TIFPA Trento Institute for Fundamental Physics and Applications

INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI FIRENZE

Azienda Provinciale per i Servizi Sanitari
Provincia Autonoma di Trento

The pRad project: development of a single-event Proton Radiography apparatus

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INFN-Firenze

INFN-PRIMA proton radiography

C. Civinini et al., 2017 IEEE-MIC Symposium DOI: 10.1109/NSSMIC.2016.8069620

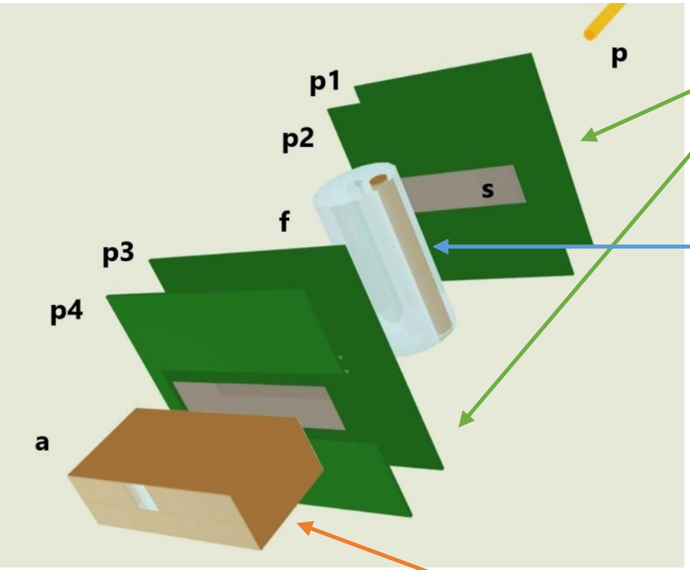
Outline

- The pRad project
  - Funded by INFN 2024-26
1. A single-event proton radiography apparatus
   - Silicon strip Tracker
   - Fast scintillating Calorimeter
2. Proton tomographies of prostheses
   - See Mara's talk tomorrow
3. SPR survey
   - SPR maps variability with respect to direct pCT mesurement on a biological phantom
- Dose measurements on a pCT acquisition run
  - PLT sensors for dose assessment

The proton CT apparatus

- Silicon strip tracker + scintillator calorimeter
- Single-event acquisition

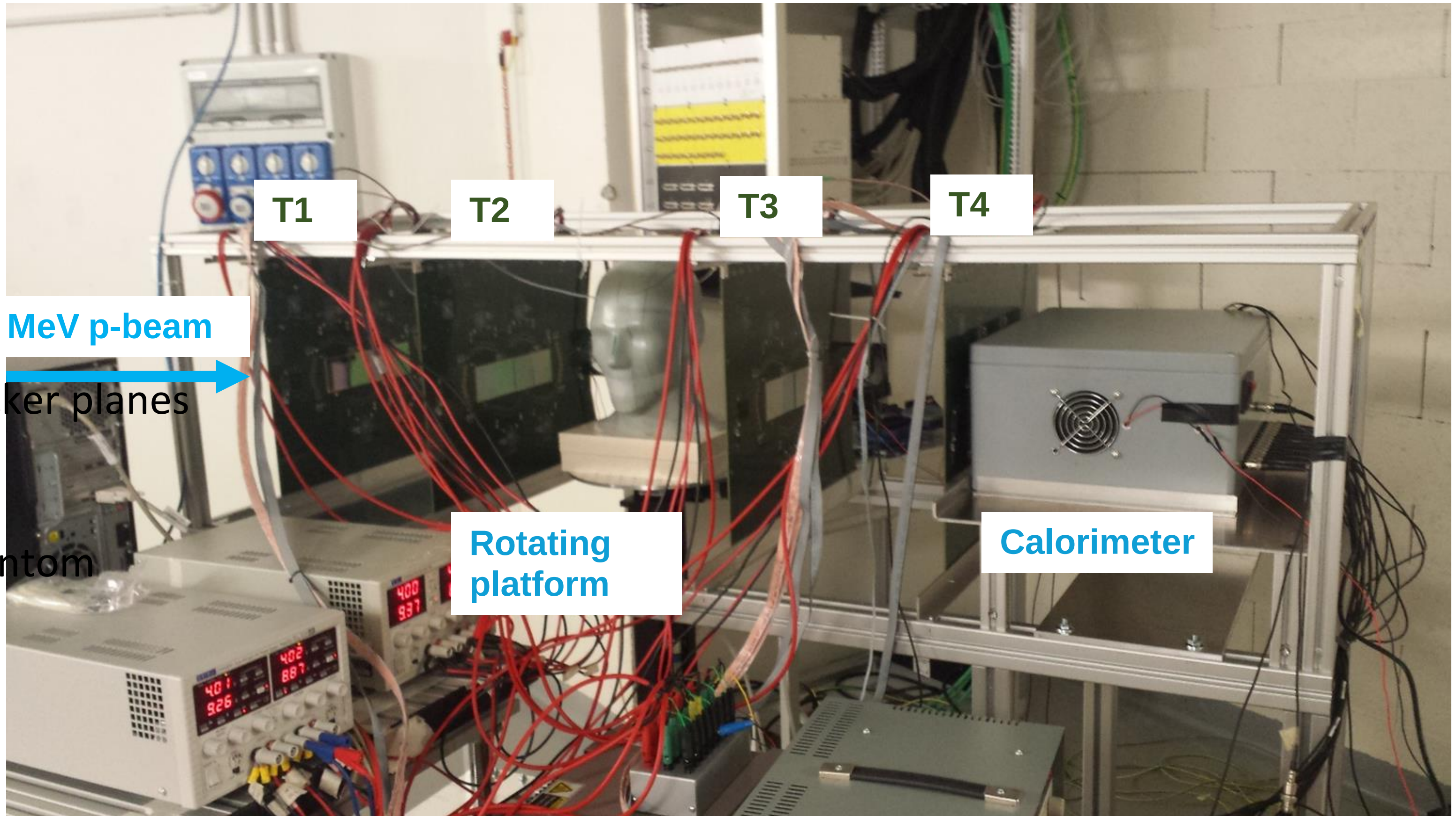
The pCT system



Tracker planes

Phantom

YAG calorimeter



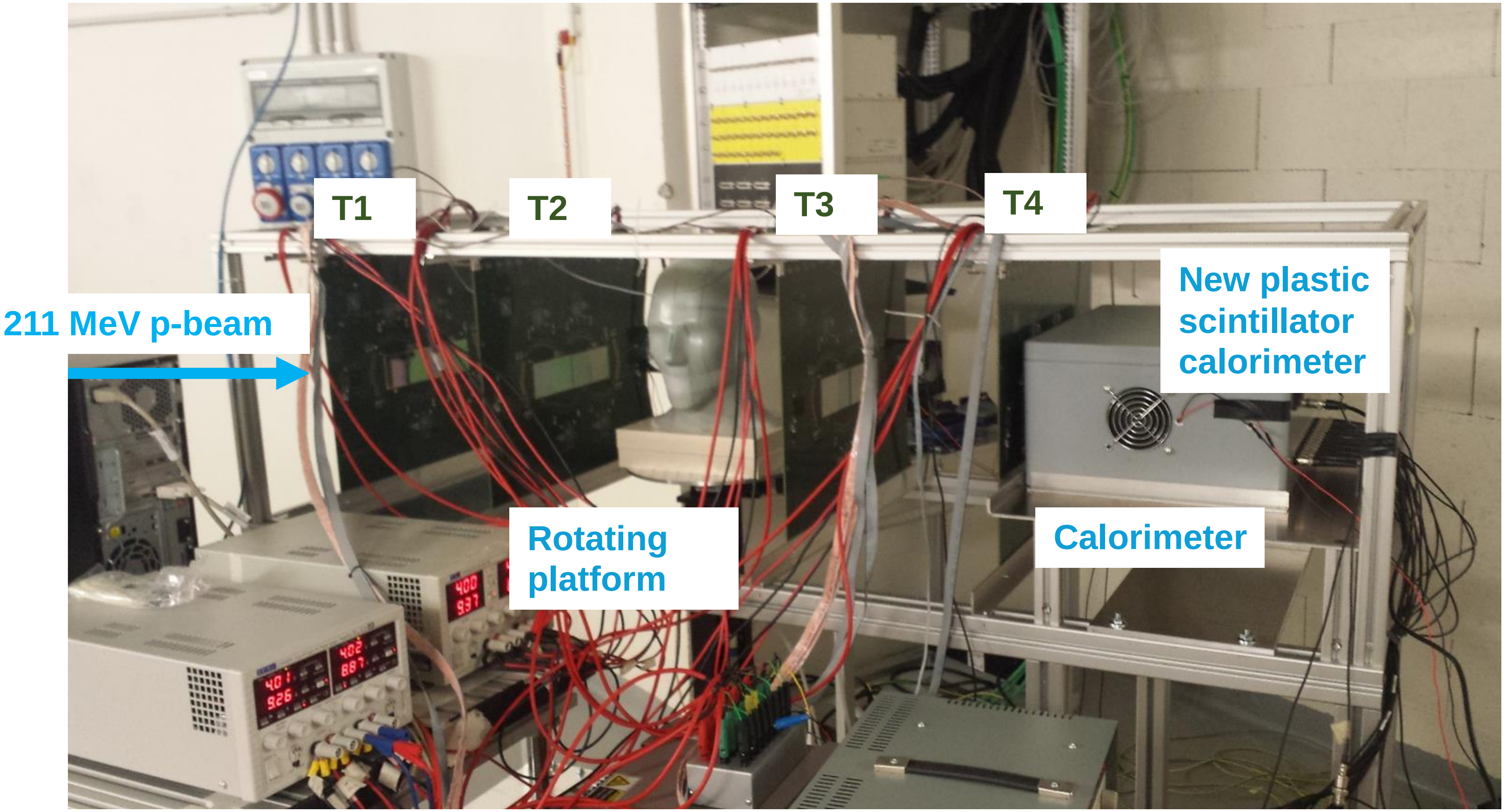
C. Civinini *et al.*, ‘Relative stopping power measurements and prosthesis artifacts reduction in proton CT’ *Phys. Med. Biol.* **65** (2020) 225012, DOI 10.1088/1361-6560/abb0c8.

