High-Power THz Source Development

A. M. M. Todd, H. P. Bluem, V. Christina, R. H. Jackson, G. P. Williams[1] and the Jefferson Laboratory FEL team[1]

Advanced Energy Systems, 27E Industrial Blvd., Medford, New York 11763, USA
[1] Thomas Jefferson National Accelerator Facility, 12000 Jefferson Avenue, Newport News, Virginia 23606, USA
e-mail: alan_todd@mail.aesys.net

Abstract

We describe a joint program between Advanced Energy Systems (AES) and Jefferson Laboratory (JLab), first to design, construct and commission a high-power, broadband, THz laboratory at the JLab free electron laser (FEL) facility, and secondly to develop a more compact, transportable, high-power THz source. The former facility can today deliver over 100W of broadband THz radiation up to several THz to user laboratories. The latter device, which has about a 50 GHz bandwidth and is tunable, is targeted to deliver on the order of 50 watts average power with a MW of peak power. It is planned for delivery to the JLab facility in 2006.

The JLab FEL High-Power THz Beamline

The short bunches of electrons which circulate in the JLab FEL [1] generate hundreds of watts of broadband THz light. The light is generated by sub-picosecond 135 pC bunches of relativistic electrons as they traverse a magnetic compression chicane prior to the cavity of the FEL facility. The repetition rate of the electron bunches, and hence that of the light pulses, can be as high as 75 MHz continuous. Thus with a duty factor of 1 ps every 13 nanoseconds, the peak THz power is over 10 MW [2].

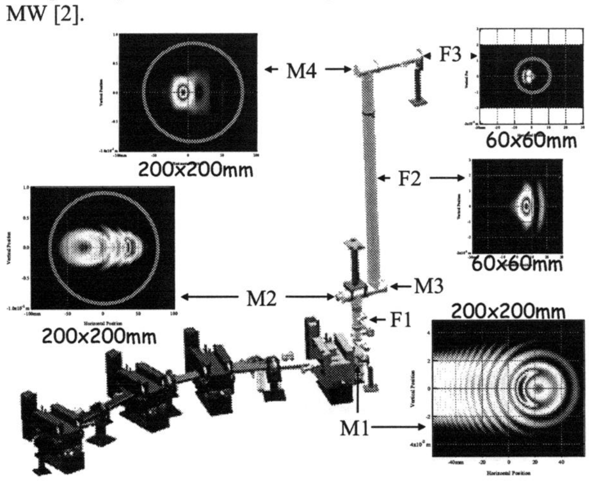

Fig. 1: JLab THz beamline. M1 to M4 are mirrors. F1 to F3 are the optical focal points. Radiation intensity patterns are shown within the beampipe (indicated as red circles) at points along the beamline.

We have designed a beamline to transport this light from the accelerator vault into a user laboratory. A schematic of the beamline is shown in Fig. 1. The beamline delivers an f/8 beam of a source in the FEL electron beamline dipole magnet that appears approximately 2mm vertical × 3mm horizontal in size. Under the present configuration, the beam is approximately 60% vertically polarized. The primary goal is to extract light emitted into a subtended angle of ~200 milliradians horizontal by ~135 milliradians vertical and transport it to user laboratory 3 of the FEL facility. The beamline is based on 150mm (6") optics and is designed such that wavelengths up to 3mm pass without significant loss. (3mm = 0.1 THz or 3 cm^{-1}). The beam is transported in vacuum, however a diamond window located at the first optical focus separates the high machine vacuum of 1×10^{-9} Torr from the 100 millitorr vacuum of the remainder of the optical transport line. Finally, the beam is delivered into air in the laboratory using a second diamond window.

The philosophy of the optical design is to use a relay optics configuration to transport the beam via reflection off metal mirrors through a series of focal points. Thus the first mirror, M1, is a 1:1 ellipsoidal mirror of focal length 625 mm, which reflects the beam vertically upwards using s-polarization providing a focus at F1. M2 and M4 are an identical pair of ellipsoids with focal lengths 705 and 2426 arranged such that M2 provides a source image at F2 magnified by 3.4, while M4 reduces this image by the same factor to give a 1:1 final image on the second diamond window at F3. F3 is 1 meter above the floor in the user laboratory.

Alongside the beamline schematic in Fig. 1, we show the intensity pattern on the various components, which was calculated using the Synchrotron Radiation Workshop (SRW) code developed by Pascal Elleaume and Oleg Chubar. This code performs a full calculation of the electric field from a relativistic electron. It does not handle multi-particle coherent

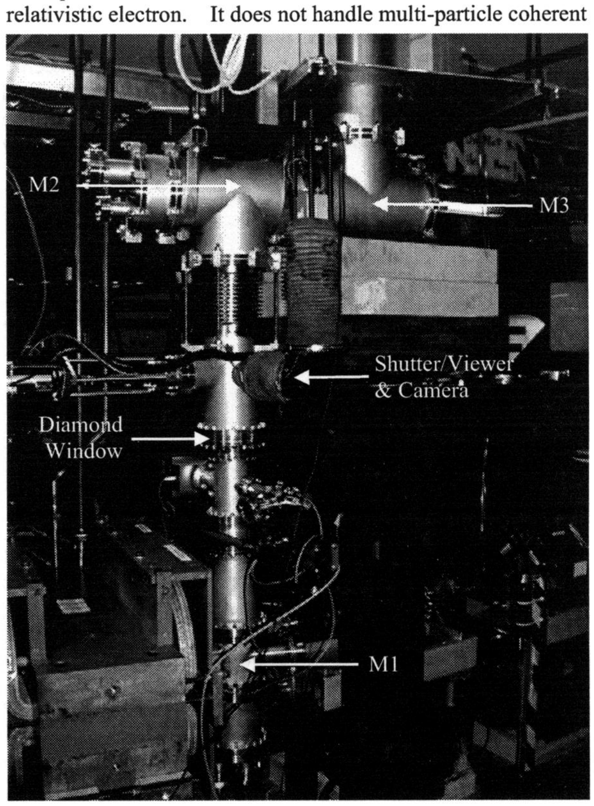

Fig. 2: Installed THz beamline on the JLab FEL.

