The UCSB MM-FEL Injection Locking System *

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Abstract

An Injection locking system has been implemented on the Millimeter Wave Free-Electron Laser (MM-FEL) at the University of California, Santa Barbara (UCSB). It it is based on a commercially available varactor multiplier source and quasi-optical isolator operating at 240 GHz. Lasing on multiple longitudinal modes is shown to collapse to a single repeatable mode by introducing a low power CW signal into the FEL resonator through a silicon-plate coupler. High power and extremely narrow linewidth operation will enable new experimental opportunities such as FEL based pulsed electron paramagnetic resonance spectroscopy.

INTRODUCTION

Injection locking of the UCSB MM-Free-Electron Laser has been demonstrated as shown in Fig. 1. Lasing that normally occurs on a number of longitudinal modes is seen to collapse to a single mode at a single repeatable frequency with less than 1 MHz linewidth. This result is important in demonstrating the suitability of an FEL for applications where extremely narrow linewidth is required.

Linewidth

The UCSB MM-FEL is based on an electrostatic accelerator. As such it does **not** exhibit the picosecond microstructure, characteristic of RF accelerator driven FELs, that Fourier transform limits their linewidth to hundreds of GHz. Instead, a several microsecond quasi-DC macropulse allows sub-MHz width.

The MM-FEL [1, 2] uses a 6.25 meter long resonator which can be described by its Fabry-Perot characteristics. It has a free-spectral range (fsr) of $c/(2L_r)$ = 24 MHz. It has finesse **F** = $\pi/(2\ \mathrm{asin}(1/F))$, where coefficient of finesse $F = 4\sqrt{1-l}\,/(2(1-\sqrt{1-l}\,)-l)$. l is the power loss per pass. Because of its length, the resonator has extremely high $Q = \mathbf{F}N$ where N is the order or simply number of half wavelengths between mirrors. For nominal 25 % loss at 240 GHz, F = 193, **F** = 21.8, Q = 218000. Linewidth is then 240 GHz / Q = 1.1 MHz.

It is important to emphasize that this linewidth is an upper limit, since line-narrowing may take place as in conventional lasers. Line-narrowing can reasonably be expected when lasing is a consequence of stimulated emission and other inhomogeneous broadening effects are correspondingly small.

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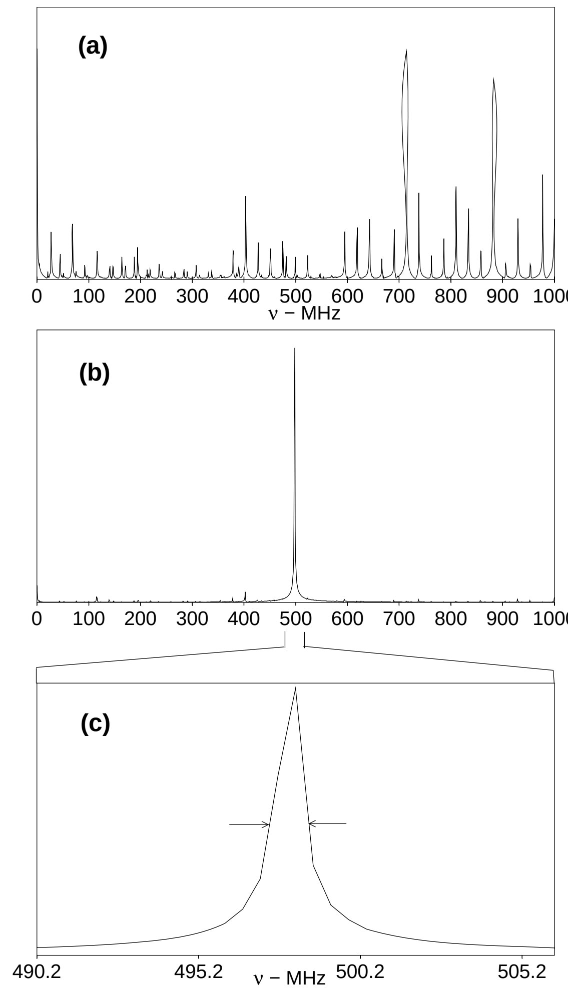

Figure 1: (a) FEL spectrum without injection locking. The spectrum show many longitudinal modes spaced by 25 MHz. (b) FEL spectrum with injection source on. Only single mode lasing with no pulse-to-pulse frequency fluctuation is observed. (c) 1 MHz width is transform limit of sampling window, indicating actual linewidth is much less.

