Dosimetry and Quality Assurance Tools for Particle Therapy

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Abstract

In the latest years, particle therapy – i.e. proton and heavy ion therapy (especially carbon) is gaining recognition as a valuable therapy method due to the possibility to deposit the beam energy within a small determined target volume, while the energy imparted before the location of the Bragg peak has a low percentage compared to the total dose.

In order to be usable as a valid therapeutic tool, appropriate dosimetry and QA tools need to be developed. In comparison to the tools developed for photon and electron beams, a number of challenges have to be met, such as:

- High mechanical precision and small scanning increments are required, especially for depth dose measurements (e.g. 10 µm increments)
- High instantaneous dose rates are encountered, however, the radiation can be considered as *continuous* radiation

The paper presents a number of such dosimetry and QA tools developed by PTW, that allow an accurate in-beam dosimetry, beam analysis, finding of the Bragg peak, and it shows some results in determining the Bragg peak in proton and carbon ion beams.

Dosimetry & Quality Assurance Tools for Particle Therapy

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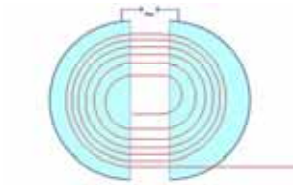
Classical Cyclotron



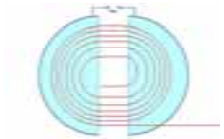
$$qvB = \frac{m_0 v^2}{r}$$ Lorentz force = centrifugal force

$$\omega = \frac{q}{m_0} B$$

$$E_{kin} = \frac{r^2 q^2 B^2}{2m_0} = \frac{m_0}{2} \omega^2 r^2$$

- Frequency ω independent on radius, can be kept constant
- Energy proportional to squares of radius and magnetic field
  → spiral gets narrower with increasing radius/energy
  → higher energies require greater r and B and therefore higher costs
- As r_{max} and ω are fixed for a specific cyclotron, only one energy for a given type of particle is possible
  → degrader required

Relativistic Cyclotron



$$\omega = \frac{q}{m} B$$

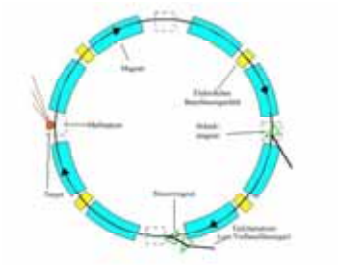
- As m increases with energy, either ω must be decreased, or B must be increased accordingly

- **Synchrocyclotron** ω is decreased, HF is synchronized with orbit time of particle
  → pulsed operation required
  Example: Still River Systems

- **Isochroncyclotron** B is increased with increasing r to keep B/m = const
  → continuous operation
  → requires spiral sectors with different B to focus the beam (Thomas Cyclotron, AVF - azimutally varying field)
  Examples: Varian/Accel 250 MeV p^+
  IBA 230 MeV p^+

Particle Accelerators

Synchrotron



$$\omega = \frac{v}{r} = \frac{q}{m} B$$

- Keep r constant to save iron in the magnets, increase ω and B by time

- Frequency and magnetic field are synchronized with particle speed
  - → pulsed operation required
  - → as $B(t)$ varies slowly spills are available only every 1 – 10 seconds
  - → variable energy

Examples: Siemens 220 MeV p^+ or 430 MeV/u ^{12}C
CERN 28 GeV p^+ at r = 70 m, 7 TeV p^+ at r = 4.3 km

Dosimetry measurements: What is so special ?

- High mechanical precision and small scanning increments are required, especially for depth dose measurements (e.g. 10 µm increments)
- High instantaneous dose rates are encountered, however, the radiation can be considered as *continuous* radiation

Absolute Dosimetry

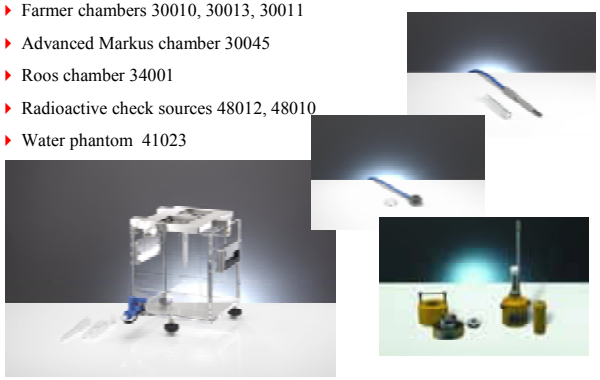
UNIDOS*webline* and Solid State Phantoms

