LNL IRRADIATION FACILITIES FOR RADIATION DAMAGE STUDIES

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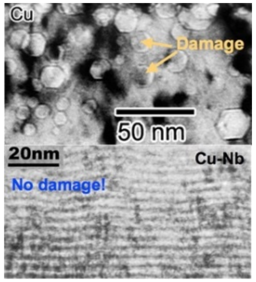
Radiation: an overview

Radiation is ubiquitous:

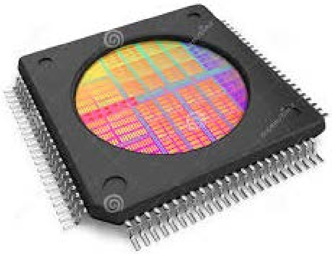
Natural human environment	Extended Natural Environment	Artificial Environment
Natural radioactivity of materials	Satellites	High Energy Physics experiments
Sea level cosmics	Deep space missions	Radiation therapy halls
	High altitude avionics	Industrial accelerators and sources
		Nuclear power plants

Radiation can damage:

Living beings



Materials



Microelectronics circuits

Radiation effects in electronics: who cares?

Space missions

Accelerator based facilities

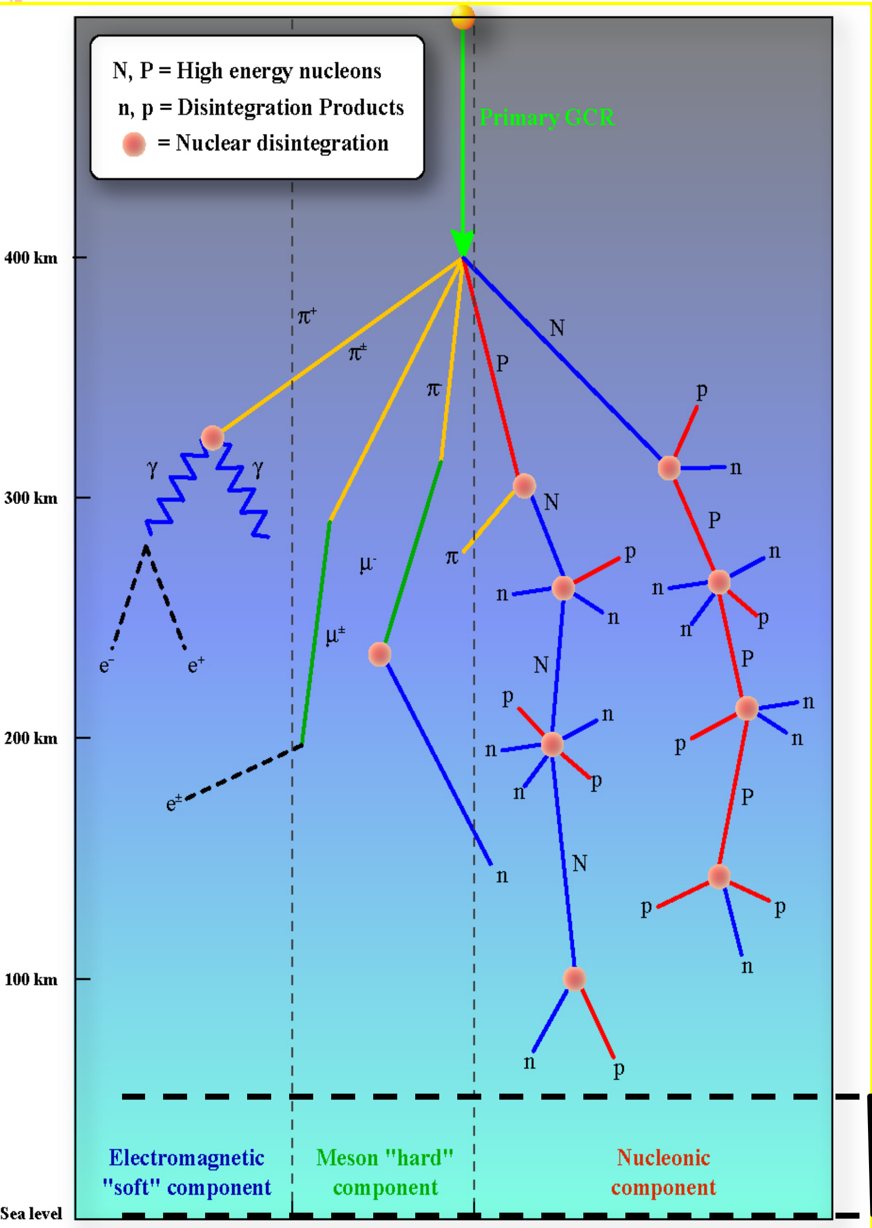
High Altitude Flights

Ground Level Electronics

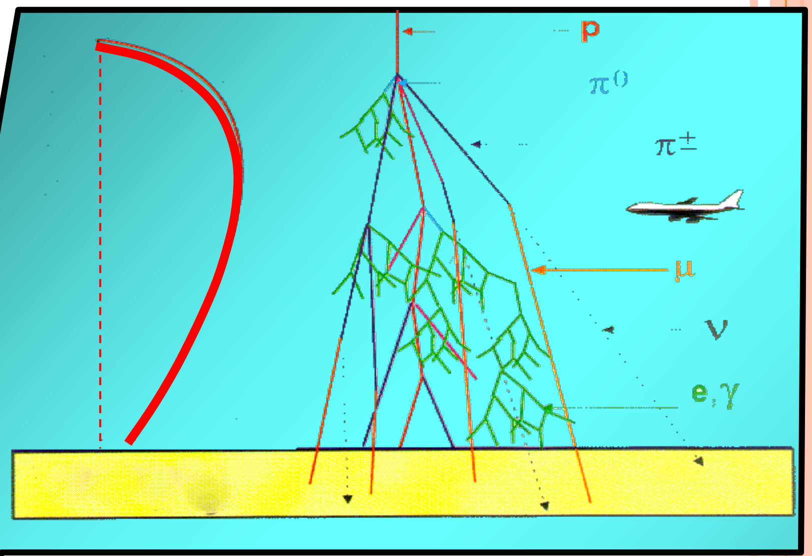
Fusion reactor projects

Nuclear Power plants

RADIATION AT GROUND LEVEL



Shower maximum at ~18 km



- Under 20 km altitude **neutrons** dominate as cause of so called Single Event Effects in avionic systems.
- In mountains and at sea level there are enough neutrons to be a real concern for electronics that play vital roles

ATMOSPHERIC NEUTRONS

Omnipresent "atmospheric neutrons" are widening problem for Electronics-based High Reliability Industry

Aviation

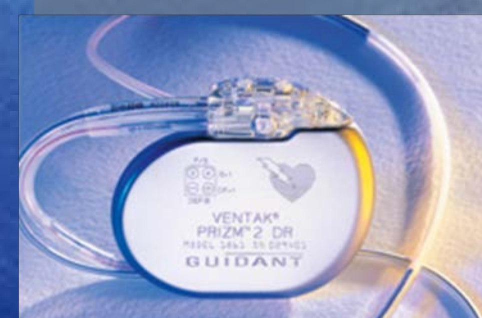
Automotive

"Radiation induced single events could be happening on everyone's PC, but instead everybody curses Microsoft."

Paul Dodd, Sandia National Laboratories

Trains

Infrastructure



Medical

Radiation Damage on microelectronic devices

Radiation Damage

When a particle strikes a microelectronics device, it can transfer energy to the medium both by atomic displacement and/or by ionization:

- **Single Event Effects (SEE)**: damage induced by the passage of a single energetic ionizing particle which releases enough ionization in a sensitive volume to induce a device/system malfunction (threshold effect)

  - ✓ Single particle
  - ✓ Ionizing radiation

- **Bulk Damage (NIEL)**: damage caused by the displacement of crystal atoms by the interaction of the incident particles with the nuclei of the lattice atoms.

  - ✓ Cumulative effect
  - ✓ Non-Ionizing radiation

- **Total Ionizing Dose (TID)**: degradation of performances of irradiated devices due to the homogeneous accumulation of charge in oxide layers and Si-SiO_2 interfaces in microelectronics circuits exposed to ionizing radiation.

  - ✓ Cumulative effect
  - ✓ Ionizing radiation

Electronics validation

- Electronics designed to work in harsh environments has to be **validated**: its reliability has to be checked for the radiation doses foreseen in the actual environment

