The SIRAD irradiation facility at LNL

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INFN

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23-27 Marzo 2015
INFN Laboratori Nazionali di Legnaro (Padova)

Outline

- The SIRAD irradiation facility at the TANDEM accelerator:

  - high energy protons and ions irradiations (low energy (7 MeV) protons and neutrons available at the CN accelerator)

- Equipment for total dose test

  - Tungsten and Molybdenum X-rays;

  - ^{60}Co γ-rays

- Future developments

  - Neutron SEE test facility at the SPES cyclotron

The SIRAD beamline

SIRAD beamline

The SIRAD irradiation facility is located in the experimental hall 1, beam line +70°, of the Legnaro Nuclear Laboratories of INFN, in Italy.

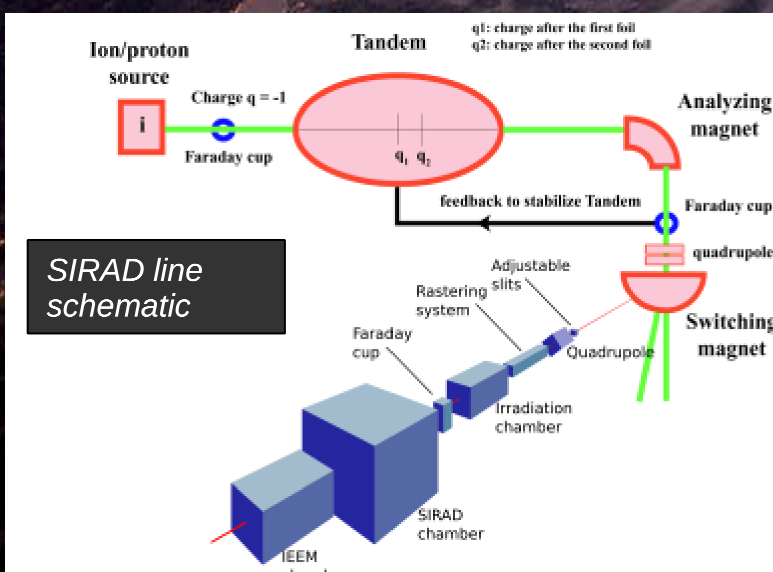
It is dedicated "to investigate radiation effects on silicon detectors, electronic devices and systems in radiation hostile environments".

It is capable of performing measurements of:

- *Total dose effects* (as a result of ionization damage);

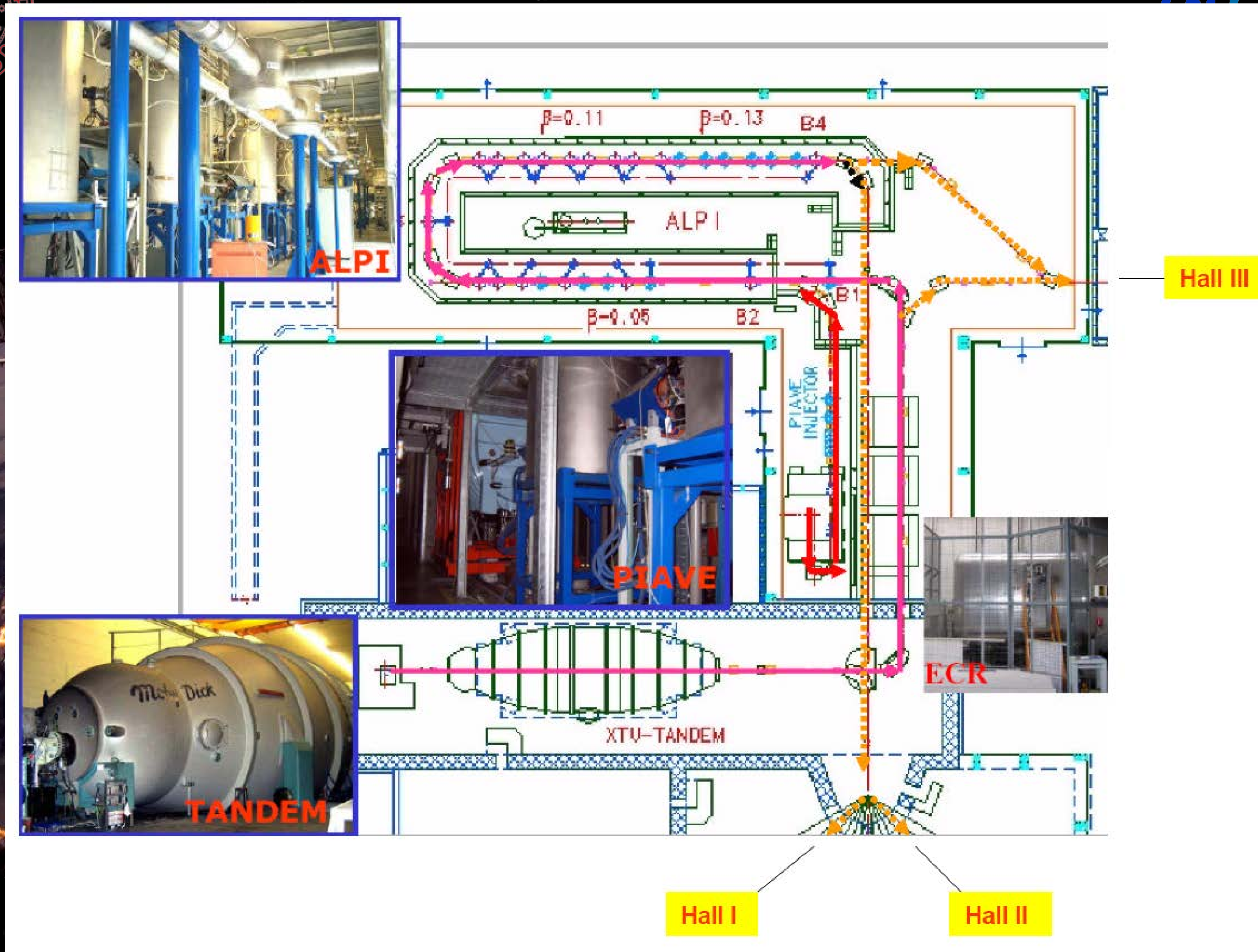
- *Bulk damage effects* (as a result of displacement damage);

- *Single event effects* (as a result of an energetic particle strike).



SIRAD line schematic

Tandem – ALPI – Piave complex



$$E_{\text{Tandem-ALPI}} = E_{\text{Tandem}} + E_{\text{ALPI}} = E_{\text{Tandem}} + Q_{\text{Tandem}} \times 35\ \text{MeV}$$

Typical ion beams at SIRAD

Ion species from ^{1}H (22-30 MeV) up to ^{197}Au (1.4 MeV/a.m.u.)
LET from 0.02 MeV×cm^2/mg (^{1}H) up to 81.7 MeV×cm^2/mg (^{197}Au)

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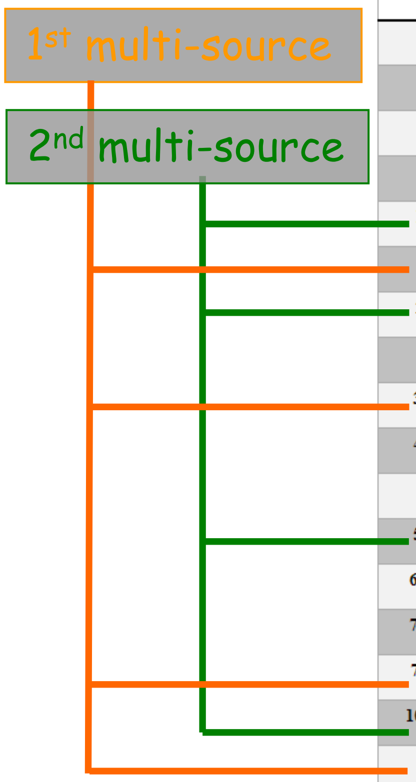
The energy values refer to the most probable q_1 and q_2 charge state, with two stripper stations, and the Tandem operating at 14 MV.



	Tandem			Tandem + Alpi		
Ion	Energy [MeV]	Range in Si [μm]	Surface LET in Si [MeV cm^2 mg^{-1}]	Energy [MeV]	Range in Si [μm]	Surface LET in Si [MeV cm^2 mg^{-1}]
^{1}H	28	4340	0.02			
^{7}Li	56	376	0.37			
^{11}B	80	185	1.13			
^{12}C	94	164	1.53	273	993	0.65
^{16}O	108	107	2.95	358	715	1.2
^{19}F	122	95	3.90			
^{28}Si	157	61	8.58			
^{32}S	171	54	11.1	556	278	5.5
^{35}Cl	171	50	12.7			
^{48}Ti	196	40	20.9			
^{51}V	196	38	22.6			
^{58}Ni	220	37	29.4	775	146	17
^{63}Cu	220	34	31.9	859	153	18
^{74}Ge	231	33	36.9	918	138	23
^{79}Br	241	33	41.8	550	67	35
^{107}Ag	266	29	58.4			
^{127}I	276	30	65.4			
^{197}Au	275	26	79.1	1475	82	90

A selection of the ions available at the Tandem/Alpi accelerators complex. A complete table is available at http://www.lnl.infn.it/~tandem/tandem_piave_alpi_beams_b.htm, and more beams can be requested at the Linac-Tandem operation team.

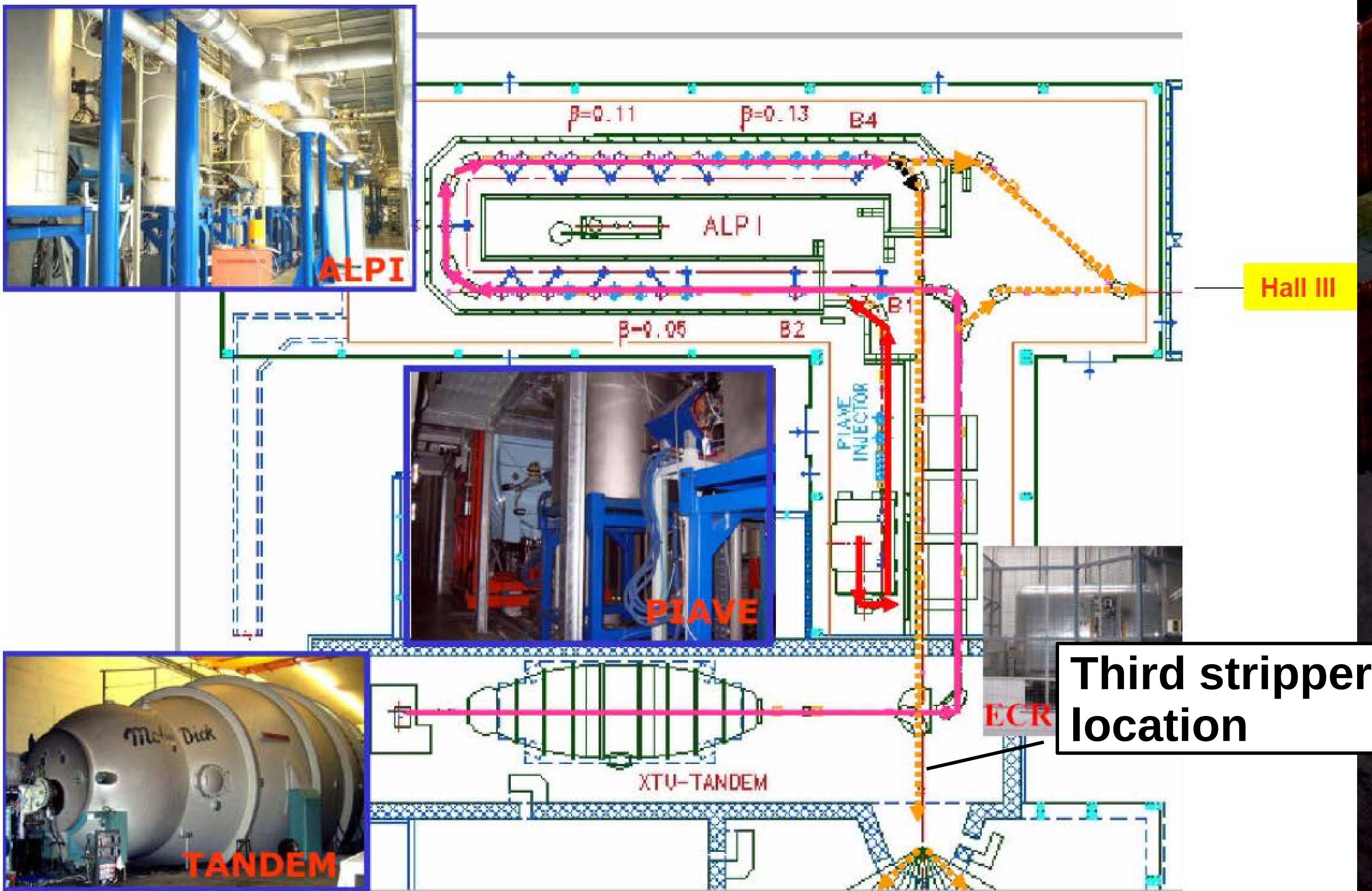
Proposed ion beams at SIRAD

Future development: use high energy ALPI and Piave beams in order to increase the ion range in Si. At the SEE Facilities routinely used by ESA (RADEF and HIF) the range is higher than 100 μm.

Piave + Alpi				
Ion	Energy [MeV]	I_{target} [pnA]	*Range in Si [μm]*	Surface LET in Si [MeV cm^2 mg^{-1}]
$^{15}N^{5+}$ (*)	251	2	568	1.1
$^{40}Ar^{9+}$	425	16	142	9.4
$^{48}Ca^{11+}$	535	12	170	9.5
$^{84}Kr^{15+}$ (*)	728	10	85	34
$^{93}Nb^{16+}$	779	8	85	40
$^{68}Zn^{17+}$ (*)	792	8	132	20
$^{92}Mo^{21+}$(**)	910	6	89	41
$^{120}Sn^{21+}$ (*)	1021	6	83	56
$^{132}Xe^{26+}$ (*)	1249	6	91	60
$^{152}Sm^{26+}$ (*)	1267	6	94	69
$^{197}Au^{30+}$ (*)	1475	4	82	90

Ions available at the Piave+Alpi accelerators complex http://www.lnl.infn.it/~tandem/tandem_piave_alpi_beams_b.htm, (*) only available in enriched form, (**) contact accelerator division before submitting proposal. More beams can be requested at the Linac-Tandem operation team.

Third stripper



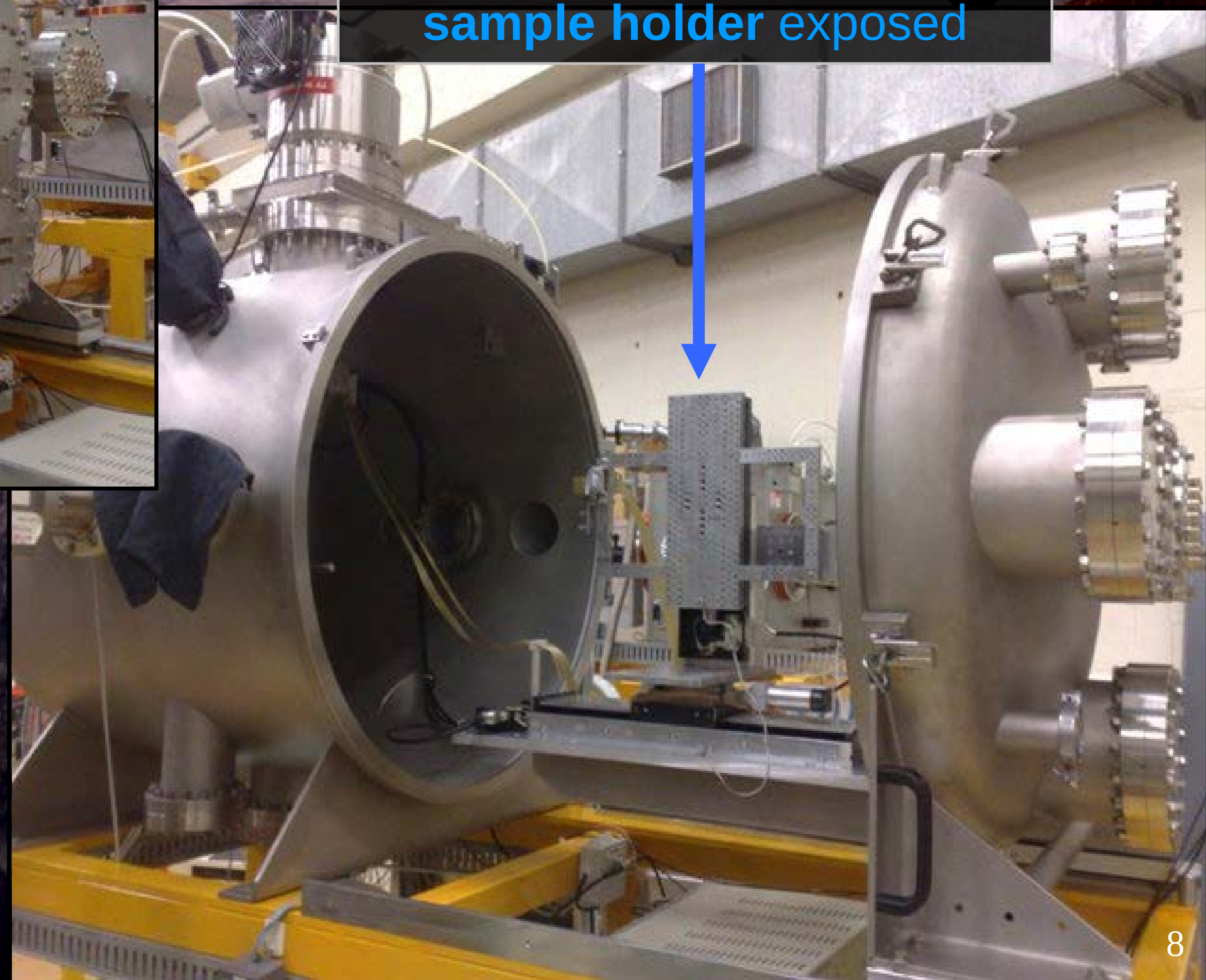
The high energy ALPI and Piave beams are characterized by a rigidity too high to be feeded by the switching magnet into the +70° beamline. By using a beam stripper (thin Carbon foil) the charge state of the beam can be increasing, thus reducing the rigdity.

