1995

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Nuclear Instruments and Methods in Physics Research A, Volume 358, (1995), pp. ABS 26 -ABS 27

http://hdl.handle.net/10945/44046

Nuclear Instruments and Methods in Physics Research A 358 (1995) ABS 26–ABS 27

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

ELSEVIER

Frequency response to an electron energy shift

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In a free electron laser (FEL) oscillator, the optical pulse evolves through mode competition as a result of mirror losses, desynchronism, and amplification by the electron beam. The finite time for this evolution determines the optical response to an electron beam energy change. The ability of the FEL operating frequency to follow modulations in electron energy has been demonstrated experimentally [1–3] and theoretically [4]. Using a self-consistent FEL theory with dimensionless parameters [5], a longitudinal multimode simulation follows the evolution of the optical pulse over many passes of a FEL oscillator.

The optical frequency response to an electron energy shift is summarized in Fig. 1. The characteristic response time n_c measures the number of passes for the optical frequency centroid to reach $1/e$ of its new steady-state position after an electron energy shift is imposed at steady-state saturation. The parameters in the simulation are chosen so that the optical pulse reaches steady-state saturation fields without the trapped-particle instability and the growth of optical sidebands. The current density j can be related to the weak-field, single-mode gain, $G \approx 0.135j$, and the energy loss at each pass is given by $1/Q$. The pulse length, σ_z, and desynchonism, d, are measured in terms of the slippage distance, $N\lambda$.

For small Q and low desynchronism d, the optical pulse resides predominantly in the region of the electron pulse. Within the bulk of the optical pulse, strong-field saturation limits changes in the optical fields and the frequency remains unchanged. In the back of the optical pulse where the fields are weak and the interaction with the energy-shifted electron beam changes the optical frequency. Desynchronism d transfers these changes toward the front of the pulse at each pass. The centroid of the optical power spectrum shifts linearly with the number of passes during the middle of the response. In Fig. 1, for a given Q and $\sigma_z = 2$ the response time n_c falls off as $1/d$.

For large Q and small σ_z, the bulk of the optical pulse resides in an exponentially decaying profile outside the interaction region. In the short interaction region, changes in the optical frequency occur in a time less than the time for light of the initial frequency to decay as determined by Q. In the limit of high d, the characteristic response time n_c is approximately equal to Q.

For a given Q, n_c is observed to increase linearly with σ_z. In Fig. 2, the characteristic response time is plotted for a longer $\sigma_z = 4.0$ showing increasing response times in comparison to Fig. 1. In general the response time n_c changes as σ_z/d for pulses longer than the slippage distance. The response time does not vary significantly with j. Response to sinusoidal electron energy modulations follow the trends of the step energy change. As the modulation period becomes much less than the response time n_c, the optical frequency is unable to follow the electron energy modulation.

Experimentally, the response time is seen to increase with Q and σ_z/d [1]. Future work will further address the issues of short pulses and the trapped-particle instability. When the electron pulse length σ_z becomes smaller than the slippage distance the optical pulse length may not be on the order of σ_z and the response time may follow

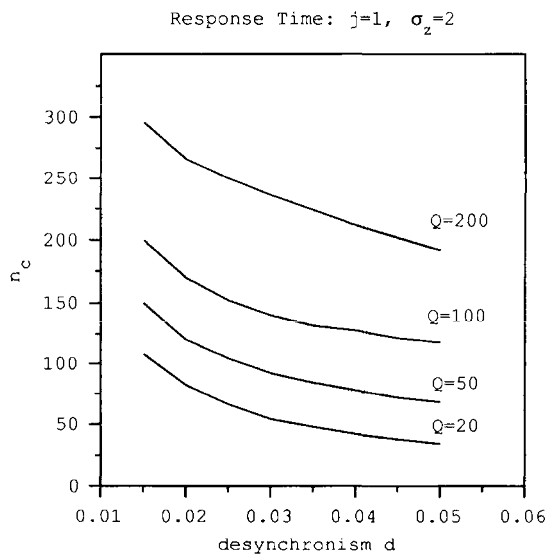

Fig. 1. Characteristic response time n_c as a function of desynchronism d and Q.

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SSDI 0168-9002(94)01308-X

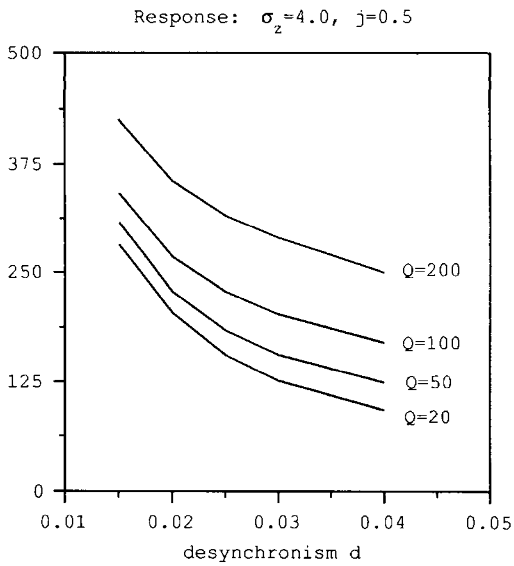

Fig. 2. Characteristic response with $\sigma_z = 4.0$.

different trends. Limit cycle behavior, which causes oscillations in the optical field, is also studied.

Acknowledgements

The authors are grateful for support of this work by the Naval Postgraduate School, Stanford University (N00014-91-C-0170), and SURA/CEBAF.

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