Development of a fast calorimeter for proton Computed Radiography

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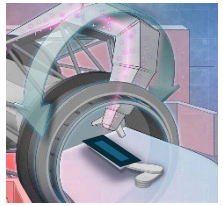
Outline

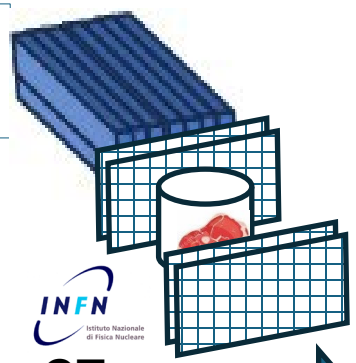
- the INFN pRad Project (2024-2026)
- The present INFN pCT apparatus
- Design of the new calorimeter
- Preliminary test beam results
- Summary and perspectives

THE pRad PROJECT (2024 – 2026)



p-Rad system in treatment room

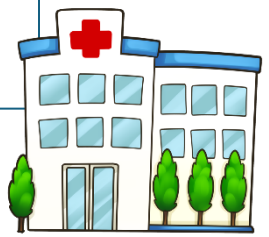
- ✓ **New Calorimeter**
- pencil beam
- reduced pile-up
- cost effective
- ✓ **Aim: perform a radiography in times ~ 1 s**



pCT

1

Reliability Test with five Institutes/Hospital in Europe



CNAO

Munchen

Dresden

Maastro

London

3

Survey

pCT

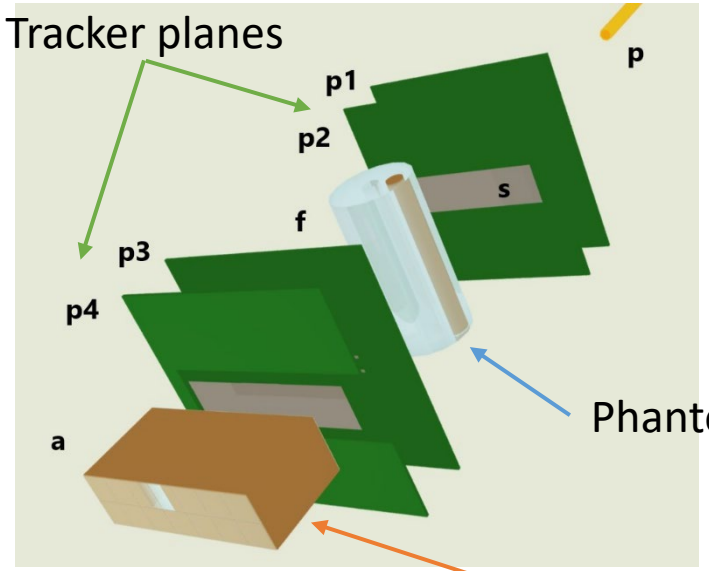
GOAL: Increased accuracy in TPS

2

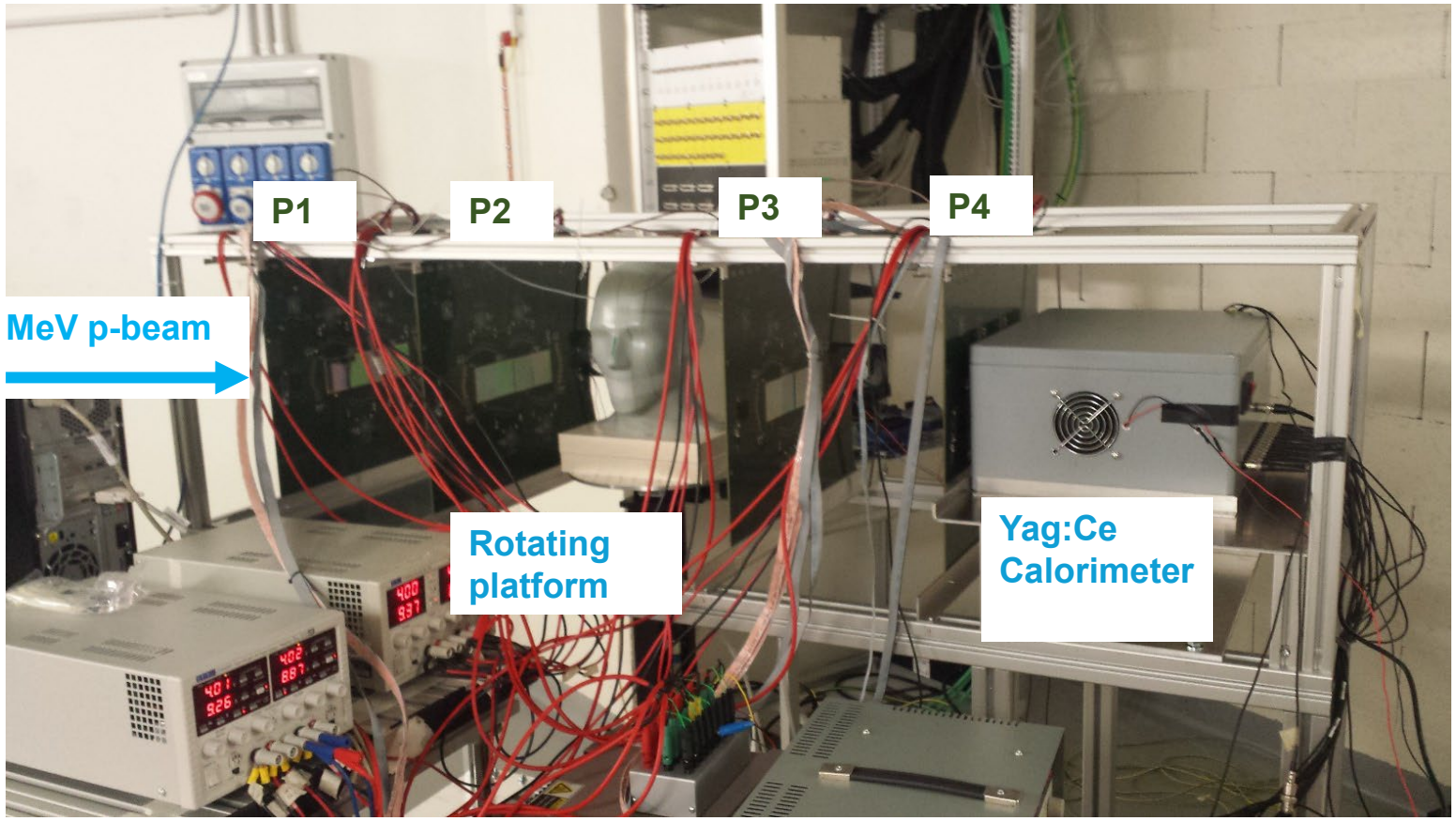
SPR direct measurement of metal implants

