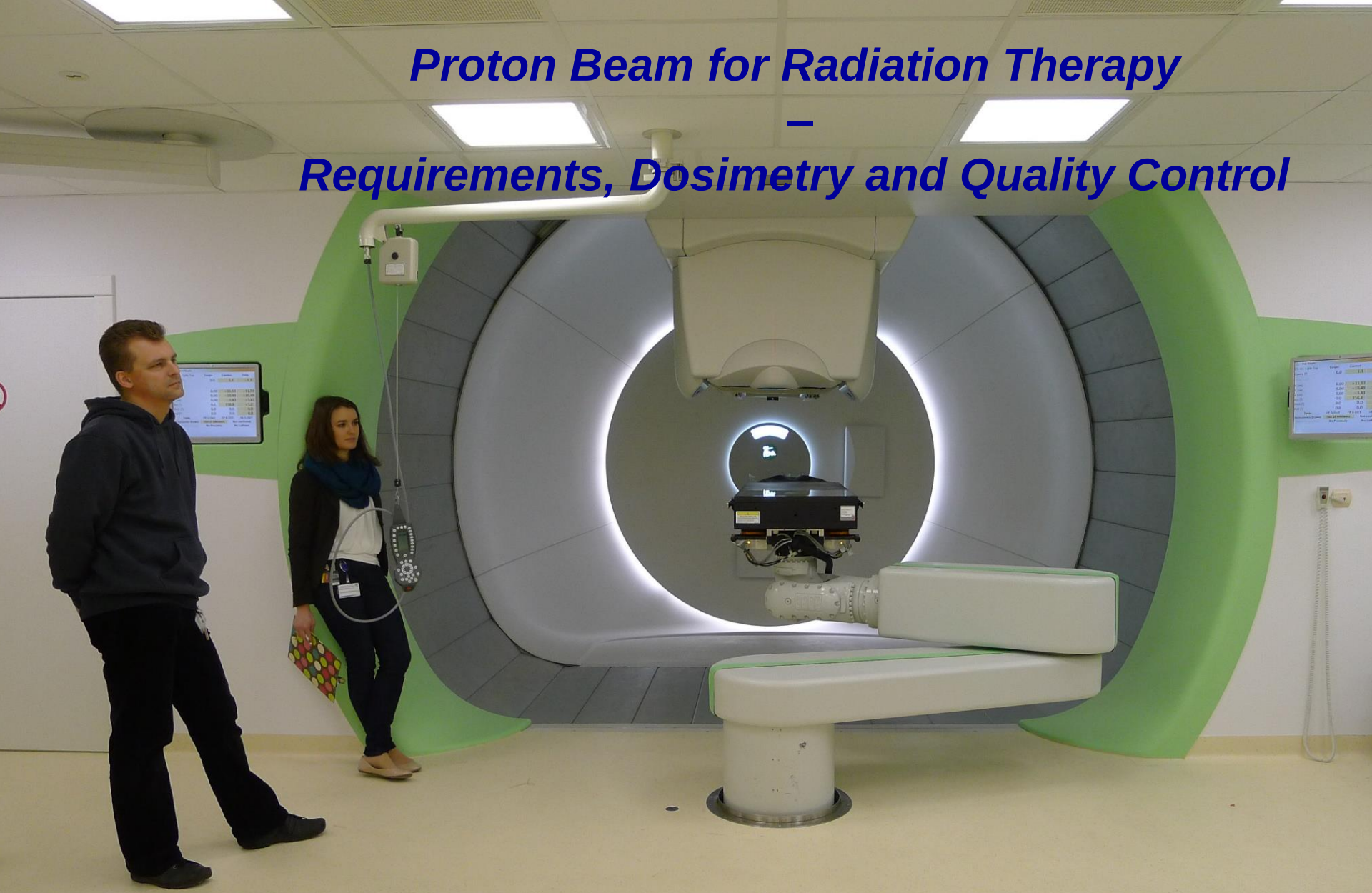
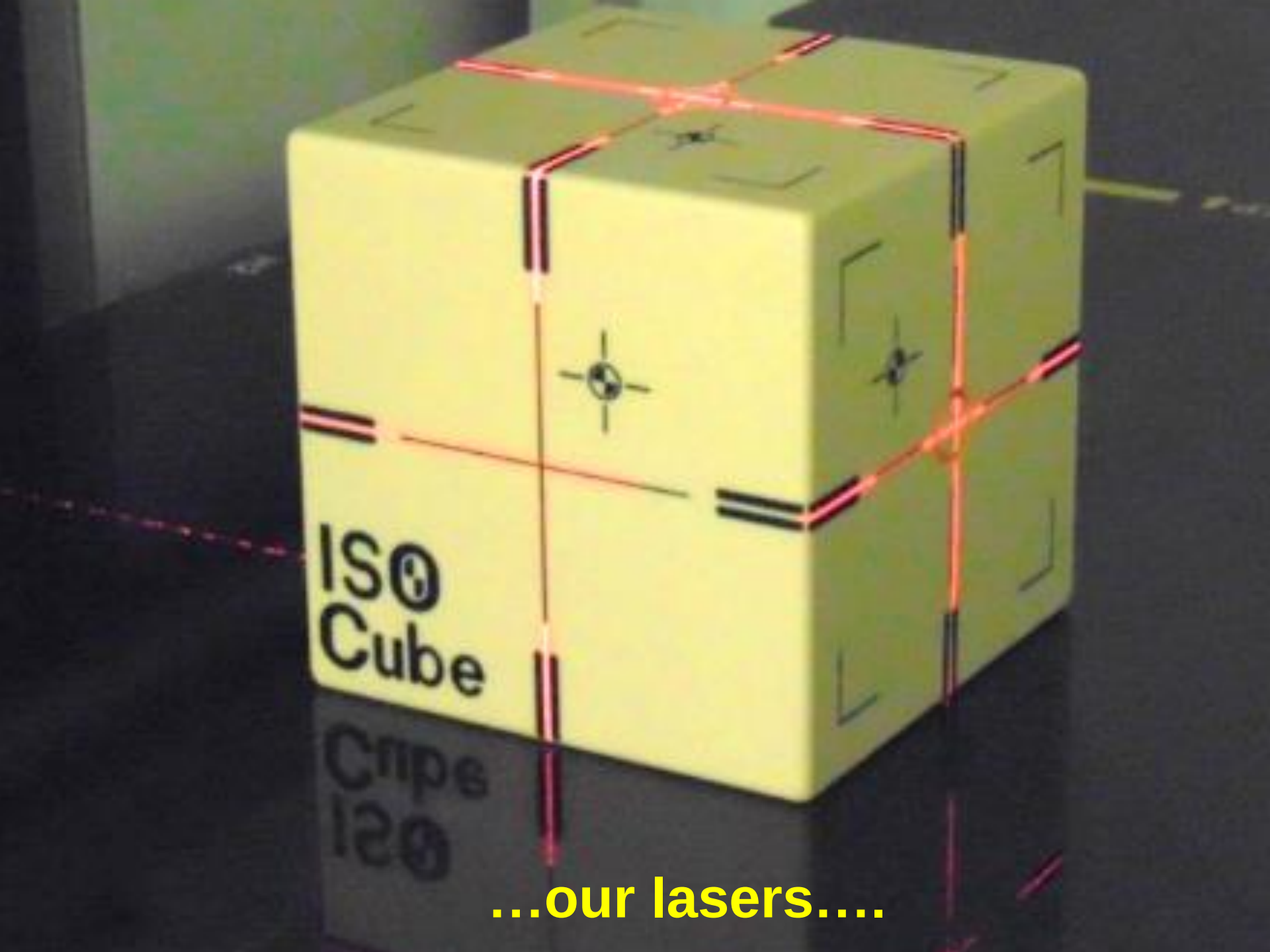
Proton Beam for Radiation Therapy
–
Requirements, Dosimetry and Quality Control



P. Olko, J.Gajewski, T. Kajdrowicz, M. Kłodowska, M. Liszka, L. Stolarczyk,
Bronowice Cyclotron Centre, Institute of Nuclear Physics PAN, Kraków, Poland

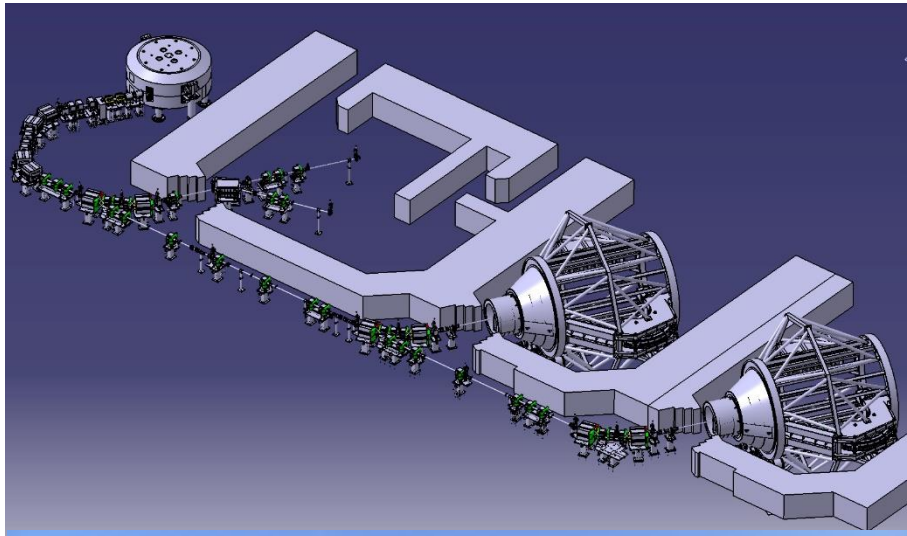


…our lasers….

Bronowice Cyclotron Centre
at the Institiute of Nuclear Physics, Kraków, Poland

60 MeV AIC-144 cyclotron
Eye treatment room

Proteus 230 MeV protons
2 scanning gantries, eye line, exp. room
Operational since 2015



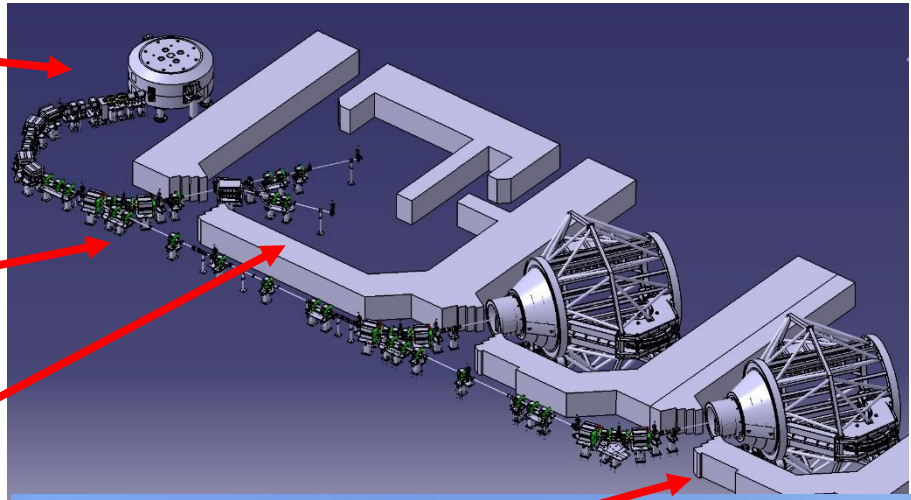
Bronowice Cyclotron Centre
at the Institiute of Nuclear Physics, Kraków, Poland

60 MeV AIC-144 cyclotron
Eye treatment room

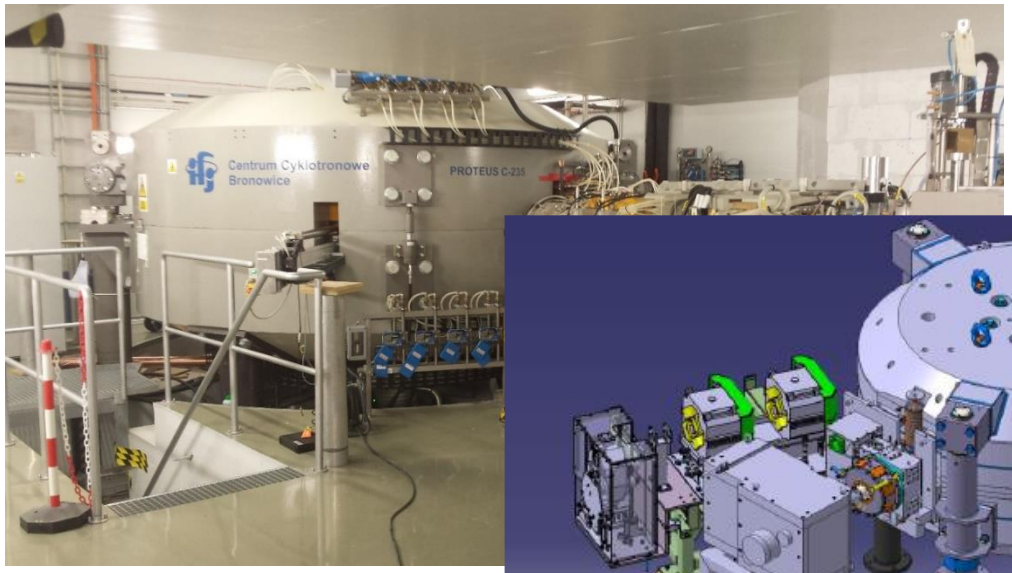
- 60 MeV proton AIC-144 built at IFJ between 1988 -2005 (J. Schwabe, J.Sulikowski)
- eye treatment room built at IFJ between 2001 – 2009 (J. Swakon)
- therapy provided by the team from the University Hospital: 120 patients treated 2011 -2015
- since 2016 cyclotron is used for research, mainly dosimetry and radiobiology

Bronowice Cyclotron Centre
at the Institiute of Nuclear Physics, Kraków, Poland

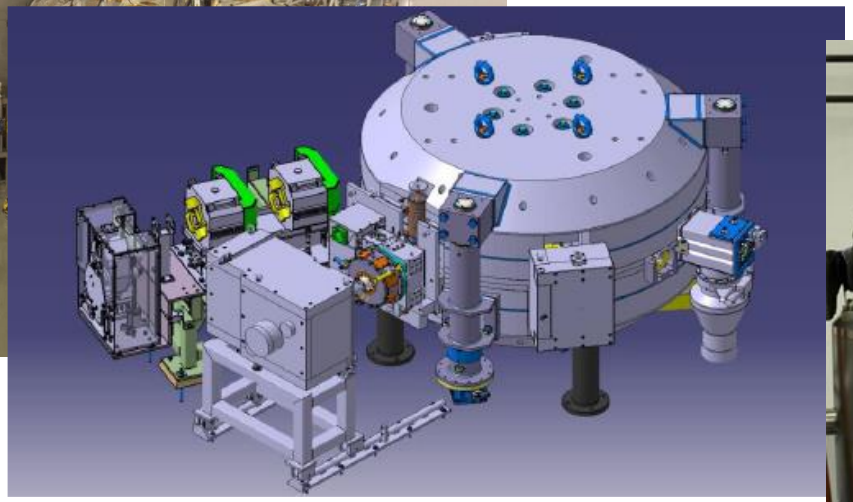
Proteus 230 MeV protons
2 scanning gantries, eye line, exp. Room
Operational since 2015



What is the baseline for the new accelarators in proton therapy?



