Department of Physics
University of Ioannina

Modern Silicon Sensor Devices and their use in HEP, space and medical applications

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INTRODUCTION

The aim of these lectures is to give to the audience a general overview on Silicon Detectors mainly from an experimental point of view:
the focus will be mainly on possible application, assembling and testing procedure, facility description etc.. , while links will be provided for more detailed description of semiconductors theory description.

Due to the amplitude of this field only few topics and examples will be described in more detail, while many other relevant topics will be skipped completely.

Feel free to contact me anytime for questions or suggestions:
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Outline

Lecture 1:

Introduction to silicon sensors.
General (tentative) classification: Strips sensors, Hybrid and Monolithic (MAPS) pixel sensors, SiPM, LGAD, others.
Overview of applications in HEP and space missions.
MAPS assembling procedure: the ALPIDE chip and the Alice ITS2 construction.
Trends for Monolithic Active Pixel Detector: studies for large area bent sensors.

Lecture 2:

Overview on the effects of radiation on silicon detectors and electronic devices:
Total Ionizing Dose (TID), Displaced Damage (DD), Single Event Effects (SEE).
Monitoring the radiation dose effects on silicon devices
The Trento proton and x-ray Irradiation Facilities and their use.
X-ray dose delivered measurement for silicon devices.
Procedures for dose evaluation and radiation hardness characterization of devices:
Useful software tools (SPENVIS, TRIM, SpekPy).

Lecture 3:

Overview on the use of radiations for cancer treatment.
Dose measurement for medical application. Beam monitoring and beam Quality Assurance (QA) devices.
Flash irradiation.
Ion therapy facilities: the CNAO and the Trento Proton Therapy Center.
Examples of HEP technologies for to medical applications:
the iMPACT project and the FOOT Experiment.

Lecture 2

References C

Suggested web reference for lecture 2

Serena Mattiazzo: SIRAD School 2019, Legnaro (Padova)
Introduction to Radiation Damage: Physics and Basic Concepts
https://drive.google.com/drive/folders/1y7AEdYsyhxjE3IfwhDP5h-Dn4tizXpvl

Jeffery Wyss: SIRAD School 2009, Legnaro (Padova)
Introduction to radiation damage: concepts, physical quantities, radiation environments
https://sirad.pd.infn.it/scuola_legnaro_2009/Presentazioni_Web/01_ScuolaLNL2009_Wyss.ppt

SiPM Radiation: Quantifying Light for Nuclear, Space and Medical Instruments under Harsh Radiation Conditions
CERN 2022
https://indico.cern.ch/event/1093102/timetable/?view=standard_numbered

Radiation Environment and its effects in EEE components and hardness assurance for space applications. CERN - ESA - SSC WORKSHOP
CERN 2017
https://indico.cern.ch/event/635099

References D

Suggested web reference for lecture 2

RD50/Michael Moll page
NIEL tables
https://rd50.web.cern.ch/NIEL/default.html

CERN x-ray irradiation facility
https://espace.cern.ch/project-xrayese/_layouts/15/start.aspx#/

CERN Irradiation facility database
https://irradiation-facilities.web.cern.ch/index.php

RADNEXT: H2020 INFRAIA-02-2020 infrastructure project
https://radnext.web.cern.ch

SPENVIS Software pakage
https://www.spenvis.oma.be

Recap about the the effect of irradiation on silicon devices (1)

Particle interactions with silicon sensors:

- Non-ionizing energy loss

  Particles (neutrons, pions, protons, ions, even electrons) can displace atoms from their usual lattice sites and produce “bulk” damage effects, also called displaced damage (DD).

- Ionizing energy loss

  Ionizing radiation, such as x-rays, gammas, and all charged particles create free charge in materials, which affects properties and performance. This effect is called Total Ionizing Dose (TID) damage.

- Single Event Effect

  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).

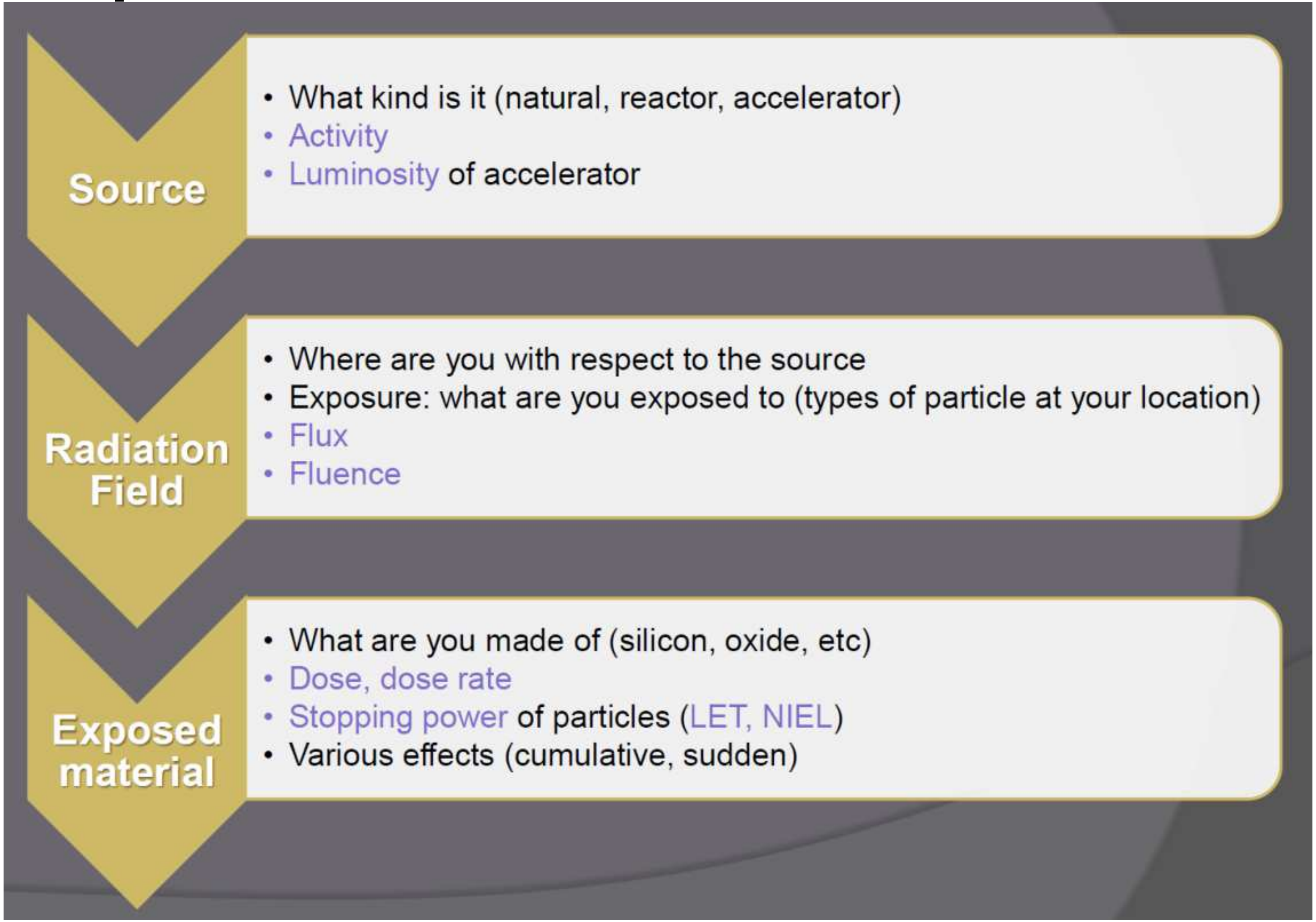
Recap about the the effect of irradiation on silicon devices (2)

Radiation: Microscopic effects → macroscopic effects

micro-effect			*macro-effect*
Small $\Delta E_{ionization}$ deposited uniformily and delivered over a long time.	charged particles	Direct or secondary ionization	**Total Integrated Ionizing Dose (TID) Effects**
Sudden large $\Delta E_{ionization}$ deposited in the '*wrong place at the wrong time'*.	heavy charged particles (protons, **ions**)	Direct ionization	**Single Event Effects**
Accumulation of small ΔE transfers to atomic nuclei (Coulomb, nuclear interactions).	protons, neutrons, high energy electrons	displacement damage of lattice	**bulk effects; enhancement of TID Effects**
Sudden high ΔE transfer to a single nucleus at the '*wrong place and time'*.	Energetic heavy particles (protons, neutrons, energetic ions)	Secondary ionization by recoil atoms and nuclear fragments	**Single Event Effects**

Slide from J. Wyss

Recap about the the effect of irradiation on silicon devices (2)



Slide from
S. Mattiazzo

Recap about the the effect of irradiation on silicon devices (2)

Radiation damage quantities (2)

- **Flux** (ϕ) is the number of particles per unit of area and per unit of time

formula	Measurement Unit
ϕ = particles/(Area $\times$ Time)	particles/(cm^2 $\times$ s)

- **Fluence** (Φ) is the number of particles per unit of area (time integral of the flux)

formula	Measurement Unit
$\Phi = \int \phi \cdot dt =$ particles/Area	particles/cm^2

Slide from
S. Mattiazzo

Recap about the the effect of irradiation on silicon devices (2)

Radiation damage quantities (3)

- **Dose** (D) is the energy deposited by radiation per unit of mass
- **Absorbed Dose:** is the energy delivered to irradiated matter per unit mass by ionizing radiation
  - 1 rad = 100 erg/g
  - 1 Gray (Gy) = 1 J/kg
  - 1 Gy = 100 rad
  - 1 rad = 0.01 Gy
- **Displacement Damage Dose**
  - The fraction of the total energy absorption (per unit of mass) that results in damage to the lattice structure of solids through displacement of atoms
- **Dose equivalent**
  - It refers to a quantity applied to biological effects. It includes scaling factors to account for the more severe effects of certain kinds of radiation

Slide from
S. Mattiazzo

Recap about the the effect of irradiation on silicon devices (2)

Glossary

Parameter	Radioactivity	Absorbed Dose
Definition	**Rate of radiation emission (transformation or disintegration)**	**Energy delivered by radiation per unit of mass of irradiated material**
Common Unit Symbol	**Curie (Ci)** 1 Ci = 37 GBq (a large amount)	**Rad** 1 rad = 100erg/g 1 rad = 0.01 Gy
International Units (SI) symbol	**Bequerel (Bq)** 1 Bq = 1 event of disintegration per second (a very small amount)	**Gray** (Gy) 1 Gy = 1J/kg 1 Gy = 100 rad

Slide from
S. Mattiazzo

Recap about the the effect of irradiation on silicon devices (2)

Dose for particles

Dose (energy/mass) = **proportionality factor** (energy×length²/mass) × **fluence** (length⁻²)

$$\text{Total Ionising DOSE (TID)} = \frac{\text{energy to ionisation}}{\text{mass}} = \text{LET} \times \Phi$$

$$\text{Displacement Damage DOSE (DDD)} = \frac{\text{energy to displacements}}{\text{mass}} = \text{NIEL} \times \Phi$$

- Typically Linear Energy Transfer (LET) and Non Ionizing Energy Loss (NIEL) expressed in MeV-cm^2/mg
- Energy deposited in a block of matter:
  - energy to ionization = LET(energy-length^2/mass) × fluence (length^{-2}) × mass
  - energy to displacements = NIEL(energy-length^2/mass) × fluence (length^{-2}) × mass

Slide from
S. Mattiazzo

TID

Slide from Marc Poizat:
https://indico.cern.ch/event/635099/contributions/2570674/attachments/1456398/2248961/Radiation_Effects_and_RHA_ESA_Course_9-10_May_2017_TID_MP_FINAL.pdf

Radiation Units

esa

TID: Deposited energy 1 Gray = 1 J/kg (International System Unit)

- Commonly used unit : **rad** (**R**adiation **A**bsorbed **D**ose)

1 Gy = 100 rad

~0.1% ΔE (→ $\Delta E_{displacement}$)

$$\Delta E = \Delta E_{ionization} + \Delta E_{displacement}$$

Energy to create one electron-hole pair:

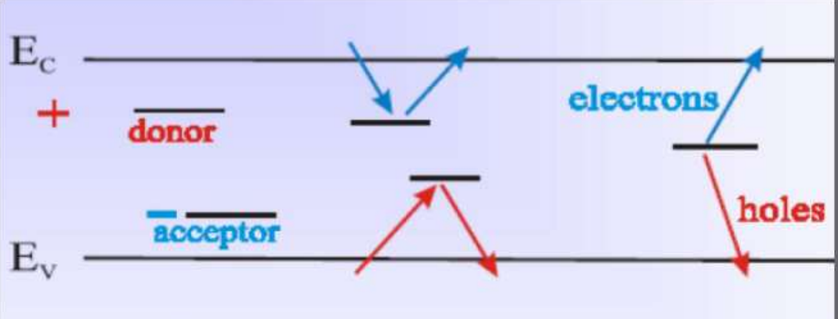
- In SiO_2: ~17 eV => ~7.8 10^{12} e-/h pair per rad.cm^3
- In Si: 3.6 eV => 4 10^{13} e-/h pair per rad.cm^3

DD: Energy to create displacement damage

- In Si: 21 eV

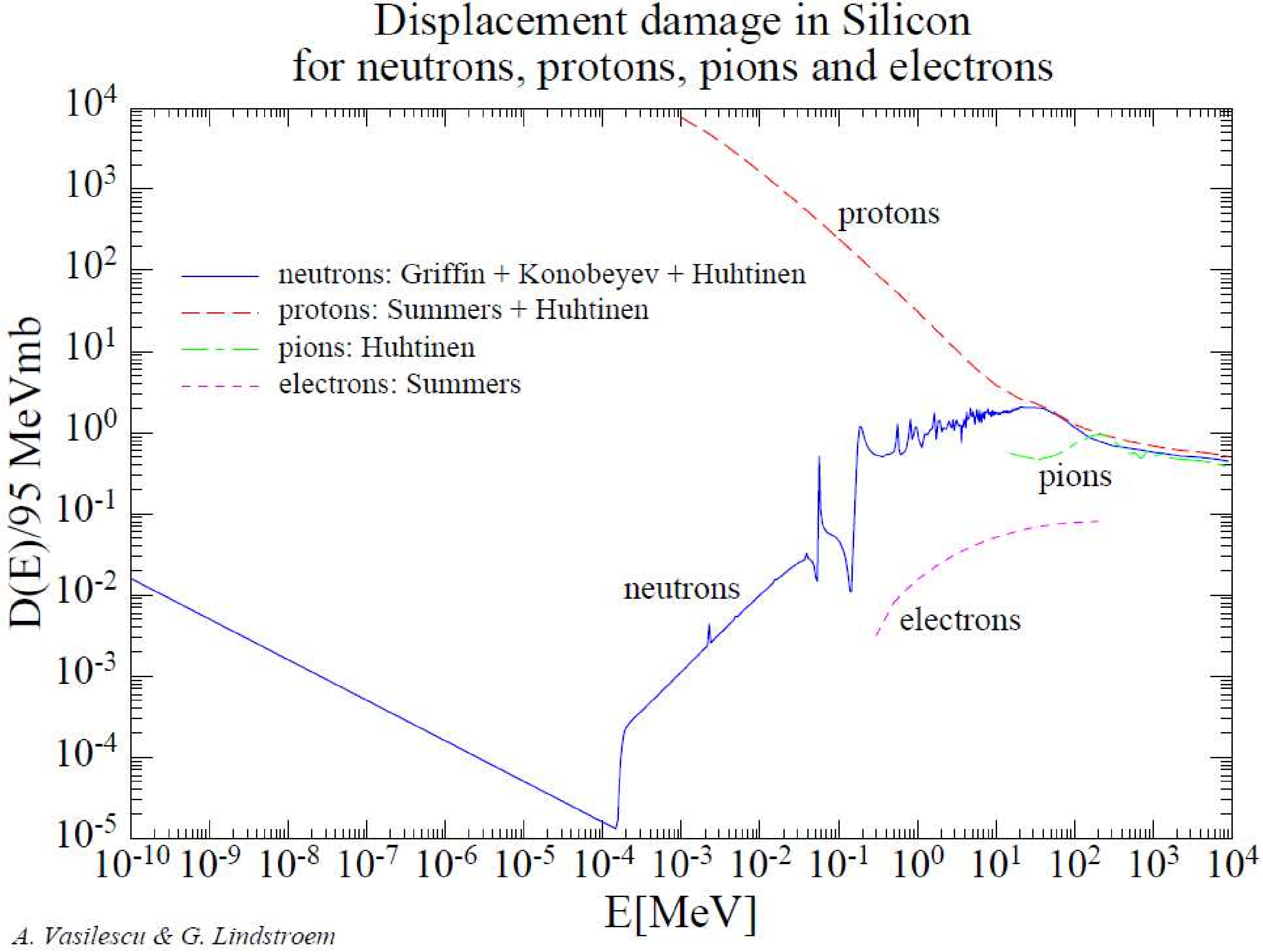
Radiation Damage in Silicon Detectors

- The two types of radiation damage to detector materials:
  - **TID ("surface damage")** due to ionization energy loss and trapping of charges in oxide layers and interfaces. It affects
    - interstrip capacitance (noise factor), breakdown behavior
  - **DDD ("bulk damage")** due to non-ionizing energy loss and build up of crystal defects. It leads to
    - changes in effective doping concentration (higher depletion voltage)
    - Increase of leakage current (increase of shot noise, thermal runaway!)
    - Increase of charge carrier trapping and hence loss of collected charge.



charged defects	trapping (e and h)	generation
⇒ N_{eff} , V_{dep}	⇒ CCE	⇒ leakage current
e.g. donors in upper and acceptors in lower half of band gap	shallow defects do not contribute at room temperature due to fast detrapping	Levels close to midgap are most effective

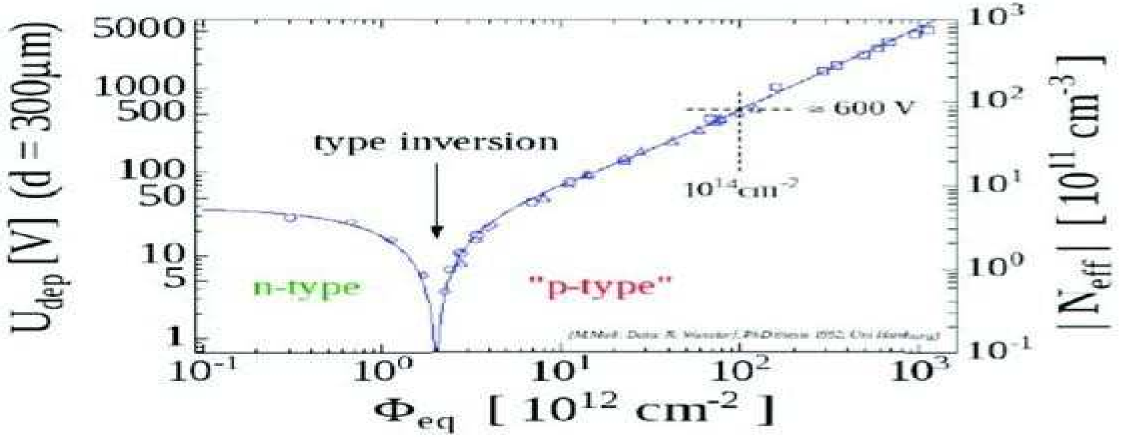
Slide from
S. Mattiazzo



From: https://rd50.web.cern.ch/NIEL/NIEL-all.pdf

Depletion Voltage

- Depletion voltage is the bias voltage required to get rid of free carriers in the bulk of the detector.
- The expected evolution depends on the dose (**Hamburg Model**):
- Before type inversion the depletion voltage decreases due to the reduction in the amount of free carriers
- After type inversion, depletion voltage steadily increases.

