Particles and Health
Advances in Imaging in Proton Radiotherapy

Hugo Simões
On behalf the ORimag group from LIP-Coimbra

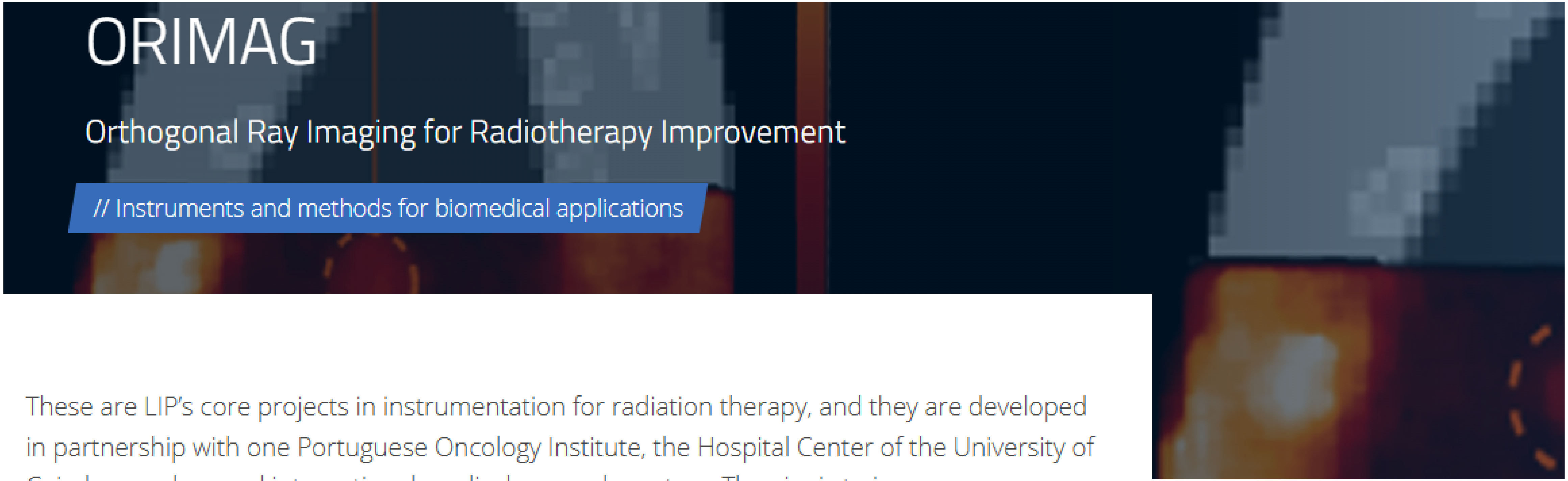
LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS

DEPARTAMENTO DE FÍSICA
FACULDADE DE CIÊNCIAS E TECNOLOGIA
UNIVERSIDADE DE COIMBRA

LIP training internship

LIP – July 10th, 2026

hugo.simoes@lip.pt



ORIMAG

Orthogonal Ray Imaging for Radiotherapy Improvement

// Instruments and methods for biomedical applications

These are LIP's core projects in instrumentation for radiation therapy, and they are developed in partnership with one Portuguese Oncology Institute, the Hospital Center of the University of Coimbra, and several international medical research centers. The aim is to improve radiotherapy by optimizing the treatment in near real time, so that the irradiation can better accommodate the tumor and spare surrounding healthy tissue. To do this, we use X- or gamma-rays emitted orthogonally to the treatment beam, and/or in-beam positron emission tomography (in-beam PET).

The OR Imaging technique may be divided into three main branches: (1) OrthoCT (orthogonal computer tomography) for monitoring radiotherapy (high-energy x-rays); (2) O-PGI (orthogonal prompt-gamma imaging) for monitoring proton therapy; and (3) in-beam PET also for monitoring proton therapy treatments.

Contacts

GROUP LEADER:

PAULO CRESPO

crespo@lip.pt

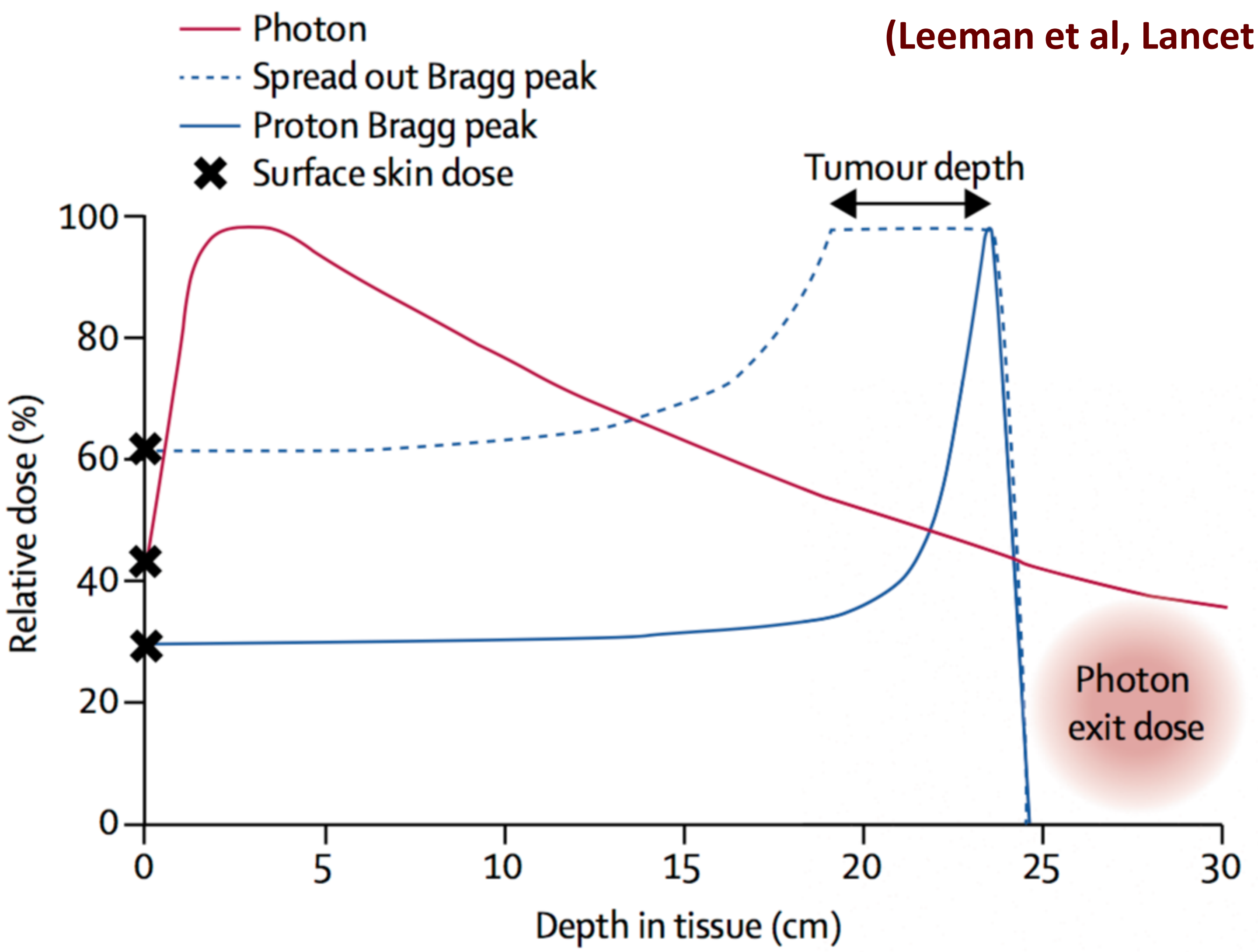
Outline

Advances in Imaging in Proton Radiotherapy

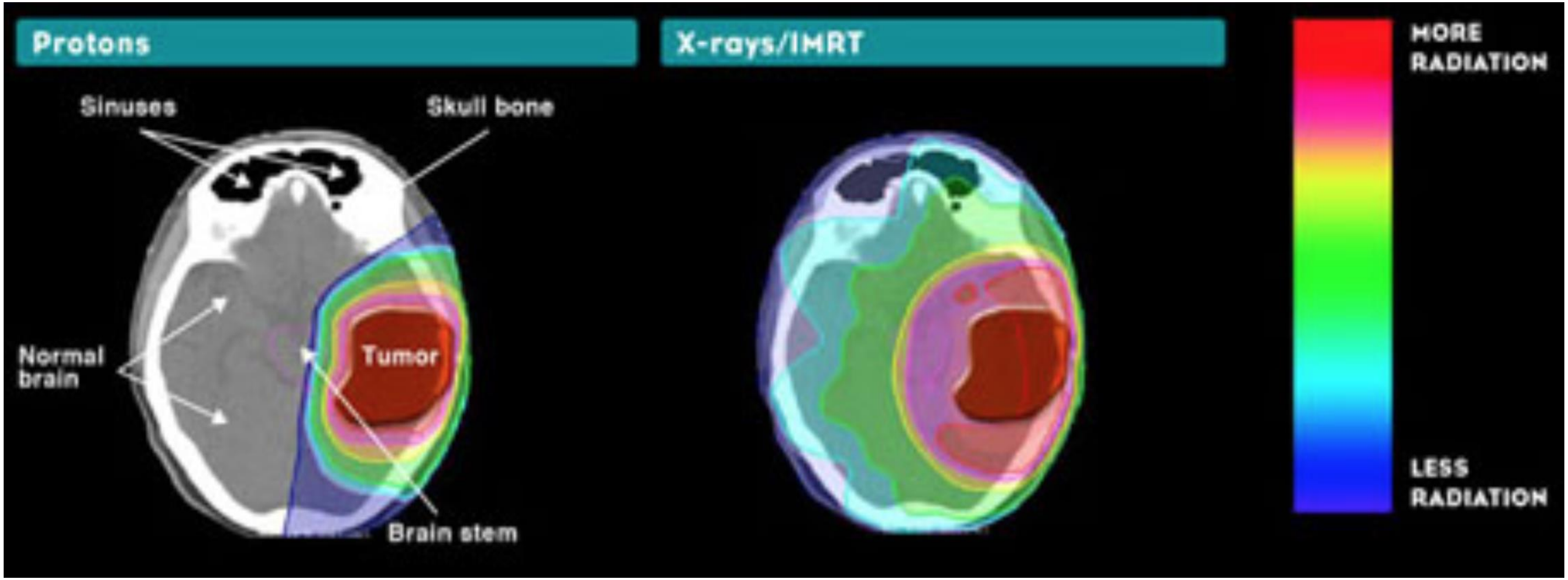
1. Motivation
2. Rationale for in-vivo imaging in proton radiotherapy (RT)
3. The multi-slat concept for prompt-gamma imaging (PGI) in proton RT
4. In-beam time-of-flight PET for proton RT