SIRAD technical characteristics

The **new irradiation chamber** a.k.a.
ESA chamber (operating since 2006)

Diameter	80 cm
Depth	80 cm

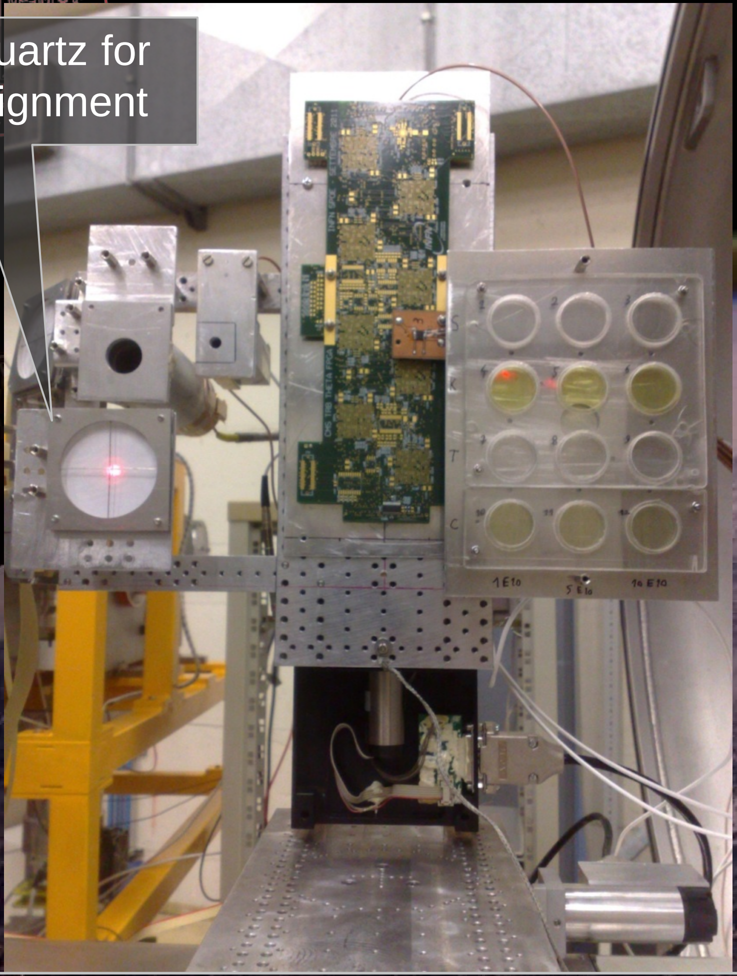
The chamber is open with the **sample holder** exposed



The ESA chamber is provided of a fully automatic vacuum system.
A pressure of 10^{-6} mbar can be reached in 30 min of pumping time

SIRAD technical characteristics

Quartz for alignment



Electrical connectors on the chamber:
24 BNC connectors in total (8 are high voltage)
2 connectors DSUB with 50 pin

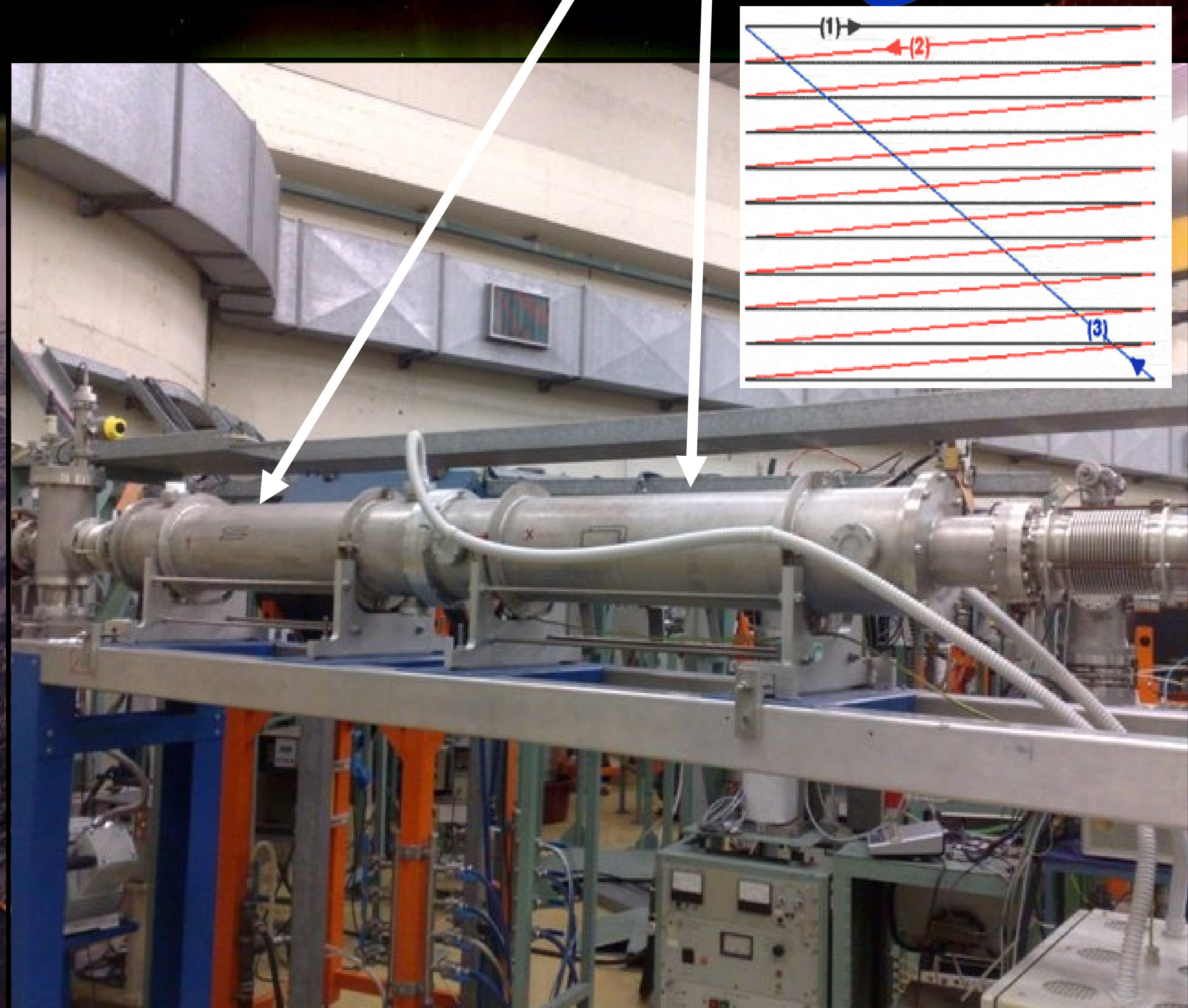
Motorized sample holder

Horizontal transl.	30 cm
Vertical transl.	15 cm
Resolution	< 10 µm
Rotation axis	vertical, +/-80^o (1^o steps)

The laser illuminated spot when the chamber is open will be the beam stroke spot when closed

SIRAD technical characteristics

Electrostatic rastering system



Focusing magnetic quadrupole

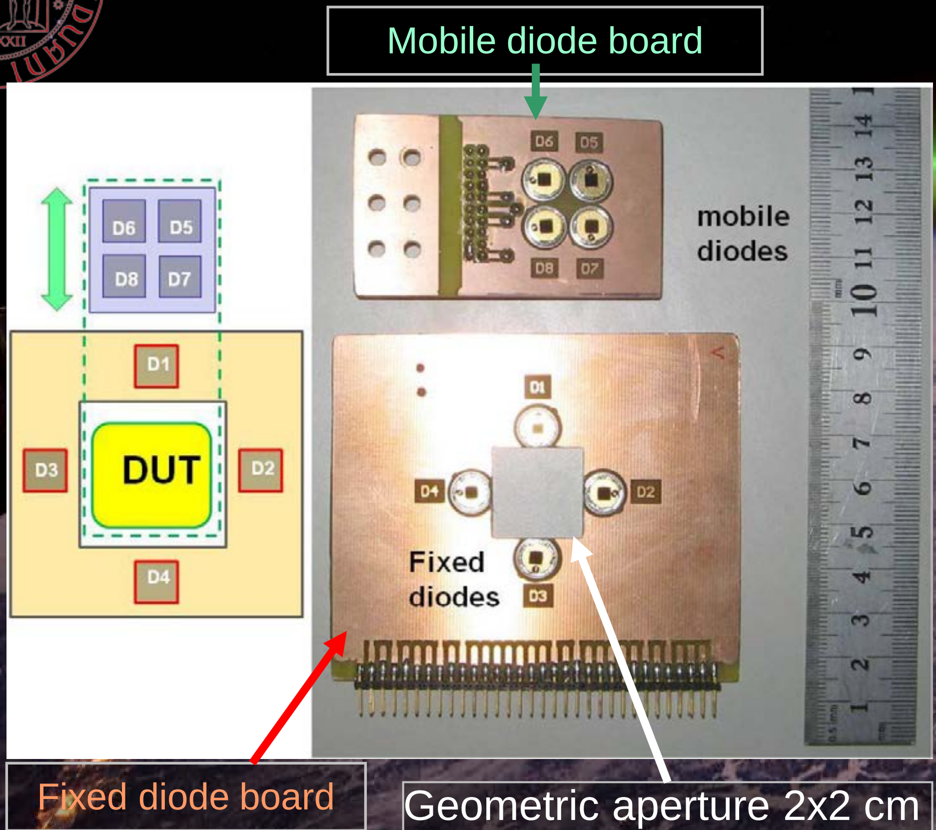
Steerer

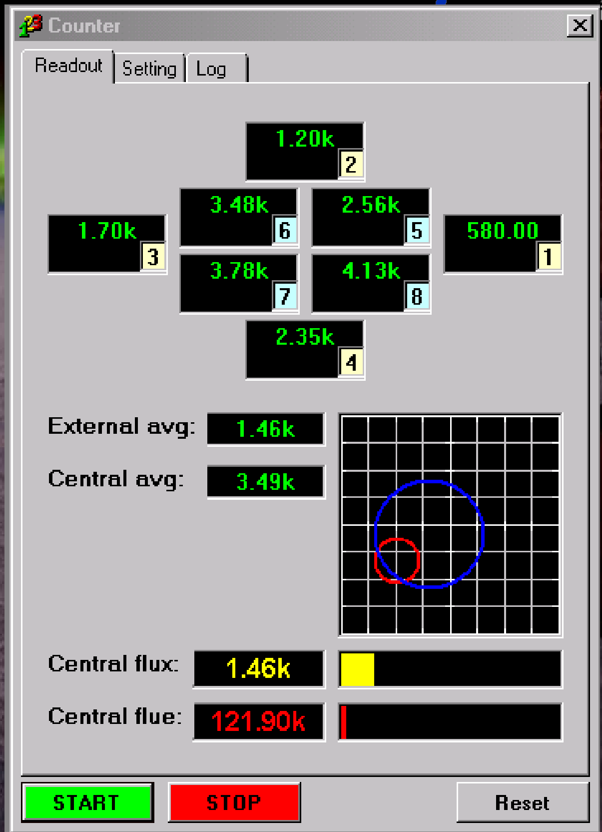
The rastering system is located 6m upstream of the target, it allows us to uniformly irradiate an area 5x5 cm^2 wide.

SIRAD technical characteristics

The **"old SIRAD irradiation chamber"** (2001-2006), now used for beam alignment and diagnostics (and to increase the vacuum impedance). It hosts a fast shutter that allows us to automatically stop the beam in 0.1 s

SIRAD dosimetry





In low flux conditions (up to 10^5 ions /(cm^2 s)) , the **ion beam flux is measured by 8 silicon diodes** with 7.7 mm^2 area and 300 µm thickness, connected to a dedicated read-out electronic and computer-controlled data acquisition system:

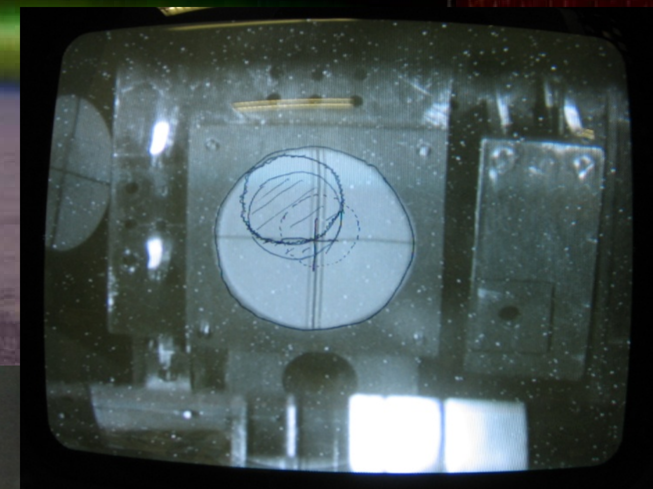
Beam flux

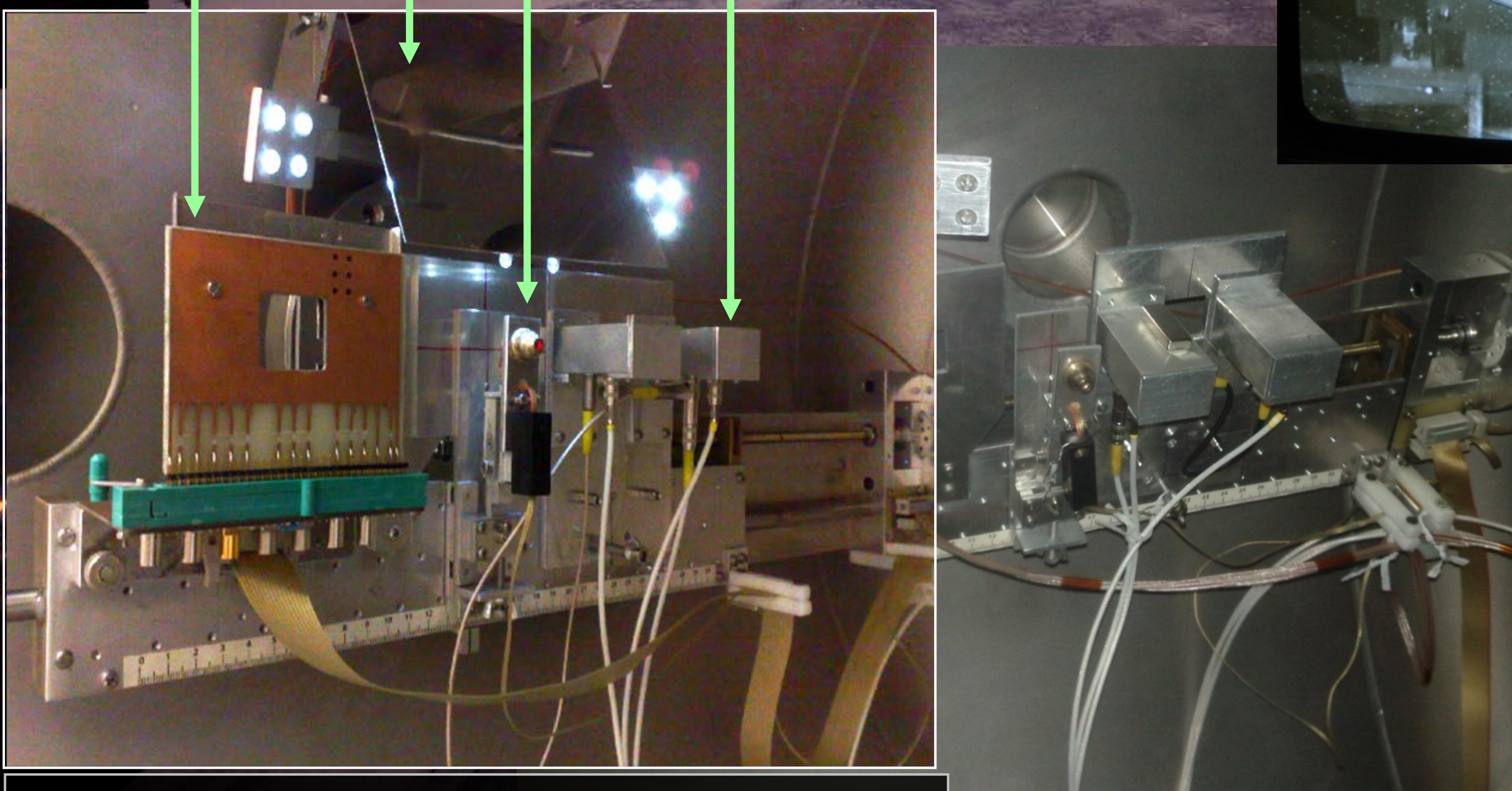
- **uniformity**: better than 10% on the device under test area;
- **range**: 10 - 5×10^5 ions/$cm^2\times$s.

SIRAD dosimetry

When the beam flux is high, >10^5 ions /(cm^2 s), Faraday cups are used for dosimetry, instead of PIN diodes.

