OPAL SIMULATIONS OF THE PSI RING CYCLOTRON AND A DESIGN FOR A HIGHER ORDER MODE FLAT TOP CAVITY*

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Abstract

The PSI cyclotron has been producing high power proton beam for 42 years. Over its lifetime it has been upgraded from producing 100 µA to 2.2 mA at 590 MeV. As the power reaches higher levels, it become more important to understand how the machine's beam dynamics will react to new devices introduced. We present an OPAL (Object Oriented Parallel Accelerator Library) model of the cyclotron and compared it to the probe measurements from the machine. This model has good agreement with the measurements over the ~180 turns in the machine. Using this same model, a higher order mode flat top cavity was inserted into the machine and the number of turns was decreased corresponding to an increase in maximum current. The HOM cavity design will also be presented.

INTRODUCTION

The Ring Cyclotron at the Paul Scherrer Institut accelerates 2.2 mA of proton beam from 71 MeV to 590 MeV. This was accomplished by progressively upgrading components, such as the four Main RF cavities that were redesigned to increase the accelerating voltage from 730 kV to 1 MV [1,2]. Currently the limiting feature in the cyclotron is the Flat Top Cavity. This cavity operates in the 3rd harmonic and increases the longitudinal acceptance of the machine. The cavity has reached its voltage limit due an inability to keep the cavity tuned caused by deformation from heating, as well as other associated problems [3,4]. A new Flat Top cavity was designed to allow for higher voltages which would ultimately lead to higher currents in the Ring. However, to show that the cavity would work as anticipated, a model of the cyclotron that could reproduce the existing beam and setup was needed.

OPAL SIMULATIONS

Prior Simulations

Object Oriented Parallel Accelerator Library, OPAL, is an open source particle accelerator simulation code capable of massive parallel processing [5,6]. OPAL-CYC, one of the suite of tools in OPAL, was used for this work. OPAL was used to model the Ring cyclotron in 2011 by Bi, but the model was only matched to the experimental data for last 9 turns [7]. The result of the model, Fig. 1, showed that OPAL could match experimental data from beam profile monitors to a high degree with initial parameters consistent with those in the control room. These simulations provided stimulus to see if the entire cyclotron could be modelled, matched to experimental data, and create a platform to test new devices.

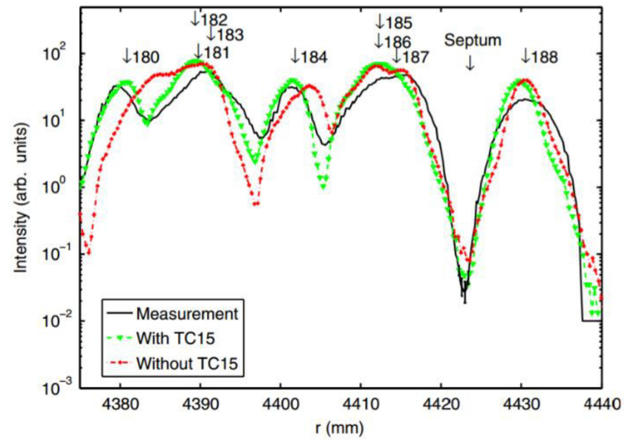

Figure 1: Bi's simulation [7] overlapped with experimental measurements for the last 9 orbits of the Ring cyclotron.

Current Simulation

The goal of this study was to obtain an accurate model of the entire Ring via orbit matching and phase matching for all orbits. Several additions were made to the existing model as well as a few modifications to OPAL itself. One such set of modifications was improved trim coil placement in the sector dipoles and the trim coil profiles themselves. In the previous model only trim coil 15 (TC15) was used, but all 18 trim coils were inserted and magnet profiles generated to create more realistic conditions, Fig. 2.

To model the entire cyclotron, identifying the exact placement of the probes, or beam profile monitors, is of critical importance to align the modelled and experimental data. No single probe covers all the turns in the cyclotron. Therefore, three profile monitors were identified (Fig. 3) that could cover all orbits, RRI2 – the injection probe, RRL – the long probe, and RRE4 – the extraction probe.