1. Motivation: Proton therapy physical advantage over photons

(Leeman et al, Lancet Oncol 2017)



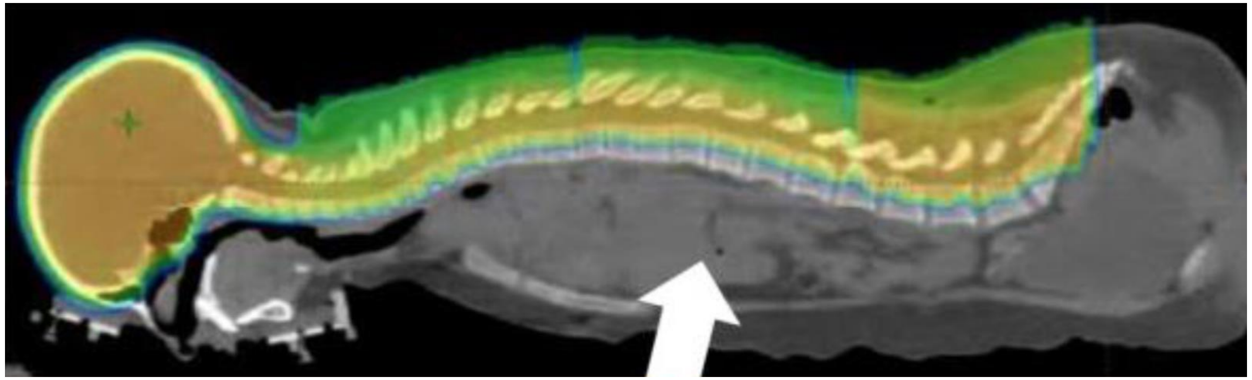
1. Motivation: Proton therapy physical advantage over photons



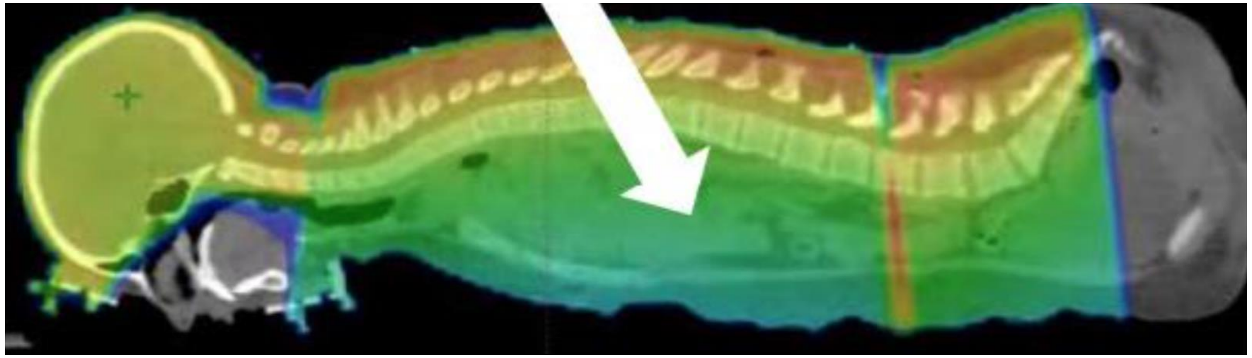
(Proton Therapy Today 2019)

1. Motivation: Proton therapy physical advantage over photons

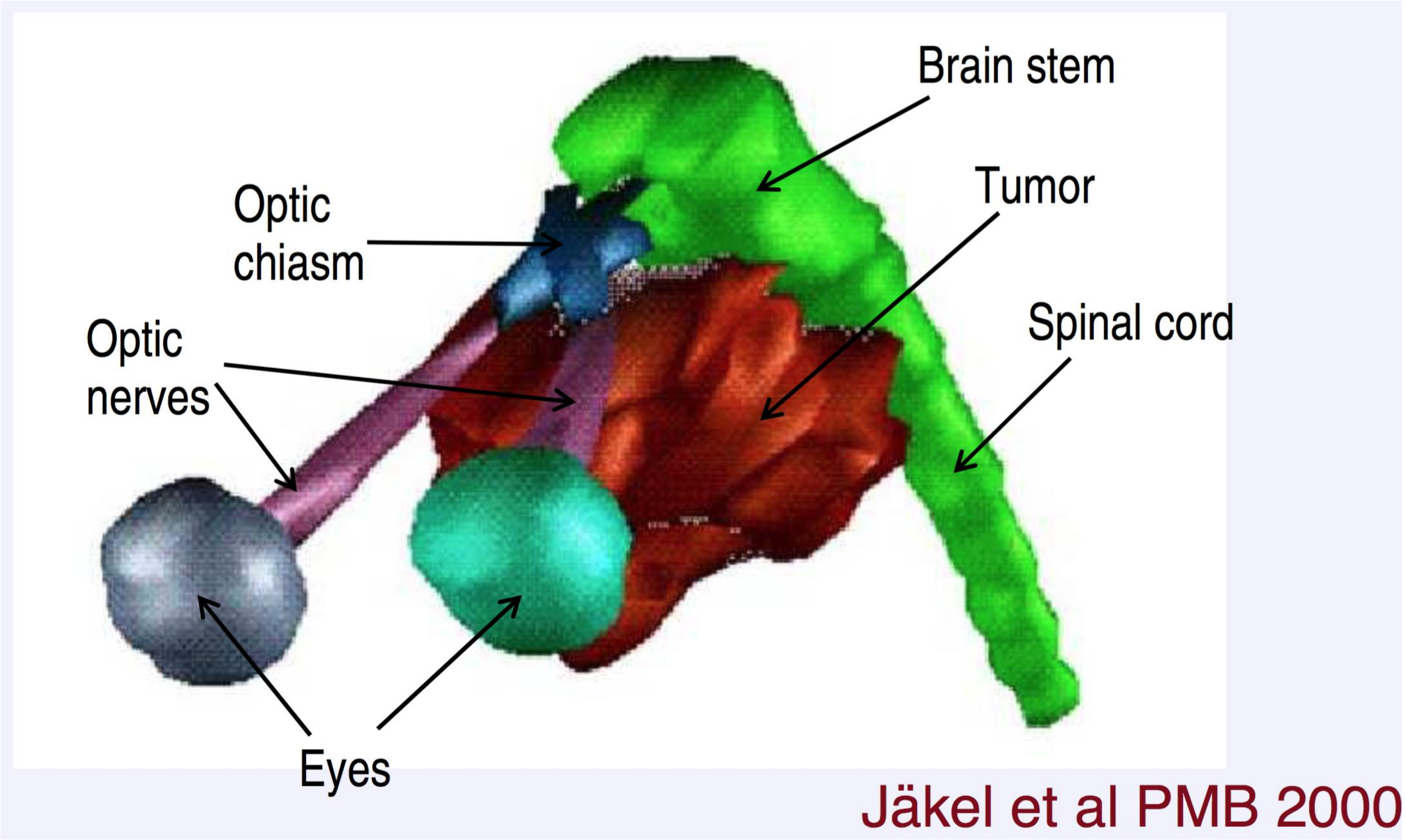
The protons stop!
The depth at which this occurs depends on their initial energy.



X-rays do not stop!
They continue to pass through the surrounding tissue.



1. Motivation: Proton therapy physical advantage over photons



1. Motivation: Proton therapy clinical benefits

Brain/Head & Neck

45% reduction in overall risk of needing a feeding tube for **nasopharyngeal cancer**

27% reduction in overall risk of needing a feeding tube for **oropharyngeal cancer**

44% increase of relative 5-year disease free survival rate for **nasal and paranasal sinus cavity cancers**

50% overall increase of disease control for **chordomas**

Less side effects during first 3 months after treatment, quicker return to normal function

50% less likely to have secondary tumor from treatment

Breast

Delivers 8-18 times less overall radiation to the heart than IMRT

50-83% less relative risk of heart attack or another major coronary event depending on age

50% reduction of clinically significant radiation doses to the heart

97% of partial breast irradiation patients experience **no breast tumor recurrence at 5 years**

90% of cases result in good to excellent cosmetic outcomes at 5 years

Liver
(Hepatocellular)

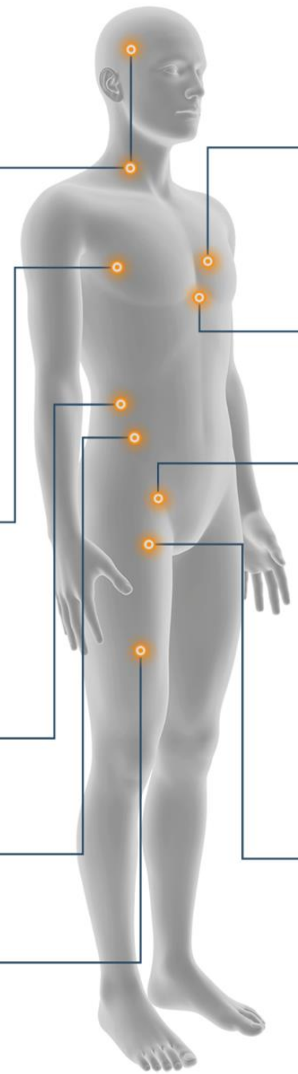
58% higher overall survival rate (2 years)

Bile Duct

54% higher overall survival (4 years)

Sarcoma

49-75% reduction in complications



Lung

56% relative reduction in incidences of grade 3 esophagitis

50% reduction in relative risk of recurrence

Higher radiation dose to the tumor while reducing risks of overall side effects

64% relative increase in 5-year overall survival

Esophageal

3 to 4-day reduction in average hospital stay

5.1-22.8% overall reduction in pulmonary complications

68% relative reduction in wound complications

Prostate

4.9% higher overall 5 year survival rate

35% less radiation to bladder and **59% less radiation** to the rectum

Proton patients are almost twice as likely to report **treatment had NO IMPACT on their quality of life** compared to surgery, conventional radiation, and brachytherapy

