STEFAN FRONTIER CONFERENCES
FRONTIER SCIENCE RESEARCH CONFERENCES
Promote and Diffuse First Rate Research Achievements in Science Worldwide

Topical Research Conference
Research Trends in Laser Matter Interaction 2010
May 7- 8, 2010
La Jolla, California 92037

COMPACT THz FREE ELECTRON LASERS FOR LABORATORY LASER-MATTER INTERACTIONS

W. B. Colson
Naval Postgraduate School,
Monterey CA

T. L. Grimm
Niowave Inc,
Lansing MI

T. I. Smith
Stanford University,
Stanford CA

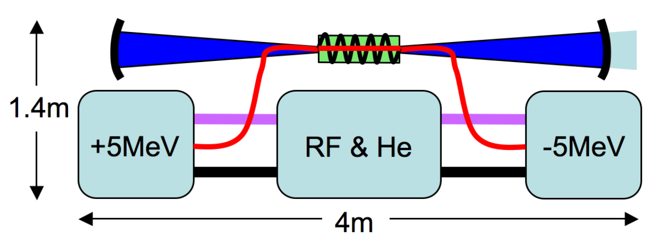
Bulletin of the Stefan University, Series B, Stefan Frontier Conferences,
Volume 22, May 2010. ISSN: 1938-3967.

There are few sources of coherent electromagnetic radiation in the wavelength range of 300µm to 100µm (1THz to 3THz frequency). Microwave technology is excellent above 1cm wavelength, and conventional laser technology is excellent at 10µm and below. For both the laser and microwave technologies, kilowatts of power are commercially available with many applications, but at the intermediate wavelengths, in the THz regime, there are no sources at these power levels. At present, THz sources are typically six orders of magnitude lower in the mW range. The idea here is to explore a compact source operating at THz wavelengths but capable of kW powers. Such a source could be used for airport security, materials detection, chemical processing and scientific laboratory research. The National Academy of Sciences Report (Levy Report, 1994) found this wavelength range to be "most compelling" and recommended that "current research and development directed toward the production of a compact free electron laser that could be purchased and operated by a single academic department or individual investigator should be continued".

The free electron laser (FEL) has already been operated in all wavelength ranges from 10cm to 1.5Angstroms, including THz, using a single, well-understood mechanism. Several existing FEL facilities produce significant power in the THz wavelength range, but they are large systems, tens of meters in length, occupying a whole laboratory and costing tens of millions of dollars. Currently, scientists must write proposals requesting a chance to travel and visit an FEL user facility in order to study laser-matter interactions requiring high peak or average powers at THz frequencies. However, it appears possible to design an FEL oscillator operating in the THz range providing powerful, coherent, tunable, radiation in a reliable system suitable for a university scientific laboratory.

A superconducting injector using a quarter-wave and/or spoke cavity at ~500MHz RF frequency is a source to consider for the FEL's relativistic electron beam. At this RF frequency, superconducting niobium accelerator cavities can be operated at 4K instead of 2K; this makes the refrigerator required much smaller and less expensive. The electron beam energy is recovered in a decelerator, drastically reducing the amount of RF power required. The motivation here is to design an FEL that is compact and inexpensive for laboratory operation in a university setting, yet powerful and tunable based on the superconducting technology being developed at Niowave Inc, Lansing MI.

At right is a sketch of an FEL system using a ~5MeV injector (at left) with the electron beam path (red) passing through the undulator to a ~5MeV recovery section. The beam energy recovery section returns most of the RF energy back to the accelerating



section. In the middle is the supply system for RF power and He refrigeration. At top are the FEL undulator and resonator with output coupling to the right. In this energy range, no neutrons or activated materials are created by stray electrons so that minimal shielding is required. Only x-rays are produced, and in a carefully designed system, it may be possible that no shielding is required other than at the electron beam dump.

A conventional Gaussian resonator is used because it can reliably establish a fundamental Gaussian mode that is tunable over a wide range. The resonator mirror separation is selected to achieve synchronism between the rebounding THz laser pulse and the sequence of electron micropulses from the accelerator. In our case, the pulse repetition frequency is selected to be ~62.5MHz so that the resonator length is 2.4m. We anticipate ~2% absorption in metal mirrors and ~10% output coupling at one mirror.

The FEL resonance condition determines the operating wavelength depending on the undulator properties and the electron beam energy. The undulator is formed from a series of alternating aligned permanent magnets causing the electrons to deflect back-and-forth and couple to the co-propagating laser light pulse. We propose an undulator period of ~3cm, as is commercially available and common to many FEL undulators. Generally, the number of undulator periods N should be minimized to optimize the natural extraction of laser energy from the electrons, but with sufficient laser gain per pass to be above threshold, say ~30% to overcome the ~10% out-coupling. The single-pass gain is proportional to N^3, and so rapidly increases with a longer undulator. The unique issue for THz FELs is the diffracting optical mode that can scrape the beam pipe at the undulator gap through which the electron beam passes. If the undulator length is too large, or if the undulator gap is too small, there will be excessive scraping of the laser mode at the ends of the undulator. This is a serious limitation for long wavelengths, even for a larger gap, which is why microwave sources at THz and lower frequencies use a waveguide to confine the wavefronts against diffraction. The FEL design proposed here will use a short undulator of ~10 periods, or less, to avoid the waveguide issue and maintain a reasonable gap.

The FEL beam pulses from the accelerator are taken to have a micropulse charge of ~200pC to ~400pC, but not every RF cycle is filled so that the average current is ~12.5mA to ~25mA. At ~5MeV, the energy in the electron beam is then substantial at ~62.5kW to ~125kW. Conversion of this energy to light occurs in the undulator interaction with the natural fraction extracted typically estimated at ~1/2N. With N too large, the extraction is reduced, but if N is too small, the single-pass gain is below the single-pass losses, below threshold, and the FEL oscillator does not work.

The accelerator must compress pulses from the cathode to ~5ps length at the beginning of the undulator. Bending magnets transport the electron beam into the undulator and around the resonator mirrors. These bends can act as dispersive elements to compress the pulse and establish the peak current needed at the beginning of the undulator, as well as to prepare the spent beam for transport to the recovery decelerator after the undulator. The electrons in each pulse self-bunch and coherently radiate at the desired THz wavelength in the resonator as they pass through the undulator with the co-propagating laser pulse. The resulting short picosecond pulses are useful for scientific studies of atomic and chemical processes. Because of the combination of short pulses and long wavelengths, the FEL spectral bandwidth will only be ~10%. It has been repeatedly observed in many FELs that there is full temporal coherence along the length of the laser pulse, and full spatial coherence across the laser wavefronts.

Atmospheric attenuation at THz wavelengths is estimated at ~50% over a ~10m range, limiting this FEL to laboratory-sized applications. Diffraction over this distance can be significant unless the beam size is maintained at several centimeters radius. The antenna design depends on the application, but ~10cm optical elements would appear feasible.

A FEL THz system would be continuously tunable by varying the amount of RF acceleration as has been demonstrated in many other FELs. Assuming modest accelerating gradients of ~5MeV/m, the system size is estimated as ~4m long with a cross-sectional area of ~2m^2. Simulations predict an output power of ~2kW to ~6kW depending the micropulse charge. This output is comparable to the today's most powerful FEL (~14kW at Jefferson Laboratory), but would represent more than x150 reduction in volume. Energy recovery of the electron beam power should lead to attractive wall-plug efficiencies. The cost of the first system is estimated at ~$5M and could probably drop down to under ~$1M for subsequent systems.