- Accelerated ground tests
  - Laser beams
  - Particle accelerators

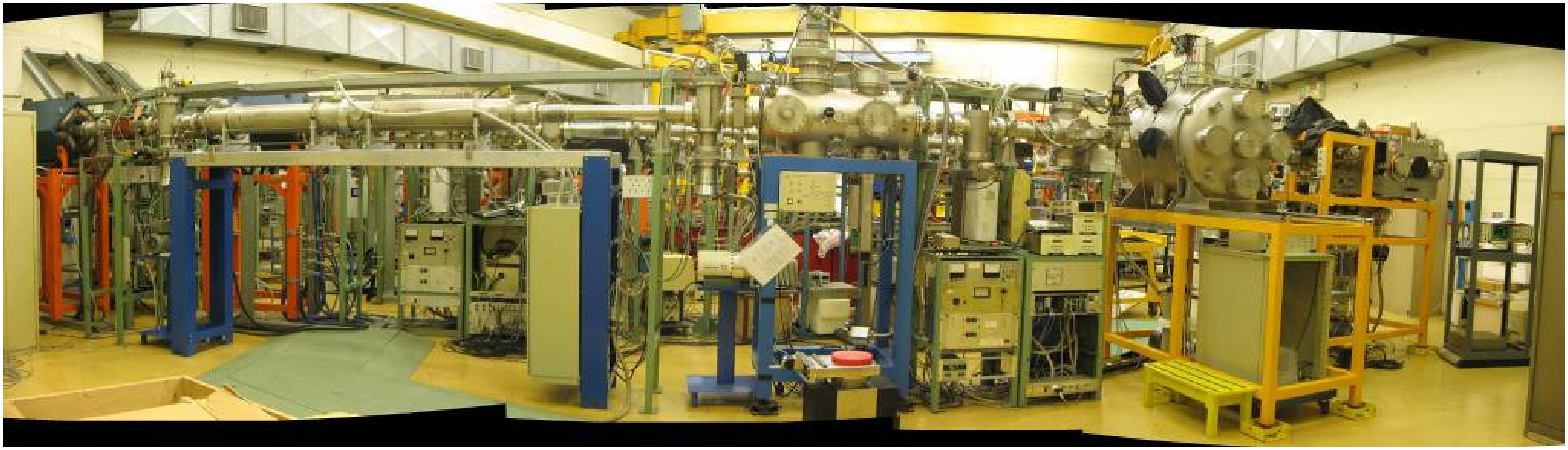
Legnaro irradiation facilities

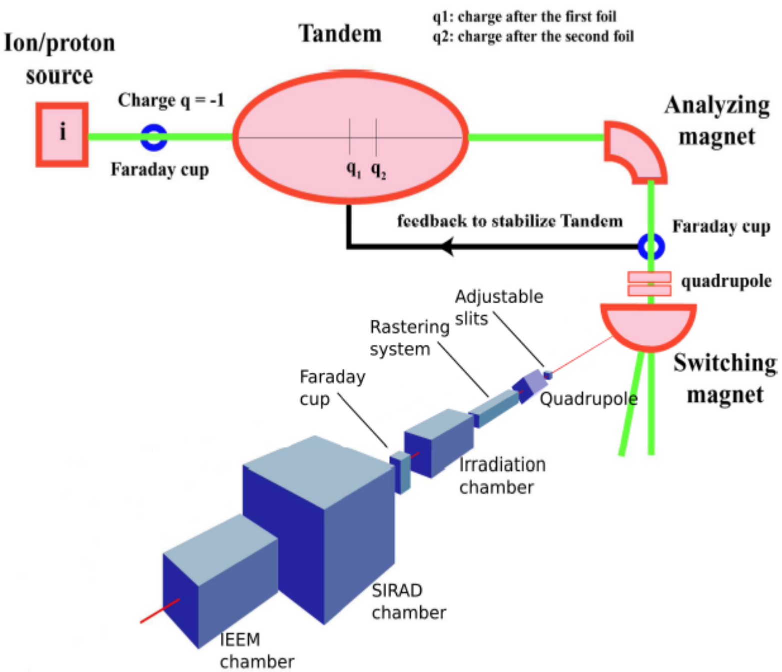
- The INFN Legnaro National Laboratories are a well known center for electronics validation
- A large number of facilities are present to test microelectronics devices and systems against the different types of radiation damage

Radiation type	SEE	TID	NIEL
Protons (CN and Tandem)	✓	✓	✓
Heavy Ions (Tandem)	✓		
X-rays		✓	
γ rays		✓	
Neutrons (CN)	✓		✓

Protons and heavy ions

The SIRAD irradiation facility





- The SIRAD irradiation facility is located at the Tandem Accelerator of the INFN National Laboratory of Legnaro
- It is dedicated to Single Event Effect studies, Total Dose and bulk damage
- Tandem accelerator: Van de Graaff type, 15MV (max voltage), two strippers,

SIRAD is located in the
Experimental Hall 1, Beam line +70°

Ion beams available at SIRAD

$$E = E_{inj} + V_0 \cdot [1 + q_1 \cdot f + q_2 \cdot (1 - f)] \qquad f = 0.25$$

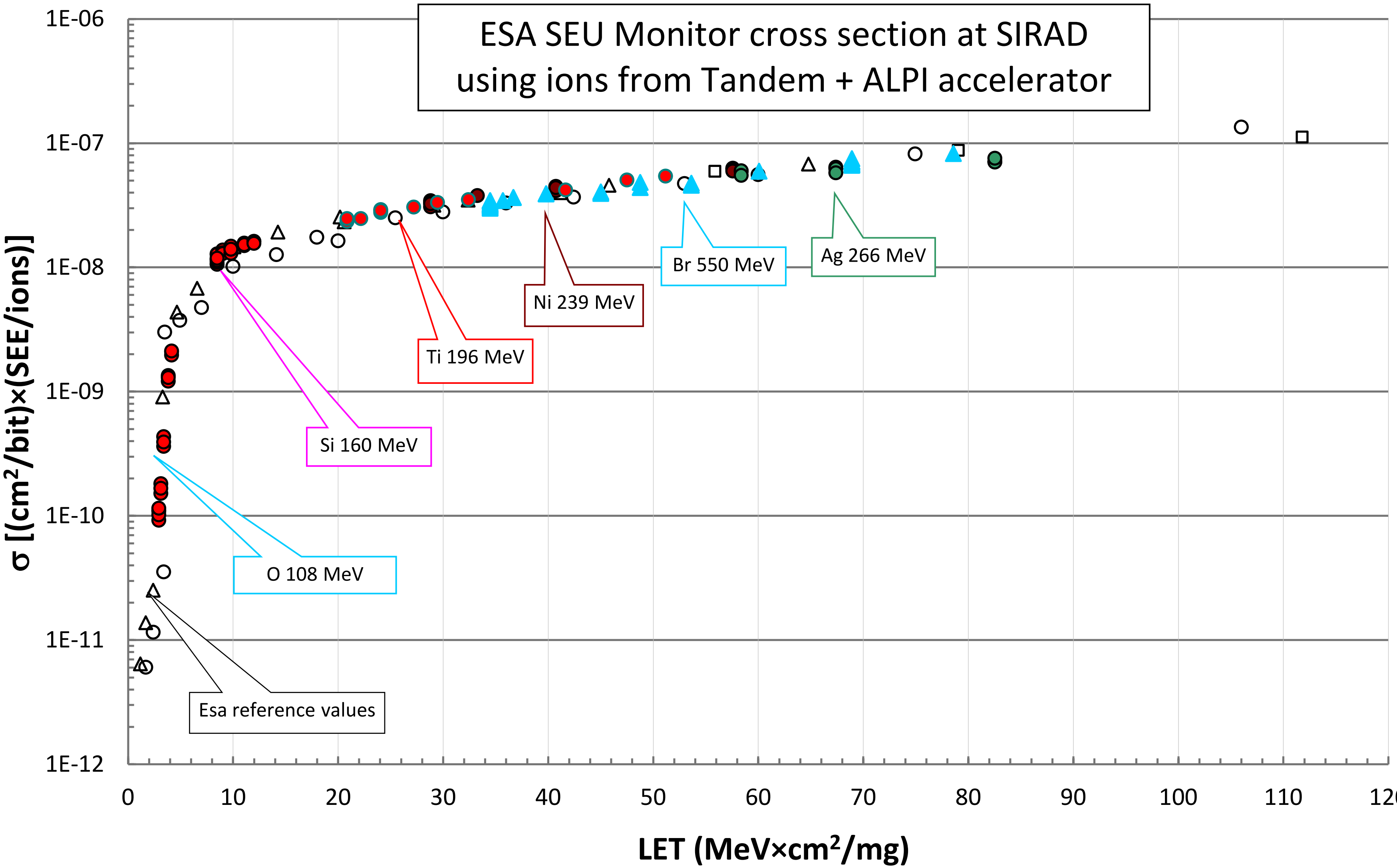
- Typical ions available at SIRAD serviced by the XTU-Tandem accelerator, assuming:
  - Tandem voltage at 14 MV,
  - the most probable charge state using two strippers.
- Note: The range and surface Linear Energy Transfer (LET) are in silicon.
- LET: energy released per unit distance
- The magnetic rigidity is also tabulated. The rigidity limit of SIRAD is ~ 1.6 T-m

Ion Species	Energy [MeV]	q_1	q_2	Rigidity [T·m]	Range in Si [μm]	Surface LET in Si [MeV×cm²/mg]
^{1}H	28	1	1	0.77	4340	0.02
^{7}Li	56	3	3	0.95	376	0.37
^{11}B	80	4	5	0.86	185	1.13
^{12}C	94	5	6	0.81	164	1.53
^{16}O	108	6	7	0.86	107	2.95
^{19}F	122	7	8	0.87	95	3.90
^{28}Si	157	8	11	0.87	61	8.58
^{32}S	171	9	12	0.89	54	11.1
^{35}Cl	171	9	12	0.93	50	12.7
^{48}Ti	196	10	14	1.00	40	20.9
^{51}V	196	10	14	1.03	38	22.6
^{58}Ni	220	11	16	1.02	37	29.4
^{63}Cu	220	11	16	1.06	34	31.9
^{74}Ge	231	11	17	1.11	33	36.9
^{79}Br	241	11	18	1.10	33	41.8
^{107}Ag	266	12	20	1.21	29	58.4
^{127}I	276	12	21	1.28	30	65.4
^{197}Au	275	13	26	1.52	26	79.1

1st multi-source (^{19}F, ^{35}Cl, ^{79}Br, ^{127}I)

2nd multi-source (^{16}O, ^{28}Si, ^{58}Ni, ^{107}Ag)

Cross section measurement at SIRAD



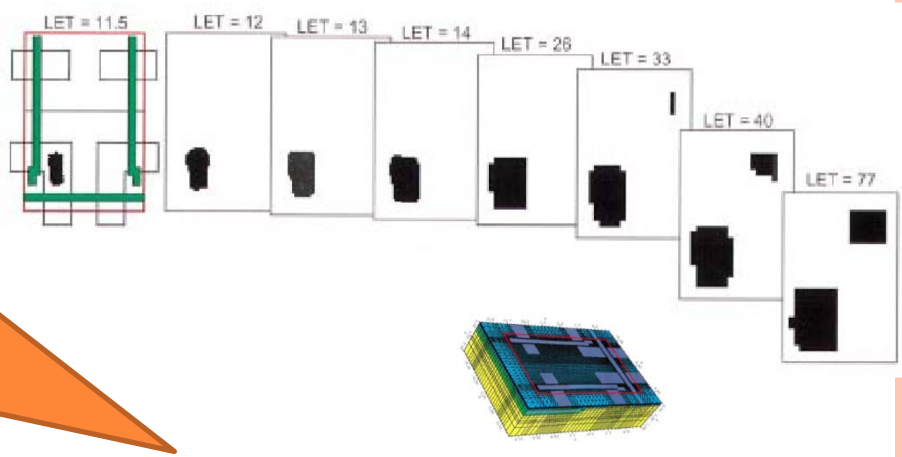
LET'S TAKE A STEP FORWARD…

- However, this approach only gives global information. It does not answer questions like:

"Where are the areas subject to ion induced Single Event Effects?"