Half as many incidences of long term (2+ years) moderate or severe bowel problems

42% reduction in relative risk of developing a secondary malignancy

Significantly fewer reports of gastrointestinal, genitourinary, endocrine, or "other" complications

Rectal/Anal

More than 50% reduction in radiation dose to critical structures including bone marrow

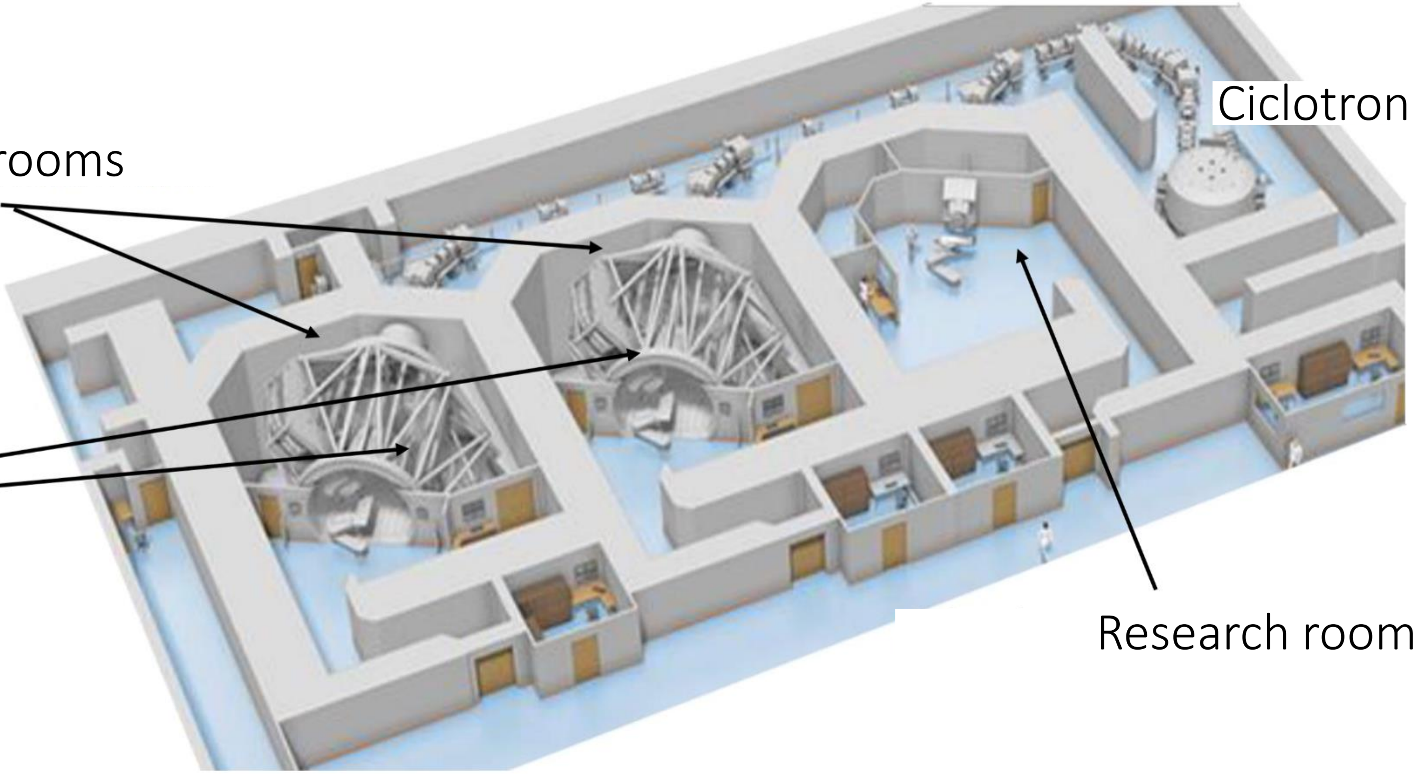
Overall

31% relative reduction in occurrence of secondary cancers after treatment

PROVISION CARES
PROTON THERAPY

**References available upon request. Results from separate studies compared in some instances. The benefits of proton therapy for each individual patient will vary based on their individual diagnosis. A personal consultation with a proton-trained physician is recommended in all cases.*

1. Motivation: A proton therapy facility in Portugal?

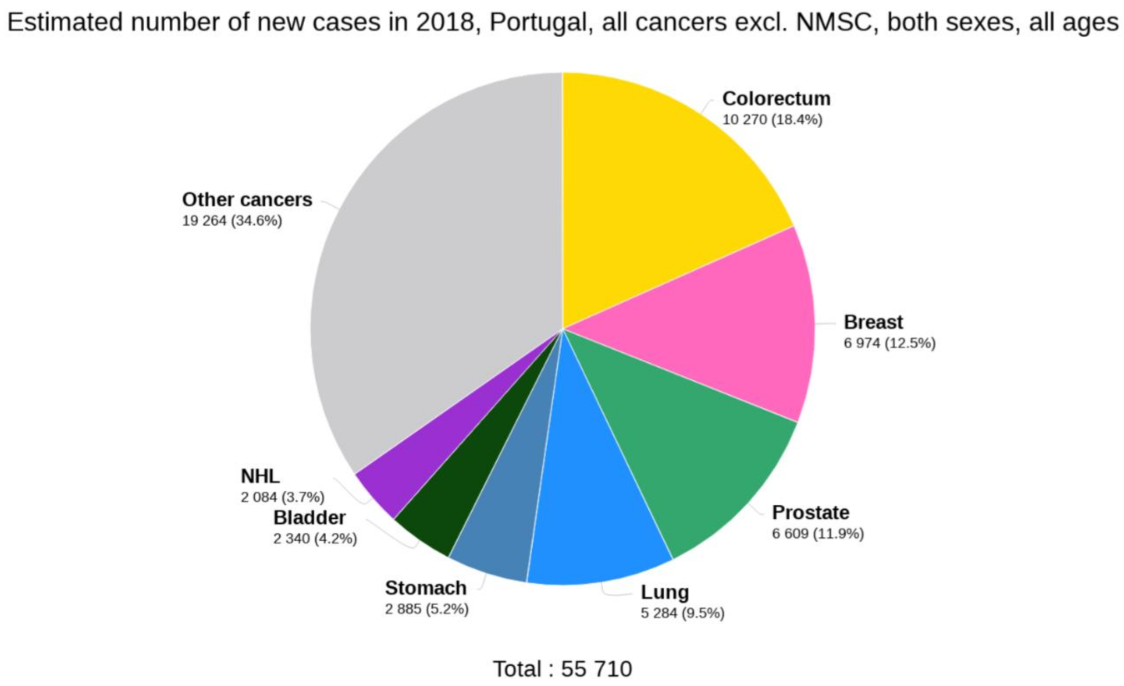


These electromechanical structures allow the proton beam to bend and rotate 360° around the patient.

https://iba-worldwide.com/proton-therapy/proton-therapy-solutions/proteus-plus

1. Motivation: A proton therapy facility in Portugal?

Incidence of different types of cancer in Portugal



Estimated number of patients recommended for proton therapy:

15% of patients recommended for radiotherapy (50% of the total): around **4200/year**

1. Motivation: A proton therapy facility in Portugal?

IPOPORTO SNS 24 CENTRO DE CONTACTO 808 24 24 24 LOGIN BEM-ME-KER LINHA DIRETA 225 084 000 PT

24 Outubro 2024

PRIMEIRO-MINISTRO ANUNCIA CENTRO NACIONAL DE PROTONTERAPIA NO IPO PORTO

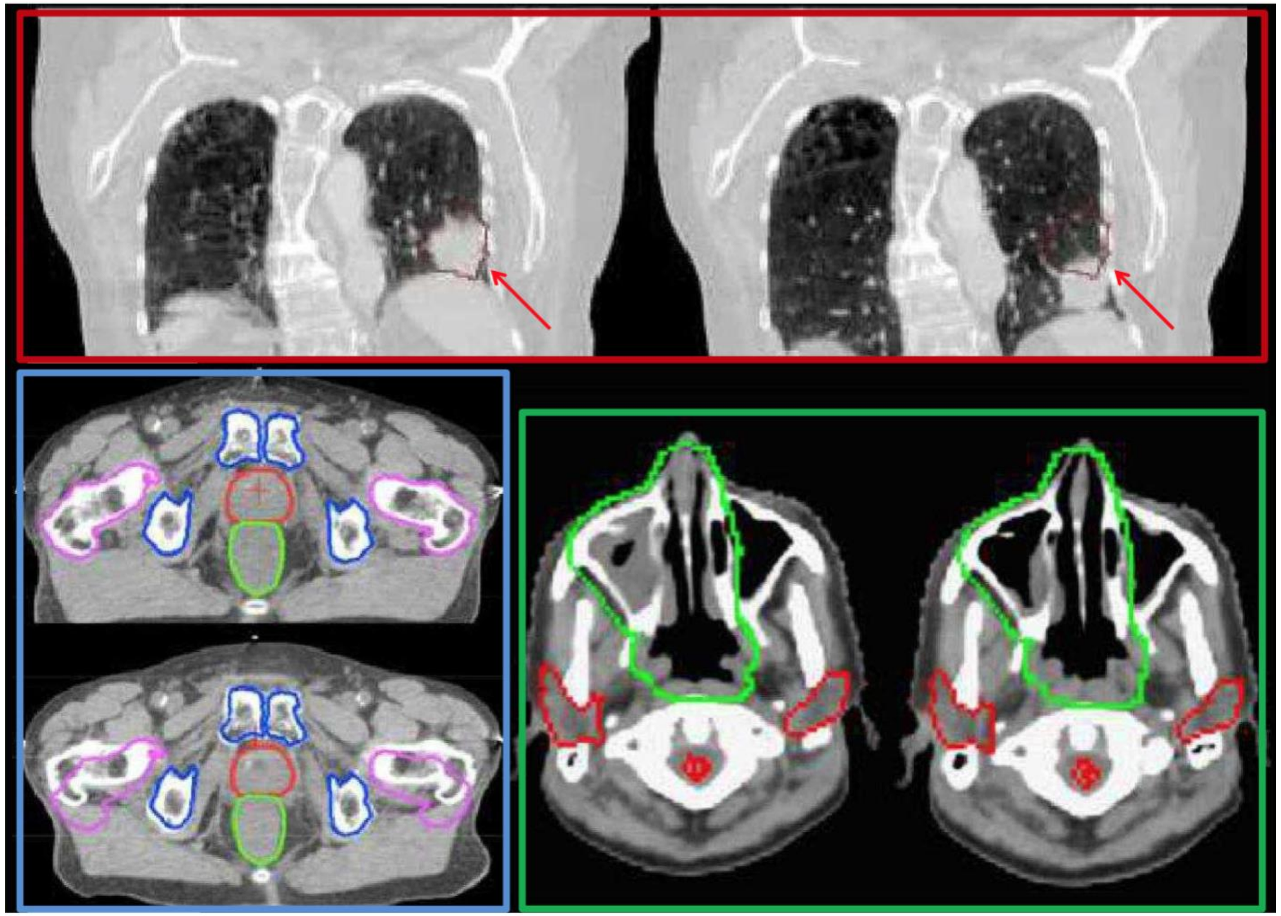
Portugal vai ter um centro de terapia do cancro com protões instalado no Instituto Português de Oncologia do Porto (IPO Porto). O anúncio foi feito hoje pelo primeiro-ministro, Luís Montenegro, na cerimónia de assinatura do acordo de compromisso com a Fundación Amancio Ortega (FAO), o IPO Porto e o Governo português para a criação do primeiro Centro Nacional de Protonterapia (CNP) em Portugal, e no Serviço Nacional de Saúde (SNS).

