A TWO-FREQUENCY RF CAVITY FOR THE PSI LOW EMITTANCE GUN

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Abstract

In the Low Emittance Gun (LEG) under development at PSI, an extremely bright electron beam is produced from field emitters and then rapidly accelerated in a diode configuration up to 1 MeV with gradients of the order of 250 MV/m. The electronic emission from such a cold cathode is expected to deliver a normalized intrinsic emittance below 0.05 mm·mrad well suited for X-ray FEL or linear collider applications. The diode is followed by an L-band RF gun-like cavity to further accelerate the beam. A third harmonic field is superimposed to the fundamental 1.5 GHz π-mode field to minimize the RF emittance growth. We report here on the design of such a two-frequency RF cavity with some details on the RF coupling. Beam dynamics studies, performed with PARMELA, are presented and compared with the results obtained for an RF cavity excited with the fundamental frequency only.

INTRODUCTION

Paul Scherrer Institut investigates the feasibility of an X-ray FEL [1] with a normalized emittance at the electron source of 0.05 mm·mrad. To achieve such an emittance, a Low Emittance Gun (LEG) based on field-emission cathodes is being developed. In this gun the emitted electrons are pre-accelerated to 1 MeV and injected in a 1.5-GHz 1.5-cell RF cavity operating in the $TM_{010-\pi}$-mode where they are further accelerated to a maximum energy of 4.3 MeV. The design of the RF cavity is such that a third harmonic RF field operating in the $TM_{012-\pi}$-mode can be superimposed to the fundamental field [2, 3].

For the fundamental frequency, the RF coupling of the two-frequency cavity is achieved with a coaxial input feed (e.g., see [4]). This arrangement suppresses the multipole field components inherent to more conventional techniques where the feed(s) is (are) radially coupled to the cavity cell(s). The third harmonic RF field would be excited by means of two radial rectangular waveguides coupled to the full cell of the cavity. Although this scheme has not been fully investigated, it is expected that the induced multipole field components will have a negligible influence on the beam dynamics. To prevent the leakage of the harmonic field in the input feed, a three-resonator coaxial filter has been designed (see Figure 1 for a cross-section view of the RF cavity including the coaxial harmonic filter).

The use of RF cavities which can support multiple frequency fields has been proposed for RF electron guns in [2, 3] and it was shown that a third harmonic RF field superimposed to the fundamental can linearize the RF forces. This behavior has been confirmed with ”zero current” PARMELA [5] simulations in the transverse phase space for our pre-accelerated configuration. The RF emittance growth can be minimized thereby allowing more flexibility in the choice of the beam parameters to control space-charge induced emittance growth.

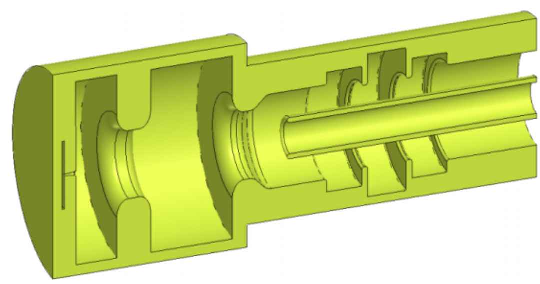

Figure 1: Cross-section view of the 1.5-GHz 1.5-cell RF cavity with the harmonic filter in the coaxial input feed.

COAXIAL FILTER AND CAVITY DESIGN

Design of the Coaxial Harmonic Filter

The filter to be located in the coaxial input feed is designed to allow propagation of the TEM mode at the fundamental frequency (1498.956 MHz) and to reflect the third harmonic (4496.868 MHz) RF fields that couple out from the cavity. The filter consists of three resonators, the side ones being identical (see Figure 2). The design was performed with the 3D finite element code HFSS [6].

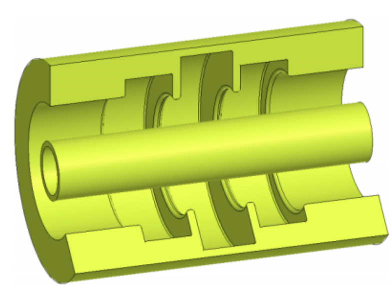

Figure 2: Cross-section view of the coaxial harmonic filter.

