PROGRESS IN THE DESIGN OF A TWO-FREQUENCY RF CAVITY FOR AN ULTRA-LOW EMITTANCE PRE-ACCELERATED BEAM

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Abstract

Today most of the X-rays Free-Electron Laser projects are based on state of the art RF guns, which aim at a normalized electron beam emittance close to 1 mm·mrad. In this paper we report on the progress made at PSI towards a hybrid DC + RF Low Emittance Gun (LEG) capable of producing a beam with an emittance below 0.1 mm·mrad. To reduce the intrinsic thermal emittance at the LEG cathode the electrons are extracted from nano-structured field-emitters. A gun test facility is under construction wherein after emission the beam is accelerated up to 500 keV in a diode before being injected and accelerated in a two-frequency 1.5-cell RF cavity. The fast acceleration in the diode configuration allows to minimize the emittance dilution due to the strong space charge forces. The two-frequency RF structure is optimized to limit the emittance blow-up due to the non-linearity of the RF field.

INTRODUCTION

Feasibility studies of an X-ray FEL [1] are performed at Paul Scherrer Institut which aim at producing an electron source with a normalized slice emittance of 0.05 mm·mrad. Such an emittance is expected to be achieved with a Low Emittance Gun (LEG) based on field-emission cathodes [2, 3]. In the final design the electrons will be pre-accelerated in a 1-MV diode before being injected and further accelerated in an RF cavity. To validate this concept, a test stand is under construction. It will consist of a 500-kV DC pulser, a field-emission cathode (arrays or single tip), a diode the gap of which can be varied and a two-frequency 1.5 cell RF cavity operating at 1.5 GHz and 4.5 GHZ in the $\mathrm{TM}_{010-\pi}$ and $\mathrm{TM}_{012-\pi}$ modes, respectively [4]. The beam line downstream the cavity will include emittance as well as charge, energy and energy spread diagnostics.

Two 1.5-cell RF cavities with different RF coupling schemes have been designed. In the first design, similar to [4], the fundamental 1.5-GHz $\mathrm{TM}_{010-\pi}$ mode is excited with a coaxial input feed whereas the $\mathrm{TM}_{012-\pi}$ mode at 4.5 GHz is excited by means of two rectangular waveguides coupled radially to the full cell. The RF leakage of the harmonic field through the coaxial feed is prevented by a three-resonator coaxial filter that acts as a band-rejection filter at 4.5 GHz and as a bandpass filter around the fundamental frequency (see [4]). In the other designed cavity the RF power at the two relevant frequencies is brought in by the coaxial input feed. With such a coupling scheme the azimuthal symmetry is fully preserved.

Beam dynamics studies *without* emittance compensation for a beam current of 5.5 A injected in the cavity with a harmonic filter have been performed with the simulation tool GPT [5] to assess the effect of the third harmonic field on the emittance growth. The interplay between normalized emittance, bunch length and energy spread has also been studied in detail.

CAVITY DESIGNS

Design of the RF Cavity with a Coaxial Harmonic Filter

The RF cavity with a coaxial harmonic filter is similar to the 1.5-cell cavity described in [4]. It only differs from the previous design in the topology of the diode gap and of the iris located in the backplane of the half cell. In the anode plane of the 4-mm diode gap is a 3.2-mm wide iris with an aperture radius of 0.75 mm through which the 500-keV electron beam pass. This first iris is followed by a 13.8-mm gap that can accommodate a pulsed focusing coil. Between the gap and the RF cavity a second iris (3 mm wide with an aperture radius of 2.5 mm) guarantees electromagnetic insulation. Figure 1 shows a cross-section view of this type of cavity. The two rectangular waveguides that would be coupled to the full cell are not depicted.

