Proton Therapy & Proton Imaging

Steve Peggs, BNL
Contents

**Proton Therapy**

Why protons? Why now? Where?
Precision 3-D multi-field irradiation of cancerous tumors

**Proton Imaging**

Proton driven PET
Proton CT
Transient devices: PRAD movies
Periodic CT = pCT + PRAD ??
Why protons?  Why now?  Where?
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
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)
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
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?
There is a national program in Japan to build proton (and Carbon-12) facilities.

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The continuous upgrade path
to
precision 3-D multi-field irradiation
of cancerous tumors
Traditional irradiation: PASSIVE SCATTERING

The sole (slow) variation: beam energy -> 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)
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

Target outlined in yellow

Critical structures in red

3 fields, passive

Bottom right is much better than top left!

1 field, active, uniform dose

1 field of 3, active, intensity modulated

3 of 3 fields, active, intensity modulated

POOR

GOOD
Proton Driven PET
Nuclear cross sections matter, and are useful!

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 $^{15}$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 (Parodi et al)

... which annihilates with an electron
Include a PET camera like this (at BNL) in a gantry room for best possible coregistration of tumor and beam.

Preliminary studies are under way at PSI (also with Carbon-12) and at BNL.
Proton Computed Tomography - pCT
The "pCT" collaboration is forming (?)
- BNL
- Loma Linda
- UC Santa Cruz
- Stony Brook

First meeting/workshop - Thurs/Fri Jan 9 & 10

The BAF beamline appears to be an ideal location for pCT R&D!
Use of Proton Beam CT: Treatment Planning

Range Uncertainties (measured with PTR)

- > 5 mm
- > 10 mm
- > 15 mm

X-ray CT use in Proton Cancer Therapy can lead to large Uncertainties in Range Determination


Alderson Head Phantom
Prototype detector at PSI

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, based on scintillating fiber technology (U. Schneider et al)
Low Contrast in Proton CT

Inclusion of 1cm depth at midpoint of 20cm H₂O

<table>
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<th>ρ [g/cm²]</th>
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Modern techniques appear to promise ultra-low dose CT!

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'

(Satogata et al)
Development of Proton Beam Computed Tomography

Collaboration
Loma Linda University Medical Center – UC Santa Cruz

- **Exploratory Study in Proton Radiography**
  - two x-y detector modules
  - Crude phantom in front

- **Theoretical Study**
  - GEANT4 MC simulation
  - influence of MCS and range straggling
  - importance of angular measurements
  - Optimization of energy

- **Experimental Study in pCT**
  - Three or four x-y Si planes
  - water phantom on turntable
Proton Energy Measurement with LET in Si

Simple 2D Silicon Strip Detector Telescope built
for Nanodosimetry (based on GLAST Design)

2 single-sided SSD
194um Pitch
400um thick
1.3us shaping time
Binary readout
Time-over-Threshold TOT
Large dynamic range
Measure particle energy via LET
Image!

Subdivide SSD area into pixels
1. Strip x strip 194µm x 194µm
2. 4 x 4 strips (0.8mm x 0.8mm)

Image is average energy in pixel
MC: Loss of Resolution in Back

First Plane, 2cm behind Object

Second Plane, 30cm behind Object: Fuzzy
MC: Use Angular Information

Effect of Angular Cut: Energy more uniform

- Less Migration
- Sharp edges (RMS and Energy)

\[ \theta \approx \text{MCS angle} \]

Hit Profile before angle cut

Hit Profile after angle cut

Imaging with MCS Angle?
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.
What should a pCT imager (on a gantry) look like -- technology choice(s) ???

- scintillating fiber?
- Silicon strips?
- GEM?
- good energy resolution?

Proton imaging spectrometer

Multiple planes of silicon for position, angle, and energy measurements
Transient devices: PRAD movies
Los Alamos beam-lines at Lansce & BNL

Add magnetic lenses - but not on a gantry (4 GeV to 24 GeV!

Double cuts on multiple scattering angles (at Fourier planes) enable crude material ID!
Proton radiograph with a multi-GeV beam (Los Alamos)

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

Can also see combustion fronts inside gasoline engines, ramjets, ...
The dependence of nuclear interaction length on Z also enables crude material ID in transmission measurements.
Periodic CT = pCT + PRAD ??
The PRAD folk are exploring "civilian, periodic" systems:
- gasoline engines
- jet engines

This is a new regime that appears to benefit greatly from a hybrid approach
- higher energies than medical
- with magnetic lenses & spectrometers
- with proton-by-proton tracking
PRAD features, in the past:
   - fast extracted beams
   - transient movies (few frames, microsecond time scale)
   - transmission (intensity) measurements
   - for material identification, play off
     1) nuclear interaction lengths
     2) multiple scattering
     3) Fourier plane imaging/collimation

Periodic high energy CT movies:
   - "slow" periodic systems (10,000 rpm?)
   - slow extracted beam (NOT U-line, not BAF?)
   - benefits from proton-by-proton tracking:
     1) virtual collimators (better MCS material ID)
     2) energy measurements (easier than medical!)
     3) many more (unique!) CT movie frames
     4) same modeling/algorithms as medical pCT

Watch this space -- any comments?
Summary

1) First generation proton therapy facilities are "proven" technology. Second generation therapy accelerators are arriving in force.

2) For a few dollars more, put proton imaging on a gantry
   a) proton driven PET: high therapy dose QA
   b) proton CT: low dose CT, treatment planning

3) What does the optimal "proton Computed Tomography"
detector look like? Silicon? GEM? Scintillationg fibers?

4) How to measure proton energies accurately?

5) There appears to be an exciting field in "CT movies" for periodic mechanical systems, by hybridizing pCT and PRAD technologies!