ISBN: 978-3-95450-205-9 doi:10.18429/JACoW-Cyclotrons2019-MOC03

UPGRADE OF THE PSI INJECTOR 2 CYCLOTRON

M. Schneider†, J.Grillenberger, Paul Scherrer Institut, 5232 Villigen PSI, Switzerland

Abstract

The high intensity proton accelerator facility at Paul Scherrer Institute (PSI) is capable of providing beam currents of up to 2.4 mA at a kinetic energy of 590 MeV. PSI is following an upgrade plan to further increase the beam power and to further minimize proton losses. Up to now, this has mainly been achieved by the installation of high gradient copper resonators in the Ring cyclotron and the installation of more powerful RF-amplifiers. Currently, PSI follows a similar approach for the Injector 2 cyclotron providing 72 MeV protons for the injection into the 590 MeV Ring cyclotron. In order to increase the turn separation in the injector cyclotron which results in lower relative beam losses, the two 150 MHz resonators operated in accelerating mode are replaced with two 50 MHz Aluminum resonators providing higher acceleration voltage. This paper describes the status of the upgrade, i.e., the replacement of the first resonator and related hardware.

INTRODUCTION

The Injector 2 cyclotron was commissioned in the 1984. The rf system consists of the Resonators 1 & 3, which are 50 MHz double cap cavities for the main acceleration. In addition, the injector is equipped with two flat top Resonators 2 & 4 operated at a frequency of 150 MHz, initially to provide a broad phase acceptance. However, it was later discovered that space charge forces lead to a Vortex motion of the particles and thus a self-focusing of the bunches [1]. It turned out that changing the phase of the Resonators 2 & 4 by 180 degrees and thus providing additional energy gain per turn leads to even lower proton losses in the cyclotron. In this configuration during several shifts of 8 hours the operation of the Injector 2 cyclotron at 2.4 mA was demonstrated.

To further increase the beam current to 3 mA and consolidate the rf system, an upgrade program of the Injector 2 rf system was started [2, 3]. This upgrade is as well essential for the amplifier chains because some of the tetrodes used in the amplifiers up to 10 kW are not anymore available on the market.

THE NEW RF SYSTEM

In the new rf system the Resonators 2 & 4 will be replaced by 50 MHz single gap cavities with a higher voltage and a field distribution with the peak shifted toward the outer radius of the Injector 2. This will lead to an even higher energy gain per turn and a better turn separation at the extraction. The gap voltage of the old and new cavities is compared in Fig. 1. Because of the change in the frequency from 150 MHz to 50 MHz, the old analog LLRF system and the amplifiers need to be replaced.

In a second phase the 50 MHz LLRF system and the amplifiers for the Resonators 1 & 3 will be as well renewed.

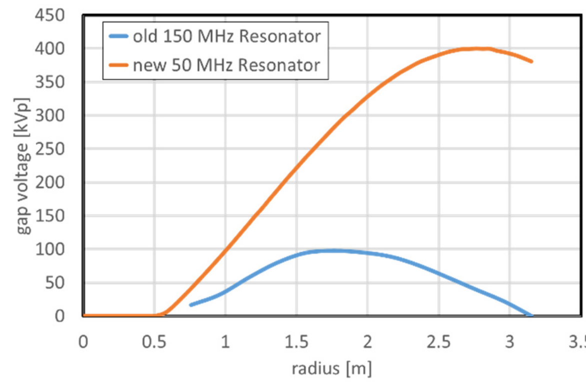

Figure 1: Gap voltage of Resonators 2 & 4.

The New 50 MHz Resonator

The rf volume of the new Resonator has an 8 shape in the cross section. On both sides there are two wings which serve as vacuum chamber towards the sector magnets (see Fig. 2). Within this space diagnostic elements and in the Resonator 4 the extraction magnets AXA/AXB are installed.