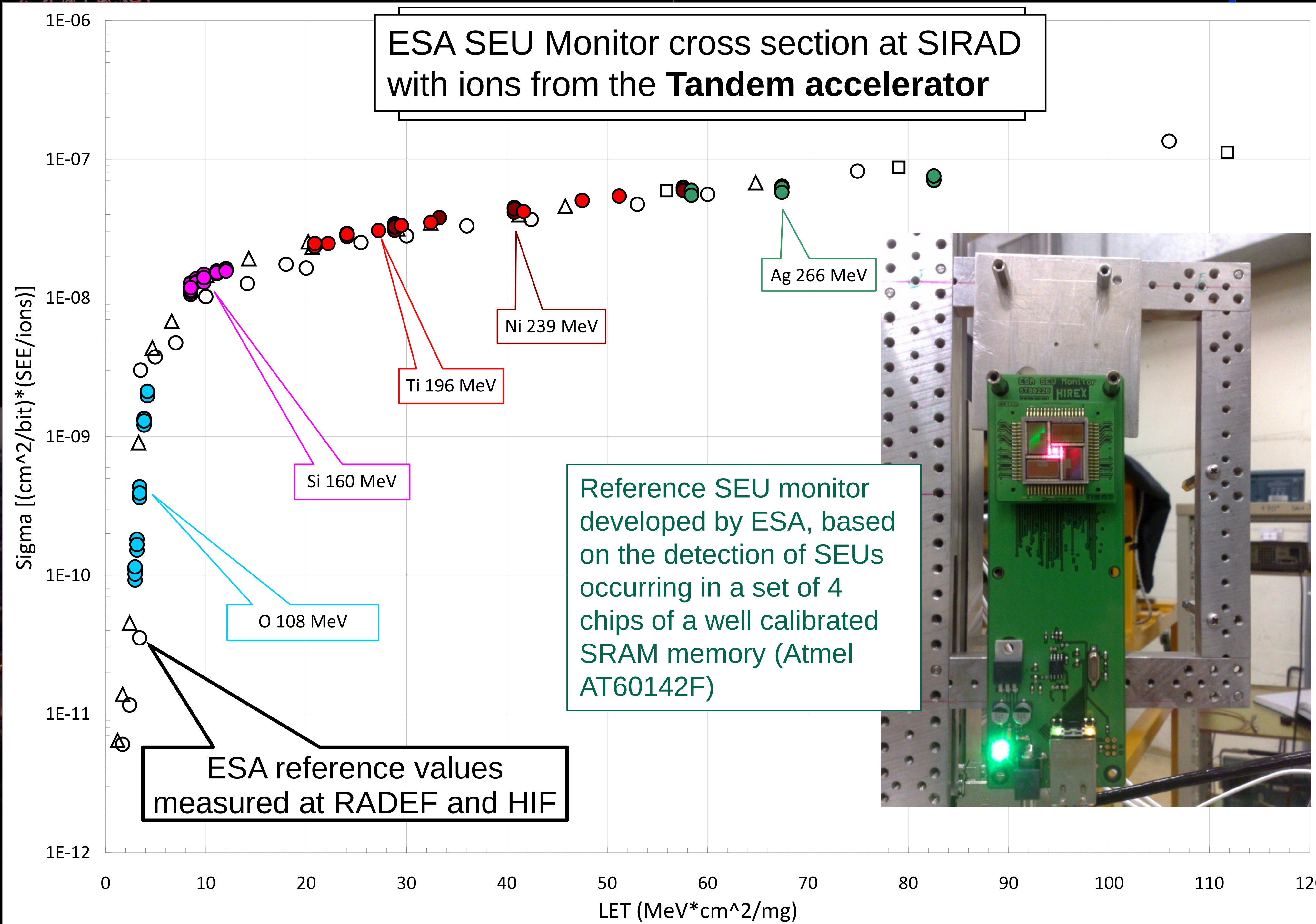
ESA chamber monitor showing the quartz window. Notice the radiation damage on the camera sensor.



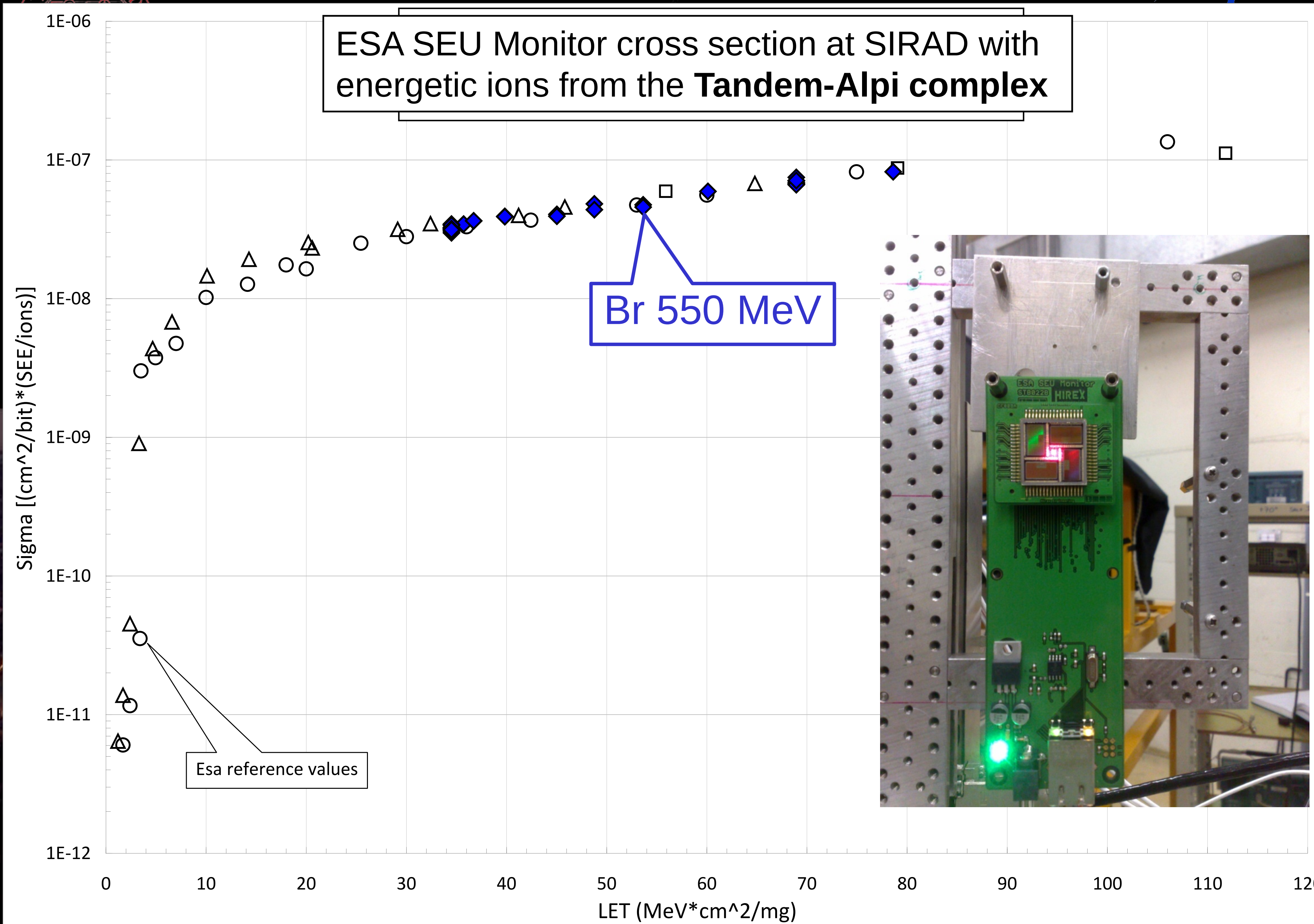


The dosimetry systems inside the ESA irradiation chamber

ESA SEU Monitor (Tandem)



ESA SEU Monitor (Tandem + Alpi)



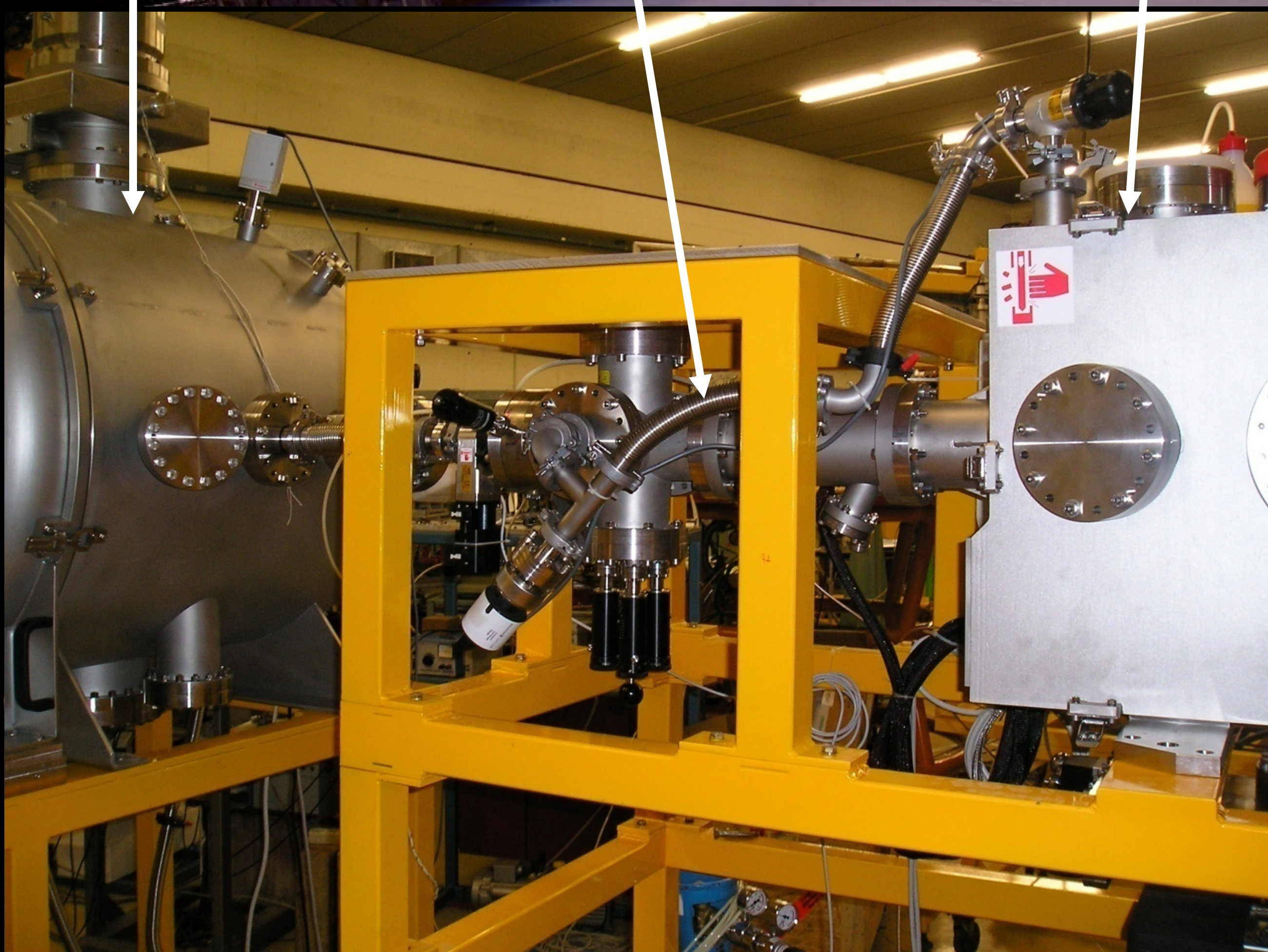
The Ion Electron Emission Microscope

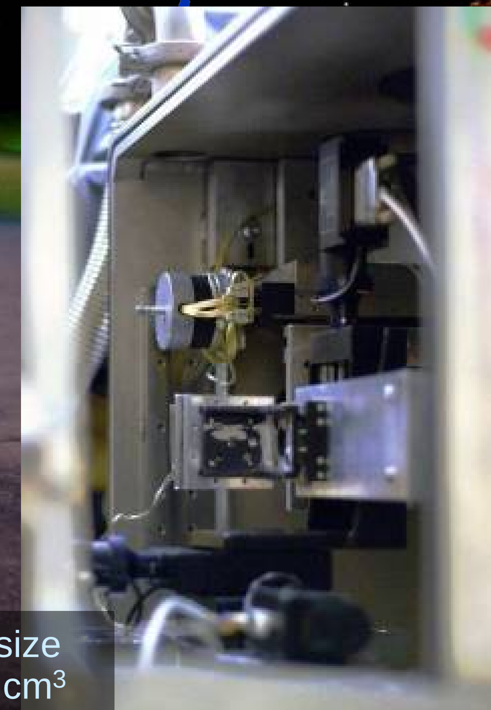
The IEEM is a tool designed to provide a map (with micrometric resolution) of the sensitivity to SEE of a microelectronic circuit

SIRAD chamber

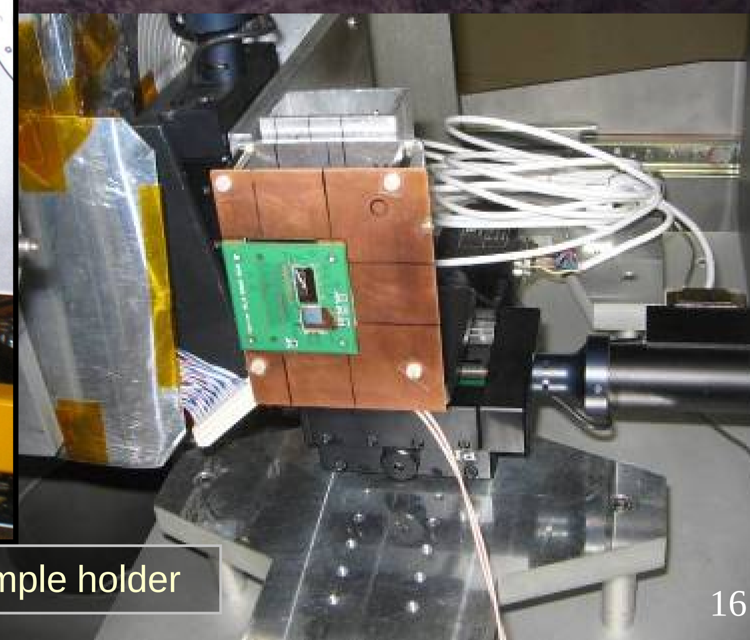
PEEM

IEEM chamber



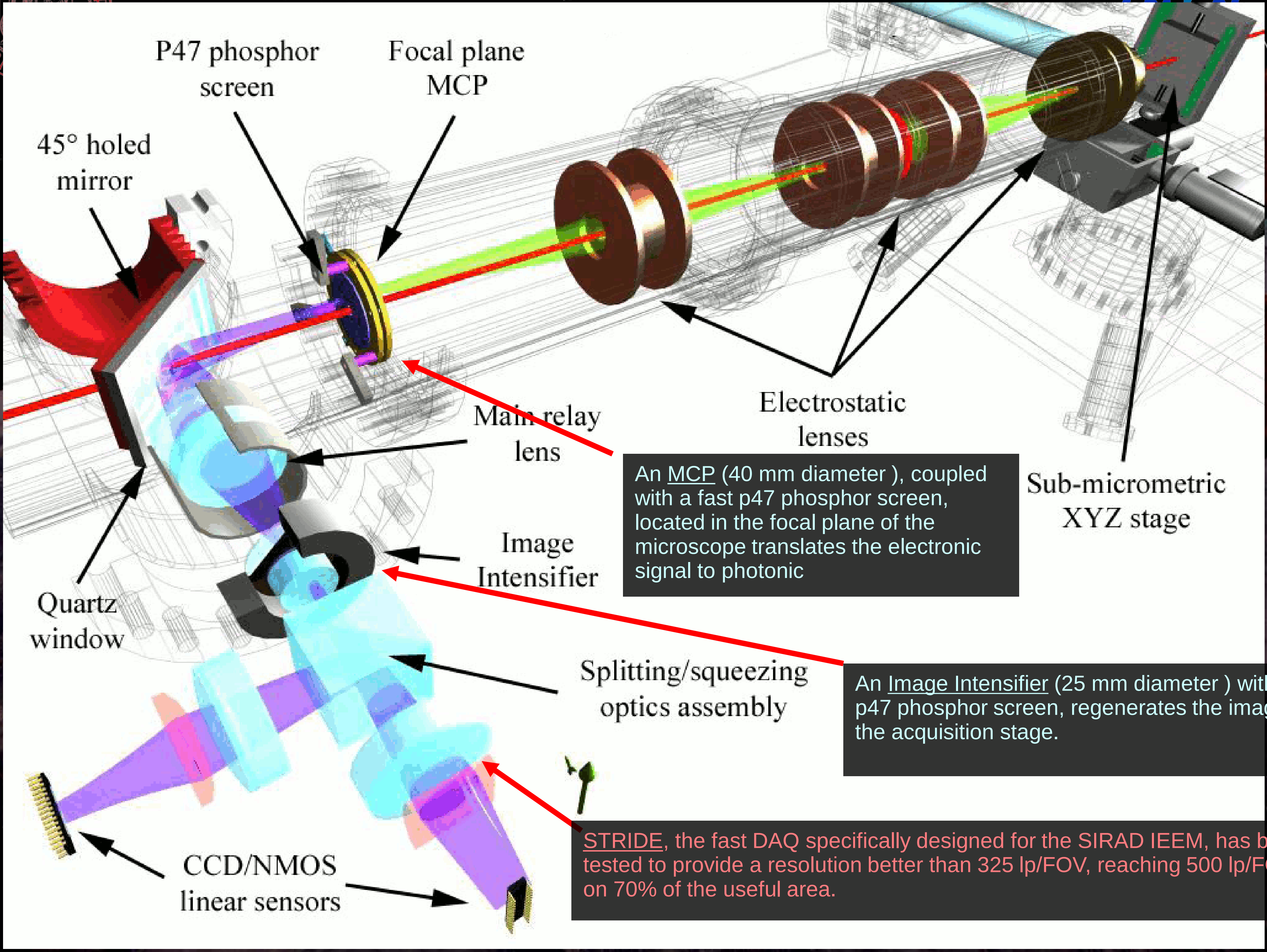


Chamber size
68x41x36 cm^3



IEEM sample holder

The Ion Electron Emission Microscope



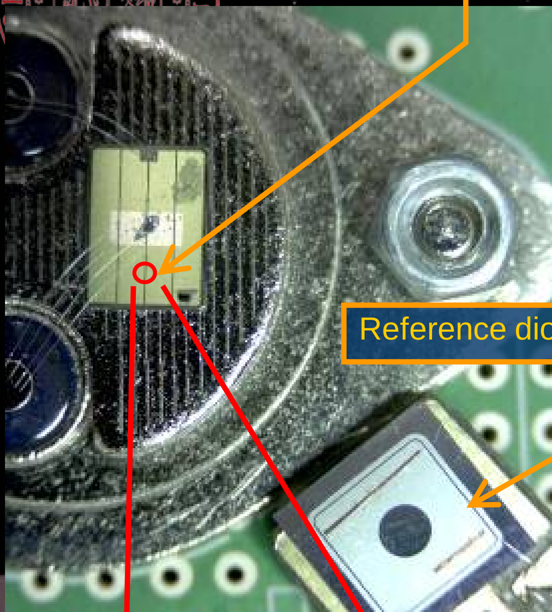
An MCP (40 mm diameter), coupled with a fast p47 phosphor screen, located in the focal plane of the microscope translates the electronic signal to photonic

An Image Intensifier (25 mm diameter) with fast p47 phosphor screen, regenerates the image for the acquisition stage.

