HIGH POWER RF SYSTEMS AND RESONATORS FOR SECTOR CYCLOTRONS

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Abstract

The Proscan cyclotron is routinely operated for medical cancer treatment and the Injector II and Ring-Cyclotron are routinely used for acceleration of a high intensity proton beam. In the framework of the high intensity upgrade, it is planned to replace two existing 150MHz resonators of the Injector II cyclotron by two new 50MHz resonators. The first prototype resonator has been manufactured by SDMS and first vacuum and RF-measurements have been carried out. Tuners, coupler and pickups have been mounted and high power RF tests are in progress on a teststand. A new building for the RF-installation has been constructed and is ready to house the power amplifiers.

INTRODUCTION

The PSI high intensity accelerator facility routinely accelerates a proton beam of about 2.2mA up to an energy of 590MeV. About 30% of protons are absorbed in the Targets M and E for meson production and 70% of the protons are used in the spallation neutron source (SINQ). This accelerator complex consists of two isochronous, fixed frequency separate sector cyclotrons. The Injector II cyclotron accelerates the proton beam up to an energy of 72MeV which is then transferred to the 590MeV Ring Cyclotron. In 2009, the overall availability of the facility reached about 90% with 8% of outages longer than 5 minutes attributed to the RF systems.

In 2004, a dedicated compact superconducting cyclotron was purchased from ACCEL Instruments GmBH. It routinely accelerates a proton beam up to 250MeV for medical cancer treatment by spot-scanning technique or for treatment of eye-melanoma.

OPERATION OF RF-SYSTEMS

Proscan

The RF-systems of the 250MeV cyclotron (COMET) for cancer treatment has been running without any major problems since 2004. Some minor problems have had to be fixed, such as a broken voltage regulation of the amplifiers. Several RF-contacts were damaged, probably because the field distribution of the dees was not sufficiently well balanced. The RF-window was covered with a metallic layer twice and had to be cleaned.

A newly developed "puller-tip" is now exchangeable and uses tungsten instead of copper to reduce the wear from sputtering.

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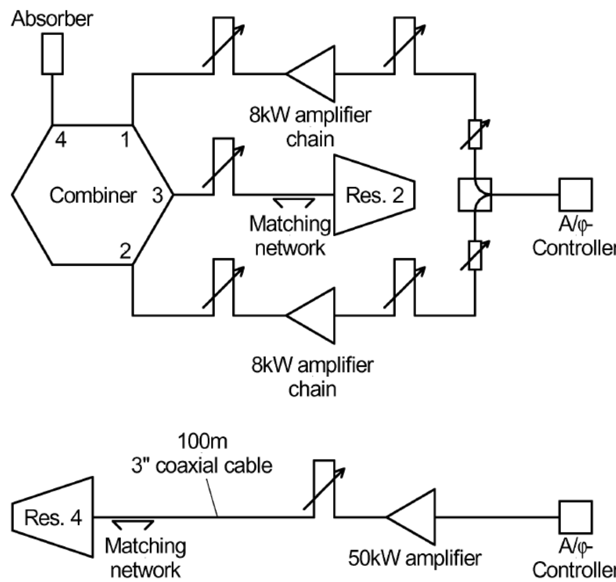

Figure 1: Power distribution in Injector II. The combiner is a 180°-Hybrid ("Rat-Race").

Injector II

The RF system of the 72 MeV Injector [1] consists currently of two double gap-acceleration resonators (50 MHz) and two smaller 150 MHz resonators, which were originally designed as flat-topping resonators. Since the proton bunches are only about 5° long, flat-topping is not efficient and the 150 MHz resonators are therefore operated in acceleration mode.

Fig. 1 shows the present power distribution in Injector II for the Resonators 2 and 4 [2]. Two 150MHz amplifiers are combined to get double power on Resonator 2. A separate power amplifier, located in a different building, is used to feed Resonator 4. This new setup was commissioned in 2003 as a temporary solution, but fortunately has been running since then without major problems. However, tuning and maintenance of the old Resonator 4 amplifier is difficult. A 3dB attenuator was inserted between driver and final amplifier in order to decouple them better and to change the operating point of the driver-amplifier.

