High Energy Physics and Instrumentation with the LHC-CERN

HEPIC
IFUSP

Radiation Effects in Electronic Devices

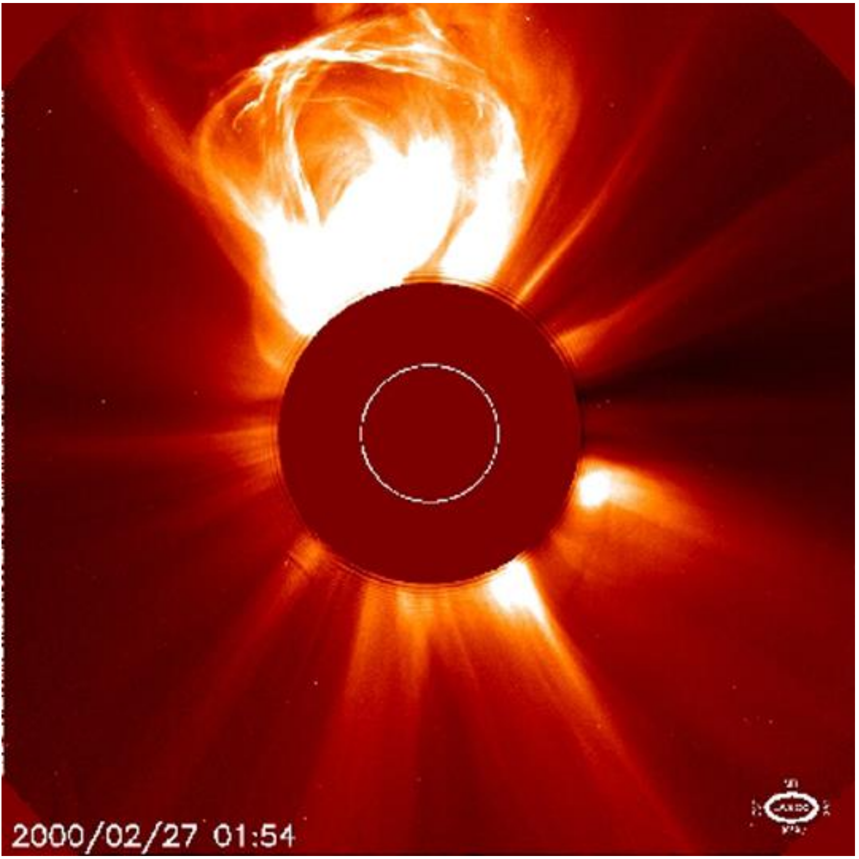
N. H. Medina

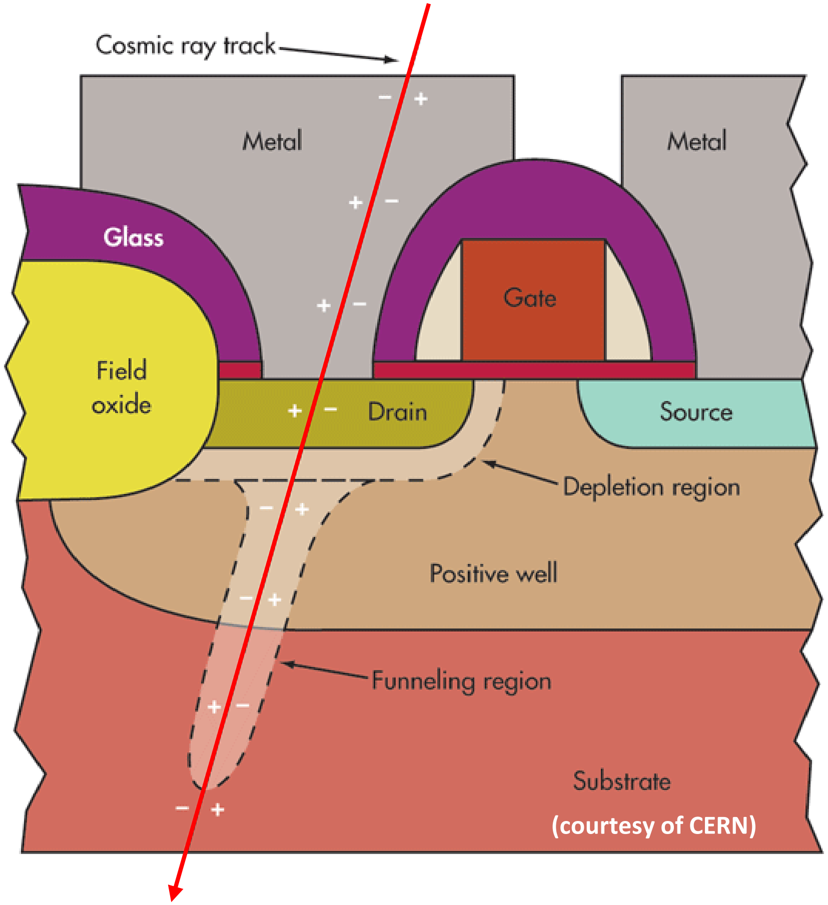
Instituto de Física da Universidade de São Paulo

OUTLINE

- *Radiation effects in electronic componentes*
- *Measurement examples.*
- *New beam line for Applied Nuclear Physics*

Coronal Mass Ejection



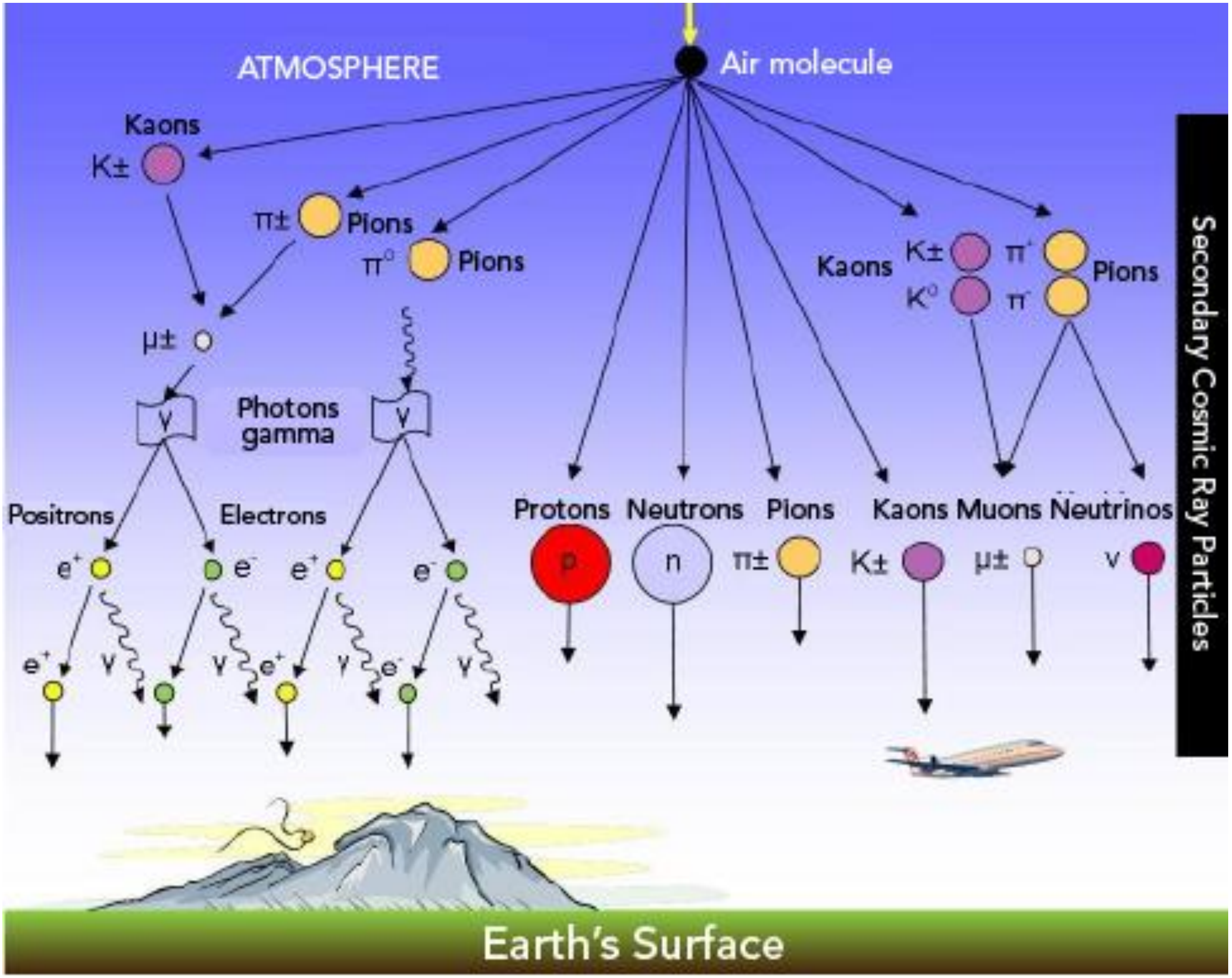


(courtesy of CERN)

A Coronal Mass Ejection (CME) blasts into space a billion tons of particles traveling millions of km/h, impacting any planet or spacecraft in its path.

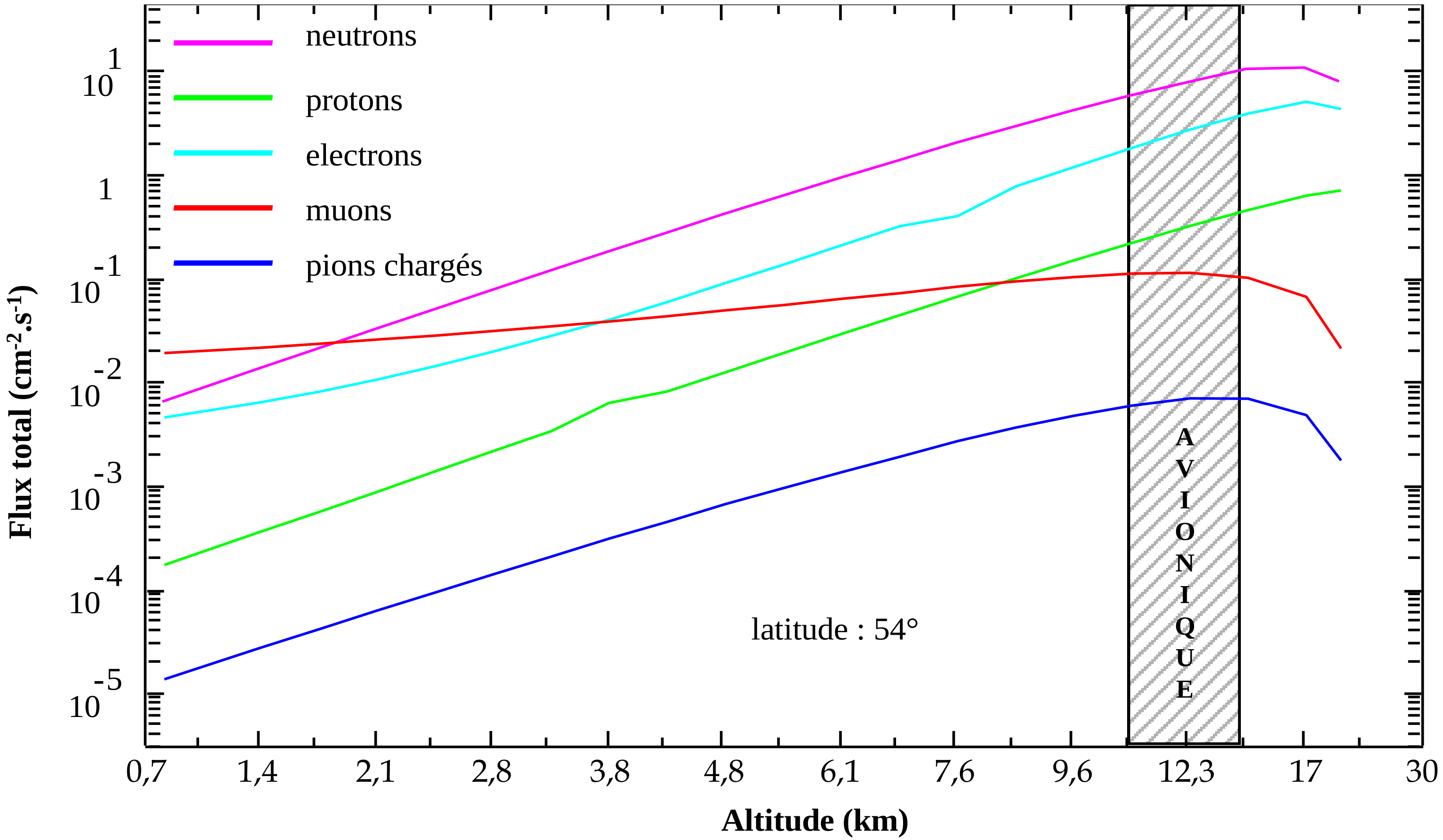
Credit: A coronal mass ejection on Feb. 27, 2000 taken by SOHO LASCO C2 and C3 (SOHO ESA & NASA) and Rudolf R. Bühler

