (muons, high-energy electrons) can also cause SEEs in devices based on the most advanced semiconductor processes.

Defining qualification requirements

<u>To be qualified for space applications an electronic device has to meet some requirements.</u>

Requirements are mission dependent:

- Orbit
- Mission duration
- Shielding (location of the device inside the spacecraft)
- Acceptable risk level

Can be defined in form of acceptable probabilities or event rates for each type of SEEs relevant for the device.

The goal of SEE testing is to collect experimental data for calculation of probability or average rate of SEEs in the target environment.

Environment characterization

The ability of a particle to produce single event effects depends on ionizing energy loss of this particle in the sensitive region of the device.

Linear Energy Transfer (LET): $\mathrm{LET} = -\left(\frac{dE}{dx}\right)_{\mathrm{ion}} = \left[\frac{\mathrm{MeV}}{\mathrm{cm}}\right] \equiv$ Linear Stopping Power

$\mathrm{LET} = -\left(\frac{1}{\rho}\frac{dE}{dx}\right)_{\mathrm{ion}} = \left[\frac{\mathrm{MeV}\cdot\mathrm{cm}^2}{\mathrm{mg}}\right] \equiv$ Mass Stopping Power

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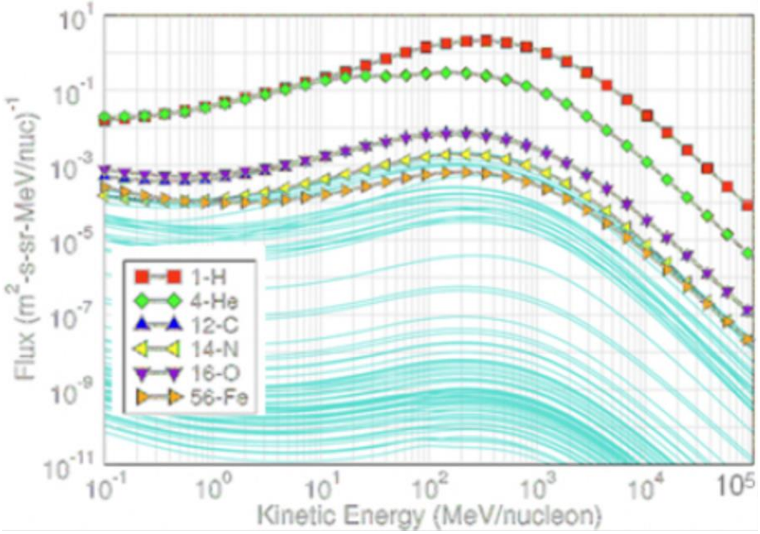
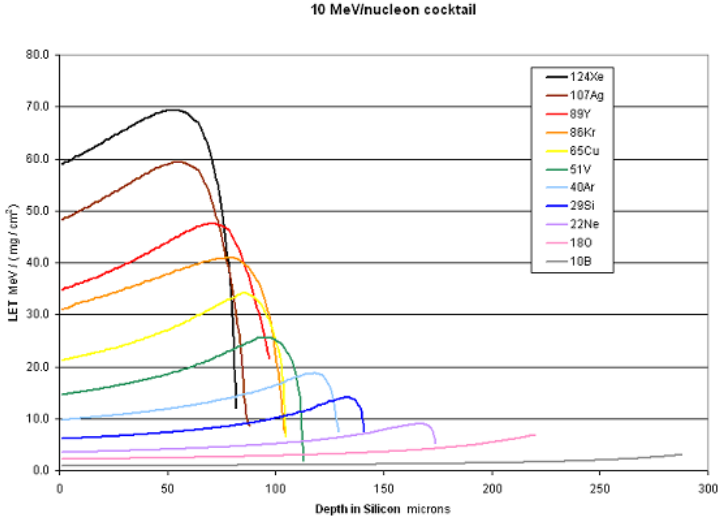
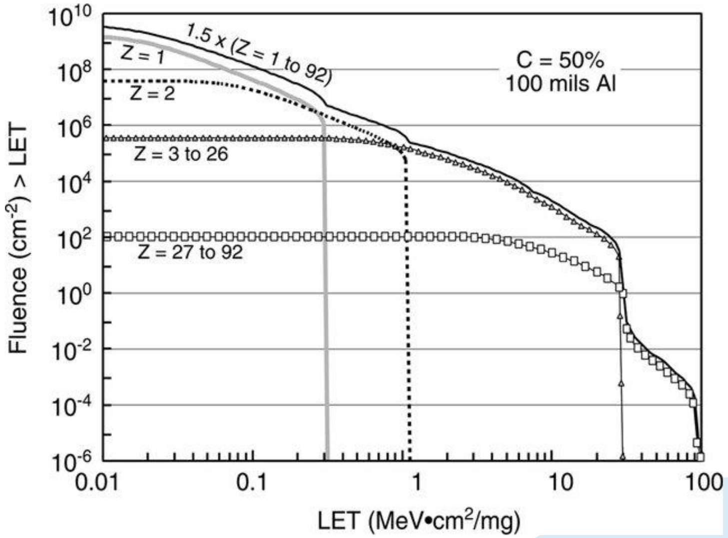
Each curve represents flux vs. energy for a different ion in the radiation environment.

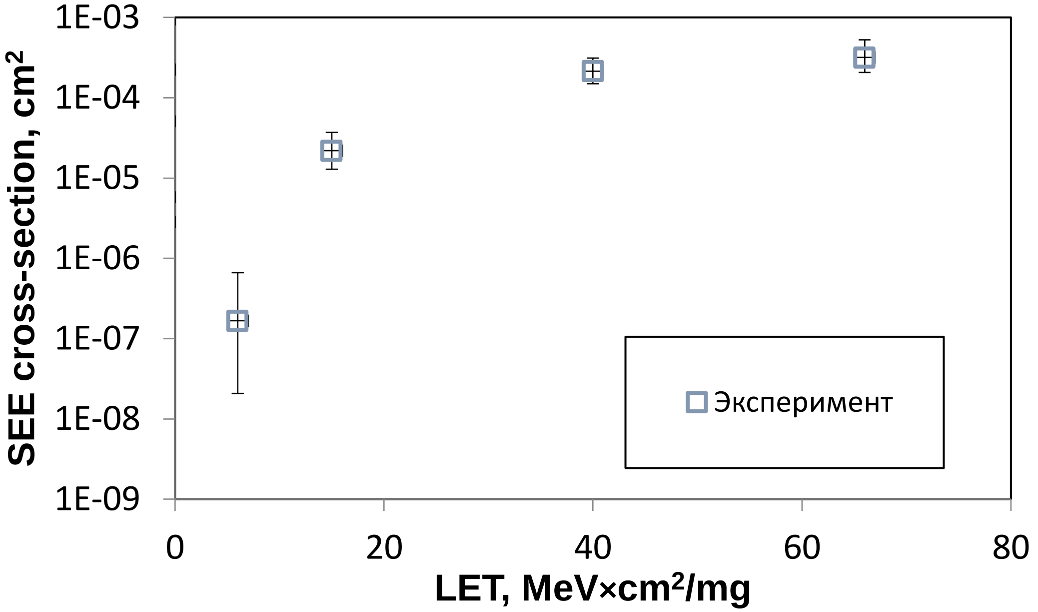






Single Event Rate (SER) calculation

Heavy ion testing used to obtain SEE cross-section dependence on LET.



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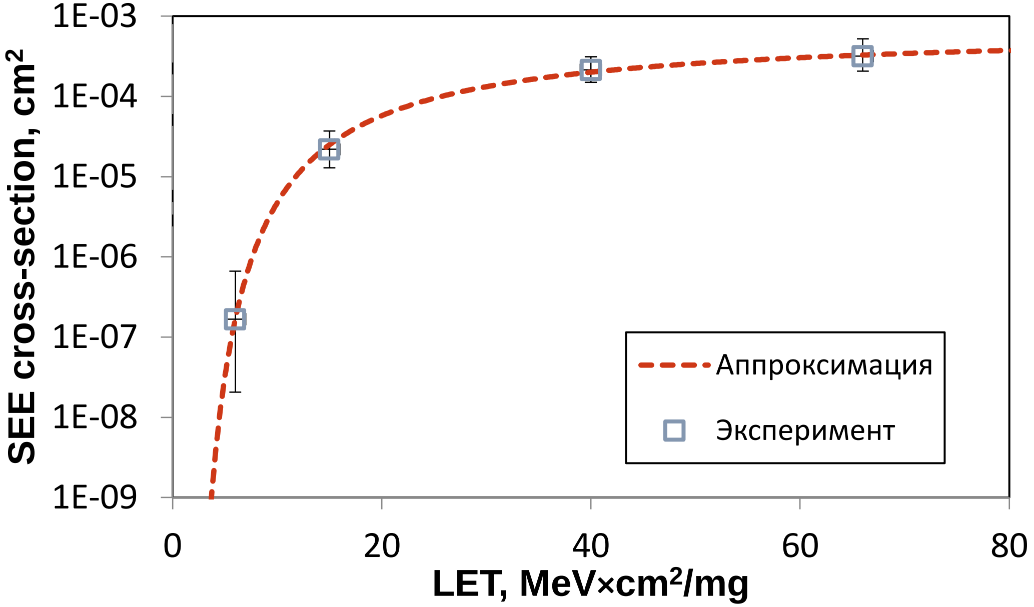

