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LA-UR--88-3858

DE89 003491

**TITLE: TIME-RESOLVED SPECTRAL MEASUREMENTS FOR THE
BOEING FREE-ELECTRON LASER EXPERIMENTS**

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**SUBMITTED TO: The Tenth International Free Electron Laser Conference, August 29 -
September 2, 1988, Jerusalem, ISRAEL**

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TIME-RESOLVED SPECTRAL MEASUREMENTS FOR THE BOEING FREE-ELECTRON LASER EXPERIMENTS

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Abstract

A time-resolved optical spectrometer based on the integration of a Jarrell-Ash 1/4-m spectrometer and a streak camera has been used to evaluate the Boeing Burst Mode Oscillator experiment. The system provides information on spectral evolution on both the micropulse (10 ps) and macropulse (50-100 μ s) time scales. We have measured the micropulse duration, a wavelength shift within a micropulse and the development of a discrete second wavelength during a macropulse.

I. INTRODUCTION

The operation of a RF-Linac-driven Free-Electron Laser (FEL) in the visible portion of the spectrum has provided the opportunity to measure the time evolution of the spectral output on both the micropulse (10 ps) and macropulse (50-100 μ s) time scales. Such information can be used both to optimize the FEL performance and to provide tests for modeling efforts on electron-photon interactions [1].

A time-resolved spectrometer based on the integration of a streak camera and a Jarrell Ash 1/4-m spectrometer was proposed by Los Alamos and was then integrated into the Boeing FEL Burst Mode experiment in collaboration with Boeing staff. The streak camera operated with a fast-sweep plug-in to provide 2- to 5-ps resolution or a slow-sweep plug-in that a time coverage of up to 600 μ s. The electron-beam properties of the Boeing FEL are 110-MeV energy, an 80 to 130- μ s macropulse, a 10-ps micropulse, and a 258 ns micropulse spacing. The streak camera could, thus, address the time regimes of interest. The Jarrell Ash 1/4-m spectrometer was equipped with two gratings of different blaze and groove spacing. Calibrations with a Hg light source showed that the spectrometer covered a span of 90 nm with 2 to 3 nm resolution or a span of 20 nm with about 1-nm resolution (first order, high groove number) when the

dispersed spectrum was directed onto the entrance slit of the streak camera. Experimental procedures and preliminary results are presented in the next two sections.

II. EXPERIMENTAL PROCEDURES

The Boeing Burst Mode Free-Electron Laser experiment has been described previously [2]. It is currently operating as an oscillator in the 630 nm wavelength regime. The nominal operating parameters are given in Table I. A number of photon diagnostic issues have been addressed as listed below:

A. Optical Micropulse Duration (Δt)

- Spontaneous emission from the wiggler interaction (cavity length, e-beam related)
- Stimulated emission (laser peak power)

B. Time-Resolved Spectral Measurements ($\lambda(t)$)

- Macropulse effects
 - spontaneous, lasing
 - e-beam energy, sidebands, lasing starts/stops
- Micropulse effects
 - wavelength chirp on a micropulse (wakefields?)
 - sidebands

A schematic view of the Burst Mode Oscillator cavity is shown in Fig. 1. The e-beam is transported onto the oscillator leg via a 180° bend. The micropulse separation of 258.3ns is matched to the round trip transit-time between the two end mirrors. A turnout magnet before the wiggler and an electron beam spectrometer after the wiggler provide an evaluation of the e-beam energy centroid and width. The light was coupled out (1/2% at 630 nm) through the end mirror on the right and optically relayed to an optical diagnostics table in the control room of the FEL. Alternatively, the pop-in mirror inserted between the spectrometer and the end mirror to intercept the spontaneous emission radiation from a single pass of the e-beam and optical beam through the wiggler. The e-beam micropulse duration has been evaluated via this mechanism. In addition, the optical spectrum centroid, width, and time slew related to the e-beam energy effects driving the spontaneous radiation, but this will be reported elsewhere [3].