The monitors have been moved over the years, and therefore the exact positions were obtained with respect to the machine center. Finding experimental data for all three probes for the same RF settings, injection energy, and trim settings was difficult. A set was identified [8], where the probe positions were exactly known, that met these requirements and were close in proximity in time to each other. The data for RRE4 and RRI2 were from July 5th 2012 and for the RRL the data was 7 days earlier.

The initial beam parameters were taken from Anna Kolano's Injector II OPAL simulation [9]. From the injector

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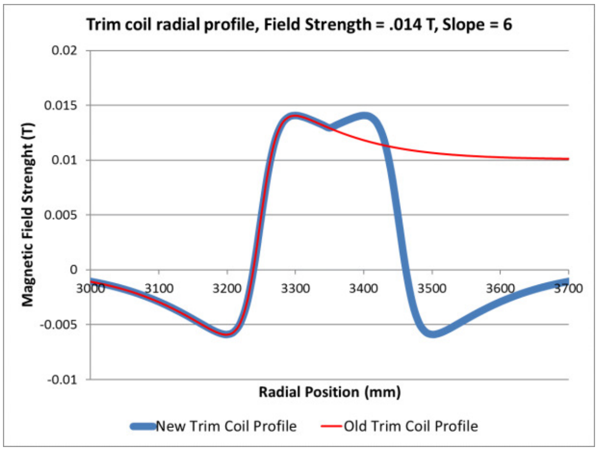

Figure 2: Old and new trim coil profile. The old profile was only used near extraction so the particles never exited the trim coil. However, for the 18 trim coils placed in the new simulation, the effect from entering and exiting the trim coils is needed.

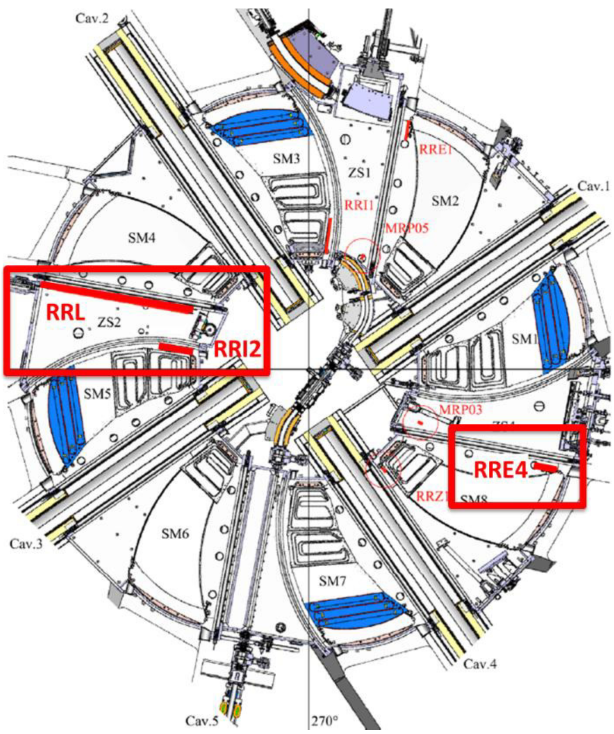

Figure 3: Diagram of the PSI Ring Cyclotron. The location of the three probes used for orbit matching are indicated by thick red lines inside the boxes. Other probes and components are also labelled.

to the Ring, the bunch passes through the IW2 – beamline that causes the beam to grow nearly 8 times larger longitudinally. Thus, the input beam for the Ring are the extracted injector beam's parameters, but elongated (19.8 mm).

The profiles for the magnets and RF cavities were inserted into OPAL. The strength of the dipoles was always held constant throughout all the models. The RF voltage of each cavity was set to the measured value. The trim coils field strengths were set to zero and gradually turned on to match the orbits. A minimum of 10,000 particles is required in the simulations to understand the behavior of the

