TOWARDS THE 2 MW CYCLOTRON
AND LATEST DEVELOPMENTS AT PSI

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D. Kiselev, A. Mezger, H. Müller, M. Schneider, A. Strinning
and others of the PSI Accelerator Team

Cyclotrons 2010, Lanzhou, China
Accelerator Facilities at PSI

p-Therapie
250 MeV, <1 μA
[M.Schippers, FRM1CO04]

Swiss Light Source
2.4 GeV, 400 mA

central control room

High Intensity Proton Accelerator
0.59 GeV, 2.2 mA

XFEL Injector
250 MeV
PSI Ring Cyclotron with team [2010]
Outline

• Facility Overview
  [accelerator chain, performance]

• Recent Performance Improvements and Developments
  [Ring resonators, ECR proton source, 10\textsuperscript{th} harmonic buncher, first beam on UCN source]

• Operational Experience
  [beam currents and losses in ’09/’10, problems with 50Hz jitter]

• Planned Upgrade Measures
  [resonators for injector II, new high power absorbers]

• Summary and Outlook
  [the case for high power cyclotrons]
Overview PSI Facility

Injector II Cyclotron 72 MeV
- isotope production
  \[ I_b < 100 \mu A \]  
- Ring Cyclotron 590 MeV

Cockcroft Walton
- 870 keV transfer channel
- 72 MeV transfer channel

\[ \mu/\pi \] secondary beamlines

2.2 mA /1.3 MW
- target M (d = 5mm)
- target E (d = 4cm)

UCN (new)

dimensions: 120 x 220 m²

proton therapie center
- [250MeV sc. cyclotron]

SINQ transfer channel

1.4 mA /0.8 MW
- CW operation

SINQ spallation source

SINQ instruments
High Power Proton Accelerators

PSI Upgrade Plan

plot: selected accelerators current vs. energy
power $\propto$ current $\cdot$ energy

PSI Parameters: [2.2mA, 1.3MW] $\rightarrow$ [3mA, 1.8MW]
Recent Performance Improvements and Developments

[Ring resonators, double seals, ECR proton source, circular beam / 10th harmonic buncher, first beam on UCN source]
major component: RF resonators for Ring cyclotron

- the shown Cu Resonators have replaced the original Al resonators (from 2008) [less wall losses, higher gap voltage possible, better cooling distribution, better vacuum sealing surfaces]
- \( f = 50.6 \text{MHz}; \ Q_0 = 4 \cdot 10^4; \ U_{\text{max}} = 1.2 \text{MV} \) (presently 0.85MV→187 turns in cyclotron, goal for 3mA: 165 turns)
- Wall Plug to Beam Efficiency (RF Systems): 32%
  [AC/DC: 90%, DC/RF: 64%, RF/Beam: 55%]
- transfer of up to 400kW power to the beam per cavity
  → very good experience so far
new inflatable double-seals

Motivation:
- frequent leaks with old seals

Issue:
- mechanically difficult design with length of ~3.5m

Experience:
- very good experience so far; practically no leaks occurred; early detection of problems via intermittent vacuum

Idea: U.Heidelberger (PSI)
design: company InnoRat
production: company Wartmann
FE computation: company Ingenis
circular beam in cyclotron with short bunches – motivation for “superbuncher”

**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

[court. R.Doelling see WEM2CIO04]
500MHz (10\textsuperscript{th} harmonic) Buncher

\textbf{status tests} [M. Humbel 2009]:

► positive effect on Ring extraction losses observed with small currents (200\,\mu A)
► at larger currents losses increase; no further studies in 2010 because of technical problems in other areas
► better phase control needed; necessity for adjusting transverse optics suspected
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New ECR-Source + Extraction System

► better reliability
► smaller emittance

[Ch. Baumgarten]
ECR Source Performance Summary

- output 12 mA...18 mA for $P_{RF}=390...600$ W
- trip rate about 1/day
- beam current noise < 1% at optimal settings
- 8 weeks of 24-h operation verified (more possible)
- beam emittance $\beta_{\gamma e_{\text{rms}}} = 0.046 \pi$ mm mrad
- plasma chamber tested with more than 700 Watts

slit emittance measurement

ECR source in place
New customer: source for Ultra Cold Neutrons

- **pulsed operation:** 8sec beam on / 900sec beam off (beam is switched between SINQ and UCN target)
- **ultra cold neutrons:** ~ 200neV
- **UCN converter using solid D$_2$ at 5K**
- **expect. density in storage vol.:** 1000cm$^{-3}$ UCN ( ~10 cm$^{-3}$ UCN today at ILL PF2)
- **application:** precision measurement of electric dipole moment (nEDM); precision n-lifetime measurement (under discussion)

UCN Tank:
- height = 6.5 m
- diameter = 1.7 m
- mass = 3.3 to

UCN storage volume, height 2.5 m, 2 m$^3$

opening for neutron guide

cold UCN-converter 30 dm$^3$ sD$_2$ at 5 K

spallation target (Pb/Zr)

heavy water moderator, 3.6 m$^3$ D$_2$O

1.3 MW pulsed p-beam

UCN Tank: 500uA for 5ms on target (Dec15, 2009)

first signals from target (Dec15, 2009)
Next:

- Operational Experience

[beam currents and losses in ’09/’10, problems with 50Hz jitter, enhanced losses]
beam current history in 2009/10

“plasma crisis” in Ring cyclotron [talk by M.Humbel, WEM2CCO03]
High loss conditions related to new ECR source matching / poor setup

- Full performance reached (2.2 mA)
- High loss from collimator
- Full performance reached (2.2 mA)
- Test operation at 2.3 mA

