TERAHERTZ LIGHT SOURCE AND USER AREA AT FACET*

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Abstract

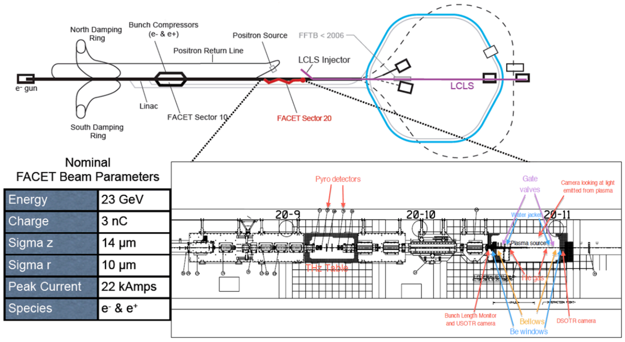
FACET at SLAC provides high charge, high peak current, low emittance electron beam that is bunched at THz wavelength scale during its normal operation. A THz light source based coherent transition radiation (CTR) from this beam would potentially be the brightest short-pulse THz source ever constructed. Efforts have been put into building this photon source together with a user area, to provide a platform to utilize this unique THz radiation for novel nonlinear and ultrafast phenomena researches and experiments.

INTRODUCTION

Being a long-time underutilized portion of the electromagnetic spectrum, terahertz (100 GHz ~10 THz) spectral range is experiencing a renaissance in recent years, with broad interests from chemical and biological imaging, material science, telecommunication, semiconductor and superconductor research, etc. Nevertheless, the paucity of THz sources especially strong THz radiation hinders both its commercial applications and nonlinear processes research. FACET — Facilities for Accelerator science and Experimental Test beams at SLAC— provides 23 GeV electron beam with peak currents of ~ 20 kA that can be focused down to 100 μm^2 transversely. Such an intense electron beam, when compressed to sub-picosecond longitudinal bunch length, coherently radiates high intensity EM fields well within THz frequency range that are orders of magnitude stronger than those available from laboratory tabletop THz sources, which will enable a wide variety of THz related research opportunities. Together with a description of the FACET beamline and electron beam parameters, this paper will report FACET THz radiation generation via coherent transition radiation and calculated photon yield and power spectrum. A user table is being set up along the THz radiation extraction sites, and equipped with various signal diagnostics including THz power detector, Michelson interferometer, sample stages, and sets of motorized optical components. This setup will also be presented. Potential THz research areas including studies of magnetism, ferroelectric switching dynamics, semiconductor devices and chemical reaction controls have already been proposed for the FACET THz area.

FACET BEAMLINE

Originally proposed as a facility to support research on plasma Wakefield acceleration using both electrons and positrons, FACET uses the first two kilometers of the SLAC linac to produce electron beam with energy in excess of 20 GeV and very small emittance. At Sector 20 in the existing linac tunnel, a new beamline is under construction with a bunch compressor, final focus system and experimental areas appropriate for plasma Wakefield acceleration research. Upstream of the focal point an optical table has been added where THz radiation is extracted and can be utilized for additional diagnostics and user driven THz experiments. Figure 1 below shows the schematic of the FACET beamline [1].



Nominal FACET Beam Parameters

Energy	23 GeV
Charge	3 nC
Sigma z	14 μm
Sigma r	10 μm
Peak Current	22 kAmps
Species	e- & e+

Figure 1: Schematic of the FACET beamline, a zoom-in at the Sector 20 experimental area, and a table of FACET nominal beam parameters.

FACET provides beamline hardware and systems that allows high charge, high peak-current beam operation. The table in Fig. 1 lists beam parameters for nominal FACET operation. At full compression, FACET offers ~3.2 nC charge per pulse at energy of 23 GeV, with 3% FWHM momentum spread and 30 Hz repetition rate. The bunch length is adjustable from 10 um to 100 um (33 fs to 333 fs). Such an intense electron beam can radiate an enormous amount of photons at wavelengths comparable to the bunch length via coherent transition radiation.

COHERENT TRANSITION RADIATION

Transition radiation is emitted at the interface when an electron travels into a different media. If the electron beam has longitudinal structure, electrons in the beam will emit coherently at wavelengths comparable to that characteristic length, and total radiation power will scale as the square of the charge number *N*. The fact that FACET beam carries $N= 2 \times 10^{10}$ charges bunched at tens of micron length ensures a high THz photon yield when the beam passes through a foil. A schematic of THz generation by inserting a metallic foil into the beam is shown in Fig. 2. The insertion angle is 45° so that the photon emission propagates transversally out of the electron beam trajectory. The foil planned to be used is 1-um thick Titanium foil spanned over a one-inch circular aperture. There will be two foil insertion sites on the FACET THz table for double THz extractions. They are 2.7’ apart from each other, empirically far enough for the electron beam fields to reform after the first CTR foil.

