Characterization of advanced detector and electronic devices performed at RBI

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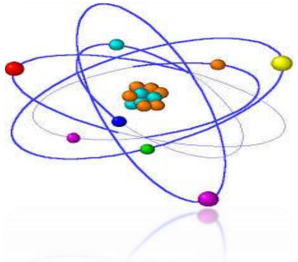
[b] Laboratory for ion beam interactions at RBI
[c] High Energy Physics group at RBI
[d] Radiation Chemistry and Dosimetry Laboratory at RBI
[e] Electronic Engineering Department of School for Engineering in University of Seville, Spain

CDSE
Centar za detektore, senzore i elektroniku

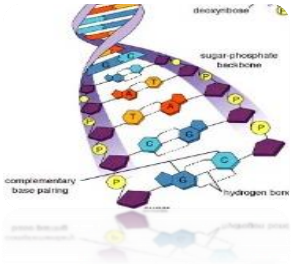
RBI - The Largest Multidisciplinary Research Institute in Croatia

PHYSICS



CHEMISTRY

LIFE SCIENCES



ENVIRONMENT

ICT

900 employees of which 360 permanent, 290 Post Doctoral and PhD students

- 5 % of Croatian researchers
- ~ 50 % of Croatian Horizon 2020
- 15 % of Croatian publications
- 30 % of Croatian top publications

Mission:

Excellent science

Strong involvement in higher education

Leading contribution to the growth of the national economy

Vision:

Croatian centre of scientific excellence

Recognized research institution at international level

Center for Detectors, Sensors and Electronics

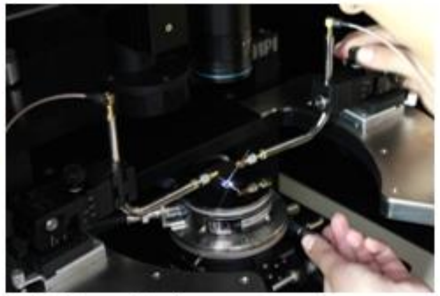
Resources and Infrastructure

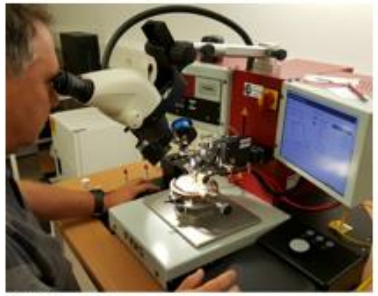
http://lnr.irb.hr/PaRaDeSEC

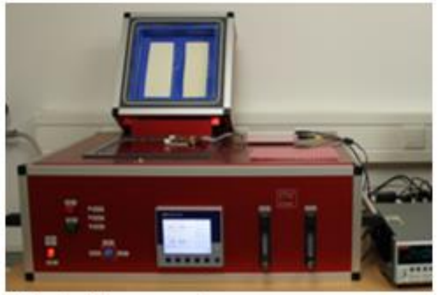
http://irb.hr

R&D Infrastructure at the CDSE


Scanning TCT setup


Probe station


Wire bonder

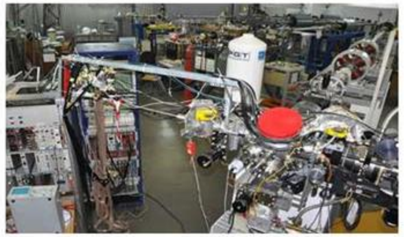

ColdBox setup

Legacy Infrastructure

- Accelerator Comlpex – Largest Experimental Complex in Croatia
- Gamma irradiation facility – 2PBq 60Co
- Neutron generator


6.0 MV EN Tandem Van de Graaff accelerator


1.0 MV HVE Tandetron accelerator


Experimental hall

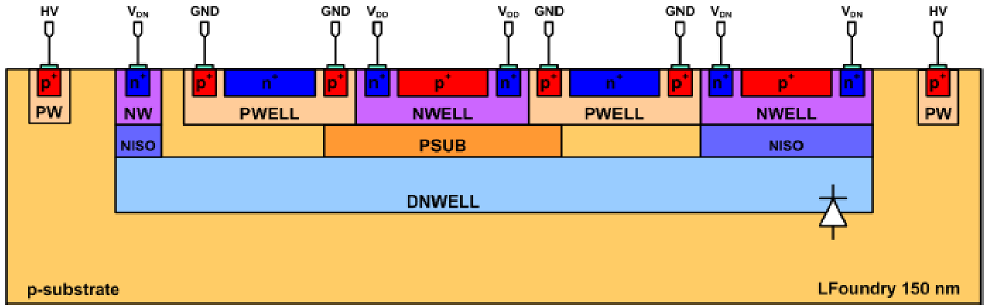
At RBI Material Physics and Chemistry Department

- Large selection of spectroscopic tools (PL, DLTS, Raman etc)

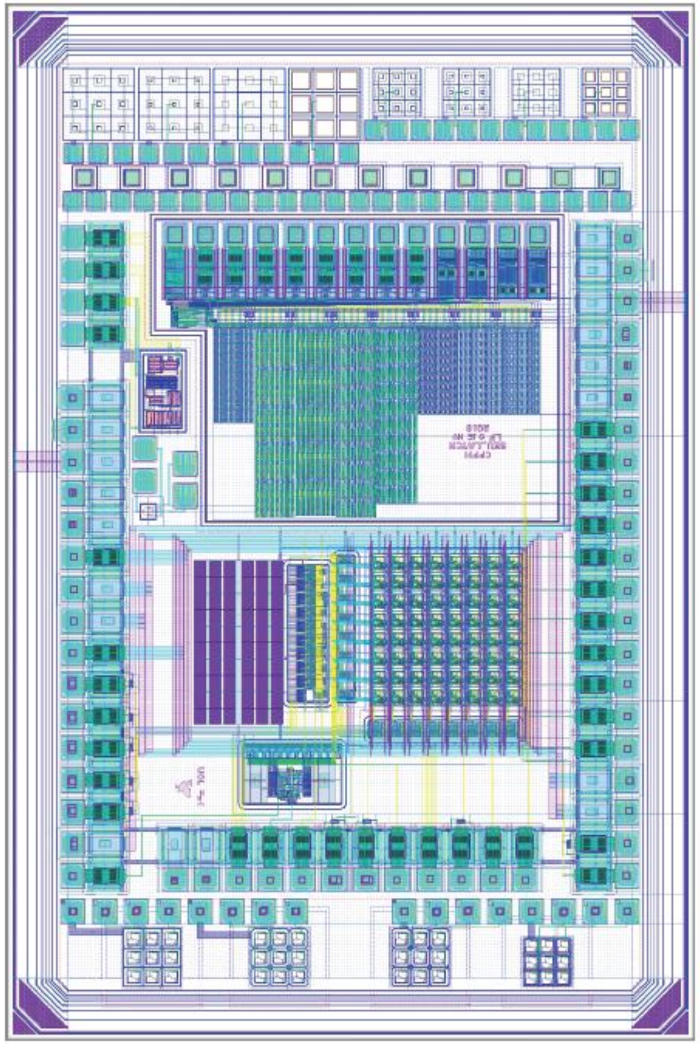
Radiation effects in Sensors and Electronics

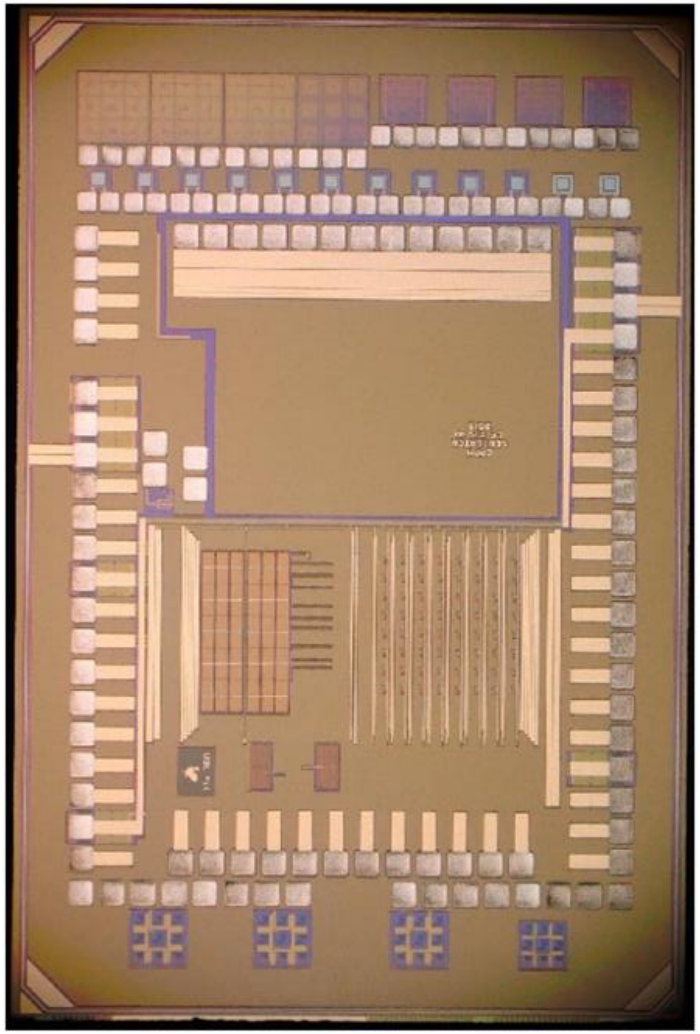
Any Monolithic Detector means you need to test for Radiation Damage (CCE, etc) but also testing for Ionization Damage (TID) and Single Event Effects:

