Trento Institute for Fundamental Physics and Applications

Istituto Nazionale di Fisica Nucleare

Ionizing and Non-Ionizing Energy Loss irradiation studies with 70-230 MeV protons at the Trento Proton Therapy Center

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Talk Outline:

Trento Proton Therapy Center description and status update

- The Trento Proton Therapy Center
- The Accelerator
- The experimental area description
- Proton irradiations modalities
  - Direct protons irradiations
  - Large area irradiations: the dual ring set-up
  - SEUs studies on large area devices

Possible scientific cases:
What type of space mission radiation damage can be tested in the Trento Proton Therapy Center Experimental area?

- Particle fluence evaluations for space mission with the SPENVIS software
  - Software description
  - International Space Station Orbit
  - HERMES pathfinder orbit (LEO equatorial orbit)
  - HERMES-like polar orbit (LEO polar orbit)
  - Other orbits and summary table
- Conclusions and acknowledges

The Trento Proton Therapy Center

The Trento Proton Therapy Center (TPTC) is a medical facility for hadron therapy specialized in the treatment of pediatric patients, located in Trento, Italy.

The facility is operated by the the *“Azienda Provinciale per i Servizi Sanitari”* (APSS), clinical activity started in 2014. The medical area is equipped with two gantry rooms for patient treatment. The experimental area (experimental cave and multidisciplinary laboratory) is completely reserved for non medical activities (sensors test, physics and biophysics experiments). In 2019-2020 a upgrade of the instrumentation and functionalities of this area took place.

The Trento Proton Therapy Center

Experimental cave

Beam distribution line

Experimental beamlines

Isochronous Cyclotron

Remote control area
and
multidisciplinary laboratory

Gantry rooms
for patients treatment

The Accelerator

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

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

Beam current (nominal, at cyclotron exit) can be tuned from ~200 p/s up to 320 nA (***). Target delivered current can be monitored and recorded with ion chambers located in the the cave.

Protons energy at the accelerator exit is 230 MeV, before the entrance in the distribution line can be lowered down until 70 MeV using a passive degrader on user request.

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

(*) Energy at the cave beamline exit window

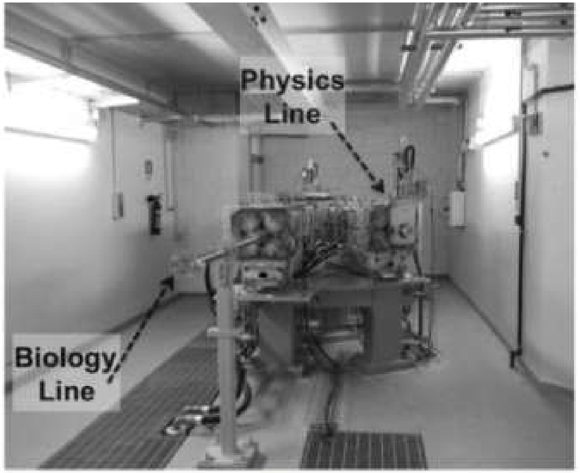
(**) Nominal flux evaluated for 1 nA nominal current

(See **REF1** for details)

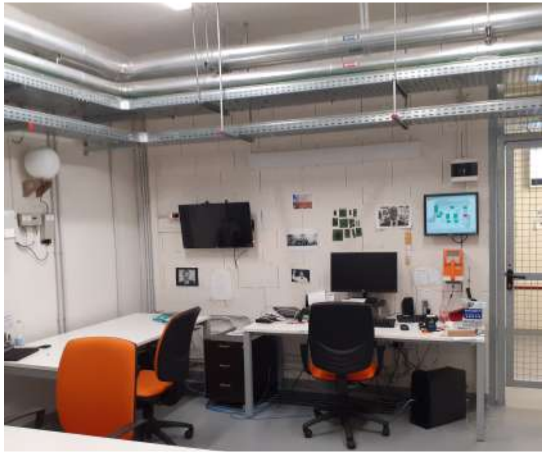
(***) Due to beam transportation losses only -20% of this nominal current is available in the experimental area

The Experimental Area

For ~3 hours every working day after the patient treatments and on Saturday morning, the beam is used for non medical experiments in the experimental area. Beam time is assigned by a PAC Committee after a experiment proposals evaluation (https://www.tifpa.infn.it/sc-init/med-tech/p-beam-research).

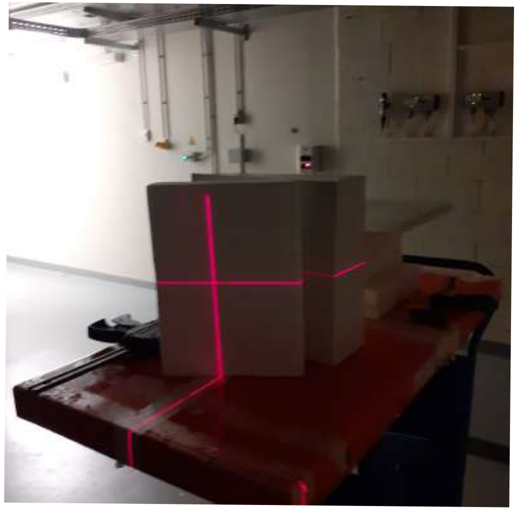


The experimental area is composed by a experimental cave (left) where irradiations are performed and the contiguous room (down) used for instruments remote control and as multidisciplinary laboratory for electronic set-up or cells preparation.



The rooms are equipped with two cable connected patch-panels (BNC, SHV, ethernet) for remote control of the instrumentation.

The Experimental Area

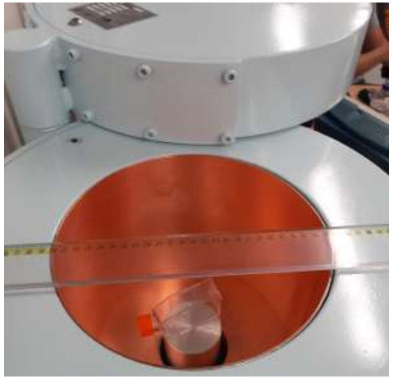


In the experimental cave two almost identical beamlines are present for “in air” irradiation of biological targets (cells), biophysics measurement or particle physics test-beam:

- the “0 degree” or biological line
- the “30 degree” or physics line

Both of them are equipped with a laser system for beam alignment. All the cave can be monitored with a remote movable camera system.

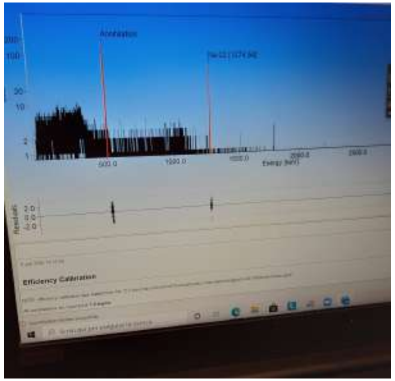
Since September 2020 the cave beam control system was updated with the new BSS Gateway System reducing significantly the control communication dead-time. A beam on target intensity increase of a factor ~2 is achieved with this upgrade.



Since June 2020 the area is equipped with

- high purified, cooled, germanium gamma spectrometer
- fast analysis software

for post-irradiation analysis of the targets.



The Experimental Area

Beam restrictions

Due to administrative limitations every day only a total nominal charge(*) of **0.5 mC** can be delivered in the experimental cave. Working for example with a 200 nA nominal beam current this limit is achieved in 2500 seconds (~41 minutes) irradiation time.

The accelerator can work in two modalities:

- dark current mode: from ~200 p/s up to ~300 kp/s
- high current mode: from fraction of nA up to 320 nA nominal current

Due to interlock restrictions, when working in high current mode, every 5 minutes of irradiation the accelerator have to stop for 5-2 minutes (depending on the irradiation current).

With these characteristics the experimental area is also a perfect place where perform

Ionizing and Non-Ionizing Energy Loss studies

with a proton beam on silicon sensor devices.

(*) a nominal charge is defined as the charge evaluated using the nominal beam current

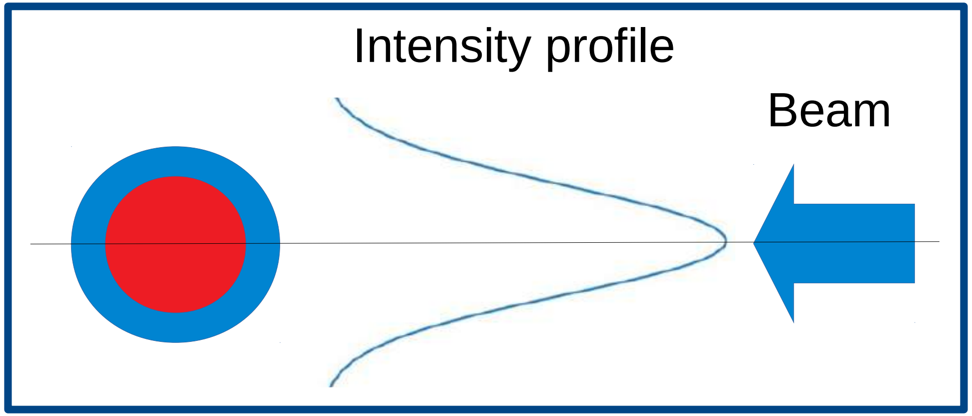
Direct proton beam irradiations

In a direct proton beam irradiation **the maximum amount of beam is delivered on the target** but the beam intensity distribution is not uniform but **gaussian**.
The gaussian sigma can be tuned from 6.92mm down to 2.73mm only changing the beam energy from 70MeV to 228MeV, but in this way also the peak intensity changes.

Considering a beam composed by 100MeV Proton beam,(*):
1nA ==> **2.4 x 10^7 p/s** on target flux(**), **5.68 mm** Gaussian sigma intensity profile.
With the 0.5mC administrative limitation, **4.32 10^12** protons can be delivered on the target in one irradiation day.

Fraction of beam in a radius r circumference:
F= 1-e^[-0.5*(r/sigma)^2](***)

r_{red} 2.5 mm ==> F =0.095
r_{blu} 3.0 mm ==> F =0.133

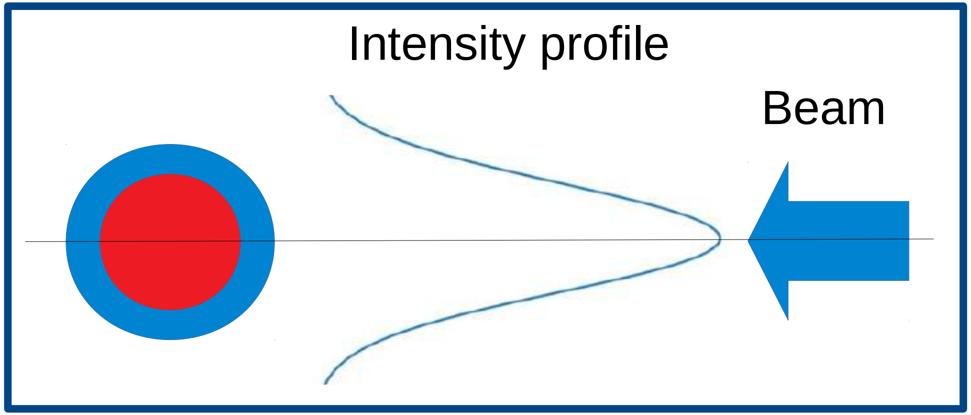


(*) Displacement damage in Silicon for 100 MeV protons: D/(95MeVmb)=**1,276E+00 (A. Vasilescu & G. Lindstroem, rd50 web page)**

(**) With the new BSS Gateway the flux on target is the double of the value in REF1, table 1

(***)See **REF1** for sigma details

Direct proton beam irradiations



With a 100 MeV proton beam,
Considering a radius r circumference, after the BSS Gateway upgrade, the following average fluences can be achieved
in one irradiation day (*):

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 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.