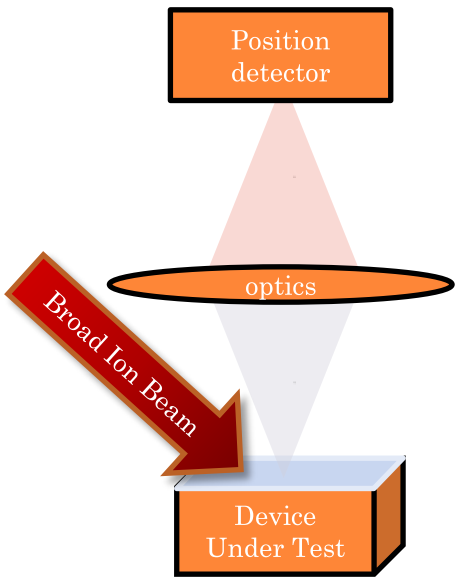
"Do the sensitive areas change as a function of the ion LET?"

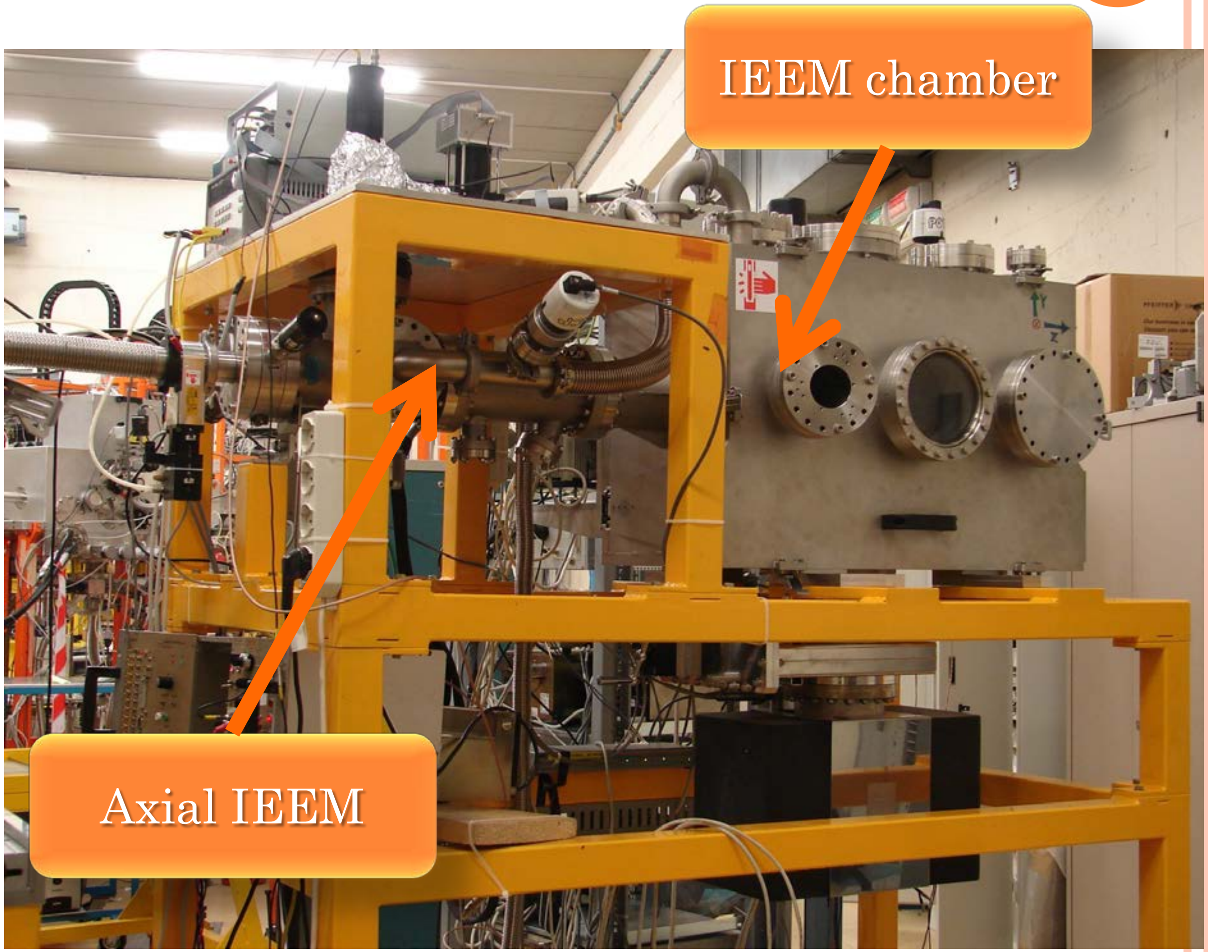
Simulation of the evolution of the SEU sensitive area as a function of the ion LET, including initially only the reverse biased NMOS drain and then also the reverse biased PMOS drain.



P.E.Dodd et al., IEEE Trans.Nucl.Sci. Vol 48 pp1893-1903, Dec. 2001

THE ION ELECTRON EMISSION MICROSCOPE





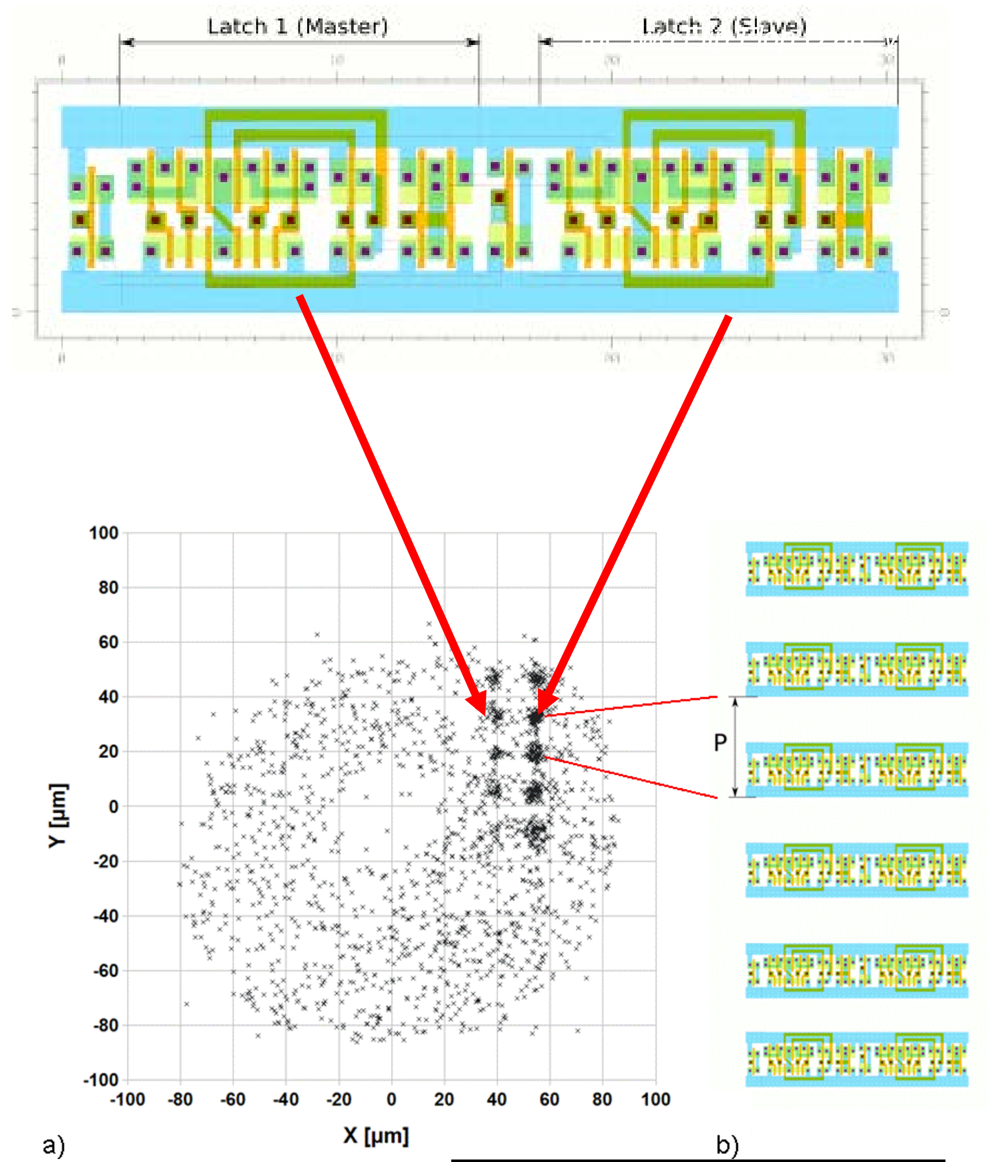
The IEEM is a novel tool. The only one other one is at SANDIA Labs (B. Doyle – the inventor of the technique)

Single energetic heavy ion impact points can be reconstructed with a resolution of a few microns at a rate of 1kHz over a circular area 180 micron diameter.

