Hadron Therapy Technologies
S. Peggs, BNL & ESS-S

Many figures courtesy of Jay Flanz

Bevalac 1950-1993
Consumer demand

1 in 3 Europeans will confront some form of cancer in their lifetime.

Cancer is the 2nd most frequent cause of death.

Hadron therapy [protons, carbon, neutrons] is 2nd only to surgery in its success rates.

45% of cancer cases can be treated, mainly by surgery and/or radiation therapy.
Rapid growth

Courtesy J. Sisterson, MGH
Clinical requirements

A hadron therapy facility in a hospital must be:

**Easy to operate**
- environment is very different from a national lab

**Overall availability of 95%**
- accelerator availability greater than 99%

**Compact**
- less than 10 m across, or
- fit in a single treatment room

**Beam parameters must deliver the treatment plan!**
- depends on details of treatment sites & modalities
- but some generalization can be made
Painting a tumor

A perfect monochromatic proton beam, with zero initial emittance:

**TOP** spreads out transversely

**BOTTOM** acquires an energy spread that blurs the Bragg peak

Steer the beam and modulate its energy to “paint” the tumor!
Beam parameters

Penetration depth
- 250 MeV protons penetrate 38 cm in water
- carbon equivalent is 410 MeV/u, with
  2.6 times the rigidity

Dose rate
- deliver daily dose of 2 Grays (J/kg) in 1 or 2 minutes
- 1 liter tumor needs (only) ~ 0.02 W
  (0.08 nA @200 MeV)
- need x10 or x100 with degraders & passive scattering

Conformity
- integrated dose must agree with plan within 1% or 2%
- dose should decrease sharply across the tumor surface
History

1930's  Experimental neutron therapy
1946    R.R. Wilson proposes proton & ion therapy
1950's  Proton & helium therapy, LBL (184” cyclotron)
1975    Begin carbon therapy in Bevalac synchrotron
        including wobbling & scanning
1984    Proton therapy begins at PSI
1990    Neutrons on gantry mounted SC cyclo, Harper-Grace
1990    Protons with 1st hospital based synchrotron, LLUMC
1993    Precision raster scanning with carbon, GSI
1994    Carbon therapy begins at HIMAC, Chiba
1996    Spot scanning, PSI
1997    Protons with 1st hospital based cyclotron, MGH
Cyclotrons
Cyclotrons, big ...

Proof-of-principle & R&D therapy was performed in national labs

National lab operation is increasingly deprecated, especially in U.S.
IBA C230
230 MeV protons, 300 nA
Saturated field ~ 3 T
200 tons 4 m diameter

1997
First C230 begins operation at MGH as 1st hospital based commercial cyclotron

Isochronous cyclotrons
Few adjustable parameters
CW beams, constant energy
– energy degraders
– larger emittance,
– larger energy spread
Easy to operate!
1980's  Design studies confirm $1/B^3$ scaling of SC cyclotrons, but leave synchrocyclotrons (swept RF frequency) out of reach.

**ACCEL Superconducting COMET** (below): 80 tons, 3 m dia. 250 MeV protons with markedly better extraction efficiency
... smallest: cyclotron on a gantry

1990  MSU / Harper-Grace
Superconducting  NbTi
~5.6 T  70 MeV neutrons

2008  MIT / Still River Systems
React-and-Wind  Nb$_3$Sn
~9 T  250 MeV protons
Synchrocyclotron  < 35 tons
pulsed bunch structure
Cryogen free (cryo-coolers)
Slow cycling synchrotrons
1990 **Loma Linda:** 1st hospital based proton therapy center
Standard against which other synchrotrons are measured

- Designed and commissioned at **FNAL**
- Weak focusing
- Slow extraction
- Space charge dominated
- Small number of operating energies
Slow extraction

Resonant extraction, acceleration driven, RF knockout, betatron core, or stochastic noise

- feedback runs against “easy operation” & “availability”
- often deforms beam distribution (enlarged beam size)
- energy degraders sometimes necessary

But it works!