STRIDE, the fast DAQ specifically designed for the SIRAD IEEM, has been tested to provide a resolution better than 325 lp/FOV, reaching 500 lp/FOV on 70% of the useful area.

IEEM results

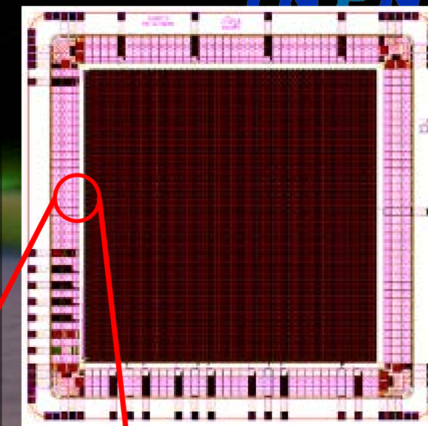
Irradiated area on a MOSFET chip



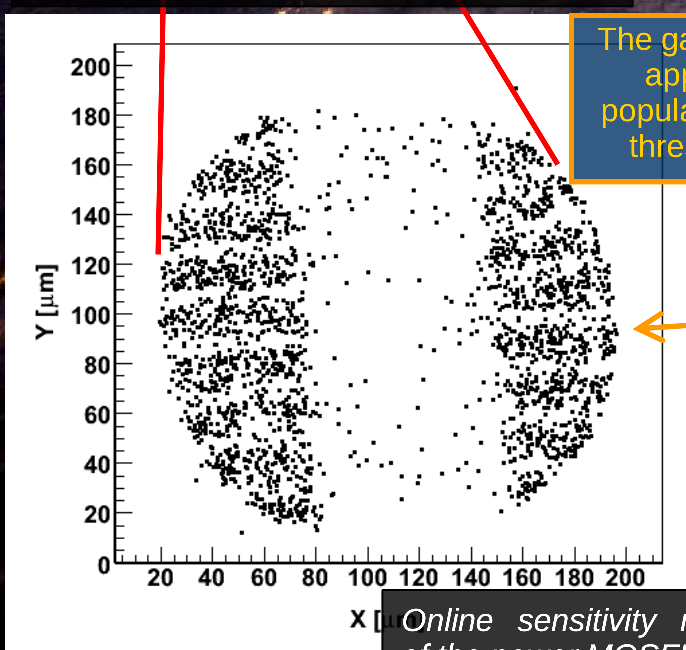
Reference diode

The power MOSFET chip near the PIN diode used for the positioning operations

These first results demonstrate the capability of the IEEM system to provide in-deep information of the structure of state-of-the-art electronic devices and to study ion-induced charge collection effects.

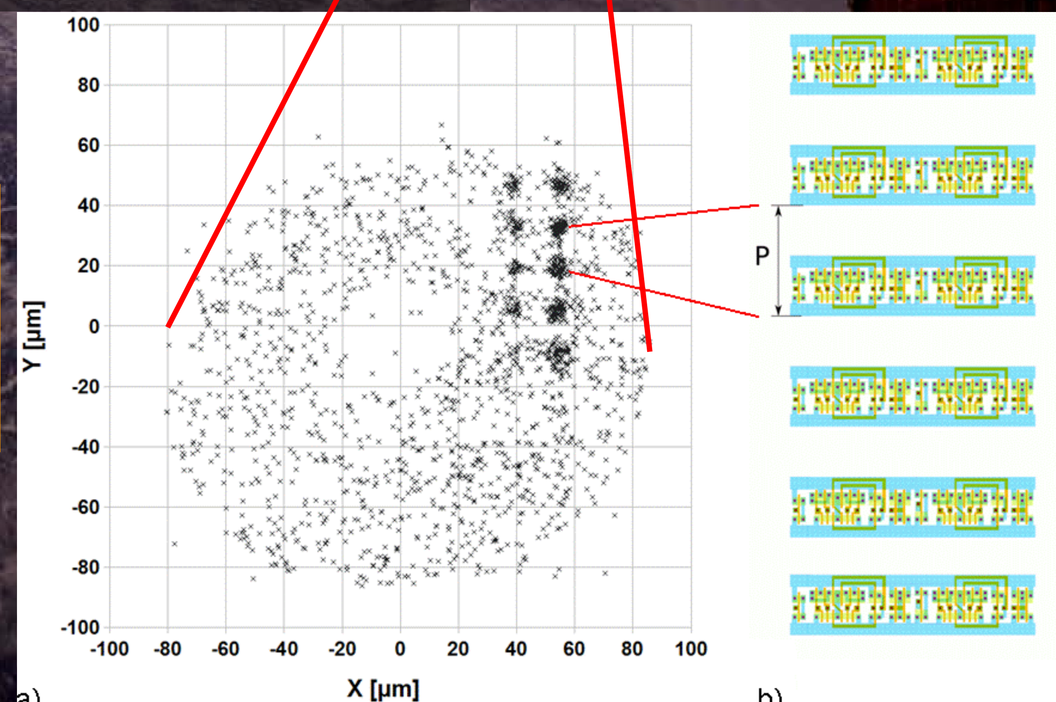


SOImager layout



The gate polysilicon lines appear as densely populated stripes of over threshold ion strikes.

Online sensitivity map of the power MOSFET



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

Total dose effects studies at SIRAD

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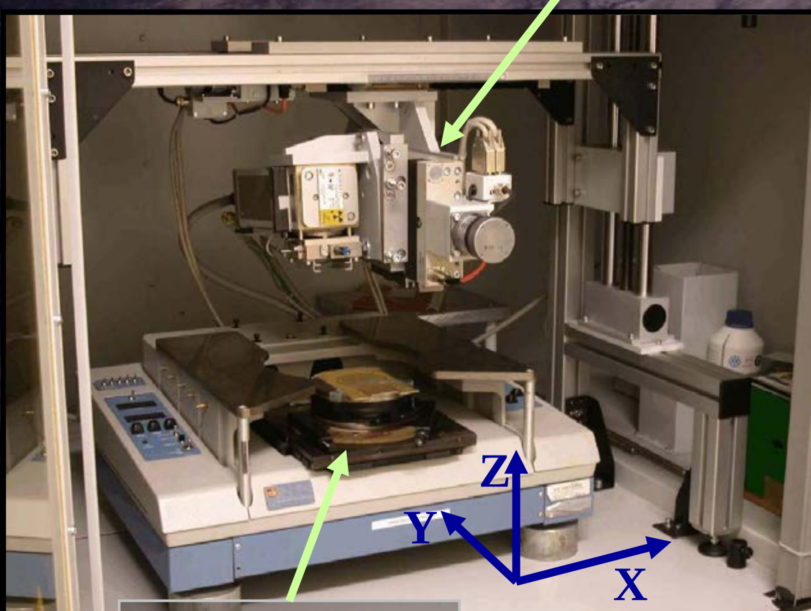
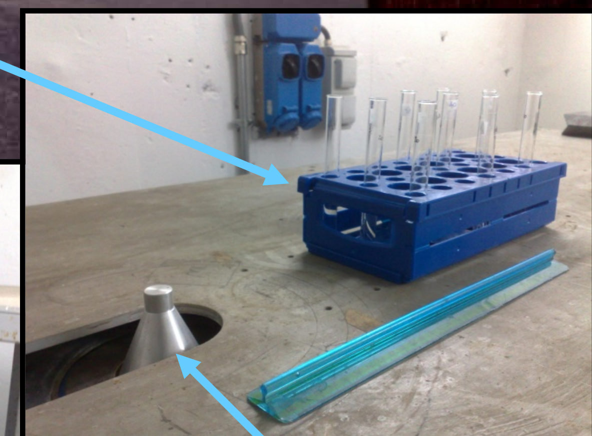
X-ray machine

- Tube with W (7.4-12.06 keV L-lines) or Mo (17.4-19.6 keV K-lines) anode.
- Tube max power 3 kW
  max voltage 60 kV
  max current 50 mA.
- X,Y (motorized) and Z (manual) axis for accurate position setting of the tube.
- Radiation hardness qualification of the APV25 chip for the CMS silicon tracker.

^{60}Co gamma-ray source (CNR-ISOF)

- Panoramic Gammabeam model 150 A, produced by Nordion Ltd (Canada)
- Photon energies: 1.165 MeV and 1.332 MeV
- Present activity: 2000 Ci ($\approx 7.4\times10^{13}$ Bq)
- Point source for D>10 cm (D=10-300 cm)
- Dose rate: ~5 rad(Si)/s at D=20 cm, ~1 rad(Si)/s at D=45 cm

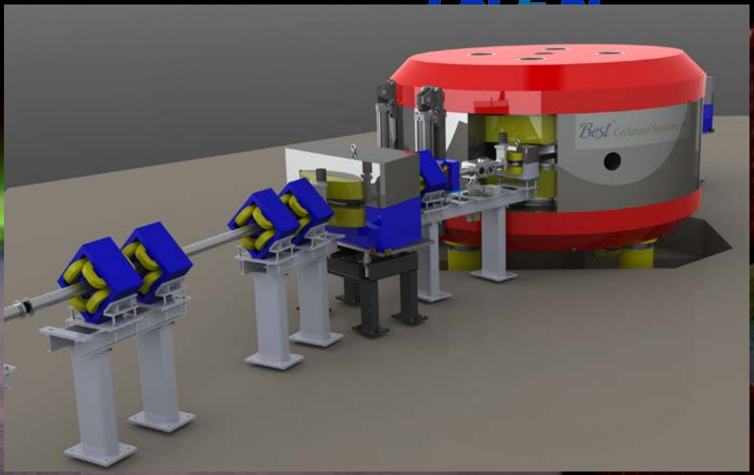




Future developments

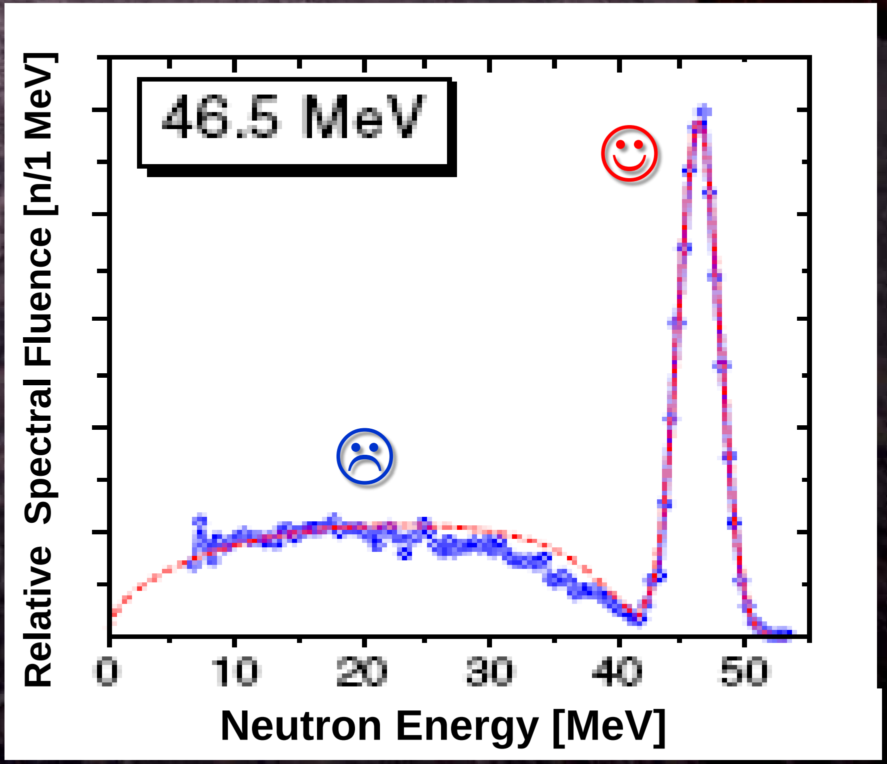
At the INFN National Labs of Legnaro (LNL), a variable energy (35-70 MeV) high current proton cyclotron (I_{max} = 750 μA) will soon come into operation.

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

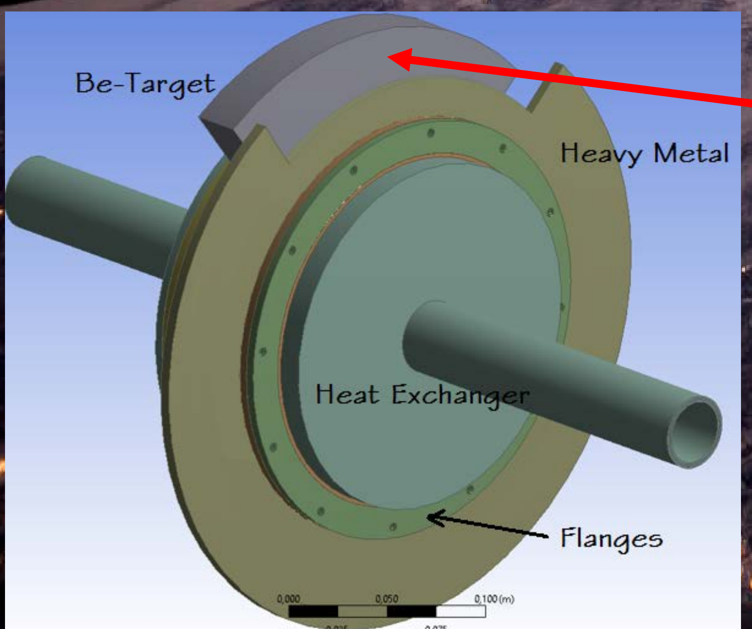
- multi-angle collimator for “tail correction
- assortment of thin (2-4 mm) Li and Be targets

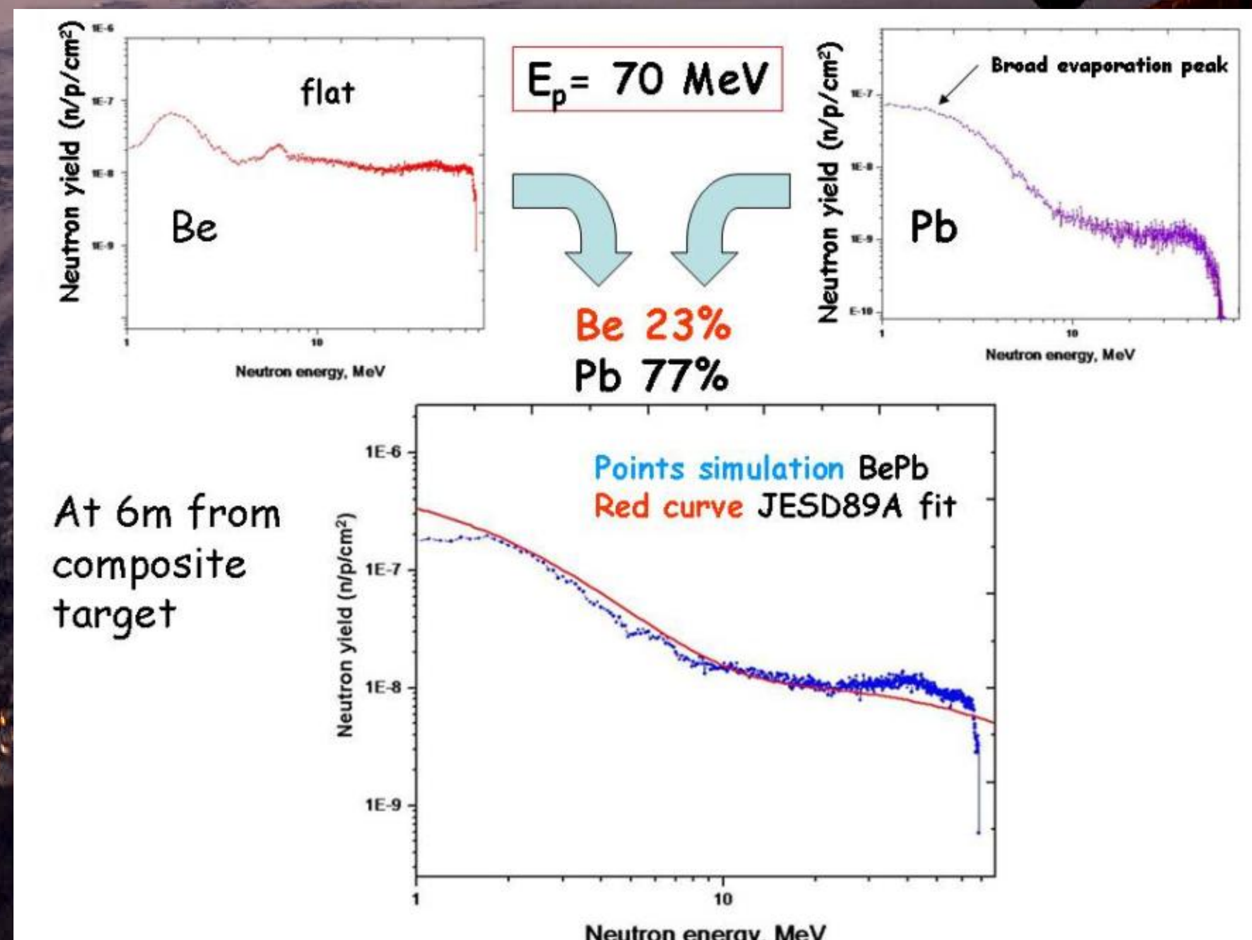


Future developments

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





The end

The SIRAD team

- Dario Bisello
- Andrea Candelori
- Serena Mattiazzo
- Devis Pantano
- Luca Silvestrin
- Mario Tessaro
- Jeffery Wyss

Backup slides follow

Summary

The SIRAD irradiation facility, installed at the 15 MV Tandem XTU accelerator can deliver ion beams from ^{1}H up to ^{197}Au with an energy range from 27 MeV up to 275 MeV, respectively. SEE and Total Displacement Damage tests are routinely performed at SIRAD by Italian and foreign Universities and Research Institutes involved in the study of radiation hardness of semiconductor detectors and electronic devices.

