Radiation Shielding of a 230 MeV Proton Cyclotron For Cancer Therapy

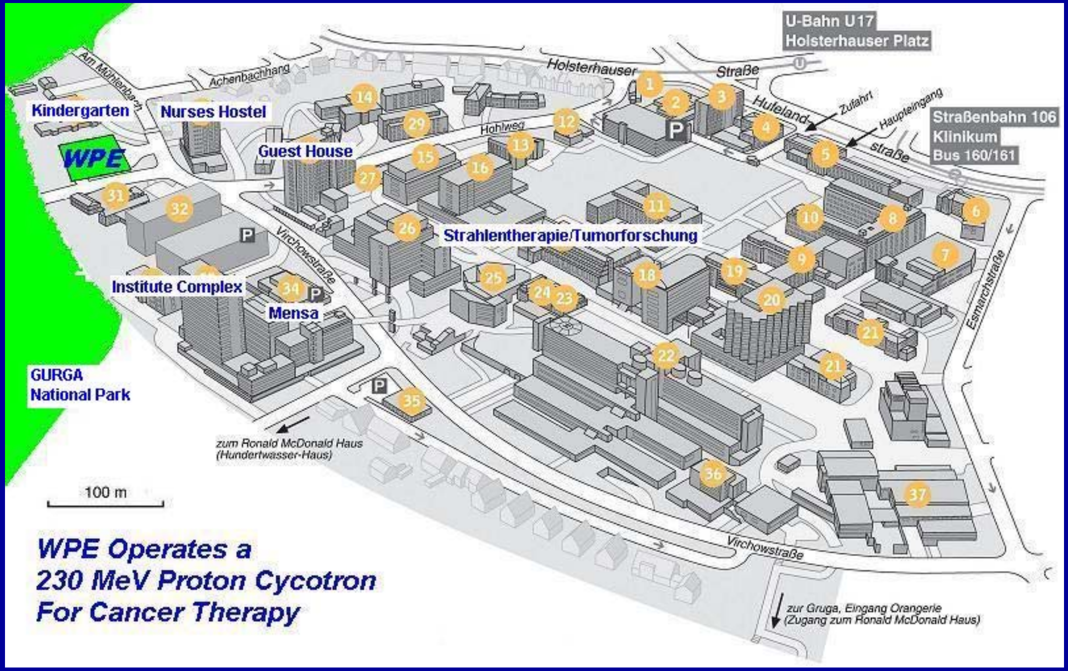
BHASKAR MUKHERJEE

Westdeutsches Protonentherapiezentrum Essen gGmbH

Joint DESY and University of Hamburg Accelerator Physics Seminar

27 August 2009

WPE is located within the Campus of Universitätsklinikum Essen



Surrounded by

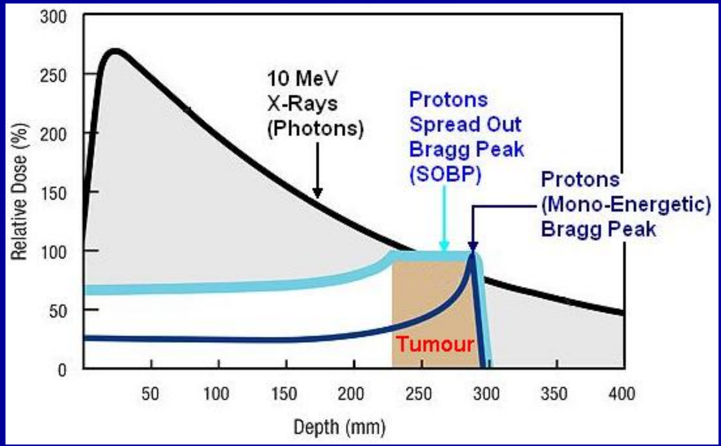
Kindergarten **Nurses Hostel** **Guest House** **Mensa**

Institute Complex (Universität Duisburg-Essen)

Strahlentherapie/Tumorforschung- UK Essen **Gurga National Park**

Hence, an Adequate Radiological Safety becomes Mandatory

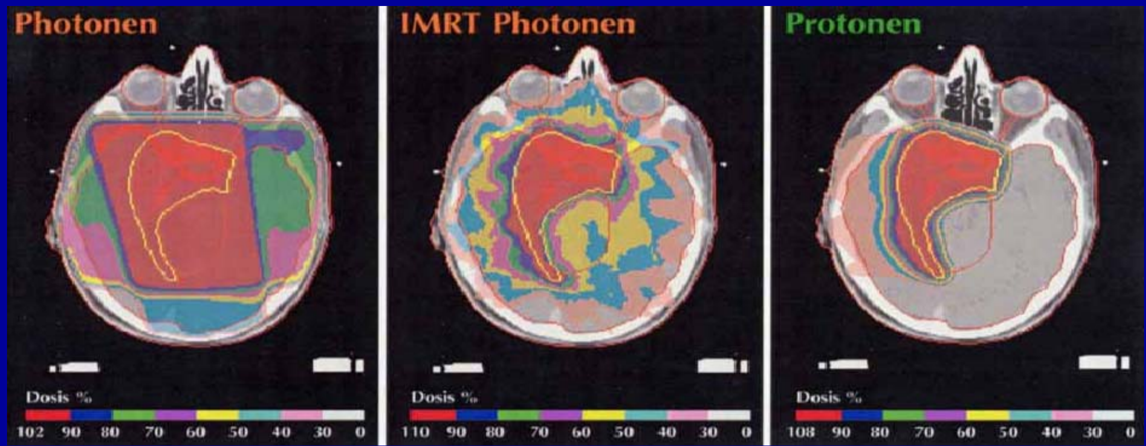
Principle of Proton Therapy



Highly localised energy delivery of protons in the tumour surrounded by healthy tissue.