Neutron production in Atmosphere



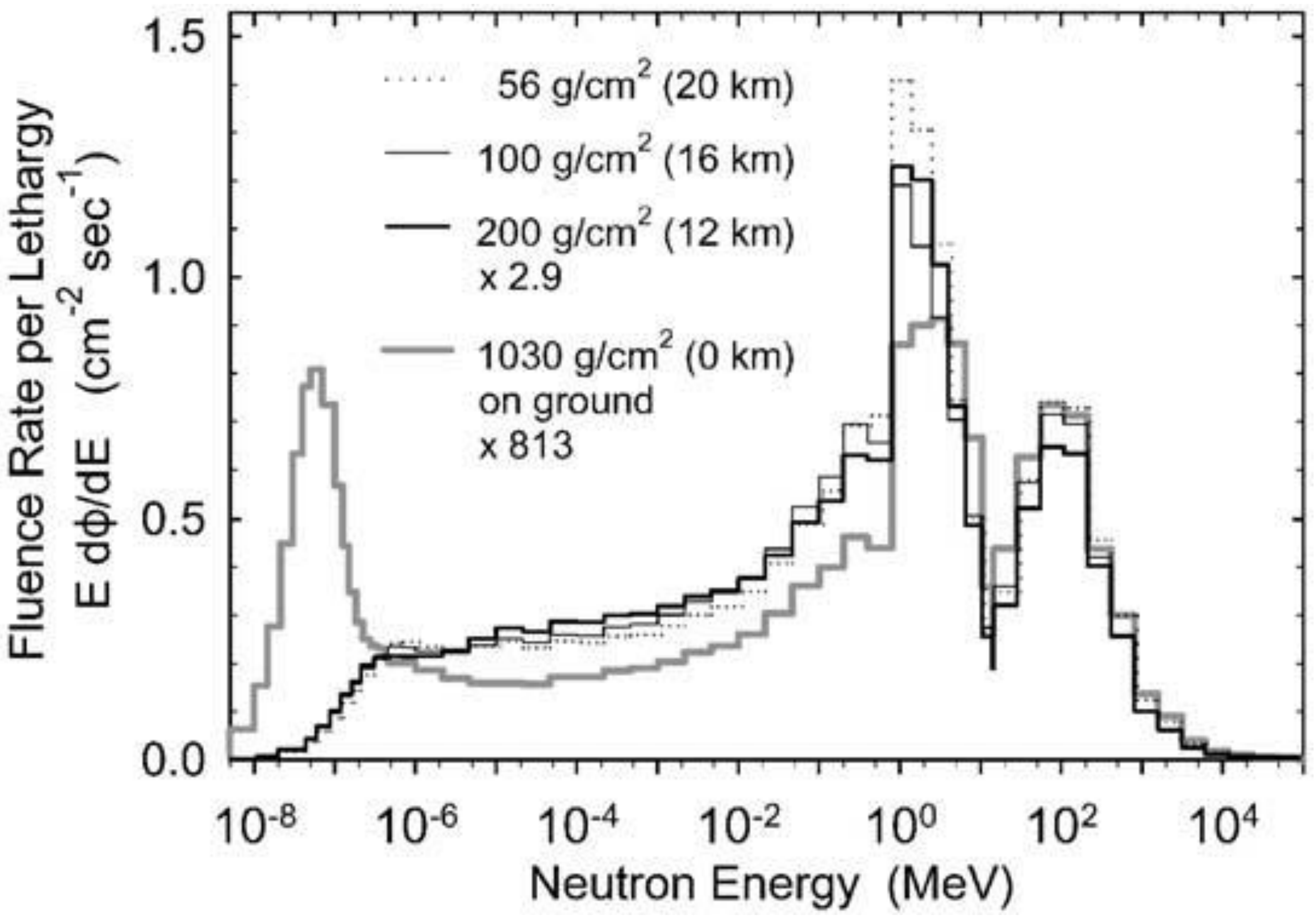
https://letstalkscience.ca/educational-resources/backgrounders/what-are-cosmic-rays

Charged Particles and Neutron Flux



R. Gaillard, EWRHE 2004 and A.Paccagnella WERICE 2014

Neutron fluence at different altitutes



P. Goldhagen et al., Nuclear Instruments and Methods in Physics Research A 476 (2002) 42–51

Neutron Flux Simulation inside the MAGNEX Experimental Hall

A dedicated simulation was performed with the FLUKA code in order to evaluate the radiation spectra and fluence as a function of the topology of the detectors inside the MAGNEX experimental hall at LNS.

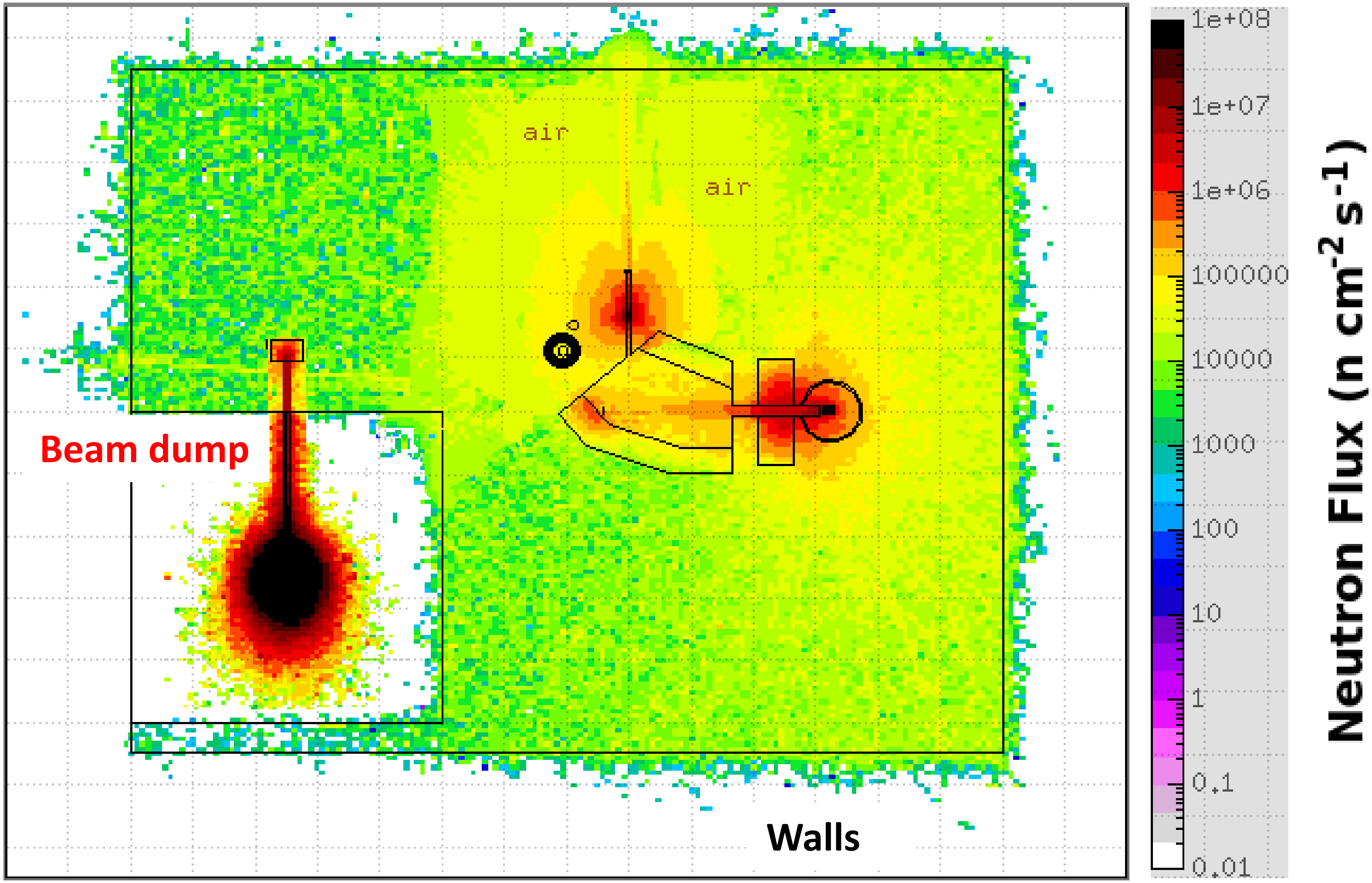
Four radiation sources were considered :

- Beam-target interaction;
- Leakage along the transport of beam line;
- Beam - beam stopper interaction.
- Secondary radiation induced by neutron interactions with the material inside the experimental hall, including its walls, floor and ceiling.

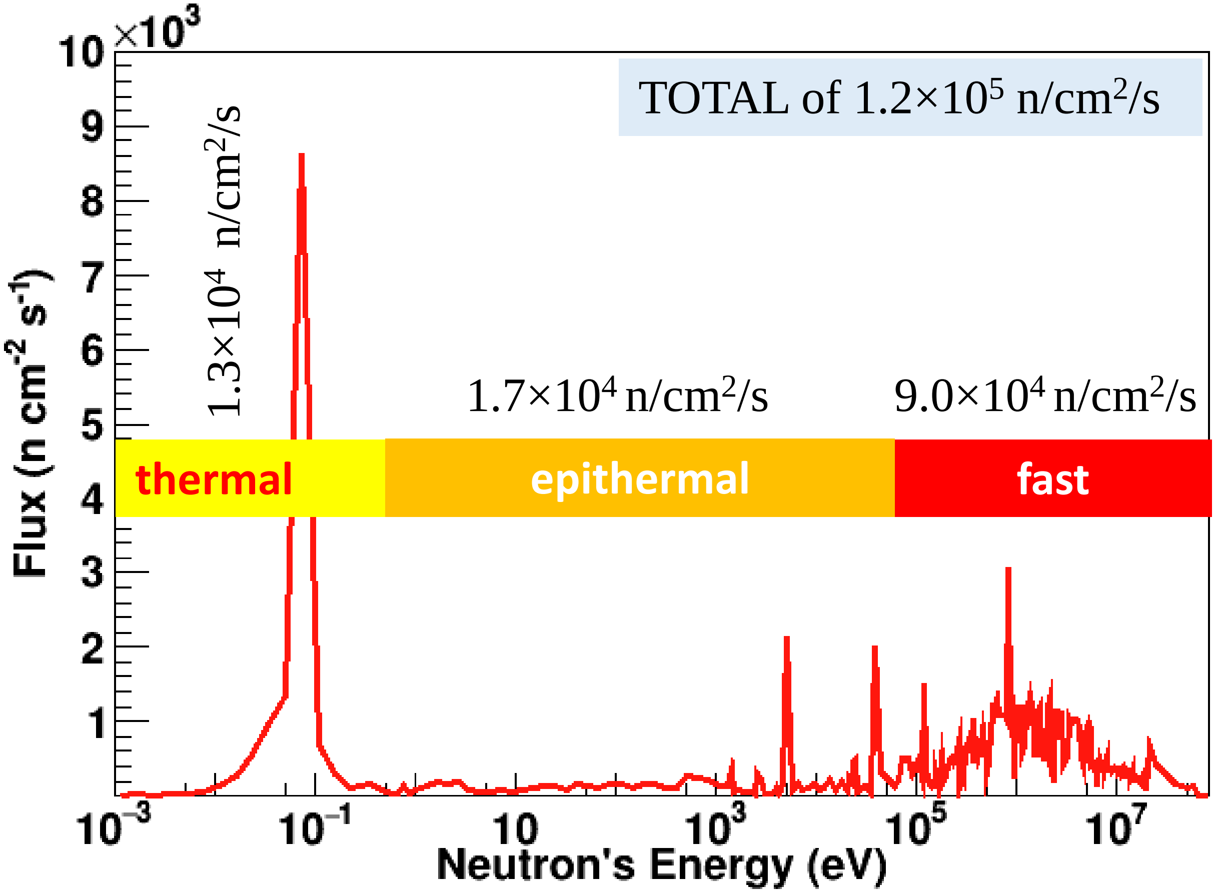
The ^{20}Ne beam interaction with a ^{76}Ge target with ^{12}C backing was simulated

Fully stripped ^{20}Ne beam with an energy of 60 MeV/A and a current of 85 eμA
The beam dump is inside a concrete bunker.

Neutron Flux inside the MAGNEX Experimental Hall



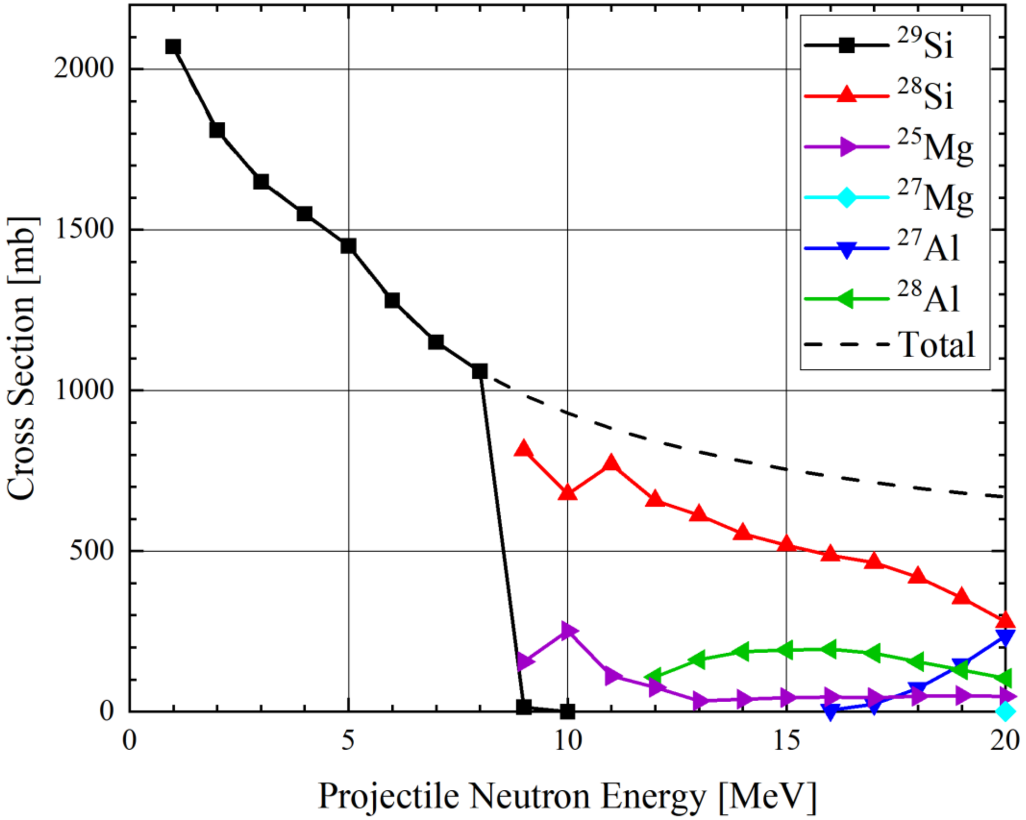
Simulated Neutron Energy Spectrum



Neutron energy spectrum obtained via FLUKA simulations for the region where the MAGNEX focal plane detector is located

