Production of particle beams: Cyclotrons

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Production of particle beams: cyclotrons

- Dose delivery techniques
- How does a cyclotron work:
  - Magnet
  - Ion source
  - RF
  - Extraction
- Very small cyclotrons
- Cyclotrons for carbon-ions
Dose delivery techniques
Dose delivery techniques: **Width**

**transversal spread:**

- **scattering** (protons only)
- **scanning** (all hadrons)

**Diagram:**

- Scatter system
- Collimator
- Scanning magnet
Dose delivery techniques: Depth

250 MeV protons

Spread-out Bragg peak

Cyclotron has fixed energy => slow down (degrade) to desired energy

Just before the patient

Entrance of beam line

fast degrader (PSI)
Energy selection system

Rolled-up wedge degrader
220-70 MeV  (IBA)

Multiple wedge degrader
238-70 MeV  (PSI)
5 mm ΔRange in 50 ms

Beam analysis: energy selection
dp/p < ± 1%
Intensity loss by degrader and collimator

**Degrader purpose:** decrease energy

- *energy spread* increases
- *beam loss* due to nuclear reactions in degrader
- *beam size* increases due to multiple scattering

Collimators define transmitted beam size

$\Rightarrow$ **Beam intensity from the cyclotron must be high enough**


$dp/p = \pm 0.6\%$

$\varepsilon_{x,y} = 44\pi \text{ mm.mrad}$
The problem in dynamical treatments:

- Organ movement

⇒ Danger to underdose and overdose

Solutions:

- Beam gating
- Multiple scans of tumor
- Adaptive scanning

⇒ increase scan speed laterally + in depth

Cyclotron optimal for this
Fast pencil beam scanning

Cont. scanning “TV” mode

kHz-Intensity modulation

After each layer:
Energy change in 80 ms

7 s for a 1 liter volume.
Target repainting:
15-30 scans / 2 min.
How does a cyclotron work?
Cyclotron as seen by a medical physicist

\[ E = 250 \pm 0.1 \text{ MeV} \]

\[ I = 100-1000 \text{ nA} \]

\[ \varepsilon = 2 \text{ mm} \times 2 \text{ mrad} \]
Cyclotron as seen by a medical doctor
Cyclotron (1930)

Ernest Lawrence (1901-1958)

At each electrode border:

Energy gain \( \Delta E = V_{\text{dee}} \)

RF-Electrodes: 2 “Dees”

Extractor: \(-HV\)

Ion source

Magnet

Production of particle beams: cyclotrons, Marco Schippers, PSI
Cyclotron

80 keV protons

12 MeV cyclotron (UC, 1940)

PSI Injector 1, 72 MeV, 1970

230 MeV cyclotron (IBA, 1996)
Circular orbits:

Centripetal force = Magnetic force

\[ \frac{m v^2}{r} = B q v \]

=> \[ T_{circle} = \frac{2 \pi m}{B q} \]

=> \( T_{circle} \) independent of orbit radius \( r \)

- \( m \) = mass
- \( v \) = speed
- \( r \) = orbit radius
- \( B \) = magnetic field
- \( q \) = charge
Circular orbits: \[ T_{\text{circle}} = \frac{2\pi m}{qB} \]

\( T_{\text{circle}} \) independent from radius \( r \)

However:

\[ m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}} \]

when \( v \rightarrow c \):

250 MeV p: \( v/c = 0.61 \Rightarrow m = 1.27m_0 \)

\( T_{\text{circle}} \) increases with radius

\( \Rightarrow \) particles lose pace with frequency of V\text{dee} (RF).
Remedies when $T_{\text{circle}}$ increases with radius:

1) decrease $f_{\text{RF}}$ with radius.
   
   (synchro-cyclotron; pulsed)

2) increase $B$ with radius

\[
T_{\text{circle}} = \frac{2\pi m}{qB}
\]

\[
m = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} m_0
\]

\[
\gamma(r) = \frac{B(r)}{B_0}
\]

\[
\gamma = 1.27
\]

\[
B_0 = 2.4 \text{ T}
\]

\[
B(r) = \gamma(r) \cdot B_0
\]

\[
\gamma = 1.27
\]

\[
3.0 \text{ T}
\]

\[
B_0 = 2.4 \text{ T}
\]
How to increase field with radius

1) Decrease pole gap at large Radius (IBA)

Elliptical gap between poles C235
2) Use SC coils to employ very strong electric current
   → very strong magnetic field
   → coil field adds to shape of magnetic field (ACCEL / Varian)
Vertical focussing is important

Particles travel 1-2 km

When $B$ decreases with radius:
Automatic vertical stability

When $B$ increases with radius:
No vertical stability
When $\phi \neq 0$:

$$\vec{B}_\theta \times \vec{v}$$

=> vertical force

Main field increases with radius

=> $\phi$ must also increase to maintain vertical focusing

=> spiral shaped “hills”
250 MeV proton cyclotron (ACCEL/Varian)

- Closed He system
  - 4 x 1.5 W @4K

- Proton source

- Superconducting coils
  - => 2.4 - 3.8 T

- 4 RF-cavities
  - ~100 kV on 4 Dees

ACCEL

- 300 kW
- 90 tons

Dimensions:
- 1.4 m
- 3.4 m
Internal proton source

- Cathode at -HV
- Anode
- ~5 cm distance
- Pole

Production of particle beams: cyclotrons, Marco Schippers, PSI
Internal proton source