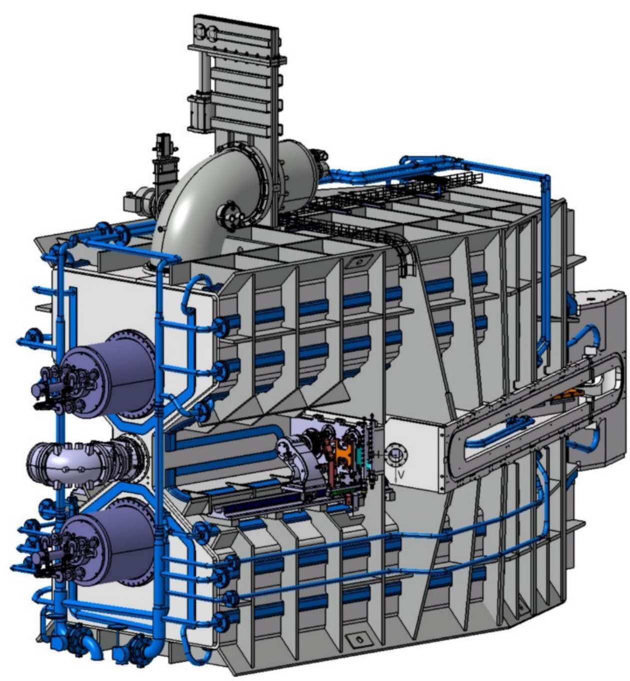

Figure 2: Isometric view of Resonator 4 with tuner, coupling loop in the front and vacuum pump on the top.

The new Resonators were made of Aluminum allowing using the existing cooling infrastructure of the Resonators 1 & 3. Both resonators were designed at Paul Scherrer Institute (PSI) and manufactured in France by the company SDMS. Some key parameters are listed in Table 1.

† markus.schneider@psi.ch

ISBN: 978-3-95450-205-9 doi:10.18429/JACoW-Cyclotrons2019-MOC03

Table 1: Parameters of the New 50 MHz Resonator

Parameter	Value
Resonance Frequency	50.6328 MHz
Q_0	24’500
Peak gap Voltage	400 kVp
Dissipated Power	50 kW
Tuning Range	200 kHz
Material Cavity RF-wall	EN AW 1050
Material Structure	EN AW 5083
Cooling Water Flow	15 m3/h
Dimension	5.6 x 3.3 x 3 m
Weight	7000 kg

Test of the new Resonator 2 The new Resonator 2 was successfully tested in our rf test stand in 2017. The cavity was first conditioned within a day to a power level of 100 kW. During a 24 hours long term run the distribution of the thermal losses in resonator was tested by measuring the temperatures with thermocouples at about 50 different locations.

For the beam entrance and exit the rf volume the resonators have a slit of 40 mm in height and 2.4 m in length on both sides. To quantify the rf leaking into the cyclotron’s vacuum chamber, the leaking power into the wings was measured with a capacitive probe. First the voltage distribution along the slit was measured with the network analyzer. Afterwards the leaking power was measured at different power levels. By shifting the electrodes of the cavity, the asymmetric leaking power on one side could be reduced significantly as shown in Table 2. The measured leaking power is in the range of 20 µW.

Table 2: Measurement of Leaking RF Power

Position of Pickup in Wing	Resonator Wall Losses	Pickup signal before shifting	Pickup signal after shifting
Beam exit	50 kW	233.5 mV	22.2 mV
Beam exit	70 kW	271.8 mV	25.1 mV
Beam entrance	50 kW	41.7 mV	25.0 mV
Beam entrance	70 kW	33.3 mV	30.4 mV

Finally, the accelerating voltage of the resonator was determined by measuring the Bremsstrahlung. Therefore, a CZT-detector (SPEAR^{TM}-detector of Kromek) was installed in a lead housing with a 1.5 mm aperture pointing towards the area with the highest electrical field of the resonator. The resonator was operated on different power levels for 8 hours and from the measured Bremsstrahlung spectrum the highest energy at the zero crossing was determined. The measurements of Resonator 2 are listed in Table 3. To be able to determine the gap voltage during regular operation of the cavity, the voltage on a reference pickup was measured. The measured wall losses of 50.3 kW for 400 keV kinetic energy is comparable to the simulations of 50 kW wall losses for a gap voltage of 400 kVp.