Neutron-induced Nuclear Reactions

Fusion-evaporation Monte Carlo Calculations



neutron + ^{28}Si E=14 MeV

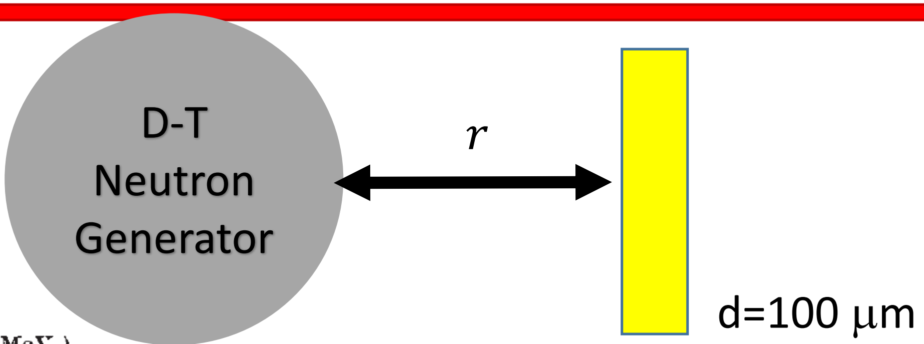
$n + {}^{28}\mathrm{Si} \rightarrow n + {}^{28}\mathrm{Si}$ Elastic scattering

$n + {}^{28}\mathrm{Si} \rightarrow p + {}^{28}\mathrm{Al}$

$n + {}^{28}\mathrm{Si} \rightarrow \alpha + {}^{25}\mathrm{Mg}$

Saulo Alberton et al. - Nuclear Reactions: Neutron-Induced Radiation Effects in Electronic Devices, SERESSA 2021

Silicon Surface Barrier Detector



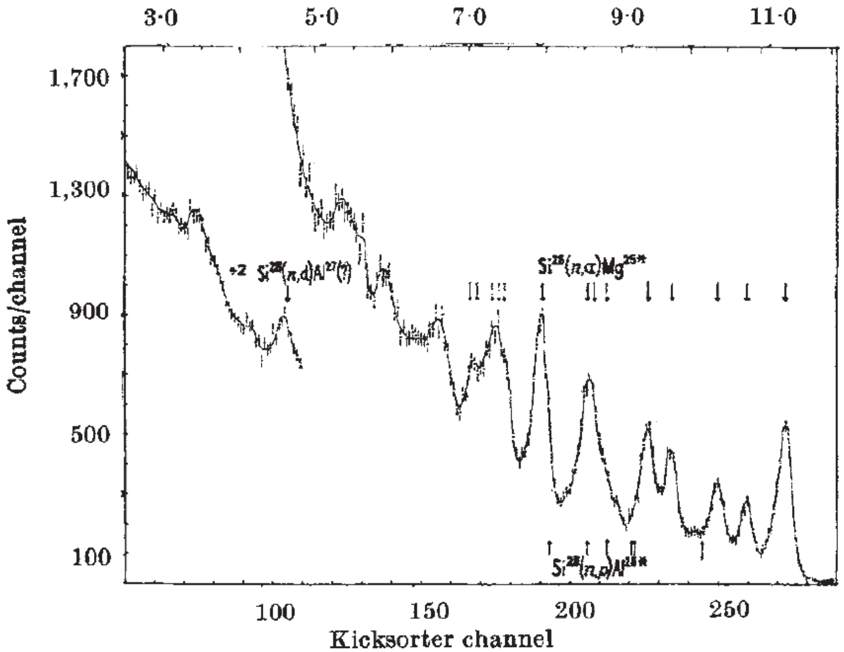
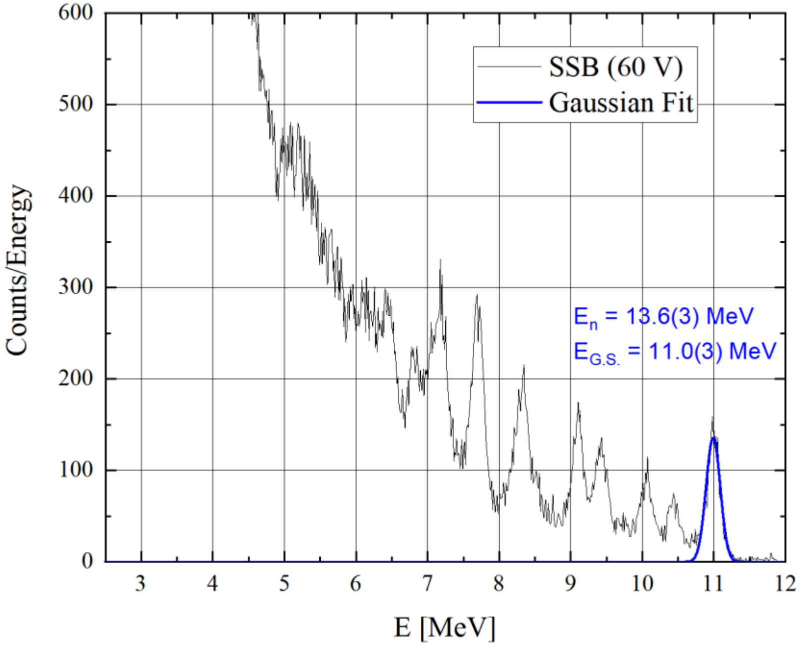


Fig. 1. Energy spectrum observed from interaction of 14·03 MeV. neutrons with a silicon surface barrier detector

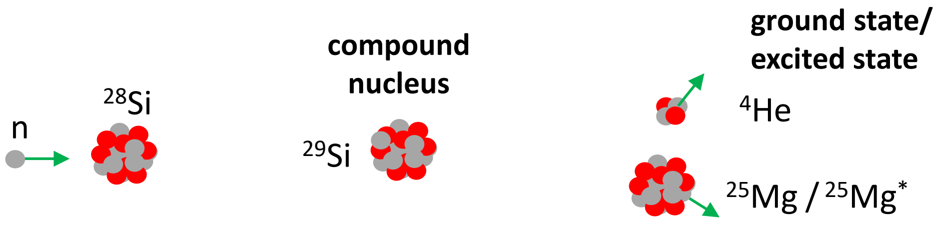
Neutron rate (4π): $1.58(5) \times 10^8$ n/s

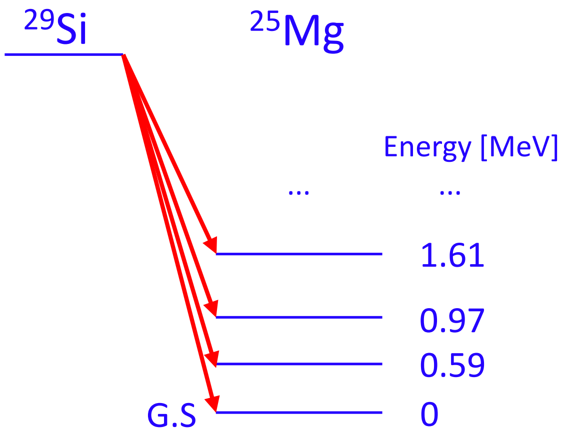


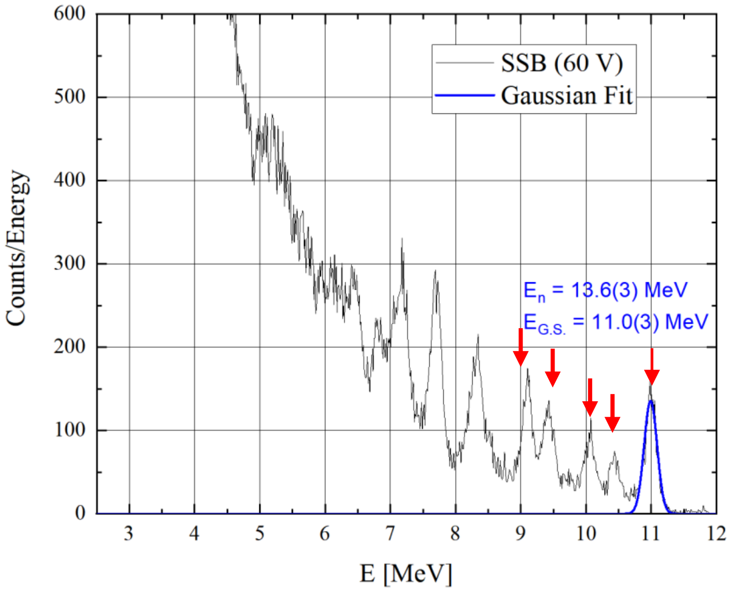
W. M. Deuchars *et al.*, Interaction of 14-MeV neutrons with a Silicon Semiconductor Nuclear Particle Detector, Nature, 1961.

Excited states of nuclear reaction channels

<table>
<tr><th colspan="2">Neutron energy: 13.64 MeV</th></tr>
<tr><td colspan="2">^{25}Mg (NuDAT 2.8)</td></tr>
<tr><td colspan="2">$Q = -2.654$ MeV (CATKIN)</td></tr>
<tr><th>E_{exc} [MeV]</th><th>E_{peak} [MeV]</th></tr>
<tr><td>0.00</td><td>10.99</td></tr>
<tr><td>0.59</td><td>10.40</td></tr>
<tr><td>0.97</td><td>10.01</td></tr>
<tr><td>1.61</td><td>9.38</td></tr>
<tr><td>1.96</td><td>9.02</td></tr>
<tr><td>2.56</td><td>8.43</td></tr>
<tr><td>2.74</td><td>8.25</td></tr>
<tr><td>2.80</td><td>8.19</td></tr>
<tr><td>3.41</td><td>7.58</td></tr>
</table>

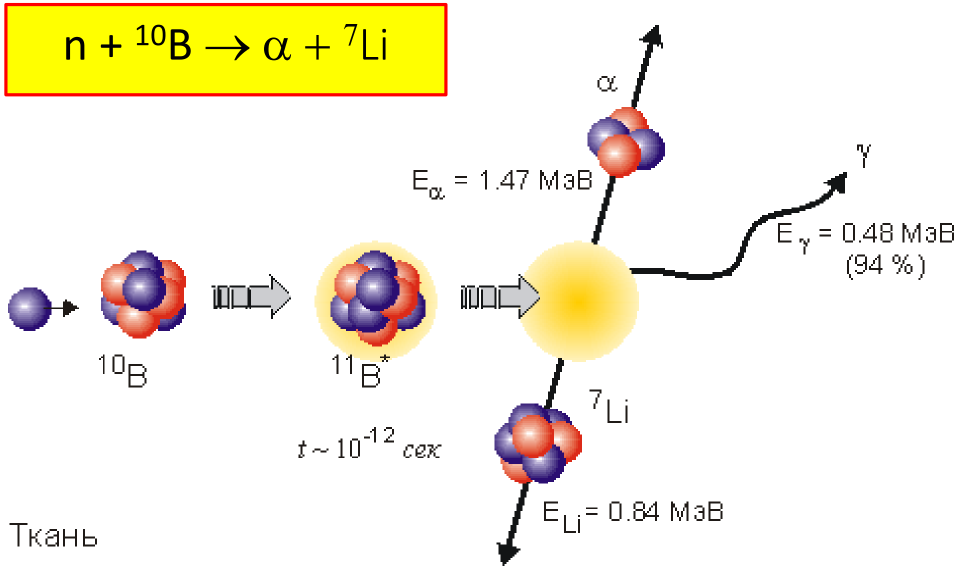






H s

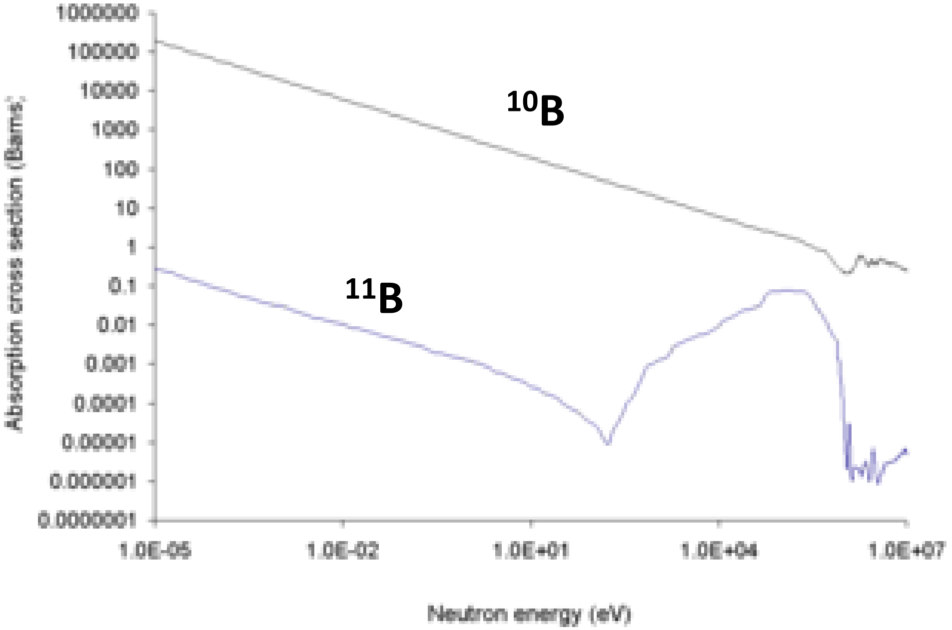
$$n + {}^{10}B \rightarrow \alpha + {}^{7}Li$$



