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DIELECTRIC WAKEFIELD ACCELERATORS: THZ RADIATION FOR MEDICAL APPLICATIONS

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Abstract

The THz spectrum reveals distinctive vibrational and rotational modes. When charged particle beams produce THz radiation, they become a promising source for generating narrowband, high-energy radiation. Particularly in dielectric wakefield accelerators (DWA), where a relativistic electron beam traverses a dielectric-lined channel, generating Coherent Cherenkov radiation (CCR). The frequency and amplitude of CCR depend on the structural geometry and the parameters of the drive beam. Simulation of a micrometer, pico-coulomb charge driver beam in a DWA structure yield longitudinal fields on the order of MV/m. The fundamental mode is associated with a resonant peak that corresponds to the process of demethylation in DNA. To achieve higher frequencies, the structure requires either a thin dielectric layer or Bragg-like boundaries to constructively reinforce the fundamental frequency.

INTRODUCTION

Dielectric wakefield accelerators (DWA) have been under investigation for the last three decades, with progression in achieved accelerating gradient from the 10 MeV/m [1] to greater than the GeV/m level [2]. Achieving high gradients required increasing the frequency to over 0.2 THz, from the pioneering work at the AWA [3]. The most recent DWA in the high frequency and high gradient regime, taking place mainly at the ATF and FACET facilities, have interesting results that pave the way to use of the DWA in advanced accelerator medical applications.

The MITHRA beamline at UCLA has a capability of generating 30 MeV beam. Photo-electrons are produced from the copper cathode in the hybrid gun using 267 nm laser from a frequency tripled, 800 nm laser system. Two S-band, 25 MW XK-5 klystrons drive the full accelerator. After the gun following the photoinjector there is 1.5 meter linac installed. The facility will also transport electron beam to the large plasma device one floor below the MITHRA lab as shown in the Fig. 1. An S-band hybrid photoinjector provides high brightness and high peak current electron beams before being accelerated at each stage [4]

DWA program at MITHRA lab is a continuation of the successful program at FACET and FACET-II, where many important phenomena were explored, such as: observation of GV/m acceleration and deceleration of electrons in dielectric structures induced-conductivity in dielectrics by high-field THz waves, and the suppression of deflecting modes in planar-symmetric dielectric wakefield accelerating structures using elliptical electron bunches [5–10].

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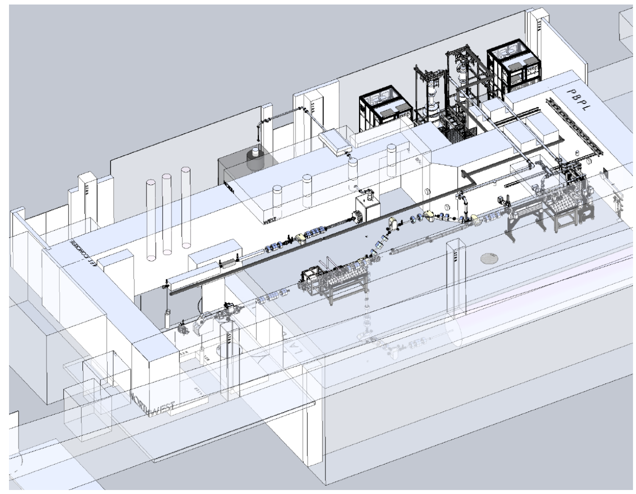

Figure 1: CAD model of the MITHRA laboratory, featuring a bunker, a klystron gallery, and an accelerator. The klystron gallery is equipped with the first 25 MW XK-5 and a modulator. It currently supports a low-energy beamline of approximately 4 MeV, with plans for a 1.5-meter linac upgrade to boost the energy to 30 MeV.

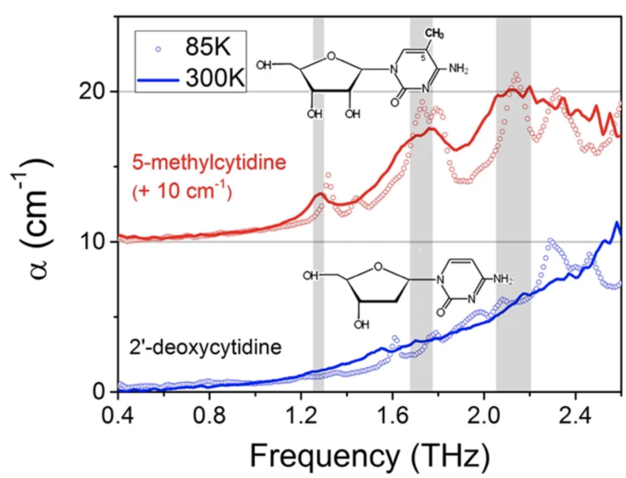

Figure 2: Absorption coefficients in the 0.4—2.5 THz range for 2-deoxycytdine and 5-methylcytidine [11].

The THz region of the electromagnetic spectrum has experienced a renewed interest in the last decade due to development of novel sources and diagnostics. The THz spectrum is often referred to as the fingerprint region since organic compounds exhibit unique vibrational and rotational modes resonant in this area. While this has obvious applications in defense and security, an under explored application of THz radiation is the resonant behavior of biological molecules

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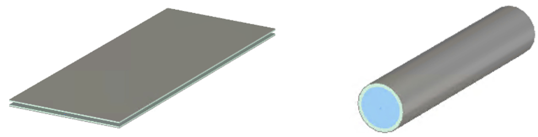

Figure 3: The structures will be used to test the radiation generated. Left plot is two dielectric slabs with metal coated on one end of the dielectric. Right geometry is a tube. The Vlasov cut design of these parallel slabs will allow us to outcouple the radiation in one direction.

with application to medicine. Recent work in cancer imaging and treatment has focused in this area, where researchers have identified unique trigger forbearers in regards to abnormal methylation of DNA occurring at a specific THz frequency. In the most promising scenario, early identification of DNA demethylation using THz sources can be key to effective imaging at higher power levels, one may conceive of treating cancer with THz waves as shown in Fig. 2.

