Department of Physics
University of Ioannina

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

Benedetto Di Ruzza
University of Foggia, Italy
benedetto.diruzza@unifg.it
ORCID: 0000-0001-9925-5254

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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:
benedetto.diruzza@unifg.it

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

Lecture 3

References E

Suggested web reference for lecture 3

Introduction to Hadrontherapy (2019)
Emanuele Scifoni: Research & Development for Hadrontherapy in Italy
Filename: Friday-03 Scifoni.pdf
In this directory:
https://drive.google.com/drive/folders/1y7AEdYsyhxjE3IfwhDP5h-Dn4tizXpvl

CERN Medical application seminar series (2015)
https://cern-medical.web.cern.ch/cern-medical/node/26.html

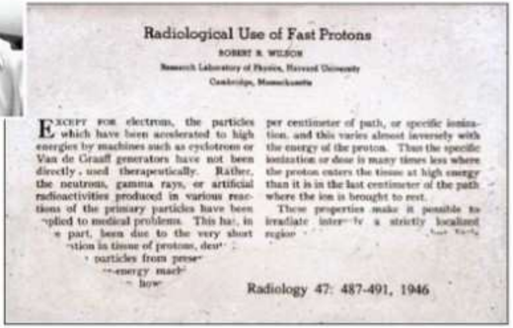
Overview of HEP techniques used for medical application (2013)
CERN: from particle physics to medical applications
https://indico.cern.ch/event/261667/contributions/581171/attachments/462124/640469/
med_app_english_2_lowres.pdf

Introduction to FLASH Radiotherapy (2021)
Emanuele Scifoni: Flash Radiotherapy
https://agenda.infn.it/event/29198/attachments/87290/116584/FLASHmysteriesPisaseminar_OK.pdf

Hadrontherapy: radiotherapy with charged particle beams

Hadrontherapy

R.R. Wilson, "Foreword to the Second International Symposium on Hadrontherapy," in Advances in Hadrontherapy, (U. Amaldi, B. Larsson, Y. Lemoigne, Y., Eds.), Excerpta Medica, Elsevier, International Congress Series 1144: ix-xiii (1997).



Radiological Use of Fast Protons

ROBERT R. WILSON

Research Laboratory of Physics, Harvard University

Cambridge, Massachusetts

Except for electrons, the particles which have been accelerated to high energies by machines such as cyclotrons or Van de Graaff generators have not been directly used therapeutically. Rather, the neutrons, gamma rays, or artificial radioactivities produced in various reactions of the primary particles have been applied to medical problems. This has, in part, been due to the very short ...tion in tissue of protons, deu... particles from prese... ...energy mach... how...

per centimeter of path, or specific ionization, and this varies almost inversely with the energy of the proton. Thus the specific ionization or dose is many times less where the proton enters the tissue at high energy than it is in the last centimeter of the path where the ion is brought to rest.

These properties make it possible to irradiate inten...ly a strictly localized region ...

Radiology 47: 487-491, 1946

- Also called
  - Ion beam therapy
  - (Charged) Particle Therapy
- Radiation Therapeutic option exploiting **charged particle beams** features, physics and radiobiological based

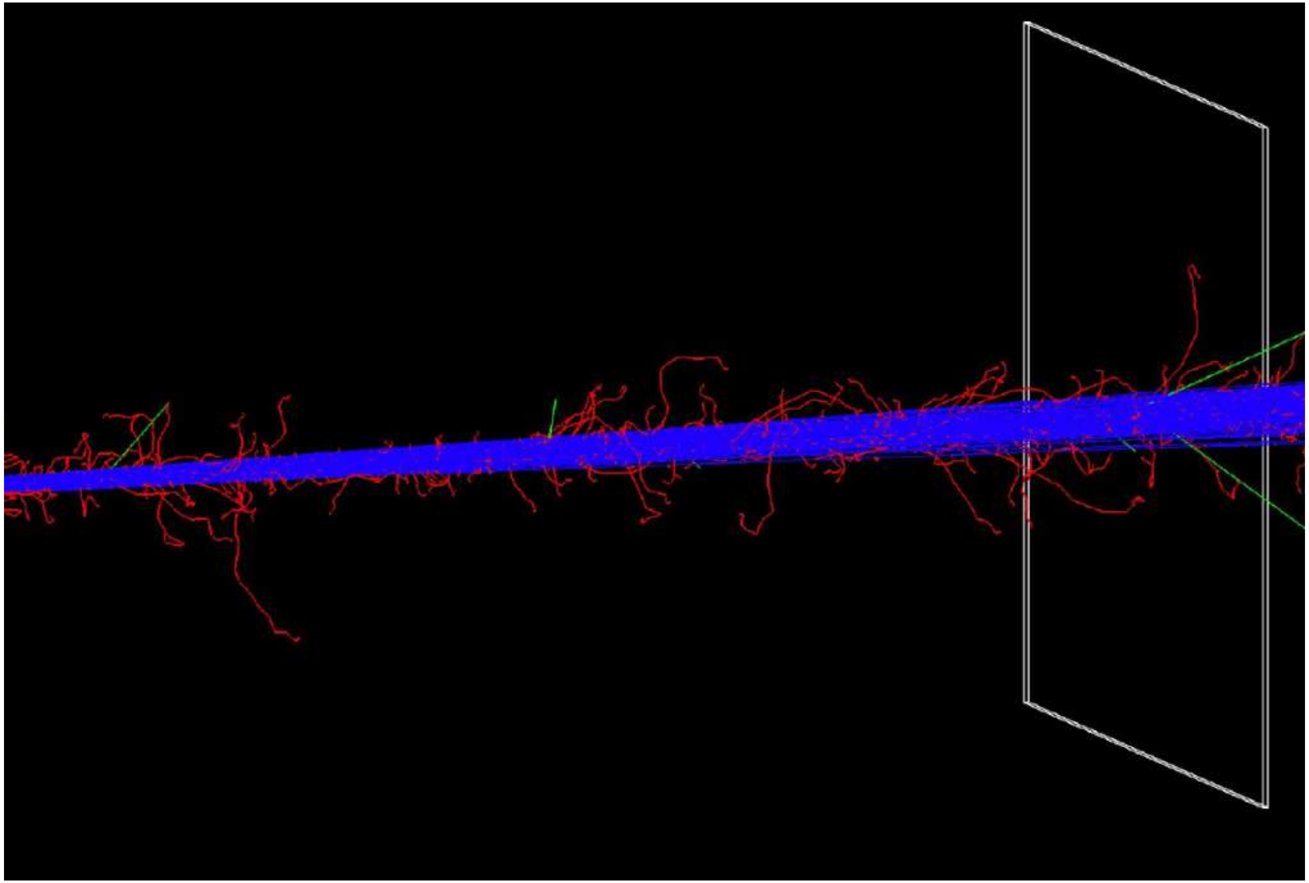
Robert Rathbun Wilson

The first Director of the Fermilab Laboratory

Slide from:
Emanuele scifoni
SIRAD school 2019

Hadrontherapy: radiotherapy with charged particle beams

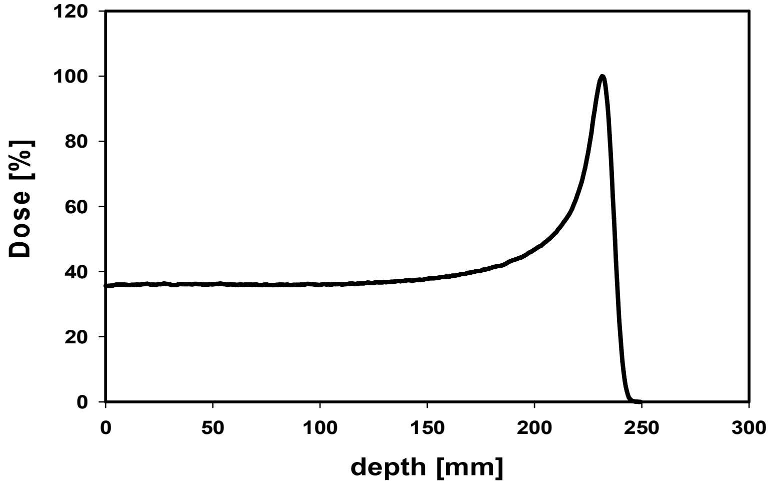
Why charged Ions?



Hadrontherapy: radiotherapy with charged particle beams

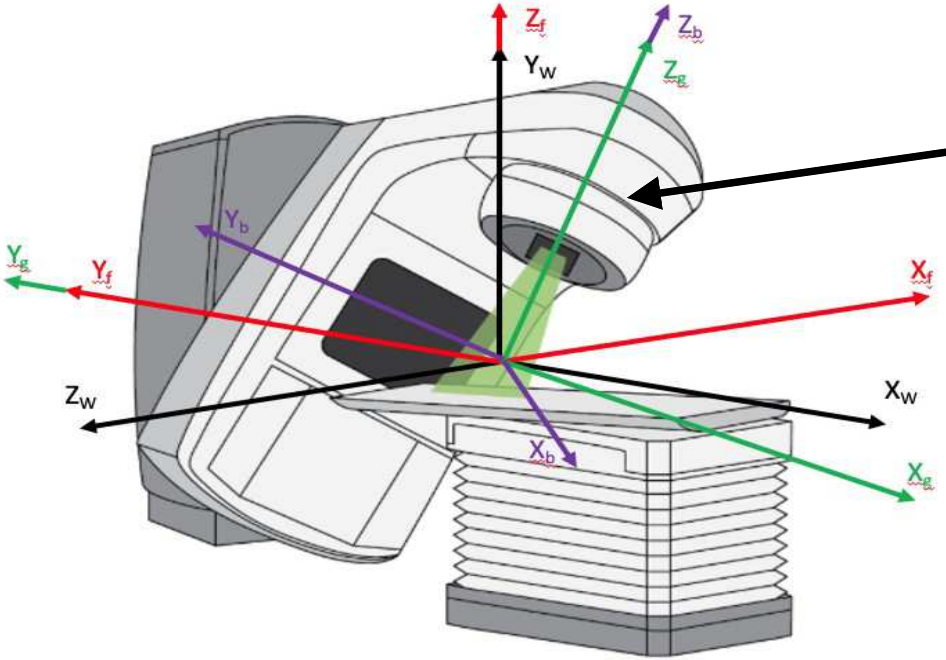
Why charged Ions?

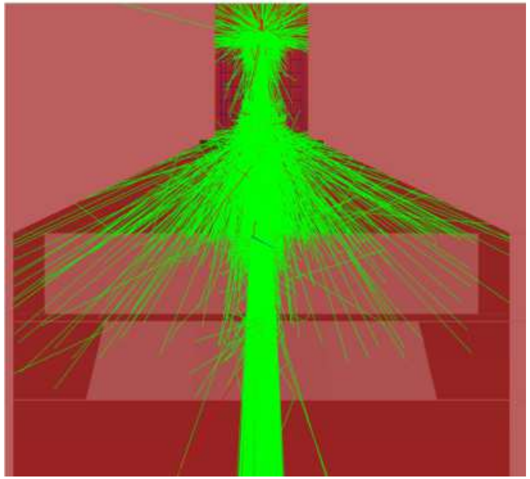
(remember: Dose= energy delivered/mass)



- Protons and Ions lose their energy in many individual interactions with medium electrons
- Protons with the same initial energy may have slightly different “Ranges”: “Range straggling”

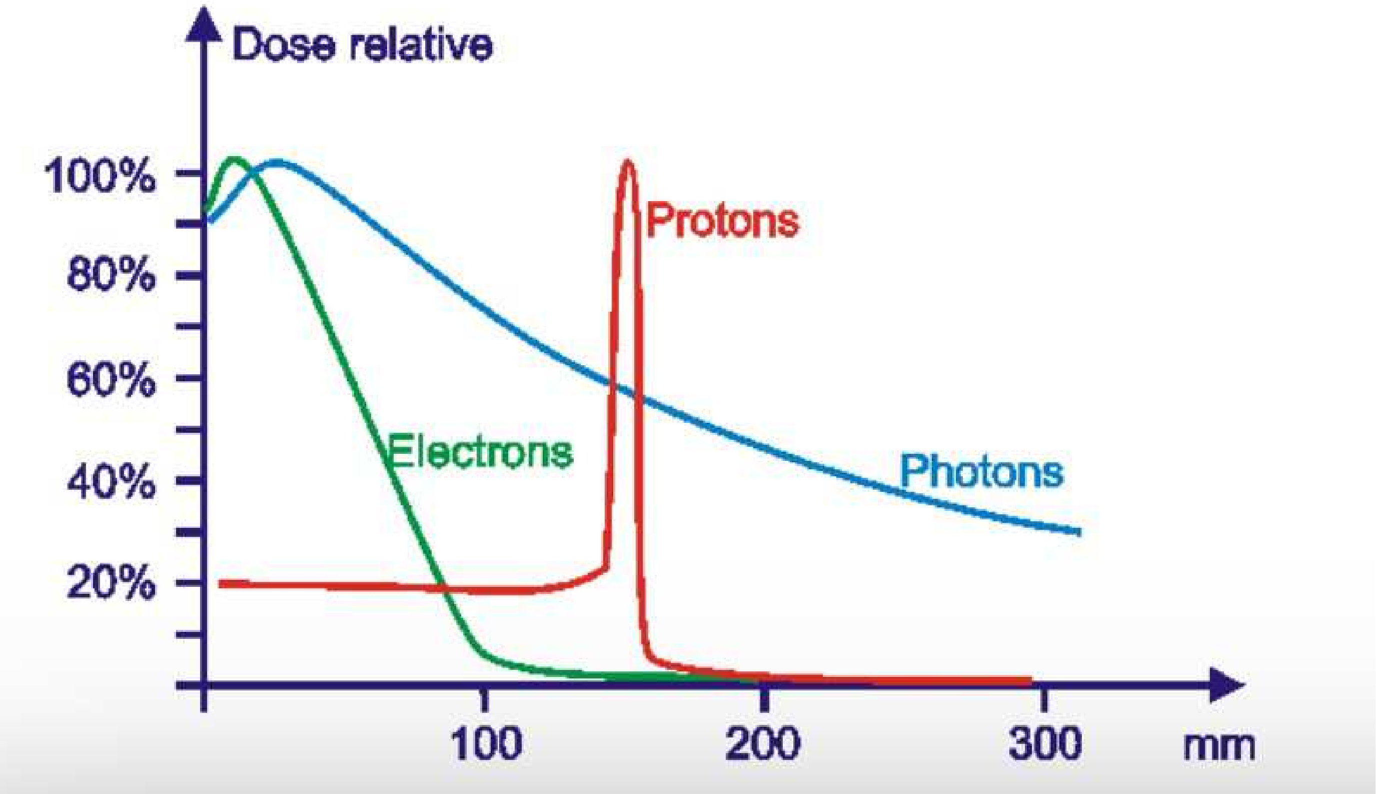
Patient treatment with electrons or photons