The proton Radiography apparatus

- Based on the existing pCT system
- Silicon strip tracker + scintillator calorimeter
- Single-event acquisition

- YAG:Ce calorimeter replaced by a plastic scintillator matrix (BC-408 o RJ-200)

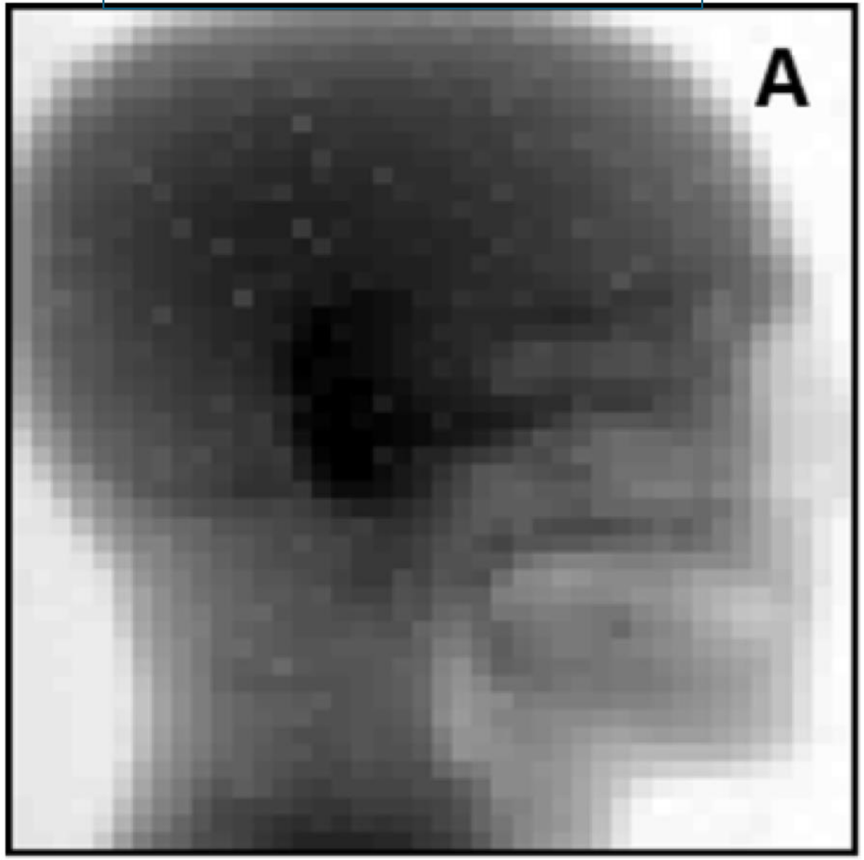
The pCT system



C. Civinini *et al.*, 'Relative stopping power measurements and prosthesis artifacts reduction in proton CT' *Phys. Med. Biol.* **65** (2020) 225012, DOI 10.1088/1361-6560/abb0c8.

Why single proton radiography?

'Integration' radiography



< 10mGyE

Dose

< 0.1 mGyE

Anthropomorphic phantom: CIRS 731-HN

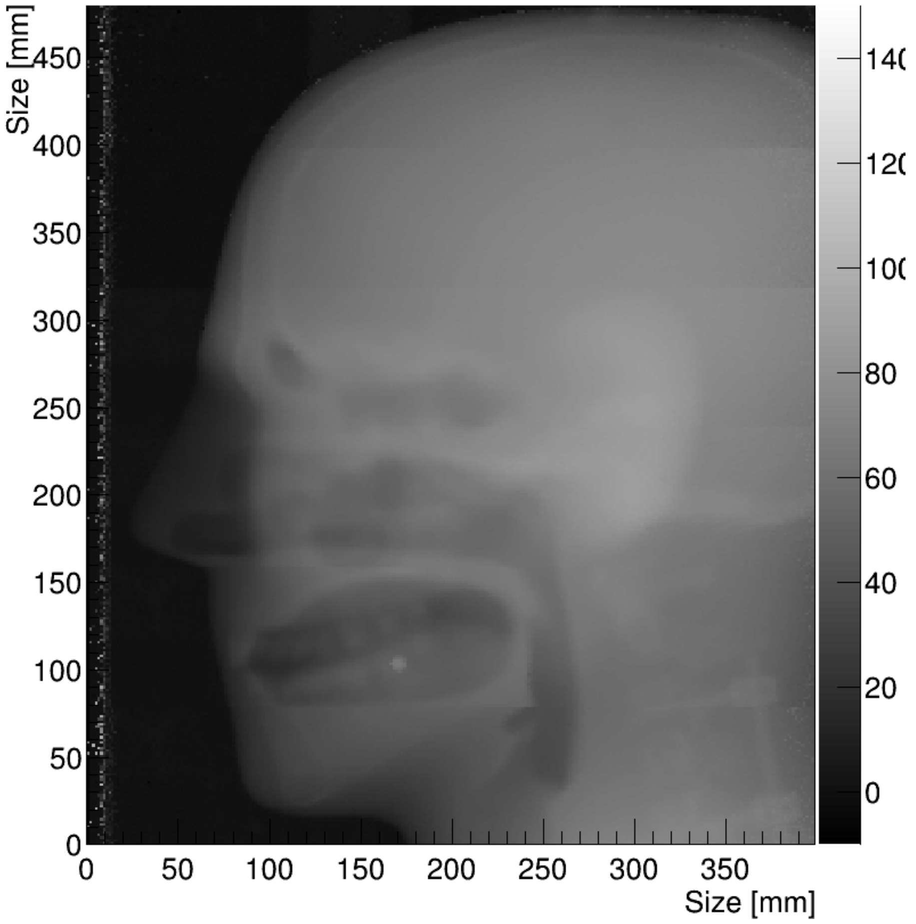
Qualitative visualization of a proton radiography acquired by a MLIC (Multi Layer Ionization Chamber) IBA Giraffe:
Mean dose < 10mGyE
P. Farace et. al., Med. Phys. 43 (12), December 2016

'Single proton' radiography

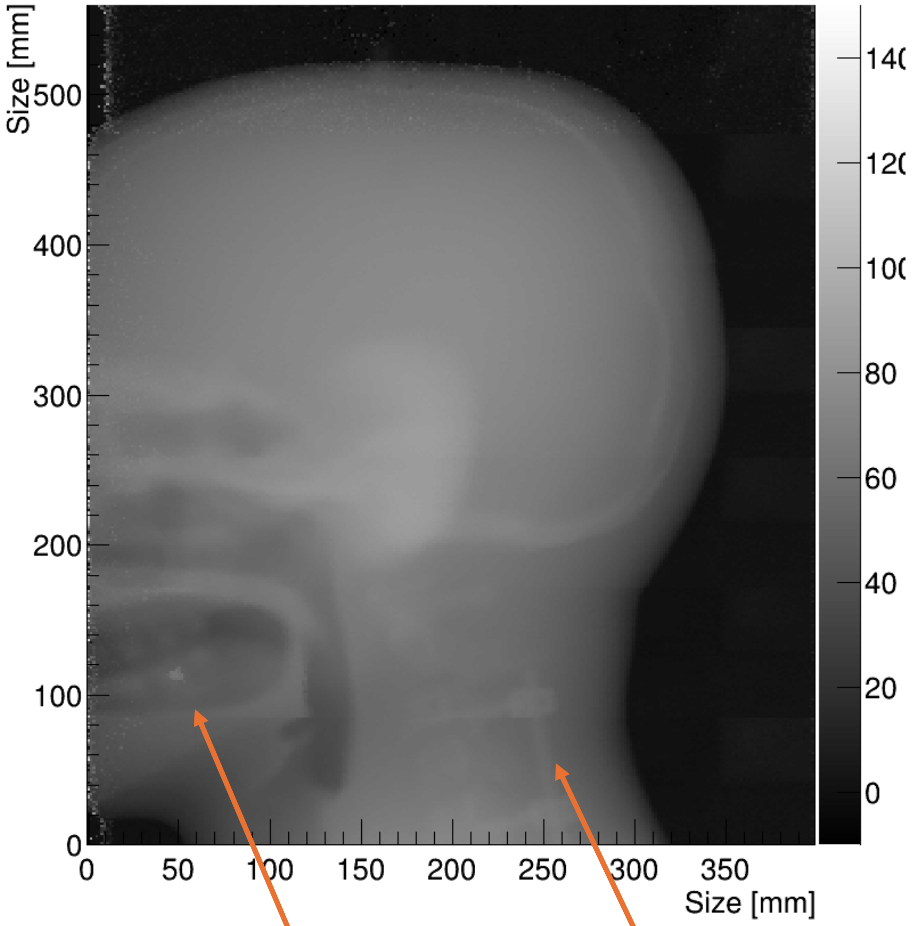
Single event proton radiography acquired by the pCT-INFN:
Mean dose< 0.1 mGyE
INFN PRIMA-RDH-IRPT collaboration
C. Civinini et al., 2017 IEEE-MIC Symposium DOI: 10.1109/NSSMIC.2016.8069620