An example: Shift Register sensitivity

The actual resolution of the IEEM does not allow us to untangle the most sensitive nodes inside the cell

(we cannot say which transistor is responsible for an upset, but it is sufficient to distinguish the sensitive regions in a complex device with a resolution of a few microns)



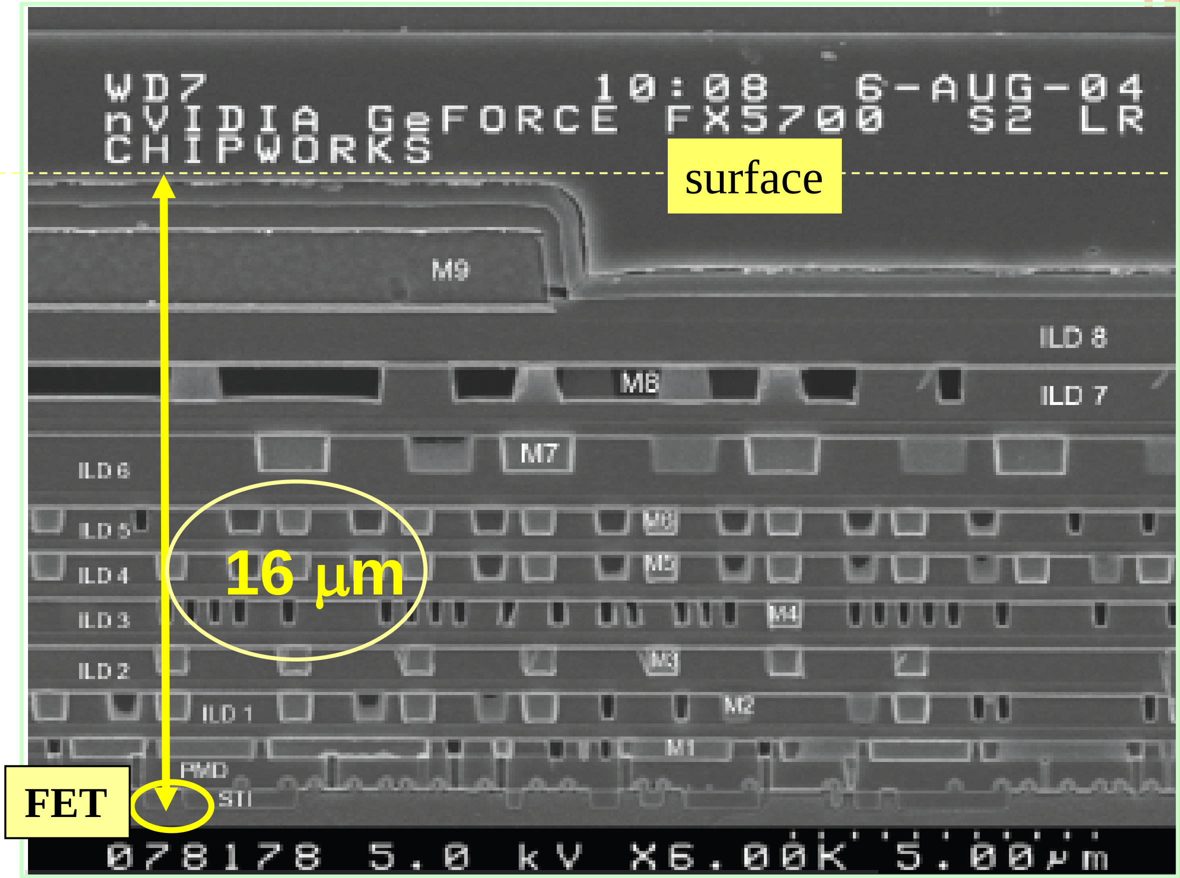
a) Shift Register sensitivity map.
b) Shift register schematics

Range and SEE testing facilities

- **Ions must have sufficient energy to penetrate overlayers**
- **Need to evaluate LET at the correct depth**

Have to keep into account any dead superficial layers (plastic lid; metallizations;…). At Tandem need naked devices (de-lidded). And there are experimental problems for <u>some types of devices</u> (see figure)

Section of a chip, Courtesy of Barney Doyle



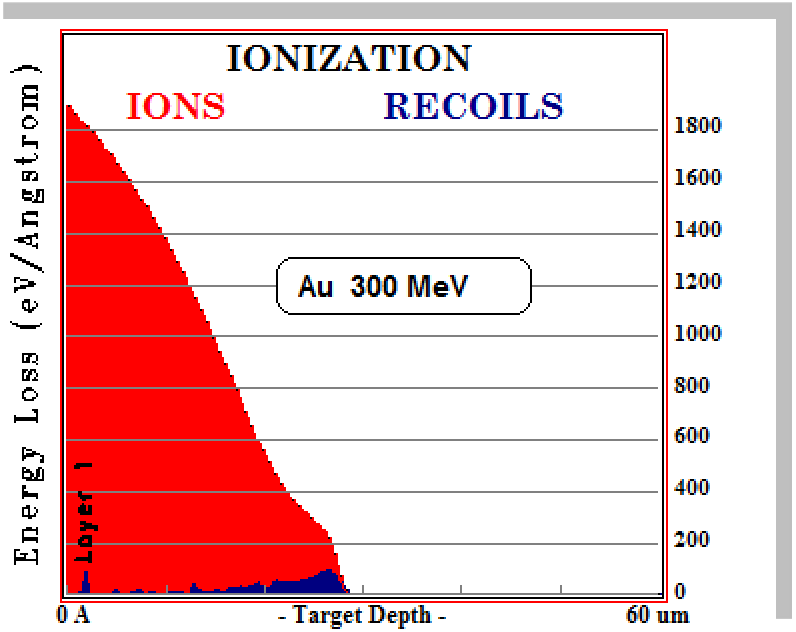
Sensitive volume is down here!

TANDEM ENERGIES ARE LIMITED…

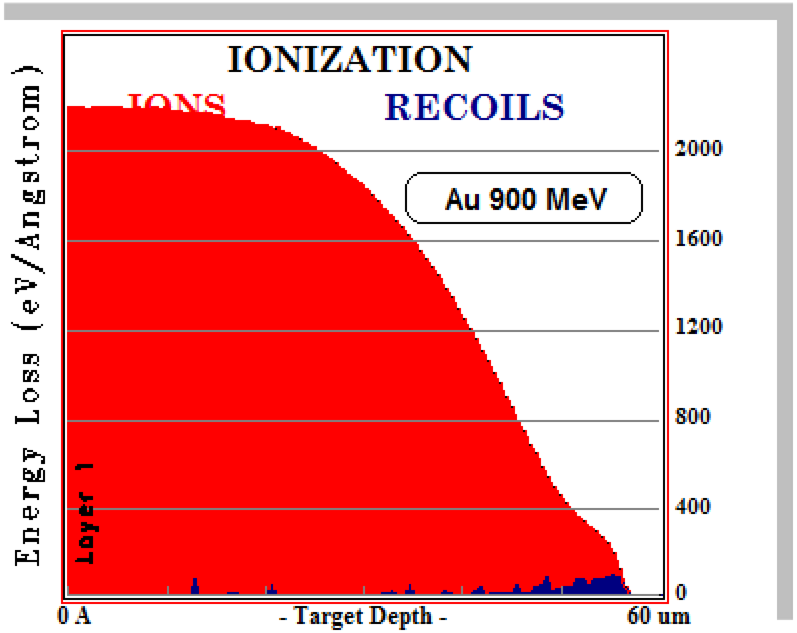
… ALPI ENERGIES ARE BETTER FOR SEE TESTS

The heaviest ions should have higher ranges in silicon than those permitted by the Tandem to ensure that the specific ionization be high where its is needed; i.e. in depth where the sensitive nodes of the DUT are located.

The LET in silicon, as a function of the ion depth, of an impinging 300 MeV Au ion falls quickly away from the surface value. (SRIM)



The LET in silicon, as a function of the ion depth, of an impinging 900 MeV Au ion presents a broad plateau before falling.



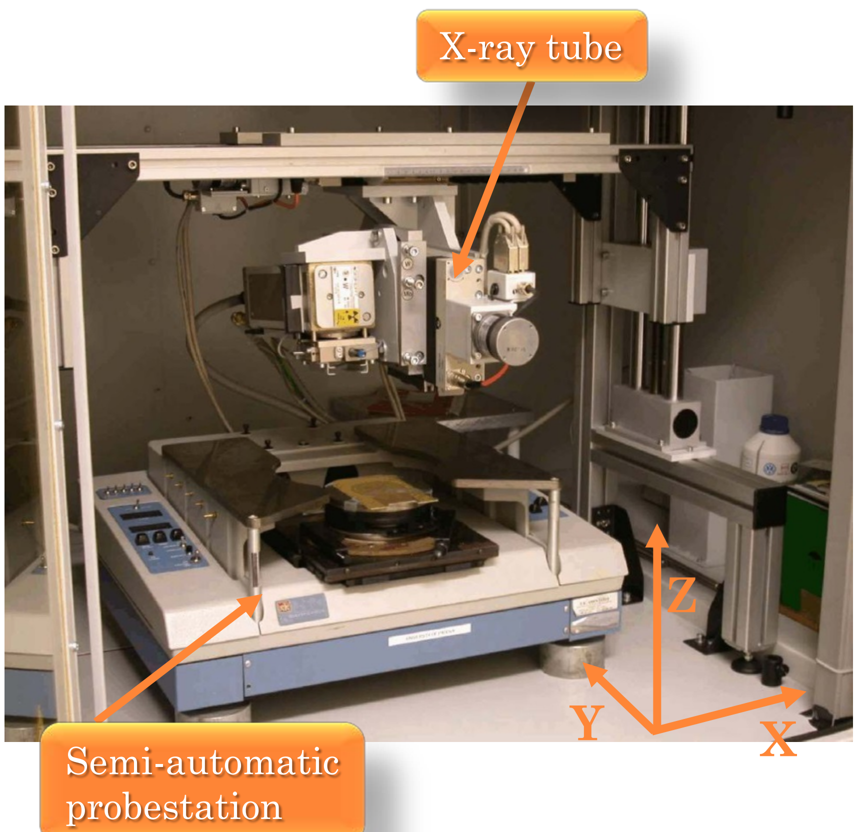
Ion beams available at SIRAD

			Tandem			Tandem+ALPI		
Ion Species	q_1	q_2	Energy [MeV]	Range in Si [µm]	Surface LET in Si [MeV×cm²/mg]	Energy [MeV]	Range in Si [µm]	Surface LET in Si [MeV×cm²/mg]
^{1}H	1	1	28	4340	0.02	-	-	-
^{7}Li	3	3	56	376	0.37	-	-	-
^{11}B	4	5	80	185	1.13	-	-	-
^{12}C	5	6	94	164	1.53	-	-	-
^{16}O	6	7	108	107	2.95	-	-	-
^{19}F	7	8	122	95	3.90	-	-	-
^{28}Si	8	11	157	61	8.58	542	373	3.9
^{32}S	9	12	171	54	11.1	591	311	5.2
^{35}Cl	9	12	171	50	12.7	591	268	6.2
^{48}Ti	10	14	196	40	20.9	686	188	10.9
^{51}V	10	14	196	38	22.6	686	171	12.2
^{58}Ni	11	16	220	37	29.4	780	147	17.3
^{63}Cu	11	16	220	34	31.9	780	135	19.1
^{74}Ge	11	17	231	33	36.9	826	121	23.8
^{79}Br	11	18	241	33	41.8	871	112	28.1
^{107}Ag	12	20	266	29	58.4	966	83	49.4
^{127}I	12	21	276	30	65.4	1011	77	61.8
^{197}Au	13	26	275	26	79.1	1185	69	92.4

