1.8 MW Upgrade of the PSI Proton Accelerator Facility

Pierre A. Schmelzbach for the PSI Accelerator Divisions

This talk:
• analyzes the potential for improvements from the ion source to the spallation target
• gives an overview of the work in progress
OVERVIEW

COCKCROFT-WALTON

870 keV TRANSFER LINE

72 MeV TRANSFER LINE

590 MeV CYCLOTRON

INJECTOR 2

IP

TARGET M

TARGET E

SINQ TRANSFER LINE

3 mA /1.8 MW

2 mA /1.2 MW

Protontherapy (+ 2006)

UCN (in construction)

2 mA /1.1 MW

1.4 mA / .8 MW

SINQ

2 mA /1.1 MW
Basic Considerations for Design and Operation

Accelerators: Cyclotrons with large turn separation at the extraction

Losses: Extraction from Injector Cyclotron, injection and extraction from Ring Cyclotron: \(< 0.5 \Omega A\) each

Beam lines: \(< 1nA / m\)

Local shielding

Remote handling

Repairs in hot cell located in machine / experimental hall
ION SOURCE

Present:
Multicusp ion source
Desadvantages:
• poor proton efficiency
• stability
• maintenance

In progress:
• development of a compact, permanent magnets, \textit{microwave (ECR) ion source}
• tests starting now
Beam Injection

Beam collimation in the centre region \text{Inj.2}

- Ion source DC beam current: 12.0 mA
- Injected beam current: 10.8 mA
- Phase defining collimator (KIP1 & KIP2): 7.2 mA
- Beam current accepted on the 1\textsuperscript{st} turn: 3.6 mA
- Collimation of phase tails on the 1\textsuperscript{st} turn (KIP3): 0.7 mA
- Vertical collimation (KIG1, KIG2, KIG3, KIV): 0.9 mA
- Radial collimation on the 4\textsuperscript{th} turn (KIP4): 0.2 mA
- Accelerated beam current: 1.8 mA
**Goal:** 2.2 mA $\gg$ 3.3 mA from *Injector Cyclotron*

**First step:** inject more beam
Implementation of a second buncher ($3^{rd}$ harmonic $\rightarrow$ 150 MHz) in the horizontal line before the vertical deflection

**Status**
- Installation in SD 2006, now in operation
- Beam width at extraction: for 2.4 mA same as previously at 2 mA 😊😊
870 keV TRANSFER LINE

The integration of the bunchers at available locations satisfies the requirements for a more efficient "round beam" injection into Inj. 2.

Energy distribution of the bunched beams

Space charge dominated bunching into the phase space accepted by the Injector 2 entrance collimators

Degrees RF

BEFORE: 12.5 mA DC 2.2 max in window
AFTER: 10 mA DC 3.5 mA in window

ACCEPTANCE window of INJ-2

arb. units

\( \frac{\Delta E}{E} \text{ [%]} \)

\( p/p \text{ [%]} \)

\( \text{arb. units} \)
INJECTOR CYCLOTRON

Step 2: acceleration / extraction >> simulation of space charge effects >> “round beam” acceleration mode >> current limit

Phase width of the extracted beam (after 90 turns) is about 2° rf
Good agreement between calculations and measurements
In the “round beam” acceleration mode the flat-top cavities are obsolete → Replacement of the flat-top system by 50 MHz accelerating cavities
### 50 MHz RESONATOR for INJECTOR-2 (2009)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>50.6 MHz</td>
</tr>
<tr>
<td>Gap voltage</td>
<td>500 kV</td>
</tr>
<tr>
<td>Dissipated power</td>
<td>120 kW</td>
</tr>
<tr>
<td>Cavity wall</td>
<td>Alu 99.5</td>
</tr>
</tbody>
</table>

**Injektor 2, Resonator 4**
72 MeV TRANSFER LINE

Implementation of a buncher
- To optimize the phase width of the beam at the injection into the main cyclotron
- To allow for operation up to 2.5 mA with the present flat-top cavity
- To allow for “round beam” acceleration in the Ring Cyclotron (?)
Status
- Built, but no power tests yet
- Infrastructure installed in SD 2006
- Waiting amplifier delivery

Technical data:
506 MHz 2-gap drift tube cavity
218 kVpp RF-voltage per gap
30 kW power (op. 10 kW)
IN PROGRESS

- Replacement of old cavities – 2 now installed. All four available in 2008.
- Test of 180 kW amplifier for flat-top cavity
- Investigation of the feasibility of the “round beam” mode of acceleration.