Large dose sparing in healthy tissue region.

On the other hand, conventional high-energy X-rays delivers the major share of radiation dose outside the tumour volume.



Example:

Radiotherapy of Brain Stem Tumour (*A. J. Lomax et al. Radio-therapy and Oncology 51(1999) 257-271*)

Conventional Photons: No dose sparing at brain stem (red zone)

Intensity Modulated Photons (IMRT): 50-60% dose sparing (yellow zone)

Proton Therapy: 0-30% dose sparing (grey zone)

Architectural Concept of the WPE Facility

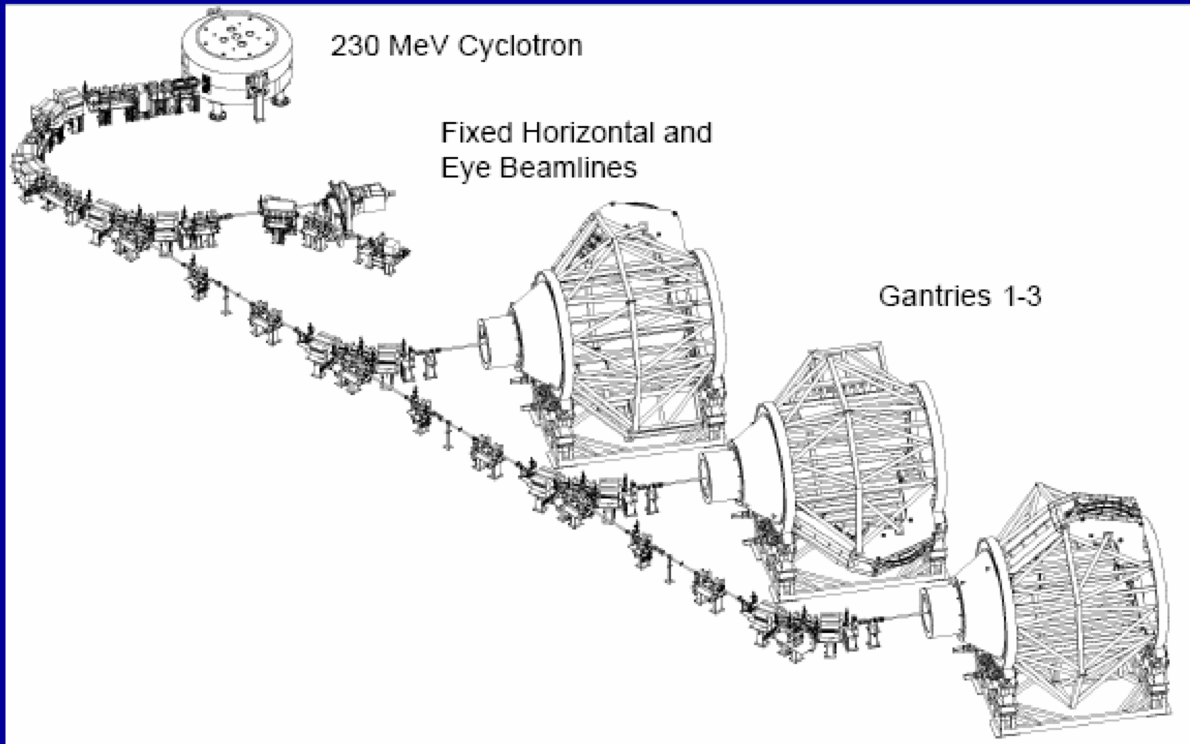
230 MeV Proton Cyclotron, Diagnostic & Imaging Facilities (CT/MRI) and Treatment (Gantry) rooms are located underground (-1 level).

Patient reception, Employees offices, Workshops and Health Physics Laboratory are located at Ground Floor (0 level).

IT Station and Storage Rooms are located at First Floor (+1 level).

Climate & Ventilation Facilities are located at Second Floor (+2 level).

The Skeletal Perspective of the WPE Cyclotron and Tumour Irradiation Facilities



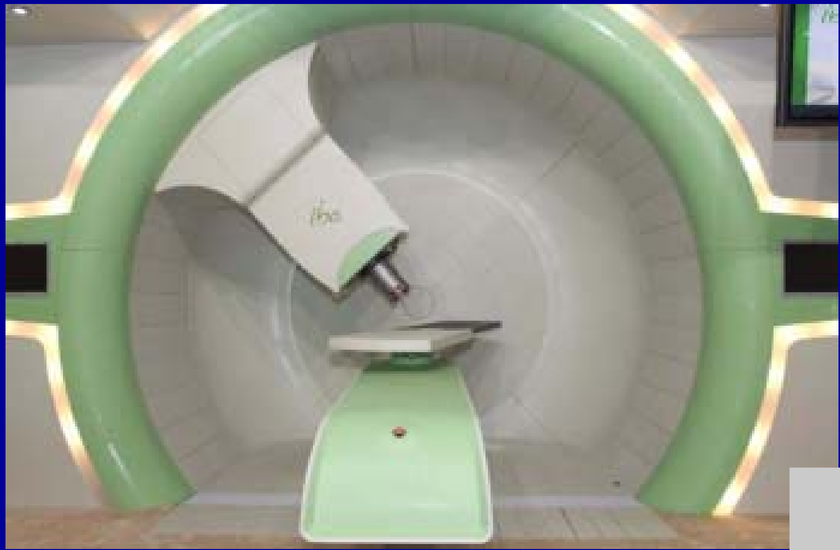
Overall Length of the Facility: approx. 120 m