Longitudinal Modes

Another important consequence of the long resonator is the number of longitudinal modes available for lasing. Fig. 2 shows the longitudinal mode structure in relation to the MM-FEL's gain curve. Hundreds of modes would be above threshold and might be expected to lase. However, this doesn't actually happen. Many fewer are seen to lase with only a few growing to dominance. This effect can be understood in terms of the stochastic nature of startup. Startup is from spontaneous emission, essentially noise, so

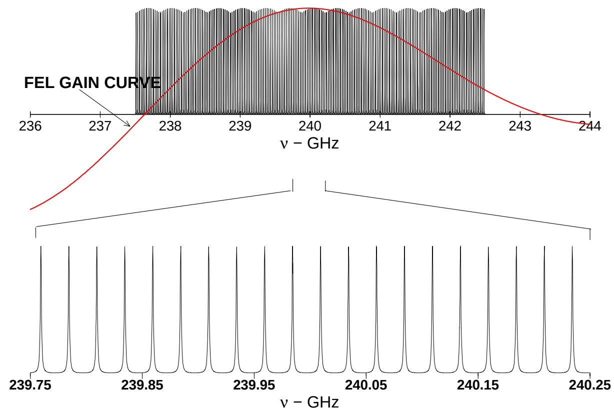

Figure 2: Resonator longitudinal mode structure in relation to gain curve. Hundreds of modes have sufficient gain to lase.

exhibits a fluctuating spectral density distribution. Its basis is "shot-noise" which represents a variance in the statistical distribution of electrons. As these electrons traverse the undulator, they become uncoupled oscillators. The small distributional non-uniformity causes random phase fluctuations that can interfere giving rise to larger amplitude fluctuations than the mere $\sqrt{n}/n$ shot noise variance would suggest. At startup, some modes then appear to enjoy a significant initial advantage over others. The process of stimulated emission then keeps multiplying the advantage. Another form of mode competition can be expected. As the advantaged modes approach saturation, they cause gain for all modes to diminishes. Since loss remains in full effect for all modes, eventually only the few advantaged ones remain above threshold while the rest die. Manifestation of this effect, however, may take longer than the available pulse duration.

Single Mode Lasing

Single mode lasing can occur naturally as has been demonstrated by for example the EA-FEL at the University of Tel Aviv [3]. Lower frequency, a shorter resonator with wider mode spacing, and other parameter differences may explain why this can happen. This clearly doesn't happen with the UCSB MM-FEL so other means of achieving single mode operation were sought. Conventional lasers use intra-cavity etalons. Use of a Fox-Smith coupler was investigated but achieving sufficiently high Q to significantly suppress adjacent 25 MHz spaced modes proved impractical. Further, proposed research with single mode capability requires that each pulse occur on the same frequency and that that frequency be precisely setable. The normal stochastic startup results in about a 0.05 % distribution of the pulse to pulse startup frequency that is unacceptable for many users' experiments.

INJECTION LOCKING

One method of improving this situation is injection-locking or seeding. This has long been used in conventional lasers [4] and is now planned for several VUV/Xray FELs in the form of harmonic injection seeding[5].

Injection locking was partially demonstrated on the original UCSB FEL [7] using a CW molecular laser as the injection source. At that time it was only possible to inject power through a tiny hole coupler which scattered most of the power into high order transverse modes. Since the source was not tunable, the FEL resonator was mechanically tuned with great difficulty. Finally, no spectrometer was available, so locking could only be inferred from a reduction in mode beating and shorter startup time. The current injection locking system overcomes all these problems so is much better suited for users' experiments.

Power Requirement

A fundamental requirement of injection locking is that the power that is finally coupled into the mode that is to lase must exceed the startup power from spontaneous emission by a some margin. The peak spectral density at zero forward angle is [3]

$$\frac{dP}{d\nu} = \frac{4\pi q^2 c\gamma^2 K^2 N n}{\lambda_u^2 (1 + K^2/2)}$$

where q= electron charge, c = light velocity, γ = Lorentz factor, K = undulator parameter, N = number of periods, $n = \lambda_u I_b/(q\beta_z c)$ = number of electrons radiating per period, and λ_u = undulator period. For the MM-FEL running at 240 GHz, γ = 6.773, K = 0.7071, N = 42, λ_u = 7.14 cm, and β_z = 0.9835. The resulting spectral density is then 1.39 x 10^{-13} Watts/Hz. For a mode-width of 1 MHz, power is 0.139 μWatts, making the estimated 28 μW that is available well exceed the requirement.

