Considerations on the third harmonic rf of the European XFEL

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Abstract

Ultra short bunches with high peak current are required for the creation of high brilliance coherent light in the x-ray range in undulators. At the European x-ray free electron laser (XFEL) they will be obtained by a two stage bunch compression scheme based on acceleration off the rf field crest and transverse magnetic chicanes. The deviation of the rf field's sine shape from a straight line leads to long bunch tails and reduces the peak current. This effect will be eliminated by adding a third harmonic rf system. This paper surveys the basic principle for the third harmonic rf, the most relevant design parameters, the actual status of beam physical examinations and potential concepts for the technical realization.

INTRODUCTION

At the linear accelerator based European x-ray free electron laser (XFEL) bunches will be generated by a normal conducting photocathode rf gun and then accelerated to 17.5 GeV by a superconducting linear accelerator based on the 1.3 GHz TESLA technology. While passing undulators the bunches emit high brilliance coherent light in the x-ray range. The emission process requires high electron peak currents and small transverse emittances. Collective effects, such as the space charge effect, restrict the minimum full width bunch length obtained from the photocathode rf gun to about 7 to 10 ps. The high peak currents are obtained by compressing the bunch length down to the 70 fs range in the first part of the superconducting accelerator (Fig. 1).

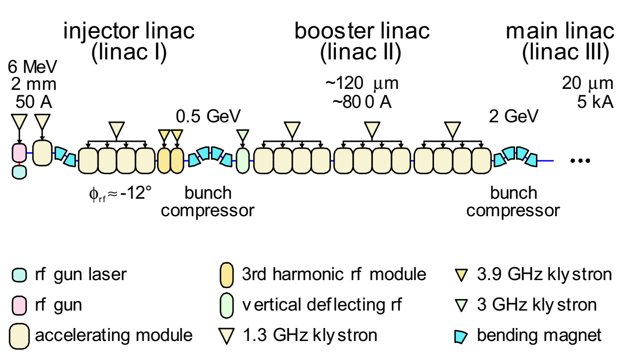

Figure 1: Sketch of the first part of the European XFEL accelerator where the bunch compression takes place.

Accelerating the bunches off the rf field crest (between -3° and -30°), results in an energy chirp from the bunch head to the tail. In transverse magnetic chicanes, called bunch compressors, the trajectory of the bunch head becomes longer than the trajectory of the bunch tail resulting in a compressed bunch after the chicanes due to the different transit time. A bunch length of 7 - 10 ps corresponds to 3.3 - 4.7° in 1.3 GHz phase. Both the sinusoidal accelerating wave and non-linear collective effects lead to asymmetric bunches with reduced peak current and long tails after the bunch compressors. By adding a higher harmonic rf system, the voltage seen by the bunches and the collective effects may be linearised. The bunch compression becomes much more effective.

LINEARISATION BY 3RD HARMONIC

With a triangular rf wave the off crest acceleration would result in an ideal linear energy chirp. A triangular wave is composed of a cosine wave with the fundamental frequency and all odd higher harmonics:

$$f(\phi) = \frac{8}{\pi^2} \sum_{n=1,3,5,\ldots} \frac{1}{n^2} \cos(n\,\phi)$$

Hence, by adding a third harmonic rf system and appropriate choice of the phasing to the fundamental rf system, phase regions with a linear voltage chirp can be created. A rather ideal rf linearisation around a fundamental beam phase operation point of ϕ_{beam} is obtained by adjusting the 3rd harmonic phase to

$$\phi_{\mathrm{3rd}} = 180^\circ + 3 \cdot \phi_{\mathrm{beam}}$$

and the 3rd harmonic amplitude to $V_{\mathrm{3rd}} = \frac{1}{9} V_{\mathrm{rf}}$ resulting in the voltage sum of

$$v_{\mathrm{rf}}(\phi) = V_{\mathrm{rf}} \left(\cos(\phi) + \frac{V_{\mathrm{3rd}}}{V_{\mathrm{rf}}} \cos 3(\phi - \phi_{\mathrm{3rd}}) \right)$$

where V_{rf} is the fundamental rf amplitude.

