Flow of Requirements
or How to Analyze an Accelerator?

Clinical Requirements → Delivery Modality → Beam Requirements → Accelerator Requirements

What is the Question??

Other Requirements
What are the (Clinical) Requirements?

- Satisfy Clinical Parameters
  - appropriate treatment in 1-2 minutes ?! (A lot in this)
  - Dosimetry (It has to work !)

- Overall System Reliability > 95% (See later)
  ⇒ Implies Accelerator Reliability of ~99%

- Fits in a “Clinical” Setting. (Perception = Reality)
  - 5-8m, effect of size depends on number of rooms.
  - Possibly small enough to fit all equipment into one room
    - Economics of this approach unproven, but there is some interest...

- Easy to Operate
  - Easy is relative, but easier than the perception of a National Laboratory Accelerator Operation (e.g. automatic, self diagnoses)
  - Also commensurate with type and number of personnel expected to work in such a facility, or a company’s operation contract
Clinical Beam Parameters of “Questionable” Importance

- Clinical
  - Patient Related
  - Dosimetry Related
- e.g.
  - Beam Time Structure
  - Peak Beam Intensity
  - “Numbers”

Beam at Target (Not Accelerator)

<table>
<thead>
<tr>
<th>Sigma</th>
<th>Random Systematic</th>
<th>Random Once</th>
<th>Technical Repainting</th>
</tr>
</thead>
<tbody>
<tr>
<td>5mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.2mm</td>
<td>0.25mm 0.2mm</td>
<td>0.75mm 0.6mm</td>
<td>Quad field ~ 0.4%</td>
</tr>
<tr>
<td>Position</td>
<td></td>
<td>Dipole field ~ 0.05%</td>
<td></td>
</tr>
<tr>
<td>Gradient</td>
<td>4% 5% 15%</td>
<td>200 usec / 4%</td>
<td></td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>50:1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>0.75mm x x</td>
<td>Dipole field ~ 0.14%</td>
<td></td>
</tr>
</tbody>
</table>
**Beam Delivery Modality: Beam Parameters Determined both by Accelerator and other Beam Modifying Devices!**

Convert Clinical Specification to Equipment Requirements!

Some Examples....

- **Range**: 32 cm
- **Field Size**: 30cm x 40cm
- **Beam Properties Appropriate**
- **2Gy Rx Less than 1min**
- **Change Energy < 2sec**
- **Fixed Energy Accelerator**
- **Paint 30 Layers < 1min**
- **Beamline**
- **Beam**
- **Nozzle**
- **Beam Loss**

---

J. Flanz CYC95 10/12/95
Beam Delivery Modality:

Implications of Scanning

• “Clinical Properties”
  – Intensity Modulation
  – Many Pixels
  – High Gradients between pixels
  – Repainting
  – Gating
  – Tracking

• “Accelerator Implications”
  – NOT JUST E, I, but;
  – $\Delta \frac{dI}{dt}, \frac{dx}{dt}$ (for continuous scanning)
  – instrumentation
Acceleration Mechanism(s)

\[ \vec{F} = q \vec{E} + q \vec{v} \times \vec{B} \]

- **Physics**: Anything that can create an electric Field which accelerates a charged particle in the direction of its motion.
  - \( E \sim dB/dt \) (changing magnetic field) (betatron)
  - \( E \sim \) Applied Voltage
    - DC Voltage
    - AC Voltage
  - “Create” an Electric Field

- **Engineering**: “Efficient use of Power”
  - One time through (Linac)
  - Reuse the Electric Field
    - Cyclotron
    - Synchrotron
    - Other?
**Time Structure:**

- **Definitions:**
  - DC; CW, Pulsed, Duty Factor
  - Duty Factor = Tb/To

- **Instrumentation Issues:**
  - Response time of Detector
  - Response time of Electronics
  - Saturation

- **Examples:**
  - 100MHz rf $\Rightarrow$ 1nsec / 10 nsec
  - Rapid Cycling Synch $\Rightarrow$ 100nsec/30 Hz

- **Biological**
  - Response time of Cell?
"Conventional" Accelerators
Proton Accelerators – 15 years ago
Choices, Questions and Answers now

• Cyclotrons
  – Will Compact Cyclotron Work? - Yes
  – Superconducting vs. Room Temperature? - Both so far
  – 250 MeV vs. 230 MeV? - Depends upon Machine
    • Size, Dose Rate (Shallow) ? - Just enough for scattering