The RF characteristics of the 1.5-cell cavity, summarized in Table 1, are close to the one presented in [4]. Note however that due to the different configuration of the iris in the backplane of the half cell the peak surface electric field is higher than in [4]. The required peak powers to achieve a flat-top on-axis peak electric field of 40 MV/m are 3.2 MW and 280 kW for the fundamental and third harmonic frequency, respectively. The field balance for the fundamental mode is then about 95 %. The coupling coefficient β (fundamental frequency) is 1.03.

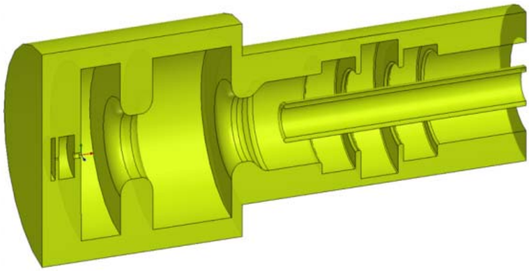

Figure 1: Cross-section view of the two-frequency 1.5-cell RF cavity with the harmonic filter.

Figure 2 and Figure 3 show the electric field contour lines, computed with the 2D electromagnetic code SUPERFISH [6], of the $TM_{010-\pi}$ mode (fundamental frequency - 1.5 GHz) and of the $TM_{012-\pi}$ mode (third harmonic frequency - 4.5 GHz), respectively.

Table 1: RF parameters - cavity with harmonic filter

Operating frequency, fundamental (MHz)	1498.956
Loaded quality factor, fund. π-mode	9,270
Unloaded quality factor, $TM_{012-\pi}$-mode	19,870
Peak on-axis field * (MV/m)	40.0
Peak surface electric field ** (MV/m)	56.3
Peak input power, fundamental (MW)	3.2
Peak input power, $TM_{012-\pi}$ mode (kW)	280

* sum of fundamental and third harmonic

** fundamental only

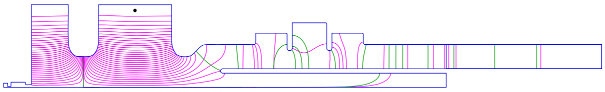

Figure 2: Electric field contour lines at the fundamental frequency - cavity with harmonic filter.

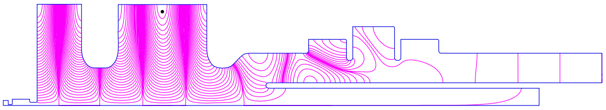

Figure 3: Electric field contour lines at the third harmonic frequency - cavity with harmonic filter.

Design of the RF Cavity without Coaxial Harmonic Filter

To preserve the axial symmetry, a 1.5-cell RF cavity has been designed where the RF power for both frequencies is brought through the coaxial input feed (see Figure 4).

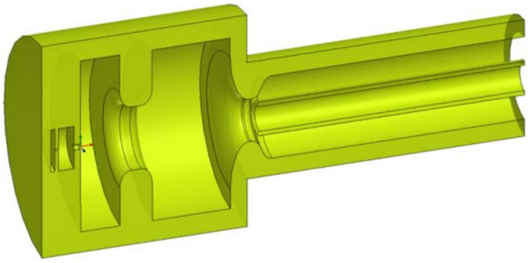

Figure 4: Cross-section view of the two-frequency 1.5-cell RF cavity without harmonic filter.

The difficulty of such a design, an RF coupling efficient for *both* the 1.5- and the 4.5-GHz frequencies, has been overcome by varying the radius and length of the full cell, the geometry of the iris between the full cell of the cavity and the coaxial feed, the radii of its inner and outer conductor, its thickness as well as the longitudinal position of its inner conductor. The requirement was to have critical coupling at both frequencies.

The RF characteristics of this 1.5-cell cavity (see Table 2) are very similar to those of the cavity with a filter. Whereas the required input power for the fundamental frequency are identical in both designs, the needed input power at the third harmonic frequency is about 16.5 % higher in the present design. The coupling coefficients β are 1.03 and 1.05 for the fundamental and third harmonic frequencies, respectively. The electric field contour lines of the $TM_{010-\pi}$ mode and of the $TM_{012-\pi}$ mode are shown in Figure 5 and Figure 6.