- UNIDOS*webline* dosimeter with TCP/IP interface
- PMMA slab phantom type 40041 (25 x 25 x 27) cm³, with temperature sensor embedded in Farmer chamber plate
- RW3 slab phantom 29672 (30 x 30 x 30) cm³; 45° holding device
- Readout unit L981179 for phantom temperature and air pressure, with TCP/IP interface

Absolute Dosimetry

Ionization Chambers and Check Sources

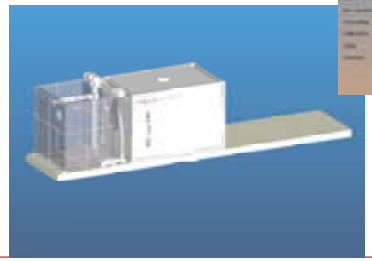
- Farmer chambers 30010, 30013, 30011
- Advanced Markus chamber 30045
- Roos chamber 34001
- Radioactive check sources 48012, 48010
- Water phantom 41023



Water Phantom

MP3-P Water Phantom and Reservoir

- Enhanced mechanical precision
- Measuring range (350 x 250 x 380) mm
- Entrance window (250 x 250 x 5) mm
- MEPHYSTO *mc²* software

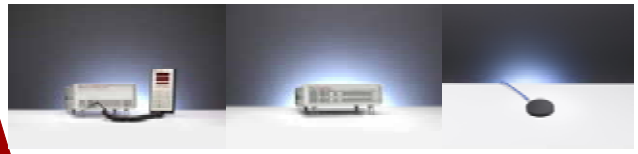


Designed for Siemens PT

Water Phantom

MP3-P Electronics and Chambers

- TBA Control Unit with Control Pendant
- TANDEM Dual Channel Electrometer
- Bragg Peak Chambers 34073 (Roos Type), 34070 (Standard) and 34080 (Thin Window)



Chambers 34073 used by DKFZ/GSI in Heay Ion beams

Water Phantom

Bragg Peak Chambers

- Types 34070 and 34080 for MP3-P measurements
- Type 34073 for MP3-P measurements in Heavy Ion beams
- Types 34080 and 34082 used in PEAKFINDER

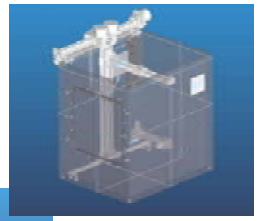
	Standard T34070	Roos-Type T34073	Thin Window T34080	Thin Window Monitor T34082
Volume	10.5 cm³	2.5 cm³	10.5 cm³	5.2 cm³
Outer diameter/height	104 mm/13 mm	68 mm/10.4 mm	104 mm/10 mm	80 mm/10 mm
Entrance window thickness	3.47 mm	1.13 mm	0.62 mm	0.62 mm
Exit window thickness	7.48 mm	1.46 mm	1.16 mm + 6 mm air	1.16 mm + 6 mm air
Electrode diameter	81.6 mm	39.6 mm	81.6 mm	57.6 mm
Electrode spacing	2 mm	2.013 mm	2 mm	2 mm
Chamber voltage	400 V	400 V	400 V	400 V
Waterproof	yes	yes	no	no
For use at different depths	yes	no	no	no

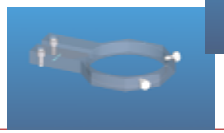
Chambers 34073 used by DKFZ/GSI in Heay Ion beams

Water Phantom

MP3-P Dual Chamber Holders

- L981422 for two Bragg Peak chambers 34073 *)
- L981423 for Bragg Peak chambers 34070 (field) and 34080 (reference) *)