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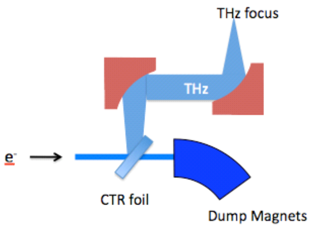

Figure 2: Schematic of thin-foil CTR THz generation, collection and focus.

CTR Calculation Results

An in-house code developed at SLAC was used to calculate THz radiation power and spectrum from the coherent transition radiation. The foil is simplified as a perfect electric conductor boundary with unity reflection coefficient over the whole frequency range considered. Formulations followed by the code could be found in [2] and [3]. The electric field for an electron bunch of 3.5 nC charge, 23 GeV energy, 50 fs bunch length in longitudinal direction, and 6 um in diameter transversal spot size is calculated and plotted in Fig. 3. For this case, the peak current is roughly 27 kAmp and the maximum electric field intensity goes up to 0.6 V/Å in the ~150 fs long quasi-half cycle pulse obtained. The power spectrum contains significant content from DC up to 6 THz, and peaks at about 1.2 THz. The total power yield per pulse is 13 mJ.

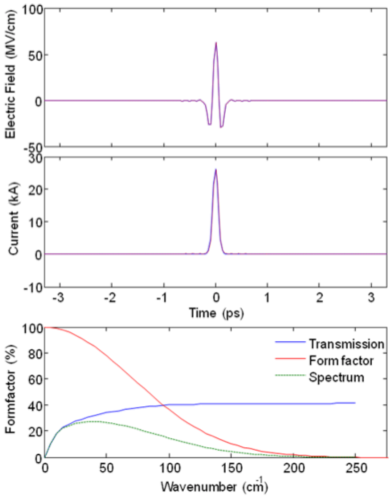

Figure 3: Calculated electron bunch peak current, CTR emission field and power spectrum using FACET beam parameters.

Highly-Elliptical Beam Spots

The THz table is located on the beamline in a region after the bunch compression is complete but before the final focus system to minimize interference with other experiments. The nominal beam size at the THz table area upstream of the focal point is highly elliptical however: the transversal spot size is σ_x = 1.2mm by σ_y = 6μm at the 1st foil, and 1.5 mm by 13 um at the 2nd foil. The discrepancy between this ribbon-like spot and a round-shape spot will affect the THz CTR. The code aforementioned currently cannot calculate the case where the incident beam has different σ_x and σ_y values. In order to evaluate the discrepancy, another code following formulations in Ter-Mikaelian's book [4, 5] was employed, where the electron number density function is described by Gaussian distributions in all three dimensions with variances σ_x^2, σ_y^2, and σ_z^2, and Fourier transformed to momentum space when calculating the CTR spectrum. Figure 4 shows the radiation spectrum form factor plot after normalized to the square of the charge and integrated over 4π solid angle. The blue curve corresponds to the elliptical spot with σ_x = 6 um and σ_y = 1.2 mm, whereas the red curve corresponds to a circular spot with σ_x = σ_y = 85 um so that they have the same transverse area. Comparison reveals that the elliptical beam results in decreased radiation mostly at the low-frequency end by about 15% maximum, and eventually converges to the circular spot case at the high-frequency end.

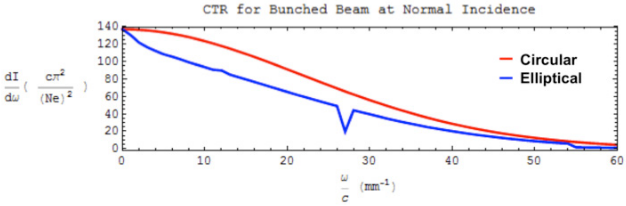

Figure 4: Normalized CTR power spectra of transversally circular and highly-elliptical electron beams of identical spot area.

Titanium is chosen because of its resistance to beam damage. The thickness of 1 μm minimizes the detrimental effects of multiple coulomb scattering on the beam quality. For THz applications, the choice of thin titanium foils raises an issue: the skin depth of Titanium at 1 THz is 0.37 um, therefore the foil is only 3 skin-depth or less thick below 1 THz and the unity reflection assumption will not be valid any more. A reduction of the CTR energy yield would be expected at the lower THz frequency range.

TERAHERTZ USER AREA

An 8' by 4' optical table has been put into the Sector 20 tunnel where two foil insertion sites sit upon, as the top drawing of Fig. 5 shows. Various optical components and THz power detectors will be equipped on the table for THz beam diagnostics as well as sample characterization purposes. They will be fully remote-controlled by motorized actuators and translation and rotation stages. A Michelson interferometer will also be installed on the table to take the spectroscopy of the THz radiation. The planned layout of the components can be found in the bottom schematic of Fig. 5. Two identical diagnostic sets will be installed for both foils, and the spectrometer will be shared. Currently the components are assembled and aligned off-site, and they will be transferred to the final table during the commissioning phase of FACET beamline. Unlike the THz table at Linac Coherent Light Source (LCLS), the nominal electron beam condition at FACET is ideal for THz photon generation; therefore the THz table operation at FACET is non-invasive to other FACET experiments.