Proteus-235



Proteus-One

Mevion

… requirements for beam, dosimetry and QA from our Krakow perspective

Outline

1. **Dose distribution**

2. **Spot properties**

3. **Dosimetry for beam and scattered radiation**

Waiting room for children

Dose distribution

1) Flatness, F

2) Distal falloff, d

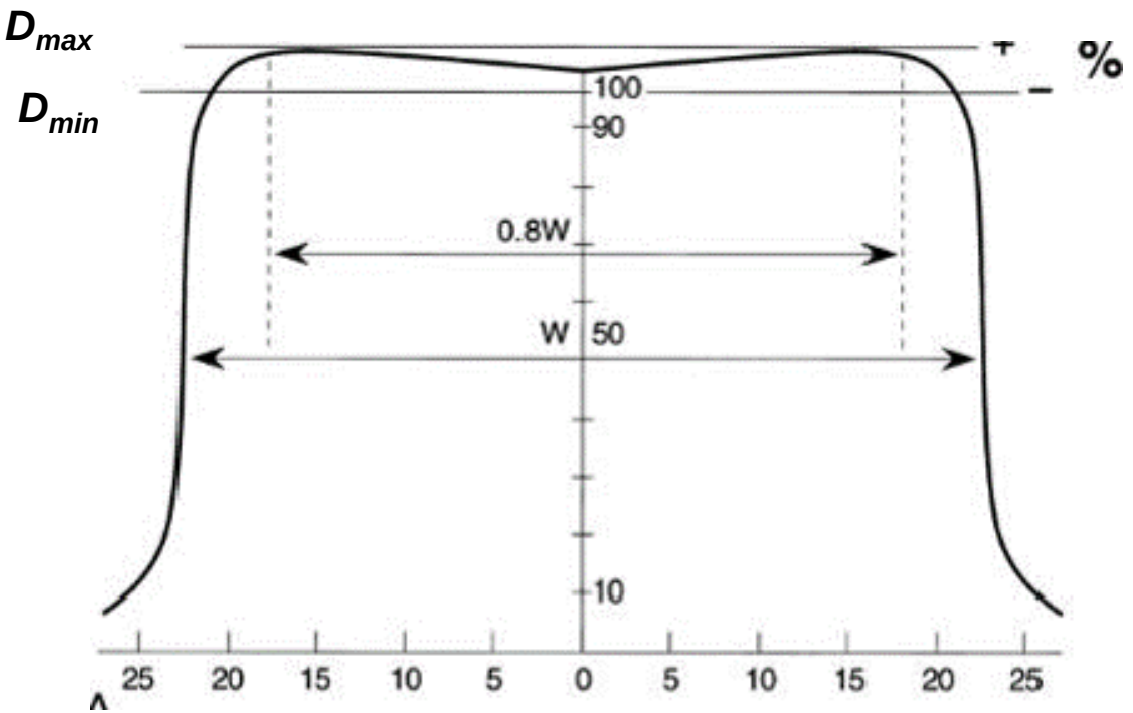
3) Penumbra, P

Dose distribution

1) Flatness, F

2) Distal falloff, d

3) Penumbra, P



$$F = \frac{D_{max} - D_{min}}{D_{max} + D_{min}} \; x \; 100\%$$

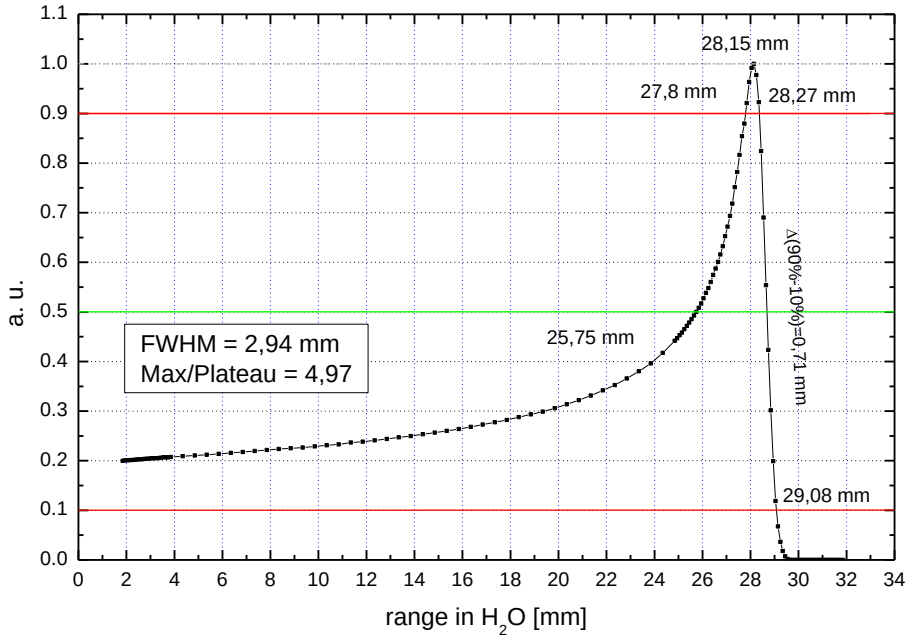
$F < 4\%$ (working limit at IFJ for eye treatment)

Dose distribution

1) Flatness, F

2) Distal falloff, d

3) Penumbra, P

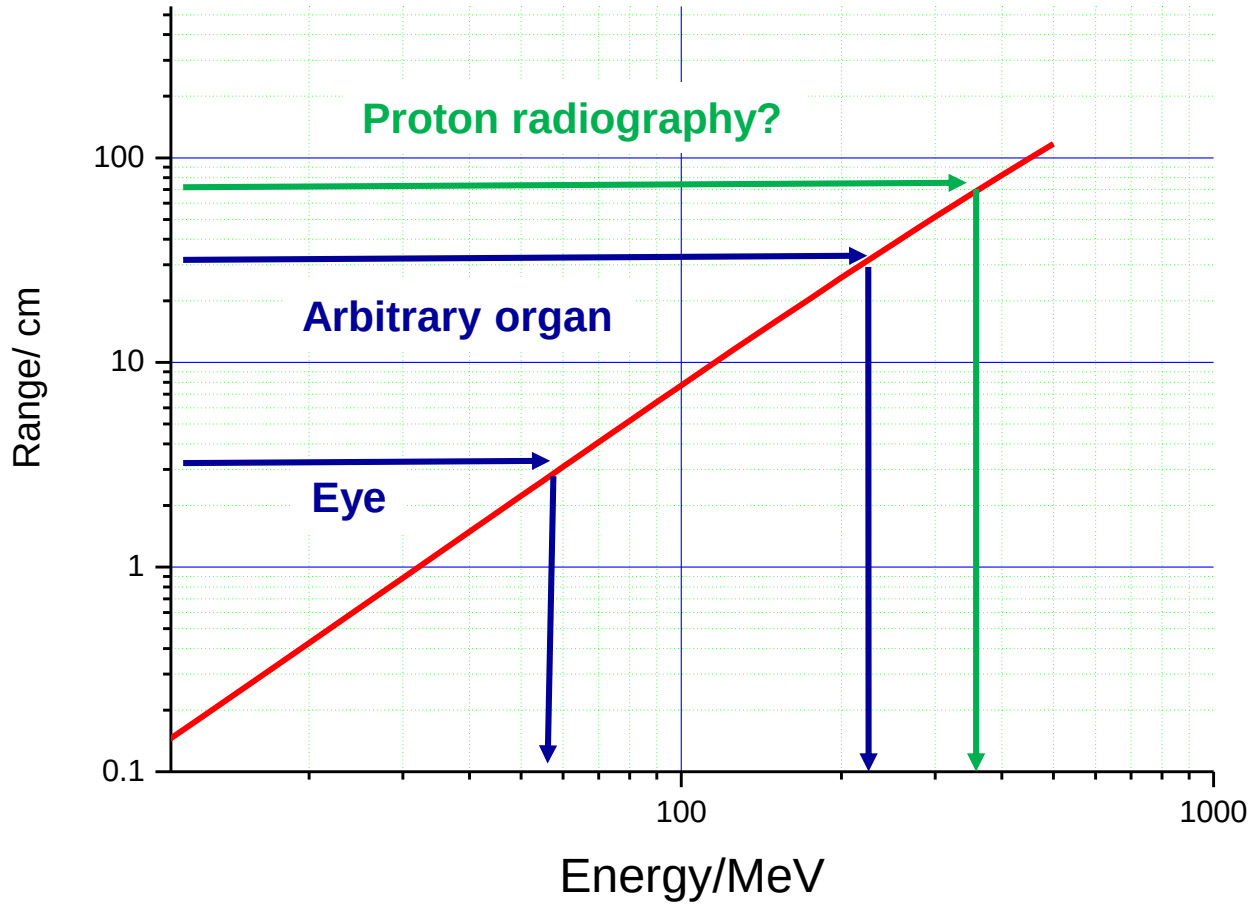


$$d = z_{20\%} - z_{80\%}$$

For eye beam : 10% -90%

Typically 1 mm < d < 10 mm

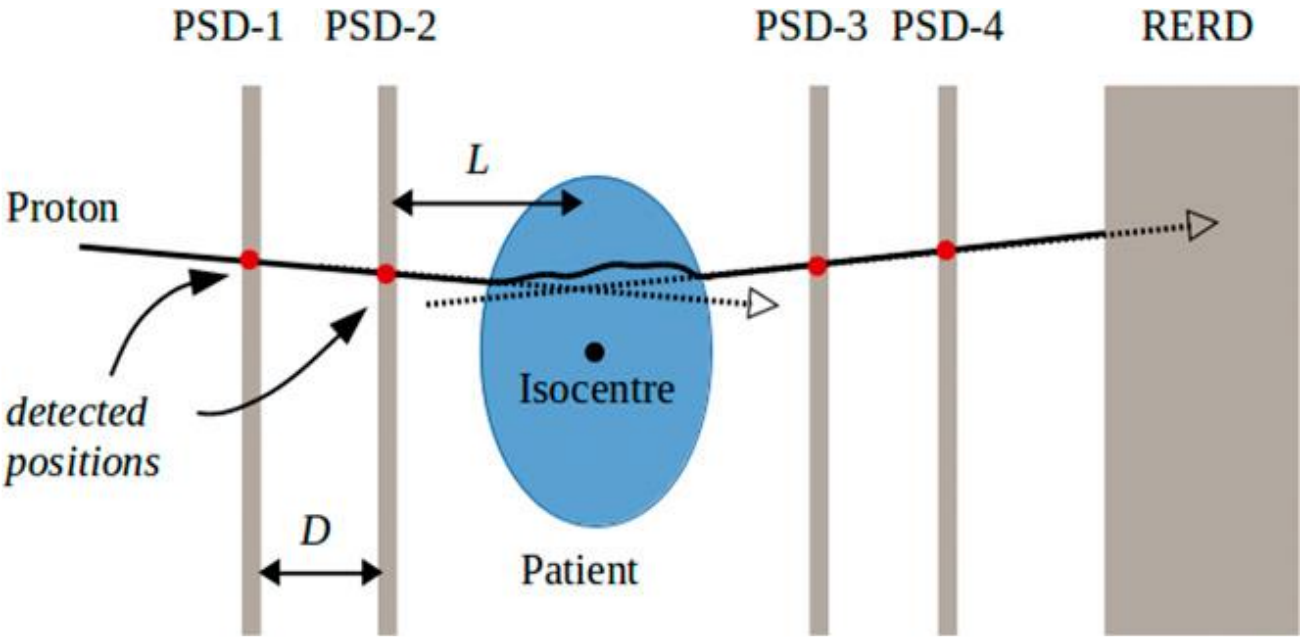
Energy of Proton Beam



Beam Energy: 70 MeV – 250 MeV

Proton radiography: 350 MeV

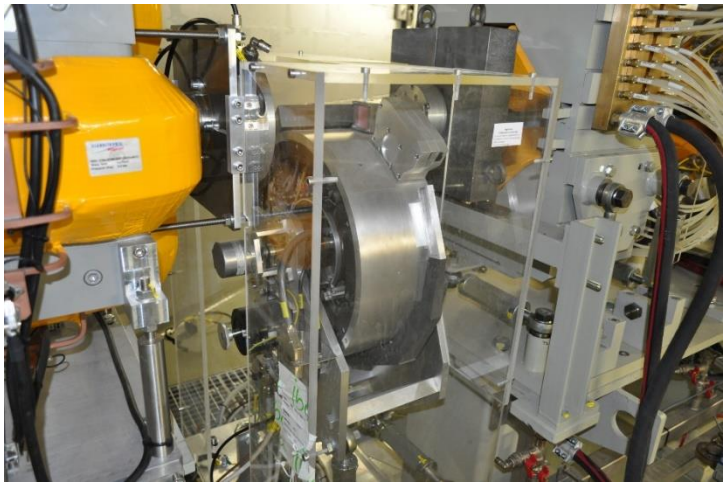
Proton radiography and Water Equivalent Thickness