<u>Electronics and Detectors embedded in the same crystal</u>



Pixel Cross-Section

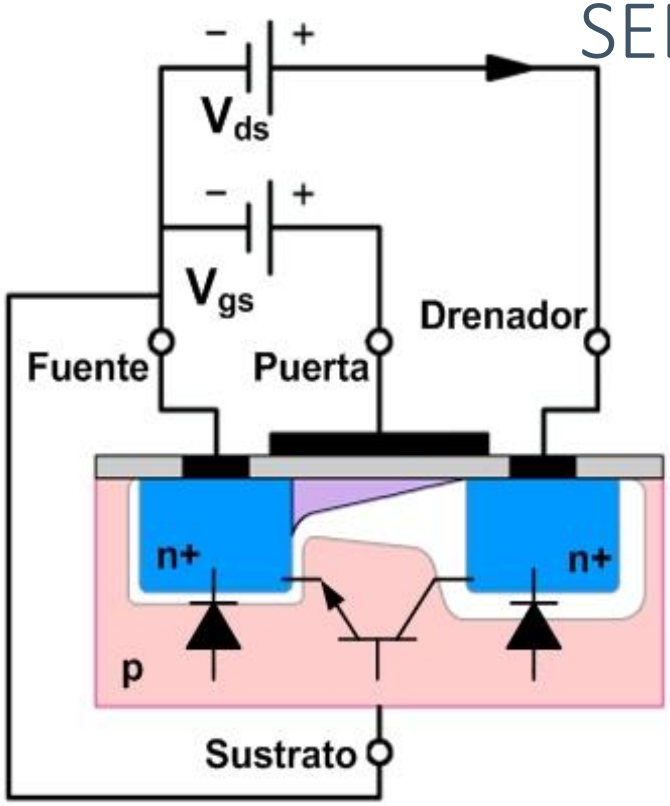


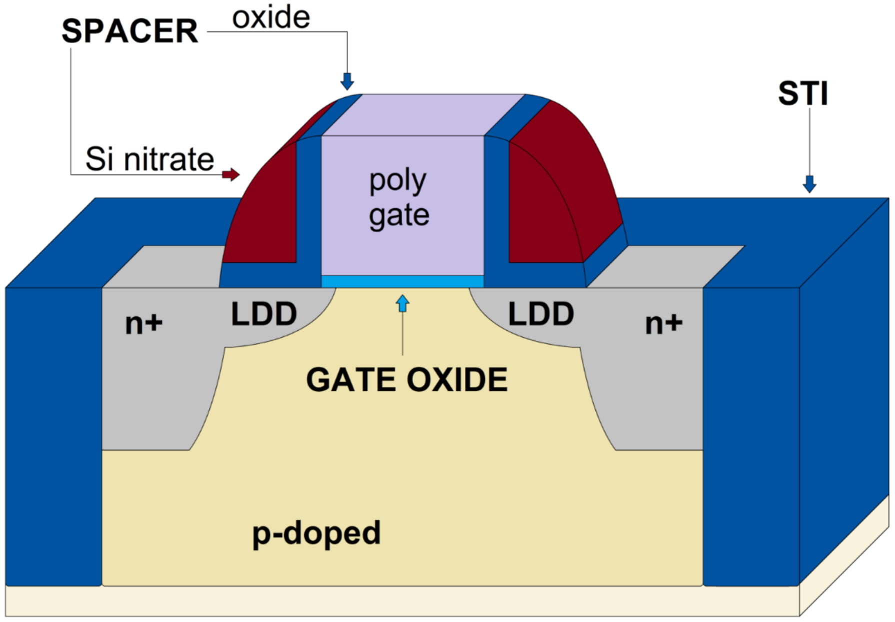


RD50 – HVCMOS MPW2 Chip

RD50-MPW2, Ch. Zhang, 13 Feb 2020, RD50 CMOS design meeting

SEE and Total Dose Overview (65nm)





Shallow Trench Isolation (STI): useful to isolate adjacent devices.

Spacers: Needed to create the Lightly Doped Source/Drain (LDD) extensions.

Small W → Large W

STI-Related Effects

Small L → Large L

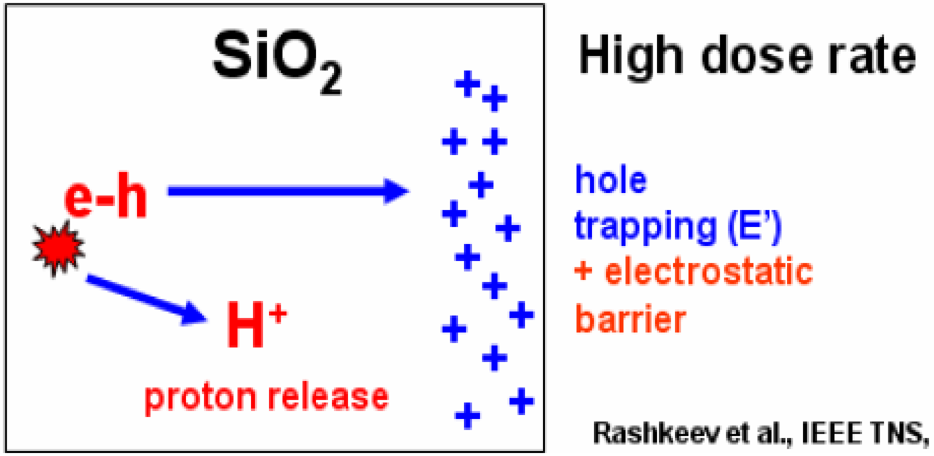
Spacers-Related Effects

Body Diodes: As they are reverse polarized they act as Non-intended particle detectors. It means Single Event Effect (SEE)

Total Ionizing Dose response of 65nm MOSFETs irradiated to ultra high doses, G.Borghello, 14 Nov 2017, RD53 collab.

Take into account the irradiator Dose Rate

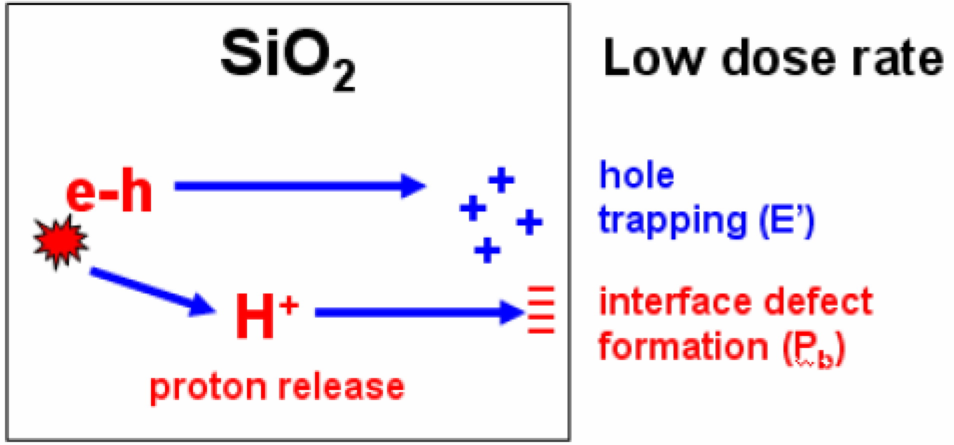
Under **high dose rate** there is a high generation of electron-hole pairs. The holes are forced to the interface by positive charge voltage, while the electrons are swept away into the gate. The buildup of holes at the interface form a positive charge barrier and repel the generated protons (H+), keeping them away from forming interface states at channel interface. They will recombine



Rashkeev et al., IEEE TNS, 2002

ELDRS (Enhanced Low Dose Rate Sensitivity)

Under **low dose rate** there is a low generation of electron-hole pairs. The holes are forced to the interface by positive charge voltage, while the electrons are swept away into the gate. The trapped hold buildup is much lower. The repelling force of the trapped holes is low enough to allow the H+ to migrate to the interface forming interface states.



Low Dose Rate means more Interface Traps

Physical model for enhanced interface-trap formation at low dose rates

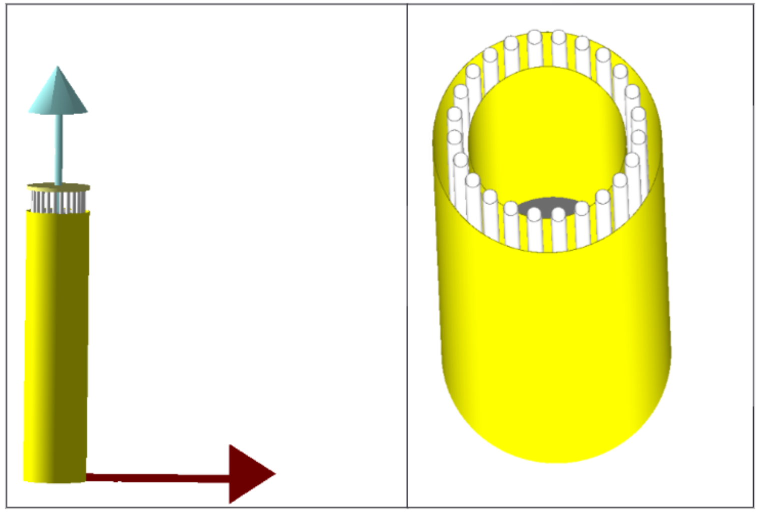
DOI: 10.1109/TNS.2002.805387

Radiation Hardening by Design, F.R. Palomo, 5 Nov 2019, R2nd Seminar on Electronics under Harsh Environments

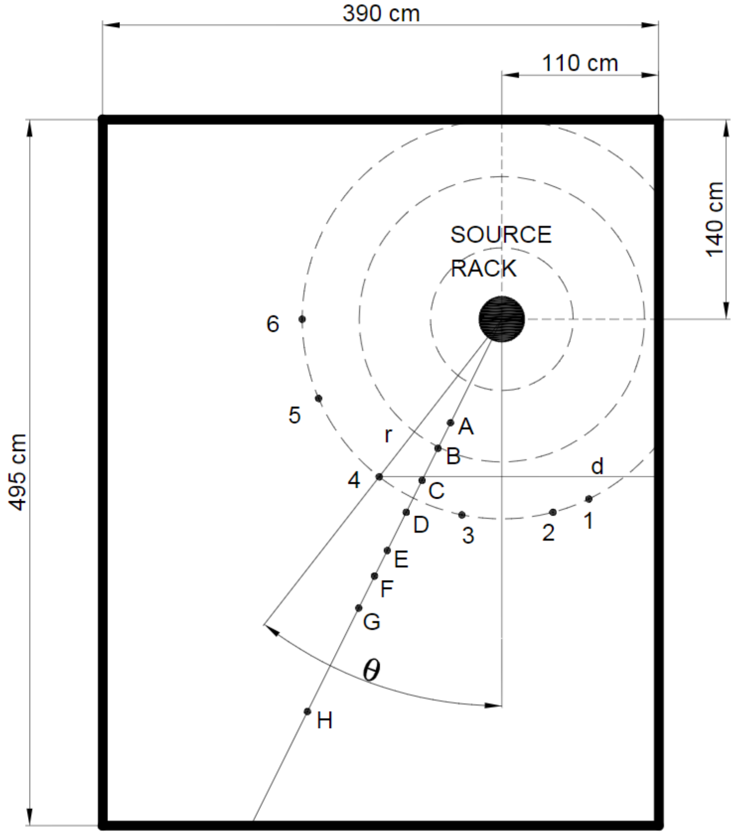
Laboratory for Radiation Chemistry and Dosimetry at RBI