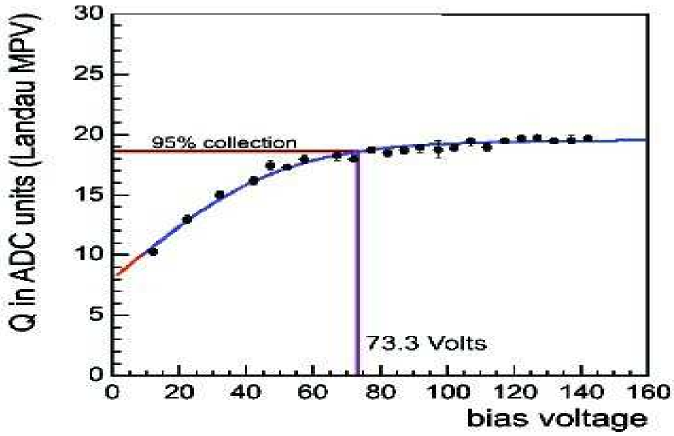


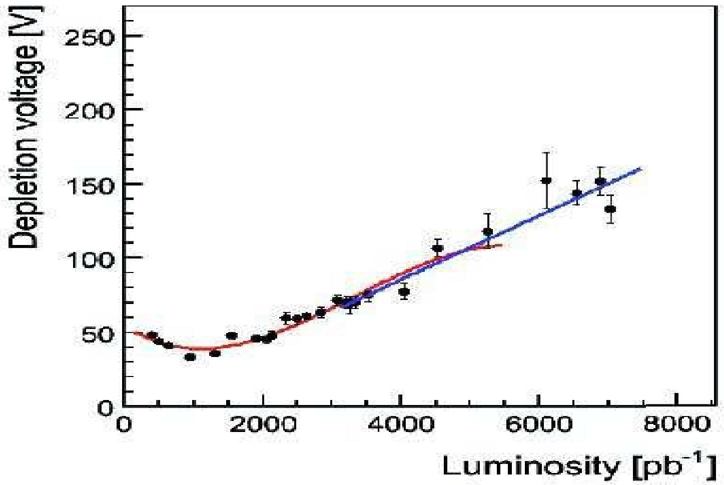
M.Moll, *PhD Thesis, (1992) UniHamburg*;

Sensor can operate while the Bias Voltage is below the Breaking Voltage

Depletion Voltage study – Signal Vs. Bias

- Plot charge for different bias voltages
- Define depletion voltage, V_d , as voltage that collects 95% of the charge at the plateau

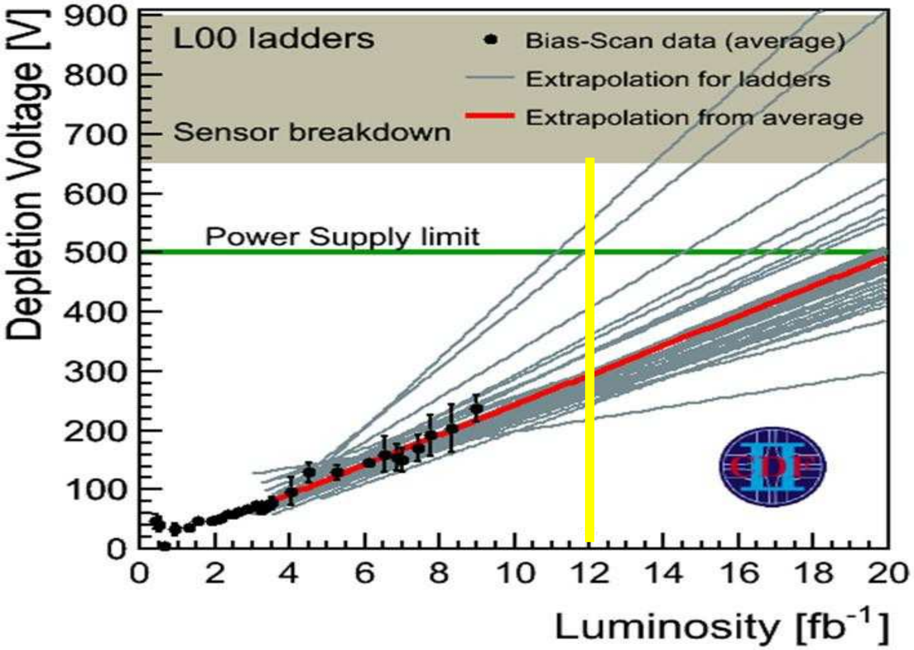




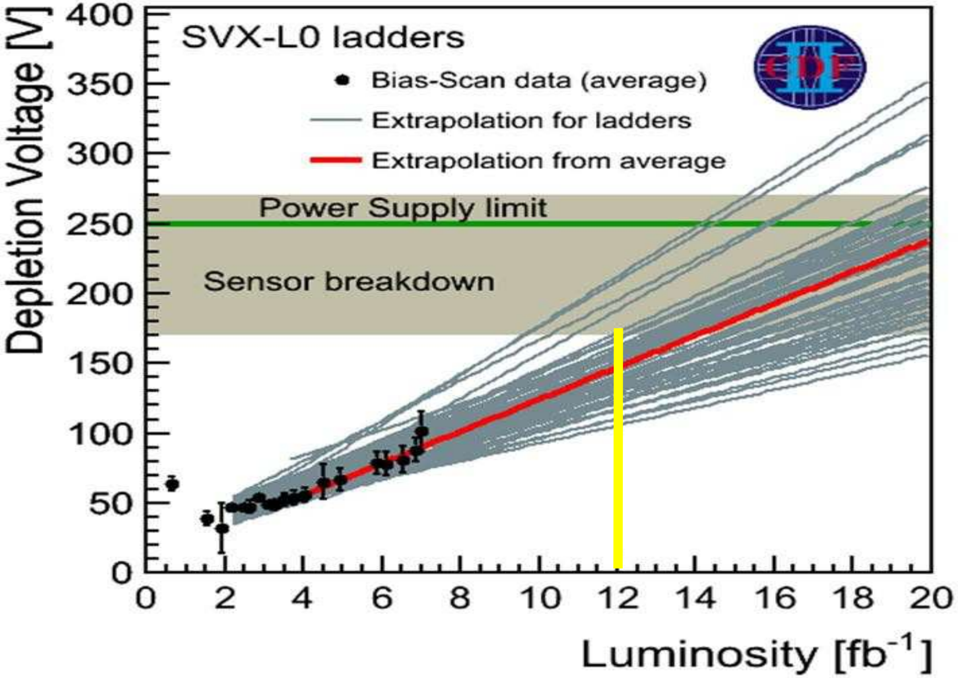
- Depletion Voltage as a function of integrated luminosity
  - 3rd order polynomial fit around the inversion point
  - Linear fit to extrapolate to the future

Depletion Voltage Projections L00-L0

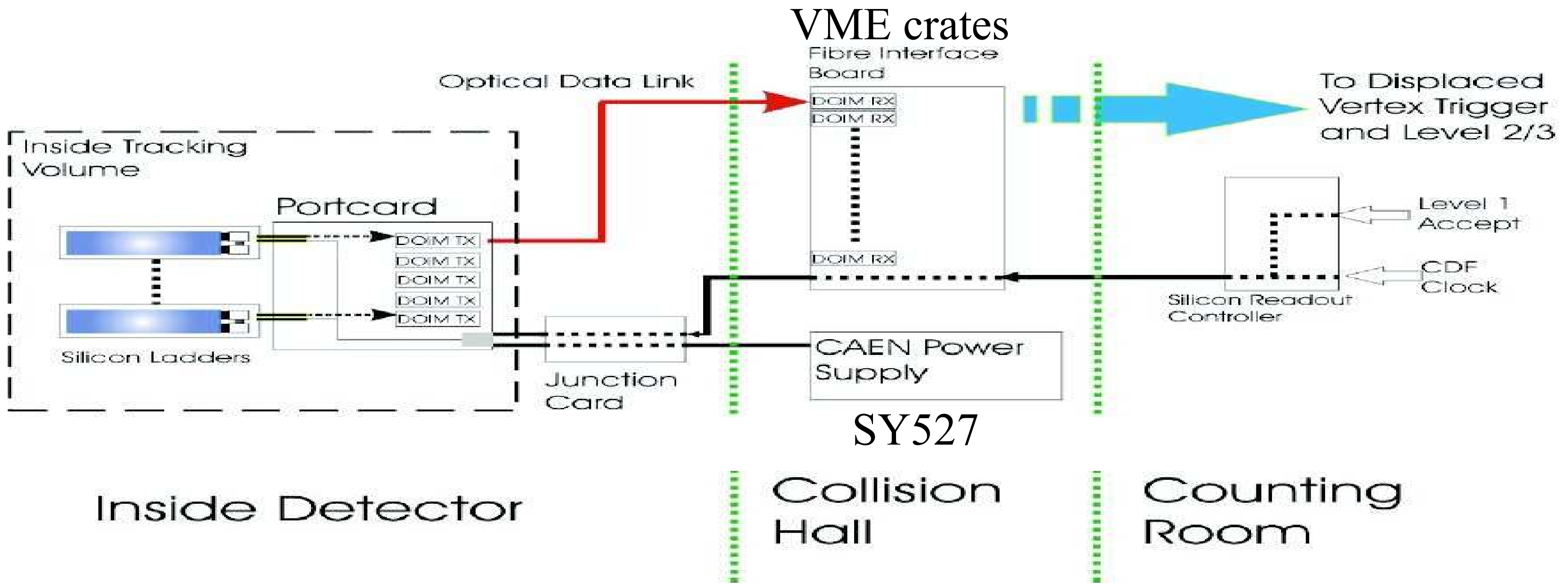
Prediction for L00



Prediction for SVX-L0



Not only the sensors are in a radiation environment



Main components:

- Silicon Readout Controller (SRC): "brain" of the system
- Fiber Interface Board (FIB): control signals and optical readout
- Portcard: chip commands and optical transmitters (DOIMs)

Dark current and Beneficial annealing effect

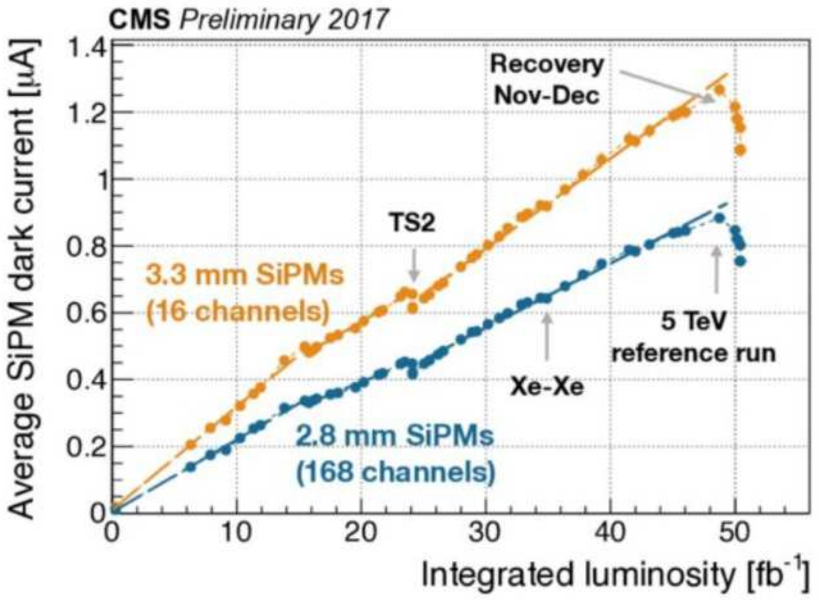
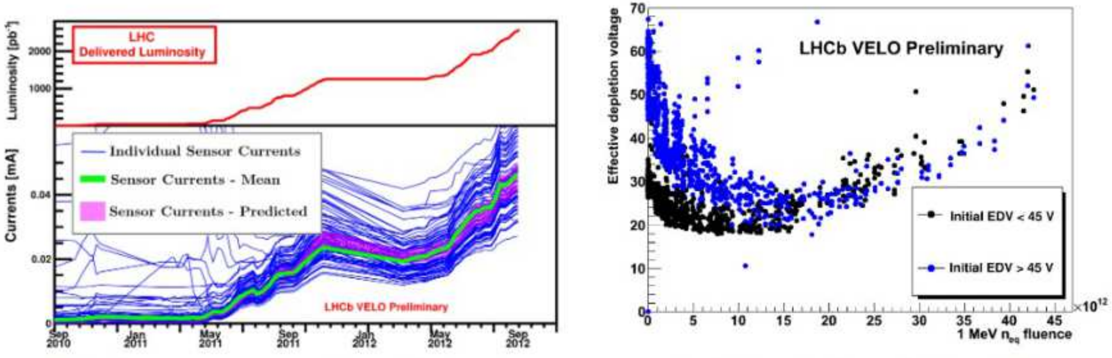


Figure 6. Dark current increases with integrated luminosity with a slope which is proportional to the SiPM area. Deviation from the linear behaviour is due to the recovery time in absence of beam and variation in instantaneous luminosity. The evolution of the dark current in 2017 is shown.

First results from the CMS SiPM-based hadronic endcap calorimeter
DOI: 10.1088/1742-6596/1162/1/012009

Dark current and Beneficial annealing effect



(a) Leakage current versus delivered luminosity (b) Effective Depletion Voltage (EDV)

Figure 3. Radiation effects on VELO. Left plot shows the measured leakage current at -8^{o}C as function of the luminosity. Each blue line corresponds to a single sensor, the green curve is the mean current value excluding those sensors with initial high currents, and the pink band corresponds to predicted currents. The effective depletion voltage (EDV) for different sensors is shown in left plot. Blue dots corresponds to sensors with initially lower leakage currents, and black to sensors with high leakage current at the beginning.

The LHCb VERTEX LOCATOR performance and VERTEX LOCATOR upgrade
2012 JINST 7 C12008
http://iopscience.iop.org/1748-0221/7/12/C12008

Facilities for Radiation Hardness characterization

Neutron irradiation for Displacement Damage Studies on Silicon Devices

- The Triga Mark II reactor in Lubiana (Slovenia)
- The Frascati Neutron Generator: a multipurpose facility for physics and engineering (Italy)

Proton Irradiation for Displacement Damage Studies on Silicon Devices

- The Trento Proton Therapy Center (TPTC)
- TPTC Experimental Area
- Experimental area beam parameters

Irradiation configurations:

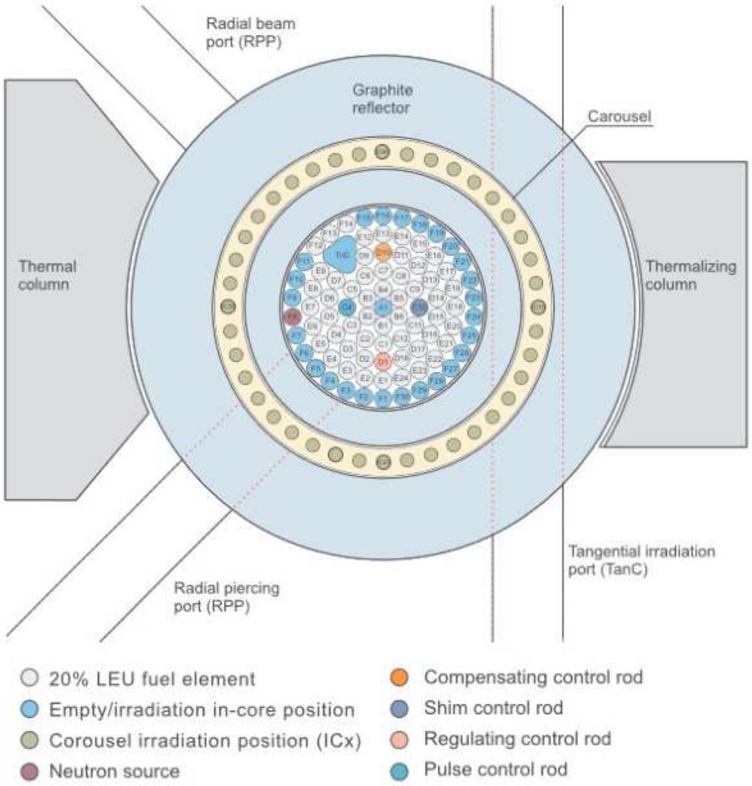
  - Small area, high proton intensity irradiation: direct irradiation configuration.
  - Large area, medium/low proton intensity irradiation: double ring configuration.
  - SEEs rate studies

X ray irradiation of for TID studies

- The TIFPA-INFN x-ray irradiation laboratory
- Tungsten emission spectrum X-ray penetration in silicon
- FBK SiPM x-ray irradiation campaign

Conclusions on radiation hardness characterization

The TRIGA MARK II reactor in Lubiana, Slovenia



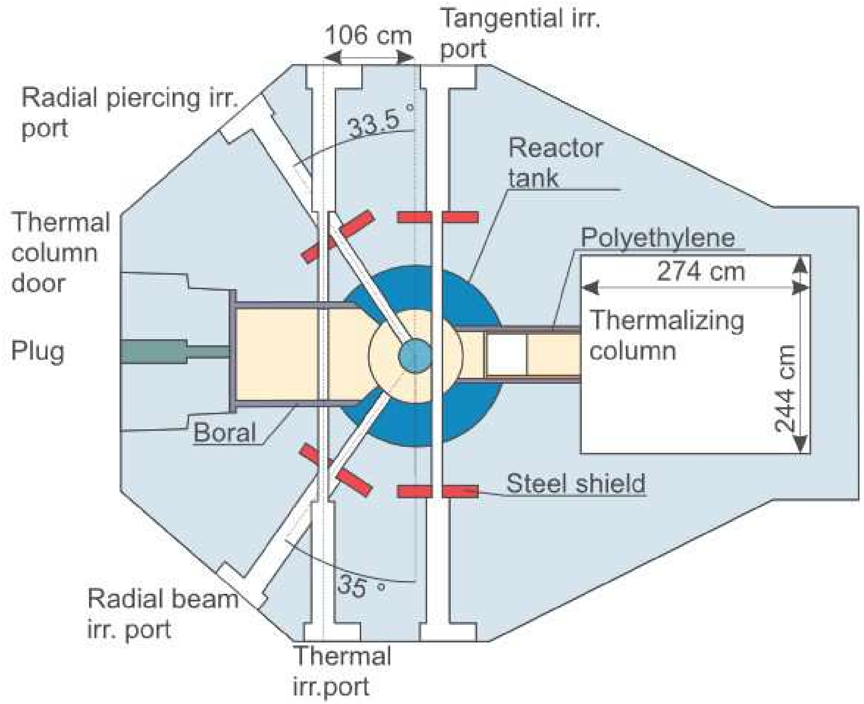
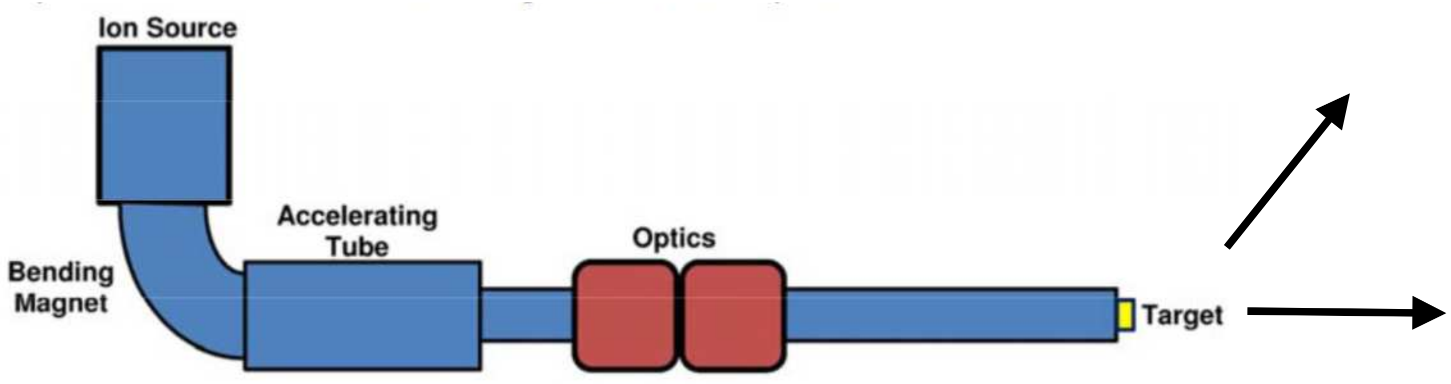


Fig. 2. Top view of the JSI TRIGA Mark II reactor, with Thermalizing and Thermal column and horizontal irradiation channels.

In-core irradiation columns

https://doi.org/10.1016/j.apradiso.2017.09.022

The Frascati Neutron Generator (FNG), Italy: A multipurpose facility for physics and engineering



Deuterons are accelerated by means of an electrostatic accelerator up to 300 kV and 1 mA current is delivered onto a Titanium target, loaded with Deuterium or Tritium, where D-D or D-T fusion reactions (namely $D+T \rightarrow n+{}^{4}He+17.6$ MeV and $D+D \rightarrow n+{}^{3}He+3.27$ MeV) take place.