G POLUDNIOWSKI et l 2015

Energy selection system in cyclotrons

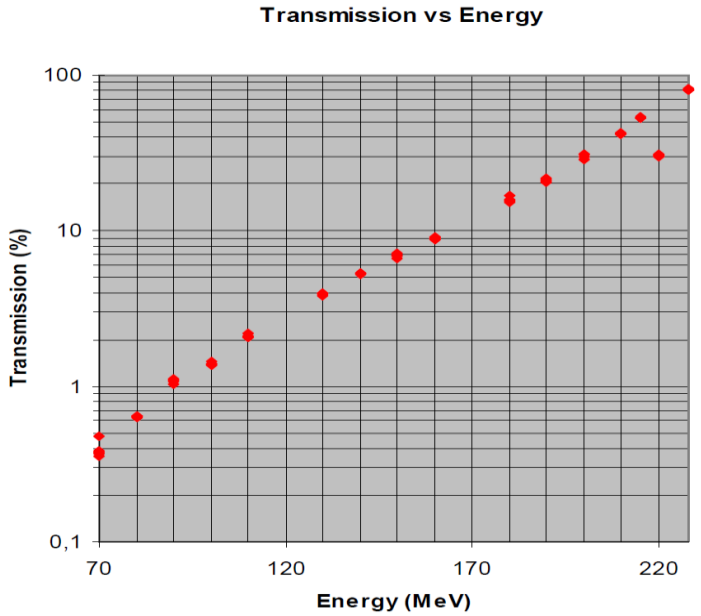
- Beam current 300 nA (500 nA for 230 MeV
- But transmission from 230 MeV to 70 MeV only 0,4% (for Be)
- For eye treatment 70 MeV, 2 nA, needed,



Energy degrader at Proteus C-235 cyclotron at IFJ PAN

☹ Neutron production (but far away from the patient)

☹ Broadening of the beam momentum spectrum -> enhanced distal falloff

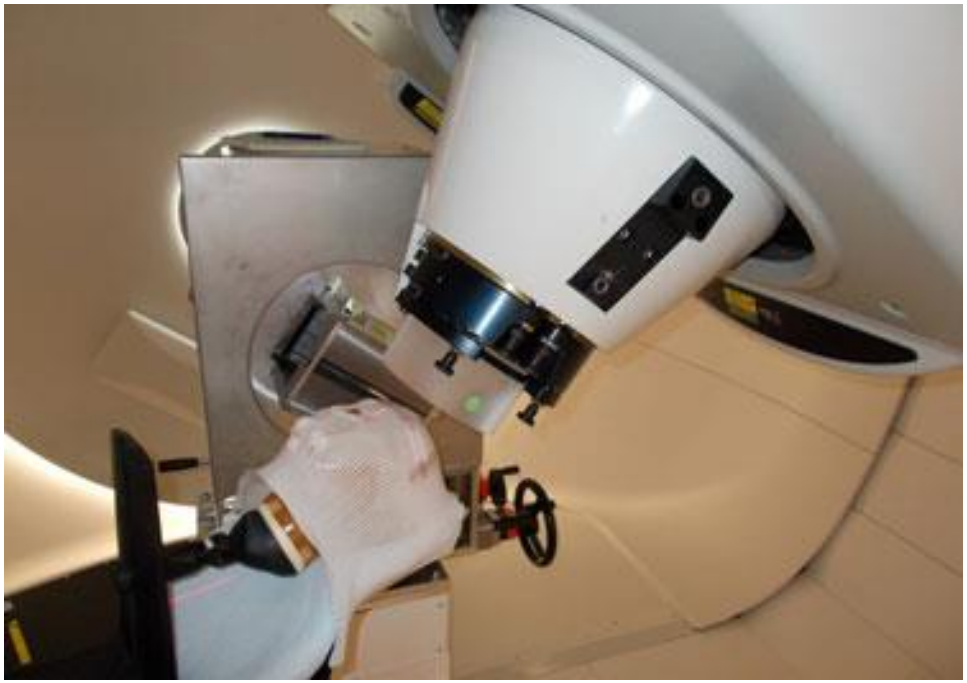


Is the distall falloff clinically relevant?

Sharp distal fall-off typically is not very relevant in clinical practice, because of range uncertainty - beam is not stopped at critical structure

But it can be important in future when the more relevant range verifiacation methods will be available

- IBA slit camera
- prompt gamma
- PET verification of induced



IBA slit camera

http://medicalphysicsweb.org/cws/article/research/64185

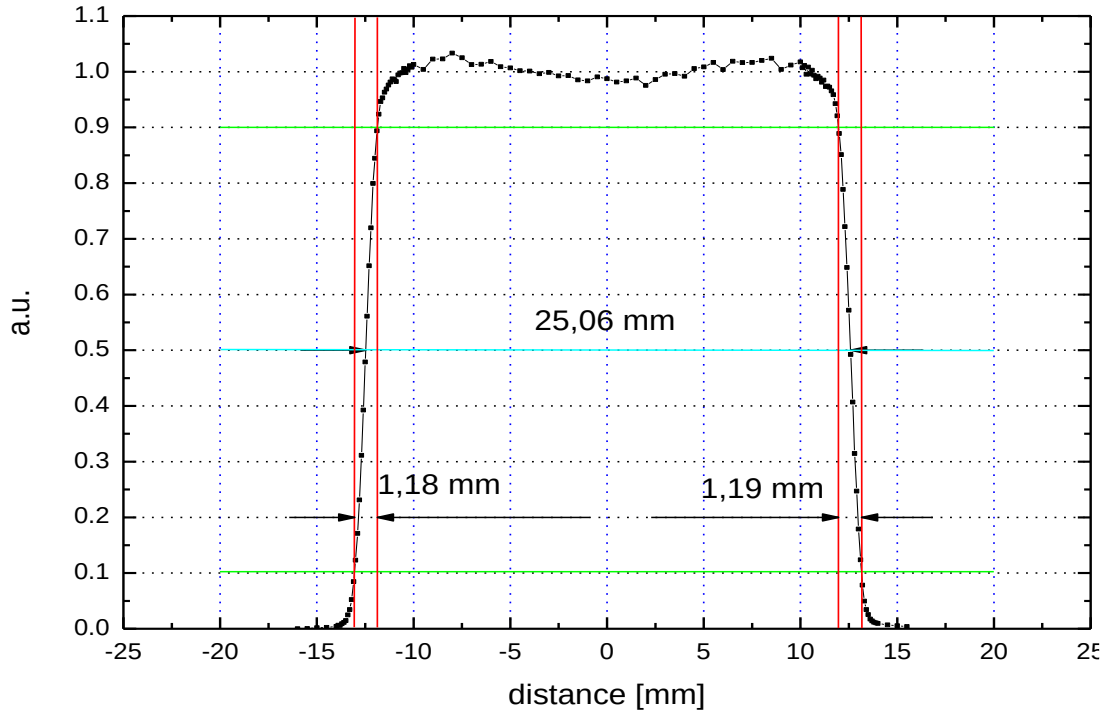
Dose distribution

1) Flatness, F

2) Distal fall-off, d

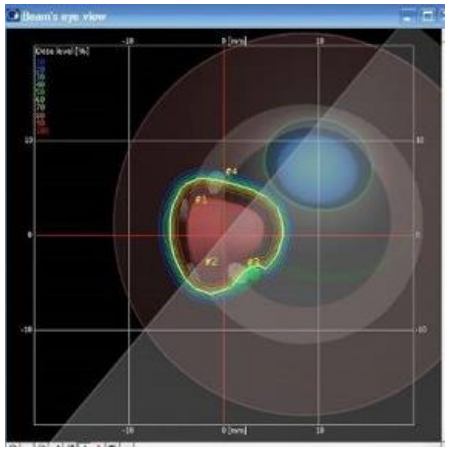
3) Penumbra, P

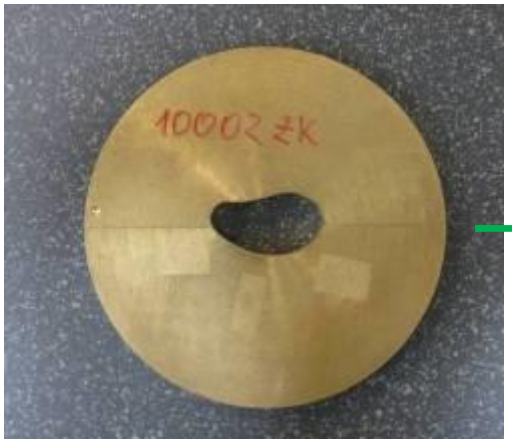
$$P = X_{20\%} - X_{80\%}$$

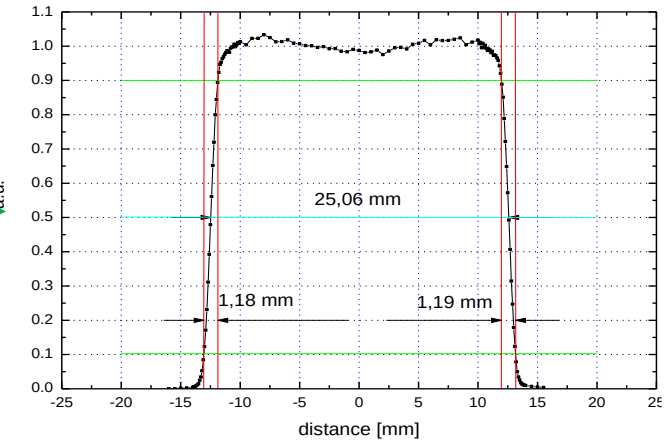


For Kraków eye line beam: P = 1.2 mm

Sharp penumbra with mechanical collimator

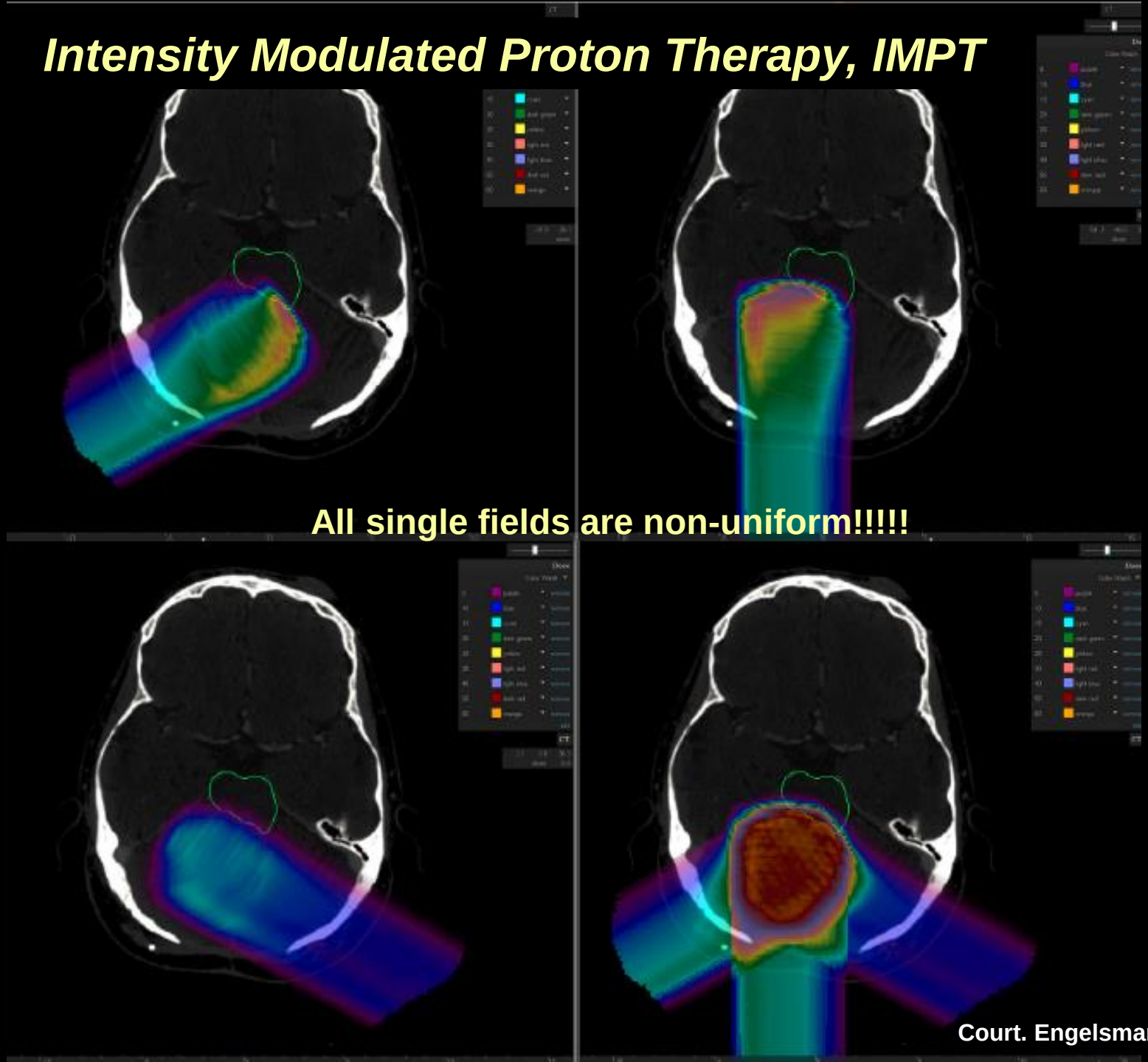






… but are we really using uniform fields?

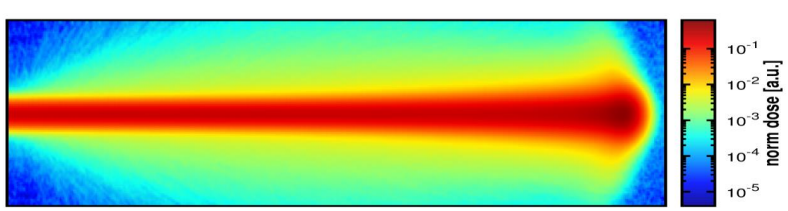
Intensity Modulated Proton Therapy, IMPT

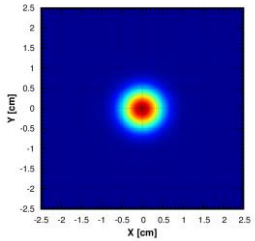


All single fields are non-uniform!!!!!

