High Intensity Operation and Control of Beam Losses in a Cyclotron based Accelerator

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for the PSI Accelerator Team
Accelerator Facilities at PSI

- p-Therapie: 250 MeV, <1 μA
- Swiss Light Source: 2.4 GeV, 400 mA
- Neutron Source and Instruments
- central control room
- High Intensity Proton Accelerator: 0.59 GeV, 2.2 mA
- XFEL Injector: 250 MeV
Outline

• overview on accelerator and it’s performance
  [facility, achieved intensity]

• cyclotrons for high intensity beams
  [separation scaling with turn number, off-center injection, space charge scaling]

• losses and resulting activation
  [measured loss statistics, activated components, service personnel dose]

• summary
Overview PSI Facility

Injector II Cyclotron 72 MeV

Ring Cyclotron 590 MeV

2.2 mA / 1.3 MW

target M (d = 5mm)
target E (d = 40mm)

UCN source

proton therapie center [250MeV sc. cyclotron]

dimensions: 120 x 220m²
PSI Ring - a sector cyclotron

- **edge+sector focusing**, i.e. spiral magnet boundaries (angle $\xi$), azimuthally varying B-field (flutter F)
  
  $Q_y^2 \approx - \frac{R}{B} \frac{dB}{dR} + F (1 + 2 \cdot \tan^2(\xi))$

- **modular layout** (spiral shaped sector magnets, box resonators)
- **electrostatic elements** for extraction / external injection
- **radially wide vacuum chamber**; inflatable seals

- **strength**: CW acceleration; high **extraction efficiency** possible: 99.98% = 1 - $2 \cdot 10^{-4}$
- **limitation**: kin.Energy $\leq$ 1GeV, because of relativistic effects

50MHz resonator 150MHz (3rd harm) resonator
history of max. current in the PSI accelerator

- license operation with 2.2mA given: **1.3MW**
- 4 new Cu Resonators in Ring
- beam current is limited by beam losses and resulting activation;
- aperture limitation removed; new ECR source; 50Hz ripple problem solved: **1.4MW**
- upgrade measures kept absolute losses constant
- new record: **1.4MW**
new beam intensity record at PSI-HIPA

- low beam losses are key issue
- recent improvements:
  - new ECR source (emittance)
  - reduced 50Hz residual beam jitter
  - aperture restrictions in Ring removed
→ higher current at same loss rate possible
• cyclotrons for high intensity beams
  [separation scaling with turn number, off-center injection, space charge scaling]
### 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>Betatron</td>
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<td>Induction</td>
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<td>Microtron</td>
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<td>Varying $h$</td>
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<tr>
<td>Classical Cyclotron</td>
<td>←</td>
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<td>Simple, but limited $E_k$</td>
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<tr>
<td>Isochronous Cyclotron</td>
<td>←</td>
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<td>←</td>
<td>←</td>
<td>←</td>
<td>Suited for high power!</td>
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<tr>
<td>Synchro-Cyclotron</td>
<td>←</td>
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<td>←</td>
<td>←</td>
<td>←</td>
<td>Higher $E_k$, but low $P$</td>
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<tr>
<td>FFAG</td>
<td>←</td>
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<td>←</td>
<td>←</td>
<td>←</td>
<td>Strong focusing!</td>
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<tr>
<td>A.G. Synchrotron</td>
<td>←</td>
<td>←</td>
<td>←</td>
<td>←</td>
<td>←</td>
<td>High $E_k$</td>
</tr>
</tbody>
</table>

Critical for cyclotrons: **extraction, tuning, space charge**
turn separation and interpretation

for clean extraction a large stepwidth (turn separation) is of utmost importance; in the PSI Ring all efforts were directed towards maximizing the turn separation

general scaling:

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

violating isochronicity:

(more general expression, possible on outer turns)

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

- limited energy (< 1GeV)
- large radius \( R \)
- high energy gain \( U_t \)

- reduce field slope, i.e. decrease field index \( k \)
Without orbit oscillations: stepwidth from $E_k$-gain (PSI: 6mm)

With orbit oscillations: extraction gap; up to 3 x stepwidth possible for $\nu_r = 1.5\pi$ (phase advance)

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

Radial tune vs. energy

Typically $\nu_r \approx \gamma$ during acceleration; but decrease in outer fringe field

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

position of extraction septum, d=50µm

turn numbers

dynamic range: factor 2.000 in particle density

qualitative explanation from last slide
tail generation: longitudinal space charge

- beam tails, blowup by long. space charge (overlapping turns)
  \[ \text{sector charge density } \times \text{time in cyc.} \rightarrow \infty \text{ (# turns)}^2 \]
- loss at extraction element [1/turn separation] \[ \rightarrow \infty \text{ (# turns)}^1 \]

In summary:
• scaling of losses \[ \sim (# \text{ turns})^3 \rightarrow \text{high gap voltage advantageous!} \]
  
  is confirmed clearly by observation at PSI

[Joho 1981; T.Planche Tuesday]

