Istituto Nazionale di Fisica Nucleare

Trento Institute for Fundamental Physics and Applications

SiPM Irradiation and Characterization with proton and x-ray beams: the TIFPA-INFN facilities in Trento (Italy)

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SiPM Radiation: Quantifying Light for Nuclear, Space and Medical Instruments under Harsh Radiation Conditions
CERN, 25-29 April 2022

OUTLINE

Proton Irradiation for Displacement Damage Studies on SiPM

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

Irradiation configurations:

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

X ray irradiation of SiPM for TID studies

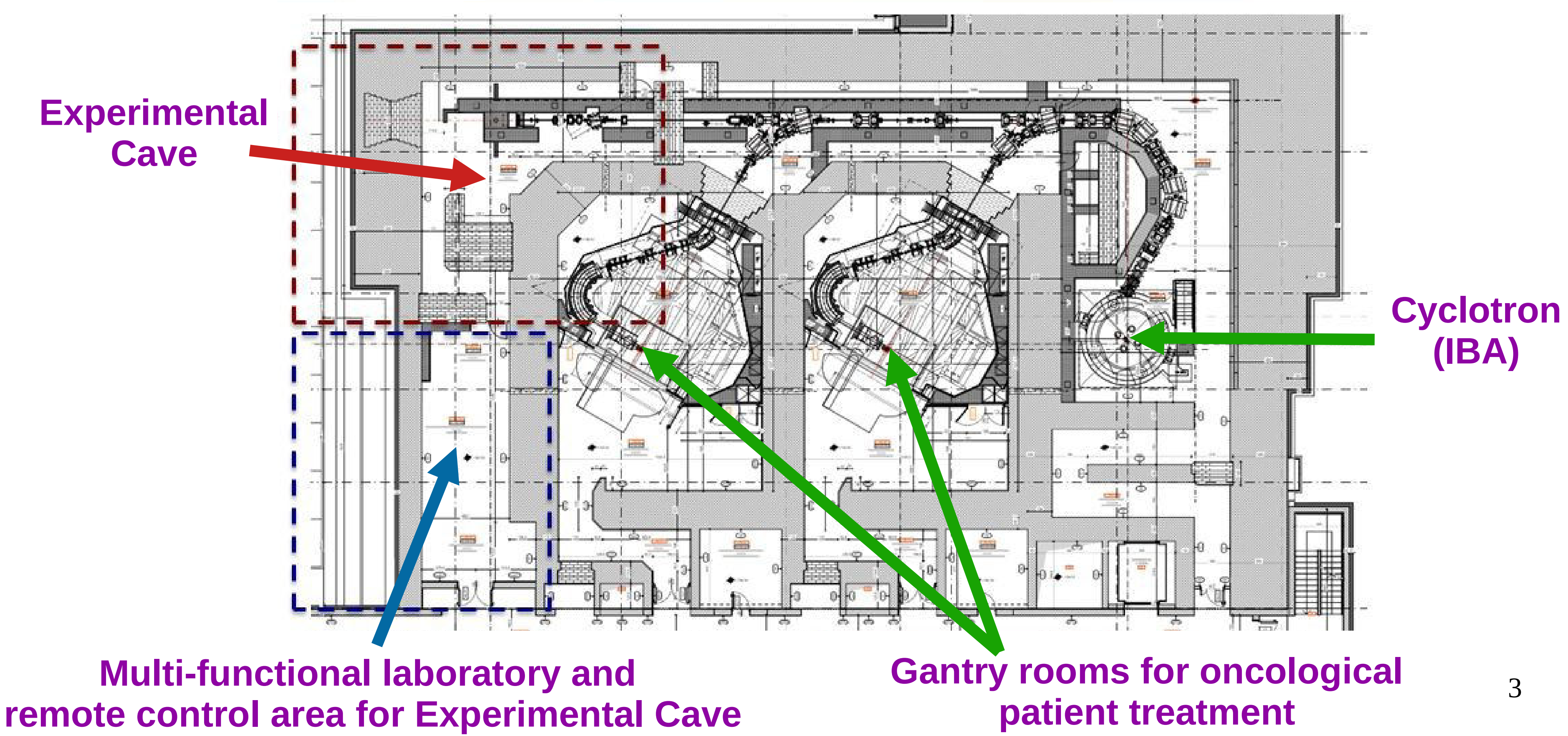
- The TIFPA-INFN x-ray irradiation laboratory
- Tungsten emission spectrum X-ray penetration in silicon
- Diode and Farmer Chamber dose measurement comparison
- FBK SiPM x-ray irradiation campaign

Conclusions

See also the **Stefano Merzi** talk in this Conference for detailed results on irradiated FBK SiPM: https://indico.cern.ch/event/1093102/contributions/4802136

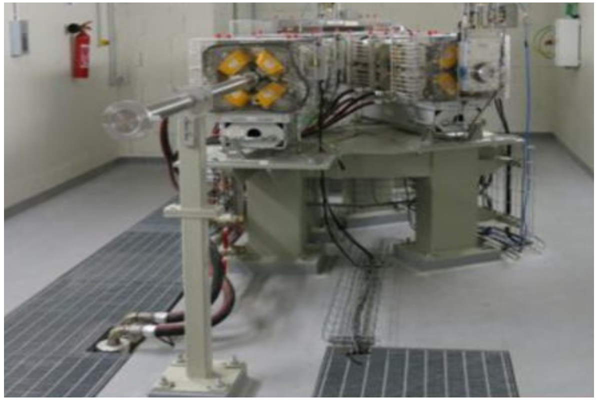
The Trento Proton Therapy Center (TPTC)

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

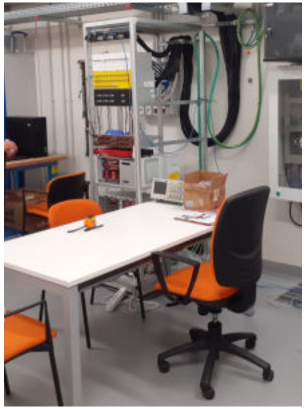


The Experimental Area

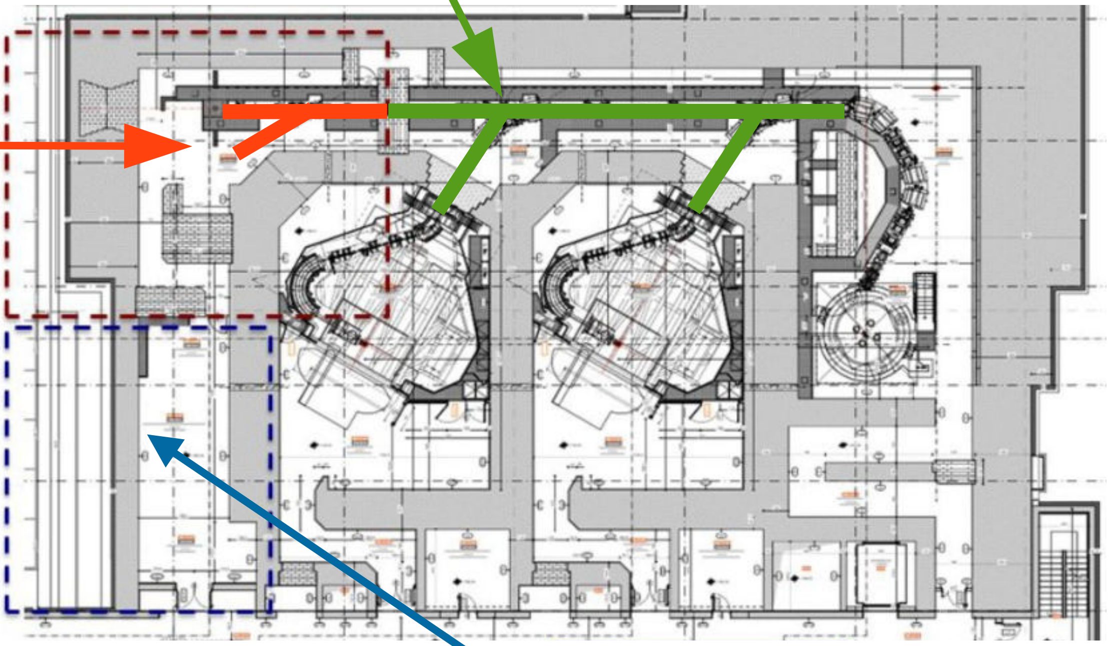
Two Experimental beamlines for in-air irradiation



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

Large 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

Small 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.