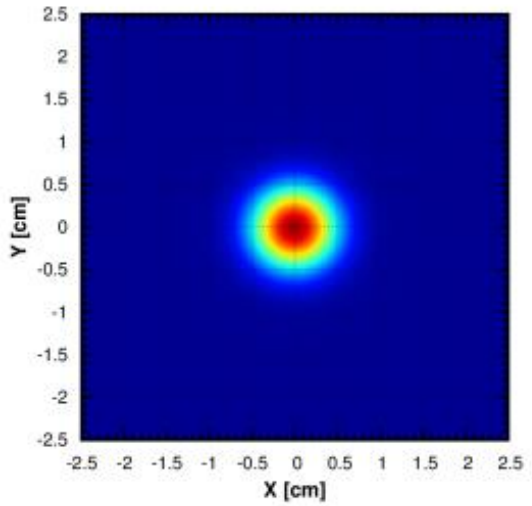
Court. Engelsmann, PSI

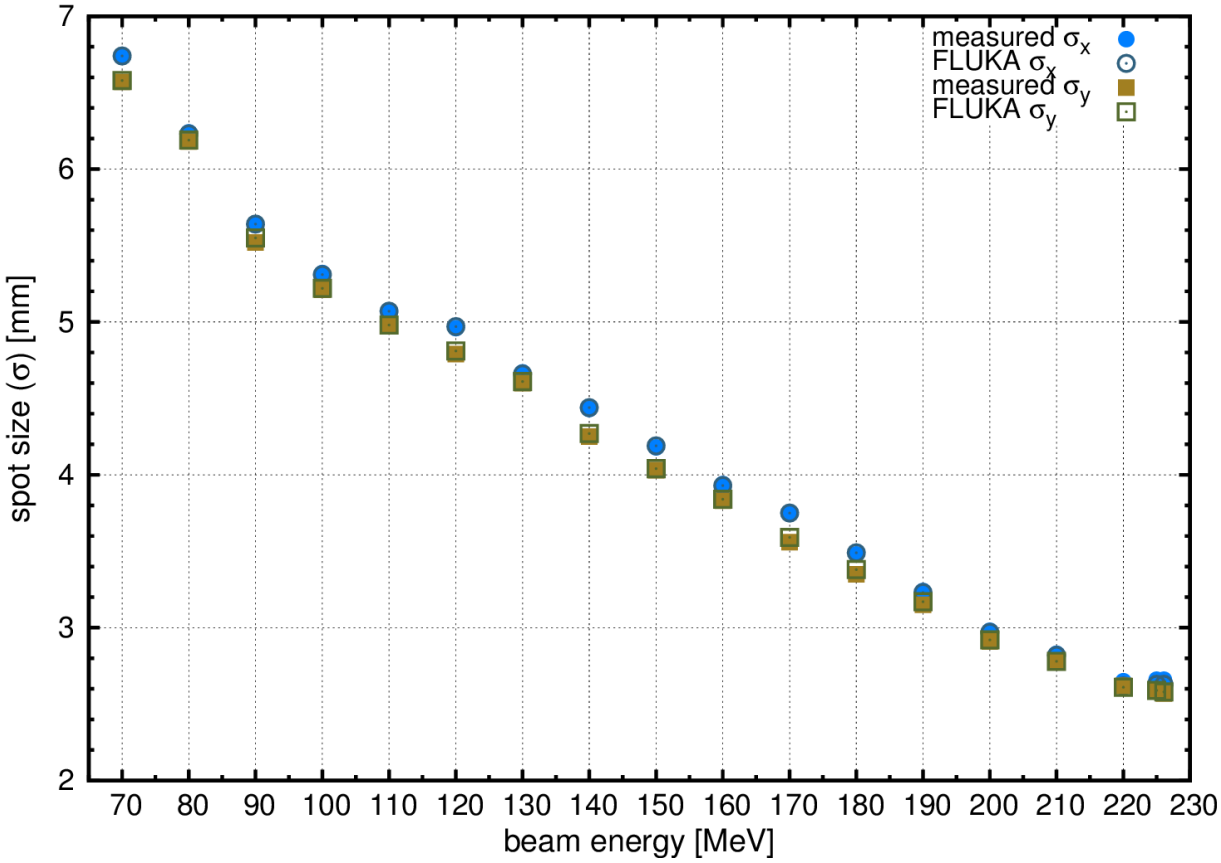
2. Spot properties





Spot size in air

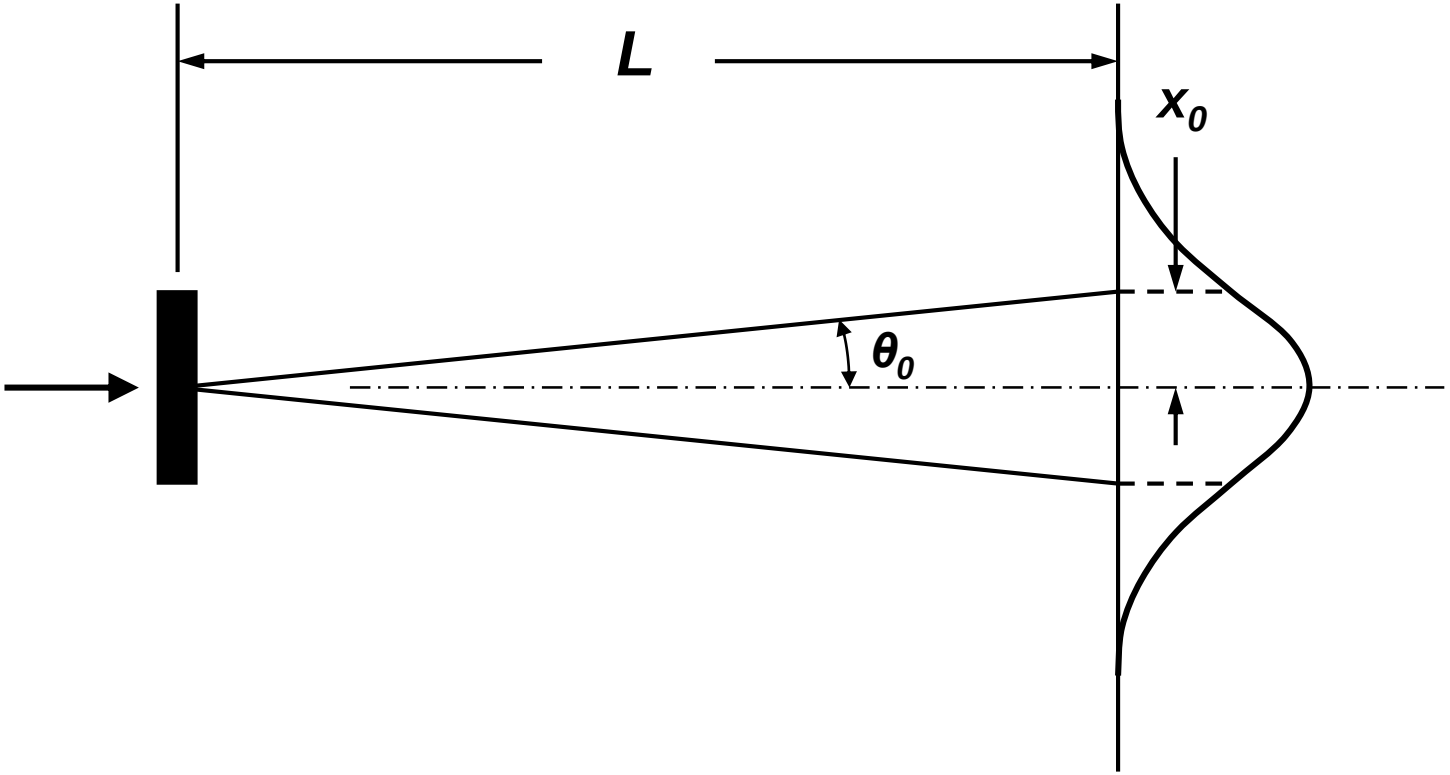




M. Kłodowska, PTFM 2015

Spot size in the isocentre, gantry-1, IFJ PAN

Scattering of protons: impact on spot size

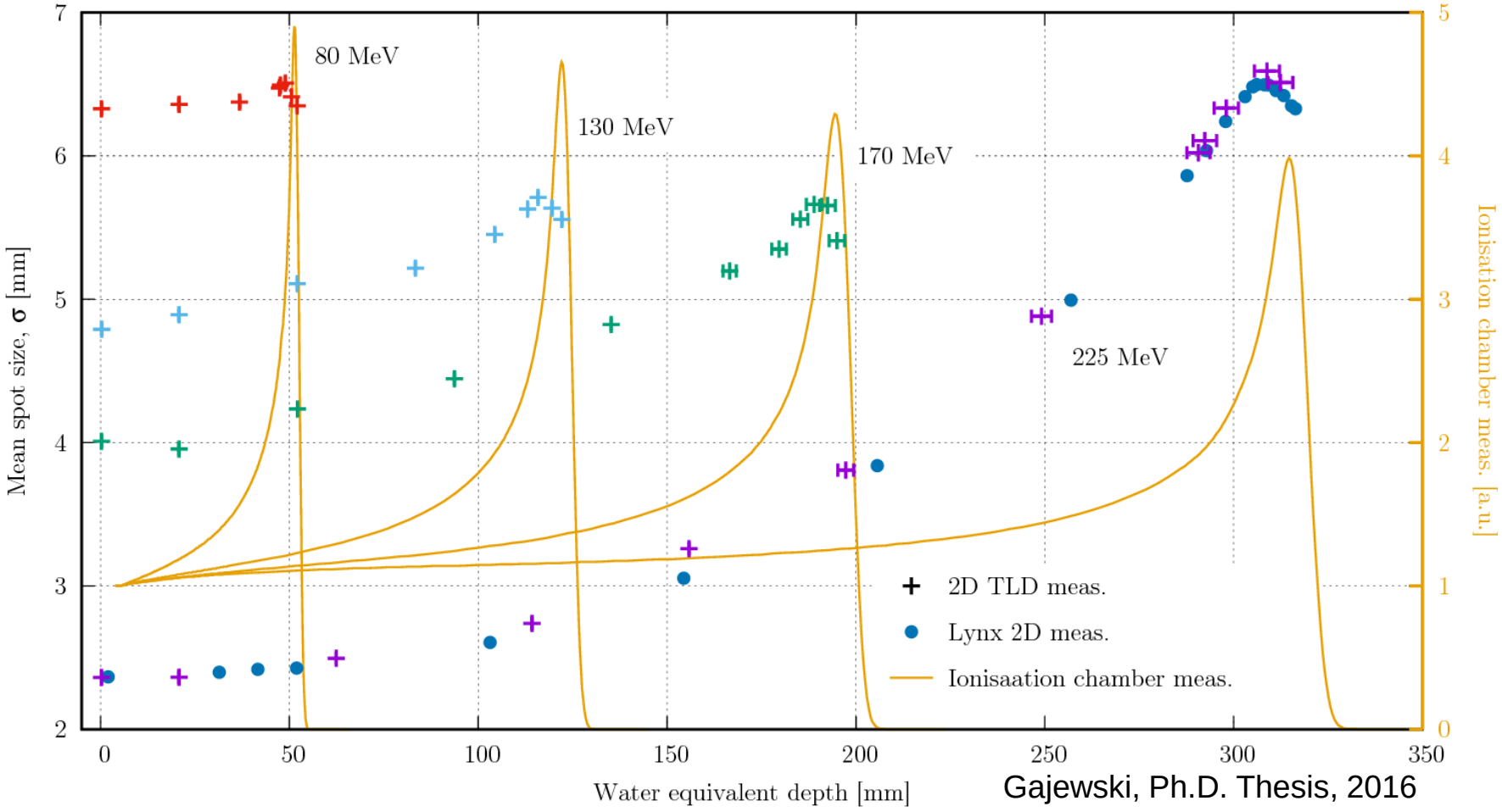


$$\theta_0 = \frac{14.1\ \text{MeV}}{pv}\, z \sqrt{\frac{L}{L_R}} \left[1 + \frac{1}{9}\log_{10}\left(\frac{L}{L_R}\right)\right] \quad \text{rad}$$

V.L. Highland (NIM 129 (1975) 497-499)

p proton momentum *L* target thickness
v proton speed L_R target radiation length - to reduce energy by factor 1/e