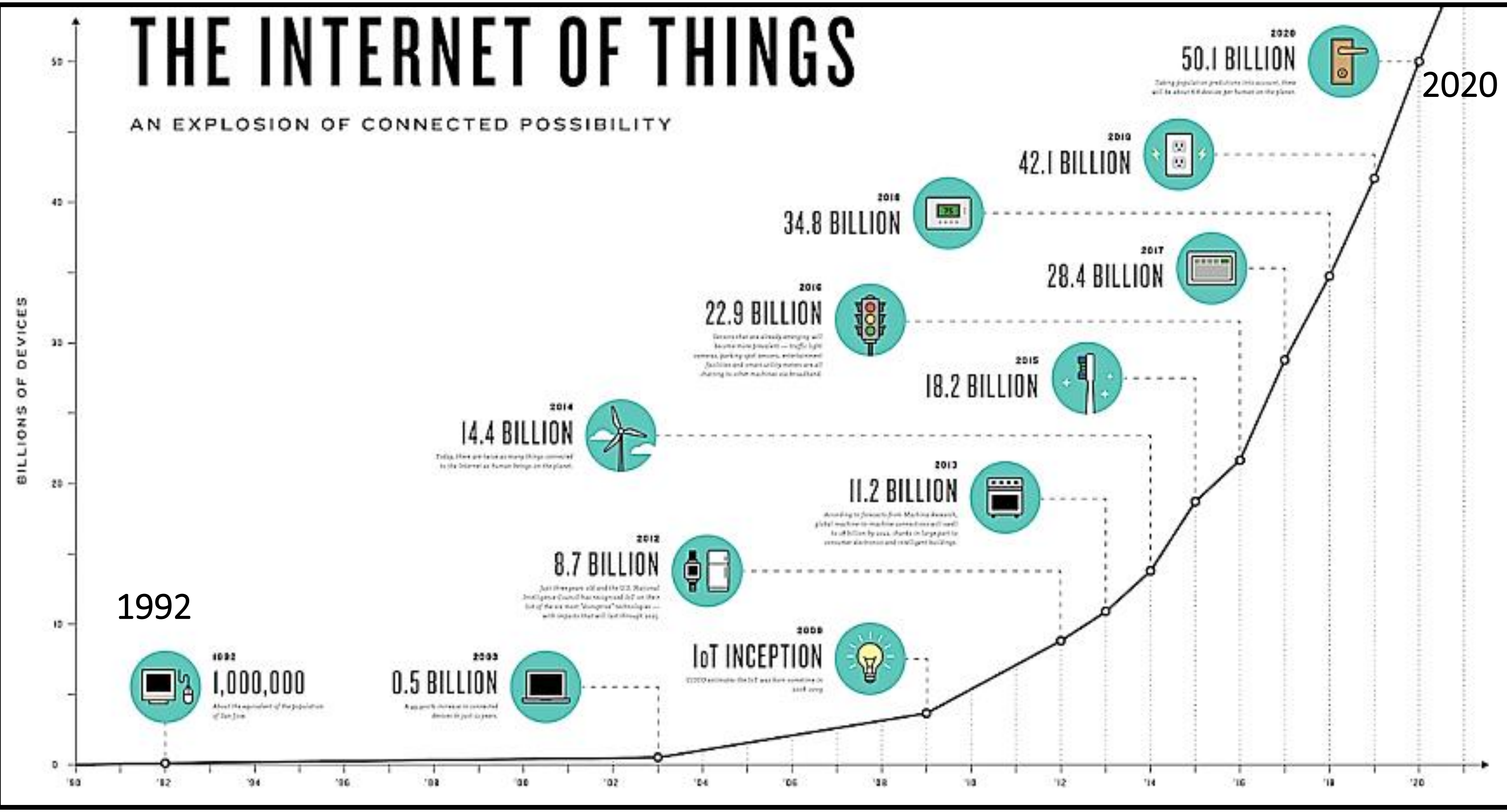
$$E \sim \frac{3}{2}kT$$

Other enviro

Ma
Syr
Nu
Nu
Ind
Foc
ser



http://scienceblogs.com/startswithabang/2011/05/09/the-future-of-colliders-beyond/



The number of transistors per chip increases exponentialy thanks to the exponential decrease of the transistor size.

Intel's Stratix-10 has the largest transistor count, containing over 30 billion transistors.

All the Electronic Devices May Suffer from Radiation Effects

Accelerator experimental hall
Space Environment
Ground High Radiation Environment
α-particle emission from radioactive contaminants

Particle and electromagnetic radiation
Ionizing and non-ionizing dose

Degradation of:
Micro-electronics, micro-processors, optical components, semiconductor detectors, front-end electronics, cabling, etc

Causing: **System shutdowns**
Circuit damage
Data corruption, etc

Radiation effects in electronic devices

TID, DD, and SEE

Electromagnetic radiation, eletrons, protons, neutrons and heavy ions

Total Ionizing Dose is a cumulative effect caused by trapped charges in the oxide. These trapped charges modify the transistor characteristics such as threshold voltage (V_{th}), mobility, leakage current, power dissipation, etc.

Atom Displacement Damage is provoked by protons, heavy ions, electron with high energy and neutrons, which change the arrangement of atoms in the lattice, modifying electrical properties of a device.

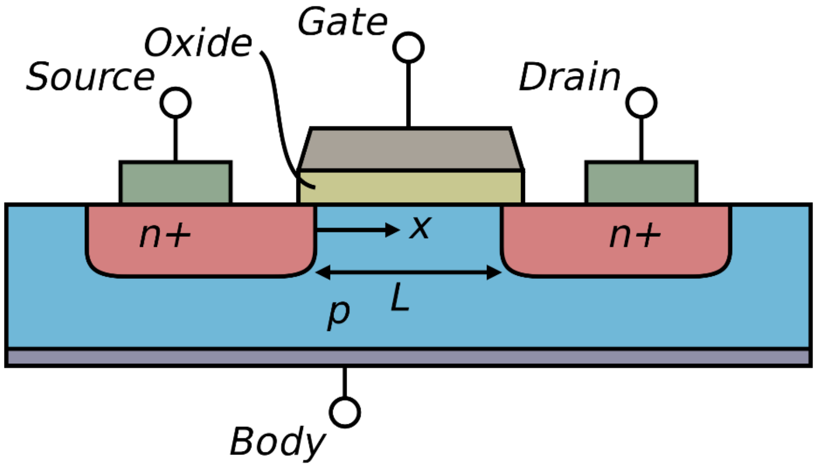
Single Event Effects are caused by particles of high LET (Linear Energy Transfer) due to, for example, the **strike of a single ion**. They can be non-destructive, causing current or voltage peaks, changing the state of a bit, or destructive, burning the device or destroying the gate oxide in a MOSFET.

Radiation Effects

Total Ionizing Dose

Cumulative effect due to the ionization in the SiO_2 due to neutrons, protons, gamma rays, X rays, heavy ions and electrons.

Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET)

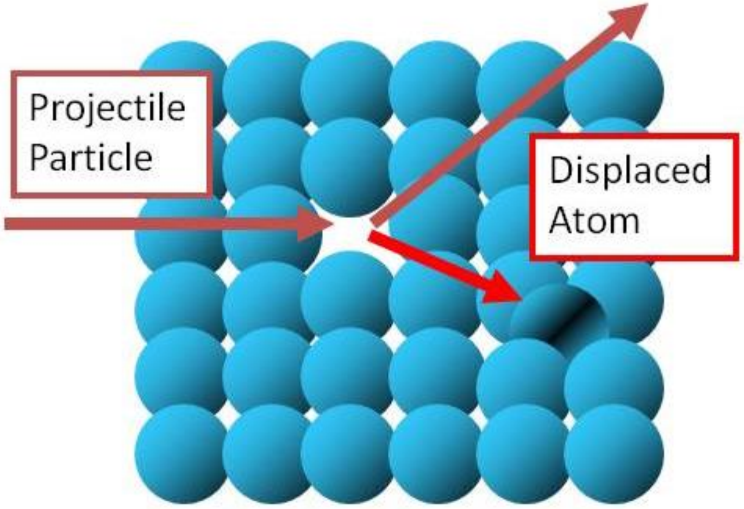


Applied voltage through the gate allows current to flow from source to drain.

Ionization in SiO_2 creates electron-hole pairs which induces defects in transistors. These trapped charges modify the transistor characteristics such as threshold voltage (V_{th}), mobility, leakage current, power dissipation, etc.

Displacement Damage

Non-Ionizing Energy Loss

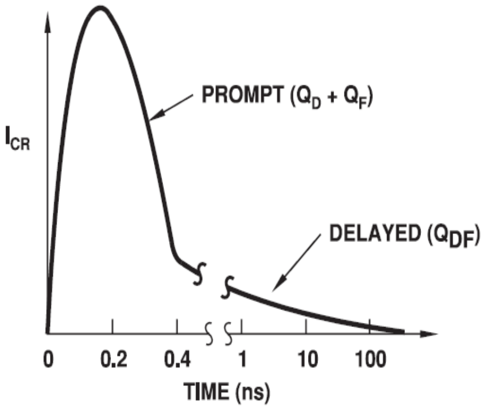


Originated from nuclear interactions, typically scattering, which cause lattice defects. Displacement damage is due to a cumulative long-term non-ionizing damage from neutrons, protons, and electrons. The collision between an incoming particle and a lattice atom subsequently displaces the atom from its original lattice position

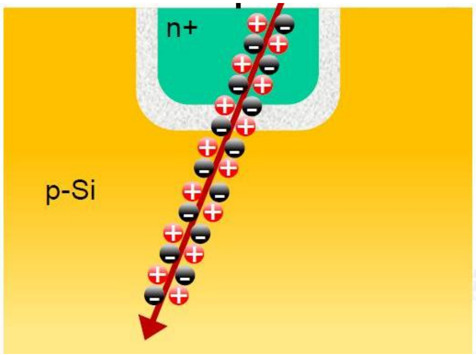
Stable defects in crystalline lattice (vacancies and interstices) modify electrical properties of electronic devices.

Single Event Effects

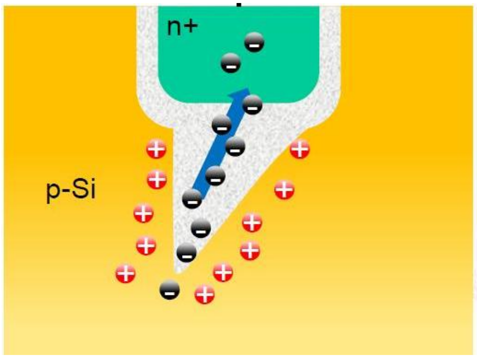
- **Charge deposition induced by a heavy ion interaction within a sensitive volume, followed by the charge collection at the output node of the circuit.**
- **High-LET particles generates a track of electron-hole pairs in semiconductor (Si) and dielectric (SiO_2).**
- 1 MeV deposited → 2.8 10^5 pairs
  → 44.5 fC
- **Charge collection occurs in three steps: drift (1), funnel (2) and difusion (3)**



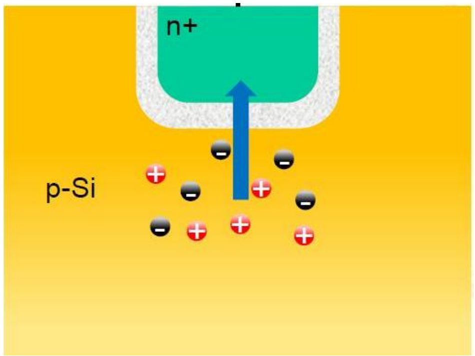
Adapted from [Gerardin, 2013] and [Schwank et al., 2008]



(1)



(2)

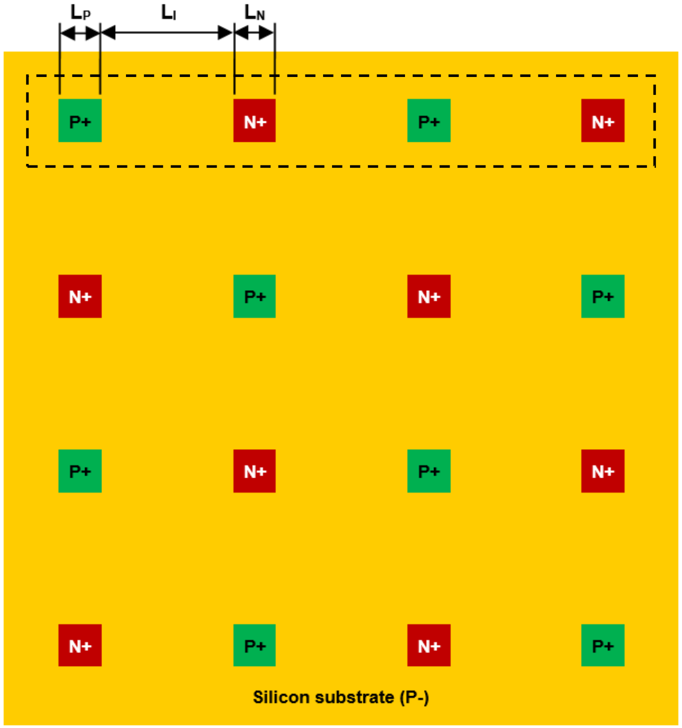


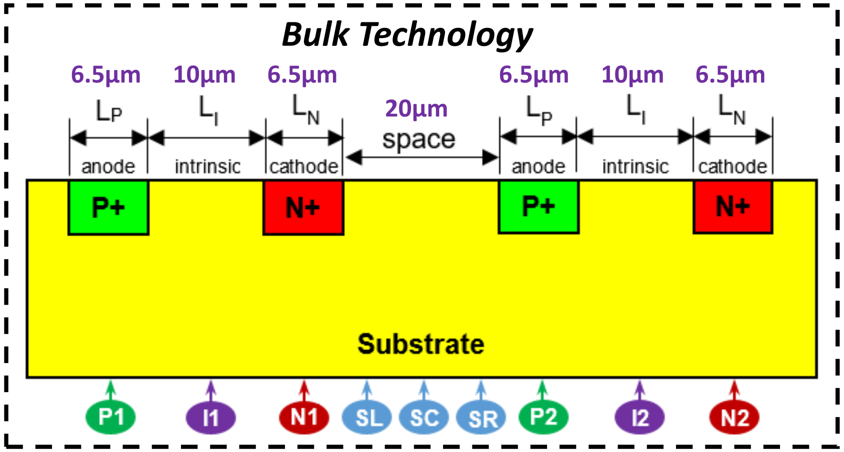
(3)

PIN DIODE SIMULATION

GF BiCMOS 8HP 130 nm technology

Proposed Array



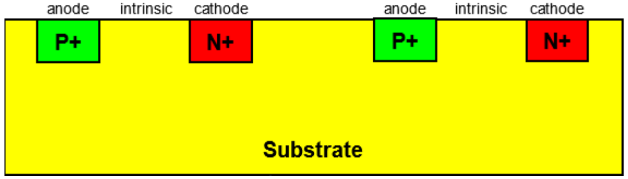


SEE Parameters:

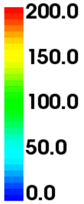
- Heavy-Ion LET = 10 MeV/mg/cm^2
- Particles Strike vertically at specified positions