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**.

Dual Ring configuration

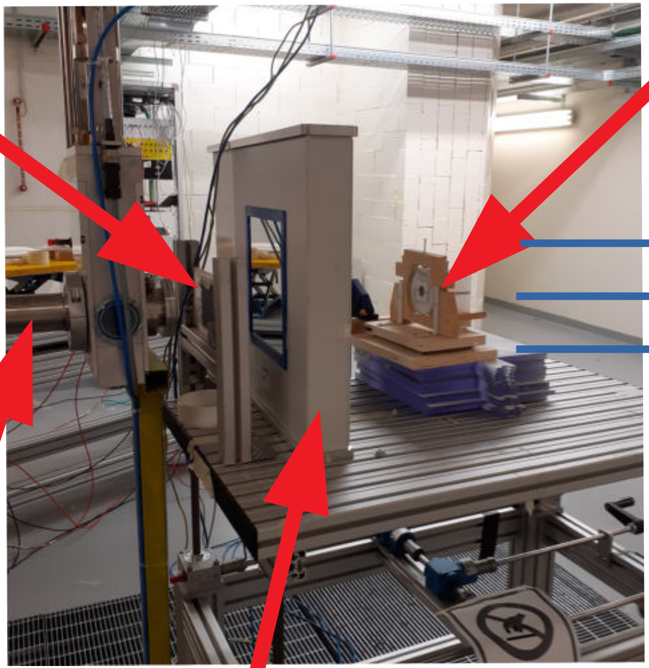
First foil

Dual ring

incoming proton beam
(gaussian profile, 148MeV)

scattered proton beam
(flat profile, ~140 MeV)

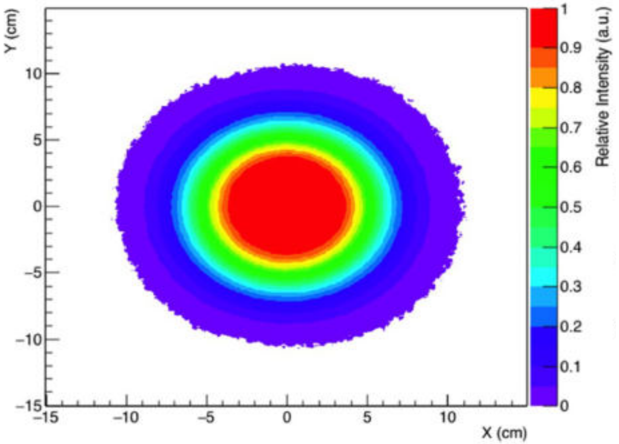
Target area



Fluence in
one irradation 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:

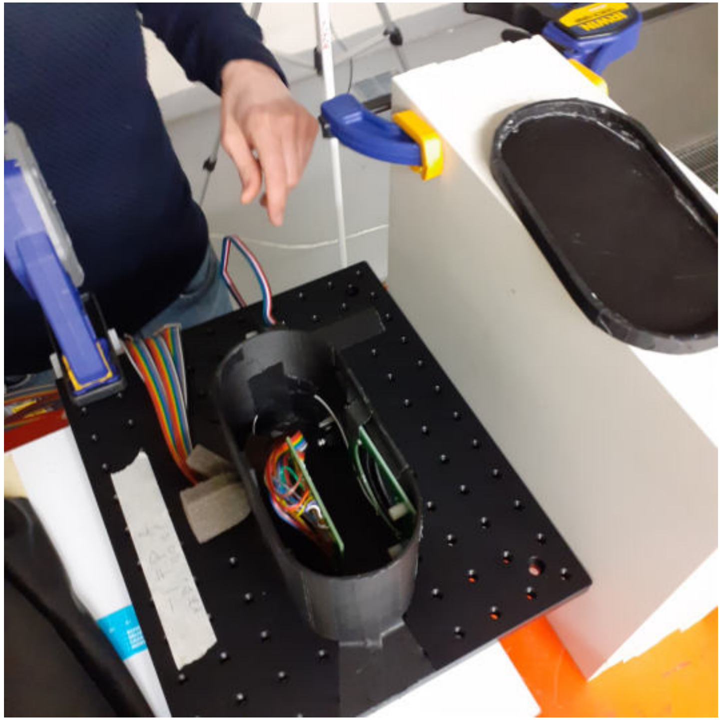
- small dual ring ==> circumference of ~3 cm radius with flat intensity profile
- large dual ring ==> circumference of ~8 cm radius with flat intensity profile

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.

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

Direct beam irradiation configuration

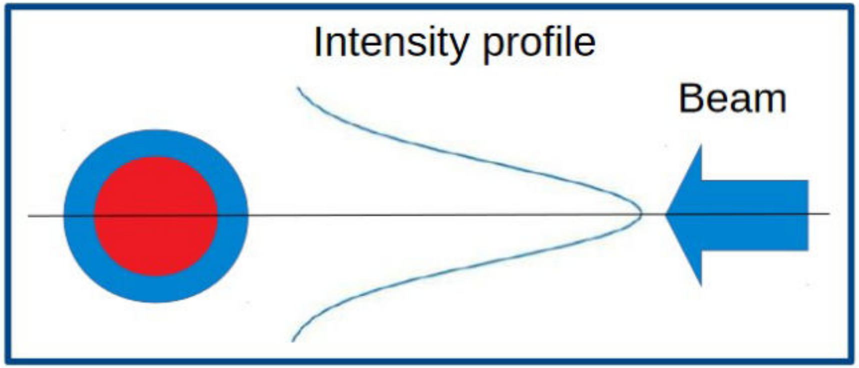
In a direct proton beam irradiation the maximum amount of beam can be delivered on the target but the beam transverse intensity distribution is gaussian instead of uniform.
The gaussian's sigma can be tuned from 2.73 mm up to 6.92 mm decreasing the beam energy from 228MeV down to 70MeV. Decreasing the 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

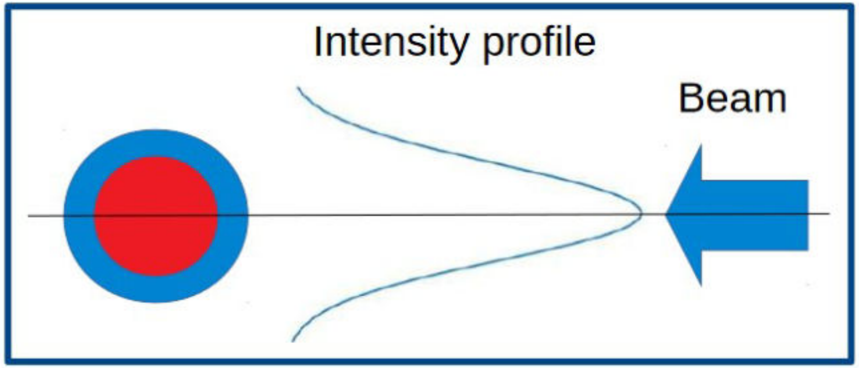
r_{blue} 3.00 mm ==> F =0.133



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.