Stability problems occurred sometimes when Resonator 4 was switched on after an interrupt. The inner surface of Resonator 4 was then coated with Aquadag [3] to prevent multipactoring by reducing the secondary electron emission coefficient of the surfaces.

590MeV Ring Cyclotron

The new copper cavities are currently operated at a gap voltage of about 850kV and leave some margin for future operation around 1MV. However, the old aluminum flat-top cavity is running at its limit. Its voltage can not be increased further because the cavity cooling is not sufficient, especially at the electrodes. Also, the pressure of the tuning-system is at its limit, as well as the high-power coaxial transmission line to the cavity and the final stage amplifier.

In order to relax the load on the coaxial transmission line, the voltage of the flat-top cavity is reduced when there is no field excited by the proton beam (zero beam current) and is ramped up when the beam-current is increased. The voltage of Cavity 1 is automatically corrected to keep the extraction energy and number of turns constant during this ramp.

The efficiency of the RF system for converting wall plug power is 0.9 for AC/DC conversion, 0.64 for DC/RF conversion and 0.55 for RF to beam power.

RF Radiation Problem in Ring Cyclotron

In 2010, the start-up suffered from plasma effects that were generated in the 590MeV Ring Cyclotron as a result of excessive RF radiation from the 150MHz flat-top cavity. The phenomenology is described also in these proceedings by Zhang et al. [4]. In order to understand the effects better,

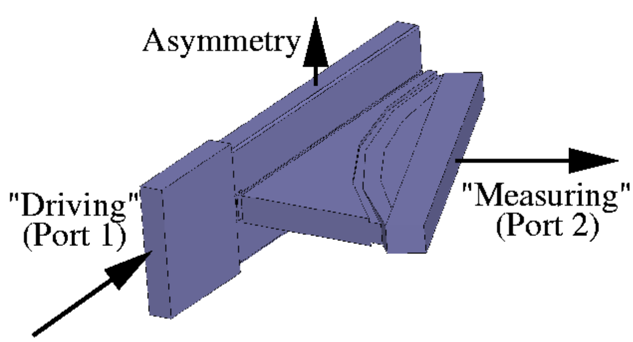

Figure 2: Geometry used for the simulation of the RF radiation from the flat-top cavity.

an attempt was made to simulate the stray RF by the HFSS harmonic solver, analogue to the the method used in 2000 for the main cavities [5]. It was found that the radiated power out of the beam-slot increases almost quadratically with offset of the upper cavity plane. The radiated power has a vertical polarization of the electric field and reaches about 2.5kW when the asymmetry of the upper to lower cavity wall is 4mm. If the flat-top cavity is perfectly symmetric, there should be almost no RF stray field and it might therefore be possible to reduce the stray field by compensating the asymmetry by the hydraulic tuning system acting on the upper and lower part of the cavity.

Since it takes some time to setup the differential tuning system, an other approach to reduce the stray field was also investigated. Unfortunately, a single bar of graphite is not sufficient to absorb the stray field well enough. Simulation and measurement showed that almost no RF power was absorbed. Only the field pattern (mode distribution at port 2) of the radiated power changed but without any benefit to reduce the plasma generation.

Preliminary simulations of a resonant "$\lambda/4$ absorber" indicate that the total radiated power could be reduced by about 5dB. However, more detailled simulations of the entire cyclotron, also with an Eigenmode solver, must be done to confirm these results.

STATUS OF RF-UPGRADE

For the future beam intensity upgrade up to 3mA [6], several RF components have already been added or modified.

- More powerful copper cavities have been installed [7] at the 590MeV Ring Cyclotron in order to increase the acceleration voltage. This increases the turn spacing at extraction of the 590MeV Ring Cyclotron and helps to reduce the turn number to overcome beam degradation due to space charge effects. Installation of the four new copper cavities in the 590MeV Ring Cyclotron was successfully completed during the shutdown 2008.
- A new 150MHz buncher cavity has been installed during the shutdown 2006 on the 870keV injection beamline of the Injector II. The new buncher configuration consists of a 50MHz main buncher followed by a low amplitude 150MHz debunching stage. Together, these two bunchers produce a long linear slope of the effective buncher voltage. Beam experiments proved that the core density of the proton beam could be substantially enhanced and allowed one to reach the nominal production beam intensity at a noticeably lower beam emittance. This results in reduced extraction losses in the Injector II, as well as in the Ring Cyclotron [8].
- A new buncher cavity, ("Super-buncher" in PSI denomination), has been installed in the 72MeV transfer line between the Injector II and the 590MeV Ring Cyclotron.
- The first prototype resonator for the Injector II cyclotron upgrade is currently tested on a high power teststand.

