IFEL DRIVEN MICRO-ELECTRO-MECHANICAL SYSTEM FREE ELECTRON LASER

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Abstract

The Free Electron Laser has provided modern science with a tunable source of high frequency, high power, coherent radiation. To date, short wavelength FEL's have required large amounts of space in order to achieve the necessary beam energy to drive the FEL process and to reach saturation of the output radiation power. By utilizing new methods for beam acceleration as well as new undulator technology, we can decrease the space required to build these machines. In this paper, we investigate a scheme by which a tabletop XUV FEL might be realized. Utilizing the Rubicon Inverse Free Electron Laser (IFEL) at BNL together with micro-electro-mechanical system (MEMS) undulator technology being developed at UCLA, we propose a design for a compact XUV FEL.

INTRODUCTION

Current short wavelength Free Electron Lasers (FEL) require long and expensive particle accelerators to produce the necessary high energy electron beams, limiting the housing of these machines to large scale national labs. In order to make this technology more readily available, it is necessary to investigate ways in which we can decrease these space and monetary constraints. In this paper, we investigate a compact design for an FEL that is driven by a beam that has been accelerated through the IFEL acceleration scheme. Furthermore, we investigate the use of micro-electromechanical system (MEMS) undulator technology to decrease both size and resonant wavelength of our FEL.

In an IFEL [1,2] a high power laser is copropagated with the electron beam in an undulator magnet. Through interactions with the undulator field, the beam undergoes transverse oscillations, allowing it to exchange energy with the laser. By tapering the undulator magnets, the beam's transverse oscillations will remain resonant with the laser frequency as it gains energy, maximizing the interaction. Utilizing laser intensities of 10-20 TeraWatts, the IFEL is capable of sustaining GeV/m acceleration gradients over meter scale distances, greatly decreasing the distance required to reach high beam energies [3]. The ability to also preserve an excellent output quality [4] makes the IFEL a great candidate for use in compact FEL design.

RUBICON IFEL

As input of our FEL amplifier we consider a beam accelerated by the Rubicon IFEL at Brookhaven National Laboratory. Rubicon utilizes a strongly tapered undulator driven by a high power 10.3 μm CO_2 laser. Utilizing 625 GigaWatt laser intensities we achieve acceleration gradients up to 100 MeV/m, accelerating the beam from 53 MeV to an energy of 98 MeV in about 50 centimeters [3].

Particles in the beam will bunch around the periodic minima of the IFEL ponderomotive potential as they gain energy propagating in the undulator. This process creates periodically spaced, short bunches of electrons with RMS widths ~1/10 of the laser wavelength while increasing the peak current by about a factor of 5, Fig. 1. Simulations and measurements from the Rubicon IFEL[5] indicate that the IFEL process preserves the initial beam quality, keeping the normalized emittance of the accelerated bunch constant throughout the interaction.

To further enhance the Rubicon IFEL's performance, efforts are currently under way to install a pre-buncher before injection into the IFEL. Utilizing an undulator section tuned to the IFEL drive laser wavelength we impart a modulation on the beam, separating the beam into periodically spaced bunches. Utilizing a chicane to tune the resonant phase of the bunches relative to the IFEL ponderomotive potential, we can inject a large fraction of particles on crest of the accelerating wave, Figure 2. Initial simulations show trapping and acceleration of 74% of the injected particles, greatly increasing the peak current while also decreasing the final energy spread to ~0.1%, providing us with a high quality, high brightness, high energy electron beam, ideal for seeding a high gain FEL amplifier.

MEMS UNDULATOR

The FEL process is achieved by sending a high energy electron beam through a magnetic undulator field with a period λu. The electrons wiggle in this field, and therefore radiate. When the wavelength of the radiation, λr slips ahead of the electron beam one period each cycle of transverse

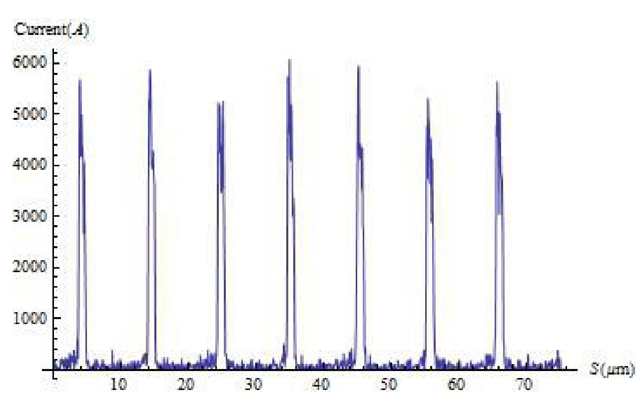

Figure 1: Current profile of Rubicon IFEL output beam.

