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First experimental data on the FEL–RF interaction at the Jefferson Lab IRFEL

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Abstract

High power FELs driven by recirculating, energy–recovering linacs can exhibit instabilities in the beam energy and laser output power. Fluctuations in the accelerating cavity fields can cause beam loss on apertures, phase oscillations and optical cavity detuning. These can affect the laser power and in turn the beam induced voltage to further enhance the fluctuations of the rf fields. A theoretical model was developed to study the dynamics of the coupled system and was presented last year [1]. Recently a first set of experimental data were obtained at the Jefferson Lab IRFEL for direct comparisons with the model. We describe the experiment, present the data together with the modeling predictions and outline future directions.

Jefferson Lab's IRFEL recently achieved cw 1.7 kW of FEL output power with 4.4 mA of average beam current [2]. No signature of longitudinal instabilities arising from the interaction of the rf fields with the FEL was observed, in agreement with the modeling predictions. As design efforts for the 10 kW FEL Upgrade project commence at Jefferson Lab, it is important to establish modeling capabilities that we can trust for the prediction of the threshold of these instabilities.

In order to test the validity of our theoretical model, an experiment was performed at Jefferson Lab's IRFEL. The accelerator consists of a 10 MeV injector followed by a superconducting rf (srf) linac. The linac uses a CEBAF–type cryomodule with eight 1497 MHz cavities operating at an average accelerating gradient of ~10 MV/m, for a resulting beam energy of 48 MeV. The beam is transported from the linac to the wiggler where lasing takes place. A transport lattice recirculates the spent beam back to the linac for deceleration and energy recovery.

In this experiment, the gradient set point of the last cryomodule cavity was modulated at constant amplitude and frequencies ranging from 500 Hz to 50 kHz. This resulted in beam energy modulation of approximately 0.1%. The response of both the

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FEL output power and the rf control system of the first cryomodule cavity was measured.

An energy fluctuation coupled to the finite M_{56} from the cryomodule exit to the wiggler will result in a phase fluctuation at the wiggler. The derivative of this phase fluctuation is proportional to the electron bunch frequency at the FEL, which is equivalent to optical cavity detuning. This effect will change the laser output power through the time–varying FEL gain function.

Furthermore, the beam energy modulation affects the rf response of all the superconducting cavities through the recirculated beam. This effect depends on whether the FEL is on or off. In the absence of lasing, energy fluctuations of the accelerating beam coupled to the finite M_{56} from the cryomodule exit to its entrance, cause fluctuations of the arrival time of the recirculated beam, to which the rf system responds. With the FEL on, there is an additional effect on the phase of the recirculated beam which depends on the FEL power and gain. We first measured the rf system response of the first cryomodule cavity with the FEL off and then we turned the lasing process on.

Figure 1 is the plot of an rf signal proportional to the phase error of cavity 1, as function of the modulation frequency, f_{mod}, with the FEL off. At high frequencies, the phase perturbations are filtered by the low pass characteristics of the closed loop system of the rf cavity with feedback. For the Jefferson Lab rf control system, the rolloff starts at approximately 10 kHz. At low frequencies one notices the effect of the additional feedback gain in the control system (originally added to suppress microphonic noise), which further suppresses the phase fluctuations. The model adequately reproduces the data both qualitatively and quantitatively.

Figure 2 is also the plot of the phase error in the first cavity as function of f_{mod}, with the FEL on. The different curves correspond to different points in the FEL detuning curve. In the absence of any modulation, when the FEL is turned on, the FEL interaction causes an energy shift in the electron beam which coupled to the M_{56} of the recirculator, shifts the arrival phase of the decelerating beam. This shift is such that the two beam current vectors, accelerating and decelerating, now better cancel each other, resulting in a smaller phase error of the resultant beam vector. Furthermore, the stronger the lasing process, the larger the energy shift, the better the cancellation between the beam current vectors. This explains why the zero–modulation phase error is maximum with the FEL off and decreases as the FEL power is increased.

As f_{mod} increases, the electron bunch arrival frequency at the wiggler changes with the derivative of the phase modulation. Therefore the bunch arrival frequency is $\propto f_{\text{mod}}$. As these changes are equivalent to optical cavity detuning, they will affect the output laser power through the gain function. Therefore there is also a lasing–induced phase error, which, to first order is $\propto f_{\text{mod}}$. This phase error adds to the phase error directly proportional to the beam energy variation, which is present with the FEL off and is unchanged as f_{mod} increases. For some value of f_{mod}, the linearly increasing term exceeds the constant term, thus creating a larger phase error signal compared to the one with the FEL off. At frequencies above ~10 kHz, the roll off of the rf control system, which to a good approximation varies as $1/f_{\text{mod}}$, reduces the effect of the lasing–induced phase error to approximately a constant, while the frequency–independent term falls as $1/f_{\text{mod}}$, resulting in a net decrease of the total phase error signal.