• Synchrotrons with Injectors
  – Can they be used for scanning? - Yes
    • Slow, Uniform, Controlled, Extraction? - Possible but not yet
  – Beam Gating? - Yes
  – Dose Rate ? - Okay
  – Rapid Cycling - Not yet

• Linacs - Not caught on yet
One Pass Linac  (R. Hamm)

### Clinical?  Reliability?  Compact?  Easy?

### "Macro Structure"

#### Figure 1. Schematic Layout of Model PL-250 Proton Therapy Linac.

#### Table 1

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerated particle</td>
<td>H^+</td>
<td></td>
</tr>
<tr>
<td>Maximum beam energy</td>
<td>250 MeV</td>
<td></td>
</tr>
<tr>
<td>Minimum beam energy</td>
<td>70 MeV</td>
<td></td>
</tr>
<tr>
<td>No. energy increments</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Peak-beam current</td>
<td>100-300 μA</td>
<td></td>
</tr>
<tr>
<td>Beam pulse width</td>
<td>1-3 μscc</td>
<td></td>
</tr>
<tr>
<td>Repetition rate</td>
<td>100-300 Hz</td>
<td></td>
</tr>
<tr>
<td>Average intensity</td>
<td>10-270 nA</td>
<td></td>
</tr>
<tr>
<td>Beam emittance (norm.)</td>
<td>&lt;0.1 πmm-mrad</td>
<td></td>
</tr>
<tr>
<td>Beam energy spread</td>
<td>±0.4 %</td>
<td></td>
</tr>
<tr>
<td>Max. rf duty factor</td>
<td>0.125 %</td>
<td></td>
</tr>
<tr>
<td>Peak rf power</td>
<td>62 MW</td>
<td></td>
</tr>
<tr>
<td>Maximum input power</td>
<td>350 kW</td>
<td></td>
</tr>
<tr>
<td>Stand-by power</td>
<td>25 kW</td>
<td></td>
</tr>
<tr>
<td>Accelerator length</td>
<td>28 m</td>
<td></td>
</tr>
</tbody>
</table>
\( \frac{mv^2}{R} = qvB \)

\[ \ldots \]

\[ f = \frac{qB}{2\pi m} \]

Particle orbital period is constant except for \( m = \gamma m_0 \)

which is compensated for by \( B \)
(isochronous cyclotron)
allowing a continuous wave beam, or

varying frequency
(synchrocyclotron) allowing only a pulse of beam for each cycle of acceleration

Figure 15.4 Geometry for treating longitudinal dynamics of uniform-field cyclotron.
Time Structure Comparison: Beam Delivery Modality

Breath

Variable Cycle Synchrotron
Beam Available

Fixed Cycle Synchrotron
Beam Available

CW Cyclotron
Beam Available

Clinical?

Reliability?

Compact?

Easy?

Okay to Deliver Beam

Comparison of Beam Utilization for Treatment Requiring Synchronization
Cyclotrons used for Proton Therapy
(Used) to be very BIG

Clinical?
Reliability?
Compact?
Easy?

TRIUMF Cyclotron

PSI Ring Cyclotron
Or Very Old used ones!

& Berkeley 184” Cyclotron

Clinical?
Reliability?
Compact?
Easy?
Scaling Down for “Public” Acceptance

NAC - South Africa and IUCF - Indiana

2,000 tons

MGH, Kashiwa, Florida, Wan Jie, Korea

200 tons

“Conventional Technology”
Synchrotrons

Bevalac 1950 - 1993
Synchrotrons getting Hospital sized

LLUMC, Tsukuba, MD Anderson, Shizuoka, Wakasa, HIMAC, Hyogo
Accelerator Development Underway

Why?

- Fixed Field Alternating Gradient
- Even Smaller Cyclotron and Synchrotron
- Dielectric Wall Accelerator
- Laser Wakefield Acceleration

Previously:
Proof of Principle;
Get it going;
Technology a company (and customer) can ‘afford’…

Proton Beam
Conventional, but more "extreme"
TABLE-TOP PROTON SYNCHROTRON RING FOR MEDICAL APPLICATIONS