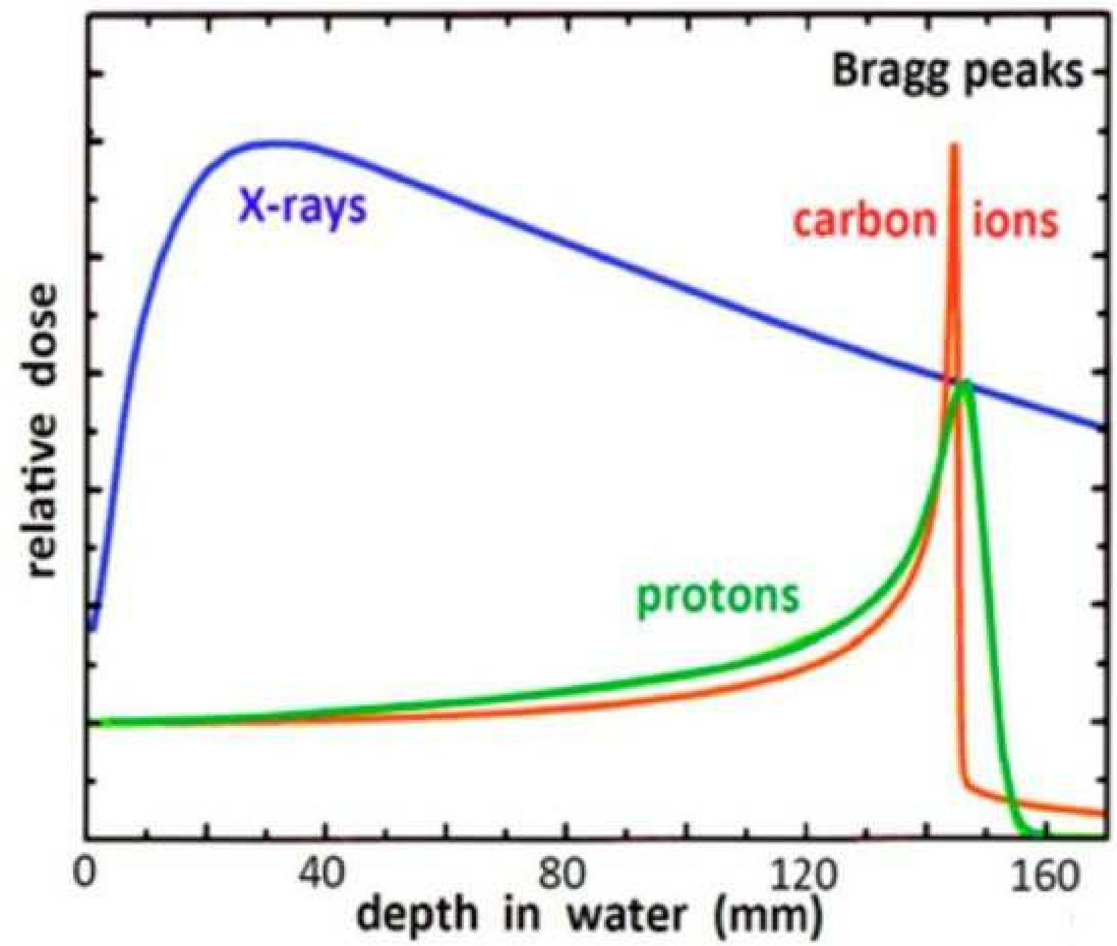


Treatment head drawing copied from https://www.cancer.ca/en/cancer-information/diagnosis-and-treatment/radiation-therapy/external-radiation-therapy/?region=on

Dose delivered: electrons, photons (~6 MeV x-rays) and protons comparison



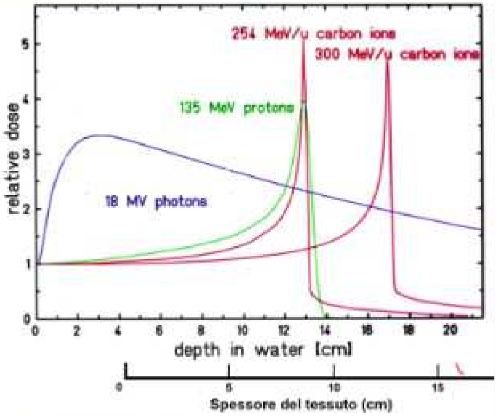
Delivered dose: x-rays ions comparison

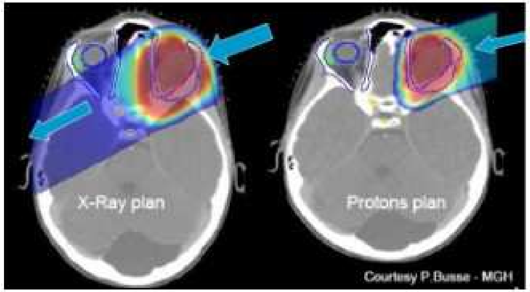


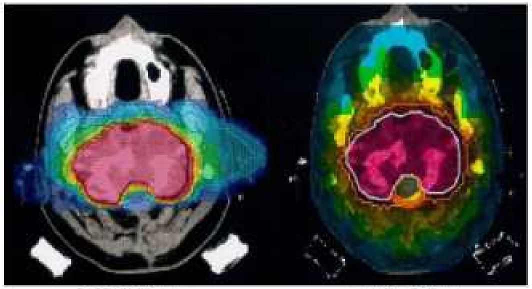
Hadrontherapy: radiotherapy with charged particle beams

Hadrontherapy Rationale

- Protons and other ions deposit less dose in healthy tissue/ OAR
  - Macroscopic **physical** advantages
  - In some cases also **biological** advantages
- Clear advantage for sustainability of a retreatment







C-12, 2 fields IMRT, 9 fields

Jäkel, Debus, Heidelberg

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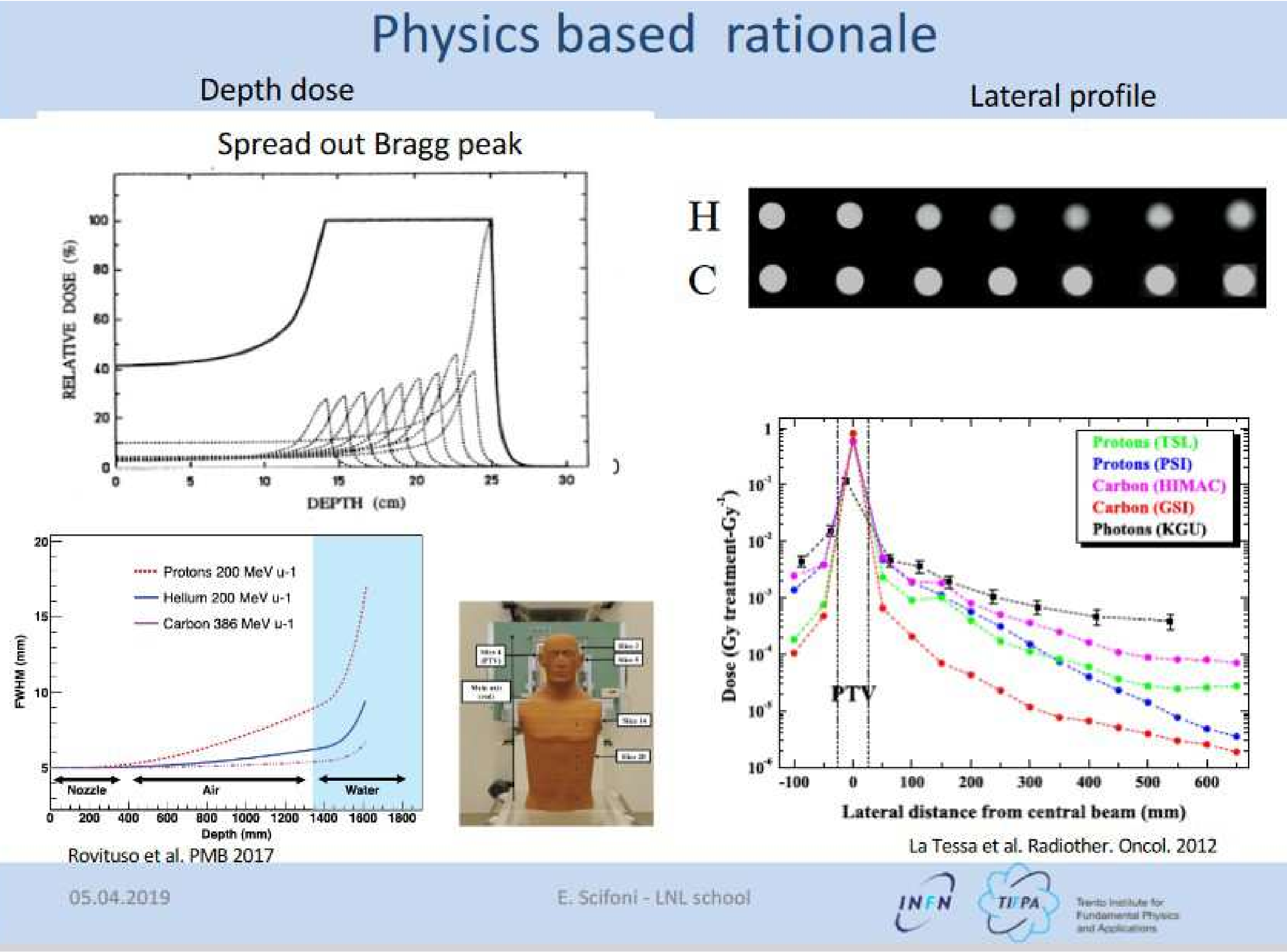
Hadrontherapy: radiotherapy with charged particle beams



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Hadrontherapy: radiotherapy with charged particle beams

In the treatment rooms, the beam is distributed into the patient, but into any target as well, with an *active beam delivery system*. To explain what this means, consider the tumour inside the patient and subdivide it in *iso-range slices*. The beam energy is at first set such that the Bragg peak is in the first slice. The beam is displaced with two *scanning magnets* to paint the slice in order to deliver the planned dose to every spot, as illustrated in Figure 2-2.

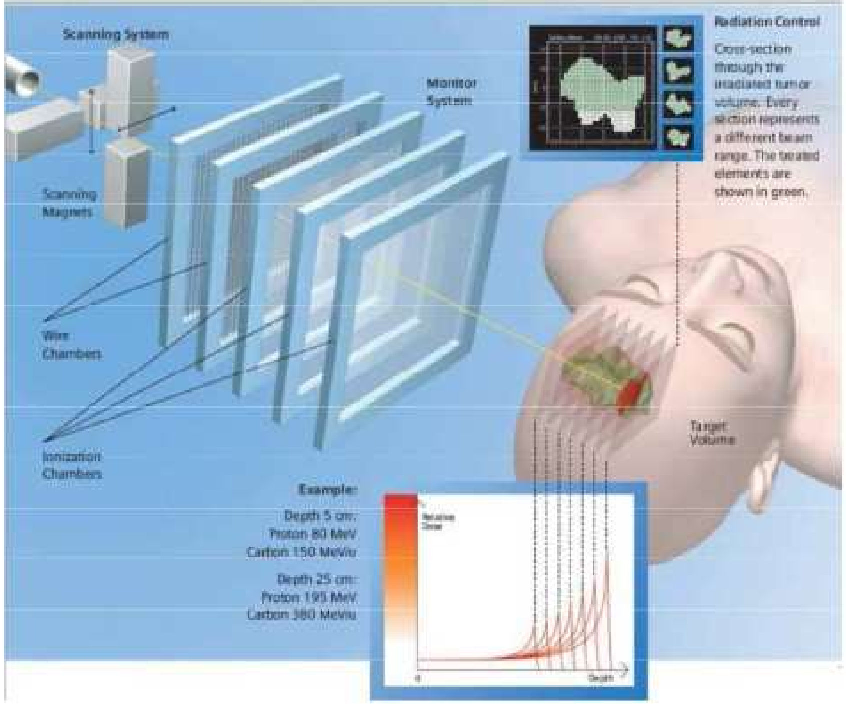

Figure 2-2. Illustration of the active scanning system (courtesy of Siemens medical).

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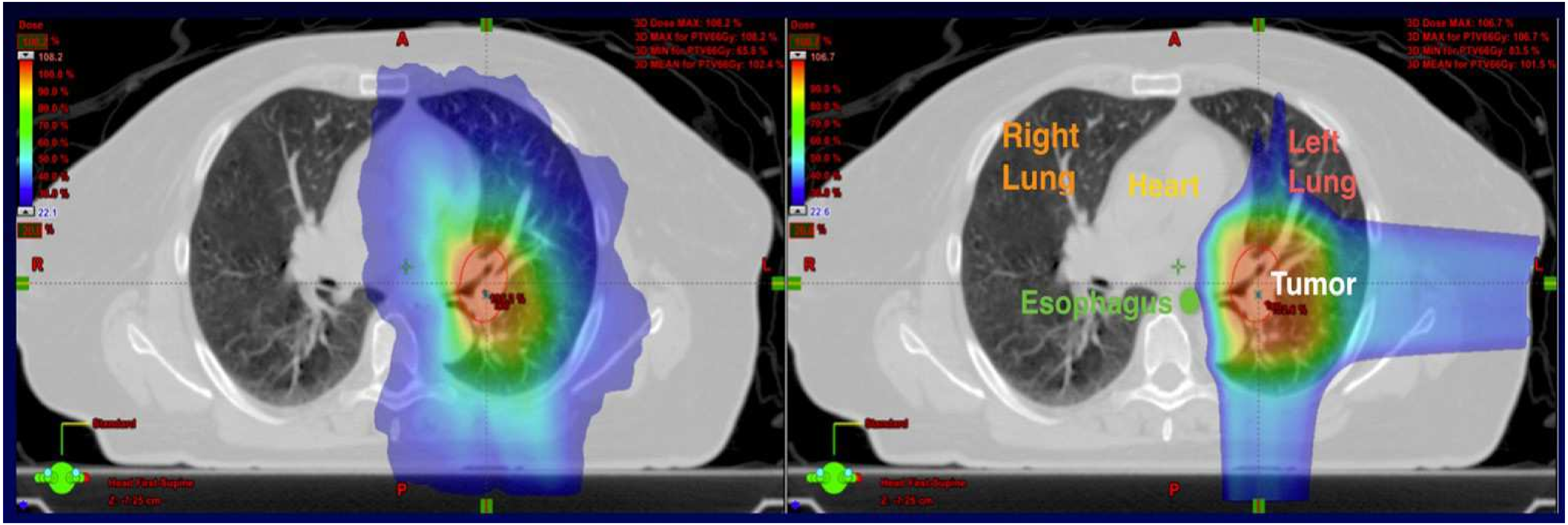
Hadrontherapy: radiotherapy with charged particle beams

Hadrotherapy: radiotherapy with charged particle beams

How the irradiation is prepared?

Monte Carlo dose calculation methods are particularly relevant in hadrontherapy



There is no transmission imaging for treatment verification

Hadrontherapy: radiotherapy with charged particle beams

A snapshot of history

- 1946 Wilson's proposition
- 1954 – Berkeley treats the first patient and begins extensive studies with various ions
- 1957 – first patient treated with protons in Europe at Uppsala
- 1961 – collaboration between Harvard Cyclotron Lab. and Massachusetts General Hospital
- 1993 – patients treated at the first hospital-based facility at Loma Linda
- 1994 – first facility dedicated to carbon ions operational at HIMAC, Japan
- 2009 – first European proton-carbon ion facility starts treatment in Heidelberg

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The CNAO Ions irradiation Facility

CNAO: National Center for Oncological Hadron-therapy

Synchrotron accelerator

The main accelerator is a 25 m diameter synchrotron designed to accelerate carbon ions and protons

The CNAO synchrotron can accelerate ions injected with an energy of 7 MeV/u up to the energy correspond-ing to the magnetic rigidity of 6.35 T m.
For C $^{6+}$ ions this corresponds to 400 MeV/u; in the case of protons, the maximum energy of 250 MeV corresponds to a magnetic rigidity of 2.43 T m, well below the maximum.