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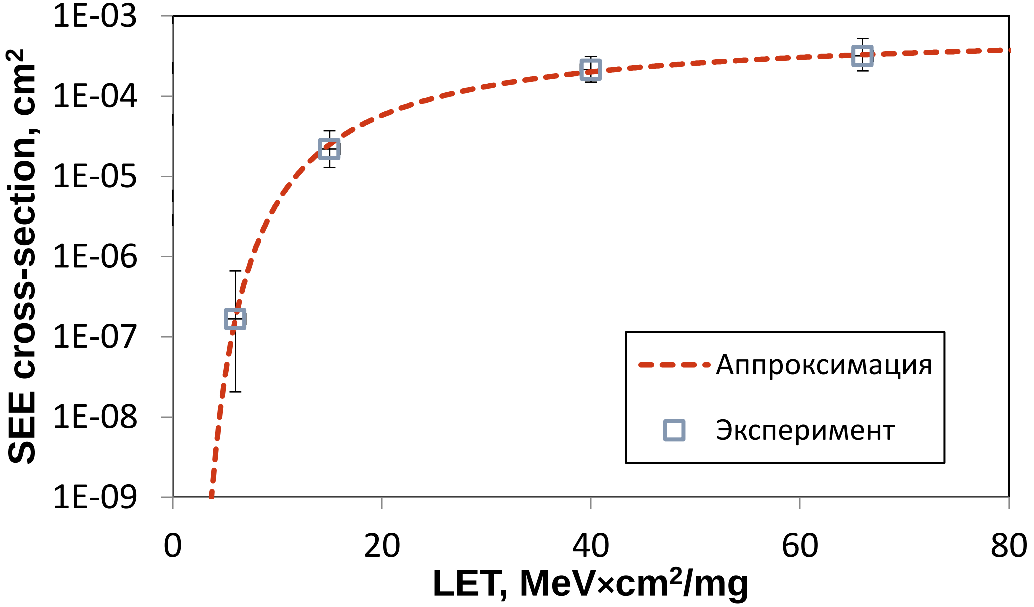
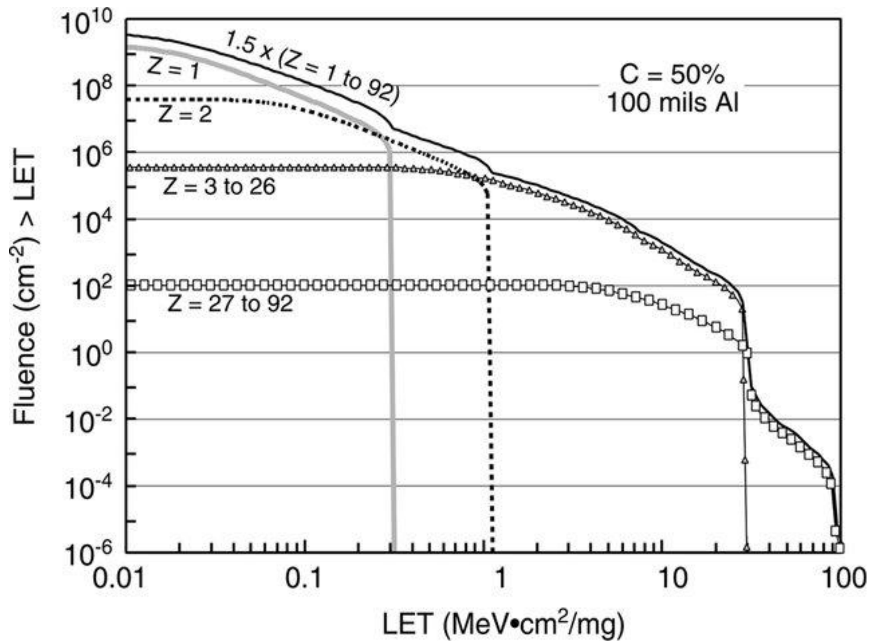


LET spectrum



$$SER = \int \sigma_{is}(LET) \cdot F(LET) \cdot \mathrm{d}\, LET$$

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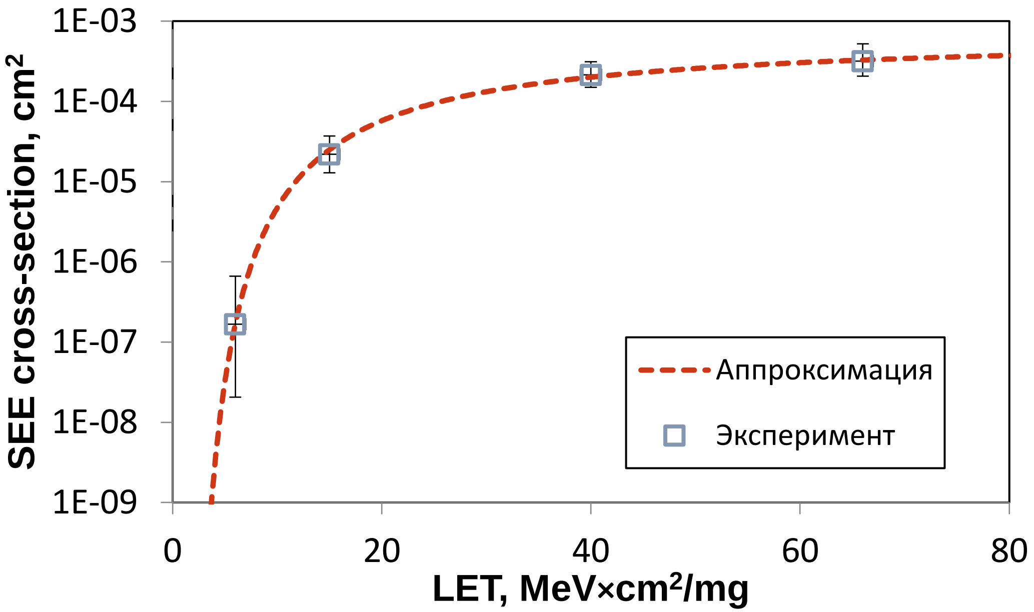
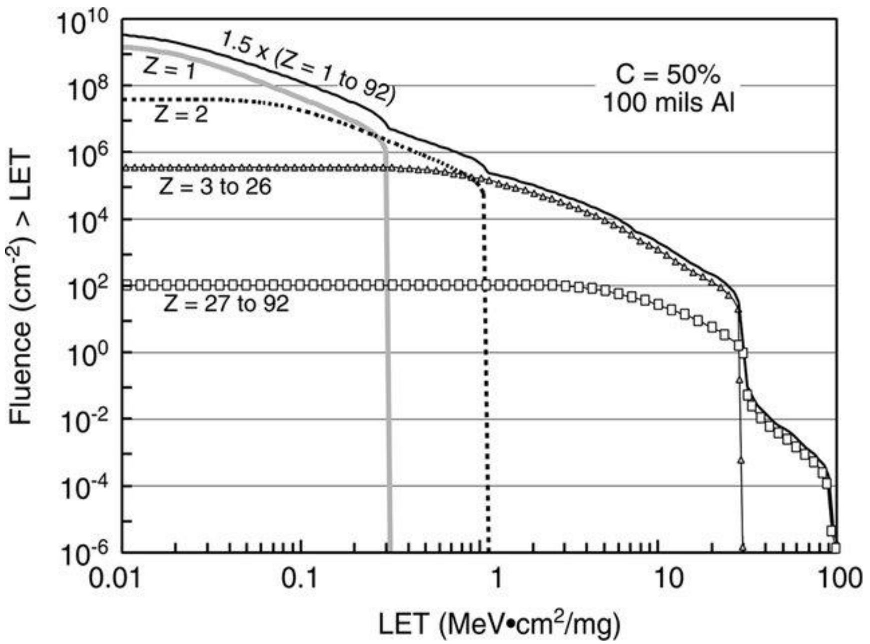


LET spectrum



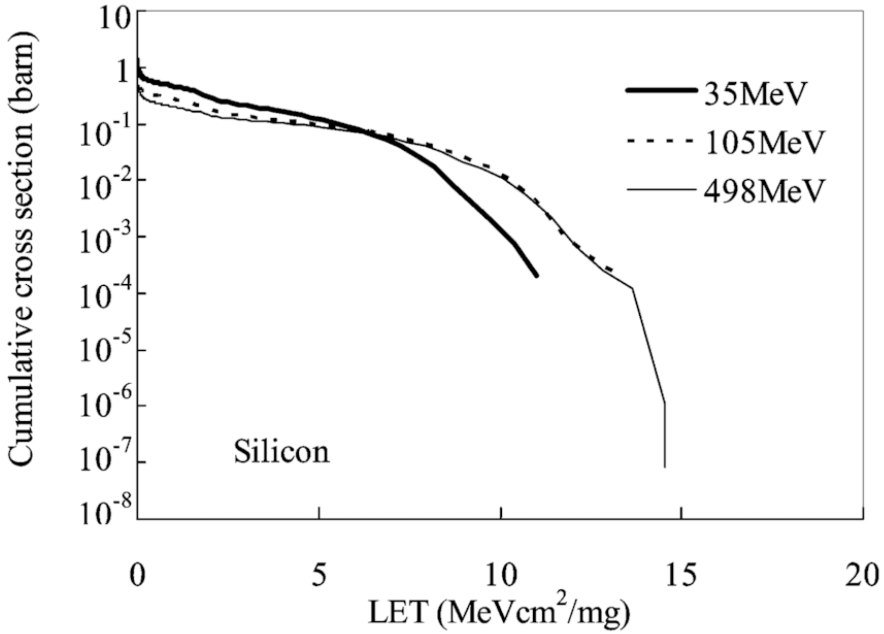
Model describing SEE angle dependence

$$\sigma_{is}(LET) = \int \sigma(LET, \Omega)\, d\Omega \quad \Longrightarrow \quad SER = \int \sigma_{is}(LET) \cdot F(LET) \cdot d\,LET$$

Protons and neutrons

Protons and neutrons generally do not contribute to SEEs by direct ionization. Because neutrons are uncharged and protons have a single charge and small LETs.

