FIELD FLATNESS AND FREQUENCY TUNING OF THE CLARA HIGH REPETITION RATE PHOTOINJECTOR

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Abstract

The High Repetition Rate Photoinjector, designed for the CLARA FEL at Daresbury Laboratory, was tuned at the manufacturers for both field flatness and frequency. Due to the high average power in the gun cavity of 6.8 kW the cavity requires significant cooling, achieved by water channels in the cavity body. These channels prohibit the use of tuning studs to tune the cavity. The cavity was tuned by taking pre-braze clamped low power RF measurements and using the data to trim the cavity cells to the optimum length for both field flatness and frequency. The optimum field flatness is 100% and the design frequency is 2998.5 MHz. Both cells were trimmed in 4 stages, resulting in a post-braze frequency of 2998.51 MHz and field flatness of 98%.

INTRODUCTION

CLARA is a new FEL test facility being developed at STFC Daresbury Laboratory in the UK [1]. The main motivation for CLARA is to test new FEL schemes that can later be implemented on existing and future short wavelength FELs. Particular focus will be on ultra-short pulse generation, pulse stability, and synchronisation with external sources.

The High Repetition Rate Gun (HRRG) was developed at Daresbury Laboratory to meet demanding requirements in bunch length and emittance for bunches of up to 250 pC. For operation at 100 Hz for CLARA FEL experiments the cathode surface electric field required is 120 MV/m. The field is lowered for the 400 Hz mode to 100 MV/m. Consequently, the photoinjector must have high power handling capabilities.

The final design is a 1.5 cell normal conducting S-band RF photoinjector [2]. It has a dual feed RF input coupler with phase adjustment of each feed to supress any dipole component in the coaxial coupler line. The cavity schematic can be seen in Fig. 1.

Operation of the CLARA requires a very stable beam arrival time at the FEL. The RF amplitude stability must be 0.1 % and the phase stability 0.1° rms, imposing a temperature stability requirement of 0.009 °C rms [3]. The RF cavity has a probe in the second cell for feed-forward amplitude correction and a thermo-stabilisation system of water channels built into the copper cavity structure and fed by a high resolution control system developed at Daresbury.

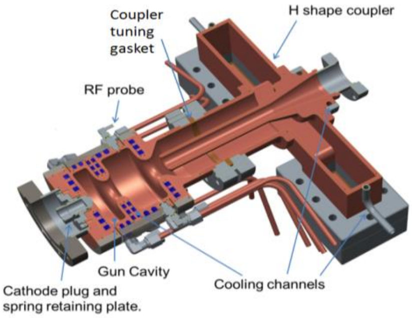

Figure 1: Schematic of the HRRG cavity showing water channels, probe, coupler tuning gasket and removable cathode plug.

Field flatness, which is defined as the ratio of electric field amplitude in cell 1 to cell 2, is essential to reach the highest possible beam momentum and evenly disperse the RF losses in the cavity. Optimum field flatness is achieved when the maximum field amplitudes are equal in each cell. Due to the extensive water channels in the cavity structure there is no scope for the tuning studs typically used to tune the field profile and frequency of a cavity. It was therefore proposed to tune the cavity before brazing using clamped RF measurements and trimming the cell lengths.

TUNING METHOD

The cavity was tuned before brazing at the manufacturers, Research Instruments GmbH [4]. Clamped low power measurements of the operating mode frequency and field were performed at 23 °C with a Cu photocathode plug and the data was used to trim the length of the cells to optimise both RF parameters. Both cells were manufactured with extra length to provide a tuning range that would cover the frequency spread possible due to the radial tolerances. The extra length for each cell was proportional to its length, keeping the field amplitude in each cell of the design cavity equal. The extra length on cell 1 was chosen to be 200 µm and on cell 2 was 422 µm.

Simulations were performed to model the effect of trimming the length of each cell on frequency and field flatness. An algorithm was developed from the simulation results to calculate the amount of length to trim from each cell to reach the target frequency and field flatness from the measured result.

The trimming was performed over 3 steps covering 1/3 of the required frequency correction each, with CMM dimensional measurements and RF measurements taken after each step. This was done to test the method so that corrections could be made if the effect of the trimming was not as expected. Due to technological limitations the minimum possible trim length was 50 µm, which defined the maximum number of trim steps possible.