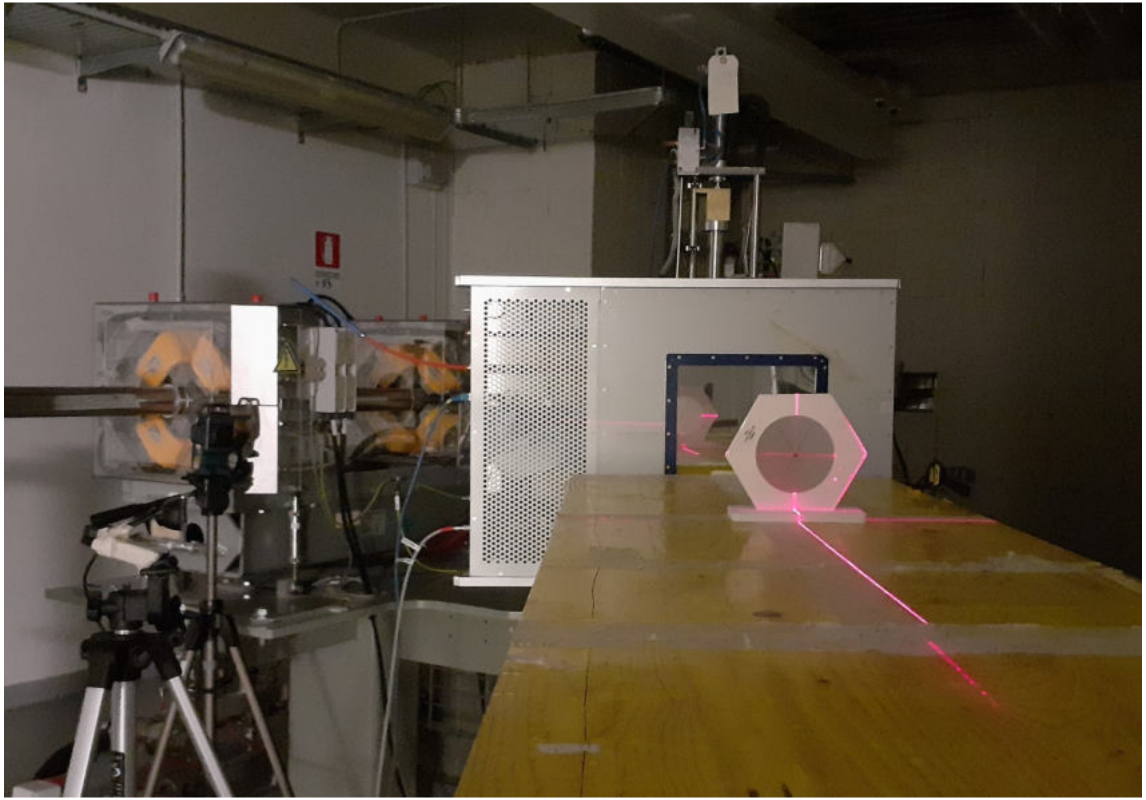
In this condition, the **average fluence** inside a radius r circumference is:



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.

Direct beam irradiation on FBK SiPM



Direct beam irradiation on FBK SiPM:

in this type of irradiation the DUT precise alignment with the beam axis is crucial

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

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 measurement inside the experimental cave, a 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

- **Beamtime applications:**
  https://www.tifpa.infn.it/sc-init/med-tech/p-beam-research

The TIFPA-INFN x-ray irradiation Laboratory

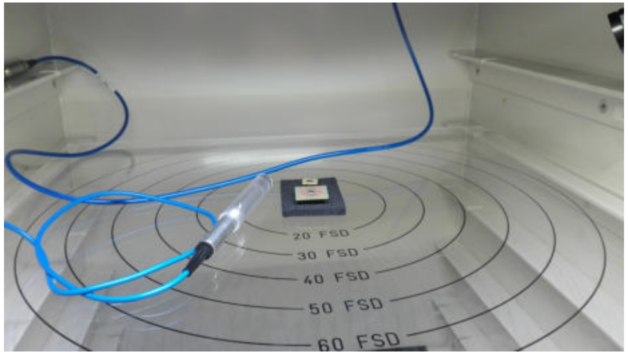
INTRODUCTION

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 SiO2 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.
Data analysis on the SiPM characterization will be published in the
Anna Rita Altamura PhD thesis.

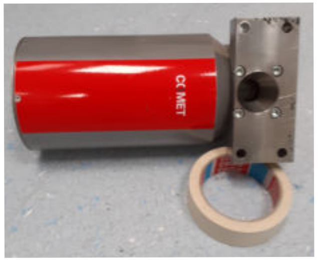
The TIFPA-INFN x-ray irradiation Laboratory

X-Ray cabinet

PTW Farmer Chamber (left) with SiPM (right)



