Accelerators for Hadrontherapy
-- Present & Future --

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Basics on Hadrontherapy
Hadrontherapy is a type of external radiotherapy that uses beams of particles made of quarks (hadrons):

- neutrons,
- protons,
- pions,
- helium, lithium, boron, carbon, oxygen... ions
- antiprotons

$$\text{carbon ion} = 6p + 6n$$

$$\text{proton (p) or neutron (n)}$$

$$\text{quarks "u" or "d"}$$
While passing through matter, a hadron loses most of its energy when it is almost stopped, at the so-called Bragg peak.

- High doses can be delivered to tumour target while providing low doses to frontal and distal healthy tissue.
Basics on Hadrontherapy

**Hadron beams in matter**

- **200 MeV - 1 nA protons**
- **400 MeV/u – 0.1 nA carbon ions** (radioresistant tumours)

- While passing through matter, a hadron loses most of its energy when it is almost stopped, at the so-called **Bragg peak**.

- **High doses** can be delivered to **tumour target** while providing **low doses** to frontal and distal **healthy tissue**.

- The position of the **Bragg peak** depends on the **energy of the hadron** at the volume entrance.

Courtesy of PSI
i) Hadron beams spare healthy tissues while providing high doses to tumour volume
Basics on Hadrontherapy

Physical properties of hadron beams

i) Hadron beams spare healthy tissues while providing high doses to tumour volume

![Bragg Peak](image)
Basics on Hadrontherapy

Physical properties of hadron beams

i) Hadron beams spare healthy tissues while providing high doses to tumour volume
Basics on Hadrontherapy

Physical properties of hadron beams

ii) Dose delivery to 3D volume
Physical properties of hadron beams

Basics on Hadrontherapy

ii) Dose delivery to 3D volume

Guided narrow, focused beam of charged particles

- **a)** lateral scan: magnets
- **b)** depth scan: beam energy

e.g. SPOT SCANNING TECHNIQUE
Basics on Hadrontherapy

Radiobiological efficiency (RBE) of carbon ion beams

Better control of radioresistant tumours

RBE = 1

X-ray

Proton

SSB
Single Strand Break

ionizations

electron

2 nm

chromosome

Courtesy of U. Amaldi
Radiobiological efficiency (RBE) of carbon ion beams

Better control of radioresistant tumours

**RBE = 1**
- X-ray
- Proton
- Single Strand Break (SSB)
- 2 nm from the chromosome

**RBE = 3**
- Carbon ion
- 40 mm from the stopping point
- Double Strand Break (DSB)
- Ionizations

Double Strand Break (DSB)
Single Strand Break (SSB)
Proton
Carbon ion
X-ray

Courtesy of U. Amaldi
Basics on Hadrontherapy

Physical and biological properties of hadron beams

i) Spare healthy tissues while providing high doses to tumoural volume

ii) Dose delivery to 3D volume:

   guided narrow, focused beams of charged particles scanned (x,y)

   for different penetration depths (z) by changing the beam energy

iii) Small diffusion
Spare healthy tissues while providing high doses to tumoural volume

Dose delivery to 3D volume:

- guided narrow, focused beams of charged particles scanned (x,y)
- for different penetration depths (z) by changing the beam energy

Small diffusion

Proton and carbon ion therapy allow...

- Conformal treatment of deep-seated tumours with milimeter accuracy

Carbon ions allow...

- Better control of radioresistant tumours
Basics on Hadrontherapy

Number of potential patients*

**X-ray therapy**

every 10 million inhabitants: 20'000 pts/year

**Protontherapy**

12% of X-ray patients: 2’400 pts/year

**Therapy with Carbon ions for radio-resistant tumours**

3% of X-ray patients: 600 pts/year

**TOTAL**

about 3’000 pts/year

(every 10 M)

* ENLIGHT (FP5) outcome: studies carried out in Austria, Germany, Italy and France
Basics on Hadrontherapy

Treating moving organs requires...

e.g. **SPOT SCANNING TECHNIQUE**

horizontal scan  vertical scan

slice  voxel
tumour volume
Basics on Hadrontherapy

Treating moving organs requires...

- **Fast Active Energy Modulation** (a couple of ms)
  - To perform a fast change of beam spot position in depth

**a) lateral scan:** magnets
- 2 ms/step

**b) depth scan:**
- beam energy
- few ms
Treating moving organs requires...

Fast Active Energy Modulation (a couple of ms)
To perform a fast change of beam spot position in depth

Fast Cycling machine (high repetition rate ~ 200-300 Hz)
Tumour MULTIPAI NTING
Present Accelerators for Hadrontherapy
Nowadays **35 facilities** all around the world offer **protontherapy**