The 50-Ω coaxial feed was chosen with inner and outer conductor radii of 18.12 mm and 41.72 mm, respectively. Regarding the filter design procedure, the outer radii and lengths of the resonators as well as the dimensions of the coupling irises were first adjusted until some pass-band around the design fundamental frequency and significant attenuation around the third harmonic frequency were found simultaneously. A second round of calculations have shown that a relatively large bandwidth around the fundamental frequency was compatible with a close enough spacing between two attenuation poles in the vicinity of the harmonic frequency. A final round of computations led to an optimized design with a return loss of 130 MHz (50 dB level) around 1.5 GHz and an insertion loss of 75 MHz around 4.5 GHz (Figure 3 and Figure 4). The dimensions of the harmonic filter are summarized in Table 1

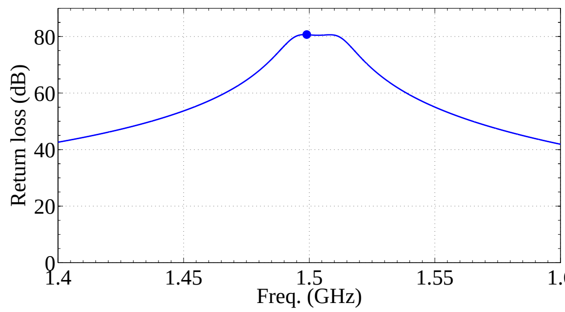

Figure 3: Return loss of the coaxial harmonic filter around the fundamental frequency.

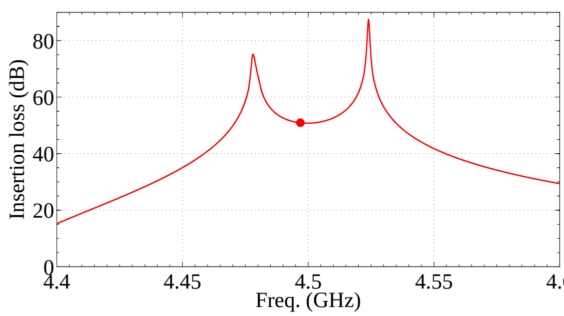

Figure 4: Insertion loss of the coaxial harmonic filter around the third harmonic frequency.

Table 1: Coaxial filter dimensions (mm).

Inner radius of coaxial feed	18.12
Outer radius of coaxial feed	41.72
Irises* thickness	5.00
Irises aperture radius	36.00
Side resonators length	30.20
Side resonators radius	52.80
Middle resonator length	33.30
Middle resonator radius	62.95

* include a curvature radius of 2 mm

Design of the RF Cavity

The two-frequency RF cavity consists of two cells, the upstream cell being about half shorter than the downstream cell, electrically coupled by an iris. In the backplane of the half cell, a 10-mm thick iris allows the injection of the 1-MeV electron beam emerging from the 4-mm diode gap and ensures electromagnetic isolation between the cavity and the diode. The downstream cell is coupled electrically to the coaxial line, the electrons leaving the cavity through its inner conductor (see Figure 1). The design of the cavity, performed with the 2D electromagnetic code SUPERFISH [7], was guided by the following requirements:

- Large mode separation between the $TM_{010-\pi}$ mode (accelerating mode) and the TM_{010-0} mode,
- Reduced peak surface electric field,
- Balanced field profile with and without the third harmonic,
- Coaxial feed adjusted for critical coupling.

