

RESONATOR SYSTEM FOR THE BEST 70 MeV CYCLOTRON

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Abstract

Best Cyclotron Systems Inc. (BCSI) is presently developing a 70MeV cyclotron for radioisotope production and research purpose. The RF system comprises two separated resonators driven by independent amplifiers to allow for the phase and amplitude modulation technique to be applied for beam intensity modulation. The resonators are presently in the commissioning phase consisting of cold test measurements to be later followed by high power commissioning in the cyclotron. The electromagnetic modeling has been done with CST Microwave Studio. All simulation results showed a very conservative design with typical parameters for the energy and size of the resonators.

INTRODUCTION

General Description

The RF System is composed from two independent resonators insulated at the center region, amplifiers and LLRF control systems interconnected through local oscillator synchronisation, clock signals and master/slave operation mode as shown in Fig. 1. The high level operation is implemented at the level of the cyclotron PLC control and graphic interface. All RF operational procedures are implemented at the level of the LLRF control digital processing module with FPGA and micro-controller technology.

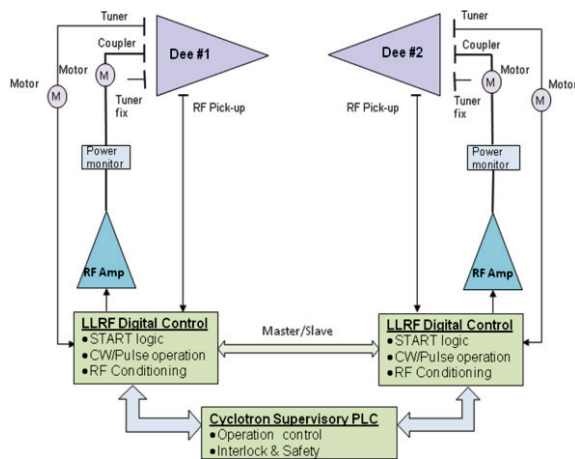


Figure 1: RF System diagram.

The RF system has to operate within specific stability requirements regarding the dee voltage amplitude and phase: dee voltage stability $< 5 \times 10^{-4}$ and phase stability $< \pm 0.1$ degrees. The initial beam intensity is designed for 700 μ A of negative hydrogen ions to be accelerated to 70MeV.

There are a few advantages in designing separate resonators for high energy cyclotrons that have been considered:

- Symmetric dee voltage distribution
- Reduced coupling power per cavity making the coupler design less critical
- Minimizes cavity mismatch with beam loading, lower VSWR
- Allow for beam intensity control through phase modulation of the accelerating electric field.

RESONATORS

Electromagnetic Model Simulations

Preliminary electromagnetic modeling has been done with CST Microwave Studio and simulation results have been reported [1] and presently updated as the detail design was completed.

The resonators are operating on 4th harmonic and are $\lambda/2$ resonant cavities with single stem design. Each resonator cavity is equipped with capacitive coupling and tuning mechanism. An additional fix tuner has been added per cavity to compensate for the slightly difference in frequency due to the dee tip configurations while keeping the same stem length.

Final simulation results are listed in Table 1.

Table 1: Resonator Simulation Results

Parameter	Value
Frequency (4 th harmonic)	56.2MHz
Quality factor Q	6800
Power loss per resonator	17.3kW
Shunt impedance	103k Ω
Dee tip/outer voltage	60 to 70.4kV
Maximum current density	5200A/m

Dee voltage distribution is shown in Fig. 2.

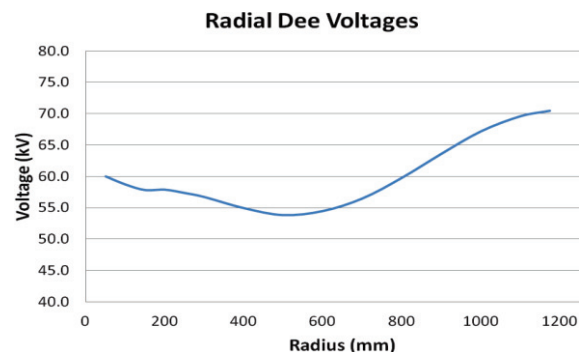


Figure 2: Radial dee voltage distribution.

The surface currents on the resonators were simulated to help identify regions of high current and thus thermal dissipation where water cooling will be primarily focused. Plots of the current density scaled down for 60kV dee tip voltage are shown in Fig. 3. The maximum surface current on the resonator dee and stem is 5200A/m with a reduced value of 3200A/m at the outer diameter where the contact fingers are placed.