Proton Radiographies with current pCT system

- Sagittal radiographies
- CIRS 731-HN



Long acquisition time (minutes)



Titanium vertebral prostesis

Tungsten dental filling

Single event proton radiography acquired by the pCT-INFN:
Mean dose< 0.1 mGyE
INFN PRIMA-RDH-IRPT collaboration
C. Civinini et al., 2017 IEEE-MIC Symposium DOI: 10.1109/NSSMIC.2016.8069620

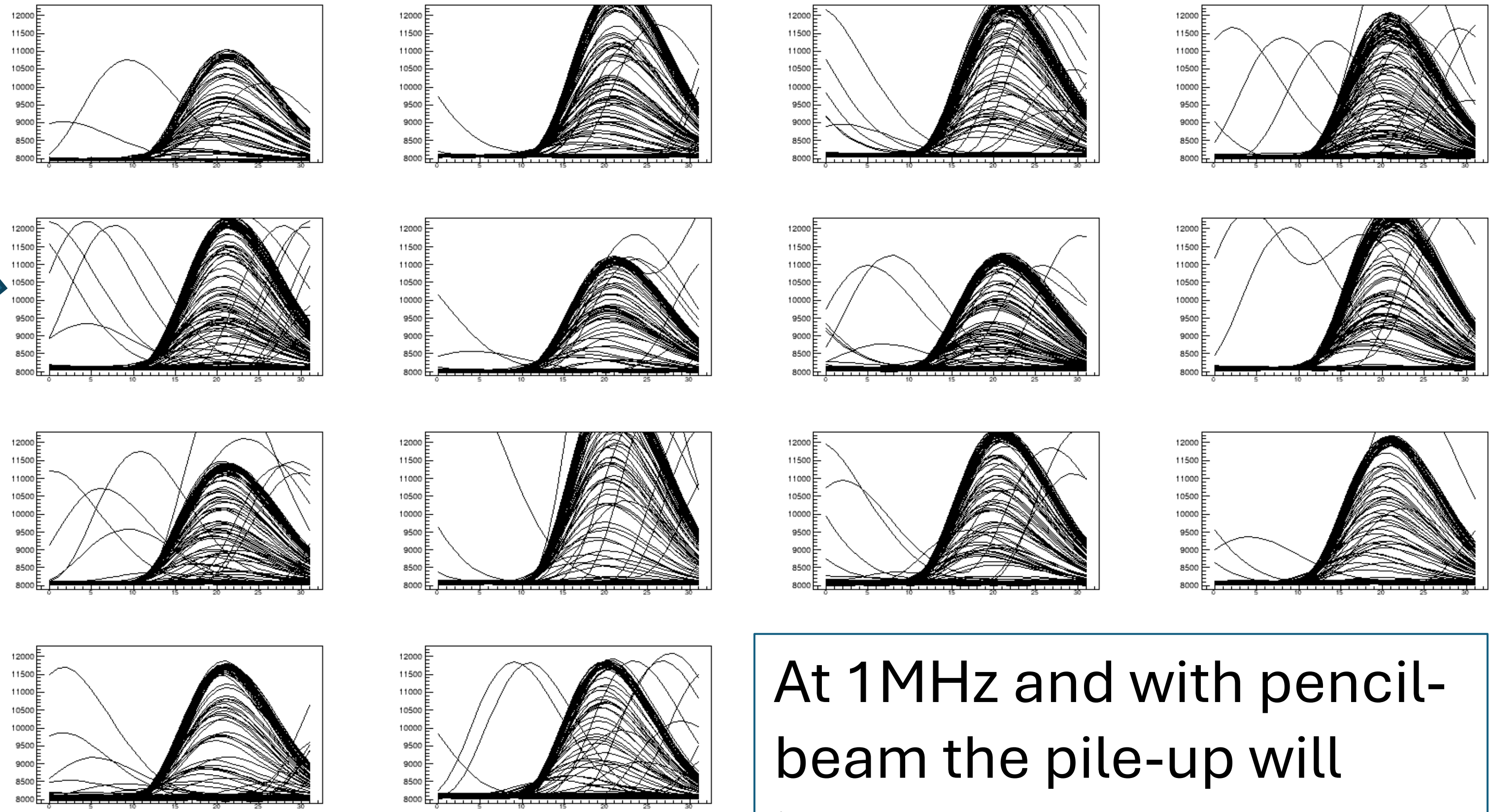
Why change the current Calorimeter (YAG:Ce)?

- Light emission YAG:Ce: $\sim 70ns$, shaping time: $1\mu s$, signal sampling: $10MHz$, sampling window: $\sim 3.2\mu s$