Maximum Diameter of the Rotating Gantry: 7 m

Weight of the Rotating Gantry: approx. 100 Tonne

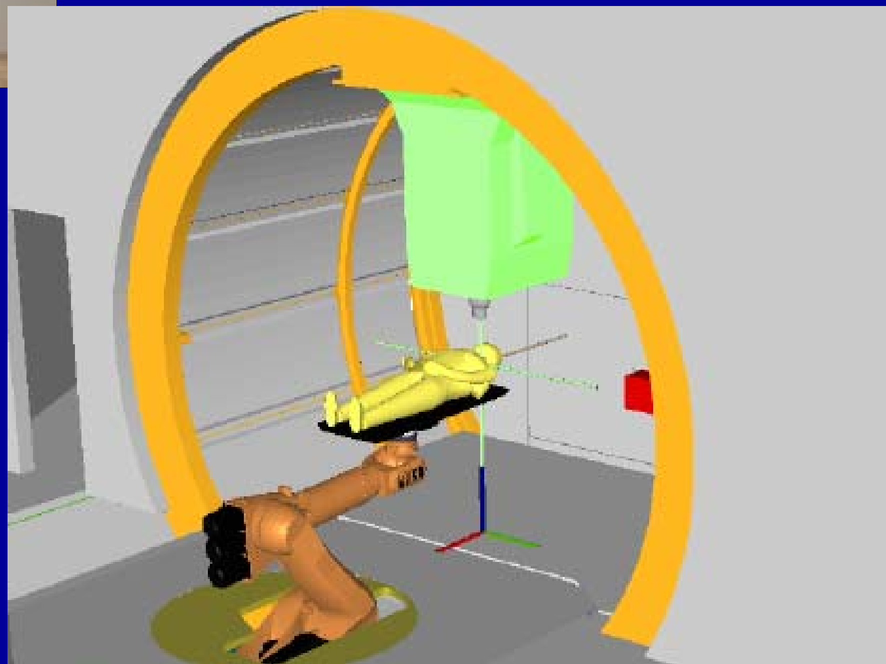
Maximum Permissible Deformation: 0.5 mm

The Isocentric Gantry



One of the three Isocentric Gantries located at WPE Treatment Rooms.

A computer simulated drawing showing the Nozzle and Robotic Patient Positioning Set up.



Motivation and Goal of this Talk

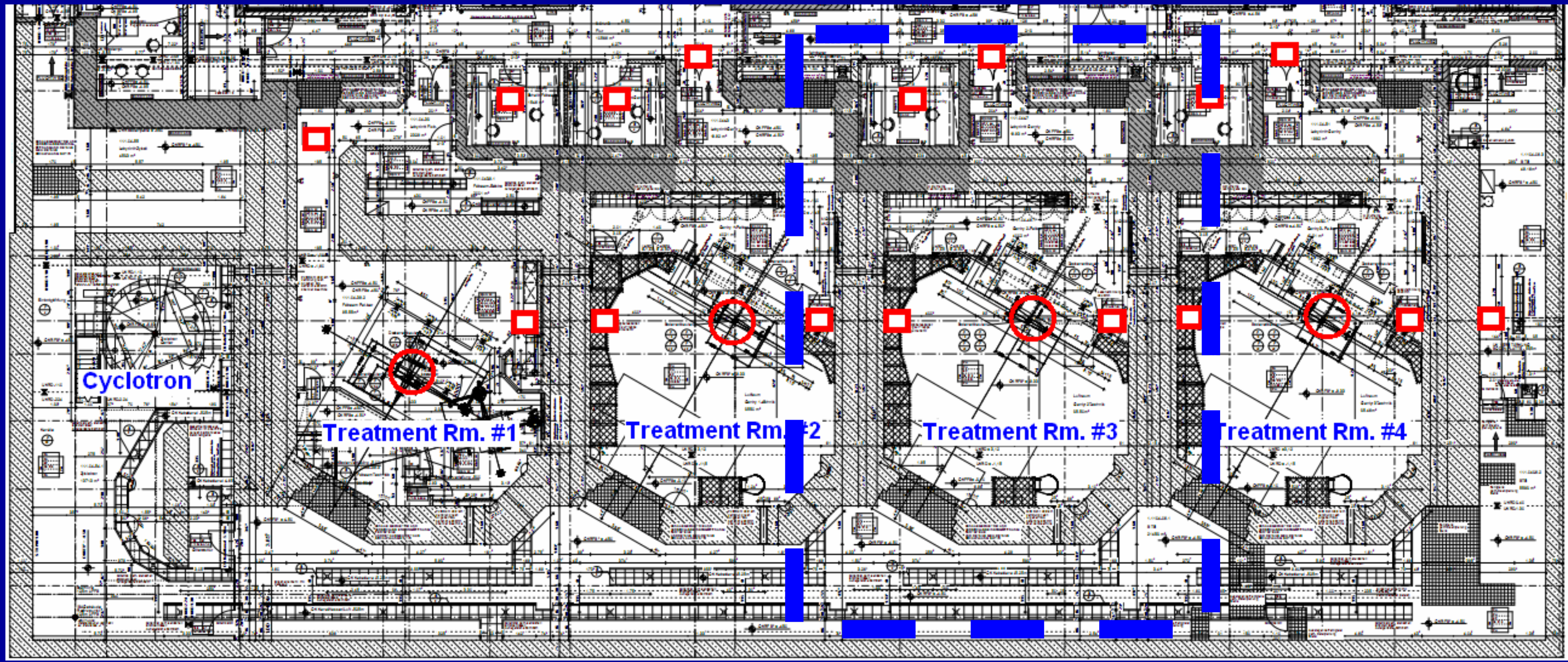
Validation of the Shielding Efficacy of the WPE Treatment Rooms housing Proton Irradiation Gantries.

