Paul Scherrer Institut
Lukas STINGELIN for the PSI RF-group
High Power RF Systems and Resonators for Sector Cyclotrons
New RF-Components

- 870 keV Line
  - New 150 MHz Buncher
  - 50 MHz Buncher moved

- 72 MeV Line
  - New 50 MHz Resonators 2&4

- Injector 2
  - New 50 MHz Resonators 2&4

- 590 MeV Ring cyclotron
  - 590 MeV beam to meson production targets and neutron spallation source

- Beams for low energy exp.

- Ring
  - New 50 MHz Cu-Cavities
Injector 2

Injection energy: 870 keV
Extraction energy: 72 MeV
Accelerator frequency: 50.63 MHz
RF system of Injector 2

Resonator 1 & 3
- 50 MHz double gap resonator
- Accelerating voltage 420 kV
- Power dissipation 150 kW

Resonator 2 & 4
- 150 MHz resonator
- Accelerating voltage 30 kV
- Power dissipation 3.5 kW
Inj. 2 Power upgrade 2003

Diagram of the power upgrade for Injector 2.
Number of turns:

- Beam current 2mA: 82
- Beam current 3mA: ~65

Higher energy gain per turn on outer radius

Replacement of resonator 2 and 4

(150 MHz by 50MHz)

including new amplifier chain and low level RF

- Resonator 2 planned before 2013
- Resonator 4 planned before 2014

Later replacement of amplifier chain and low level RF of resonator 1 and 3

Using same system as for resonator 2 and 4

Gap voltage versus Radius of existing resonators
New 50 MHz Resonator 2&4, Injector 2

Specification

- Resonance frequency: 50.6328 MHz
- Accelerating voltage: 400 keV
- Dissipated power: 45 kW@400kV
- Tuning range: 200 kHz
- Cavity RF-wall: EN AW 1050
- Structure: EN AW 5083
- Vacuum pressure: 1e-6 mbar
- Cooling water flow: 15 m3/h
- Dimension: 5.6x3.3x3.0 m
- Weight: 7‘000 kg
New 50 MHz Resonator 2&4, Injector 2

Status

Delivery of Res. 2 to PSI: June 2009
Tuner (PSI Workshop): Mid June
RF-Power tests: fall 2010
Manufacturing Res. 4 13 Month
Simulation and measurement results  50 MHz
Resonator 2&4

<table>
<thead>
<tr>
<th></th>
<th>Simulation</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qo</td>
<td>28’159</td>
<td>24’814</td>
</tr>
<tr>
<td>Tuning range</td>
<td>190kHz</td>
<td>197.6kHz</td>
</tr>
<tr>
<td>Vacuum drift</td>
<td>-59.2kHz</td>
<td>-65.5kHz</td>
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<tr>
<td>Thermal drift</td>
<td>-32.6</td>
<td>-30.4</td>
</tr>
</tbody>
</table>

Temperature distribution, Design case 100kW

Deformation, atmospheric pressure, RF-Power
The Coupling Loop

Air side

Spark detection electrode

AQUADAG
Spark Detection by the Coupling Loop

The RF is blanked for about 100µs in case of spark detected at the coupling loop.

This is enough time for the ions cloud to vanish.

Without blanking  With blanking
Block diagram of the pulsing startup and interlock control circuitry
Using limiting amplifiers with an operating range of more than 60dB, it is possible to tune the resonators at very low level, below multipacting level as well as at a very high pulse level.
After successful high power tests, it was discovered that several RF contacts were bent. Design of RF contacts still has to be improved. (No problem of rf-current, but mechanical tribology)
# Amplifier chain for Resonator 2 / 4

<table>
<thead>
<tr>
<th>Component</th>
<th>Power Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LLE</td>
<td>2 kW</td>
<td>Predriver (2 kW) Solid state amplifier</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Driver stage (35 kW) Tetrode Amplifier</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thales RS 2048 CJC New design by PSI</td>
</tr>
<tr>
<td></td>
<td>35 kW</td>
<td>Final stage (180 kW) Tetrode Amplifier</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thales RS 2074 HF Copy of 1MW design Reduced power supply</td>
</tr>
<tr>
<td>OWA</td>
<td></td>
<td>Higher harmonic absorber</td>
</tr>
<tr>
<td>OWA</td>
<td>180 kW</td>
<td>Resonator 2</td>
</tr>
</tbody>
</table>

- **3 1/8” EIA transmission line**
- **6 1/8” EIA transmission line**
Inj. 2 vault and WHFA

- Power supplies
- Plate power supplies
- Amplifiers
- Driver stages
New building WHFA

End of 2007

End of March 2008
Buncher between Inj. 2 and Ring

- Proton bunch length at the exit of Injector 2 is about 6 cm.

- Increases up to about 20 cm at the end of the 58 m injection line for the ring cyclotron due to energy dispersion and space charge repulsion.

- Buncher between Inj. 2 and Ring.

- Design studies on 150 MHz and 500 MHz.

- 30 kW tetrode amplifier at 500 MHz from LURE.
500 MHz Buncher, between Inj. 2 and Ring

Assembly of buncher

Resonance frequency: 506.328 MHz
Gap voltage: 218 kV
Quality factor: 34'000
Dissipated power: 10 kW, max 30 kW
Hydraulic tuning system range: 2.34 MHz
Cavity wall: Cu-OFHC
Super-buncher bead-pull measurement

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<tr>
<td>Qo</td>
<td>34'000</td>
<td>30'340</td>
</tr>
<tr>
<td>Tuning range</td>
<td>2.34MHz</td>
<td>2.3MHz</td>
</tr>
<tr>
<td>Vacuum drift</td>
<td>-127kHz</td>
<td>-120kHz</td>
</tr>
<tr>
<td>Thermal drift</td>
<td>-270kHz @30kW</td>
<td>-260kHz @20kW</td>
</tr>
</tbody>
</table>

Electric Field on Axis [a.u.]