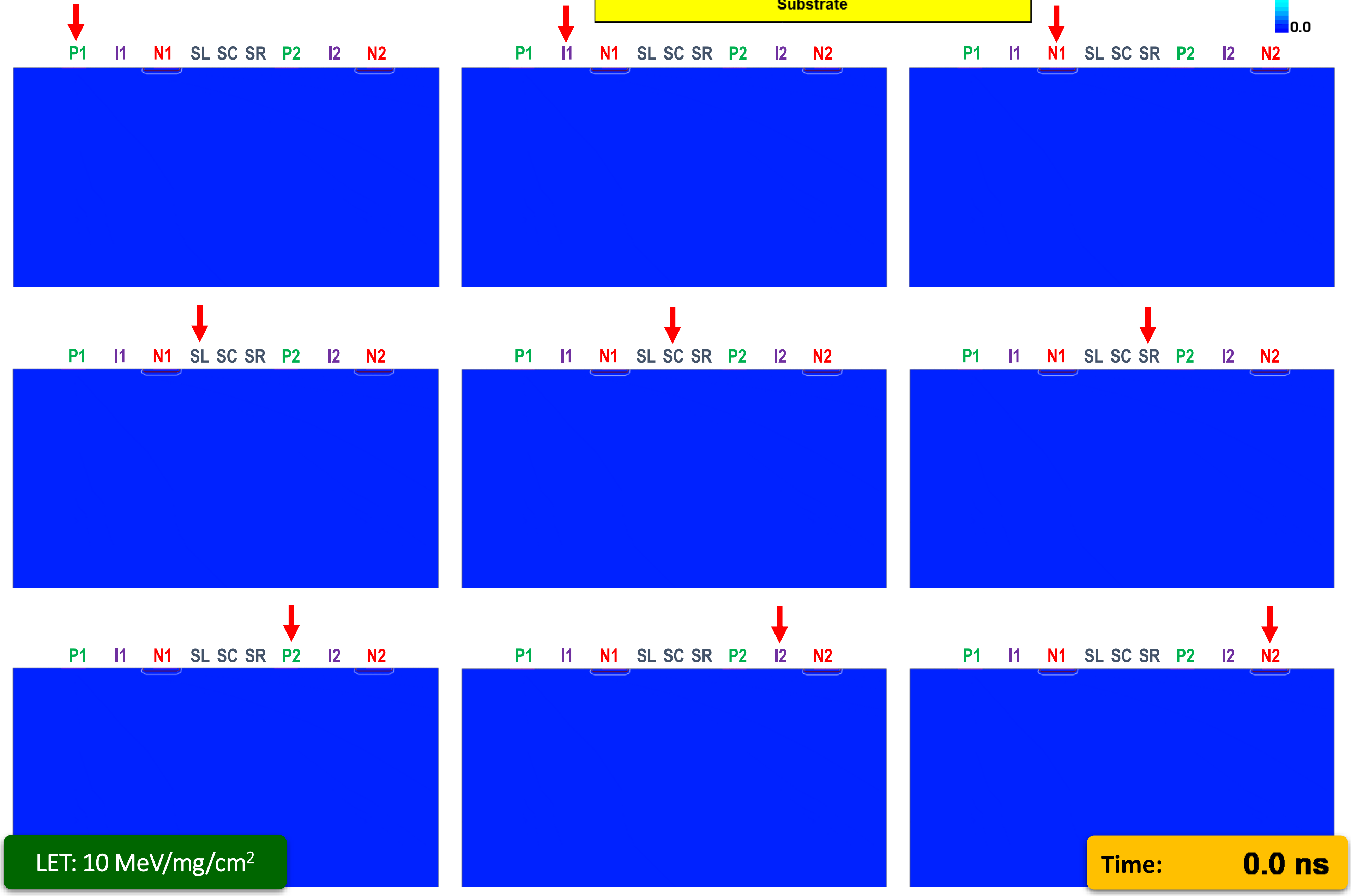
Rudolf R. Bühler and Renato Giacomini
Centro Universitário FEI

Incident Particle – 10 MeV/mg/cm^2
Calculations by Rudolf R. Bühler (FEI)



Abs Total Current Density [A/cm^2]|



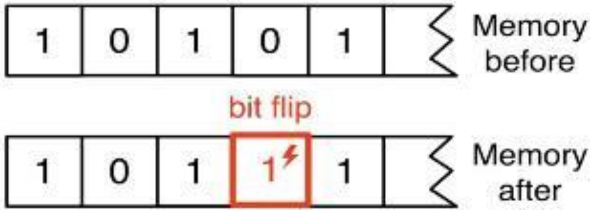


LET: 10 MeV/mg/cm^2

Time: 0.0 ns

Single Event Effects

Non-destructive Effects

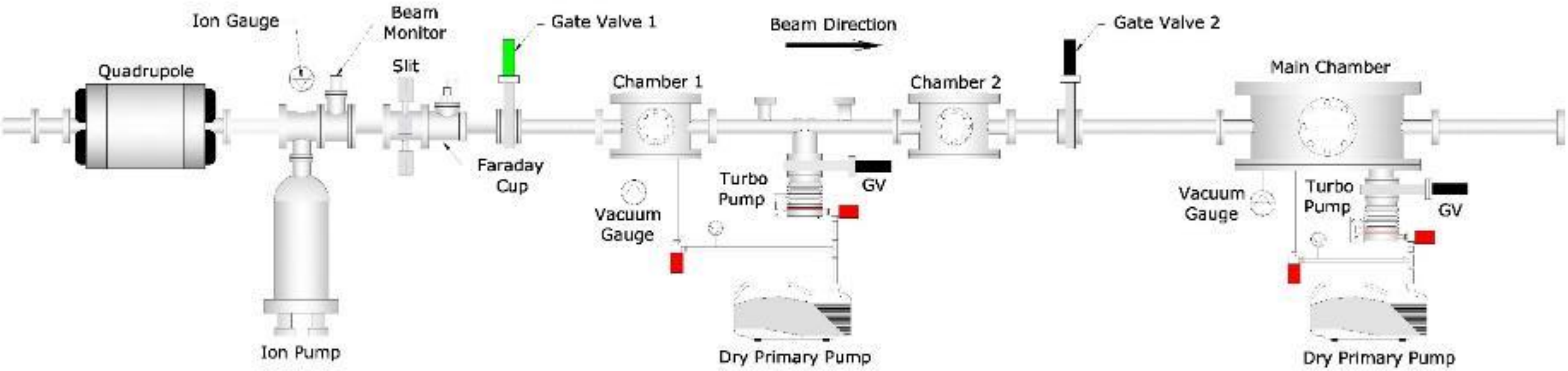


- Single event upset (SEU)
  - e.g. memory bit-flip (logic error)
- Single event transient (SET)
  - A transient effect (voltage/current pulses) which may provoke a SEU
- Single event functional interrupt (SEFI)
  - Logical malfunction in programmable devices

Destructive Effects

- Single event latch-up (SEL)
  - high current flux overheated power transistors, affecting *e.g.* CMOS devices
- Single event gate rupture (SEGR)
  - dielectric breakdown of the oxide layer of a MOSFET
- Single event burnout (SEB)
  - Similar to SEL. The high current damage irreversibly , *e.g.* power MOSFET

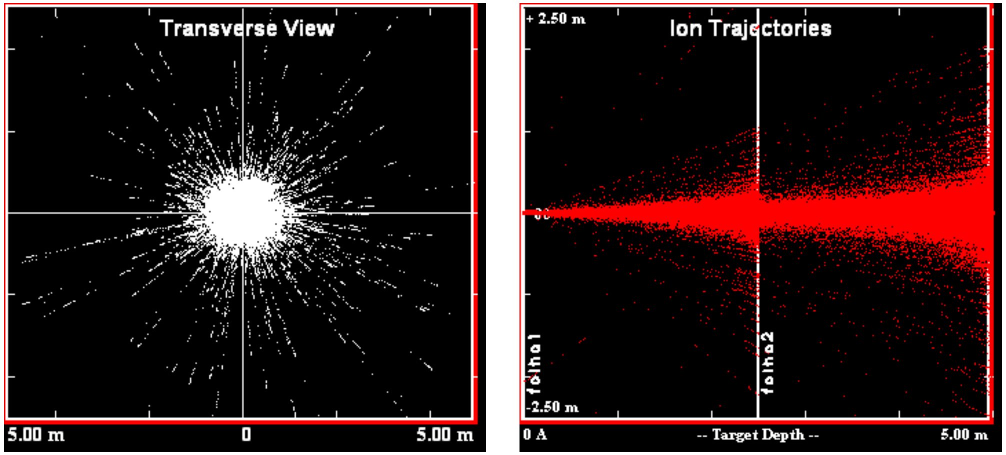
New beamline for SEE tests



Beam optics simulation

ESA requirements:

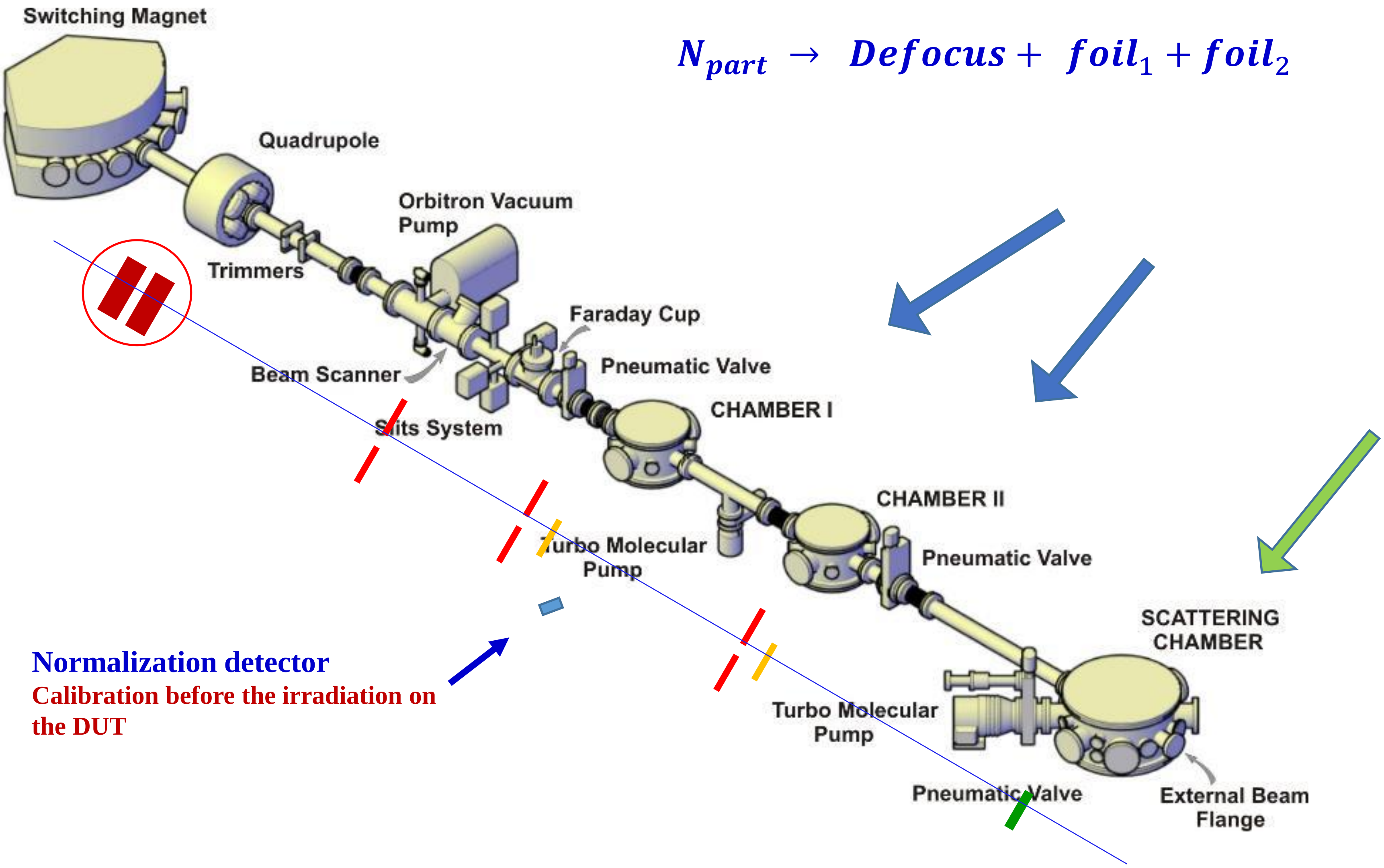
Flux 100 to 100,000 part/cm^{2}s
Fluence 10^6 to 10^7 part/cm^2
< 10% uniformity variation
30 μm depth



ESCC Basic Specification n. 25100 – ISSUE 1 – October 2002
Vitor Aguiar, Tese de doutorado, IFUSP (2019)