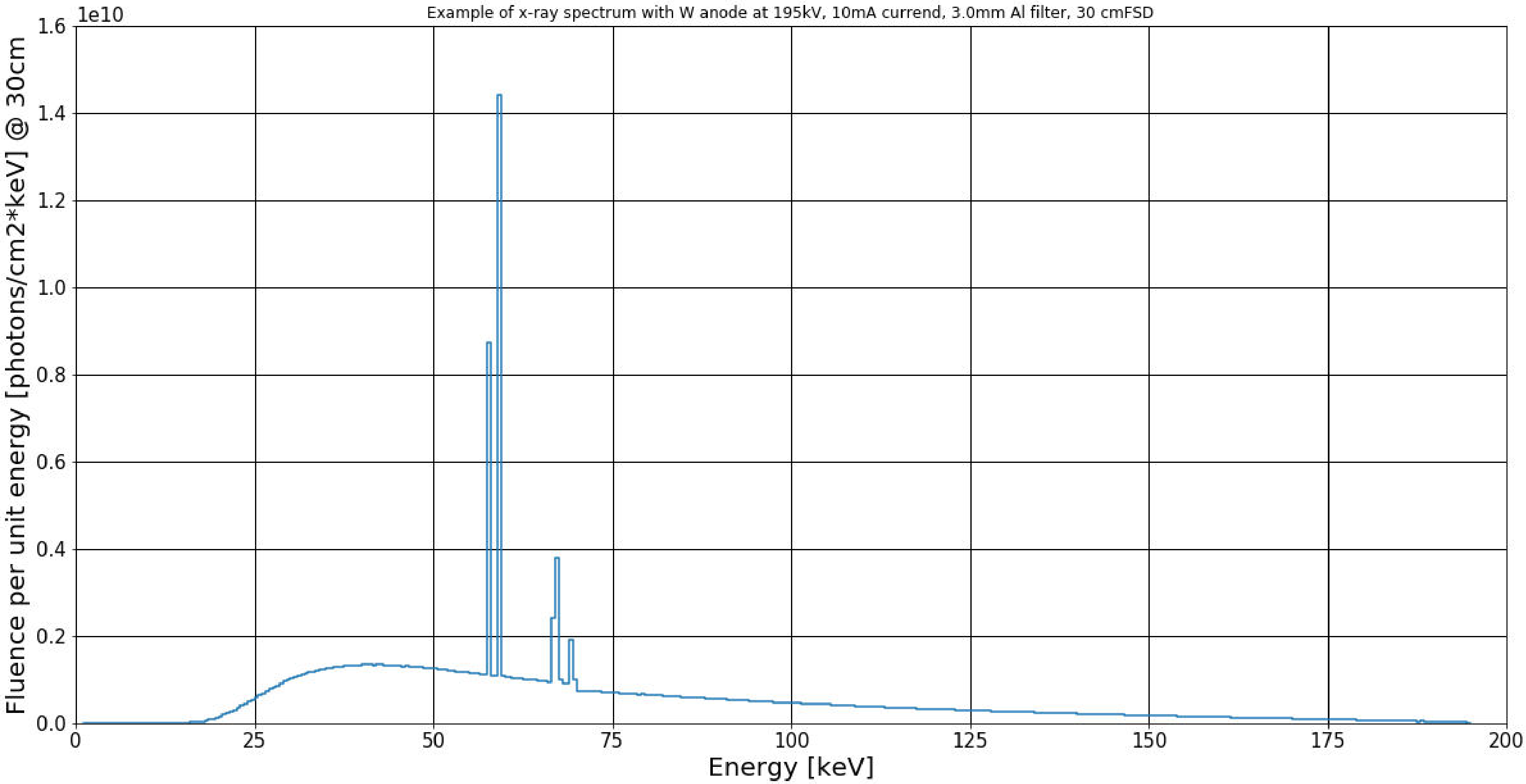
Tube detail



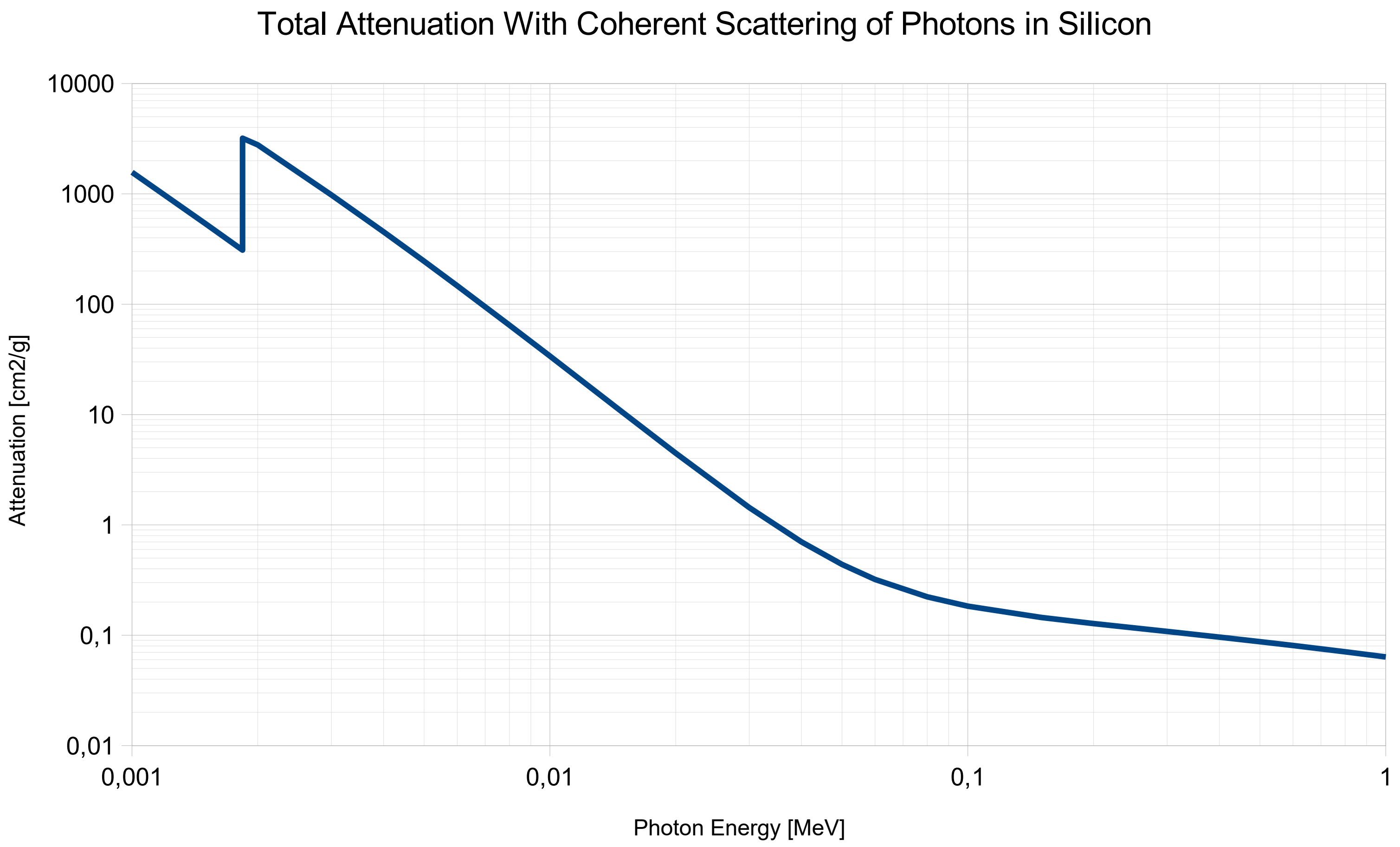
PTW Electrometer

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

Tungsten emission spectrum

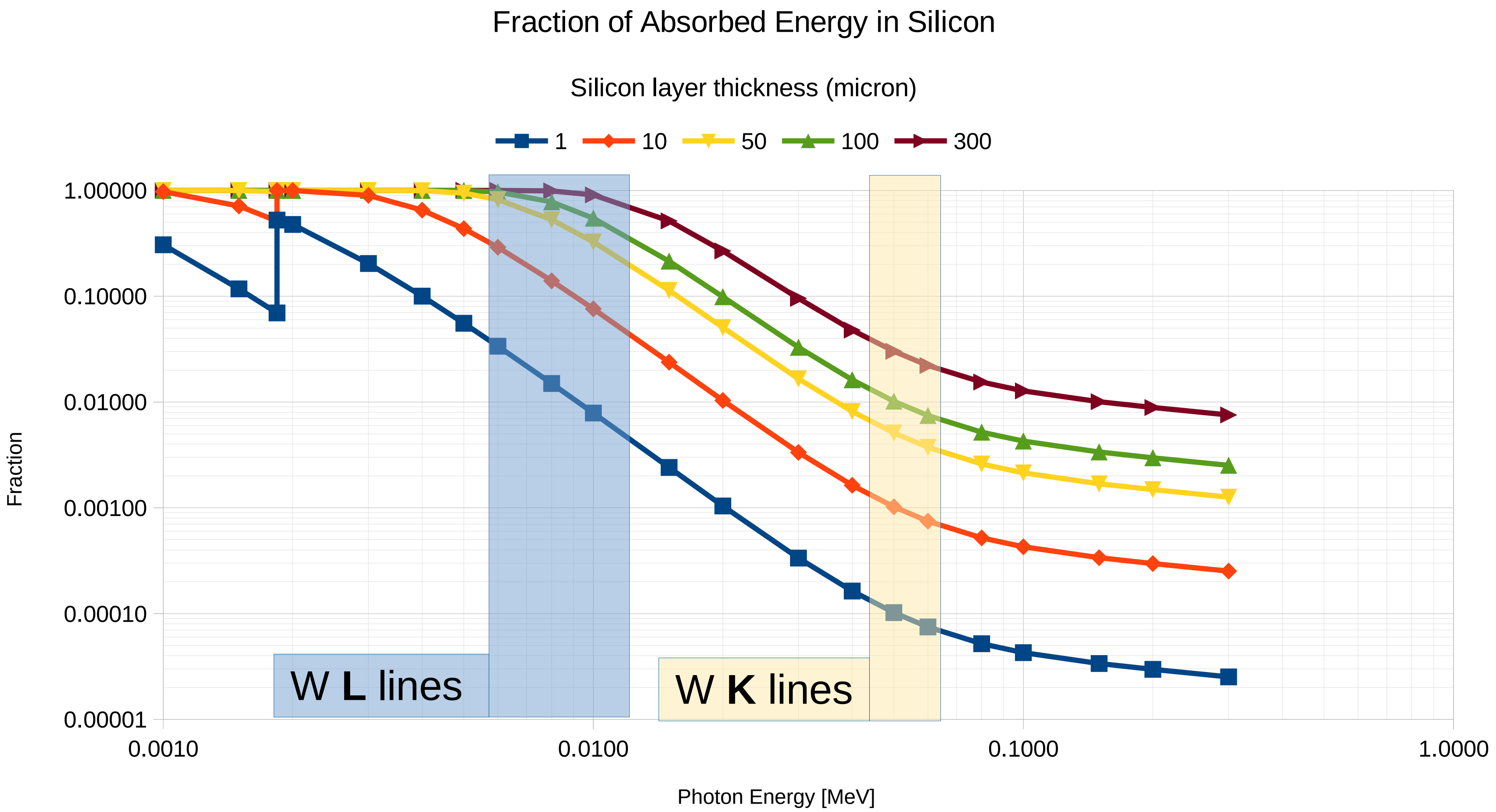


X-ray in silicon



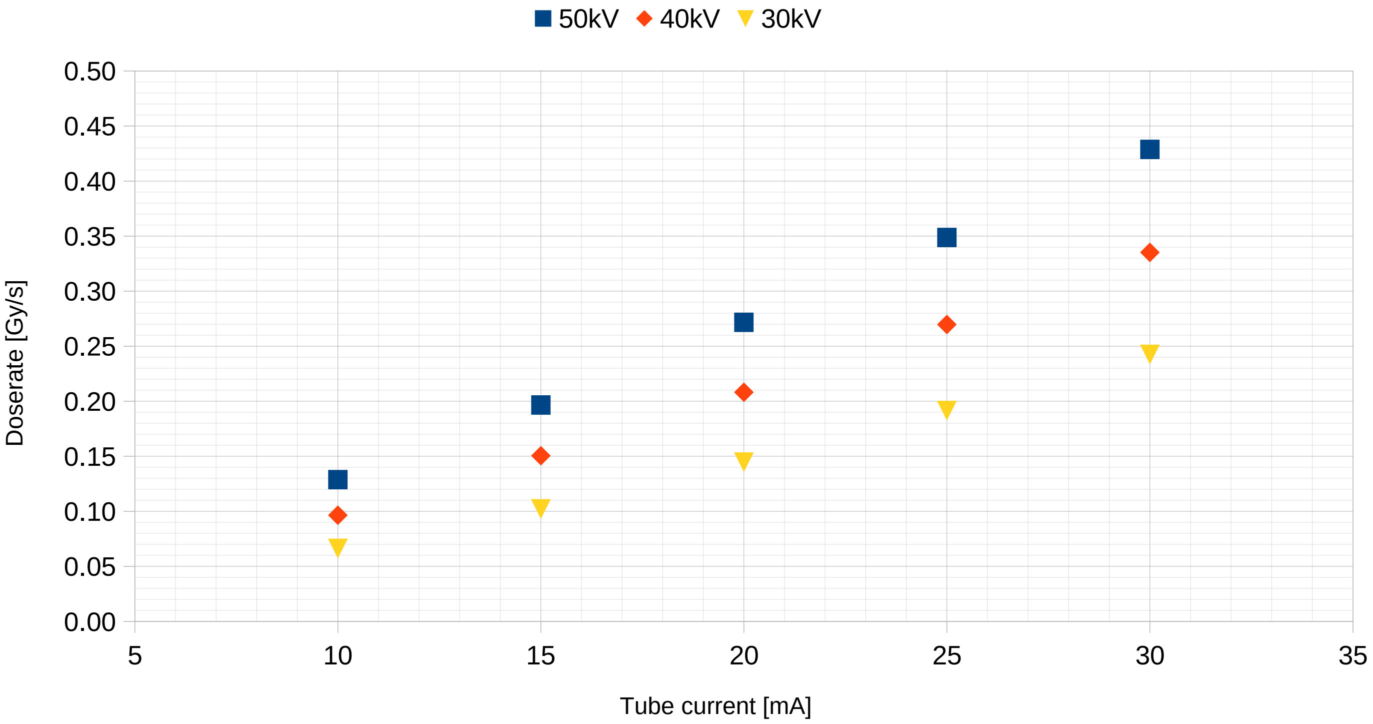
Data from NIST: https://www.nist.gov/pml/x-ray-mass-attenuation-coefficients