The main difficulty consists in tuning the $TM_{012-\pi}$ mode to three times the frequency of the fundamental π-mode. It was observed that the rate of increase of the fundamental π-mode is much less than for the $TM_{012-\pi}$ mode when the cell radius is made smaller. Similarly, an increase of the iris thickness affects much more the $TM_{012-\pi}$ mode than the fundamental π-mode. The frequency separation between the two fundamental modes is achieved by increasing the iris radius and/or decreasing the iris thickness. In our final design, the iris radius a and the iris thickness are 30 mm (a/λ=0.15) and 29.27 mm, respectively, resulting in a 12-MHz mode separation. The closest mode to the $TM_{012-\pi}$, the TM_{012-0} mode with a frequency of 4427.303 MHz, is far enough to allow proper operation. To reduce the peak surface electric field, the cross-section of the tip of the iris is elliptical and has an eccentricity of 1.5. Figure 5 and Figure 6 show the electric field contour lines for the two operating modes. To obtain a total peak flat-top on-axis electric field of 40 MV/m when the two modes are in phase opposition, the required fundamental and third harmonic amplitude are 42.8 MV/m and 3.15 MV/m, respectively, corresponding to peak input powers of 3.3 MW and 280 kw, respectively. The peak surface field of the fundamental mode is then 48.1 MV/m. Figure 7 shows the on-axis electric fields for the fundamental operating mode, the $TM_{012-\pi}$ mode and their sum when the modes are in phase opposition. The field balance is higher than 99.9 % for the fundamental mode.

The adjustment of the longitudinal position of the coaxial input feed allows to achieve critical coupling for the operating mode without major changes of its field distribution.However, the effect on the third harmonic fields is more sensitive. The final tuning of the third harmonic mode is achieved by varying the position of the coaxial filter in the input feed. The main design parameters are summarized in Table 2.

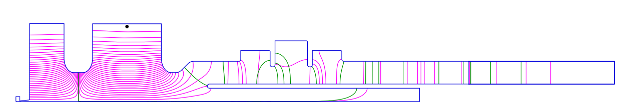

Figure 5: Electric field contour lines at the fundamental frequency.

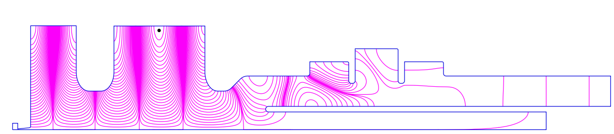

Figure 6: Electric field contour lines at the third harmonic frequency.

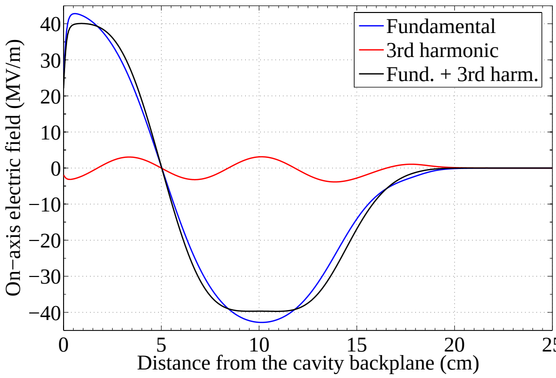

Figure 7: On-axis electric fields for the fundamental π-mode, the $TM_{012-\pi}$ mode and their sum.

Table 2: RF cavity parameters

Operating frequency, fundamental (MHz)	1498.956
Mode separation, fundamental (MHz)	12
Loaded quality factor, fund. π-mode	9,340
Quality factor, fund. 0-mode	11,260
Unloaded quality factor, $TM_{012-\pi}$ mode	19,840
Peak on-axis field * (MV/m)	40.0
Peak surface electric field ** (MV/m)	48.1
Peak input power, fundamental (MW)	3.3
Peak input power, $TM_{012-\pi}$ mode (kW)	280

* sum of fundamental and third harmonic
** fundamental only

BEAM DYNAMICS STUDIES

The effect of the harmonic fields on the beam dynamics was evaluated with PARMELA [5] simulations in the "zero current" case. When the beam current is negligible the transverse dynamics is entirely dominated by the electrostatic lens at the diode iris and by the transverse components of the RF fields in the post-accelerating cavity.

If the space-charge effects are negligible the projected emittance growth in the cavity depends only on the RF transverse fields and increases when the bunch is longer. The third harmonic compensates the RF non-linearity of the fundamental mode along the bunch, reduces the emittance growth and, possibly, linearizes the energy distribution.