Resources and Infrastructure

https://www.irb.hr/Radiation-Chemistry-and-Dosimetry-Laboratory



^{60}Co irradiation chamber



- Isotope life time – 5.27 years
- Main decay mode – 2 photons (1.17 MeV and 1.33 MeV)
- The source consist of 24 rods with 20 cm active cobalt pencils
- Total activity of the source is 1.8 PBq
- Smaller samples could be placed in the center of the cylinder where the dose rate is about 2.1 Mrad/h
- A dose of 34 krad/h can be delivered at the corner of the room or 1.2 m from the center of the source

Low dose rate study

RD53A Chip

- CERN – L.M. Jara Casas, A. A. Ahmed , A. Tsirou , E. Albert, J. F. Pernot
- RBI, RCDL - B. Mihaljević, M. Majer, M. Nodilo, I. Sajko, V. Trputec, S. Jančić
- RBI, HEPL- D. Ferenček, M. Roguljić
- RBI, CDSE - A. Karadzhinova-Ferrer, A. Starodumov,

Resources and Infrastructure

https://www.irb.hr/Radiation-Chemistry-and-Dosimetry-Laboratory

Goals and Tasks

- Goal: Check if radiation effects depend on dose rate
- Dose rate ~ 36 kRad/h, similar to dose rate of HL-LHC at 3cm from the interaction point
- Controlled temperature
- Constant monitoring and running tests, daily qualifications
- Targeting to accumulate several tens of Mrad
- Compare the results to high dose-rate tests

Setup at the irradiation chamber

- Bottom box cooled with chiller, top box with chiller + Peltiers
- 3 SCCs per box, each SCC powered by a PSU in the control room and connected with a display port cable to its FPGA outside the irradiation chamber
- Room temperature chips at 20° C, cold chips at 5° C

Status of the low dose rate radiation setup at RBI,
M. Roguljić , 4 Jul 2019, IT ASIC meeting

Low dose rate study

RD53A Chip

- CERN – L.M. Jara Casas, A. A. Ahmed , A. Tsirou , E. Albert, J. F. Pernot
- RBI, RCDL - B. Mihaljević, M. Majer, M. Nodilo, I. Sajko, V. Trputec, S. Jančić
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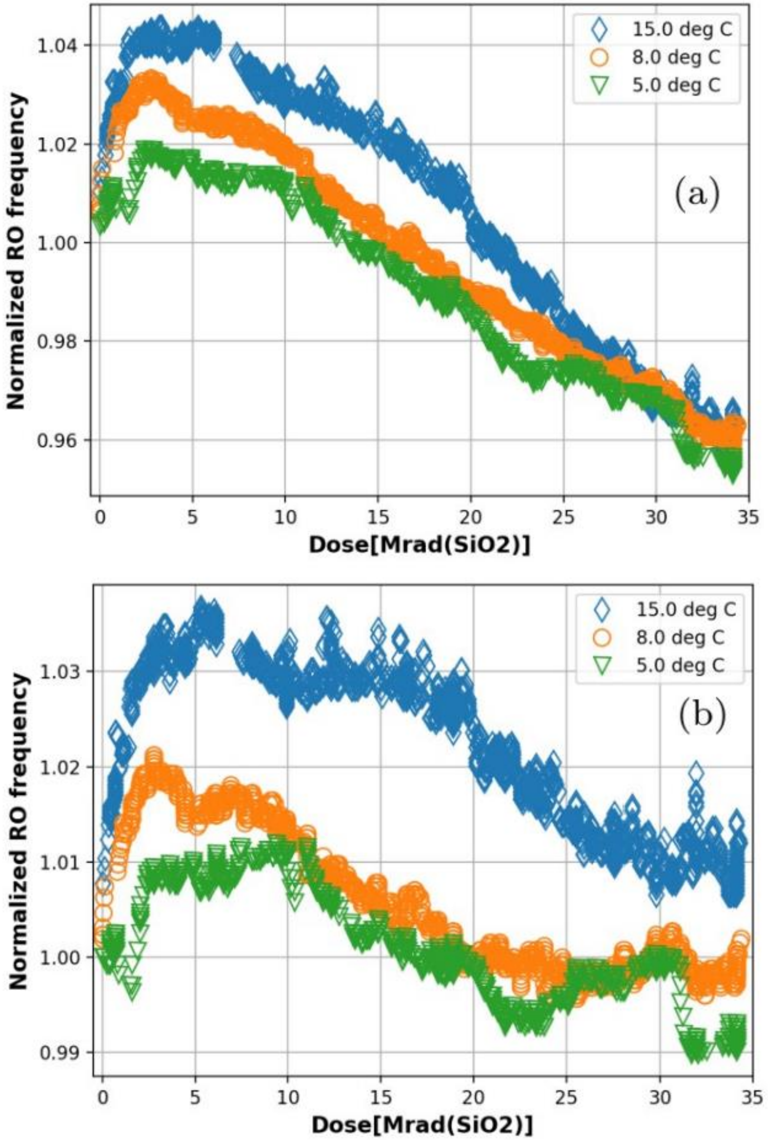
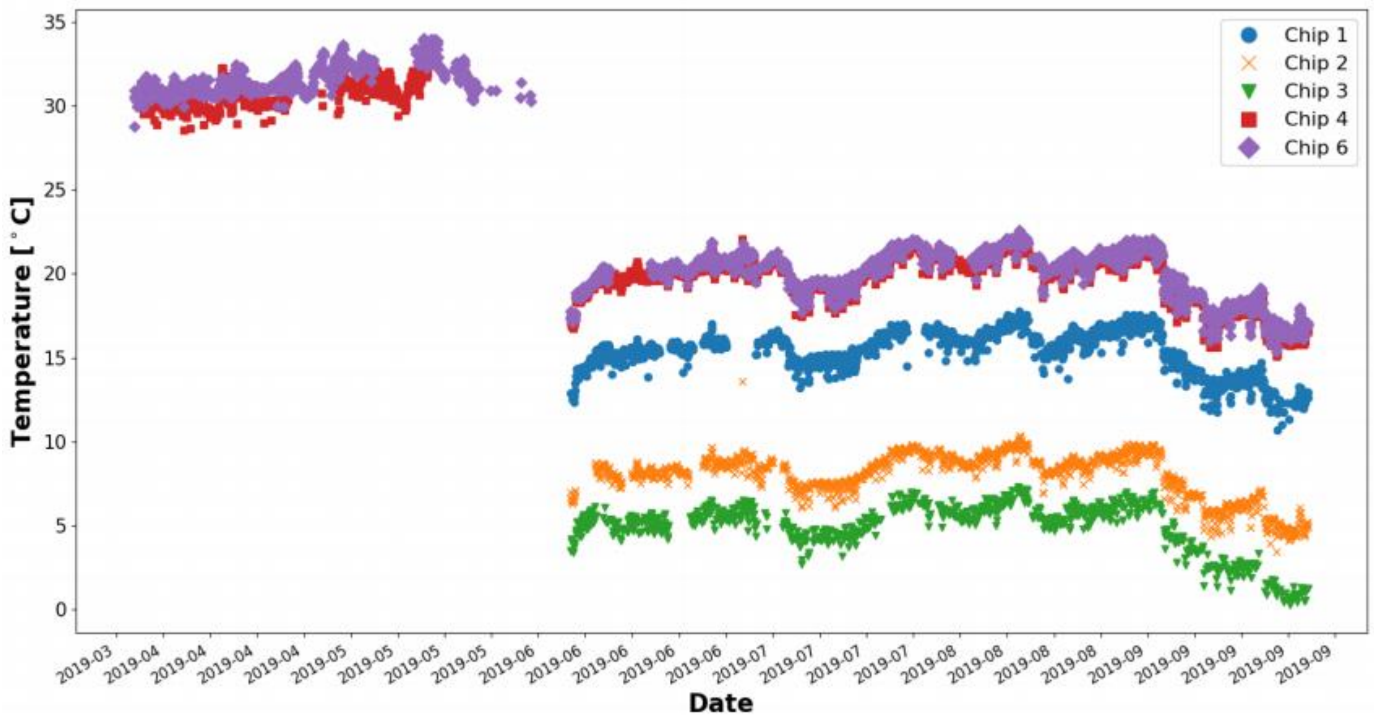


Comparison of the InverterClock ring oscillator structure with driving strength 0 (a) and driving strength 4 (b). Ring oscillator frequency is normalized to unity at the start of irradiation. Fluctuations in the frequency originate from temperature fluctuations.

Low dose rate ^{60}Co facility in Zagreb, M. Roguljić



Temperature for chips cooled with Peltiers (1-3) and two chips without Peltier cooling (4 and 6).