(*) considering the administrative 0.5 mC limit

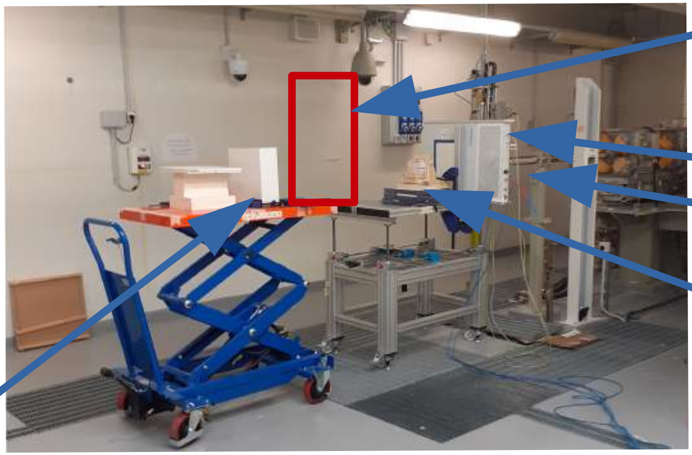
Large area irradiations: Dual Ring set-up

In order to have a “almost flat” intensity beam profile instead of the gaussian one, a specific set-up can be assembled on the biological line: the dual ring.
Using a passive scattering system this set-up allows to have a flat irradiation fields of 6 and 16 cm diameter starting from a fix pencil beam at 148 MeV. (See **REF2** for details)

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.
- The energy on target is ~140MeV.
- Can be lowered at 70MeV adding solid water degrader.



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

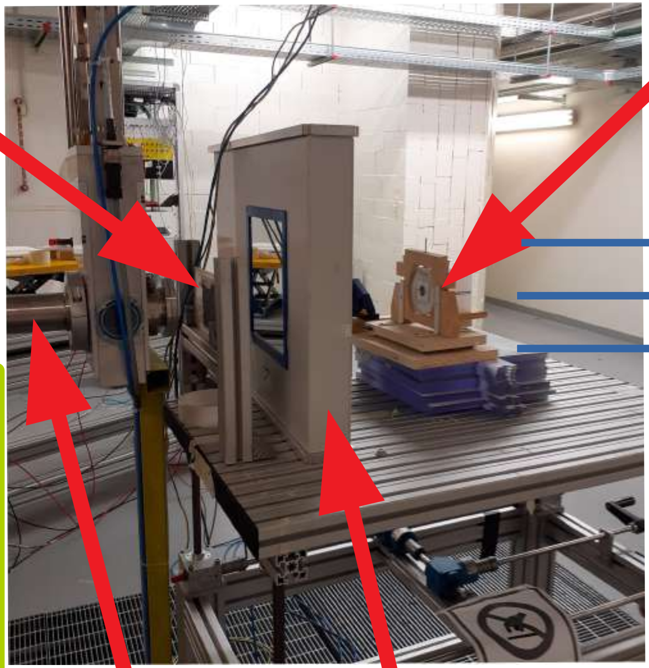
Large area irradiations: Dual Ring set-up

(See **REF2** for details)

First foil

Dual ring

incoming proton beam
(gaussian profile)

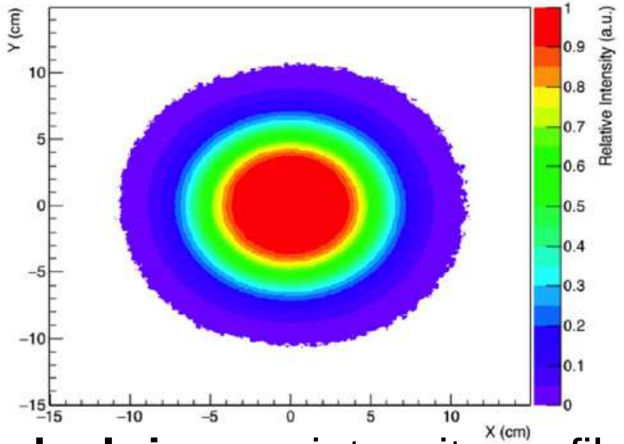


scattered proton beam
(flat profile)

Target
area

beampipe

Monitor drift chamber



Small dual ring x-y intensity profile

After the BSS gateway upgrade can be achieved in **one irradiation day(*)** using the **small dual ring set-up,** a fluence of:

- **~5.5 * 10^11 p/cm^2**
  for 140 MeV on target protons energy
- **~5.0 * 10^11 p/cm^2**
  for 70 MeV on target protons energy

(*) considering the administrative 0.5 mC limit

SEUs studies on large area devices

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

The HERMES collaboration 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.

(photo courtesy of the HERMES collaboration)

Possible Scientific Cases Achievable

In the TPTC Experimental Area can be performed, between the others, the following irradiations:

- **100 MeV proton beam: ~2*10^12 p/cm^2**
  on small area objects
  using a **direct beam irradiation**
  with not uniform but **gaussian beam intensity profile** with **5.68 mm sigma.**

- **140 MeV proton beam: ~5.5 * 10^11 p/cm^2**
  on large area objects
  using the **small dual ring set-up**
  with **uniform** beam intensity profile on a **30 mm radius circumference.**

- **70 MeV proton beam: ~5.0 * 10^11 p/cm^2**
  on large area objects
  using the **small dual ring set-up** and a **degrader**
  with **uniform** beam intensity profile on a **30 mm radius circumference.**

Using the **SPENVIS software,** can be evaluated in what type of space missions these proton fluences are achieved.

SPENVIS software

The SPENVIS software is used for online calculation of particle fluences on satellites with different orbit parameters:

https://www.spenvis.oma.be

From these fluences, silicon displacement damage can be easily calculated.

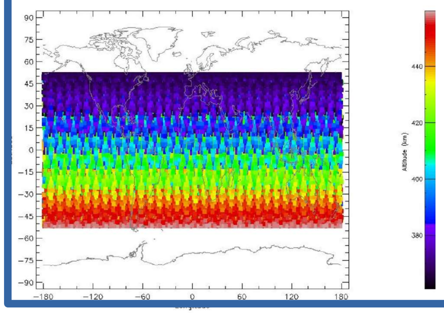
In the following slides proton fluences are calculated considering a 5 years space mission and:

1) considering only omnidirectional magnetosphere trapped protons with energy E>0.1 MeV, using the AP-8 solar minimum model.
2) Ignoring sun particle fluences.
3) Ignoring galactic particle fluence.

For the ISS orbit also electron fluences are calculated considering a 5 years space mission with only omnidirectional magnetosphere trapped electron with energy E>0.04 MeV and using the AE-8 solar maximum model .

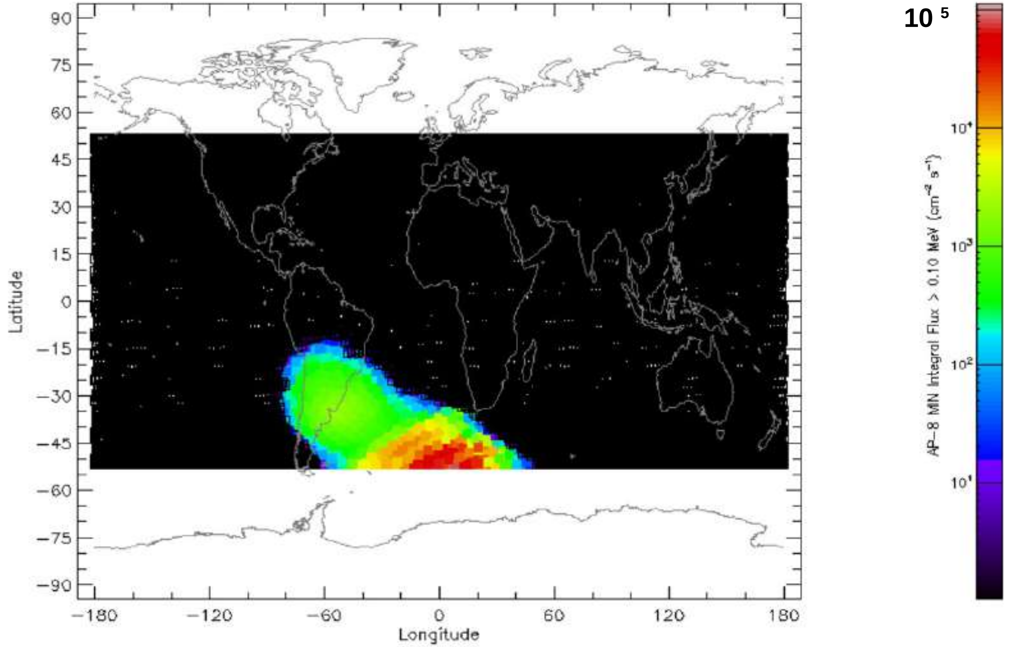
International Space Station (ISS)

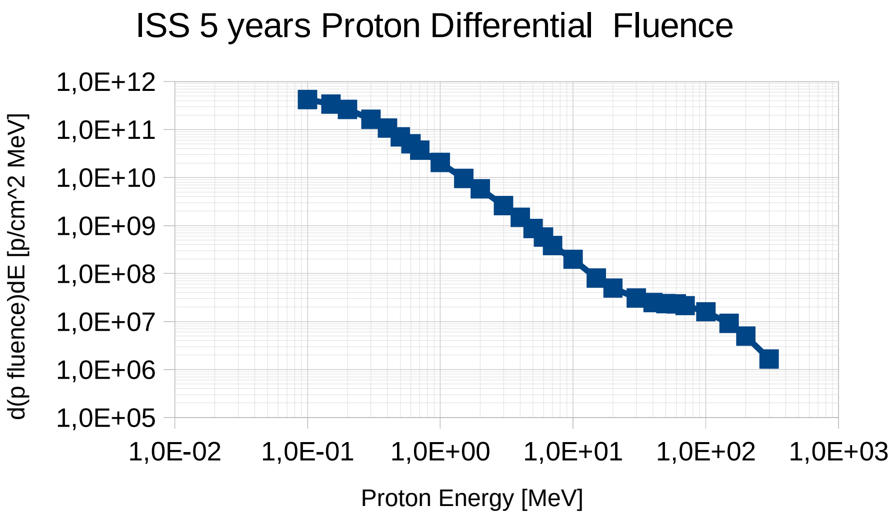
Orbit Parameters:
370-460 km altitude, 51.6 deg. inclination