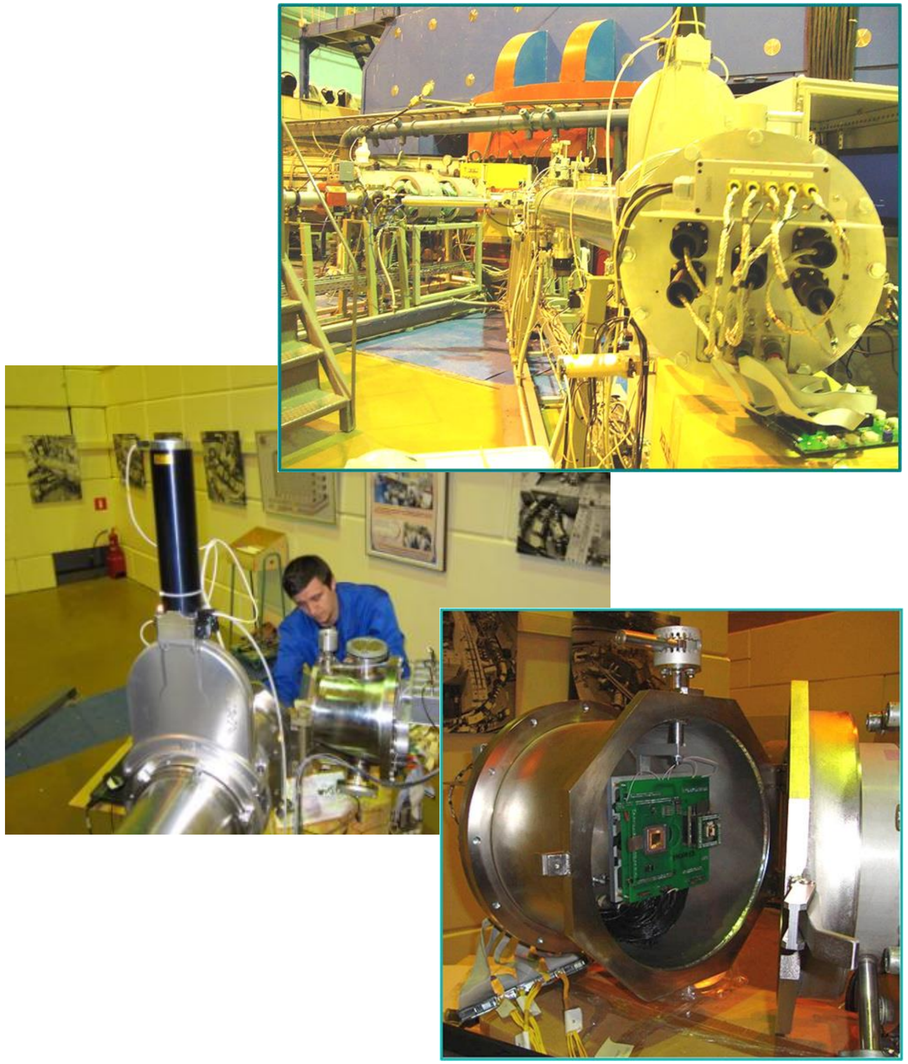
However, when high-energy protons and neutrons interact with the silicon nuclei they produce secondary particles with larger masses, and larger LETs (up to 15 MeV·cm^2/mg).



Devices with lower threshold LETs might have to be tested using proton accelerators to obtain cross-section dependence on energy and perform separate SER calculations.

However proton and neutron sources are usually not very useful for SEE tests by themselves because LETs up to 15 MeV·cm^2/mg are not sufficient for estimations of device performance in target environment.

Ion cyclotrons (Roscosmos testing facilities)



<u>Features and limitations</u>:

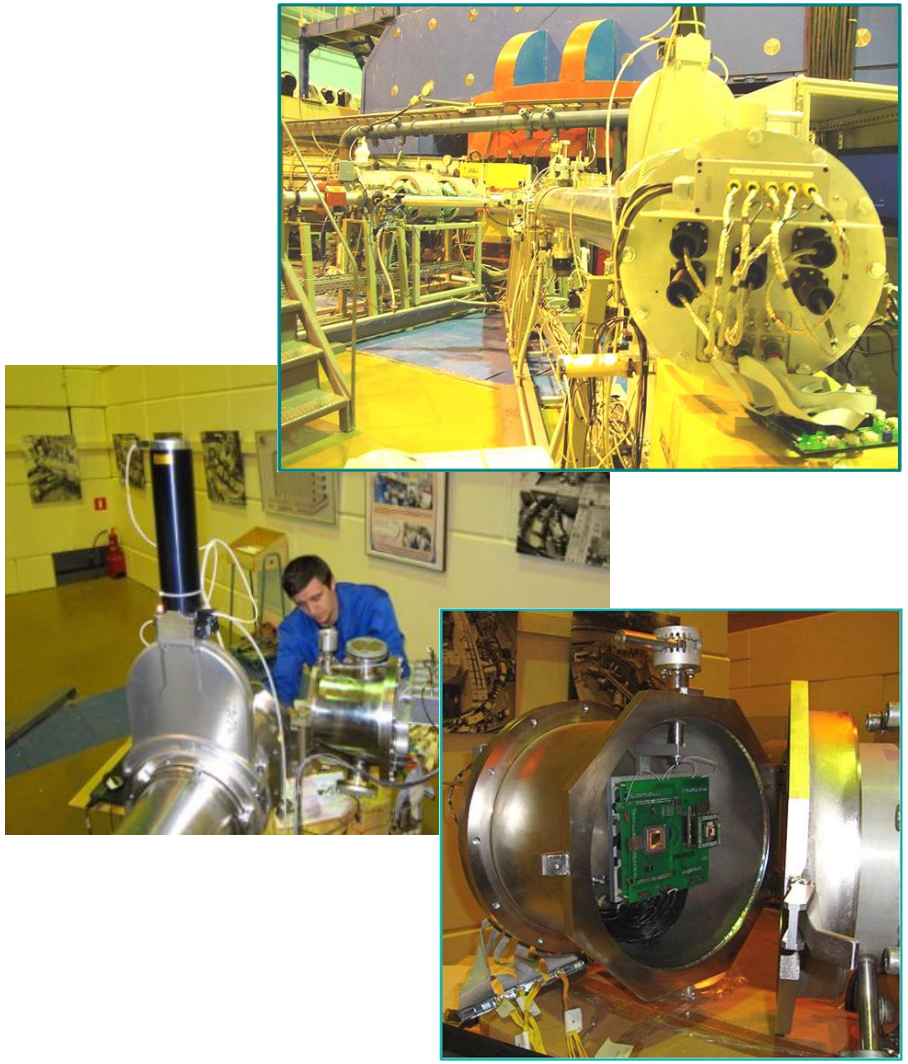
Ion ranges for LET 60 MeV·cm²/mg:

30…40 um (~ 3MeV/nucl)

100…150 um (~ 20MeV/nucl)

- **Package modification is required to ensure ion beams can reach sensitive volumes in the device**
- **Even with modified package some devices cant be tested (flip-chip, stacked dies, multi-chip assemblies, devices with large sensitive regions)**

Ion cyclotrons (Roscosmos testing facilities)



<u>Features and limitations</u>:

Vacuum chamber

- **Heat dissipation and thermal stabilization**
- **Testing boards must meet requirements**

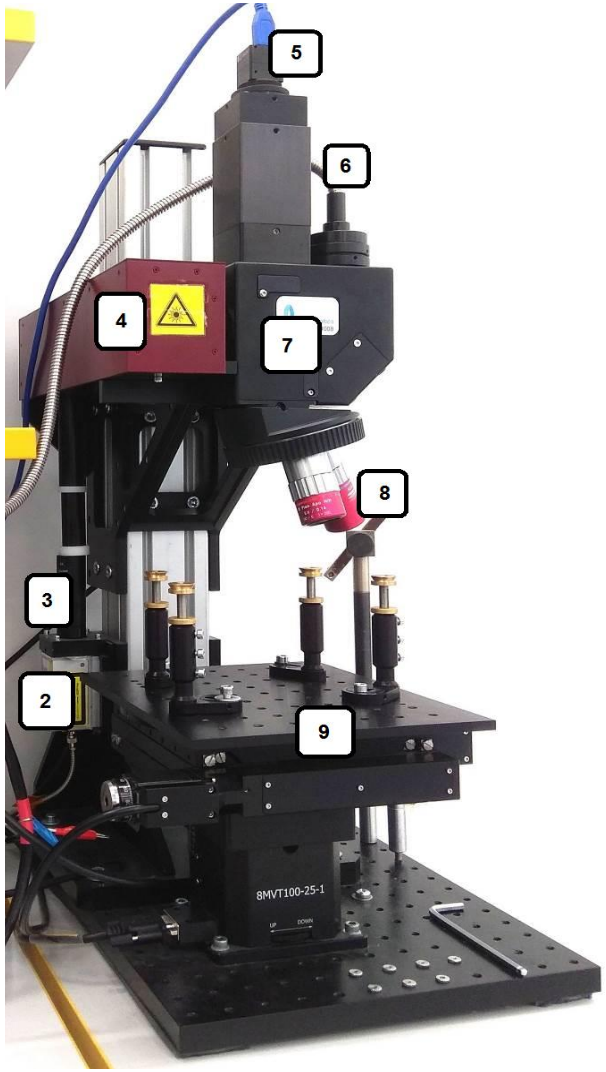
No ion cocktail. Switching between ions takes a lot of time.
Several weeks might be required to obtain 4 LET points.