Particles available:

- Protons: from 70 MeV up to 250 MeV
- Carbon C $^{6+}$: from 115 MeV/u up to 400 MeV/u

Intensity:

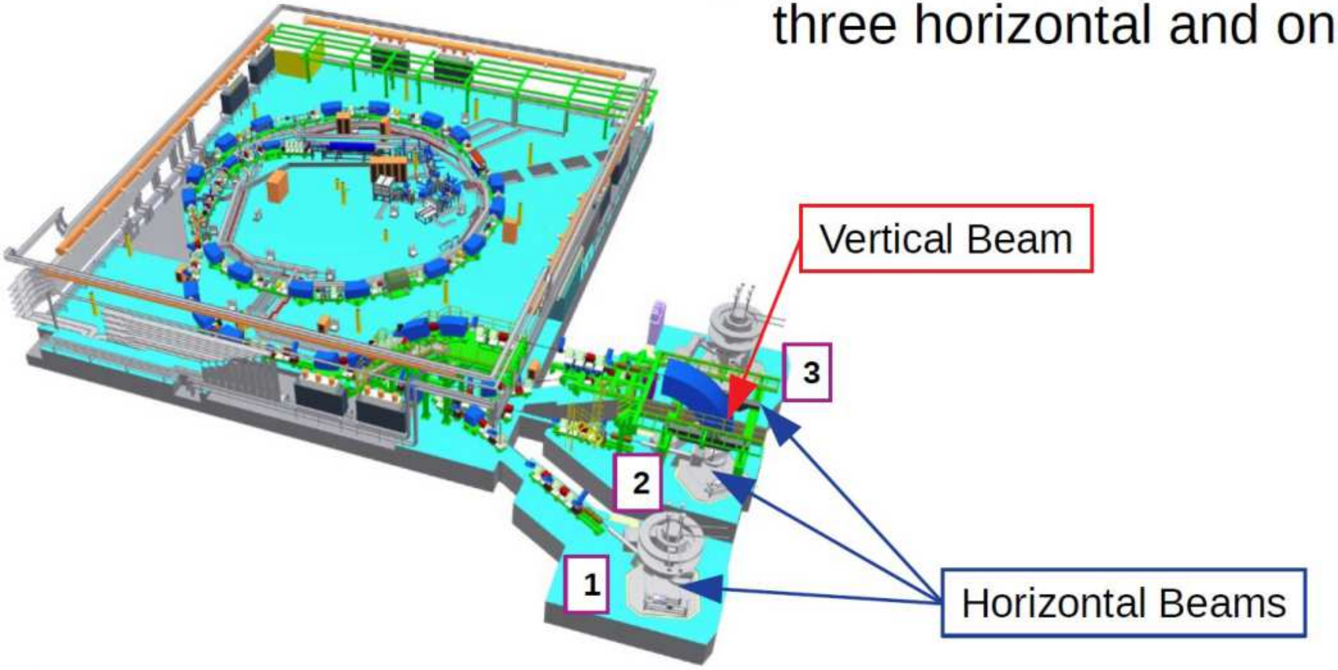
- max 10^8 part/s

https://fondazionecnao.it/en/

The CNAO Ions irradiation Facility

CNAO: National Center for Oncological Hadron-therapy

Three patients treatment rooms with four beams: three horizontal and one vertical



https://fondazionecnao.it/en/

The CNAO Ions irradiation Facility

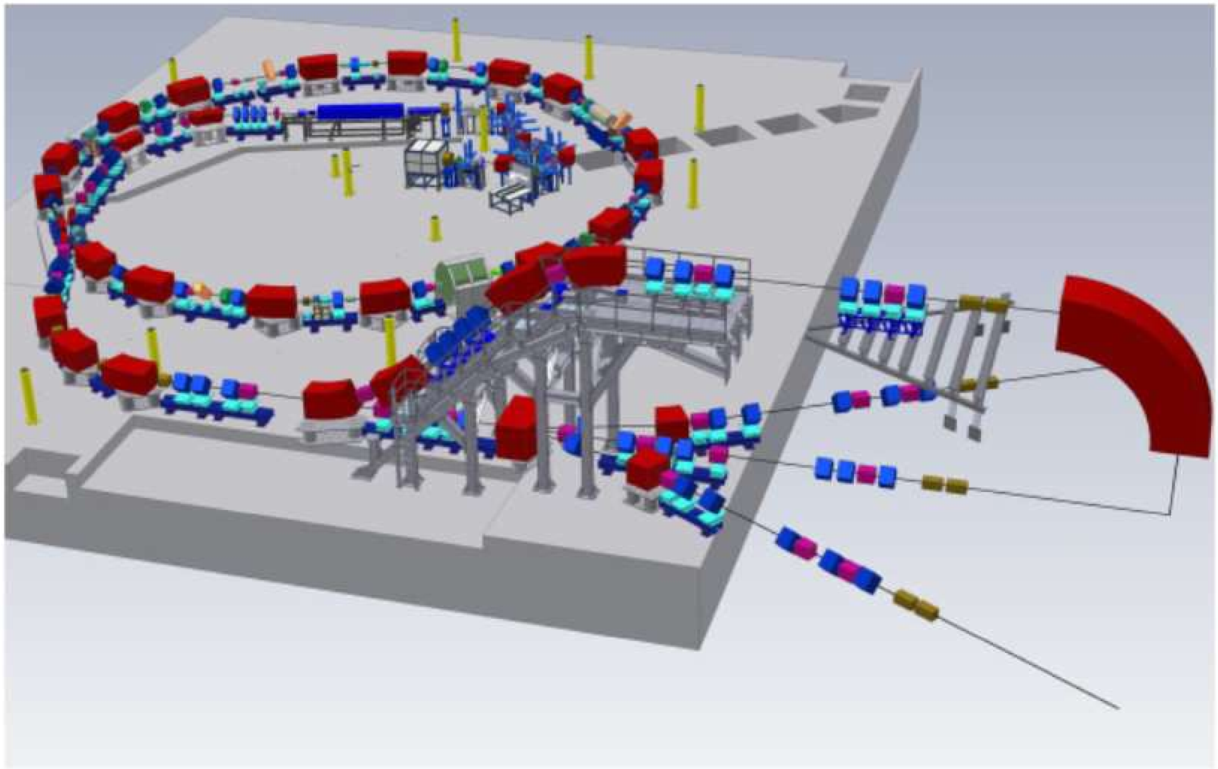


Figure 1: 3-D scheme of the whole CNAO machine, from the injector (inside the ring) to the 4 extraction lines.

https://fondazionecnao.it/en/

The Trento Proton Therapy Center (TPTC)

The Trento proton Therapy Center (TPTC)
Is a medical facility for hadron therapy
located in Trento, Italy.
It is operated by the *"Azienda Provinciale per i Servizi Sanitari"* (APSS).

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

The facility is equipped with two gantry rooms for patient treatment
and an experimental room for physics and biophysics experiments.
Clinical activity started in 2014.

The Trento Proton Therapy Center (TPTC)

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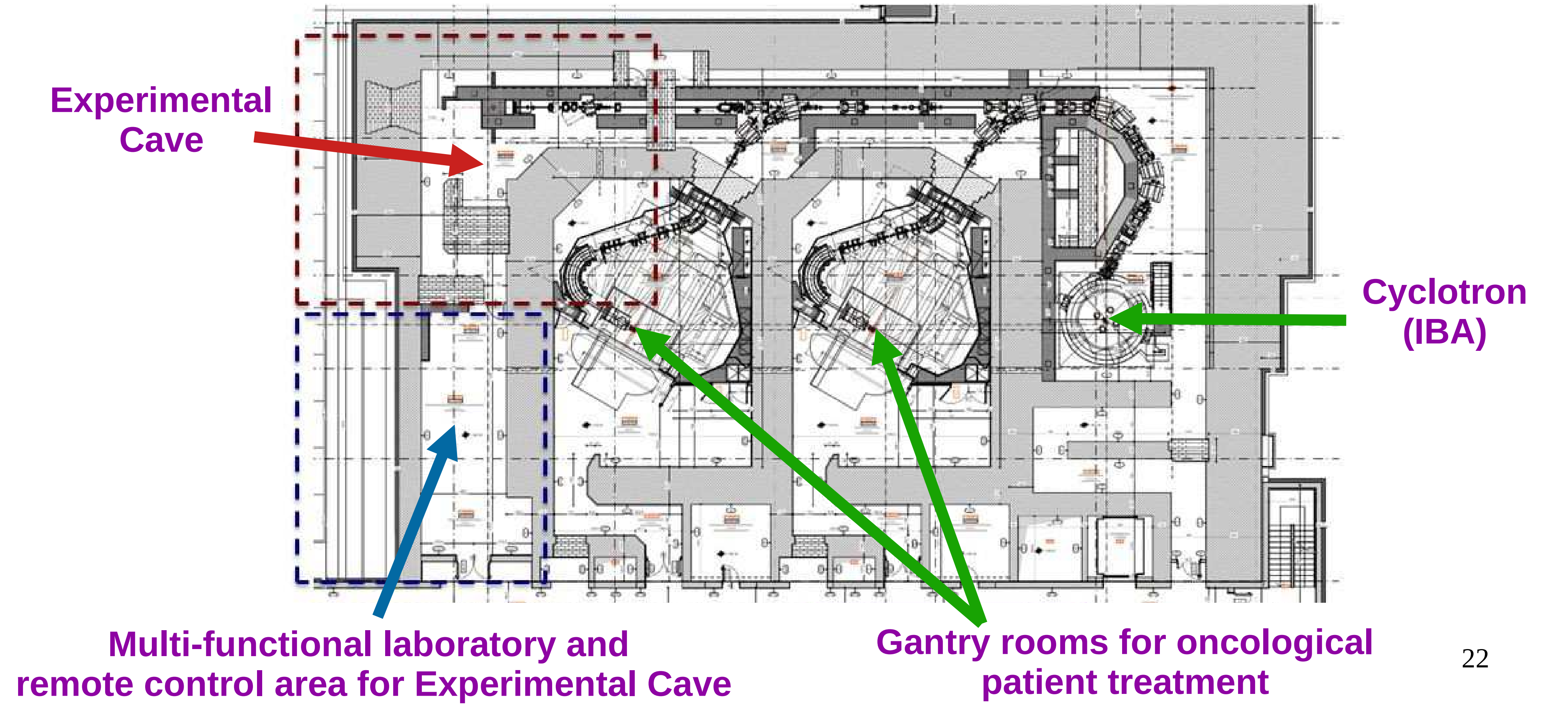

The Trento Proton Therapy Center (TPTC)

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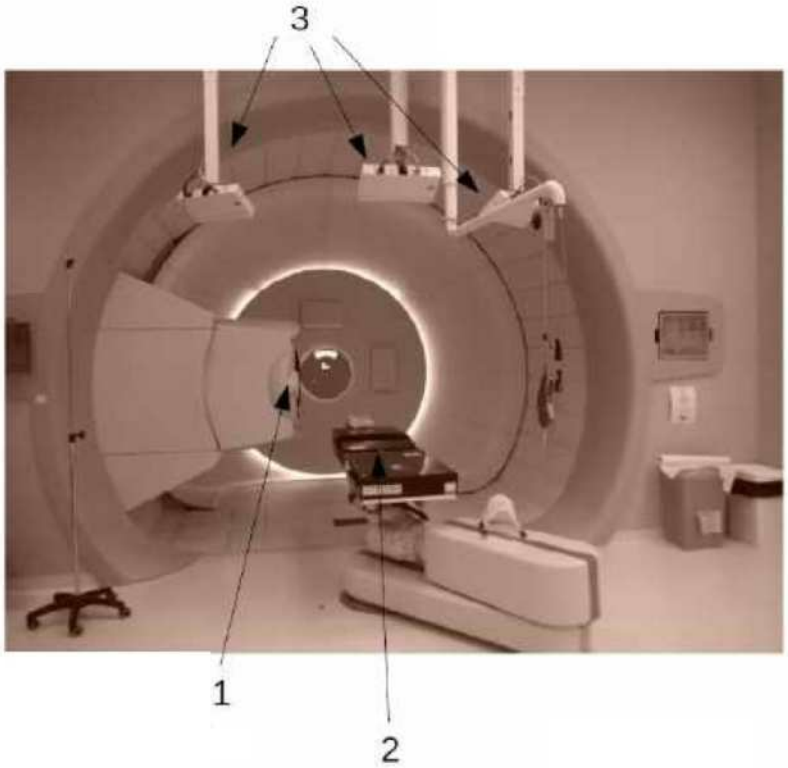
The TPTC Gantry rooms



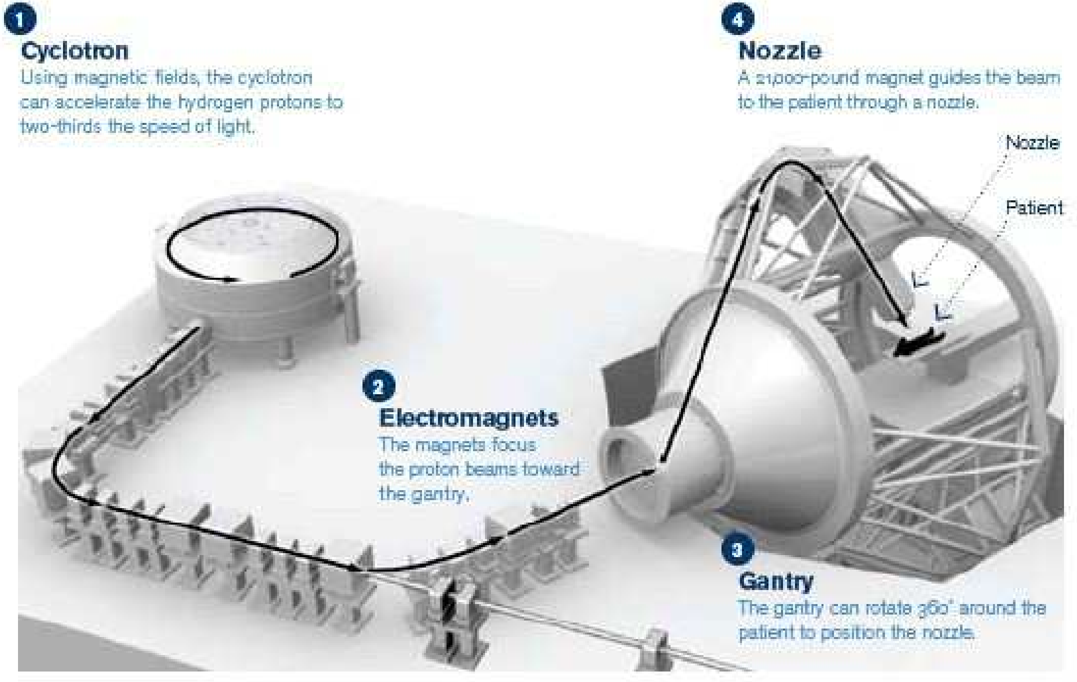
The TPTC is equipped with the two gantry rooms realized by IBA (https://iba-worldwide.com/).

In each treatment room the gantry (1) can rotate 360 degrees, while the exact position of patient on the patient couch(2) can be monitored using non-invasive technique like infrared cameras (3).

Each gantry room includes a patient positioning system featuring a robot-controlled patient couch.

Proton beam energy can be tuned from 70 MeV up to 226 MeV.

(* Photo by the author)



https://www.drmanojsharmaoncology.com/proton-therapy https://www.oncolink.org/cancer-treatment/radiation/types-of-radiation-therapy/proton-therapy/overviews-of-proton-therapy/proton-therapy-behind-the-scenes

Trento Gantry (service area)

The Trento Proton Therapy Center (TPTC)

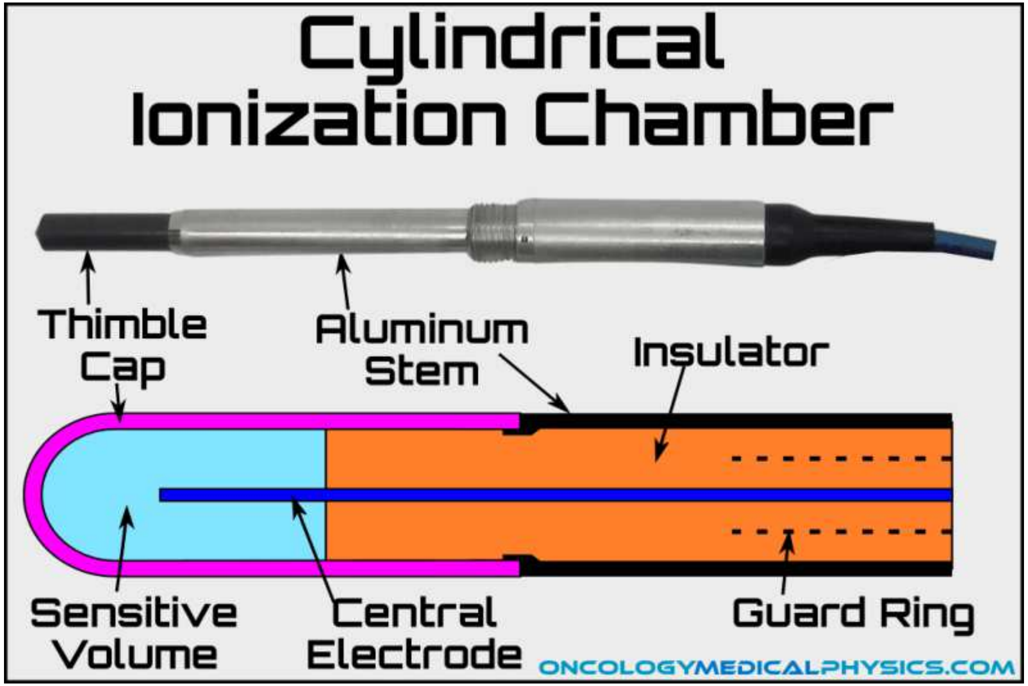
https://protonterapia.provincia.tn.it/eng/?/switchlanguage/to/protonterapia_eng

The Trento Proton Therapy Center (TPTC)

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

Dosimetry

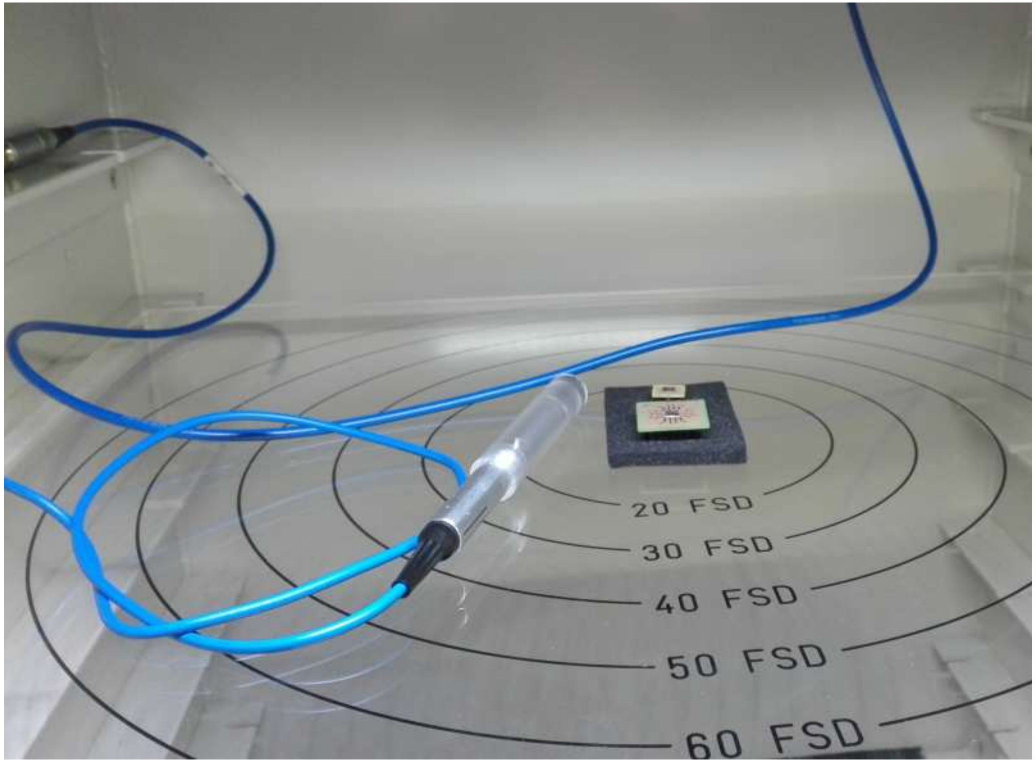
From:
https://oncologymedicalphysics.com/
ionization-chamber-design-and-operation**/**



Farmer Chambers
Key Point: Farmer chambers
are thimble ionization chambers widely used in reference dosimetry.