ISS 30 days
Orbit map

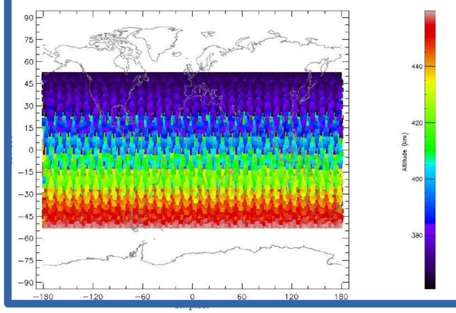
ISS 30 days protons flux map





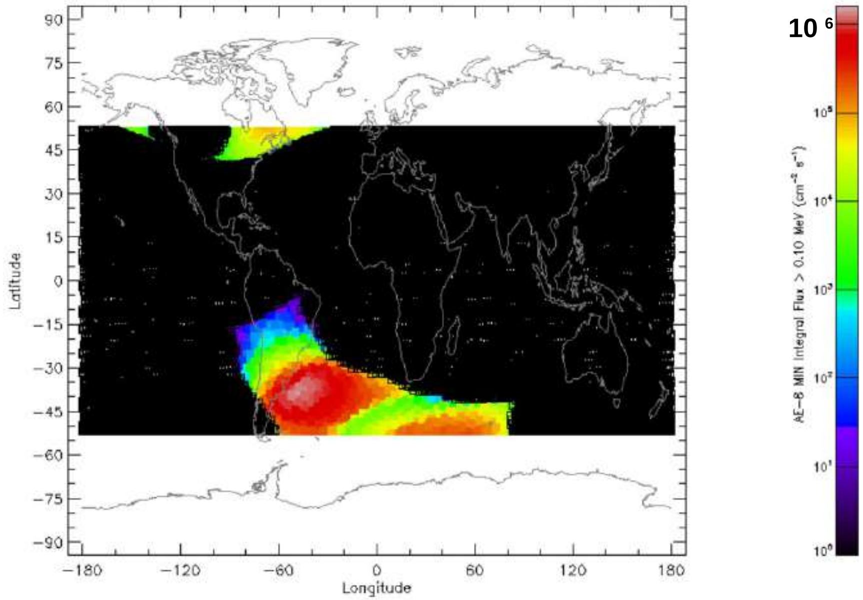
International Space Station

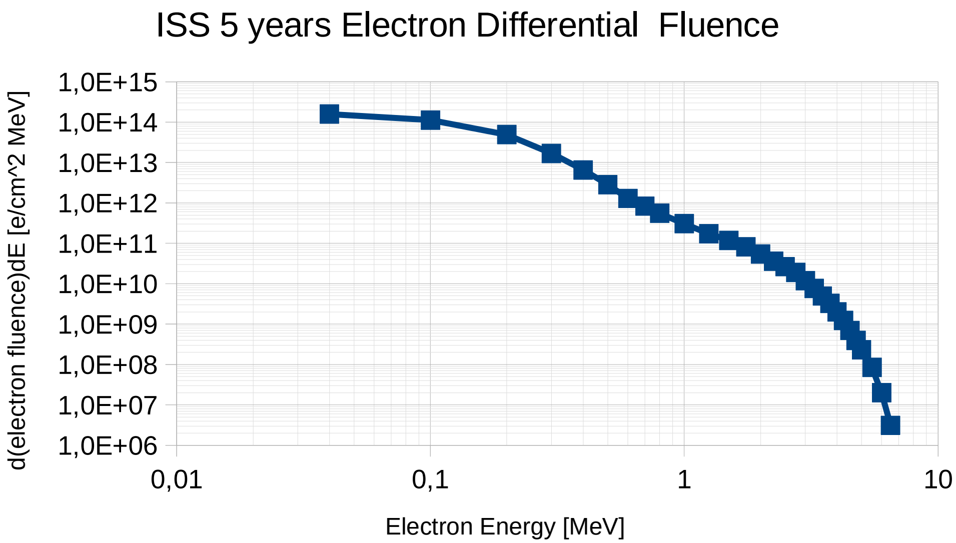
Orbit Parameters:
370-460 km altitude, 51.6 deg. inclination

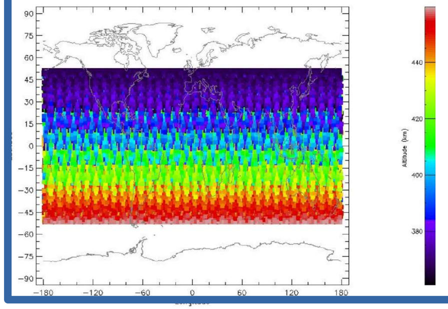


ISS 30 days
Orbit map

ISS 30 days electrons flux map







ISS 30 days
Orbit map

International Space Station

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

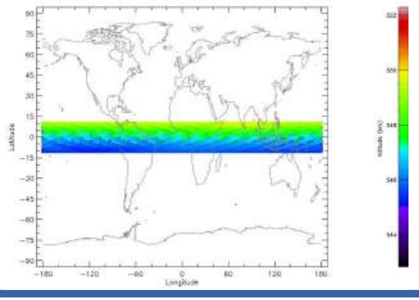
Displacement damage in Silicon, induced by protons and electrons for this orbit can be evaluated for a 5 years mission using the **Vasilescu & G. Lindstroem** radiation damage evaluation tables (RD50 collaboration):

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)

Since the contribution of the electrons to the displacement damage in silicon, for these type of orbits is two magnitude order lower, it will be ignored in the following calculations.

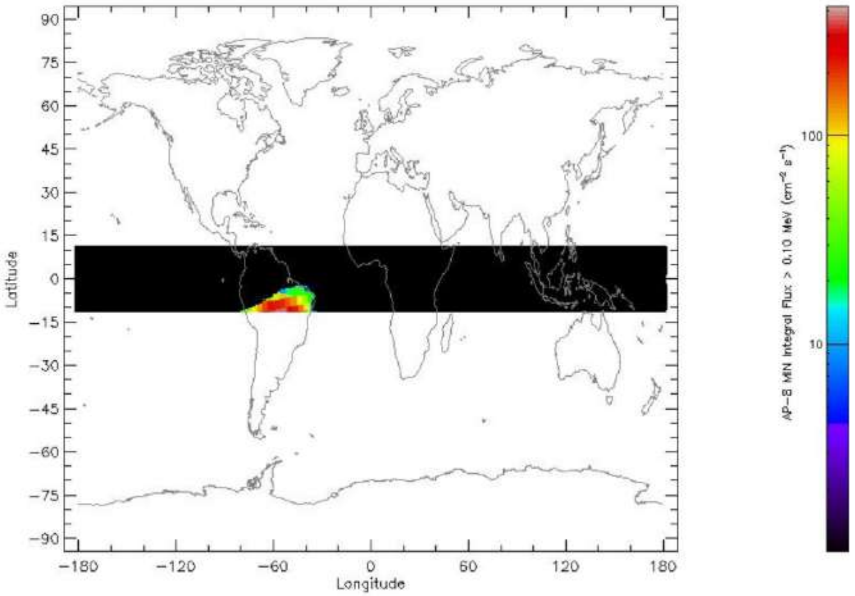
HERMES Scientific Pathfinder
(https://www.hermes-sp.eu)

