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Precise On-line Position Measurement for Particle Therapy
Introduction
Radiation and particle therapy

PSI Facility
Gantry 2
Spot scanning technique

Ionization Strip Chamber as on-line beam position monitoring and QA tool

Beams at Gantry 2 and Reconstruction Methods

Operation Stability

Conclusions & Outlook
Radiation therapy

Relative irradiation dose

- **18 MeV photon**
- **250 MeV carbon**
- **135 MeV proton**
- **Tumor**

The depth beneath the skin (CM)

Bragg peak

Picture from: Front.Med. doi: 10.1007/s11684-012-0196-4
Radiation therapy: Why charged particles?

- Bragg peak
- 18 MeV photon
- 250 MeV carbon
- 135 MeV proton
- Tumor

Relative irradiation dose vs. The depth beneath the skin (CM)

- Low entrance dose
- Narrow peak (few mm)
- Depth of penetration depends on the proton’s energy
- “No” exit dose
Superconducting cyclotron
Varian, 250 MeV

First spot scanning Gantry worldwide
In operation since 1996

Ocular tumors
OPTIS1 (1984-2010)
OPTIS2 since 2010

Fast energy change for volumetric repainting
Extend to new clinical indications
Parallel Lateral Scanning
- T sweeper magnet 2 cm/ms
- U sweeper magnet 0.5 cm/ms
- Scan area 20 x 12 cm
- Field patching for larger fields
Energy
- Degrader based energy change within < 100 ms
  merit of optimized magnets and power supply
- Energies from 70 to 230 MeV
  (corresponding range 4.3 - 33 cm)
- Dose down to 5e05 protons per spot

Parallel Lateral Scanning
- T sweeper magnet 2 cm/ms
- U sweeper magnet 0.5 cm/ms
- Scan area 20 x 12 cm
- Field patching for larger fields
Beam Position Precision Requirements

**Longitudinal** accuracy (depth) depends on beam energy uncertainties.

- 1 MeV at high energy → 2 mm in range → ~5% in dose variation

**Transverse (lateral)** accuracy depends on spot position, grid and size.

- Spot shift: large dose inhomogeneity > 5% for 1 mm shift

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**The goal to deliver dose homogeneity of ~1% require:**

- Longitudinal accuracy better than 2mm
- Lateral accuracy at sub-millimeter level
Tool for on-line lateral position and dose monitoring

Dose Monitors:
Ionization Chambers (0.5,1 cm, air gap)

Position Monitor
• Choice is based on Gantry 1 experience
• No aging effect (~ 20y experience Gantry 1)
• Stability and flexibility in operation
• (Sub-)optimal material budget (technical limitations)

Beam broadening due to multiple scattering

Spot Size at patient location

Aim: small spot size
Tool for on-line lateral position monitoring

Read-out
- 16 bit TTL digital output
- 10 MHz digital count frequency
- 200 fC Quantum of charge

\[ t = \frac{d^2}{\mu*V_a} \]

\( \mu = 1.4 \) (dry air) is the mobility of charged particles in the electric field

\( V = 1800 \) V applied HV

\( d = 1 \) cm air gap

Since 2009 commercialized by

2 TERA06 chips
- 128 channels each

0.2 \( \mu \)m Mylar foil

1 cm air gap

T-anode 88 channels / 2mm

U-anode 128 channels / 2mm
- 50 \( \mu \)m kapton foil
- with 17 \( \mu \)m Cu electrodes

One 2-sided Al cathode
On-line Signal Readout Process

Signal collection
ADC
Front-end electronics
Back-end

Spot
Beam ON
100us - ~ min
Goal < 2 ms

1ms
100 µs
~1ms

Dose Element
Charge collection

Data logging & verification

TERA dse
SB

TERA DSE System Serializer Board(SB) FPGA

High Speed Optical link

PMC
CPU

COG Reconstruction
Position visualization
Save Data

OK
NOK
Continue
ILK
On-line Signal Readout Process

Signal collection ➔ ADC ➔ Front-end electronics ➔ Back-end

Signal collection

100us - ~ min

Goal < 2 ms

1ms

100 µs

~1ms

Dose Element

Charge collection

Data logging & verification

TERA DSE System Serializer Board(SB) FPGA

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Save Data

OK

NOK

Continue ILK
Integrated Quality Assurance

Therapy Verification System

Single LogFile with on-line reconstructed mean, sigma and integral for each dose spot

Optional for QA

Full profiles logging for Nozzle and additional Strip or MiniStrip chamber mounted at ISO for

- DailyQA
- Sweeper maps
- Back projection

MiniStrip Chamber
7x7 cm active area
32 channels/side
0.22 cm spacing
### Signal Reconstruction Algorithm(s)

**COG algorithm**
- Fast enough for on-line reconstruction
- Implemented in a FW
- Sensitive to noise/spikes
- Reconstruction uncertainties at the detector edge

**Gaussian Fit**
- More precise position calculation
- Robust for events at the detector edge
- Less sensitive to noise
- Time consuming
- Implemented only in SW

#### 80 MeV U-beam profile at ISO

<table>
<thead>
<tr>
<th>Channel number</th>
<th>Counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>80</td>
<td>0</td>
</tr>
<tr>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>120</td>
<td>0</td>
</tr>
<tr>
<td>140</td>
<td>0</td>
</tr>
</tbody>
</table>