Super-buncher

The goal of the Super-buncher [9] is to restore the narrow phase width of the beam bunches observed at extraction from Injector II at injection into the 590MeV Ring Cyclotron [10, 11]. Since the flat-top cavity of the 590MeV Ring Cyclotron is currently running at the limit of tolerable temperatures and hydraulic pressure of the tuning system,

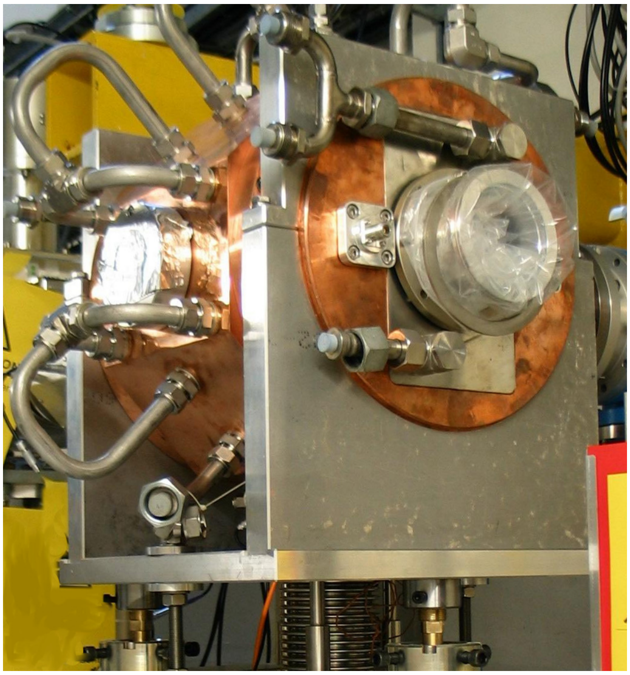

Figure 3: Installation of the Super-buncher in the 72MeV Transferline.

the Super-buncher might help to relax the flat-top cavity or even make it superfluous, as in the case of Injector II.

The Super-buncher is a two-gap drift-tube cavity, operating in the 2π mode [9]. One single stem supports the drift-tube. A standard ELETTRA-type input power coupler is used and a plunger of 6cm diameter and 6cm penetration depth is used for fine-tuning of the resonance.

Table 1: Specification of Super-buncher.

Parameter	**Simulated**	**Measured**
Resonance	506.328	
Gap Voltage [kV]	218	
Quality factor [ ]	34000	30'340
Dissipated power [kW]	10	max 20
Tuning range [MHz]	2.34	2.34
Freq. drift vacuum [kHz] [1]	**-127**	**-120**
Freq. drift thermal [kHz] **@ RF-Power [kW]**	**-270** 30	**-260** 20
Max. curr. density [A/cm] **on RF-contact @ [kW]**	**52** 20	
Cavity wall material	Cu-OFHC	

Note:

1 The simulated frequency drift from air to vacuum takes only the change of dielectric constant into account. Since the structure is relatively rigid, the geometrical deformation is almost negligible for this case.

The Super-buncher has been manufactured in the PSI main workshop in 2005 from forged OFHC copper. Before the final assembly, it was screwed together, its resonance frequency measured and then fine-machined to get the exact resonance frequency. Tab. 1 shows the comparison of calculated and measured RF-parameters. Simulations have been done with ANSYS multiphysics [12]. Bead-pull measurements also showed very good agreement, within a few percent, of the electric field strength on beam axis with the calculated field distribution.