- 2009
- 2010
Observation of higher losses in early 2009

- graphite collimator (chamber protection) probably deformed or misaligned by RF heating → reduced vertical aperture
- decision: complete removal; rely now on (much improved) interlock system
beam loss statistics w/o collimator

- after removal of collimator operation at 2.2mA without problems
- plot: occurrence of combinations of extraction loss and beam current

![Graph showing beam loss statistics with and without vertical collimator](image-url)
enhanced losses in 2010 - attempt to detect beam tails (poor 2010 vs. good 2009 conditions)

**Method:** measure integrated distribution of particle action @72MeV for Gaussian distribution the integrated distribution of particle action "percentage outside certain emittance" is purely exponential; → no beam tails visible down to $10^{-3}$

$$\rho(I_x) = \frac{1}{\varepsilon_x} \exp\left(-\frac{I_x}{\varepsilon_x}\right), \quad \langle I_x \rangle = \varepsilon_x$$

$$\eta(I_x) = \int_{s=I_x}^{\infty} p(s) \, ds = \exp\left(-\frac{I_x}{\varepsilon_x}\right)$$
tomographic phase space reconstruction using five wire scanners

[D. Reggiani]

72 MeV: $\varepsilon_x = 6$ mm mrad

method: maximum entropy
50 Hz ripple modulates the beam

- 50 Hz ripple was always present in HIPA, but was strongly enhanced after installation of the new ECR source
- **position modulation of $\approx 1$rms beam width** (!) was observed
- it could be traced to a modulation of the RF power in the source, caused by an AC modulation of the filament heating of the magnetron
Next:

- Planned Upgrade Measures
  [resonators for injector II, new high power absorbers]
under production: new 50 MHz Resonator 2&4, Injector 2

**Specification**

- **Resonance frequency:** 50.6328 MHz
- **Accelerating voltage:** 400 kV
- **Dissipated power:** 45 kW@400kV
- **Tuning range:** 200kHz
- **Cavity RF-wall:** EN AW 1050
- **Structure:** EN AW 5083
- **Vacuum pressure:** 10^{-6} mbar
- **Cooling water flow:** 15 m3/h
- **Dimension:** 5.6x3.3x3.0 m
- **Weight:** 7000kg

(status: first resonator delivered; tested at 100kW !)

[design: PSI, company: SDMS/France]

[see talk by Lukas Stingelin, WEM2ClO01]
high power collimators behind Meson production target

- power: \(~85\text{kW}/2\text{mA per absorber}, \sim130\text{kW}\) for upgrade
- new collimator required with improved cooling / more even power distribution
- material GlidCop under discussion
- inspection of presently installed collimator: estimated dose \(12..35\text{dpa}(!))\)
- estimated activation \(\sim150\text{Sv/h}(!))\) @ 20cm distance

[D.Kiselev, J.Y.Lee]

target E (d = 4cm)
inspection of highly activated collimator in hot cell

prediction of dose rates near activated components:
beam deposition → rad.nuclide distribution in space → prediction of dose rate at probe position

observed:
thin flitter of Cu;
bulk copper intact;
no swelling

[D.Kiselev]
codes: Cinder’90
MCNPX

dose rates:
measurement and prediction

probe position

Collimator
Next:

- Discussion and Summary

[cyclotrons for high intensities, cyclotrons vs. linacs]
Discussion: high intensity beam in cyclotrons

critical: extraction loss

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

\[
\frac{dR}{dn_t} = \frac{R}{\gamma(\gamma^2 - 1)} \lessgtr \frac{U_t}{m_0c^2} \approx \frac{\gamma}{1 + \gamma} \frac{R}{v_r^2} \frac{U_t}{E_k}
\]

Extraction electrode
Placed between turns

In summary:
- scaling of losses \(\sim (\# \text{ turns})^3\) [Joho, 1981]
  \(\rightarrow\) high gap voltage!
- large radius (non-compact cyclotron!)
- \(E_k < 1\text{GeV}\)
PSI Ring cyclotron – turn separation at extraction

beam profile scan of outer turns in Ring Cyclotron comparison of simulation and data

Simulation work
[Y.J.Bi CIAE Beijing, Poster: MOPCP045, A. Adelmann, PSI, talk: THM2CIO01]
**Discussion**

<table>
<thead>
<tr>
<th>Cyclotron</th>
<th>Superconduct. Linac</th>
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<tbody>
<tr>
<td><strong>Pro</strong></td>
<td><strong>Pro</strong></td>
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<tr>
<td>compact in-expensive design, efficient power transfer, only few resonators needed, relatively simple</td>
<td>large beam aperture, no bending fields, tuning straightforward, high energy possible</td>
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<tr>
<td><strong>Con</strong></td>
<td><strong>Con</strong></td>
</tr>
<tr>
<td>injection/extraction critical, complicated bending field, elaborate tuning required, energy limited 1GeV</td>
<td>non-compact accelerator, power coupler critical, needs large cryogenic facility</td>
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<tr>
<td><strong>Oth.</strong></td>
<td><strong>Oth.</strong></td>
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<tr>
<td>naturally CW operation</td>
<td>pulsed operation possible</td>
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Summary

- excellent progress at PSI in recent years; the PSI accelerator delivers **1.3MW** beam power in CW mode; average reliability is **90%**; **25-50 trips** per day
- upgrade to 1.8MW is under way; next steps involve new resonators/amplifiers in injector II; new high power collimators behind target E
- the cyclotron concept presents an effective alternative to generate a high power beam e.g. for ADS; **1GeV/10MW cyclotron** seems feasible in next step; in comparison to LINACS beam dynamics and tuning of cyclotrons are difficult, though.
Thank you for your attention!