Current limit as a function of the number of turns in the Ring Cyclotron

- Joho: limit due to space charge prop. N^{-3}
- General: Same dependence if emittance of injected beam included
  
  \[ > \frac{dx}{dR/dn} = 0.6 \text{ or } dR/dn = 7 \]

- >> extraction losses (septum) 0.02%

Improved beam quality from Injector (improved bunching in 870 keV line, “round beam”, cleaning slit after extraction)
Extraction losses: history and extrapolation

Strahlverluste für verschiedene Ausbaustufen des Ring Zyklotrons

1993
267 Umläufe

1994
269 Umläufe

1995-2004
217 Umläufe

2005
209 Umläufe

180 Umläufe

160 Umläufe
RING CYCLOTRON

OLD CAVITY
- $f_R = 50.6$ MHz
- Gap voltage = 750 kV
- $Q_0 = 32'000$
- Dissip. Power = 300 kW
- Power to beam = 350 kW

NEW CAVITY
- $f_R = 50.6$ MHz
- Gap voltage > 1 MV
- $Q_0 = 48'000$
- Dissip. power = 300 kW
- Power to beam = 500 kW
TARGET E

TARGET WHEEL

COLLIMATOR K1

ABSORBERS

COLLIMATORS K2 + K3
TARGET E

Thermal limits exist for the target and the subsequent collimators

2.0 mA - 2.6 mA
• OK for target with 4 cm length

2.6 mA - 3.0 mA
• OK for target with 4 cm length
• Collimators K2 and K3 must be replaced or shorter target without replacement
• SINQ target must be replaced

> 3.0 mA
• Target wheel radius must be increased
• Target chamber must be replaced
• SINQ Targetsystem must be redesigned

Target E sets the limit on the performance of the facility!
CURRENT LIMITS OF TARGET E COMPONENTS

- Kollimator 2
- Target
- Local Shielding
- Beam Dump

Max. Strom MHC4 (mA) vs Dicke Target E (cm)

- 3 mA
- 2.6 mA

Target evaporation

G. Heidenreich
OPERATIONAL LIMITS OF THE ROTATING CARBON & BERYLLIUM TARGET CONES

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>D[m]</td>
<td>0.28</td>
<td>0.19</td>
<td>0.45</td>
</tr>
<tr>
<td>l[mA]</td>
<td>0.15</td>
<td>0.12</td>
<td>3.0</td>
</tr>
<tr>
<td>$\mathcal{M}_*$</td>
<td>0.6</td>
<td>0.6</td>
<td>0.75</td>
</tr>
</tbody>
</table>

$I$ proton current
$D$ mean target diameter
$\mathcal{M}_*$ effective emissivity = $F$ (emissivity, view factors, areas of radiating surfaces)
SINQ TRANSFER LINE

LOSS RATE < 1 nA/m
OK for 3 mA
SINQ TARGET

**STATUS**
The target is designed for a maximum current load of 50 - 55 $\text{mA/cm}^2$. The actual load is 40 $\text{mA/cm}^2$ for 4 cm target length and 2 mA from the cyclotron (= 1.4 mA on SINQ).