K. Endo, K. Mishima S. Fukumoto and S. Ninomiya, KEK, Tsukuba, Japan
G. Silvestrov, BINP, Novosibirsk, Russia

<table>
<thead>
<tr>
<th>Ring</th>
<th>Proton</th>
<th>C++ ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. energy (MeV/u)</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Injection energy (MeV/u)</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Max. dipole field (T)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Length of dipole (m)</td>
<td>1.126</td>
<td>1.126</td>
</tr>
<tr>
<td>Bending radius (m)</td>
<td>0.7165</td>
<td>1.4331</td>
</tr>
<tr>
<td>Number of dipoles</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Max. quad gradient (T/m)</td>
<td>42</td>
<td>42</td>
</tr>
<tr>
<td>Length of quad (m)</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Number of quads</td>
<td>12</td>
<td>28</td>
</tr>
<tr>
<td>CTe circumference (m)</td>
<td>11.3</td>
<td>24.2</td>
</tr>
<tr>
<td>Superperiod</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Tune (hor / ver)</td>
<td>2.25 / 1.25</td>
<td>2.75 / 1.75</td>
</tr>
<tr>
<td>Max. beta function (x / y)</td>
<td>4.42 / 11.33</td>
<td>4.40 / 14.73</td>
</tr>
<tr>
<td>Max. dispersion (m)</td>
<td>0.42</td>
<td>0.85</td>
</tr>
<tr>
<td>RF frequency (MHz)</td>
<td>1.7 - 15.0</td>
<td>0.6 - 7.0</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Max. Acc. Voltage (kV)</td>
<td>13</td>
<td>26</td>
</tr>
<tr>
<td>Acc. time (msec)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Number of RF cavities</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Repetition (Hz)</td>
<td>&lt;10</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Unit cell structure</td>
<td>ODOFBF</td>
<td>ODOFBFDD FBF</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BINF</th>
<th>Frascati</th>
<th>KEK</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. energy</td>
<td>200.0</td>
<td>200.0</td>
<td>200.0</td>
</tr>
<tr>
<td>Inj. energy</td>
<td>1.0</td>
<td>12.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Circumference</td>
<td>4.7</td>
<td>6.4</td>
<td>10.5</td>
</tr>
<tr>
<td>Av. diameter</td>
<td>1.5</td>
<td>2.0</td>
<td>3.3</td>
</tr>
<tr>
<td>Bending radius</td>
<td>0.43</td>
<td>0.54</td>
<td>0.72</td>
</tr>
<tr>
<td>Max. dipole field</td>
<td>5.0</td>
<td>4.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Period</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Tune, /</td>
<td>1.4/0.45</td>
<td>1.42/0.54</td>
<td>1.4/0.75</td>
</tr>
<tr>
<td>Max. dispersion</td>
<td>0.4</td>
<td>0.63</td>
<td>1.0</td>
</tr>
<tr>
<td>Cell structure</td>
<td>FODB</td>
<td>BODO</td>
<td>OFOBDB</td>
</tr>
<tr>
<td>Total weight</td>
<td>~1</td>
<td>~1.5</td>
<td>~2</td>
</tr>
</tbody>
</table>

**Clinical?**
**Reliability?**
**Compact?**
**Easy?**

Figure 1: Present ring layout.
Smaller Cyclotron on a Gantry

- Harper Hospital Neutron Therapy
- Rumors of a New one being designed - 9.5 Tesla.
Scaling DOWN Cyclotrons - Quantitatively

![Graph showing the decrease in tons and radius over time.](image)
Not "Conventional"
**FFAG – Fixed Field Alternating Gradient**

- Strong Focusing – Alternating Gradient Cells
- A Ring of Magnets like a Synchrotron, BUT Fixed Field like a Cyclotron.
- Beam Orbit moves within the magnets, but a very small amount, allowing small, light magnets to be used, over a wide range of momentum.
- Fast Acceleration, Variable Energy
- High Average Current (Possible large rep rate, short injection pulse)

Proof of Principle Machine! 2000 KEK
(Remember when that was possible?)

Interest in:
- Japan
- BNL
- UK

“Macro Structure”
Proton Options  Proven Solutions, New **FFAG** Options

4 m Diam

Proton energy 230MeV
Intensity >100nA
Rep. Rate 20-100Hz, respiration mode
Diameter ~8m
Extraction fast, multi-port

Flanz FFAG 2006
Heavier Ion Options  All NEW Options

- 25 m Diam
- 20.5m Diam
- 6.3m Diam
- 15m Diam

Scaling/Non-Scaling

Mitsubishi

*Flanz FFAG 2006*
What is needed is a way to implement a ‘new’ idea to its best advantage!

Mitsubishi - Laptop

Diameter 10cm
Energy 60 keV to 1 MeV
Rep. Rate 1kHz

Non-Scaling FFAG?