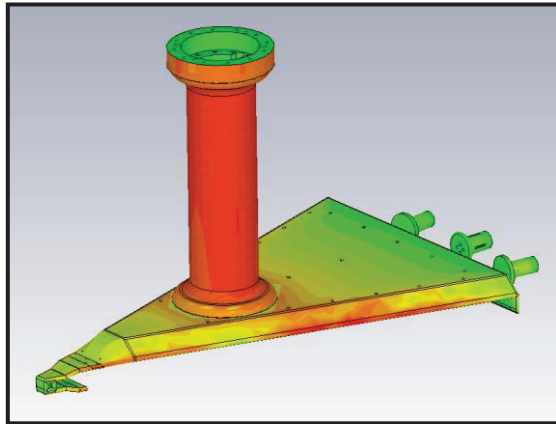


Figure 3: Surface currents on the resonator and stem, 5200A/m.

Coupler matching has been studied in detail for various coupler shapes and separation to dee plate to compensate for beam loading. Figure 4 represents the internal unloaded quality factor Q_{int} and external quality factor Q_{ext} required to achieve perfect matching during beam loading.

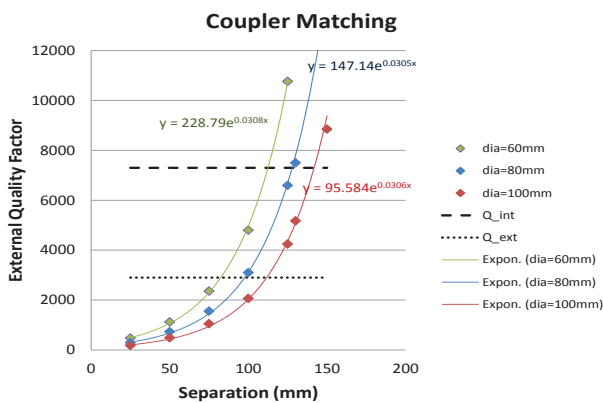


Figure 4: Coupler matching for various coupler positions and face diameter.

Mechanical Model

The resonator design has also been mechanically and thermally optimised through simulation in ANSYS. The design is light weight through the use of dee plates designed for RF surface covering and hollow structure. The resonator consists of one circular stem design located centrally on the dee and a shallow valley depth of 350mm. The stem is advancing within the magnet bore through a coaxial cavity structure to reach the resonant design frequency of 56.2MHz. Stem and dee plate are separate sections connected with screws, typical design

for large resonator structures. The cooling has been optimised to maintain the copper temperature increase below 14°C. The resonators are manufactured from OFHC copper.

A transparency view of the resonator model is shown in Fig. 5.

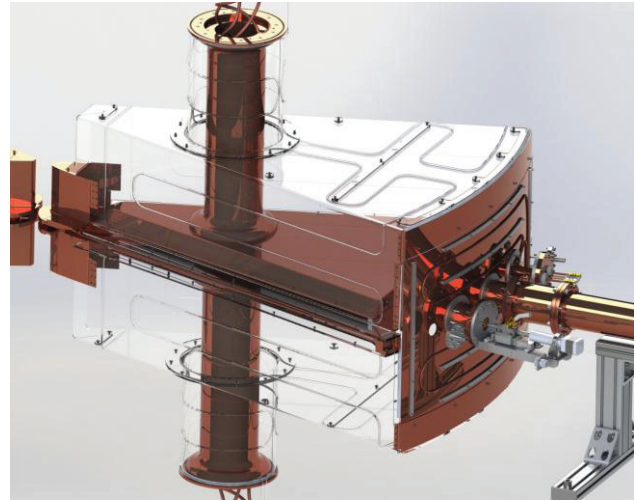


Figure 5: Resonator mechanical model.

The resonator dee plate/stem assembly is separating and opening with each lower and upper section being permanently attached to the corresponding liner. A very simple three dimensional adjustment mechanism has been implemented at the base of the stem to allow for alignment and mechanical support of the dee/stem assembly. The electrical conductivity between dee plates when closing is ensured with removable finger contacts at the tip and end section of the dees.

Resonator Cold Test Set-up

The resonator final characteristics will be determined in a cold test set-up outside of the cyclotron magnet. A dedicated support frame reproducing the magnet valley has been designed for one cavity assembly as shown in Fig. 6. The stem sections have adjustable length. The set-up will be used to characterise both cavities by replacing the dee tip only.



Figure 6: Resonator cold test set-up.