- Typical Sensitive Volume: **0.6cc** (approximately cylindrical, 0.3cm radius, 2cm length)
- Typical Response: **20nC/Gy**
- Effective Point of Measurement:
  - Photons: 0.6rcav (~0.18cm) upstream of central axis
  - Electrons: 0.5rcav (~0.15cm) upstream of central axis

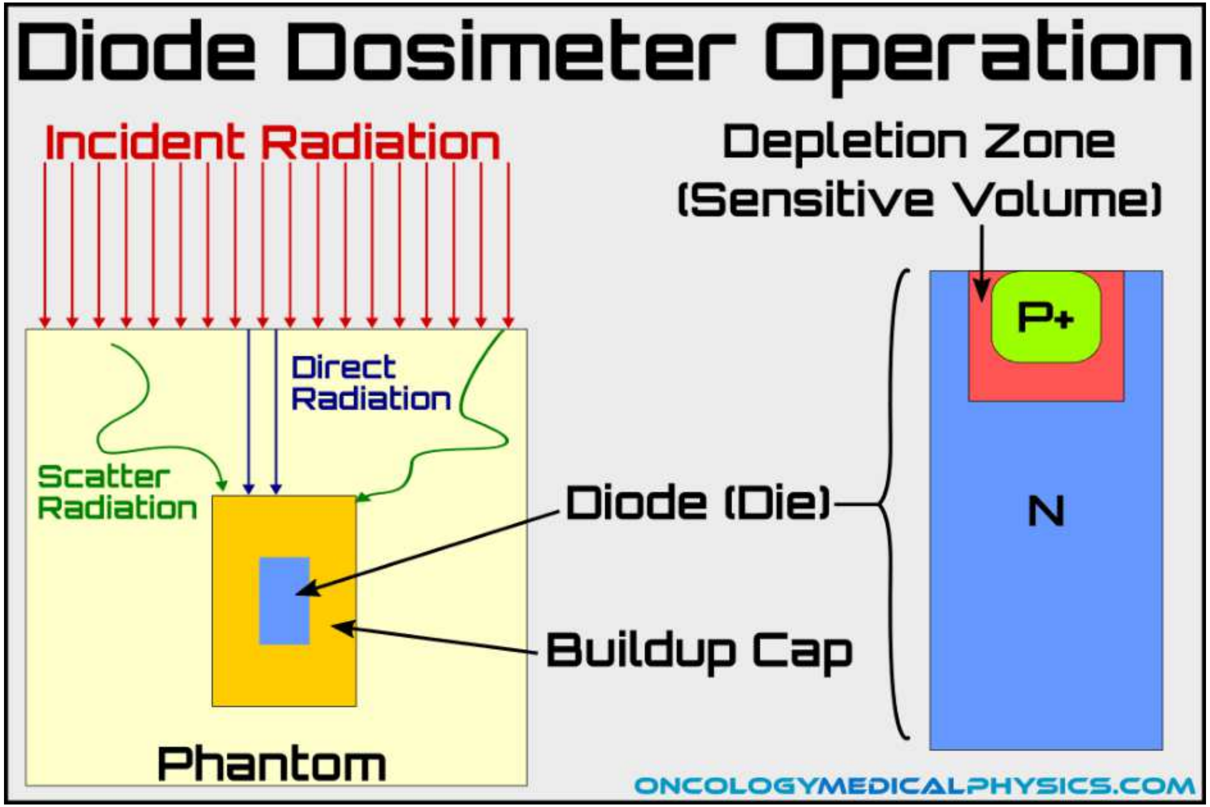
Dosimetry



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

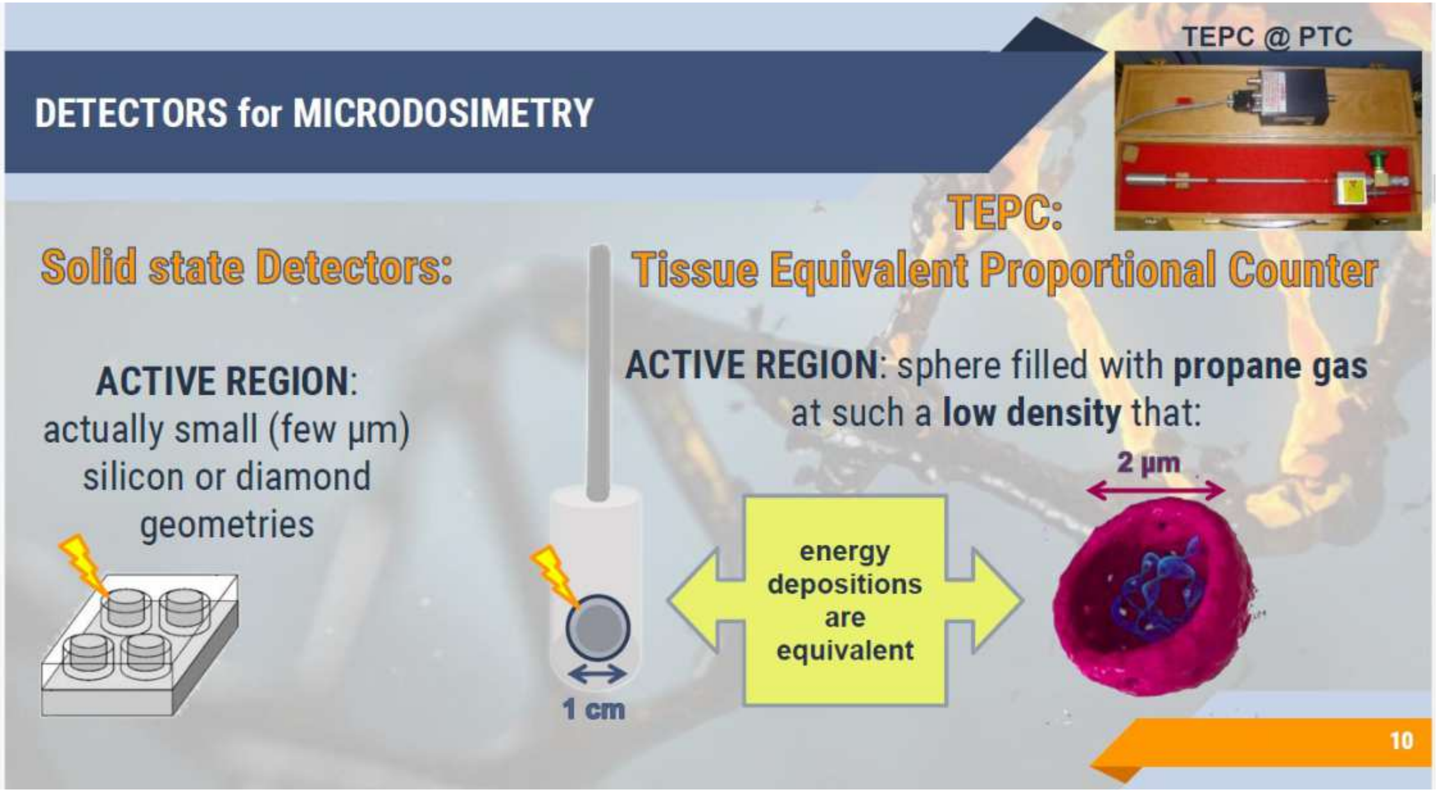
Trento PTW Farmer chamber

Dosimetry



https://oncologymedicalphysics.com/diode-detectors/

Micro-Dosimetry



Slide from
Marta Missiaggia

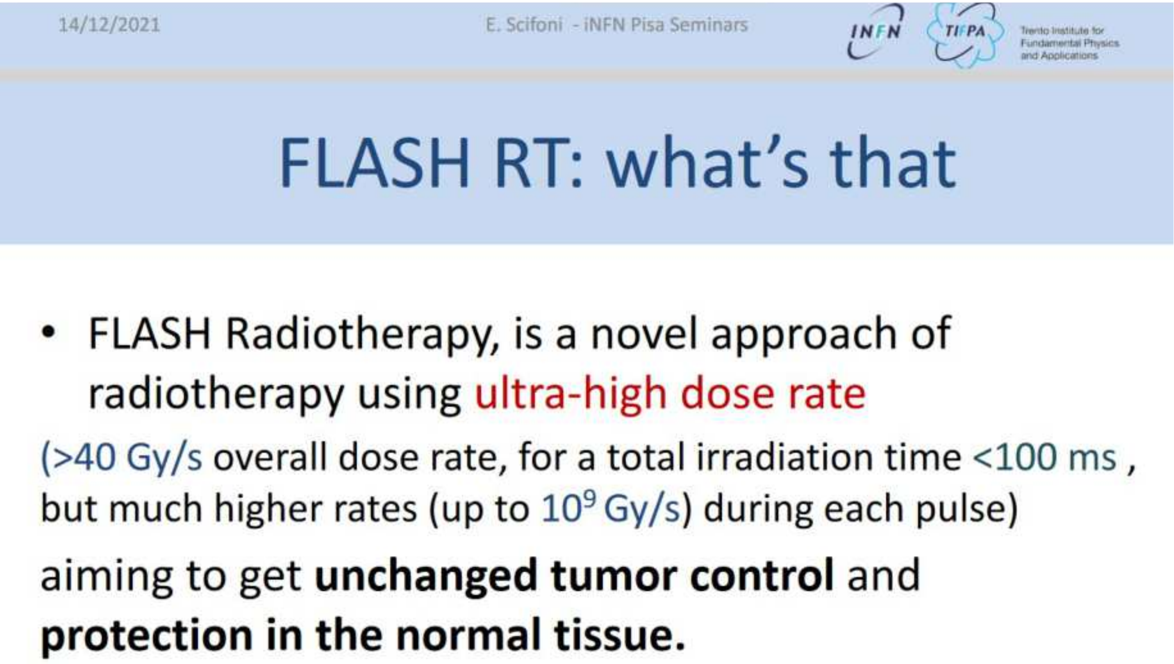
TIFPA Trento Beam Line worshop 2020

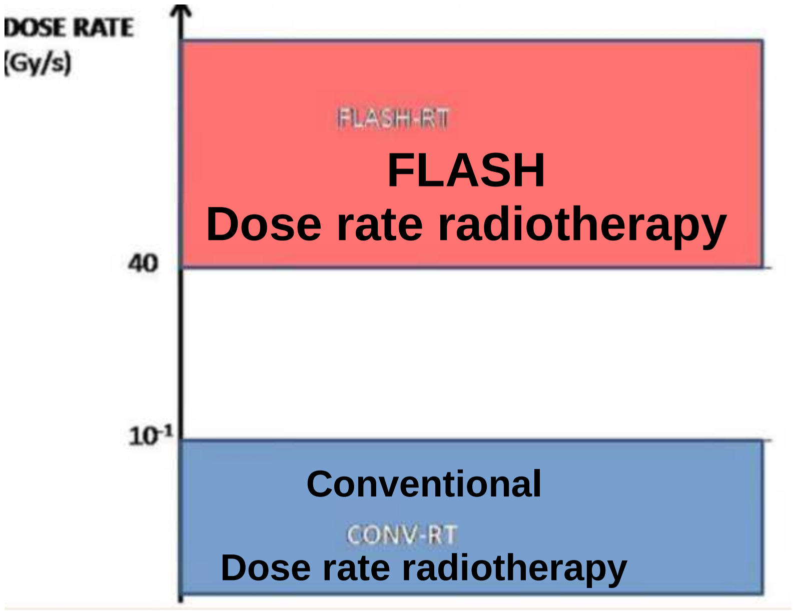
Water phantom

IBA water phantom
https://www.iba-dosimetry.com/product/wp34-calibration-water-phantom

Picture credits: IBA

FLASH IRRADIATION





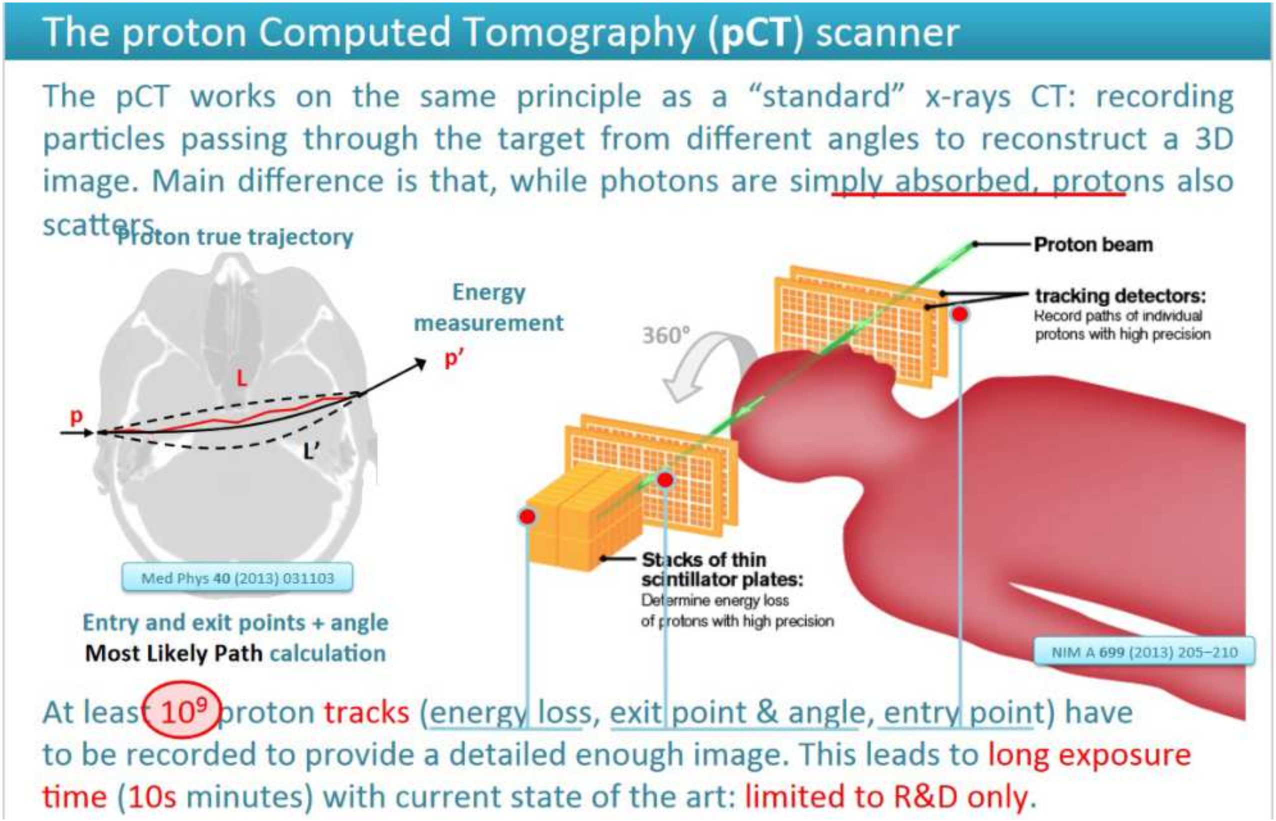
This emerging irradiation technique is requiring a new generation of extremely fast beam control devices, dosimeters …

HEP techniques used for medical application:

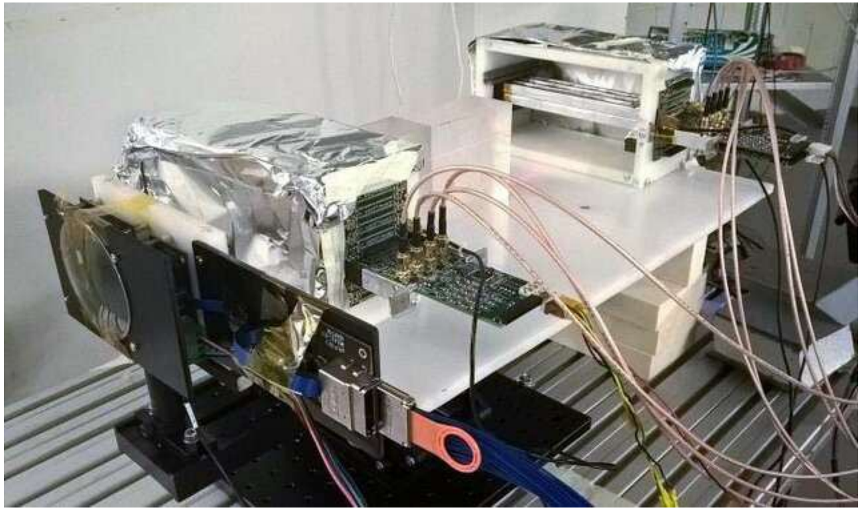
HEP techniques used for medical application: the iMPACT Project

X-ray 3D CT cannot distinguish tissue densities with the required precision: proton therapy limit today (bigger systematic error, up to 5%). But protons actually can (and with much less dose, ≈ 1.5 mGy vs. 10-100 mGy).

