Application of medical accelerators

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Student seminar 16/05/2019
Outline

- **Introduction**
  - Review of existing accelerators
  - Cancer treatment methods

- **Application in hadron-therapy**
  - Hadron-therapy
  - Requirements in accelerator technology for hadron therapy

- **The main types of medical accelerators**
  - Circular or cyclic RF accelerators
  - Linear accelerators

- **RF design of HG acceleration structures**

- **Overview of hadron-therapy centers**

- **Conclusions**
## Existing accelerators

There are more than 17,000 particle accelerators in the world (with energy above 1 MeV)

<table>
<thead>
<tr>
<th>Research</th>
<th></th>
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<tbody>
<tr>
<td>Particle physics</td>
<td>0,5%</td>
</tr>
<tr>
<td>Nuclear physics, solids, materials</td>
<td>0,2 a 0,9%</td>
</tr>
<tr>
<td>Biology</td>
<td>5%</td>
</tr>
</tbody>
</table>

| Medical application                       | 35%   |
|Diagnosis / treatment with X-rays or electrons | 33%   |
|Radioisotope production                    | 2%    |
|Proton and ion treatment                   | 0,1%  |

| Industrial applications                   | 60%   |
|Ion implantation                          | 34%   |
|Cutting and electronic welding            | 16%   |
|Polymerization, ...                       | 7%    |
|Neutron treatment                         | 3.5%  |
|Non-destructive testing                   | 2,3%  |
Transfer technologies
from high energy physics to medical applications

Accelerate particle beams

Hadron therapy

Detect particles

Medical imaging

Large scale Computing (Grid)

Grid computing for medical data management and analysis

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Today: cancer incidence

- Every year millions of new cases globally;
- 9.6 million death from cancer in 2018: nearly 1 in 6 deaths is due to cancer (WHO);
- The main cause of death between the ages of 45 and 65 in Europe, Canada and the US;
- Cancer is the second leading cause of death globally.

Treatment options:

Primary tumour

- Surgery
- Radiotherapy
  - X-ray, IMRT
  - Hadron therapy

Metastasis

- Other treatments
  - Hormones; Chemotherapy; immunotherapy; Cell therapy; Genetic treatments...

Local control

Survival quality of life
Most frequent cancer type

A genetic **predisposition** to a particular type of cancer (a tendency to develop a disease).

184 countries

- (n) number of countries in which that cancer is the most common: data from GLOBOCAN 2012, IARC (Lyon, France)
Conformal irradiation of tumour volume (= reduced damages to healthy tissues)

What advantages with hadrons?
+ PRECISION
+ EFFICACY

Conformal irradiation of tumour volume (= reduced damages to healthy tissues)

Increased radiobiological efficacy of carbon ions (= DNA of tumour cells destroyed in multiple hits)
Photons and electrons

- Physical dose high near surface;
- DNA damage easily repaired
- Biological effect lower
- Effect not localised

Hadrons

- Dose highest at Bragg Peak
- DNA damage not repaired
- Effect is localised:
  - Tumours close to critical organs
  - Tumours in children
  - Radio-resistant tumours

Treatment plan for protons and X-rays by Universitätskliniken Wien & Innsbruck
Accelerators for medicine

The potential of accelerators: a bloodless surgery and imaging

penetrate into the human body to treat diseases and to observe internal organs without using surgical tools.
Charged particles: Protons, light ions (He 2+, C 6+, O 8+)

Energy range: 70-230 MeV for protons, 100-430 MeV / amu - C6+

Dose: 1 to 2 Gray per minute per liter of tissue

Rapid changes in beam energy: \( E < 5 \text{ MeV} \) for 1-2 s

Low emissivity: 1–3 \( \pi \text{ mm-mrad} \)

Low power consumption: 100 to 300 kW

Low maintenance and ease of use.

A small “foot print” for placement in clinics.

Low impact of neutrons on personnel / low activation of equipment.