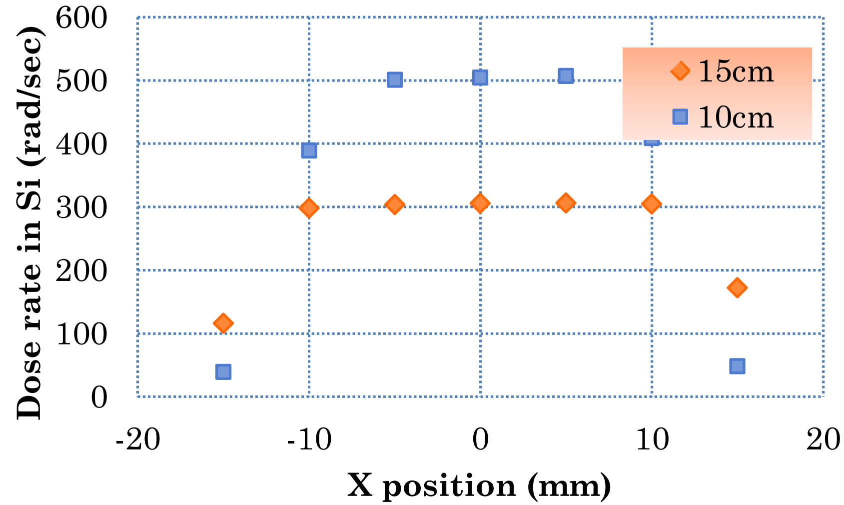
X and γ rays

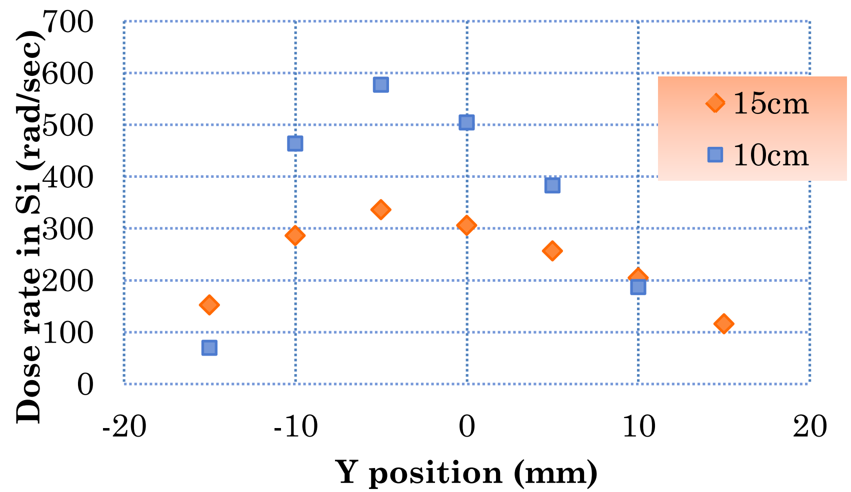
TOTAL DOSE STUDIES: X-RAY MACHINE

- Tube with **W** (7.4-12.06 keV L-lines) anode.
- Maximum tube voltage 60 kV. Maximum tube current 50 mA.
- X,Y and Z (manual) axis for accurate position setting of the tube.



Dose rate in *x* and *y*



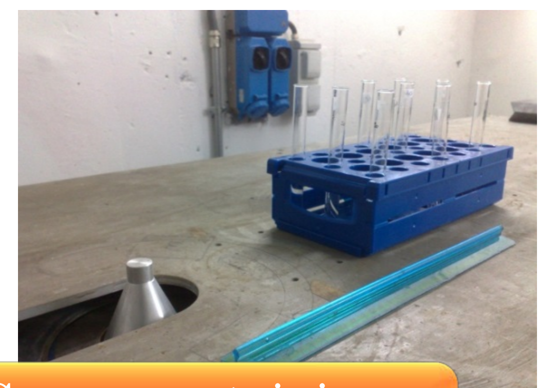


TOTAL DOSE STUDIES: ^{60}CO γ SOURCE

- Managed by Legnaro LNL Laboratories
- Irradiation Facility: Panoramic Gammabeam model 150 produced by Nordion Ltd (Canada)
- Photon energies: 1.165 MeV and 1.332 MeV
- Point source for D>10 cm (D=10-300cm)

Distance from source	20 cm	45 cm
Dose rate in Si (Jan 2013)	1.85 rad/s	0.37 rad/s
	6.67krad/h	1.32 krad/h

^{60}Co source shielding



Source-containing retracted cylinder

Neutrons

CN ACCELERATOR

- Electrostatic accelerator (Van de Graaff type)
- Maximum terminal working voltage: 7MV
- Available accelerated ions:
  - $^{1,2}H$, ^{3}He, ^{4}He single and double charged
  - D, double charged
- Continuous and pulsed beam
- 1 experimental hall, 7 beamlines

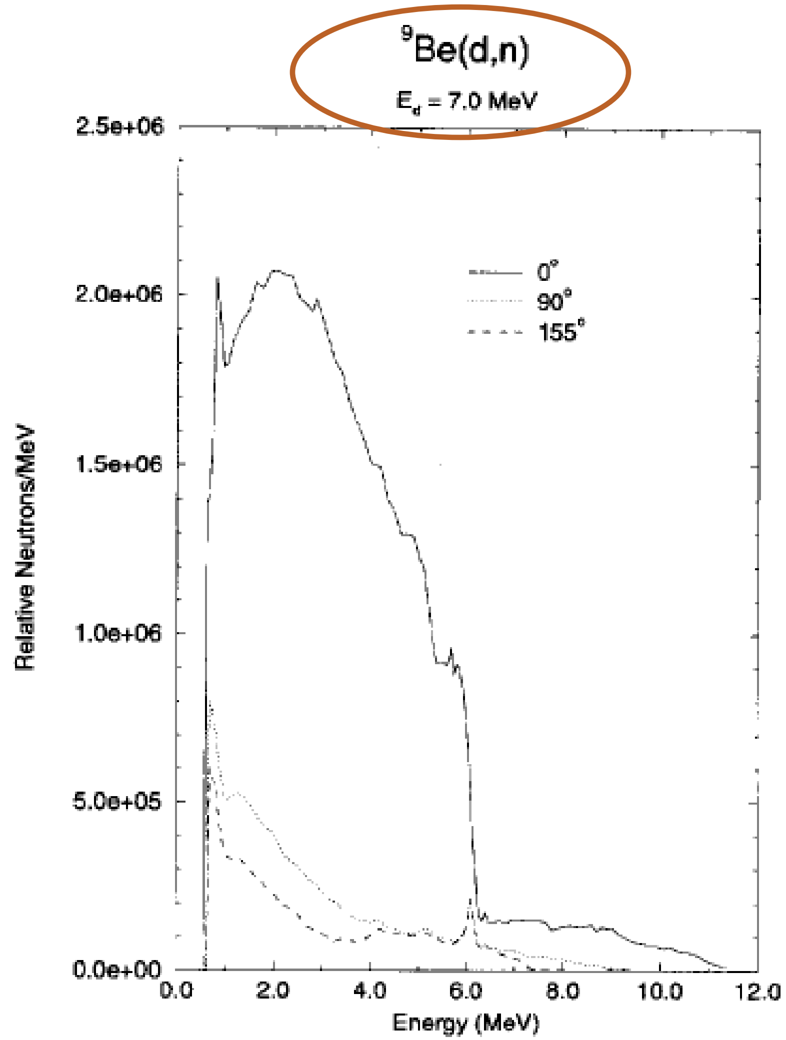
For single charged particles (^{1}H, ^{2}H, ^{4}He)

- Energy range: 0.85-6 MeV
- Beam current:
  - <5 μA (depending on the channel, and limited mainly by radioprotection reasons) on a spot size of 2-3mm^2
  - Low limits not set by the machine; beam intensity can be decreased with the use of unfocused beam, slits, etc (a «single ion microbeam» facility is also available, down to few particles/s with a spot size of ~ 5 μm)

NEUTRON BEAM

Reaction	E_{beam} (MeV)	I_{max} (nA)	Spectrum	$E_{neutrons}$ at 0° (MeV)
$D + {}^9Be \rightarrow n + {}^{10}B$	2-7	300	Continuous	0.06-11.4

- ✓ The neutron flux peaks in the forward direction



Future plans

At the INFN National Labs of Legnaro (LNL), a variable energy (35-70 MeV) high current proton cyclotron ($I_{max} = 750\ \mu A$) will soon come into operation.

It will open up the **prospect of high flux neutron facilities in Italy** that could perform various research activities.

Quasi Mono-energetic Neutrons (QMN) from 35-70 MeV protons

- multi-angle collimator for “tail” correction
- assortment of thin (2-4 mm) Li and Be targets

Continuous energy (white) ***atmospheric-like*** **neutrons** from intense 70 MeV protons. **Two high power targets:**

- a “conventional” ***thick (stopping)*** W-based target and moderator system (49 kW)
- a “novel” rotating BePb (or BeTa) composite target system, ***relatively thick*** (non-stopping), without moderator