HEP techniques used for medical application: the iMPACT Project

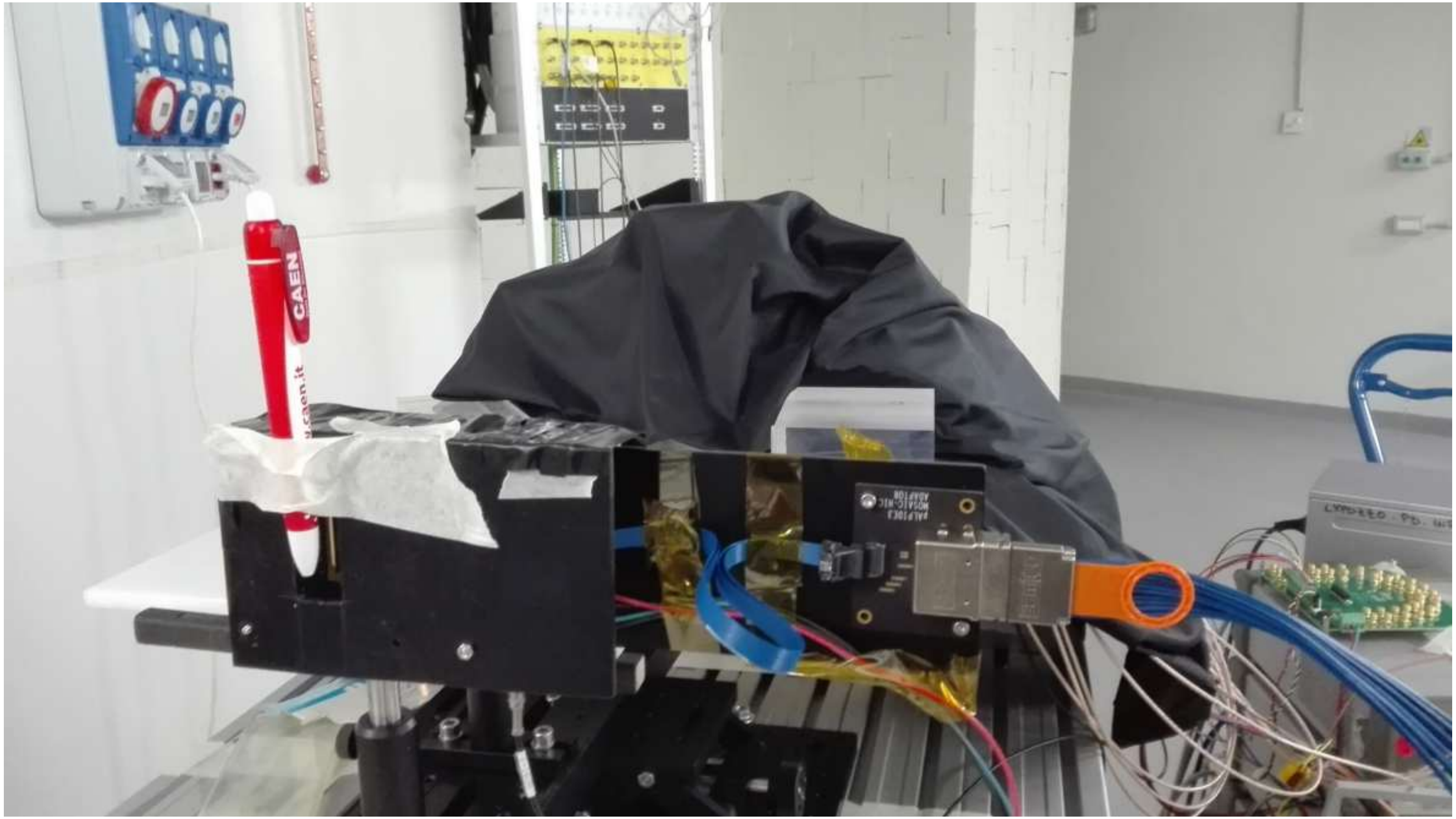


HEP techniques used for medical application: the iMPACT Project



2017 test beam set-up

HEP techniques used for medical application: the iMPACT Project



Proton Tomography scan of a pen

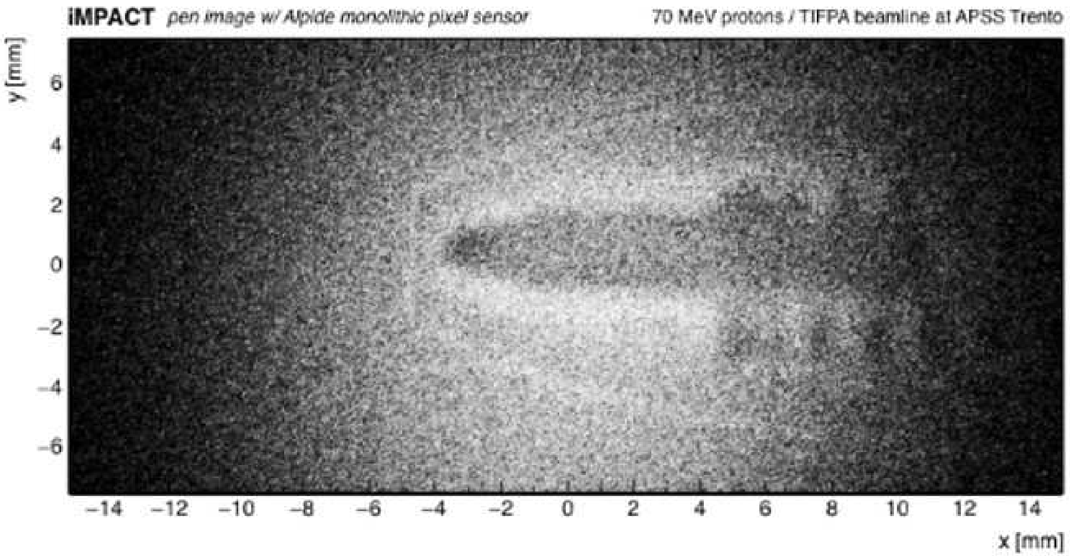


Fig. 4. Proton radiography of a pen with the ALPIDE sensor, taken during the TIFPA test beam.

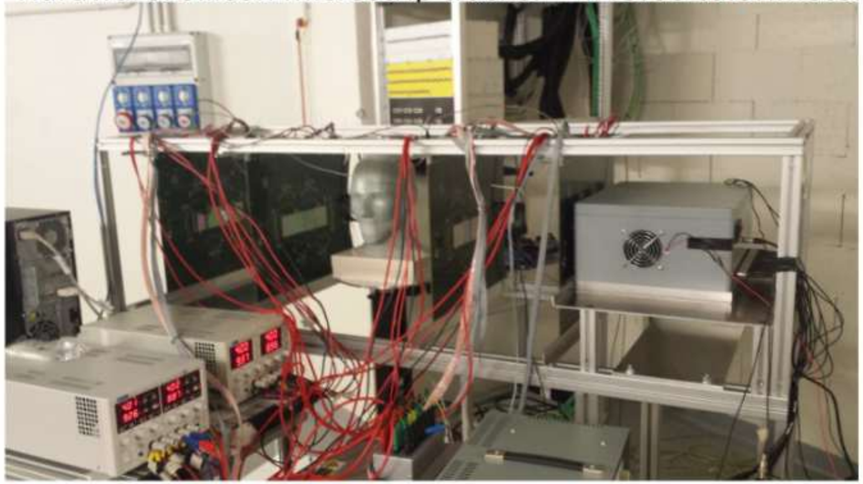
Again Proton Tomography with different sensors: the INFN-pCT aparatus

The INFN-pCT apparatus

Manufactured by INFN-Florence and Catania (2014 – 2017) running since 2018

Now installed in operation at the Trento proton therapy center's experimental beam line

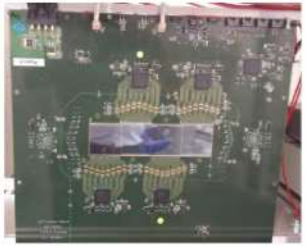
Hardware: Silicon microstrip tracker + YAG:Ce calorimeter

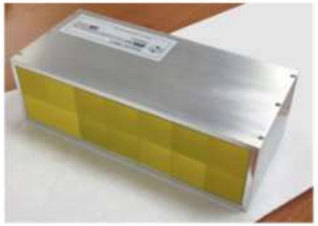


INFN pCT system under test with an anthropomorphous head phantom at Trento proton therapy center's experimental beam line

Silicon microstrip tracker 5x20cm² field of view

- 4x2 silicon microstrip detectors 200µm pitch, 320µm thick active area 5x20cm²
- front-end chips and 2 levels FPGA





Calorimeter

- 2x7 YAG:Ce crystals 3x3x10 cm³ ; 70 ns scintillating light decay time
- photodiodes + Analogue amplifier + shaper (1µs)

<1% energy resolution @ 200 MeV

Mara Bruzzi - A pCT approach to CT calibration in proton therapy treatment planning- 2022

Slide from
Prof.ssa Mara Bruzzi

https://ionimaging.org/assets/talks/ws2022munich-mara-bruzzi.pdf

HEP techniques used for medical application:

FOOT: the FragmentatiOn Of Target experiment

The main purpose of the FOOT experiment (FragmentatiOn Of Target) is to improve the hadrontherapy tumor treatments by studying the **nuclear fragments** produced during therapy applications in the **Interactions** of the **particle beams** with the **nuclei** constituting the **human tissues**.

The **nuclear fragments** are an important **source of biological damage**, both for cancer cells and for nearby healthy tissues, and it is of fundamental importance to have a **deep knowledge of this process** in order to make the most **effective and safe medical treatment**.

HEP techniques used for medical application:

FOOT: the FragmentatiOn Of Target experiment

In hadrontherapy treatment many fragments can be created: from the **fragmentation of the target** cell nuclei (mainly composed by carbon, oxygen or hydrogen atoms), or from the **fragmentation of the beam elements** (mainly carbon, under studying oxygen and helium) when ions are used for the treatment.

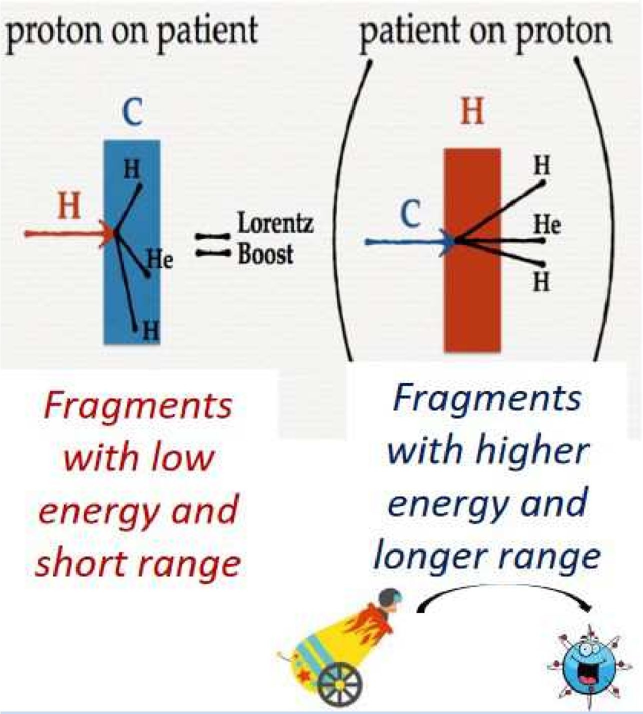
Foot will realize these precise cross-section fragmentation measurements using the ***reverse kinematic technique:*** the measurements will be realized using carbon, helium and oxygen beams on **C** and **CH targets.**

In order to perform precise cross-section measurements, two different configurations will be used:

- The ***Electronic Configuration***, for the cross-section measurements of heavy fragments (Z>2) mainly produced in a small angle below 20deg.)
- The ***Emulsion Configuration***, for the cross-section measurements of light fragments (Z<=2) mainly produced in a large angle, up to 70deg.)