Description: DOI 10.1088/1742-6596/1021/1/012004
Contact person: Salvatore Fiore (salvatore.fiore@enea.it)

FNG is includedud in the RADNEXT H2020 program:
https://radnext.web.cern.ch

The Trento Proton Therapy Center (TPTC)

https://protonterapia.provincia.tn.it/eng/?/switchlanguage/to/protonterapia_eng

Experimental Cave

Cyclotron (IBA)

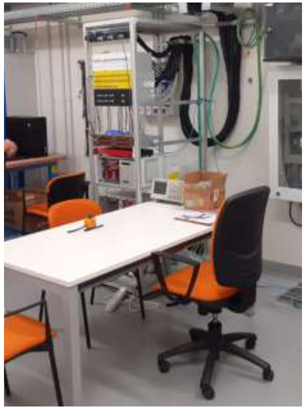
Multi-functional laboratory and remote control area for Experimental Cave

Gantry rooms for oncological patient treatment

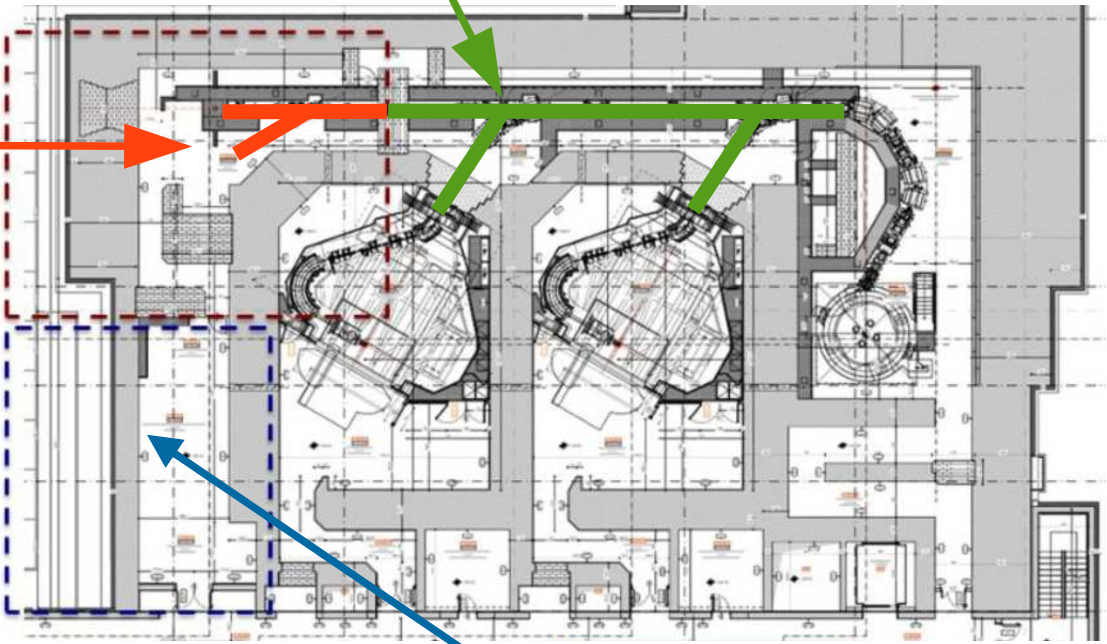
The Experimental Area

Two Experimental beamlines for in-air irradiation

Operated by
TIFPA-INFN
www.tifpa.infn.it



Beam distribution line



Patch-panel for
remote control room – cave cables connection
(ethernet, BNC, SHV, serial, USB)

Beam parameters

The TPTC accelerator and beam distribution system was realized and is operated by the Ion Beam Accelerator Company (IBA, https://www.iba-worldwide.com).

The proton accelerator is a IBA Proteus 235 cyclotron working at 106 MHz.

Beam current:

- Dark current mode:
  from ~200 p/s up to ~200 kp/s
  (mainly for tracking experiments)
- High current mode:
  From ~0.1nA up to 320 nA(***)

The proton energy at the cyclotron exit is 230 MeV, this energy can be lowered down until 70 MeV using a passive degrader.

The beam delivered in the experimental area has a **gaussian transverse intensity profile** with sigma and peak value depending on the beam energy.

Parameters of the proton beam in the Experimental Area

Energy(*) [MeV]	**Average sigma (gaussian profile)** [mm]	**Flux(**)** [p/s]
70.2	6.92	3.8x10^6
100.0	5.68	1.2x10^7
142.9	4.56	3.6x10^7
169.4	4.00	7.4x10^7
202.4	3.48	1.4x10^8
228.2	2.73	2.3x10^8

(*) Nominal energy at the beamline window

(**) Nominal flux evaluated for 1 nA current

(See **REF1** for details)

(***) Due to beam transportation losses only ~10% of this nominal current is available in the experimental area

Irradiation Configurations

Small target area and **high beam intensity: direct beam irradiation** configuration.
Irradiation performed with non uniform intensity beam. The gaussian profile of the beam can be tuned changing the beam energy.

Large target area and **medium/low beam intensity**: **double ring** configuration.
Two set up available:

- small dual ring ==> circumference of ~3 cm radius with flat intensity profile medium beam intensity
- large dual ring ==> circumference of ~8 cm radius with flat intensity profile low beam intensity

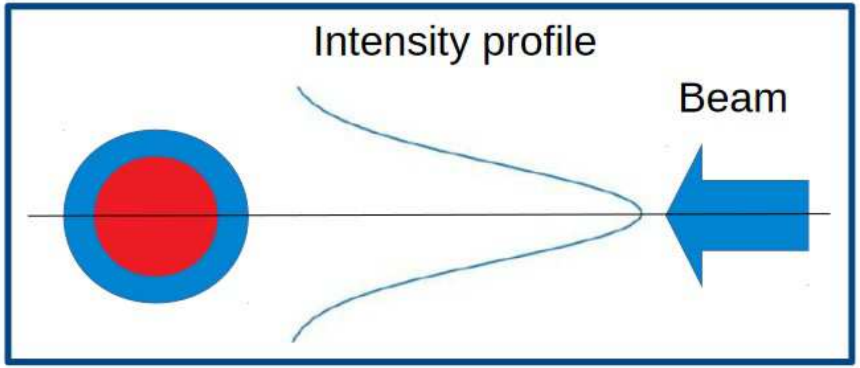
Due to **administrative restrictions**, in the experimental cave can be delivered a maximum amount of charge **equal to 0.5 mC every day.**
With this limitation **only around ~4*10^12 protons** can be delivered on the target in **one irradiation day**.

Direct beam irradiation configuration

In a direct proton beam irradiation the maximum amount of beam can be delivered on the target but the beam transverse intensity distribution is not uniform but gaussian.
The gaussian's sigma can be tuned from 2.73 mm up to 6.92 mm decreasing the beam energy from 228MeV down to 70MeV. Decreasing the beam energy also the beam intensity decreases: this happen because the beam energy is lowered in a passive way adding stopping material in the beam path after the cyclotron beam exit.

For a **100MeV Proton beam** with a 5.68 mm Gaussian sigma profile, **the fraction F** of the total beam with gaussian intensity profile delivered inside a radius r circumference can be evaluated as follow:
F= 1-e^[-0.5*(r/sigma)^2]

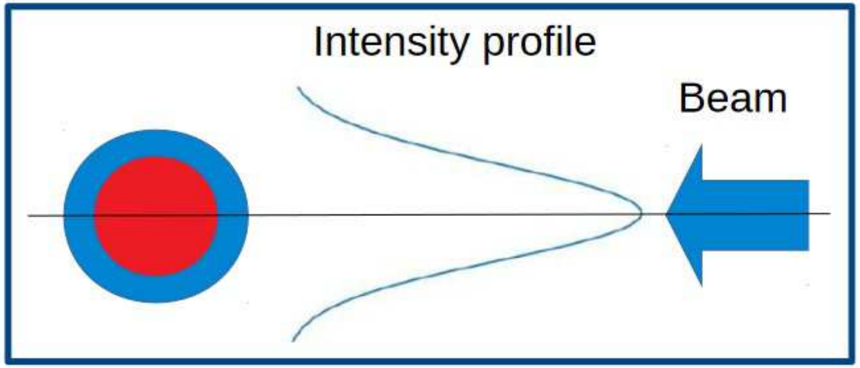
Considering r=2.5 and 3.0 mm :
r_{red} 2.50 mm ==> F =0.095
r_{blue} 3.00 mm ==> F =0.133



Direct beam irradiation configuration

With a 100 MeV proton beam, with the 0.5mC administrative limitation, a total amount of 4.32 10^12 protons can be delivered on the target in one irradiation day.

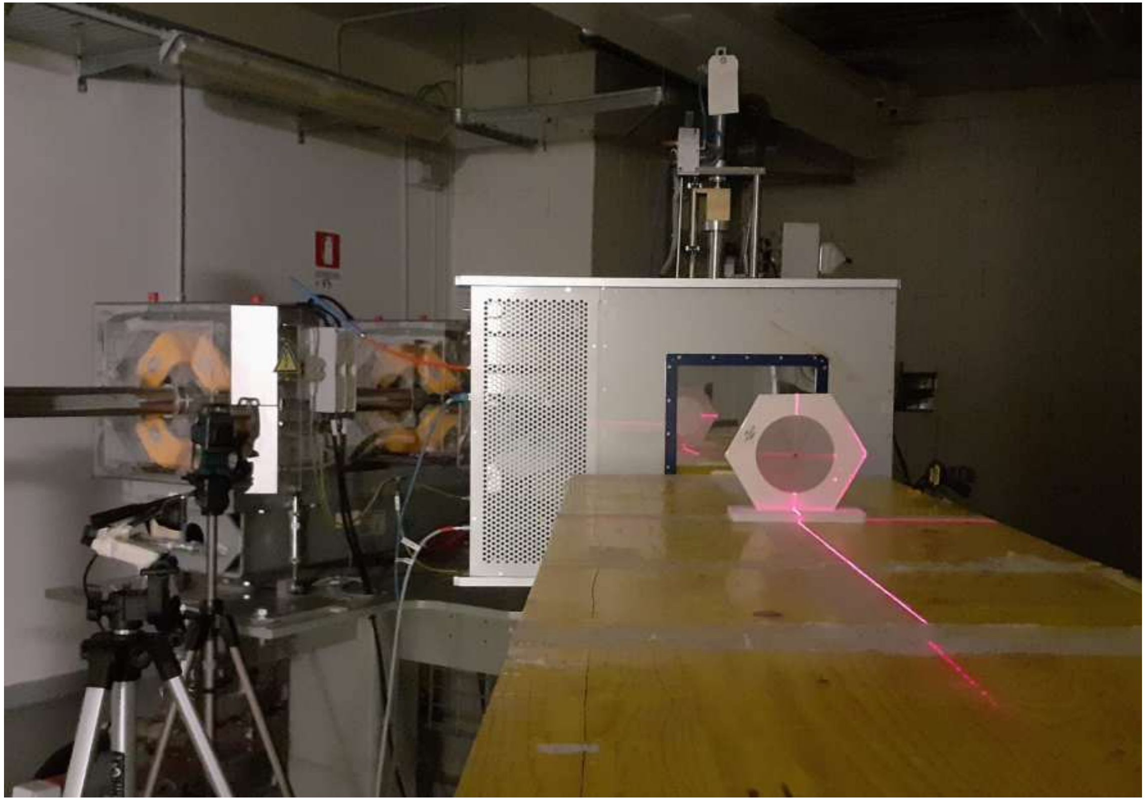
In this condition, the **average fluence** inside a radius r circumference is:



r_{red} 2.5 mm ==> average proton fluence =2.1*10^12 protons/cm^2
r_{blu} 3.0 mm ==> average proton fluence =1.6*10^11 protons/cm^2

100 MeV Energy is a good trade-off between beam intensity (increasing with energy) and beam spreading (decreasing with energy).
Even if **the beam fluence is not uniform** and the area considered is small, these configuration are interesting for SiPM and single pixels prototypes irradiation studies.

Case application: Direct beam irradiation on FBK SiPM



Direct beam irradiation on FBK SiPM:

in this type of irradiation the
Detector Under Test (DUT) precise
alignment with the beam axis is crucial

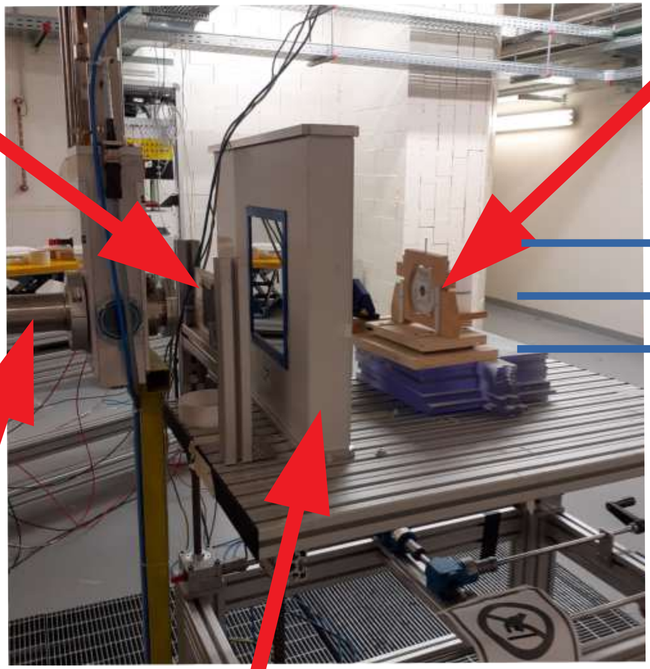
Dual Ring configuration

First foil

Dual ring

incoming proton beam
(gaussian profile, 148MeV)

scattered proton beam
(flat profile, ~140 MeV)

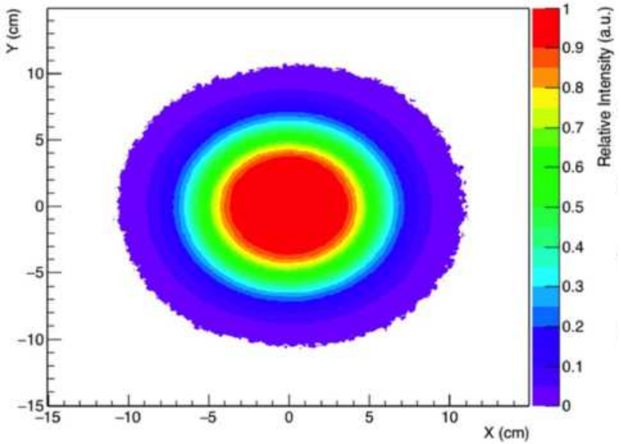


Target area

Fluence in
one irradiation day:
~5.0 * 10^11 p/cm^2

beampipe

Monitor drift chamber



Small dual ring intensity profile

(See **REF2** for details)

Dual Ring configuration

The dual ring set-up can be assembled in two configurations:

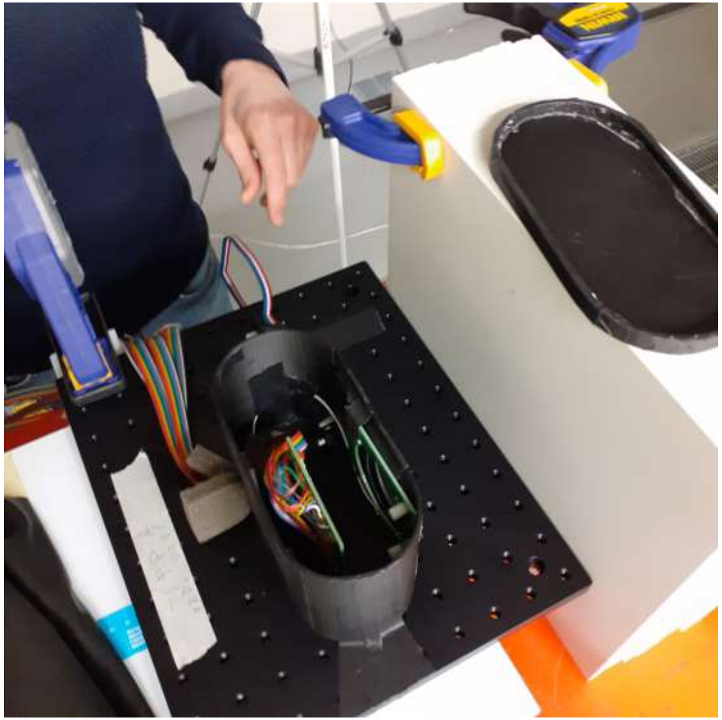
- small dual ring ==> circumference of ~3 cm radius with flat intensity profile
- large dual ring ==> circumference of ~8 cm radius with flat intensity profile

The intensity peak is different in the two configurations.
(See **REF2** for details)

This configuration is commonly used for large area irradiation on cells culture or radiation damage studies on electronic devices and silicon sensors.

Case application: Dual Ring used for FBK SiPM Irradiation

- Small dual ring configuration used.
- On target proton energy lowered to 70 MeV using additional degrader (solid water).
- Additional Dark Box (by FBK) with remote controlled window for SiPM characterizations between irradiation steps.



See **Stefano Merzi** talk in this Workshop for detailed results:
https://indico.cern.ch/event/1093102/contributions/4802136

Case application: SEEs studies on large area electronic devices

On October 2021, for the first time,
the **small dual-ring set-up** was used also for
Single Event Upset rate measurement.

The HERMES-SP collaboration (https://www.hermes-sp.eu)
equipped a special daisy-wheel remotely controlled with
commercial electronic boards to be tested on the spokes.

Each board was powered on and irradiated, meanwhile
a controller located in the center of the wheel
was checking the status of the board.
In this way was possible to measure the number of
board failures for each fluence step for every board.

The daisy-wheel set-up allowed to test in short time
8 different boards without entering in the irradiation cave.

Final considerations on proton irradiation and references

- Since the TPTC is a medical facility the beam in the experimental area is available only at the end of medical treatment, that is from ~19.30 up to 22:30 Mon-Fri, 8-13 on Sat.
- For high dose irradiation the 0.5 mC/day administrative limit can force to split the operations in multiple days.
- In order to allow precision DUT measurement inside the experimental cave, also the electromagnetic background characterization was performed.

- **Proton beam characterization REF1:**

Proton beam characterization in the experimental room of the Trento Proton Therapy facility
F. Tommasino *et al*, 2017; DOI:10.1016/j.nima.2017.06.017
https://www.sciencedirect.com/science/article/abs/pii/S0168900217306654

- **Dual ring description REF2:**

A new facility for proton radiobiology at the Trento proton therapy centre: Design and implementation
F. Tommasino *et al.;* Physica Medica 58 (2019) 99–106; DOI: 10.1016/j.ejmp.2019.02.001
https://www.physicamedica.com/article/S1120-1797(19)30021-3/fulltext

- **Experimental cave electromagnetic background characterization:**

Experimental Assessment of the Electromagnetic Background Noise in the Trento Proton Therapy Center
B. Di Ruzza et al, DOI: 10.1109/ICECET52533.2021.9698549
https://ieeexplore.ieee.org/document/9698549

The TIFPA-INFN x-ray irradiation Laboratory

INTRODUCTION

The TIFPA-INFN center is equipped with a x-ray tungsten irradiation station optimized for medical/biophysical irradiation: 195kV, 5mA current, 3mm Al filter and PTW Farmer Chamber Dose measurement system.
After a filter replacement, the station was used for SiPM TID studies at 40kV and 20mA current.
The x-ray spectrum of the new tube configuration was checked using simulations realized with the SpekPy toolkit and doserate measurement.

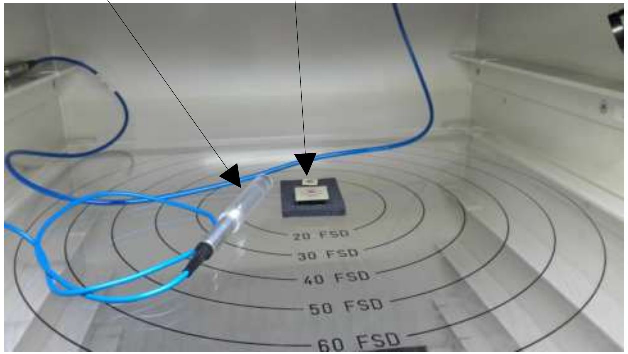
The ratio diode doserate (both SiO_2 and Si dose) / **Farmer Chamber doserate**
was evaluated performing PTW Farmer Chamber dose measurements in the
Padova INFN x-ray irradiation station.

Using this configuration a 10Mrad irradiation was successfully performed in 3 working days
in Trento (using only the Farmer Chamber for dose measurement) performing also SiPM
characterizations at different irradiation dose levels.