A cerimónia contou com a presença da Ministra da Saúde, Ana Paula Martins, o Ministro Adjunto e da Coesão Territorial, Manuel Castro Almeida.

O desafio lançado pelo IPO do Porto à FAO, com o envolvimento e empenho do Governo de Portugal, irá permitir a concretização, num horizonte de 3 a 4 anos, da criação do Centro Nacional de Protonterapia, um projeto de desígnio nacional.

2. Rationale for in-vivo imaging in proton RT

Morphologic changes / patient positioning



Engelsman and Bert 2011
Luchtenborg PhD 2012

Very high conformality provides high-precision and highly accurate RT, but need for RT imaging also increases

2. Rationale for in-vivo imaging in proton RT

Beam verification approaches:

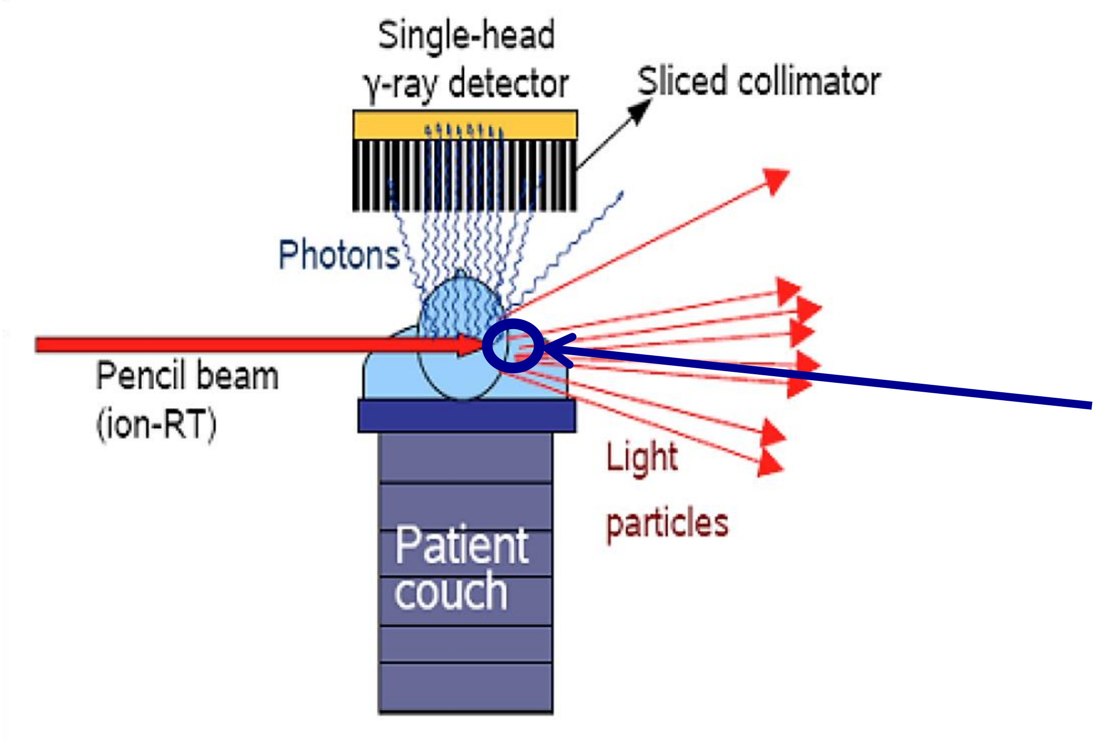
Positron Emission Tomography (PET)

- Interaction of the beam with the body generates positron emitters, such as ^{15}O, ^{11}C, ^{13}N
- PET scanners can be used to verify beam range by comparing the reconstructed image with the simulated activity distribution

Prompt Gamma (PG) imaging

- Beam also generates prompt gammas with the energy sufficient to escape the body without interactions
- Measured distribution of the emission positions can be compared with the simulation to verify the beam range

3. The multi-slat concept for PGI in proton RT



(Cambraia Lopes *et al*, Physica Medica 2018)

Provides real-time images of selected region without rotation of beam source.

Image with prompt gammas "stops" at beam range

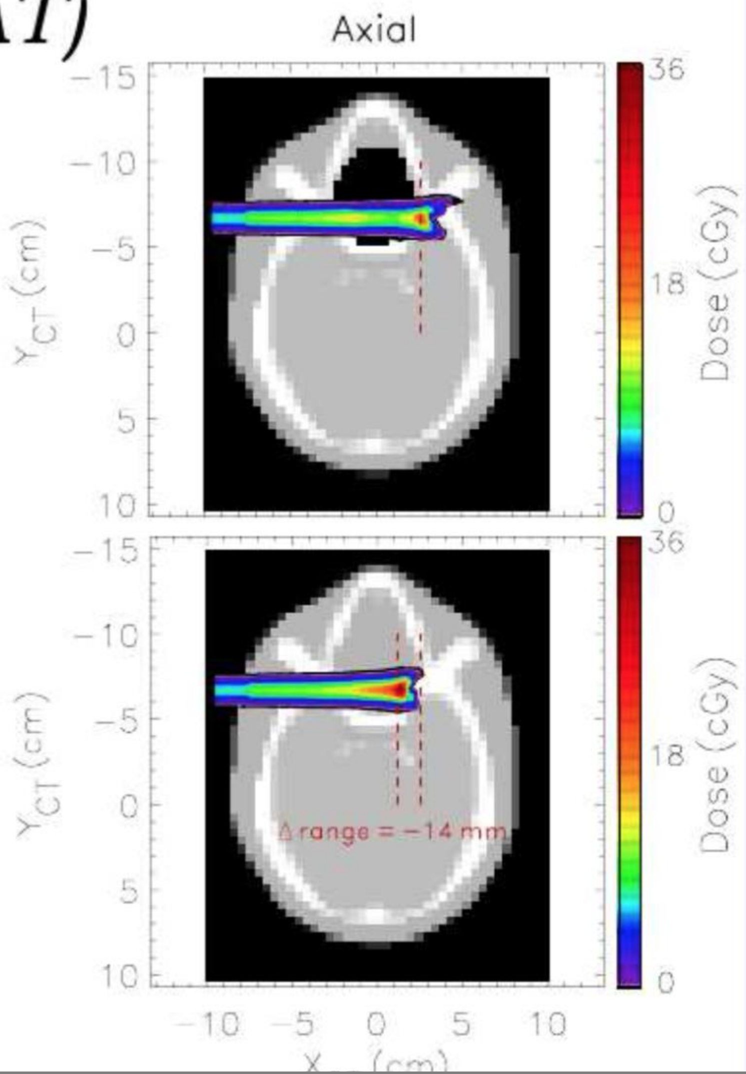
3. The multi-slat concept for PGI in proton RT