Irradiations at SIRAD started in 1997 with protons and in 1999 with ion beams. The facility was upgraded in 2006 with the installation of a new irradiation chamber.

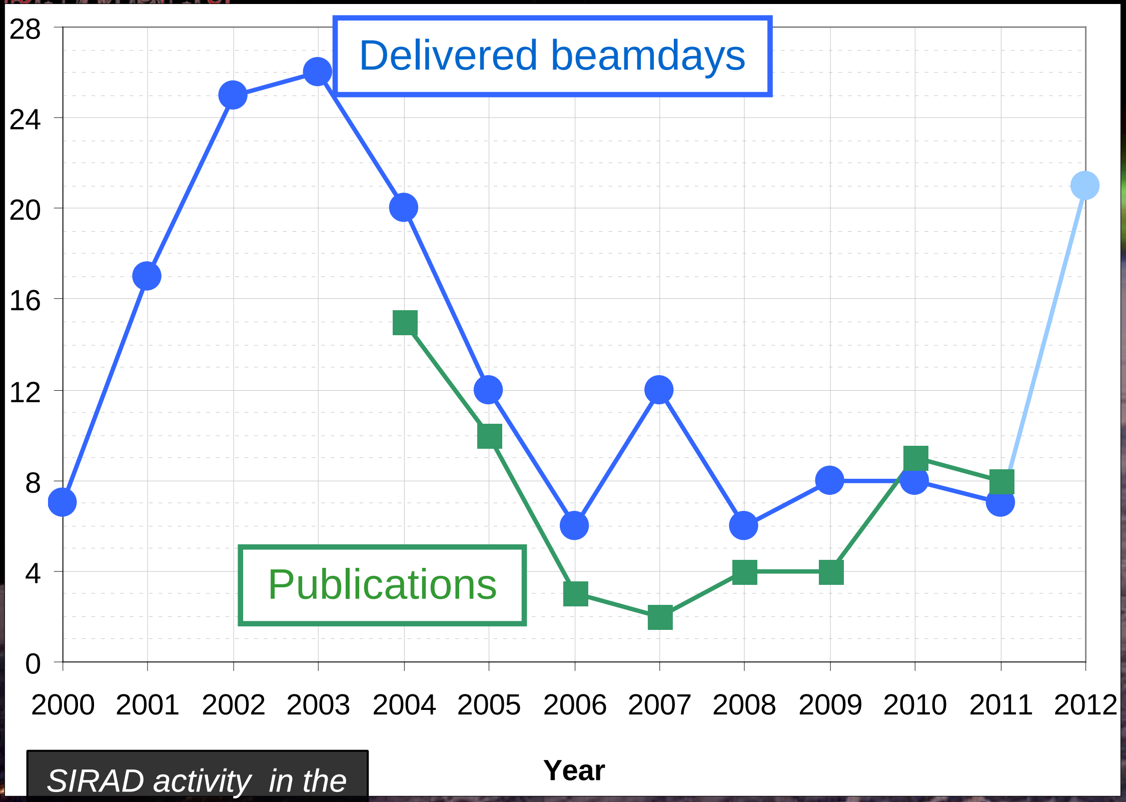
The typical beam spot size diameter of a focused beam at SIRAD is 3-4 mm and in order to irradiate a large target an electric rastering system is used. The low fluxes, ~100 ions/cm^{2}×s, required to perform SEE studies are obtained by defocusing and then collimating the ion beam.

Post-accelerated beams will be available at SIRAD starting from this year. The ALPI post-accelerator increases the energy of the heavy ion beams produced by the Tandem by a factor 3-4, allowing SEE studies of devices with thick superficial layers of metallization and back-side irradiation. The Ion Electron Emission Microscope (IEEM) is a tool devised to provide sensitivity maps of Single Event Effect of microelectronic circuits and systems for space and high energy physics applications.

The SIRAD capability in the field of SEE studies is improved by an Ion Electron Emission Microscope (IEEM) system [15], installed at the end of the beam line, that can reconstruct the positions of individual ion impacts with a resolution of few micrometers. Any SEE signals induced by ions in the DUT may be used to temporally tag the IEEM reconstructed events. This information is then used to display a map of the regions of the DUT surface which are SEEsensitive to the impinging ions.

Finally an RP-149 Semiconductor Irradiation System from Seifert (Ahrensburg, Germany) equipped with a standard tube for X-ray diffraction analysis: maximum power 3000 W, maximum voltage 60 kV, tungsten anode and a panoramic Gammabeam model 150 A produced by Nordion Ltd (Canada) based on a ^{60}Co γ-ray source.

SIRAD beamtime



SIRAD activity in the last 12 years

COLLABORATIONS

- **Dip. di Fisica and INFN Padova**
- **INFN Laboratori Nazionali di Legnaro**
- **Dip. Ingegneria dell’Informazione, Padova**
- **SELEX Sistemi integrati, Roma**
- **Dip. Informatica e Telecomunicazioni, Trento**
- **INAF sezione di Milano**
- **IASF Bologna, INAF Bologna**
- **Dip. Automatica e Informatica, Politecnico di Torino**
- **INFN sezione di Torino**
- **Dip.Ingegneria Elettronica, Università Roma 2**
- **DAEIMI e DSM, Università di Cassino**
- **CERN (Ginevra, Svizzera)**
- **Santa Cruz Institute for Particle Physica (California, U.S.A)**
- **and many others in the past…**

Outline

SIRAD irradiation facility

- The beamline: irradiation chambers and beam diagnostic
- SIRAD X-ray machine
- 60Co radioactive source

Sensitivity micromapping:

- Microprobe VS Ion Electron Emission Microscopy (IEEM)
- First IEEM results achieved with the SIRAD IEEM:
  - A IEEM imaged and Time Resolved *IBICC experiment with a power MOSFET;*
  - The SOImager shift register sensitivity map to SEU.

Actual work

- Global irradiations:
  - DEI Commercial memories/FPGA tests
  - Vela Uslenghi
  - Carugno irradiations
  - Selex

Future developments

- IEEM with improved resolution/efficiency
- Surface modification via ion beam irradiation (V. Rigato)
- ESA

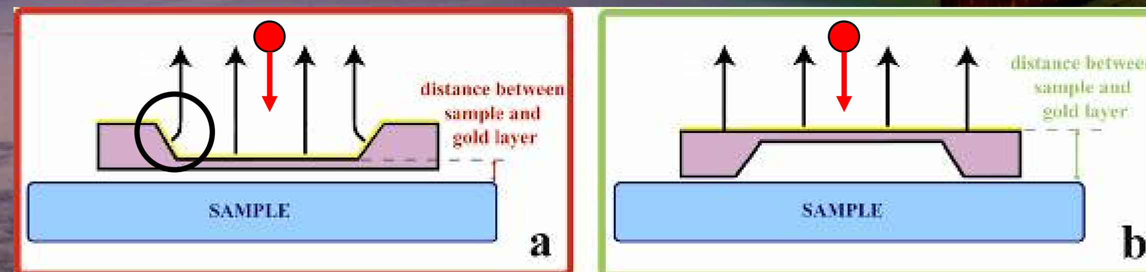
Conclusions

The gold membrane

The surface of a silicon integrated circuit is often passivated, hence an unreliable secondary-electron emitter.

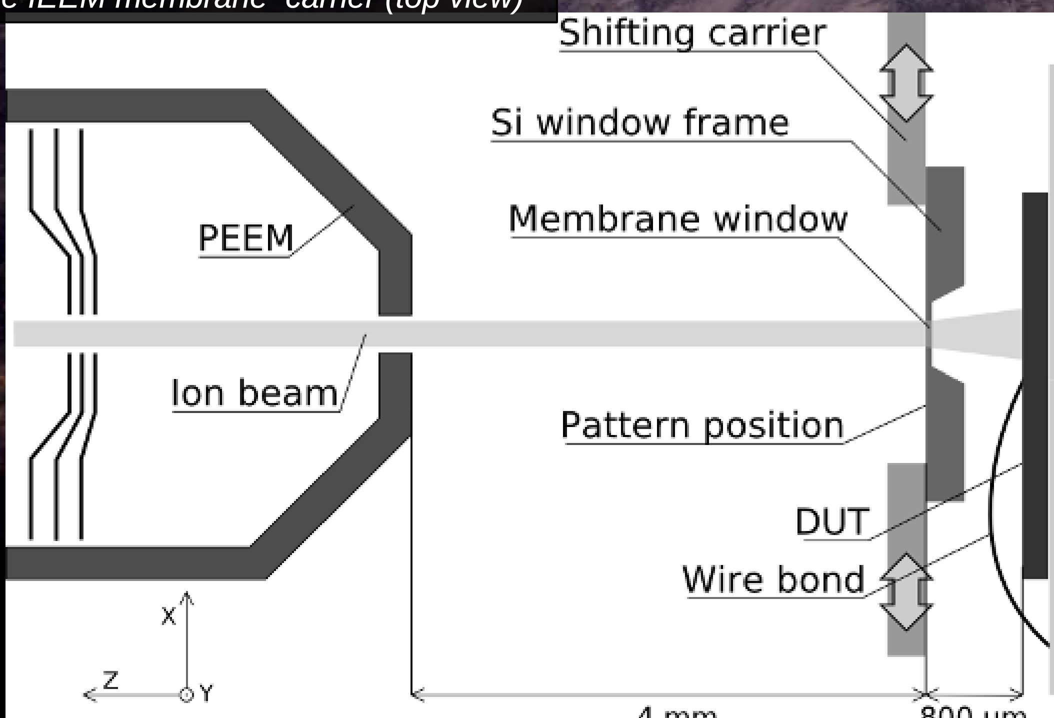
A ultrathin gold membrane (40 nm Au on 100 nm Si_3N_4) is used to ensure a uniform and abundant secondary electrons emission.

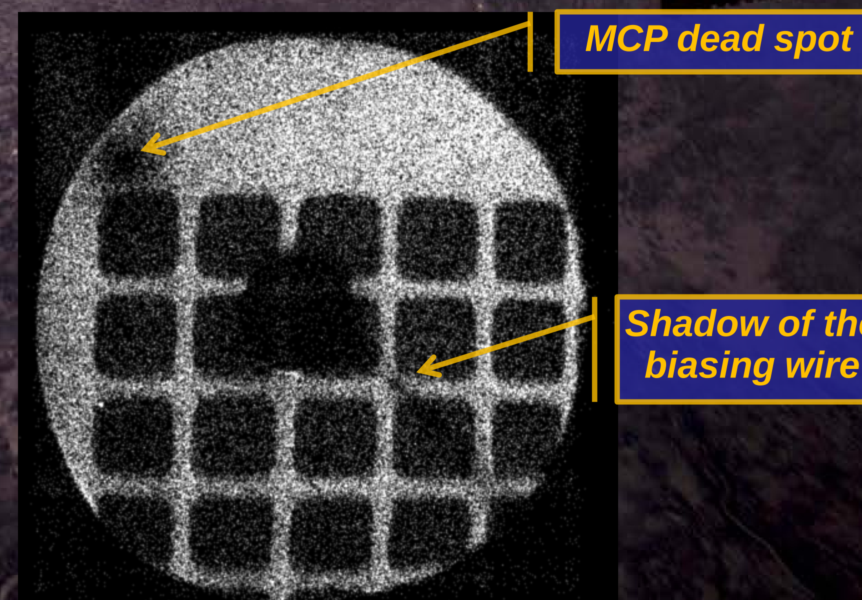
The big Si_3N_4 membrane. (To avoid the bulge provoked by the electrostatic pressure, the membrane actually used in the IEEM is smaller: 0.5x0.5 mm)



(a) Former membrane configuration, with the electric field perturbation provoked by the bulge. (b) Actual configuration: the electric field is uniform.

The IEEM membrane carrier (top view)





Membrane focusing pattern: 16x16 squares (25 µm), separated by 5 µm wide gold strips.

Membrane: pros & cons

Advantages

☺ The device under test is not exposed to electric field of the IEEM (no sparking; no E-field perturbations that distort image)

☺ Protects DUT from UV-photons used to focus IEEM on a pattern. UV-focusing is easy and reliable (pattern is on the membrane frame and hence on the same plane)

☺ Suitable for any device (Ready to go!)

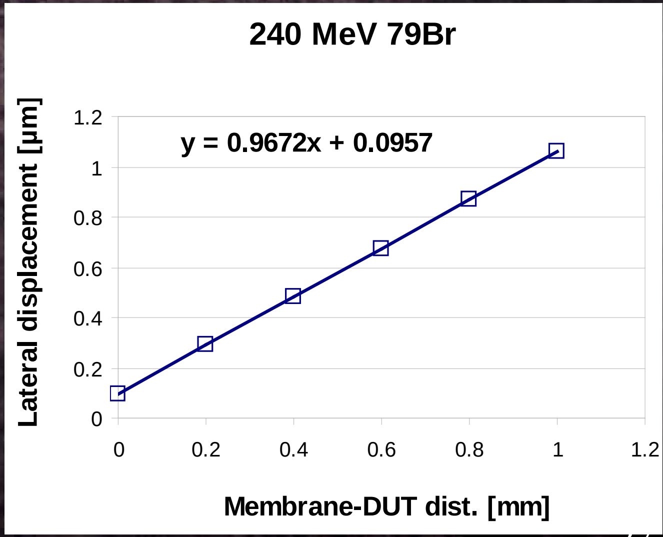
Disadvantages

☹ Resolution degradation (proportional to the distance of the membrane from the device under test).

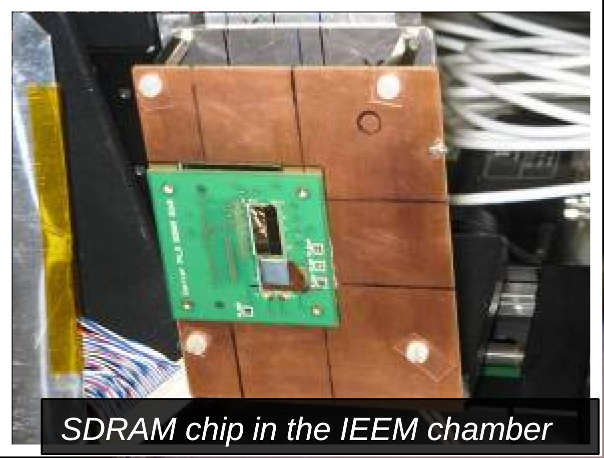
Is 3×☺ greater than ☹ ?