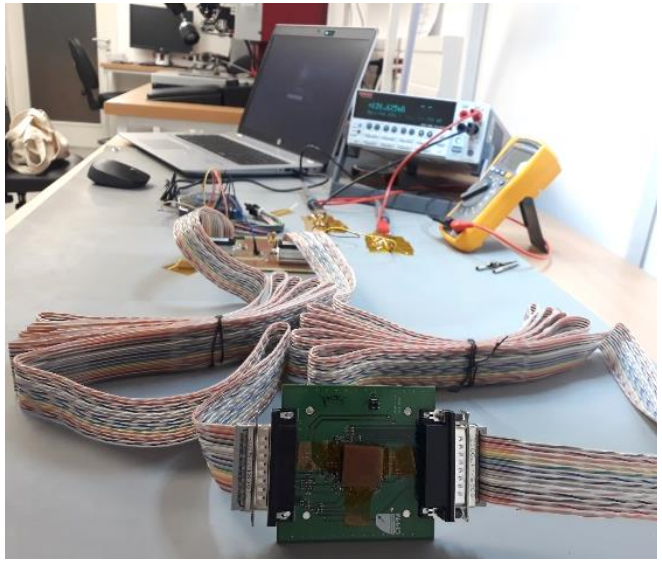
TID study

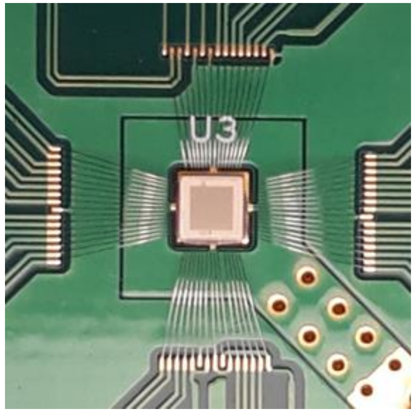
RD53SEU Chip

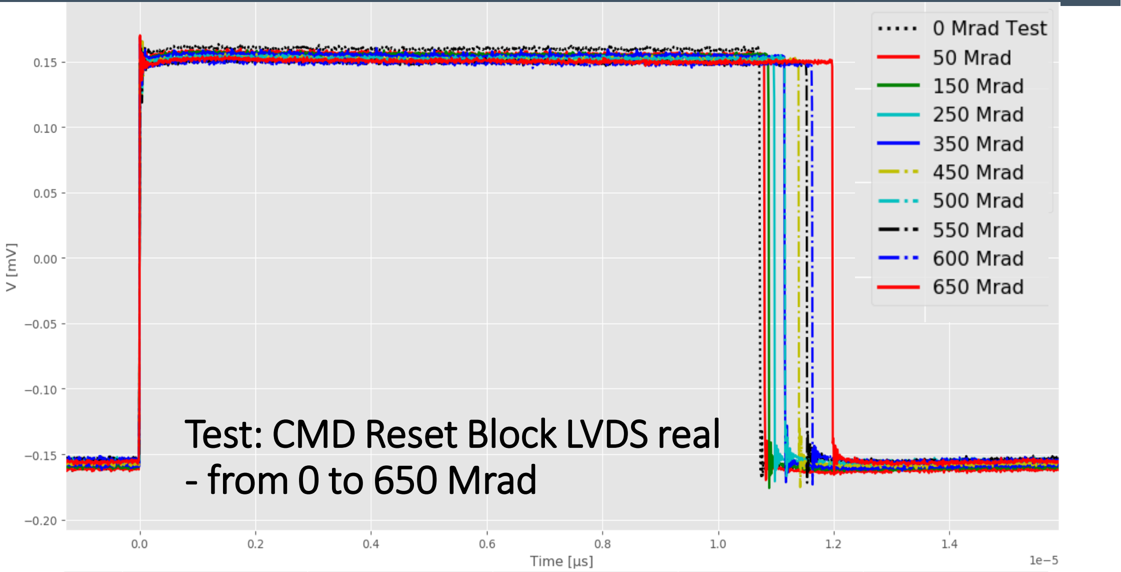
• RBI, RCDL - B. Mihaljević, M. Majer, I. Sajko, V. Trputec, S. Jančić
• RBI, CDSE - A. Karadzhinova-Ferrer
• University of Seville - F.R. Palomo

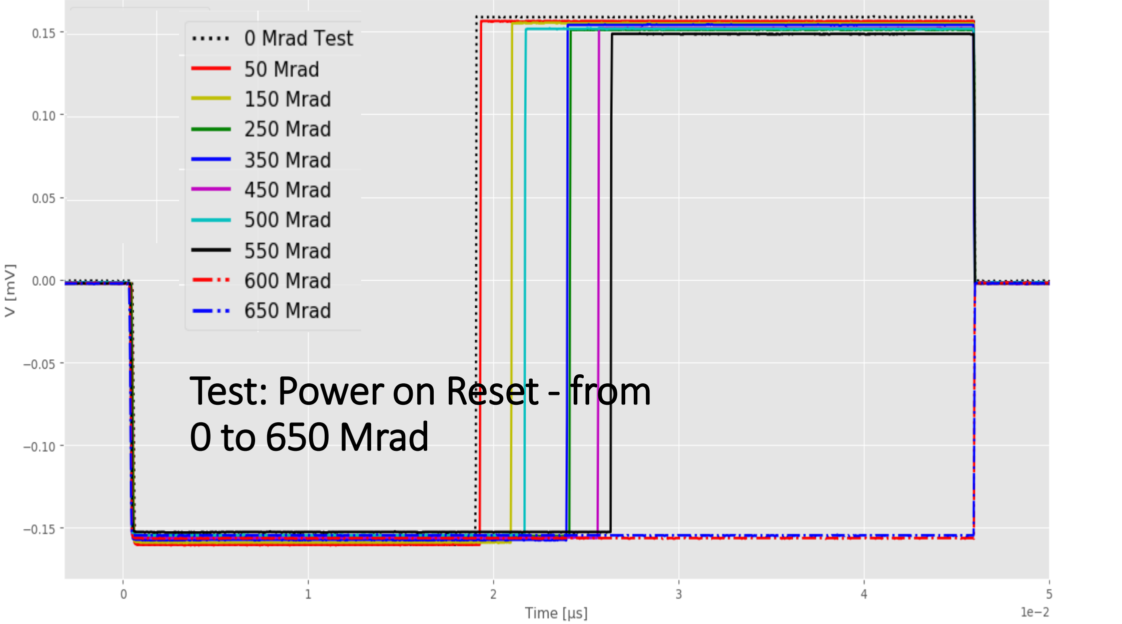
Resources and Infrastructure

https://www.irb.hr/Radiation-Chemistry-and-Dosimetry-Laboratory









Goals and Tasks

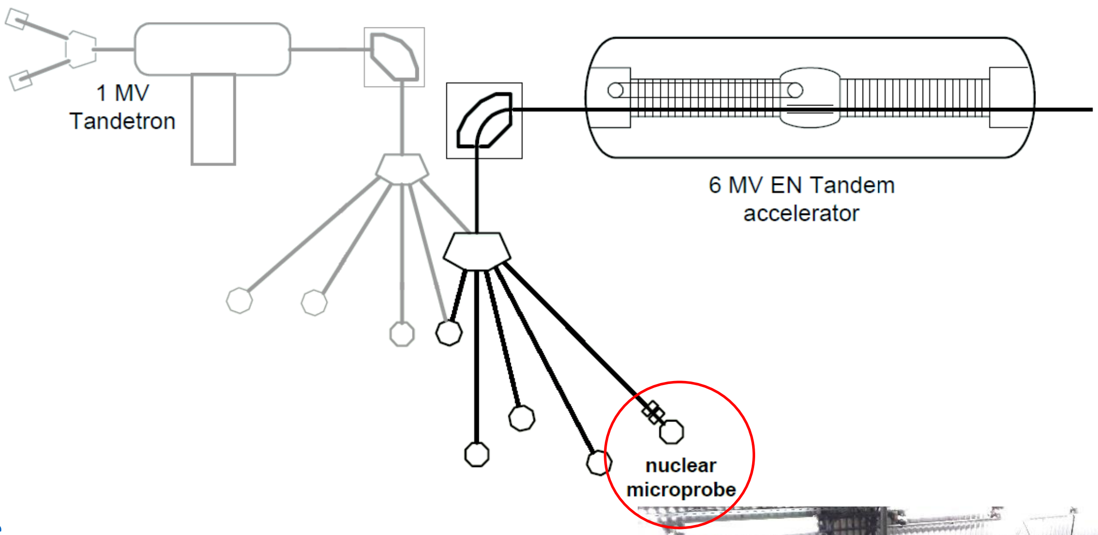
- Goal: Confirm the designed 550 Mrad TID
- Dose rate ~ 2.37 Mad/h
- Both the chip's irradiation and measurements were performed at room temperature
- Due to annealing we observed a partial recovery in both circuits.

* RBI was closed due to COVID 19 lockdown for 43 days

Laboratory for Ion Beam Interactions at RBI

Resources and Infrastructure

https://www.irb.hr/Laboratory-for-ion-beam-interactions

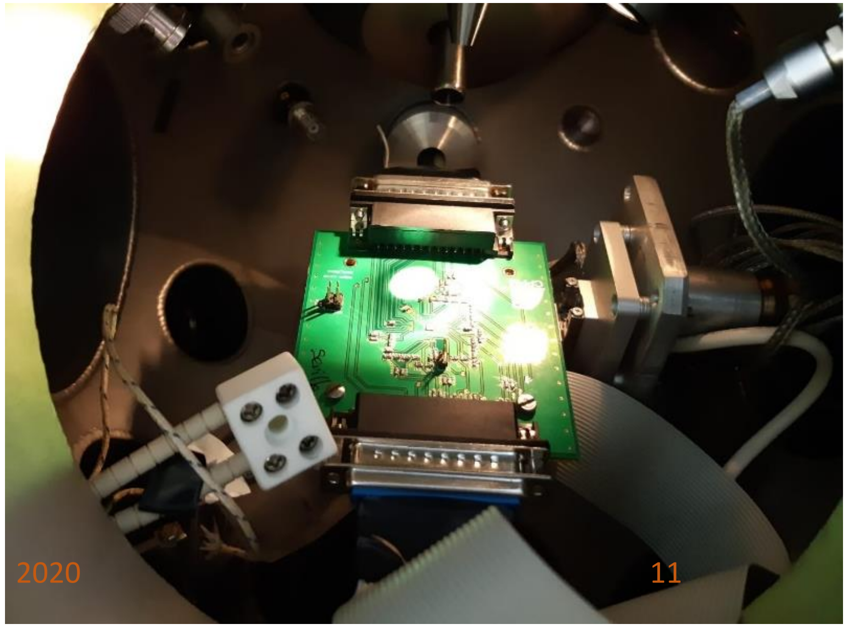


Nuclear Microprobe

- Two accelerators, 6.0 MV Tandem Van de Graaff and 1.0 MV Tandetron
- Protons (0.4 to 8 MeV), Ions up to ME/q^2 ratio of 25 MeV
- Beam spot size can be as low as 250 nm, in normal use ~ few µm
- Scanning area from 1.5 mm down to a few µm

Other existing beam lines of EN Tandem accelerator:

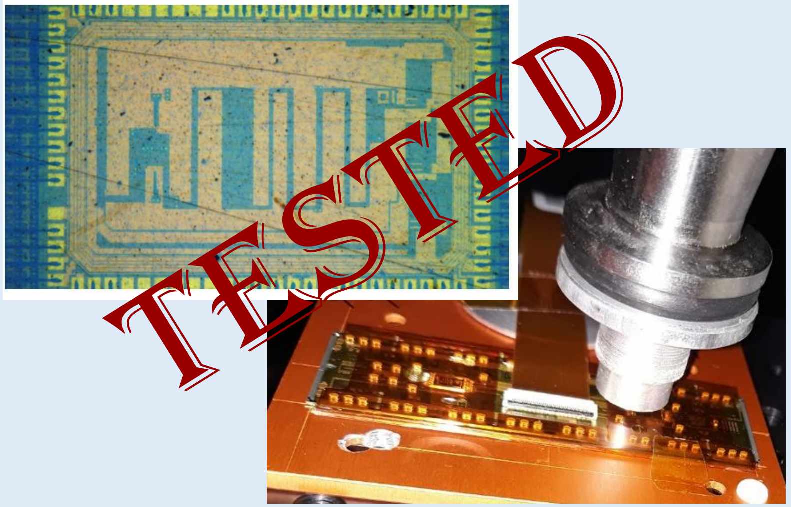
- IAEA beam line - routine PIXE/RBS
- TOF ERDA
- Nuclear reactions chamber
- High resolution PIXE / ion implant.