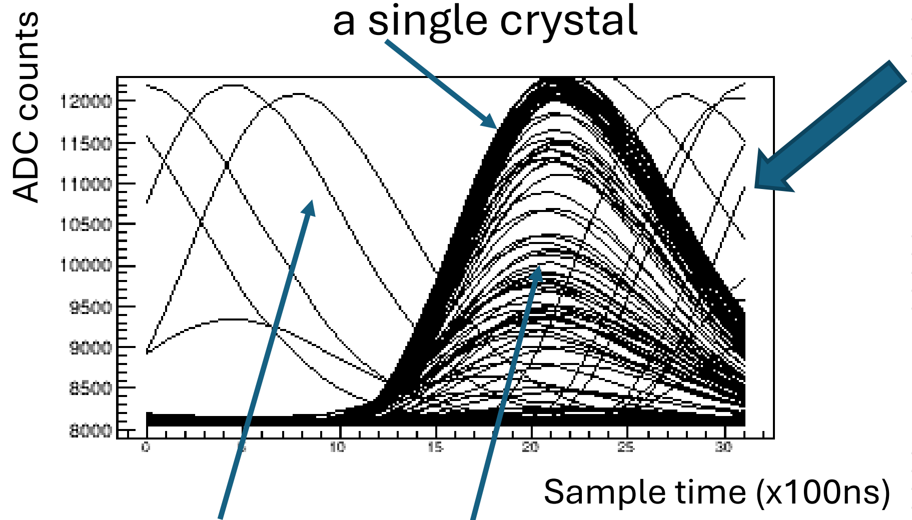
14 YAG:Ce crystals @$100kHz$ beam rate

1000 overlapped triggers

<u>Spreaded beam</u>



Protons fully contained in a single crystal

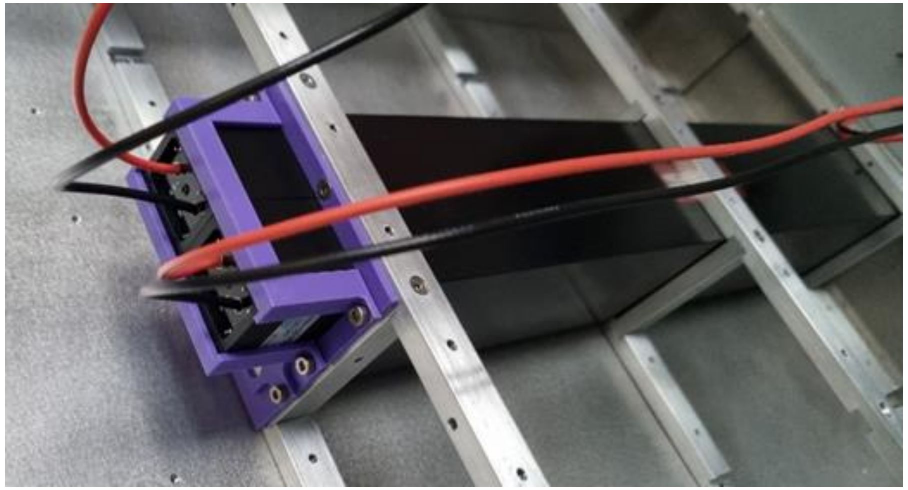


Pile-up

Protons in more than one crystal + nuclear interactions

At 1MHz and with pencil-beam the pile-up will increase too much

Calorimeter 2x2 prototype with PMTs

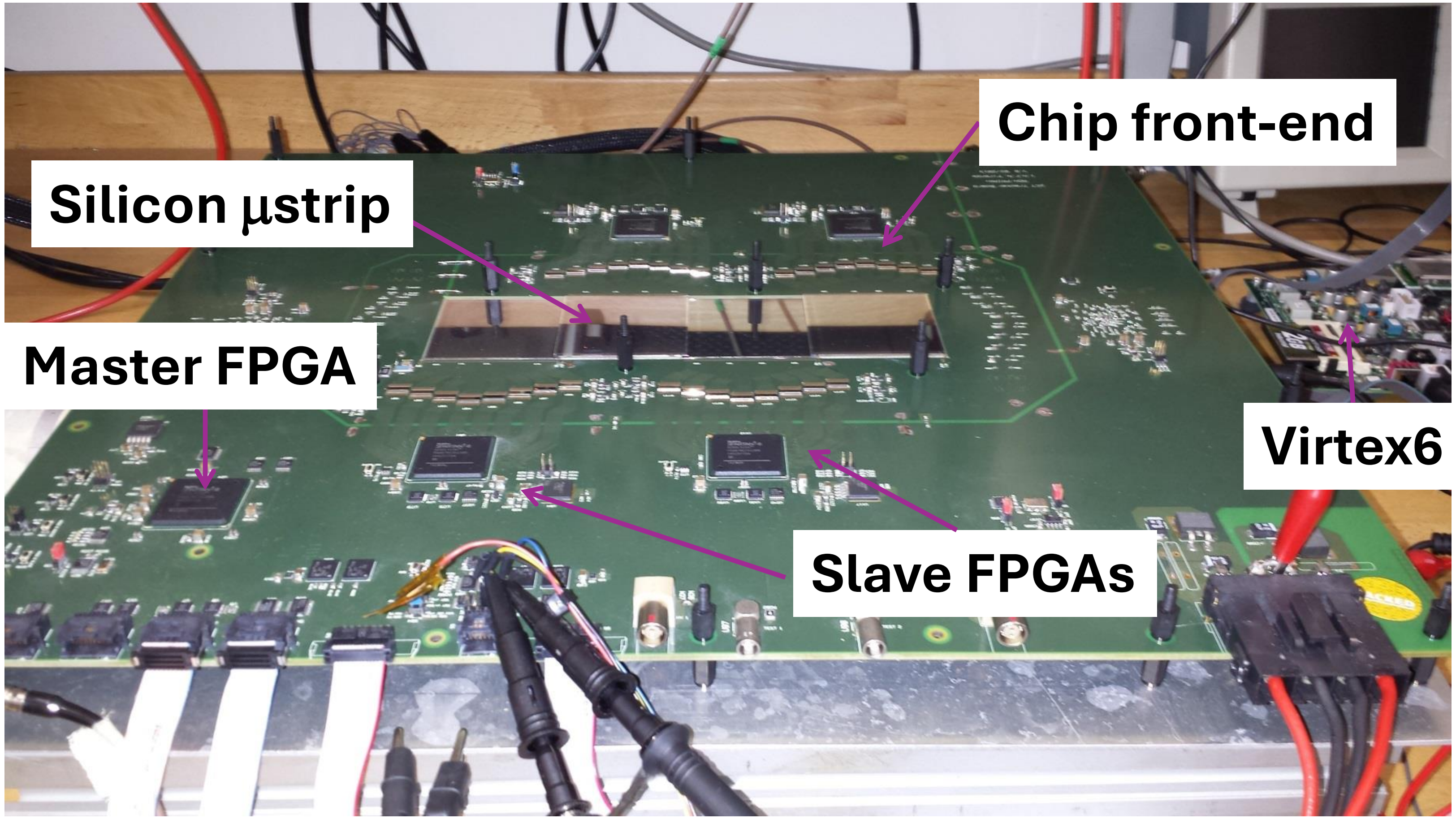


New pRad calorimeter

- Goal: $1\ MHz$
- Plastic scintillators (BC-408 o EJ-200)
  - light emission $\sim 2.5\ ns$
- PMT (Hamamatsu H11934 series) + voltage amplifier
- The tracker will remain the same (Si micro-strip)
- System rate capability: $\times \sim 10$ limited by the time resolution of the tracker (presently $\sim 100 ns$ which includes also current trigger jitter)

- Calibration/reconstruction techniques were extensively studied on the present pCT calorimeter →Linearity -Uniformity-Energy resolution
  - M. Scaringella *et al.*, 'The INFN proton computed tomography system for relative stopping power measurements: calibration and verification', 2023 *Phys. Med. Biol.* **68** 154001, DOI: 10.1088/1361-6560/ace2a8

The Silicon Strip Tracker



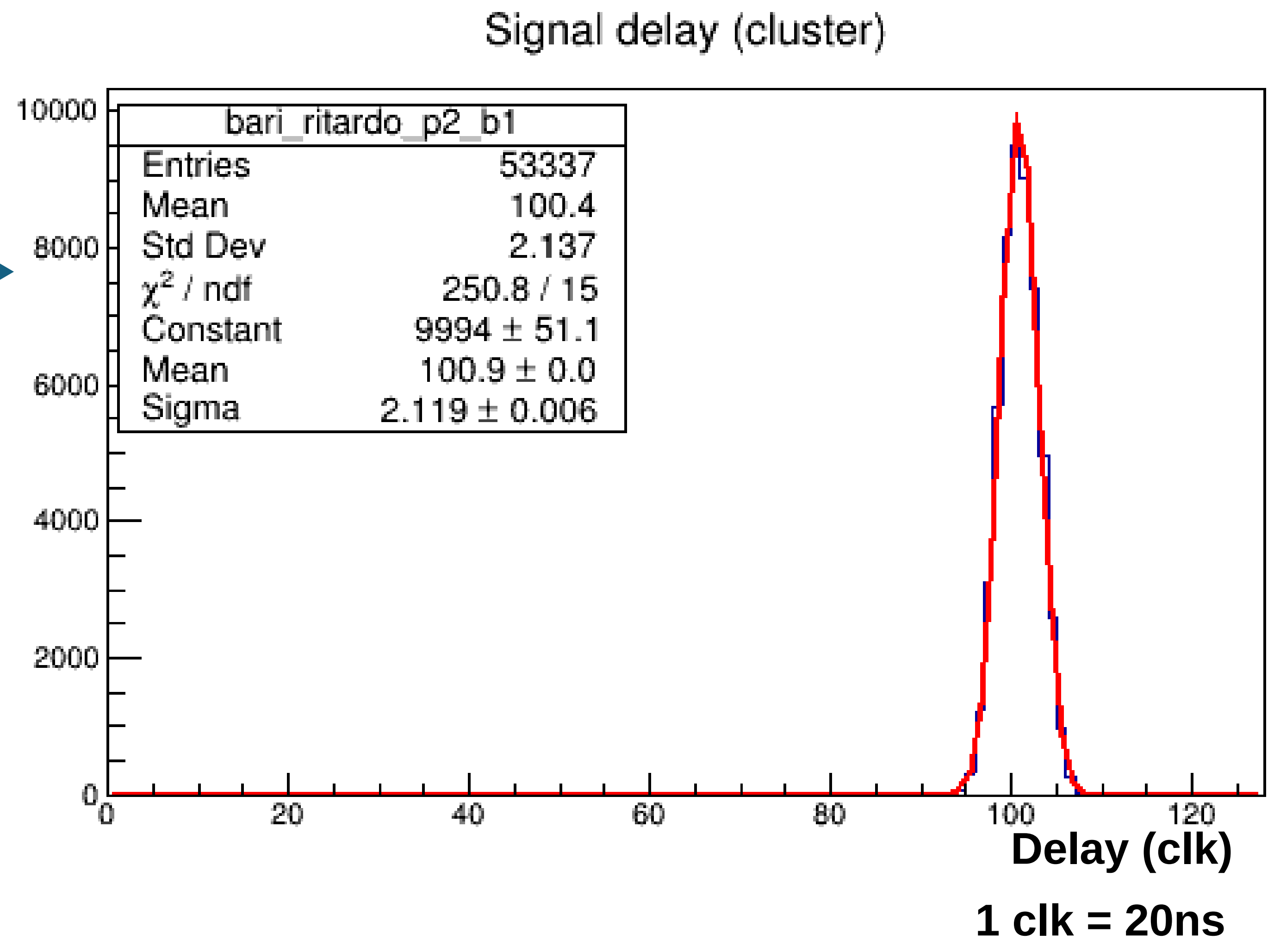
8 silicon microstrip sensors (5.1x20 cm^2)
48 front-end chips (1536 channels)

Pile-up on Silicon Strip Tracker

- The probability to have two protons on the same strip is very low
  - $O(10^{-2} - 10^{-4})$ → depends on the beam dimension (pencil – spread) and it is proportional to the area of the strip
- Viceversa the probability to find two protons on the same sensor is quite high
  - $O(1 - 10^{-1})$ → (pencil-spread)
- To deal with this, in the pCT silicon tracker the hit on a strip is saved together with its delay with respect to the trigger: $\Delta \boldsymbol{t_{x,y}}$
- To find out which is the correct x-y association, removing the ghosts, the difference of the time of the two hits is asked to be: $\left|\Delta \boldsymbol{t_x} - \Delta \boldsymbol{t_y}\right| < 100ns$
- Nota bene: most of the time resolution on $\Delta \boldsymbol{t_i}$ comes from the trigger time jitter because of the $1\mu s$ shaping time of the YAG:Ce calorimeter → this contribution will be substantially reduced when the faster scintillator and calorimeter electronics will be deployed.

