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FREQUENCY-DETUNING DEPENDENT TRANSIENT COAXIAL RF COUPLER KICK

Y. Chen* [1,2], H. Qian[1], M. Krasilnikov[1], F. Brinker[2], W. Decking[2], J. Good[1], M. Gross[1], P. Huang[1], I. Isaev[1], C. Koschitzki[1], S. Lal[1], X. Li[1], O. Lishilin[1], G. Loisch[1], D. Melkumyan[1], R. Niemczyk[1], A. Oppelt[1], H. Shaker[1], G. Shu[1], F. Stephan[1], G. Vashchenko[1]

[1]DESY, 15738 Zeuthen, Germany; [2]DESY, 22603 Hamburg, Germany

Abstract

A transverse kick which results from the coaxial RF coupler in the L-band RF gun at the Photo Injector Test facility at DESY in Zeuthen (PITZ) has been modeled and characterized. The used RF pulse is typically 600 μs long and used to produce a train of up to 2700 electron bunches. The kick is transient and found to be dependent on the detuning of the resonance frequency of the gun cavity. The frequency-detuning within the RF macro-pulse results in a variation in the kick strength along the pulse. This leads to a downstream orbit and size change of individual bunches within the train. Using 3D RF field distributions, calculated at detuned frequencies of the cavity, particle tracking simulations are performed to simulate the behavior of the transient kick onto the electron bunch. The temperature of the cooling water for the gun is tuned, allowing detailed characterization of the frequency-detuning within the RF pulse and thereby measurements of the kick which are of practical interest. Systematic measurements of the kick along the bunch train have meanwhile been carried out. The results will be presented and discussed.

INTRODUCTION

The European X-ray Free-Electron Laser (XFEL) provides excellent opportunities in pursuing excellence in physics and advanced applications of coherent x-ray radiation [1]. The photoelectron source in use at the European XFEL is a photocathode RF gun developed at the Photo Injector Test facility at DESY in Zeuthen (PITZ) [2,3]. The key component of the PITZ gun is a 1.6-cell 1.3 GHz copper resonator. The gun can be operated with a high electric field gradient of about 60 MV/m on the cathode surface with long RF pulses of up to 650 μs at a repetition rate of 10 Hz. This allows the production of a maximum number of 27000 bunches per second at the XFEL and results in a high peak RF power of about 6.5 MW in the cavity while a high average RF power of about 42 kW dissipates in a rather short cavity length of about 20 cm and a cavity radius of about 9 cm. The RF power in the gun is supplied by a 10 MW multi-beam klystron. The power is coupled from the input waveguide via a door-knob transition into the rotationally symmetric coaxial coupler and the gun cavity.

A transient transverse kick, due to the disturbed RF fields of rotational symmetry by the transition from the input rectangular waveguide to the coaxial power coupler of the PITZ gun, has been simulated and quantified in [4]. In this paper, we present the dependency of the kick on the detuning of the resonance frequency of the gun cavity within the RF pulse. The effect is then demonstrated in both simulation and experiment. Consequently, measurements of the resulting downstream orbit and size change of individual bunches along the train are reported.

* ye.lining.chen@desy.de

KICK VS. FREQUENCY-DETUNING

The reflection coefficient (S_{11}) is defined as the ratio of the reflected power over the forward power for a resonant cavity with a resonance frequency f_0 (~1.3 GHz for the PITZ case) fed by the RF with a frequency f. In order to protect the microwave source (klystron), the reflected power from the cavity must be low (typically $\ll$ 2 MW). This requires a resonant frequency kept close to the RF frequency. The frequency-detuning, $\Delta f = f - f_0$ is then used to describe how much the cavity is detuned from its resonance.

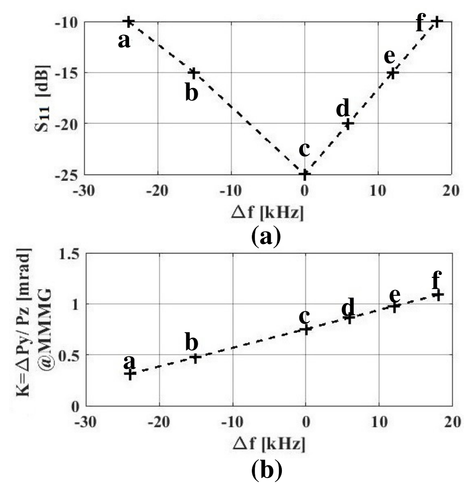

Figure 1: Simulated reflection coefficient and kick dependency on frequency-detuning.

