Cyclotrons
for high intensity beams

Mike Seidel
Paul Scherrer Institut
Switzerland
Cyclotrons - Outline

• classical cyclotron
  – concept, classification of circular accelerators, relativistic relations, isochronicity, scalings

• separated sector cyclotrons
  – concept, focusing, space charge, injection/extraction, high intensity related aspects...

• cyclotron subsystems
  – RF, magnets, vacuum, diagnostics, electrostatic elements

• examples of existing high intensity cyclotrons
  – PSI-HIPA, RIKEN-SRC, TRIUMF

• discussion of pro’s and con’s
Classical Cyclotron

First cyclotron:
1931, Berkeley
1kV gap-voltage
80kV Protons

Powerful concept:
- Simplicity
- CW operation
- Multiple usage of accelerating voltage

Lawrence & Livingston, 27inch Zyklotron

Two capacitive electrodes „Dees“, two gaps per turn
Internal ion source
Homogenous B field
Constant revolution time (for low energy, $\gamma \sim 1$)
### Classification of Circular Accelerators

<table>
<thead>
<tr>
<th></th>
<th>Bending Radius</th>
<th>Bending Field vs. Time</th>
<th>Bending Field vs. Radius</th>
<th>RF Frequency vs. Time</th>
<th>Operation Mode (Pulsed/CW)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.G. Synchrotron</td>
<td>![Image 31]</td>
<td>![Image 32]</td>
<td>![Image 33]</td>
<td>![Image 34]</td>
<td>![Image 35]</td>
<td>High ( E_k )</td>
</tr>
</tbody>
</table>
basics – cyclotron frequency and $K$ value

- **cyclotron frequency** (homogeneous) $B$-field:
  \[ \omega_c = \frac{eB}{\gamma m_0} \]

- **cyclotron $K$-value**:
  \[ K = \frac{e^2}{2m_0} (B \rho)^2 \]

  $K$ is the **kinetic energy reach** for protons **from bending strength** in non-relativistic approximation. $K$ can be used to rescale the energy reach of protons to other charge-to-mass ratios:
  \[ \frac{E_k}{A} = K \left( \frac{Q}{A} \right)^2 \]

  $K$ in [MeV] is often used for naming cyclotrons.

examples:  
K-130 cyclotron / Jyväskylä  
cyclone C230 / IBA
basics – isochronicity and scalings

• magnetic rigidity:
\[ B \cdot R = \frac{p}{e} = \beta \gamma \frac{m_0 c}{e} \]

• orbit radius from isochronicity:
\[ R = \frac{c}{\omega_c} \beta = R_\infty \beta \]
\[ = \frac{c}{\omega_c} \sqrt{1 - \gamma^{-2}} \]

• since \( R \propto \beta; \ B \cdot R \propto p \propto \beta \gamma \)
\[ \rightarrow B \propto \gamma \]

• turn number:
\[ n_t = \frac{m_0 c^2}{U_t} (\gamma - 1) \]

radius increment per turn decreases with increasing energy because the revolution time must stay constant
\[ \rightarrow \text{extraction becomes more and more difficult at higher energies} \]
basics – focusing in the classical cyclotron

• field index:

\[ \zeta = \frac{R}{B_z} \frac{\partial B_z}{\partial R} \quad (= \gamma^2 - 1) \quad \text{from isochronicity} \]

• betatron frequencies:

\[ \begin{align*}
\nu_r &= \frac{\omega_r}{\omega_c} = \sqrt{1 + \zeta} \approx \gamma \\
\nu_z &= \frac{\omega_z}{\omega_c} = \sqrt{-\zeta} \\
\end{align*} \quad \nu_r^2 + \nu_z^2 = 1 \]

obtained from equations of motion and first order expansion of magnetic field \( B_z \); note: \( \text{curl} B = 0 \) provides relation between \( B_z \) and \( B_r \)

to obtain vertical focusing: \( \frac{\partial B_z}{\partial R} < 0 \)

however, isochronicity requires: \( B_z \propto \gamma \), i.e. \( \frac{\partial B_z}{\partial R} > 0 \)

\( \rightarrow \) kinetic energy of classical cyclotron is limited because of lack of vertical focusing
Relativistic quantities in the context of cyclotrons

**Energy**

\[ E = \gamma E_0 \]

**Kinetic energy:**

\[ E_k = (\gamma - 1)E_0 \]

**Velocity**

\[ v = \beta c \]

**Momentum**

\[ p = \beta \gamma m_0 c \]

**Revolution time:**

\[ \tau = \frac{2\pi R}{\beta c} \]