KEK 2003

EMMA

Flanz FFAG 2006
**Acceleration Mechanism(s)**

\[ \vec{F} = q \vec{E} + q \vec{v} \times \vec{B} \]

- **Physics**: Anything that can create an electric Field which accelerates a charged particle in the direction of its motion.
  - \( E \sim \frac{dB}{dt} \) (changing magnetic field) (betatron)
  - \( E \sim \) Applied Voltage
    - DC Voltage
    - AC Voltage
  - “Create” an Electric Field
- **Engineering**: “Efficient use of Power”
  - One time through (Linac)
  - Reuse the Electric Field
    - Cyclotron
    - Synchrotron
    - FFAG
Backpack Sized Proton Accelerator?

Clinical?
Reliability?
Compact?
Easy?
DWA - Dielectric Wall Accelerator

• 250 MeV in 2.5 meters
  – It may fit in a typical clinic.

• Pulse-to-pulse energy variation

George Caporaso et. al., LLNL

Developing Compact Proton Beam Cancer Therapy

Traditional x-ray and gamma-ray therapy are often used for treating cancerous tumors. However, the radiation may damage healthy tissue it passes through on its way to a targeted tumor. This may limit the amount of radiation that can be applied to a deep-seated tumor.

Protons, because of their charge and mass, retain most of their energy until they reach the cancer site. As a result, proton beam therapy is expected to become the next “big thing” in radiation treatment for certain localized cancers. This type of therapy has been available in hospitals only since 1990. But, because of their size (as large as a basketball court) and cost (as much as $150 to $200 million to build) there are only a few proton therapy centers in the United States and only about 20 in the world.

Lawrence Livermore National Laboratory (LLNL) and the UC Davis Cancer Center are collaborating in a project to develop proton accelerators that could fit into a single room and be built for one-tenth the current cost. Success in this project would mean that proton therapy could become available in many oncology clinics across the country.

The project would use a LLNL-developed technology called the Dielectric Wall Accelerator (DWA). This device enables protons to be accelerated to the required energies without using bending magnets or techniques that generate excess space and generate unwanted radiation.

The dielectric wall uses a high-voltage-gradient insulator to handle electric-field stresses. A dielectric wall only 2.5 meters long could withstand the 10 million volts required to treat deep-seated tumors. LLNL researchers have successfully tested small scale models.

Though a number of technical challenges remain, developers are optimistic about building a full scale prototype soon, in order to demonstrate the operation of samples and characteristics.

For the full story, see: http://www.llnl.gov/pro/news/science/features2006/S7_06_04_02.htm
Laser Wakefield Acceleration
The interaction of an intense light field with matter yields the generation of a hot plasma and the subsequent acceleration of electrons up to relativistic energies\textsuperscript{11,12}. Protons and ions are accelerated by a well controlled mechanism known as ‘target normal sheath acceleration’ (TNSA)\textsuperscript{13} following the initial electron acceleration (Fig. 1). Fast electrons are accelerated by an intense laser pulse (intensity $I \approx 10^{19}$ W cm\textsuperscript{-2}) from the surface of a thin metal foil in the forward direction. They penetrate the foil and ionize atoms along their paths. Within about a picosecond, those electrons leaving the target at the rear surface (that is, the back surface with respect to laser irradiation) build up a quasi-static electric field. The field acts normally to the target surface, has cylindrical symmetry and decreases in the transverse direction. Owing to the ultrashort duration of the electron bunch and its high charge, this field may reach values of several TV (10\textsuperscript{12} V m\textsuperscript{-2}) close to the axis and thus the potential can attain several tens of MeV (ref. 3).

**Laser Acceleration Mechanism**

- Intense Laser Pulse ($10^{20}$ W/cm\textsuperscript{2})
  - Femtosec --> Picosec
- Plasma is created which accelerates electrons OUT of the target.
- Protons from a proton rich deposit follow, being accelerated by the large Electric field generated ($10^{12}$ V/m)
- Energy Gain of several tens of MeV, depends upon intensity of laser pulse, target capability…
- e.g. theoretical example:
  - Laser = $10^{21}$ W/cm\textsuperscript{2}, 30 fs pulse
  - Target 2\textmu m
  - $\Rightarrow$ 180 MeV

**Vol 439 26 January 2006/nature04492**

H. Schwoerer
Laser Proton Beam Energy Properties

Energy Spectrum Measurement

Predicted Energy Capability

E. Fourkal et. al. Med. Phys. 29,

V. Malka et. al., Med. Phys. 31
Structured Target

- Electric field has a very strong dependence in the transverse direction.
- Advantageous to contain protons at center of field.

- Possible way to monochromatize the energy spectrum, by putting very small targets at the exact center of the laser beam.
Laser Equipment Required

Clinical?
Reliability?
Compact?
Easy?

Victor Malka
End Slides

PTCOG 2007
Accelerators
Flanz