Table 2: RF parameters - cavity without harmonic filter

Operating frequency, fundamental (MHz)	1498.956
Loaded quality factor, fund. π-mode	9,310
Loaded quality factor, $TM_{012-\pi}$-mode	9,400
Peak on-axis field * (MV/m)	40.0
Peak surface electric field ** (MV/m)	53.2
Peak input power, fundamental (MW)	3.2
Peak input power, $TM_{012-\pi}$ mode (kW)	240

* sum of fundamental and third harmonic

** fundamental only

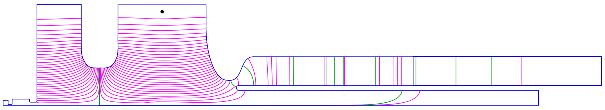

Figure 5: Electric field contour lines at the fundamental frequency - cavity without harmonic filter.

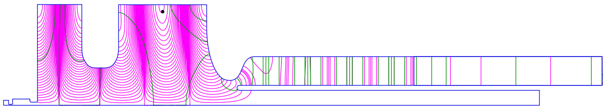

Figure 6: Electric field contour lines at the third harmonic frequency - cavity without harmonic filter.

BEAM DYNAMICS STUDIES

The effect of the third harmonic fields on the beam dynamics in the cavity with the harmonic filter was evaluated with the particle-in-cell code MAFIA [7] and the particle tracking program GPT [5] for a beam current of 5.5 A (no emittance compensation). The beam dynamics in the diode part were simulated with MAFIA. The launched beam was 40-ps long and had a uniform longitudinal as well as radial distribution. The radius of the beam at the cathode was 0.30 mm. The initial conditions for the GPT simulations, with which the beam dynamics in the RF cavity were calculated, were obtained from the MAFIA calculation of the radial positions and momenta of the macroparticles in the plane located 6 mm downstream the cathode plane. The accelerating DC voltage of the diode was 500 kV. The amplitudes of the fundamental and third harmonic RF fields were chosen so that when they are superimposed the total peak on-axis field is 40 MV/m whatever the phase difference of the two RF fields.

The lowest projected emittance (see Figure 7) is 0.3 mm·mrad and is obtained for a fundamental phase at injection of 260° with a third harmonic phase of 160°. Note that this injection phase is defined as the rf phase of the field when the first electron of the bunch is injected in the simulation volume. The average kinetic energy is then about

3.85 MeV and the relative energy spread is slightly higher than the energy spread obtained without the harmonic fields (Figure 8). The rms bunch length is also slightly higher than the bunch length obtained without the harmonic fields indicating that the cavity operates in a debunching regime (Figure 9).

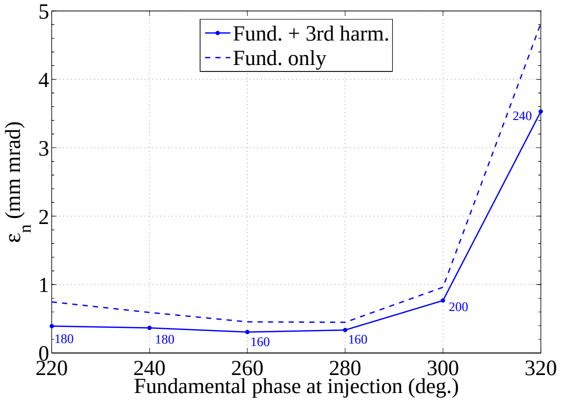

Figure 7: Normalized emittance vs. injection phase for the fundamental mode only and for the optimum harmonic phase.