The time resolved diagnostics consisted of a Jarrell Ash 1/4m monochromator (used as a spectrometer) coupled to a Hamamatsu C1587 streak camera. This portion of the diagnostics is shown in Fig. 2. The optical radiation from the oscillator cavity was transported to a second

tier on the optics table where the removable mirrors M1S and M2S directed the beam through the spectrometer and onto the entrance slit of the streak camera. With M1S and M2S removed, the beam went directly onto the slit. In the former case, time-resolved spectra recorded on either the micropulse (2-5 ps resolution, 200-ps span) or macropulse (0.6 μ s resolution, $\sim$ 60 μ s span) time scales. In order to minimize the trigger jitters involved in selecting micropulses, the synchronous delay unit was used to phase-lock the electronics to the prime 108 MHz signal of the *r/f* system. The micropulse was selected via a countdown circuit provided by Boeing for their streak camera. Figure 3 shows a schematic of the circuit which reduced trigger jitter in the electronics from about 100 ps to 20 ps. The wavelength axis of the streak/spectrometer system was calibrated using a Hg light source positioned at the entrance slit of the monochromator. Figure 4 shows three of the resolution and coverage options that were available to us. The spectral doublet at 577 and 579 nm was used as a resolution test. When we changed from the 150 G/mm grating in first order to the 600 G/mm grating in first order the resolution improved from about 2 nm to 1 nm while the wavelength coverage was reduced from $\sim$ 85 nm to $\sim$ 20 nm. Initial estimates for sideband position were about $1/2\%$ longer than the fundamental wavelength. Thus, this system could readily detect such an effect. An etalon was used at the entrance slit of the streak camera in a second setup to verify the deflection calibrations provided by the manufacturer were still appropriate.

III. EXPERIMENTAL RESULTS AND DISCUSSION

During the lasing experiments in April, May and June, 1988, the FEL's performance steadily improved. Samples of some of the data are given below including both micropulse and macropulse spectral effects.

While monitoring the lasing micropulse through the end mirror path in April, we observed an apparent spectral shift and temporal shift on a single micropulse. Figure 5 shows a streak image of the spectrum. In the upper figure, the vertical axis is the time scale and the horizontal axis is the wavelength scale. The intensity profile (I) is displayed at the left for the analysis window set on the long wavelength component. By positioning the analysis window on the right side of the image an 8-ps temporal shift was measured. In the lower figure an analysis window has been set on the horizontal or wavelength axis. In this case, the vertical axis was the intensity scale for the wavelengths that were emitted. One can see the approximate doublet (or triplet) spectral structure with the 3 nm interval indicated below the horizontal axis. We believe this to be the first observation of a spectral shift within an optical micropulse of an FEL. Lasing on different portions of the electron beam micropulse has been observed via effects on the electron-beam energy at Los Alamos.

Although it is believed that the FEL could track an energy shift that occurred during the micropulse by wavelength chirp, we also have an alternative, and perhaps more probable, explanation for these data. Figure 6 shows measurements of the spontaneous emission micropulse under good bunching (8-10 ps) and poor bunching (~14-16 ps) conditions in the injector. It is possible that the injection of the poorly bunched beam resulted in two microbunches 8 ps apart. Depending on the relative phases, they would have been accelerated by different portions of the r/f fields (this is about 4° of phase at 1300 MHz) and attain energies differing by about $1/4\%$. The wiggler resonance condition dependence on $1/\gamma^2$ would shift the spectral output by twice this amount or $1/2\%$. A series of controlled experiments and parameter searches would probably be needed to delineate such mechanisms, but have not been executed to date.

For the macropulse time scale, the streak system was set for 30 or 60 μs of coverage depending on the observed lasing. Experiments in May showed more extensive lasing so the 60 μs range was used. Figure 7 shows the data from two different shots where, in both cases, signal was transmitted through the neutral density filters and detected for 30 to 40 μs . A wavelength chirp on the macropulse scale appears to have occurred early (the top of the left figure) as evidenced by a few nm shift to longer wavelengths at the early, higher power levels. In Fig. 8 an even more distinct effect is shown in the streak image where a discrete second wavelength developed about $1/2\%$ longer in wavelength and 9-10 μs later in time than the initial wavelength. The left portion shows the time images and the right figure shows the wavelength doublet with the 3 nm or $1/2\%$ shift. In Fig. 9 the time (vertical) analysis window for the two wavelengths are displayed. The ratio of initial wavelength to second wavelength intensity varied in time, and the two wavelength intensities peaked at about the same time. The initial wavelength did decrease in intensity after the time of peak power time sooner than the second wavelength. Several features of these data are consistent with sideband simulations for this oscillator [4]. However, an electron-beam energy droop during the macropulse can not be precluded does reduce because simultaneous e-beam data were not recorded. Further experiments with time-correlated optical and e-beam information are planned.