Limited number of available ions (LET values).
Shape of cross-section dependence on LET can be hard to determine.

Focused Pulsed Laser Sources

Focused Laser sources provide additional data:

- Additional datapoints for cross-section dependence on LET (when calibrated against heavy ions);
- Preparation and debugging of SEE detection equipment ahead of HI tests;
- Testing of devices in Flip-Chip packaging (only backside of the die is accessible);
- Identification of sensitive regions of the device;
- Additional measurements and test requiring reproducible effects. Estimation of effectiveness of SEE mitigation techniques.



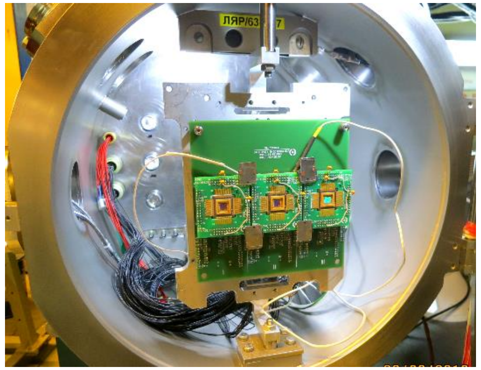
Heavy Ions + Pulsed Laser

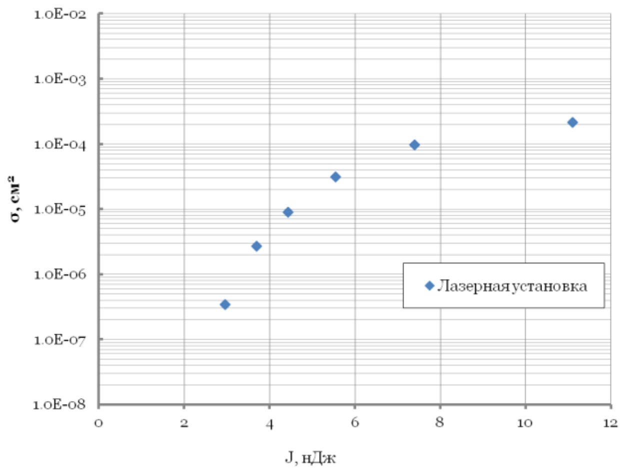
Focused laser source

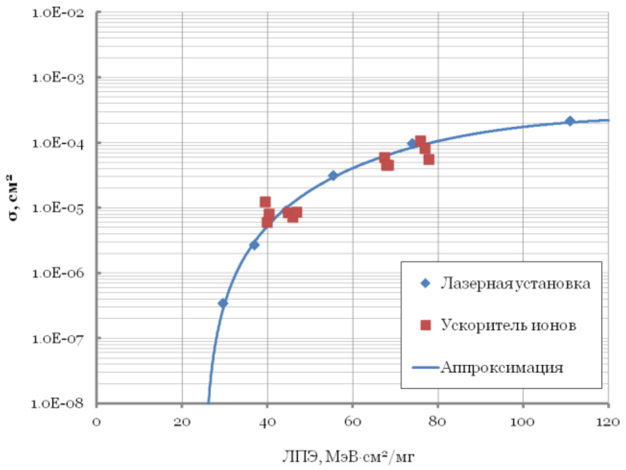
$$LET_{ie} = K_j \cdot J$$

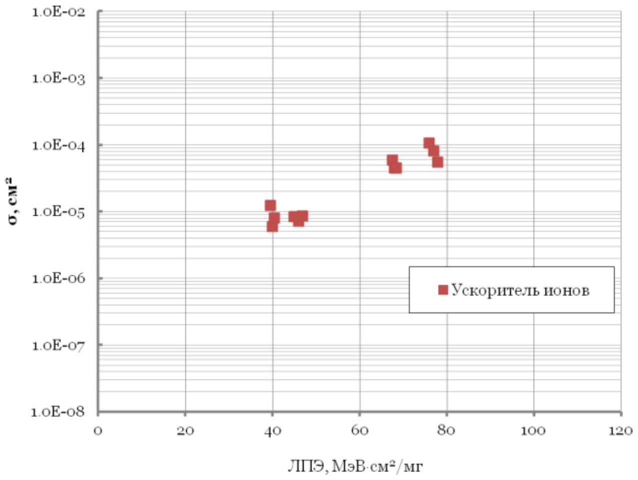
$$\sigma_{ie} = K_\sigma \cdot \sigma_l(J)$$

Heavy ion accelerator



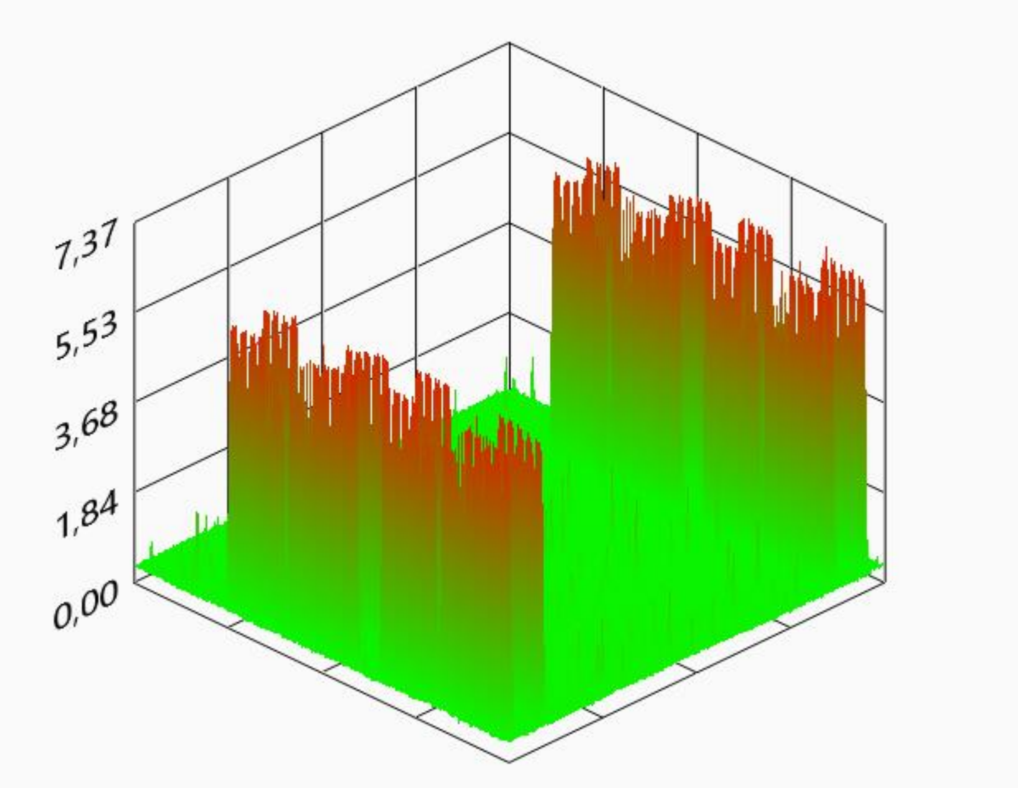




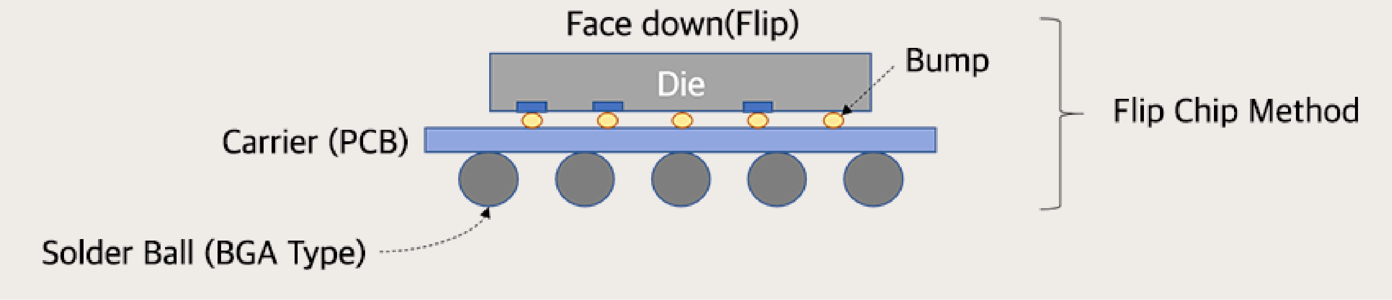


More datapoints for more accurate description of SEE cross-section dependence on LET