In this Shielding Calculation we have used the well proven Deterministic Moyer Model

The Source Terms for this Shielding Calculation were derived from Experiments carried out under Clinical Conditions at PSI as well as FLUKA Simulations

Results to be confirmed by §5 and §46 of German StrSchV

Introduction



Footprint of the WPE Treatment Rooms and 230 MeV Proton Cyclotron

All four Treatment Rooms have basically the same physical dimensions

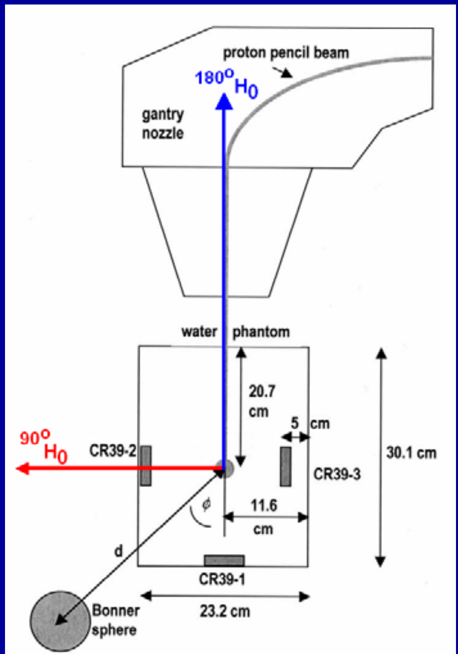
Therapeutic Proton beam delivered to one treatment room at a time

We have considered Treatment Room #3 for this Shielding Calculation

Neutron Source (circle) and Dose Calculation Points (rectangle) are indicated

Neutron Source Term

Neutron Dose Equivalent at Target => Shielding Calculation Kernel



Proton Irradiation Experiment at under Clinical Condition (Collaboration with PSI Switzerland)

177 MeV Pencil Beam Stopped in Water Target

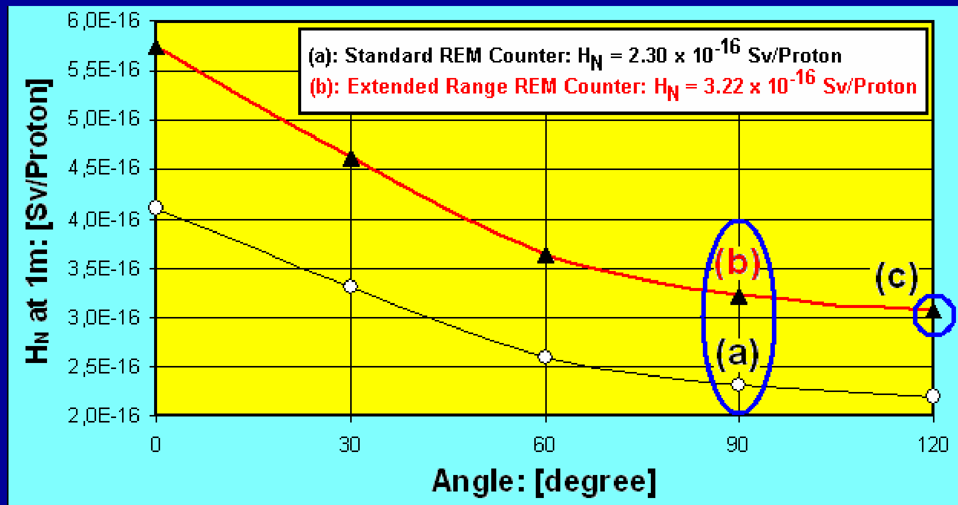
Neutron Dose Equivalent (DE) evaluated at different angles using a LB 6411 Neutron Rem Counter

Neutron DE at 1m measured at 0º, 30º, 90º and 120º are presented below: (a) standard LB 6411 Rem Counter, (b) corrected (x 1.4) corresponding to an extended range Rem Counter, (c) Extrapolated to 180º (reverse direction)