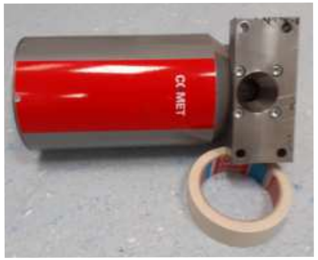
The TIFPA-INFN x-ray irradiation Laboratory

X-Ray cabinet

PTW Farmer Chamber
with SiPM



Tube detail

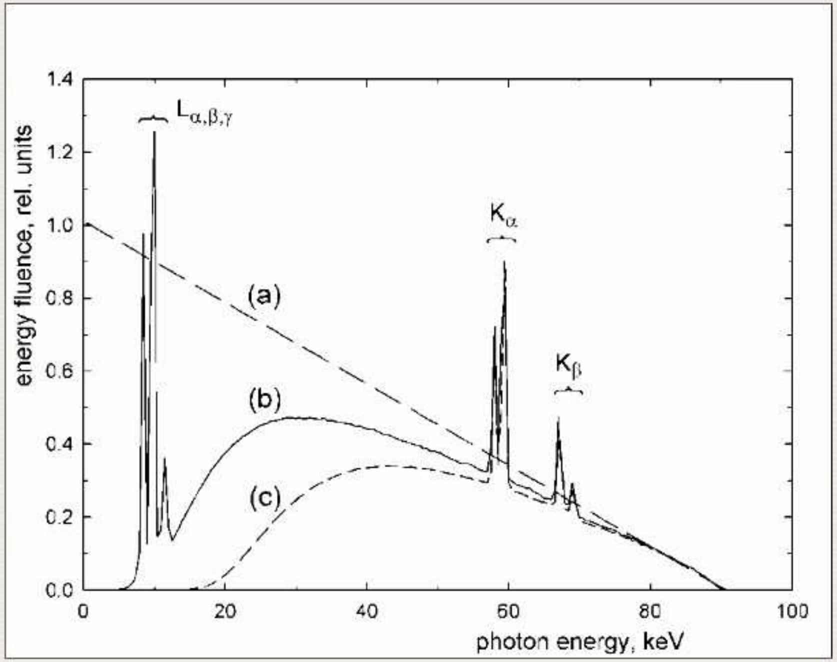


PTW Electrometer

https://www.ptwdosimetry.com/en/

TIFPA-INFN: www.tifpa.infn.it
UniTN Biological Department: https://www.cibio.unitn.it

X-Ray spectrum emission



a) Ideal **Bremsstrahlung** spectrum for a tungsten anode (tube voltage 90 kV)

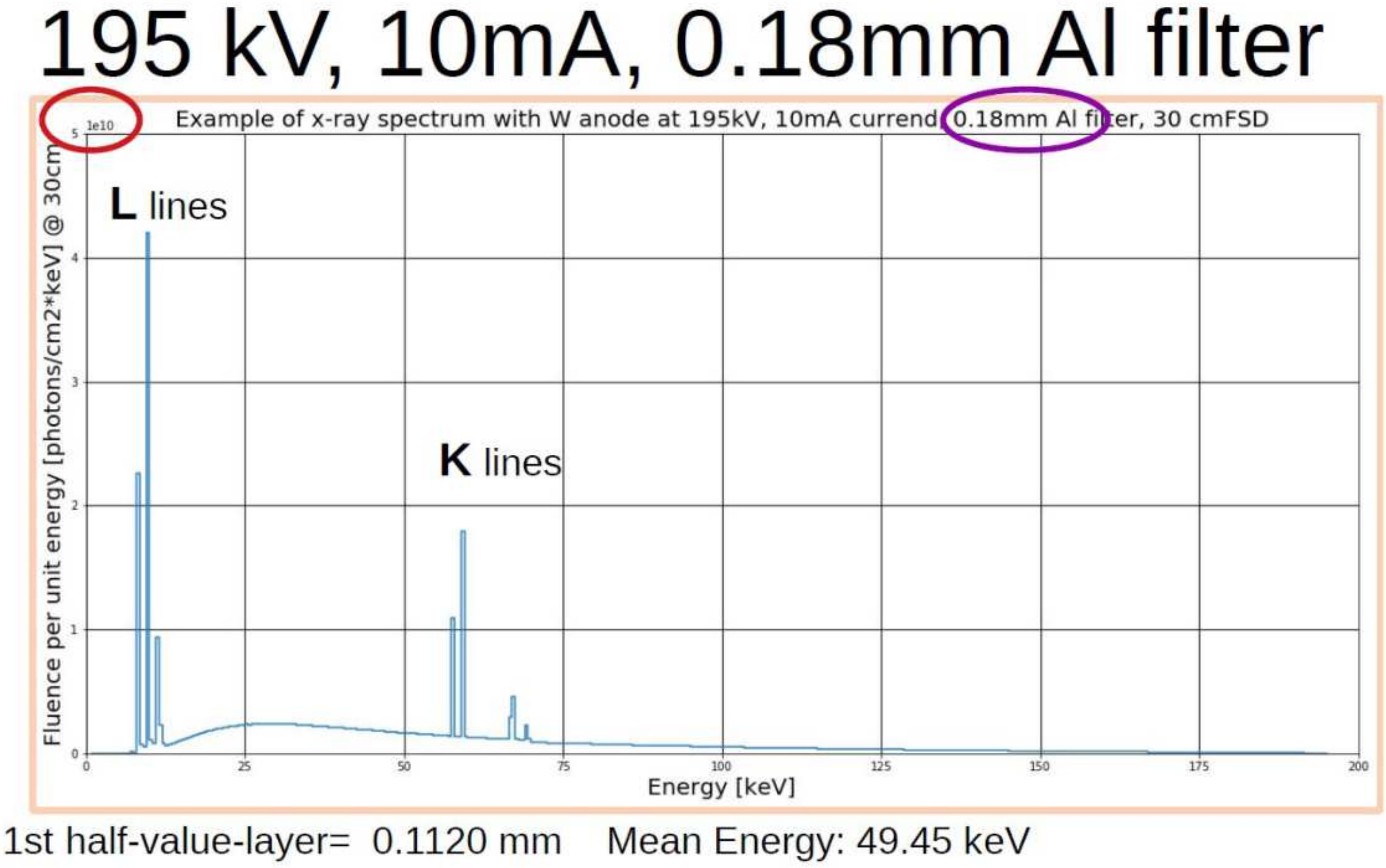
b) An **Actual** spectrum at the beam exit port with characteristic X rays (anode angle: 20°, inherent filtration: 1 mm Be)

c) The spectrum **Filtered** with an equivalent of 2.5 mm Al

IAEA

Diagnostic Radiology Physics: a Handbook for Teachers and Students – chapter 5, 15

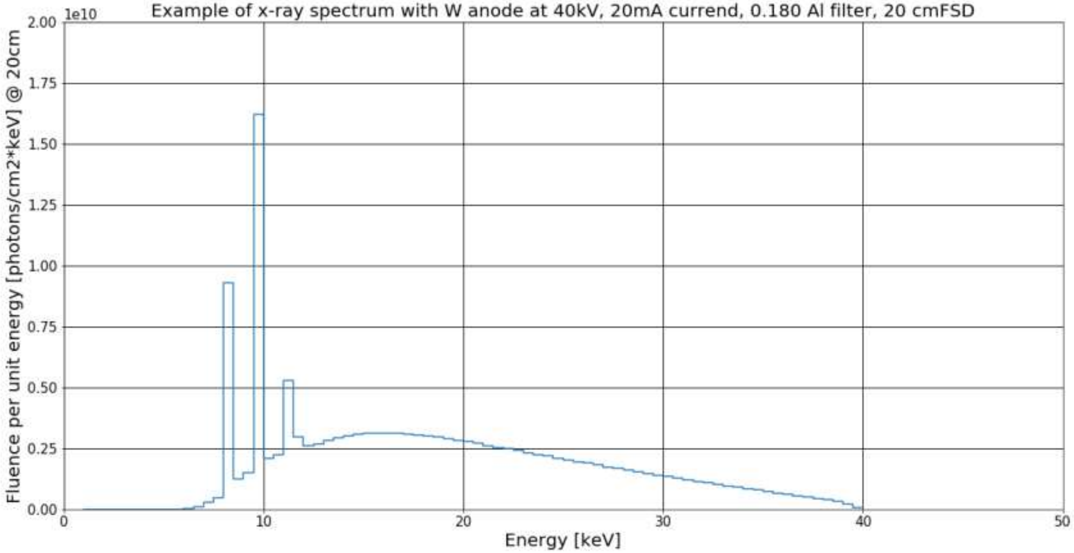
Tungsten emission spectrum simulation (SpekPy*)



(*) https://doi.org/10.1016/j.ejmp.2020.04.026

Tungsten emission spectrum simulation (SpekPy*)

SiPM Radiation Field simulation with the the SpekPy* software toolkit:

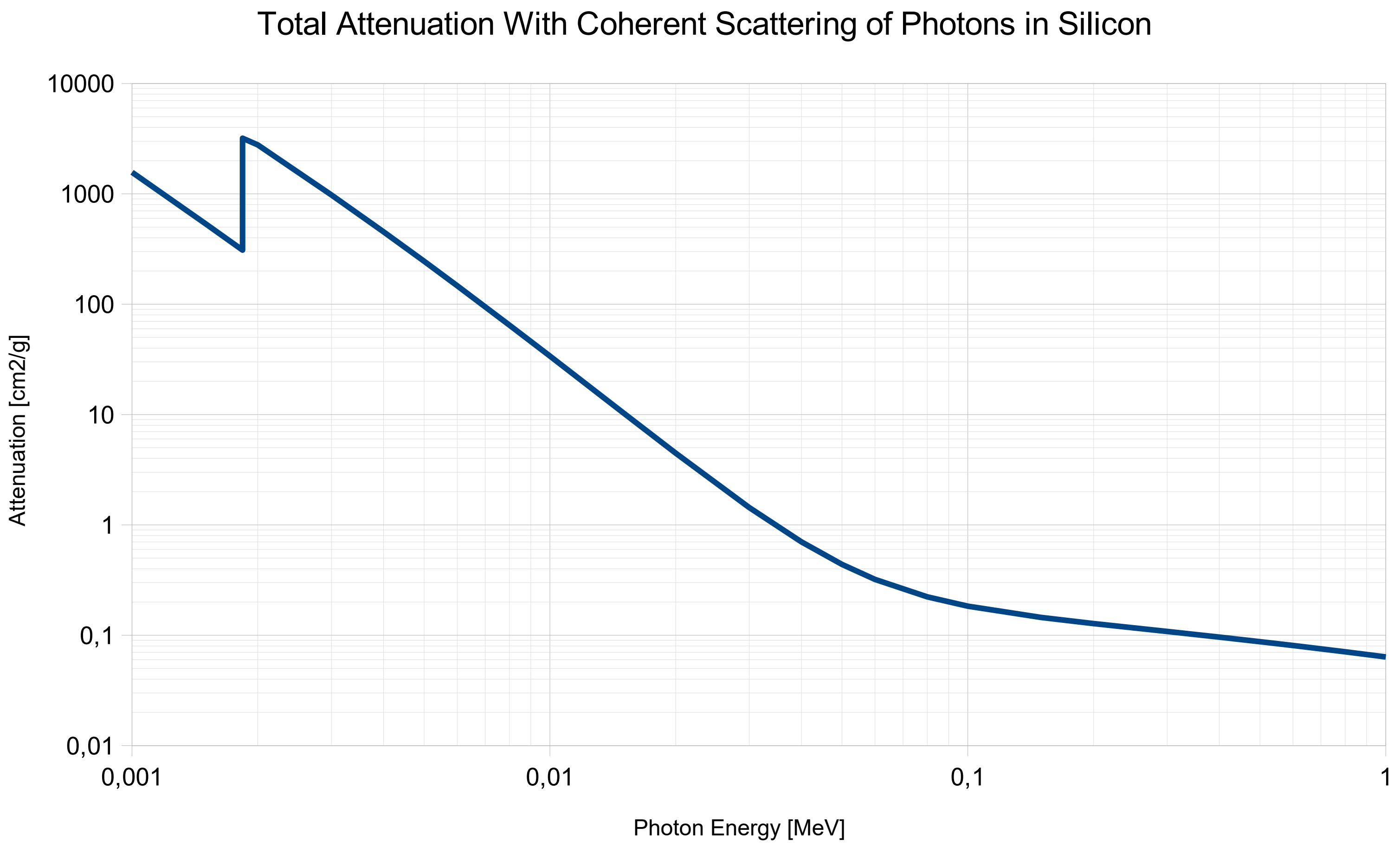


Considered tube configuration:

tungsten anode, 0.8mm Be window;
40kV anode tension, 20mA current, 0.180 mm Al filter,
20 cm FSD target position.

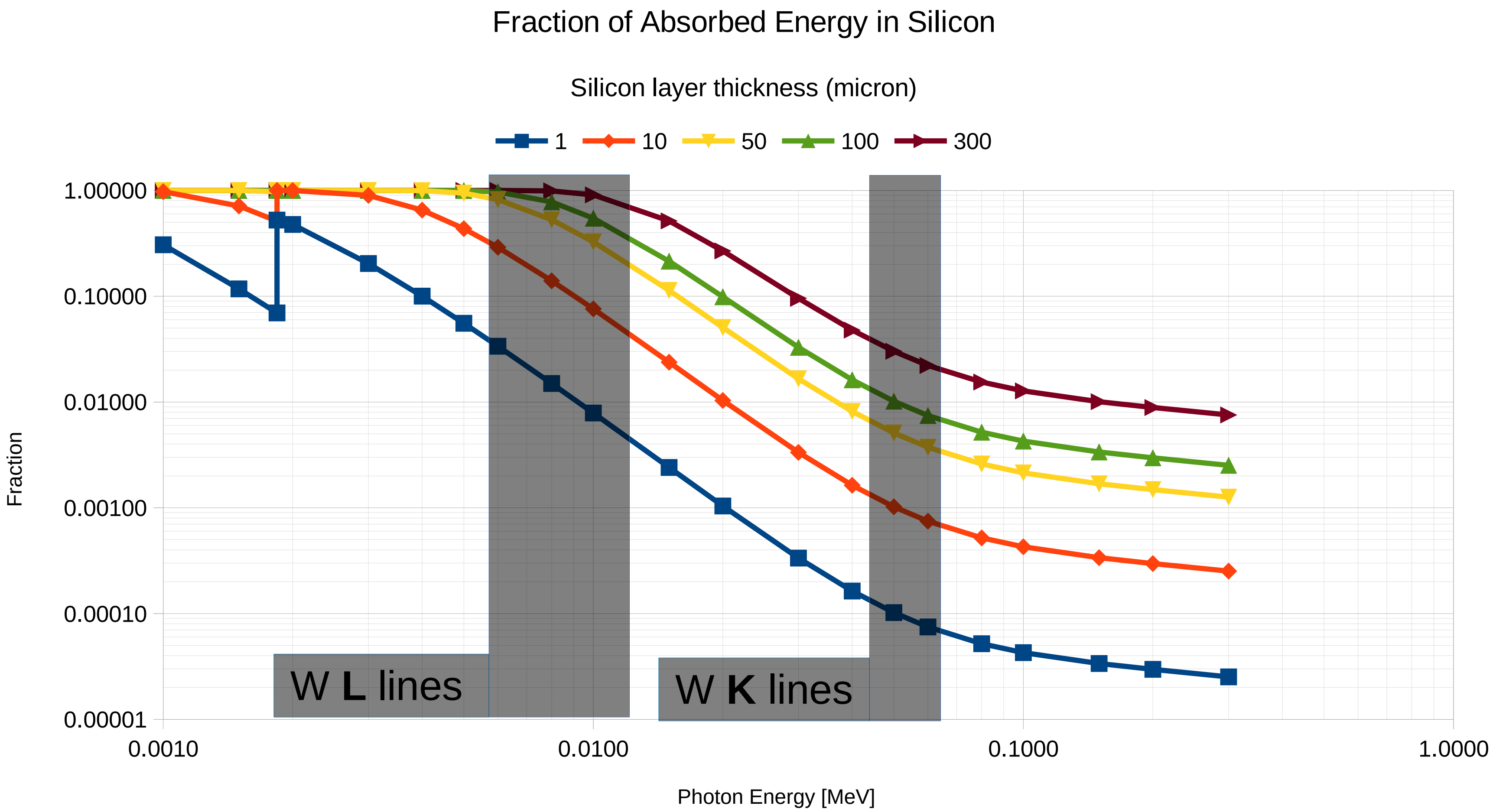
(*) https://doi.org/10.1016/j.ejmp.2020.04.026

X-ray in silicon



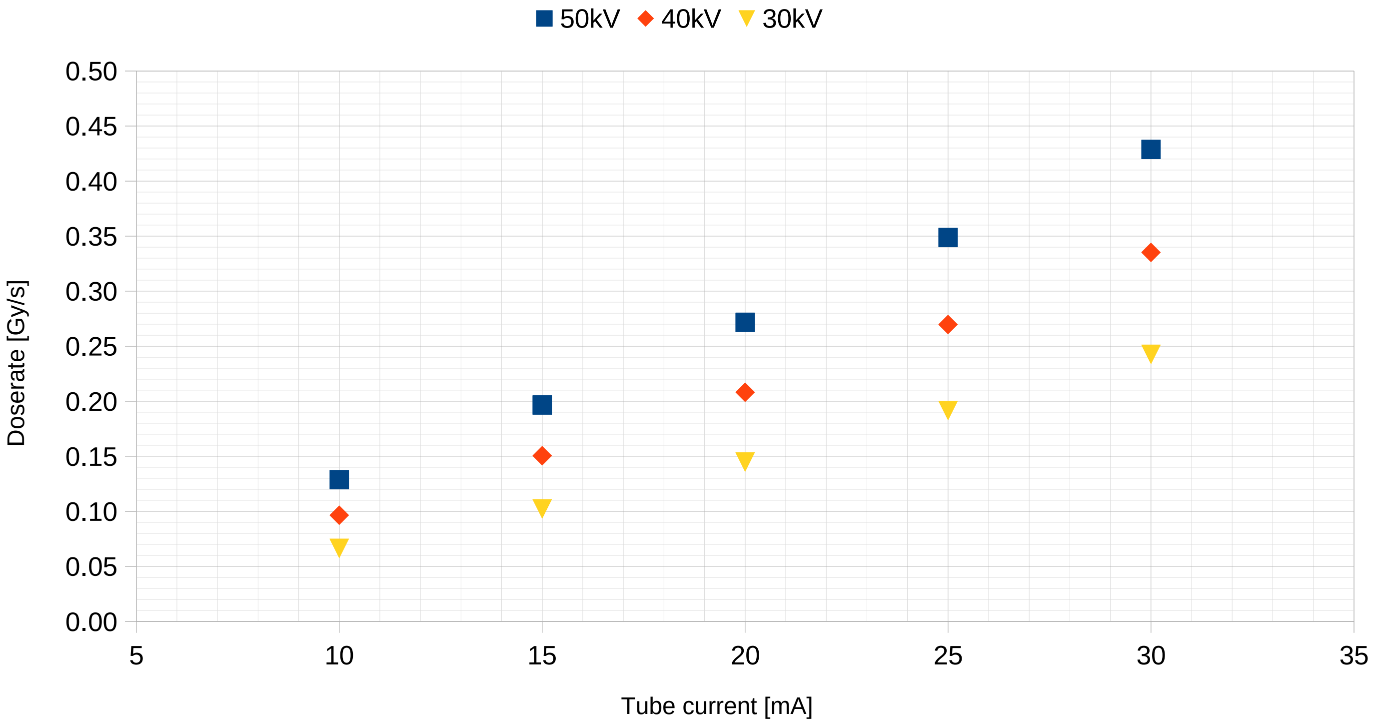
Data from NIST: https://www.nist.gov/pml/x-ray-mass-attenuation-coefficients

X-ray in silicon



Evaluated from NIST data: https://www.nist.gov/pml/x-ray-mass-attenuation-coefficients

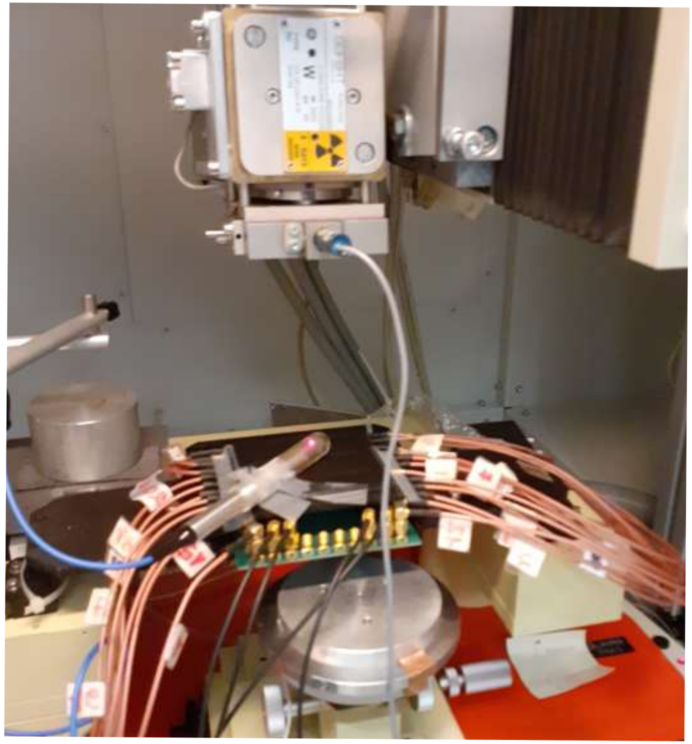
The TIFPA-INFN x-ray irradiation Laboratory



Tube voltage: 30, 40 e 50 kV
Tube current: 10-30 mA
Filter: 0.180 mm Al
Target distance: 20 FSD

Dose Instrument used:
Calibrated PTW
Farmer Chamber

The TIFPA-INFN x-ray irradiation dose measurement



Calibrated diode/PTW farmer chamber
Comparison in the Padova laboratory

For x-ray irradiation on silicon devices the dose measurem system is performed with calibrated diodes described in this CERN link:
https://espace.cern.ch/project-xrayese/_layouts/
15/start.aspx#/Calibration/Forms/AllItems.aspx

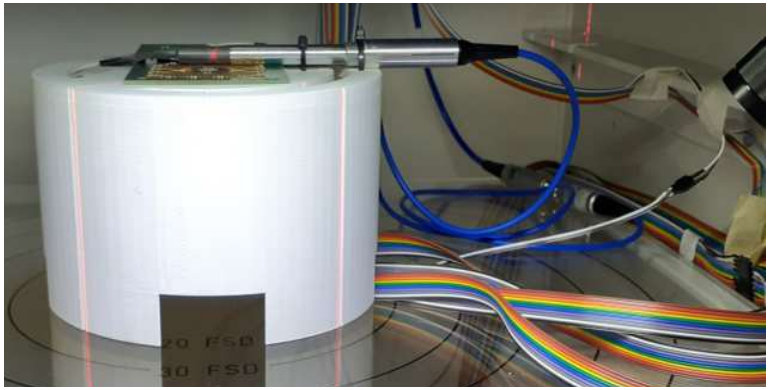
In the Trento x-ray laboratory, in order to use the available PTW Farmer Chamber dose measurement system, a preliminary comparison Framer chamber vs calibrated diode read-out were Performed in the Padova INFN x-ray station using exactly the planed SiPM radiation field.
In this way was evaluated
the read-out ratio farmer chamber dose/Si dose .