**Bending strength:**

\[ BR = \beta \gamma \frac{m_0 c}{e} \]
useful for calculations – differential relations

\[
\frac{d\beta}{\beta} = \frac{1}{\gamma(\gamma + 1)} \frac{dE_k}{E_k}
\]

\[
\frac{dE_k}{E_k} = \gamma + \frac{1}{\gamma} \frac{dp}{p}
\]

\[
\frac{dp}{p} = \gamma^2 \frac{d\beta}{\beta}
\]
next: Sector Cyclotrons

the cyclotron concept suited for high intensity operation focusing, space charge, injection/extraction, high intensity related aspects...
today: Separated Sector Cyclotrons

- **edge+sector focusing**, i.e. spiral magnet boundaries, azimuthally varying B-field → next slide on focusing
- **modular layout**, larger cyclotrons possible, sector magnets, box resonators
- **external injection** required, i.e. pre-accelerator
- **radially wide vacuum chamber**; inflatable seals etc.
- Detailed **field shaping for focusing and isochronisity** required

- Strength: **CW acceleration**; higher energy up to 1GeV, high **extraction efficiency** possible:
  
  e.g. PSI: 99.98% = (1 - 2·10^{-4})

- **resonator**: 50MHz resonator
- **resonator**: 150MHz (3rd harm) resonator
focusing in sector cyclotrons

• hill / valley variation of magnetic field (Thomas focusing):

  Flutter factor:

  \[ F = \frac{B_z^2 - B_{\overline{z}}^2}{B_z^2} \]

  vertical betatron f.:

  \[ \nu_z^2 = -\frac{R}{B_z} \frac{\partial B_z}{\partial R} + F \]

• with additional spiral angle of bending field:

  \[ \nu_z^2 = -\frac{R}{B_z} \frac{\partial B_z}{\partial R} + F(1 + 2 \cdot \tan^2 \delta) \]
radius increment per turn

- losses at extraction are typically limiting the intensity
- the electrode of an extraction element is placed between last two turns
  → thus the radial stepwidth should be as large as possible

use orbit radius and turn number from previous slides:

\[
\frac{dR}{dn_t} = \frac{dR}{d\gamma} \frac{d\gamma}{dn_t} = \frac{R}{\gamma(\gamma^2 - 1)} \frac{U_t}{m_0 c^2}
\]

with isochronicity

\[
\frac{dR}{dn_t} = \frac{\gamma}{\gamma^2 - 1} \frac{R}{\zeta + 1} \frac{U_t}{m_0 c^2}
\]

more general;
\(\zeta\) - field index

- desirable: large radius
- desirable: large energy gain \(U_t\) (resonator voltages)
- field shaping at extraction radius helps
- note: strong decrease at relativistic energies (>1GeV not realistic for high intensity)
extraction with off-center orbits

Betatron oscillations around the “closed orbit” can be used to increase the radial stepwidth by a factor 3!

**radial tune vs. energy**
- Typically $v_r \approx \gamma$ during acceleration;
- But decrease in outer fringe field

**Without orbit oscillations:**
- Stepwidth from $E_k$-gain (PSI: 6mm)

**With orbit oscillations:**
- Extraction gap; up to 3 x stepwidth possible for $v_r=1.5\pi$ (phase advance)

**Particle density**

**Phase vector of orbit oscillations** $(r,r')$
extraction profile measured at PSI Ring Cyclotron

dynamic range: factor 2.000 in particle density

turn numbers

red: tracking simulation; black: measurement

position of extraction septum
d=50µm
PSI Ring Cyclotron – tune diagram

- coupling resonance – pass quickly!
- \( Q_r \) decreases towards extraction – enhance turn separation

**comments:**
- running on the coupling resonance would transfer the large radial betatron amplitude into vertical oscillations, which must be avoided
- special care has to be taken with fine-tuning the bending field in the extraction region
longitudinal dynamics – flattop resonator

- variation of accelerating voltage over the bunch length increases energy spread
- thus a third harmonic flattop resonator is used to compensate the curvature of the resonator voltage w.r.t. time
- optimum condition: $U_{\text{tot}} = U_0 (\cos \omega t - \frac{1}{9} \cos 3\omega t)$

broader flat region for bunch; available voltage reduced!
longitudinal space charge

• with overlapping turns use current sheet model; shielding of vacuum chamber must be considered; after W. Joho, Cyclotron Conf. Caen (1981)
• non-relativistic approximation
• accumulated energy spread couples to transverse plane and broadens beam

accumulated energy spread: $$\Delta E_k = \frac{16}{3} \frac{eZ_0}{\beta_{\text{max}}} \cdot I_{\text{peak}} \cdot n_t^2$$

thus beam width scales as $$n_t^2$$

orbit separation scales as $$U_t \propto n_t^{-1}$$

→ thus with constant losses at the extraction electrode the maximum attainable current scales as: $$I_{\text{max}} \propto n_t^{-3}$$

historical development of current and turn numbers in PSI Ring Cyclotron
different regime for very short bunches: formation of circular bunch

**in theory**
strong space charge within a bending field leads to rapid cycloidal motion around bunch center
[Chasman & Baltz (1984)]
→ bound motion; circular equilibrium beam distribution

**in practice**
time structure measurement in injector II cyclotron → circular bunch shape observed

blowup in ~20m drift
**Plot:** distribution after 100 turns, varying initial bunch length → short bunch stays compact, no tails!