The INFN pCT apparatus

- Silicon strip tracker + YaG:Ce scintillator calorimeter
- Single-event acquisition



Experimental room of the Trento Proton Therapy center



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.

Proton radiography: CIRS 731-HN

Integration mode radiography

< 50-60cGyE

Dose

< 0.01 cGyE

single proton radiography

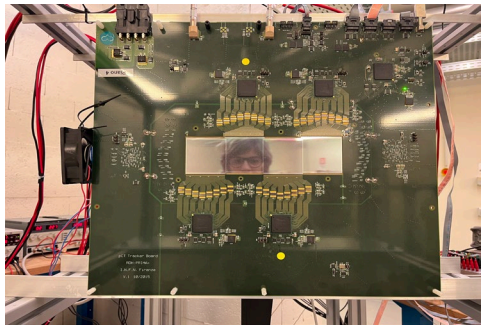
Flat Panel' Phoenix, IBA Dosimetry
Average dose 50-60 cGy
C. Seller Oria et al., Med Phys. 2023;50:1756–1765.

proton radiography acquired with the INFN system (only 2 planes between phantom and calotimeter):
Average dose < 0.01 cGy
INFN PRIMA-RDH-IRPT collaboration
C. Civinini et al., 2017 IEEE-MIC Symposium DOI: 10.1109/NSSMIC.2016.8069620

Rate requirements

To reach the pRad requirements the DAQ rate has to increase from 100 KHz to 1-2 MHz

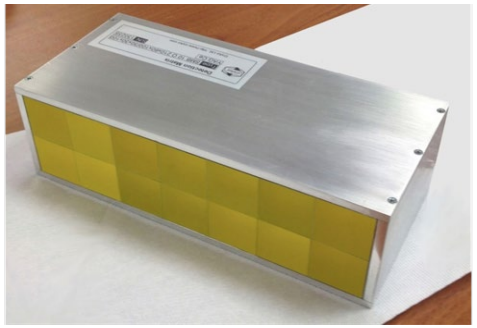
Si tracker plane



- 5x20 cm^2 active area
- 200 μm pitch Si microstrip (XY)
- **Front-end shaping time ~ 200 ns**
- **Segmentation area 10 – 20 mm^2 (X -Y)**

The tracker needs only firmware modification

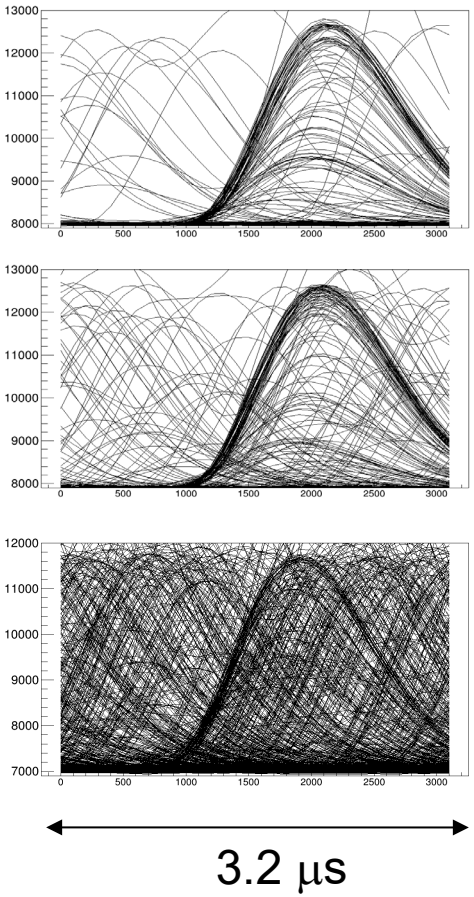
YAG:Ce calorimeter
+ Si photodiode



- 6x21 cm^2 active area
- 7x2 crystals array 3x3x10cm^3
- **Front-end shaping time ~ 1 μs**
- **Segmentation area: 900 mm^2**

The calorimeter needs to be replaced

1000 superimposed waveforms of YAG response



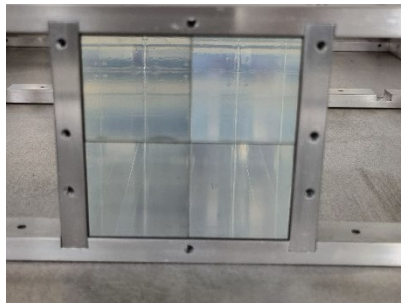
Requirements for the pRad calorimeter

- Fast: able to sustain a ~1 MHz proton rate with minimal pile-up
- Energy resolution < 1% @ 200 MeV (0.9% for YAG:Ce)
- Compliant to treating room environment:
  - EMC certified
  - immune to magnetic field variations