3.1 Filling of nasal cavity

Head irradiation *(NCAT)*

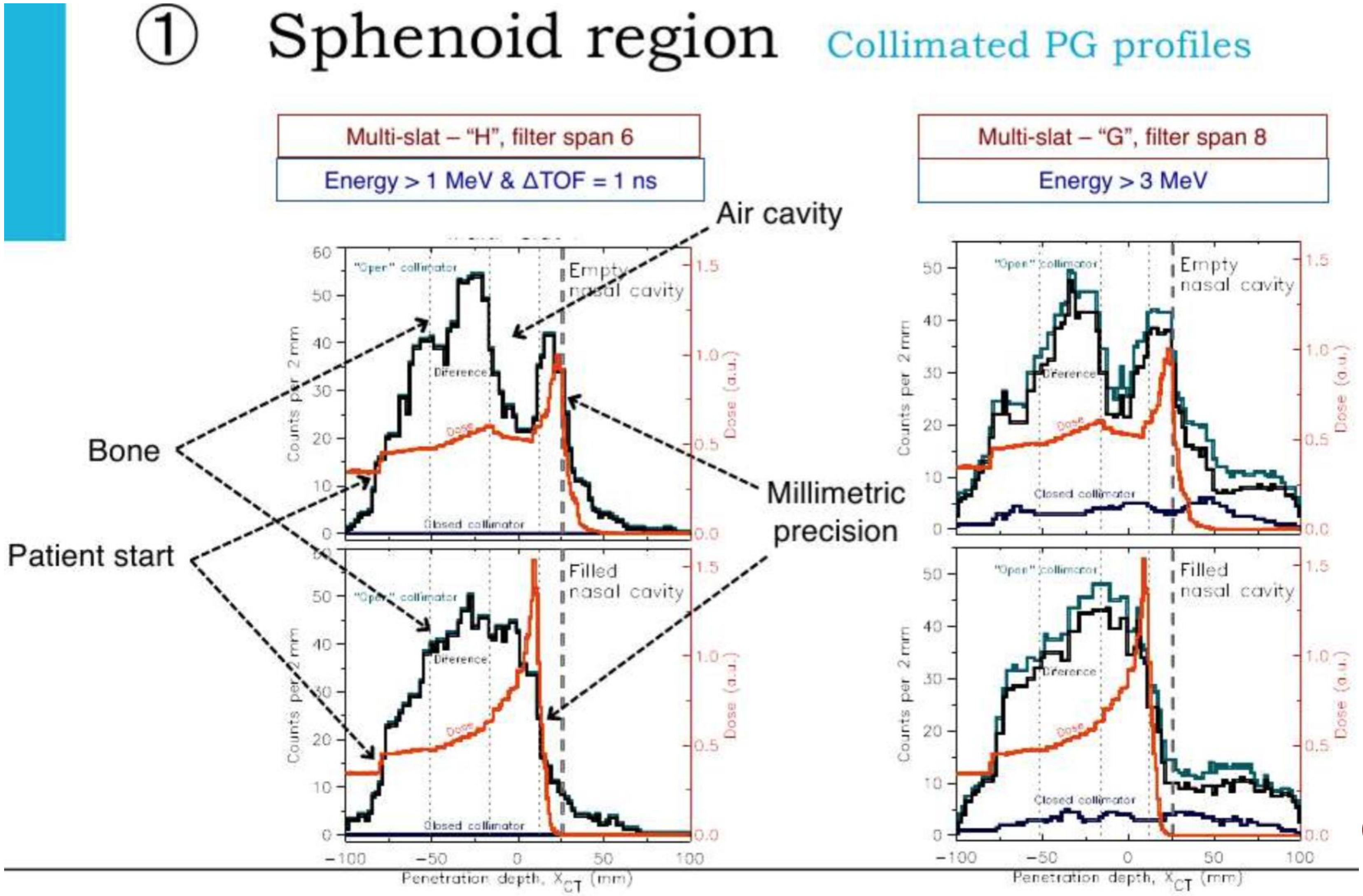
① Sphenoid region

- Treatment plan:
  - Irradiation of a hypothetical tumor located in the sphenoid bone region
  - **Empty nasal cavity** (air-filled)
- Compromised treatment:
  - **Filled nasal cavity** with PMMA-like material
  - Under-range shift of 14 mm
  - Possible causes:
    - Patient cold → presence of mucus
    - Response after irradiation → edema, tissue swelling
    - Tumor growth



3. The multi-slat concept for PGI in proton RT

3.1 Filling of nasal cavity

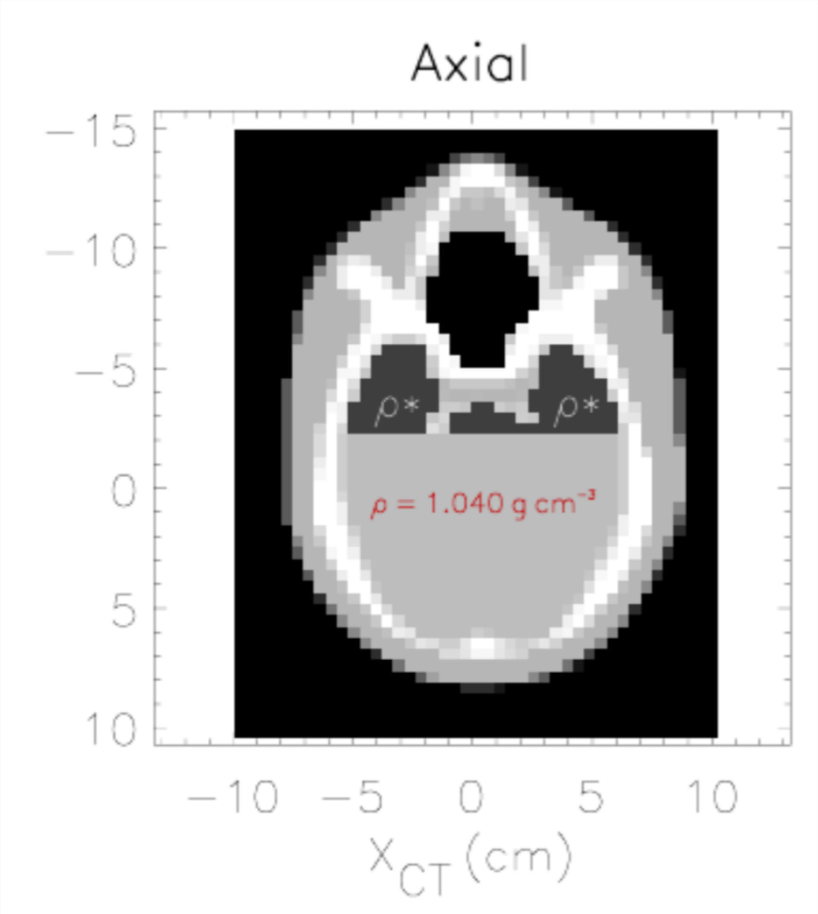


(Cambraia Lopes PhD 2017)

3. The multi-slat concept for PGI in proton RT

3.2 Change of brain density due to fractionated RT

- Conjecture: brain tissue hypo/hyperdense due to fractionated RT Denham et al Radiother Oncol 2002

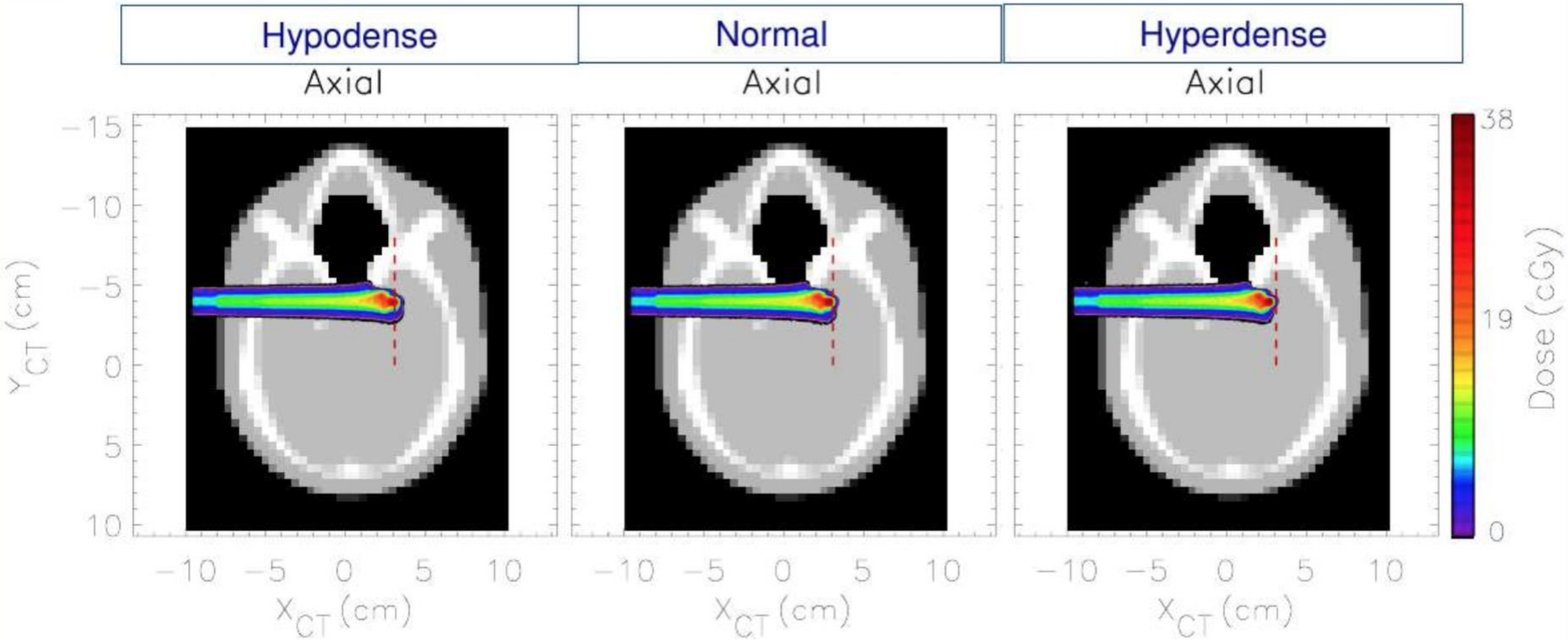


(Cambraia Lopes PhD 2017)

3. The multi-slat concept for PGI in proton RT

3.2 Change of brain density due to fractionated RT

- Conjecture: brain tissue hypo/hyperdense
- Corresponding dose distributions (protons):

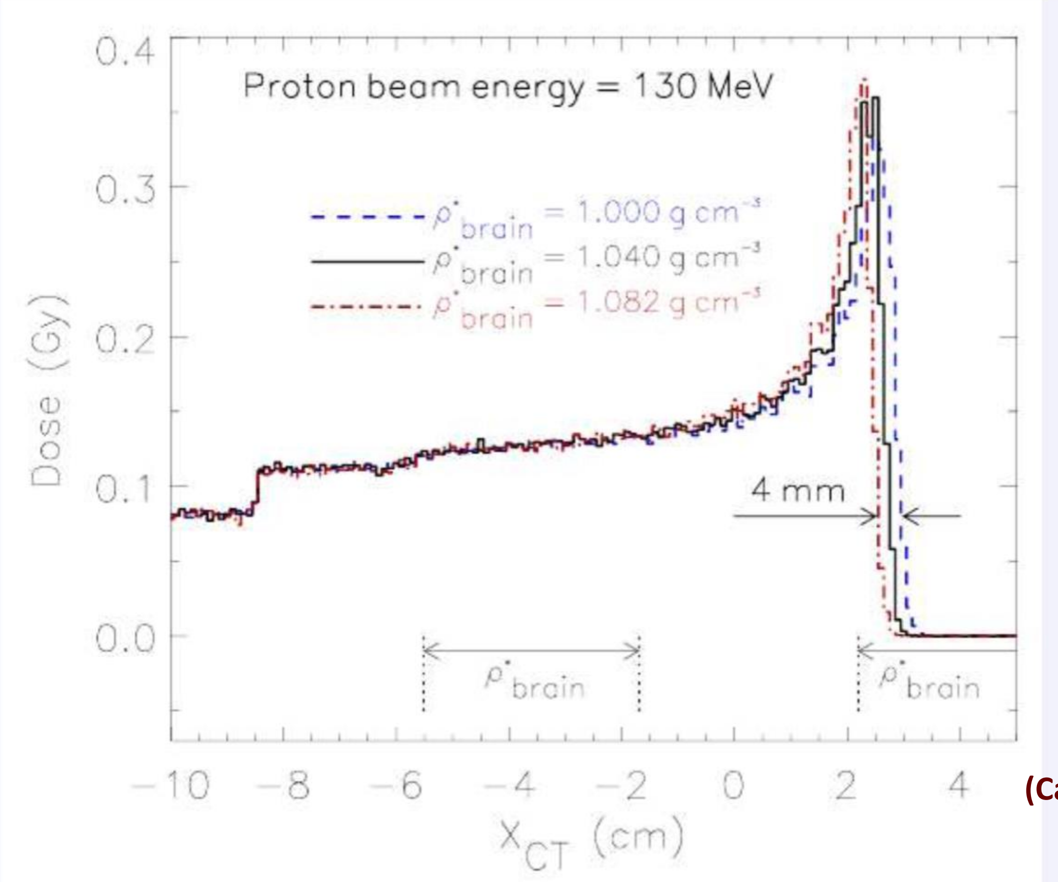


(Cambraia Lopes PhD 2017)