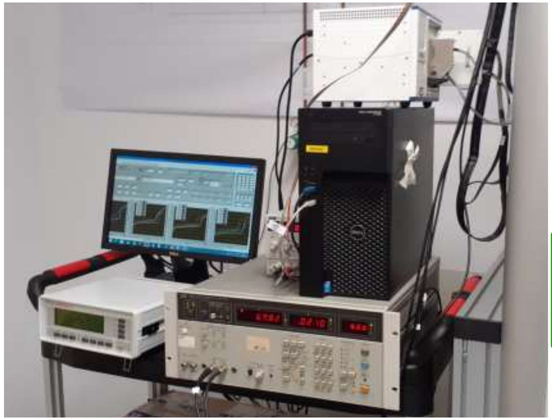
Case application: FBK SiPM Irradiations

Overview of the irradiation set-up

X Rays beam

Farmer chamber and SiPM support (FBK)





SiPM online characterization system (FBK)

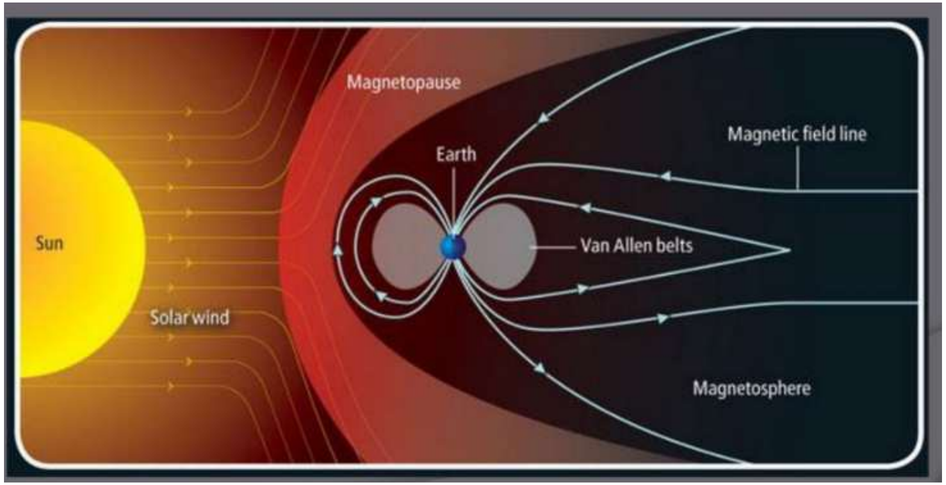
For results see:
DOI: 10.1016/j.nima.2022.167502

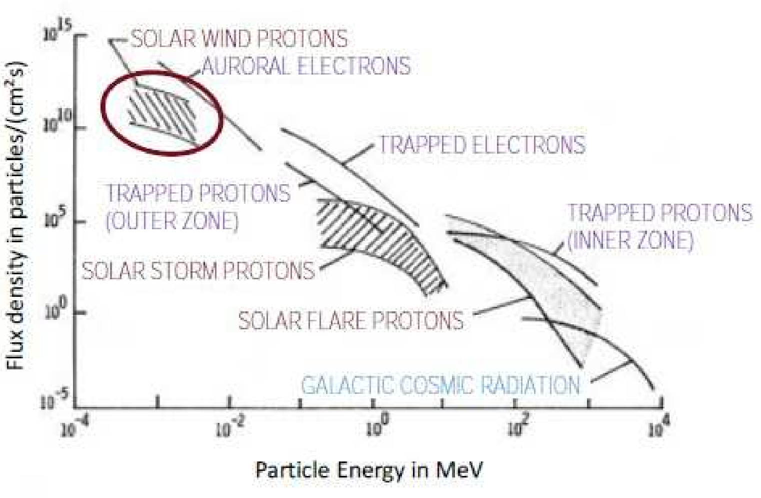
Lesson learned: **a proton medical facility** and a **general purpose x-ray irradiation cabinet** can be successfully used for silicon sensors radiation hardness characterization.

For this irradiation work I want to thanks:
Anna Rita Altamura, Fabio Acerbi, Stefano Merzi (FBK),
Federico Faccio (CERN), Riccardo Campana (INAF),
Devis Pantano, Simona Mattiazzo, Jeff Wyss (INFN Padova),
I. Rashevskaya, G. Battistoni, E.Scifoni (TIFPA-INFN)
F. Tommasino (UniTN)

Usefull software tools

Particle fluence evaluation in Space





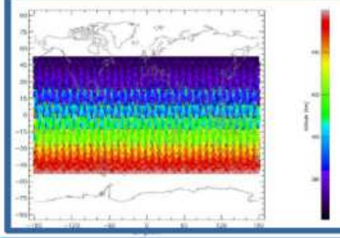
From: Schimmerling & Curtis 1978

SPENVIS:

particle fluence evaluation and spectrum evaluation

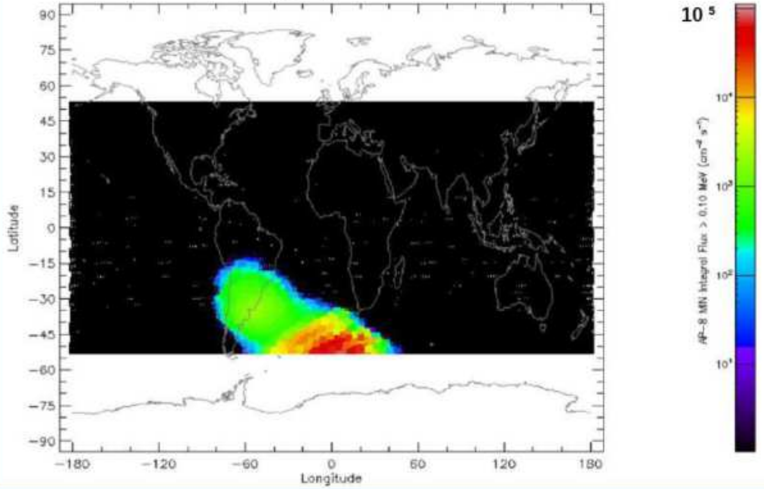
International Space Station (ISS)

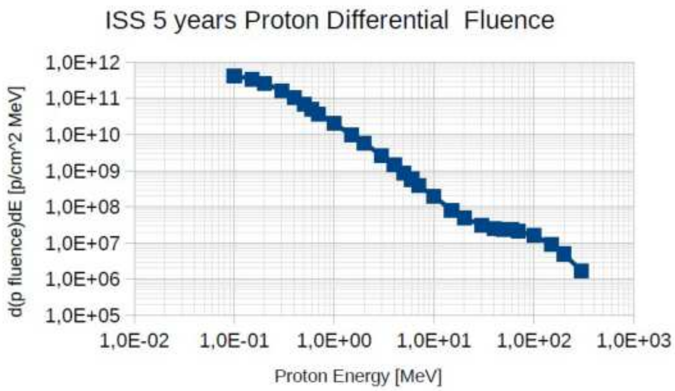
Orbit Parameters:
370-460 km altitude, 51.6 deg. inclination



ISS 30 days
Orbit map

ISS 30 days protons flux map





https://www.spenvis.oma.be

SPENVIS:

particle fluence evaluation and spectrum evaluation

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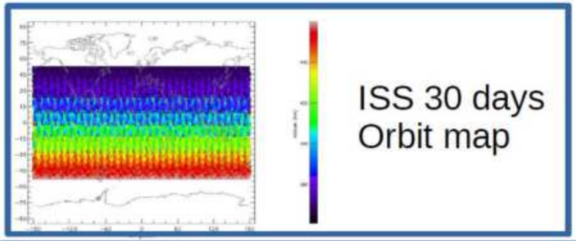

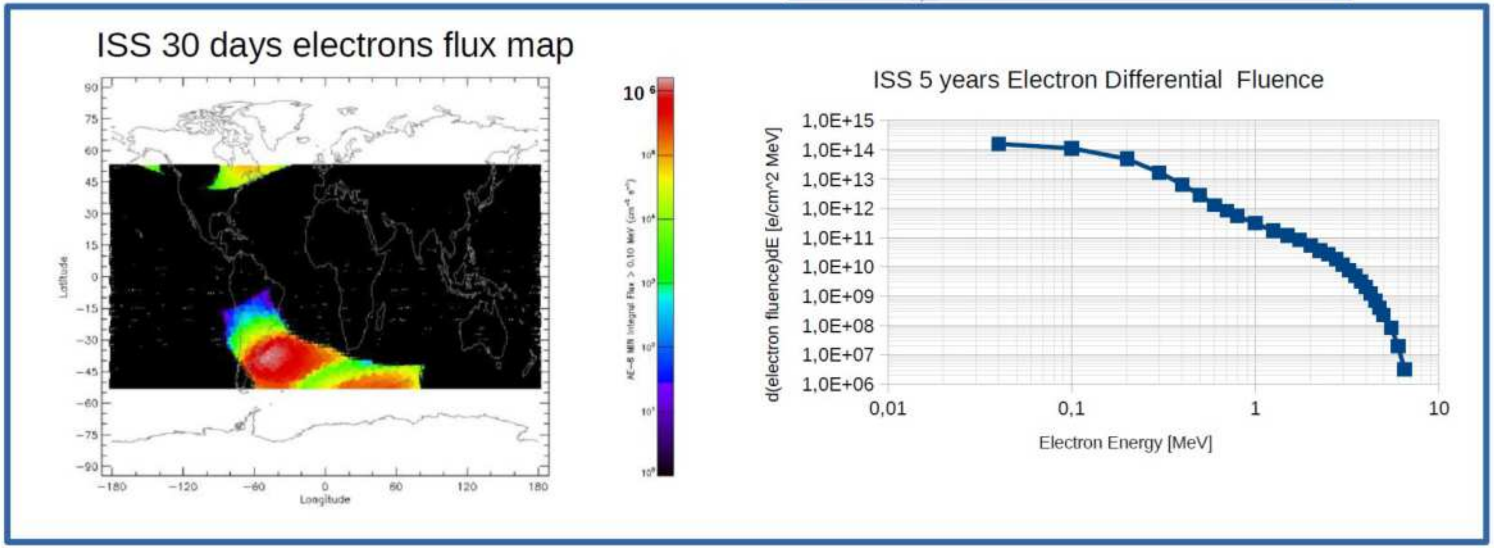

https://www.spenvis.oma.be

SPENVIS:
particle fluence evaluation and spectrum evaluation

International Space Station

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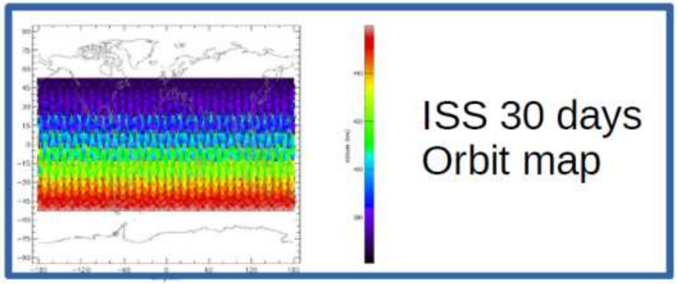
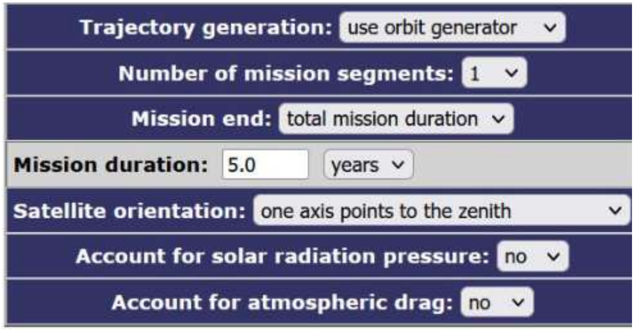


Displacement damage in Silicon, induced by protons and electrons for this orbit can be evaluated for a 5 years mission using the **Vasilescu & G. Lindstroem** radiation damage evaluation tables (RD50 collaboration):

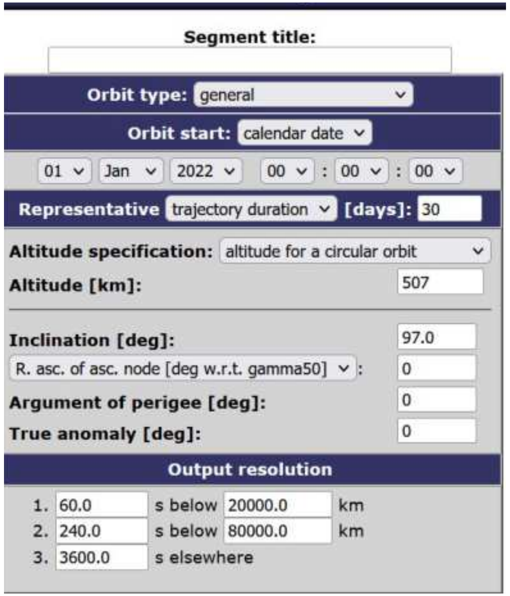
Proton spectrum: D/95MeV mb= **1.60E+13** (proton energy range: 0.1MeV – 300 MeV)
Electron spectrum: D/95MeV mb= **1.03E+11** (electron energy range: 0.04MeV – 7 MeV)

https://www.spenvis.oma.be

5 years LEO Polar mission



Trajectory generation:	use orbit generator
Number of mission segments:	1
Mission end:	total mission duration
Mission duration:	5.0 years
Satellite orientation:	one axis points to the zenith
Account for solar radiation pressure:	no
Account for atmospheric drag:	no

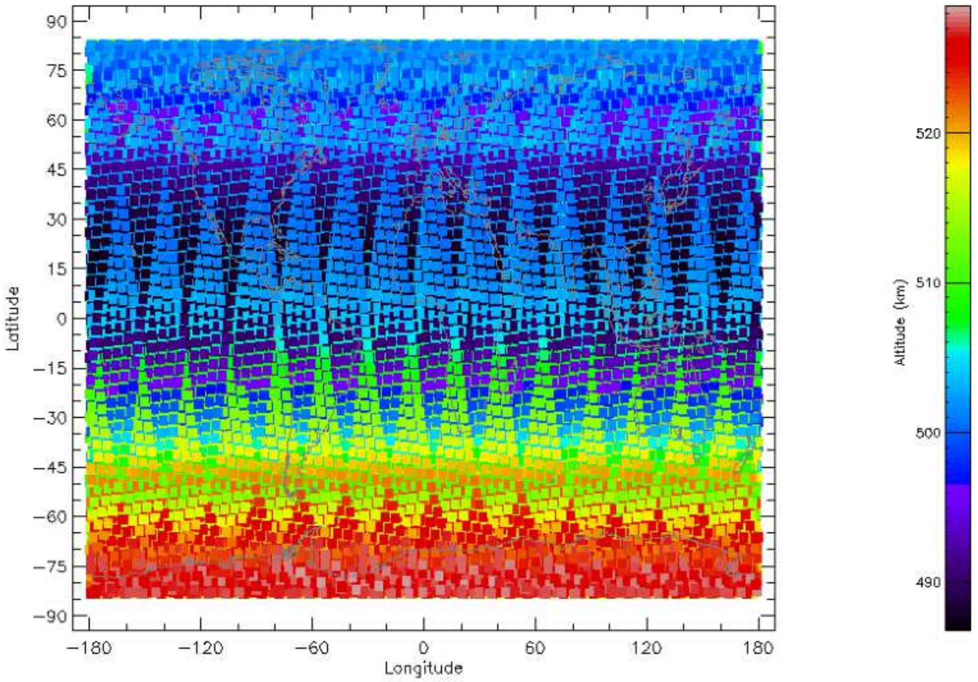


Segment title:

Orbit type:	general
Orbit start:	calendar date
01 Jan 2022	00 : 00 : 00
Representative trajectory duration [days]:	30
Altitude specification:	altitude for a circular orbit
Altitude [km]:	507
Inclination [deg]:	97.0
R. asc. of asc. node [deg w.r.t. gamma50]:	0
Argument of perigee [deg]:	0
True anomaly [deg]:	0

Output resolution

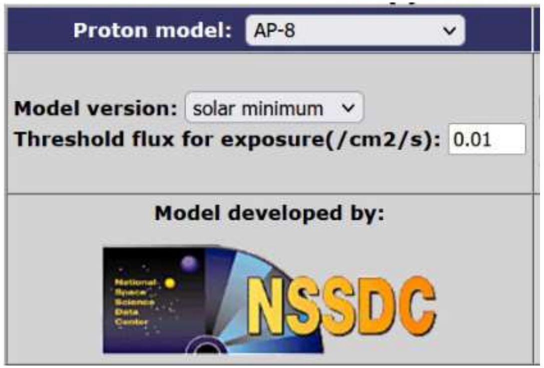
1. 60.0 s below 20000.0 km
2. 240.0 s below 80000.0 km
3. 3600.0 s elsewhere