**Cut-off**

- **ROI min**
- **ROI max**

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**Data**

**Gaussian Fit**
Gantry 2 beams: signal amplitude

150 MeV beams of various dose

Counts

Channel number

SNR still acceptable for lowest dose signal
⇒ can be reconstructed for all energies and pre-absorber positions

Preabsorber position

• Dose can be varied over 4 orders of magnitude
• Signal-to-noise ratio is important for low weighted spots

6e05 protons beams of various energies

Counts

Channel number
Gantry 2 beams: spot size without preabsorber

Beam Profile 70MeV - 230 MeV

Signal normalized to 1

σ = 2.5-5 mm

1 cm

27 cm

70 cm

Iso-center
Gantry 2 beams: spot size with preabsorber

Beam Profile 70MeV - 230 MeV

- 230 MeV
- 210 MeV
- 190 MeV
- 170 MeV
- 150 MeV
- 130 MeV
- 110 MeV
- 90 MeV
- 70 MeV

Signal normalized to 1

Channel number

Influence of preabsorber on beam size at different distances:

- 1 cm
- 27 cm
- 70 cm

Unaffected iso-center
Stability of the signal

Data sample:
- Energies 230-70 MeV 10 MeV step
- Dose 2e08 – 6e05 protons
- 100 repetitions / each combination

- Position reconstruction is highly reproducible
- Overall lateral position reconstruction fluctuation 0.17 < mm if fit is used
- For GOG reconstruction max fluctuation < 0.2 mm

Fulfill requirements also for lowest weighted spots
Stability of operation

- Gantry 2 is in clinical operation on **November 27, 2013**
- Daily verification of the beam position was performed using mini strip-chambers at ISO:
  - at different gantry angles
  - all clinically used energies
- Detector alignment is uncertainty ~ 0.5 mm
Conclusions

- The strip ionization chambers have proven to be an appropriate on-line verification and QA tool for the scanning proton beam therapy system
- Device has demonstrated an efficient and extremely stable operation over several years
- Sub-optimal material budget allow low multiple scattering which especially important for protons
- Efficient readout electronics (however, physics is still a limiting factor)
- The system demonstrates a sub-millimetre precision of the lateral position reconstruction even for lowest dose

Dose homogeneity of better than 1% guarantee a highest patient treatment quality
Higher dynamic in scanning will require new hardware developments:

Detector optimization possibilities
- Air gap optimization for faster transmission $\Rightarrow$ smaller signals challenge
- Lighter material for electrodes
- Optimal detector strip size
- Using gas instead of the air (e.g. Nitrogen) to increase charge mobility
## Proton vs Carbon

<table>
<thead>
<tr>
<th>Proton Advantages over Carbon</th>
<th>Proton Beam Therapy</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Lower cost</td>
<td></td>
</tr>
<tr>
<td>• Able to be delivered via gantry, allowing multiple beam angles</td>
<td></td>
</tr>
<tr>
<td>• More narrow range of RBE (1-1.1) and greater certainty leading to smaller variations in actual delivered dose.</td>
<td></td>
</tr>
<tr>
<td>• Decreased risk of late normal tissue damage due to lower RBE.</td>
<td></td>
</tr>
</tbody>
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<tr>
<th>Carbon Advantages over Proton</th>
<th>Carbon Ion Therapy</th>
</tr>
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<tbody>
<tr>
<td>• RBE is similar to photon radiation and increased tumor control would not be expected.</td>
<td>• Higher RBE particularly at distal edge of Bragg peak which may permit greater tumor control.</td>
</tr>
<tr>
<td>• Larger lateral penumbra which can cause greater dose to normal tissue structures than carbon ion.</td>
<td>• Smaller lateral penumbra which may permit a more conformal dose laterally and limit normal tissue damage.</td>
</tr>
</tbody>
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<tr>
<th>Similarities of Proton and Carbon</th>
<th>Both proton and carbon ion limit the integral dose and therefore are predicted to reduce the risk of secondary malignancies over photon therapy, particularly in the pediatric population.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Both proton and carbon ion research is limited, largely consisting of small series of patients where definitive conclusions are difficult to make.</td>
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</table>
Strip Chamber Read-out

TERA DSE System

- TERA DSE Board
  - Power distribution
  - SB Power
  - DSE Power
  - Board Config
  - DAC
  - Analog
  - Digital
  - PlugIn
  - SERDES interface
  - Serial LVDS

- Serializer Board
  - FPGA
  - Virtex PRO
  - XC2VP4
  - Rocket IO

- High Speed Optical Communication

- FPGA IO interface

TERA 06 Board

- Analog Current Inputs
  - TERA 06
  - Reserved for other sensor inputs

- TERA Interface board
  - LabView readout system
  - Serial LVDS
  - ILK signals

- LabView readout system

- Digital

- DAC

- Analog

- ADC

- Reserved for other sensor inputs

TVS

- VME bridge

- FPGA IO

- FPGA

- Virtex-5 Xilinx

- Alpha Data

- PMC1

- PMC2

- Verification Board (VB)

- FPGA IO interface

- PCI path

- 3.3V

- 5V

- Slot 1

- Slot 2

- VME erate

Oxana Actis, Position Sensitive Detectors Conference, 7-12 September 2014, Surrey UK
Photons vs Protons

(a) 

(b) 

Dose [Gy]

Dose [CGE]