3. The multi-slat concept for PGI in proton RT

3.2 Change of brain density due to fractionated RT

- Conjecture: brain tissue hypo/hyperdense
- Corresponding dose profiles (protons):

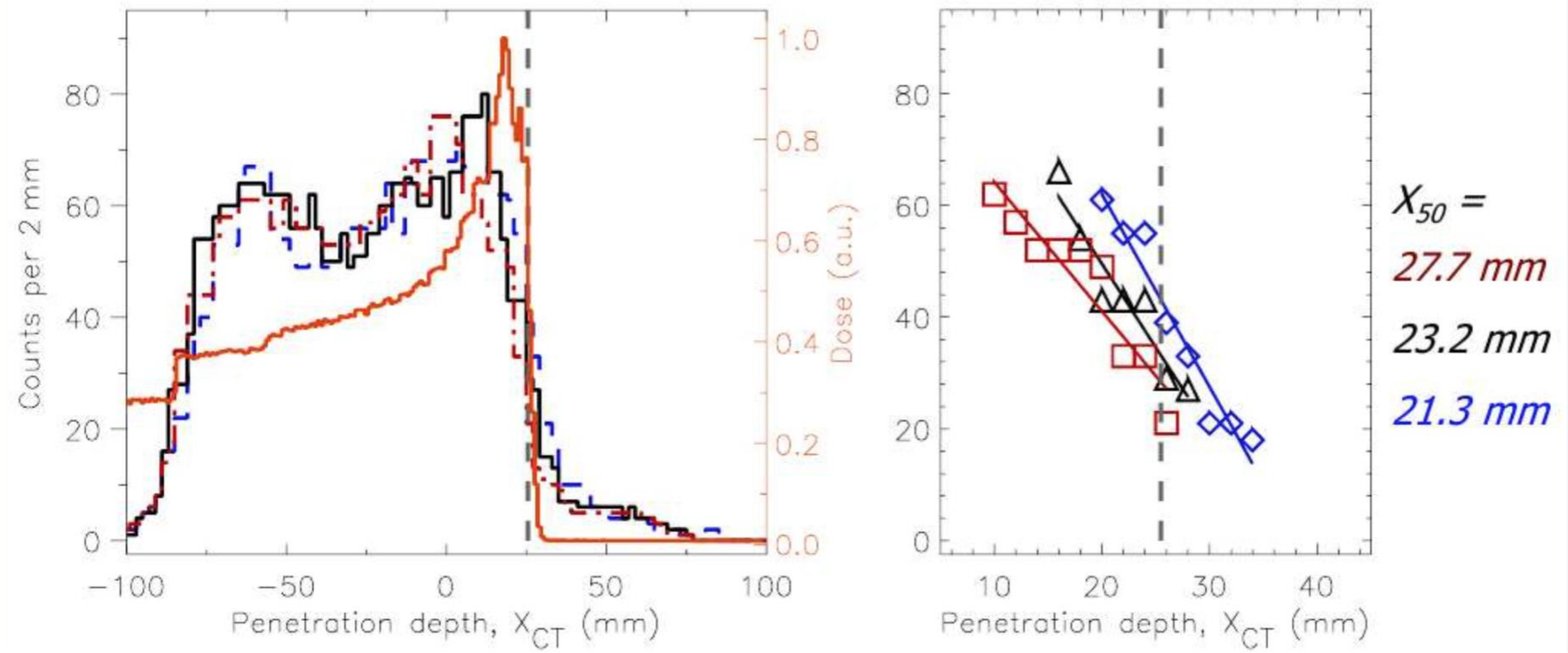


(Cambraia Lopes PhD 2017)

3. The multi-slat concept for PGI in proton RT

3.2 Change of brain density due to fractionated RT

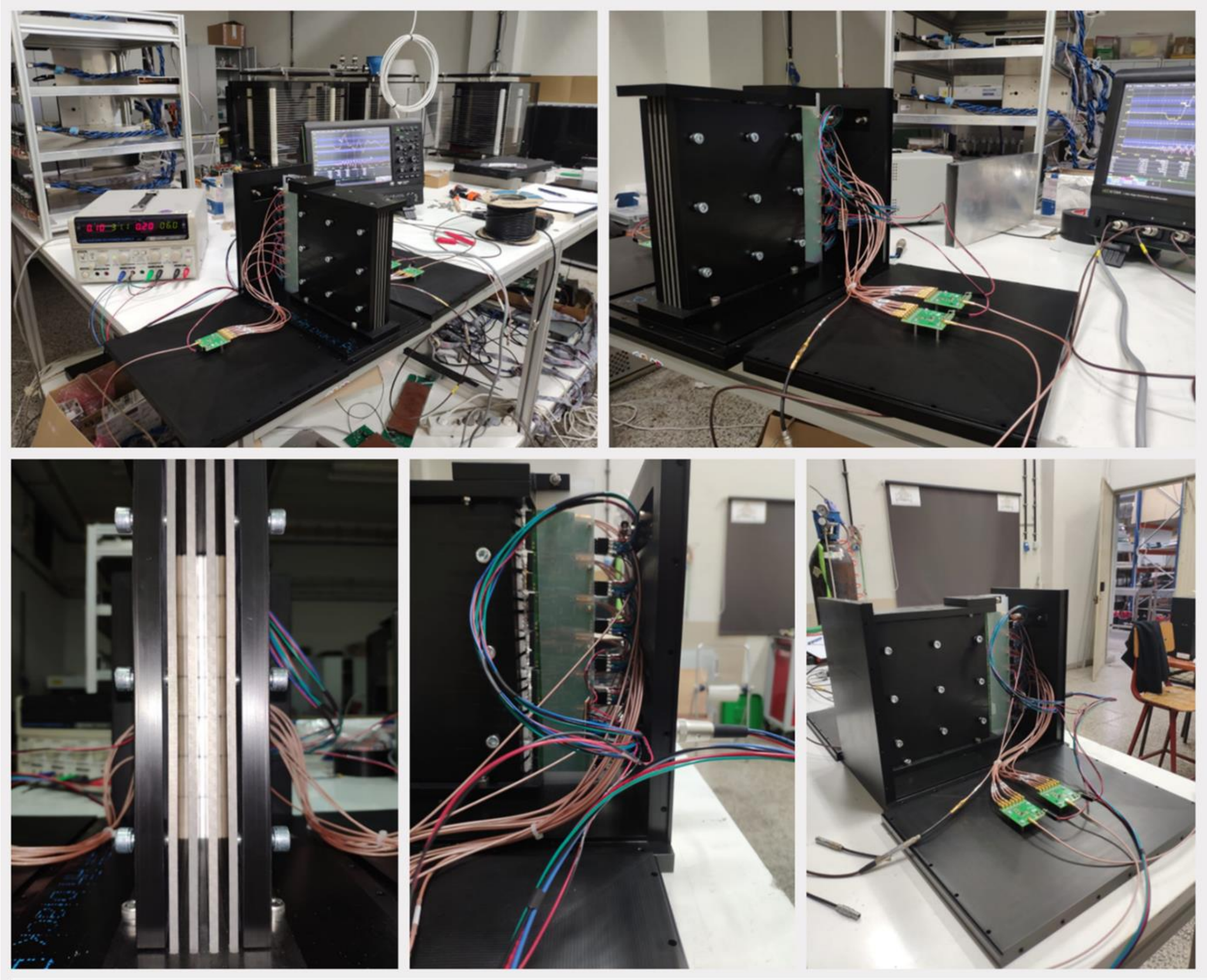
- Conjecture: brain tissue hypo/hyperdense
- Monte Carlo results with proposed detector (Geant4):



(Cambraia Lopes PhD 2017)

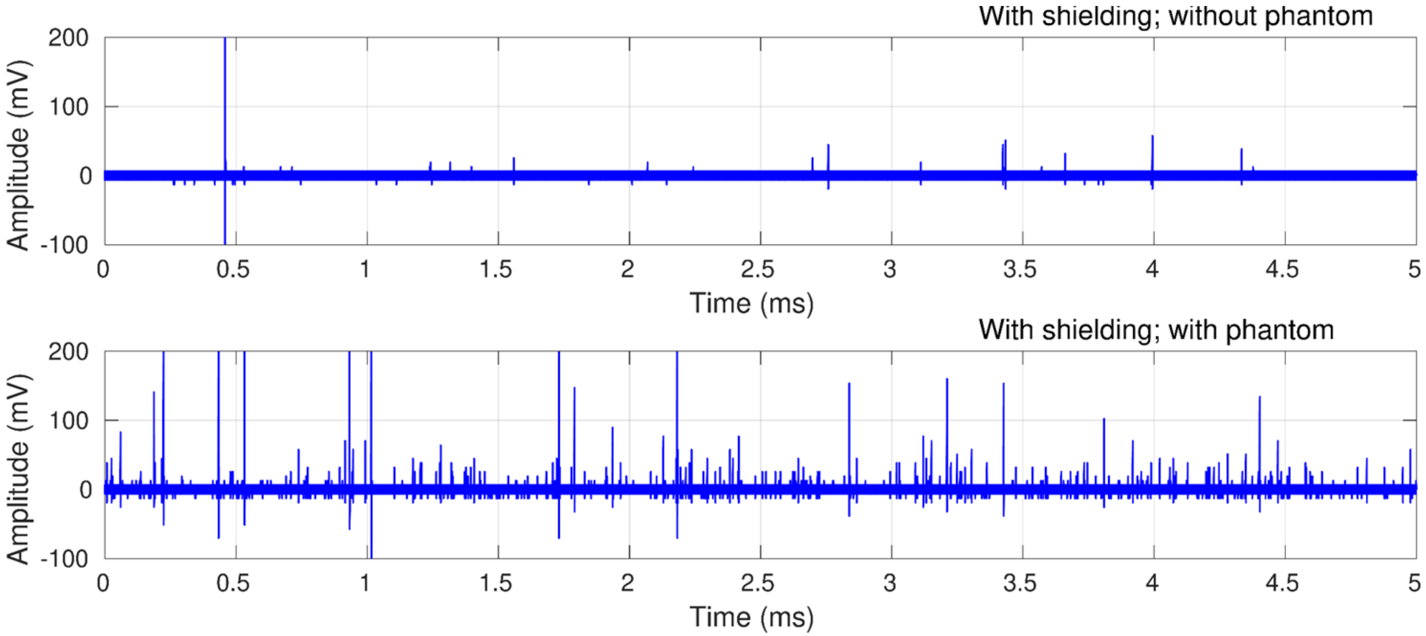
3. The multi-slat concept for PGI in proton RT