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

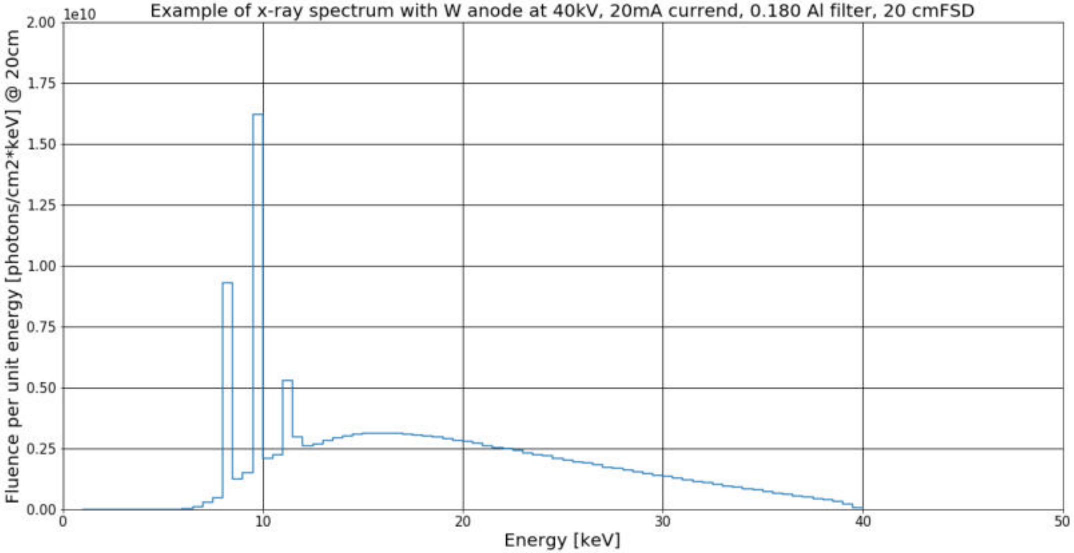


Tube voltage: 30, 40 e 50 kV
Tube current: 10-30 mA
Filter: 0.180 mm Al
Target distance: 20 FSD

Instrument used:
Calibrated PTW
Farmer Chamber

The TIFPA-INFN x-ray irradiation Laboratory

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

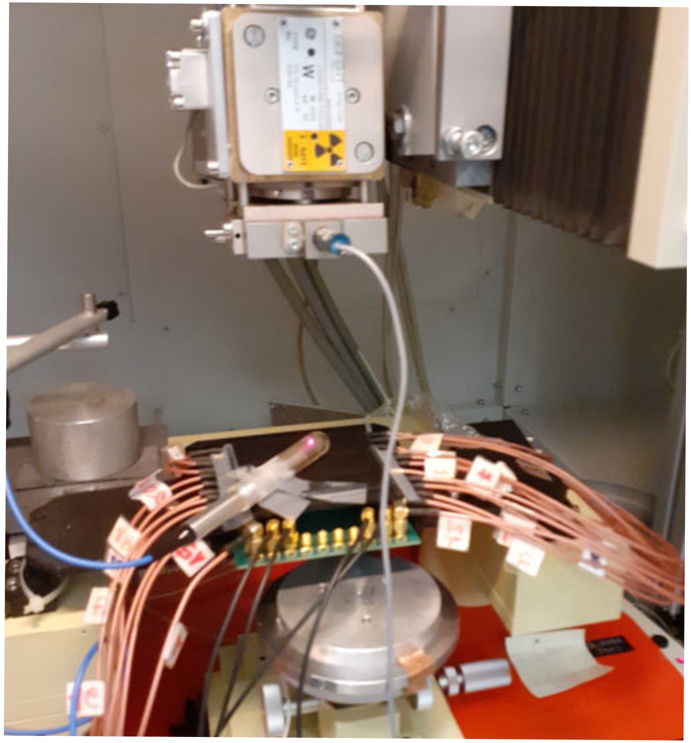


Considered tube configuration:

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

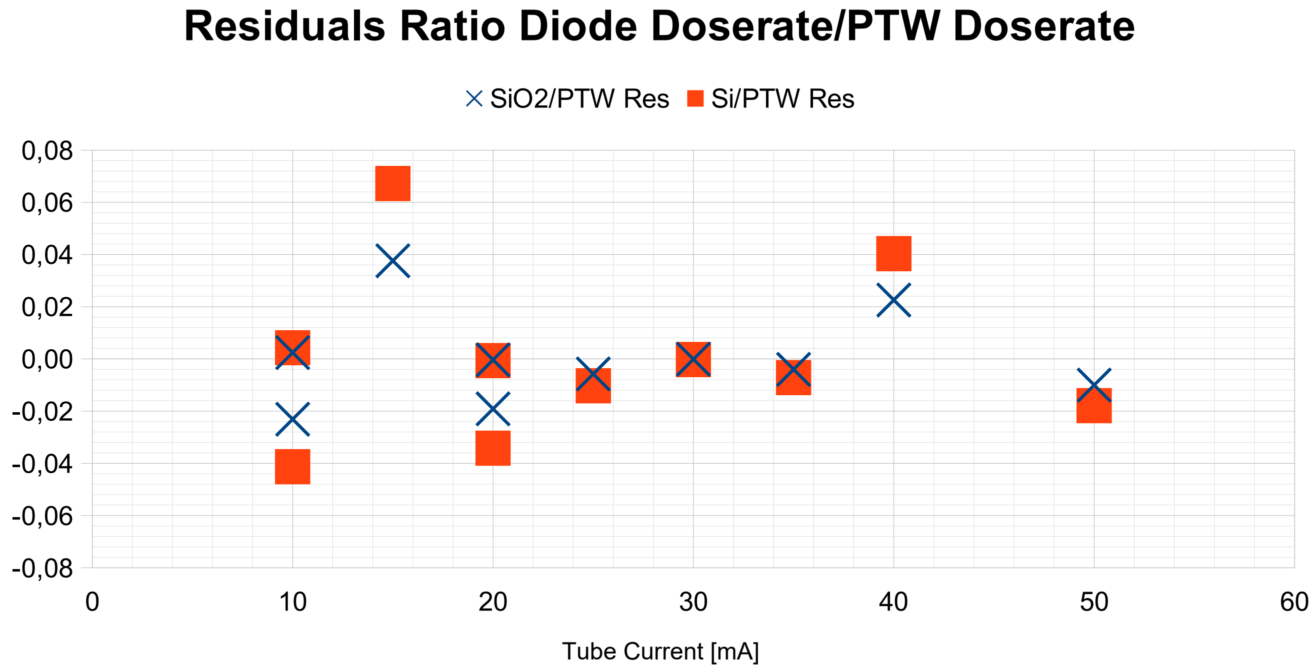
(*) https://doi.org/10.1016/j.ejmp.2020.04.026

In order to use the PTW Farmer Chamber dose measurement system, 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 .