Beam Line Project

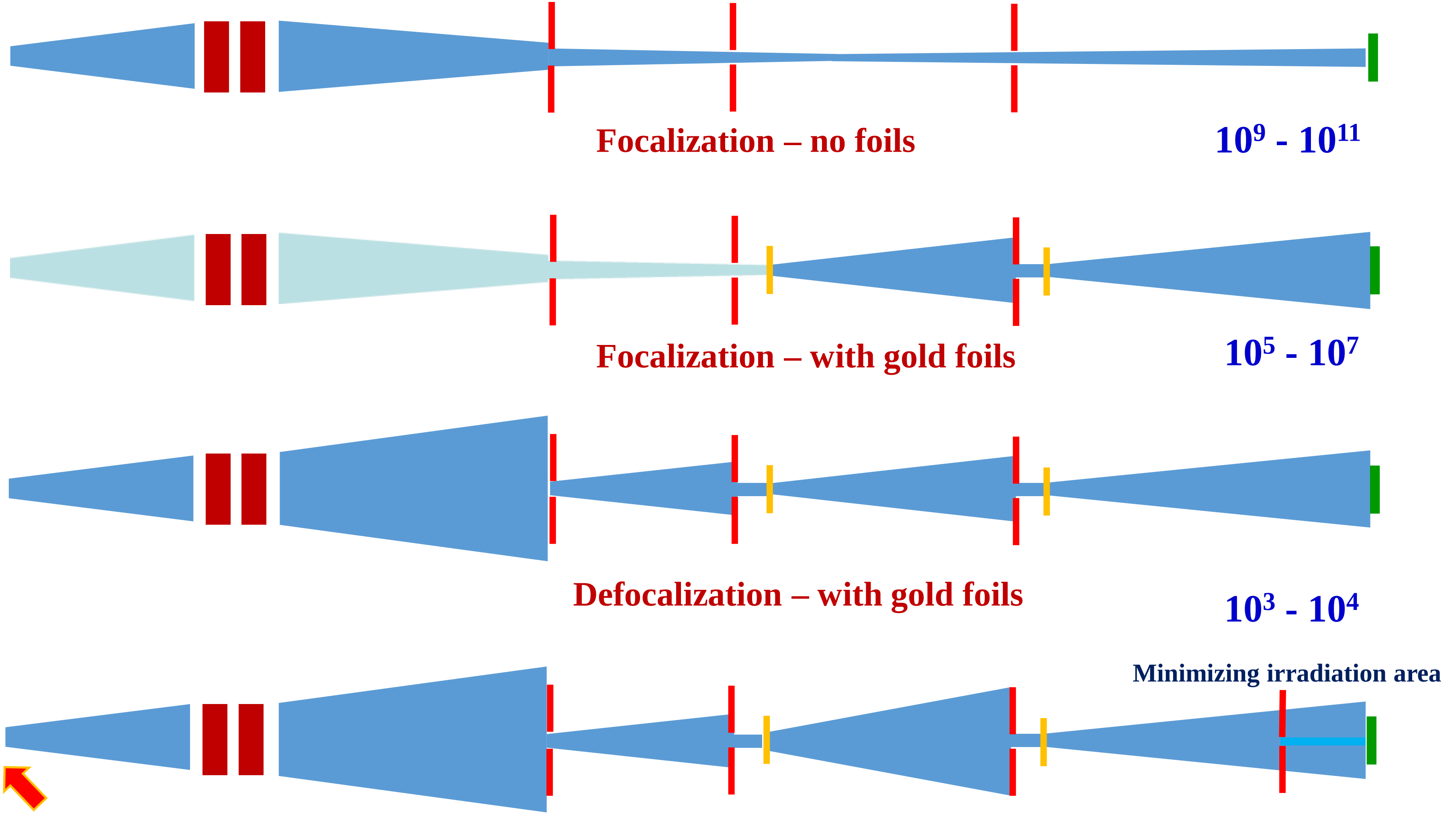
$$N_{part} \rightarrow Defocus + foil_1 + foil_2$$



Normalization detector

Calibration before the irradiation on the DUT

Particle flux control



Focalization – no foils

10^9 - 10^{11}

Focalization – with gold foils

10^5 - 10^7

Defocalization – with gold foils

10^3 - 10^4

Minimizing irradiation area

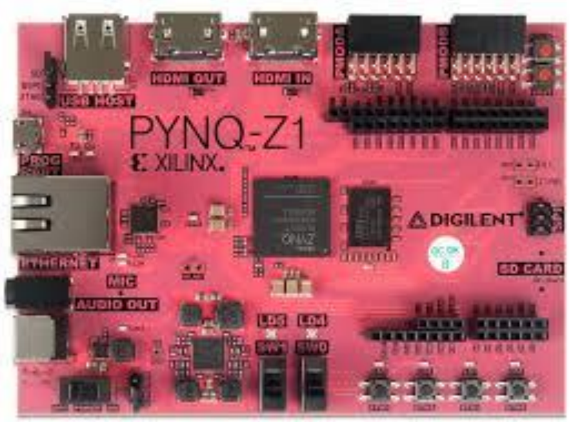
10^2 - 10^3

Reducing the beam before the beam line

Performed Measurements

Analogic devices
- 3N163 transistors
- Power Transistors
- Pin diode
- Solar cells

Digital devices – Hardware and Software
- System On Module (SOM)
- Field Programmable Gate Array (FPGA)
- Processors
- Memories



CITAR Project

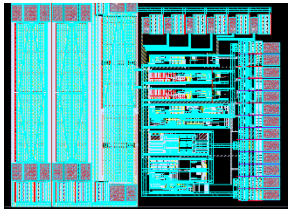
Radiation Tolerant ICs & Test Facilities

INPE

AGÊNCIA ESPACIAL BRASILEIRA

UNIVERSIDADE DE SÃO PAULO

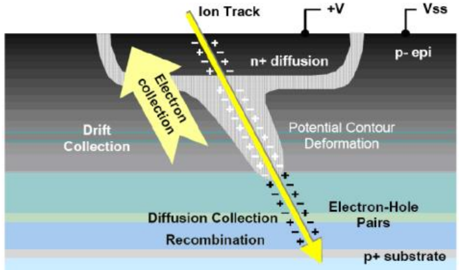
End user - Satellites



Telecommand ASIC

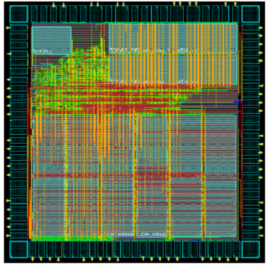
Centro de Tecnologia da Informação Renato Archer

System & IC design

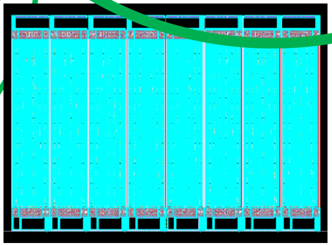


INSTITUTO MAUÁ DE TECNOLOGIA

MAUÁ



SpaceWire IP & ASIC



Power Switch ASIC

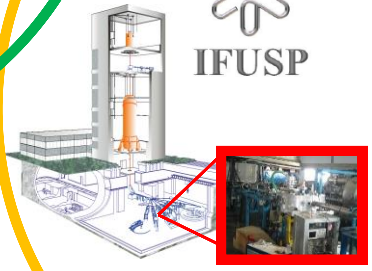
SEE

TID

IFUSP

IEAv

centro universitário FEI



Radiation Testing

Facti

FINEP

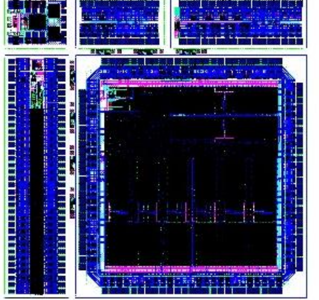
CNPq
Conselho Nacional de Desenvolvimento Científico e Tecnológico

ASIC – Application Specific Integrated Circuit

SEU in SpaceWire ASIC chip CTI-USP-FEI Collaboration

CITAR MPW

- 5 x 5 mm
- SpaceWire
- LVDS
- MultiGates
- 1V8 Reg
- Test structs



Radiation tolerant chip developed to the Brazilian Space Agency (AEB) and INPE

180 nm technology

SpaceWire is a standard for high-speed links and networks for use onbord spacecrafts

Interconection of: sensors, memories, processing units, and telemetry sub-systems

- Bit-flip tests in flip flop registers (SEU)
- Memory tests (mitigation techniques)
- SpaceWire communication

Results

No failures in the flip-flop registers with heavy-ion beams.

Mitigation procedures worked properly for the SRAM memories.

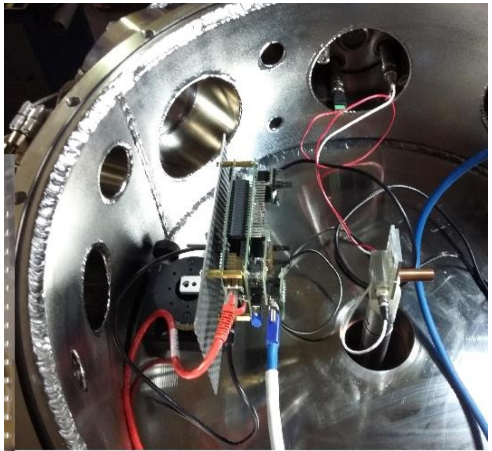
SpaceWire comunication is tolerant to radiation.

The SpaceWire chip was aged with X-rays up to 500 krad with no significant modification

Next steps – other tests with heavy ion beams

ASIC tele command

ASIC Power switch

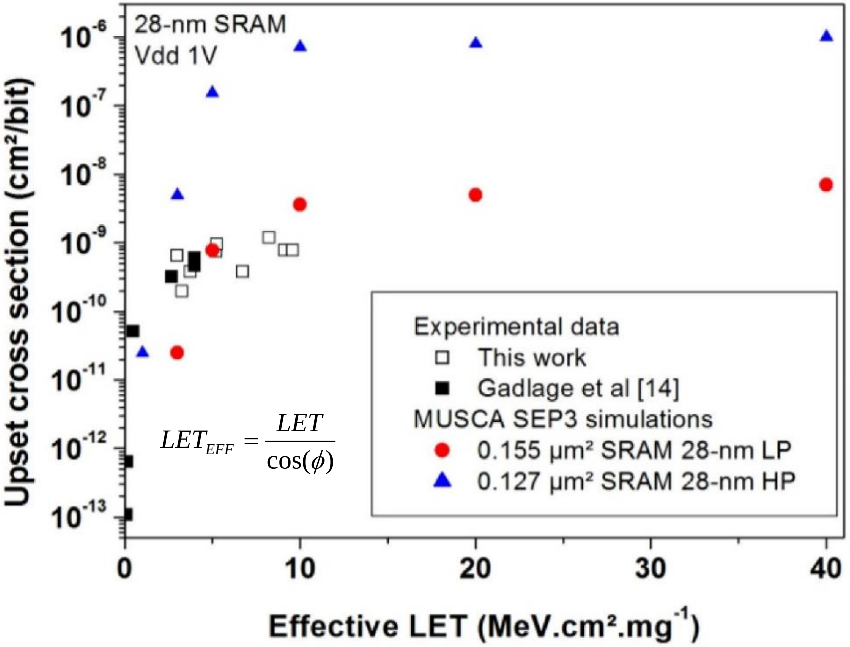


Scattering chamber

D. De Lázari and S. Finco – Private communication

Collaboration with UFRGS

Algorithm Tests



Analyzing the Influence of the Angles of Incidence and Rotation on MBU Events Induced by Low LET Heavy Ions in a 28-nm SRAM-based FPGA

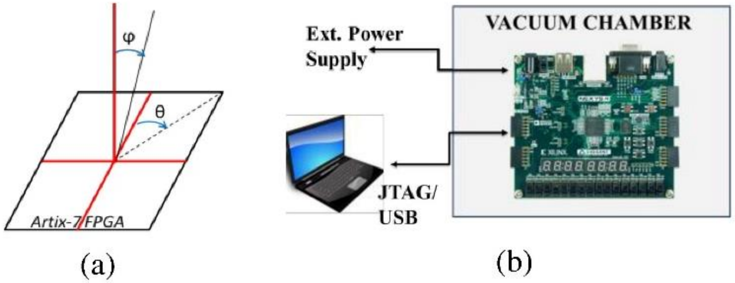


Fig. 1. In (a) Beam incident angle (φ) and rotation angle (θ) of the board in the vacuum chamber. In (b) the test setup for heavy ion testing.

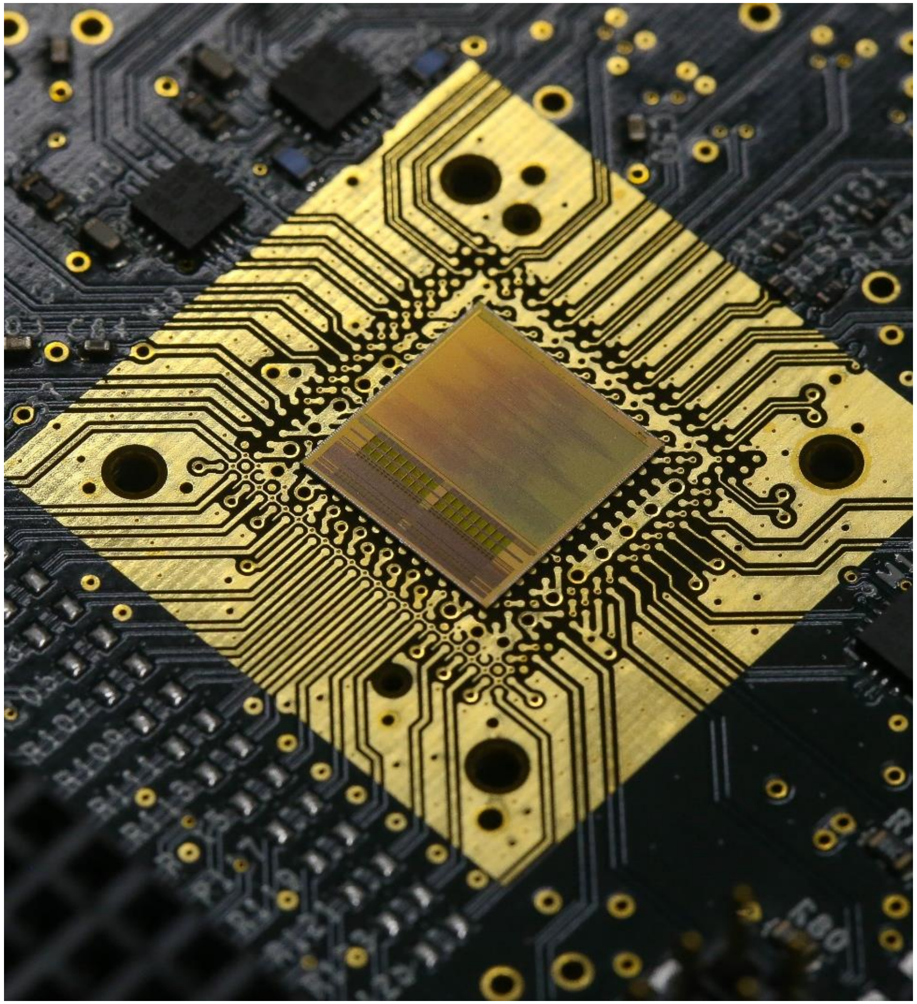
- **Reliability on ARM Processors Against Soft Errors Through SIHFT Techniques.**
- **Analyzing Reliability and Performance Trade-Offs of HLS-Based Designs in SRAM-Based FPGAs Under Soft Errors**
- **Heavy Ions Induced Single Event Upsets Testing of the 28 nm Xilinx Zynq-7000 All Programmable SoC.**

J. Tonfa et al., IEEE Transactions on Nuclear Science , vol 64, n. 8., 2017
E. Chielle et al., IEEE Transactions on Nuclear Science, vol. 63, n. 4, 2016.
L. Tambara et al., IEEE Radiation Effects Data Workshop (REDW), 2015
L. Tambara et al., IEEE Transactions on Nuclear Science, vol. 64, n. 2, 2017