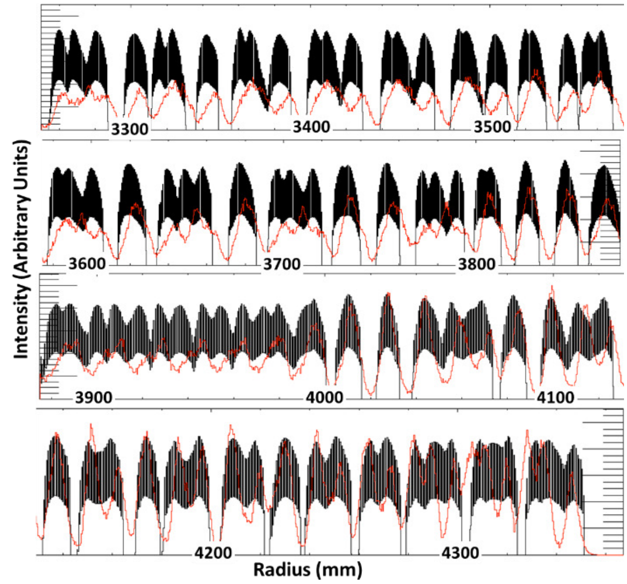

Figure 4: The last 89 turns, as seen from the RRL probe, of the modelled beam (red) and the measured beam (black) are overlapped. There is excellent agreement and all orbits accounted for in the RRL probe.

beam in the cyclotron. If significantly less particles are used, slight modifications can cause variations that are not reproducible when higher fidelity runs are computed.

Simulation Results

Early into the investigation it became clear that the injection energy is a key parameter for orbit matching. It determined the spread between orbits from injection to extraction. Bi's study used an injection energy of 72 MeV. This model found the best matching existed between 71.2 to 71.8 MeV. Experimental measurements recently performed in the IW2 transfer line show that the energy is between 71.2 and 71.4 MeV, matching the model's findings.

Two methods were used in the model to determine the effect of the trim coils on the beam: orbit matching and phase matching. The orbit matching was accomplished by overlapping the modelled beam profile monitor data with the experimental data. The second method required the insertion of a phase monitor into the cyclotron model. This was done by inserting a dummy RF cavity that provided no voltage but still provided the phase of the RF when the beam passed through. This was compared to the phase measurements (MRF diagnostics) in the control room for the dates selected.

One of the predominant questions was how many turns are in the machine. Bi's model indicates 188 orbits. Looking at the experimental data on RRL, the number of turns seen by the probe is 174. The orbits were individually tracked in OPAL and it was determined the first orbit that could be seen by both RRI2 and RRL was turn 7. Thus, the actual number of turns in the machine should be 180 turns.

To achieve this number of turns, no amount of trim could be added in the model to achieve this result. The trim coils were all placed at zero field and the cavities' voltage was gradually increased until the beam was extracted after 180 turns. This resulted in a net increase of 4.4% to the cavity

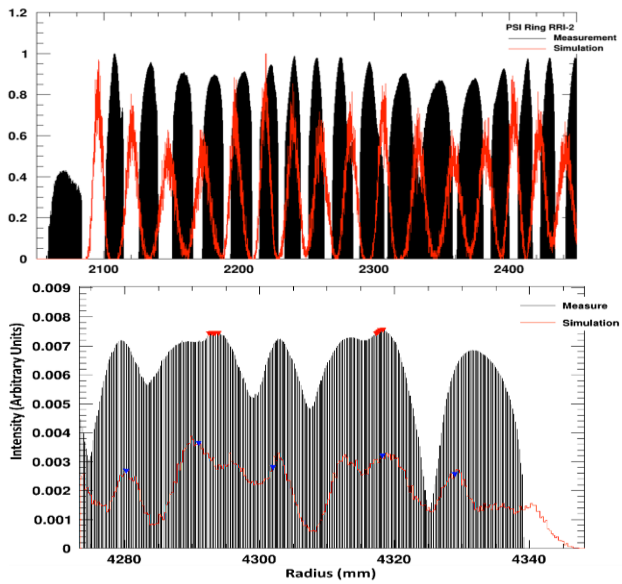

Figure 5: Top: The first few turns, as seen by RRI2, of the modelled beam (red) and the measured beam (black). They are not well matched (exclude first black peak), but reasonably close. Only first 6 are not seen by RRL, and could be better aligned with optimized trim coils. Bottom: The last 7 turns overlapped as seen by RRE4. There is good agreement in the location of the orbits. The magnitude is in arbitrary units for the measured and modelled data.

voltages in the model. This increase is well within the measurement error of the Ring's cavity voltage monitors. The injection energy was then tuned to match the RRI2 orbit spacing and phase measurements.