IV. SUMMARY AND CONCLUSIONS

In summary, the streak/spectrometer system provided a versatile and powerful diagnostic for the Boeing FEL. On the micropulse time scale (10 ps) the pulse duration and spectral shifts or position shifts were detectable. On the macropulse time scale (~100 μs) beam position drifts, spectral shifts, and intensity (charge) changes were detectable. The existence and evolution of spectral effects such as chirp or sideband formation could be addressed on either time scale. Such capabilities can be used on-line for FEL optimization and then off-line for model

verification. The basic technique described in this paper could be adapted for a broad spectral regime spanning the ultraviolet to the infrared, ~120 nm to 1300 nm. Finally, these data demonstrate the potential to observe correlated e-beam and optical beam temporal behavior in FELs.

V. ACKNOWLEDGEMENT

The authors express their appreciation to Stuart Ferrier and Richard Heeke of Boeing for assistance in integrating the Los Alamos streak/spectrometer system into the Boeing FEL experiment. In addition, we acknowledge the support of John Adamski, Denis Pistoresi, Richard Lowrey, and Lee Tyson in the Boeing operations. We thank Jerry Watson of Los Alamos for authorizing the loan of the streak system and Steve Baumgart of EG&G (Los Alamos) for the loan of the Jarrell-Ash monochromator for these experiments.

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Table I.

Nominal Burst Model FEL Parameters

Electron Beam

- 110-MeV energy
- 100 - 300A peak-current
- 8- to 10-ps FWHM micropulse
- 1% FWHM energy spread
- 4-MHz micropulse rep rate
- 60- to 100- μ s macropulse width

Laser

- 0.63- μ m wavelength
- ~2-nm FWHM linewidth
- ~8- to 10-ps FWHM pulsewidth
- Outcoupled power ($1/2\%$ each end)

- Fig. 1. A schematic view of the Boeing Burst Mode Oscillator cavity. The cavity end mirrors, wiggler, e-beam diagnostics, and the popin mirror are indicated.
- Fig. 2. Schematic of the streak/spectrometer system located on the control room optical diagnostics table.
- Fig. 3. Schematic of the circuit for phase-locking the streak camera triggers to the reference 108 MHz clock.
- Fig. 4. Wavelength calibration data for the streak/spectrometer using the Hg source.
- Fig. 5. Streak/spectrometer data for a single lasing micropulse showing an 8-ps time shift.
- Fig. 6. Streak camera measurement of spontaneous emission micropulse under good and poor bunching conditions at the injector.
- Fig. 7. Time-resolved spectra for two lasing macropulse cases.
- Fig. 8. Time-resolved spectrum for a lasing macropulse showing the development of a second discrete wavelength.
- Fig. 9. Temporal profiles for the two wavelengths observed in Fig. 8.

Schematic View of Burst Mode Oscillator Cavity

Fig. 1

Schematic Layout of Los Alamos Streak/Spectrometer System

Fig. 2

Streak Camera Trigger Phaselocked to 108 MHz (For low jitter)

**TIMING SCHEMATIC
FOR STREAK CAMERA**

Mercury Light Source Used to Calibrate Streak/Spectrometer

SPECTRAL EFFECTS OBSERVABLE ON A SINGLE MICROPULSE (< 10ps)

Fig. 5

Streak on Spontaneous Emission Measured Electron Pulsewidth

- 2 ps resolution streak camera data

- Good bunching 8 ps FWHM

- Poor bunching - (injector deliberately mistuned several degrees)
15 ps FWHM.

Fig. 6

**LASING DURATION EXTENDED
IN MAY OPERATIONS AS SHOWN
BY STREAK/SPECTROMETER DATA**

Fig. 7

Streak/Spectrometer Data Show Second Wavelength Developed During a Macropulse

Fig. 8

Two Wavelengths Exhibit Different Evolutions in Time

INITIAL
 λ

INTENSITY

$9 \mu s$

TIME

SECOND
 λ

INTENSITY

TIME
($63 \mu s$ span)

Fig. 9