The lateral displacement with the Membrane-DUT distance = 1 mm is 1 µm for 240 MeV ^{79}Br

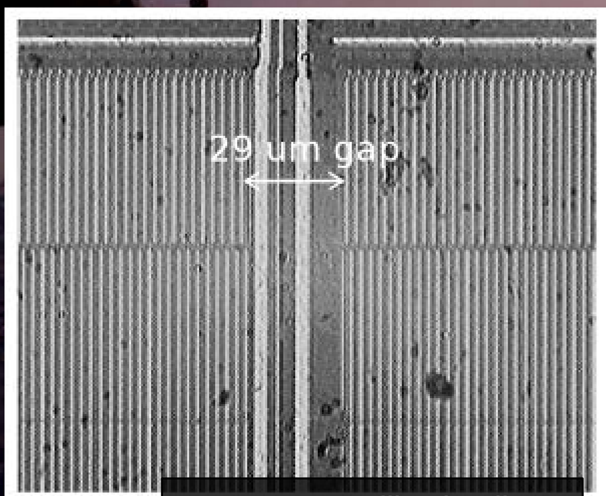
The energy loss in crossing the membrane is negligible: <1% for 240 MeV ^{79}Br and <0.5% for 170MeV ^{35}Cl



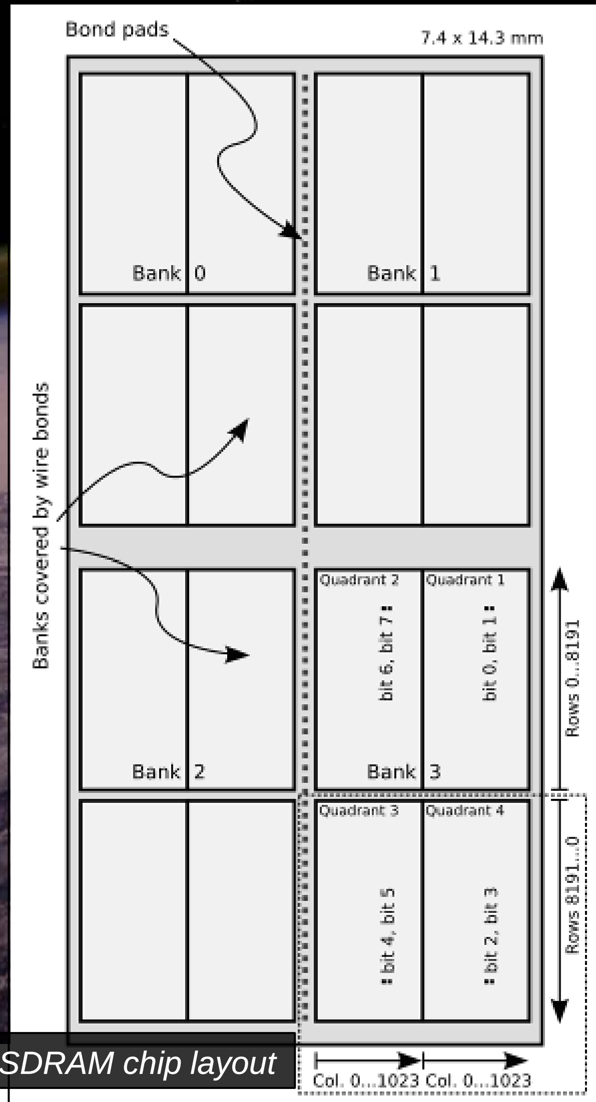
The SDRAM system



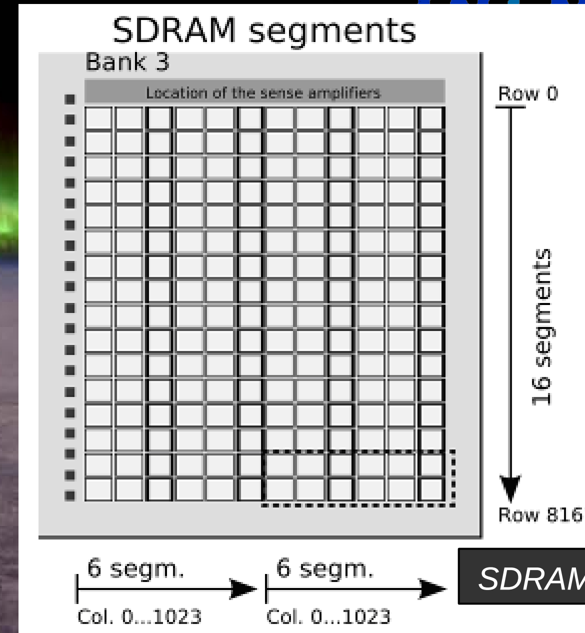
SDRAM chip in the IEEM chamber



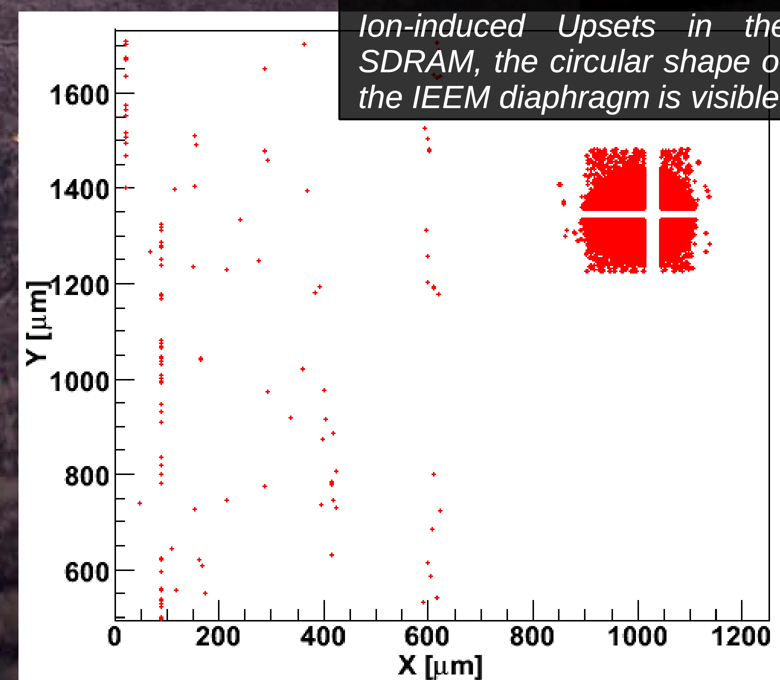
SDRAM metallization lines



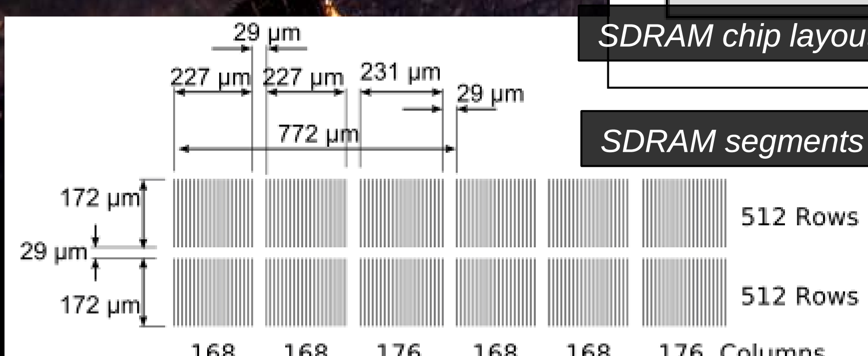
SDRAM chip layout



SDRAM chip detail

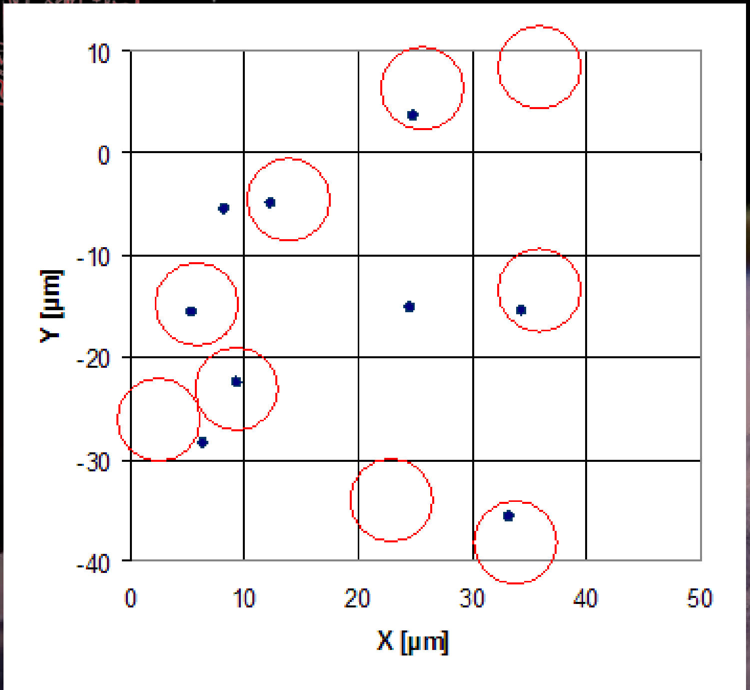


Ion-induced Upsets in the SDRAM, the circular shape of the IEEM diaphragm is visible.



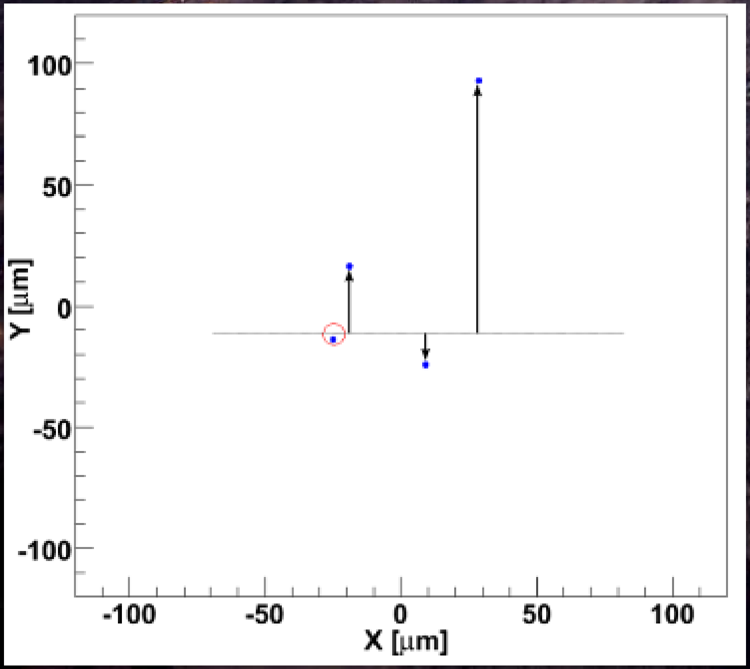
SDRAM segments

IEEM resolution with ions



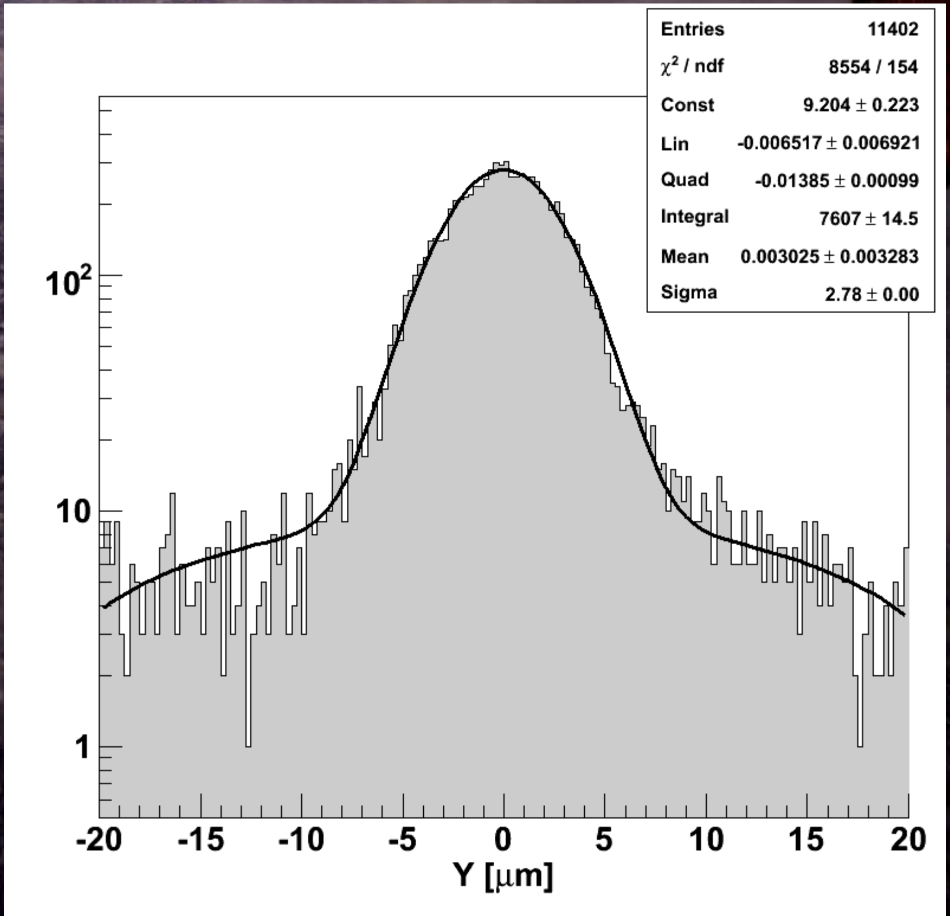
The red circles (radius 4 µm) are centred at the positions of the centroid of nine SDRAM clusters.

The blue dots are IEEM events that are temporally associated to the clusters.



The histogram presents a Gaussian shaped correlation peak above a quadratic combinatorial background

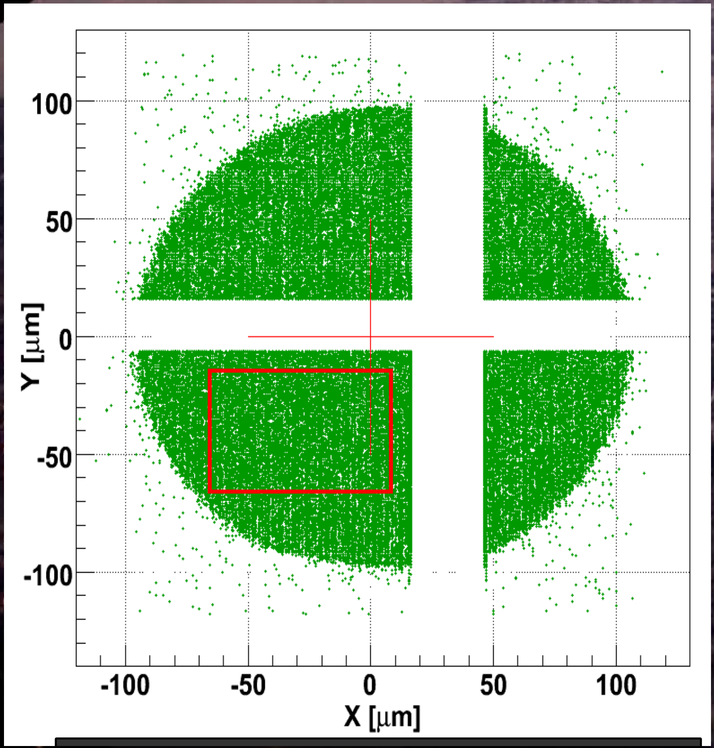
σ = 2.8 ± 0.1 µm



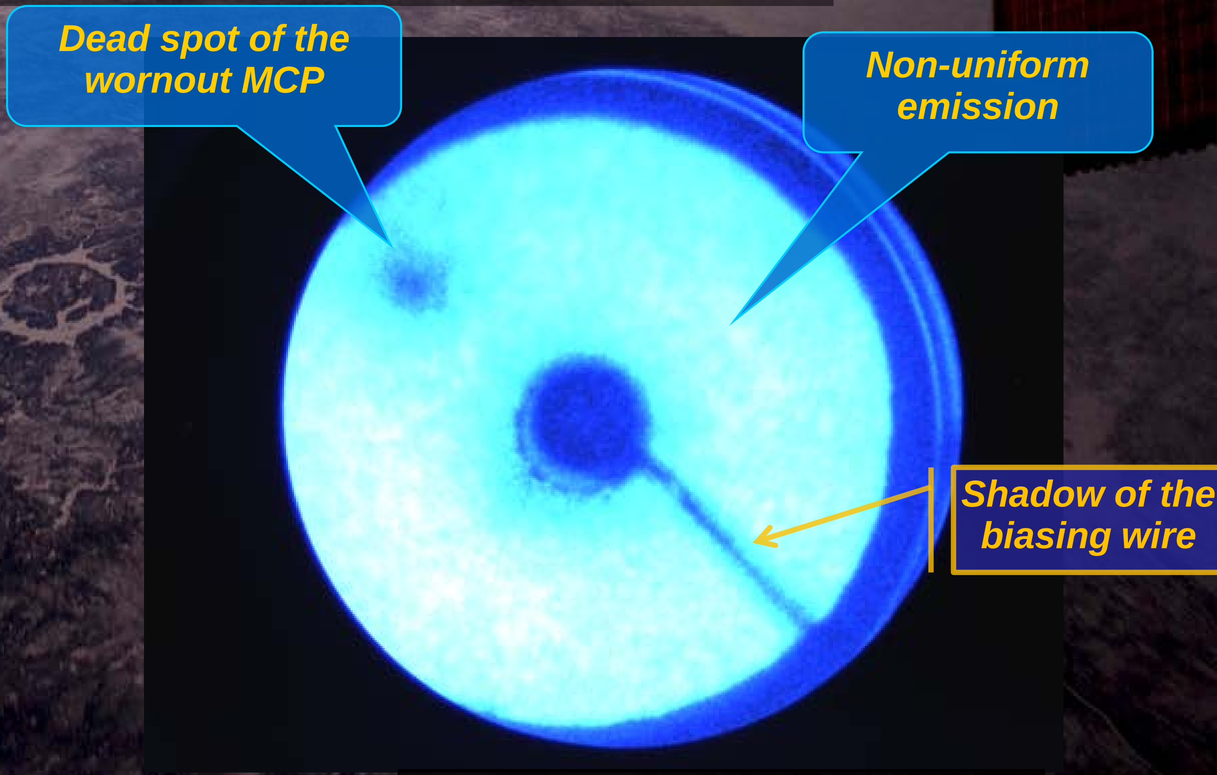
Reconstruction efficiency

IEEM reconstruction efficiency: $E_R = \frac{e_{IEEM}^{corr(s,t)}}{e_{SDRAM}} = 61\%$

Previously reported efficiency 90% .
[*S. Bertazzoni et al., "Ion Impact Detection and Micromapping with a SDRAM for IEEM Diagnostics and Applications", IEEE Trans. Nucl. Sci., vol. 56, pp. 853-857, June 2009*].