Figure 2 shows the resulting voltage linearisation for the case of $\phi_{\mathrm{beam}} = 12^\circ$. Due to the decelerating phase of the third harmonic system the accelerating voltage drops by 13% as compared to acceleration by the main rf alone.

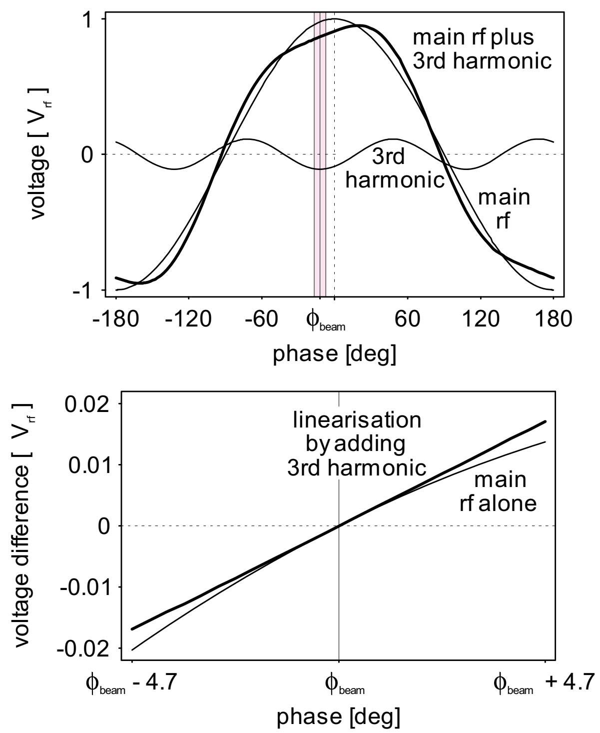

Figure 2: Linearisation of the voltage chirp seen by the beam adding a third harmonic rf system with decelerating phase.

But, as a result the voltage chirp within the phase region covered by the beam becomes linear.

At the XFEL the nominal rf phases differ from the ideal case described. The reason is the two stage bunch compression scheme (Fig. 1) applying a higher harmonic rf system only in front of the first bunch compressor but also linearising the rf of the second stage. Simulation taking into account collective effects like the space charge effect, energy dependent dispersion and wake fields are used for the determination of the nominal rf phases and amplitudes [2]. This scheme requires a third harmonic voltage up to 108 MV.

CLOSE ALIGNMENT TOLERANCES

Longitudinal $\mathcal{W}_{\|}$ and transverse wake fields $\mathcal{W}_{\perp}$ (per unit of length) scale with the second and third power of the frequency respectively

$$\mathcal{W}_{\|} \propto \omega^2 \quad \text{and} \quad \mathcal{W}_{\perp} \propto \omega^3.$$

The third harmonic cavities under development for FLASH [3, 4] and also foreseen for the XFEL are scaled down superconducting nine cell TESLA type cavities with a different beam pipe diameter (Fig. 3).

The active length of these 3.9 GHz cavities is one third of the 1.3 GHz TESLA type cavities. Therefore the transverse wake per cavity scales by about one order of magnitude: $3^3/3 = 9$. As a consequence care has to be taken

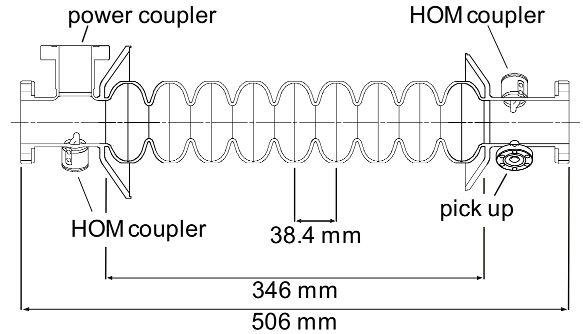

Figure 3: Side view of a nine cell 3.9 GHz cavity with the main power coupler, the pick up probe, and two higher order mode (HOM) couplers.

with the alignment between the cavities and the beam trajectory to keep the transverse emittance blow up caused by short range wake fields acceptable, e.g. below 5%. At the third harmonic system for FLASH, an alignment accuracy of better than 0.5 mm is required. The alignment tolerance for the XFEL is under investigation but assumed to be smaller than the FLASH tolerance.