Table 3: Results from the Bremsstrahlung Spectrum Measurements of the New Resonator 2

RF Power	Voltage on Reference Pickup	Zero Crossing in Bremsstrahlung Spectrum
35 kW	2.936 V	323 keV
46 kW	3.402 V	382 keV
56 kW	3.714 V	422 keV
66 kW	4.040 V	467 keV
75 kW	4.280 V	483 keV
85 kW	4.560 V	500 keV

Installation of the new Resonator 2 During the shutdown 2018 the old 150 MHz Resonator 2 was removed from the Injector 2 and replaced by the new 50 MHz Resonator (see Fig. 3). This requires the decommissioning of the old 150 MHz rf system (amplifiers and LLRF) and setting up the new 50 MHz system during beam operation. The resonator was installed without coupling loop and without tuners and is therefore used as vacuum chamber only. Since only 3 resonators are available, the Injector 2 is currently operated at a reduced beam current of 2 mA. Nevertheless, the new resonator was already equipped with all necessary parts for beam control and diagnostic and the beam operation with 3 resonators could successfully be started after the shutdown in 2018. The Injector 2 is presently operating in this regime.

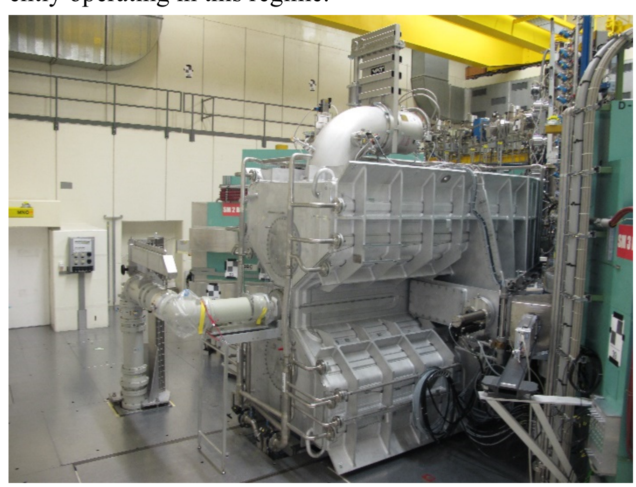

Figure 3: The new 50 MHz Resonator 2 installed in the Injector 2 Cyclotron.

Test of the new Resonator 4 The Resonator 4 was manufactured first and previously tested in 2016/ 2017 at full power without any problems. The Resonator 4 was then stored in a separated building, because the test stand was used for the tests of Resonator 2, which was intended to be installed in the cyclotron first. At the end of 2018, the Resonator 4 was moved back to the test stand and the test program was restarted. During a long term run at 60 kW

ISBN: 978-3-95450-205-9 doi:10.18429/JACoW-Cyclotrons2019-MOC03

we observed a 27 °C higher temperature on the bottom than on the top side of the cavity. This problem is still under investigation. We observed a change of the input impedance at about 3 kW incident power, which indicates the ignition of a discharge in the cavity which persist up to higher power levels. Obviously, a suitable treatment of the wall surface of the bottom has to be performed to avoid this effect. This could be cleaning or painting with Aquadag® to change the secondary emission coefficient of electrons.

Tuning system For tuning the cavity two plungers of about 500 mm diameter are installed. The plungers can be shifted by a hydraulic system by 200 mm, which results in a frequency shift of 200 kHz. Figure 4 illustrates the tuner.

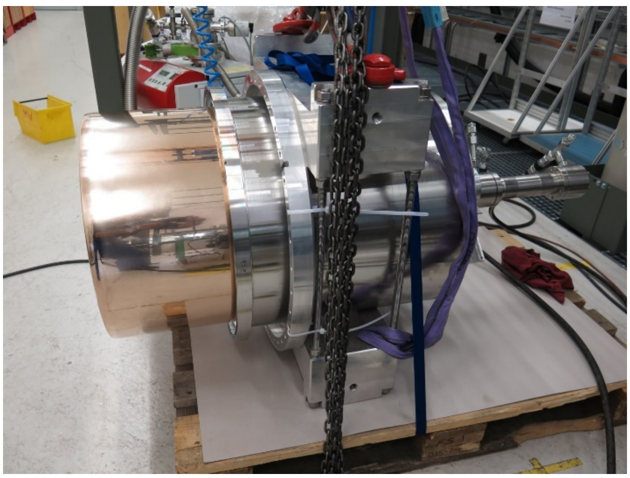

Figure 4: The tuner for the new 50 MHz resonator.

The plungers are made out of copper and are water cooled. The plungers are hard gold coated on the outside and there are finger contacts of silver graphite for the rf current flow to the cavity wall. During the tests the finger contacts showed some weakness requiring a consolidation before going into operation. After 1 month of tests abrasion of the silver graphite contact material was observed which leads to dust in the cavity and scratches in the gold plated copper. This is not acceptable for an operation in the cyclotron and caused a delay of the project. Until now different materials and contact types were tested, but no satisfactory results have been found. At the moment a version of the tuner without finger contacts is under test.