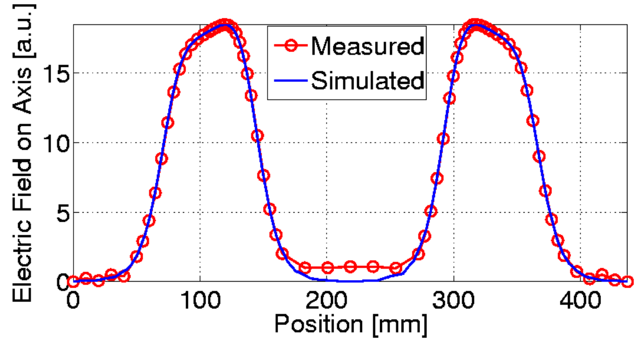

Figure 4: Comparison of simulated and measured electric field on axis by bead-pull method.

The diagram for power tests and operation is indicated in Fig. 5. Several problems had to be faced in the high power teststand:

- At 2 kW CW RF power, a small ceramic window of the inductive RF-pickup probe broke. It was found that the penetration of the pickup was too deep inside the cavity and therefore too much RF power was picked up and the probe over heated. RF pickup probes were then retracted to solve the problem.
- When the RF power was ramped up, the circulator at the output of the power amplifier broke. It is thought that the circulator had been damaged already during the transport to PSI. The circulator was then shipped back to the manufacturer for repair and installation of an arc-detector.
- After a 6h testrun at 10kW, the RF contacts of the tuning plunger were broken (partially melted due to overheating). The contact ring, made of beryllium bronze, was then silver plated and the contact force increased. Unfortunately, subsequent inspection showed scratches on the outer diameter of the plunger. The plunger was then plated with hard gold and the contact force slightly relaxed again.

After solving these problems, the Super-buncher ran successfully for many days at a power level of 15kW. It was then installed in the 72MeV transfer- line in fall 2009. Since then, several beam-dynamics experiments have been carried out with the Super-buncher. Unfortunately, it has not yet been possible to find the proper operating parameters which might allow one to run the flat-top cavity of the 590MeV Ring Cyclotron at a lower power level, or to increase the beam intensity [13]. Beam experiments also

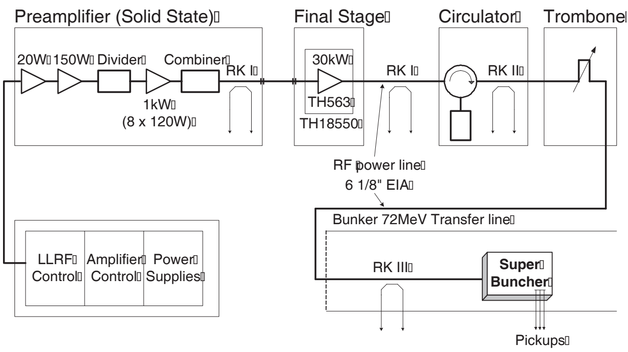

Figure 5: Schematic of Super-buncher Installation.

indicate that the phase of the Super-buncher changes with respect to the beam phase when the beam intensity is modified. In order to ease the optimization of the operation point, it is planned to install an additional phase-shifter which allows one to shift quickly the phase of the Injector II RF with respect to the Ring Cyclotron and Super-buncher.

New 50MHz Resonators for Injector II

The 72 MeV injector cyclotron has already demonstrated [13] the capability to accelerate and extract more than 2.3 mA. However, in the framework of the high intensity upgrade [7] to 3 mA, it is planned to replace the 150 MHz resonators by new, more powerful 50 MHz resonators [14]. The additional energy gain per turn will help to reduce the total number of turns and also increase the turn separation at extraction location. This will reduce the extraction losses and therefore allow the acceleration of more intense beam currents. Fig. 6 shows a 3d CAD sketch of the Injector II with new 50MHz resonators at the location of Resonator 2 and 4.

In 2007, an order was placed at the company SDMS "la chaudronnerie blanche" in France to build the two new aluminum resonators. Fig. 7 shows the prototype resonator after manufacture. Tab. 2 indicates its main parameters.