*(cyclotron or synchrotron*-based facilities)*

and **6 centers** provide **carbon ion therapy**

*(only synchrotron-based facilities)*
Nowadays **35 facilities** all around the world offer **protontherapy**
 (*cyclotron or synchrotron*-based facilities)

and **6 centers** provide **carbon ion therapy**
 (*only synchrotron-based facilities*)

* **Commercial solutions available!** (mainly protons): IBA, Varian, Mitsubishi, Hitachi, ...
Hadrontherapy in the world

Typical Proton Therapy Facility

Beam Transport

Cyclotron

Irradation systems:
Fixed

Irradation systems:
Rotating Gantry
A Proton therapy system is **much more than an accelerator:**

*it is most often a complex, multi-room treatment system*

The treatments rooms are larger than the cyclotron/synchrotron vault

About **one third** of the total investment is **for the accelerator**;
the rest is for the building, equipment, etc.
In the 90’s the consensus was that... the best accelerator for protontherapy was a synchrotron
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However today... most protontherapy centers use cyclotron technology (IBA, Varian, Still Rivers...)
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most protontherapy centers use cyclotron technology (IBA, Varian, Still Rivers...)

Over these 15 years, users appreciated advantages of cyclotrons:
- Simplicity
- Reliability
- Lower cost and size
- Most importantly:
  rapid and accurate proton beam current modulation
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the **best accelerator** for **protontherapy** was a **synchrotron**

However today...
**most protontherapy centers** use **cyclotron** technology (IBA, Varian, Still Rivers...)

**Over these 15 years**, users appreciated **advantages of cyclotrons**:
- Simplicity
- Reliability
- Lower cost and size
- Most importantly:
  - **rapid and accurate** proton beam current modulation

...**but** cyclotrons deliver a **fixed energy beam**...
so **absorbers** needed to vary the beam energy
Hadrontherapy in the world

Synchrotrons for Proton Therapy

**Advantages:**

- Variable *energy* operation
- Modified *Flat-Top* operation
- Easy *dose* management

*Synchrotrons* deliver a *pulsed beam*...
Advantages:
- Variable energy operation
- Modified Flat-Top operation
- Easy dose management
- Relatively low intensity

Some protontherapy centers use the synchrotron technology (Hitachi, Mitsubishi...), but all the ion beam centers (p, C) use synchrotron

→ Possibility of proton&carbon therapy with the same accelerator
Hadrontherapy in the world

Typical Synchrotron-based Proton Facility

University of Tsukuba

- Two Passive Nozzles with Rotating Gantries
- Operation Started in 2001
- Over 1000 Patients Treated

Synchrotron (70-250MeV)
Hadrontherapy in the world

Heidelberg Ion Therapy (HIT)

Ion Beam Facility

Protons and helium, oxygen and carbon ions

Ion Sources
Synchrotron
LINAC
Treatment Halls by Siemens
Beam Transport Lines
Gantry
~ 22 m
~ 13 m
~ 600 tones

~ 13 m
**Gantry**: beam line that directs and focuses the beam onto the patient at whatever angle is required for the treatment plan optimization.
Hadrontherapy in the world

Key issue: compact gantries

Protons e.g. PSI gantry-2

~ 8 m

~ 12 m

~ 100 tones
Carbon ions

HIT gantry (unique worldwide)

Key issue: compact gantries

Hadrontherapy in the world

Ion Sources

Synchrotron

LINAC

Beam Transport Lines

~ 22 m

~ 13 m

~ 600 tones

Gantry

Treatment Halls by Siemens

Heidelberg Ion Therapy (HIT)
Future Accelerators for Hadrontherapy
Cyclotrons: compact, reliable, easy to operate

*however... fixed energy beam ↔ movable absorbers*
  → long Energy Selection System line
  → neutron activation and carbon fragmentation
  → energy modulation in 80-100 ms

Synchrotrons: variable energy beam

*but...* → energy modulation in 1-2 s
Hadrontherapy in the world

**Present accelerators for hadrontherapy**

**Protontherapy**
(200-250 MeV protons)

- CYCLOTRONS (*) (Normal or SC)
- SYNCHROTRONS

(*) also synchrocyclotrons

**Carbontherapy**
(400 MeV/u carbon ions)

- SYNCHROTRONS

[6-9 metres]

[18-25 metres]

[M. Shippers, PSI]
The existence of **compact, reliable accelerators**

with **advanced beam performances**

would facilitate the access to hadrontherapy to more patients.