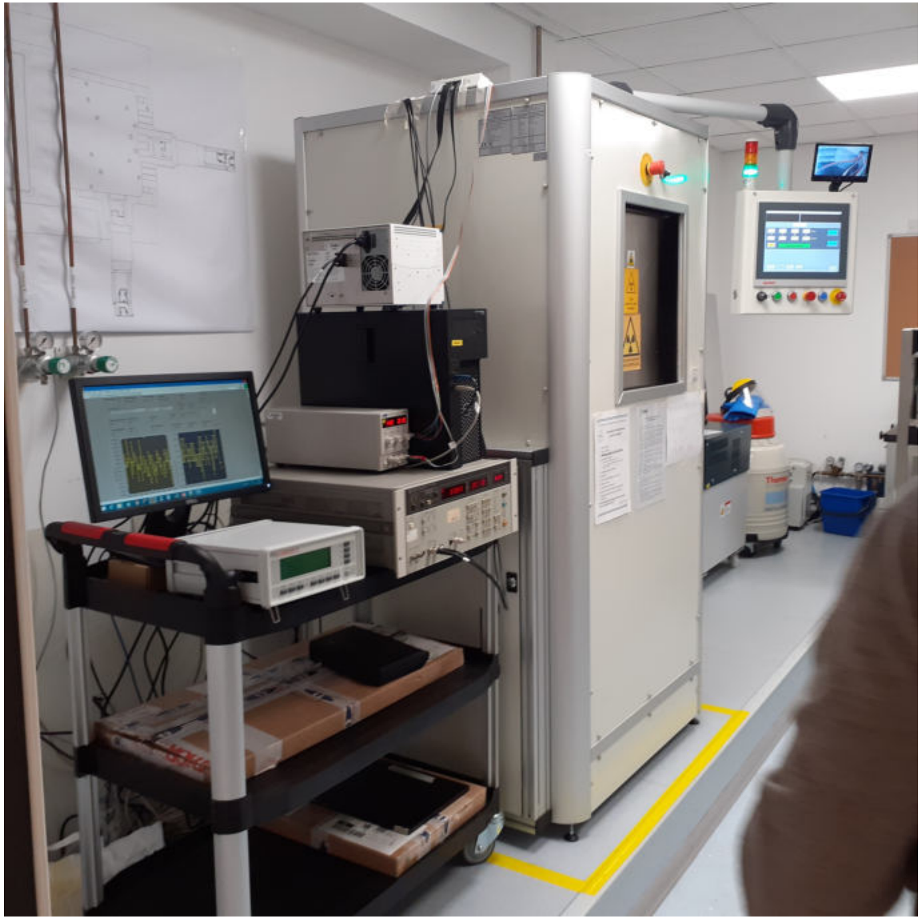


Diode - Farmer Chamber doserate comparison at the Padova x-ray irradiation laboratory

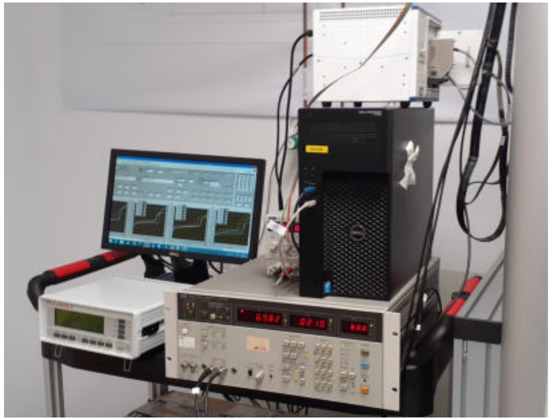
Ratio Diode Doserate/PTW Doserate		
SiO2=7.72+-0.04		Si=13.79+-0.07



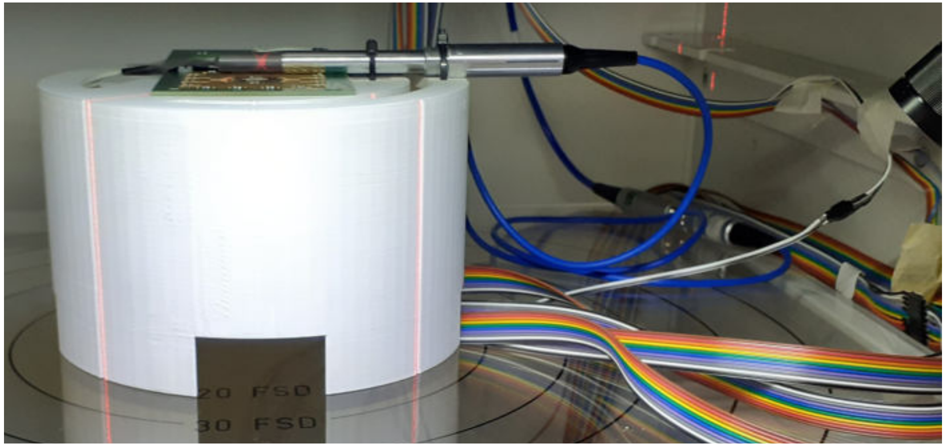
FBK SiPM Irradiations



Overview of the irradiation set-up



SiPM online characterization system (FBK)



Farmer chamber and SiPM support (FBK)

Conclusions

- In this set-up configuration the x-ray uniform spot is a circumference of 4.5 cm radiusand can be used for sensors or electronic circuits TID characterization studies requiring total dose of the order of 1-50 Mrad.
- After the success of this measurement campaign the implementation of a calibrated diode dose measurement system is under study.

Thank you for your attention!

And contact me for any other question!

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Thanks to:

Anna Rita Altamura, Fabio Acerbi, Stefano Merzi, Alberto Mazzi (FBK),
Federico Faccio (CERN), Riccardo Campana (INAF),
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F. Tommasino, R. Dolesi (UniTN)
for the help, the suggestions and the support in this work!

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

Abstract

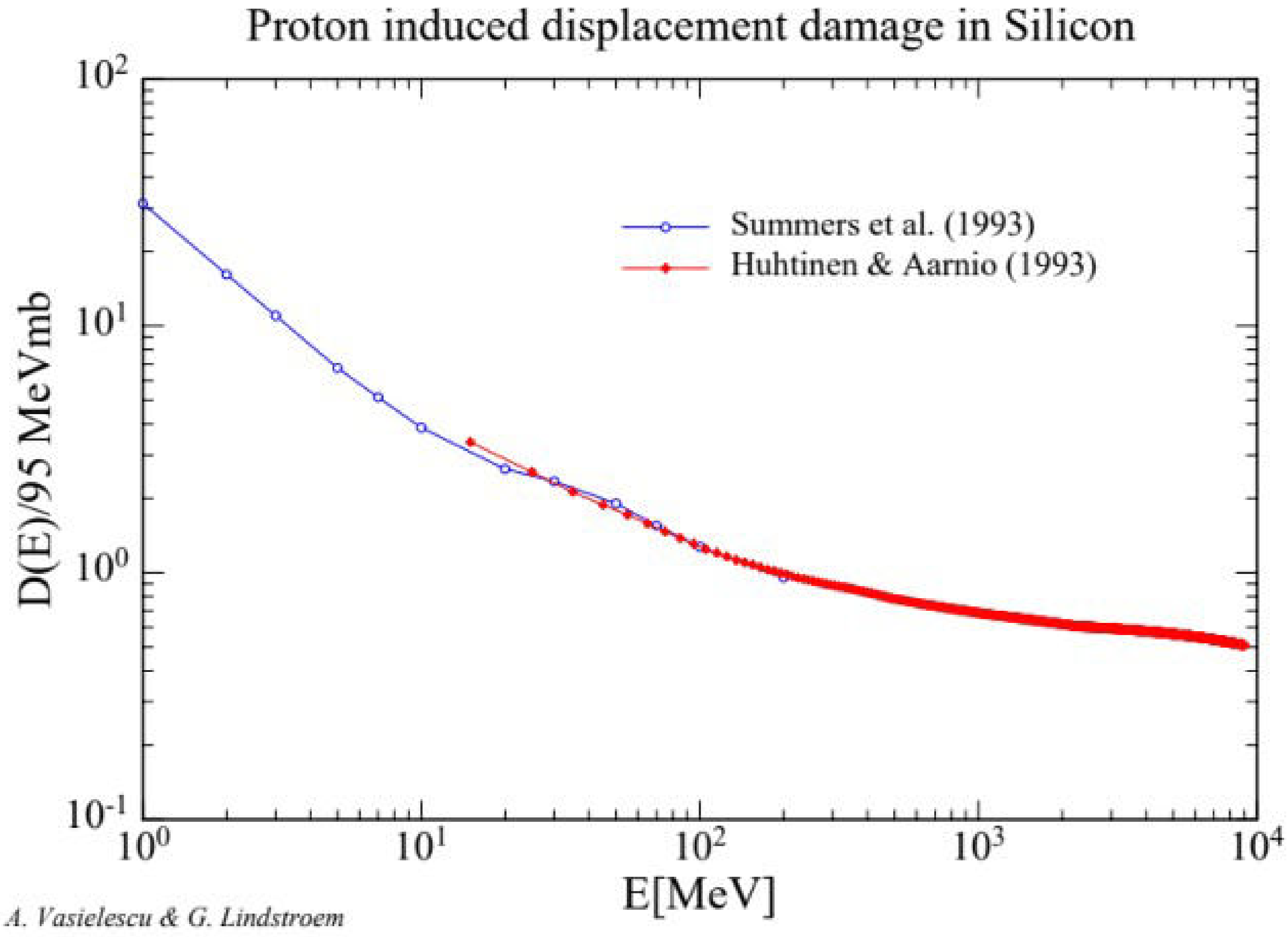
Total Ionizing Dose and Displacement Damage Effects on SiPM are standard required characterizations for applications of SiPM in every Nuclear, Space and Medical Instruments. The TIFPA-INFN Center in Trento (Italy) is equipped with two facilities, the Proton Experimental Area and the x-ray Irradiation Laboratory, where these characterizations can be performed with a proton beam and a x-rays beam. The Proton Experimental Area is part of the Trento Proton Therapy Center, a medical facility where protons are used for the treatment of oncological patients. Proton energy can be tuned in the [70-230] MeV range, the typical proton energy range used for medical applications. The x-ray Irradiation Laboratory is a biological/biophysics laboratory equipped with a x-ray irradiation cabinet containing a 3kW x-ray tube with tungsten anode and [30-195] kV tunable voltage.