- multiparticle simulations
- $10^5$ macroparticles
- precise field-map
- bunch dimensions:
  \[ \sigma_z \sim 2, 6, 10 \text{ mm}; \]
  \[ \sigma_{xy} \sim 10 \text{ mm} \]

Simulation: J.Yang, CAEA/Beijing; A.Adelmann, PSI
transverse space charge

with overlapping turns use current sheet model!

vertical force from space charge: \( F_z = \frac{n_v e^2}{\varepsilon_0 \gamma^2} \cdot z \)

particle density: \( n_v = \frac{N}{\sqrt{(2\pi)^3} \sigma_y D_f R \cdot \Delta R} \)

focusing force: \( F_z = -m_0 \gamma \omega_c^2 \nu_{z0}^2 \cdot z \)

\( \rightarrow \) equating space charge and focusing force delivers an intensity limit for loss of focusing!

tune shift from forces: \( \Delta \nu_Z \approx -\frac{2\pi r_p R^2 n_v}{\beta^2 \gamma^3 \nu_{z0}} \)
Components

resonators, magnets, vacuum, diagnostics, extraction/injection (electrostatic elements)
components: cyclotron resonators

cyclotron resonators are basically box resonators

resonant frequency: \[ f_r = \frac{c}{2} \sqrt{\frac{1}{a^2} + \frac{1}{l^2}} \]
cross sections of PSI resonators

original Al-Resonator
Oper. freq. = 51 MHz
Max. gap voltage = 760 kV
Power dissipation = 320 kW
$Q_0 = 32'000$ (meas. value)

new Cu-Resonator
Oper. freq. = 51 MHz
Max. gap voltage > 1MV
Power dissipation = 500 kW
$Q_0 \approx 48'000$

loop coupler @ 50MHz
copper resonator in operation at PSI’s Ring cyclotron

- \( f = 50.6 \text{MHz}; \ Q_0 = 4,8 \cdot 10^4; \ U_{\text{max}} = 1.2 \text{MV} \) (presently 0.85MV)
- wall plug to beam efficiency (RF Systems):
  32\% \ [\text{AC/DC: 90\%, DC/RF: 64\%, RF/Beam: 55\%}]
- transfer of up to \textbf{400kW power to the beam} per cavity
components: sector magnets

- cyclotron magnets typically cover a wide radial range → magnets are heavy and bulky, thus costly

PSI sector magnet

- iron weight: 250 tons
- coil weight: 28 tons
- orbit radius: 2.1...4.5 m
- spiral angle: 35 deg
components: sector magnets

- focusing and isochronicity need to be precisely controlled → sophisticated pole shaping including spiral bounds, many trim coil circuits
- modern cyclotrons use superconducting magnets; but for high intensity compactness is generally disadvantageous
cyclotron vacuum system

- pressure of $10^{-6}$ mbar is sufficient
- vacuum chamber with large radial width $\rightarrow$ difficult to achieve precisely matching sealing surfaces $\rightarrow$ noticeable leak rates must be accepted
- important design criterion is easy access and fast mountability
- use cryo pumps with high pumping speed and capacity

example: inflatable seals installed between resonators; length: 3.5m
injection/extraction schemes

• deflecting element should affect just one turn, not neighboured turn → critical, cause of losses
• often used: electrostatic deflectors with thin electrodes
• alternative: charge exchange, stripping foil; accelerate H\(^-\) or H\(_2^+\) to extract protons (problem: significant probability for unwanted loss of electron)
injection/extraction with electrostatic elements

principle of extraction channel

parameters
extraction chan.: 
$E_k = 590\text{MeV}$
$E = 8.8 \text{MV/m}$
$\theta = 8.2 \text{mrad}$
$\rho = 115 \text{m}$
$U = 144 \text{kV}$

major loss mechanism is scattering in $50\mu \text{m}$ electrode!

electric rigidity:

$$E\rho = \frac{\gamma + 1 E_k}{\gamma q} \approx \frac{2 U_k}{q}$$

for small energy; $U_k =$ accelerating voltage the particle has passed
cyclotron instrumentation
example: PSI 72MeV injector cyclotron

transverse probes «wire scanners»

phase probes «RF pickups»
injection channel

extraction channel
instrumentation: radial probe for turn counting / orbit analysis

wire scanner with three tilted wires delivers radial beam profile and some vertical information

radial: positions of individual turns

vertical/radial orbit positions and stored reference orbit (crosses)