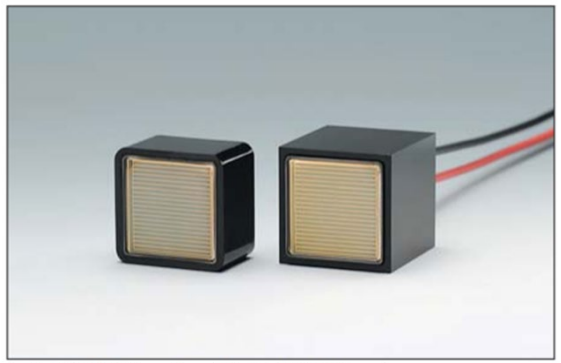
Plastic scintillator: EJ200

	YAG:Ce	EJ200
Scintillation Efficiency (photons/1 MeV e-)	30000	10000
Wavelength of Maximum Emission (nm)	550	425
Decay Time (ns)	70	2.1
Density (g/cm3)	4.57	1.023

First prototype:
2x2 matrix 30x30x400 mm^3

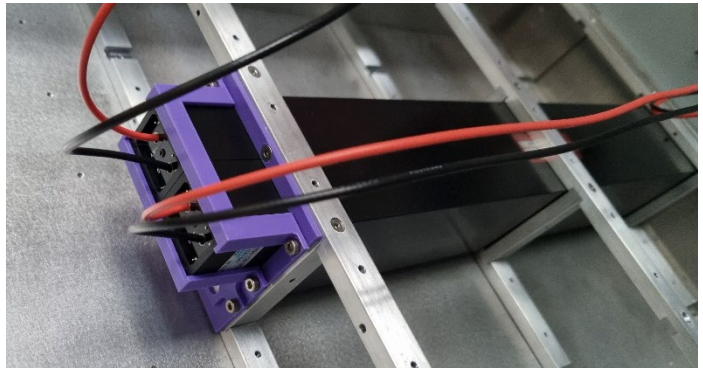


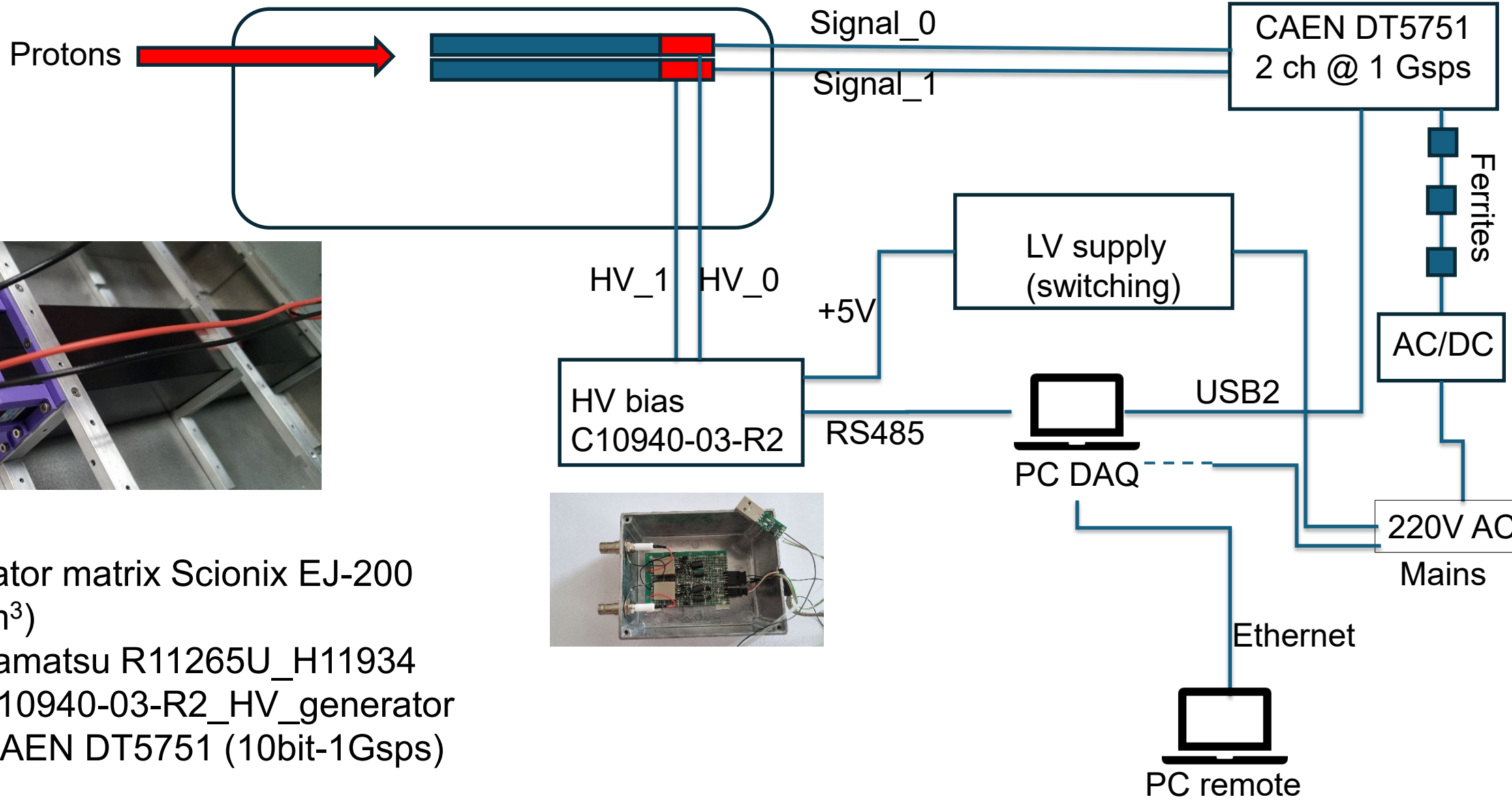
PMT readout



Left: R11265U series, Right: H11934 series

First pRad prototype

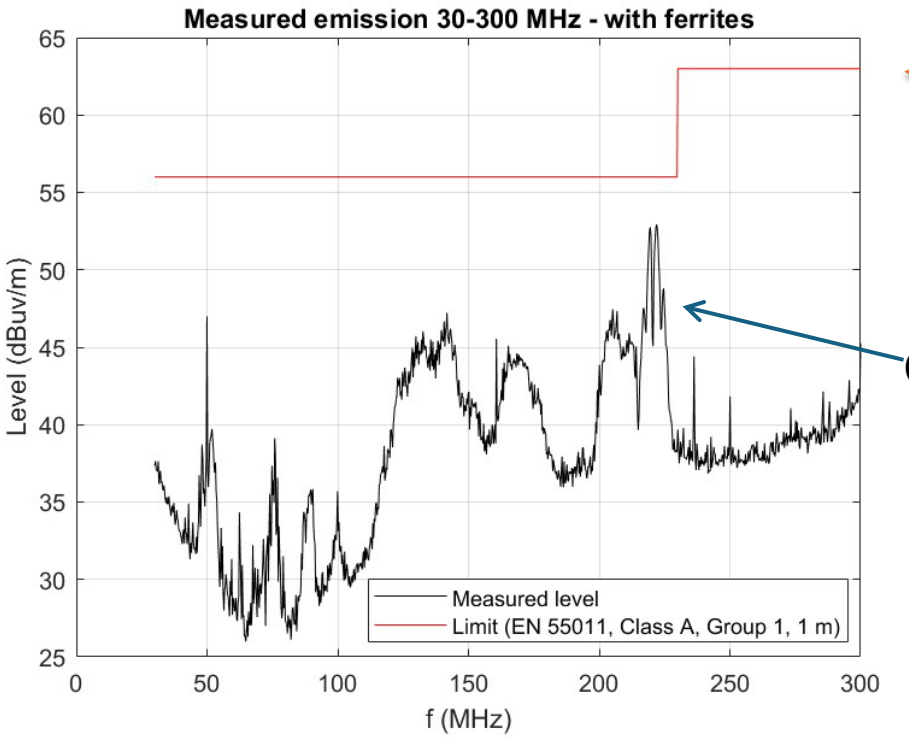




2x2 scintillator matrix Scionix EJ-200 ($3x3x40\ cm^3$)
PMT: Hamamatsu R11265U_H11934