Orbit Parameters:
550 km altitude, 10 deg. inclination

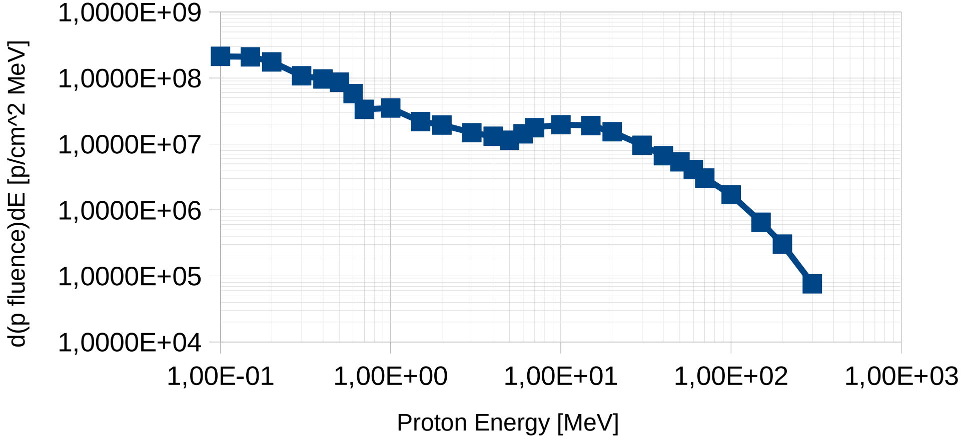


HERMES (equatorial)
30 days
Orbit map

Hermes 30 days protons flux map

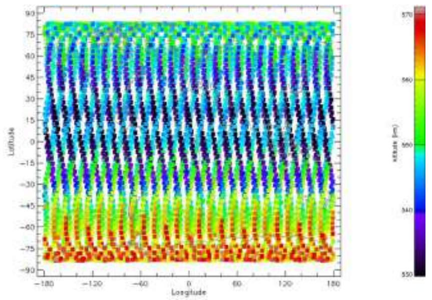


5 years HERMES Orbit Proton Differential Fluence

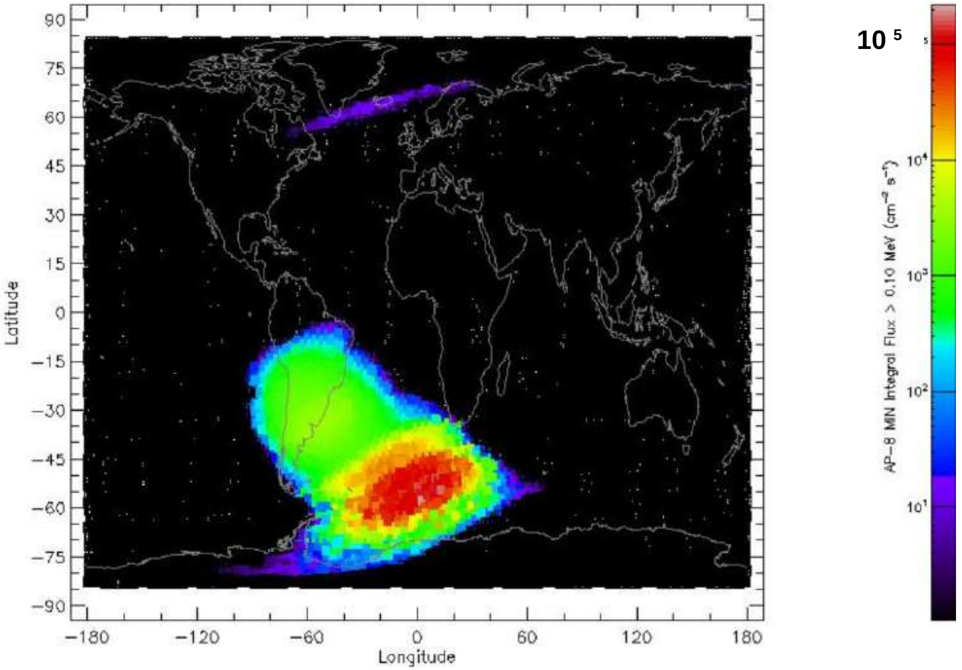


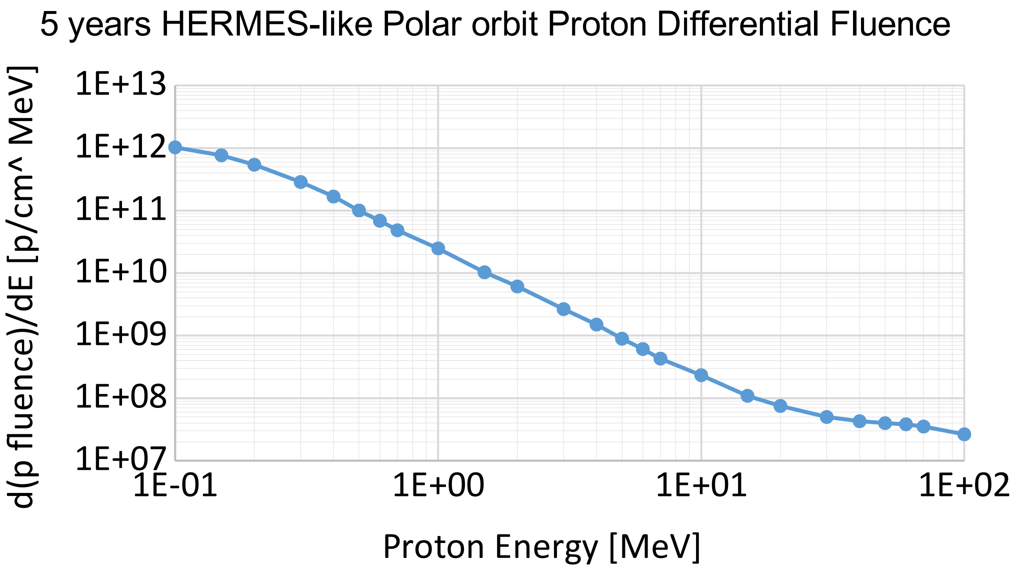
HERMES-like polar orbit satellite

Orbit Parameters:
550 km altitude, 97 deg. inclination



HERMES-like polar
30 days
Orbit map





Global summary

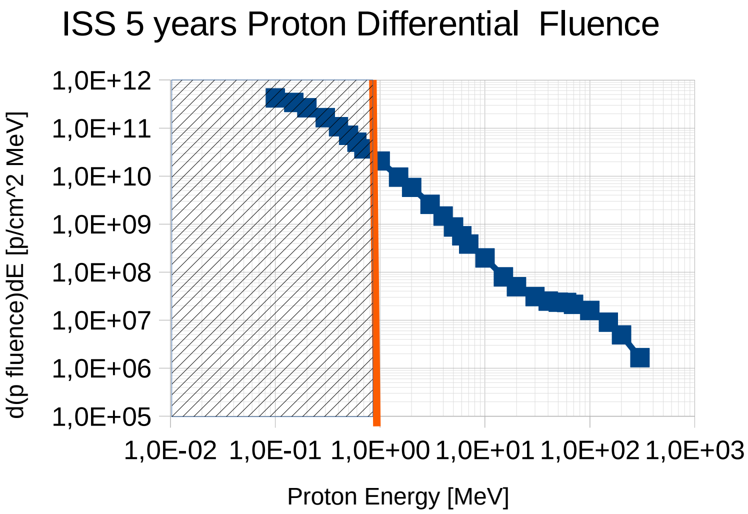
Evaluation of displaced damage in silicon devices for 5 years mission

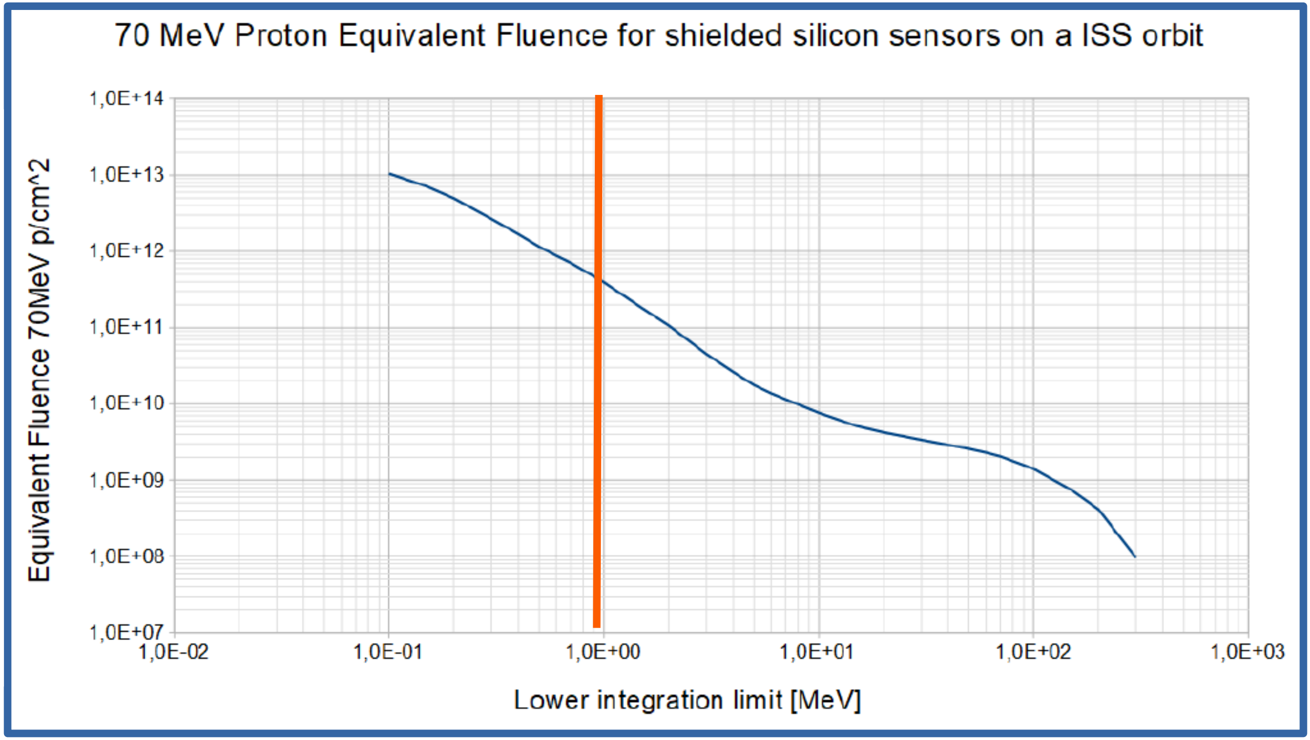
	total proton fluence 5 years [p/cm^2]	total damage D/95 MeVmb	70MeV protons equivalence [p/cm^2]
a) ISS orbit	1.14E+11	1.60E+13	1.05E+13
b) HERMES equatorial orbit	8.92E+8	1.37E+10	9.00E+ 9
c) HERMES-like polar orbit	1.94E+11	3.32E+13	2.18E+13
d) 6000km radius, equatorial	1.65E+15	1.14E+17	7.48E+16
e) 6000km radius, polar	1.15E+15	1.60E+17	1.05E+16
f) 12000km radius, equatorial	3.79E+16	4.81E+18	3.15E+18
g) 12000km radius, polar	1.04E+16	1.47E+18	9.68E+17

- Silicon Devices in **orbit b)** can be tested in **one irradiation day** at the TPTC.
- Silicon Devices in **orbit a) or c)** can be tested in **one irradiation** day at the TPTC only if they are **shielded inside the satellite**, allowing a cut in the lower limit of the differential proton fluence spectrum integral.
- Silicon Devices in **other orbits** can be tested only in multiple irradiation days at the TPTC.

Damage evaluation

for objects in a 5 years mission in a ISS orbit considering shielding

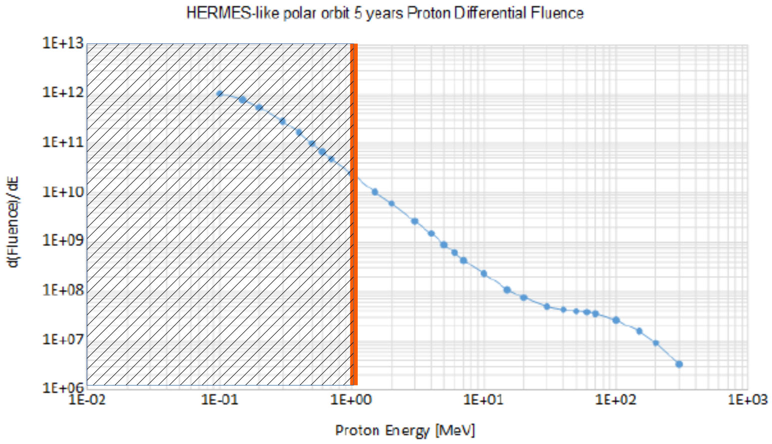


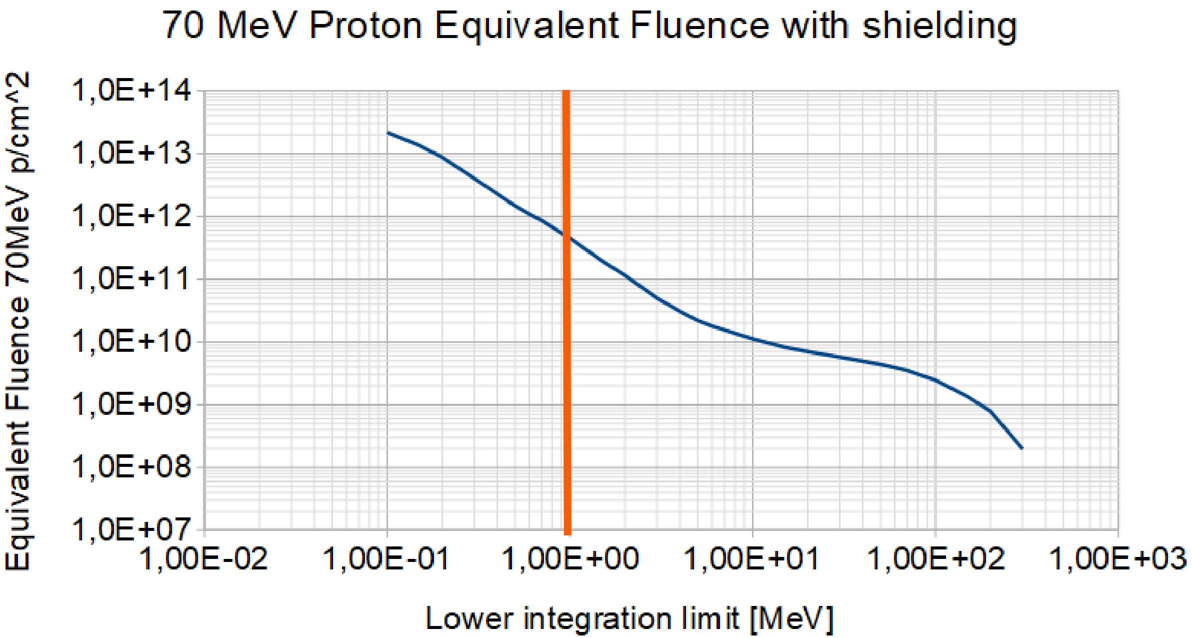


Result for the ISS orbit considering **only** [1.0 - 300] MeV protons effect:
70 MeV equivalent fluence: **3.94E+11 p/cm^2**

Damage evaluation

for objects in a 5 years mission on a HERMES-like polar orbit considering shielding





Result for a HERMES-like polar orbit considering **only** [1.0 - 300] MeV protons effect:
70 MeV equivalent fluence: **4.51E+11 p/cm^2**

Conclusion

In the TPTC Experimental Area can be performed the following irradiations:

100 MeV proton beam:

~2*10^12 p/cm^2 **on small area objects with direct beam irradiation**

140 MeV proton beam

~5.5 * 10^11 p/cm^2 **on large area objects using the small dual ring set-up**

70 MeV proton beam

~5.0 * 10^11 p/cm^2 **on large area objects using the dual ring set-up and a degrader**

With these fluence capabilities magnetosphere trapped Proton induced Displacement damage in Silicon and SEUs can be measured for a:

- **5 years space mission on a HERMES equatorial orbit without shielding**
- **5 years space mission on a ISS-like orbit with shielding**
- **5 years space mission on a HERMES-like polar orbit with shielding**

Thanks to:

Anna Rita Altamura, Fabio Acerbi and Alberto Mazzi (FBK), Riccardo Campana (INAF),
E. Verroi, C. Manea, F. Tommasino, I. Rashevskaya, E.Scifoni and R. Dolesi (TIFPA and UniTN)
for the help, the suggestions and the support in this work!

