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DESIGN OF A QWR CAVITY FOR THE NEW ISIS MEBT

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Abstract

The quarter wave resonator (QWR, a.k.a. λ/4 resonator) for the new ISIS MEBT is a bunching cavity that longitudinally compresses the H^- beam into smaller bunches. It has 2 gaps with a distance of βλ/2 between mid-gaps, and works in π mode at the resonant frequency of 202.5 MHz, with a phase angle of -90 degrees. The maximum voltage per gap (E_0L) is set to 55 kV. A detailed RF model has been developed to tune the main dimensions to the required frequency and to estimate the Kilpatrick ratio and the RF power dissipation. The cavity is designed to be made of copper plated stainless steel, which has a considerable effect on the design of the cooling system; the thermal calculations include a thermo-mechanical analysis to estimate the dynamic tuning requirements. The cavity has two tuners to allow for a fine and a coarse tuning of the resonant frequency. The manual tuner coarsely adjusts the frequency to cope with the manufacturing tolerances. The automatic tuner finely tunes the frequency within a range of working temperatures. The tuners are heavily coupled both in terms of frequency resolution and tuning range, which presents some challenges to the design. The design of the power coupler was adapted to the QWR from another project and the coupling coefficient was adjusted to the new cavity. A sensitivity analysis for the critical dimensions was also developed, but is not presented here.

DESIGN PARAMETERS

The ISIS LINAC directly connects the RFQ to the first DTL tank at an energy of 665 keV. There is a desire to install a MEBT between both devices to improve the beam matching. The new MEBT consists of four QWRs, a beam chopper and eight quadrupole magnets. The QWR cavities are required to compress the H^- beam into smaller bunches (Table 1). A QWR saves space versus a pillbox type design.

Table 1: QWR Main Design Parameters

Parameter	Value	Units
Cavity type: 2 gap λ/4 resonator in βλ/2 mode (π mode)	N/A	N/A
E_0L (voltage per gap) – operating	50	kV
E_0L (voltage per gap) – max.	55	kV
Frequency	202.5	MHz
Particle energy	665	keV
RF power duration at 50 Hz	500	µs
Beam aperture (diameter)	30	mm
Tuning frequency range	~1.4	MHz
Tuning resolution in the one sided 3 dB bandwidth	~200	steps/mm
Approx. flange to flange dimension	116	mm

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GEOMETRY AND RF SIMULATIONS

The initial dimensions for the QWR tank were estimated from the cell length and from ¼ of the resonating wavelength. The cell length (L_c) is equal to βλ/2 = 27.8 mm for this design. After several iterations to find the optimal shape of the accelerating gaps, the proposed shape and components for the QWR are shown in Fig. 1.

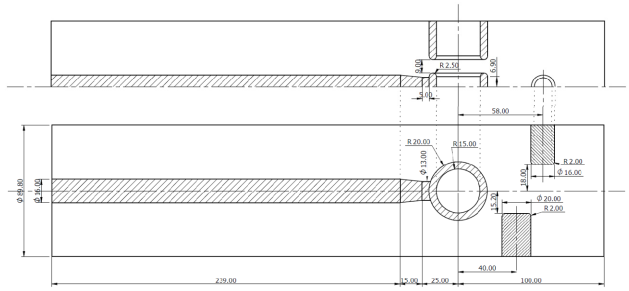

Figure 1: QWR sketch.

The diameter of the stem was optimized to maximize the shunt impedance of a quarter wave resonating cavity for a fixed tank inner diameter of 90 mm. The first electric tuner was located in a low magnetic field area to reduce heating. A second manual tuner (coarse tuner) was added to the design after noticing that the first single tuner did not have enough tuning steps in the one sided 3 dB bandwidth to accurately match the resonating peak.

A copper plated stainless steel tank was selected over a solid copper design; besides several manufacturing advantages over the solid copper tank, it also allowed for the maximization of the tank inner diameter for a fixed flange-to-flange length, as it required a smaller wall thickness (3 mm). The selected copper plating thickness was 100 µm to improve the durability of the plating, which resulted in an internal tank diameter of 89.8 mm.

The final dimensions of the geometry shown in Fig. 1 were obtained from a parameterized model developed in COMSOL Multiphysics [1]. The final model also included the geometry of the power coupler with an active absorbing coaxial port for increased accuracy (Fig. 2).