LEFT: Hitachi synchrotron at MDACC

Strong focusing

Synchronize beam delivery with respiration!
Carbon

“Synchrotrons are better suited to high rigidity beams” (but SC cyclotron designers are pushing towards carbon)

LEFT: Pavia design uses PIMMS (CERN) design synchrotron

Avoids a gantry in the initial layout

Siemens/GSI carbon synchrotron at HIT includes a gantry (commissioning)

Med-Austron / CERN
New & revisited concepts
Perception ...
FFAG reprise

Ring of magnets like a synchrotron, fixed field like a cyclotron.

Fast acceleration (think muons)

Compact footprint

Magnet aperture must accept large momentum range

KEK

Variable energy extraction?

Possible very high rep rate

Much world wide interest.

Demo machines in early operation, construction & design
FFAG - continued

**TOP RIGHT:**
cascaded rings

**LEFT:**
“robot” gantry
60 keV – 1 MeV

**RIGHT:**
ing ring gantry

EMMA
Linacs

< 10 MeV/m
complex RF

"TOP" @ ENEA
SCDTL
200 MeV
protons
1st in hospital?

HERE: 1999
R. Hamm PL-250
Fast neutrons proposal

Table 1
Preliminary Specifications for a Dedicated Proton Therapy Linac

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerated particle</td>
<td>H⁺</td>
</tr>
<tr>
<td>Maximum beam energy</td>
<td>250 MeV</td>
</tr>
<tr>
<td>Minimum beam energy</td>
<td>70 MeV</td>
</tr>
<tr>
<td>No. energy increments</td>
<td>11</td>
</tr>
<tr>
<td>Peak beam current</td>
<td>100-300 μA</td>
</tr>
<tr>
<td>Beam pulse width</td>
<td>1-3 μsec</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>100-300 Hz</td>
</tr>
<tr>
<td>Average intensity</td>
<td>10-270 nA</td>
</tr>
<tr>
<td>Beam emittance (norm.)</td>
<td>&lt;0.1 πmm-mrad</td>
</tr>
<tr>
<td>Beam energy spread</td>
<td>±0.4 %</td>
</tr>
<tr>
<td>Max. rf duty factor</td>
<td>0.125 %</td>
</tr>
<tr>
<td>Peak rf power</td>
<td>62 MW</td>
</tr>
<tr>
<td>Maximum input power</td>
<td>350 kW</td>
</tr>
<tr>
<td>Stand-by power</td>
<td>25 kW</td>
</tr>
<tr>
<td>Accelerator length</td>
<td>28 m</td>
</tr>
</tbody>
</table>

Figure 1. Schematic Layout of Model PL-250 Proton Therapy Linac.
“High Gradient Induction Accelerator”
G. Caporaso et al, LLNL

250 MeV protons in 2.5 m?
Pulse-to-pulse energy & intensity variation
“Hoping to build a full-scale prototype soon”
Gantries
Proton gantries

Normal conducting proton gantries:
- weight: > 100 tons
- diameter: ~ 10 m
- max deformation: ~ 0.5 mm
Carbon gantries

It is hard to bend same-depth carbon ions
(2.6 times the rigidity of protons)

Heidelberg carbon gantry
13 m diameter
25 m length
630 tons !!
New gantry technologies – for Carbon?

Emerging technologies mainly aimed at carbon gantries
- direct wind iron-free NbTi superconducting magnets
- High Temperature Superconductor magnets one day?
- cryo-coolers
- FFAG optics

Small beams (eg the BNL RCMS)
enable small light magnets & simple light gantries
Superconducting gantry magnets

SC magnets + small beam size = practical light gantries

New SC magnets are light & strong
Iron-free (coil dominated fields)
Solid state coolers (no He)
Field containment
“Direct wind” construction
BNLs
Rapid Cycling Medical Synchrotron
RCMS
Multiple RCS proposals, from 25 Hz to 60 Hz

Inject in one turn, extract on any single turn (any energy)
Beam scanning rates

What rates do current “point-and-shoot” slow extraction facilities deliver?