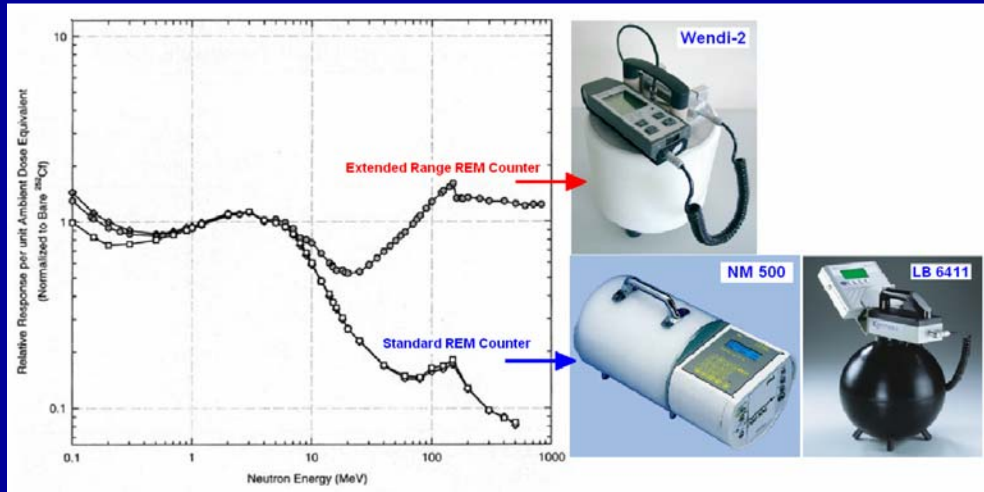
Source Terms calculated to be:

$^{90^o}H_0 = 7.25\ mSv.h^{-1}.nA^{-1}$
(Lateral Direction)

$^{180^o}H_0 = 6.24\ mSv.h^{-1}.nA^{-1}$
(Reverse Direction)



Notes on High-Energy Neutron Rem Counters

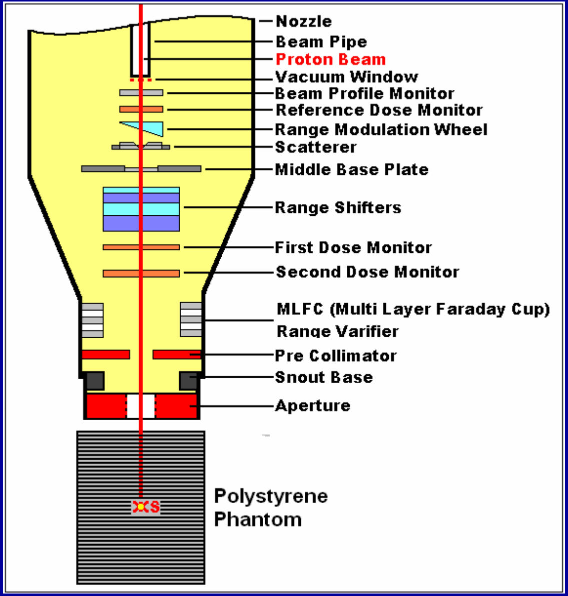


At higher (E_n > 10 MeV) neutron energies "Standard Rem Counters" (i.e. LB 6411 or NM 500) under response relative to "Extended Range Rem Counter" (Wendi-2).

At WPE high energy neutrons prevail. Hence, for Radiation Measurement and Dosimetry the usage of Extended Range Rem Counter (Wendi-2) becomes mandatory.

Attribute	NM 500	Wendi-2	LB6411
Detector	BF_3	^3He	^3He
Moderator	Polyethylene	Polyethylene & Tungsten	Polyethylene
Weight	11.5 kG	13.5 kG	11.5 kG
Gamma-Discrimination	Low	High	High
Detection Range	10 nSv.h^{-1} – 100 mSv.h^{-1}	10 nSv.h^{-1} – 100 mSv.h^{-1}	10 nSv.h^{-1} – 100 mSv.h^{-1}
Energy Range	0.025 eV – 10 MeV	0.025 eV – 5 GeV	0.025 eV – 10 MeV