See Wyss’s (today) and Silvestrin’s (tomorrow) talks

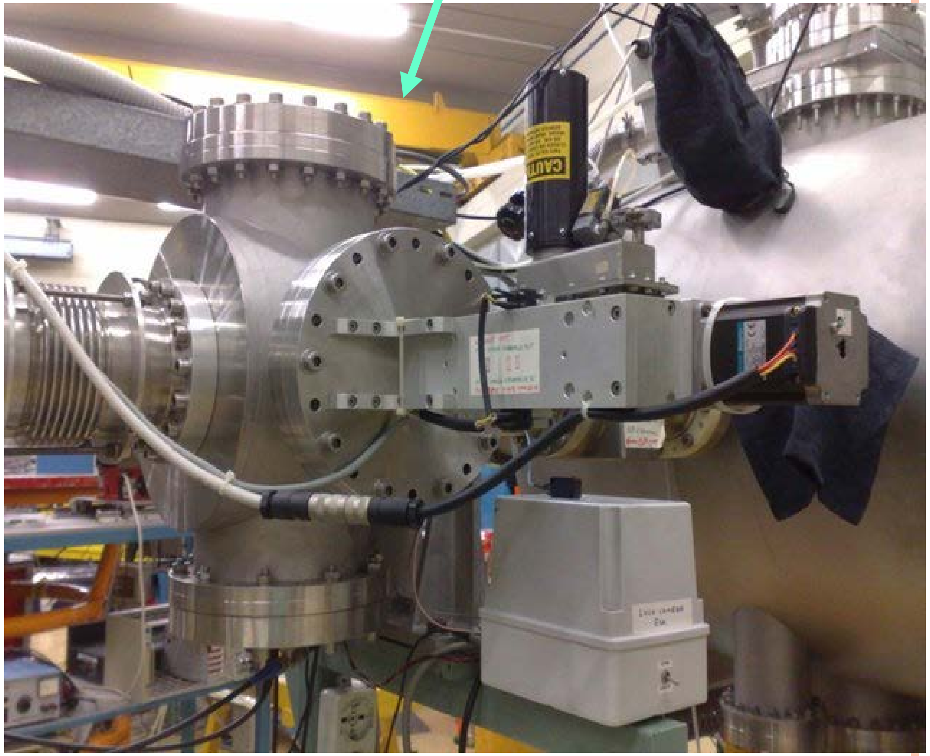
CONCLUSIONS

- **Radiation damage** is a critical issue for a large number of applications
- Legnaro has a long experience in electronics **validation**
- Giving the shrinking of the feature size of modern transistors, neutron induced Single Event Effects are becoming critical for industrial applications: it is important to provide a proper **neutron beam**

Description of the SIRAD beamline

The **"old" irradiation chamber** (2001-2006), now used for beam alignment and diagnostics (increases the vacuum impedance)

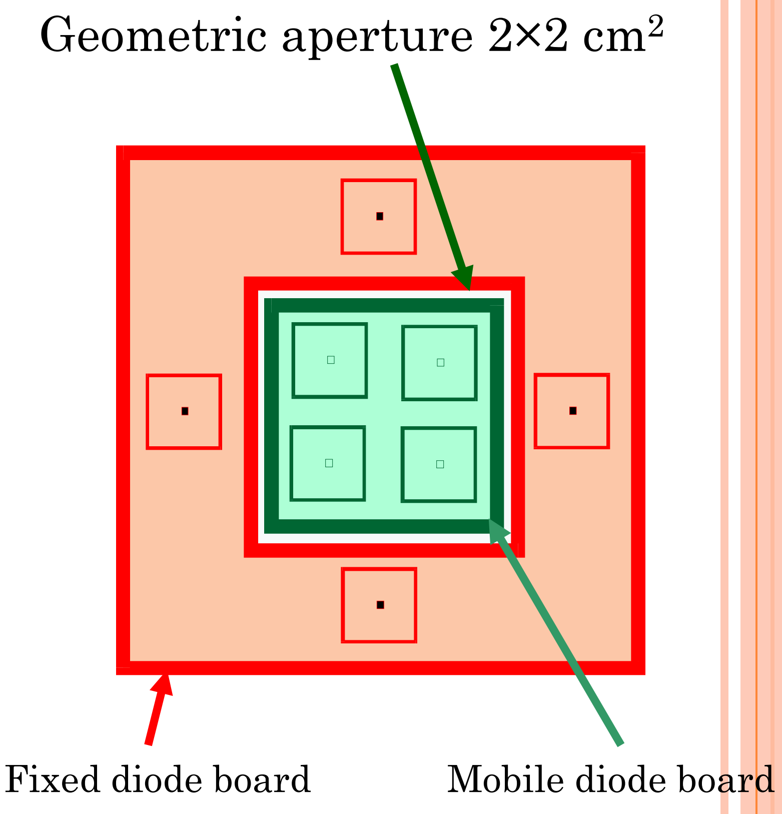
Motorized Faraday cup



DOSIMETRY FOR LOW FLUX (10^2-10^5 IONS/CM$^2\times$S)

- A **low ion beam flux is measured by 8 silicon diodes** with 0.5×0.5 cm^2 area and 300 μm thickness, connected to a dedicated read-out electronic and computer-controlled data acquisition system:

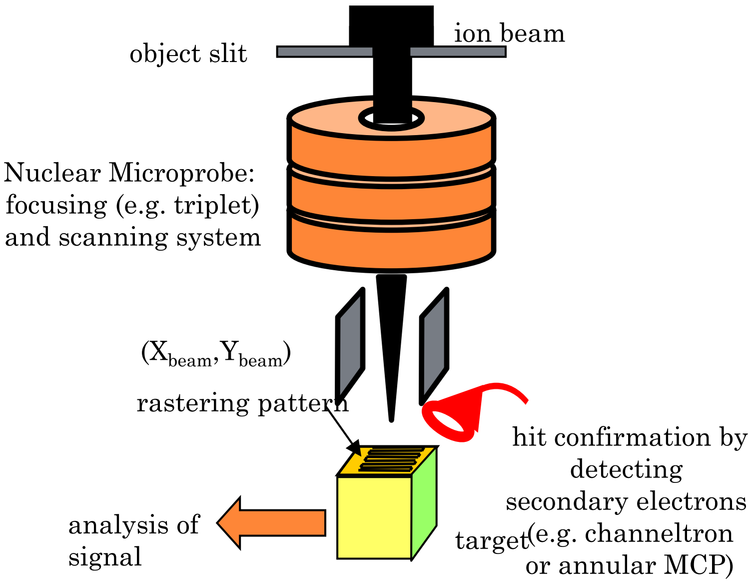
- **Beam flux**
  - **uniformity**: better than 10% on the device under test area;
  - **range**: 10 - 5×10^5 ions/cm^2×s.



In agreement with
"ESA ESCC basic specification 25100"

MICROMETRIC SENSITIVY STUDIES: TWO APPROACHES

⊙ Nuclear Microprobe analysis

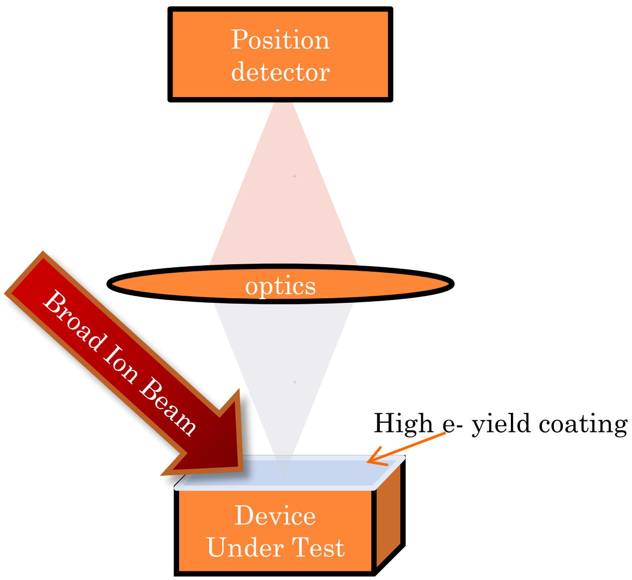


➢ A Nuclear Microprobe (NMP) focuses ions into spots of 0.5-1 μm FWHM (best) in diameter

➢The device is scanned with the microfocused beam to provide information about its local sensitivity to single event effects

➢ This approach was taken into consideration, but is was too expensive in terms of money, hardware and human resources

⊙ Ion Electron Emission Microscopy



B. L. Doyle, et al., "A new approach to nuclear microscopy: the ion–electron emission microscope" Nucl. Instr. Meth. B 158 (1999) 6.

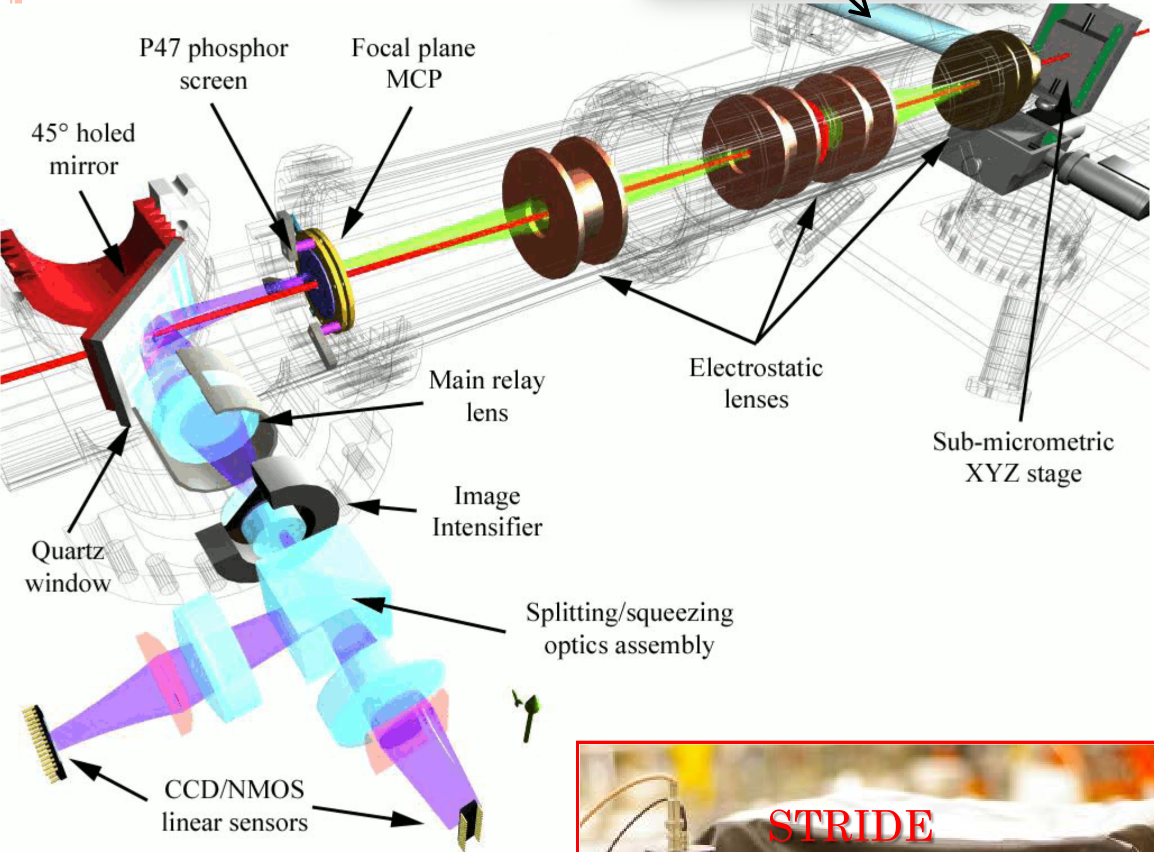
➢ The IEEM does not focus high-energy ions but it determines the position at which an individual ion enters the surface of the sample by imaging the secondary electron which are emitted as a consequence of the interaction.