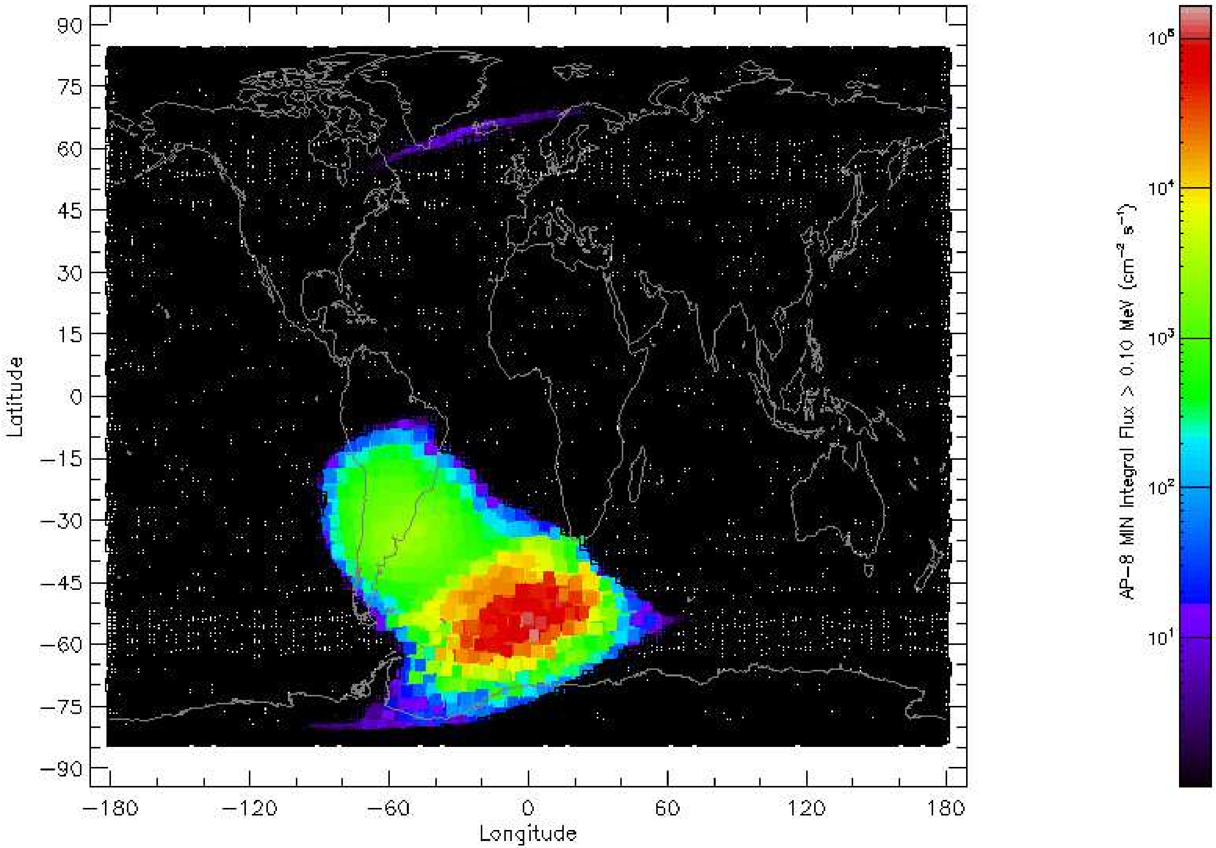
5 years LEO Polar mission

Orbit parameters:
507 km rcircular orbit radius
97 degree inclination

Protons:
Trapped radiation models



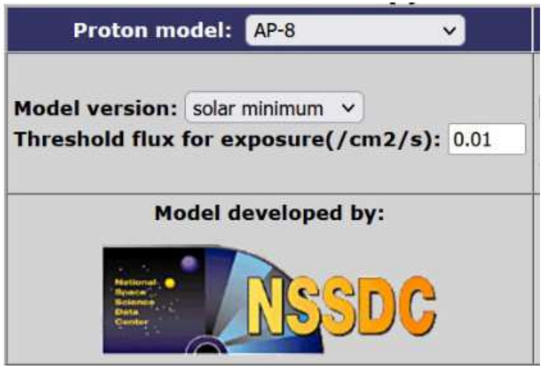
30 days proton flux

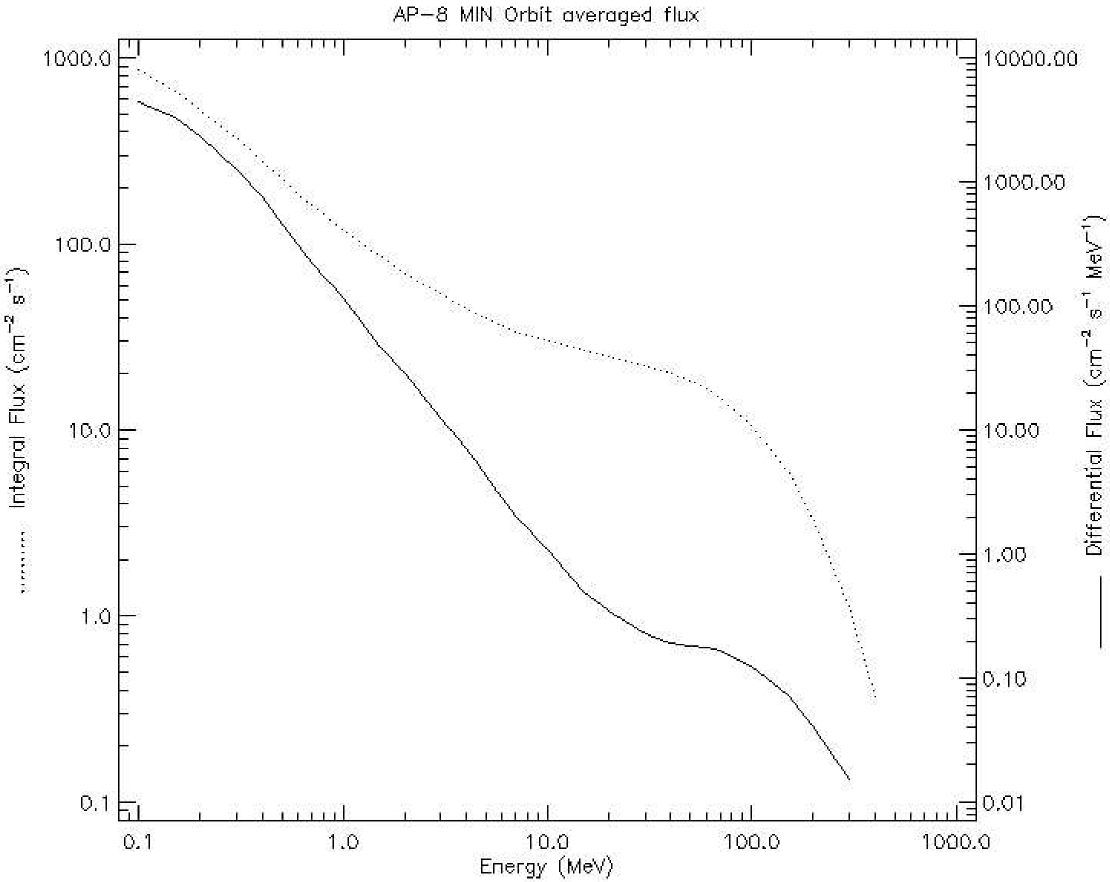


5 years LEO Polar mission

Orbit parameters:
507 km rcircular orbit radius
97 degree inclination

Protons:
Trapped radiation models

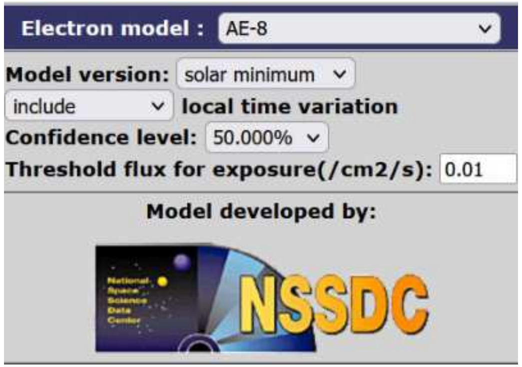




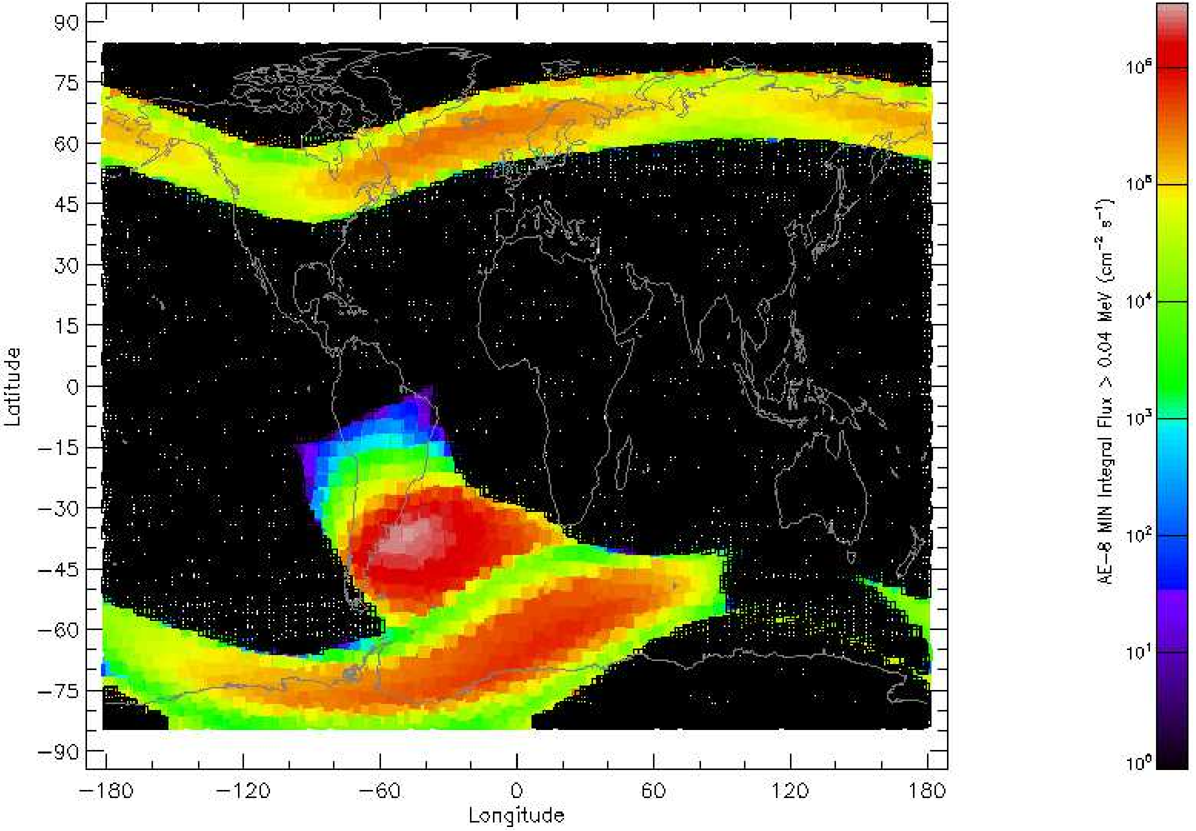
5 years LEO Polar mission

Orbit parameters:
507 km rcircular orbit radius
97 degree inclination

Electrons:
Trapped radiation models



30 days electron flux



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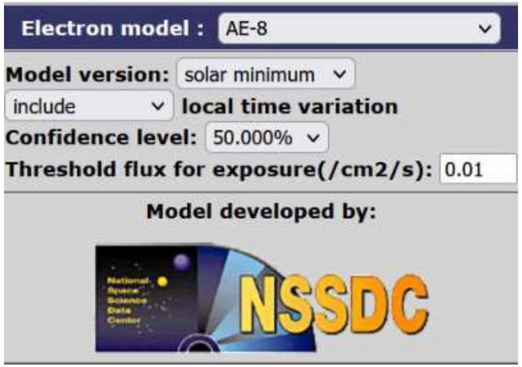
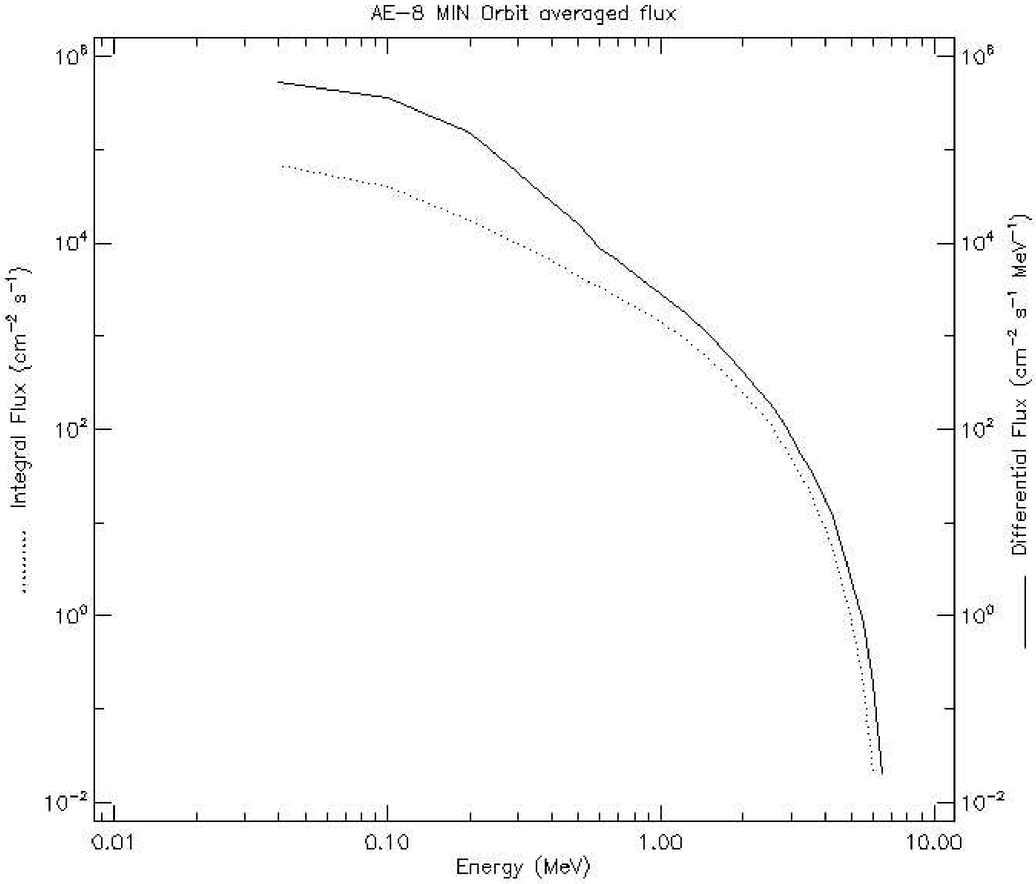
Trapped radiation models

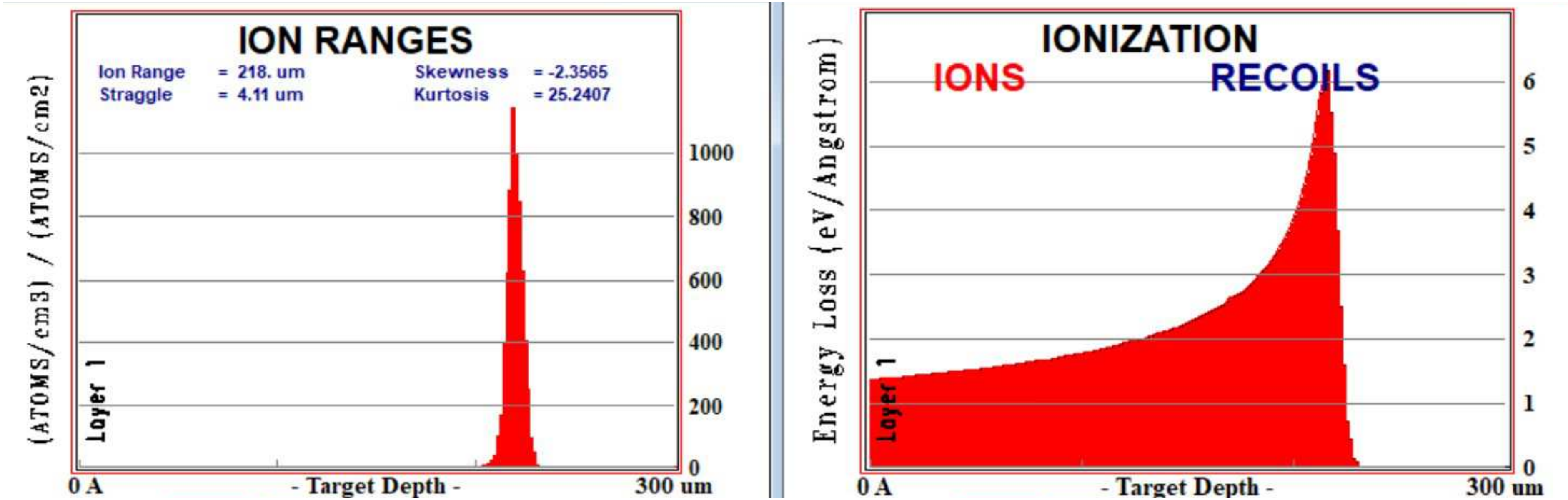




SRIM:

ions ranges and ionization evaluation for elements and compounds

5 MeV protons in silicon

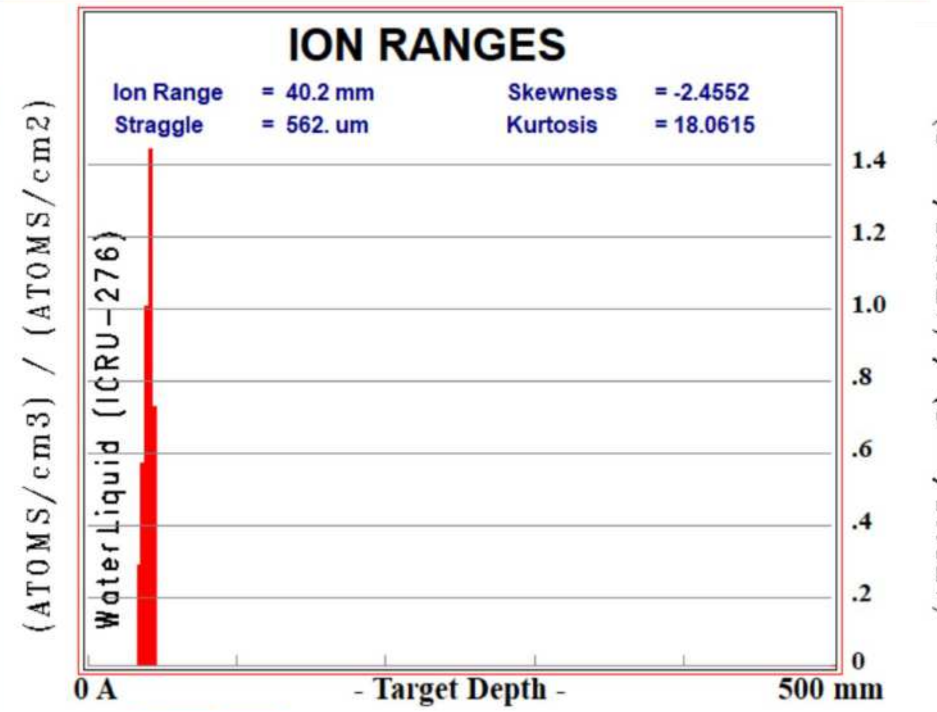


http://www.srim.org/SRIM/SRIMLEGL.htm

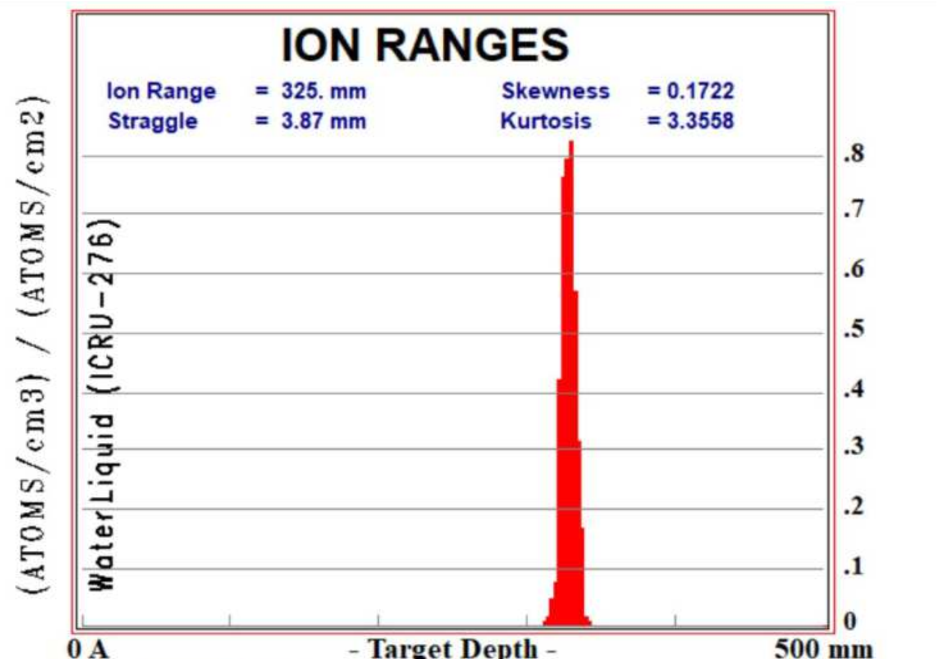
SRIM:

ions ranges evaluation for elements and compounds

70 MeV protons in water

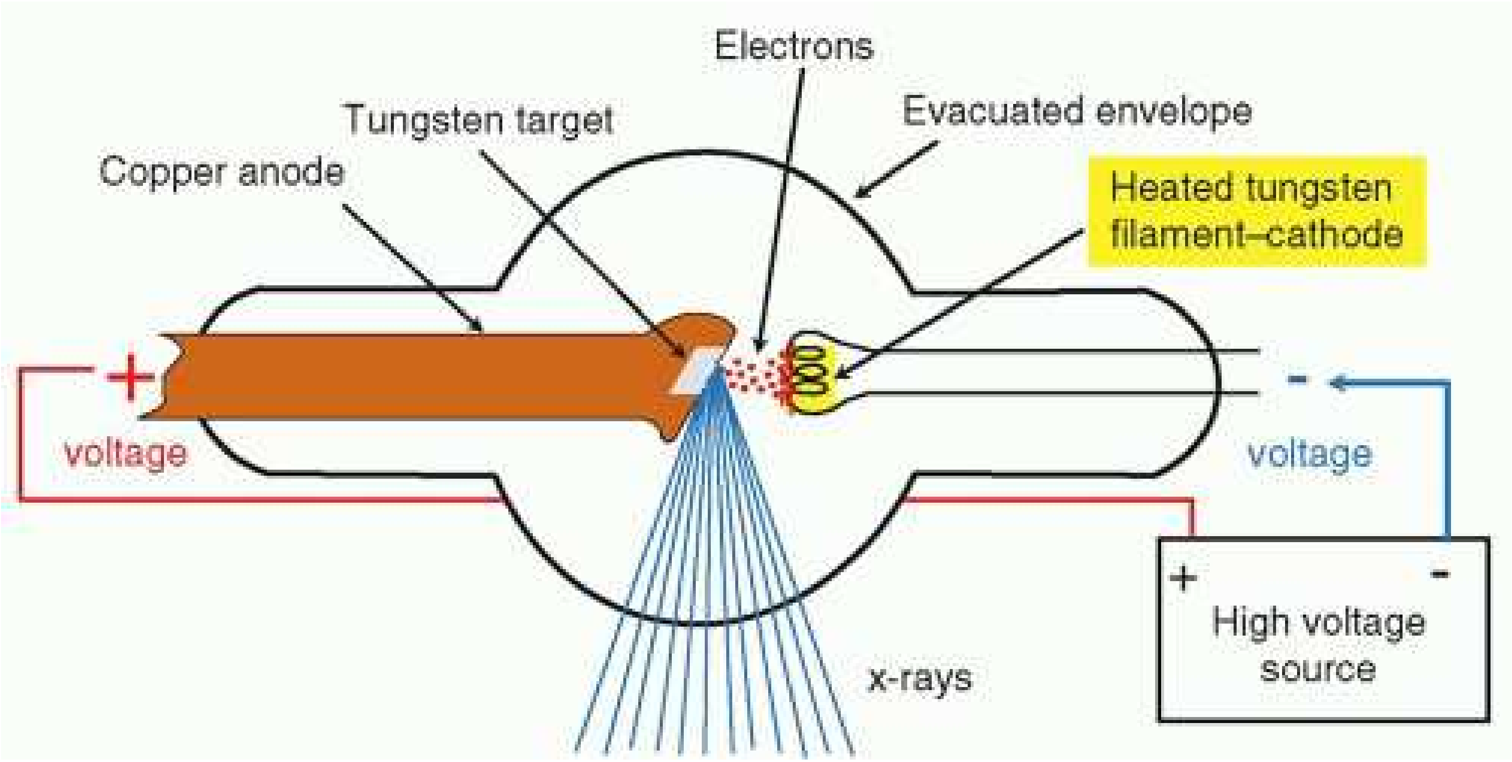


230 MeV protons in water



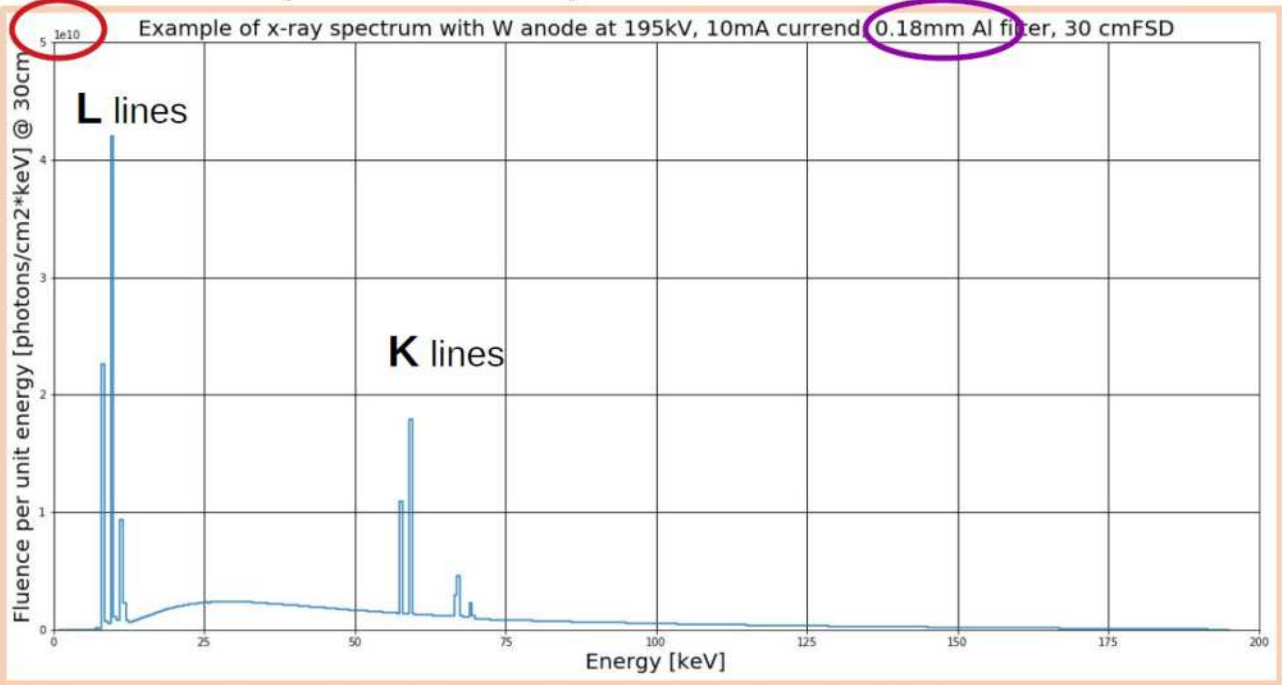
http://www.srim.org/SRIM/SRIMLEGL.htm

X-ray tube structure



SpekPy:

195 kV, 10mA, 0.18mm Al filter

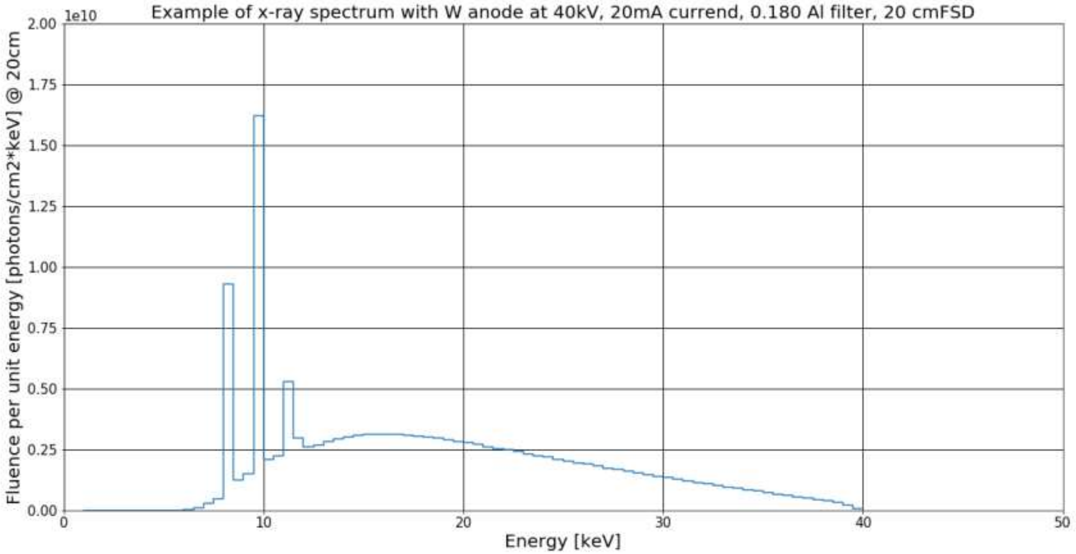


1st half-value-layer= 0.1120 mm   Mean Energy: 49.45 keV

https://aapm.onlinelibrary.wiley.com/doi/full/10.1002/mp.14945

Tungsten emission spectrum simulation (SpekPy*)

SiPM Radiation Field simulation with the the SpekPy* software toolkit:



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20 cm FSD target position.

(*) https://doi.org/10.1016/j.ejmp.2020.04.026

End part 2

Thanks for you attention!

comments, questions ... suggestions ?

benedetto.diruzza@unifg.it

Back-up slides

ICHEP 2020 Conference: Benedetto Di Ruzza

Proton and x-ray irradiation of silicon devices at the TIFPA-INFN facilities in Trento (Italy)
slides: https://indico.cern.ch/event/868940/contributions/3815732
proceeding: DOI: 10.22323/1.390.0685; https://pos.sissa.it/390/685

16th "Trento" Workshop on Advanced Silicon Radiation Detectors 2021: Benedetto Di Ruzza

Ionizing and Non-Ionizing Energy Loss irradiation studies with 70-230 MeV protons at the Trento Proton Therapy Center
slides: https://indico.cern.ch/event/983068/contributions/4223200

WEBLINKS

- Trento Institute for Fundamental Physics and Applications (**TIFPA**): https://www.tifpa.infn.it/about-tifpa
- TIFPA Activity Reports: https://www.tifpa.infn.it/contacts/downloads
- Bruno Kessler Foundation (**FBK**): https://www.fbk.eu/en

WEB References

TIFPA-INFN: www.tifpa.infn.it
APSS: https://protonterapia.provincia.tn.it/eng
Physics UniTN: https://www.physics.unitn.it/en
Biology UniTN: https://www.cibio.unitn.it
IBA: https://iba-worldwide.com

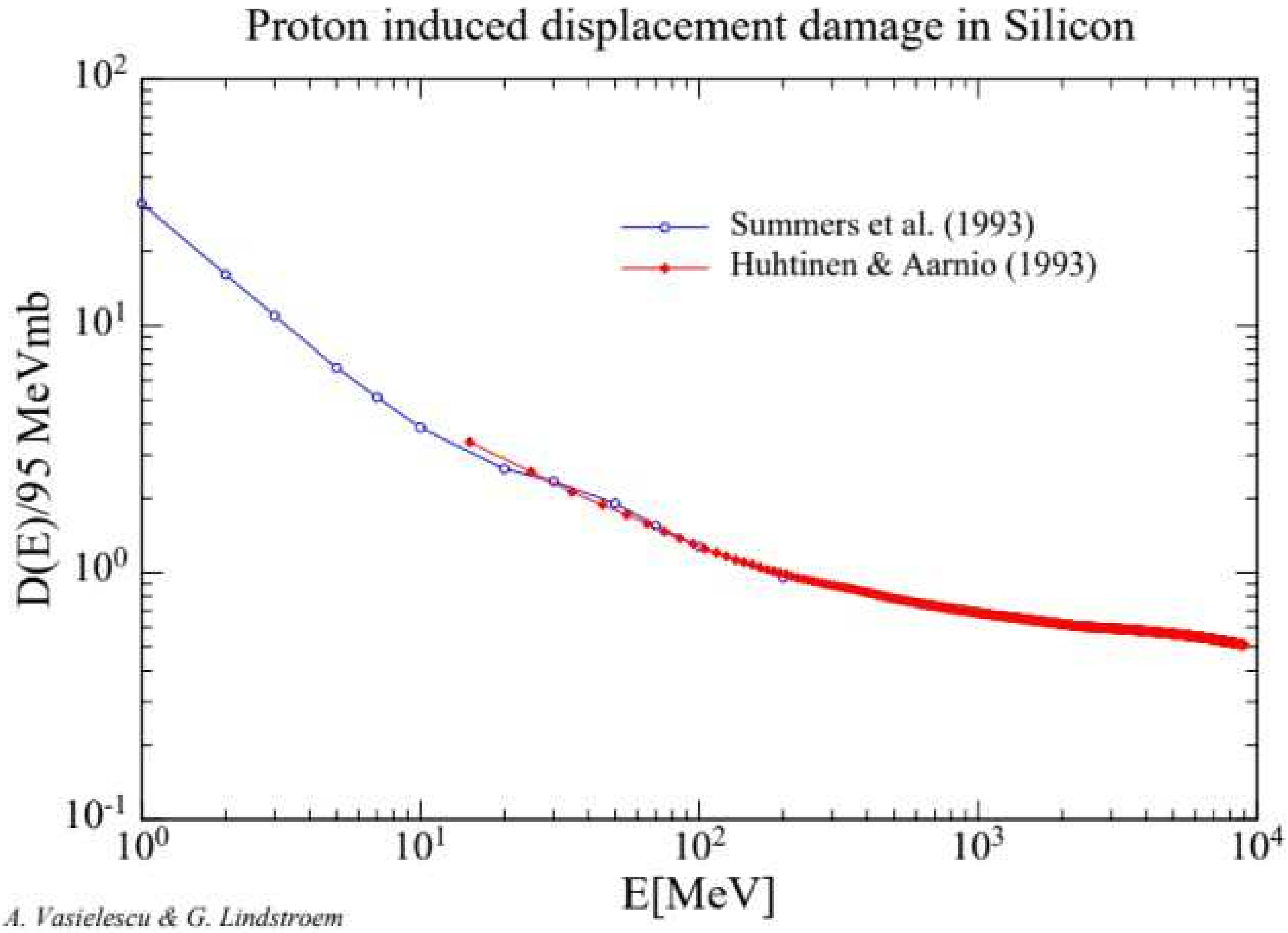
Trento Proton Therapy Center:
Experimental Area info and Beam Time applications:
http://www.tifpa.infn.it/sc-init/med-tech/p-beam-research

TIFPA Activity Reports:
https://www.tifpa.infn.it/contacts/downloads

Experimental area beam characterization:

REF1 – *Proton beam characterization in the experimental room of the Trento Proton Therapy facility*
F. Tommasino et al. NIM A 869 (2017) 15–20.
DOI: http://dx.doi.org/10.1016/j.nima.2017.06.017

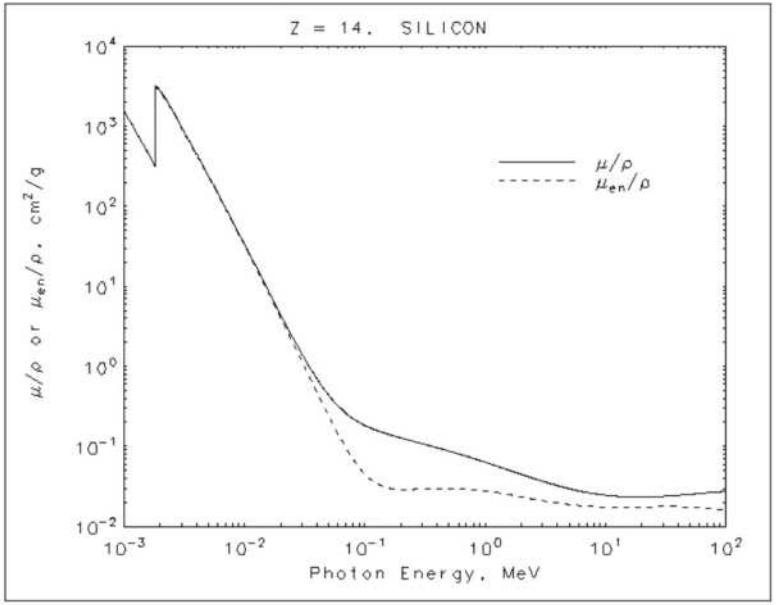
REF2 – *A new facility for proton radiobiology at the Trento proton therapy centre: Design and implementation*
F. Tommasino et al. Physica Medica 58 (2019) 99–106
DOI: https://doi.org/10.1016/j.ejmp.2019.02.001

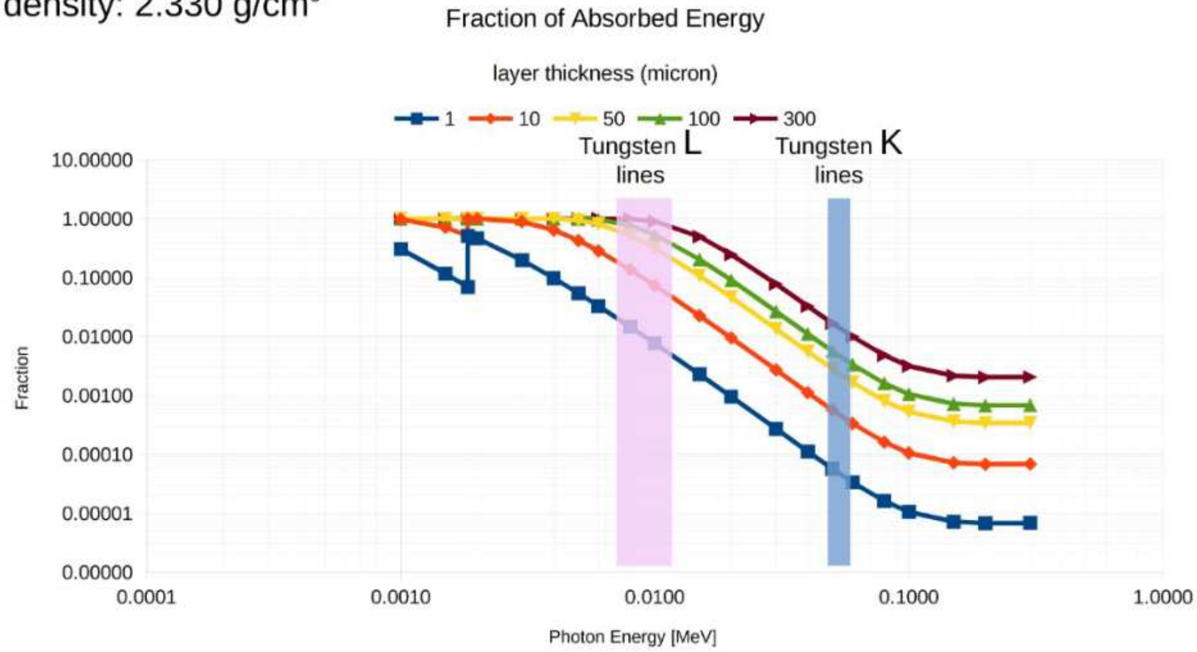


Proton induced displacement damage in Silicon
Summers et al. (1993)
Huhtinen & Aarnio (1993)
D(E)/95 MeVmb
E[MeV]
10^{2}
10^{1}
10^{0}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
A. Vasielescu & G. Lindstroem

The TIFPA-INFN x-ray irradiation Laboratory

silicon density: 2.330 g/cm^3

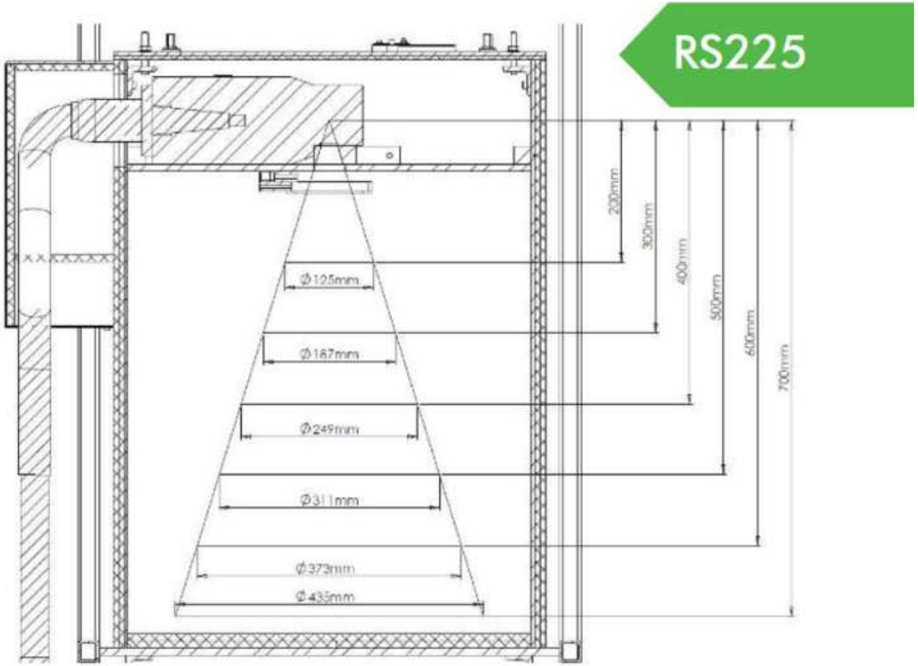




Cabinet Xstrahl RS225

X-Ray Tube Output Limits	
Voltage	Up to 220kV
Current	1.0mA to 30mA
Power	3000W (broad focus for designated stability)
X-Ray Cabinet Dimensions	
Height	2010mm
Width	1105mm
Depth	960mm
Weight	1100kg
Lead Shielded Irradiation Chamber Dimensions	
Height	650mm
Width	570mm
Depth	600mm

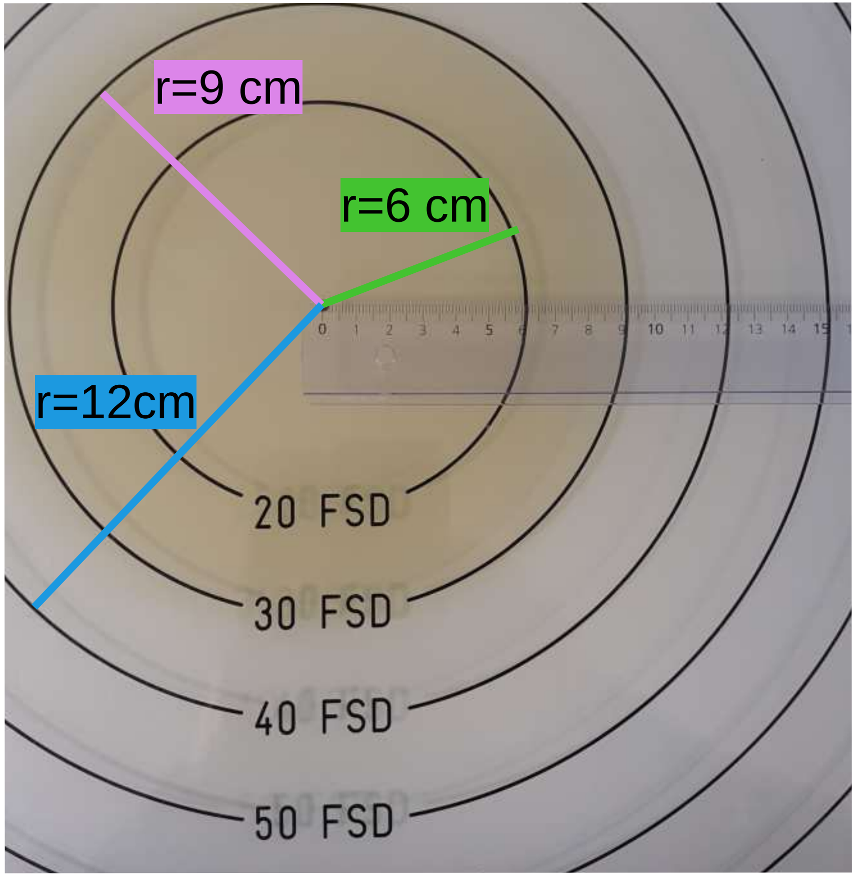
Shielding of cabinet to ≤ 2μSv/hour at 5 cm from any accessible surfaces as per IRR'99 guidelines.

