Demonstration of Wavelength Stabilization in a Free-Electron Laser

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Abstract—**Wavelength stabilization of a free-electron laser (FEL) through the use of negative feedback has been successfully demonstrated at the Stanford Picosecond FEL Center. Short-term wavelength fluctuations have been reduced by an order of magnitude and drift has been virtually eliminated.**

INTRODUCTION

SINCE its realization in 1976 [1], the free-electron laser (FEL) has gained popularity as a scientific tool. Its use as a tunable high-power coherent-light source in sophisticated experiments requires that the FEL optical-beam quality be at least as good as that of conventional laser systems. Although the pointing and timing stability of the FEL are very good, its wavelength stability has sometimes been a problem as a result of sensitivity to the electron-beam energy and other parameters. Stabilization of the wavelength can be expected to substantially improve the utility of the FEL as a serious research instrument.

The Stanford FEL emits picosecond laser pulses every 85 ns for the duration of each macropulse; macropulses are several milliseconds long and occur at a repetition rate of 10 Hz. The fractional wavelength fluctuation (peak to peak) within a macropulse can be as small as 2×10^{-4}, but more typically is an order of magnitude larger. The spectral linewidth (FWHM) of an FEL is limited by the Fourier transform of the electron pulse length. For a Gaussian pulse, the spectral width is

$$\frac{\Delta\lambda}{\lambda} = \frac{2\lambda \ln 2}{\pi c\, \Delta T} \tag{1}$$

where ΔT is the pulse length (FWHM) in seconds and λ is the wavelength in meters. For an FEL operating at $\lambda = 4$ μm with 3 ps long pulses, $\Delta\lambda/\lambda = 2 \times 10^{-3}$. In many experiments, it is essential that the FEL optical spectrum not shift in frequency by more than 10 percent of its width. The fractional wavelength variation must therefore be consistently less than a few parts in 10^4 for FEL operation with the above parameters. For certain experiments [2], or different FEL parameters, even greater stability may be required.

The FEL wavelength is subject to fluctuation and drift as a result of changes in wiggler parameters, electron-beam steering and focusing, and electron-beam energy. Stabilizing the FEL wavelength directly avoids the difficulties involved in measurement and control of all of the individual parameters that can affect it. Direct stabilization can be accomplished by measuring the FEL wavelength and adjusting the electron-beam energy to correct for any deviation from a wavelength value set by the user. Such a negative feedback system has been successfully implemented. This paper discusses the performance of the stabilization system and the parameters that influence it.

SYSTEM RESPONSE TO SMALL SINUSOIDAL CHANGES IN BEAM ENERGY

Before negative feedback can be applied to a system, its response to the feedback signal over the desired frequency range must be studied. In the Stanford case, the system to be stabilized can be broken down into two separate systems: the Superconducting Accelerator (SCA) that generates the electron beam and the FEL. The SCA is composed of several superconducting structures whose RF fields are controlled by RF-stabilization loops [3]. Each structure's loop sets the RF-field amplitudes to a level determined by the loop's energy-control input. The electron-beam energy can be controlled by varying the voltage applied to one structure's energy-control input. The amplitude and phase response of the electron-beam energy modulation resulting from a small amplitude modulation of the energy-control input is the SCA transfer function. The amplitude and phase response of the optical wavelength modulation of the FEL as a result of small amplitude modulation of the electron-beam energy is the FEL transfer function. These transfer functions, particularly the FEL's, can be nonlinear and time varying. Furthermore, they depend on a large number of parameters that may vary rapidly and unpredictably. Fortunately, an approximate characterization of these functions is sufficient for design purposes.

The SCA amplitude and phase response were measured and found to have much poorer high-frequency response than expected [3]. The RF-stabilization electronics were modified to improve the high-frequency response of the loop, but the phase response, which by 15 kHz was shifted 180° from its dc value, remains a problem. This phase reversal in the response is the primary factor in limiting the bandwidth of wavelength stabilization. Though the

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poor high-frequency characteristics of the SCA response can be partially attributed to the high Q_L (10^6) of the superconducting RF cavities, redesign of the RF-stabilization loop may result in substantial improvement.