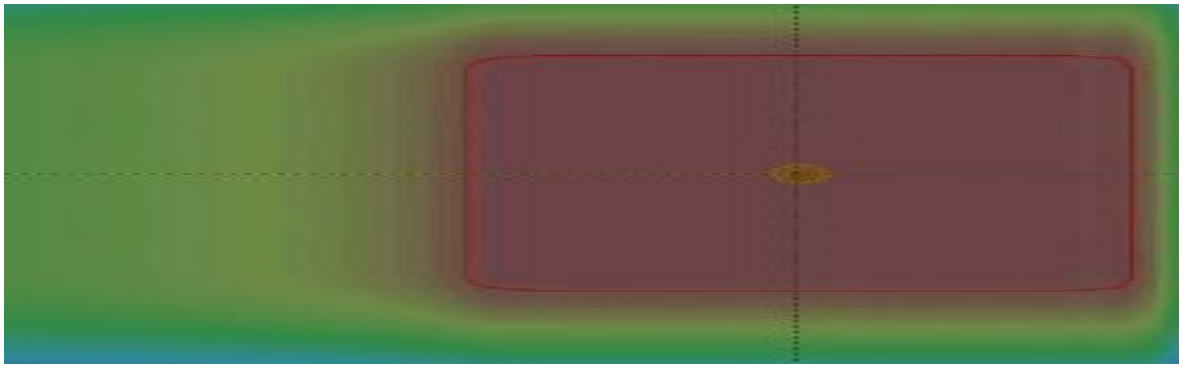
Spot size versus depth in water

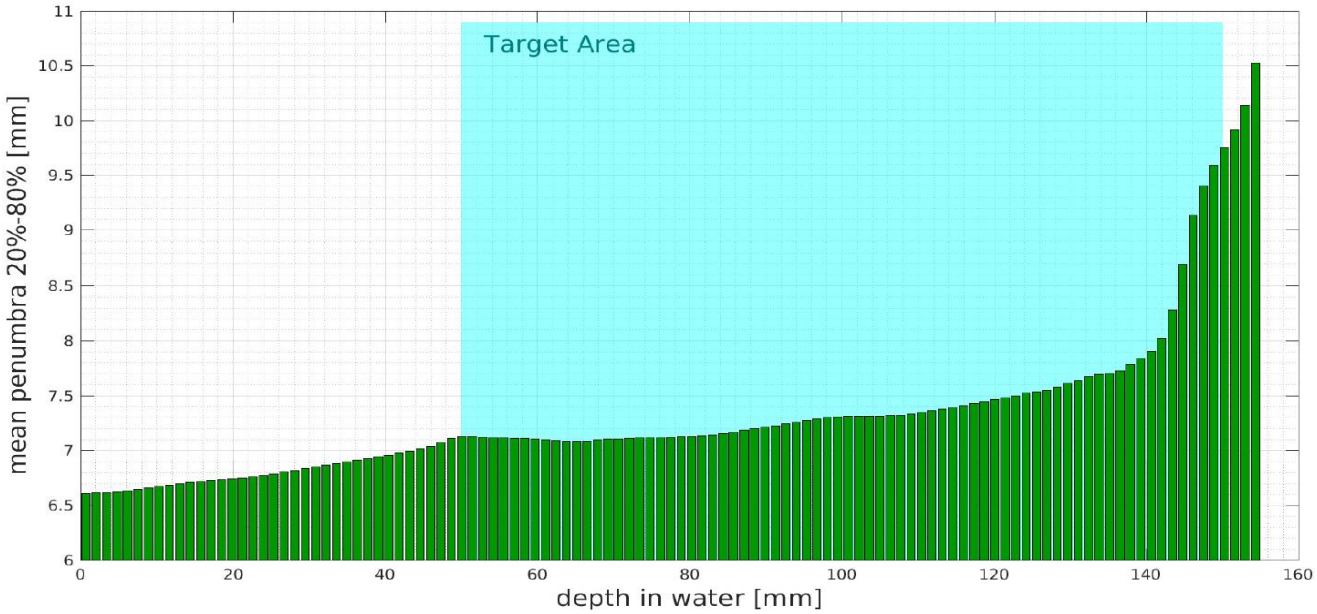


Gajewski, Ph.D. Thesis, 2016

The spot size (σ) growth with depth and depends on initial energy

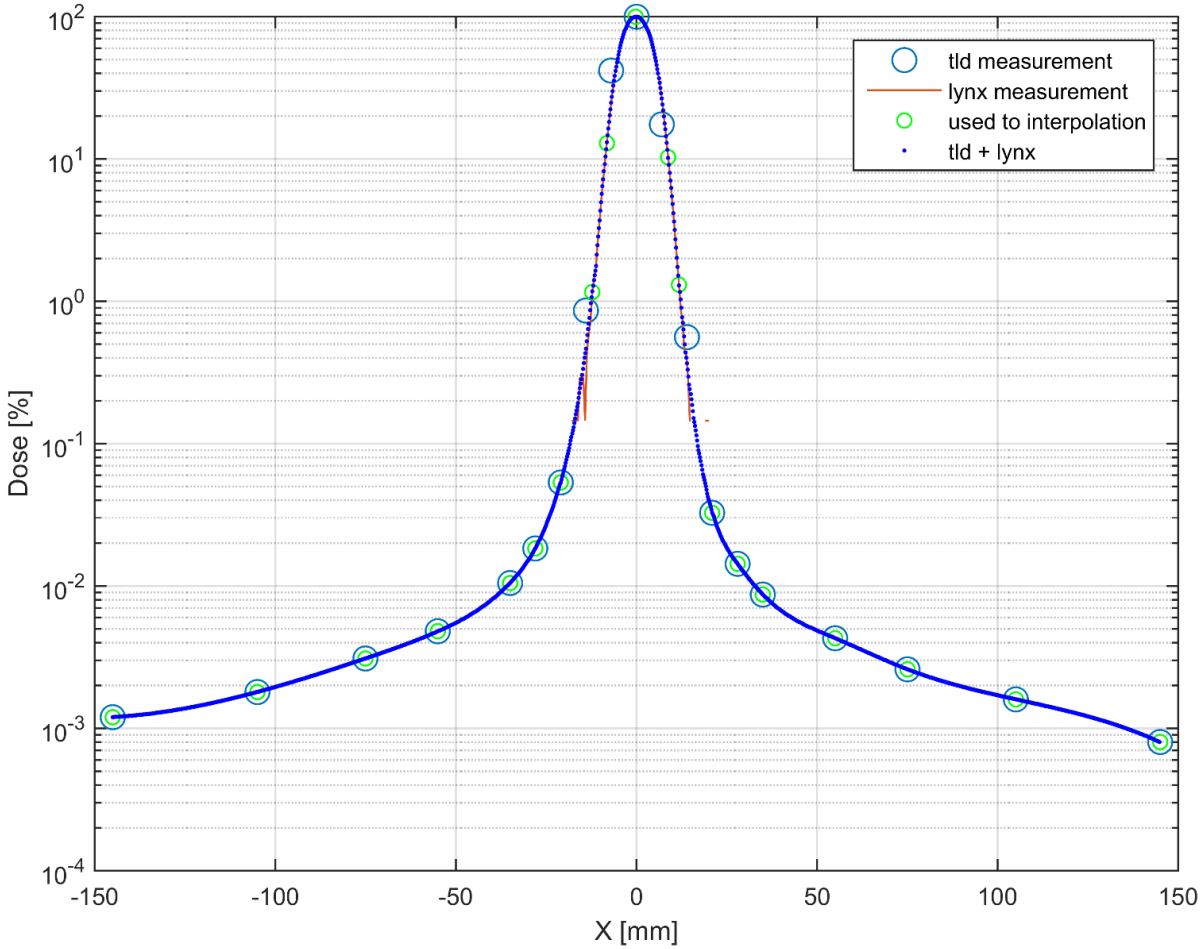
Penumbra for the spot scanning





Example of penumbra in water for scaning gantry calculated with Eclipse 8.6 for gantry-1 in IFJ Kraków

Scattering of protons: spot as a double Gauss



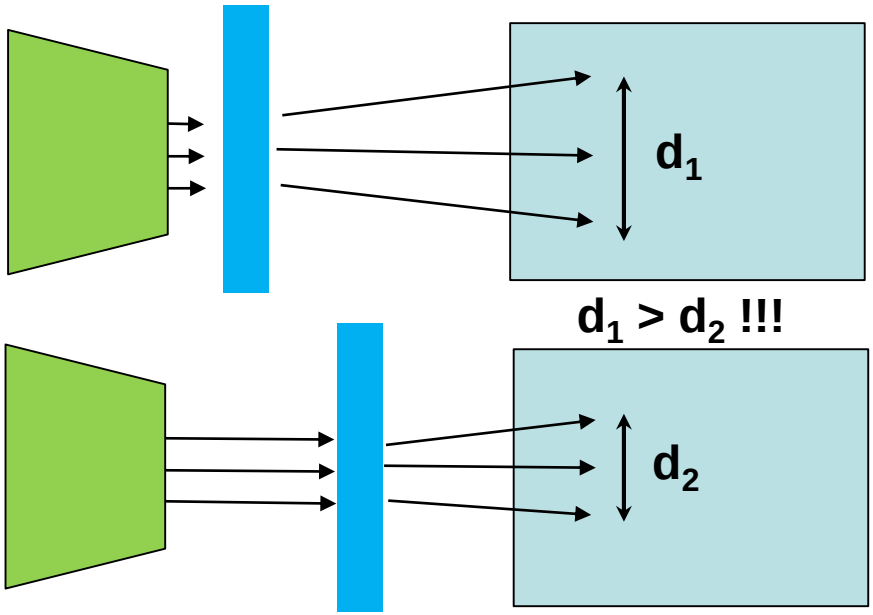
court. L.Stolarczyk, D. Krzempek, W. Komenda, M. Liszka

Scattered radiation far from the spot axis contributes significantly (up to a few %) to dose

Range shifters in spot scanning?

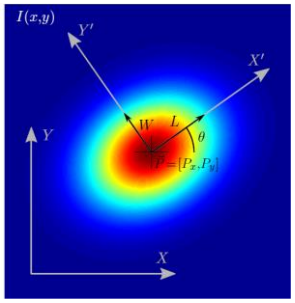
In cyclotrons and synchrotrons energy down to 70 MeV
the range shifter may be required

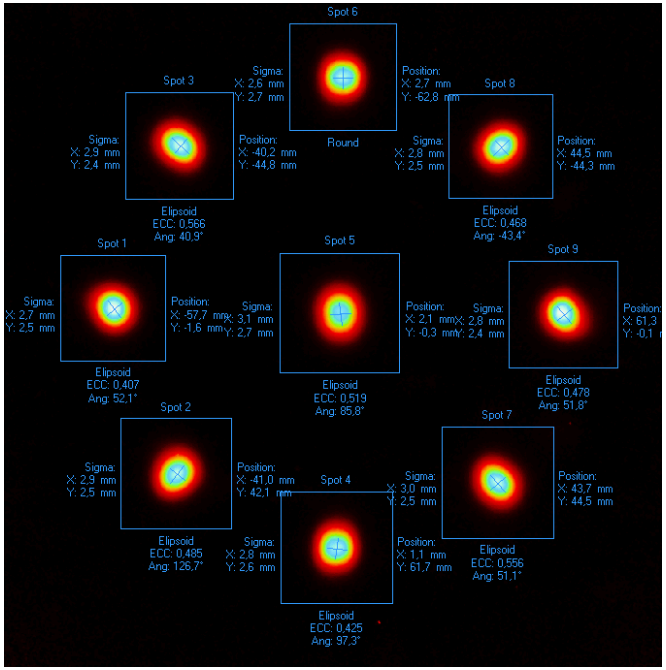
Range shifer at IBA dedicated gantry, IFJ Kraków

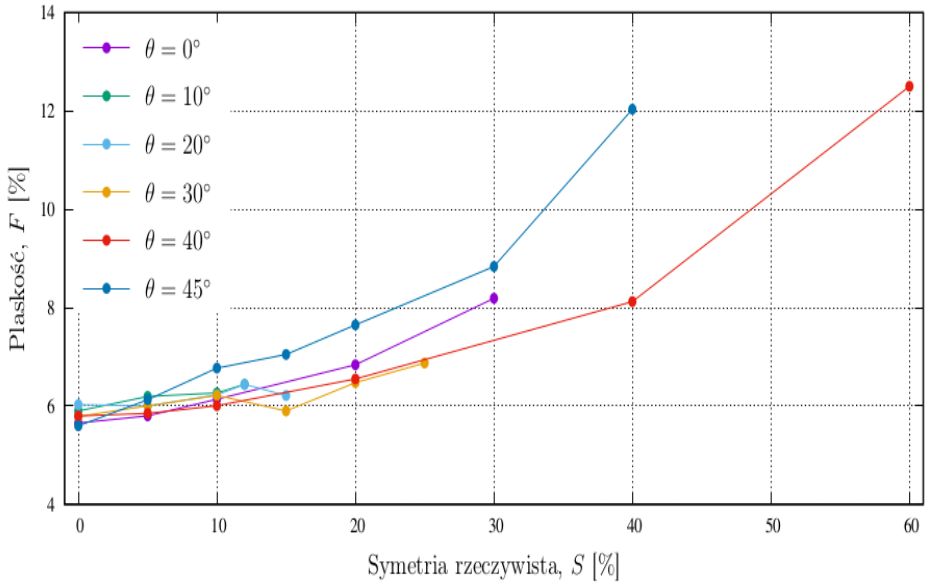


… not optimal solution, better to have protons directly from accelerator down to 30-40 MeV

Spot symmetry





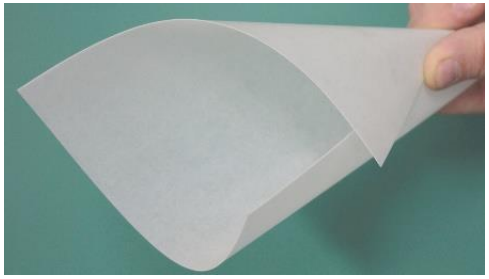


Variation of spot shape with regard to gantry position

J. Gajewski, Ph.D. Thesis

Spot symmetry affects flatness and penumbra

Two dimensional thermoluminescence dosimetry (2D TLD)