Testing devices in flip-chip packaging



SET response map of Flip-Chip device



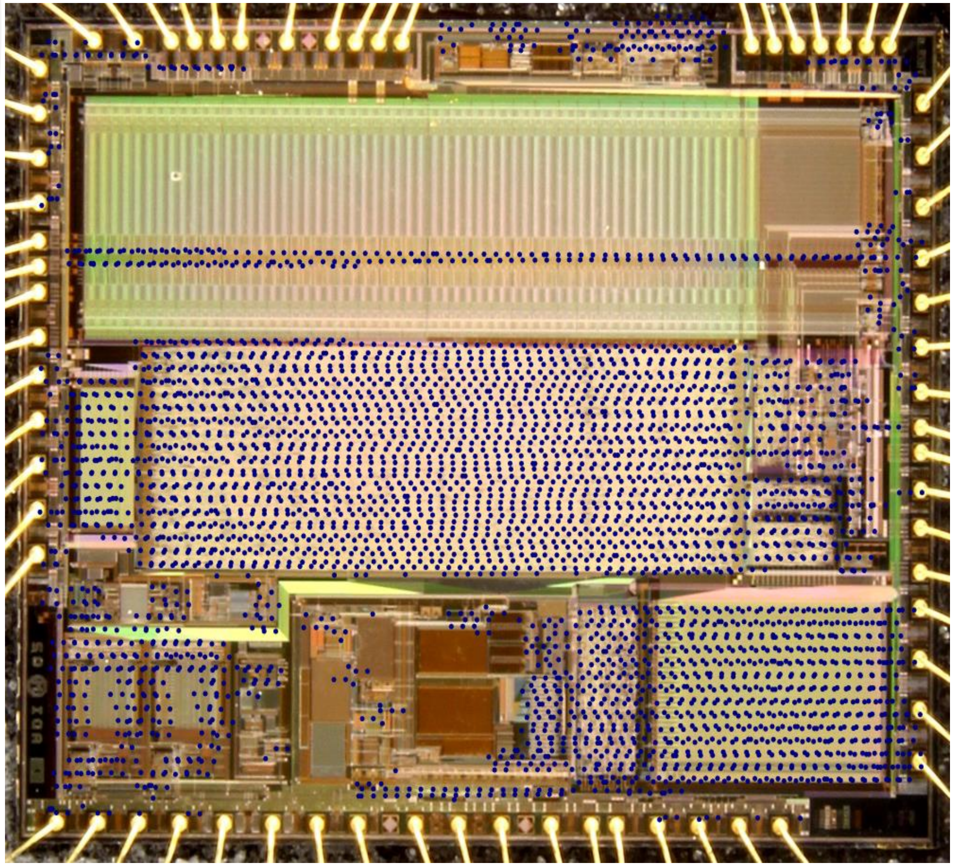
Silicon die has a backside of the die facing up which makes sensitive active regions unaccessible for short-range heavy ions

Backside irradiation using laser source:

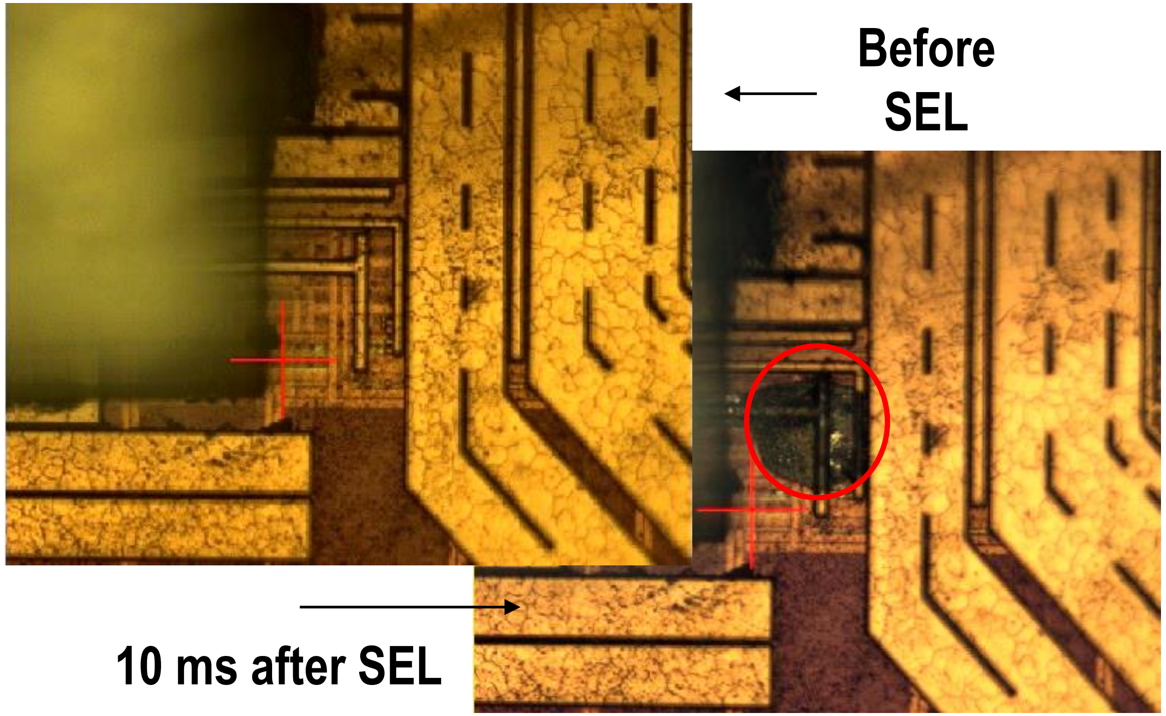
- 1064 nm wavelength is suitable for Si;
- Energy loss in the substrate, refraction of the laser beam at the silicon-air boundary and reflection by metallization layers have to be taken into account

Without heavy ion calibration testing of flip-chip devices using laser sources can be used to obtain some limited data such as **saturation cross-section** at high pulse energy and **location of sensitive regions.**

Identification of sensitive regions



SEL sensitivity map

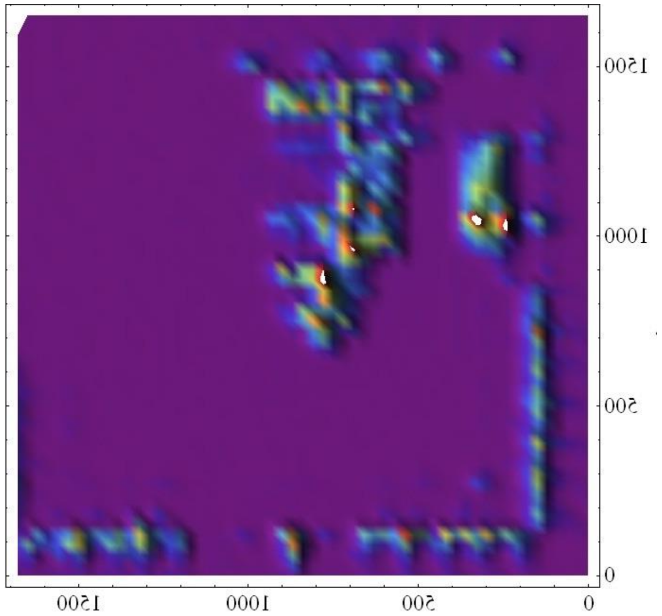


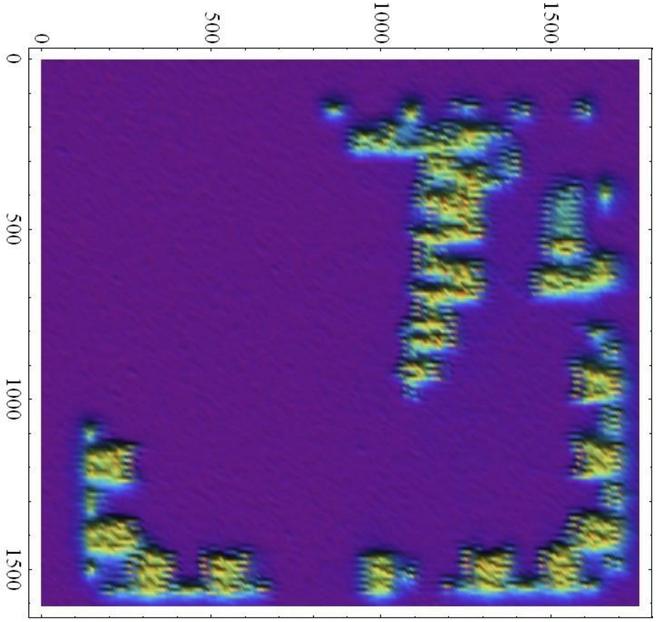
- Identification of sensitive regions
- Studying effects of sustained high current state caused by SEL at each sensitive region