**PSI** 50 Hz (Med. Phys. 31 (11) Nov 2004)
- 20 to 4,500 ml per treatment volume
- 1 to 4 fields per plan
- 200 to 45,000 Bragg peaks per field
- 3,000 Bragg peaks per minute
- Few seconds to 20 minutes per field

**MDACC** ~ 70 Hz (PTCOG 42, Al Smith, 2005)
- 10x10x10 cm tumor treated in 71 seconds
- 22 layers, 5,000 voxels
RCS advantages & challenges

Advantages

“No” space charge
High efficiency (eg antiprotons?)
Small emittances enable small light (air-cooled?) magnets
Light gantries
Extreme flexibility – the sharpest possible scalpel

Challenges

Rapid RF frequency swing (eg 1.2 MHz to 6.0 Mhz in ms)
Eddy currents
  – ISIS 50 Hz, Cornell 60 Hz, transformers 50/60 Hz
Nozzle beam diagnostics with short (100 ns) bunches
# RCS vs Cyclotron

<table>
<thead>
<tr>
<th></th>
<th>Rapid Cycling Synch.</th>
<th>Cyclotron</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy flexibility</strong></td>
<td>Flexible (fast extraction)</td>
<td>Fixed (needs degraders)</td>
</tr>
<tr>
<td><strong>Typical diameter</strong></td>
<td>5-7 m</td>
<td>4 m</td>
</tr>
<tr>
<td><strong>Power consumption</strong></td>
<td>Low (resonant)</td>
<td>High (except SC)</td>
</tr>
<tr>
<td><strong>Typical beam size</strong></td>
<td>1 mm</td>
<td>10 mm</td>
</tr>
<tr>
<td><strong>Typical energy spread</strong></td>
<td>$&lt; 2e-3$</td>
<td>$&gt; 5e-3$</td>
</tr>
<tr>
<td><strong>Beam intensity</strong></td>
<td>High</td>
<td>Very high</td>
</tr>
<tr>
<td><strong>Complexity</strong></td>
<td>Flexible</td>
<td>Simple</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>Light (7-10 tons)</td>
<td>Heavy (100-200 tons)</td>
</tr>
<tr>
<td><strong>Approximate cost</strong></td>
<td>$10M</td>
<td>$10M</td>
</tr>
<tr>
<td><strong>Other costs</strong></td>
<td>Lower</td>
<td>Higher</td>
</tr>
</tbody>
</table>
The BNL RCMS

**Racetrack design**
- 2 super-periods
- Strong focusing minimizes the beam size
- FODO/combined function mags with edge focusing
- 2x7.6m straight sections, zero dispersion, tune quads
- Working tunes: 3.38, 3.36

**Compact footprint**
- Circumference: 27.8 m
- Area: 37 sq m
Zero dispersion in straights: injection/extraction/RF
Room for two RF cavities, long injection/extraction
Strong focusing: small beam, large $\gamma_T$, large natural negative chromaticities, improved beam stability
RCMS arc magnets

Latest design (2007) has improved field quality
Careful shaping of pole tips; broader pole face; air cooled
2.5% change through cycle for quad gradient, optimized for injection
RCMS RF cavities

½ RF cavity design is ready for early prototyping

Ferrites procured and tested for large frequency swing
- 1.3-6.6 MHz
- 60 Hz is aggressive, feasible

60 Hz requires two cavities
- Expected voltage limit is about 6-7 kV/cavity
Proton Imaging
Conventional CT measures the wrong thing

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
Advanced proton cameras are under development

(Potentially) a very nice example of tech transfer from HEP/NP
Silicon strip/pixel detectors defeat blurring!

Simple proton radiography is rejected because multiple scattering makes blurry images.

Modern silicon strip detectors can acquire individual proton trajectories at high bandwidth.

Track reconstruction enables sharp images of the right thing!
Conclusion – the Environment
Why is the U.S. accelerator industry so strikingly underdeveloped in comparison with EU and Japan?

Medical accelerators provide the clearest example: (ACCEL), Danfysik, Hitachi, IBA, Mitsubishi, Siemens, ...

The U.S. Department of Energy HEP/NP program is the “steward” of Accelerator Science at a time when:

1) HEP/NP budgets are in decline
2) Accelerator Science & Technology blossom
3) The economy suffers

How to teach & do research in Accelerator Science, across University & national lab boundaries?
1) Accelerator Physics is a science in its own right, not just a provider of technology for particular users

2) “Centers for Accelerator Science & Engineering” need reinventing, across laboratory & university boundaries

But accelerator technology needs direct stimulation:

3) “What challenges should be put to accelerator companies to make them profit sources, and not tax sinks, in the global economy?”

What is the “third way” that synthesizes these apparently antithetical statements?