HV bias: C10940-03-R2_HV_generator
Digitizer: CAEN DT5751 (10bit-1Gsps)

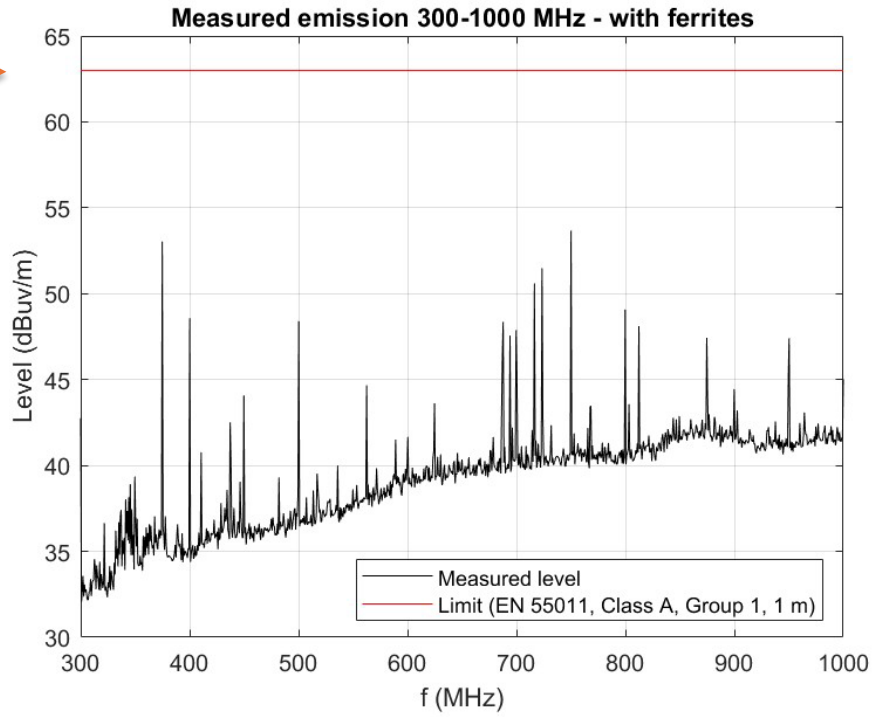
Electromagnetic emission of the prototype

- Requested by Trento Protontherapy center before entering in treatment room with a non CE equipment
- Emissioni measurements performed in reverberation chamber at Electronic Engineering Department of Florence University
- Emissions with the prototype on and running are below the limits in CEI EN 55011
- Higher emissions are around 200 MHz and due to the power supply cable of the CAEN DT5751 digitizer – decreased after inserting some ferrite rings