TLD reader and foil developed at IFJ PAN J. Gajewski, L. Czopyk, M. Kłosowski

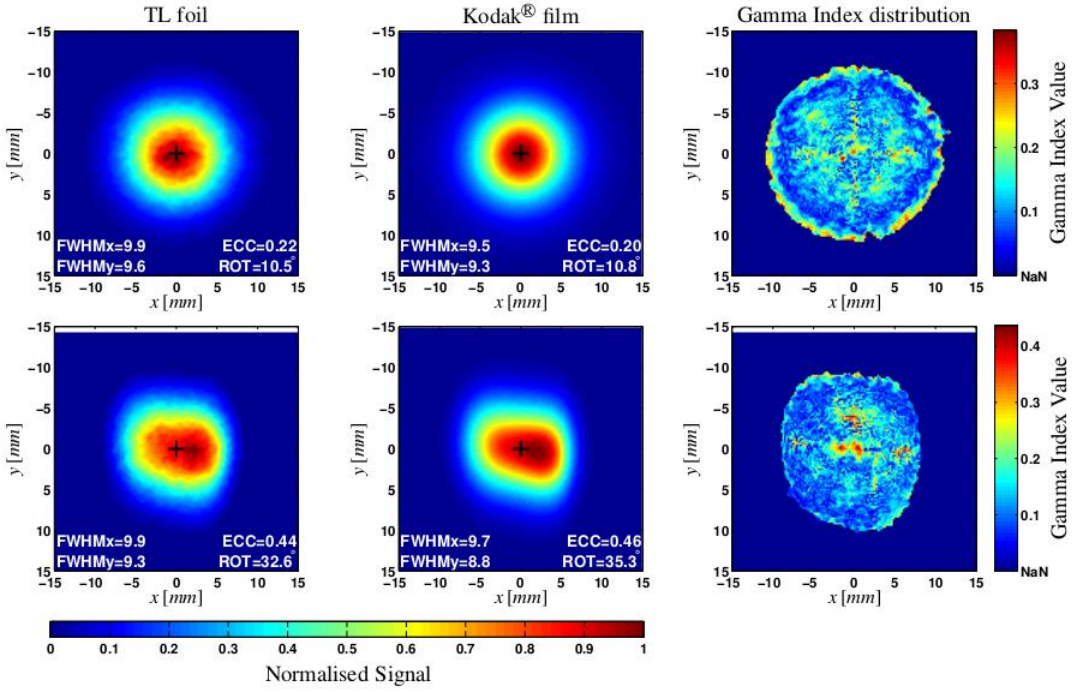
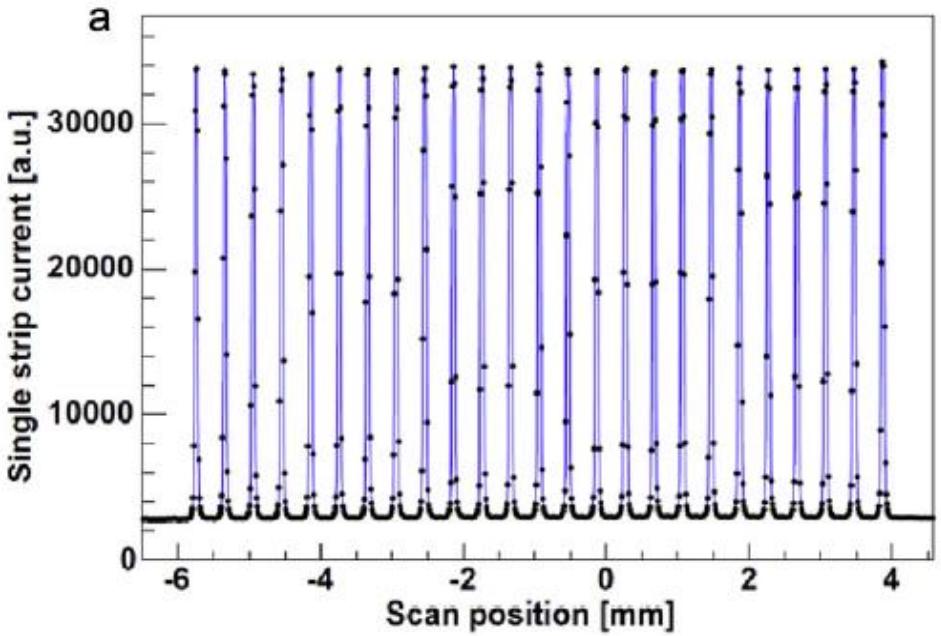


Figure 3: The same proton (E=210.11 MeV, FWHM=9.8 mm) and carbon (E=390.75 $\frac{\text{MeV}}{\text{u}}$, FWHM=9.8 mm) ion spots measured with two methods. First row presents proton and the second carbon ion beam. The three columns show spots measured with TLD foil, Kodak® EDR2 film, and gamma index map respectively. Black crosses indicate CM of spots.

Jan Gajewski, Ph.D. Thesis, 2016

Is it worth to go to very narrow proton beams?

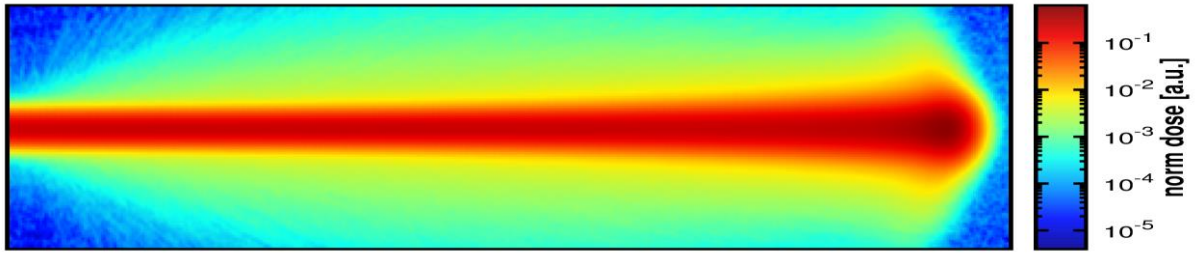
X-ray Microbeam radiation therapy (MRT) at the European Synchrotron, ESRF, Grenoble

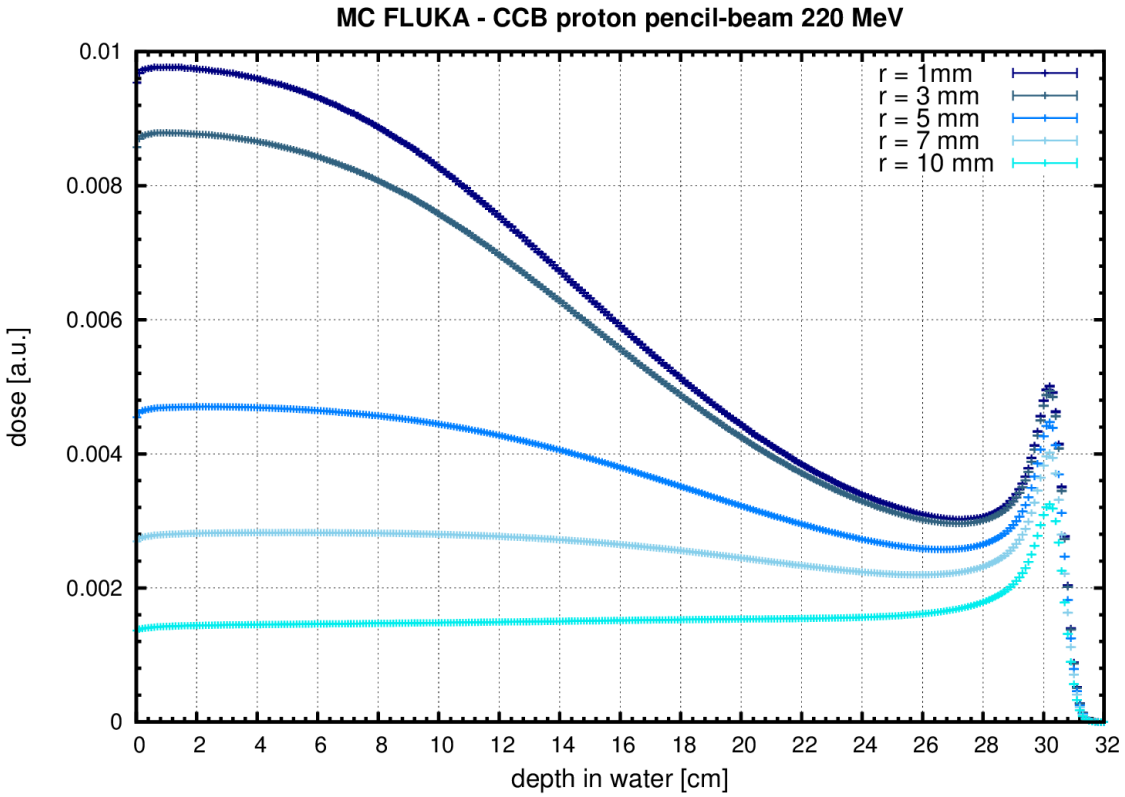


E. Brauer-Kirsch et al. Phys. Medica 2015

Collimated synchrotron X-ray microbeam (100 – 400 μm width) are considered as a promising beam for tumor therapy because of saving the healthy tissue

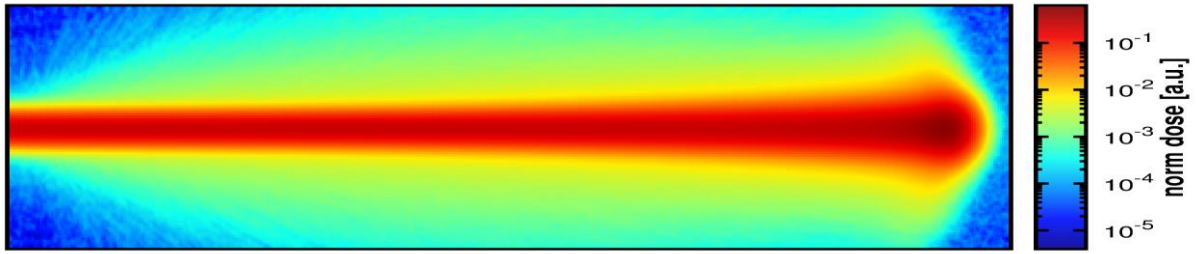
Radial distance from the beam axis: the impact on the Bragg peak

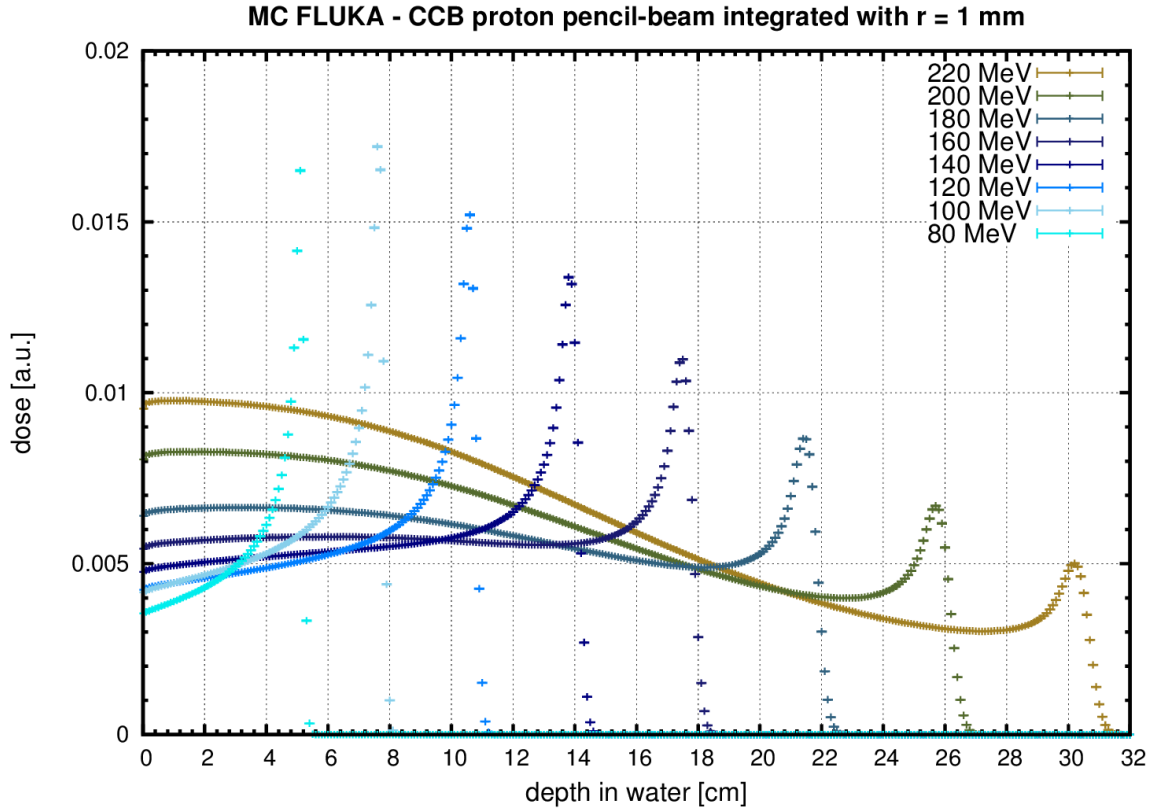




M. Kłodowska, 2015

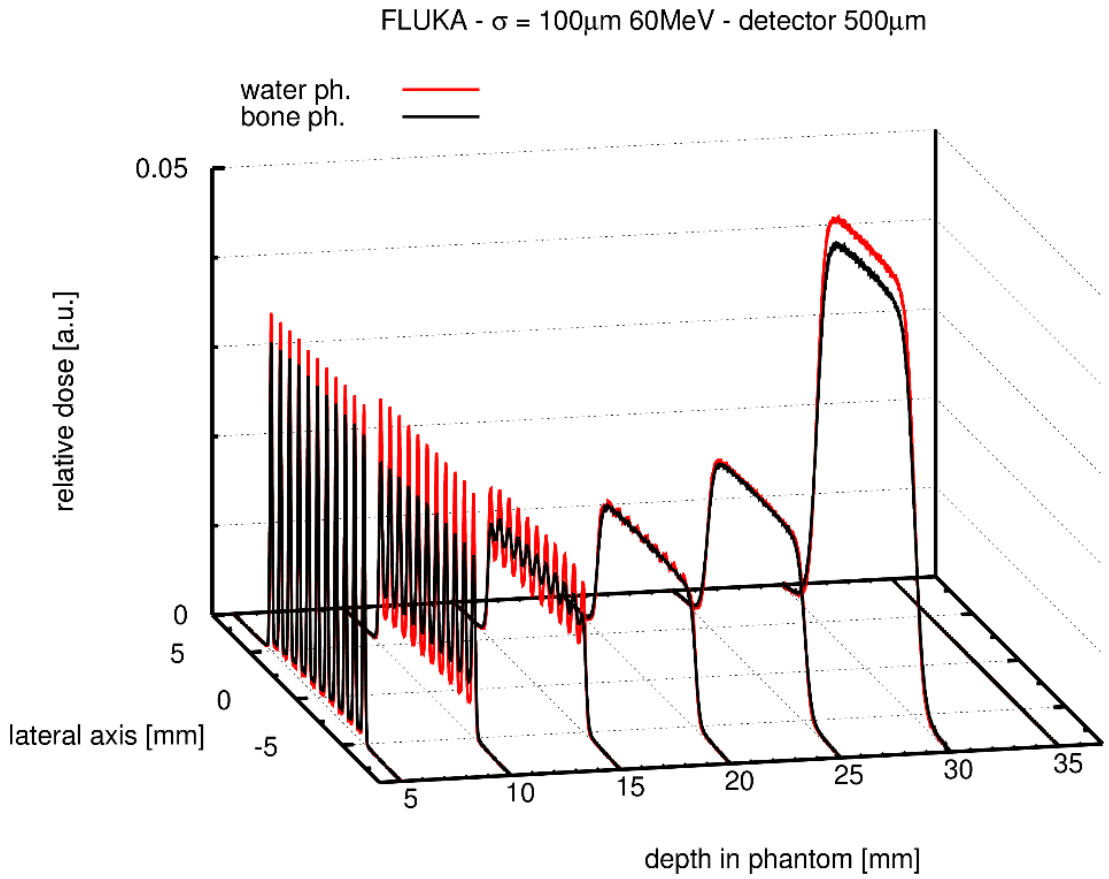
Radial distance from the beam axis: the impact on the Bragg peak





M. Kłodowska, 2015

Is it worth to go to the very narrow proton beams?