«pseudo tomography» with tilted wires
phase probes are radially distributed RF pickups that detect the arrival time (phase) of bunches vs radius → adjustment of isochronicity

measured phase vs. radius; green: reference phase for «good conditions»

trim coil settings (12 circuits across radius) green: predicted from phase measurement
cyclootron examples
TRIUMF, RIKEN, PSI Ring
cyclotron examples: TRIUMF

- p, 520MeV, up to 110kW beam power
- diameter: 18m (largest n.c. cyclotron worldwide)
- extraction by stripping H\(^-\) → variable energy; multiple extraction points possible

photo: iron poles with spiral shape \((\delta_{\text{max}} = 70^\circ)\)
cyclotron examples: RIKEN (Jp) superconducting cyclotron

K = 2,600 MeV
Max. Field: 3.8T (235 MJ)
RF frequency: 18-38 MHz
Weight: 8,300 tons
Diameter: 19m
Height: 8m

superconducting
Sector Magnets: 6
RF Resonator: 4
Injection elements.
Extraction elements.

utilization:
broad spectrum of ions up to Uranium
RIKEN SRC in the vault
examples: PSI High Intensity Proton Accelerator

- Ring Cyclotron 590 MeV
  - 2.2 mA / 1.3 MW
  - Diameter: 15 m

- SINQ spallation source

- Meson production targets

- Proton Therapie center
  - [250 MeV sc. cyclotron]

- Dimensions: 120 x 220 m²
losses and resulting activation in PSI Ring

- maximum intensity is limited by losses (typ. 200-400nA) and **activation**
- losses at extraction dominate the activation
- thus efforts at optimizing performance are concentrated on the extraction
  → **largest possible turn separation; design of electrostatic septum**

**activation level allows for necessary service/repair work**
- personnel dose for typical repair mission 50-300μSv
- optimization by adapted local shielding measures; shielded service boxes for exchange of activated components
- detailed planning of shutdown work

**example (2010):**
**personnel dose for 3 month shutdown:**
47mSv, 186 persons
max per person: 2.9mSv

*map interpolated from ~30 measured locations*
# Comparison of Cyclotrons

<table>
<thead>
<tr>
<th></th>
<th>TRIUMF</th>
<th>RIKEN SRC (supercond.)</th>
<th>PSI Ring</th>
<th>PSI medical (supercond.)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Particles</strong></td>
<td>H⁻ → p</td>
<td>ions</td>
<td>p</td>
<td>p</td>
</tr>
<tr>
<td><strong>K [MeV]</strong></td>
<td>520</td>
<td>2600</td>
<td>592</td>
<td>250</td>
</tr>
<tr>
<td><strong>Magnets (poles)</strong></td>
<td>(6)</td>
<td>6</td>
<td>8</td>
<td>(4)</td>
</tr>
<tr>
<td><strong>Peak Field Strength [T]</strong></td>
<td>0.6</td>
<td>3.8</td>
<td>2.1</td>
<td>3.8</td>
</tr>
<tr>
<td><strong>R&lt;sub&gt;inj&lt;/sub&gt;/R&lt;sub&gt;extr&lt;/sub&gt; [m]</strong></td>
<td>0.25/3.8...7.9</td>
<td>3.6/5.4</td>
<td>2.4/4.5</td>
<td>-/0.8</td>
</tr>
<tr>
<td><strong>P&lt;sub&gt;max&lt;/sub&gt; [kW]</strong></td>
<td>110</td>
<td>1 (86Kr)</td>
<td>1300</td>
<td>0.25</td>
</tr>
<tr>
<td><strong>Extraction Efficiency (tot. transmission)</strong></td>
<td>0.9995 (0.70)</td>
<td>0.9998 (0.63)</td>
<td>0.9998</td>
<td>0.80</td>
</tr>
<tr>
<td><strong>Extraction Method</strong></td>
<td>stripping foil</td>
<td>electrostatic deflector</td>
<td>electrostatic deflector</td>
<td>electrostatic deflector</td>
</tr>
<tr>
<td><strong>Comment</strong></td>
<td>variable energy</td>
<td>ions, flexible</td>
<td>high intensity</td>
<td>compact</td>
</tr>
</tbody>
</table>
Discussion

arguments for or against cyclotrons for high intensity beam production
pro and contra cyclotron

pro:  
- compact and simple design  
- efficient power transfer  
- only few resonators and amplifiers needed

con:  
- injection/extraction critical  
- energy limited to 1GeV  
- complicated bending magnets  
- elaborate tuning required

other:  
- naturally CW operation
thank you for your attention!