SDRAM centroids. The events in the red rectangle are used for the efficiency measurement.



CCD camera integrated image of the non uniform emission of the MCP

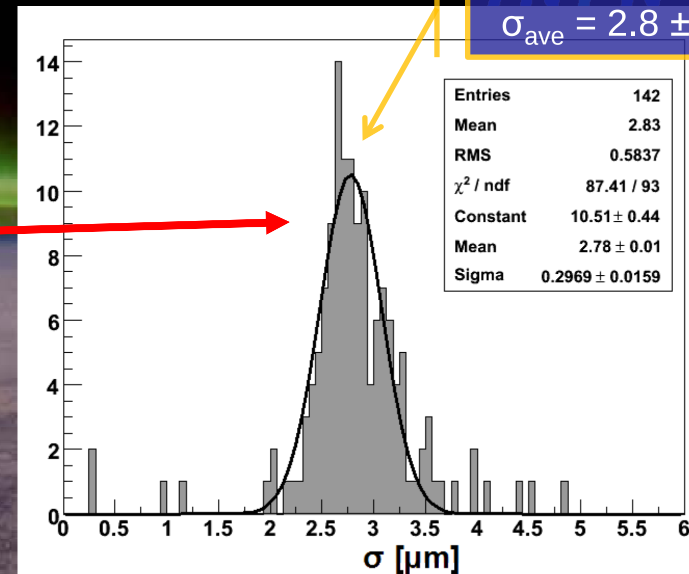
Resolution degradation: Distortion

The central part of the FOV was divided into 14x14 square regions (area *10x10 μm²*) *, in every region the correlation peak analysis was performed.*

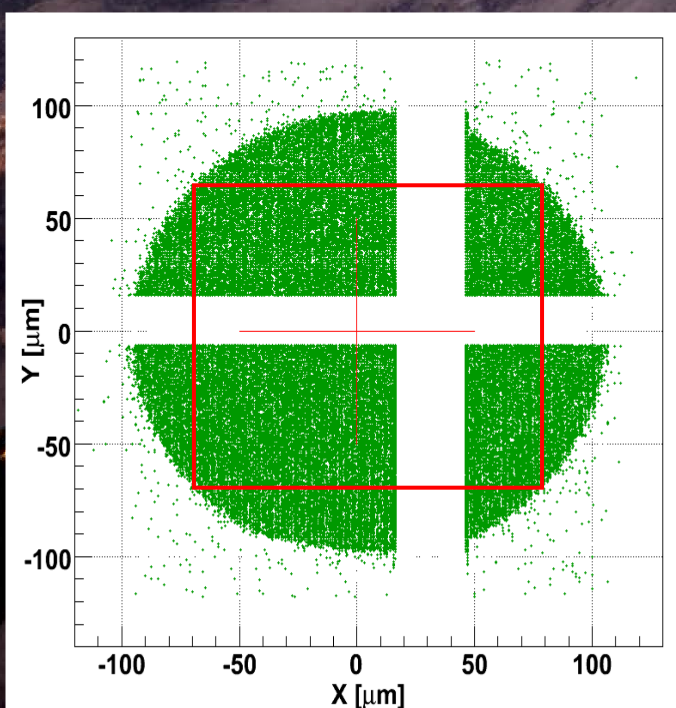
The distribution of the sigma parameter of the gaussian fit is a measure of the local resolution and its uniformity.

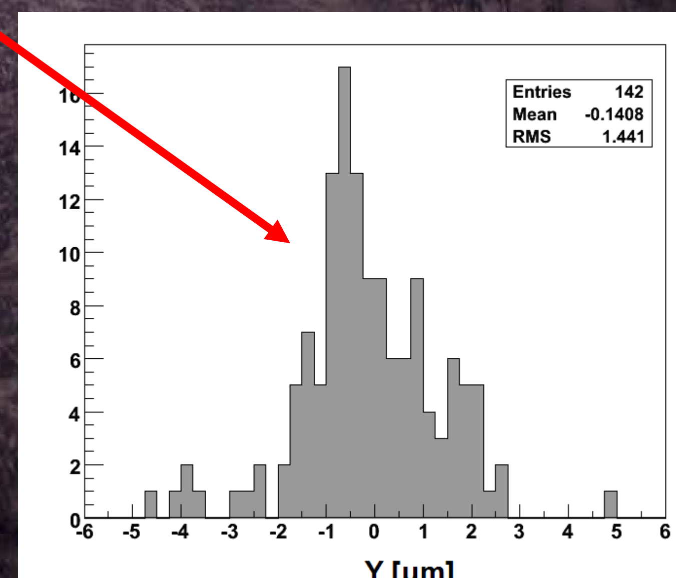
The displacement of the correlation peak centroid from the average value is a measurement of the distortion: for more than 90% of the areas the difference is less than 2 *μm.*

$\sigma_{ave} = 2.8 \pm 0.4$ μm



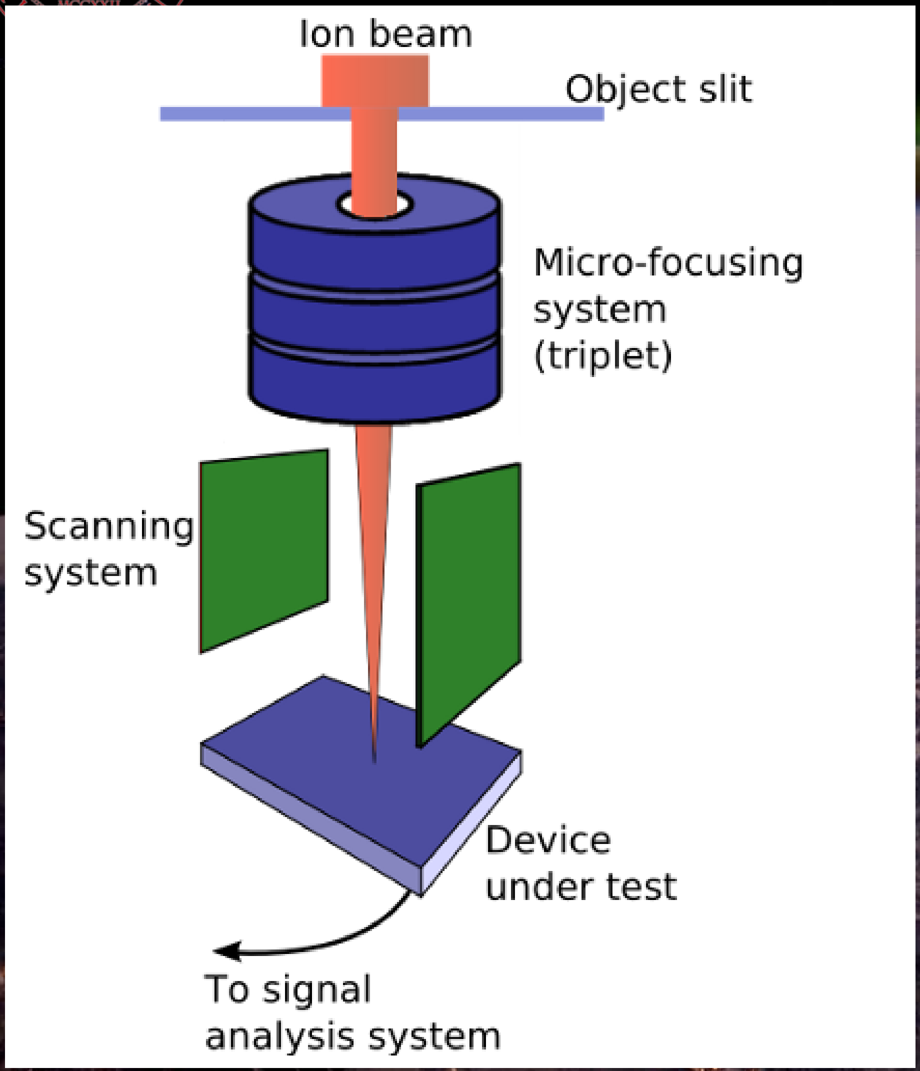
Distribution of the sigmas of the Y-coordinate correlation peaks in the 10x10 μm² *areas .*





Distribution of the differences from the average value of the means of the Y-coordinate correlation peaks in the 10x10 μm² areas .

Nuclear microprobe



Focusing heavy ions beam is difficult:

High *LET* => high *Z* => Strong bending magnetic field

High range requires very energetic ions

Tandem: stable and monochromatic, limited energy;

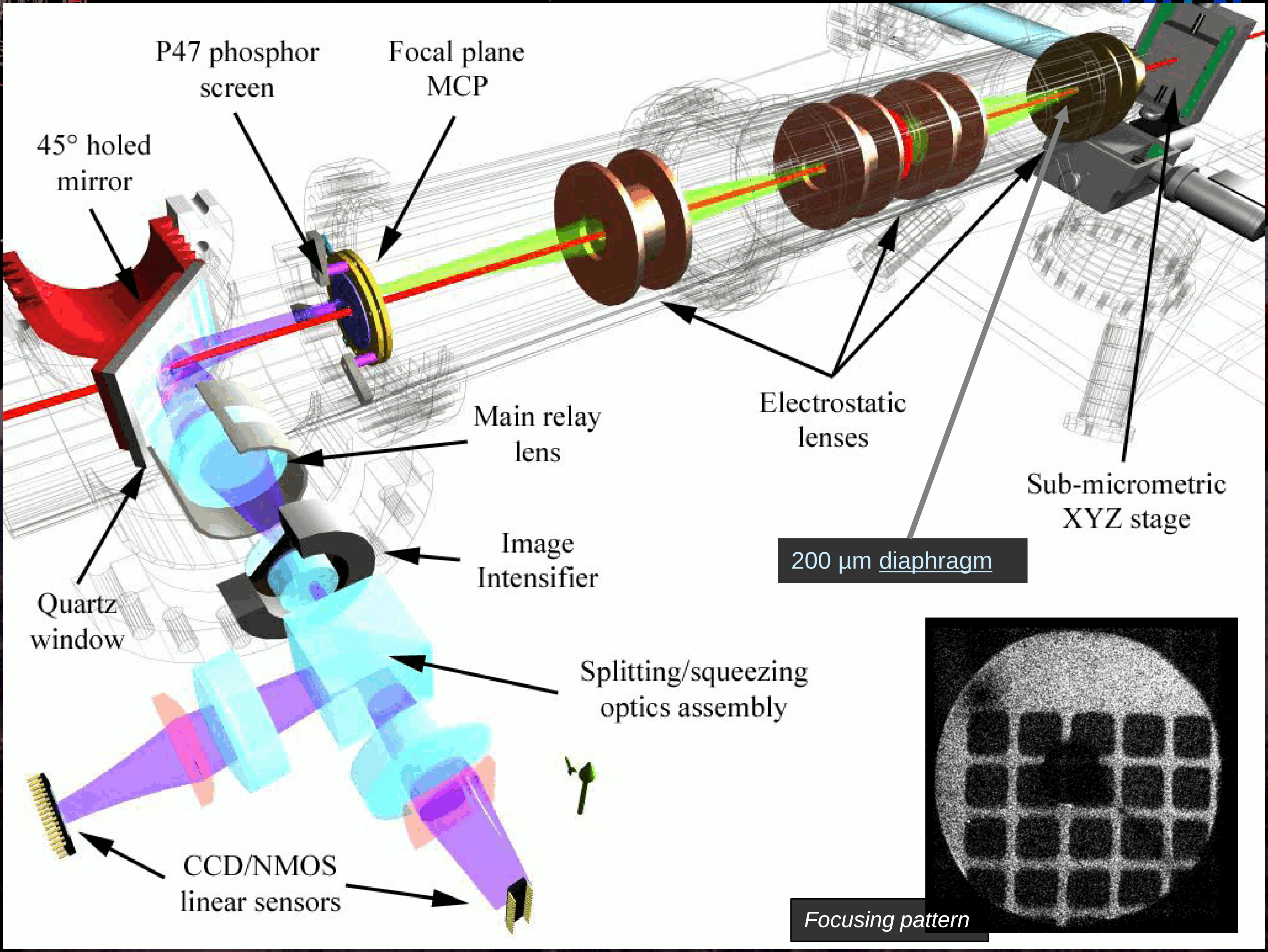
Cyclotoron: higher energy, but typically less monochromatic

Typical heavy ion microprobe spot size 0.5-1 µm

The system resolution is determined by the beam optics: the spot size and the positioning system.

For mapping the sensitivity of electronic devices and systems to single ion impacts, the SIRAD facility is upgraded with an Ion Electron Emission Microscope (IEEM).

The axial SIRAD IEEM

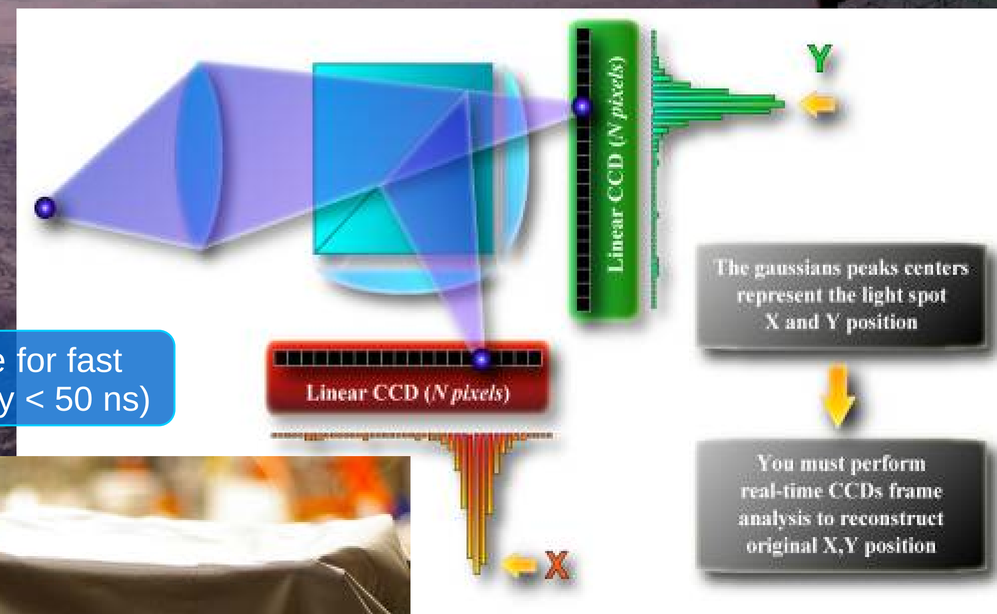


The STRIDE system

STRIDE stands for ***Space and Time-Resolving Imaging DEvice***, it is the fast Data Acquisition System of the SIRAD IEEM.

It is able to acquire both the spatial and temporal coordinates of every single light spot with a maximum effective rate of 1000 events/s (temporal resolution 100 μs).

A beamsplitter provides 2 copies of the light spot, each image is then squeezed by a barrel lens to a blade-shape and focused on one of the linear NMOS detectors.



To acquire the position of single light spots with a 2D array pixel sensor, an enormous amount of output data must be read and processed.

STRIDE implements two linear NMOS array, each composed of 256 photo receptors. In this way the readout of 2N pixels, instead of N^2, must be processed.

Phototube for fast signal (delay < 50 ns)

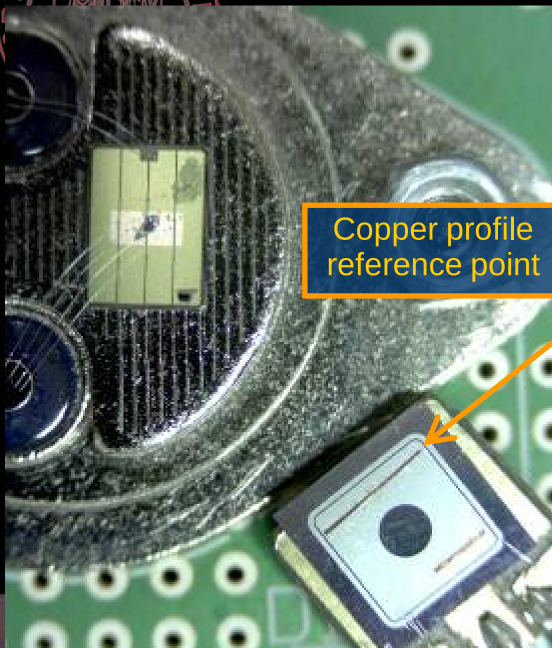
To improve speed, the pixels readout of the two arrays is processed in parallel by an FPGA (Xilinx Virtex II).