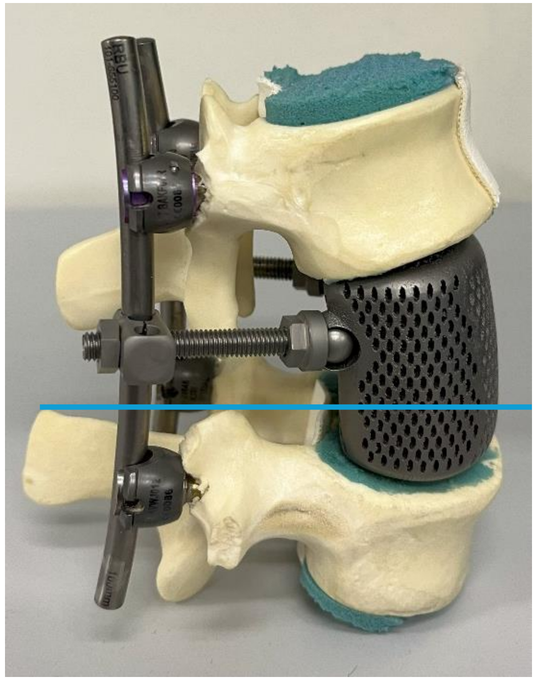
Timing on tracker (current pCT system)

- Silicon strip Tracker hits
- Delay with respect to the calorimeter trigger
- $\boldsymbol{FWMH \cong 100\ ns}$ Trigger jitter + Tracker timing resolution
- Reducing the trigger jitter the width of the tracker hit delay distribution will decrease

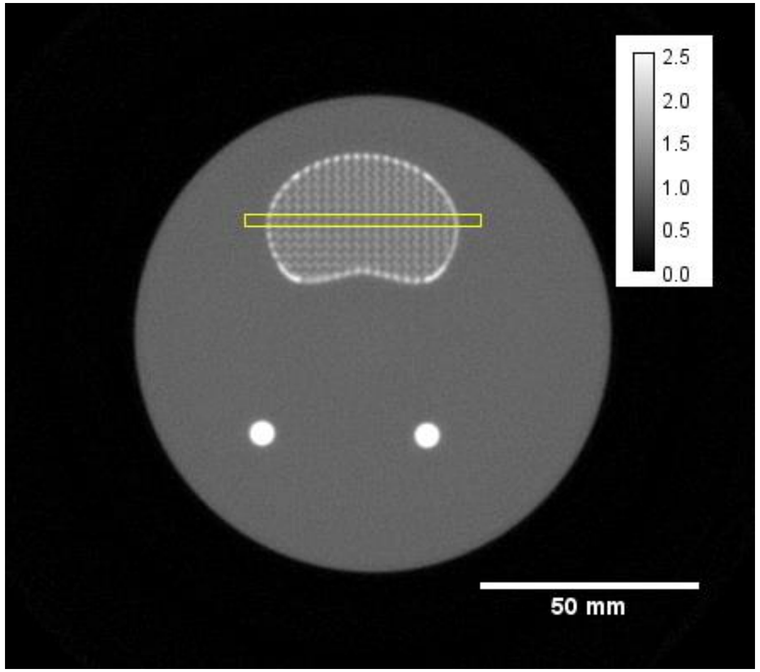


pRad project: Proton CT of prostheses

- Exploiting the reduced sensitivity of the pCT images on metals, our system is being used to build a 'library' of SPR of artificial prostheses and materials
- This could help in optimize treatment plans in presence of implanted prostheses



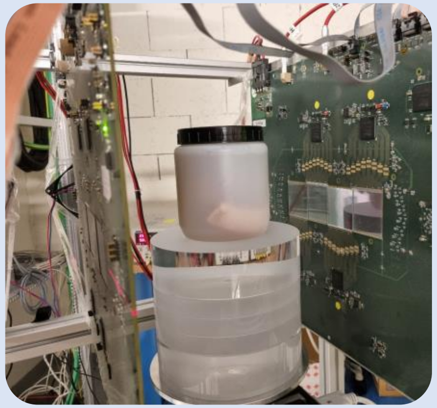
Axial section of the pCT tomography



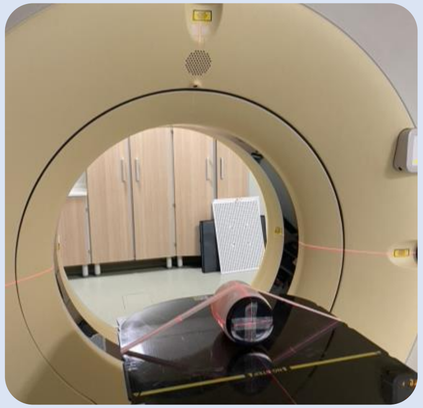
More details on Mara's talk tomorrow

pRad project: SPR - European Survey

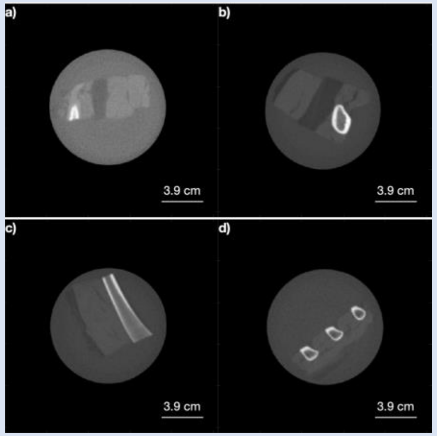
A novel approach for pCT implementation in proton treatment planning: pCT + bio-phantoms



pCT



SECT

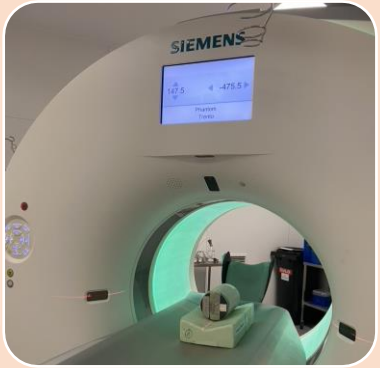


Characterization of bio-phantoms as clinical tool for verification and enhancement of the SECT calibration methods

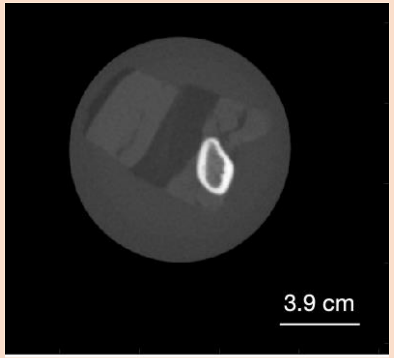
Fogazzi E. et al., Phys Med Biol (2024a) 69 135009

pCT

PCCT



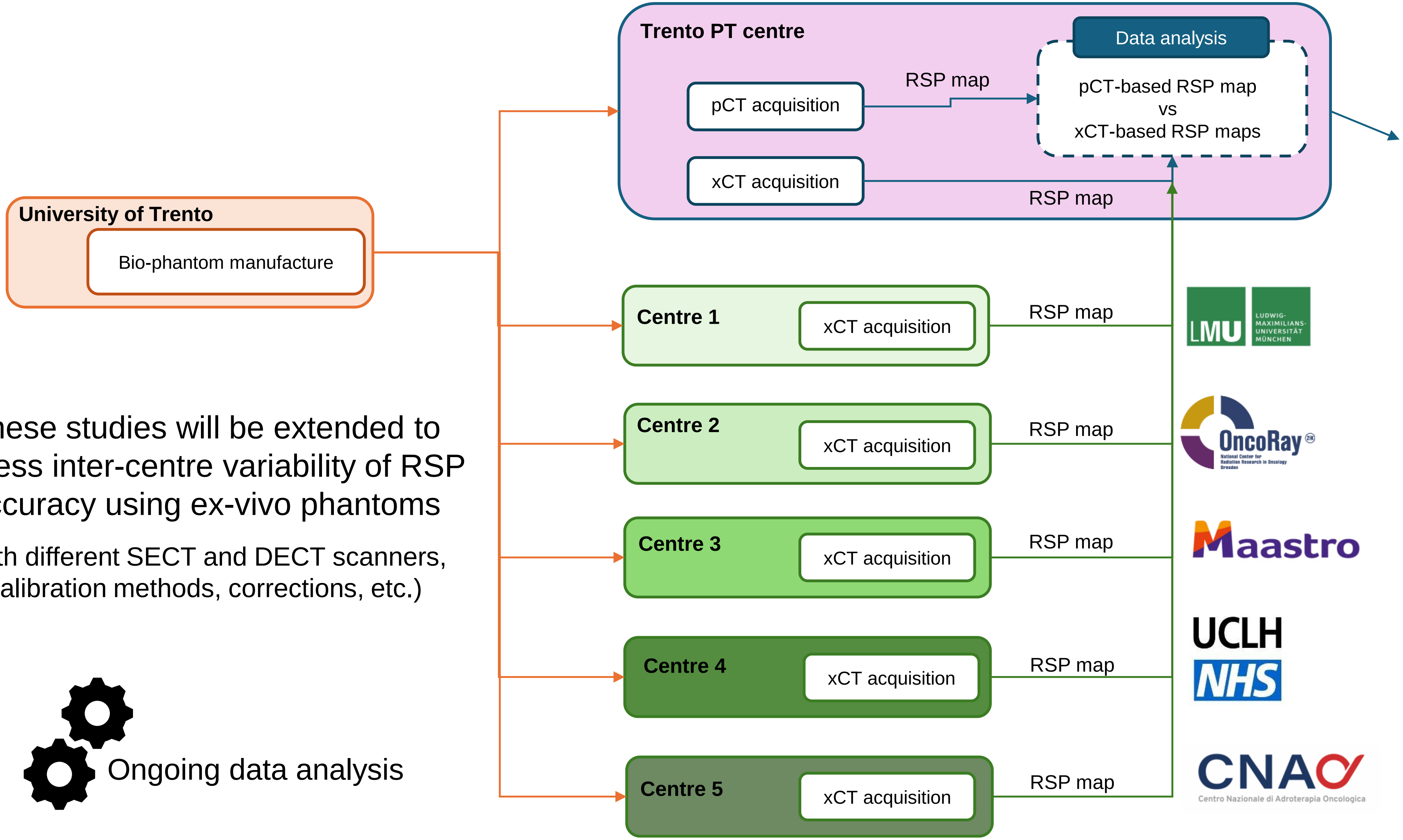
DECT



Extension of the study for verification of multi-energy CT calibration methods

Fogazzi E. et al., Phys Med Biol (2024b) 69 175021

European survey: pCT+ bio-phantom as inter-centre clinical tool



Inter-centre variability of RSP accuracy

(with different xCT scanners, calibration methods, corrections, etc)

These studies will be extended to assess inter-centre variability of RSP accuracy using ex-vivo phantoms