SAMPA CHIP

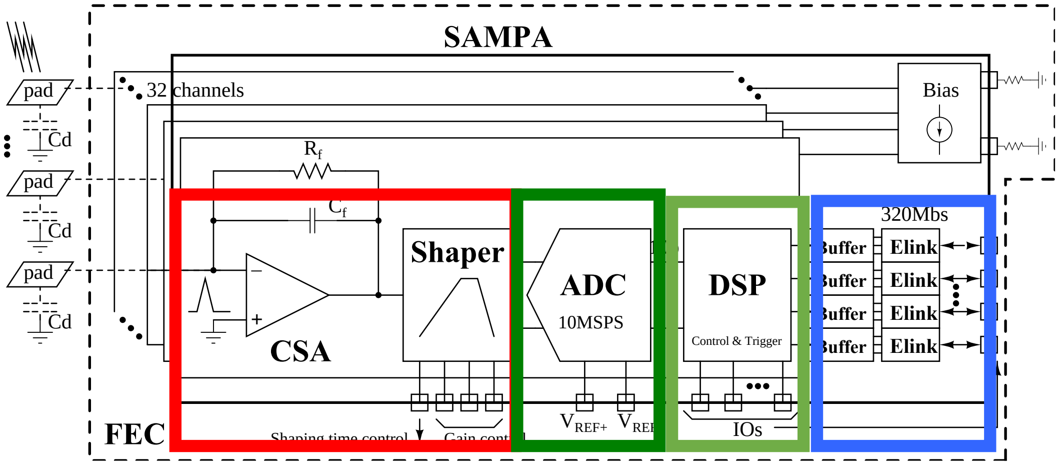
- Upgrade of the Detection System of the ALICE experiment (LHC)
- Increase of about 100 times the Data Aquisition Rate.
- Brazilian Project:

IFUSP (HEPIC), POLI (LSI) and UNICAMP

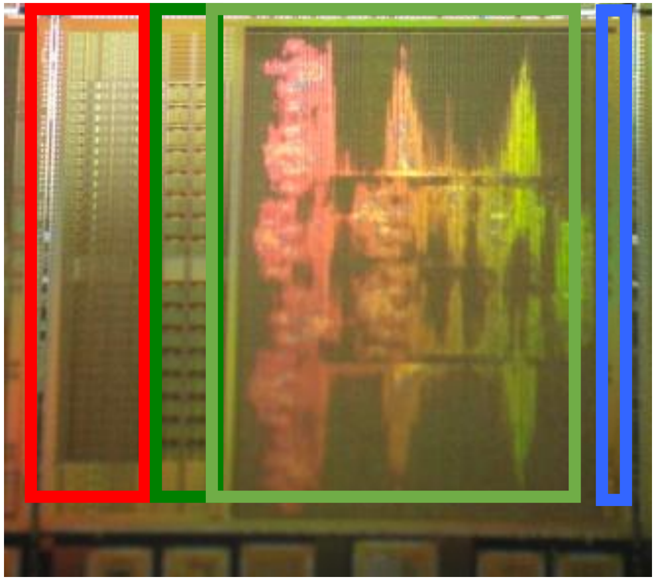


SAMPA Chip: The new 32 channels ASIC for the ALICE TPC and MCH upgrades J. Adolfsson et al., JINST 140P 1116 (2016)
FAPESP Project n 2012/04583-8 and Project n. 2014/ 12664-3

SAMPA CHIP



DSP: Digital Signal Processor
FEC: Front-End Card
CSA: Charge Sensitive Amplifier



32 FEs (CSAs + Shapers)

32 ADCs

Output Drivers

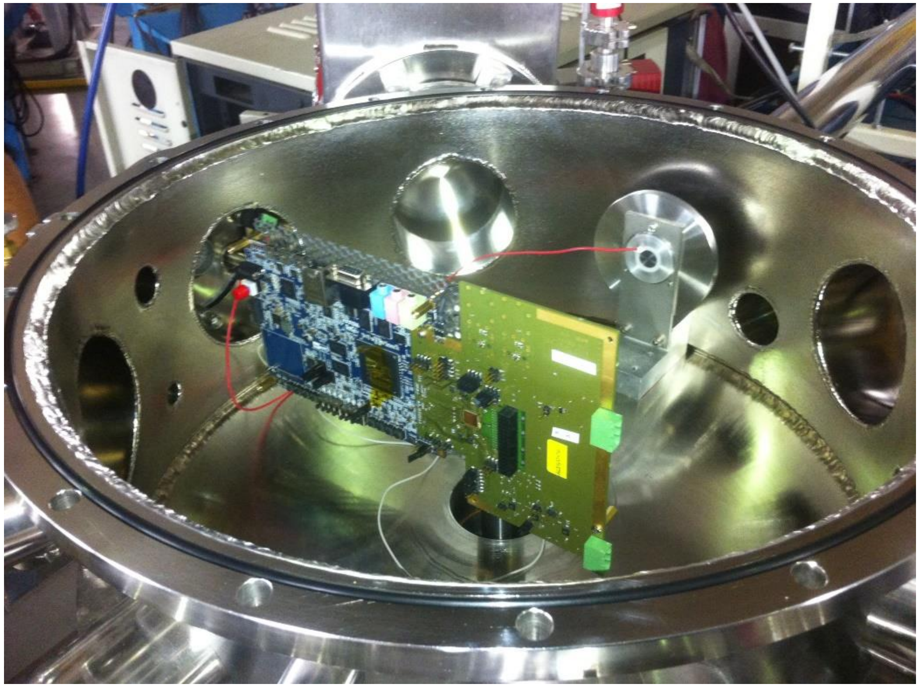
DSP

32 channel ASIC (Application Specific Integrated Circuits) , CMOS 130 nm technology

Radiation Tests
Proton and ^{16}O Beams

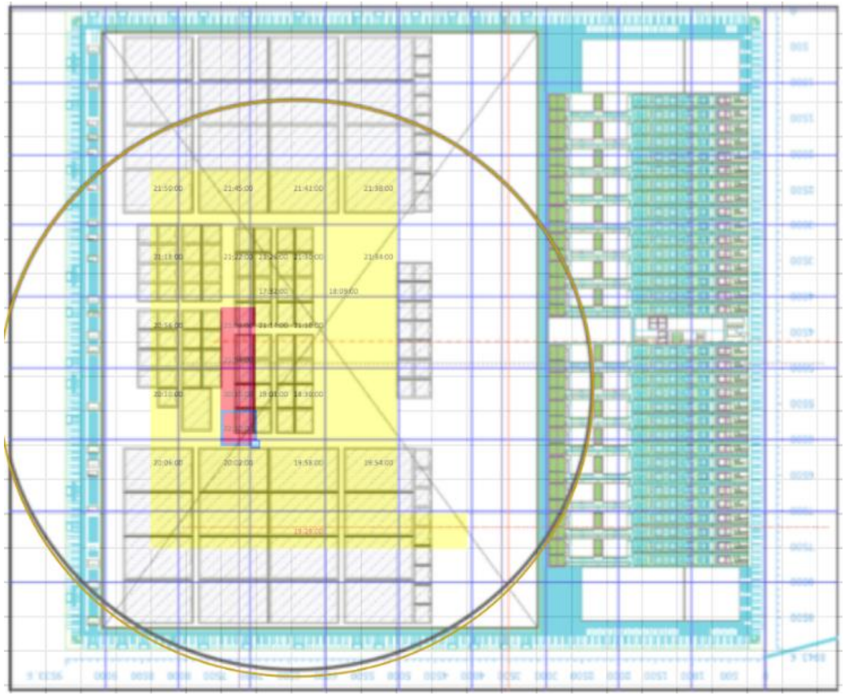
- The component will be subject to very high radiation doses in the ALICE experiment.
- Some complementary tests with proton beams were performed in the new beam line of the 8 MV Pelletron accelerator.
- Analogic systems (*e.g.* amplifier) were tested with ^{16}O beams to scan specific regions of the chip.

Scattering chamber



Radiation Tolerant Tests

- The results indicate that one of the memories chosen in the initial project was too sensitive to radiation. These memories were changed to another version in the final chip project.
- These tests were crucial for the final chip design.



Instrumentation with the LHC-CERN

Ultra-Fast silicon detectors

The state of the art in the development of Ultra-Fast Semiconductor Detectors (UFSD) devices, that are capable of timing resolutions of few picoseconds, came with the introduction of Low Gain Avalanche Detectors (LGAD), a novel structure pioneered by the RD50 collaboration that incorporates a very thin intrinsic charge multiplication layer in order to fulfill the performance requirements for the High Luminosity-LHC (and beyond) experiments.

Based on the simulation results, the group will design and fabricate prototypes of LGAD and AC-LGAD sensors (and the equivalent PIN diode as a non-multiplication device reference), **characterize and perform the irradiation of the sensors using the facilities available in Sao Paulo (Laboratorio de Sistemas Integraveis (LSI) from EPUSP, IFUSP and FEI).**

The goal in this part of the project is to fully characterize the SAMPA chip and LGAD semiconductor sensors tolerance for radiation using different probes, from gamma and X rays to protons, neutrons and heavy ions.

Nilberto H. Medina, Saulo Alberton,
Vitor A.P. Aguiar, Nemitala Added, and
Eduardo L.A. Macchione

Universidade
de São Paulo

Marcilei A. Guazzelli, Rudolf R. Bühler,
Renato Giacomini, Roberto Baginski dos
Santos and Alexis Villas Bôas

centro
universitário
FEI

INCT-FNA
INSTITUTO NACIONAL DE CIÊNCIA E TECNOLOGIA
FÍSICA NUCLEAR E APLICAÇÕES

CNPq

SAFIIRA SYSTEM

Thank you for your attention

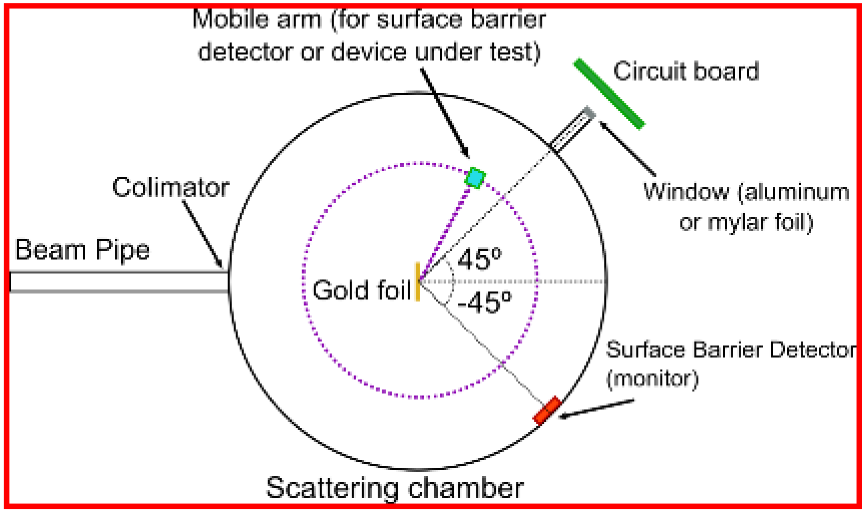
Pelletron Accelerator 30B Beam Line

Rutherford Scattering

ESA beam requirements:

Flux 10^2 to 10^5 part/cm^{2}s

< 10% uniformity variation



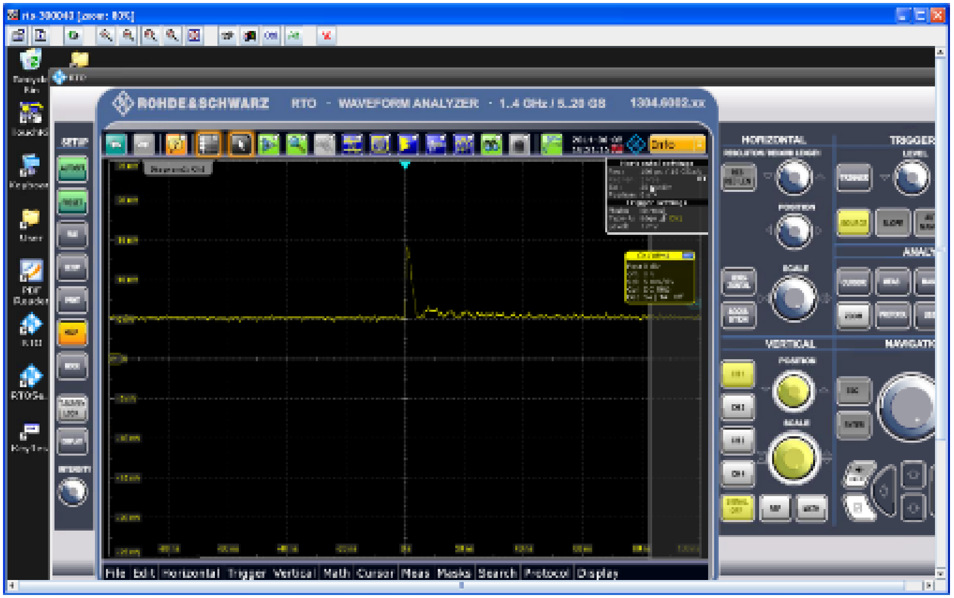
30B beam line

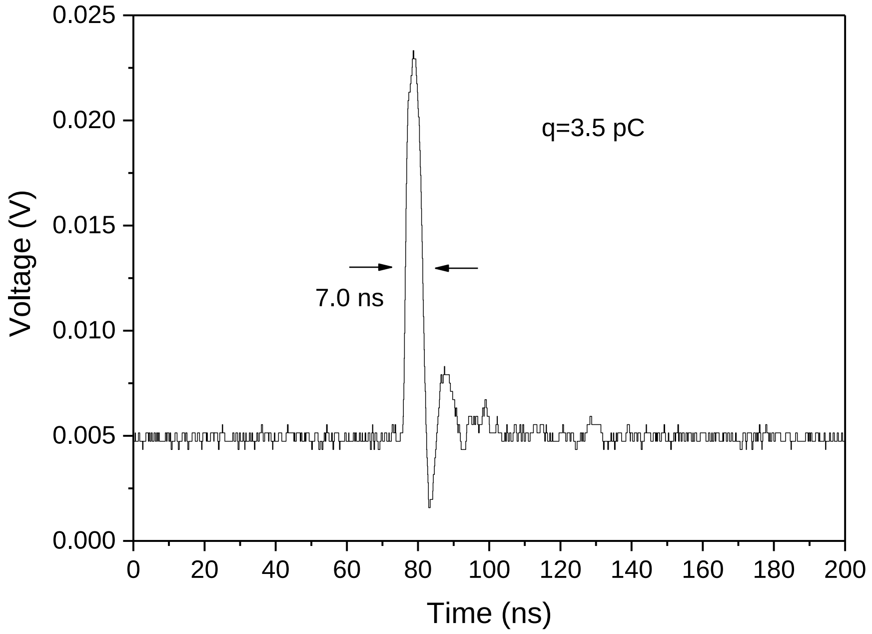
External beam setup

Vitor Aguiar - Master thesis USP 2014 and V.A.P. Aguiar et al., NIM B 332 (2014) 397

SEU measurements in a p-channel MOSFET transistor (3N163)
USP-FEI Collaboration

SEU signal observed with an oscilloscope due to ^{35}Cl heavy ion beam at 75 MeV.