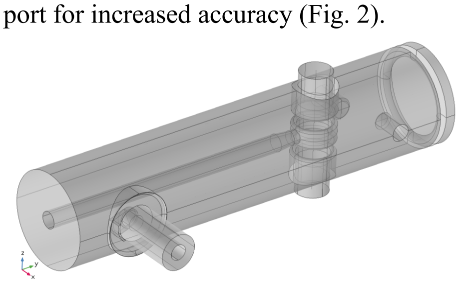

Figure 2: Geometry of the RF model in COMSOL.

The simulated resonant frequency (202.504 MHz) matched very well the nominal frequency and the Kilpatrick ratio was about 1.12. Therefore, no major problems were expected with regards to electrical breakdown.

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The accelerating electric field on the beam axis for a static voltage E_0L = 55 kV per gap and a 0º RF phase is shown in Fig. 3. The field extends clearly inside the beam pipe more than the tank radius. Therefore, all the integrals to calculate the voltage, the average field and the transit time factor were taken between -2L_c and 2L_c.

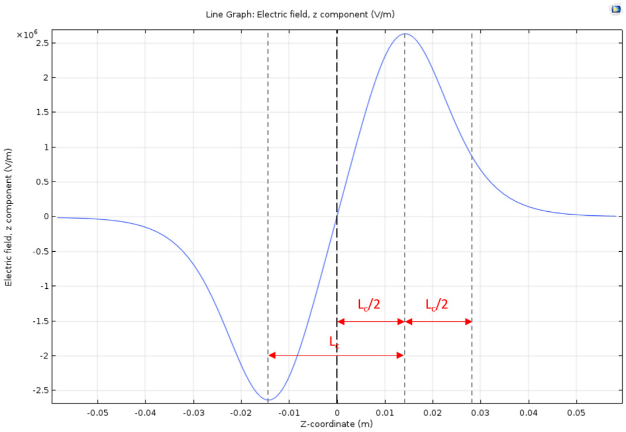

Figure 3: Accelerating electric field on beam axis.

The constant β transit time factor calculated using Eq. (1) as defined in [2] was 0.61773 for a 90º out-of-synch particle. That resulted in an effective voltage (E_0TL) of 33.975 kV per gap, calculated only as a design reference for this bunching cavity.

$$T = \frac{\int_{-2Lc}^{2Lc} E_z \sin\left(\omega Z/_{\beta c}\right) dZ}{\int_{-2Lc}^{2Lc} |E_z| dz} \qquad (1)$$

POWER DISSIPATION AND COOLING

The peak power losses on the internal surfaces of the cavity were calculated using the equivalent RF surface resistance and the tangential H fields, so no impedance boundary condition was required in FEM. The distribution of losses on the critical surfaces of the QWR during the active phase of the RF power is shown in Fig. 4.

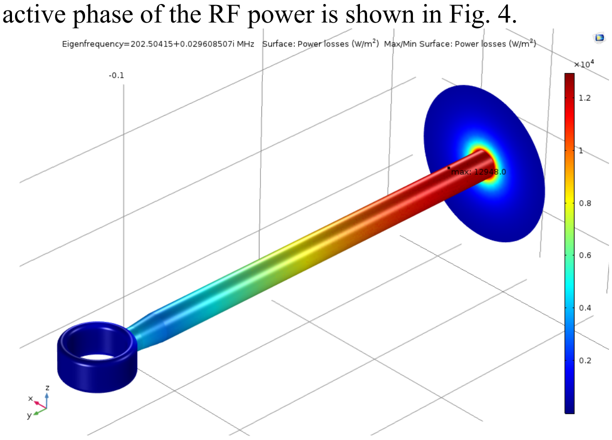

Figure 4: Loss distribution (W/m^2) on stem and lid.

The lower efficiency of the real cavity (RF joints, surface finish, etc.) was accounted for by assuming that the unloaded quality factor would be only 80% of the calculated Q_0, i.e. 3703. The minimum estimated shunt impedance (LINAC definition: $(2V_{gap})^2/P$), was 2.19 MΩ.

A summary of the maximum expected power losses in the various QWR components is shown in Table 2, where the total values are useful for the cooling calculations and later to select the required RF amplifier.