Small enough to rotate around the patient.
## The main type of medical accelerators

<table>
<thead>
<tr>
<th>Type of acc.</th>
<th>Electron therapy</th>
<th>Proton therapy</th>
<th>Ion therapy</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electron LINAC</strong></td>
<td><strong>Cyclotron</strong></td>
<td><strong>Synchrotron</strong></td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Type of particle</th>
<th>Electron, proton</th>
<th>Protons</th>
<th>Ions (proton, carbon)</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th># in the world</th>
<th>40 000</th>
<th>~ 60</th>
<th>6</th>
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</table>
Proton Cyclotron

At present, the cyclotron is the best accelerator to provide proton therapy reliably and at low cost.

Critical issues with cyclotrons:
Energy and current is constant (degrader, modulator)
1. **Energy modulation** is obtained with degraders (sliding plates) that are slow and remain activated.
2. **Large shielding**
Synchrocyclotron

type of cyclotron in which the frequency of the driving **RF electric field** is varied to compensate for relativistic effects of the particles

- Acceleration depends on the frequency, the work is pulsed.
- Strong electric fields for high acceleration are not required.

- SC medical cyclotron at 250 MeV diameter ~ 1 m

**Disadvantages:**

- Presence of **weak focusing**,
- RF generators lose efficiency with increasing frequency,
- produces high energy ions but relatively **low intensity**.

- accelerating voltage ~ 20 kV
- RF power 10 - 100 kW
- frequency of repetitions 100 - 400 Hz
Synchrocyclotron

type of cyclotron in which the frequency of the driving RF electric field is varied to compensate for relativistic effects of the particles

1. Synchrocyclotron with superconducting coil: S2C2
2. New Compact Gantry for pencil beam scanning
3. Patient room

ProteusONE Smart-scaled, single-room IMPT
Synchrotron

- Protons and C ions
- Slow energy variation
- Acceleration of beams to the desired extraction energy

**Disadvantages:**
- Size
- Cost
- 1 Hz

Proton: 60 – 250 MeV (NCR: 800)
Carbon: 120 – 400 MeV/u

**MedAustron,** Vienna, Austria
Scan: Pencil beam scanning

Bragg peak of the proton beam with
- set initial position (x)
- energy (E)
- pulse (p)

Typical beam parameters:
Δx=±3 mm, Δθ=±10 mrad, Δp/p=±0.5%

Benefits:
✓ heterogeneous energy layers;
✓ intensity modulation: x, p, N_protons;
✓ dose formation within the target (organ motion errors)
Linear accelerator (LINAC)

**Electron linac**

- Direct use of electrons or protons;
- X-rays: electrons generating collimated X-ray beams through “bremsstrahlung” when stopped at an internal target.

**Proton linac**

- Compactness
- Relative availability
The most successful accelerator

**Electron Linac** (linear accelerator) for **radiotherapy** (X-ray treatment of cancer)

In the world radiation oncologists use **20 000 electron linacs:**

2000 patients/year every in 1 million inhabitants
Alternative solutions: Linear Accelerator

The linear accelerator (Linac) looks as the most promising option on terms of size, complexity and efficiency.

Advantages:

✓ active energy variation (pulse to pulse),
✓ treatment time (a high repetition rate).

TULIP: Single-room proton therapy

Advantages: footprint (200 m², 70 ton), shielding

CABOTO: CAarbon BOoster for Therapy in Oncology

Advantages: beam current, power consumption

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High Gradient Technology: What is it?

- Accelerating structures;
- Fabrication technology;
- HG RF test stand;
- Prototype performance;
- High-efficiency klystrons and RF components.
HG acceleration structures for protons

- **Traveling wave structure**
  - BTW prototype: 60 MV/m

- **Standing wave structure**
  - PROBE Structure: 54 MV/m

**High peak fields** increase the **structure performance** in areas of:

- Higher acceptance (larger emittance beams);
- Greater space charge capability;
- Shorter size;

But also have the effect of:

- Increased probability of sparking;
- More RF power required;
- Tighter machining and alignment tolerances.
RF structure fabrication procedure

**ENGINEERING DESIGN**
- 3D models and 2D drawings, including thermo-structural simulations

**MACHINING**
- Cleaning, assembly of couplers, alignment, bonding/brazing cycles, QC, RF measurements, final vacuum baking
- Tendering, contract adjudication, QC at factory (dimensional control, Ra)

**ASSEMBLY**
- Installation, leak tightness, tuning, high power test

**TESTING**

*RF lab integration*

*IFIC*

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Involved technologies

- Power supplies
- Laser, RF system, HV etc.
- Cooling system
- Vacuum system
- Beam diagnostics
- C&C system and software
- Interlock & safety systems
- Plasma diagnostics
Strategy of Medical accelerators

Competitor in the global market

State-of-the-art and market leader:

**IBA superconducting synchrocyclotron**

Can a linac based solution be competitive?