As one moves closer to the peak of the detuning curve, the slope of the error signal increases with the increase of the laser power, until, close to the peak of the detuning curve, the energy fluctuations lead to an unstable behavior and the beam is lost for modulation frequencies above 10 kHz. Preliminary analysis shows that the model reproduces qualitatively the measured behavior of the system (Figure 3), although quantitative agreement fails, especially at high frequencies.

Finally, the amplitude of the FEL output power was measured as a function of modulation frequency, and the relative amplitude was plotted in Figure 4. These data were taken with 1.5 mA of beam current and approximately 300 W of FEL output power. Notice the nearly linear increase of the power with frequency at low frequencies as well as the "saturation" effect for frequencies above 10 kHz, consistent with the phase error behavior. Here too the model fails to quantitatively reproduce the high frequency behavior of the data, while at low frequencies the agreement is reasonable and the overall behavior is qualitatively the same.

To conclude, we point out that at nominal operating parameters of the Jefferson Lab IRFEL, this interaction is stable except when operating close to the peak of the detuning curve, in agreement with the model. In the future we plan to refine both the experimental technique and the data analysis and comparisons with the model. Once benchmarked, the model will be used to address the issue of FEL/rf stability as a limiting factor in using recirculating, energy–recovering linacs for high average power FELs.

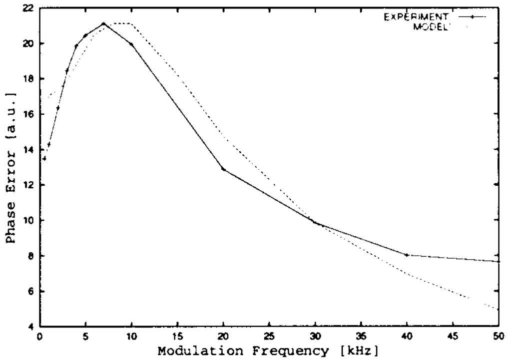

Fig. 1. RF phase error vs f_{mod} with FEL off.

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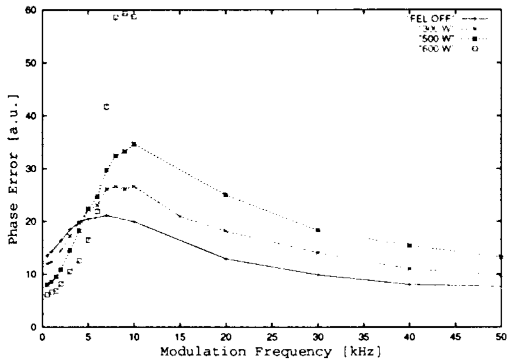

Fig. 2. RF phase error vs f_{mod}, FEL on. I_b ~1.5 mA.

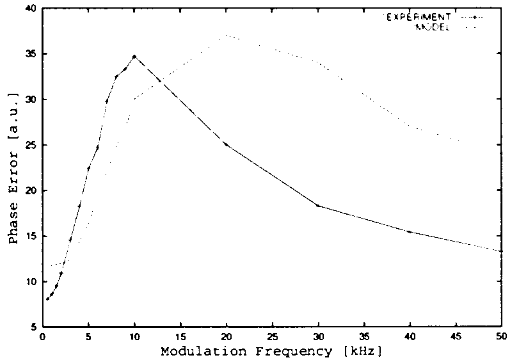

Fig. 3. RF phase error with FEL on: Theory vs experiment.

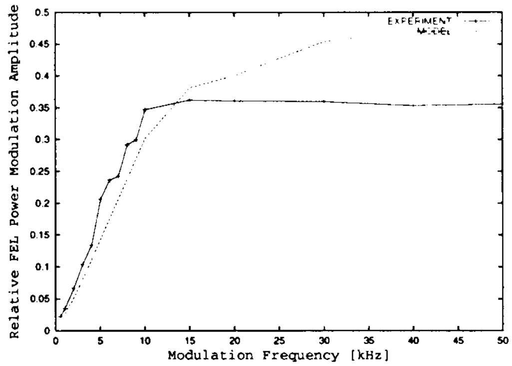

Fig. 4. FEL output power: Theory vs experiment.