Table 2: Power Loss Distribution in the QWR

QWR section	CW power loss (W)	Averaged power loss (W)
Stem	4325	108
Tank lid	331	8.3
Tank	741	18.5
Nose cones	2 x 21.5	2 x 0.54
Manual tuner	0.47	0.012
Automatic tuner	0.029	0.0007
Power coupler	86	2.16
TOTAL	5528	138

The QWR was designed with 3 water circuits in series (stem, tank and tank lid) at an identical flow rate of 4.4 l/min. The stem cooling was done by a coaxial water circuit, and a copper cooling ring was machined on the solid copper lid. Cooling channels welded to the stainless steel tank were designed to cover a sensible area due to the poor thermal conductivity of the material; an equivalent heat transfer coefficient was calculated to avoid meshing the thin walled channels [3] (Fig. 5). Water cooling was avoided for the power coupler to reduce its complexity.

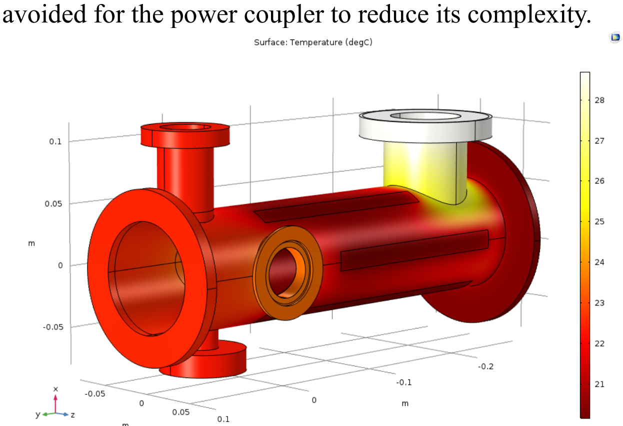

Figure 5: Temperature distribution (ºC) in the tank.

The change in shape of the different parts of the cavity due to the different thermal expansion may distort the useful fields in the gap and also change the resonant frequency of the cavity. The maximum calculated deformation was only around 25 µm (Fig. 6), and mainly produced by the lack of specific cooling around the power coupler port.

The most critical deformation (for the frequency detuning and the electric field shape) is the one that misaligns the stem ring from the nose cones. The stem misalignment was calculated as 16 µm in X direction and less than 1 µm in Y direction. The length increase of the gaps is about 1.5 µm (symmetric). The total frequency detuning due to the overall thermal expansion of the cavity was -4.7 kHz, which defines the minimum automatic tuning range, and should be easily compensated by the automatic tuner movement during the warming up process of the cavity.

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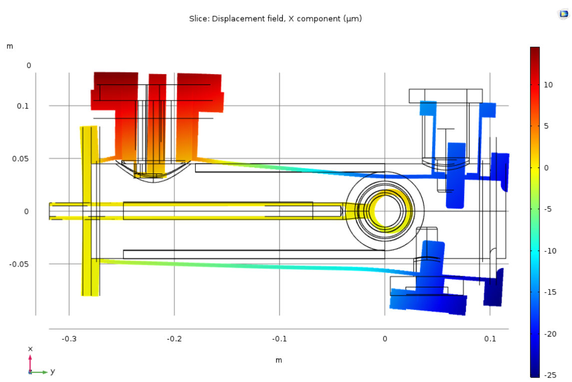

Figure 6: Thermal displacements in X and scaled deformed shape (XY cross section).

TUNING AND COUPLING

Two tuners were designed to cope both with the static manufacturing tolerances and the smaller dynamic thermal effects. Given the strong coupling between the tuners, an optimization problem was solved with the insertion position for both tuners to find the optimal frequency ranges. The tuning range of the manual tuner was f_{res} = 202.5 MHz, +689 kHz, -731 kHz (Fig. 7). This was barely affected by the insertion position of the automatic tuner.

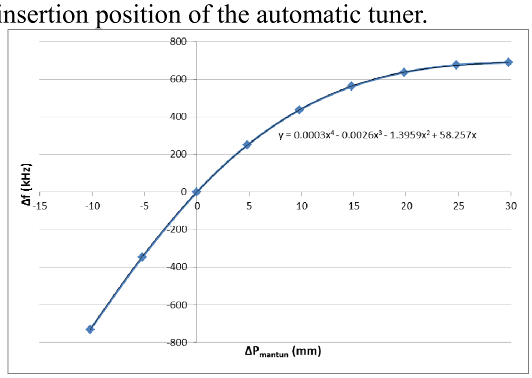

Figure 7: Frequency shift in the manual tuner range.