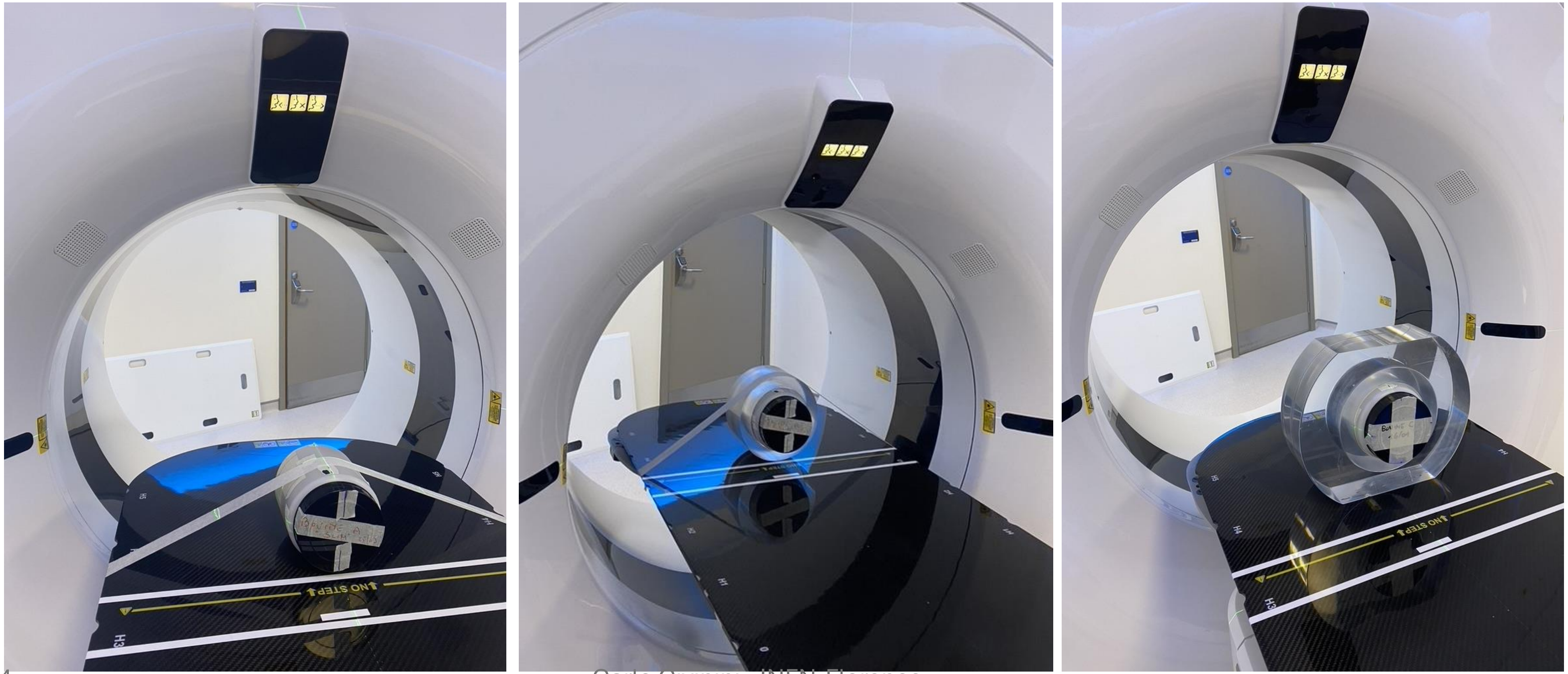
(with different SECT and DECT scanners, calibration methods, corrections, etc.)

Ongoing data analysis

SECT and DECT scanners, with different calibration approaches and scan protocols (e.g. reconstruction, beam hardening corrections, etc.).

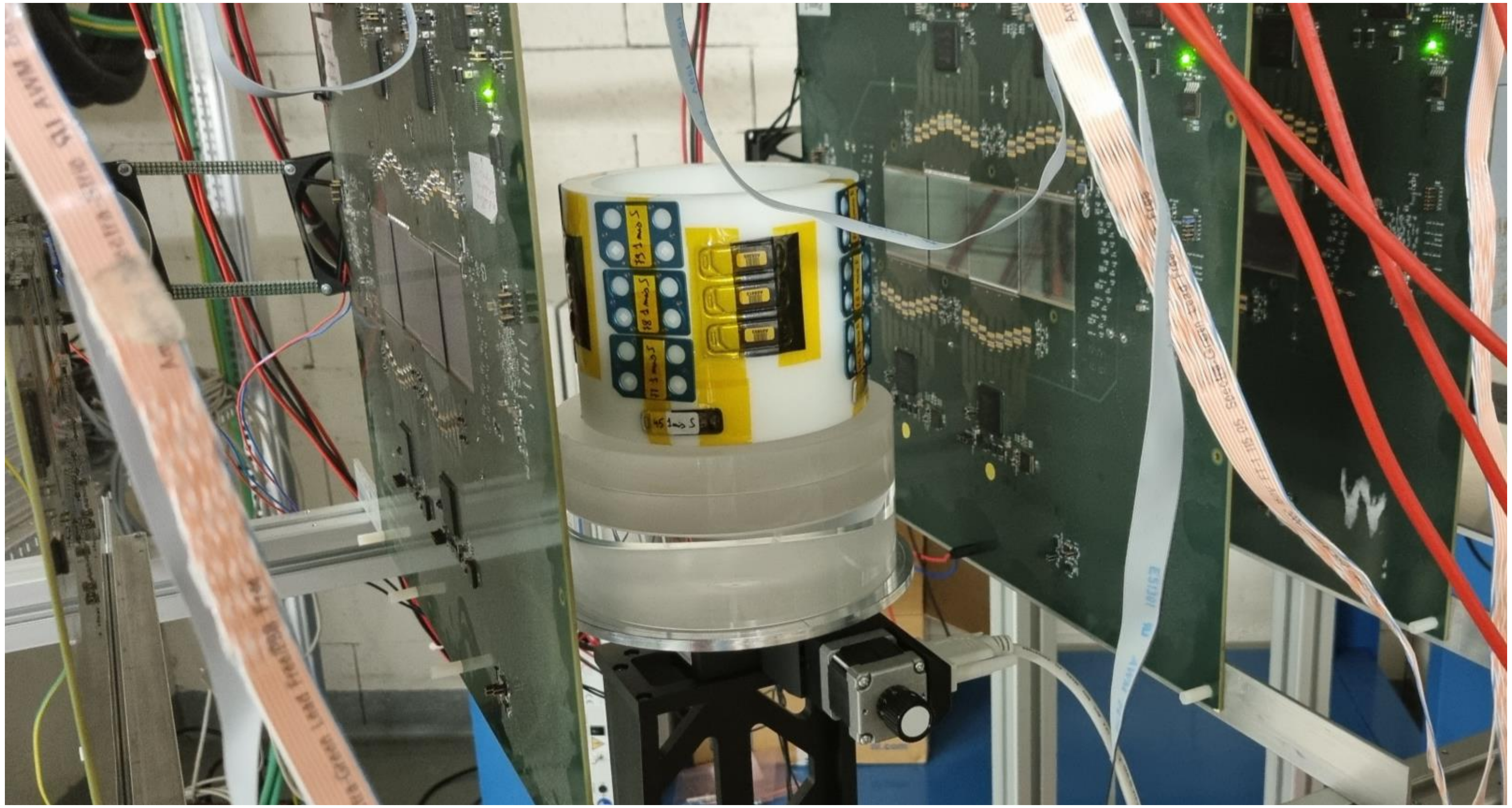
The bio-phantom was scanned in three different configurations, to assess the impact of phantom size.

Each center provide the RSP map, to be compared with the pCT image.



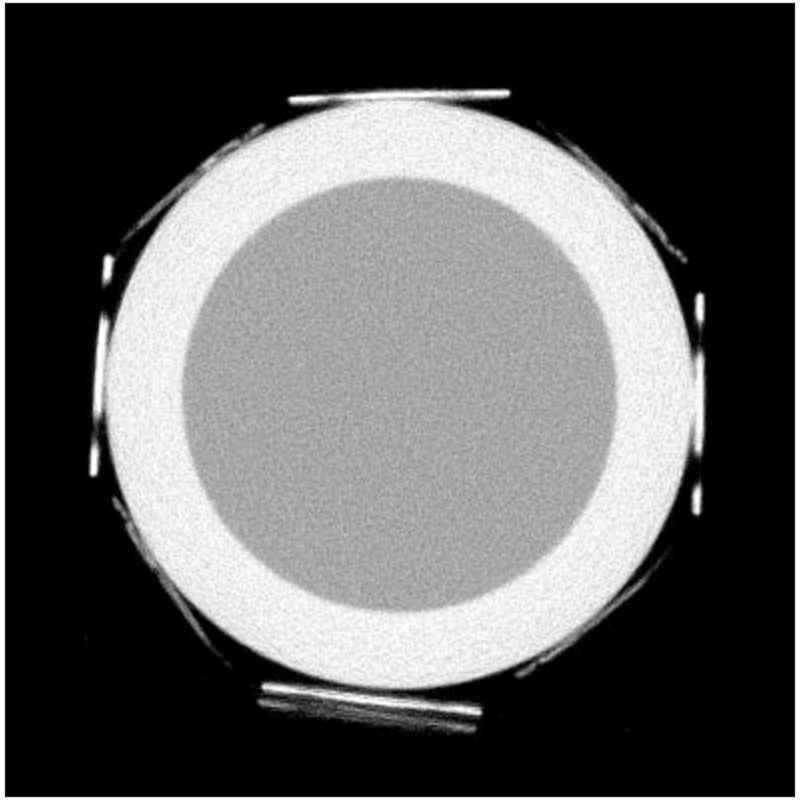
pCT dose measurement

- A set of PLD dosimeters (AOU Careggi, Florence, Italy) have been calibrated on the 211 MeV proton beam of the APSS-Trento
- A pCT acquisition run, at a rate of $\sim 100kHz$, of a water phantom with PLD dosimeters on it has been carried out
- The statistics of this run was $4 \times 10^6\ p/cm^2$