Devices successfully tested at RBI

Resources and Infrastructure

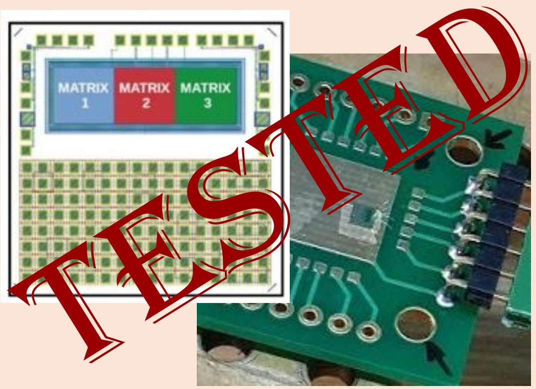
https://www.irb.hr/Laboratory-for-ion-beam-interactions



TBM Chip for CMS Pixel module

May and July 2019

H^{1+} 6 MeV (LET= 0.05 MeV-cm²/mg)
Li^{7+} 4 MeV (LET= 1.73 MeV-cm²/mg)
C^{5+} 12 MeV (LET= 4.47 MeV-cm²/mg)



Pseudo Matrix Test Chip

August 2019

H^{1+} 2 MeV (LET=0.11 MeV-cm²/mg)

Fully Depleted MAPS in 110-nm CMOS Process With 100–300-µm Active Substrate,
DOI: 10.1109/TED.2020.2985639

RD53SEU Test Chip

August 2019

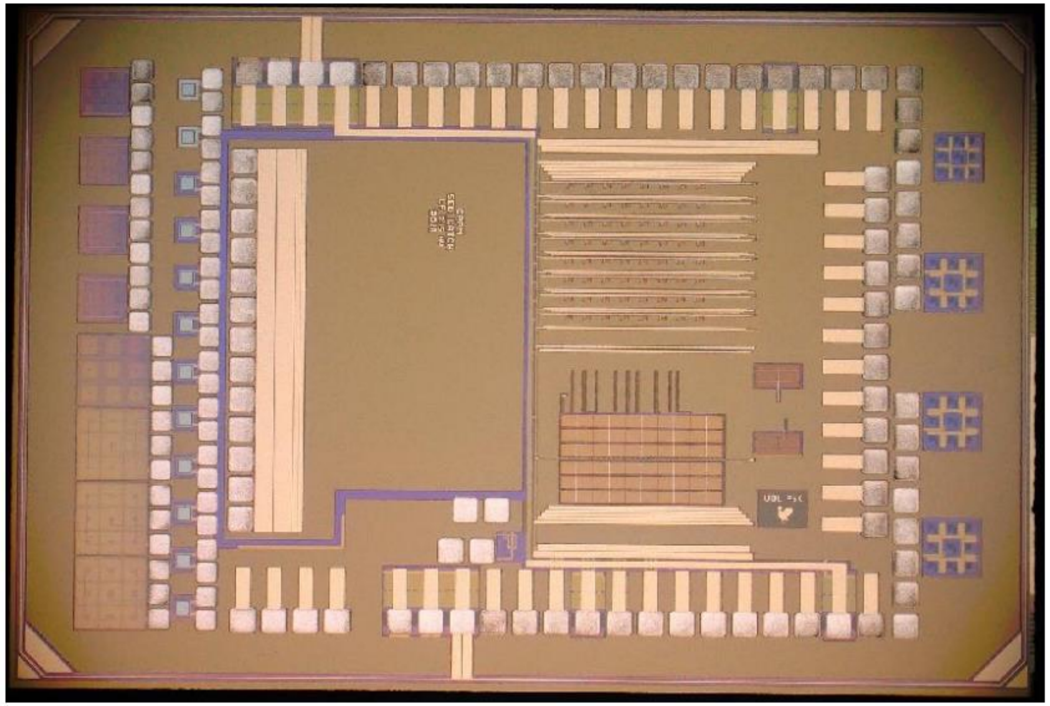
Li^{3+} 9 MeV (LET=1.26 MeV-cm²/mg)
C^{5+} 14.6 MeV (LET=4.22 MeV-cm²/mg)

SEE Sensitivity Mapping at RBI

Resources and Infrastructure

https://www.irb.hr/Laboratory-for-ion-beam-interactions

WANTED



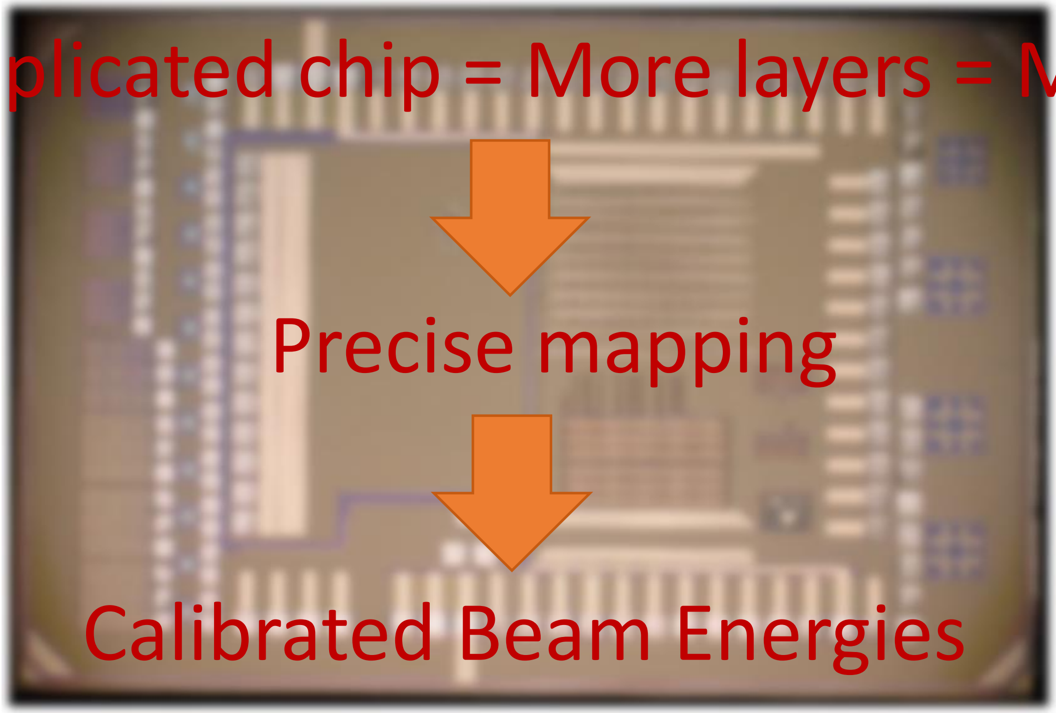
RD50 – HVCMOS MPW2 Chip

Resources and Infrastructure

https://www.irb.hr/Laboratory-for-ion-beam-interactions

WANTED

More complicated chip = More layers = More features



Precise mapping

Calibrated Beam Energies

RD50 – HVCMOS MPW2 Chip

Which is the expected LET_{max} at LHC?

Resources and Infrastructure

https://www.irb.hr/Laboratory-for-ion-beam-interactions

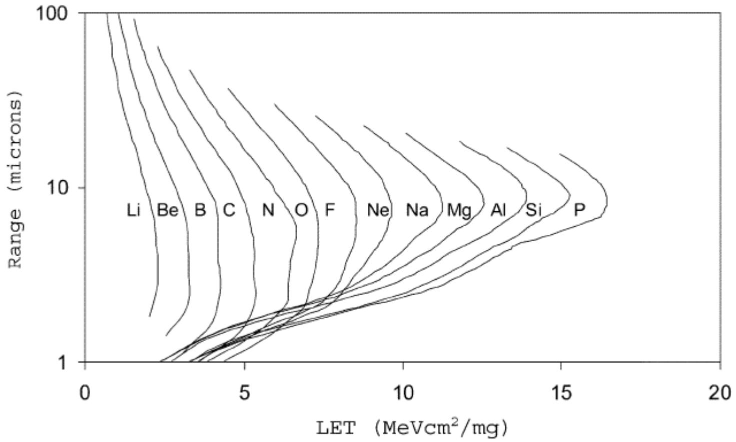


Fig. 1. Range versus LET of nuclei produced by protons in silicon.

LET Spectra of Proton Energy Levels From 50 to 500 MeV and Their Effectiveness for Single Event Effects Characterization of Microelectronics, David Hiemstra and Ewart Blackmore,

DOI: 10.1109/TNS.2003.821811

- ✓ SEU rates in LHC will in most devices be dominated by hadrons with E>20MeV. It is reasonable to assume in the estimate that all hadrons above 20MeV have the same effect
- ✓ To estimate error rates in LHC, use proton beams of 60-200MeV to measure the cross-section of the circuits. Multiply the measured s for the flux of hadrons with E>20MeV in the location where the circuit has to work. This procedure has been adopted by all LHC experiments as a “standard” for circuit qualification
- ✓ A useful information to situate the sensitivity of circuits in the LHC is the maximum LET of recoils from nuclear interaction of hadrons with the Si nuclei. The maximum LET is for a Si recoil and the LET is about 15 $MeVcm^2mg^{-1}$. This information can be used to judge if a circuit for which Heavy Ion data is available will experience a high error rate in the LHC.