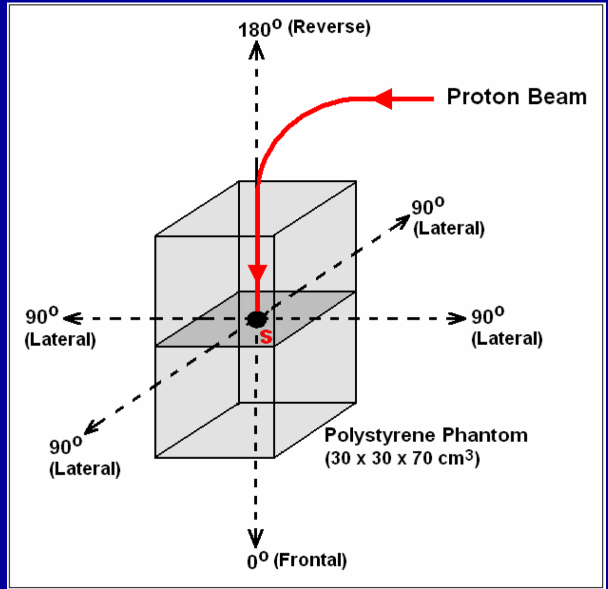
FLUKA Simulation of Neutron Source Term

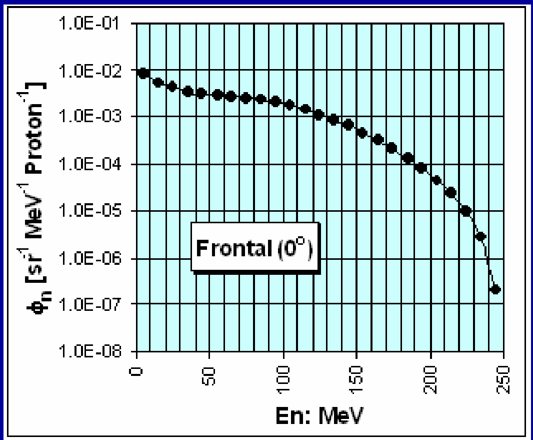


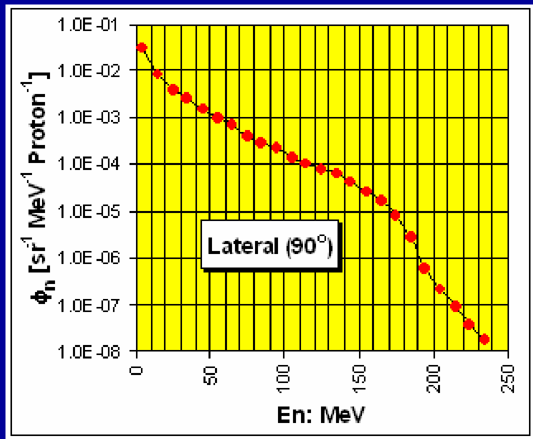
Irradiation Set up

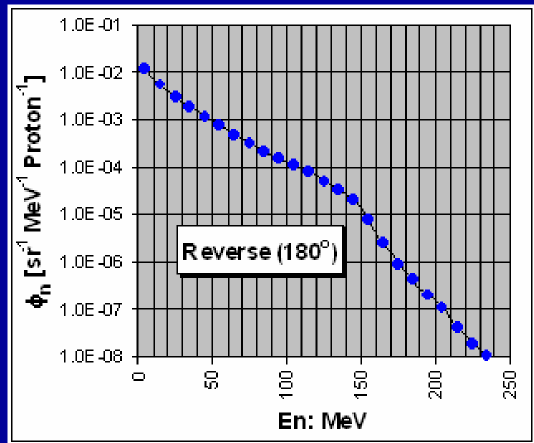
E_p = 230 MeV

FLUKA Model



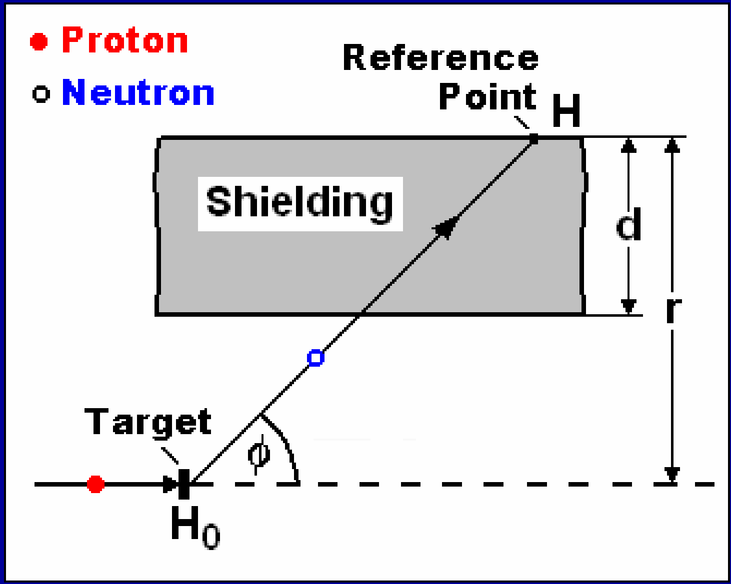






FLUKA Simulated Secondary Neutron Spectra (Source Term)

The Moyer Model for Shielding Calculation



Following Criteria to be fulfilled

Sufficiently thick shielding (d > 1m)

Point size radiation source (neutron producing Target)

Large Target to Reference point distance (r >> d)

Valid only for Neutron Shielding

Neutron Dose Equivalent at Reference Point is given as

(1) Lateral Direction

$H = {}^{90^o}H_0 (r/\sin\phi)^{-2} \exp(-d/\lambda \sin\phi)$

or, $H/{}^{90^o}H_0 = (r/\sin\phi)^{-2} \exp(-d/\lambda \sin\phi)$

(2) Reverse Direction

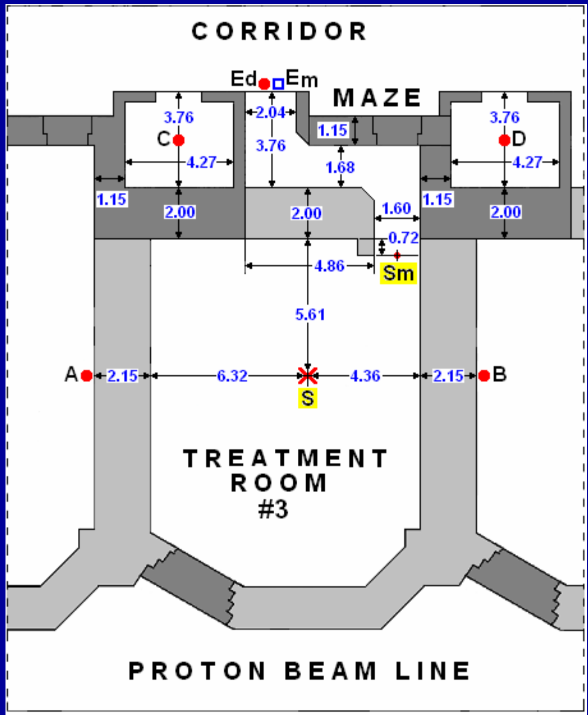
$H = {}^{180^o}H_0 (r)^{-2} \exp(-d/\lambda)$