Coupling loop To couple the power into the resonator an inductive coupling loop is used. During the power runs in the test stand the input impedance of the resonator was matched to 50 Ohm. For the operation in the Injector 2 the impedance will be adapted to 81 Ohm, which results in a loop length of 84 mm. Due to the beam loading a perfect matching to 50 Ohm will be reached at a beam current of 2.0 mA.

Transmission Line

The transmission lines between the resonators and the final stage of the amplifiers are purchased from the German company Spinner. The standard RL 100-230 is used at the connection of the amplifier and on the resonator side: In between, the line is reduced to EIA 6 1/8". The length of the transmission line between the amplifier and the cavity is matched by high power phase shifters to a multiple length of lambda half to avoid having impedance transformation along the transmission line.

Amplifiers

The power requirements of the amplifiers for the different resonators are listed in Table 4. These levels include some margin for the LLRF system, load mismatches, higher beam currents and an operation with only 3 resonators.

Table 4: Amplifier Power Requirements

RF System	Driver	IPA	PA
Resonator 1	2 kW	35 kW	360 kW
Resonator 2		10 kW	180 kW
Resonator 3	2 kW	35 kW	360 kW
Resonator 4		10 kW	180 kW

Power Amplifiers (PA) The final stage is a tetrode (RS2074HF) based amplifier, running in grounded grid configuration. This amplifier was designed at PSI for the Ring cyclotron where it is running at a power level of 650 kW. For the Injector 2 upgrade project the same rf design is used with an adapted working point on lower power level. As the rf circuits are installed in a trolley, the amplifier can be used either for the Injector 2 or for the Ring cyclotron. This facilitates stock-keeping of spare parts and allows for the flexibility to switch between the accelerators. Five new amplifiers were produced for the Injector 2 upgrade project (see Fig. 5). In case of a failure, the amplifier can be replaced within 3 hours.

Figure 5: Amplifier hall with 5 power amplifiers.

The plate voltage power supply is capable to deliver up to 15 kV and 40 A. It is a Pulsed Step Modulator, where the output Voltage can be adjusted. The advantage of this technology is to have less stored energy and no crowbar system is needed. The prototype was tested by the manufacturer on a load. All 4 power supplies were delivered to PSI and currently the installation is ongoing. The grid and screen power supplies are commercial power supplies from the industry. PSI is now performing the system integration and building up the amplifier control system for the final stage.