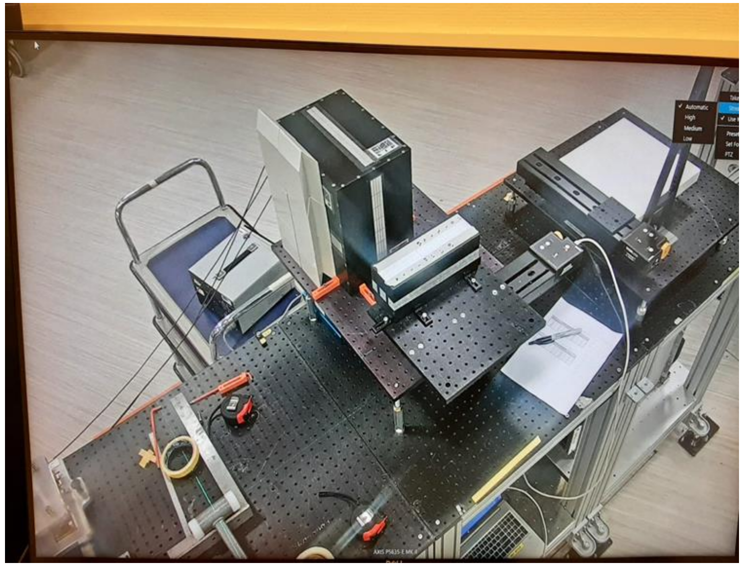
Small-scale multi-slat O-PGI prototype

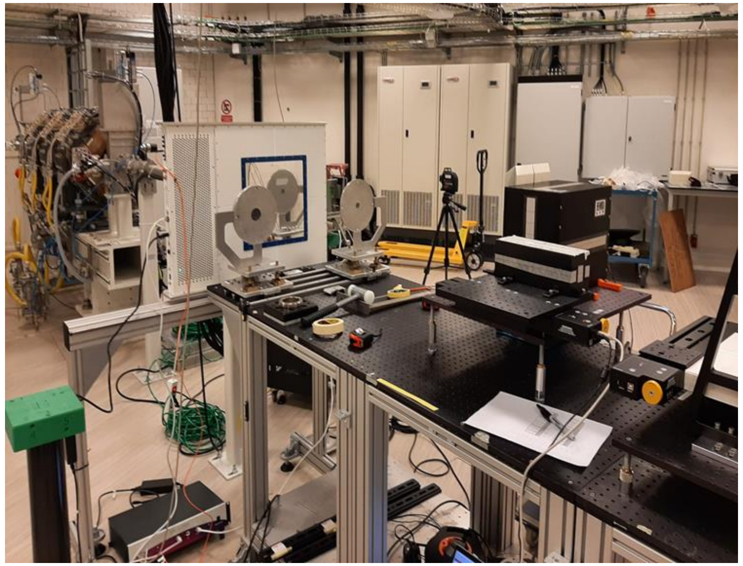


3. The multi-slat concept for PGI in proton RT

Radiation coming from the phantom



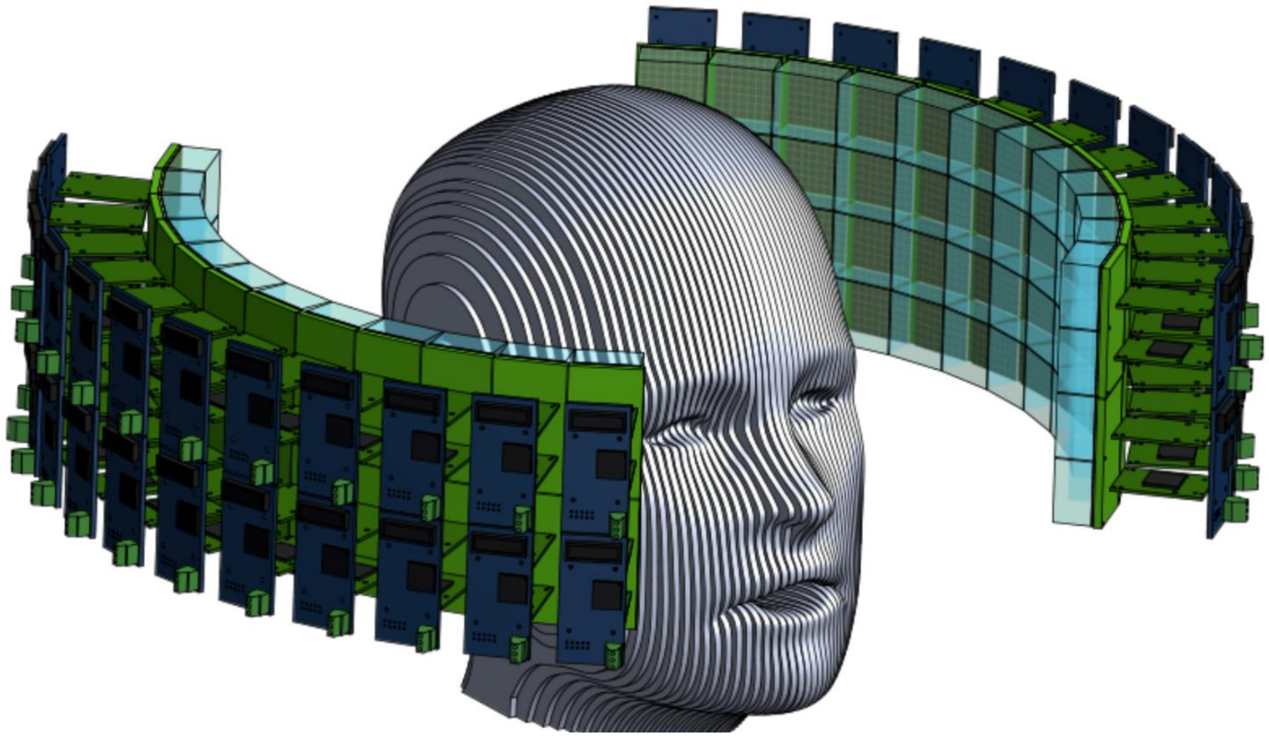




4. In-beam time-of-flight PET for proton RT

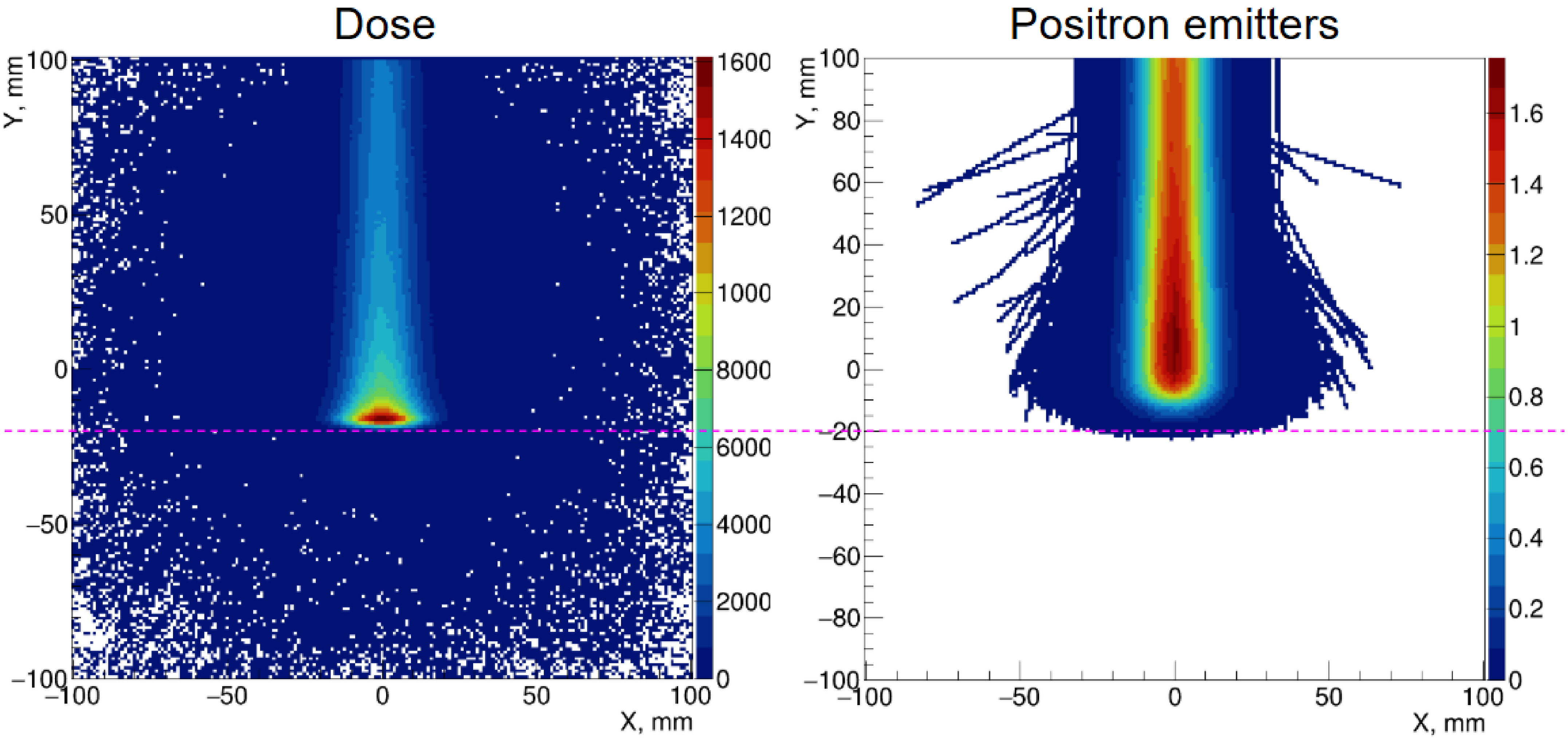
TOF-PET for Proton Therapy (TPPT) – In-beam Time-of-Flight (TOF) Positron Emission Tomography (PET) for proton radiation therapy