SEU Cross Section

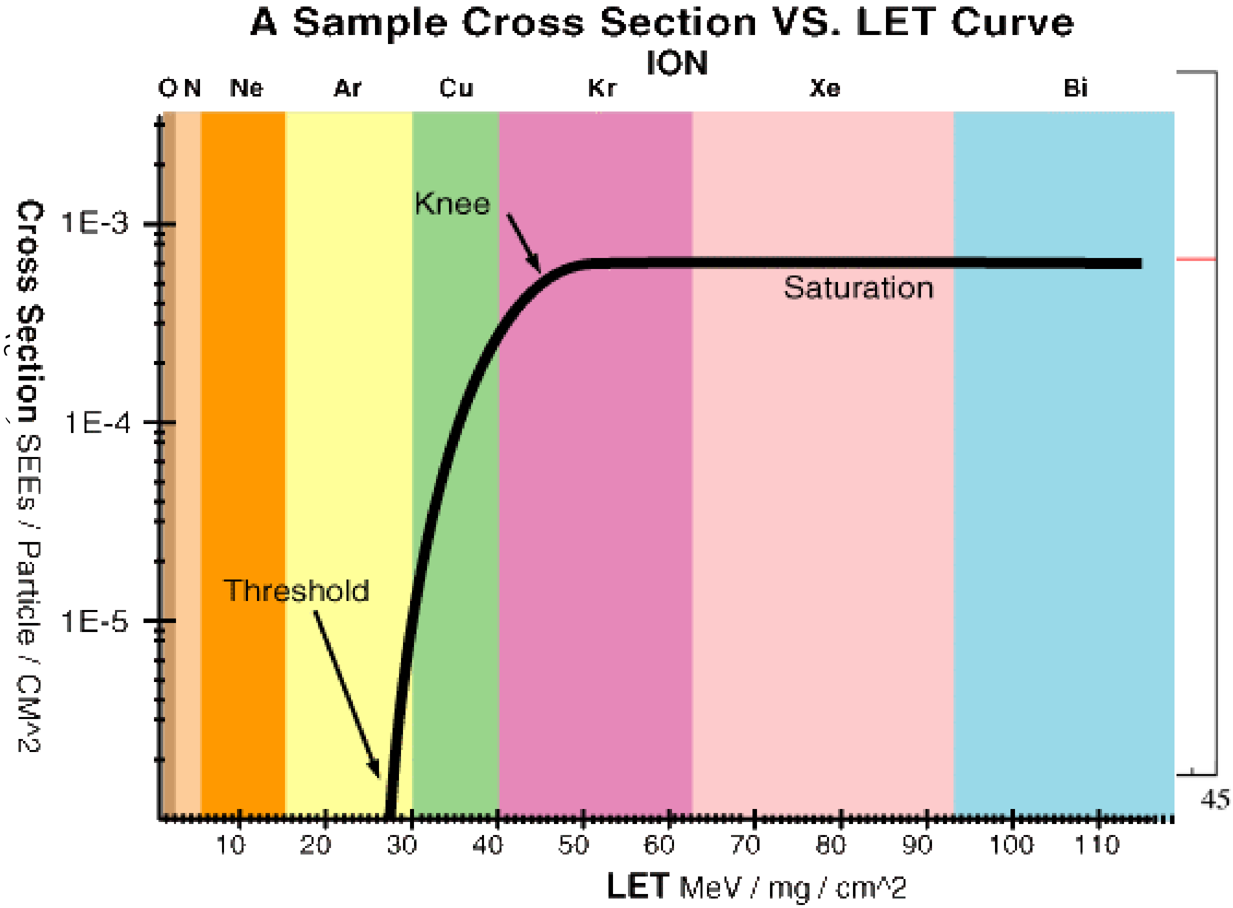
p-channel MOSFET transistor (3N163)

$$\sigma_{SEE} = \frac{events}{\Phi}$$

$$\Phi = \frac{particles}{cm^2}$$

Weibull Function

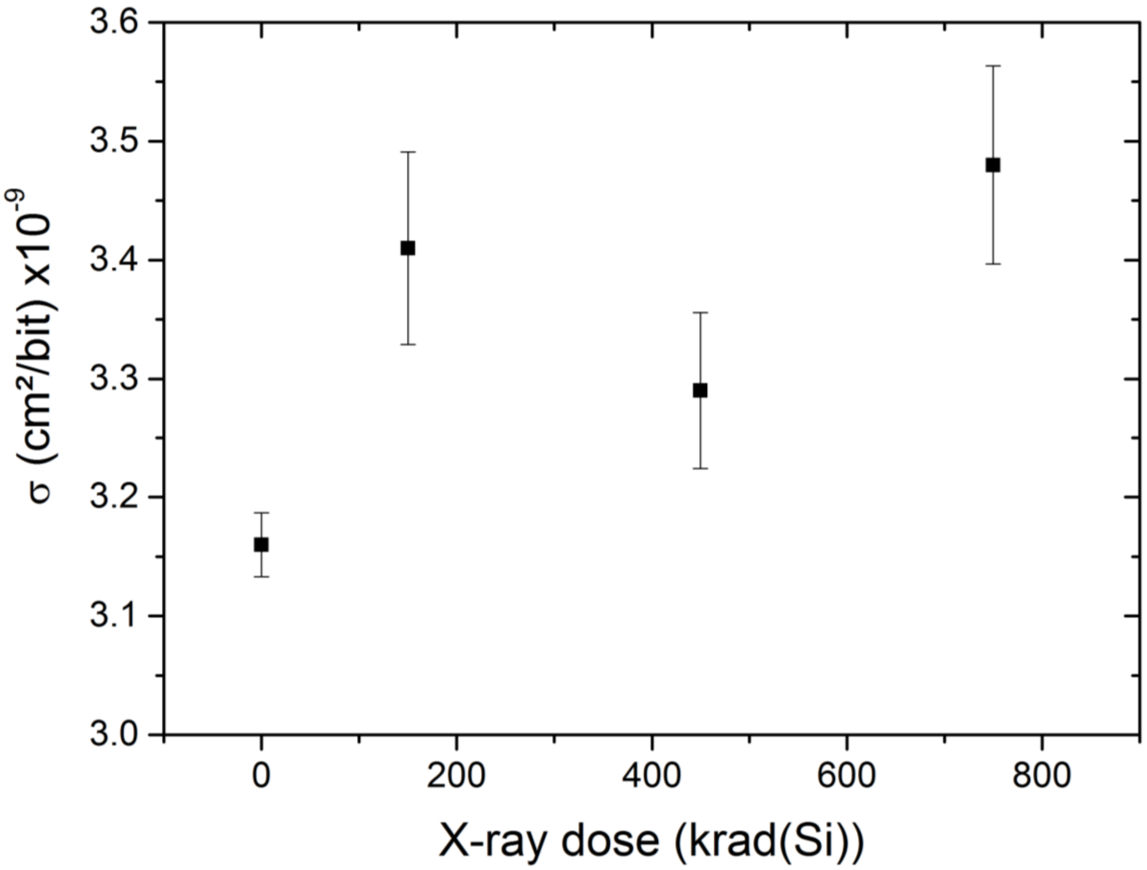
$$\sigma = \sigma_{sat}\left[1 - e^{\left(\frac{LET - LET_{th}}{W}\right)^{s}}\right]$$



σ_{sat} = 294(10)10^{-5} cm^2
LET$_{th}$ = 2.35(36) MeV/mg/cm^2
W= 1.06(11) MeV/mg/cm^2
S = 0.62(10)

N.H. Medina et al., Proc. 2014 IEEE Radiation Effects Data Workshop, Paris, France, pg 272

SEU + X-ray TID in Xilinx FPGA Spartan 3



^{16}O beam; E_b= 50 MeV LET = 5.0 MeV/mg/cm^2
10-keV effective energy (X-ray)

N.H. Medina et al., Jour. Nucl. Phys, Mat. Scie. Rad. Appl. v4 (2016) 13

Collaboration with PUC-RS and FEI

- **Analysis of SRAM-Based FPGA SEU Sensitivity to Combined EMI and TID-Imprinted Effects**

- **Analysis of Single-Event Upsets in a Microsemi ProAsic3E FPGA**

Industrial, communications and medical applications with commercial and industrial temperature devices. ProASIC3 FPGAs can be delivered with specialized screening for automotive and military systems.

SRAM – Static Random Access Memory
COTS – Commercial Off-The-Shelf
ARM - microcontroller Advanced RISC Machine
Used in cellphones, calculators, computers, industrial applications
RISC - Reduced Instruction Set Computer
FPGA – Field-Programable Gate Array

J. Benfica et al., IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 63, NO. 2, APRIL 2016

P. Villa et al., 18th IEEE Latin American Test Symposium, 2017

SEU in FPGA Microsemi ProAsic3
CTI-USP-FEI Collaboration

To study the basic characteristics when chips are submitted to heavy ion beam

130 nm technology

- Mitigation techniques
- FLASH and SRAM memories
- Flip-flop registers

8UD Pelletron accelerator low flux

Ion Beam	LET (MeV/mg/cm^2)
^{12}C	3
^{16}O	5
^{35}Cl	17
^{107}Ag	40

Results

Validation of error detection, correction algorithms and redundancy techniques

Flash memory is radiation tolerant

Failures in SRAM memories and flip flops

Necessity to implement new circuits to become more tolerant

Validation of the techniques to be used in the SpaceWire chip.

D. De Lázari and S. Finco – Private communication

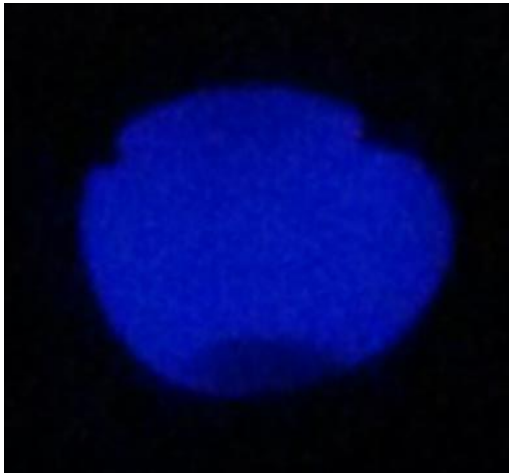
ASIC – Application Specific Integrated Circuit

SAFIIRA SYSTEM

SistemA de Feixes Iônicos para IRradiações e Aplicações

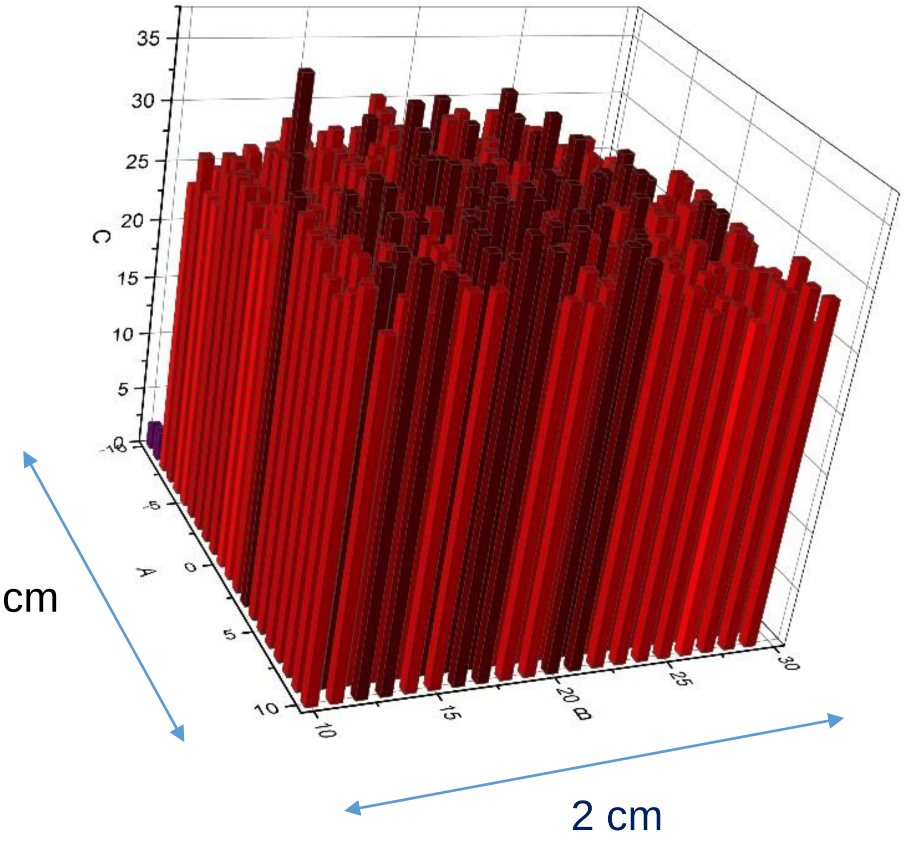
Ion Beam System for Irradiations and Applications

Experimental Beam Uniformity



ZnS fluorescence

^{16}O beam E= 42 MeV



(2,0 x 2,0) cm^2 beam area
Fluxes from 10^2 to 10^5 part/s/cm^2
Observed uniformity around 93%

ESCC Basic Specification n. 25100 – ISSUE 1 – October 2002