Upgrade of the PSI Proton Accelerator Facility to 1.8 MW

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

590 MeV CYCLOTRON

INJECTOR 2

COCKCROFT-WALTON

870 keV TRANSFER LINE

72 MeV TRANSFER LINE

TARGET M

TARGET E

SINQ TRANSFER LINE

IP

2 mA /1.2 MW

3 mA /1.8 MW

1.4 mA /0.8 MW

2 mA /1.1 MW

Protontherapy (+ 2006)
UCN (in construction)

SINQ
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: $< 0.5 \mu A$ each

Beam lines: $< 1nA / m$

Local shielding

Remote handling

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

Present:
Multicusp ion source
Disadvantages:
- poor proton efficiency
- stability
- maintenance

In progress:
- development of a compact, permanent magnets, microwave (ECR) ion source
- will be installed in 2008
INJECTOR CYCLOTRON

Beam Injection

Beam collimation in the centre region Inj.2

- ion source DC beam current: 12.0 mA
- collimators in the 870keV beam transport line: 1.2 mA
- injected beam current: 10.8 mA
- phase defining collimator (KIP1 & KIP2): 7.2 mA
- beam current accepted on the 1st turn: 3.6 mA
- collimation of phase tails on the 1st turn (KIP3): 0.7 mA
- vertical collimation (KIG1,KIG2,KIG3,KIV): 0.9 mA
- radial collimation on the 4th turn (KIP4): 0.2 mA
- accelerated beam current: 1.8 mA
Goal: 2.2 mA >> 3.3 mA from Injector Cyclotron

First step: inject more beam
Implementation of a second buncher (3rd 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.
**INJECTOR CYCLOTRON**

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

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**Figure 4** (color): Charge density in a.u.: Turn 1 and 6.

**Figure 5** (color): Charge density in a.u.: Turn 10 and 60.

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

Beam Width at the Extraction of Injector 2

- **Adelmann’s “round beam” Simulation**
- **Limits with 4 Resonators (Eg = 1.6 MV)**
  - Turn Separation = 38 mm (= 7 sigma)
  - Same absolute loss as at 2 mA
- **Present limit with 2 Resonators (Eg = 1 MV)**
  - Turn separation = 23 mm (= 7 sigma)
- **Measurements (BRAV, 4 sigma)**
- **Fit, Extrapol with I^{1/3}**
50 MHz RESONATOR for INJECTOR-2 (>2009)

- Frequency: 50.6 MHz
- Gap voltage: 500 kV
- Dissipated power: 120 kW
- Cavity wall: Alu 99.5

Injektor 2, Resonator 4
Flat-top and space charge

Motion

Force

with SC

$\Phi_3 = 20^\circ$ $V3 = -13\%$

$\Phi_0 = -10^\circ$ $F_3 = 13.0$
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 (?)

150 MHz V=714 kV

500 MHz V=218 kV

72 MeV BUNCHER
**Status**
- Built, but no power tests yet
- Infrastructure installed in SD 2006/7

**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

- 2004-2008: 750 >> 1000 kV Cavities
- 1989-1995: 430 >> 750 kV Cavities

Improve beam quality from Injector (improved bunching in 870 keV line, "round beam", cleaning slit after extraction)

Joho: limit due to space charge prop. N^3

General: Same dependence if emittance of injected beam included

>> dx/(dR/dn) = .6 or dR/dn = 7σ

>> extraction losses (septum) 0.02%
Extraction losses: history and extrapolation

Strahlverluste für verschiedene Ausbaustufen des Ring Zyklotrons

1993
267 Umläufe

1994
239 Umläufe

1995-2004
217 Umläufe

2005
209 Umläufe

180 Umläufe

160 Umläufe
RING CYCLOTRON

OLD CAVITY

\( f_R = 50.6 \text{ MHz} \)
Gap voltage = 750 kV
\( Q_o = 32'000 \)
Dissip. Power = 300 kW
Power to beam = 350 kW

NEW CAVITY

\( f_R = 50.6 \text{ MHz} \)
Gap voltage > 1 MV
\( Q_o = 48'000 \)
Dissip. power = 300 kW
Power to beam = 500 kW
TARGET E

- TARGET WHEEL
- COLLIMATOR K1
- ABSORBERS
- COLLIMATORS K2 + K3

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**Status:**
- became a very reliable component
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

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

- Kollimator 2
- Target
- Local Shielding
- Beam Dump

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>
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<tr>
<td>D[m]</td>
<td>0.28</td>
<td>0.19</td>
<td>0.45</td>
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<tr>
<td>I[mA]</td>
<td>0.15</td>
<td>0.12</td>
<td>3.0</td>
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<tr>
<td>$\varepsilon^*$</td>
<td>0.6</td>
<td>0.6</td>
<td>0.75</td>
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$I$ proton current
$D$ mean target diameter
$\varepsilon^*$ effective emissivity = $F$ (emissivity, view factors, areas of radiating surfaces)
SINQ TRANSFER LINE

Loss Rate < 1 nA/m
OK for 3 mA
The target is designed for a maximum current load of 50 - 55 µA/cm². The actual load is 40 µA/cm² for 4 cm target length and 2 mA from the cyclotron (= 1.4 mA on SINQ).

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 (◊ Zirkalloy)
- ♣ Liquid metal / ceramic target (Al₂O₃)
Mesh of RF structures and vacuum chamber, created with tetrahedral elements, using CUBIT (Sandia Lab)

1.2 M 2nd order elements, 6.9 M degrees of freedom

Measurced spectrum (Network analyzer data)
SIMULATIONS

Fundamental Acceleration Cavity Modes

Parasitic Cyclotron Modes:

- E-field of simulated 54 MHz mode
- Measured spectrum (Network analyzer data)

Field-Particle Interaction Simulation

Another Example of Large Scale Electromagnetic Modeling:
The PSI 4 Sector 250 MeV, Medical Cyclotron (ACCEL GmbH)

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SIMULATIONS

2.0 mA >> 3.0 mA

- Improved understanding of space charge compensation in simulations of 870 keV transfer line
- Beam dynamics with second 870 keV buncher
  1 D 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’

In progress / DONE