The dynamic response of the FEL wavelength to perturbations in the electron-beam energy is complex and difficult to measure. However, the dependence of this response function on frequency and other parameters can be estimated analytically. The optical wavelength generated by an FEL is generally written as

$$\lambda = \frac{\lambda_{\text{wig}}}{2\gamma^2}(1 + a_w^2) \qquad a_w = \frac{eB_0\lambda_{\text{wig}}}{2\sqrt{2}\,\pi m_0 c} \tag{2}$$

where $\gamma m_0 c^2$ is the electron energy, λ_{wig} is the wiggler period, and B_0 is the peak wiggler field. For small changes in the electron-beam energy, the wavelength changes as

$$\frac{\Delta\lambda}{\Delta\gamma} = -2\frac{\lambda}{\gamma}. \tag{3}$$

In these equations, it is implicitly assumed that the electron-beam trajectory through the wiggler is unaffected by the energy change. In the Stanford FEL, the transport system that injects the electron beam into the wiggler is dispersive, and the assumption is not valid. In this system, the wiggler beam line is parallel to the accelerator beam line, but offset by about 10 cm in order that the electron beam from the linear accelerator not strike the mirrors that form the optical resonator. The electron beam is translated the necessary 10 cm for injection into the wiggler by a matched pair of electromagnets. An identical pair of magnets places the electron beam back on its original path after it has passed through the wiggler (see Fig. 1). As a result of these magnets, electron-beam energy changes result in changes in the entrance position of the beam into the wiggler. Furthermore, the orientation of the wiggler field relative to the deflecting magnets is such that these position changes excite betatron oscillations in the electron beam's trajectory as it travels along the wiggler. These betatron oscillations decrease the longitudinal velocity of the electrons and increase the output wavelength [4]. If the electron beam is assumed to be injected parallel to the wiggler axis, but offset by a distance x_0 from the center, then the FEL's output wavelength can be written as

$$\lambda = \frac{\lambda_{\text{wig}}}{2\gamma^2}\left[1 + a_w^2(1 + x_0^2 k_w^2)\right] \qquad k_w = \frac{2\pi}{\lambda_{\text{wig}}}. \tag{4}$$

In our dispersive system, x_0 is a function of γ. Thus, for our parameters,

$$\frac{\Delta\lambda}{\Delta\gamma} = -2\frac{\lambda}{\gamma}\left(1 - \frac{x_0 a_w^2 k_w^2}{1 + a_w^2}\gamma\frac{dx_0}{d\gamma}\right) \approx -2\frac{\lambda}{\gamma}(1 - 10x_0) \tag{5}$$

where $x_0 k_w$ is assumed $\ll 1$ and x_0 is in centimeters. Note that an injection error of as little as 1 mm can completely cancel the effect of energy changes on the FEL's wavelength. While it is possible to imagine circumstances in which this might be advantageous, in the present case it is clearly undesirable. Although we have explored the effect of different offsets, in the remainder of this paper it will be assumed that the beam is properly steered on the wiggler axis (x_0 is zero).

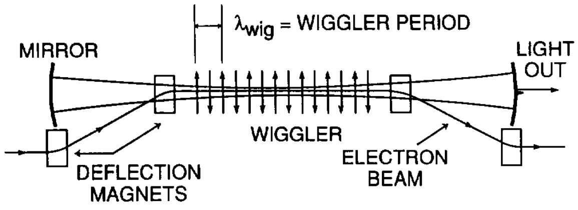

Fig. 1. FEL electron beam transport system and wiggler.

In the simplest model of the FEL cavity, it is assumed that the cavity Q (Q = energy stored in cavity/energy lost each round-trip) determines the maximum rate at which the laser wavelength can be shifted. For the Stanford FEL, with a round-trip time in the optical cavity of 85 ns, the dynamic response for wavelength shifts is approximately described by

$$\frac{\Delta\lambda}{\Delta\gamma} \propto -\frac{2\lambda}{\gamma}\frac{1}{1 + j\omega Q \times 85\text{ ns}}. \tag{6}$$

For an optical cavity Q of 100, the roll-off frequency is near 20 kHz and a roll-off in the phase response should become visible at a lower frequency. Measurements of the FEL transfer function up to 20 kHz are consistent with this prediction.

PERFORMANCE OF A LINEAR FEEDBACK CIRCUIT

Upon consideration of the system response described above, a linear, analog, feedback system was determined to be adequate as a first attempt at wavelength stabilization. The system, shown schematically in Fig. 2, consists of a wavelength diagnostic apparatus that sends a wavelength error signal to a feedback compensator circuit; this circuit filters and amplifies the signal and sends it to the SCA RF-stabilization circuit, which adjusts the accelerator energy accordingly. The wavelength is detected by a SPEX 1000M grating spectrometer with a PbSe two-element detector at its output. The detector generates an error signal proportional to the difference between the FEL wavelength and the setting on the spectrometer. The compensation circuit is designed to provide the maximum possible low-frequency loop gain without causing loop oscillations at higher frequencies.

The wavelength fluctuation over one macropulse measured with and without stabilization is shown in Figs. 3 and 4. Wavelength fluctuations have been reduced by a factor of 10. Furthermore, long-term drift has been virtually eliminated, and the center wavelength of the FEL can be set simply by entering a new wavelength setting in the spectrometer.