**Compact gantries** are needed!
C400, about 6.3 m-diameter, superconducting coils

Courtesy of IBA
The cyclinac: cyclotron + high frequency linac

- Cell Coupled Linac
- Standing-wave structure
- RF frequency: 5.7 GHz
- 2.5 µs-long pulse at 300 Hz

CABOTO
(Carbon BOoster for Therapy in Oncology)

Courtesy of TERA
A compact gantry based on the *cyclinac* idea

- **Cell Coupled Linac**
- **Standing-wave structure**
- **RF frequency:** 5.7 GHz
- **2.5 μs**-long pulse at 100 Hz

**TULIP** (TUrning Linac for Protontherapy)

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**Future Accelerators for Hadrontherapy**

**C-band linac Section 1**

**C-band linac Section 2**

**Line with 2% momentum acceptance**

**Beam dose delivery**

**RF rotating joints**

**RF Power sources**

**W₀**

**W₁**

**W₂**

**SM₁**

**SM₂**

**W₀**

**W₁**

**W₂**

**SM₁**

**SM₂**

**TULIP** (TUrning Linac for Protontherapy)

**Cell Coupled Linac**

**Standing-wave structure**

**RF frequency:** 5.7 GHz

**2.5 μs**-long pulse at 100 Hz

**TULIP** (TUrning Linac for Protontherapy)
Future Accelerators for Hadrontherapy

**SLAC X-band Proton Therapy Solution**

- **70 MeV Cyclotron**
- **130 MeV X-band standing wave linac**
- **Pulse compressor**
- **50 MeV X-band standing wave structure to accelerate and decelerate the p+ beam.**
Future Accelerators for Hadrontherapy

Cyclotron mounted on gantry

Monarch 250, courtesy of Still River
Future Accelerators for Hadrontherapy

**FFAGs** - Fixed-Field Alternating-Gradient accelerators

- Ring of magnets like synchrotron, fixed field like cyclotron

Dense lattice of EMMA, the first NS-FFAG (for electron acceleration)

Courtesy of C. Johnstone
The Cyclinac

Machine Performances: **Compactness**

done to scale!
Far future
Accelerators for Hadrontherapy
Future Accelerators for Hadrontherapy

**Dielectric Wall Accelerator (DWA)**

- 200 MeV protons in 2 meters
- Energy, intensity and spot width variable pulse to pulse
- Nanosec pulse lengths
- At least 200 degrees of rotation
- Up to 50 Hz pulse repetition rate
- Less neutron dose (neutrons still produced in the patient)
- System will provide CT-guided rotational IMPT

TomoTherapy has licensed the DWA technology from the Lawrence Livermore National Laboratory and CPAC has a Cooperative Research and Development Agreement (CRADA) with LLNL.
Future Accelerators for Hadrontherapy

Laser-driven proton beam therapy

Courtesy of JAEA Photo-Medical Research Center (PMRC)
Summary
## Accelerators for Hadrontherapy

### Requirements

<table>
<thead>
<tr>
<th>Beam Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min./Max. Extraction Energy [MeV/u] (range variation: 3-32 cm)</td>
<td>60/230 (protons) 110/430 (carbon ions)</td>
</tr>
<tr>
<td>Beam Intensity [nA] (average dose rate: 2 Gy/min/L)</td>
<td>1 (protons) 0.1 (carbon ions)</td>
</tr>
<tr>
<td>Repetition Rate [Hz] (+ fast scanning (in milliseconds) ) to treat moving organs</td>
<td>200-300</td>
</tr>
</tbody>
</table>

Preferably,  
*energy modulation without absorbers*

In addition...  
*reduced size and cost*
Hadrontherapy in the world

Present accelerators for hadrontherapy

**Cyclotrons:** compact, reliable, easy to operate

- *however...* fixed energy beam ↔ movable absorbers
  - → long Energy Selection System line
  - → neutron activation and carbon fragmentation
  - → energy modulation in 80-100 ms

**Synchrotrons:** variable energy beam

- *but...* → energy modulation in 1-2 s
Novel Accelerators for Hadrontherapy

different accelerator types have been proposed...

Fixed-Field Alterning-Gradient (FFAG) accelerators:
- high-repetition rate (~ kHz), active energy modulation
- but... → so far not so compact
- → challenging injection and extraction systems (dense lattice!)

Cyclinacs (cyclotron + RF linac):
- high-repetition rate (~ kHz), active energy modulation

Long-term candidates

Dielectric Wall Accelerators (DWA):
- Compact if required accelerating gradients are achieved (1 → 100 MV/m)

Laser-driven accelerators:
- Is it possible to get clean, monoenergetic beams?
Some material belongs to…

• Ángeles Faus-Golfe, “Present & Future of Accelerators for Hadrontherapy”, IFIMED’09 symposium, June 2009, Valencia (Spain)


• Silvia Verdú-Andrés, “Comparison between RF linacs and FFAGs for hadrontherapy”, PARTNER deliverable (2011).

Bibliography

• GAP (Group of Accelerator Physics) of IFIC (project leader: Ángeles Faus-Golfe): http:\gap.ific.uv.es
• U. Linz and J. Alonso, *What will it take for laser driven proton accelerators to be applied to tumor therapy?*, Physical Review Special Topics – Accelerators and Beams, Volume 10 (9) American Physical Society (APS) – Sep 1, 2007

Thanks for your attention