Limitations of pulsed laser sources

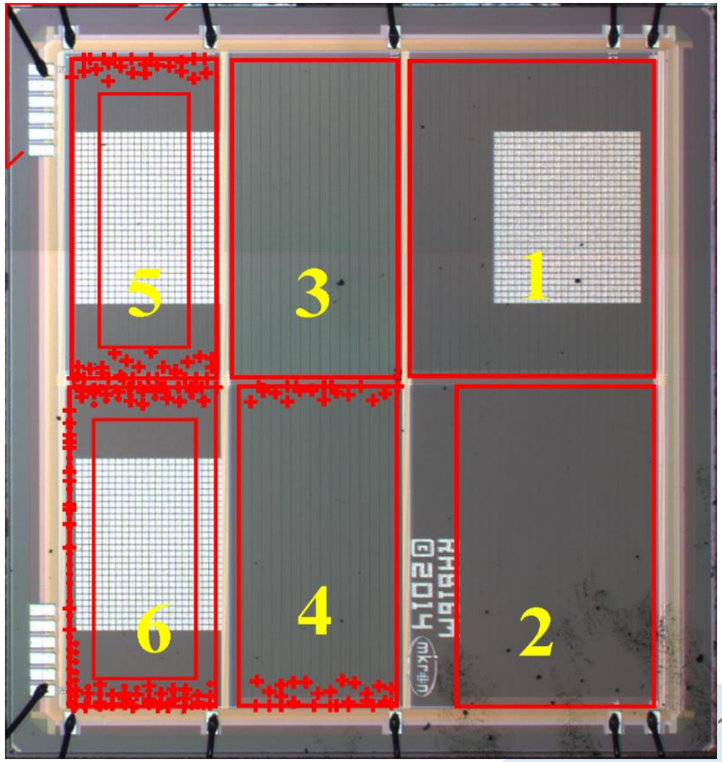
In modern devices with high number of metallization layers, energy deposition at the surface of the substrate can be highly non-uniform

SET maps (ADC) for frontside (left) and backside (right) irradiations





Laser effectiveness is higher at the boundaries of the die blocks



Frontside irradiations are only usable for devices with up to 2 metallization layers

High-range heavy ion testing station at NICA (SODIT)

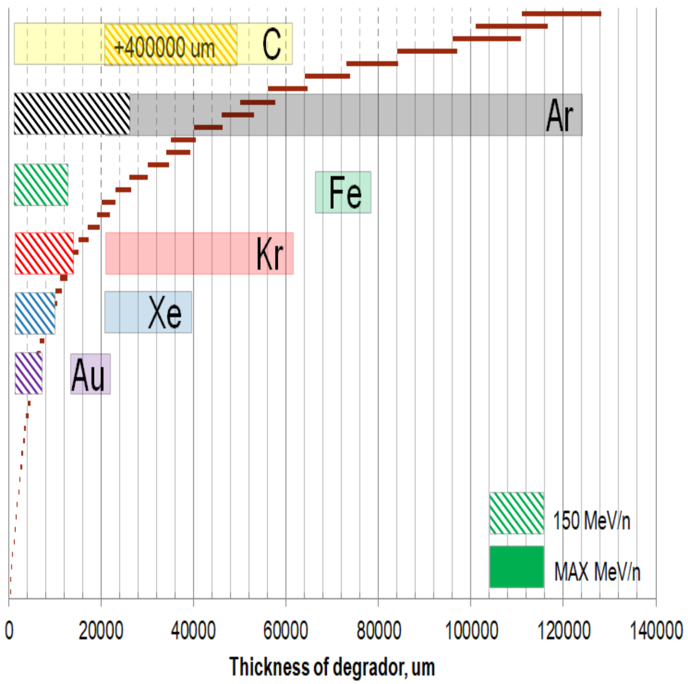
	Ion	Energy MeV/n	Range (in Si) mm	LET (in Si) $\frac{MeV\ cm^2}{mg}$
Ion types and energies	$^{197}Au^{79}$	150..350	3,5…12	16..94
	$^{131}Xe^{54+}$	150..367	9..36	8..69
	$^{84}Kr^{36+}$	150..392	12..58	3..41
	$^{56}Fe^{26+}$	150..449	11..73	2..29
	$^{40}Ar^{18+}$	150..426	21..122	1..19
	$^{12}C^{6+}$	150..507	46..357	0,1..4
Flux, *ion/(cm^2·s)*		10^2 .. 3×10^5		
Irradiation area without scanning, mm		∅29		
Uniformity without scanning		10%		
Beam diameter, mm		∅73		
Irradiation area with scanning, mm		200×200		
Uniformity with scanning		15%		

SODIT features

- Located at one of the Nuclotron exits
- Atmosphere operation
- High-range ions
- Possibility of high and low temperature testing
- Large irradiation area
- For high LETs **energy has to be lowered to** 3-10 MeV/n
- The entire LET range of interest can be covered by only two ions (Fe and Au)

Energy degrader system

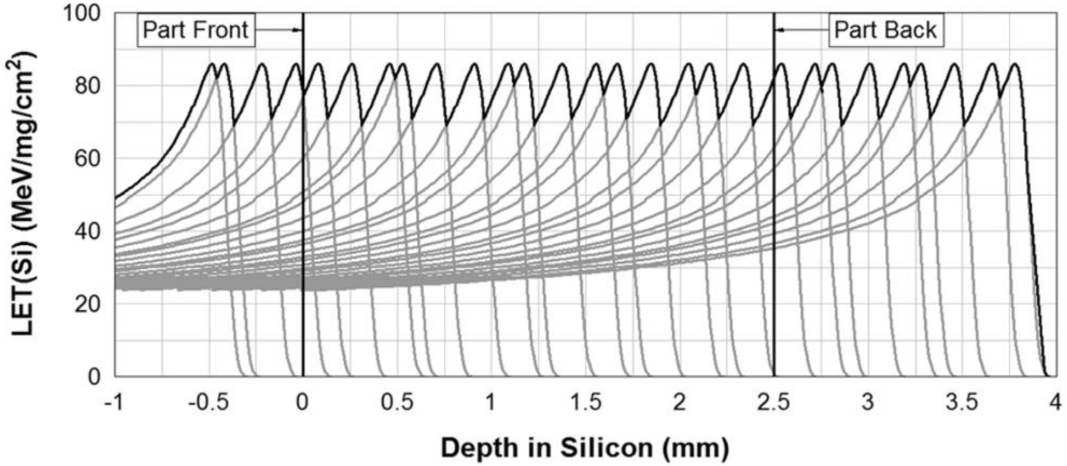
Energy ranges after degrader for several ions

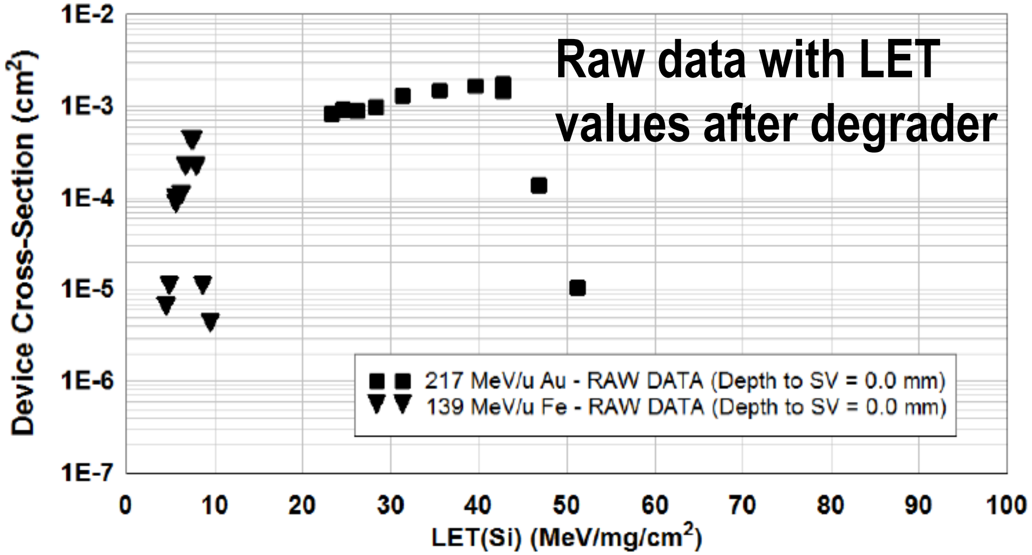


Degrader system's parameters

- Degrader material - polycarbonate.
- 20 slabs with thickness values 135, 170, 250, 1000, 2000, 6000, 10000 um.
- Total thickness from 200 um to 12 cm
- 10 um precision possible due to high quality of the slabs and rotation mechanism for gradual change of thickness (up to 30 degrees angle)

Variable Depth Bragg Peak (VDBP) Method





Data from C. Foster et al. IEEE Nucl. Sci. V. 59 N.6. 2012

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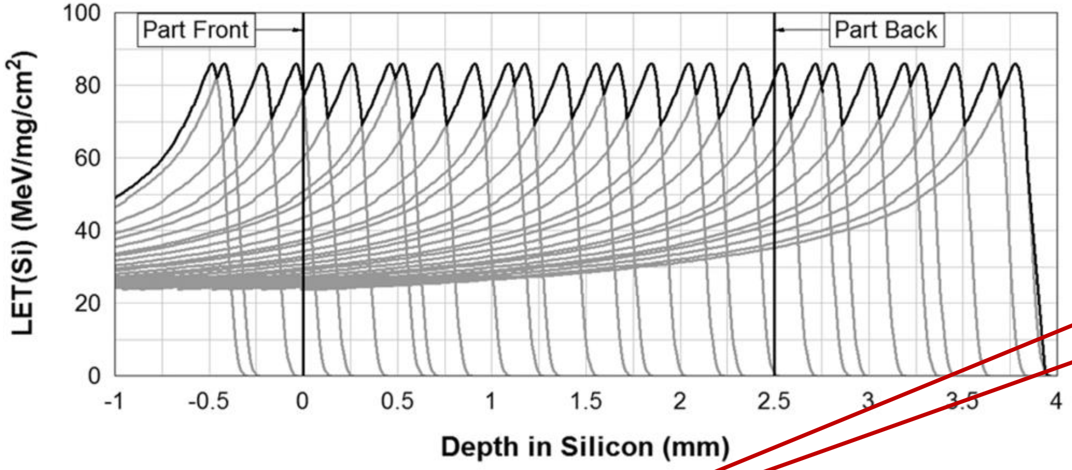