HEP techniques used for medical application:

FOOT: Inverse kinematic approach



- Protons @ E_{kin}= 200 MeV (β~0.6) on a "patient" (98% C, O, and H nucleus)

⬇

- can be replaced by ^{16}O, ^{12}C ion beams (E_{kin} ~ 200 MeV/n β~0.6) impinging on a target made of protons
- by applying the Lorentz transformation (well known β) it is possible to switch from the ***lab. frame*** to the ***patient frame***

05.04.2019 *courtesy of V.Patera* E. Scifoni - LNL school

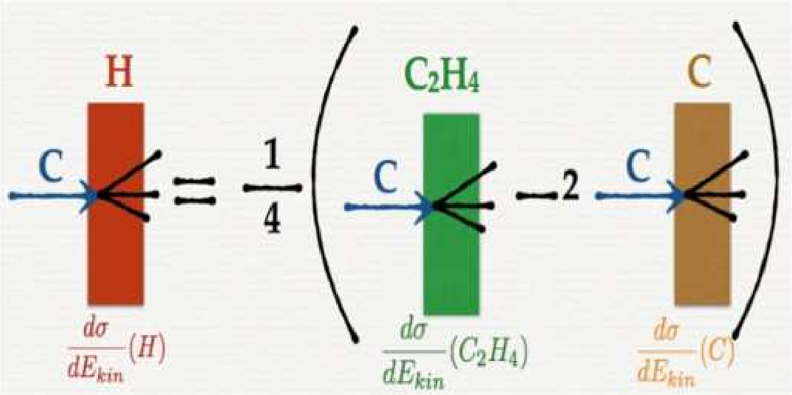
Slide from:
Emanuele scifoni
SIRAD school 2019

HEP techniques used for medical application:

Double target strategy

- H target? Use twin targets made of C and polyethylene $(C_2H_4)_n$ and obtain the results on H target from the difference
- C➔H cross-section can be estimated by C➔C_2H_4 and C➔C cross-section

$$\frac{d\sigma}{dE_{kin}}(H) = \frac{1}{4}\left(\frac{d\sigma}{dE_{kin}}(C_2H_4) - 2\frac{d\sigma}{dE_{kin}}(C)\right)$$



courtesy of V.Patera

INFN TIFPA Trento Institute for Fundamental Physics and Applications

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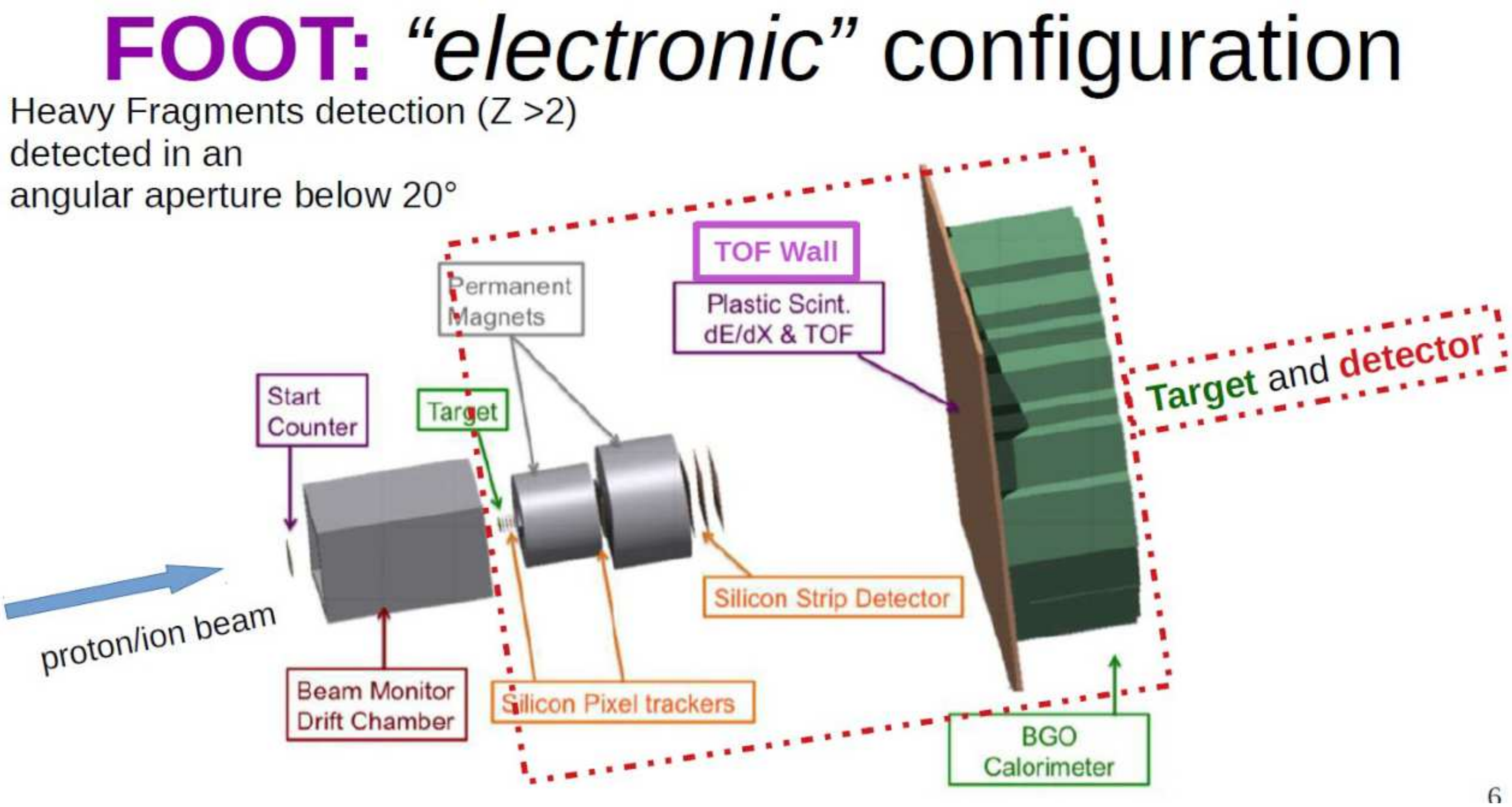
HEP techniques used for medical application:



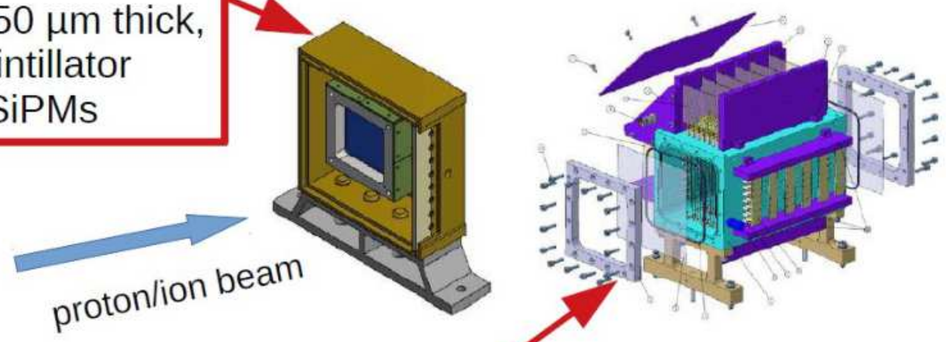
HEP techniques used for medical application:

FOOT: *“electronic”* configuration

Start Counter and Beam Monitor

START COUNTER (SC):
EJ-228 plastic scintillator 250 μm thick,
the light produced in the scintillator
is collected laterally by 48 SiPMs

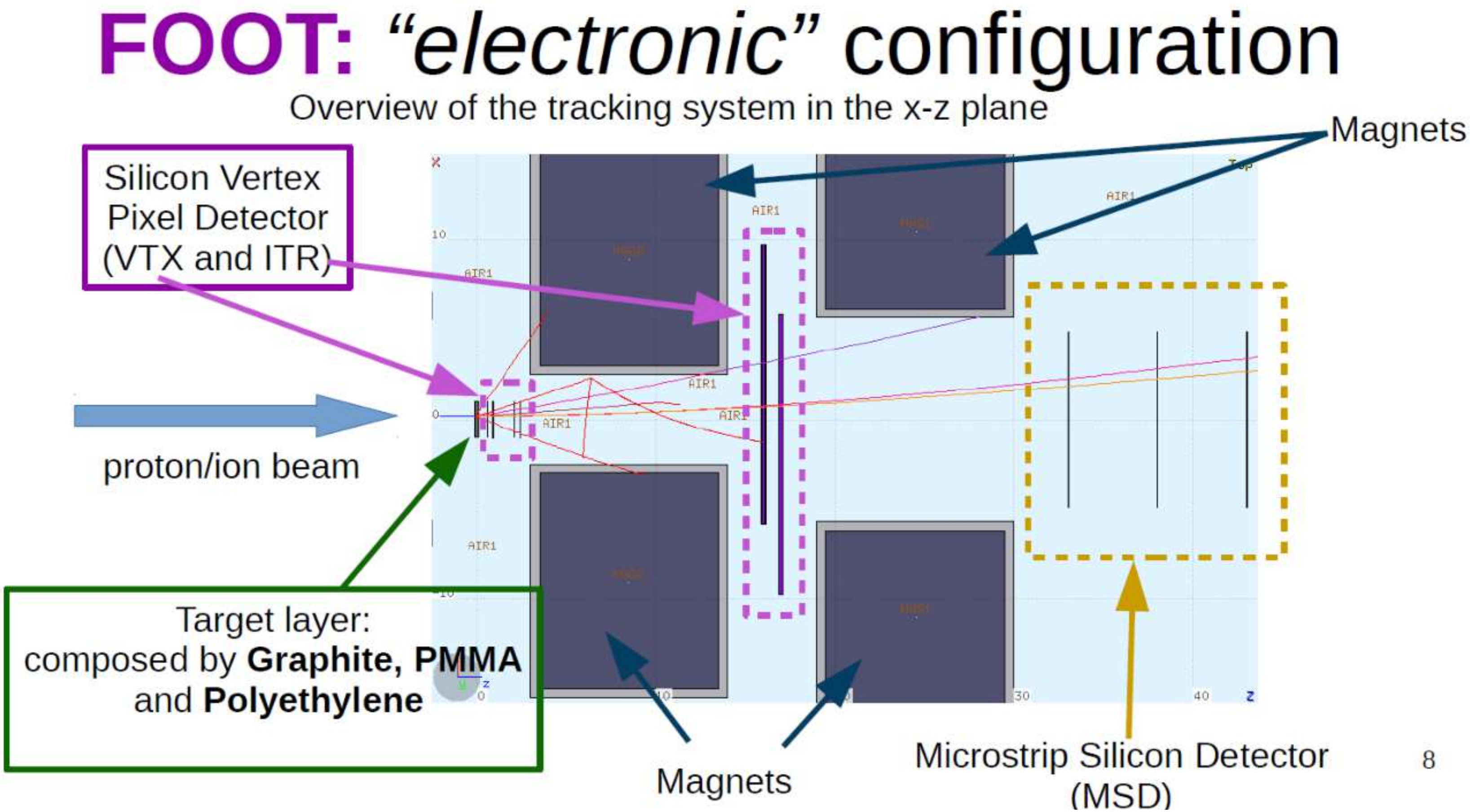
The SC provides an event trigger and a time reference for TOF measurements



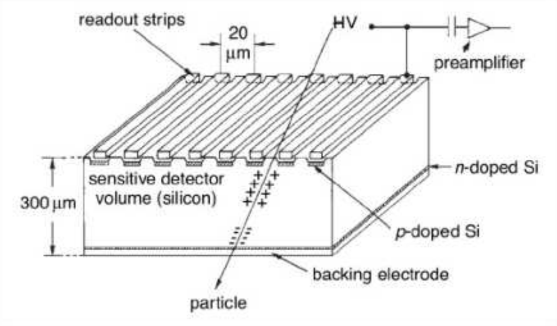
BEAM MONITOR CHAMBER (BM):
Drift Chamber composed by 12 layers. Used for precise measurement of the beam profile after the interaction with the start counter foil.
The same chamber is also used in the emulsion configuration

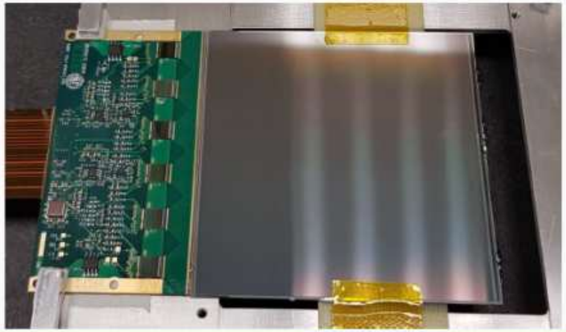
7

HEP techniques used for medical application:



HEP techniques used for medical application:





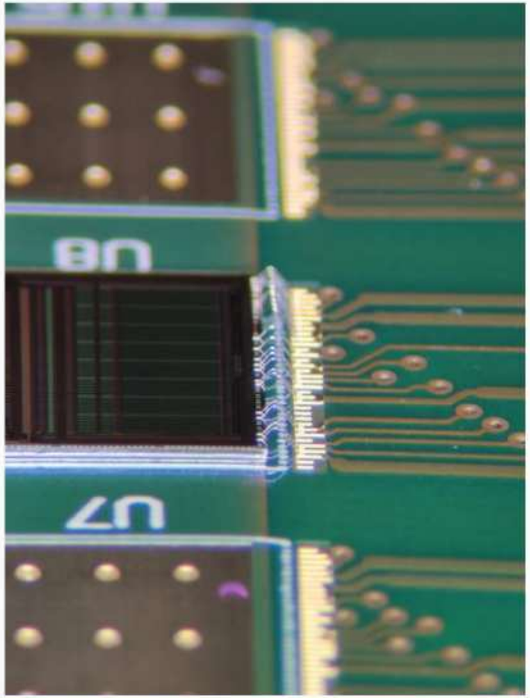
- Part of the tracking apparatus outside to the magnets
- Charged particle detectors with segmented electrodes in strip form
- P-N junction operated in full depletion regime
- Spatial resolution of the order of tens of microns
- Low noise / high channel count readout circuit required
- Typical thickness reduction required to limit the effects of Multiple Coulomb Scattering

Microstrip Silicon Detector

1st Workshop "Trento Proton Beam Line Facility" - 09 November 2020

Slide Gianluigi Silvestre

HEP techniques used for medical application:



- IDE1140 (formerly VA140)
- 64-channel preamplifier-shaper circuit
- Low noise/low power with high dynamic range
- Analogue multiplex reading
- Updated version of ASIC VA64HDR9A already in use in other experiments
- Characterisation of performance required
- Comparison with the performance of the previous version **(3 old version chip + 3 new version bonded on the same sensor)**

Front-end Readout ASIC IDE1140

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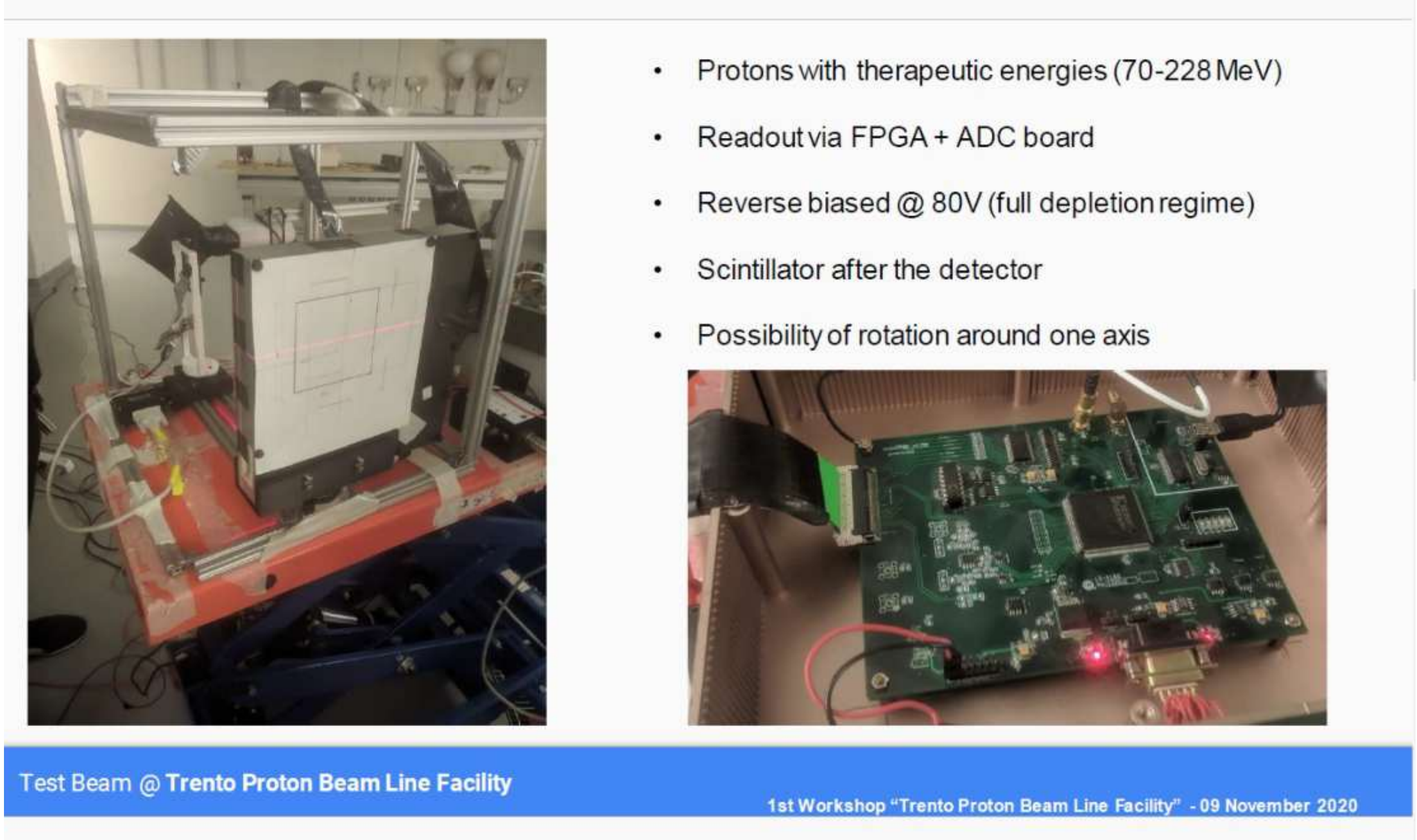
HEP techniques used for medical application:



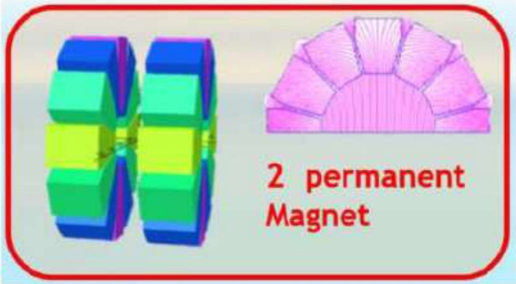
Slide Gianluigi Silvestre

HEP techniques used for medical application:

FOOT: *“electronic”* configuration

Overview of the tracking system

PERMANENT MAGNETS:
two cylindrical Halbach arrays of permanent magnets.
maximum intensity of 1.4 T and 0.9 T along the y axis
in the internal cylindrical hole.