References and documentation

TIFPA-INFN:	www.tifpa.infn.it
APSS:	https://protonterapia.provincia.tn.it/eng
Physics UniTN:	https://www.physics.unitn.it/en
FBK:	https://www.fbk.eu
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:
Full list and description of the activities performed at the TPTC
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

Documentation

RD50 home page for radiation damage documentation:

https://rd50.web.cern.ch

SPENVIS software: **https://www.spenvis.oma.be**
SRIM software: **http://www.srim.org/SRIM/SRIMLEGL.htm**

Other TPTC description talks:

TALK1 - *Physics and Radiobiology Experimental Beam Tests at the Trento Proton Therapy Center*
B. Di Ruzza et al., BTTB9 Workshop 2021
https://indico.cern.ch/event/945675/contributions/4160465

TALK2 - *Proton and x-ray irradiation of silicon devices at the TIFPA-INFN facilities in Trento (Italy)*
B. Di Ruzza, ICHEP Conference 2020
https://indico.cern.ch/event/868940/contributions/3815732

TALK3 - *Education initiatives in the experimental area of the Trento Proton Therapy Center (Italy)*
B. Di Ruzza, ICHEP Conference 2020
https://indico.cern.ch/event/868940/contributions/3814048

TALK4 - *4DPhantom: An innovative device for oncological proton treatment uncertainties minimization*
B. Di Ruzza et al., 106 Congress of the Italian Physical Society SIF2020
https://agenda.infn.it/event/23656/contributions/120640

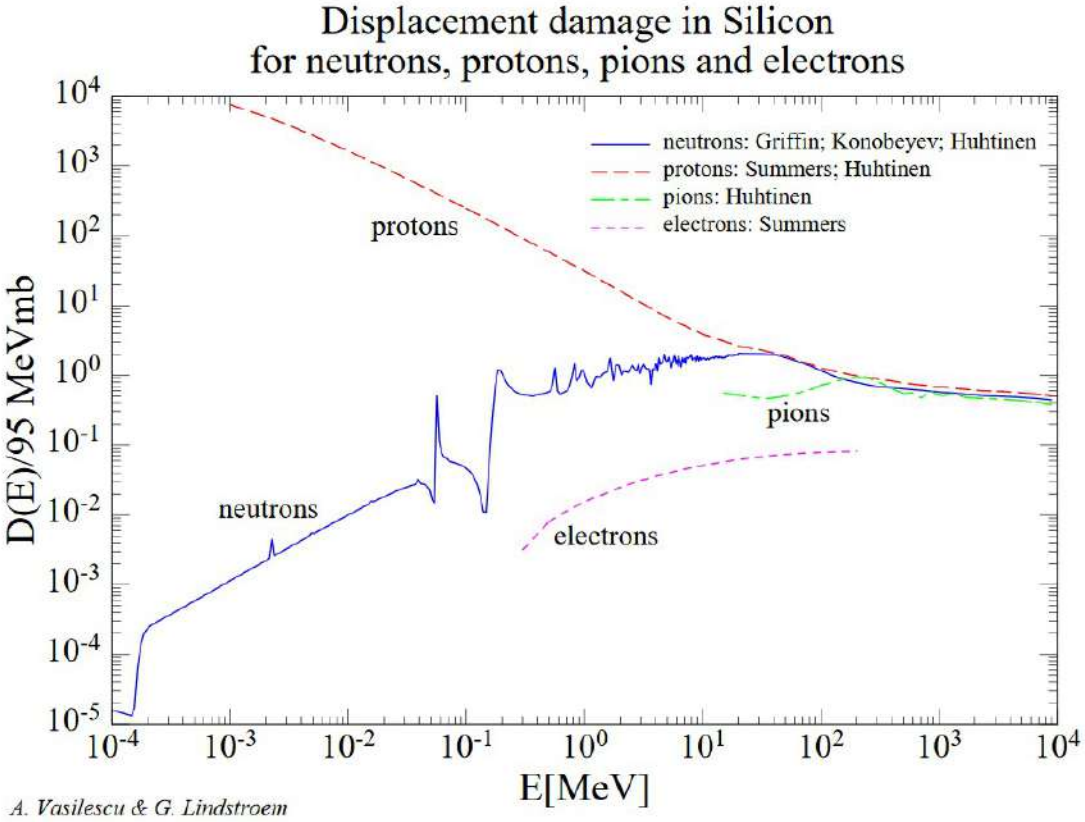
Review on accelerators for medical applications:

REV1 - Yves Jongen, *REVIEW ON CYCLOTRONS FOR CANCER THERAPY*
Proceedings of CYCLOTRONS 2010, Lanzhou, China
https://accelconf.web.cern.ch/Cyclotrons2010/papers/frm1cio01.pdf

Back-up slides

Abstract:

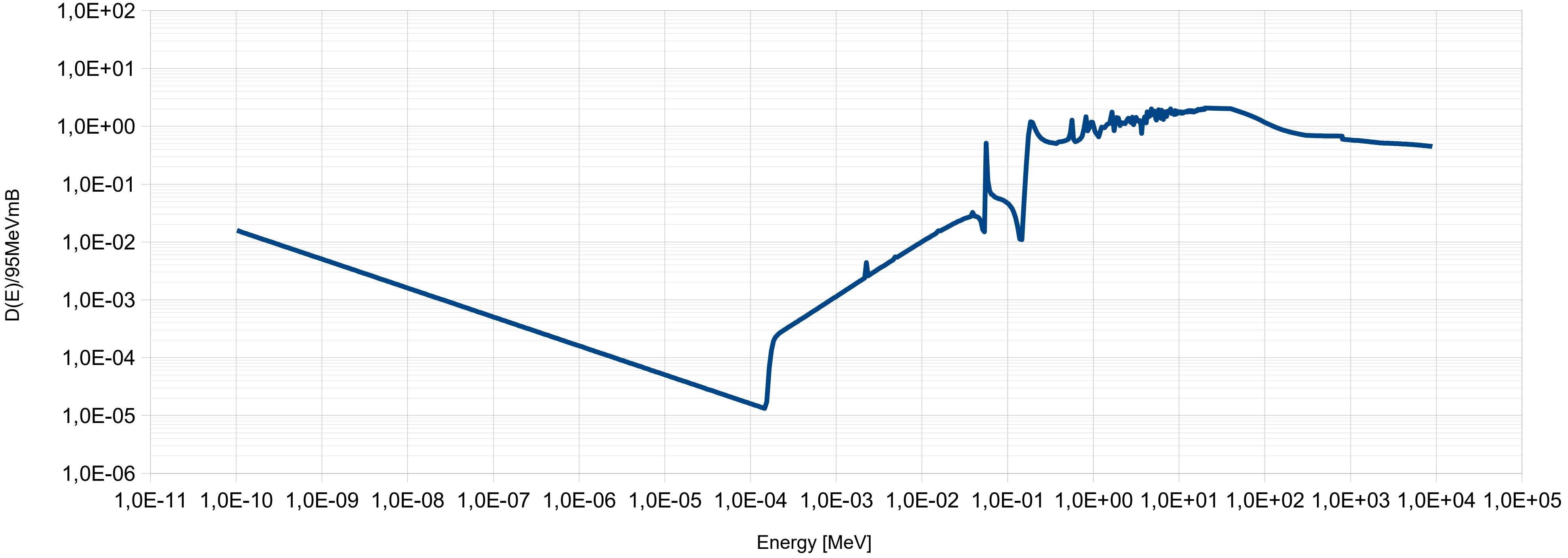
Proton induced Ionizing and Non-Ionizing energy loss campaigns are required studies for silicon sensors and electronic devices qualification when designed for medical, space and high energy physics applications.
The Experimental Area of the Trento Proton Therapy Center offers the possibility to perform these studies using a 70-230 MeV proton beam designed for medical treatment of oncological patients. This area, used only for non medical applications, is equipped with two beamlines reserved for biological experiments, silicon sensor tests and electronic device qualifications. One of these lines is also equipped with a unique passive beam modulator system, called double ring, where large area proton irradiation on silicon sensors and electronic devices can be performed.
In this talk a description of the beam parameters and irradiation regime possibilities will be given, and also the description of a new set-up used in September 2020 for single event upset rate measurement on a electronic device.



Displacement damage in Silicon
for neutrons, protons, pions and electrons
neutrons: Griffin; Konobeyev; Huhtinen
protons: Summers; Huhtinen
pions: Huhtinen
electrons: Summers
protons
neutrons
pions
electrons
D(E)/95 MeVmb
E[MeV]
A. Vasilescu & G. Lindstroem

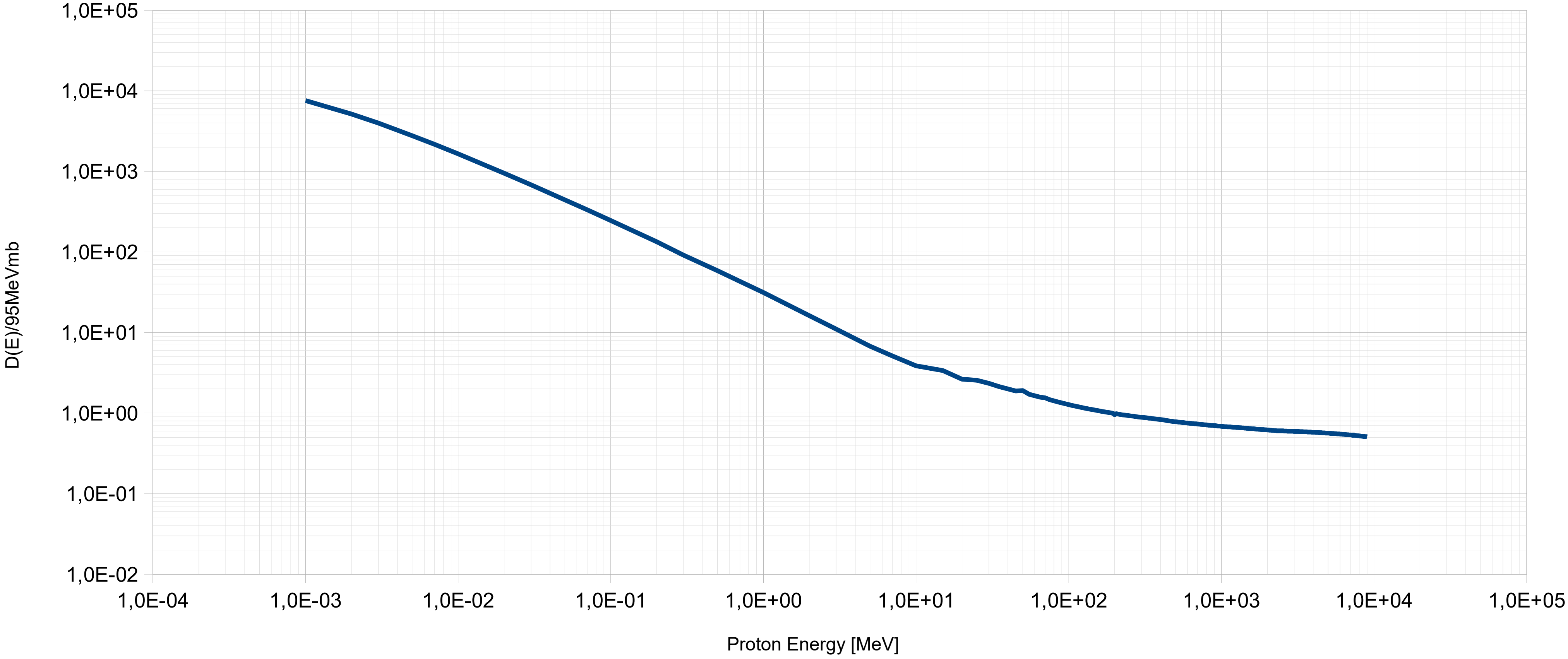
Neutron Damage (full range)