In this talk will be described in details all the irradiation configurations of the Proton Experimental Area and how the the x-ray irradiation cabinet can be used for SiPM irradiation. The preparation and execution of a proton and x-ray irradiation campaign performed on SiPMs designed and produced by FBK in 2021 will be described also, showing the software packages used for the planification and the configurations adopted in these two facilities for this campaign.

References:

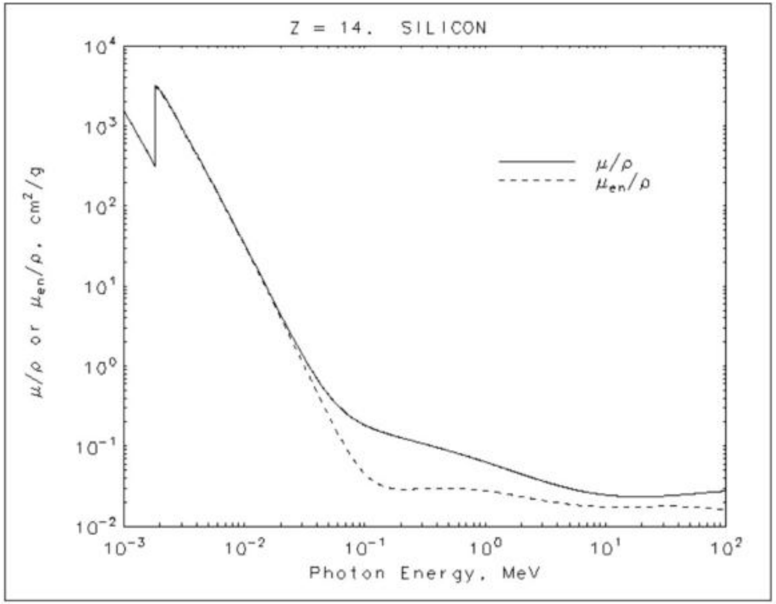
[1] Altamura A. R., Acerbi F., Di Ruzza B., Verroi E., Merzi S., Gola A.;
“Radiation damage on SiPMs for Space Applications”
https://arxiv.org/abs/2112.08089
[2] Di Ruzza B., Scifoni E., Donelli M., Cristoforetti L.;
“Experimental Assessment of the Electromagnetic Background Noise in the Trento Proton Therapy Center”
DOI: 10.1109/ICECET52533.2021.9698549; https://ieeexplore.ieee.org/document/9698549
[3] Di Ruzza, B.;
“Possibility of Total Ionizing Dose Effects measurements for LHC experiments elements in a medical facility: the TIFPA-INFN experience”
doi: 10.22323/1.397.0247; https://pos.sissa.it/397/247

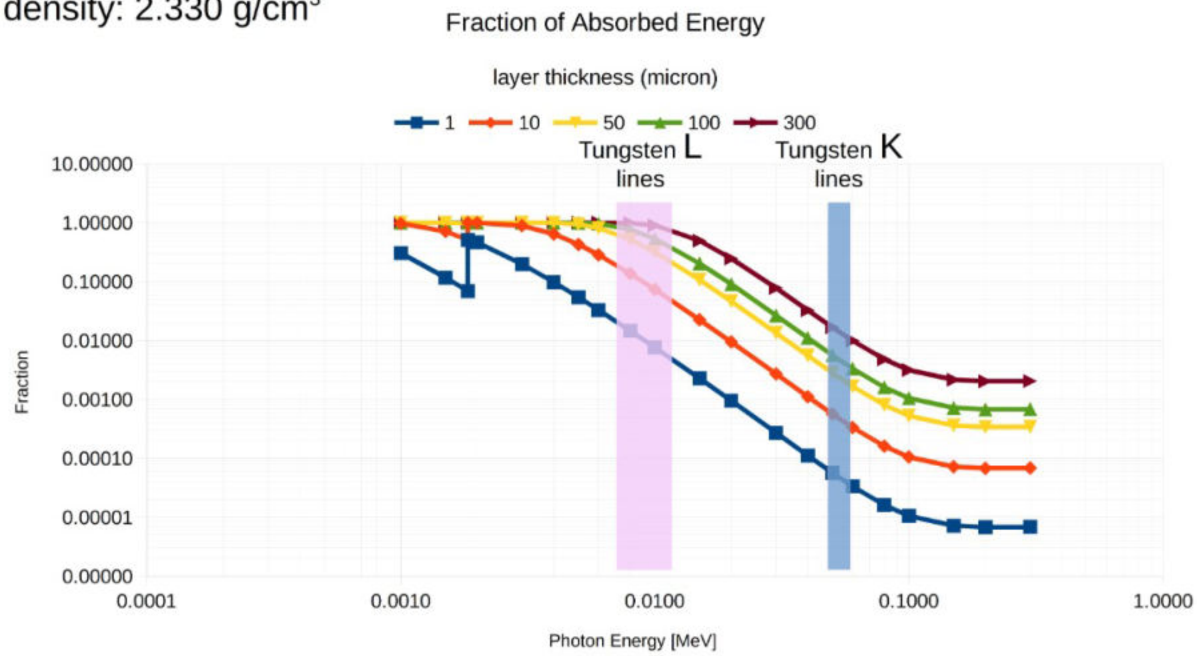
https://indico.cern.ch/event/1093102/timetable/#20220429.detailed


Proton induced displacement damage in Silicon
Summers et al. (1993)
Huhtinen & Aarnio (1993)
D(E)/95 MeVmb
E[MeV]
A. Vasielescu & G. Lindstroem