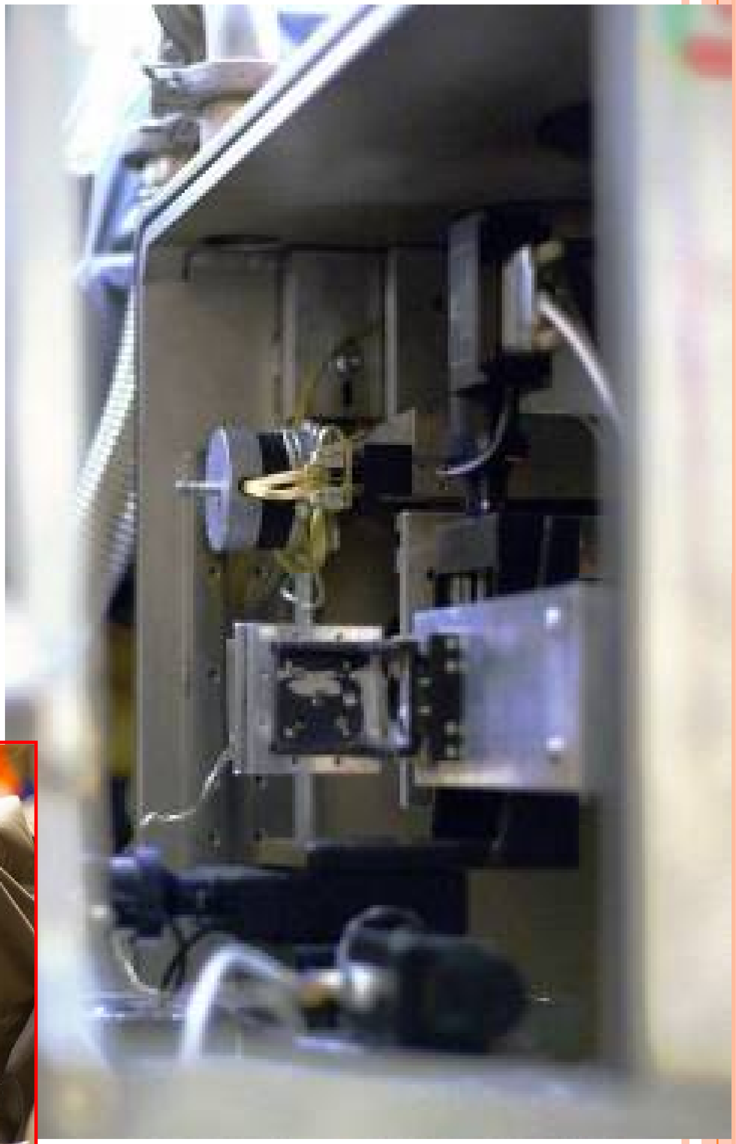
➢ The reconstructed positions are put in temporal correlation with the ion-induced signal in the Device Under Test

➢ It is a low cost (and size!) solution, with comparable resolution (FWHM 3 μm IEEM with a 180μm FOV), which could be quite easily integrated with the pre-existing SIRAD facility

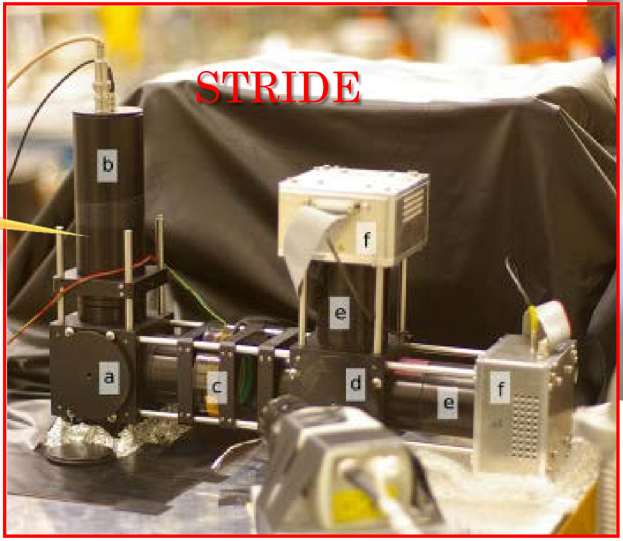
Axial IEEM

UV light for focusing





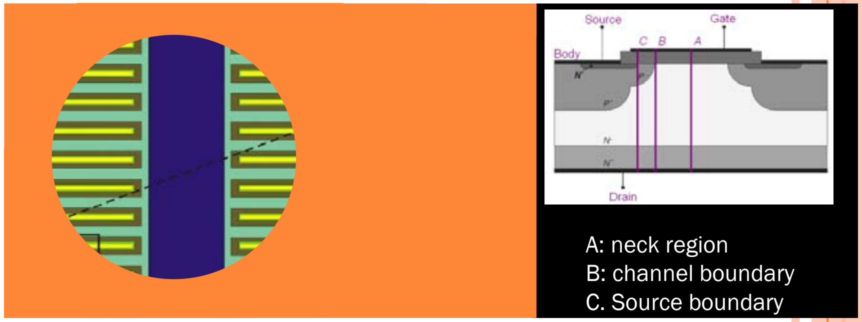
Phototube for fast signal (delay < 50 ns)



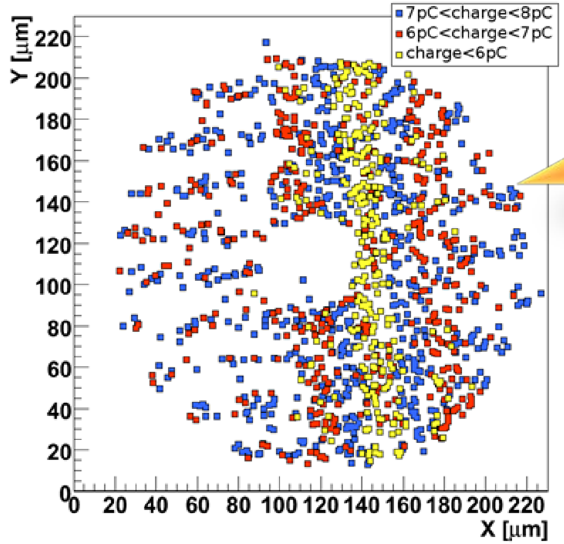
a) Beam splitter
b) PMT
c) Image Intensifier
d) STRIDE beam splitter
e) Squeezing optics
f) NMOS sensors

Sensitivity map

- The IEEM has been used to perform an Ion Beam Induced Charge Collection (IBICC) type experiment irradiating a **power MOSFET device** with 223 MeV ^{79}Br ions.
- The power MOSFET is made of thousands of strip-shaped cells, with lateral size of 20 μm and several hundreds μm long.
- Device simulations show that, for ion impacts above the neck and the channel region, the electric field inside the oxide layer can reach values so high as to cause a significant transient conduction in the oxide and the subsequent formation of a latent damage in it. Latent damage can lead to the gate oxide rupture (Single Event Gate Rupture, SEGR).



The charge collected at the MOS contacts for an ion impact is correlated to the damage induced in the gate oxide and can be used to reveal the onset of degradation phenomena like latent damages or SEGR

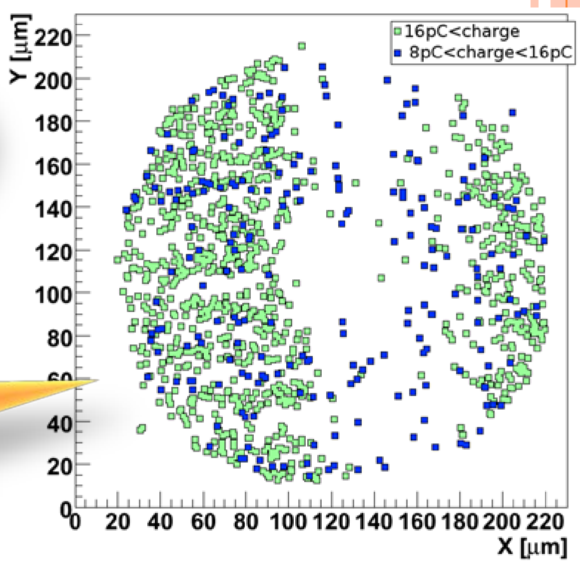


Low charge events:

- threefold structure of the electrical field below the gate distribution line.
- Low charge impacts in the neck regions

High charge events:

- the largest part of these impacts takes place in the device active areas (source and channel regions)