Position [mm]
Test facility Superbuncher

RF-station 506 MHz / 30kW

Test vault
Commissioning of Super-buncher

Low level measurements

Amplifier tested on dummy load up to 20 kW

Tests on Superbuncher:
  a lot of multipactoring

At 2 kW dissipated power
  ceramic tulip for RF-pickup broken

At 5 kW dissipated power
  circulator broken

Inductive pickup with ceramic tulip
6 1/8 " EIA Circulator for Superbuncher

Disk with ferrites

Outer conductor of circulator

Circulator in repair till April 2008 -> Circulator equipped with ARC-detector
3rd device killed, contact finger burned

Contact fingers
After 6 hours @ 10kW (nominal power)

Contact ring Ag plated
Contact force increased
Contact surface of the plunger had then been plated with hard-gold and contact force slightly reduced.
Since then, no hardware failure of the Super-buncher system.
590 MeV Ring Cyclotron

- 8 Sector Magnets 1 T
- Injection energy: 72 MeV
- Extraction energy: 590 MeV
- Accelerator frequency: 50.63 MHz
- 4 new Cu-Cavities: 850 kV
- Beam current: 2.2 mA

For 3 mA beam current
- 4 Accelerator Cu-Cavities: ~ 1 MV
- Number of turns: ~ 160
<table>
<thead>
<tr>
<th></th>
<th>Al-Cavity</th>
<th>Cu-Cavity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>50.6 MHz</td>
<td>50.6 MHz</td>
</tr>
<tr>
<td>Voltage</td>
<td>750 kV&lt;sub&gt;p&lt;/sub&gt;</td>
<td>&gt;1 MV&lt;sub&gt;p&lt;/sub&gt;</td>
</tr>
<tr>
<td>Dissipated Power</td>
<td>300 kW</td>
<td>500 kW</td>
</tr>
<tr>
<td>Q-value</td>
<td>28'000</td>
<td>45'000</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>1.8 kHz</td>
<td>1 kHz</td>
</tr>
<tr>
<td>Tuning Range</td>
<td>240 kHz</td>
<td>560 kHz</td>
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</tbody>
</table>
50 MHz 1 MW amplifier chain for Ring cyclotron

4-STAGE POWER AMPLIFIER CHAIN, EMPLOYING POWER TETRODE TUBES

<table>
<thead>
<tr>
<th>Tube Types:</th>
<th>Cooling Method:</th>
</tr>
</thead>
<tbody>
<tr>
<td>YL 1056</td>
<td>forced air</td>
</tr>
<tr>
<td>RS 2022 CL</td>
<td>forced air</td>
</tr>
<tr>
<td>RS 2074 HF</td>
<td>water</td>
</tr>
<tr>
<td>RS 2074 HF</td>
<td>water</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Setup</th>
<th>Power dissipated in Cavity (no Beam)</th>
<th>Beam power at 2 mA beam current</th>
<th>Beam power at 3 mA beam current</th>
<th>Total Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alu cavity 202 turns</td>
<td>350 kW</td>
<td>300 kW</td>
<td></td>
<td>650 kW</td>
</tr>
<tr>
<td>Cu cavity 202 turns</td>
<td>250 kW</td>
<td>300 kW</td>
<td></td>
<td>550 kW</td>
</tr>
<tr>
<td>Cu cavity 160 turns</td>
<td>400 kW</td>
<td></td>
<td>450 kW</td>
<td>850 kW</td>
</tr>
</tbody>
</table>
Potential problems for 3mA at the Ring cyclotron

Limit of RF-power coupler unknown (1MW?)

Water cooling system for tubes at power limits
now
PA=500kW
Inlet 55°C  Outlet 80°C
Inlet 45..50°C  Outlet 80°C

Heavy beam loading
no beam
P = 400 kW  Zin ~ 85 Ohm
3 mA
P = 850 kW  Zin ~ 40 Ohm

Amplifiers pushed to limits
-> reliability
-> lifetime of tubes?

Flattop system is working on the limits
Cavity, transmission line, amplifier

With Super-buncher flattop voltage might be reduced
Conclusions:

...Upgrade is delayed by at least 3 years.

...Power tests of new Resonators for Injector II are promising. RF contacts have to be improved.

...RF stray fields should be investigated further. Reduction might lead to improved availability and performance.
Simulation Model without Absorber

- Up-down asymmetry: Cavity top wall moved up by 2mm
- Left-right symmetry assumed to reduce model size
- Power input from Cavity side-wall (Port 1) and attenuation recorded at waveguide extension attached to intermediate vacuum chamber (Port 2)
- Simulation method produces same fields in cavity, with the advantage to avoid narrow bandwidth simulation.
2.57m x 0.15m long Graphite Absorber

No impedance-step from sector magnet taken into account
Only limited simulation domain, (Simulation is more accurate if absorber is more efficient…)
Simulation in driven frequency domain by HFSS. Graphite with 7000S/m modeled as 0.2mm thick layer with 0.1 micro meter roughness.
Graphite plate 2cm thick, ends 2cm below beam plane

Almost no change in total radiated power, only mode-pattern at port 2 changes.
λ/4 absorbing Resonator: preliminary Results

Comparison of attenuations to case without absorber:
→ $S(2:1,1:1)$ gets 5dB lower
→ Flattop-Voltage could be almost doubled for same radiated power