COUPLER KICKS

The 3.9 GHz cavity beam pipe diameter is a factor of two smaller than that of the 1.3 GHz cavity. Hence, the power coupler is closer to the beam and rf field distortions caused by it are more prominent. These field distortions deflect the beam transversally. Installing the cavities in pairs with the power couplers opposite to each other the residual effect of such kicks becomes minimal.

Figure 4 shows possible cavity arrangements for installing the power couplers alternately opposite to each other. With the FLASH solution a shorter module vessel hosting the four cavities can be used. This has been a hard design requirement due to tight space requirements. But, a residual kick remains for beam on the design trajectory. For the proposed XFEL arrangement all coupler kicks cancel each other for beam on axis.

The effect of coupler kicks on off axis beam may influence the alignment tolerances. Quantitative examinations using rf field and beam physics simulation are under way.

CAVITY PERFORMANCE

The number of cavities required to establish a 3rd harmonic voltage of 108 MV depends on the average cavity gradient and performance respectively. To keep the beam dynamical effects and costs for the high power rf low an average operable cavity gradient higher than 20 MV/m would be desirable. Then a single string of 16 cavities (of length $16 \cdot 608\,\mathrm{mm} = 9.73\,\mathrm{m}$) may be installed in a cryomodule with the diameters of a fundamental rf cryomodule used for eight 1.3 GHz cavities ($8 \cdot 1385\,\mathrm{mm} = 11.08\,\mathrm{m}$).

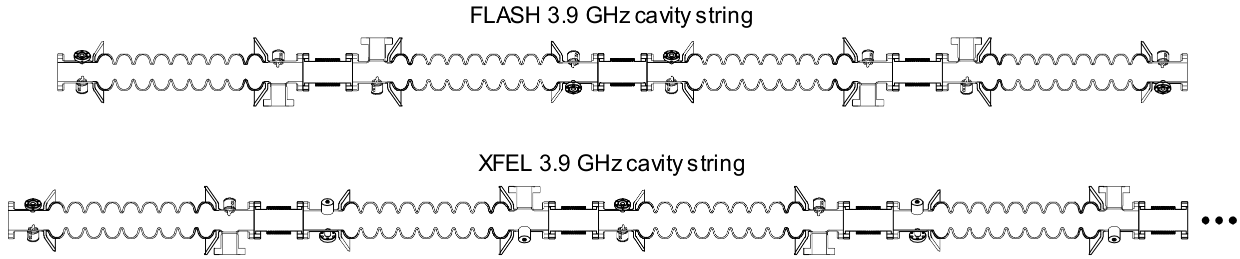

Figure 4: Possible cavity arrangements for installing the power couplers alternately opposite to each other.

Basing the design on a more conservative average operable cavity gradient, e.g. 15 MV/m, 22 to 24 higher harmonic cavities mounted in at least two cryomodules would be required.

Using the quality factors measured at the 3.9 GHz cavities produced for the FLASH 3rd harmonic module (Fig. 5) the power dissipation per cavity would be 4.5 W for a gradient of 20 MV/m and 0.6 W for a gradient of 15 MV/m at 30 Hz rf pulse (1 ms duration) repetition rate. The diameter of the helium vessel chimney results in a cooling capacity of 25 W per cavity [5] which would also be sufficient for 20 MV/m operation.

Before fixing the design gradient, we agreed to wait for the horizontal test results showing the cavity performance with the helium vessels and tuners mounted.

CRYOMODULE DESIGN

The XFEL 3rd harmonic cryomodule design can not yet be fixed due to the many open questions still to be addressed.

With respect to the alignment tolerances resulting from beam dynamical requirements like moderate transverse wake fields and coupler kicks different scenarios are under consideration.

The FLASH module serves as a prototype and will show the obtainable measurement accuracy of the electrical cavity axis, the cavity string, module alignment and installation accuracy and as well the resistance of the alignment against transportation. If the alignment tolerances are easily met and simulation shows that the XFEL beam dynamics requires similar tolerances as compared to FLASH, the XFEL 3rd harmonic module design may be very close to the FLASH module.