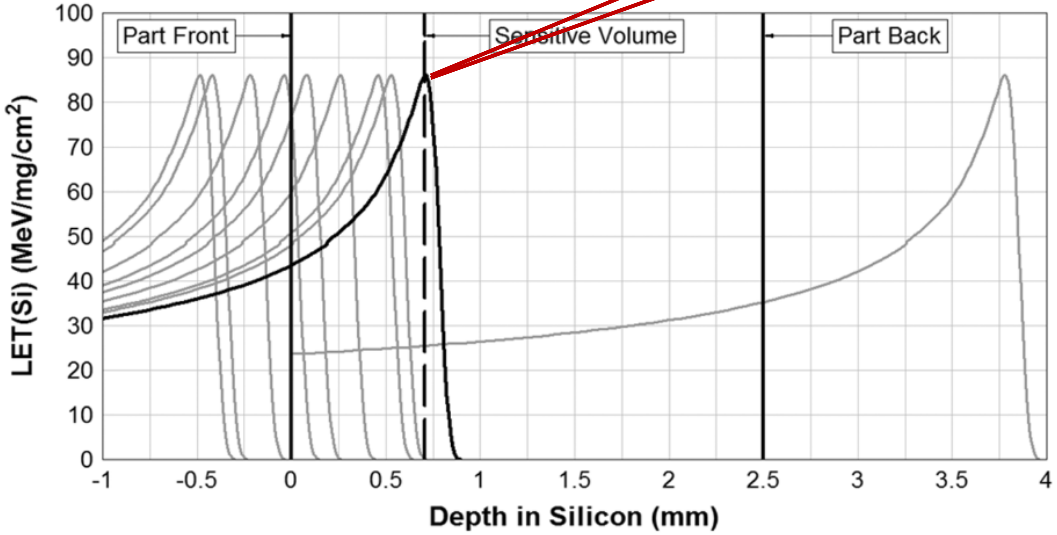

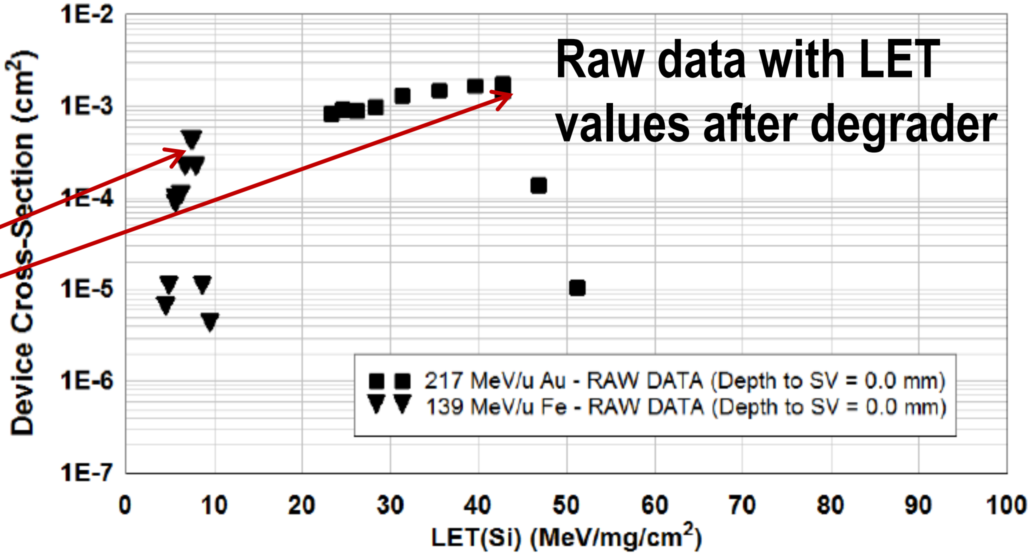

Highest cross-section values correspond to Bragg peak at depth corresponding to sensitive volume depth

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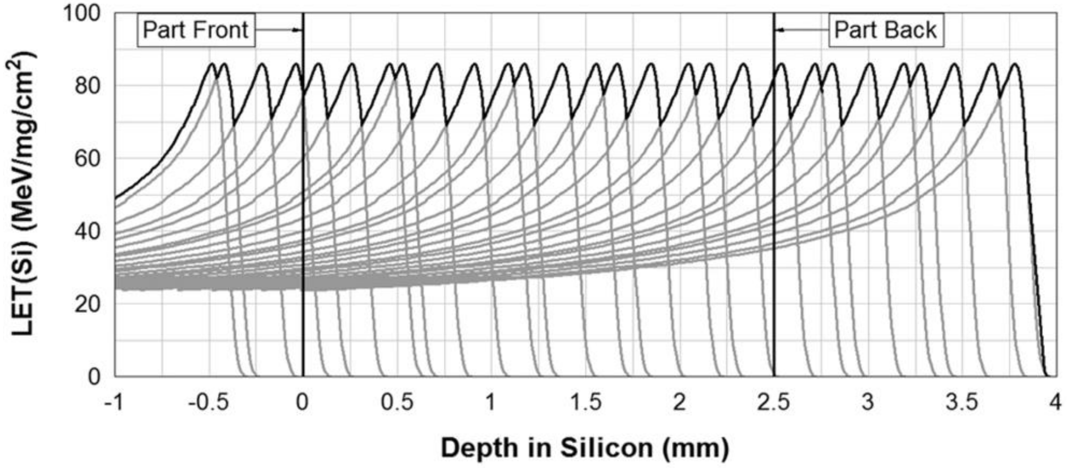