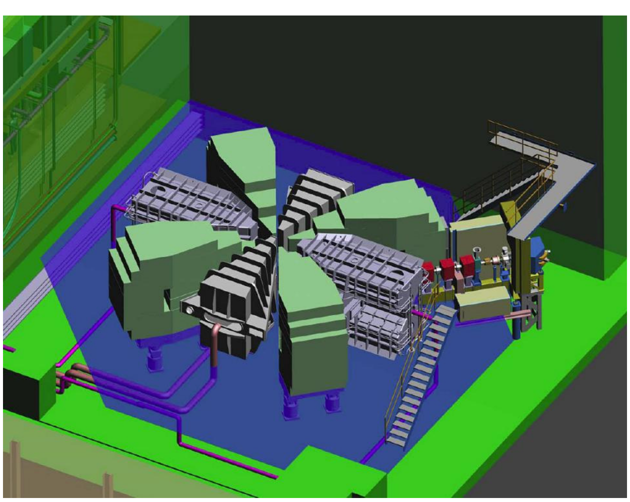

Figure 6: CAD model of Injector II with new Resonators 2 and 4.

Figure 7: LLRF-measurements of new 50MHz prototype resonators for the Injector II cyclotron at SDMS.

Resonator Design

The cavity is operated at the fundamental mode and its gap-voltage increases therefore almost linearly from 0 kV at injection to the maximum value at the extraction location [14]. In order to achieve the required maximum gap-voltage of 400kV, the cavity dissipates about 45kW of wall losses. The resonator has water cooled electrodes near the beam plane in order to reduce the transit time factor and to increase the electric field near the beam.

During the fabrication process, there were two coarse frequency adjustment possibilities of the resonator. After first measurements of the resonance frequency, the total length of the cavity was adapted for a first coarse tuning before the end-wall was welded to the cavity (-5.4kHz/mm). Later, the position of the electrodes was slightly adjusted in order to compensate the remaining fabrication tolerances and to achieve the correct initial frequency.

Two plungers of diameter 48.3 cm were installed on the end-wall, each at a distance of 61 cm from the beam plane with a maximum insertion depth of 20 cm. They are moved by hydraulic pistons and cooled by demineralized water. Their maximum tuning range is 189.3kHz.

The input power coupler is located at the end wall of the resonator, in the beam plane. It is the same inductive coupler, as used in the cavities of the 590 MeV cyclotron, but with a shorter loop length.

Conditioning and Power Tests

In 2010, the prototype resonator was installed at the high power test stand. Conditioning of the resonator went very smoothly and operation at a power of 100kW could be reached after about 3 hours. A 24 hour power test at 100kW was then successfully carried out. During conditioning and power tests, the vacuum gradually improved and reached

Table 2: Specification and comparison of simulation and measurements.

Resonance Frequency [MHz]	50.6328
Accelerating Voltage [kV]	400
Dissipated Power (for 400kV) [kW]	45
Vacuum Pressure [mbar]	$< 10^{-6}$
Material (RF walls) (support structure)	Alu. EN AW 1050 Alu. EN AW 5083
Dimensions (l,w,h)	ca. 5.3 m, 3.3 m, 3.0 m
Weight	ca. 6 t

Parameter	**Sim.**	**Meas.**
Q_0 (tuner out) [ ] [1]	28'159	24'814
Tuning range [kHz]	190	197.6
Power dissipation [kW]	100	100
Flowrate [m^3/h]	15	22
Forced convection cooling α_k $[W/m^2K]$	7'000-10'000	
Natural convection α_{kn} $[W/m^2K]$	5	
Cooling water temp [°C]	35	35.1
Ambient air temp. [°C]	25	30.8
Uniform start Temp. [°C]	25	35.1
Max. temperature (on Electrodes)	**76.5°C**	
Freq. drift vacuum [kHz] [2]	-75.2+16 =**-59.2**	(-63.9) corr. **-65.5**
Freq. drift thermal [kHz] [3]	**-32.6**	(-18.36) corr. **-30.4**

Notes:

1 If a resistance of 20mΩ is assumed per RF contact at the plunger and coupler, the simulated unloaded quality factor gets reduced to about 27'000.

2 72.2kHz correspond to geometrical deformation and 16kHz to change in dielectric. The air pressure was 976mbar in the case of measurement and 1000mbar in the case of simulation.

3 Since the uniform start temperature is 10.1°C higher in the measurement, the measured thermal frequency drift can not directly be compared to the simulated one. With a temperature coefficient of 1.195kHz/°C for aluminum, the corrected thermal frequency drift gets -32.6kHz, close to the predicted value.