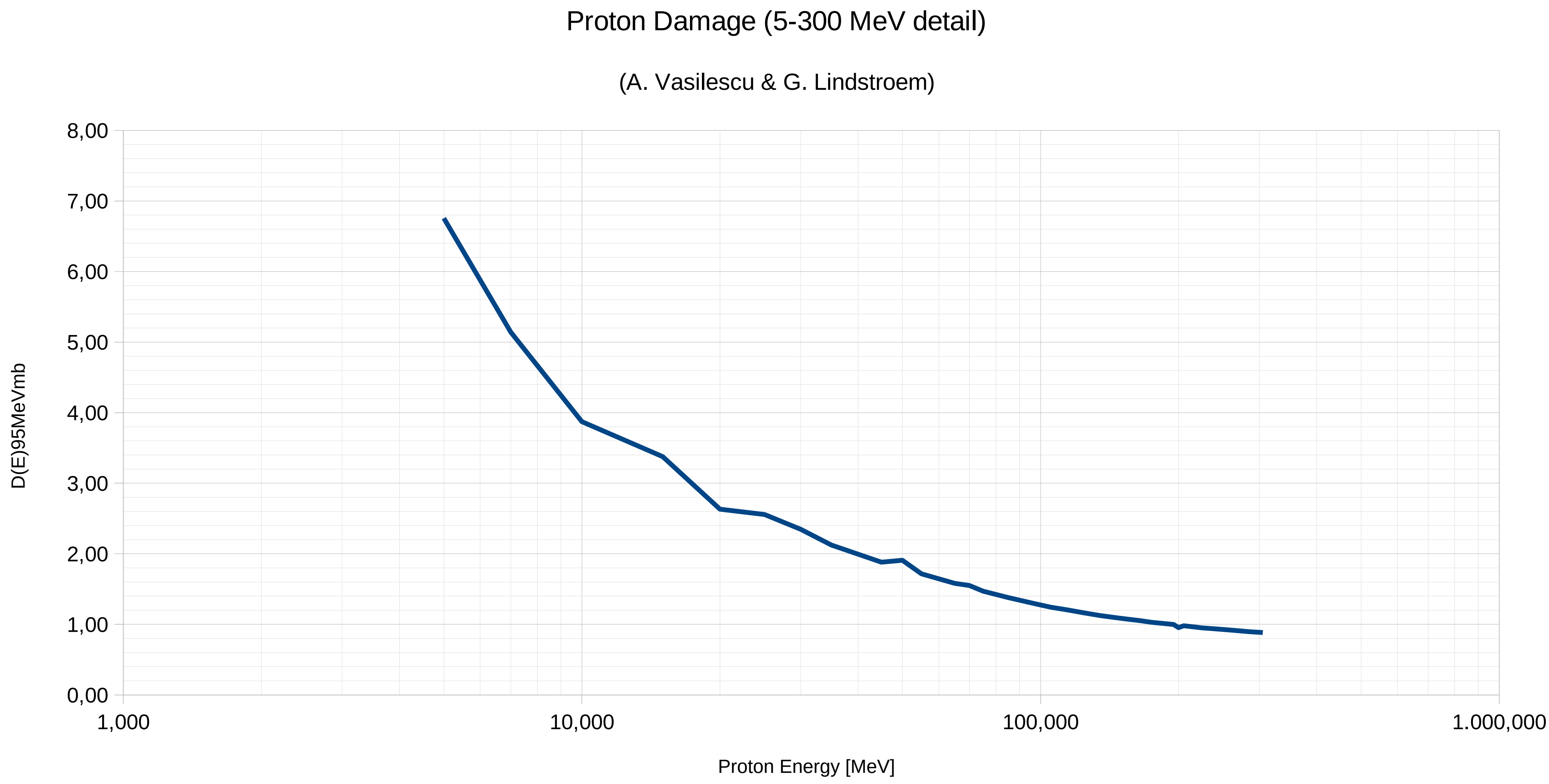
(A. Vasilescu & G. Lindstroem)

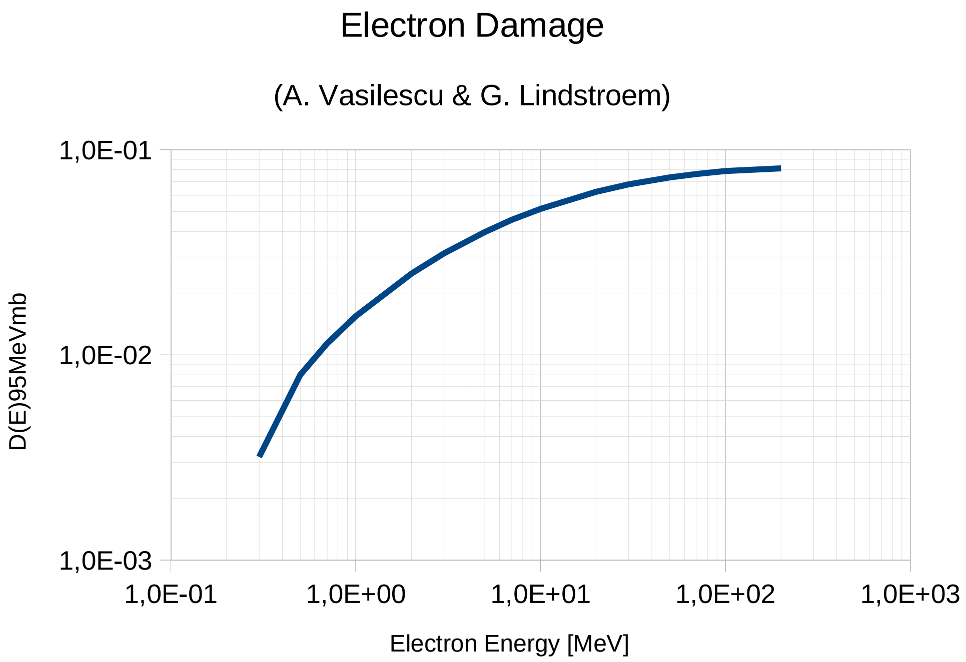


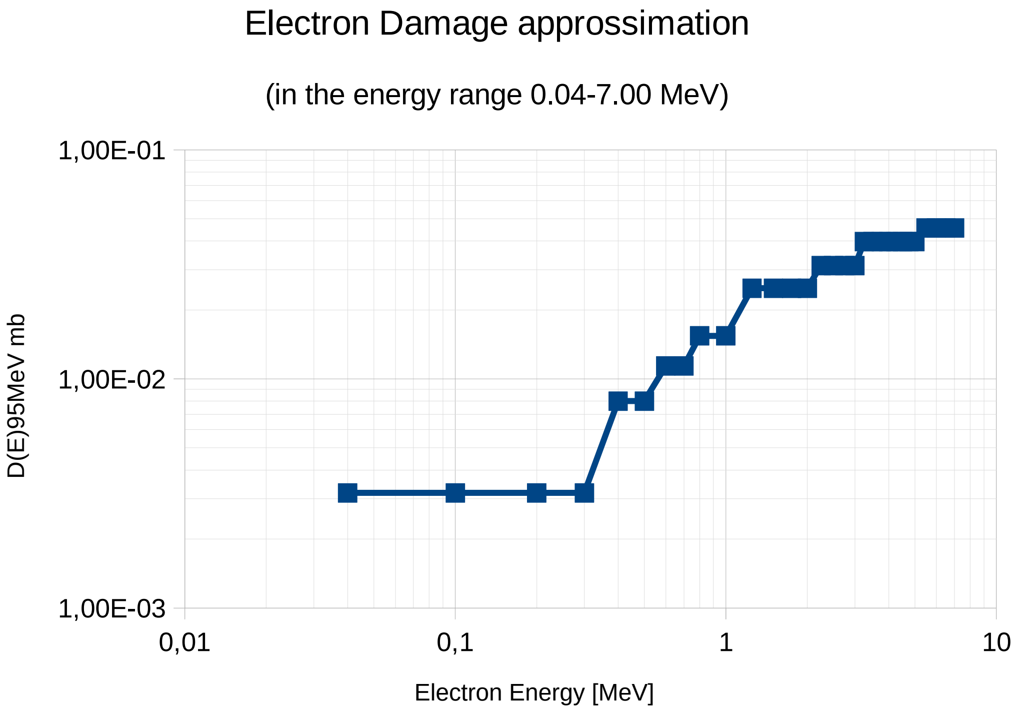
Proton Damage

(A. Vasilescu & G. Lindstroem)




Proton Damage (5-300 MeV detail)
(A. Vasilescu & G. Lindstroem)
8,00
7,00
6,00
5,00
4,00
3,00
2,00
1,00
0,00
D(E)95MeVmb
1,000
10,000
100,000
1.000,000
Proton Energy [MeV]