Simulation

To simulate the kick behavior in response to the frequency-detuning, a simplification is made in the simulations: the RF frequency is varied at the port position of the input waveguide (see Fig. 1 in Ref. [4]) for defining the detuned frequency w.r.t. the cavity resonance. This allows computing 3D RF field distributions of the gun cavity at the detuned frequencies in frequency domain calculation. Using the obtained field distributions, particle tracking simulations using CST Particle Studio [5] are enabled and the kick strength

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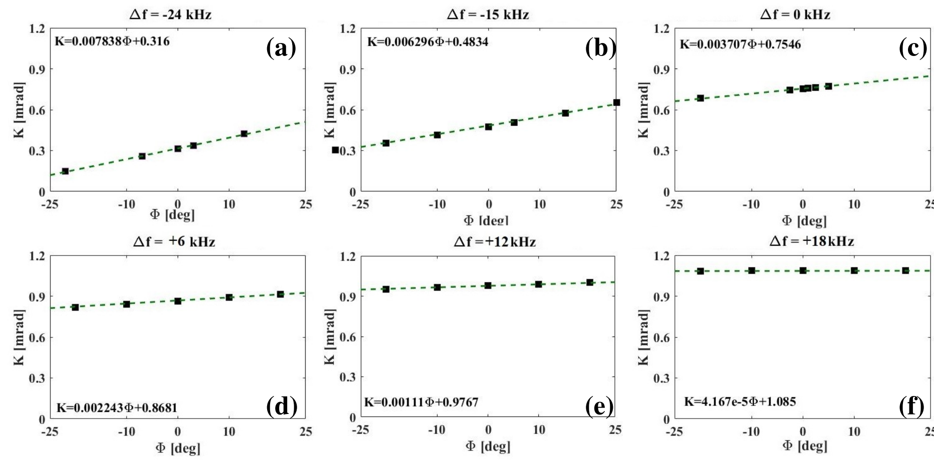

Figure 2: Simulated phase slopes of the kick vs. Δf. Green lines: linear fits to the simulation results. Φ: gun phase w.r.t. MMMG.

(K, the ratio of transverse beam momentum change over longitudinal momentum) can thus be computed at the detuned frequencies.

Figure 1 (a) shows the simulated S_{11} as a function of Δf with points $a - f$ as the set-points for frequency-detuning. Figure 1 (b) illustrates the change of the kick strength over the detuned frequencies at the maximum mean momentum gain (MMMG) phase of the gun for the individual cases $a - f$. The beam momentum at the MMMG phase is kept the same (~6.8 MeV/c) for all cases by adjusting the amplitudes of the applied RF field distributions in the simulations. As shown, the kick strength varies with the frequency-detuning, and for the chosen set-points, this shows a nearly linear behavior.

In Fig. 2, the phase dependency of the kick is shown for each case defined in Fig. 1 at the specified Δf, respectively. It is important to note, that the phase slope of the kick varies with the change of the frequency-detuning. An overheating state ($\Delta f > 0$) of the gun cavity renders smaller phase slopes than in the overcooled cases ($\Delta f < 0$). More specifically, the effect leads to a flattened phase slope in the overheated case (f) while resulting in the most significant slope (or curvature) for the overcooled case (a). Since a phase slope of the kick can result in the mismatch of slices within the bunch, an emittance growth on the order of 0.02~0.04 μm can be expected for a 20 ps bunch based on preliminary studies. This also suggests, that operating the gun at its overheated state can effectively reduce (and even avoid) the emittance growth caused by the phase-dependent kick for single bunch operation.

Experiment

Measurements of the kick dependencies on the frequency-detuning have been carried out. Due to thermal expansion, the resonant frequency of a cavity is linearly proportional to the temperature of the cavity. The latter is controlled by adjusting the cooling water temperature of the cavity. The frequency-detuning (w.r.t. the timing of the electron bunch) within the RF pulse can thus be adjusted by tuning the temperature of the cavity cooling water. Figure 3 (a) shows the measured S_{11} versus the cavity temperature with cases A, B and C denoting the cooling states of the gun as overcooled, at resonance and overheated, respectively. For each case, the kick strength is measured in terms of the bunch position change (Δr). This is conducted at a downstream observation screen (~5.27 meters from cathode) as the gun phase is scanned. As shown, the phase slope of the kick is reduced as evolving from overcooling to overheating. Case A (Δr_{p2p}~0.9mm) shows the strongest linear slope while case C (Δr_{p2p}~0.4mm) delivers the smallest phase slope, particularly for the phase range of MMMG ± 5 degrees (Δr_{p2p}<0.05mm). This is in fairly good consistency with the simulated kick behavior, as shown in Fig. 2. Figure 3 (e) shows the measured kick strength varies as the cavity temperature (frequency-detuning) changes. The resonance temperature of the gun cavity is at ~73.2°C. The green line shows a linear fit to the measurement data (black dots with error bars).

IMPACTS ON BUNCH TRAINS

For the operation with long RF pulses of several hundred microseconds, the impacts of the characterized kick onto the properties of electron bunch trains are experimentally investigated. The position and size change of the bunches along the train are measured. This is done through measuring transverse properties of a single witness bunch moving along the long RF pulse by varying the cathode laser timing. The frequency-detuning seen by the witness bunch and thus the frequency-detuning dependent kick strength can be varied and measured. Note that the bunch charge and momentum are kept the same for all measurements. Figure 4 shows the bunch position change along a 240 μs train for a fixed beam momentum of ~6.35 MeV/c at the MMMG phase of the gun. A peak to peak (P2P) position change of ~650 μm is obtained, which corresponds to roughly a P2P kick difference of 0.13 mrad between the head and tail of the bunch train. Experimentally operating such a bunch train within a 300 μs long RF pulse results in roughly a 6 dB

