Proton Accelerators for Therapy & Imaging

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Why protons? Why now?
Protons are much better than X-rays

Scan the energy to make a Spread Out Bragg Peak (SOBP) that spans the tumor

Most dose is deposited in the sharp "Bragg Peak", with no dose beyond

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 NSS/MIC, Nov 13, 2002
Conventional X-ray gantries are "small"

Almost all of it is visible in this photograph!
Proton gantries appear similar to the patient

But there is a lot more "behind the wall"

Paul Scherrer Institute (PSI), Zurich
It's much harder to bend 250 MeV protons

And the strong-back to hold 1 mm tolerances is formidable

Massachusetts General Hospital (MGH)
Where are the facilities? When?
High and low patient throughput

Loma Linda and MGH (hospital based facilities) lead the world in high patient throughput.

The state-of-the-art is also being pushed in facilities at national labs with low throughput.
**PSI (Zurich)** (left)
- cyclotron source
- part of a national lab
- upgrade in progress
- low throughput, high tech
- new facility in progress

**GSI (Darmstadt)** (not shown)
- synchrotron
- national lab
- Carbon-12
- new facility at Heidelberg?
Loma Linda (California)
- synchrotron source
- built/commissioned at Fermilab
- world leading patient throughput

MGH (Boston)
- cyclotron source (IBA)
- 1st patient Nov 2001
- coming up to speed
There is a national program in Japan to build proton (and Carbon-12) facilities.
Many sites are (considering) entering the field

Including:

- Karolinska (Stockholm)
- MD Anderson (Houston)
- "TERA" sites (Europe)
- U. Penn (left)
- U. of Florida (Gainesville)
How is BNL involved?

Rapid Cycling Medical Synchrotron (RCMS)
BNL/ACCEL/AES/U. Penn(Physics)

RCMS is a second generation synchrotron
- rapid cycling (30 Hz)
- strong focusing
- fast extraction
- ultimate flexibility
The continuous upgrade path to precision 3-D multi-field irradiation of cancerous tumors
Traditional irradiation: PASSIVE SCATTERING

The sole (slow) variation: beam energy \(\rightarrow\) depth
Contemporary irradiation: ACTIVE SCANNING

Three variables:
- H & V steering
- energy

Although "simpler", active scanning has a higher controls burden

Hybrid schemes are also practical (PSI, left)
- 1.5 D steering
- range shifter
Active scanning - a much improved 3-D conformal dose

(Patient treatment demos courtesy of PSI)
The basic principles of overlapping doses are simple (and surprisingly effective) ...

... although fully realistic Patient Treatment Planning is a complex software challenge ...

Fourth dimension: intensity (left)

Fifth dimension: field angle (over)
Multiple angles with a water "phantom"

One angle

360 degrees

60 degree coverage

Ultra-low level collateral radiation with protons ...

... if ultimate multi-dimensional flexibility can be achieved!
A treatment planning example (Goitein et al, "Physics Today", Sept '02)

1 field, passive scattering  
POOR

3 fields, passive  
Target outlined in yellow  
Critical structures in red

1 field, active, uniform dose  
3 fields, active, uniform dose  
GOOD

1 field of 3, active, intensity modulated  
3 of 3 fields, active, intensity modulated  
Bottom right is much better than top left!
Technology choices
Which particle?

Some facilities favor light ions, eg Carbon or Neon

- better clinical results?
- sharper Bragg peak
- "knock-on" nuclear fragments
- require MUCH more magnetic field for same penetration depth
Cyclotron or Synchrotron source?

A facility with a synchrotron source looks much like one with a cyclotron source (to a bird)

- similar cost ~ $10 million
- modest fraction of total

But the technical comparison goes beyond just "simplicity vs flexibility" ...
Modern cyclotron features
(ACCEL superconducting cyclotron for RPTC, Munich)

Fixed energy output, at constant current

- Energy degrader reduces the energy
- Collimators scrape the beam
- Large "intrinsic" beam size (emittance) in all 3 dimensions
Modern synchrotron features
(Rapid Cycling Medical Synchrotron, RCMS)
(see Cardona et al, N5-5)

Accelerate variable amount of beam to a variable energy output

- No energy degrader
- Small intrinsic beam size

Accelerate EITHER

- a little beam often, extract in 1 turn
- a lot of beam rarely, extract slowly in many turns
Rapid cycling - energy flexibility

- permitting ultimate energy flexibility
- discrete low intensity beam delivery
- intrinsic safety!