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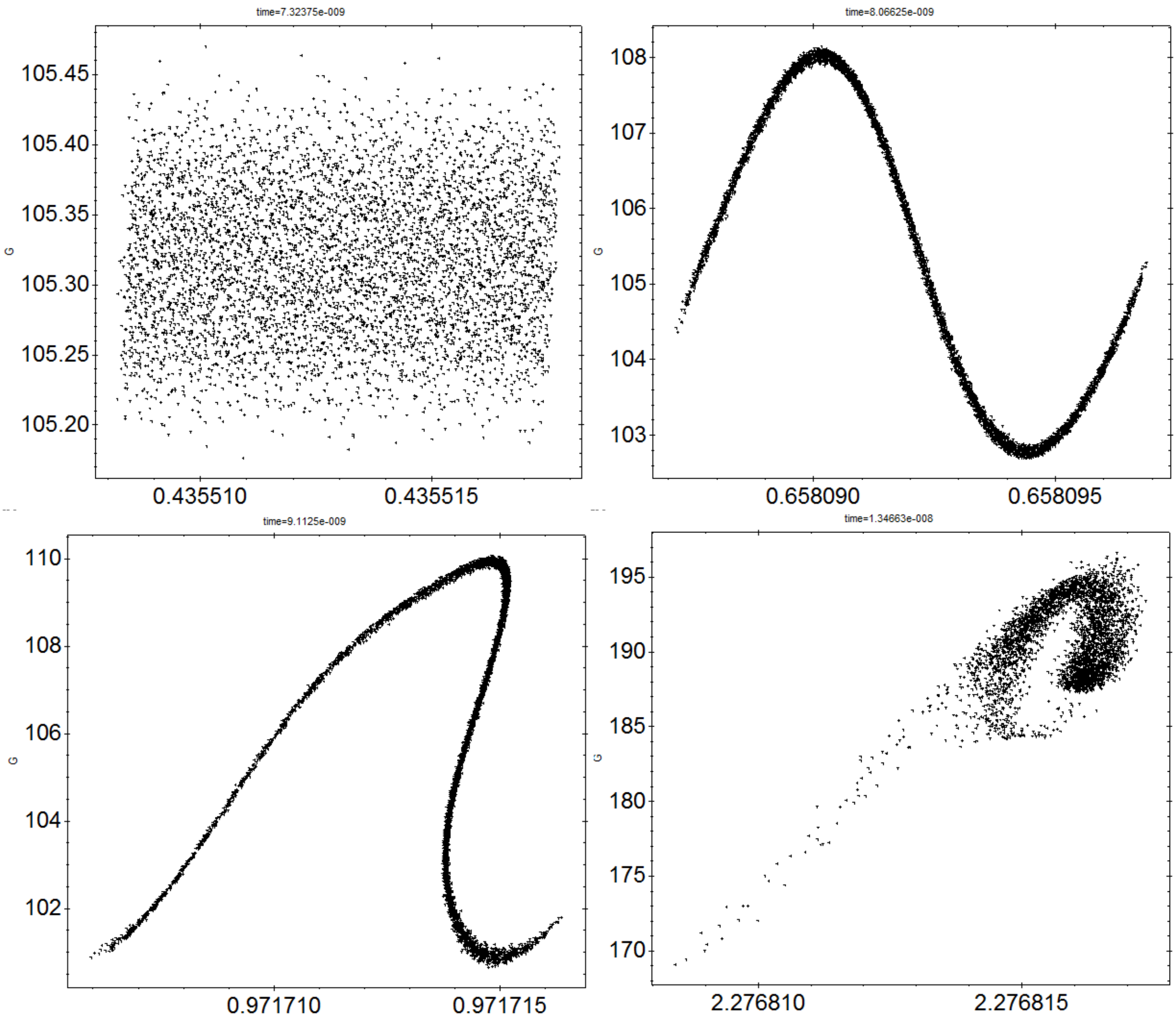

Figure 2: GPT simulation of single bunch γ vs. z phase space in Rubicon IFEL with pre-buncher. (Top Left) Incoming Beam. (Top Right) Beam after pre-buncher modulator. (Bottom Left) Beam after pre-buncher chicane phase shifter. (Bottom Right) Beam after IFEL acceleration.

oscillation, constructive interference occurs. This corresponds to the resonant condition:

$$\lambda_r = \lambda_u \frac{(1+K^2)}{2\gamma^2}$$

where K = eB0/2π mc is the undulator normalized vector potential, B0 is the peak undulator magnetic field, γ is the electron beam energy, and e and m are the charge and mass of the electron.