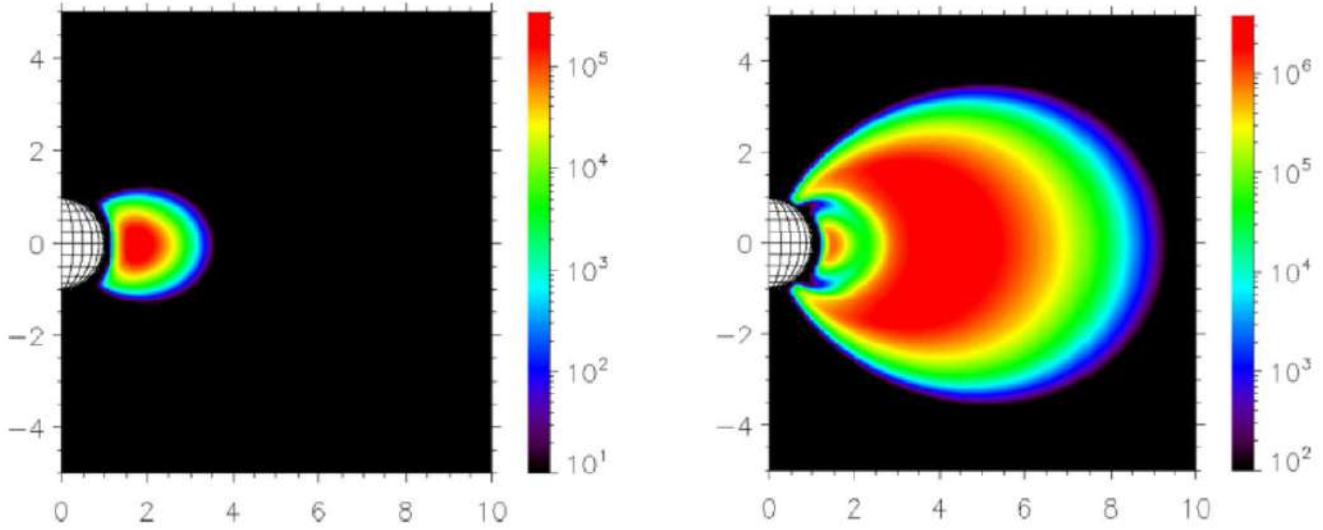

Electron Damage
(A. Vasilescu & G. Lindstroem)
1,0E-01
1,0E-02
1,0E-03
D(E)95MeVmb
1,0E-01
1,0E+00
1,0E+01
1,0E+02
1,0E+03
Electron Energy [MeV]


Electron Damage approssimation
(in the energy range 0.04-7.00 MeV)
1,00E-01
1,00E-02
1,00E-03
D(E)95MeV mb
0,01
0,1
1
10
Electron Energy [MeV]

Andrea Candelori
https://agenda.infn.it/event/3245/contributions/45303/

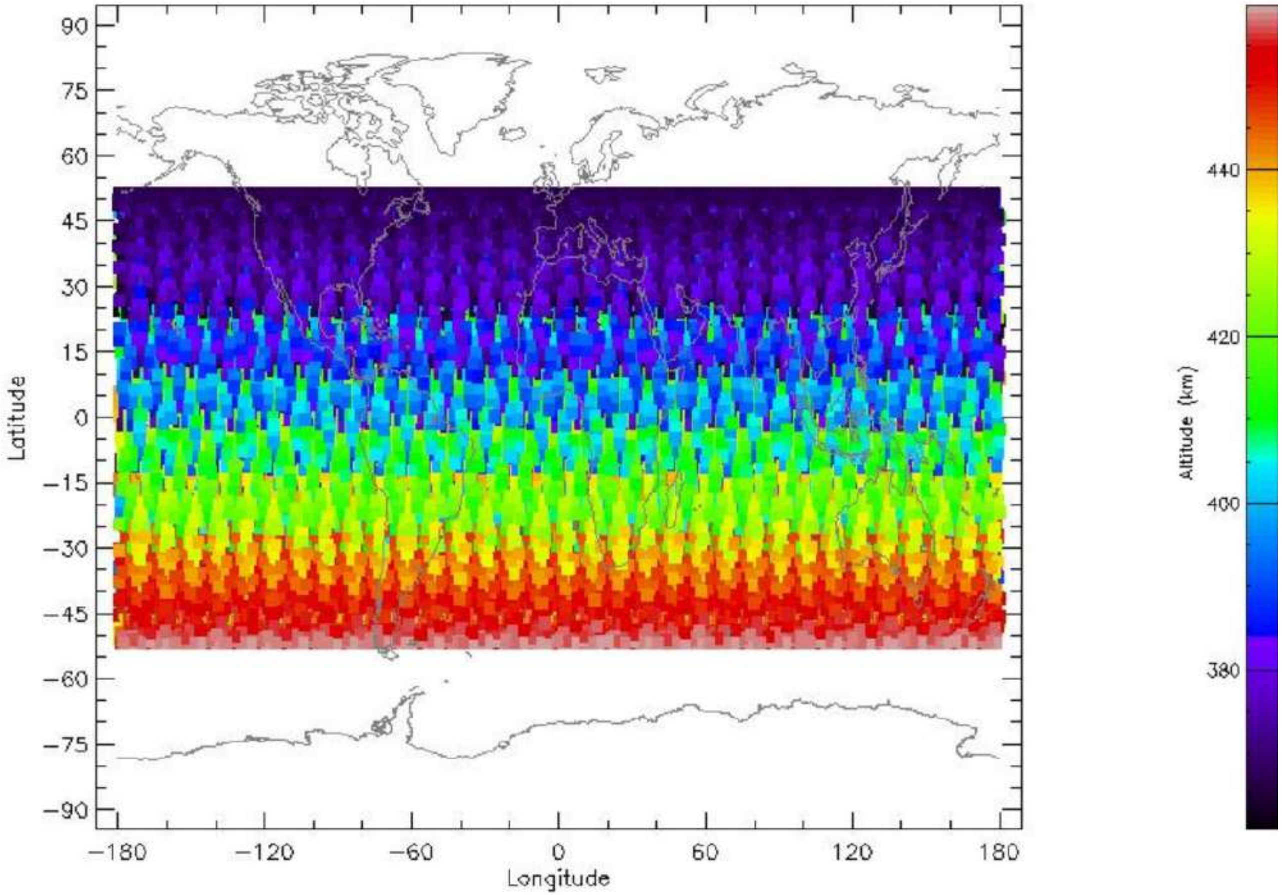
Le radiazioni presenti nelle fasce di Van Allen

	Particle	Energy	Extension (Earth radii)
Earth	e-	1 keV-10 MeV	1-10
	p+	1 keV-300 MeV	1-7

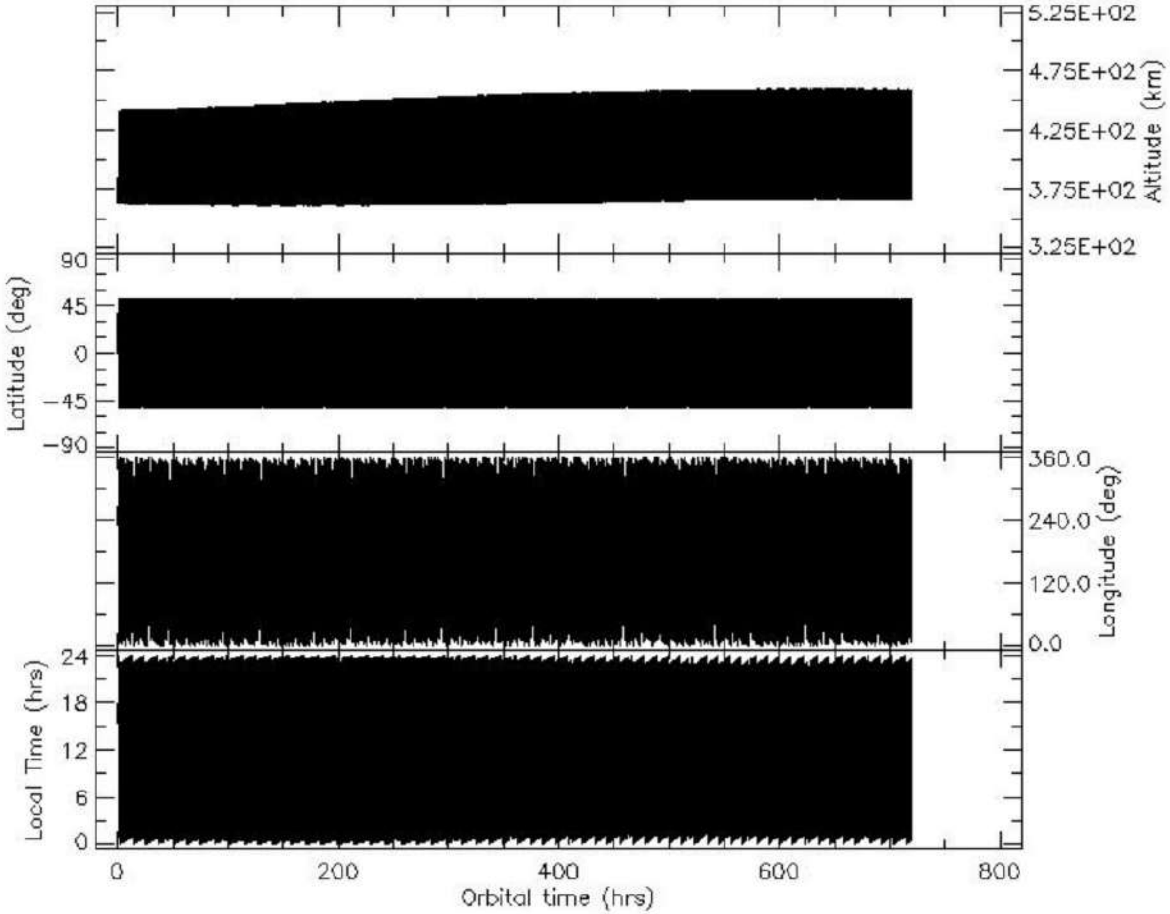


Flusso omnidirezionale di protoni (protoni/cm²×s) con energia >10 MeV [a sinistra] ed elettroni (elettroni/cm²×s) con energia >1 MeV [a destra] intrappolato nelle fasce di Van Allen, dal modello AE8 al massimo dell'attività solare. La mappa evidenzia le coordinate magnetiche in unità di misura di raggi terrestri.

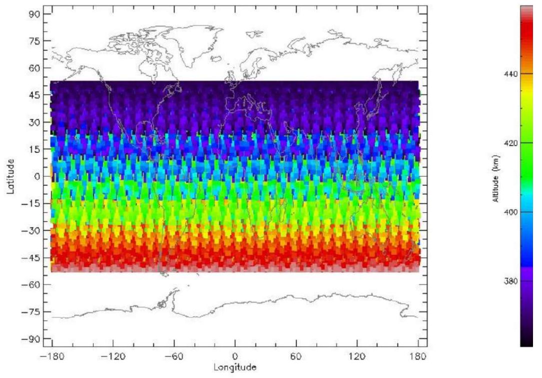
ISS 30 days orbits (370-460 km, 51.6 deg.)

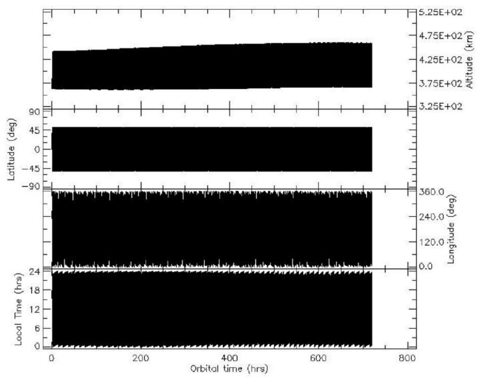


ISS 30 days orbits (370-460 km, 51.6 deg.)