pCT dose measurement

- Axial view of the water cylinder with the PLDs



pCT image

- Section in corrispondence of a dosimeter

pCT image

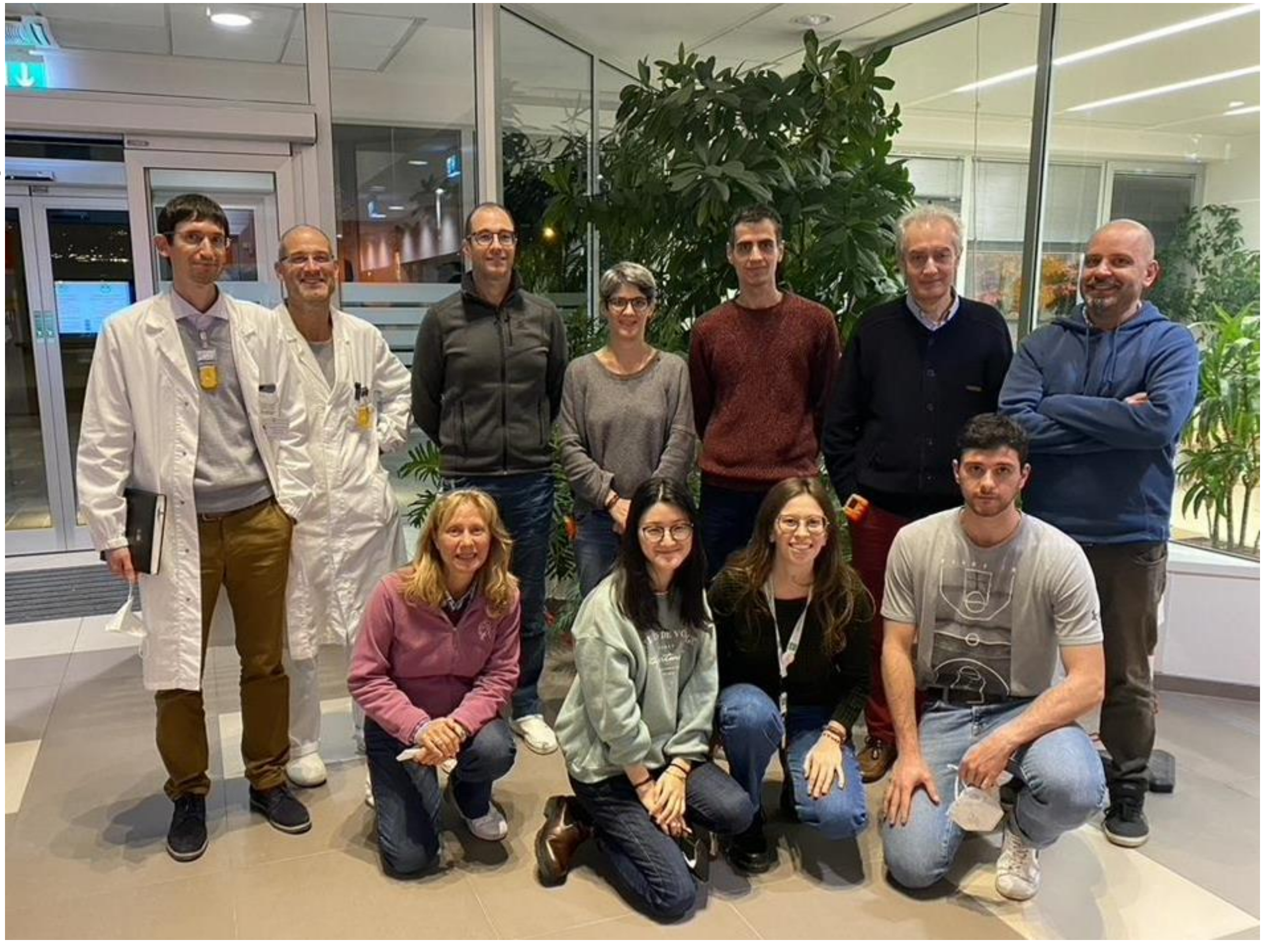
Preliminary results:

Total dose full tomography = $5.6 \pm 0.6\ mGy$
Dose per 10^6 p/cm^2 = $\mathbf{1.39 \ \pm 0.15\ mGy}$

The measurement result is compatible with a MC estimation
(C. Civinini et al., 2017 JINST 12 C01034)

Conclusions

- The pRad experiment aims at producing a single-event proton radiography system working at 1 MHz acquisition rate
- This system will be based on a fast calorimeter integrated with the silicon tracker of the current pCT sytem
- Two other 'work packages' of the experiment are working on prostheses studies and on evaluation of the SPR variability



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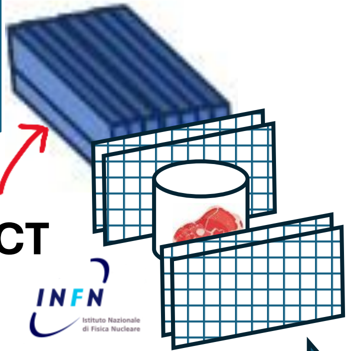
6: Health Physics Unit, AOU Careggi (Firenze University Hospital), Italy

THE pRad PROJECT

A three years project started in 2024

p-Rad system in treatment room



- ✓ **New Calorimeter**
  - pencil beam
  - reduced pile-up
  - cost effective
- ✓ **Range verification for stabilized bio-phantom**

pCT

1

GOAL:
Increased accuracy in TPS

2

SPR direct measurement of metal implants

3

Reliability Test with four Institutes/Hospital in Europe

Survey

CNAO

Munchen

Dresden

UCLH-NHS

Maastro

pCT

Why single proton radiography?

‘Integration’ radiography

Qualitative visualization of a proton radiography acquired by a ‘Flat Panel’ Phoenix, IBA Dosimetry : :
Mean dose < 500-600 mGyE
C. Seller Oria et al., Med Phys. 2023;50:1756–1765.

< 1cGyE

Dose

< 0.01 cGyE

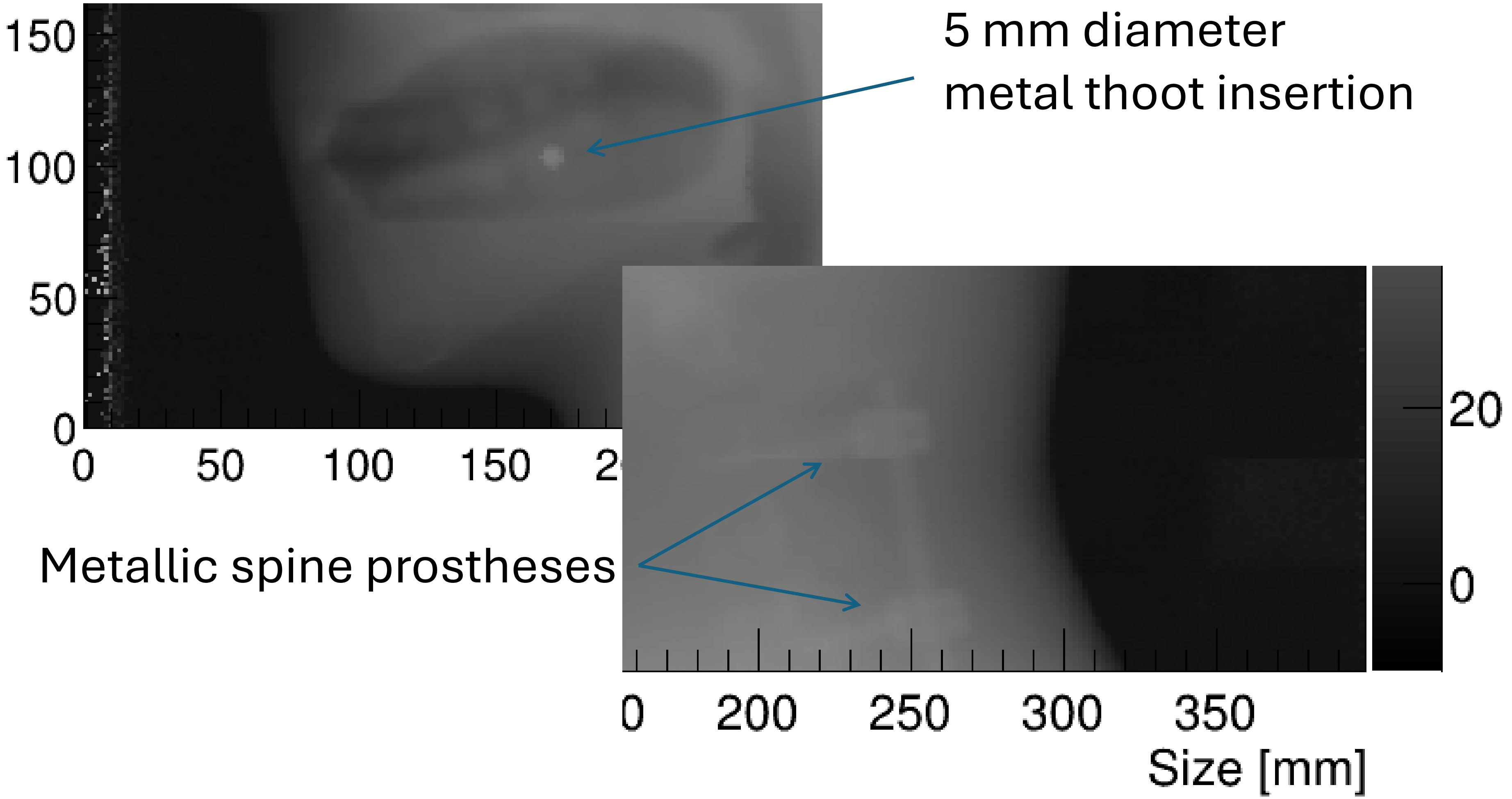
Anthropomorphic phantom: CIRS 731-HN

‘Single proton’ radiography

Single event proton radiography acquired by the pCT-INFN:
Mean dose< 0.1 mGyE
INFN PRIMA-RDH-IRPT collaboration
C. Civinini et al., 2017 IEEE-MIC Symposium DOI: 10.1109/NSSMIC.2016.8069620