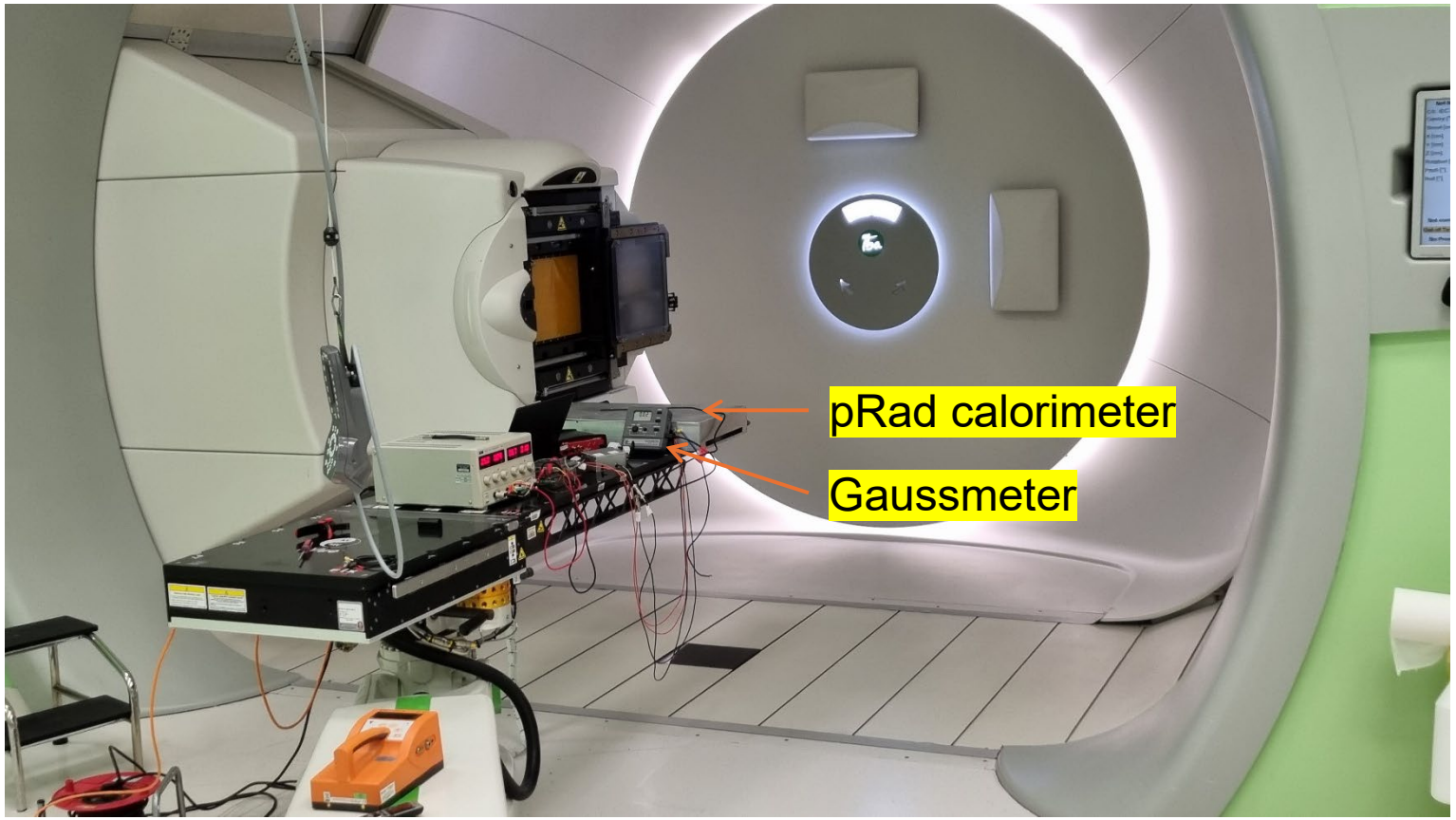


CEI EN 55011 limits

CAEN DT5751



Residual magnetic field – treatment room

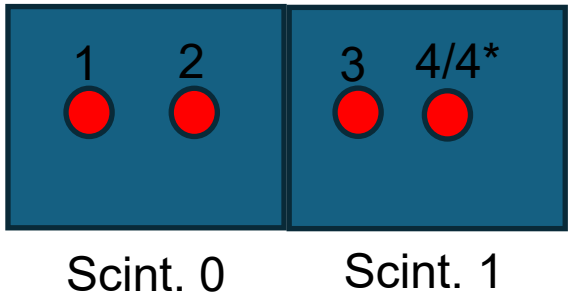


- pRad calorimeter mounted in treatment room in Trento (novembre 2024)

Residual magnetic field – treatment room

- Prad prototype in Trento treatment root
- Pencil beam pointed to different areas in the calorimeter by changing the current value in the steering magnets
- Magnetic field monitored by a portable gaussmeter (no significant variation)
- Offline control of the signal peak position in the variuos configurations

* focussing magnet ON



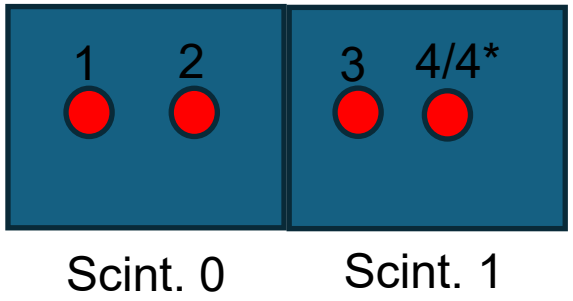
Approximate beam position

Residual magnetic field – treatment room

- Signal mean value of the two scintillators with pencil beam

run	position	Baseline 0	Peak 0	Baseline 1	Peak 1	Signal 0	Signal 1	
300	1	957,8	348,3	-	-	609,5	-	Scint. 1 OFF
301	1	957,9	348,4	957,7	566,1	609,5	391,6	
302	2	957,8	348,9	958,1	567,7	608,9	390,4	
303	3	957,4	348,6	957,8	568,2	609,0	389,6	
304	4	957,6	350,9	957,8	567,0	606,7	390,8	
305	4*	957,5	350,8	958,2	567,5	606,7	390,7	