enhancement, but is significantly different from all the other synchrotron radiation calculations because it retains a term called the Coulomb term.

The mirrors are all made of machined and polished aluminum. They are approximately 25mm thick and elliptical in shape consistent with 150mm diameter optics. The power loading of M1 varies from a few hundred watts to a kW and it is therefore cooled by a copper braid attached to a 1" diameter Cu feed-through to prevent thermal runaway. The installed beamline is shown in Fig. 2.

Presently, we are calibrating diagnostics and preparing for the first run of THz user experiments that will begin imminently. Initial experiments are focused on explosive detection and THz imaging of concealed material.

Compact THz Source

While the power produced from the JLab FEL is copious and it is thus a unique R&D device, the size of the radiation source (65m in length) ensures that users must perform experiments at the facility and that copies of the system are impractical for specific applications. We have therefore considered how to produce a compact, economic source of high-power THz radiation that can be operated where needed and serve to commercialize THz applications requiring high-power.

Present Auston switch THz sources [3] typically produce $\leq$ 1mW of power and single-frequency quantum cascade lasers (QCL), should deliver up to 100mW above about 2THz [4]. For standoff imaging and spectroscopy applications or high-throughput non-destructive evaluation (NDE), watts of tunable or broadband THz radiation are needed.

We are focused on THz sources based on electron beam radiation mechanisms, as in the JLab FEL, since these sources can, in principle, deliver the power levels we seek. However, certain economic and practical constraints must be considered. Firstly, systems based on photocathode electron sources, while excellent choices for R&D THz generation, are expensive and require maintenance attention. Systems that accelerate electron beams above 9MeV introduce radiation concerns. Consequently, systems utilizing short electron bunches and coherent synchrotron radiation (CSR) in bends or photocathode laser short-pulse techniques [5] are not considered to be readily commercializable.

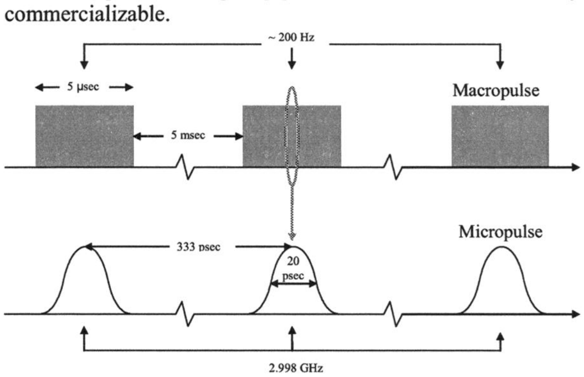

Fig. 3: Pulse structure of compact THz source.

We are developing a tunable source, based on the ubitron concept [6], utilizing an S-band RF gun with the pulse structure shown in Fig. 3 [7]. Our simulations project the source will deliver up to 50W of THz output power, tunable over a large fraction of an octave, with about 50GHz bandwidth. The device will operate at 0.1% duty factor with micropulses of about 20psec FWHM to deliver peak powers of around a MW. Fig. 4 shows the source with a Chi wiggler [8], though our eventual plans call for a permanent magnet arrangement. A prototype lower-duty-factor (uncooled for simplicity) device is in fabrication for testing at JLab in 2006.

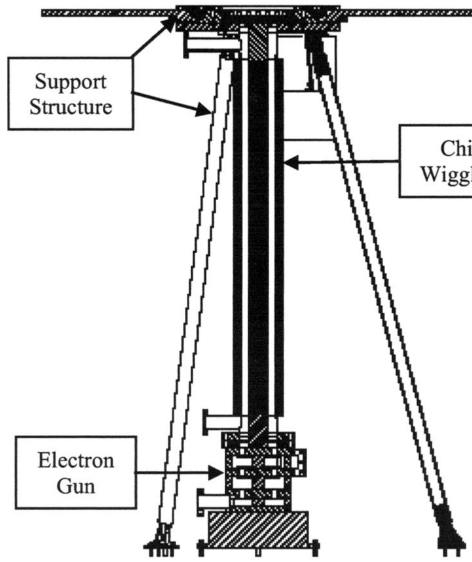

Fig. 4: Diagram of the compact THz source.

We are also considering integrated systems. The source pulse structure is well matched to detector concepts we have entertained for stand-off detection and high-throughput NDE. We project requiring a few $pW/Hz^{1/2}$ of noise equivalent power (NEP) from the detectors.

Summary

We have described a commissioned facility at JLab that delivers well over 100W of broadband radiation up to 10THz to user laboratories [10]. Additionally, a compact THz source, capable of on the order of 50W average power, will be delivered to the JLab facility in 2006. These THz sources will be used to develop explosive detection and NDE techniques.

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