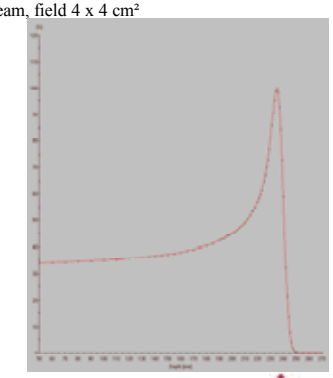


*) For use in horizontal beams only

Water Phantom

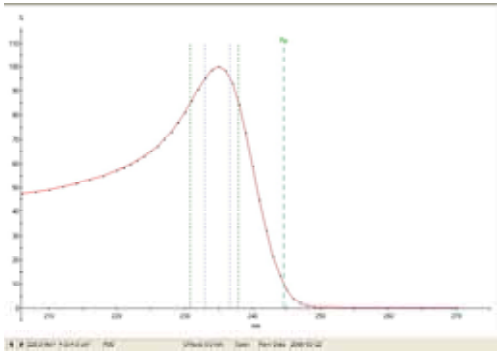
Bragg Peak Measurement Example

- Bragg Peak of 225 MeV proton beam, field 4 x 4 cm²
- MP3 system, Advanced Markus chamber, horizontal beam
- 1 mm increments
- Measured at MD Anderson, USA, March 2006



Water Phantom

Bragg Peak Evaluation



Water Column

PEAKFINDER

- Can be used in any spatial orientation, closed construction
- Measuring depths (20 … 360) mm, diameter 100 mm
- Spatial resolution 10 µm, accuracy 100 µm, ≤ 10 mm/s
- Servo control unit with feed-back system for positioning check
- TANDEM Dual channel electrometer, Gate input for spill-by- spill measurements
- PeakScan software

Water Column

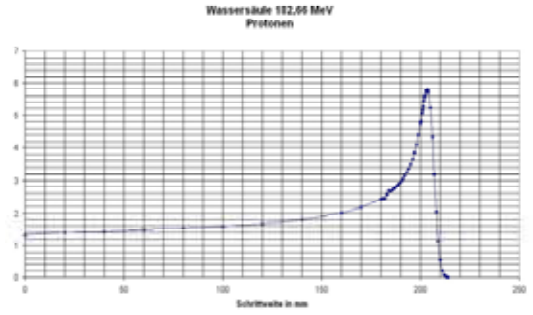
PEAKFINDER w/o Cover

- Built-in thin window Bragg Peak chambers T34082 (Monitor) and T34080 (Field)
- Column windows 3 mm Quartz glass

Water Column

Bragg Peak Measurement Example

- measured with PEAKFINDER
- by Siemens PT at HIT, Heidelberg, May 2007



Water Column

Bragg Peak Measurement Example

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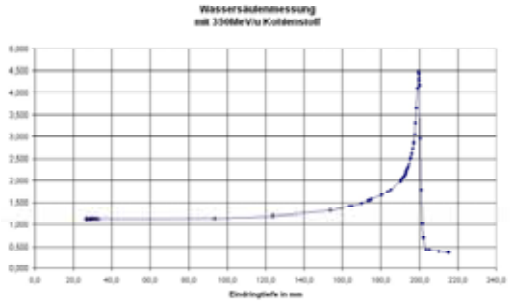
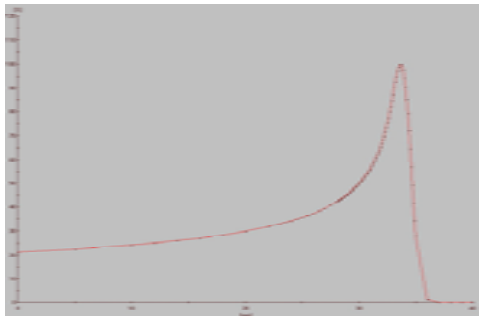


Water Column

Bragg Peak Measurement Example

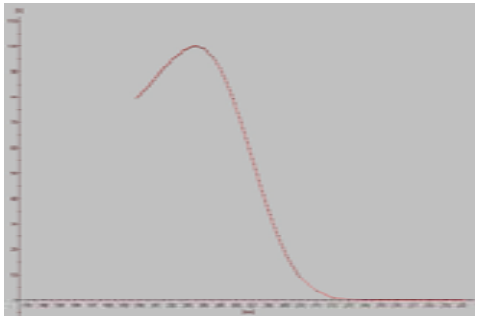
- protons measured with PEAKFINDER, 0.1 mm increments in peak area
- by HIT, Heidelberg, preliminary raw data, August 2007



Water Column

Bragg Peak Measurement Example

- protons measured with PEAKFINDER, 0.1 mm increments
- by HIT, Heidelberg, preliminary raw data, August 2007

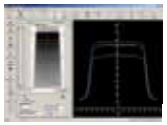


Film Dosimetry

Film Scanner and Holder

- Digital film scanner EPSON 10000XL, A3 format
- FilmAnalysis software for MEPHYSTO *mc²*
- Holder 40040 for X-Omat V films (265 x 325) mm²; optional 45° holding device