**Advantages:**

- pulsed with fast energy (200 Hz),
- follow body motion,
- cost, ~40 M$
Proton/carbon therapy facility in the world

Cumulative operation therapy centers

- Proton therapy facilities
- Proton therapy facilities, under construction
- Carbon therapy facilities
- Carbon therapy facilities, under construction

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Carbon therapy facility in the world

Carbon Ion Centers Worldwide: 11
(in operation by April 2018)

Europe
- HIT Heidelberg
- MIT Marburg
- CNAO Pavia
- MedAustron

Asia
- 7

© MedAustron • Data: PTCOG, April 2018
HIT – Heidelberg (Germany, since 2010)

Carbon ions: pilot project in Europe

G. Kraft (GSI) & J. Debus (Heidelberg)
450 patients treated with carbon ions

The HIT heavy ion gantry, weight about 600 tons
PROSCAN at PSI, Switzerland

ACCEL
SC cyclotron
250 MeV protons

Hadron Therapy Center in Italy - CNAO

CNAO

~55 x 55 m²

Room 2
Room 1

S. Rossi

CNAO - Pavia

22 m
In March 2018 the SEEIIST (8 Balkan countries) has decided to build a combined cancer therapy and biomedical research facility (preferred to a synchrotron light facility).

- Funding (150-200M) primarily from structural and preaccession EU funds.

- 2 years to prepare a TDR.
Positron emission tomography (PET) is a nuclear medicine functional **imaging technique** that is used to observe metabolic processes in the body as an aid to the diagnosis of disease.

Annihilation of a positron stopped in the tissue of the body, with one of the electrons, generates two gamma rays (an energy of 511 keV, flying at an angle of 180).

- carbon-11 (T½ = 20.4 min)
- nitrogen-13 (T½ = 9.96 min)
- oxygen-15 (T½ = 2.03 min)
- fluorine-18 (T½ = 109.8 min)
A radioisotope (radiotracer) is produced by an accelerator (usually a cyclotron).

- Isotopes and radiochemical drugs are shipped by road or air to the hospital (FDG half-life 1h50’).
- This scheme works well in Europe and US (shows limits in Asia and rest of world).

Alternative accelerator systems under study: Isotope production in hospitals

AMIT superconducting cyclotron for isotope production in hospitals

The CERN design of a 2-stage HF-RFQ system to 10 MeV. Footprint: 15 m²
Conclusions

Medical accelerators is a vast and promising field, connected to one of the main technology drivers of XXIst century:

- wide space for improvement
- requires the development of new technologies

Open questions:

**How to get to 350 MeV?**
- Synchrotrons (slow)
- Linear boosters (fast but big)
- Cyclotrons (limited to ~ 250 MeV)

**Are carbon ions better than protons?**

However, the accelerator is only a (small) part of facilities devoted to delivering medicine to patients.
Thank you for your attention!
EXTRA SLIDES

History of hadron therapy

- Proposed by R.R. Wilson
- 1st patient at Berkeley by Lawrence
- 1st patient in Europe at Uppsala
- MedAustron (Austria)
- CNAO, Pavia (Italy)
- HIT (carbon), Heidelberg (Germany)
- PSI, Switzerland
- Eye tumours, Clatterbridge, UK
- GSI carbon ion pilot, Germany
- CPO (Orsay), CAI (Nice), France
- Loma Linda (clinical setting) USA
- Boston (commercial centre) USA
- NIRS, Chiba (carbon ion) Japan
- PIMMS
- ENLIGHT 10th year

Manuela Cirilli, Manjit Dosanjh
Knowledge Transfer Group

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