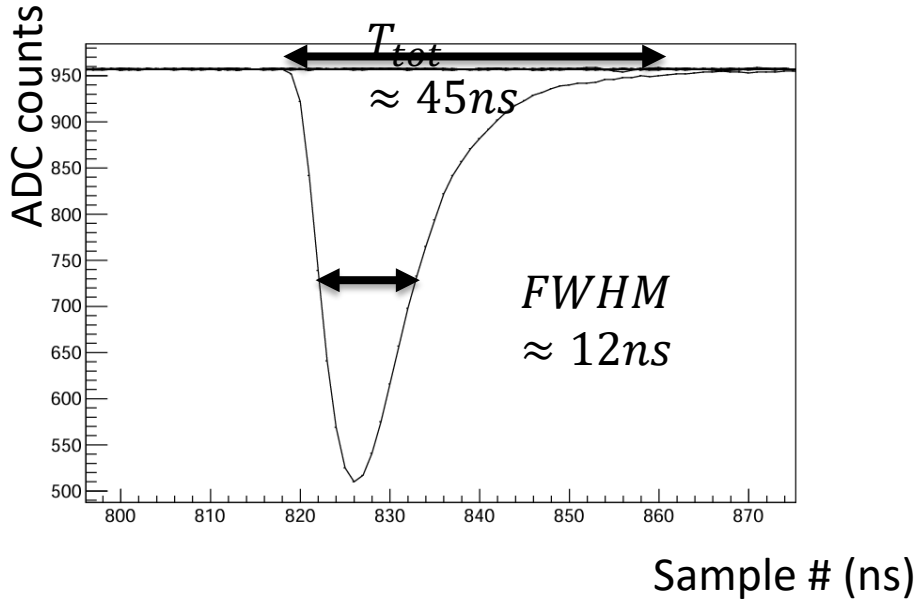
* Focusing magnets ON



Approximate beam position

Time response

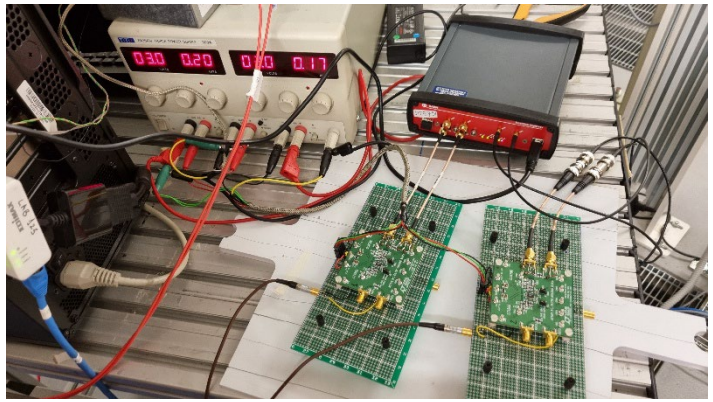
PMT signal sampled at 1GHz for a 228 MeV proton



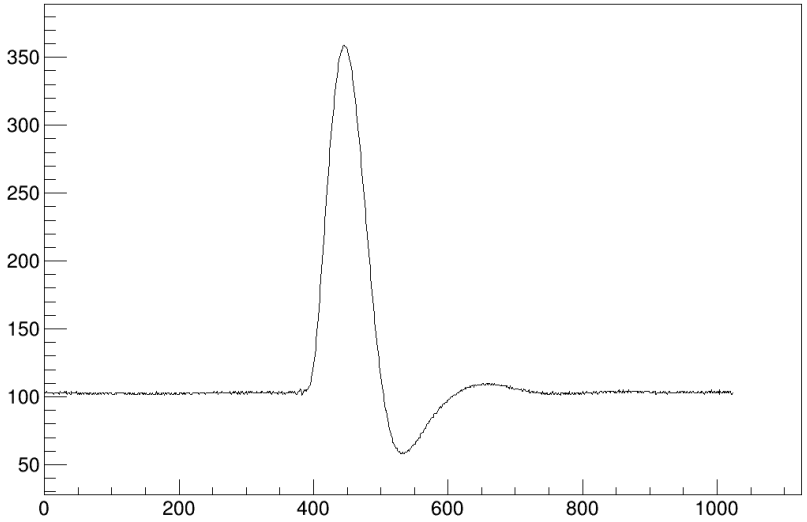
- To integrate the readout of the calorimeter with the tracker a new custom DAQ board is being designed
- To contain cost and complexity of the board the ADC frequency will be ~ 100 MHz