In the simulations we used a 60-ps long bunch with a uniform longitudinal distribution to accentuate the RF effects. The radial distribution is also uniform with a radius of 0.25 mm (as expected from the LEG cathode). A more realistic longitudinal distribution for the LEG bunch would be a Gaussian bunch with σ_z=14.4 ps. Particles with zero thermal emittance are emitted by the cathode with no energy spread and accelerated up to 1 MeV in the diode gap. The diode iris acts as an electrostatic lens and introduces some defocusing. In this study no focusing was added to correct this effect. The results summarized here were taken downstream the cavity, 21.4 cm from the cathode.

Figure 8 shows the rms normalized emittance versus the RF phase at injection in the diode with the cavity excited by the fundamental mode only and a peak on-axis field of 40 MV/m (reference case). This injection phase is defined as the rf phase of the electric field when the first electron of the bunch is emitted. The transit angle for the center of the bunch to reach the cavity backplane is 26.5°. In the same figure the projected emittance is compared to the slice emittance for slices located in the middle of the bunch at the injection. Since the beam enters the RF cavity with a normalized velocity β of 0.94, the phase slippage experienced by the electrons is considerably lower than in the usual RF guns. The injection phase is consequently higher allowing higher acceleration. For the injection phases ranging from 140° to 220°, the projected RF emittance growth is of the order of 0.1 mm·mrad.

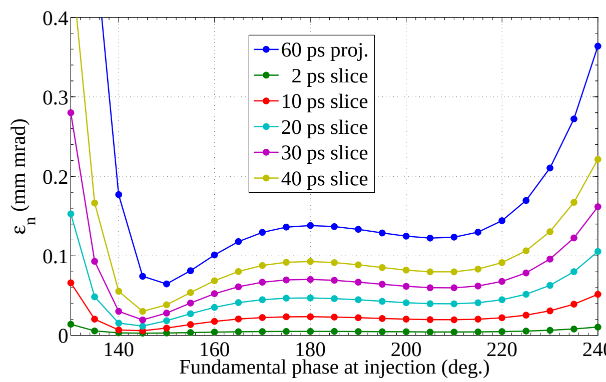

Figure 8: Normalized emittance vs. injection phase for the fundamental mode only.

The projected emittance can be further optimized for each injection phase of the fundamental by varying the harmonic phase and amplitude. For this preliminary study we chose the RF amplitude of both modes to obtain a 40-MV/m on-axis flat-top field when the modes are in phase opposition (see Figure 7 and above). When scanning the harmonic phase, both amplitudes were kept constant. The results of these simulations are shown in Figure 9 for each optimum harmonic phase.

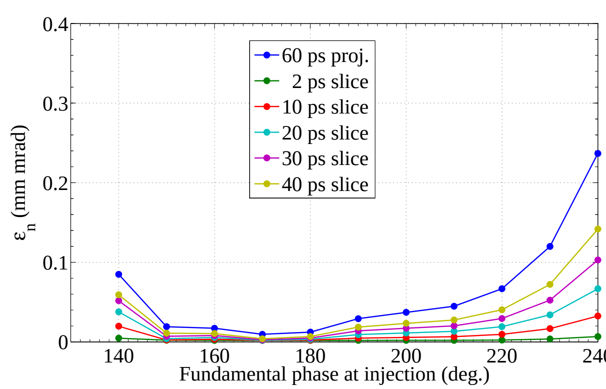

Figure 9: Normalized emittance vs. injection phase for optimum harmonic phase.

The projected emittance can be reduced by a factor 3 to 7, well below the targeted 0.1 mm·mrad normalized emittance, over a wide range of injection phases. This result is important because the emittance dilution at the RF cavity entrance, for the LEG nominal peak current of 5.5 A, is already 0.05 mm·mrad [8]. Moreover, the harmonic has a larger influence on the energy spread at lower injection phase (Figure 10). The reduction of the bunching can be seen in Figure 11. Figure 12 shows the wide variation of the normalized projected and slice (10-ps slice) emittances along the structure for an injection phase of the fundamental of 150° without third harmonic fields and with an optimum harmonic phase of 120°.