In addition to adjusting the stem length for the design frequency and to confirm the quality factor the cavity will also be characterized for tuning capability range for both fixed and movable tuner, coupling impedance and VSWR variation with the coupling factor. The design values are listed in Table 2.

Table 2: Resonator Tuning Characteristics

Parameter	Value
Tuner frequency range	$\Delta f \approx 150$ to 200kHz
Tuning sensitivity	12.5 to 15kHz/mm
Fix tuner range	400kHz
Stem adjusting sensitivity	45kHz/mm

AMPLIFIERS

Two radiofrequency power amplifiers are required, one for each cavity, to provide the necessary power to generate and sustain the accelerating field and additional energy transfer to the beam. The power balance for one amplifier is considering the following:

- P resonator ≈ 18 kW
- P beam (half) ≈ 25 kW (for 700 μ A)
- P margin additional 20%

The total power for one amplifier is estimated at 55kW. The amplifiers are purchased units specified for narrow band operation at 56MHz with 55kW of output power. The final stage is strip line design operating with the Eimac tube 3CW40000A7 that can safely deliver 60kW of RF output. The driver stage is a 3kW strip line tube amplifier and the pre-amplifier stage is a 250W solid state narrow band amplifier. The amplifiers fully contain all power supplies, power monitoring and controls as well as remote control interfacing with the cyclotron PLC for automation as shown in Fig. 7.

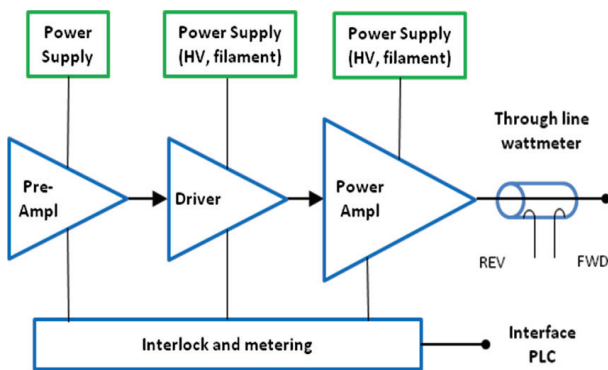


Figure 7: RF Power amplifier block diagram.

Amplifiers Test

The amplifiers have been successfully tested to the maximum design power of 55kW for continuous operation of 48 hours. The final stage efficiency is 62% and harmonic content below -25dBc.

LLRF CONTROLS

The LLRF circuit design is based on proprietary DSP design of the digital control board and a dedicated radiofrequency application board providing the interface between the LLRF and all the low level radiofrequency monitoring signals in the system. The circuit assembly is shown in Fig. 8.

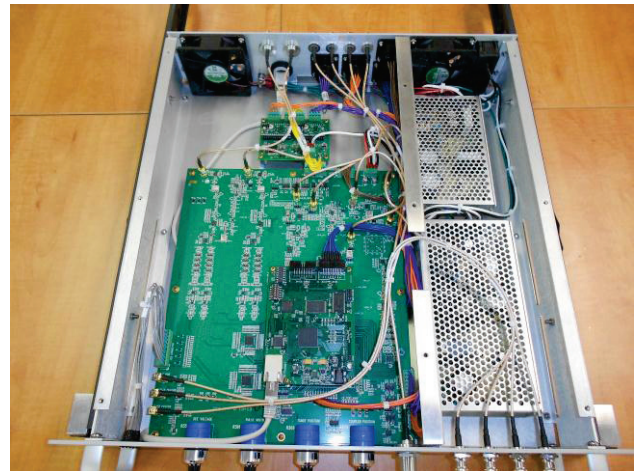


Figure 8: LLRF digital control circuit.

The LLRF controller is ensuring all typical operations required to control, stabilize and operate the RF system:

- Amplitude control loop
- Frequency control loop
- Phase stability
- Phase and amplitude modulation for beam intensity control

Automated operations:

- Start and Stop procedures
- CW and Pulse Mode conditioning procedures
- Spark control and Recovery procedures

The LLRF Control system design is presented in more detail at this conference [2].

REFERENCES

- [1] G. Gold et al., "Simulation and Design of a 70MeV Cyclotron RF System," IPAC 2012, New Orleans, May 2012, THPPC001, p. 3269.
- [2] G. Gold, V. Sabaiduc, "Design of a Digital Low-level RF System for BEST Medical Cyclotrons", TUPPT024, this conference.
- [3] Tianjue Zhang, Shizhong An, Chuan Wang, et al., "Physics design of a 70MeV High Intensity Cyclotron, CYCIAE-70", Proc. of 10th ECAART 2010, Athens.