The FEL amplification induces a periodic energy modulation in the beam as the FEL radiation interacts back with the electron beam causing the electrons near the crest of the field to accelerate forward and those near the trough to decelerate. As the beam propagates in the undulator, this energy modulation is converted into density modulation, creating a train of micro bunches separated by the resonant wavelength. As the bunching becomes stronger, the electrons in the bunch radiate in phase and the FEL exhibits exponential gain [6].

The main problem of directly using the output of an IFEL accelerator to seed an FEL is related to the spiky longitudinal structure of the beam as it exits the laser. With a beam energy of ~100 MeV, using convential permanent magnet undulators, (K~1, λu~0.01m) we exhibit a resonant wavelength of λr~300nm. With an IFEL drive laser wavelength of 10.3 µm, we expect current spikes to have widths on the order of 1 µm. We can see that after 1 or 2 periods the radiation will have slipped out of the current spike halting the gain process.

In order for us to utilize the outcoming beam from the Rubicon IFEL effectively it is necessary for us to use an undulator with a small period and a small K in order to

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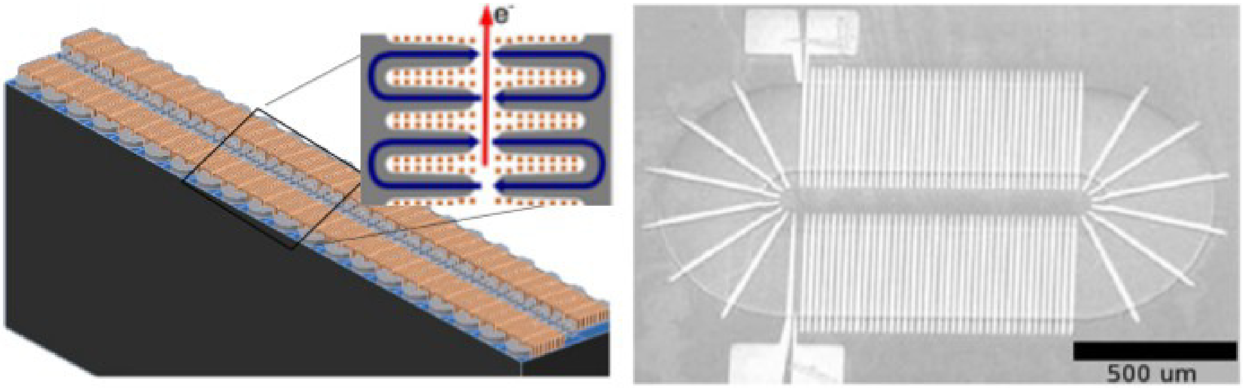

Figure 3: (Left) CAD of an MEMS undulator showing the yoke structure for flux direction in an undulator period. (Right) Racetrack solenoidal coil Scanning Electron Micrograph fabricated at UCLA. (image courtesy of Harrison et al.)

create radiation with a wavelength small compared to the width of the current spikes. In this paper we investigate the usage of MEMS technology being developed currently at UCLA [7]. In particular, we consider an undulator with λu=1 mm and K=0.1 allowing us to achieve λr~15 nm. With our current spikes now being ~60-70 λr long, it is possible for the radiation created in the tail of the bunch to slip forward, driving the FEL feedback process responsible for gain.

MEMS technology requires three main components, a coil to produce magnetomotive force (MMF) , a magnetic yoke to direct the created magnetic flux, and magnetic pole tips that increase the flux density. The MEMS devices being developed at UCLA utilize a racetrack solenoidal coil to generate the necessary flux, Figure 3. This particular design allows more coils to be be fit in a given surface area, allowing a larger flux per period compared to typical planar designs. To maximize the peak field and decrease magnetic fringing, MMF flux is directed by yokes placed on both sides of the undulator. Initial studies show achievable undulator wavelengths, λu=25→1000 μm with K ranging from K=0.0009 to K=0.1 respectively.

SIMULATION RESULTS

Simulations of the MEMS undulator FEL were done using the 3-D simulation code Genesis 1.3. The current profile input into Genesis was taken from General Particle Tracer simulations of the Rubicon IFEL as seen in Figure 1. Input parameters for the simulation can be found in Table 1.