The TIFPA-INFN x-ray irradiation Laboratory

silicon density: 2.330 g/cm^3

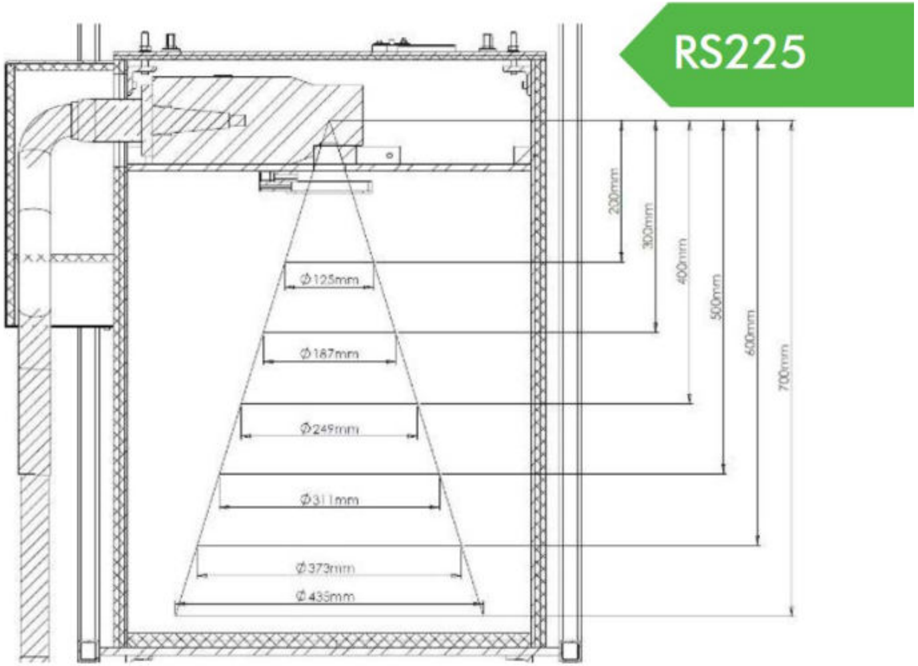




Cabinet Xstrahl RS225

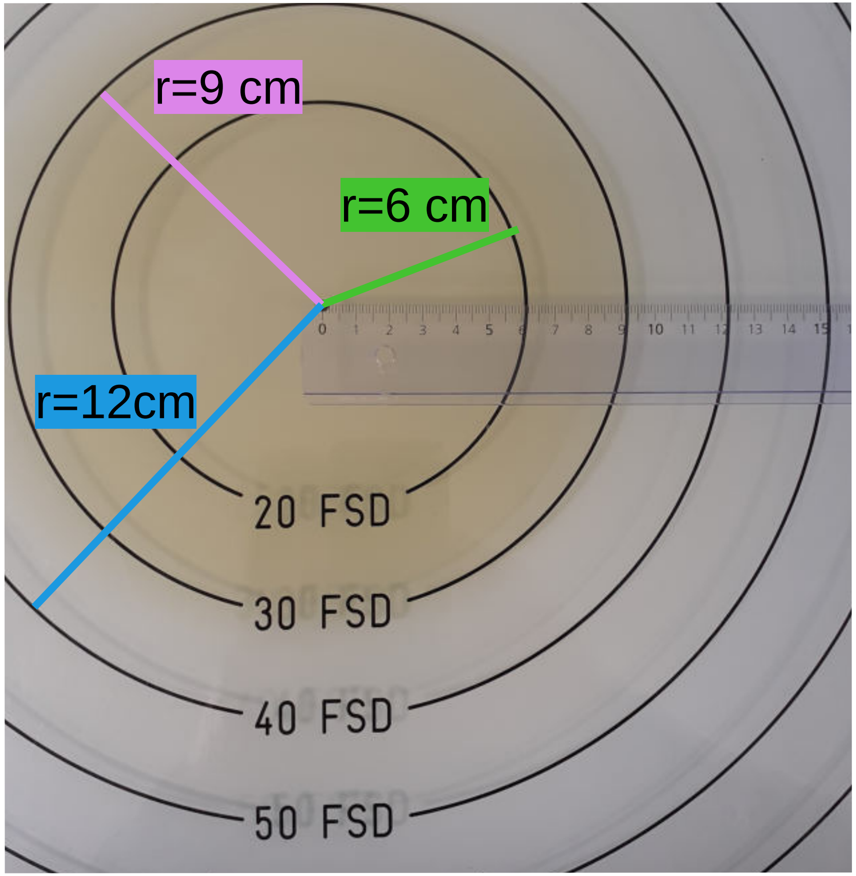
X-Ray Tube Output Limits	
Voltage	Up to 220kV
Current	1.0mA to 30mA
Power	3000W (broad focus for designated stability)
X-Ray Cabinet Dimensions	
Height	2010mm
Width	1105mm
Depth	960mm
Weight	1100kg
Lead Shielded Irradiation Chamber Dimensions	
Height	650mm
Width	570mm
Depth	600mm

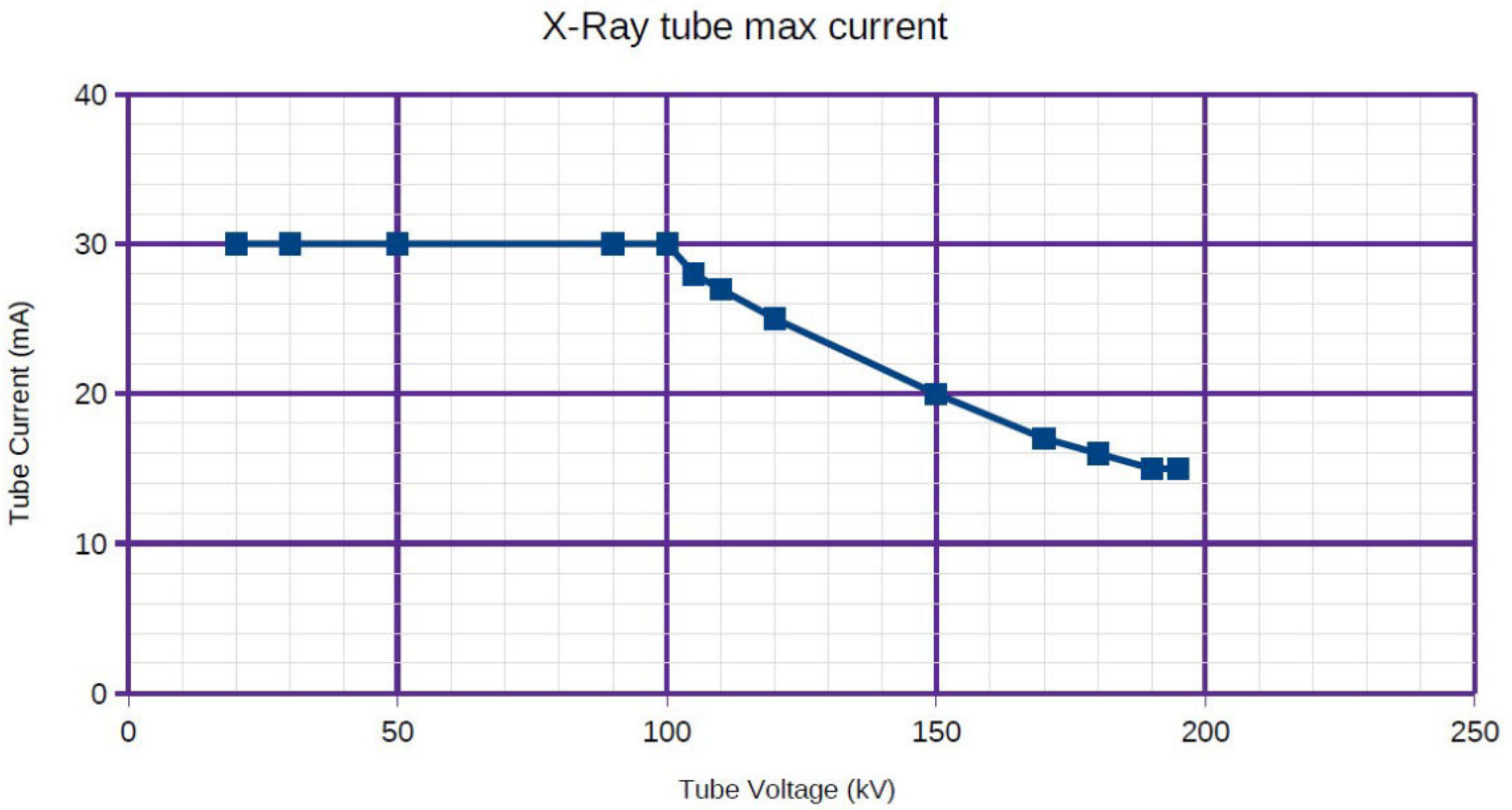
Shielding of cabinet to ≤ 2μSv/hour at 5 cm from any accessible surfaces as per IRR'99 guidelines.



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

R-X support plane




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