VTX and ITR:
Respectively four and two planes of MAPS Silicon Pixels sensors Mimosa28 assembled in two different ladders geometry. Pixel pitch: 18.4 µm.

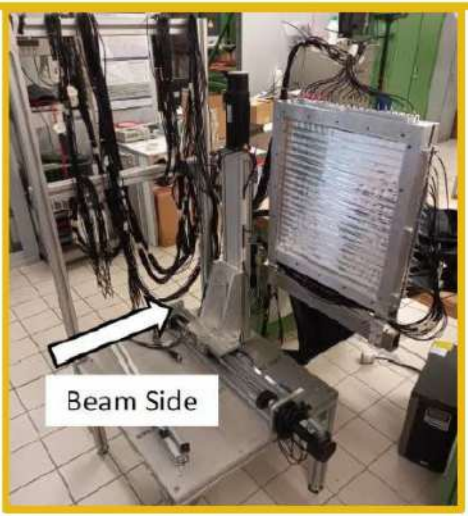
Microstrip Silicon Detector MSD: 3 planes, each plane is composed by two perpendicular Single-Sided Silicon Detector (SSSD) sensors thinned down to 150 µm with analog read-out. Expected space resolution of 40 µm.

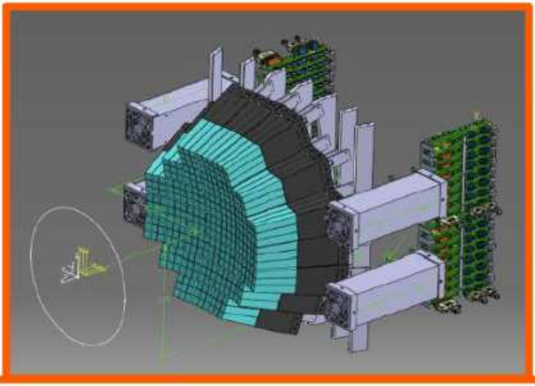
HEP techniques used for medical application:

FOOT: *“electronic”* configuration

TOF Wall and Calorimeter

TOF Wall: two layers of 20 plastic scintillator bars (EJ-200) orthogonally arranged with SiPMs and fast digitizers read-out. Used, together with the SC, for TOF measurements with time resolution below 100 ps, and for energy loss measurements with $\sigma(\Delta E)/\Delta E \sim 4\text{-}5\%$.





BGO Calorimeter: 320 BGO crystals with SiPM readout.
Energy resolution $\sigma(E_{kin})/E_{kin}$ below 2%.

HEP techniques used for medical application:

FOOT: *"emulsion"* configuration

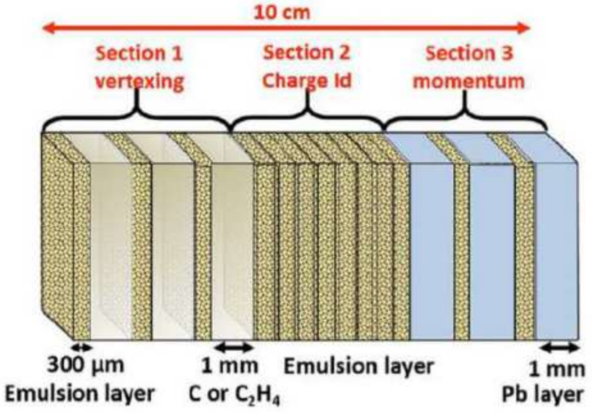
Used for measurements of tracks from light fragments with very short path and large angle spread.

The emulsion configuration is composed by a sandwich of **emulsion layers** and other materials organized in 3 sections:

Vertexing section:
target layers and emulsions.

Charge identification section:
only emulsion layers.

Momentum measurements section:
lead and emulsion layers.



The *emulsion detector technique* was developed and successfully used in tau neutrino detection experiments.

HEP techniques used for medical application:

Data taking

FOOT scientific program started using the **Emulsion Configuration** at **GSI** (Darmstadt, Germany), in 2019 with ^{16}O ions at 200 and 400 MeV/nucleon on C and C_2H_4 targets, and in 2020 with ^{12}C ions at 700 MeV/nucleon, on the same targets. Data analysis is still in progress.

The **Electronic Configuration** setup is under completion, tests and data taking are being scheduled at the GSI with a ^{16}O beam and at the **CNAO** (Pavia, Italy), using ^{12}C ions at 200 MeV/nucleon.

End part 3

Thanks for you attention!

……… and see you again! :-)

comments, questions ... suggestions ?

benedetto.diruzza@unifg.it

Back-up slides

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

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:

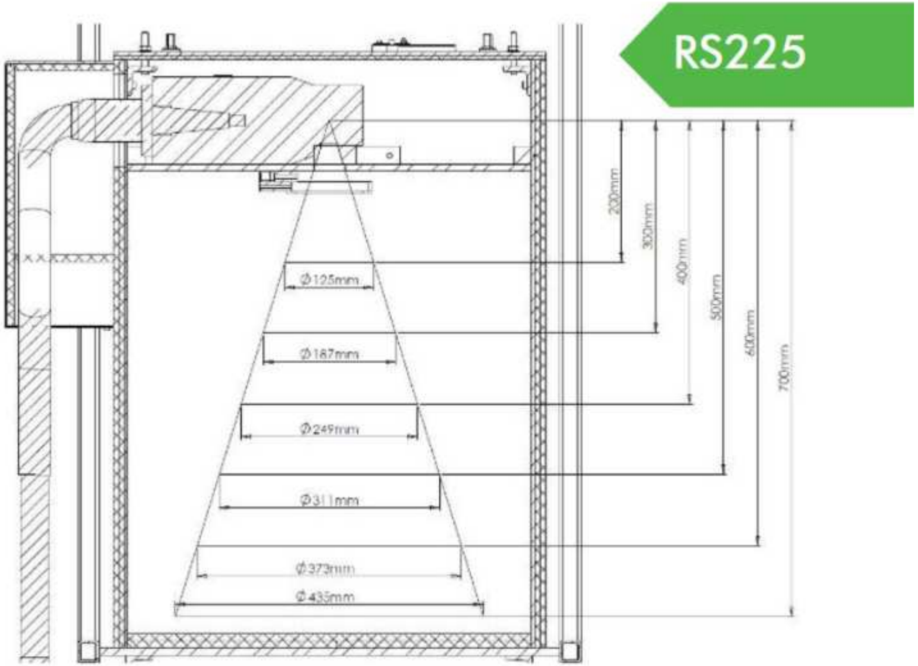
REF1 – *Proton beam characterization in the experimental room of the Trento Proton Therapy facility*
F. Tommasino et al. NIM A 869 (2017) 15–20.
DOI: http://dx.doi.org/10.1016/j.nima.2017.06.017

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

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

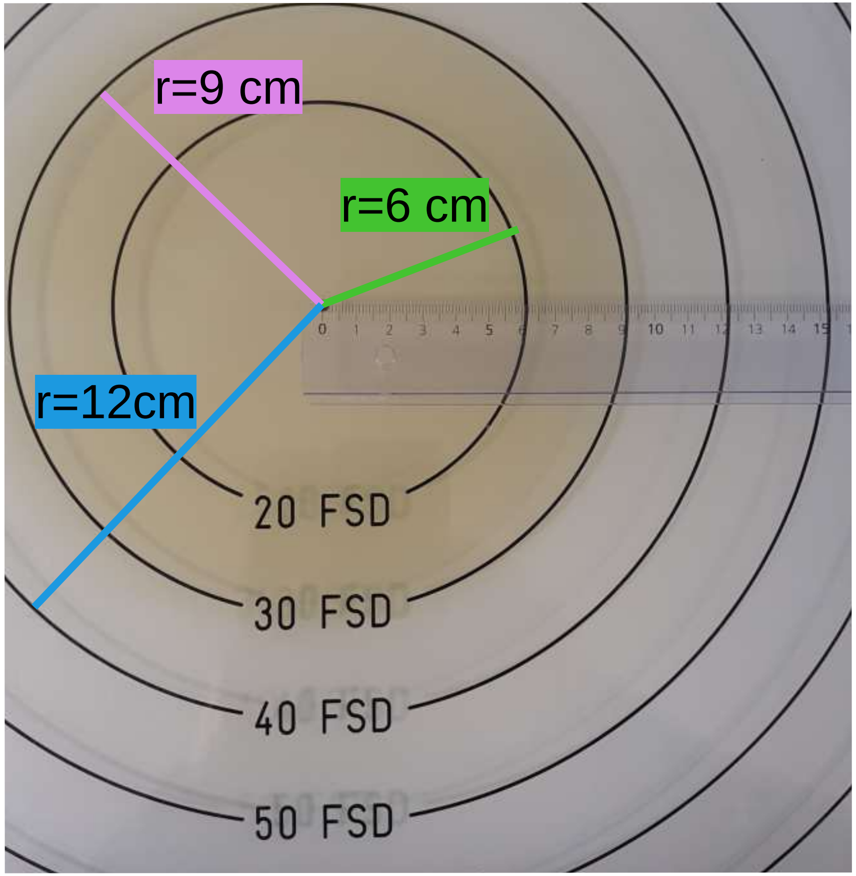
Shielding of cabinet to ≤ 2µSv/hour at 5 cm from any accessible surfaces as per IRR'99 guidelines.

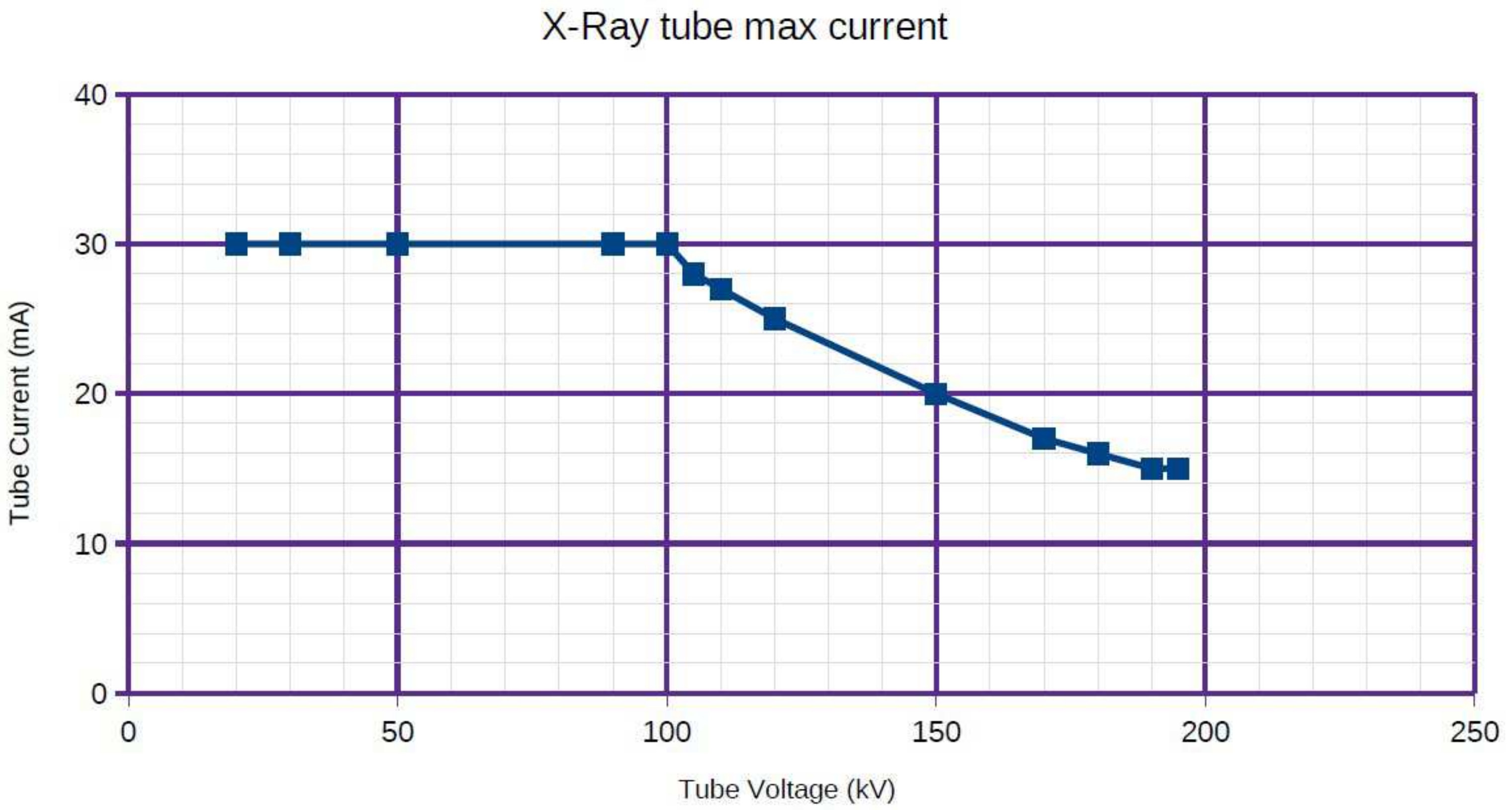


Focal Spot Distance and Irradiation Field Size (Dimensions in mm) RS225 (above) and RS320 (below).

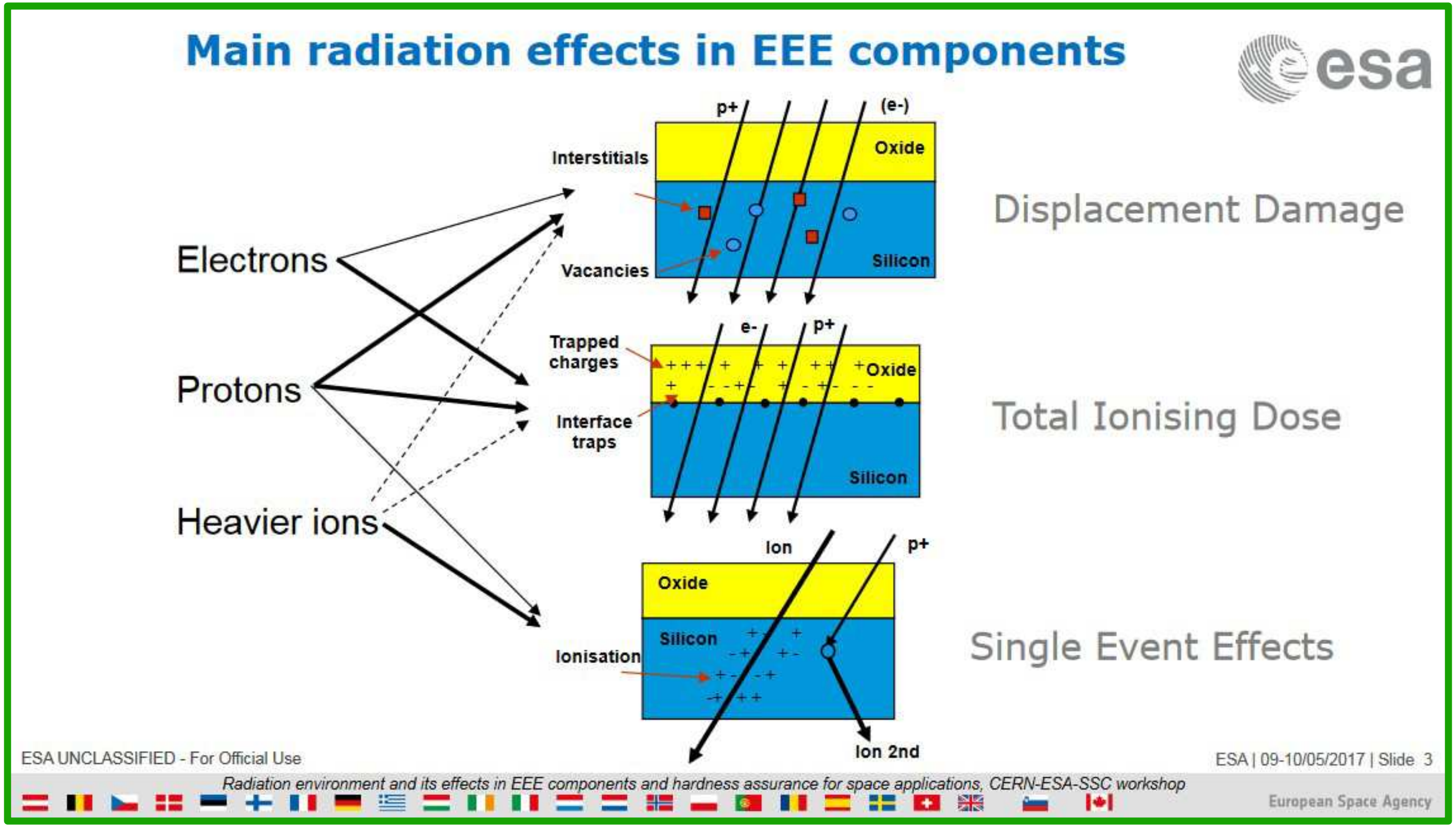
- In this set-up configuration the x-ray uniform spot is a circumference of 4.5 cm radius and can be used for sensors or electronic circuits TID
- characterization studies requiring total dose of the order of 1-50 Mrad.