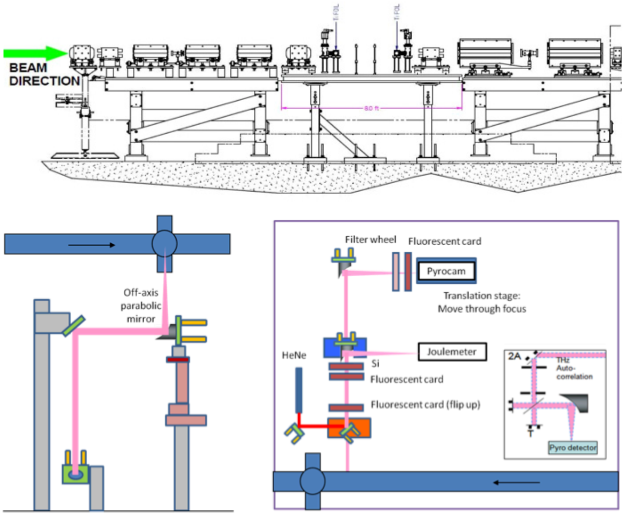

Figure 5: Top: THz user table along the FACET beamline. Bottom: layout of the proposed optical setup on the THz table.

THz Power Measurement

Experimental measurement of the emitted THz power are challenging mainly due to the lack of well-calibrated THz detector over such a broad frequency range and at such a high input power level. Detectors for high-power pulse measurement are usually coated by a highly reflective layer to limit the transmitted signal, whose reflection coefficient needs to be carefully characterized in order for an accurate input power reading. THz power measurements at LCLS using two different detectors have exhibited a three fold difference.

A scheme using two identical detectors to measure both the incident power P_{in} and the (oblique) reflection coefficient R of the detector could be implemented. THz photons will be obliquely incident onto the detector senor area, get partially reflected, and then pin onto a second identical detector along the same incidence angle. Two power readings will be obtained from the two detectors, which are:

$$M_1 = (1 - R) * P_{\text{in}},$$

$$M_2 = R * (1 - R) * P_{\text{in}},$$

admitting no transmission behind the detector and same detector responsivities that can be cancelled out. The two unknowns R and P_{in} can then be solved:

$$R = M_2 / M_1,$$

$$P_{\text{in}} = M_1^2 / (M_1 - M_2).$$

This calibration scheme will be carried out in the future power measurement.

THz Transport Line

A long-distance THz transport line through the existing penetration at Sector 20 has been proposed. The THz beam can be directed upstairs where the user tables could be relocated, and THz experiments could be carried out fully free from the limited space and access time in the linac tunnel. Possibility of directing THz into a laser room upstairs also opens up the opportunity to have high-power laser and THz beams simultaneously for pump-probe experiments. Current estimation of the transport distance is around 40 meters, which requires a periodic focusing mirror system involving a lattice of large-aperture focusing parabolic mirrors or lens, the larger the aperture the fewer components needed. The pipeline also needs to be under vacuum or at least Nitrogen purged, since THz signal suffers great attenuation in water vapour. An alternative method is to construct the transport line using parallel-plate waveguide, which supports TEM mode and has been demonstrated to propagate THz pulse with extremely low loss and low dispersion [6, 7]. Metal breakdown issue is yet to be explored though when transporting such an intense THz field.

CONCLUSION AND FUTURE WORK

Coherent THz radiation source at FACET based on thin foil CTR method has been introduced. With the unique electron beam FACET provides, intense THz pulse with peak field approaching 1 V/Å and frequency content from below 1 THz up to tens of THz could potentially be achieved. Such a strong THz source offers opportunities for novel nonlinear spectroscopy and ultrafast processes research. A final table accommodating various THz beam characterization optics is in construction, and will be ready to facilitate users for their THz experiments. Initial radiation power and spectrum measurements, as well as new concepts such as two-detector calibration scheme and long-distance THz transportation will be tried out following the commissioning of FACET beamline in the summer of 2011.

REFERENCES

[1] FACET Conceptual Design Report, Sept. 2009.
[2] H. Loos et al., SLAC-PUB-13395, Aug. 2008.
[3] J. D. Jackson, Classical Electrodynamics, J. Wiley & Sons, New York, 1975.
[4] Ter-Mikaelian, High-Energy Electromagnetic Processes in Condensed Media, p.223, J. Wiley & Sons, New York, 1972.
[5] J. England, private communication.
[6] G. Gallot et al., J. Opt. Soc. Am. B 17, 851 (2000).
[7] R. Mendis and D. M. Mittleman, J. Opt. Soc. Am. B 26 (9), A6 (2009).