$\rightarrow$ CURRENT LIMIT: 2.5 – 2.7 mA

**for 3 mA**
Modification of the SINQ target:
- Reduction of the 'canelloni' cross section in the center of the beam intensity distribution ($\rightarrow$ Zirkalloy)
- Liquid metal / ceramic target ($\text{Al}_2\text{O}_3$)
SIMULATIONS

Fundamental Acceleration Cavity Modes

- Plot of a cavity with indicated modes and frequency

Parasitic Cyclotron Modes:

- Graph of E-field and measured spectrum

Field-Particle Interaction Simulation

- Diagram showing particle orbit and interpolated RF-fields

Another Example of Large Scale Electromagnetic Modeling:

- Image of a device with components labeled

EPAC'06 / P.A.Schmelzbach
SIMULATIONS

- Improved understanding of space charge compensation in simulations of 870 keV transfer line
- Beam dynamics with second 870 keV buncher
  1D simulations ready
- Injection + High intensities in INJ-2
- Beam dynamics in 72 MeV transfer line (collimators / halo)
  Performance of the 72 MeV buncher
- Beam dynamics in the main cyclotron (Higher Order Modes, overlapping turns, “round beam” acceleration)
- Optics in the SINQ transfer line

Ideally: STS, source to target simulations

2.0 mA >> 3.0 mA

In progress / DONE
Bewilligung für den Betrieb der Beschleunigeranlagen und die damit verbundene Durchführung von Experimenten am Paul Scherrer Institut (PSI) in Villigen 20. Mai 2003

Bundesamt für Gesundheit, Strahlenschutz, 3032 Bern

W. Zeller

Zuständig: Bundesamt für Gesundheit, Strahlenschutz, 3032 Bern

REZ: 16.03.2003

Die Bewilligung ist gültig bis zum 01.07.2003.

Bundesamt für Gesundheit
<table>
<thead>
<tr>
<th>TIME</th>
<th>ACTIVITY</th>
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<tbody>
<tr>
<td><strong>2005</strong></td>
<td>Construction of 870 keV buncher</td>
</tr>
<tr>
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<td>Construction of 72 MeV buncher</td>
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<tr>
<td></td>
<td>Design of the 50 MHz resonators for INJ-2</td>
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<tr>
<td><strong>Shut Down (SD) 2006</strong></td>
<td><strong>Installation of the 2\textsuperscript{nd} ring cavity</strong></td>
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<tr>
<td></td>
<td><strong>Installation of the 870 keV buncher</strong></td>
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<td></td>
<td>Infrastructure of the 72 MeV buncher</td>
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<tr>
<td></td>
<td>Temperature tests of Flattop cavity</td>
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<td>INJ-2 shielding reinforcement</td>
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<td><strong>2006</strong></td>
<td><strong>Installation of the 72 MeV buncher</strong></td>
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<tr>
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<td>Commissioning of the buncher systems</td>
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<tr>
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<td>Design of the 50 MHz resonator for INJ-2</td>
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<td>Design of improved SINQ Target</td>
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<td>Design of new collimators K2 and K3</td>
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<td></td>
<td><strong>Routine production ( \sim 2.0 \text{ mA} )</strong></td>
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<td><strong>SD 2007</strong></td>
<td>Upgrade of BX2 cooling</td>
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<tr>
<td>TIME</td>
<td>ACTIVITY</td>
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<tr>
<td>-----------</td>
<td>--------------------------------------------------------------------------</td>
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<tr>
<td>2007</td>
<td>Construction of 50 MHz resonators for INJ-2</td>
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<td>Design of SINQ Target</td>
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<tr>
<td></td>
<td>Delivery and Test of 2 Ring cavities</td>
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<td></td>
<td><strong>Current increase to 2.4 mA</strong></td>
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<tr>
<td>SD 2008</td>
<td>Installation of the remaining 2 ring cavities</td>
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<tr>
<td>2008</td>
<td>(Upgrade of Flattop cavity)</td>
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<tr>
<td></td>
<td>Construction of SINQ Target</td>
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<td><strong>Current increase to 2.6 mA</strong></td>
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<tr>
<td>SD 2009</td>
<td>Target E - Implementation of collimators K2 and K3</td>
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<tr>
<td></td>
<td>Implementation of new SINQ target</td>
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<tr>
<td></td>
<td><strong>Installation of 50 MHz resonators in INJ-2</strong></td>
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<tr>
<td>2009 &gt;&gt;</td>
<td><strong>Gradual current increase to 3.0 mA</strong></td>
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