R-X support plane



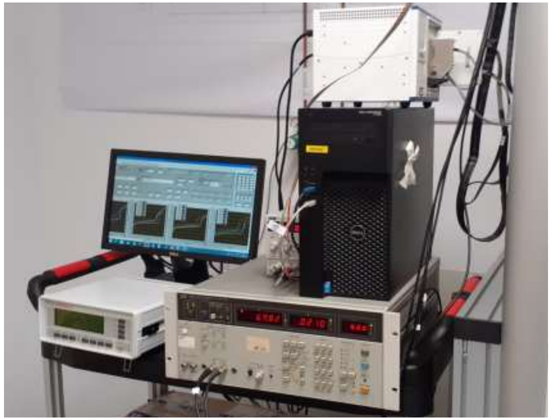

X-Ray tube max current
Tube Current (mA)
40
30
20
10
0
0
50
100
150
200
250
Tube Voltage (kV)

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



Case application: FBK SiPM Irradiations

Overview of the irradiation set-up

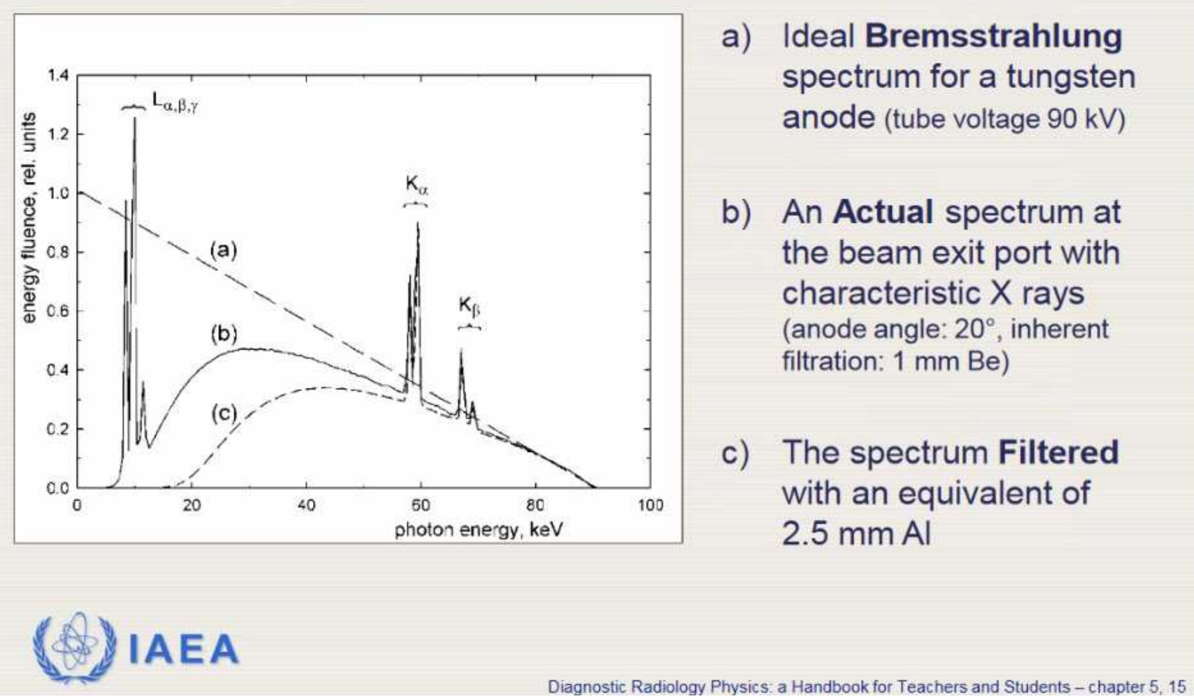


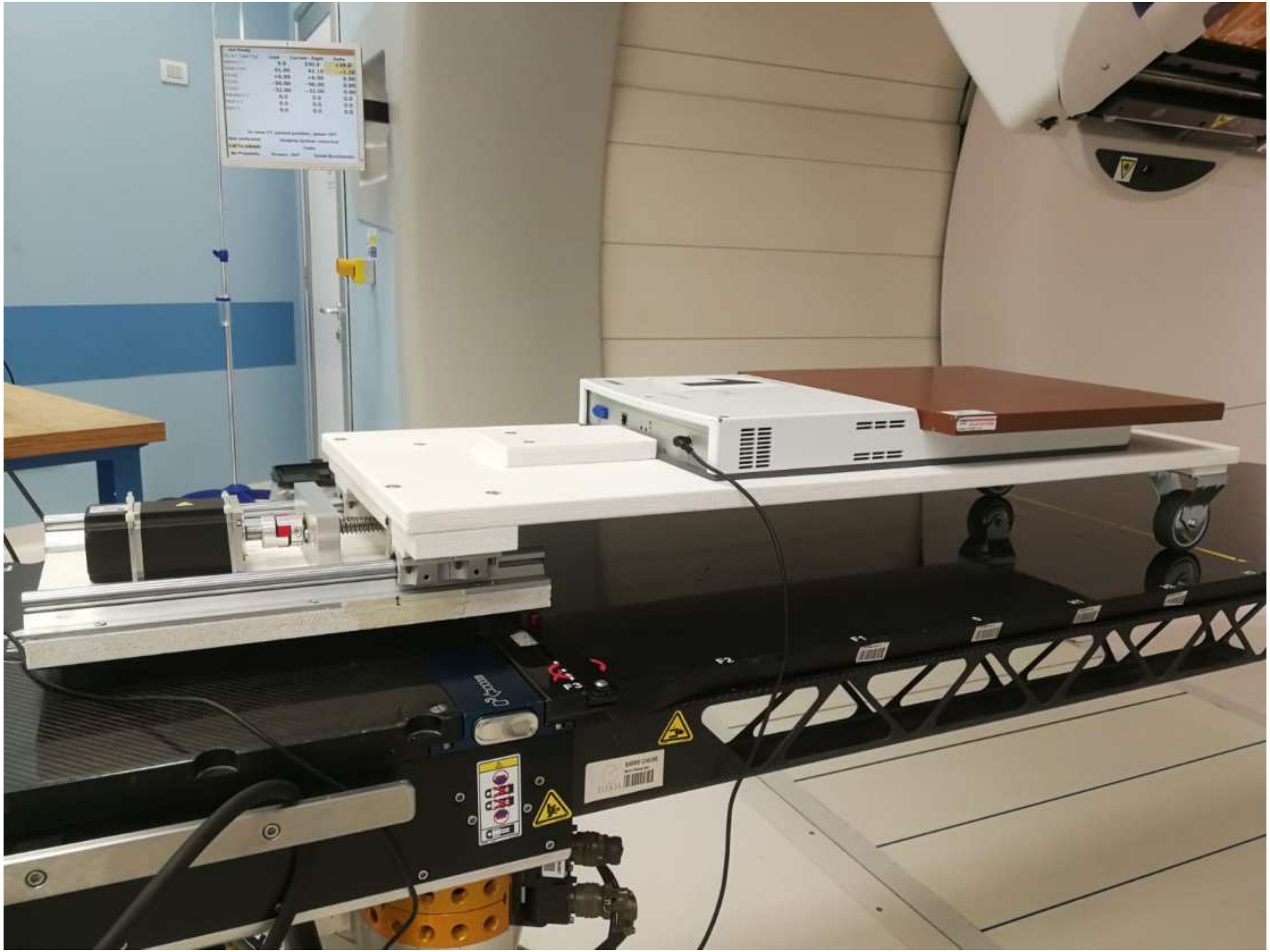
SiPM online characterization system (FBK)

Farmer chamber and SiPM support (FBK)

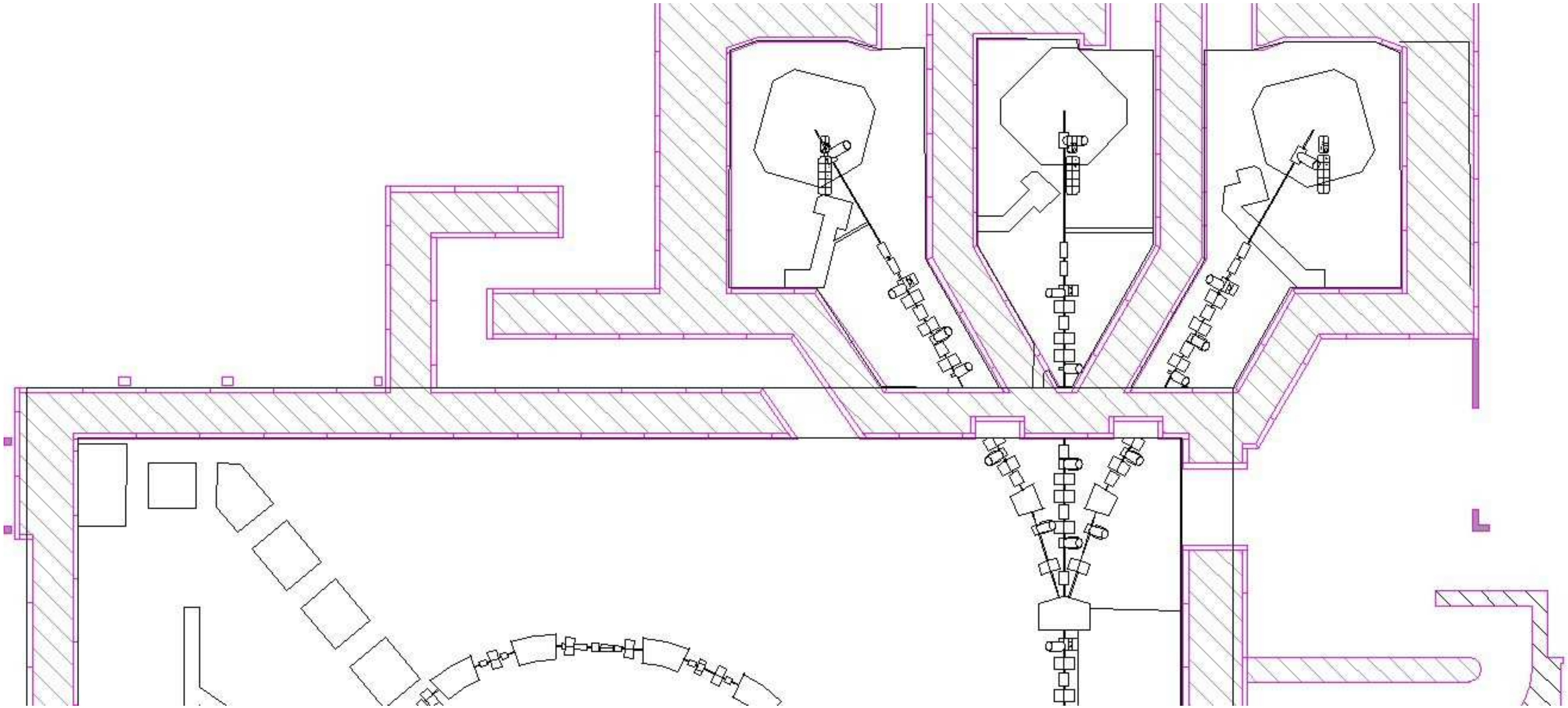
For results see:
DOI: 10.1016/j.nima.2022.167502

IAEA documents





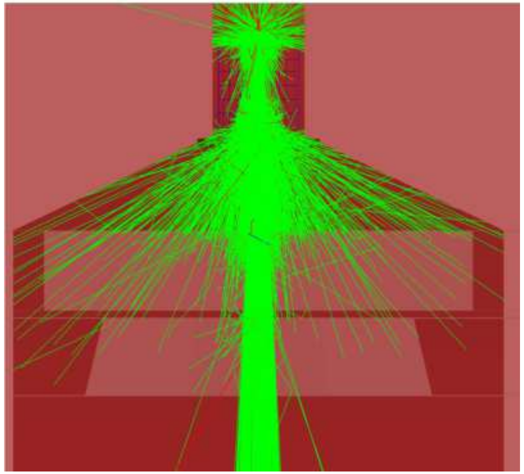
CNAO

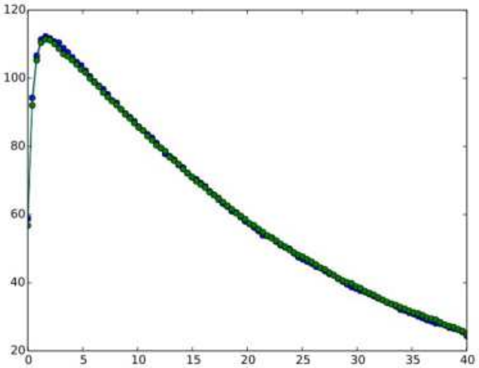


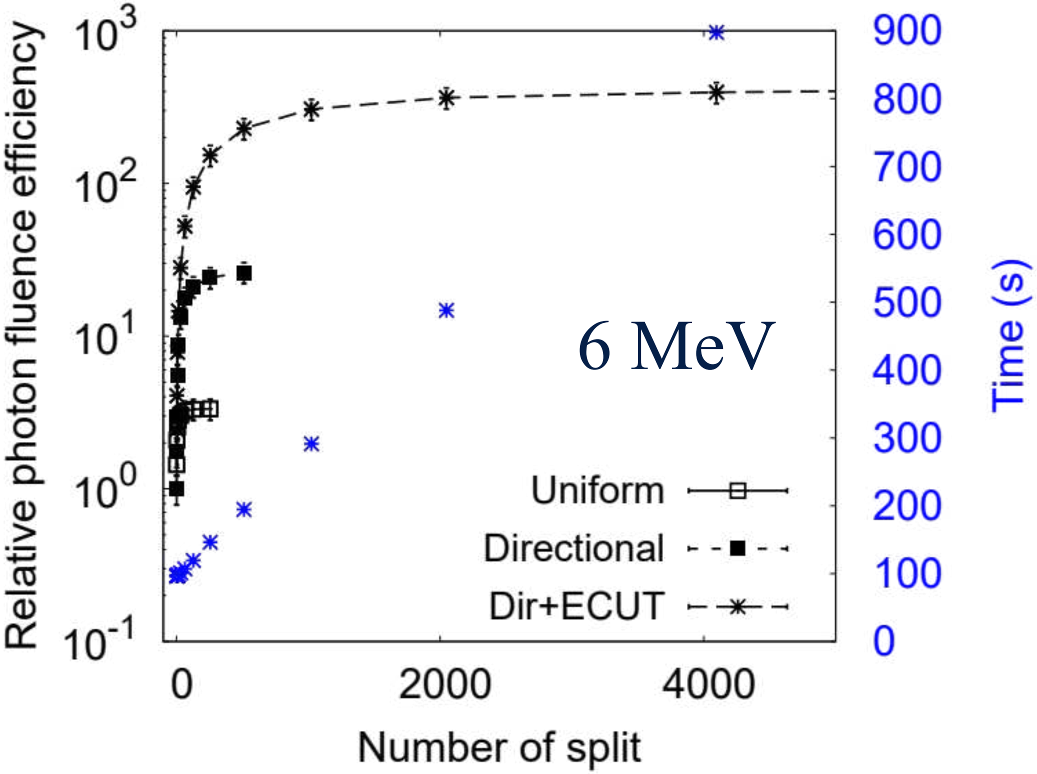
The Trento Proton Therapy Center (TPTC)

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

X-ray linac simulation with VRTs.







:Ph/Default/LowestElectronEnergy = 189 keV