Modifications to the design may be caused by adding the possibility to align the cavities from outside to enable beam based fine alignment. For this purpose the alignment bolts at the support posts of the helium gas return pipe may be made accessible even while the module is cold [6].

An alternative may be to install beam steering magnets just inside the module. Whether focusing quadrupole magnets are required inside the module because of beam optics reasons is under investigation.

In all cases, we plan to use the higher order mode signals to examine the beam trajectory and the alignment of the electrical cavity axis respectively [7].

The number of cavities per module remains to be discussed.

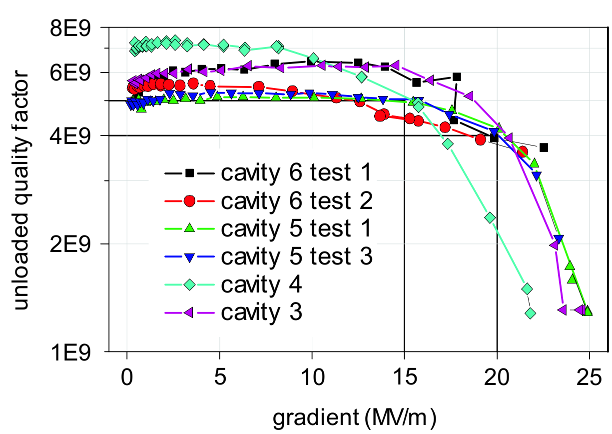

Figure 5: Vertical test results of 3.9 GHz cavities produced for the FLASH 3rd harmonic module.

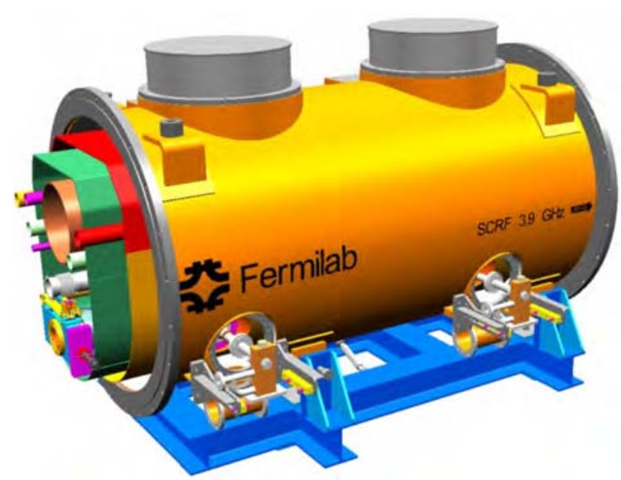

Figure 6: FLASH 3rd harmonic module manufactured at Fermilab. Experience gained with this module will influence the XFEL 3rd harmonic module design.

HIGH POWER RF

The XFEL will accelerate bunches of 1 nC with bunch repetition rate of up to 5 MHz resulting in a maximum beam current of 5 mA. Beam loading usually degrades the rf field in accelerating cavities and external rf power is required to keep the gradient at a constant level. Due to the decelerating operation of the 3rd harmonic rf the gradient could be sustained by the beam itself with a well chosen external coupling. For an R/Q of the cavities of 375 Ω [8] and a cavity voltage of 5 MV (15 MV/m) this would correspond to a loaded quality factor of $Q_L = 1.33 \times 10^6$. As a result, at least 6.4 kW of RF power would be required at each cavity input to fill the cavity.

By doubling the loaded quality factor to $Q_L = 2.66 \times 10^6$ the power requirement can be reduced to 3.2 kW per cavity. But, rf power is now required to preserve the gradient during the flat top and a phase flip of 180° has to be performed after filling.

Choosing a different design gradient the numbers would scale accordingly by leaving the overall power requirement constant.

At present it is assumed that the klystrons will be installed in a gallery at the injector building 120 m away from the third harmonic section. This causes waveguide losses of 2.6 dB. Waveguide bends and circulators attenuate with 0.3 dB. Adding an overhead of 30% for compensating detuning and for rf control 8.2 kW per cavity will be required. Powering the klystrons via high voltage pulse cables the waveguide length can be reduced to 10 m reducing the power requirement to 4.7 kW per cavity.