Input beam parameters such as emittance, beam size, and energy spread were chosen based on Ming Xie optimization, noting that the beam quality entering the Rubicon IFEL will be conserved. We are able to achieve a 3-D gain length of ~0.018. Knowing that the current spikes are ~1 μm wide and that the radiation will slip ahead ~15 nm per 1 mm undulator period, we find that radiation from the tail will slip out of the beam after ~70 mm, and thus experience about 4 3-D gain lengths before exiting the current spike. This allows radiation from the back of the current spike to gain as it slips ahead, driving the micro bunching process

Table 1: Genesis Simulation Input Parameters

γ	183.4
ε_n (mm-mrad)	0.15
σ_r (μm)	5.51
Δγ/γ	0.001
λu	1
K	0.1
λr	15.2
ρ	0.004
Lg3D	0.0176
Saturation (λu)	600
Power (MW)	13

responsible for the high gain FEL interaction. This process will continue until the particles in the current spike are maximally bunched, at which point saturation power is reached. In Figure 4, we see the radiation pulse from maximally bunched particles in the 4th current spike.

Looking at the power as a function of z in Figure 5, we can see that saturation is reached around 0.6 m. In Figure 6, we see the spectrum of the outcoming radiation centered around 15.2 nm.

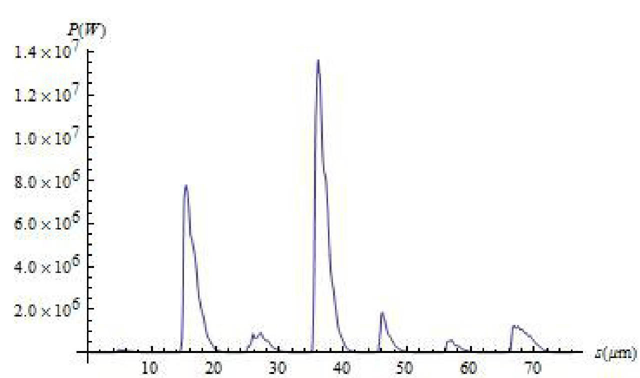

Figure 4: Power output of FEL after 600 λu.

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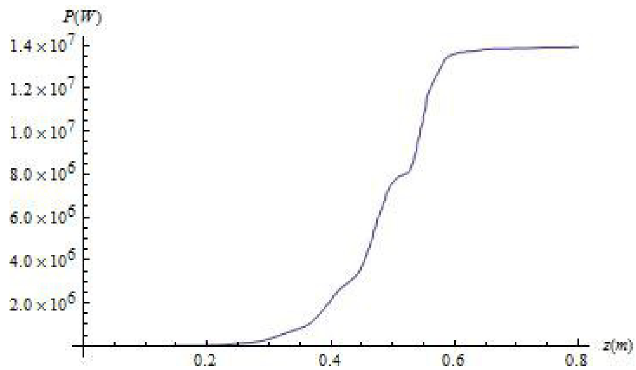

Figure 5: Maximum radiation power along undulator. Saturation is reached at z~0.6 m.

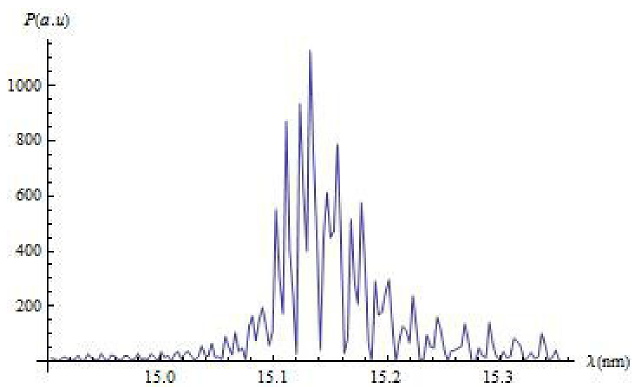

Figure 6: Spectrum of output radiation at saturation.

CONCLUSION

We have demonstrated a potential strategy for manufacturing a tabletop XUV FEL utilizing the Rubicon IFEL at BNL with modern MEMS technology. IFEL acceleration gradients allow us to achieve the necessary beam energy in only 0.5 m and small undulator periods allow us to reach FEL saturation power in only 0.6 m, providing a cost and space effective alternative to modern FEL machines. Increases in the laser power driving the IFEL could lead to even higher acceleration gradients and thus higher beam energies, possibly allowing us to utilize the same technology to produce high power X-Rays.

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