ISBN: 978-3-95450-205-9 doi:10.18429/JACoW-Cyclotrons2019-MOC03

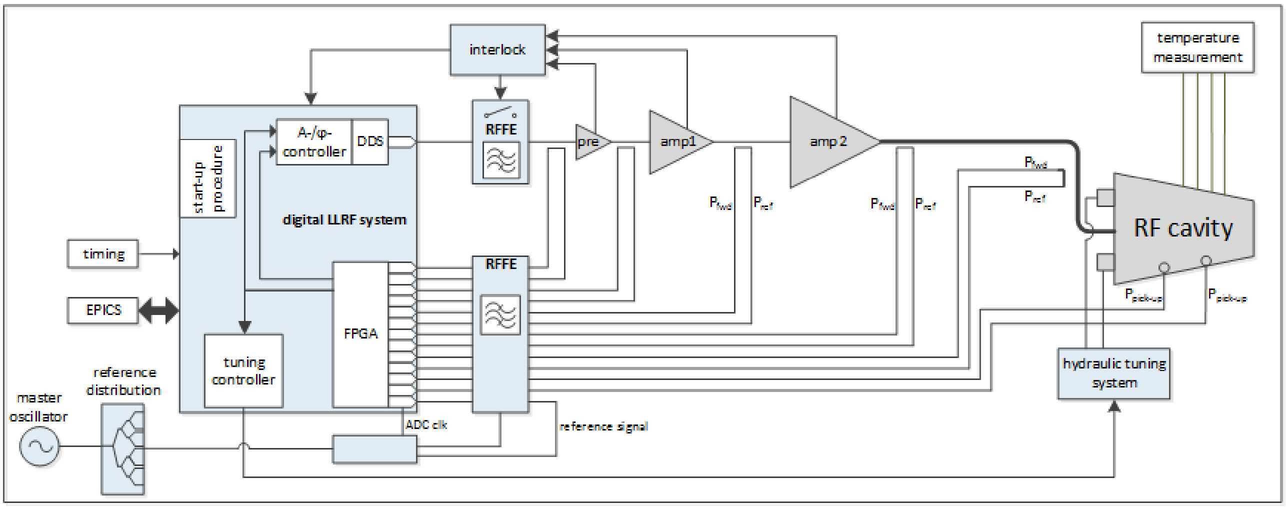

Figure 6: Overview layout of an rf station with digital LLRF system, amplifiers and cavity.

Intermediate Power Amplifier (IPA) In the rf stations for Resonator 2 & 4 a 10 kW solid state amplifier (SSA) is used as driver. Two BBL200A10000 were bought from the company Rhode & Schwarz. Both amplifiers have been delivered to PSI in 2019 and were successfully tested on a load.

For resonator 1 & 3, we consider a tetrode based IPA with a 2 kW SSA or alternatively a 35 kW SSA.

The first amplifier chain will be tested in 2020 on an rf load.

Digital LLRF System

A new digital system is intended to replace the existing analog LLRF System and will improve maintainability due to better diagnostics capabilities and integration into the control system (EPICS). The concept foresees a new LLRF system that is based on PSI's standard processing board, FMC mezzanine cards and a specific rf front-end to condition the rf signal for direct sampling. The demodulated signals are used for amplitude and phase feedback, for monitoring and calculation of the drive signal for the mechanical cavity tuners. In Fig. 6 an overview of an rf station is given.

The tuning system is realized as a master/slave system. The slave tuner follows the positon of the master tuner. The master can either be in position control, where the plunger moves to a given position or in the phase control mode, where the resonator is kept on resonance by comparing the phase of the incident power of a directional coupler with the phase of a cavity pickup.

The main objective of the LLRF system is to keep the amplitude and phase of the cavity in the required stability by setting the rf signal feed to the amplifier chain. To start up the system a startup sequence is implemented to bring the cavity quickly through the multipactoring levels by pulsing the rf [4].

The LLRF system includes an interlock system that supervises the whole rf station and can switch it of in case of any failure. The rf is inhibited in case of a subsystem, a bad vacuum, if the cooling water for the cavity, tuner or plunger is missing, and in case of a temperature of the cavity is too high.

CONCLUSION

The new Resonator 2 was successfully tested and characterized under full power. Different redesign options to solve the issues with the finger contacts on the tuners are under investigation. The installation of the amplifier chain and new digital LLRF system should be finish until summer 2020 for the commissioning of the new system in the second half of 2020 and to demonstrate the operation of Resonator 2 with beam. This will allow to operate the Injector 2 at a beam current of 2.4 mA beam currents and to complete the upgrade with the implementation of Resonator 4.

ACKNOWLEDGEMENTS

There a many different groups at PSI involved in this upgrade and without their effort for the project we wouldn't have reached the current state. Many thanks to all the people involved.

A special thanks goes to Hansruedi Fitze, Sebastian Jetzer and Erich Wüthrich of the rf group, who performed many measurements and tests on the new resonators.

REFERENCES

[1] S. Adam, "Calculation of Space Charge Effects in Isochronous Cyclotrons", in *Proc. 11th Particle Accelerator Conf. (PAC'85)*, Vancouver, Canada, May 1985, pp. 2507-2510.

[2] L. Stingelin, M. Bopp, and H. Fitze, "Development of the new 50 MHz resonators for the PSI Injector II Cyclotron", in *Proc. 18th Int. Conf. on Cyclotrons and their Applications (Cyclotrons'07)*, Giardini-Naxos, Italy, Oct. 2007, pp. 467-469.

[3] L. Stingelin *et al.*, "High power RF systems and resonators for sector cyclotrons", in *Proc. 19th Int. Conf. on Cyclotrons and their Applications (Cyclotrons'10)*, Lanzhou, China, Sep. 2010, paper WEM2CIO01, pp. 332-337.

[4] J. Cherix and P. Sigg, "Pulsed-RF to start the cyclotron cavities in a short time", in PSI - Scientific and Technical Report 2004 / Volume VI, Paul Scherrer Institute, Villigen PSI, Switzerland, 2004, pp. 16-17.