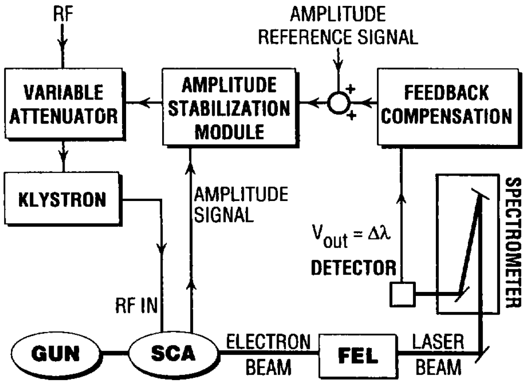

Fig. 2. Schematic diagram of wavelength stabilization system.

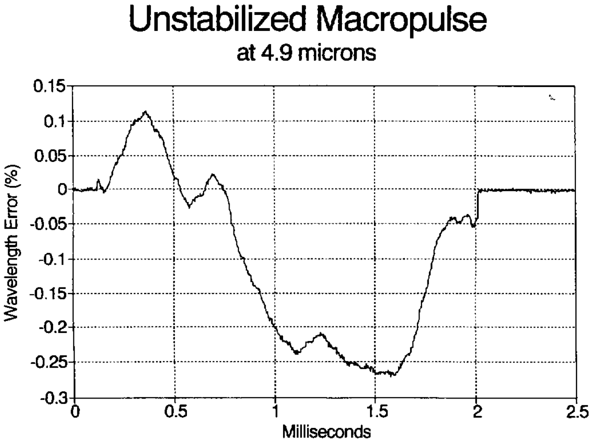

Fig. 3. FEL macropulse wavelength before stabilization.

Possibilities for Improvement

Further improvement of the wavelength-stabilization loop will most likely require an increased loop bandwidth. Due to the inherent low-pass characteristic of the FEL cavity, it seems possible that if a sufficiently high bandwidth could be obtained in the feedback loop, the inherent stability of the optical cavity would eliminate wavelength fluctuations at frequencies beyond this bandwidth. As we have calculated, the bandwidth may need to be extended to beyond 100 kHz before this will occur.

In the Stanford SCA FEL, the loop bandwidth may be increased by adding a low-Q room-temperature RF cavity to the SCA beamline with RF circuitry designed specifically to allow fast modulation of the RF fields.

Finally, a nondispersive electron-beam transport system would eliminate problems associated with the loop-gain dependence on steering.

Conclusion

Wavelength stabilization on 100 μs time scales has been demonstrated. Wavelength fluctuations within a macropulse were reduced by an order of magnitude and long-term drift was virtually eliminated, improving the laser's reliability and flexibility as a scientific tool.

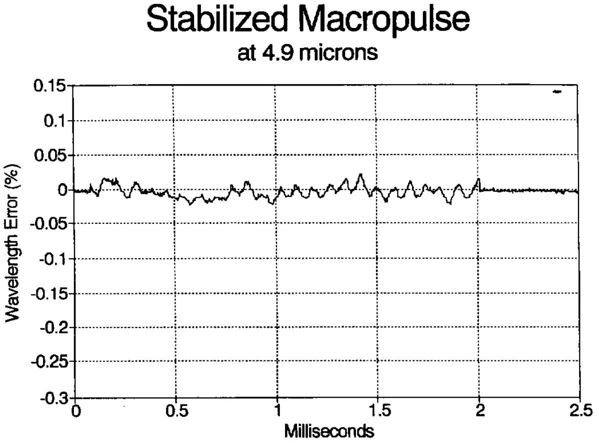

Fig. 4. FEL macropulse wavelength after stabilization.

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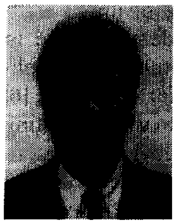

Andre Marziali was born in Milan, Italy on November 11, 1966. He received the B.A.Sc. degree in Engineering Physics from University of British Columbia, Vancouver, Canada, in 1989. He entered the Ph.D. program in Physics at Stanford University in 1989 where he is engaged in research on the Superconducting Accelerator/Free Electron Laser. His Ph.D. dissertation is mostly concerned with microphonic effects in superconducting linear accelerators and with wavelength stabilization of free electron lasers.

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Since 1973 he has been at Stanford University, where he has been a Professor of Physics (Research) since 1989. At Stanford his research interests have included the generation of very high brightness electron beams using superconducting linear accelerator technology, achieving a better understanding of Free-Electron Laser (FEL) physics, FEL device development, and the use of FEL produced photon beams to do experiments in other fields.

He is a member of APS, AAAS, IEEE, and $\Sigma\Xi$. He received the 1965 Sigma Xi Award for outstanding research from Rice University, and the 1990 Free Electron Laser Prize.