Heavy Ion Tumor Therapy
Accelerators and Application

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Overview

1. Acquiring Heavy Ions
2. Accelerators
   - Cyclotrons
   - Synchrotrons
3. Beam Delivery
   - Passive Systems
   - Active Systems
   - Gantries
   - Patient Movement
4. Dose Monitoring
Acquiring Heavy Ions
Acquiring Heavy Ions

- Long distance transport of ions is inefficient
  → ions have to be generated on site

- Generate plasma from working element
  → apparatus are fit to material & demands
Electron Impact Ionization

Acquiring Heavy Ions
Plasma Generators

Acquiring Heavy Ions

Diagram showing a plasma generator with labeled parts: Multicusp magnets, Gas inlet, Filament, Plasma, and Ion Beam.
Accelerators
Magnetic Rigidity

Accelerators

\[ B \cdot r = \frac{\gamma \cdot m \cdot v}{q} \]

\( B \hat{=} \text{magnetic field strength} \)
\( r \hat{=} \text{path radius} \)
\( \gamma \hat{=} \text{Lorentz-factor} \)

\( m \hat{=} \text{ion mass} \)
\( v \hat{=} \text{ion velocity} \)
\( q \hat{=} \text{ion charge} \)
Cyclotrons
Accelerators
Cyclotrons

Pros & Cons

Advantages:
- compact setup
- easy operation
- stable beam intensity

Drawbacks:
- no energy variation
- typically low energies
TRIUMF ($d \approx 18\,\text{m}$) produces protons at $\sim 520\,\text{MeV/u}$

→ uses 4000 t magnet with $B \approx 0.46\,\text{T}$

$E_{\text{kin}}$ for $^{12}\text{C}$ ions:

$$v = \frac{B \cdot r \cdot c \cdot q}{\sqrt{B^2 \cdot q^2 \cdot r^2 + c^2 \cdot m^2}}$$

$\approx 0.1\,c$  \quad  \approx 5\,\frac{\text{MeV}}{\text{u}}$
Ion Range

Cyclotrons
Synchrotrons
Accelerators
Setup
Synchrotrons
Pros & Cons
Synchrotrons

Advantages:
- fast energy variation
- higher energies

Drawbacks:
- pre-acceleration needed
- operation more complex
- typically large
Range: $p$ vs. $C^+$

Synchrotrons
Assume 1.8 T dipole magnets (used at SIS18 at GSI):

\[
\frac{E_{\text{kin}}}{m} = 131.46 \ \text{MeV} \ \frac{u}{u} \ \Rightarrow \ \nu \approx 0.5 \ c
\]

\[
r = \frac{\gamma \cdot m \cdot \nu}{q \cdot B} \approx \frac{1}{\sqrt{1 - 0.5^2}} \ \frac{1 \ u \cdot 0.5 \ c}{e \cdot 1.8 \ T}
\]

\[
\approx 1 \ m
\]
C\(^+\) at 250 \(\text{MeV}_u\) has the same range as p at 131.46 \(\text{MeV}_u\):

\[
\frac{E_{\text{kin}}}{m} = 250 \frac{\text{MeV}}{u} \quad \Rightarrow \quad v \approx 0.6 \, c
\]

\[
r \approx \frac{1}{\sqrt{1 - 0.6^2}} \frac{12 \, u \cdot 0.6 \, c}{\epsilon \cdot 1.8 \, T}
\]

\[
\approx 15 \, \text{m}
\]
FAIR building site
Synchrotrons
Beam Delivery
Beam Delivery

- particles need to be transported to treatment area

- beam should be accurately distributed over PTV

- two basic strategies:
  - passive beam shaping
  - (active) scanning
Passive Systems
Beam Delivery
Beam Shaping

Passive Systems

Diagram showing various components and their interactions in beam shaping for tumor therapy.

- Scattering system
- Range modulator
- Range shifter
- Collimator
- Compensator
- Tumor
- Skin

Dose profiles illustrating the distribution of energy along the z-axis.
Active Systems
Beam Delivery
Idea:

- divide PTV into layers of equal depth
- cover each layer with grid of voxels

→ deliver dose sequentially to these voxels
Spot-Scanning
Active Systems

[Diagram showing a wobbler magnet, beam pipe, range shifter, He gas, Bragg Peak, monitor system, patient transporter with dosimetric phantom]
Gantries
Beam Delivery
Motivation

Gantries

- Treatment planning uses imaging techniques.
- Patient should be in same position during treatment.
- Possibility of irradiation from any direction desirable.
Gantry Design

Gantries
Gantry - HIT
Gantries
Gantry - HIT

Gantries

- 360° rotation
- 25 m long
- 13 m in diameter
- 600 t in weight
- < 1 mm uncertainty

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Heavy Ion Tumor Therapy

08.07.2019 26 / 36
Gantry - HIT: treatment area

Gantries
Gantry - HIT: treatment area

Gantries
Patient Movement
Beam Delivery
PTV Shift
Patient Movement
Respiratory Gating
Patient Movement

![Graph showing respiratory gating and patient movement over time](image)

- **Relative voltage**
- **Time [s]**

The graph illustrates the relationship between respiratory gating and patient movement over time, depicting how the gating mechanism synchronizes treatment delivery with patient motion.
Tracking Patient Movement
Dose Monitoring
Fragmentation

Dose Monitoring

Abrasions

Ablation

projectile

target

$V_p$

$V_f \approx V_p$

evap.

fireball

$p, d, t$

$\alpha, n$

projectile fragment

target fragment
PET (in situ)
Dose Monitoring

Ion beam

$^{12}\text{C}$

$^{11}\text{C}$

PET camera
Autoactivation Profile

Dose Monitoring
Measurement vs. Prediction

Dose Monitoring

planned dose distribution    predicted $\beta^+$-activity    measured $\beta^+$-activity
[4] https://commons.wikimedia.org/wiki/File:Cascade-process-of-ionization.svg; Original by user 'Rudolfensis', parts were rotated
[16] https://upload.wikimedia.org/wikipedia/commons/3/34/Aerial_view_of_FAIR.JPG; Alexander Blecher
[26], [27] https://www.helmholtz.de/gesundheit/die-groesste-waffe-gegen-krebs/

[29] https://commons.wikimedia.org/wiki/File:Clinac.jpg; Original by user 'Egg'