Extraction electrode
Placed between turns [D.Reggiani, Wednesday]

consider rotating sectors of charge
test particle sees charge density within a circle
tomographic phase space reconstruction – no tails visible (within resolution)

action distribution, straight line = Gaussian \( \exp[-J/\epsilon] \)

590 MeV after Ring D. Reggiani
comment on tuning

• **systematic strategy for general setup**; e.g. using intermediate beam dumps to divide the machine into sections; using measurements of beam properties to identify problems
  
  [radial probes, radial probes with tilted wires, phase probes, loss monitors, masks with current measurement, collimators, wire scanners, inductive BPM’s, ionization chambers]

• beam **loss fine tuning** (last 20%..50% of full current) is done **completely empirically**; subtle effects lead to population of beam tails; all machine sections starting from the ion source can contribute to the tails
• losses and resulting activation

[measured loss statistics, activated components, service personnel dose]
loss development at PSI-HIPA

plots:
- loss current [nA] vs. beam current [µA]
- color code = frequency of operation at particular working point
- limit at 2200µA for standard operation; beyond that: test operation

100nA ≈ 5E-5
component activation – Ring Cyclotron

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

activation map of Ring Cyclotron
(EEC = electrostatic ejection channel)

personnel dose for 3 month shutdown (2012):
41mSv, 149 persons
max per person: 3.2mSv

cool down times for service:
2200 → 1700 µA for 2h
0 µA for 2h

map interpolated from ~30 measured locations
comments on radiation safety at PSI

- only small fraction (~150-190) of monitored personnel really involved
- group of 10 colleagues responsible for radiation safety of accelerator facility
- monitoring of radiation in facilities by TLD/CR39 dosimeters (~100) + grid of remotely readable dosimeters (12+4); some (~5) dosimeters outside PSI area
- 10 hand and foot monitors at exits of experimental hall
- access to hot-cell and specific radioanalytics

![Graph showing yearly accumulated charge and collective dose](image)

- History of accumulated charge and collective dose
  - [note: step in number of considered persons]
Summary

• excellent progress at PSI in recent years; 1.3MW CW beam power is standard (record 1.4MW); the relative loss level is of the order $1 \cdot 2 \cdot 10^{-4}$, i.e. < 300 Watts; average availability is 90%; 25-50 trips per day

• all stages of the accelerator contribute to halo generation; **empirical tuning** is most successful → depends on experience of operator

• very **high power operation** of accelerators requires special expertise in certain areas such as
  – loss monitoring/instrumentation, interlock and permit systems
  – thermo-mechanical and cooling problems
  – handling/characterization/disposal of activated components
  – licensing
message: good concepts are sustainable!

first cyclotron:
1931, Berkeley
Lawrence

Stammbach et al
1GeV/10MW
proposal (1997)
HB2012, Beijing

Thank you for your attention!
spare transparencies
longitudinal space charge; evidence for third power law

• at PSI the maximum attainable current indeed scales with the third power of the turn number

• maximum energy gain per turn is of utmost importance in this type of high intensity cyclotron

→ thus with constant losses at the extraction electrode the maximum attainable current scales as:

\[ I_{\text{max}} \propto n_t^{-3} \]
Losses – required vacuum quality

- losses are caused by inelastic scattering at residual gas molecules
- use inelastic reaction cross section to estimate losses
- convert to mean free path
- compute pressure for $10^{-5}$ relative loss

common gases:

<table>
<thead>
<tr>
<th>Gas</th>
<th>Mean Free Path (m)</th>
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<tbody>
<tr>
<td>air</td>
<td>747</td>
</tr>
<tr>
<td>CO</td>
<td>753</td>
</tr>
<tr>
<td>H$_2$</td>
<td>6110</td>
</tr>
<tr>
<td>Ar</td>
<td>704</td>
</tr>
</tbody>
</table>

mean free path:

$$\lambda_{\text{inel}} = \frac{A}{\rho N_A \sigma_{\text{inel}}}$$

$$\lambda_{\text{eff}} = \left( \frac{1}{P_0} \sum \frac{P_i}{\lambda_{\text{inel}}^i} \right)^{-1}$$

beam loss:

$$\frac{N_0 - N(l)}{N_0} = 1 - \exp(-l/\lambda_{\text{eff}}) \approx l/\lambda_{\text{eff}}$$

pressure for loss $< 10^{-5}$: $P_i(\text{air}) > 0.01$ mbar $\rightarrow$ easily achievable, vacuum no problem!
electrostatic elements for inj./extr.

principle of extraction channel

major loss mechanism is scattering in 50µm electrode!

parameters extraction channel:

\[ E_k = 590 \text{ MeV} \]
\[ E = 8.8 \text{ MV/m} \]
\[ \theta = 8.2 \text{ mrad} \]
\[ \rho = 115 \text{ m} \]
\[ U = 144 \text{ kV} \]
HIPA beam trip statistics:
non-interrupted run durations

these are integrated histograms
at a certain time you read how many
events with such duration or longer
occur per day
radiation monitoring: dosimeter network in experimental hall

[A.Fuchs, B.Amrein]