The automatic tuner port was located in the cavity to increase its resolution (lower sensitivity), and it was very influenced by the insertion position of the manual tuner. Its minimum range (~39 kHz, see Fig. 8) should account for the dynamic thermal effects, and occurs when the manual tuner is at its maximum insertion position.

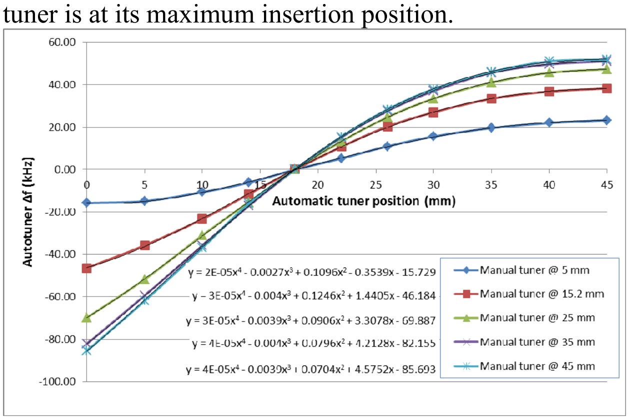

Figure 8: Frequency shift in the automatic tuner range at different manual tuner insertion positions.

The QWR will be coupled to an external RF power source using an existing power coupler design intended to handle a peak power of 8 kW at a duty factor of 0.1 with no active water cooling. In the QWR, the power coupler will need to handle an averaged power about 6 times smaller (see Table 2), so the design can be safely reused with minimal changes, saving the design effort required to do a full coupler from scratch. The power coupler design includes 20° sliding holes in the flange (18° effective) to be able to rotate it and change the coupling coefficient β [Eq. (2)] during the commissioning of the cavity.

$$\beta = \frac{P_{ex}}{P_c} = \frac{Q_0}{Q_{ex}} \qquad (2)$$

The coupler loop area and the starting angular position were optimized (Fig. 9) to achieve overcoupling at Q_{ex}<0.8*Q_0 and to ensure critical coupling between the rotation limits.

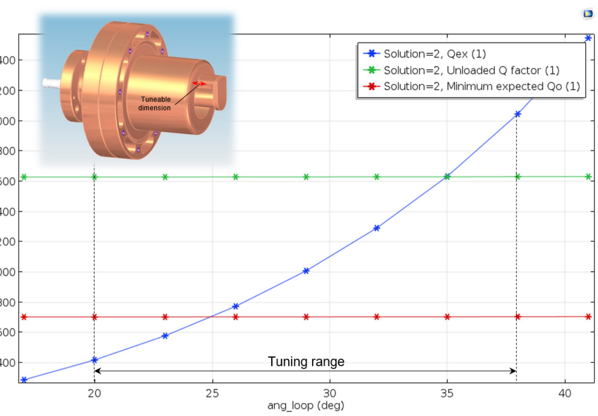

Figure 9: Q_{ex} variation with rotation angle.

CONCLUSION

The design of a QWR for the new ISIS MEBT has been presented, comprising the RF simulations, the cooling system, the tuning and the power coupling. The RF study showed sensible results that predict a reliable design. The use of a multiphysics FEA software permitted a better overall approach to the engineering design, by calculating the thermal expansion from the non-homogeneous RF heat to estimate the shift on the resonant frequency and then act on the design of the cavity tuning system. A sensitivity analysis to estimate the manufacturing tolerances has also been developed and will be presented elsewhere. The mechanical model and drawings are ready and the manufacturing is now in progress.

REFERENCES

[1] COMSOL AB, “COMSOL Multiphysics® software”, `https://www.comsol.com`

[2] T. P. Wangler, *Principles of RF Linear Accelerators*. New York, NY, USA: John Wiley & Sons, 1998, pp. 88-93.

[3] I. Rodriguez, “QWR for the ISIS MEBT – Technical Design Report”, Rutherford Appleton Laboratory, UK, Feb. 2019.

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