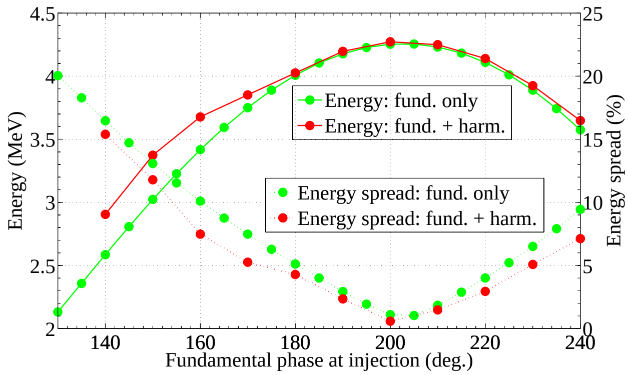

Figure 10: Average energy and energy spread vs. injection phase for fundamental alone and fundamental + harmonic.

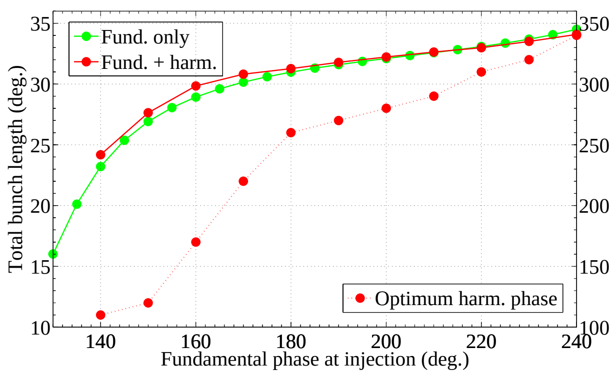

Figure 11: Total bunch length and optimum harmonic injection phase vs. fundamental injection phase.

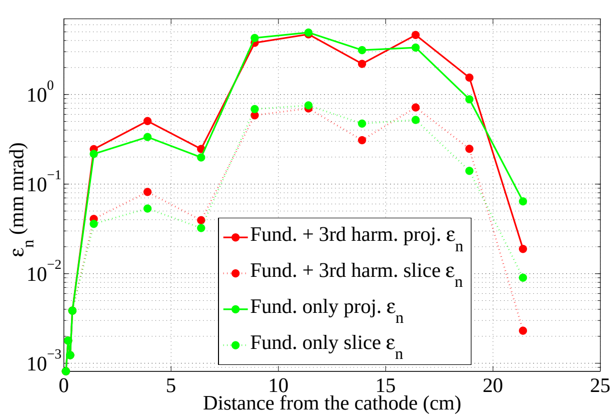

Figure 12: Normalized projected emittance and slice emittance (10-ps slice) vs. distance from cathode.

The two-frequency cavity increases the flexibility of the gun especially in the bunching regime which corresponds to injection phase between 140° and 150°. This is of particular interest for a scheme that would include a velocity-bunching section after the RF gun-like cavity. From this viewpoint, the possibility to correct the RF non-linearity in the accelerating structures following the RF-gun-like cavity with a proper tuning of the third harmonic has to be considered. For the LEG parameters the space-charge effects obviously cannot be neglected and an emittance compensation scheme has to be investigated.

CONCLUSIONS

A 1.5-GHz 1.5-cell two-frequency RF cavity where the second mode, the $TM_{012-\pi}$ mode, is tuned to the third harmonic frequency of the fundamental $TM_{010-\pi}$ mode was designed. This RF cavity has a 12-MHz mode separation between the fundamental π-mode and the 0 mode. The input coaxial feed has a filter which allows axial propagation of the TEM mode at the fundamental frequency and prevents the leakage of the third harmonic fields. When the fields of the two operating modes are in phase opposition, the required peak input power for the fundamental and the higher-order modes are about 3.3 MW and 280 kW, respectively. In this particular case, the peak on-axis electric field is flat-topped and has an amplitude of 40 MV/m. Beam dynamics simulations in the ”zero current” case showed that without the third harmonic the RF emittance growth is relatively weak. However, it could still compromise the gun operation with target emittance below 0.1 mm·mrad. With the third harmonic, the projected emittance can be reduced by a factor 3 to 7. Moreover, such a two-frequency scheme allows more operational margin in the bunching regime.

ACKNOWLEDGMENTS

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