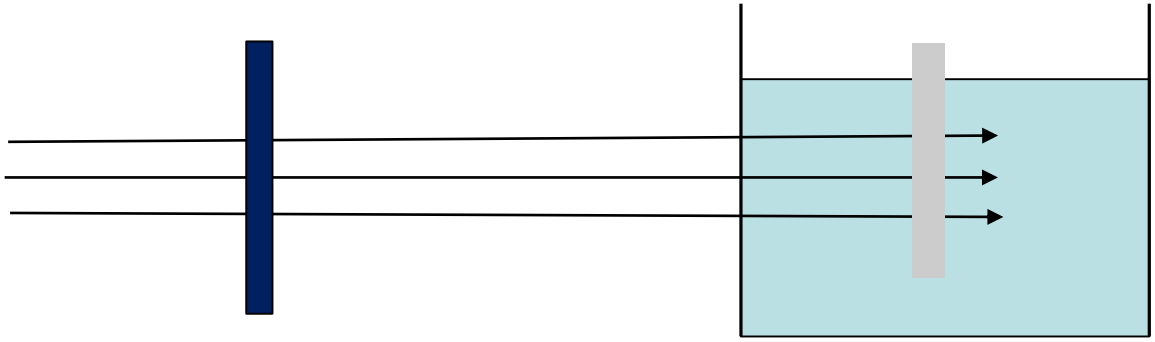


M. Klodowska, Physika Medica, 2015

Proton microbeams, due to scattering, overlap into the uniform beam. This technique could possibly save healthy tissue at the first 10 mm depth e.g. scull bones in children

Beam Dosimetry and Dosimetry for Scattered Radiation

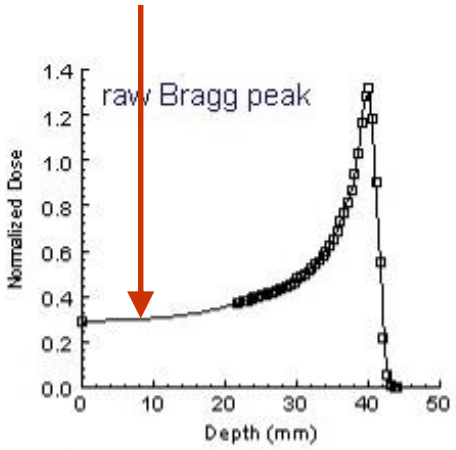
Reference dosimetry for proton beam



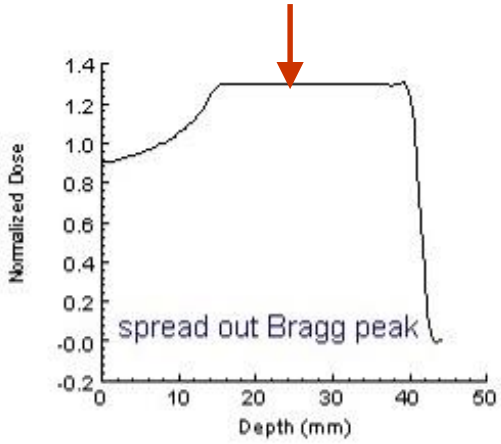
Beam monitor

Ionization chamber, IC

IC for scanning beam



IC for scattered beam



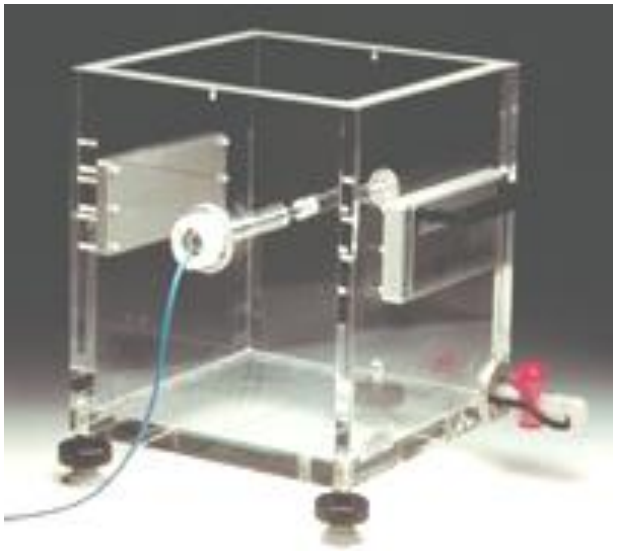
Reference dosimetry

$$D_{w,Q} = M_Q \, N_{D,w,Q_o} \, k_{Q,Q_o}$$

Corrected readout after proton irradiation

Calibration coefficient for Co-60

Quality coeff. for protons versus Co-60



Dosimetric phantom

IC with the electrometer

Matrix of ionization chambers

Number of chambers: 1020

Active area: 24.4 x 24.4 cm2

Sensor layout: matrix in a plane arranged in a 32 x 32 grid

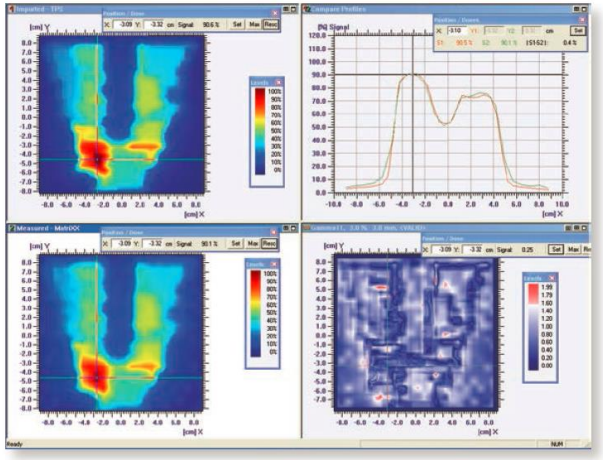
Pixel distance: 7.62 mm center-to-center

Chamber type: vented pixel ionization chambers

Chamber size: 4.5 (d) x 5 (h) mm, chamber volume 0.08 cm3

Typical sensitivity: 0.42 nC/Gy / 2.4 nC/Gy

MatriXX PT



OmniPro IMRT

Is the dose rate an issue?

Double scattering system: ~ 1 Gy/min

Eye line: 0.2 – 1.0 Gy/s

Scanning gantry (IBA) 2Gy 1 liter volume = 60 s

spot time 5 ms → D = ~100 Gy/s

IBA synchrocycloron (SC-2) 40 Gy/s (dose rate in a pulse)

Mevion 2 Gy 1 liter volume = 8 s

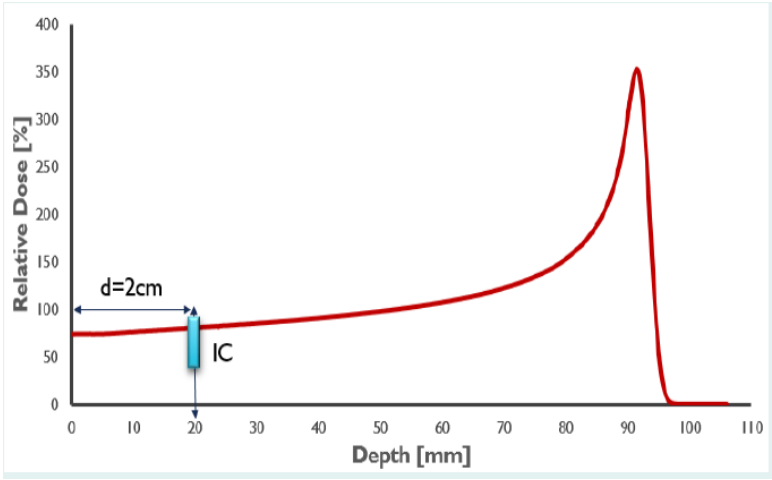
Dosimetry must be adapted to higher dose rates

Recombination in Ionization Chamberin PBS?

$$D_{w,Q} = M_Q \, N_{D,w,Q_o} \, k_{Q,Q_o} \, k_s \, k_p$$

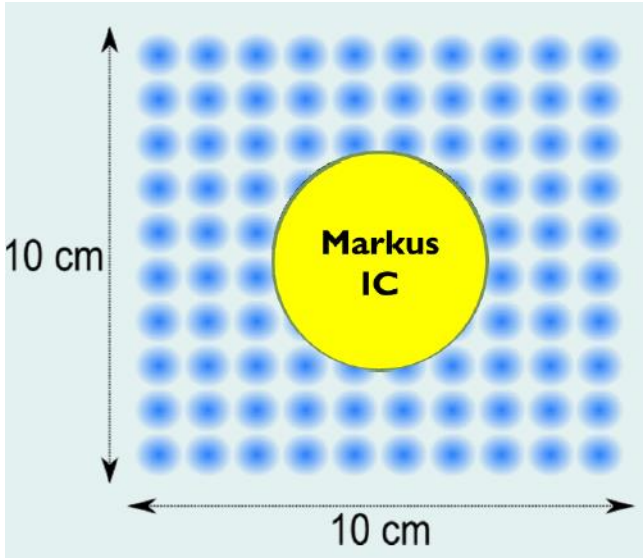
Saturation coefficient

Polarization coeff.



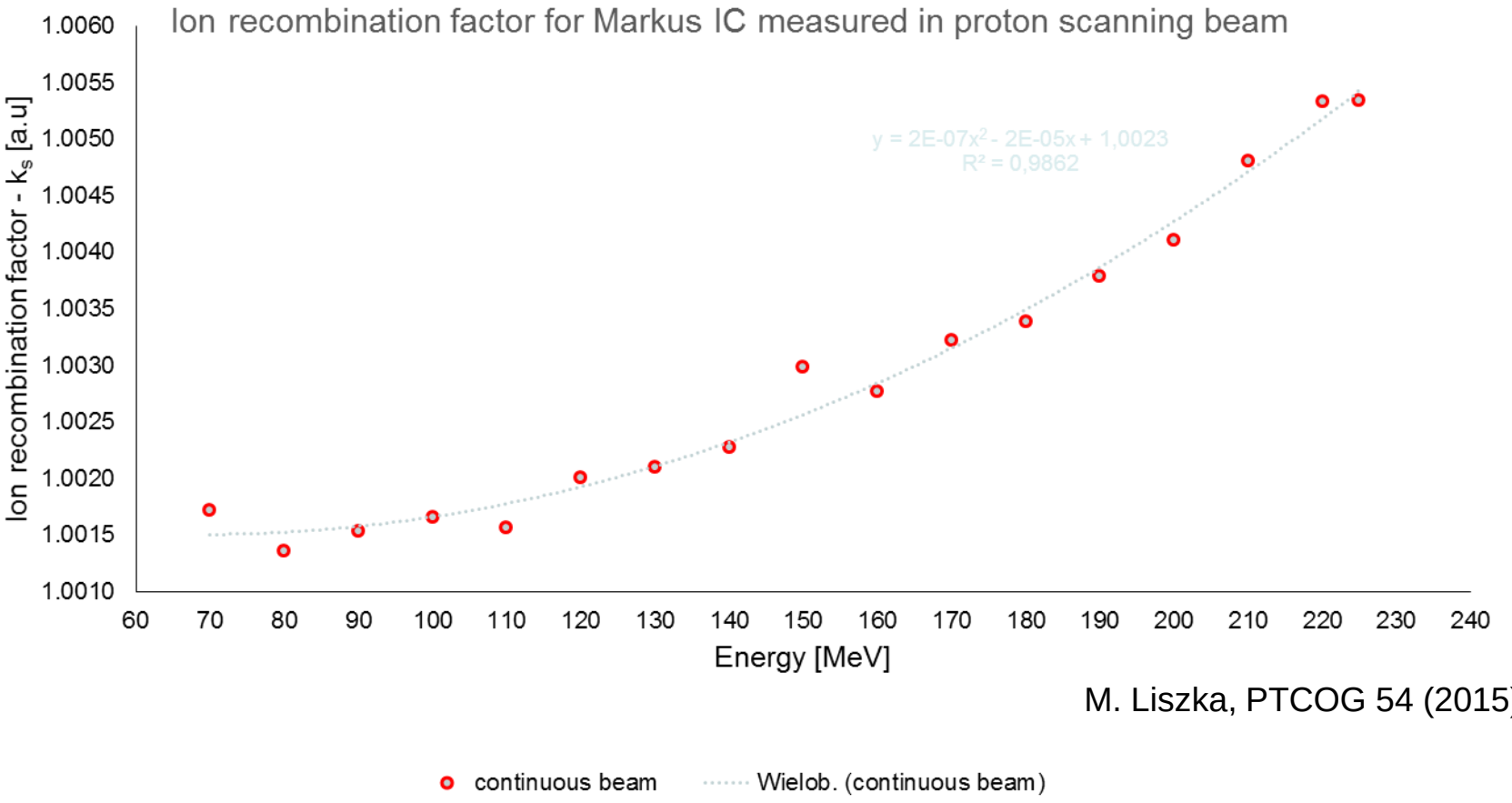
For MV X-rays dose rate: < 0.1 Gy/s

Local dose rate in the spot: 100 Gy/s !!!



M. Liszka, PTCOG 54 (2015)

Recombination in Ionization Chamber for PBS ?



M. Liszka, PTCOG 54 (2015)

YES: correction needed k_s : ~ 0.5%

Secondary neutrons – is it a problem?