or, $H/{}^{180^o}H_0 = (r/)^{-2} \exp(-d/\lambda)$

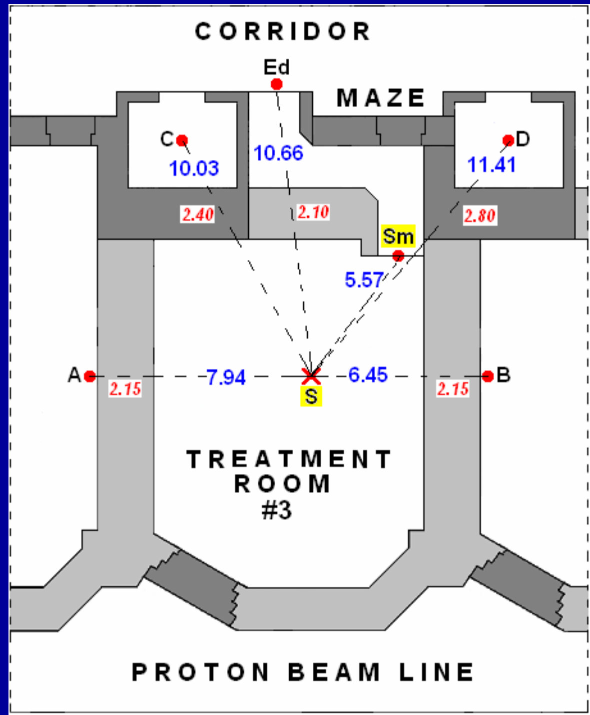
$H/{}^{90^o}H_0$ and $H/{}^{180^o}H_0$ are the Neutron Transmission Factors (Shielding Efficacy)

λ = Neutron Attenuation Length in Concrete (SLAC PUB 130339

Shielding Calculation (i)



Footprint of Treatment Room #3



Path Lengths "r/sinϕ" and "d/sinϕ"

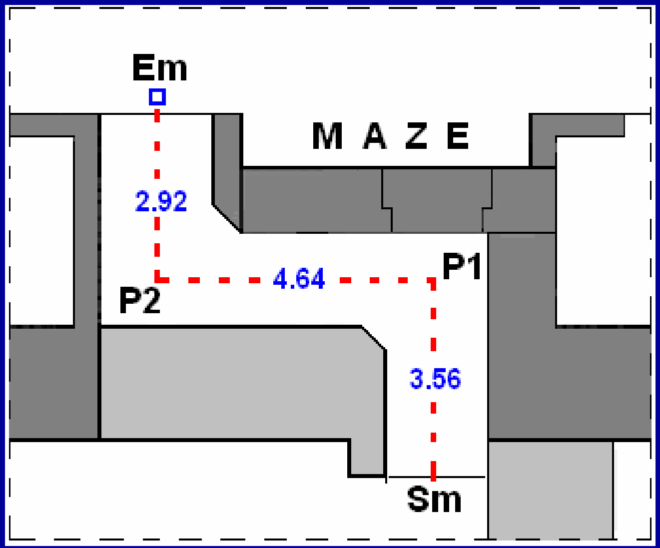
Shielding Efficacy at reference points A, B, C, D and E_d given as:

$H/^{90^o}H_0 = (r/\sin\phi)^{-2} \exp(-d/\lambda \sin\phi)$; Results are presented in TABLE 1

Neutrons transmitted along the 3 legged maze (Em) heve been calculated (next section)

Shielding Calculation (ii)

Neutron Attenuation through the Maze



Dimensions of the 2.6 m high maze. E_m and S_m represent the reference point and virtual radiation source respectively.

1st Leg: $H_1/H_0 = 0.98 \exp(-0.80 r_1/\sqrt{A}) + 0.2$

2nd Leg: $H_2/H_0 = 0.74 \exp(-10 r_2/\sqrt{A}) + 0.21 \exp(-1.6 r_2/\sqrt{A}) + 0.05 \exp(-0.54 r_2/\sqrt{A})$

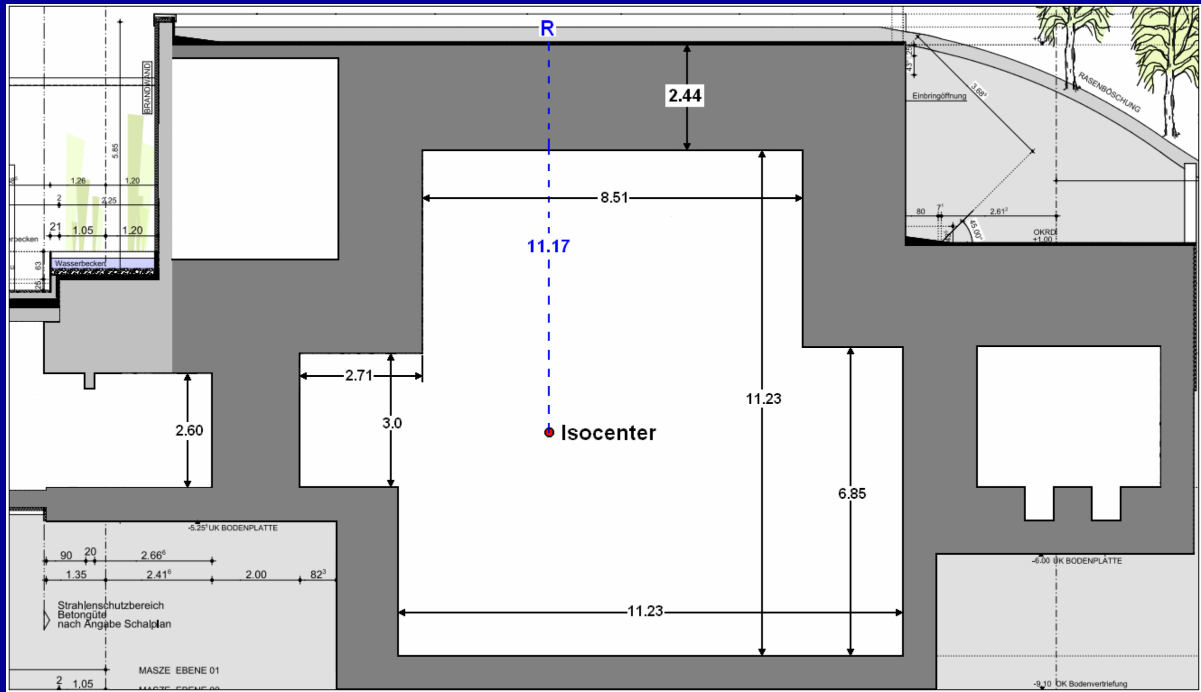
3rd Leg: $H_3/H_0 = 0.81 \exp(-3.8 r_3/\sqrt{A}) + 0.19 \exp(-0.70 r3/\sqrt{A})$