Talk given by Federico Faccio , IN2P3 school, May 2005

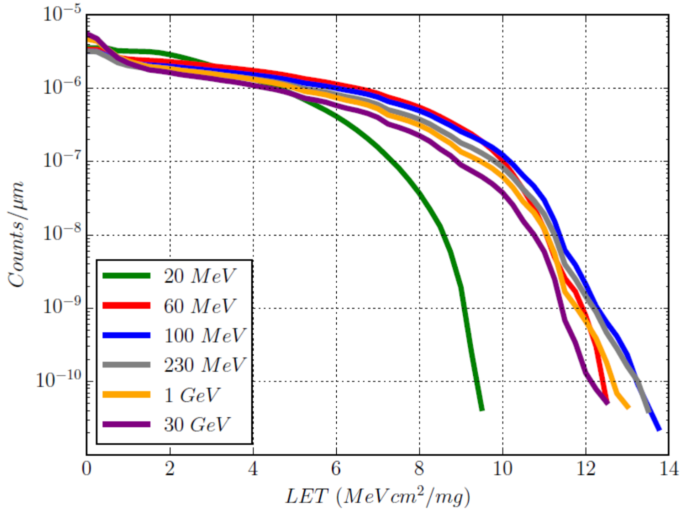


Fig. 4.8. LET reverse integral of the inelastic products ($Z \geq 2$, $E_{kin} > 100\ keV$) generated in proton-silicon interactions using the FLUKA production code. Results are normalized to the inelastic interaction cross section divided by the atom density.

Radiation Fields in High Energy Accelerators and their impact on Single Event Effects, PhD Thesis of Rubén GARCÍA ALÍA,

LET Calibration

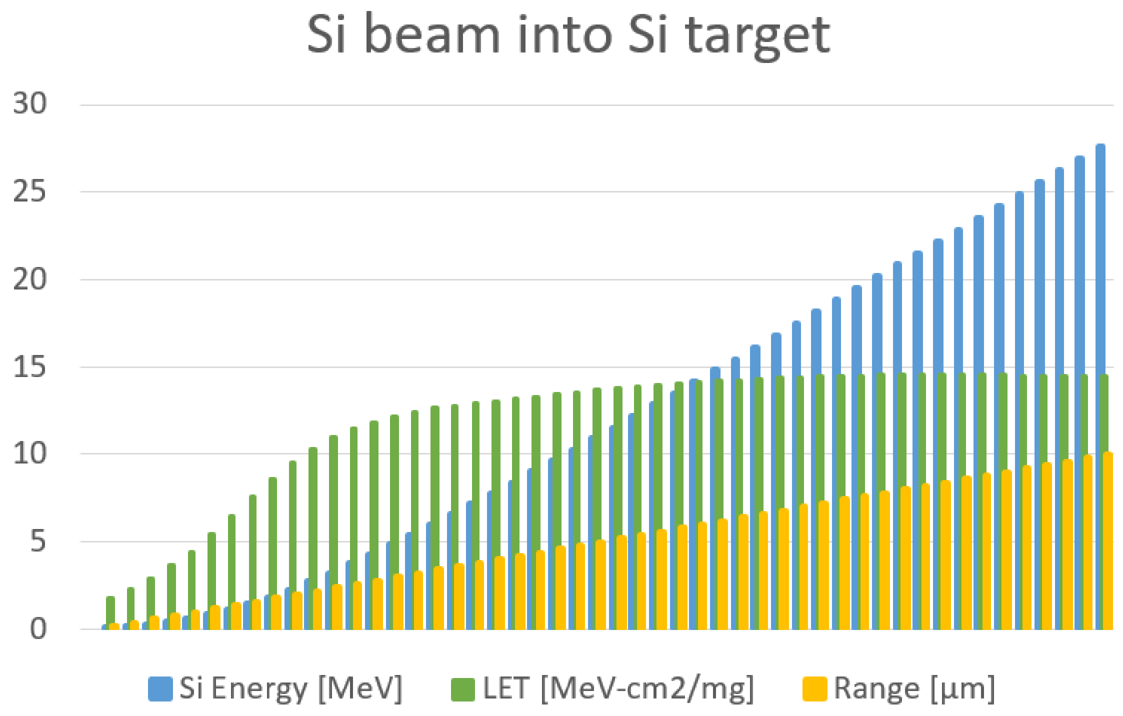
• RBI, LIBI – A. Crnjac, T. D, M. Jaksic
• RBI, CDSE - A. Karadzhinova-Ferrer
• University of Seville - F.R. Palomo

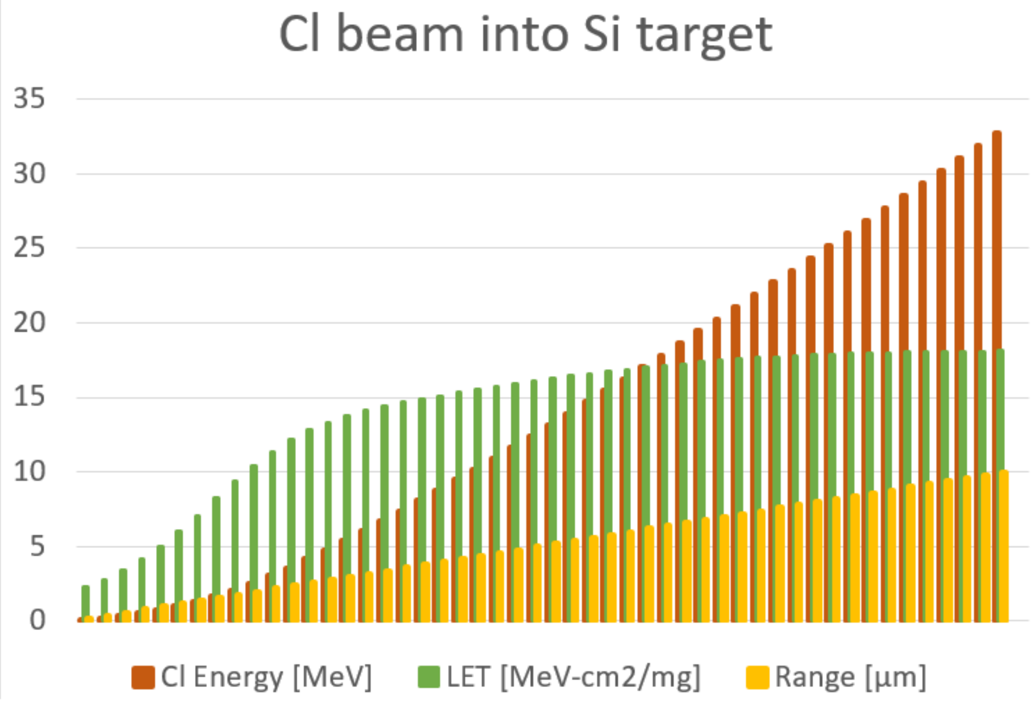
https://www.irb.hr/Laboratory-for-ion-beam-interactions

Goals and Tasks

- Verify the ion panoplia and energies available
- LET calculations to define the desired energies
- Preliminary SRIM simulations of the experimental setup
- Experimental measurements with several ion panoplia and energies

LET $_{MAX}$ for LHC is 15 MeV-cm^2/mg





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Resources and Infrastructure

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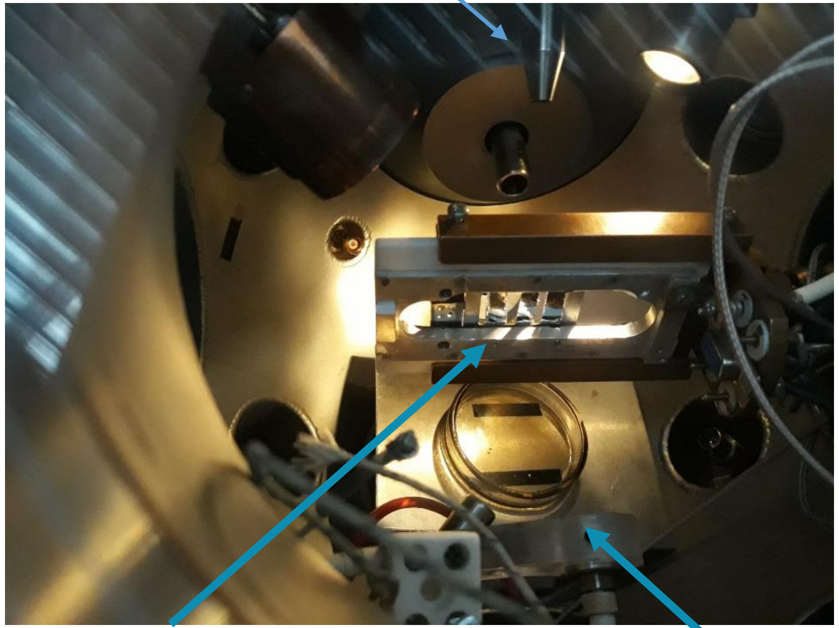
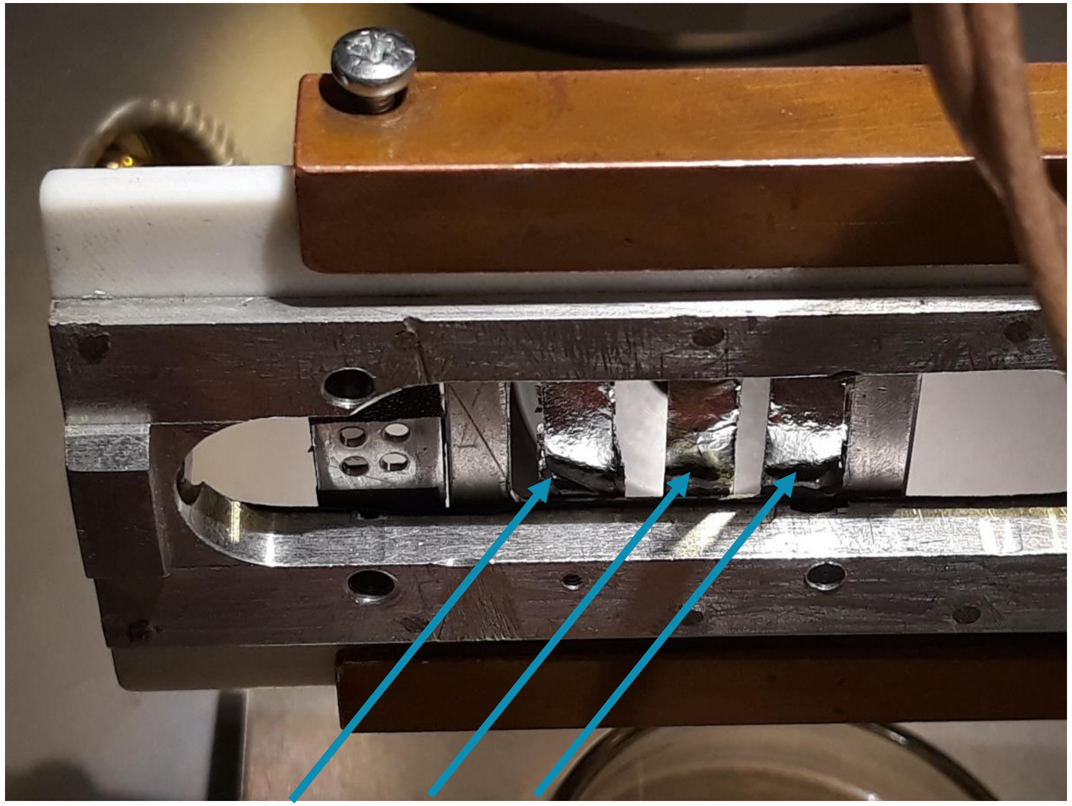
Microbeam Outport