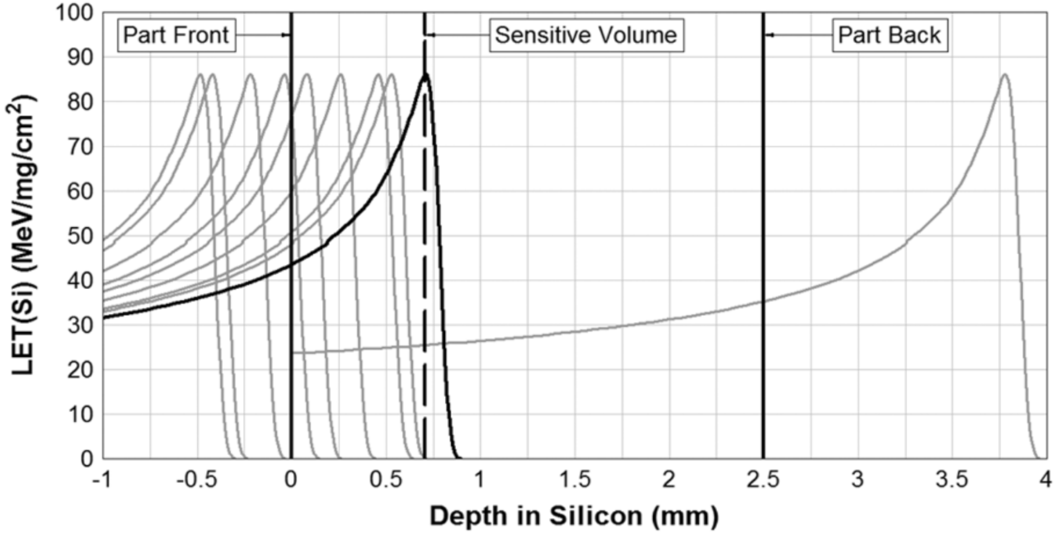

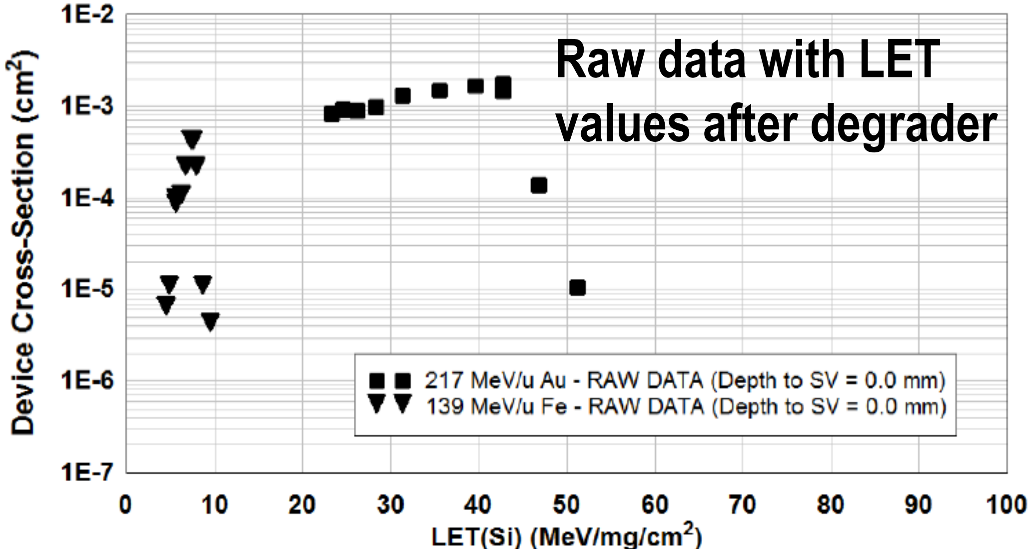

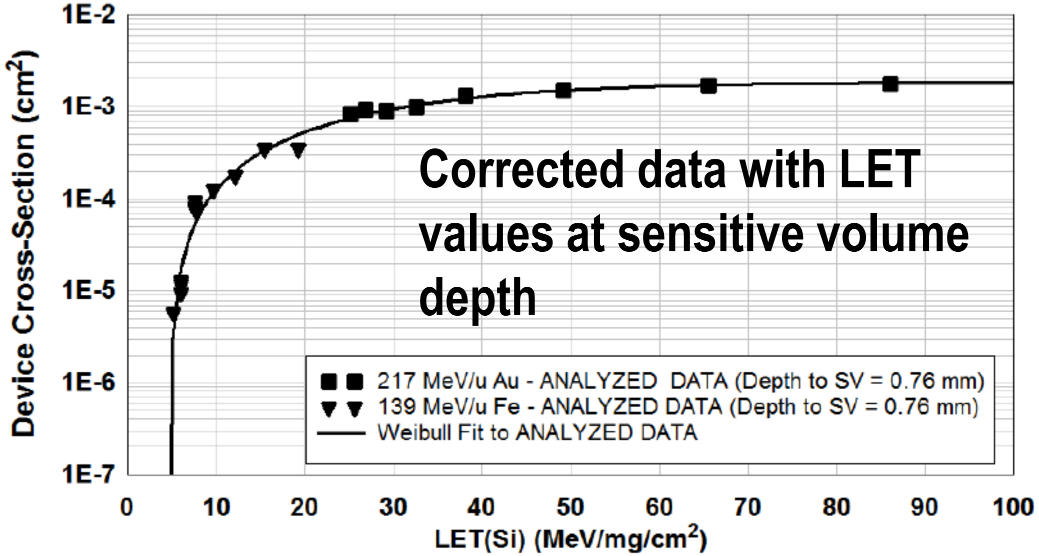

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SODIT applications

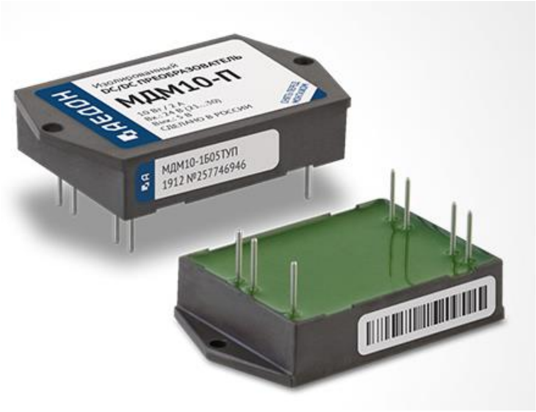
- SEE testing of devices with packaging or structure requiring high-range ions:

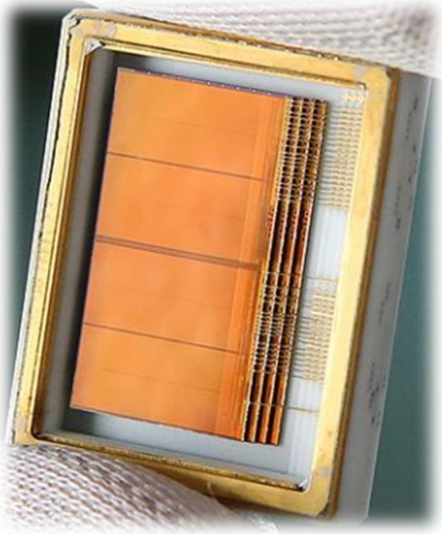
  Flip-chip, 3D assemblies, stacked dies, plastic packaging that can be modified without damage to the device etc.

- SEE testing of high-power transistors, including tests at negative temperature

- SEE testing of devices with high thermal budget that can be effectively cooled in a vacuum chamber.

- Obtaining a lot of data points for cross-section dependence on LET in a short time (days instead of weeks)





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	$^{12}C^{6+}$		44	4
Flux, *ion/(cm²·s)* Pulsed mode		10^3 .. 10^5		
Irradiation area, mm		∅29		
Uniformity		10%		
Beam diameter, *mm*		∅73		

SOCIT features

- Located at technological exit of the beam extraction channel between HiLAC and booster
- Pulsed operation mode (3 pulses with 30 us width, every 4 seconds)
- Vacuum chamber
- Relatively high dose rate (about 10^6 rad/s for flux 10^5 ion/(cm^2.s) and 30 us width.
- Two boards with mounted device samples can be placed inside the chamber and irradiated using positioning system without opening the chamber
- Temperature control system for high temperature irradiation

Conclusion

The use of low range ion facilities becomes increasingly challenging for some types modern devices using advanced packaging techniques or devices with high thermal budgets.

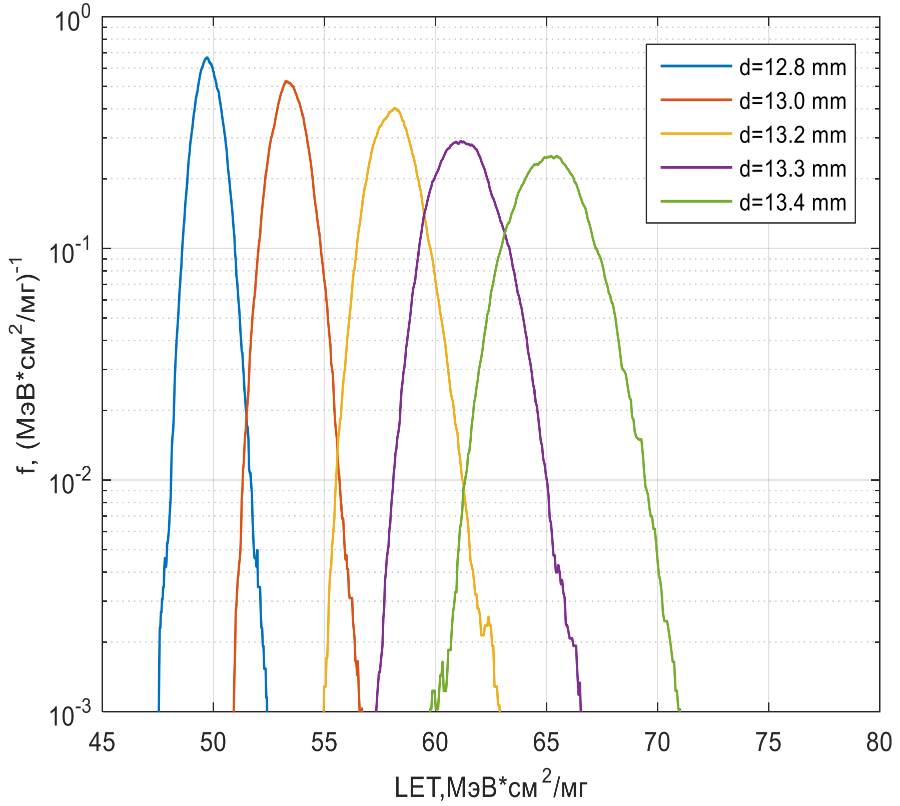
Some additional test can be conducted using laser sources but they have limited use as an independent tool for SEE testing.

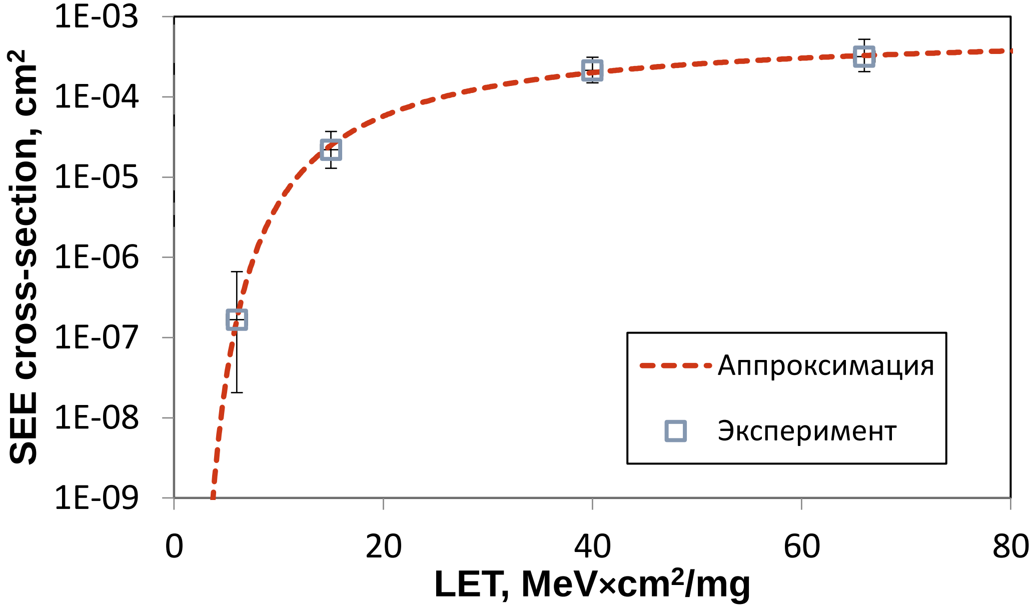
New high-range testing facility enables SEE testing of these types of devices as well as provides as with more data for more accurate estimations of device performance in target environments.

Thank you for your attention!

Anatoly Smolin, aasmol@spels.ru
Dmitry Bobrovsky, dvbob@spels.ru
Alexander Chumakov, aichum@spels.ru

Backup slides





Number of observed effects