Time response

- LT1568 evaluation board
- Configurable LP filter up to 10 MHz

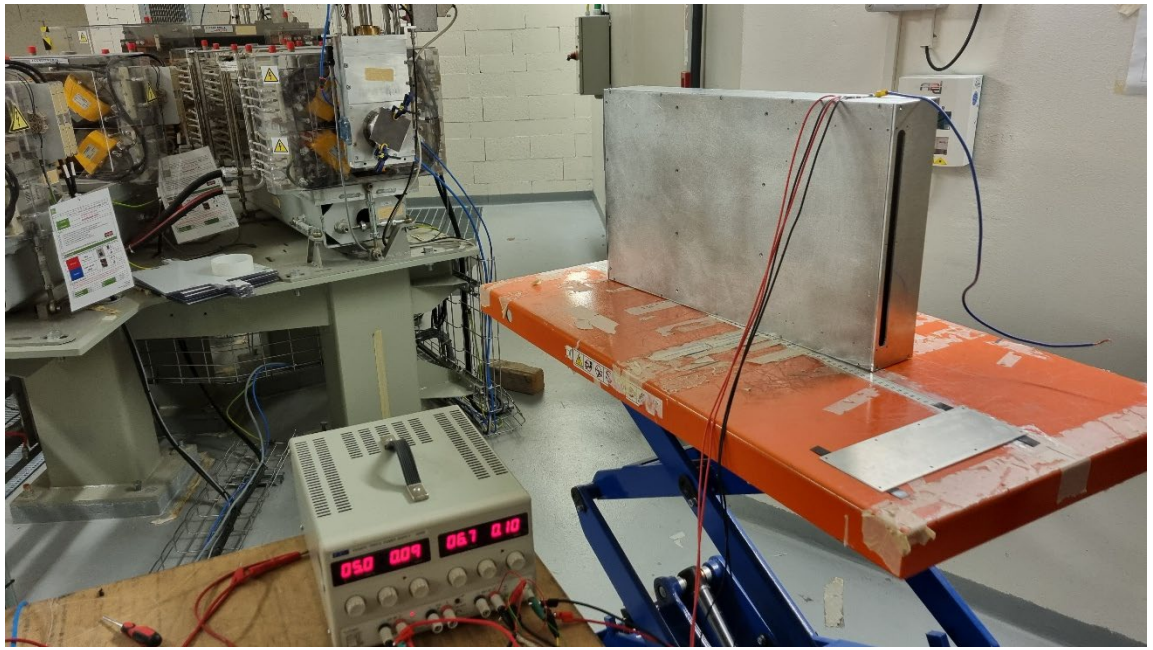


Butterworth 4 order low pass 10 MHz



Energy calibration

Experimental room of Trento proton therapy center

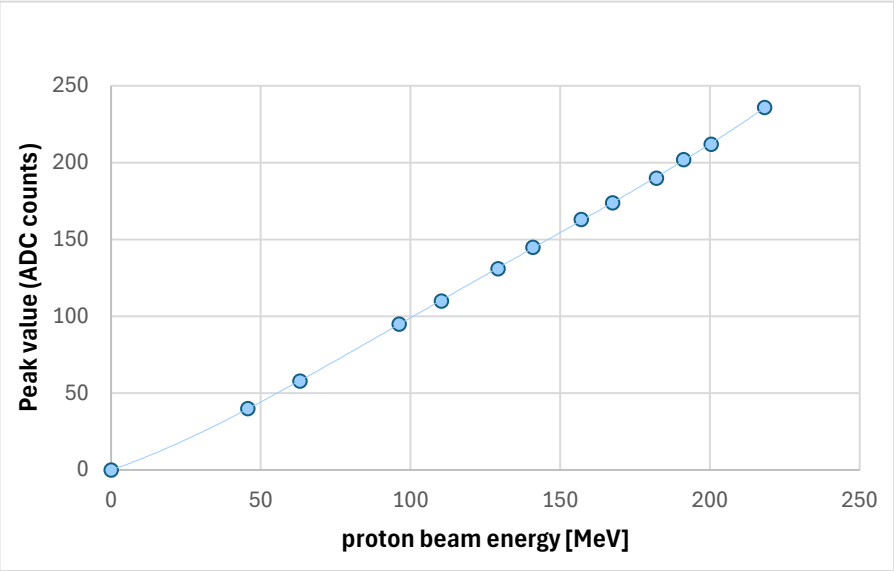


- Calorimeter at isocenter (1.25 m from the beam)
- 12 proton energy point from 60 to 220 MeV
- Tantalum foil at beam exit to spread-out the beam
- Energy values at calo calculated by GEANT4/NIST

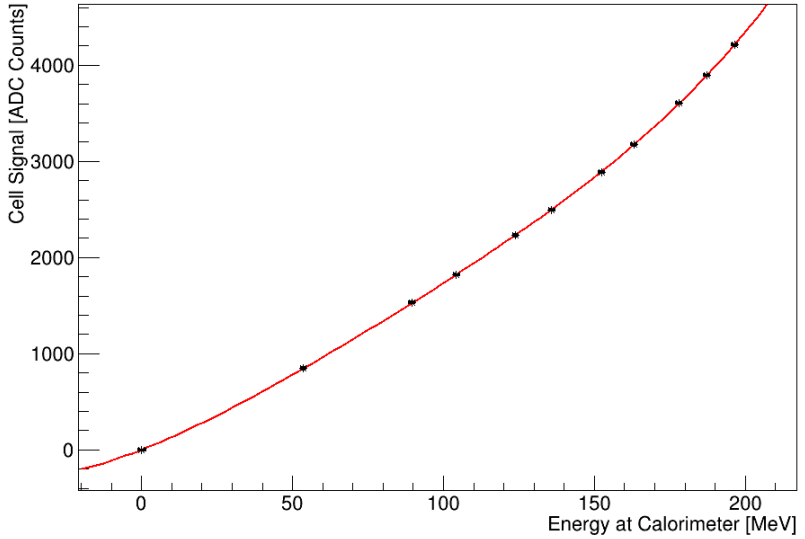
Nominal energy (MeV)	Energy at calo (MeV)
70	45,684
83	63,0814
112	96,224
125	110,339
143	129,241
154	140,842
169	156,999
179	167,53
193	182,141
202	191,247
211	200,407
228	218,26

Calibration curve

EJ-200



YAG:Ce calorimeter



Birk's law

$$\frac{dL}{dx} = S\frac{\frac{dE}{dx}}{1 + kB\frac{dE}{dx}}$$

- Gaussian fit of histograms peaks for each energy
- Non linearity at low energies due to Birks effect, much less pronounced than in YAG
- Corrections are needed when protons share signal between bars

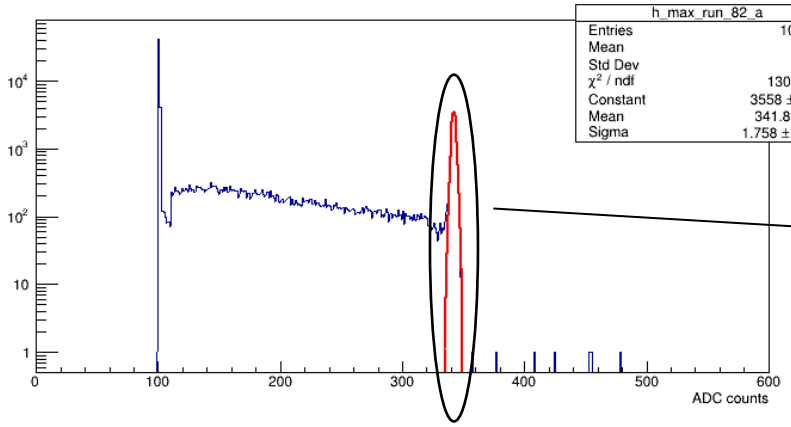
M. Scaringella et al, Phys. Med. Biol. 68 (2023) 154001