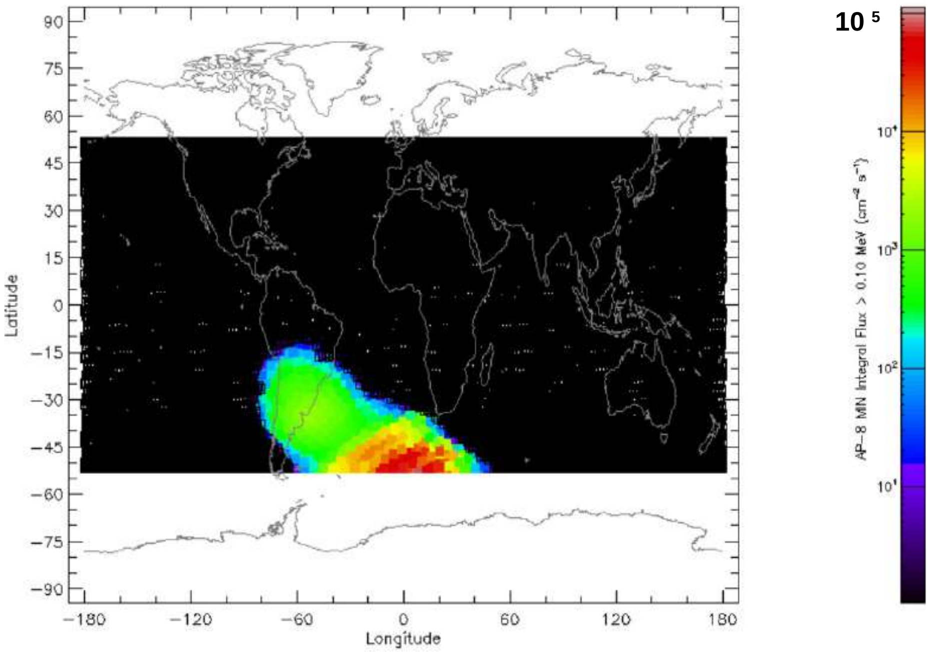


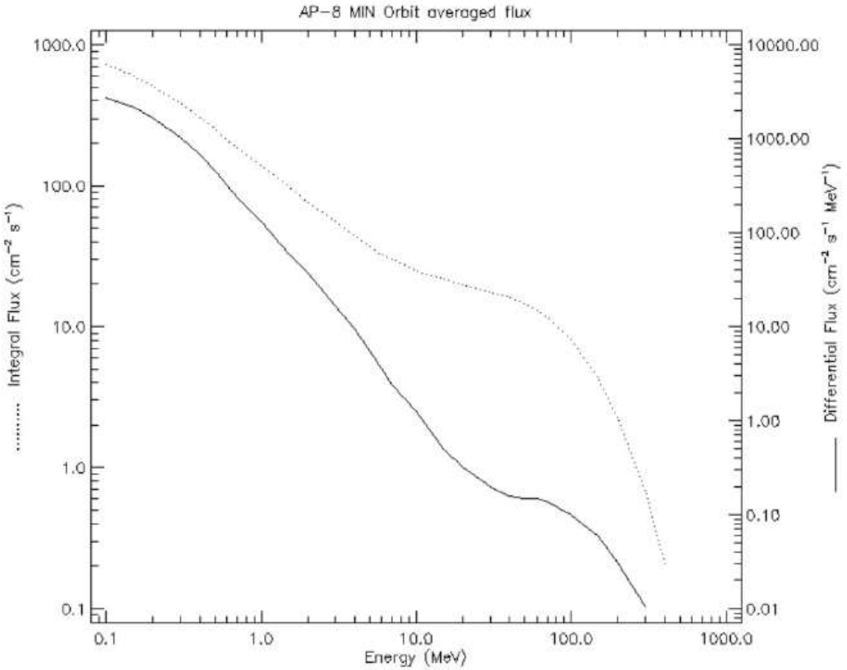
ISS 30 days orbits.
Parameters:
370 km-460 km, 51.6 deg.



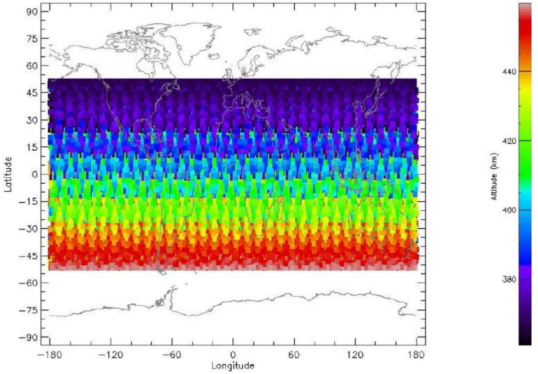


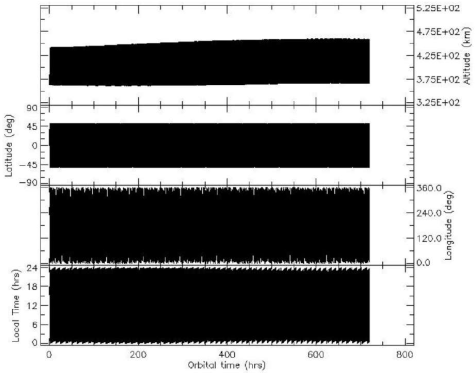
ISS 30 days protons



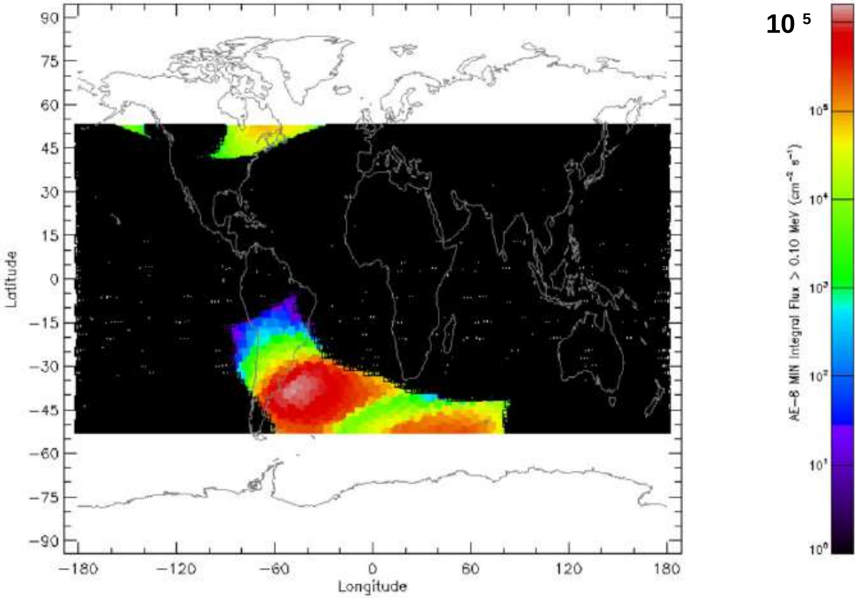


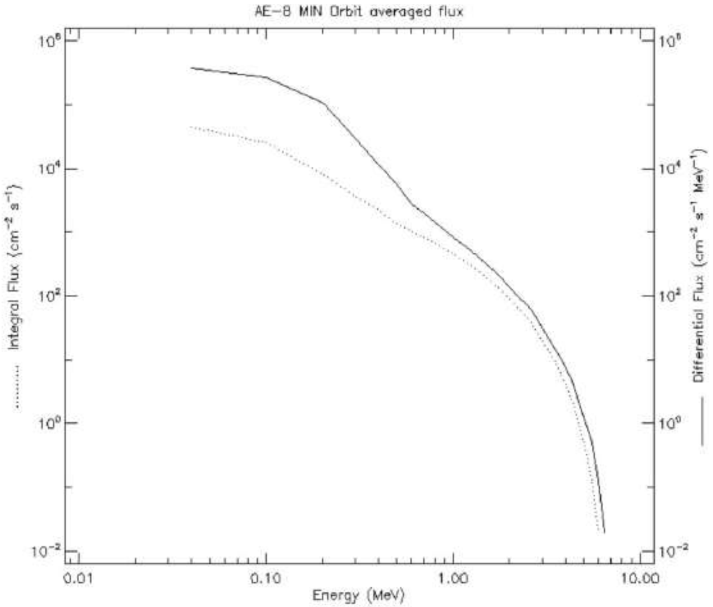
ISS 30 days orbits.
Parameters:
370 km-460 km, 51.6 deg.





ISS 30 days electrons



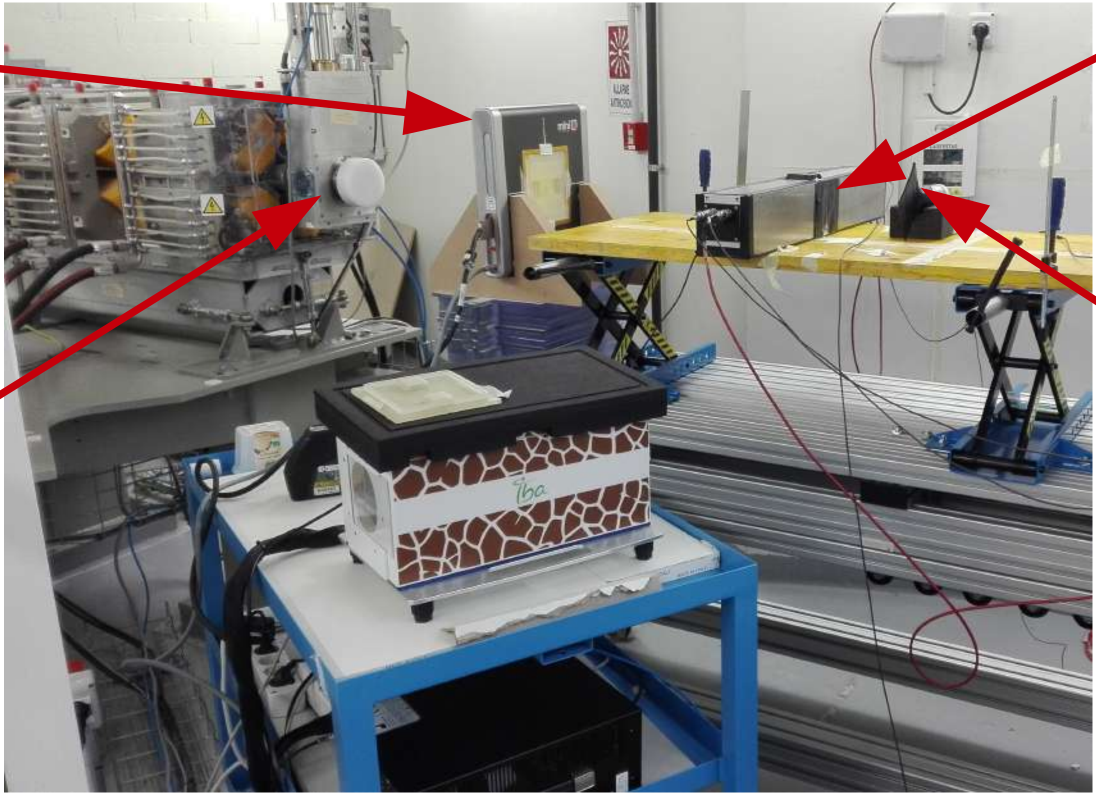


Physics beam line

Typical experiment configuration in dark current mode,
used for test on silicon pixel, strips, lgad etc.

Beam monitor

DUT



Beamline
exit window

Event trigger
(plastic scintillator)

(photo courtesy of the **HERMES** collaboration https://www.hermes-sp.eu)