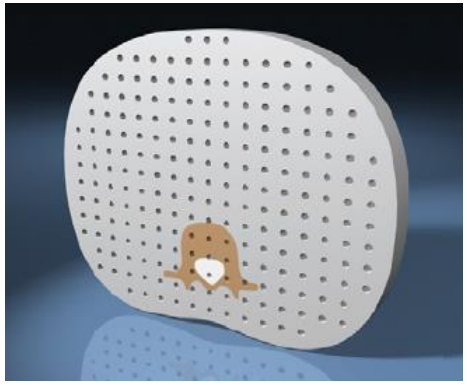
Scattered radiation in proton therapy- WG9 EURADOS collaboration

- **16 – 18 October 2014, Kraków**
- 25 participants from 8 scientific institutions
- Secondary radiation dose measurements for paediatric patients
- Measurements of secondary neutron spectra in the clinical conditions

In phantom measurements of secondary neutrons and γ radiation in proton spot scanning RT beam

Track detectors:

PADC CR-39 (UAB Barcelona, NPI Prague, IRSN)

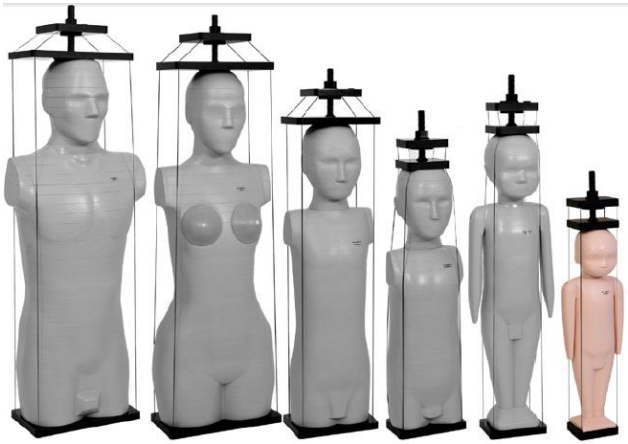


TLDs with ^{6}Li and ^{7}Li:

MTS-6, MTS-7, TLD-700 (IFJ Krakow, NPI Prague, RBI Zagreb)

RPL:

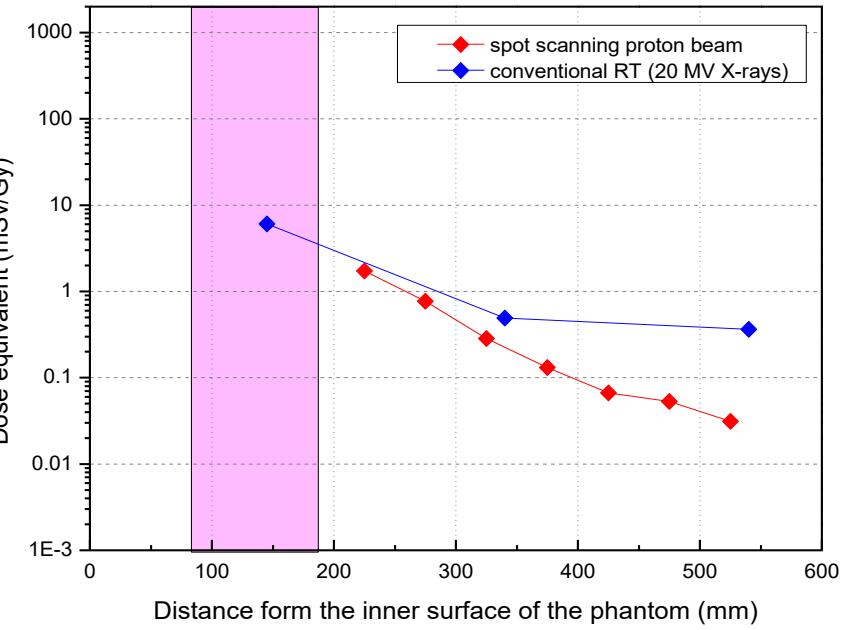
GD 352 (RBI Zagreb)



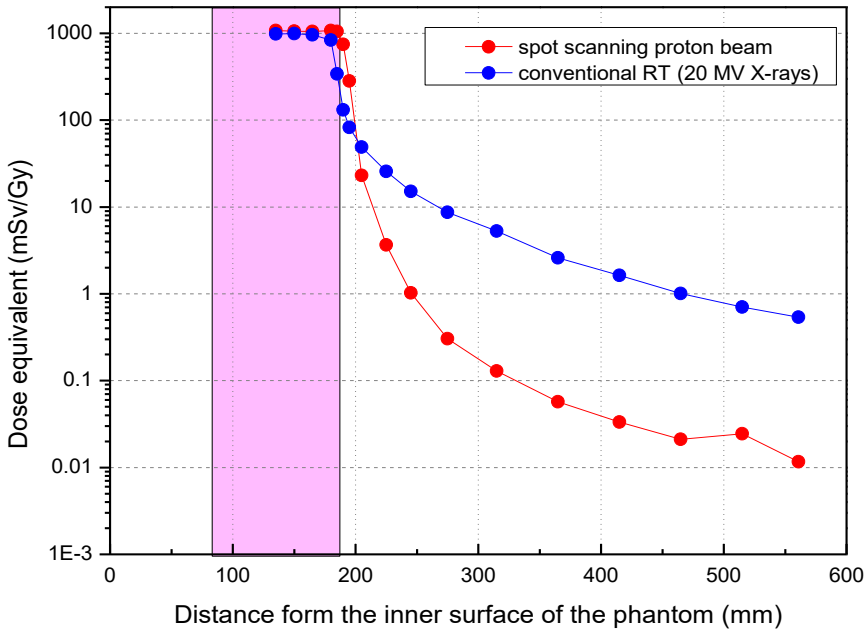
CIRS ATOM® Phantoms

Measured doses in proton spot scanning RT beam

NEUTRONS



γ – RADIATION



Secondary radiation doses inside water phantom are smaller for proton spot scanning radiotherapy then for conventional radiotherapy.

Saveta Miljanic, et al., RBI, Marie Davidkowa, et al., NPI, Liliana Stolarczyk, et al., IFJ, Carles Domingo, et al., UAB, Angela Di Fulvio, et al., UP

Neutron Spectrometry

HMGU - Bonner Sphere Spectrometer with ^{3}He-Detectors
V. Mares et all, Helmholtz Zentrum Munchen

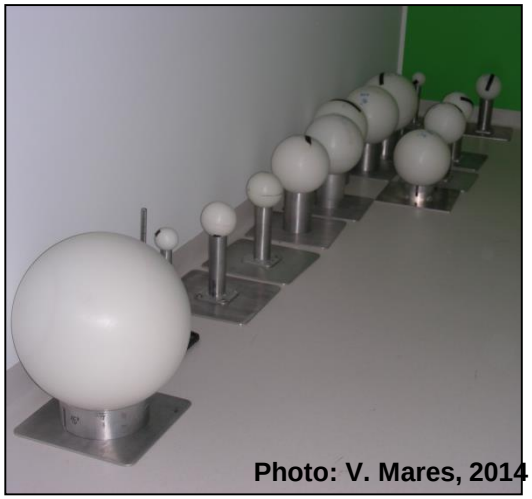
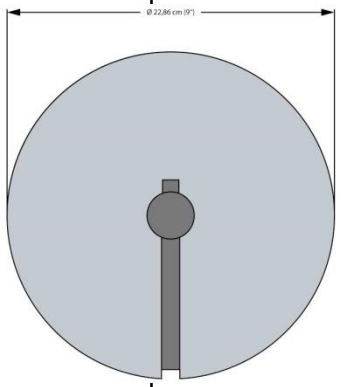


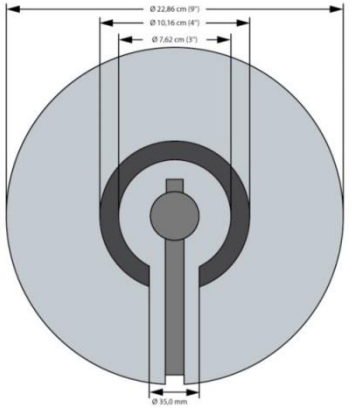
Photo: V. Mares, 2014

Photo: V. Mares, 2014

9“ PE

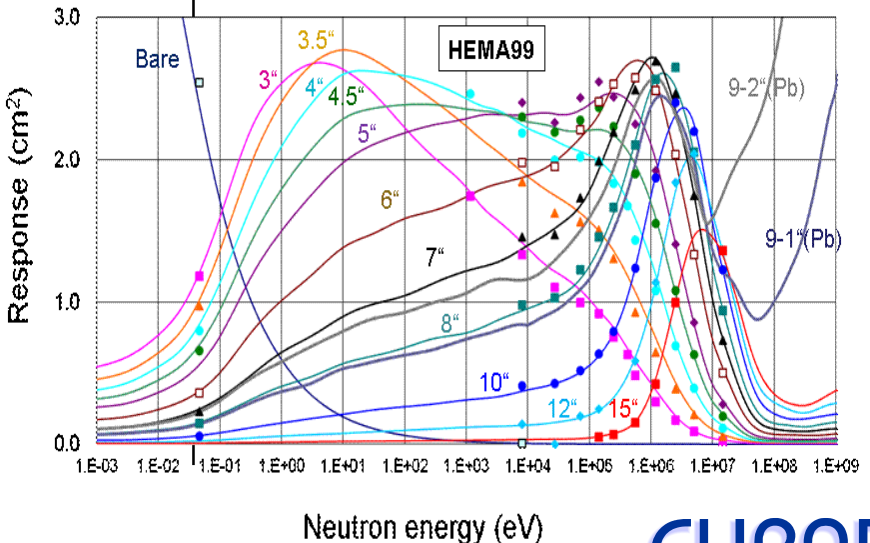


9“ PE (0.5“Pb)

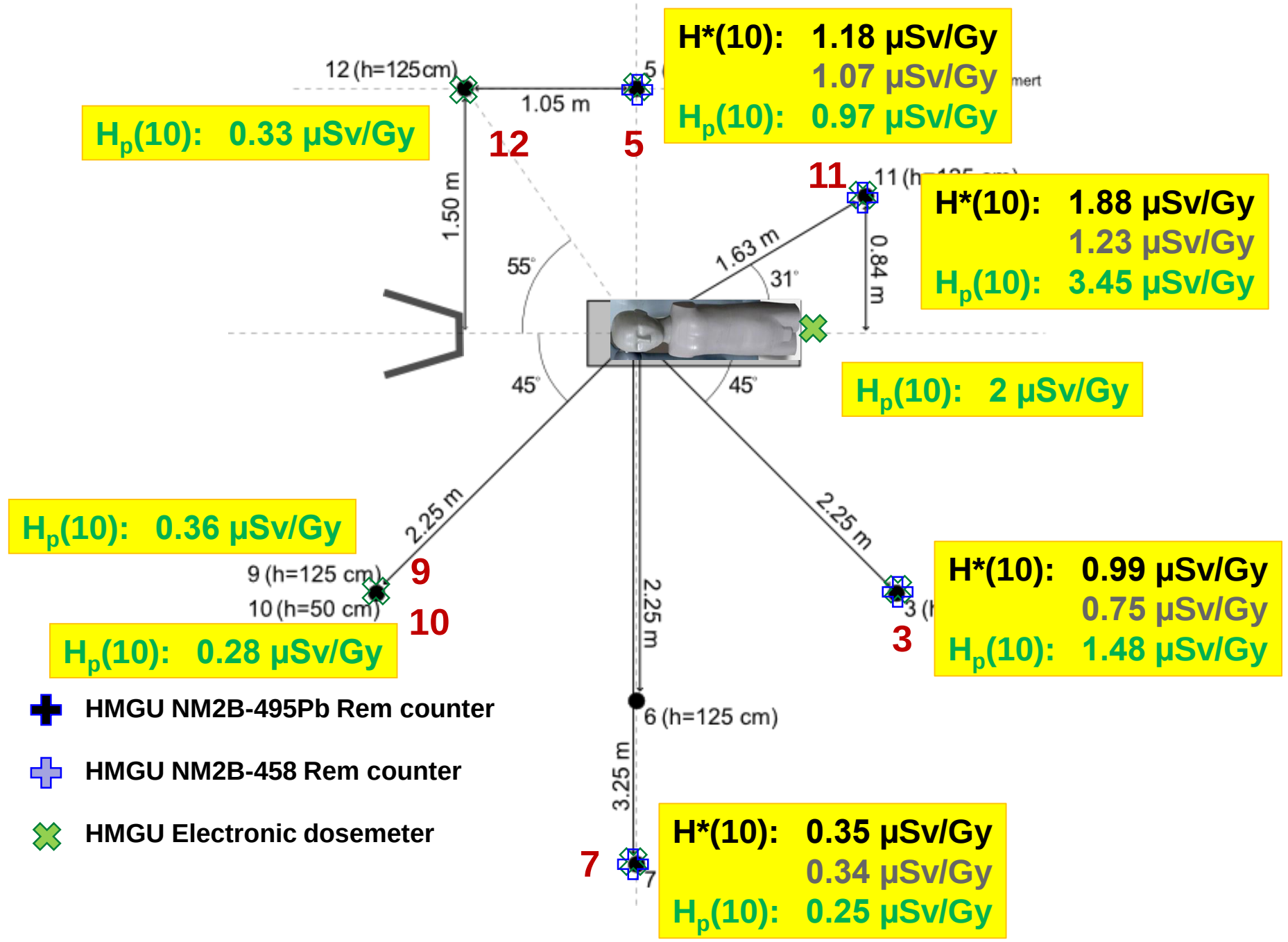


MC calculated and measured Φ-response

(Mares et al.1991,1998; Alevra et al.1992, Thomas et al.1994)



EURADOS


12 (h=125cm)
1.05 m
1.50 m
12
5
H*(10): 1.18 µSv/Gy
1.07 µSv/Gy
Hp(10): 0.97 µSv/Gy
Hp(10): 0.33 µSv/Gy
11
1.63 m
0.84 m
55°
31°
45°
45°
H*(10): 1.88 µSv/Gy
1.23 µSv/Gy
Hp(10): 3.45 µSv/Gy
Hp(10): 2 µSv/Gy
2.25 m
2.25 m
9 (h=125 cm)
10 (h=50 cm)
9
10
Hp(10): 0.36 µSv/Gy
Hp(10): 0.28 µSv/Gy
2.25 m
3
H*(10): 0.99 µSv/Gy
0.75 µSv/Gy
Hp(10): 1.48 µSv/Gy
6 (h=125 cm)
3.25 m
7
7
H*(10): 0.35 µSv/Gy
0.34 µSv/Gy
Hp(10): 0.25 µSv/Gy
HMGU NM2B-495Pb Rem counter
HMGU NM2B-458 Rem counter
HMGU Electronic dosemeter

Summary and Conclusions

1. Specification for clinical proton beam is more and more complicated.

2. At the same time it is expected that new accelerators will at least mimic the beam properties of the existing technologies.

3. Scanning is presently „the must" for proton therapy. However, Quality Control and dosimetry of Pencil Beam Scanning are complicated.

4. Dosimetry must be adapted to the beam delivery systems (dose rate).

5. Dosis from scattered neutrons are low for proton scanning beam

Thank You!!!!