MEASUREMENT METHODS

Resonant Frequency

The resonant frequency of the cavity operating mode was measured using a Vector Network Analyser to perform a measurement of the coefficient of reflection of the cavity. The cavity was excited through the dual feed power coupler. Because there are two input ports, a method developed at CERN [5] was used to calculate the coefficient of reflection Γ of a theoretical 2 port device. Equation (1) shows the calculation where ports 1 and 2 are the two phase matched symmetrical input ports and V_r and V_i are the normalized forward and reflected complex voltages at the theoretical single input port.

$$\Gamma = \frac{V_r}{V_i} = S_{11} + S_{21} = S_{22} + S_{12} \qquad (1)$$

The frequency value for which the reflection coefficient is minimal is taken as the resonant frequency f_0. This is then scaled to operating conditions of 50° and vacuum. The room temperature, humidity and air pressure were measured and the frequency change calculated, taking into account linear expansion of the cavity and the change in relative permittivity inside the cavity.

Field Flatness

The field flatness was determined using a bead-pull technique. A thread was strung through the centre axis of the cavity, through a 0.5 mm diameter hole in the cathode. On the string was a small cylindrical dielectric bead ~1 mm in diameter. The bead was pulled through the cavity and the change in combined Γ phase measured.

The cathode hole size was chosen to have a minimal effect on the field flatness and resonance frequency. Simulations of a 0.5 mm diameter hole show it shifts the frequency by 10 kHz, and has a negligible effect on the field profile when compared to a cathode with no hole.

Close to the cathode the field perturbed by the bead is composed of both the unperturbed electric field and the additional field caused by the image charge of the bead on the cathode face. The unperturbed on-axis field was extracted by fitting a curve to the normalized electric field profile.

Power Coupling

The power coupling match coefficient β was calculated from the maximum and minimum values of the linear magnitude of Γ as shown in Eq. (2).

$$\beta = \frac{\Gamma_{max} - \Gamma_{min}}{\Gamma_{max} + \Gamma_{min}} \qquad (2)$$

The loaded quality factor Q_L was measured from the 3 dB bandwidth of the transmission signal to the probe port, defined, analogously to the reflection, as $S_{31} + S_{32}$.

TUNING RESULTS

Resonant Frequency

All frequency results are scaled for temperature, air pressure and humidity to expected operating conditions for easy comparison. The cavity was clamped and the frequency measured then unclamped. This was repeated three times. The frequencies measured differed by a maximum of 91 kHz.

The average measured frequency of the structure with the full trimming length (200 µm on the first cell and 422 µm on the second cell) was 2996.53 MHz. This can be compared to the value predicted for a perfect cavity with such extra lengths: 2996.21 MHz, a difference of 320 kHz, and the value predicted using the Coordinate Measuring Machine (CMM) measurements of the cell radii: 2996.63 MHz, a difference of 100 kHz. This 100 kHz is likely due to other non-conformities of the cavity geometry to the ideal.

Three trim steps were carried out. The nominal length for each trim and the actual trim measured on the CMM showed a maximum deviation of 18 µm and an average deviation of 10.8 µm.

The cavity frequency measured at each step was within 250 kHz of the value predicted using the ideal trimming amount. This was the frequency limit predefined to judge if the tuning was accurate enough. The length of each cell was measured with the CMM and the adjusted predicted frequency calculated.

The intended frequency, predicted frequency taking into account the measured length, and measured frequency for each trimming step are shown in Fig. 2. For the points before trimming the predicted results take into account the measurements of the radii as well as the length.

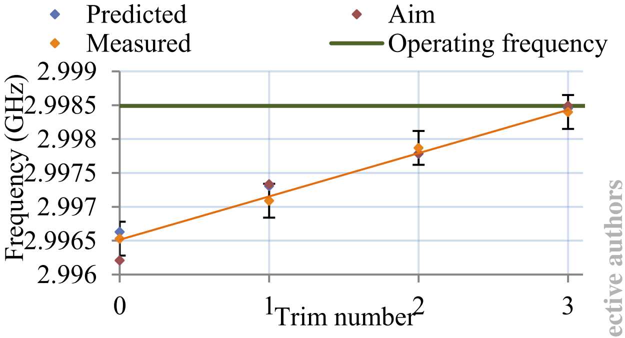

Figure 2: The frequency aim, prediction from dimensional measurement, and low power measurement at each of 3 trimming steps. The error bars show the 250 kHz limit.

The final pre-braze frequency was 2998.4±0.1 MHz. The operating frequency will be 2998.5 MHz. The cavity is -100 ±100 kHz off frequency; which in the worst case can be corrected by a 4°C water temperature decrease.

Field Flatness

The field flatness measured differed by a maximum of 1% each time the cavity was clamped. The measured field flatness of the structure with the full trimming length (200 µm on the first cell and 422 µm on the second cell) was 98.9 %. This is very good for a cavity that has not been tuned. This meant that all that was needed was to retain the field flatness whilst tuning the frequency. Unfortunately the accuracy of the length trimming was such that there was some variation the field flatness throughout the process.