Targets of Al foil with different thickness

STIM detector

Microprobe chamber



Targets of Al foil with thickness of 2, 3 and 5 μm (from left to right, respectively)

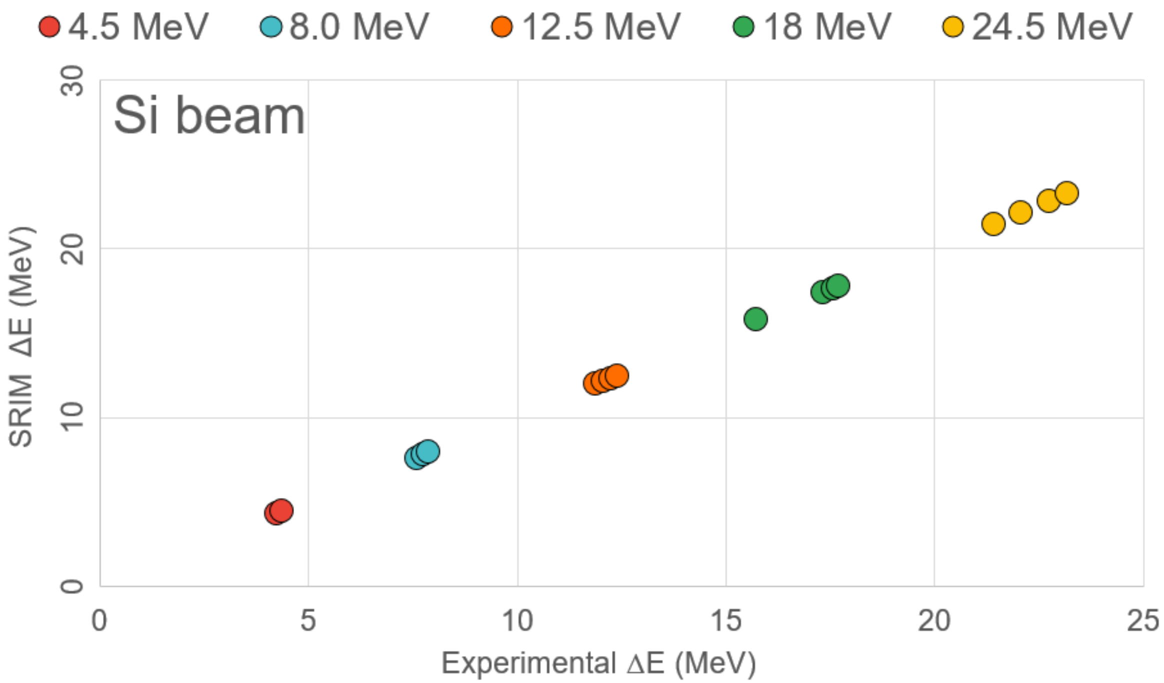
LET Calibration

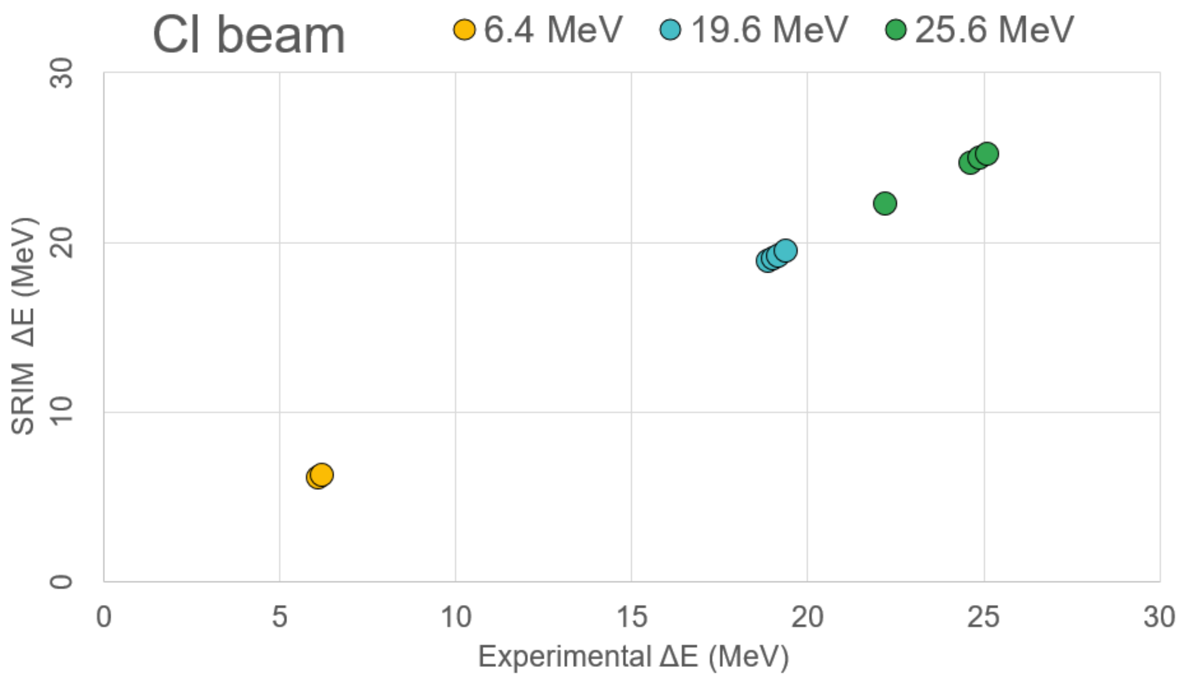
• RBI, LIBI – A. Crnjac, T. D, M. Jaksic
• RBI, CDSE - A. Karadzhinova-Ferrer
• University of Seville - F.R. Palomo

The following ion panoply and energies were selected based on the preliminary studies and the available sources

- Si => 3^+, 4^+, 5^+, 6^+ and 7^+ (LET= 11.98 – 14.51 MeV-cm^2/mg)
- Cl => 3^+, 7^+ and 8^+ (LET= 14.27 – 17.90 MeV-cm^2/mg)

The experimental results were compared to SRIM simulation





LET Calibration

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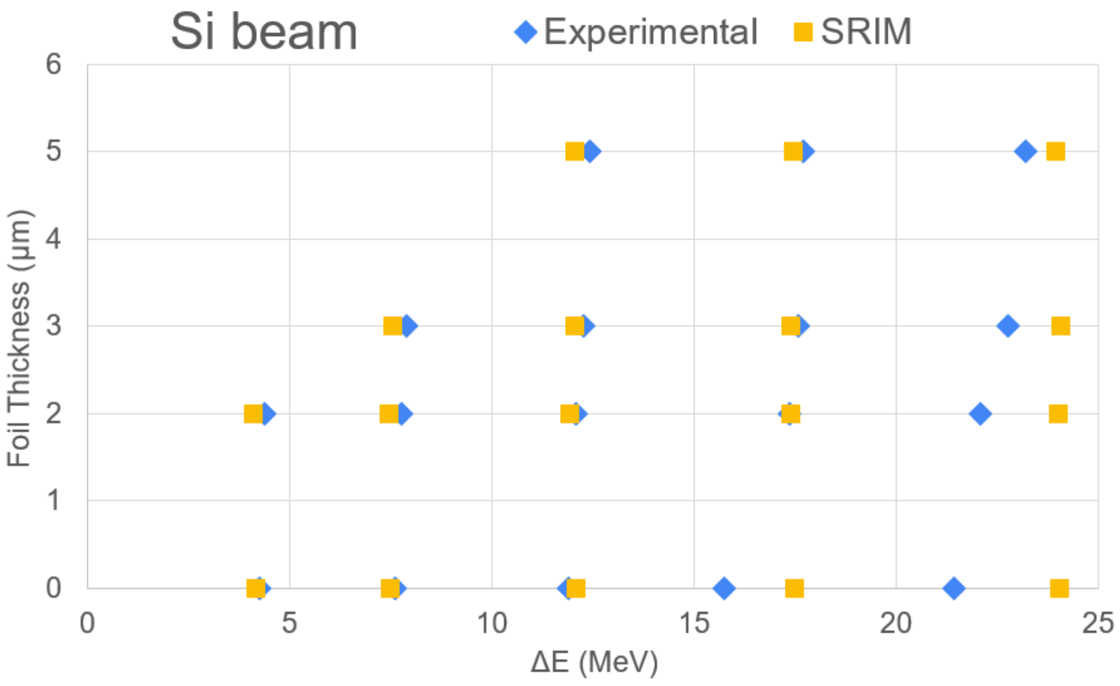
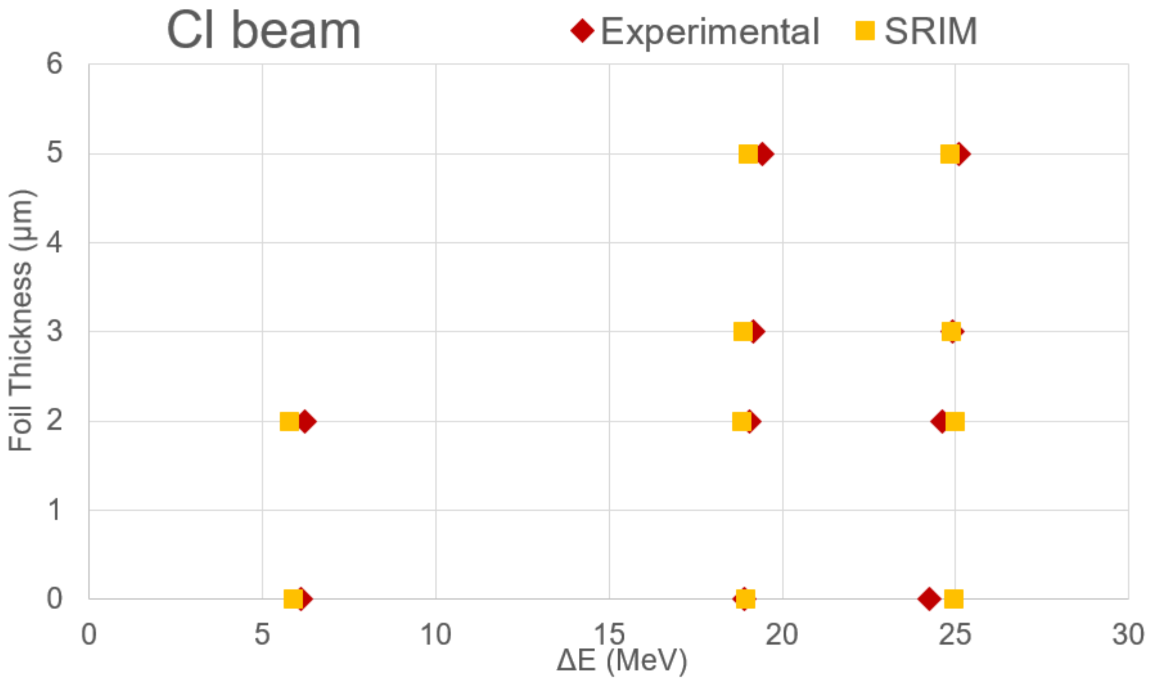