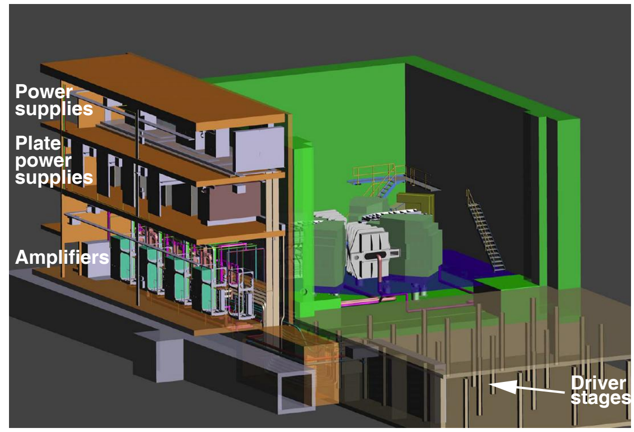

Figure 8: Layout of Injector II with new building for power amplifiers on the left.

a value of about $1.6{\cdot}10^{-7}$ mbar (a combination of turbo and cryopump is used). The maximum temperature of the resonator of about 46 to 49°C was measured at the PT100 located on the wall close to the electrodes near the center of the cyclotron and near the input power coupler.

During and after the power tests, the parameters of the quick-start electronics were optimized such that the resonator can be switched on fully automatically. The quick-start electronics uses an RF-pulse sequence to start the resonator in a short time [15].

Inspection after venting the resonator and removing the coupling loop showed scratches from the RF contacts on the plungers. After removing the plungers, it was found that some RF contacts had been bent. Therefore, the design of the RF contacts has still to be improved further. There is a also slight colouring of pickup-windows and some dark spots, probably from multipactoring during conditioning, on the lower resonator wall and the electrodes.

Amplifiers, Building and Infrastructure

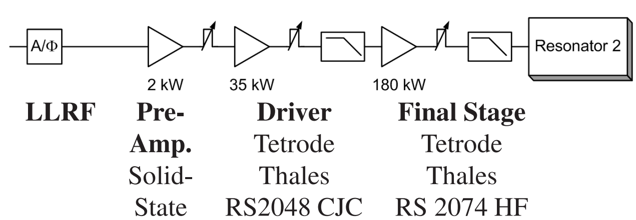

Figure 9: New amplifier chain for Resonator 2 and 4. A lowpass filter-absorber unit is inserted before the driver amplifier and the resonator to absorb higher harmonics.

A new building for the RF installation was built and completed in 2008. It will house the four final stage power amplifiers of the Injector II cyclotron, its plate, grid and filament power supplies. The driver amplifiers will be located at the place where currently the final stage amplifiers for Resonator 1 and 3 are located, in the basement of the

Injector II supply building. The new building is a metal support construction and isolated according to "Minergie" standard of Switzerland.

Fig. 8 shows a CAD drawing of the Injector II and the new building for RF power amplifiers. The layout of the new RF power amplifiers and distribution for the new Resonators 2 and 4 is indicated in Fig. 9. A 2kW solid state amplifier is chosen as pre-driver. The new 35kW tetrode coaxial cavity amplifier is currently beeing developed at PSI and will be based on a Thales RS2048CJC tube. It is planned to build the same 50MHz final stage power amplifiers as currently used for the 1MW final stage of the 590MeV Ring Cyclotron. However, a less powerful high voltage power supply will be installed. All tube-amplifiers are operated in grounded grid configuration. Higher harmonic absorbers will be installed between the driver and final stage amplifiers and the resonator. Trombones will be used to adjust the length of the coaxial lines to $n\lambda/2$ in order to avoid complex transformation of the impedances.

It is planned to install the first of the new resonators before 2013 and to have all the infrastructure ready before 2014 so as to complete the upgrade of Injector II.

CONCLUSIONS

Compared to the initial schedule [14], the upgrade program is delayed by at least 3 years.

If future beam-dynamics experiments with the Superbuncher are also not successful, a powerful flat-top cavity system for the 590MeV Ring Cyclotron might be a backup-solution for the intensity upgrade program.

Radiation of RF stray fields in the cyclotron should be investigated more in detail. This might help to improve the performance and availability of the accelerator.

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