After 2 trimming steps a thinner gasket was introduced into the coaxial coupler to optimize the cavity coupling β. The thick gasket was 6 mm and the thin gasket 4.41 mm. This affected the field flatness by ~1%. For the final tuning step the aim was to have the cavity field flat with the thin gasket as this was closer to what would be used in operation. The results are shown in Fig. 3. The final pre-braze field flatness was 99.9 ± 1 %.

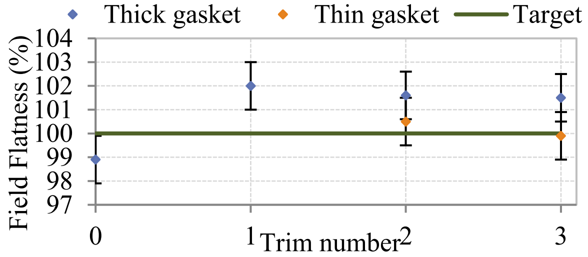

Figure 3: Field flatness measurements at each of three trimming steps with a thick and a thin gasket in the outer coaxial coupler to optimise the power coupling.

Power Coupling

The coupling of the cavity was the least repeatable of the measured values. β varied by 15% with re-clamping and Q_L varied by 6.5%.

No significant trend was seen for either coupling figure of merit versus trim steps. The β increased from 0.65 ±0.1 to 0.83±0.1 when the gasket in the coaxial coupler was reduced from 6 mm to 4.41 mm. This gasket controls the penetration of the inner part of the coaxial coupler into the cavity. Q_L was unchanged at 7230±470. Calculating Q_0 from these values we obtain 13230±2160. All coupling values are given at room temperature.

β, Q_L and Q_0 were expected to change with brazing. At 50 °C the conductivity of copper decreases by 9.7 % from 23 °C [6] so a decrease in Q_0 would occur; however brazing creates better RF contact than clamping which would give an increase in Q_0. Further tuning of these values was therefore delayed until after brazing when the Q_0 was fixed and the repeatability of measurement was improved.

RESULTS AFTER BRAZING

The cavity was brazed at the manufacturers. The final brazed structure can be seen in Fig. 4. The frequency measured at 50°C and scaled to vacuum conditions was 2998.51±0.005 MHz, requiring a less than 2° C water temperature increase to tune to operating frequency. The field flatness remained excellent at 98±1 %.

Repeatability testing of cathode plug and RF spring replacement was performed after delivery of the cavity to Daresbury Laboratory. Copper and molybdenum cathode plugs were used and beryllium-copper springs, some uncoated and some gold coated with a rhodium interstitial. The combination of molybdenum plug and uncoated spring showed an RF leak and subsequently a lower than expected coupling (β). This was rectified when using the gold coated spring with the same cathodes.

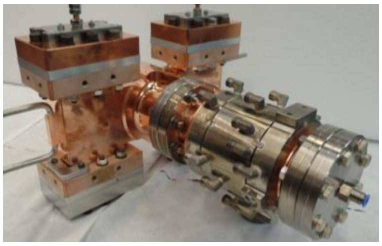

Figure 4: The final brazed assembly of the photoinjector.

The coupling was tuned further with the gasket in the outer coaxial line to an average β of 1.06 ± 0.02 with the 6 molybdenum cathode plugs. The Q_L measured 6465±95 and Q_0 is 13358±283 for the Mo plugs with gold coated spring. The slight over-coupling gives an appreciable increase in Q_0 for a modest (0.08%) power reflection. The over-coupling is higher for the copper plug. With this plug β is 1.12 ± 0.01, Q_L is 6697±10 and Q_0 is 14230±50. This could be explained by the copper cathode achieving better RF contact with the spring. However, scratches from the spring are evident on this cathode and due to the possibility of cavity contamination a full copper cathode will not be used under vacuum.

The dual feed coupler was tuned by ensuring that Eq. (1) was true. This tuning will need to be repeated once the RF splitter has arrived as there may be phase offset from the splitter that will need to be accounted for.

CONCLUSION

The pre-braze tuning of the HRRG was completed in three steps, each bringing the frequency linearly closer to the operation frequency. The final frequency before brazing was 2998.4±0.1 MHz and 2998.51±0.005 MHz afterward. The field flatness was 99.9±1% before brazing and 98±1% afterward. The cavity is ready for installation on the VELA beam-line for high power RF commissioning.

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