The acquired data is sent via a USB cable to the control PC, that provides the matching of the X and Y coordinates of the detected events

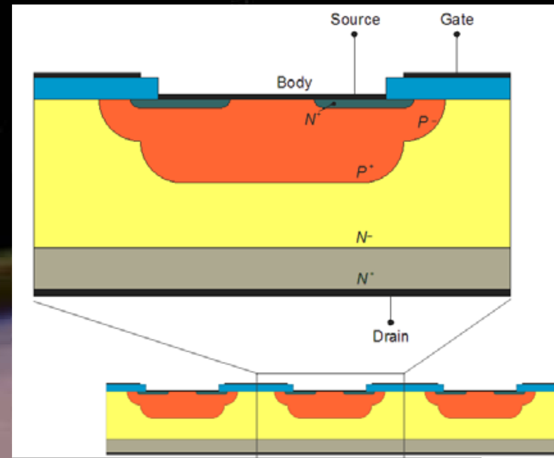
The tag signal

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

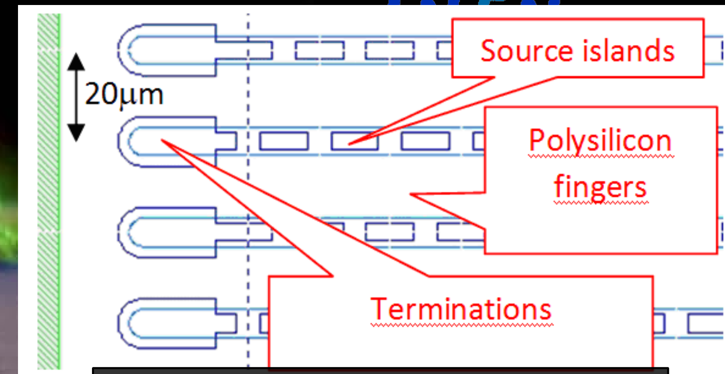
The Power MOSFET



The power MOSFET chip near the PIN diode used for the positioning operations

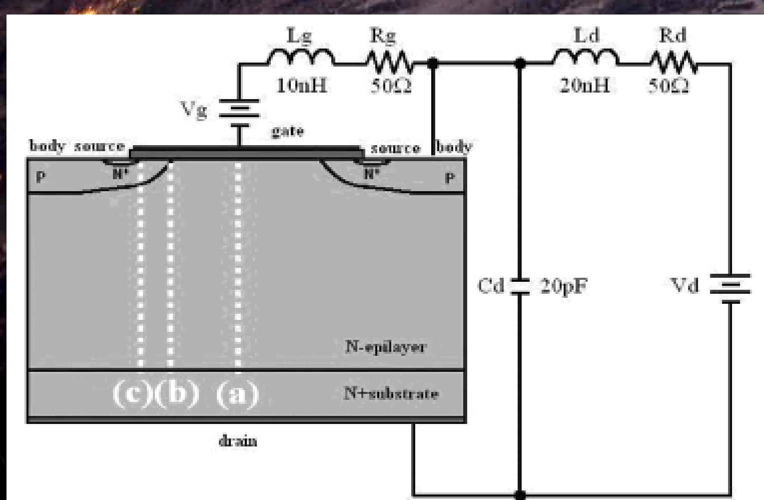


Internal structure of the power MOSFET (detail).

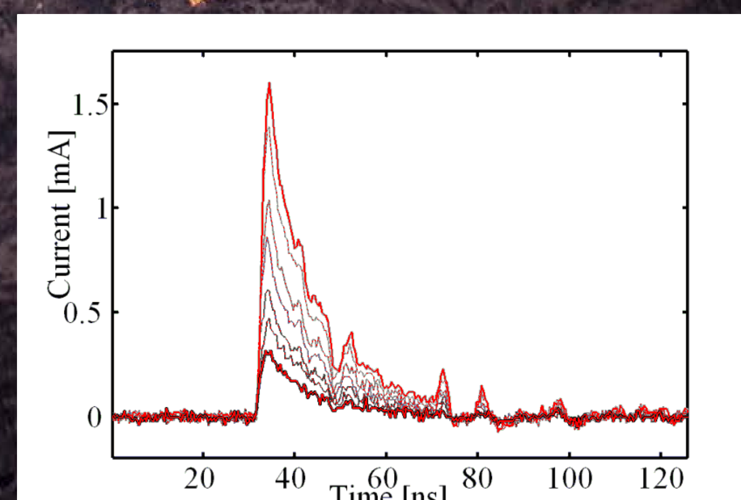


Power MOSFET metallization layout

The power MOSFET we used was developed by ST Microelectronics; transistors like this are commonly implemented in DC-DC converters used in satellites.
The high operational voltage makes theme prone to radiation effects.



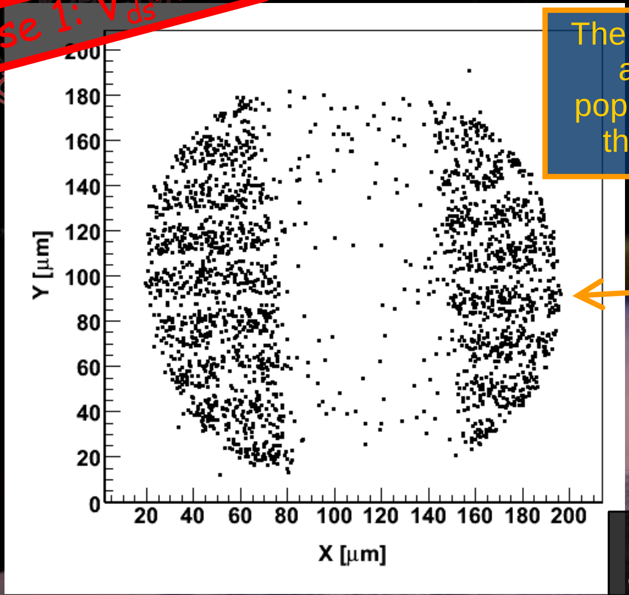
Mixed-mode circuit used for the finite-elements analysis.



Drain current pulses caused by ion strikes

TRIBICC experiment

Phase 1: V_{ds}=10V



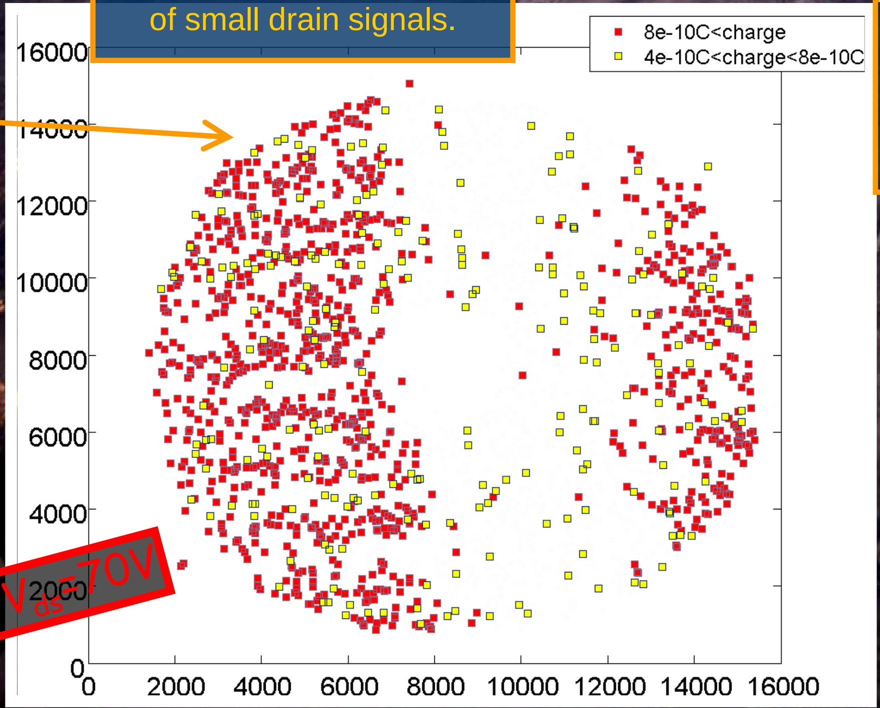
The gate polysilicon lines appear as densely populated stripes of over threshold ion strikes.

Online sensitivity map of the power MOSFET

Online sensitivity map makes it easier the localization of points of interest in the DUT

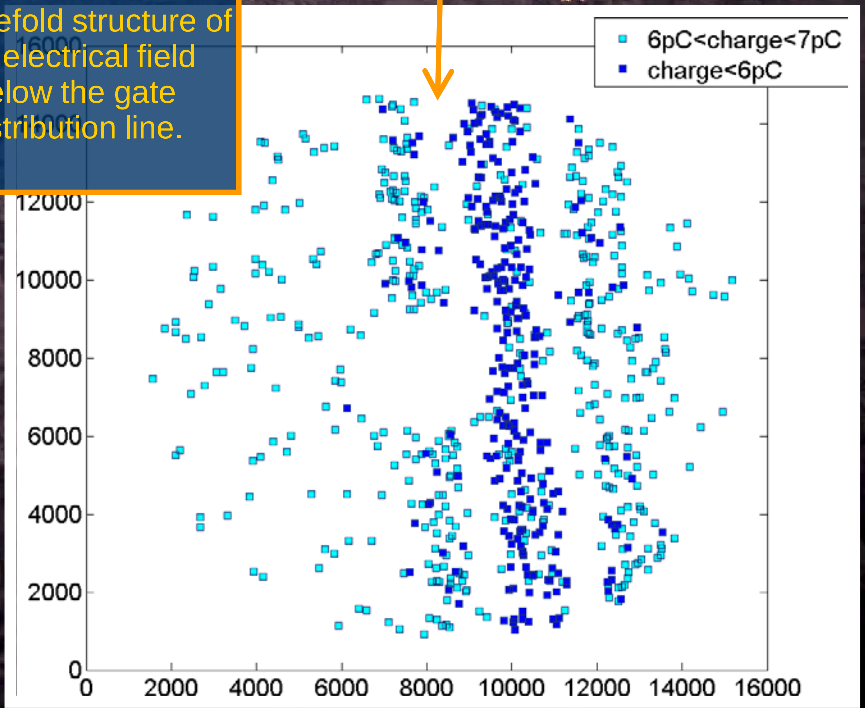
These first results demonstrate the capability of the IEEM system to provide in-deep information of the structure of state-of-the-art electronic devices and to study ion-induced charge collection effects

The source metal contacts are still discernable as areas of small drain signals.



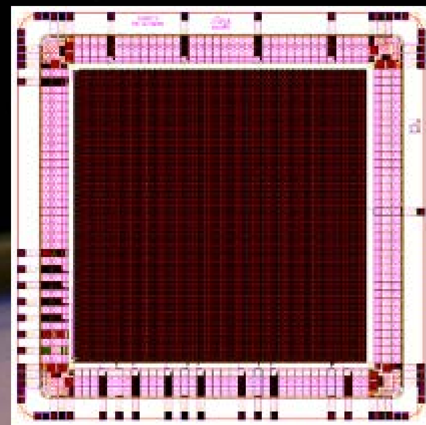
Phase 2: V_{ds}=70V

The separation between the densely populated bands reveal a threefold structure of the electrical field below the gate distribution line.



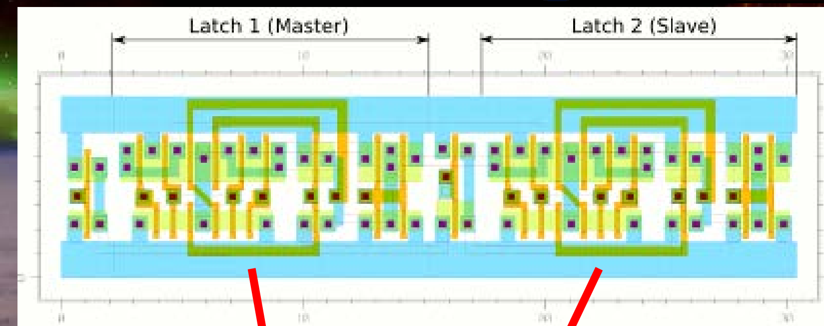
SOImager Shift Register

The SOImager board



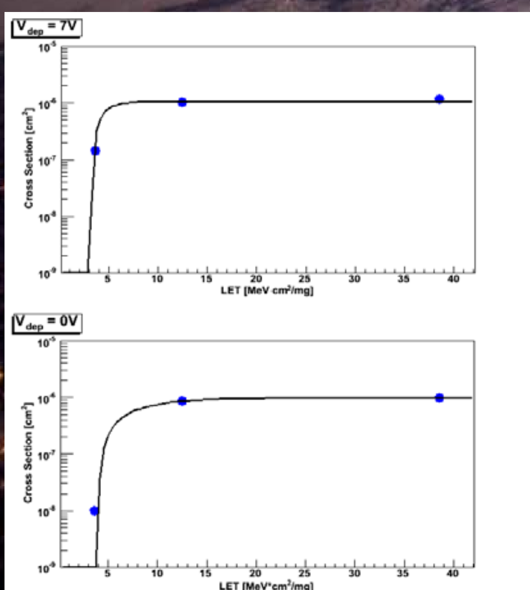
SOImager layout

Shift register cell schematics: the two Flip Flop D are visible

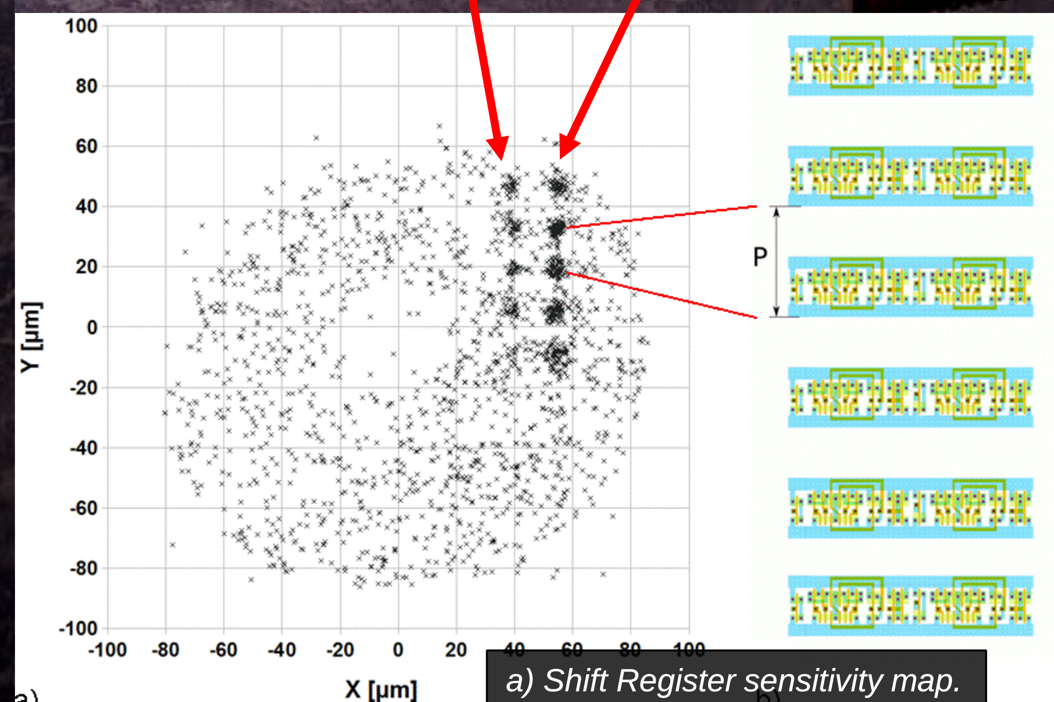


The actual resolution of the IEEM does not allow us to untangle the most sensitive nodes inside the cell (we cannot say which transistor is responsible for an upset), but it is sufficient to distinguish the two Flip-Flops and characterize their relative sensitivity:

the sensitivity of the Master Flip-Flop is 2.6 ± 0.1 times that of than the Slave one.



Shift Register cross section: Weibull fits with V_{bias}=7V (top) and V_{bias}=0V (bottom)

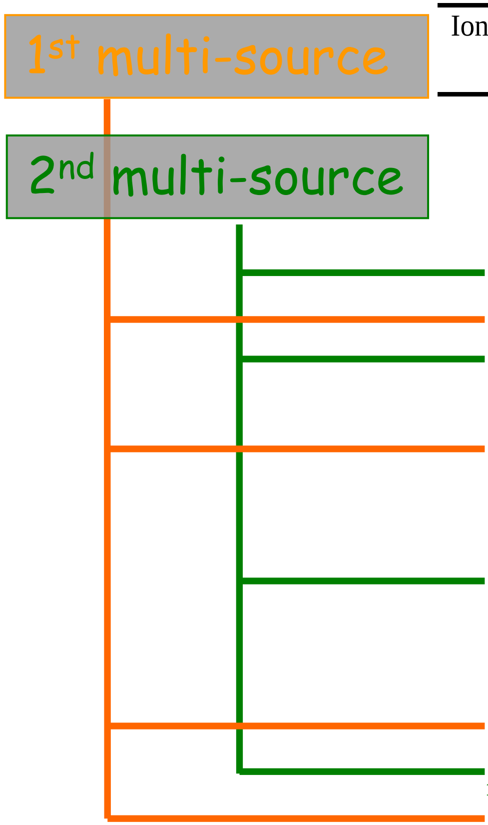


a) Shift Register sensitivity map.
b) Shift register schematics

Typical ion beams at SIRAD

Ion species from ^{1}H (22-30 MeV) up to ^{197}Au (1.4 MeV/a.m.u.)
LET from 0.02 MeV×cm^2/mg (^{1}H) up to 81.7 MeV×cm^2/mg (^{197}Au)

The energy values refer to the most probable q_1 and q_2 charge state, with two stripper stations, and the Tandem operating at 14 MV.



			Tandem			Tandem-ALPI		
Ion Species	q_1	q_2	Energy (MeV)	Range in Si (μm)	Surface LET in Si (MeV×cm^2/mg)	Energy (MeV)	Range in Si (μm)	Surface LET in Si (MeV×cm^2/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

Future development: use ALPI beams in order to increase the ion range in Si. At the SEE Facilities routinely used by ESA (RADEF and HIF) the range is higher than 100 μm.