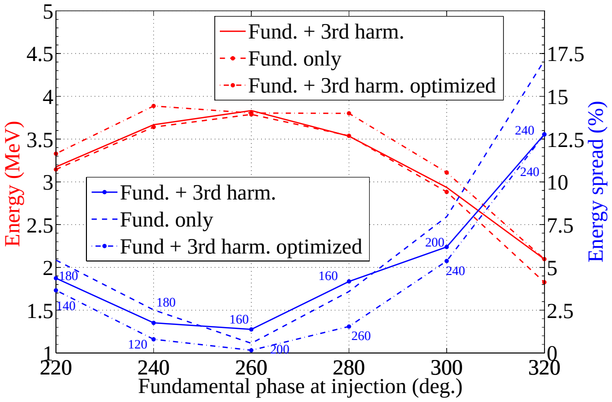

Figure 8: Average energy and energy spread vs. injection phase for fundamental alone, fundamental and optimized harmonic for minimum normalized emittance and optimized harmonic phase for minimum energy spread.

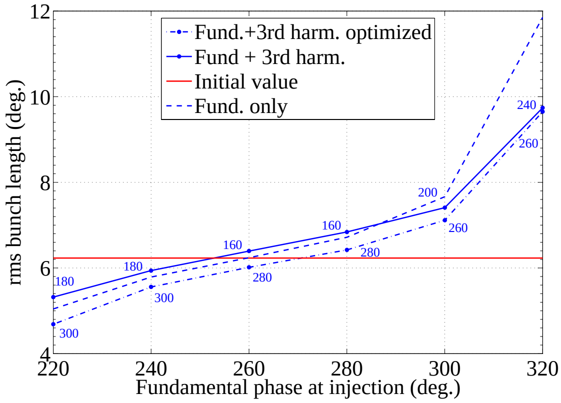

Figure 9: rms bunch length vs. injection phase for fundamental alone, fundamental and optimized harmonic for minimum normalized emittance and optimized harmonic phase for minimum rms bunch length.

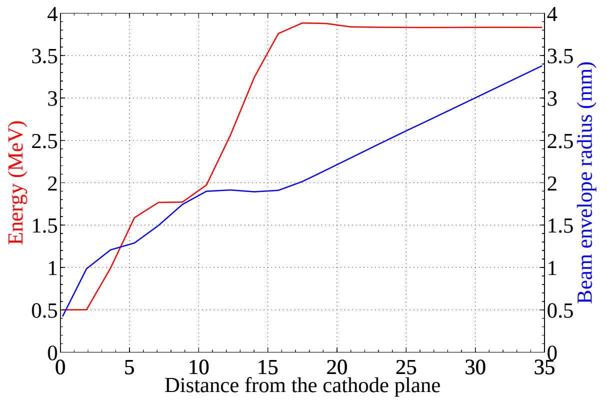

Figure 10: Average energy and beam envelope radius vs. distance from the cathode plane.

Figure 10 shows the average kinetic energy and the envelope radius of the beam along the RF cavity. The envelope radius increases up to 2.3 mm at the axial location where the field amplitudes are negligible, a consequence of the absence of any emittance compensation scheme.

CONCLUSIONS

Two 1.5-cell RF cavities that can operate simultaneously at 1.5 GHz and 4.5 GHz have been designed. In the second design the RF power for both frequencies is brought in by a coaxial input feed which has the advantage of preserving the axial symmetry of the whole structure. Beam dynamics studies performed with MAFIA and GPT proved that a projected emittance below 0.5 mm·mrad is achievable *without* emittance compensation for a 40-ps long bunch and a current of 5.5 A with peak on-axis field of 40 MV/m. However, the reduction of the projected emittance by superimposing third harmonic fields is much less impressive than the results obtained in [4] where the beam dynamics studies did not include the space-charge effects. The beam parameters are such that the emittance increase is induced by the Coulombian repulsion. Our current efforts are concentrated on the design of a pulsed focusing coil to be located between the diode and the RF cavity and on an emittance compensation scheme to focus the beam in the cavity.

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