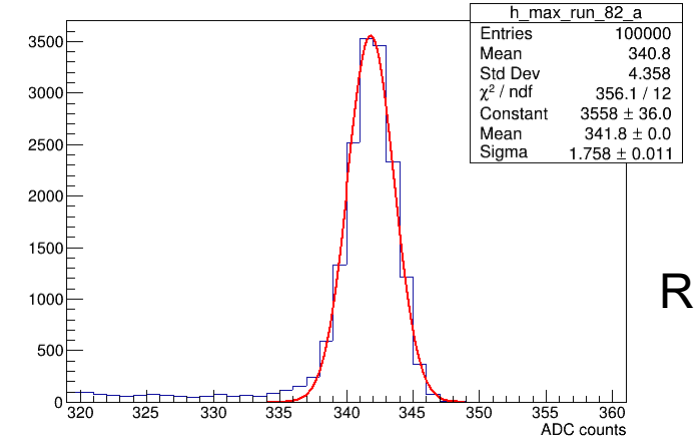
Resolution with 228 MeV protons

Signal = peak –baseline
R = sigma/signal

PMT signal peak value

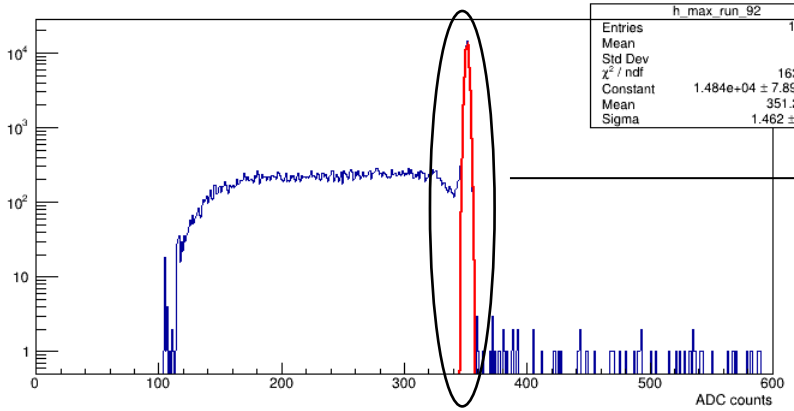
Spread out beam

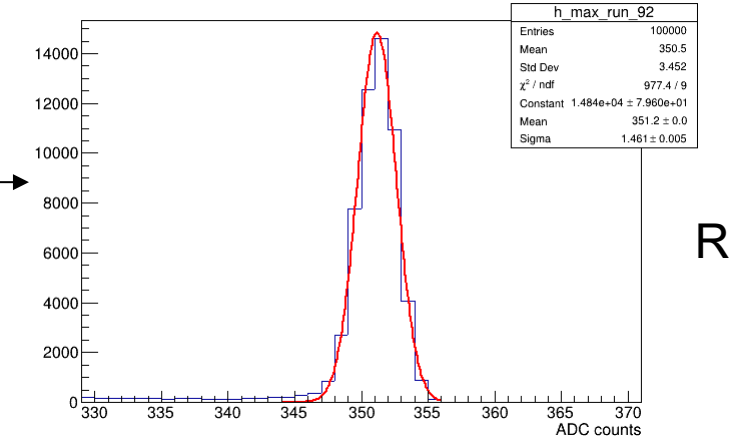




R = 0.73%

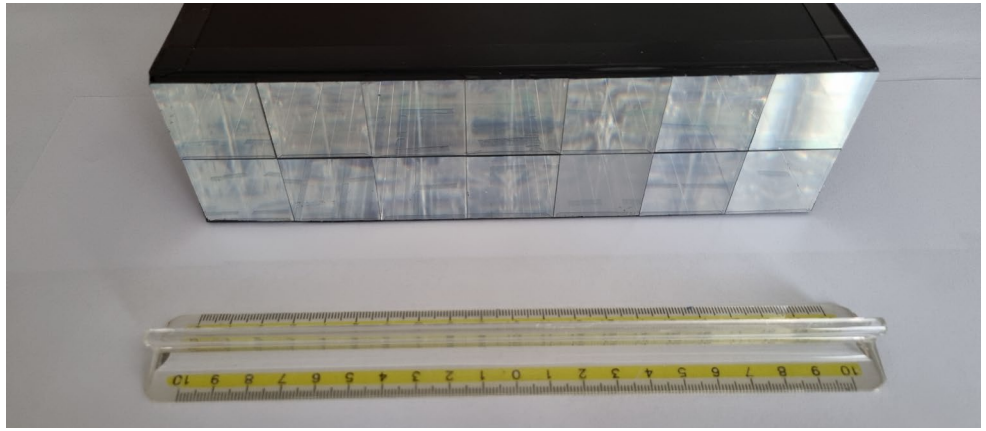
focussed beam
Ta foil removed





R = 0.58%

Present status



- The full 2x7 EJ-200 (31x31x400 mm^3) scintillator matrix has been aquired
- 14 Hamamatsu PMT ordered
- A new DAQ board with faster ADCs under develompent

Conclusions

- A fast calorimeter for single-particle proton radiography is under development in the framework of the pRad project
- A first small prototype based on plastic scintillator and PMT has been assembled and measured to be compliant with CEI EN 55011 standard
- First measurements have been carried out in the treatment room of Trento proton therapy center, showing negligible dependance on magnetic field variations
- A complete calibration curve has been acquired for protons in the range 50-220 MeV
- The energy resolution proved to be excellent, downto 0.58%
- The full sized detector will be assembled in the next few months

Thank you for your attention