Injection System

Fig. 3 is an illustration of the injection locking system. The CW injection source was built by Virginia Diodes Inc. (VDI) [9], consisting of a 15 GHz phase-locked oscillator, doubler, RF amplifier, and three varactor doubler stages, which provides as much as 30 mW power at 240 GHz. The source frequency is tunable within small frequency range by employing a tunable 100 MHz digital synthesizer as a reference for the source's oscillator. This tunability is essential to match the injection source frequency to the FEL's resonator and to precisely set operating frequency for users. A key component is a quasi-optical, Faraday-rotation, isolator developed by Thomas-Keating Ltd. [8] that provides more than 50 dB isolation. Insertion loss is about 6 dB. This is essential to protect the last multiplier stage from the FEL power following startup. Table 1 shows approximate power budget for the injection signal.

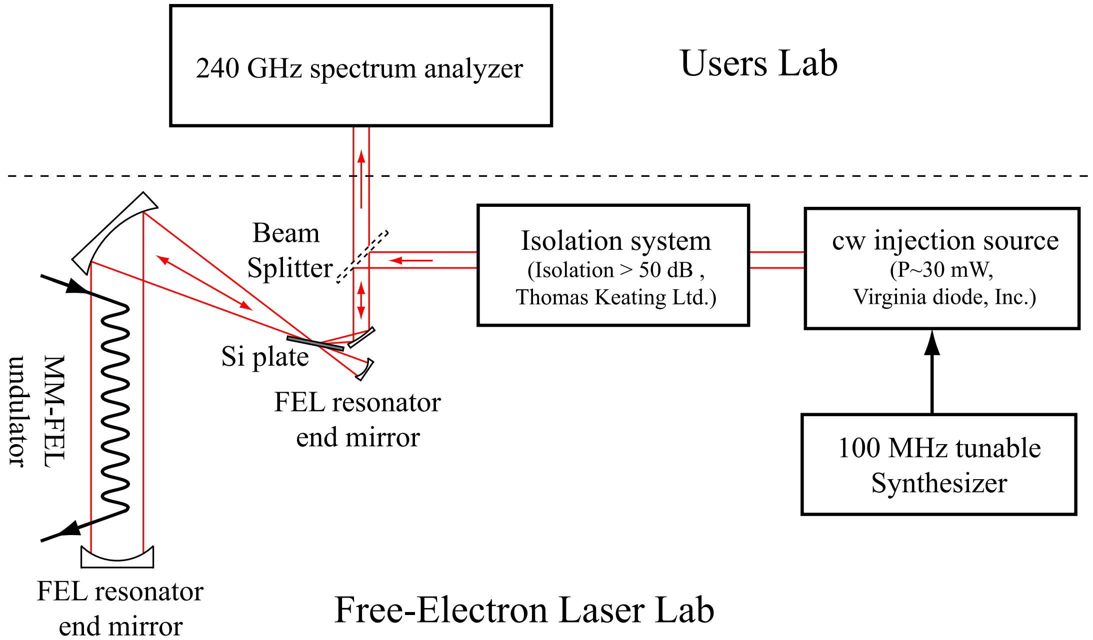

Figure 3: Schematic of the injection locking system for the UCSB MM-FEL. The injection source, the isolator and a tunable 100 MHz synthesizer are located in free-electron laser lab. Output radiation is sent to the users lab through vacuum optical transport system.

Table 1	**Power Budget**
30 mW	VDI Source output
7.5 mW	Isolator output (6 dB insertion loss)
6.9 mW	TPX window (∼92 % transmission)
690 μW	Beam splitter
552 μW	quartz window (∼80 % transmission)
28 μW	silicon plate (5 % coupling)

Optics

When used with injection locking, the FEL's resonator is used in a two arm configuration as shown in Fig. 2. The resonator is a parallel-plate waveguide terminated with cylindrical mirrors. A plano-ellipsoidal mirror couples the main arm to the secondary arm. The lowest order mode has $\cos^2$ intensity distribution in the vertical plane and Gaussian horizontally. Horizontal waists are formed in each arm. Parameters are given in table 2.