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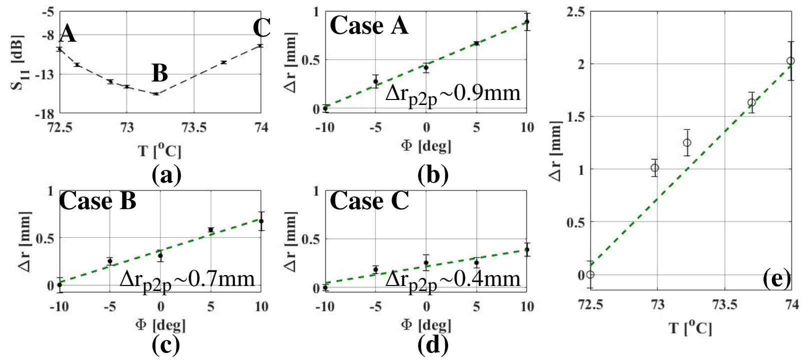

Figure 3: Measured kick dependencies on gun phase and frequency-detuning (or cavity temperature). Green lines: linear fits to the data. Φ: gun phase w.r.t. MMMG.

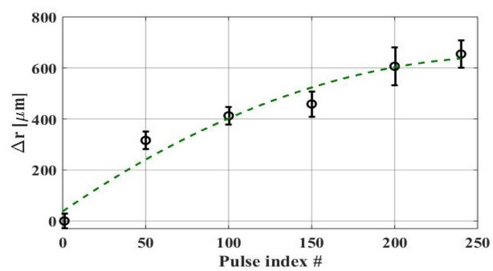

Figure 4: Measured bunch position change along a 240 μs train at ~5.27 meters downstream from cathode. The solenoid current is fixed. Green curve: a fit to the data.

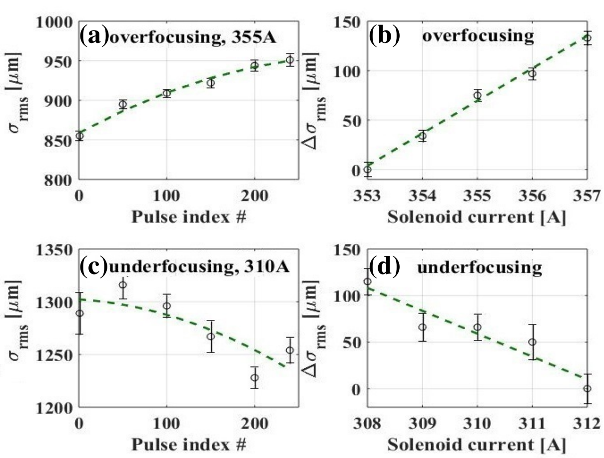

Figure 5: Measured RMS bunch size and size change along a 240 μs train for both the over- and under-focusing case.

difference in the measured S_{11} between the head and tail of the train. This is in correspondence to the simulation results as shown in Fig. 1 (a) for emulating the bunch train operation in between case c and case d in the overheated state of the gun. As shown in Fig. 1 (b), the difference in the simulated kick strength along the train can be estimated as 0.11 mrad, which is in fairly good consistency with the experimental findings although the simulated curvature of S_{11} is not yet optimized to precisely match the measured S_{11} at exactly the same beam momentum. Furthermore, an RMS bunch size change has been measured for both the overfocusing and underfocusing case when the gun solenoid is set to 355 A and 310 A, respectively. As shown in Fig. 5 (a) and (c), a size change of ~90 μm is obtained for the overfocusing case while ~65 μm is measured for the case of underfocusing. Since the bunch size change is equivalent to the change of solenoid focusing, the effect can also be evaluated by means of solenoid focusing change which is more relevant for the SASE tuning at FEL facilities. In Fig. 5 (b), a solenoid scan around 355 A leads to a change of ~33.8 μm per ampere (overfocusing case). Likewise, ~28.8 μm per ampere is given for the underfocusing case (Fig. 5 (d)). This defines roughly a 2.7 A focusing change along the 240 μs bunch train for the overfocusing case and a 2.3 A change for the case of underfocusing. These effects should be more prominent for longer RF pulses. The change of the orbit and size degrades the quality of the bunch train and may disturb the overall tuning for the SASE lasing in FELs.

CONCLUSION

A frequency-detuning dependent RF coupler kick is analyzed in both simulation and experiment, where the transient behavior of the identified kick is consistent. The resulting orbit and size change along the electron bunch train are exemplarily quantified for a 240 μs train along a 300 μs RF pulse. The beam momentum is kept at ~6.35 MeV/c, which corresponds to gun operation at ~5.7 MW at the MMMG phase. A P2P difference in the kick strength between the head and tail of the bunch train is estimated as 0.13 mrad, which is consistent with the simulation results. A P2P focusing change along the same train is quantified as ~2.7 A and ~2.3 A for the case of overfocusing and underfocusing, respectively. Schemes for the correction and compensation of the kick effects onto the bunch train operation are currently under discussions.

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