Proton Radiographies - details

- Lateral radiographies (using stopping power maps)
- CIRS 731-HN



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C. Civinini et al., 2017 IEEE-MIC Symposium DOI: 10.1109/NSSMIC.2016.8069620

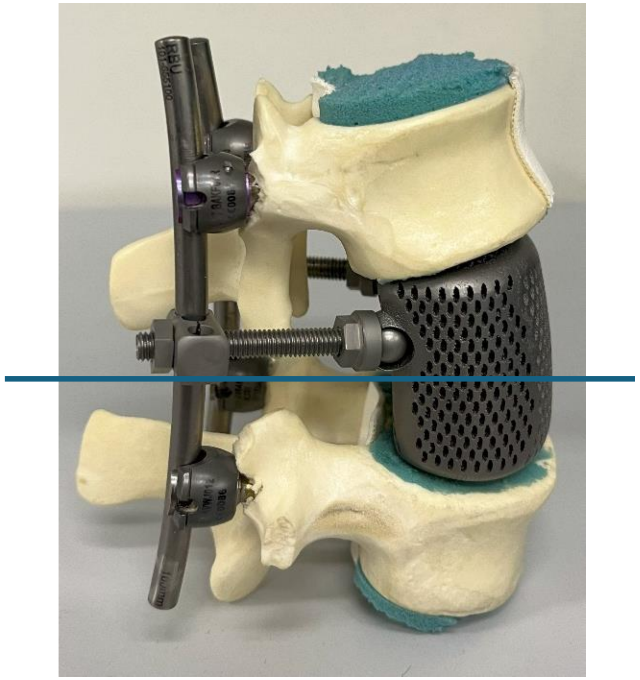
pRad calorimeter read-out electronics

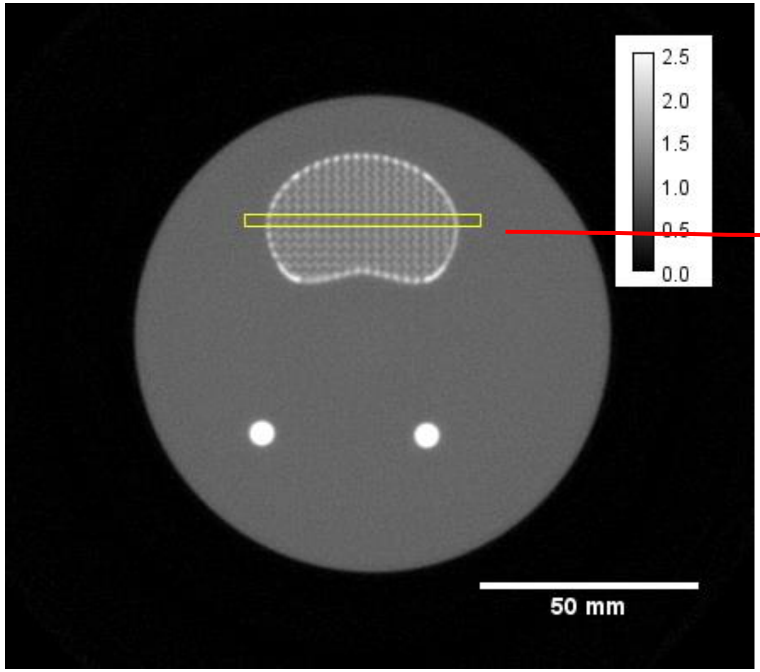
- Option 1: PMT + voltage amplifier
  - Pro: high signal, low noise, reduced complexity
  - Cons: possible signal saturation, magnetic field sensitivity
- Option 2: SiPhotodiode + charge integrator
  - Pro: magnetic field insensitivity
  - Cons: charge integrators, signal pile-up at high rate, front-end complexity

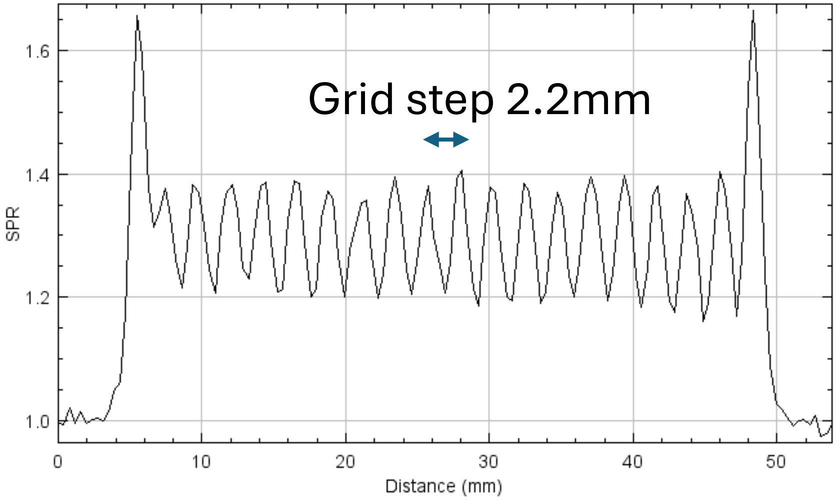
- Test planned to verify option 1
  - Measurements in both experimental and treatment room at Trento proton Therapy center
  - Static beam → static magnetic field → energy corrections from calibration
  - Dynamic beam (pencil beam) → variable magnetic field

Proton CT of prostheses

- pCT image of vertebral prosthesys with titanium cage;
- Statistics $\sim 1.3 \times 10^9$ trigger → $16.9\ mGy$ dose

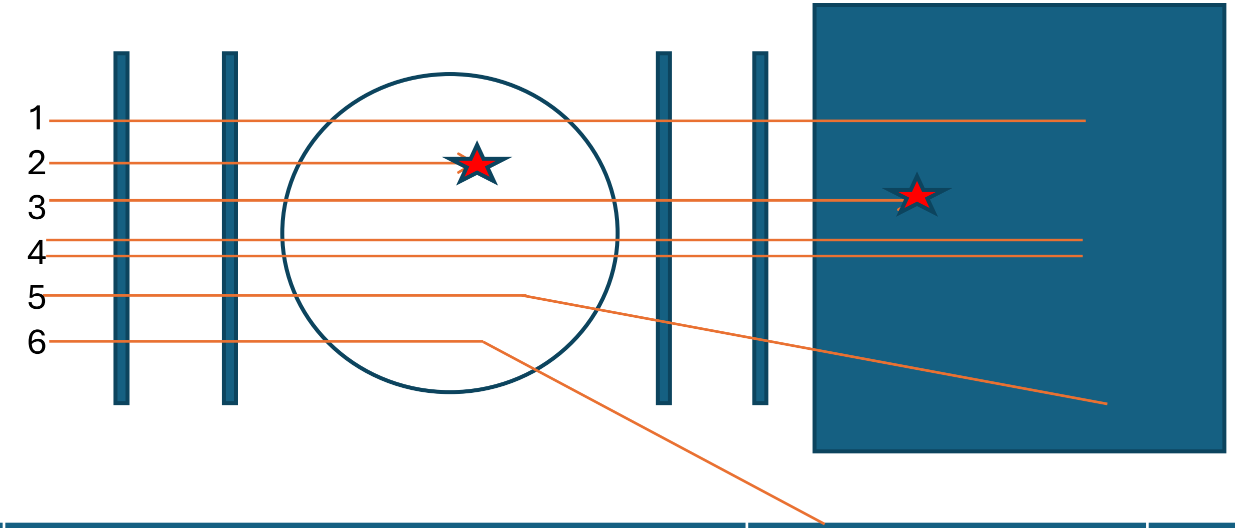






More details on Mara's talk tomorrow

pCT dose estimation



Dose required for a fraction of a tomography (10^6 p/cm^2) : ~**1.3mGy**

C. Civinini et al., 2017 JINST 12 C01034

Category	Relative abundance to Cat. 1	ΔE Phantom	Event type
1	1	50 MeV	Useful event
2*	0.088	175 MeV	Nucl. Int. Phantom
3	0.54	50 MeV	Nucl. Int. Calorimeter
4			Multiple protons in Calorimeter
5	0.043	50 MeV	Too much scattering
6*	0.041	50 MeV	Geometry leakage

* Events not triggerd by DAQ: number estimated by Geant4 simulations

Extended study

These studies will be extended to assess inter-centre variability of RSP accuracy using ex-vivo phantoms

(with different SECT and DECT scanners, calibration methods, corrections, etc.)

Ongoing data analysis