Table 2	**Resonator Parameters**
Length	L_r = 6.253 m
Mirror 1	R = 2.970 m
Mirror 2	f_1 = 0.501 m
	f_2 = 3.375 m
Mirror 3	R = 0.0796 m
Waist 1	w = 1.962 cm
Waist 2	w = 3.051 mm

A silicon plate, offset slightly from Brewster' angle, is located at the waist in the short arm and couples injection power in and FEL power out. This allows full coupling to the FEL resonator's fundamental mode. This will also serve as cavity dump coupler when we acquire a suitable doubled-YAG drive laser. The Si plate is rotated to less then Brewster's angle and provides variable coupling to optimize FEL performance. The highly elliptical beam profile, reflected from the silicon plate, is also reflected from a second flat mirror that rotates with the silicon plate to maintain beam alignment. The narrow horizontal dimension diffracts much more rapidly than the large vertical dimension, so a combination of conical and plano-paraboloid mirrors are used to transform the beam to a larger, approximately round, collimated one. A second beam-splitter directs about 90 % of the FEL power to the users lab. Beam transport is through an evacuated, periodic focussing system. Note that 240 GHz does not correspond to any strong atmospheric absorbtion lines so can be transported short distances through air. In fact, both the source and isolator are outside the vacuum system.

Spectrum Analyzer

A spectrum analyzer located in the users' lab measures the FEL's radiation spectrum. It is based on a double heterodyne detection system shown in Fig. 4. The FEL radiation is attenuated and directed to a sub-harmonically pumped mixer driven at 115 GHz by a second digitally controlled VDI multiplier chain as Local Oscillator (LO). The 10 GHz intermediate frequency (IF) signal is then amplified, filtered, and sent to a second mixer for final downconversion to a 1 GHz band centered at 500 MHz. A steep-walled bandpass filter in the 10 GHz IF chain prevents negative frequency artifacts in the final down-conversion. A 2 channel, 8 bit, 5 GS/s digitizer (Tektronix TVS 625A) records both the 500 MHz, and rectified 10 GHz, IF signals.

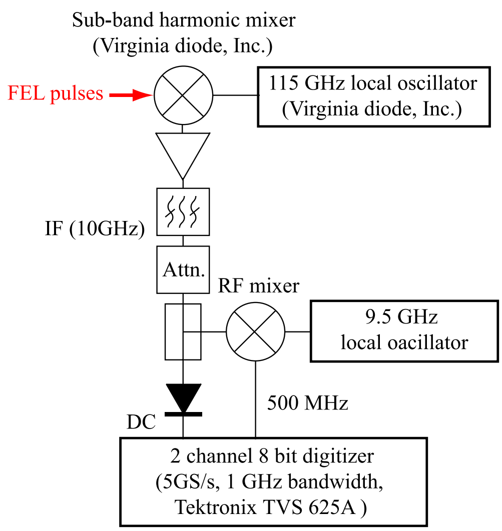

Figure 4: Schematic illustration of the 240 GHz spectrum analyzer.

A Labview program does fast Fourier transform processing for immediate display. A more accurate analysis can be applied to saved data using the Wiener-Khinchin theorem, DFT, and more sophisticated windowing later as needed.

RESULTS

Fig. 1(a) shows the recorded spectrum without injection locking. Many longitudinal modes with 25 MHz spacing are seen. Fig. 1(b) is the spectrum with injection on. The effect is immediate and unequivocal. Lasing is seen to always occur at one frequency on the same longitudinal mode selected by the injection source frequency. The injection locking is observed only when the source frequency matches one of the resonator's longitudinal modes. The linewidth shown in Fig. 1(c) corresponds to the analysis window, indicating an actual linewidth less then 1 MHz as expected.

CONCLUSION

In summary, we have demonstrated injection-locked FEL operation with sub-MHz bandwidth using a tunable solid state source as an injection source. The high-power, tunability, and extremely narrow linewidth of the FEL opens up the possibility for new applications such as a high-power, high-frequency, pulsed EPR spectroscopy. We wish to thank David Enyeart for his support of the injection locking system installation and FEL operation.

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