Consortium between PETsys Electronics (Lisbon), LIP (Lisbon & Coimbra), ICNAS-UC, IST, Un. Texas at Austin, USA, MDACC (Houston), USA

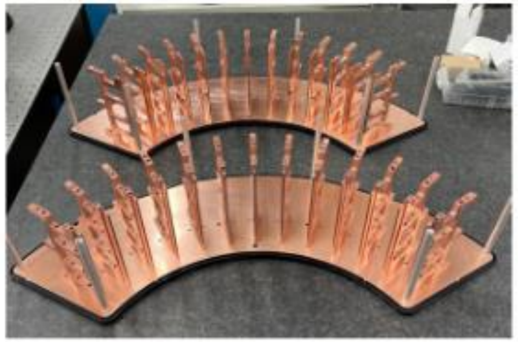


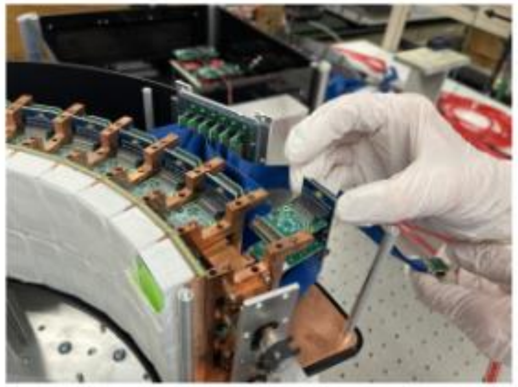
Coincidence time resolution of 200 ps FWHM (corresponds to Gaussian with 3 cm FWHM)

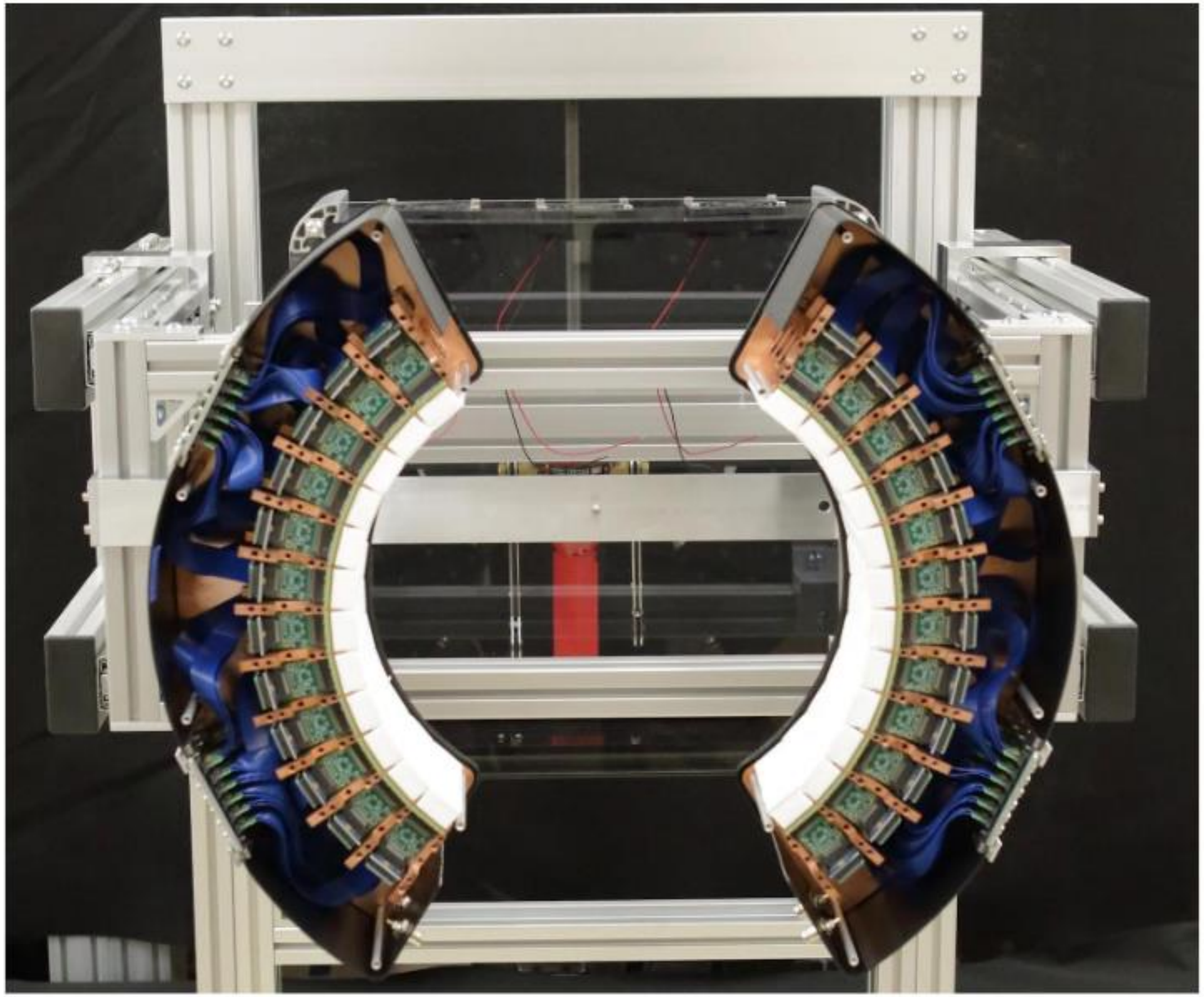
4. In-beam time-of-flight PET for proton RT



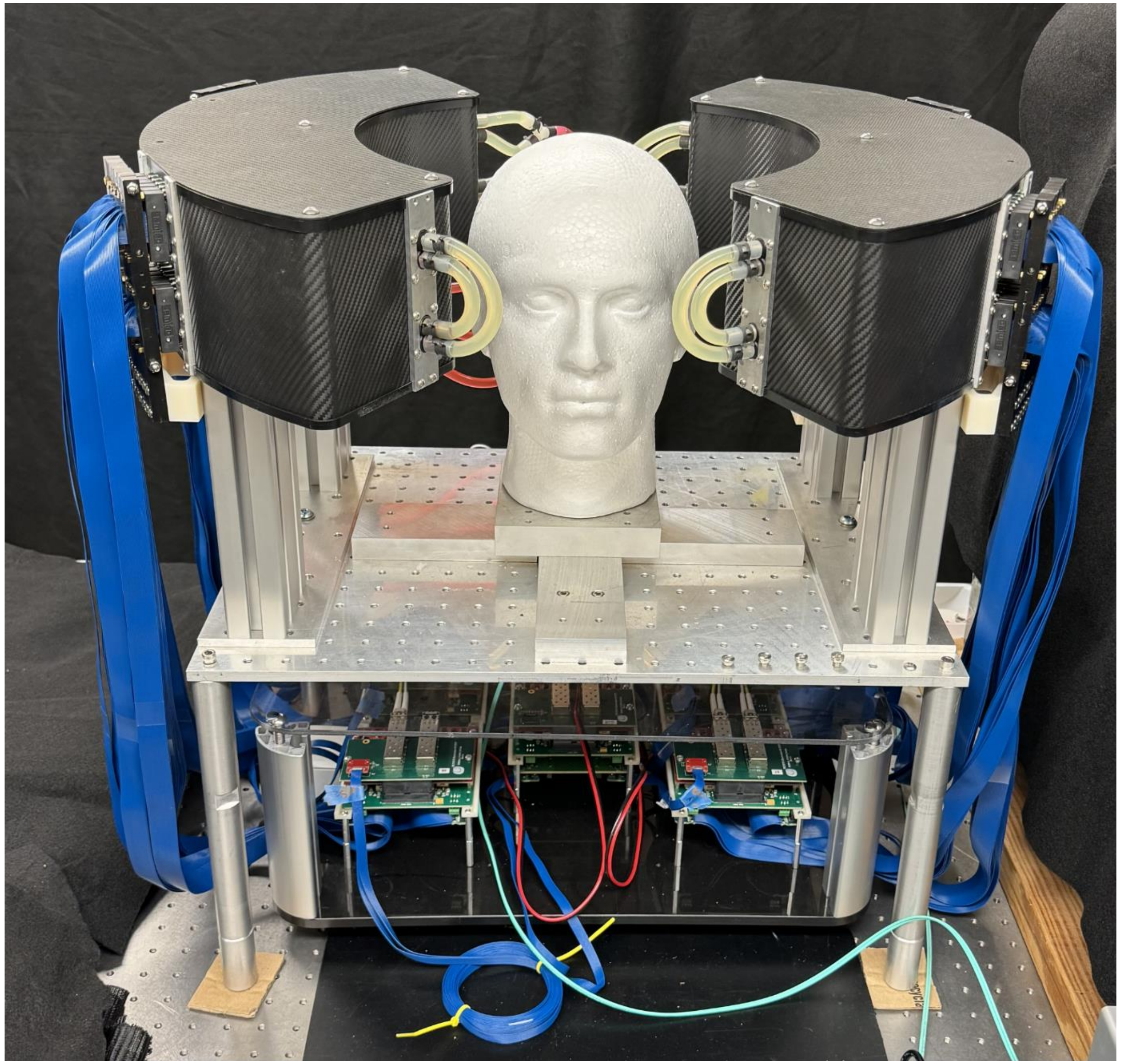
4. In-beam time-of-flight PET for proton RT







4. In-beam time-of-flight PET for proton RT



Thank you for your attention