RCMS "rings" like a transformer.
Flexible beam size at patient

Small emittances (with synchrotrons)
- small transverse beam size
- small beam pipes
- small cross section magnets
- light gantries
- flexible spot size at the patient (eg, factor of 10)
<table>
<thead>
<tr>
<th></th>
<th>Synchrotron</th>
<th>Cyclotron</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy flexibility</strong></td>
<td>Very high (fast extraction)</td>
<td>Fixed (needs degraders)</td>
</tr>
<tr>
<td><strong>Typical diameter</strong></td>
<td>7 m</td>
<td>4 m</td>
</tr>
<tr>
<td><strong>Power consumption</strong></td>
<td>Low</td>
<td>High (except supercon.)</td>
</tr>
<tr>
<td><strong>Typical beam size</strong></td>
<td>1 mm</td>
<td>10 mm</td>
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<tr>
<td><strong>Typical energy spread</strong></td>
<td>&lt; 0.1%</td>
<td>~ 0.5%</td>
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<tr>
<td><strong>Beam intensity</strong></td>
<td>High</td>
<td>Very high</td>
</tr>
<tr>
<td><strong>Beam delivery efficiency</strong></td>
<td>&gt; 95%</td>
<td>1% – 95%</td>
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<tr>
<td><strong>Complexity</strong></td>
<td>Flexible</td>
<td>Simple</td>
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<tr>
<td><strong>Weight</strong></td>
<td>Light</td>
<td>Massive</td>
</tr>
<tr>
<td><strong>Approximate cost</strong></td>
<td>10 M$</td>
<td>10 M$</td>
</tr>
<tr>
<td><strong>Other costs</strong></td>
<td>Lower</td>
<td>Higher</td>
</tr>
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</table>
Proton Imaging:

- proton driven PET
- proton radiography  \(< 500\) MeV)
- proton movies  \(\text{(multi GeV)}\)
Proton driven PET

A small but significant fraction of proton dE/dx loss is due to nuclear interactions, some of which generate positron emitters.
Is the (high) therapy dose going to the right place?

Occasionally a proton generates an $^{15}\text{O}$ isotope ...

... that decays by emitting a positron ...

Place a PET camera on the gantry to observe where such nuclear interactions occur

Nuclear cross sections vary rapidly with energy ...

Interesting work is also going on with C-12 driven PET, eg at GSI

(see Parodi et al, M7-53)

... which annihilates with an electron
Proton Radiography

The protons go through the patient
Higher energy, small dose

Radiograph of a phantom
Uwe Schneider PhD thesis (PSI)
The PSI therapy gantry, with prototype detector in place
Multiple scattering!

Historically, proton radiography was rejected because multiple scattering made blurry images.

Modern reconstruction algorithms can make sharp images ... 

... with knowledge of incoming and outgoing displacements and angles.
How might such a detector be implemented?

see

- Sadrozinski, M2-1
- Sadrozinski et al, M6-2
- Yoshida et al, N22-3
Modern techniques appear to promise ultra-low dose CT!

![Graph showing transmission vs depth]

The very steep slope of transmission vs depth allows high sensitivity with few protons...

...at especially low dose since the Bragg peak is outside the patient.

Energy flexibility is desirable...

...but is mitigated by the use of a "distal bow tie"

(see Satogata et al, M10-204)
Proton Movies (multi-GeV)

Lensing system (4 to 24 GeV) in place at BNL - not on a gantry!
Proton radiograph with a multi-GeV beam (Los Alamos)

Sub-millimeter resolution
Stills from a movie of a mock "device" imploding (Los Alamos)

Can also see combustion fronts inside gasoline engines, ramjets, ...
Summary

1) First generation proton therapy facilities are now "proven" technology

2) They are one (or more) orders of magnitude more complex, and expensive, than conventional (electron/photon) facilities

3) Second generation proton therapy accelerators are arriving in force

4) For a few dollars more, put proton imaging on a gantry?
   a) proton driven PET       high therapy dose QA
   b) radiography            low dose CT

5) What does the optimal radiography detector look like?