-80 kV

Dee 1

pole
Intensity control

Max. intensity set by:
proton source

Deflector plate:
sets requested intensity
- within 50 µs
- 5% accuracy

Slit position => beam alignment
Slit aperture => beam intensity

Beam Intensity

Intensity control

- $V$
- $+V$

+ slits
Cyclotron beam structure: regulated, DC

Beam intensity

Control signal

60 sec

Stable beam =>

Example from IBA, 1998

fast intensity modulation

σ=3%

Production of particle beams: cyclotrons, Marco Schippers, PSI
Important parameters:

- Voltage on Dee
- Number of Dee’s

⇒ Energy gain per turn
⇒ Orbit separation
⇒ Extraction efficiency
RF system: Dee

- Dee
- RF current
- Coupler
- Short plate
  => resonance frequency
- RF signal
- Hill
- Magnet pole
resonant extraction

With field bump

![Graph showing energy vs. radius with septum and HV labels]
Self-extraction: Realization by IBA

Small elliptical hill gap ⇒ allows for sharp radial gradients
‘magnetic septum’ ⇒ groove machined in the pole

Pole with groove
Extraction from cyclotron

Electrostatic extraction elements

Extraction - channel

80%

“Low” radioactivity

(ACCEL / Varian)
beam on/off

**In cyclotron:**
- vertical deflector plate → \( V_{\text{max}} \)
- RF → Power off or low
- ion source → off
- mechanical stopper → in

**In beam line:**
- mechanical beam stopper in
- fast kicker magnet
Cyclotron as seen by the financial director
Small cyclotron on a gantry

Proposal of H. Blosser et al., 1989:
- 250 MeV
- 52 tons, on gantry
- B(0) = 5.5 Tesla

H. Blosser, NSCL (~1990):
cyclotron for neutron therapy;
30 MeV p, mounted on a gantry
Used in Harper Hospital, Detroit

FIG. 9 -- Drawing showing synchrocyclotron rotating gantry arrangement with energy shifting wedge just after the cyclotron. Energy shifting can optionally be accomplished just ahead of the patient.

Fig. 2 Photo of the superconducting medical cyclotron on its gantry. Dr. William Powers and
Small cyclotron on a gantry

Gantry with integrated accelerator and ESS
Small cyclotrons with strong field

Small cyclotron => **very strong** magnetic field

=> iron is saturated ("air like")
=> hills and valleys do not work
=> vertical focussing only by decreasing $B(r)$

and: $m$ increases with energy (relativity)

=> $T_{\text{circle}}$ increases with radius

**Remedy:**

=> decrease $f_{RF}$ with radius. (synchro cyclotron)

\[ T_{\text{circle}} = \frac{2\pi m}{qB} \]

=> pulsed beam (1 kHz)
Synchro-Cyclotron

8-10 T Synchro-cyclotron on a gantry

Still River

— Pulsed beam
— No scanning
— Neutrons ?
— Activation ?
— No beam analysis
— Beam sharpness ?
— Reliability ?
(@ limit of current technology)
Carbon-ion cyclotrons
Carbon-ion cyclotrons

- Proton (250 MeV) (250 MeV/nucl)
  - Range in water = 38 cm
  - 2.43 Tm

- Helium 2+ (α) (250 MeV/nucl)
  - Range in water = 4.86 Tm

- Carbon 6+ (450 MeV/nucl)
  - Range in water = 6.83 Tm

⇒ For carbon ions cyclotron needs 2.8 times larger radius
⇒ So ~2.8^2 = 8 x more iron => 700-800 tons

Synchrotron Ø = 25 m + injection
Cyclotron Ø = 7 m
Archade project

IBA

Carbon ions
protons

700 tons
SC coils
Ø 7 m

Int. Conf. Cyclotron and appl, Tokyo 2004
IBA C400 CYCLOTRON PROJECT FOR HADRON THERAPY
Y. Jongen, M. Abs, W. Beeckman, A. Blondin, W. Kleeven, D. Vandeplasche, S. Zaremba, IBA, Belgium
Catania design  250 → 300 MeV/nucl

Figure 3: Layout of the cyclotron with overdrawn the extraction trajectories by E.D. and by stripper. The E.D. and the M.C. positions are also shown.

LNS CATANIA PROJECT FOR THERAPY AND RADIOISOTOPE PRODUCTION
L. Calabretta, G. Cuttone, M. Re, D. Rifuggiato, LNS-INFN, Catania, Italy
M. Maggiore, University of Catania, LNS-INFN, Italy

Cyclotron conference, Tokyo 2004
Start with protons AND

- $\alpha$ + (up to 12.5 cm:) Carbon
- Second step: also 450 MeV/nucl Carbon
Relevant cyclotron specs for therapy

- Energy + its stability
- Beam size (emittance)
- Beam intensity + stability (kHz) + adjustability (range, speed)
- Extraction efficiency

- Frequency of unplanned beam interrupts
- Start up time after „off“ and after „open“
- Modular control systems + comprehensive user interface
- Maintenance interval, maintenance time, maintenance effort
- Activation level (person dose per year)

- Ions: time to switch ion species
- Synchro cycl: rep. rate, dose/pulse adjustable (scanning)?
Thank you!!