The resulting model was then plotted against RRI2 (Fig. 5), RRL (Fig. 4), and RRE4 (Fig. 5). The model shown had an injection energy of 71.5 MeV, which was very close to the experimental measurements, and an extraction energy of 586.81 MeV. The overall distribution in peak shape will be different due to the current in the simulation being 2.2 mA to match to RRI2 and RRE4, but RRL has a current limit of 400 micro amps.

The alignment of the modelled and experimental peaks for the injection probe is not good. All the orbits are accounted but are not well aligned. However, the extent is not so bad as to have experimental and modelling peak crossing two or more orbits. The alignment of RRL is extremely good given 174 orbits need to be aligned. Similarly, RRE4 is in good agreement with the experimental data, including the clean separation of the last orbit for extraction. Improvement is expected when the trim coils are activated, especially near the injector, and optimized in future studies.

NEW FLAT TOP CAVITY DESIGN

The Flat Top Cavity might need to be replaced in the future and methods to increase its capabilities were investigated. The limitation was to ensure that the new cavity could reside in the current allowed real estate. Several options were explored but rounding the ends of the cavity provided several nice features, see Fig 6.

The rounded ends provide a more uniform flat topping profile across all 180 turns and a more advantageous heat load distribution. However, this cavity has the interesting feature of being upgraded. If irises are moved in by 4 cm, the cavity can be operated in a Higher Order Mode that flat tops at injection where it is needed the most and accelerates the beam on the outer orbits. This HOM reduces the number of turns and therefore increases the current able to be transported in the Ring as Joho showed [10],

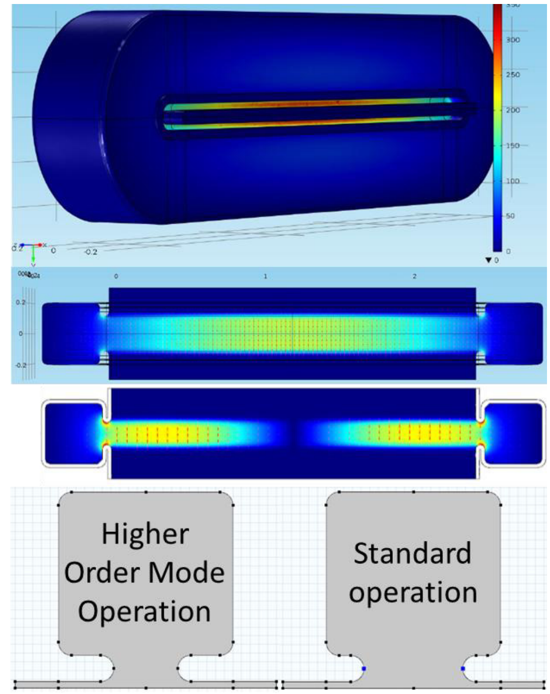

Figure 6: (Top) Rounded ends of a Flat Top Design. (Middle) The electric field of the flat topping mode of the rounded cavity compared to the HOM operational mode. (Bottom) The geometry change required to switch modes in the cavity, which require 4cm of slide in the irises.

$$\langle I \rangle_{max} \propto \frac{1}{n^3} \propto V_{cavity}^3, \tag{1}$$

where n is the number of orbits. Inserting the HOM cavity into the model the number of orbits is reduced to 157 orbits. Using the Joho relation, this would allow a maximum of 3.4 mA in the Ring. In the event that the superbuncher is used in the IW2 beamline, and therefore longitudinally squeezing the beam, the Flat Top could be used as an accelerating cavity further reducing the turn number. The cavity could also be operated in flat topping mode as well.

If the cavity is constructed out of copper, instead of aluminium, the corresponding voltage for the same heat load would allow the Main RF cavities to reach their 1 MV potential. If the Main were set to 1 MV and the Flat top to 650 kV, the number of turns is reduced to 135 using the HOM mode, corresponding to a maximum current of 5.3 mA.

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