r_1, r_2 and r_3 represent the length of maze legs and A the cross section area.

Results are presented in TABLE 2

Shielding Calculation (iii)

Neutron Dose Equivalent at Roof



Vertical Cross Section of Treatment Room #3

Shielding Efficacy at reference point R (opposite to Isocenter) is given as

$$H/^{180^{O}}H_0 = (r)^{-2} \exp(-d/\lambda) \; ; \; r = 11.17m \text{ and } d = 2.44m$$

Results are presented in TABLE 1

Results

Location (Fig. 5a, b, c)	r/sin ϕ [m]	d/sin ϕ [m]	H/H_o
A	7.94	2.15	2.3×10^{-5}
B	6.45	2.15	3.6×10^{-5}
C	10.50	2.40	6.3×10^{-6}
D	11.41	2.80	1.6×10^{-6}
R	11.17	2.44	4.9×10^{-6}
Ed	10.66	2.09	2.6×10^{-5}
Em	n.a.	n.a.	4.1×10^{-5}
Ed + Em	n.a.	n.a.	6.7×10^{-5}

Table 1: Neutron path lengths "r/sinϕ", effective shield thickness "d/sinϕ" and neutron transmission factor "H/H_0" evaluated using Moyer Model. Neutron transmission factor at maze entrance is composed of direct component "E_d" and transmitted (maze) component "E_m" (s. Table 2).

Reference Points	Leg Nr.	r [m]	r/(A^0.5)	H/H_0
P1	1: (Sm – P1)	3.56	1.75	2.78×10^{-2}
P2	2: (P1 – P2)	4.64	2.27	5.61×10^{-4}
Em	3: (P2 – Em)	2.92	1.43	4.11×10^{-5}

Table 2: Showing the reference points along the maze, length of maze leg and the corresponding neutron transmission factor.

Worst Case Exposure Scenario

A 10 nA pencil proton beam (E_P = 177 MeV) completely stopped in a water target

§46 of StrSchV: Permissible Dose to Public is 1.0 mSv in 2000 hours per Year.

This corresponds to a Dose Equivalent rate of $H_{StrSchV}$ = 0.5 μSv.h^{-1}

Transmitted neutron DE rate (shielding efficacy) is compared to permissible DE rate according to §46 of StrSchV (TABLE 3).

Location	Description	H_{year} : mSv	$H_{year}/H_{StrSchV}$
A	At Treatment Room #2 wall	0.43	0.43
B	At Treatment Room #4 wall	0.65	0.65
C	Gantry Control Room (Left)	0.12	0.12
D	Gantry Control Room (Right)	0.03	0.03
R	At the Roof above target	0.08	0.08
E	Maze entrance Treatment Room #3	0.04	0.04

Table 3: Transmitted neutron Dose Equivalent Rate (worst case scenario) at selected reference points (Treatment Room #3) evaluated using Moyer Model. Results were compared to the permissible Neutron DE to public according to §46 of German StrSchV ($H/H_{StrSchV}$) and presented in Column 4.

Conclusions and Recommendations

We have validated the existing radiation shielding of the WPE Treatment Rooms for 177 MeV protons using Deterministic Moyer Model.

Highly conservative operational scenarios have been taken into account.

These calculations confirm the adequacy of the existing radiation shielding, applicable to locations outside the WPE treatment rooms and roof.

FLUKA simulations have been carried out for shielding calculation at the highest proton energy (230 MeV).

Experiments will be carried out at clinical environment at our facility to confirm the FLUKA results shortly.

We have developed a composite material of high attenuation capability for fast neutron shielding at future particle therapy facilities.

Recent activities of our group are highlighted in the APPENDIX

APPENDIX

European Cyclotron Progress Meeting (ECPM XXXVII)
Groningen, The Netherlands, 28-31 October 2009

Accepted Oral Presentations

B. Mukherjee, J. Farr, C. Bäumer and R. Hentschel. ***Radiation Shielding Design for Proton Therapy Treatment Rooms.***

B. Mukherjee, R. Hentschel, C. Bäumer and J. Farr. ***Monte Carlo Simulation of a Novel Composite Shielding for High-Energy Neutrons produced by Proton Therapy Cyclotrons.***

THANK YOU FOR YOUR KIND ATTENTION