We plan to use klystrons with 80 kW output power (64 kW at life end), a gain of 40 dB and a beam current of 7.78 A. The high voltage modulators have to provide a klystron voltage of 37 kV.

With those parameters three klystrons will be required with the long waveguides or two with the short ones.

RF CONTROL

At the XFEL, the phasing between the fundamental rf and the 3rd harmonic rf has to be controlled better than 0.01° (in 1.3 GHz phase) for proper compensation of the 1.3 GHz rf non-linearity, energy dependent dispersion and wake fields. It is planned to control the 3rd harmonic rf using digital electronics also controlling the fundamental rf (Fig. 7). These are field programmable gate arrays (FPGAs) for fast proportional rf feedback [9] and beam based beam loading compensation [10] acting within rf pulses and digital signal processors (DSPs) used for adaptive control like adaptive feed forward (AFF) operating from rf pulse to pulse [11].

Until now, no operational experience controlling superconducting 3.9 GHz cavities exists. This situation will change with the first rf tests of the 3.9 GHz FLASH module foreseen for spring 2008. For these tests, we plan to down convert 3.9 GHz to 1.3 GHz and vice versa so that we

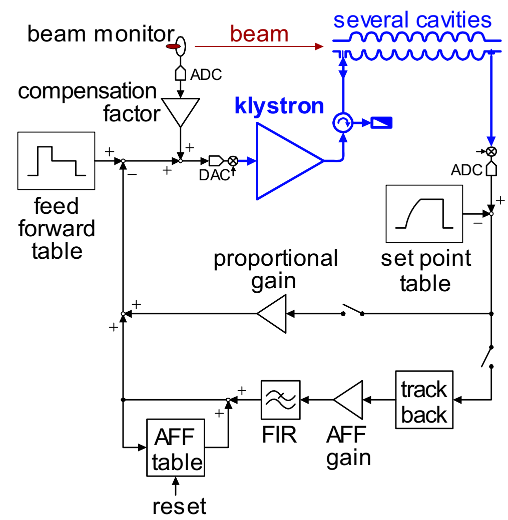

Figure 7: Potential scheme of the digital third harmonic rf control (black) surrounding the high power rf (blue). DACs in front of the vector modulator (⊗) and ADCs after down converters (⊗) are part of the digital electronics.

can use a 1.3 GHz type controller without hardware modification. At 1.3 GHz accelerating modules the proportional control gain values resulting in the most stable beam are presently restricted by the sensor noise [10] rather than by limitations derived from control theory [9]. Hence, to enable high proportional gain values rf sensors detecting directly 3.9 GHz rf may be used at the XFEL [12] rather than detecting 3.9 GHz down converted to 1.3 GHz which is expected to add noise.

Beam based beam loading compensation and adaptive feed forward techniques applied at superconducting rf show quite promising results and are both still capable of improvement [10, 11].

SUMMARY AND OUTLOOK

The third harmonic rf module, presently under development, construction and assembly at Fermilab will serve as basis for the design of that for the European XFEL. Nevertheless, some open questions have to be answered before a final design of the XFEL third harmonic rf can be fixed.

These are questions with respect to beam dynamical effects like emittance blow up by transverse wake fields due to misaligned cavities and coupler kicks. Depending on the sensitivity of the beam to these effects and the resulting tolerances, design modifications allowing beam based fine alignment of the cavities and additional steering magnets may be considered.

Furthermore, the total number of cavities depends on the average design gradient which should be based on a experimentally well established value. We intend to await the horizontal test results of the third harmonic cavities built for FLASH before fixing this number. With a conservative average design gradient of 15 MV/m 22 to 24 cavities probably installed in two crymodules will be required, whereas an average design gradient of more than 20 MV/m would result in 16 cavities which may be hosted in one cryomodule. With the high gradient solution a later upgrade of the XFEL to cw operation would require lowering the gradient to keep the cryogenic load reasonable.

Whether the klystrons will be installed near the third harmonic section in the tunnel to keep rf power losses in waveguides small or in the injector building for easy maintenance remains to be discussed.

Use of rf control concepts developed for the 1.3 GHz accelerating structures is foreseen. We will gain first rf control operational experience when the FLASH third harmonic module will be tested at the cryomodule test-bed (CMTB) at DESY.

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