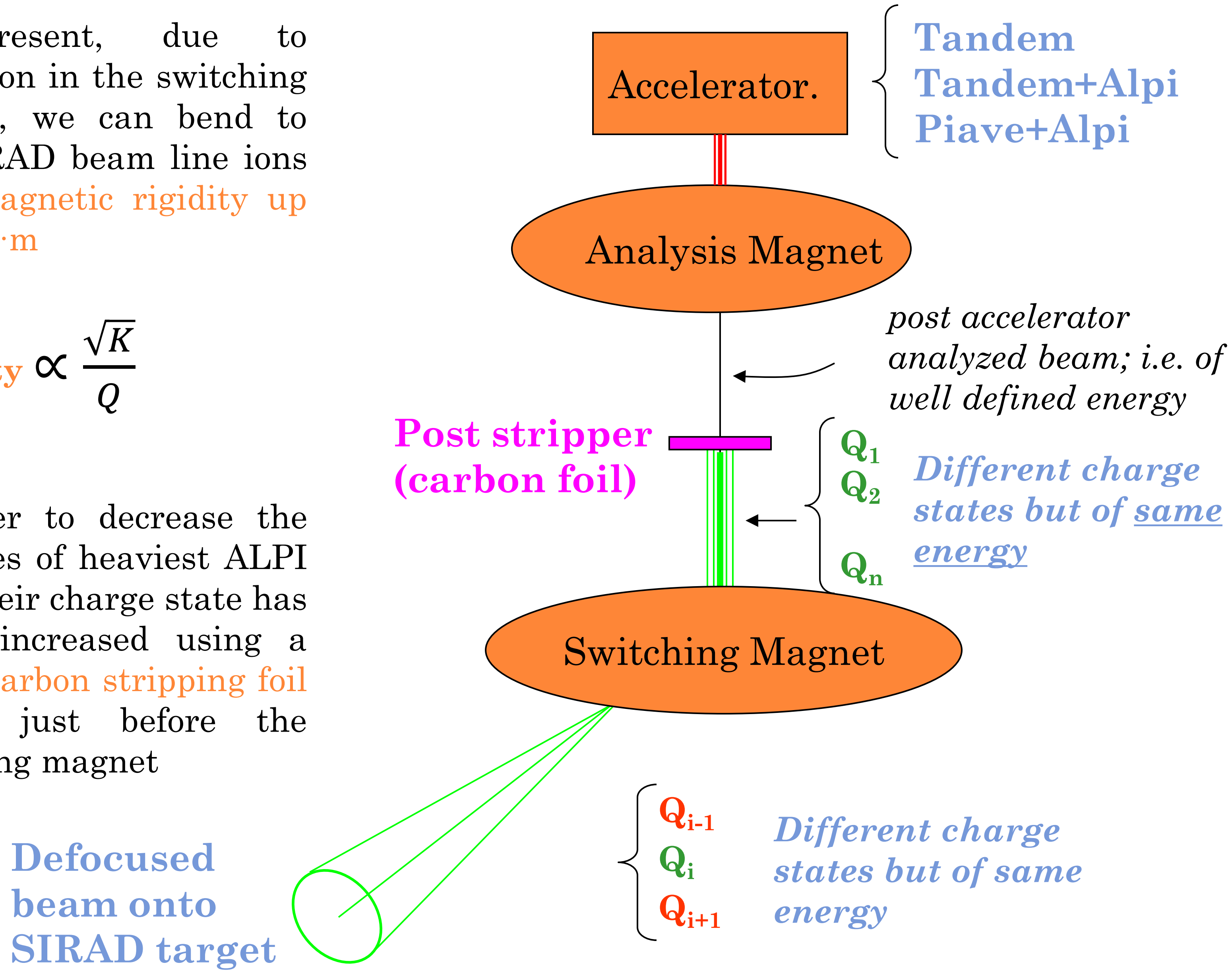


The idea to deal with rigidity limit

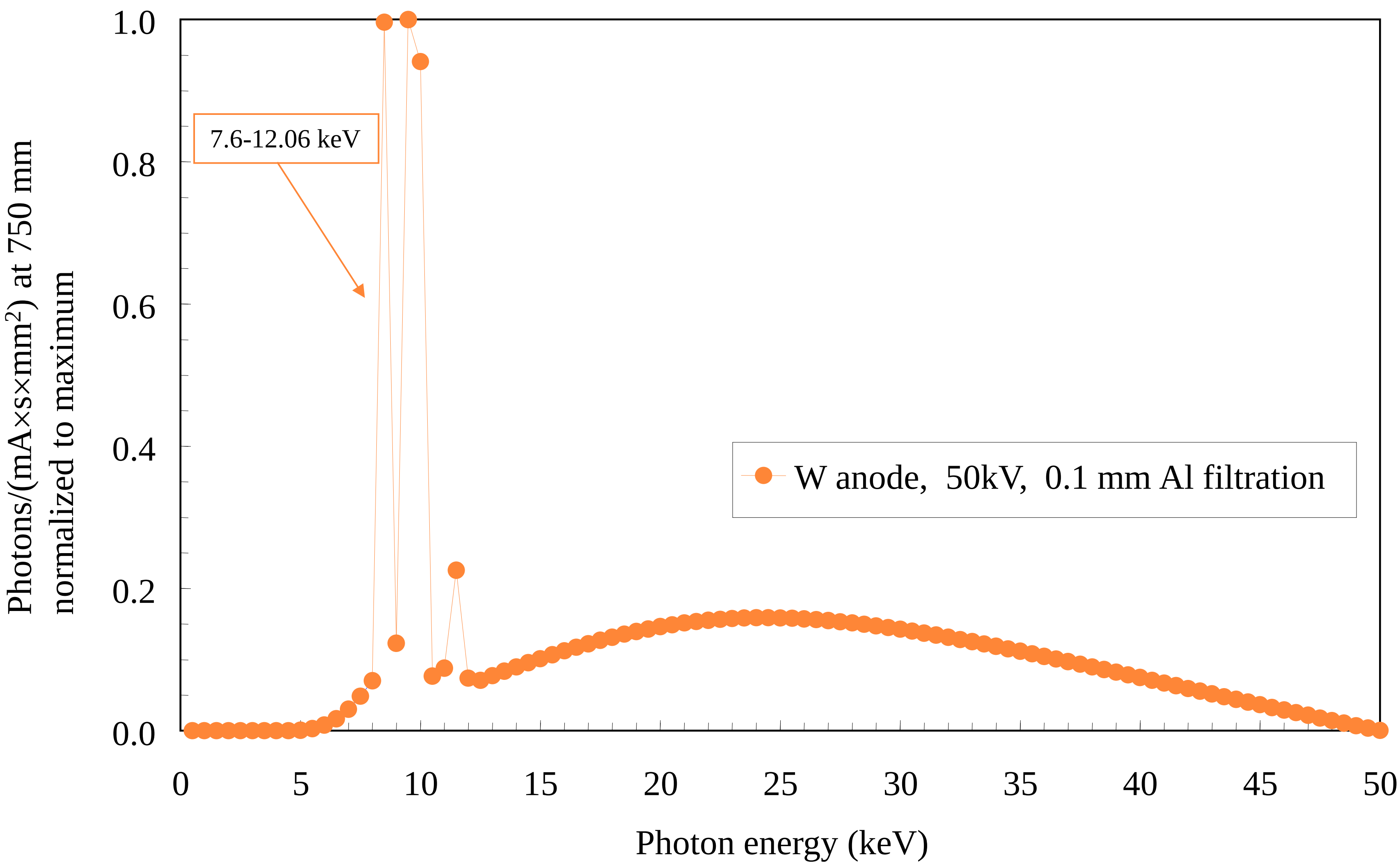
- At present, due to limitation in the switching magnet, we can bend to the SIRAD beam line ions with magnetic rigidity up to 1.6 T·m

- **Rigidity** $\propto \frac{\sqrt{K}}{Q}$

- In order to decrease the rigidities of heaviest ALPI ions, their charge state has to be increased using a single carbon stripping foil placed just before the switching magnet



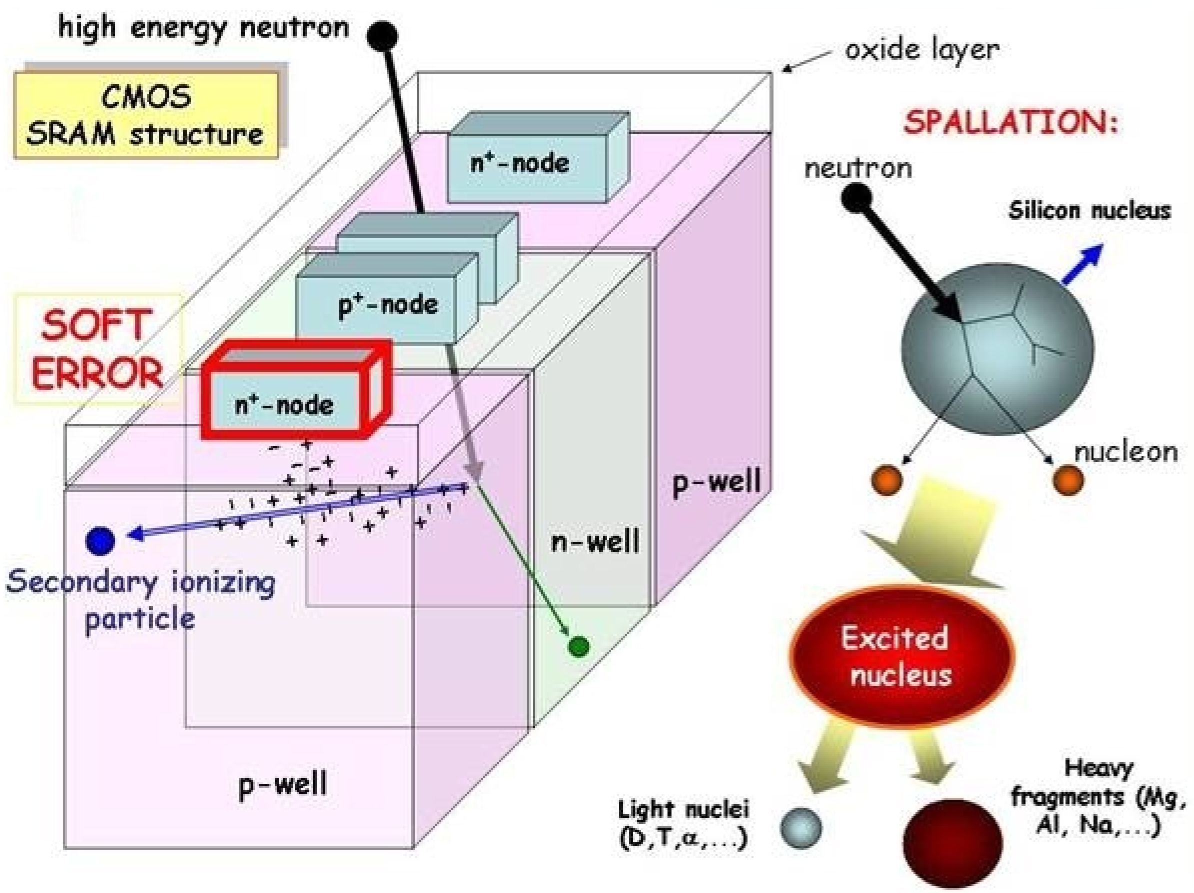
EMISSION SPECTRUM



Physics of neutron-induced SEE

(1) Primary neutron
(accelerator, cosmic-rays,…)

(2) neutron-nucleus reactions with production of ionizing secondaries
(Nuclear Physics)



(3) Generation of electron-hole pairs
(radiation physics and solid-state physics)

(4) Charge transport in device
(device physics)