Conclusions

RBI has unique facilities for characterization of advanced detector and electronic devices

- ❑ The ^{60}Co irradiation facility already has experience and had already delivered the required irradiation on Phase 2 HDI samples, PROCV4 chips , Pixel Modules, PROC600 chips, RD53A chips, RD53SEU chip and more
- ❑ Proven results with Low Dose Rate and Total Ionization Dose studies
- ❑ Improvements to the atmospheric quality inside the Irradiation chamber are ongoing
- ❑ Soon to be add to the CERN irradiation facilities map

Conclusions

RBI has unique facilities for characterization of advanced detector and electronic devices

- The Ion Beam facility have performed Sensitivity mapping of various devices, such as the RD53SEU Test chip, the CMS TBM Functional chip and the Monolithic ARCADIA chip
- The LET certification to be continued with specifically designed calibration chip with several metallization layers
- We are looking forward of having RD50 HVCMOS MWP2 chip for SEE Sensitivity mapping tests at the IBA Microprobe
- RADIATE Transnational Access

Thank you for your attention!

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 669014. The content on this website is the sole responsibility of the RBI and can in no way be taken to reflect the views of the European Union.

Backup slides

Low dose rate study

RD53A Chip

- CERN – L.M. Jara Casas, A. A. Ahmed , A. Tsirou , E. Albert, J. F. Pernot
- RBI, RCDL - B. Mihaljević, M. Majer, M. Nodilo, I. Sajko, V. Trputec, S. Jančić
- RBI, HEPL- D. Ferenček, M. Roguljić
- RBI, CDSE - A. Karadzhinova-Ferrer, A. Starodumov,

Resources and Infrastructure

https://www.irb.hr/Radiation-Chemistry-and-Dosimetry-Laboratory

Dosimetry

- Dose rates measured in several locations and verified with Geant4 simulation
- Ethanol-chlorobenzene dosimeters placed outside the box, in front of the chips
- Dose rates: Cold chips at 32 kRad/h, Room temperature chips at 36 kRad/h

Setup outside

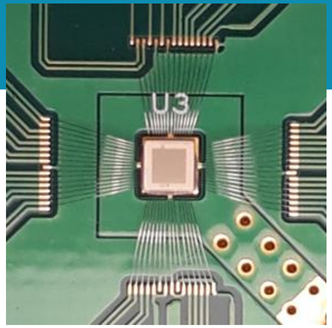
- FPGAs on top of the concrete wall separating the corridor from the irradiation chamber, protected from radiation
- Connected by a 5m display port cable to the SCCs
- Cables and pipes routed through the corridor

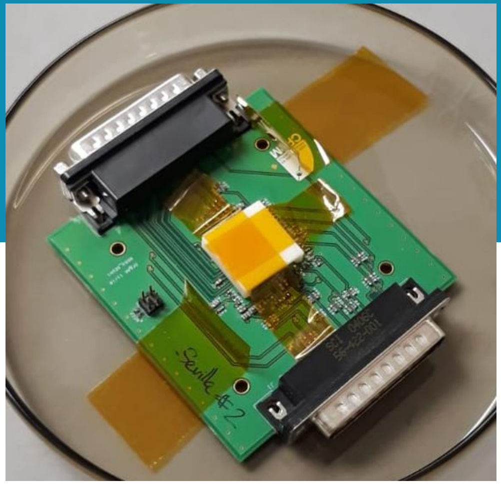
Status of the low dose rate radiation setup at RBI,
M. Roguljić , 4 Jul 2019, IT ASIC meeting

TID study

- RBI, RCDL - B. Mihaljević, M. Majer, I. Sajko, V. Trputec, S. Jančić
- RBI, CDSE - A. Karadzhinova-Ferrer
- University of Seville - F.R. Palomo

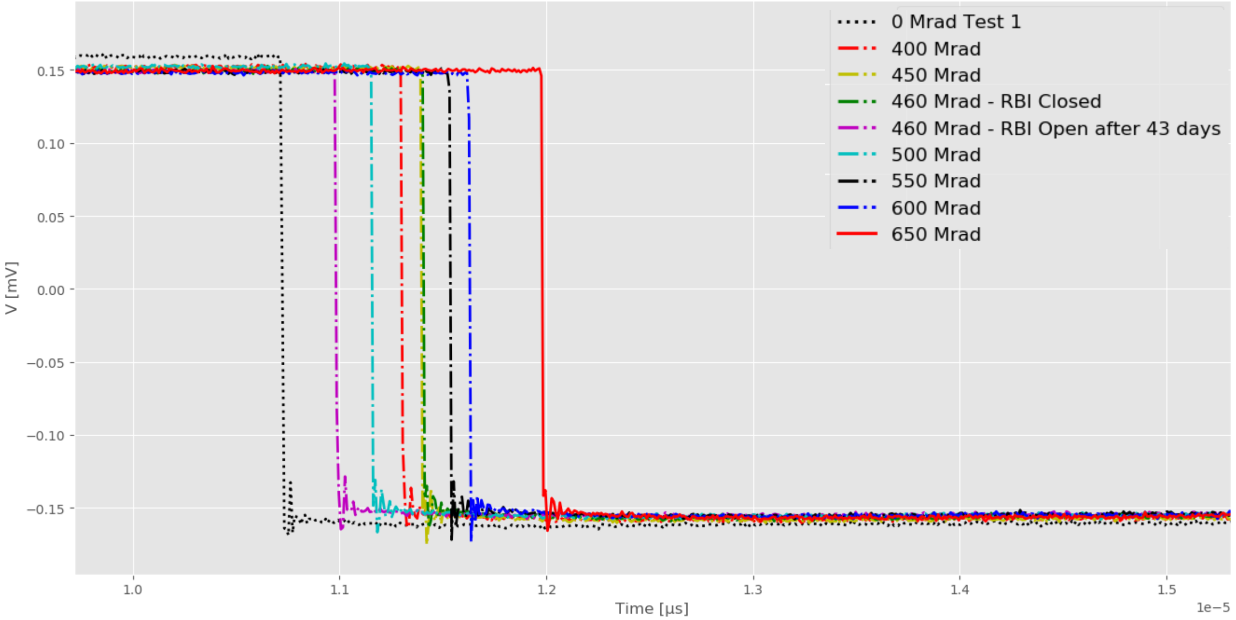
RD53SEU Chip



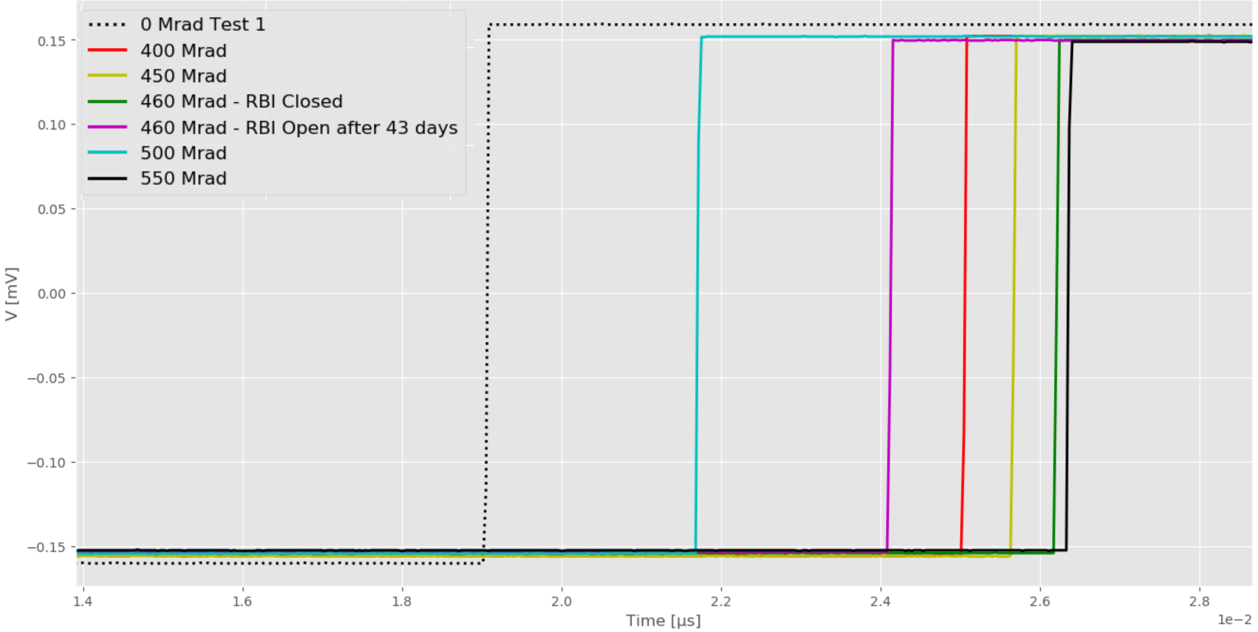


Impact of the RBI shutdown due to COVID 19

Test: CMD Reset Block LVDS real - from 0 to 650 Mrad



Test: Power on Reset - from 0 to 550 Mrad



Shortly after 450 Mrad RBI went into shutdown, the chip was taken out of the irradiation chamber and stored at room temperature for 43 days