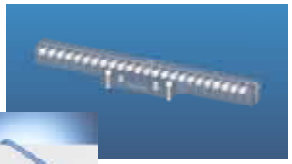


Holder designed for Siemens PT

1D Dose Distribution

MULTIDOS with 12 PinPoint Chambers

- MULTIDOS 12-channel electrometer, with detector connection box
- Linear Detector Holder, mounts to MP3-P system, holds up to 24 PinPoint chambers (0.03 cm³, T31015), covers 250 mm measuring length

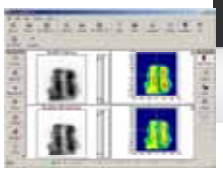
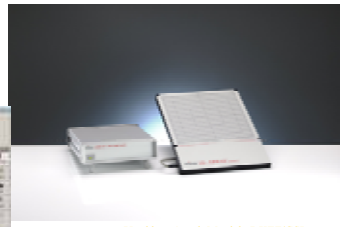



Holder designed for Siemens PT, no software provided by PTW

2D Dose Distribution

2D-ARRAY *xdr*

- 729 vented ionization chambers, 27 x 27 field size
- dynamic range adapted to high dose rates (1 … 100 Gy/min)
- extended high voltage (900 V) for better saturation
- VeriSoft software

Used by: Accel, Munich, DKFZ/GSI
Tested at: PSI Villigen, HMI Berlin

3D Dose Distribution

MULTIDOS with 3D Detector Block

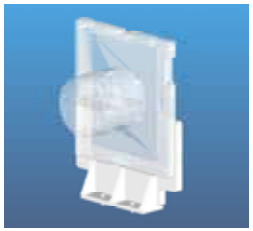
- MULTIDOS 12-channel electrometer, with detector connection box
- 3D Detector Block, mounts to MP3-P system
- Holds up to 24 PinPoint chambers (0.03 cm³, T31015)
- Detector spacing 10 mm and 12 mm

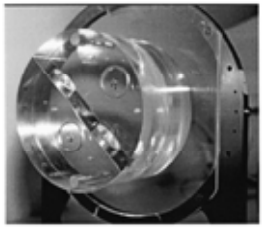


Used at GSI (Jäkel, Hartmann et al), no software provided by PTW

Positioning Phantom

- PMMA phantom type 43029 (150 mm diameter, 150 mm height), with internal markers
- Checks positions in digital images (DRR, CT, MR) versus laser coordinates

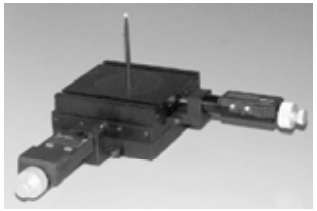




Used at GSI (Jäkel, Hartmann et al)

Sphere with Micrometer Drives

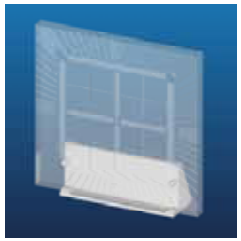
- 2 mm sphere, adjustable in 1 µm increments; optional 5 mm sphere with adjustment cube
- Checks isocentric rotation of treatment couch
- Checks isocentric beam position at different energies
- Radiation shadow is monitored by film

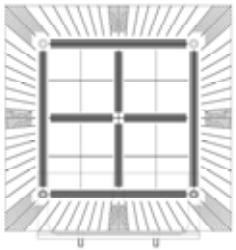


Used at GSI (Jäkel, Hartmann et al)

Robot Calibration Plate

- Accuracy of engravings 0.1 mm
- Checks congruence between laser positions and robot coordinate system
- Checks linear and angular scales

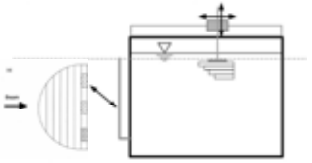




Designed for Siemens PRT

Inhomogeneity Phantom

- PMMA phantom, 200 mm in diameter
- 11 inhomogeneities, diameter 20 mm, length 10 mm. Densities from 0.001 … 1.82 g/cm³
- Adaption plate for up to 24 PinPoint chambers
- Can be mounted to entrance window of MP3-P water tank for measurements with the 3D detector block
- Checks the system's ability to irradiate inhomogeneous targets



Used at GSI (Jäkel, Hartmann et al)

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Finnaly finished, everyone can breathe

Thank you!