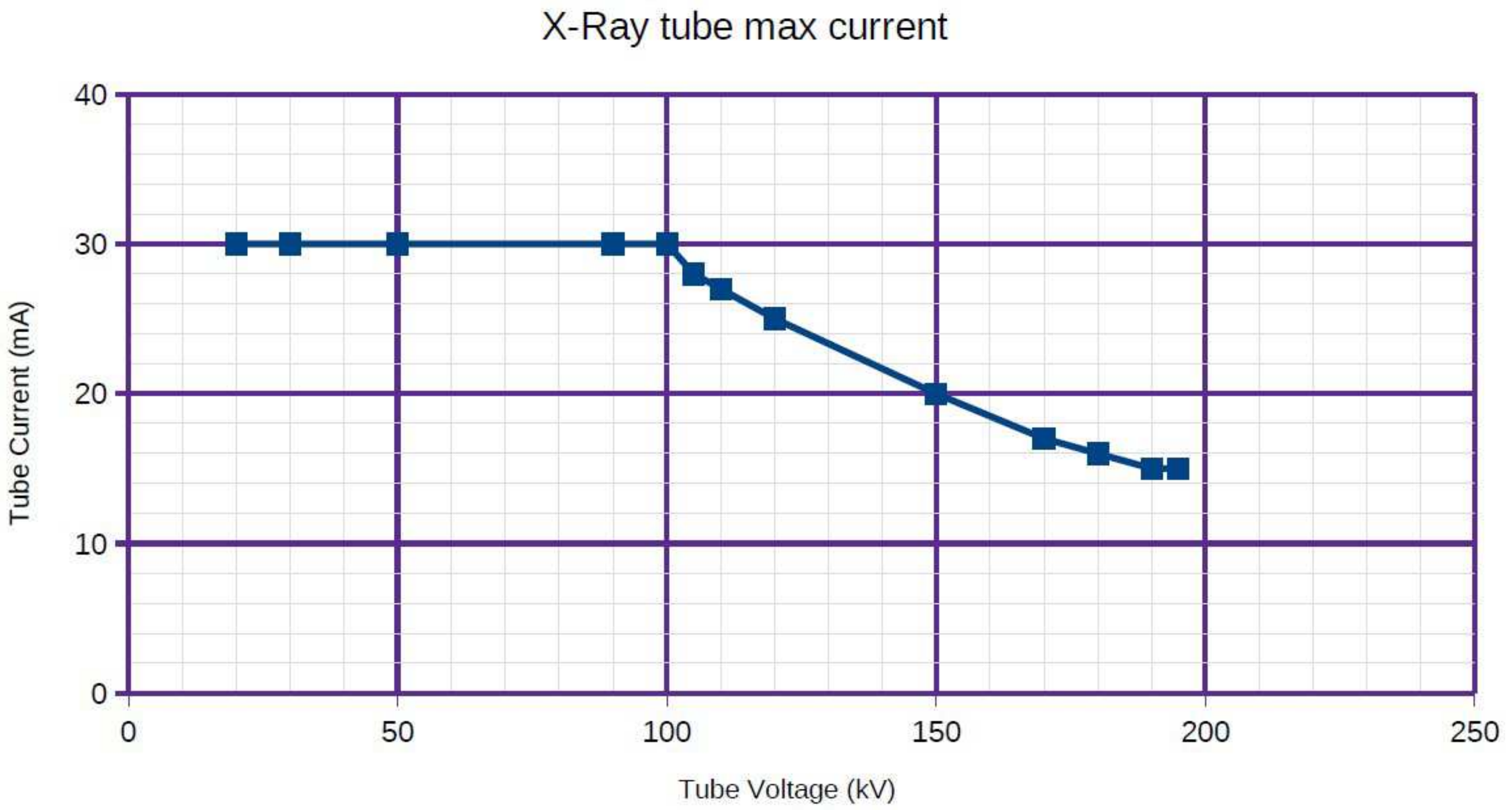


Focal Spot Distance and Irradiation Field Size (Dimensions in mm) RS225 (above) and RS320 (below).

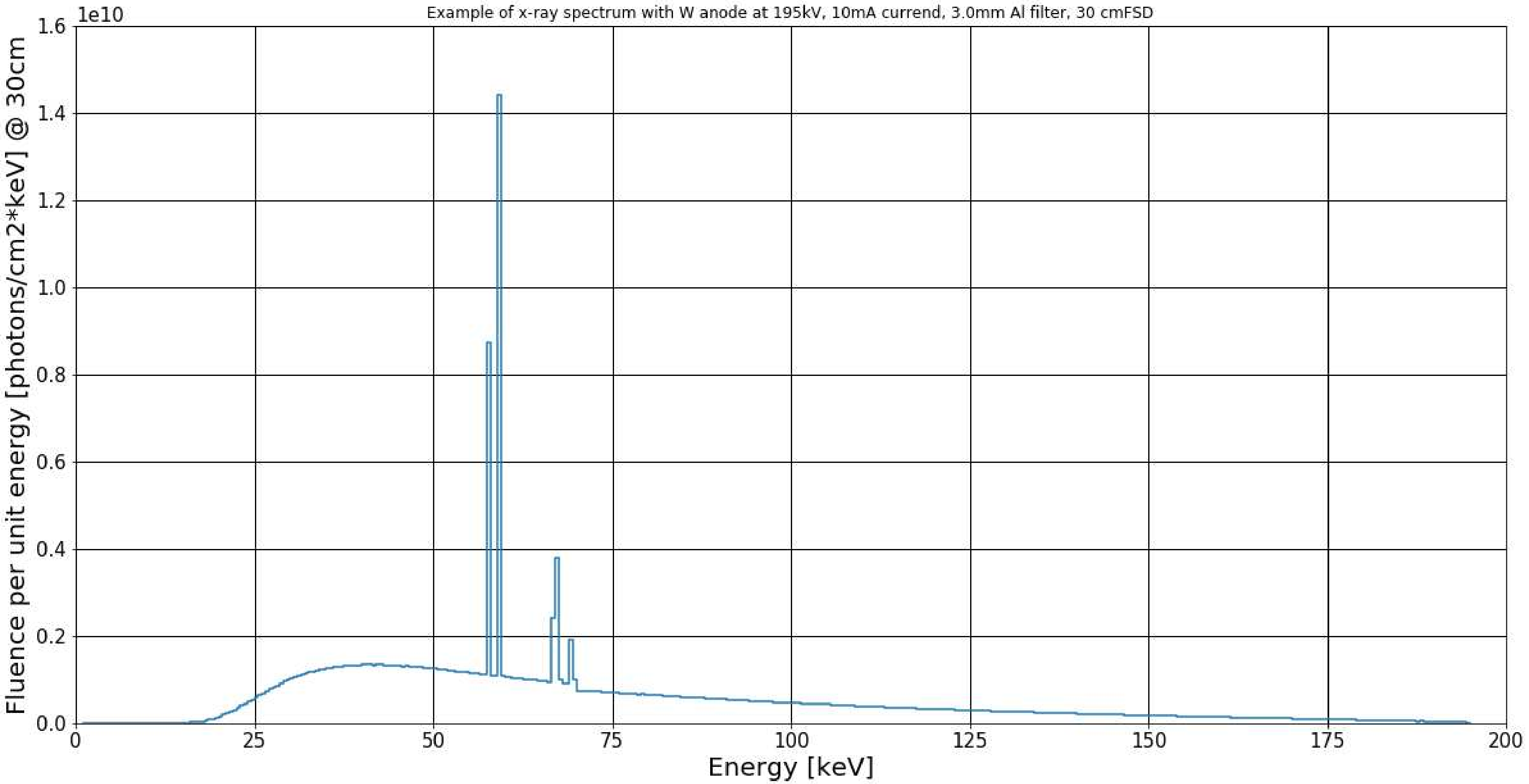
- In this set-up configuration the x-ray uniform spot is a circumference of 4.5 cm radius and can be used for sensors or electronic circuits TID
- characterization studies requiring total dose of the order of 1-50 Mrad.

R-X support plane



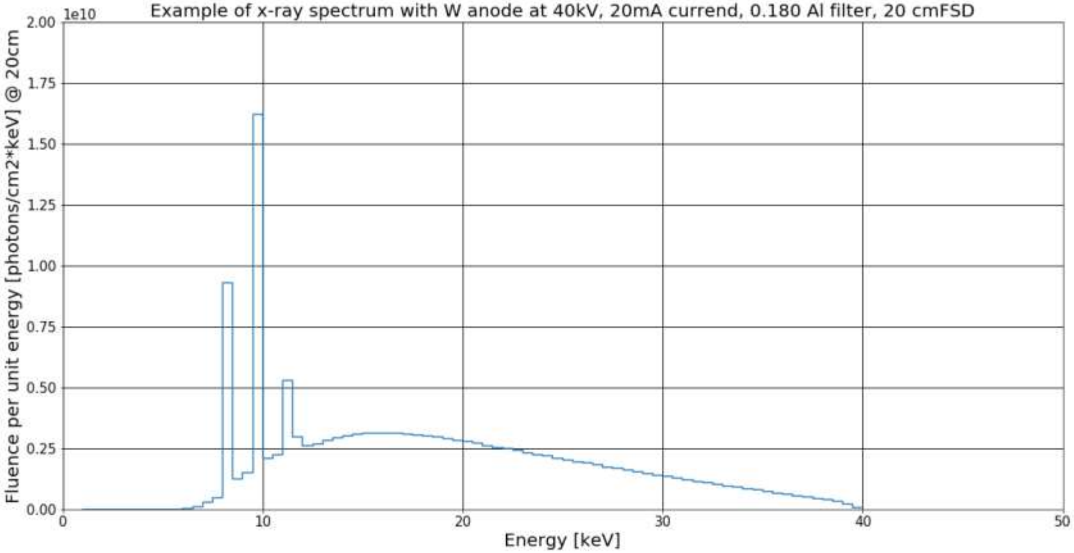

X-Ray tube max current
40
30
20
10
0
Tube Current (mA)
0
50
100
150
200
250
Tube Voltage (kV)

Tungsten emission spectrum



The TIFPA-INFN x-ray irradiation Laboratory

SiPM Radiation Field simulation with the the SpekPy* software toolkit:



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40kV anode tension, 20mA current, 0.180 mm Al filter,
20 cm FSD target position.

(*) https://doi.org/10.1016/j.ejmp.2020.04.026

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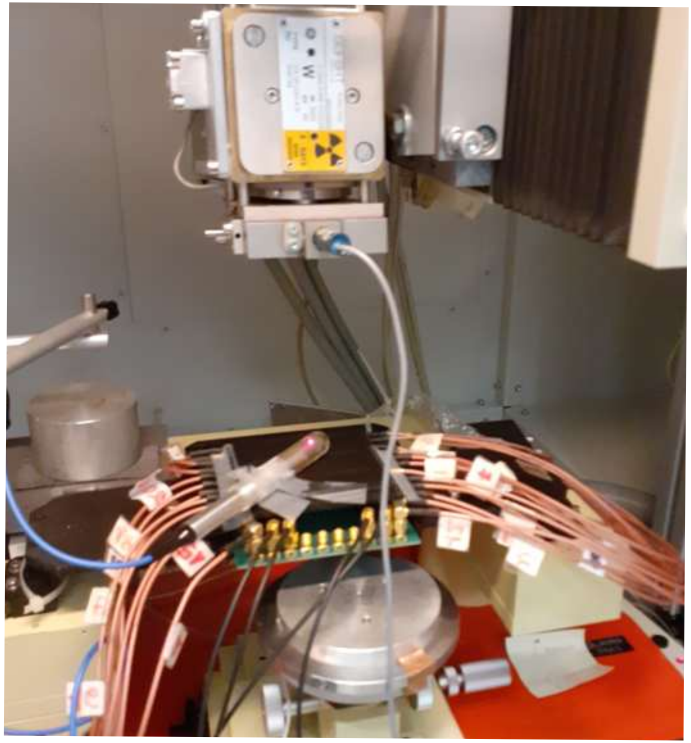
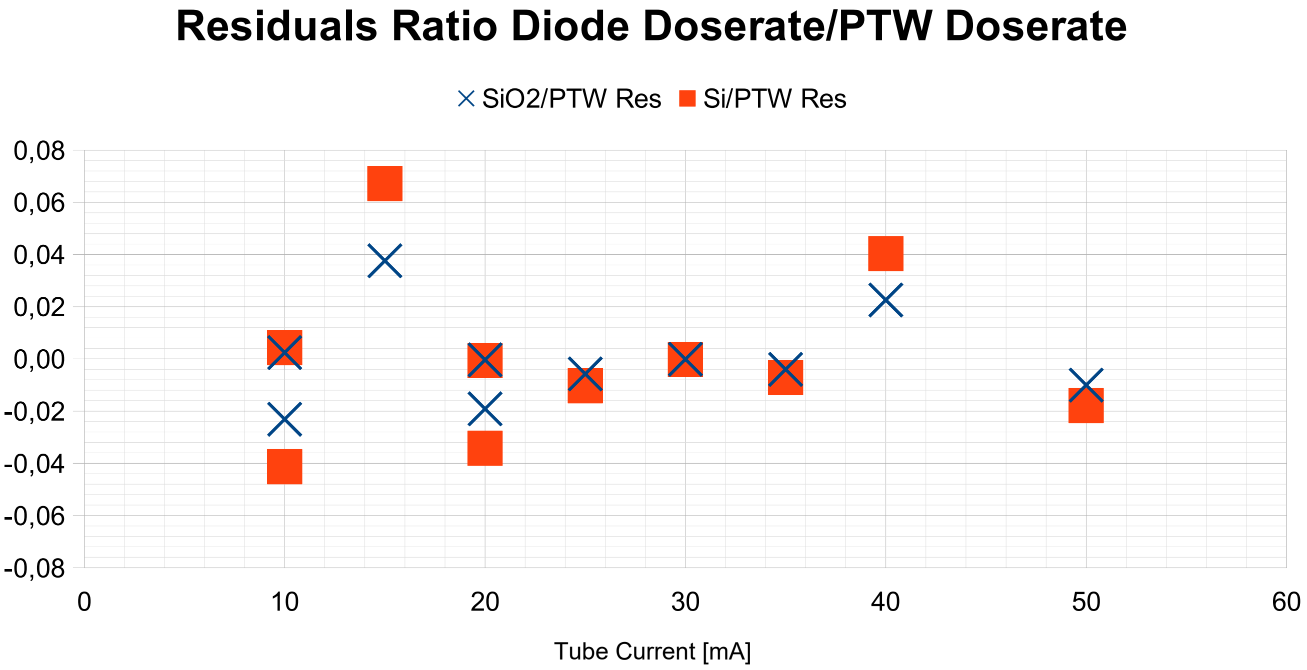
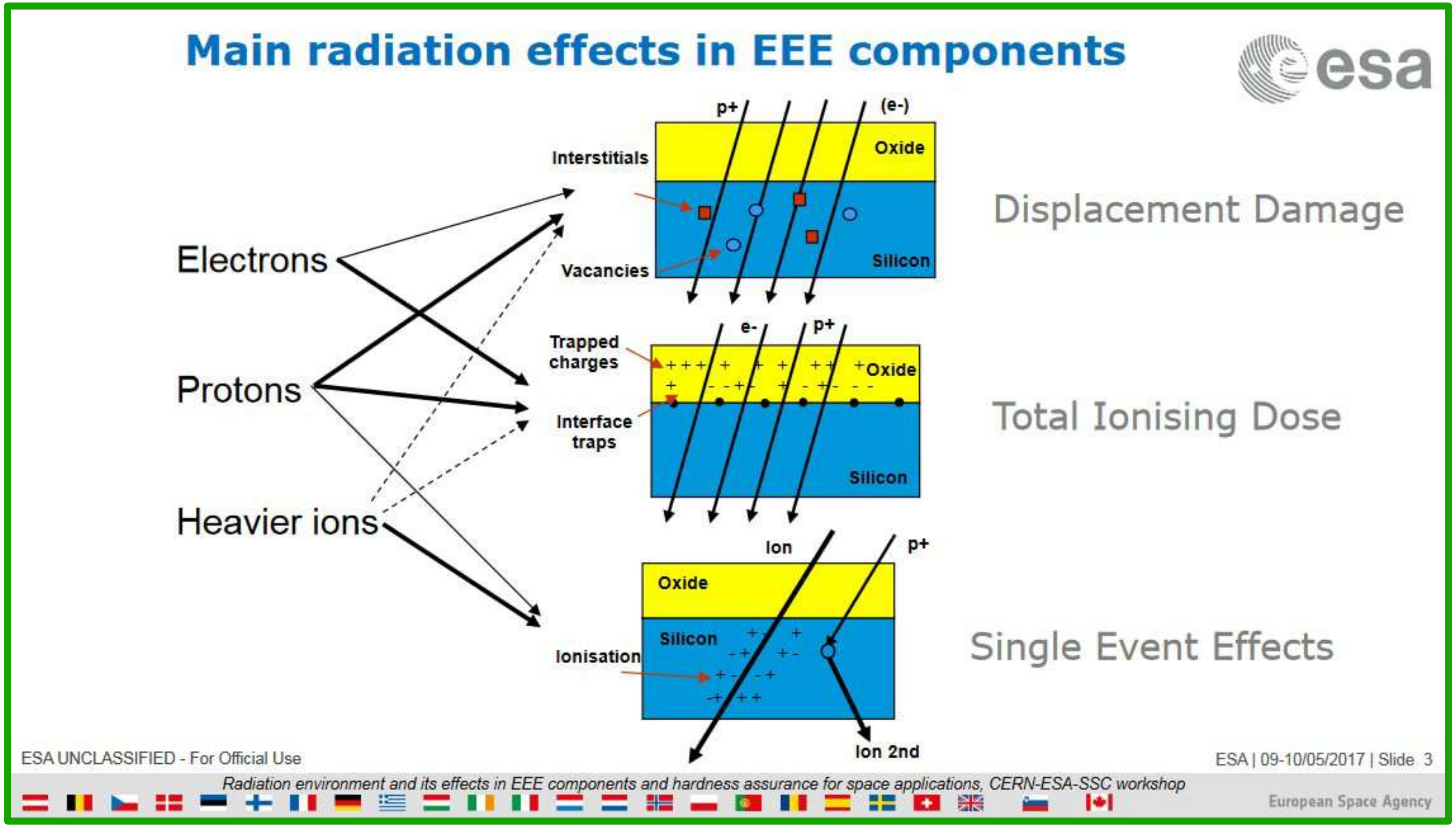


Diode - Farmer Chamber doserate comparison at the Padova x-ray irradiation laboratory

Ratio Diode Doserate/PTW Doserate	
SiO2=**7.72+-0.04**	Si=**13.79+-0.07**



Slide from Marc Poizat:
https://indico.cern.ch/event/635099/contributions/2570674/attachments/1456398/2248961/Radiation_Effects_and_RHA_ESA_Course_9-10_May_2017_TID_MP_FINAL.pdf



INTRODUCTION

Lecture 1 26/9, 2 - 5 pm :	Introduction to silicon sensors – Use of silicon sensors as imaging and tracking devices in HEP, space mission and medical applications
Lecture 2 27/9, 2 - 5 pm :	Silicon Sensors radiation hardness characterization
Lecture 3 28/9, 2 - 4 pm :	Medical application of photons and charged particles for cancer treatment – Facilities for radiation therapy – Dose measurement devices

Image Credit: NASA/SOHO