The majority of present day THz sources are laser-based, using nonlinear recombination in crystals, to generate relatively broadband radiation. Broadband sources are desirable for spectroscopic applications, such as identification of specific resonant peaks. However, for imaging and, more important for targeted treatment, narrowband sources with high-pulse energy are preferred. In this regard, THz radiation produced by charged particle beams is apt for the generation of narrowband, high-energy radiation in the THz regime. Specifically, in dielectric wakefield accelerators, where a relativistic electron beam traverses a dielectric lined channel, coherent Cerenkov radiation (CCR) is produced. The CCR frequency and amplitude is dependent on the structure geometry and drive beam parameters. Recent work by the applicant team on THz production in dielectrics has shown tunable, narrowband CCR at FACET, the ATF, the AWA, and other facilities.

SIMULATION SETUP

Here we discuss the first possible experiment at the UCLA MITHRA beamline to generate terahertz radiation from dielectric structures as shown in Fig. 3. In the past PBPL has done several DWA experiments at SLAC, UCLA and AWA lab [3].

Table 1: MITHRA Beam Parameter and DWA Parameters

Parameter	Unit	Value
Charge	pC	250
Energy	MeV	30
γ_{Beam}	constant	64
ϵ_x, ϵ_y (initial)	mm mrad	1,1
σ_x, σ_y (initial)	µm	20, 20
σ_z (initial)	µm	90

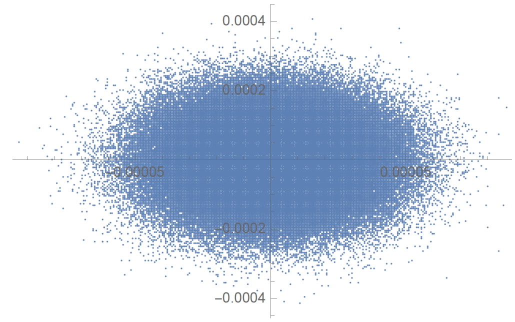

Figure 4: The MITHRA beam profile generated using mathematica. σ_x and σ_y are 20 µm whereas σ_z is 90 µm.

We simulated two cylindrical and parallel slab dielectric structures comprised of SiO_2 with a thickness of 20 µm and 10 µm metal coating. The inner channel which the bunches pass through has a diameter of 60 µm, outer radius of 100 µm, and 3 mm length. The wavelength of the fundamental mode excited in the dielectric with these parameters is 180 µm. The electron as shown in Fig. 5 beam will pass through the structures creating the frequency modes. The relevant beam and structure parameters are summarized in Table 1 and shown in Fig. 4.

The frequencies generated in the THz regime are shown in the following figures: Fig. 6 display the frequency of radiation generated in cylindrical and slab dielectric structures using a wakefield solver, respectively. Fig. 7 show the frequencies using a PIC solver. THz sources that exist today are low intensity MITHRA facility will have capability of generation high intensity THz radiations. Our method of using dielectric structures is good as it generates narrow peak band, frequency match. A relevant absorption peak under study in medicine occurs between 1.63–1.76 THz, which is a marker of the demethylation of DNA.

APPLICATIONS

Unlike X-rays, THz radiation does not ionize biological molecules and does not cause any damage that leads to the breakdown of human keratinocytes [11]. We extend the previous studies of CCR production deeper into the THz, to construct a source operating at 1.65 THz, within a narrow spectral band and with high pulse energy. The choice of 1.65 THz is relevant as it is associated with a resonant peak corresponding to the process of demethylation in DNA, a precursor to carcinogenesis. To achieve higher frequency, the structure should employ a thin dielectric layer, or a structure with Bragg-like boundaries to constructively reinforce the fundamental frequency.

Mode frequencies and amplitudes generated inside the structure can provide important insight into both the material response to the fields and behavior of the beam as it interacts with the dielectric boundary. Dissipation of the CCR pulse within the structure can be attributed to the peak field experienced within the dielectric, while the presence and relative strength of hybrid electric and magnetic modes

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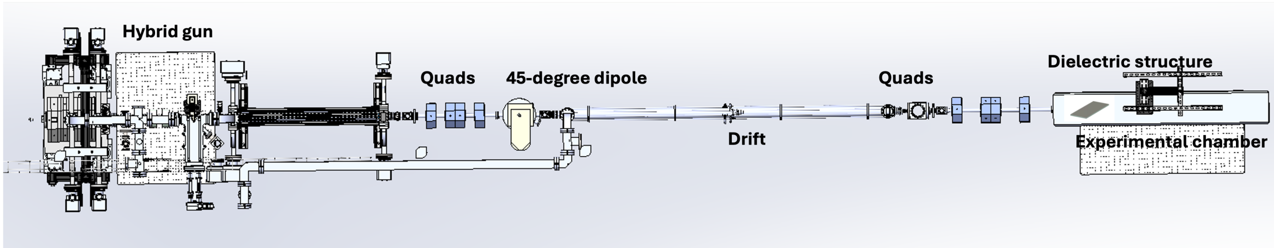

Figure 5: MITHRA lab Dielectric wakefield accelerator experimental setup

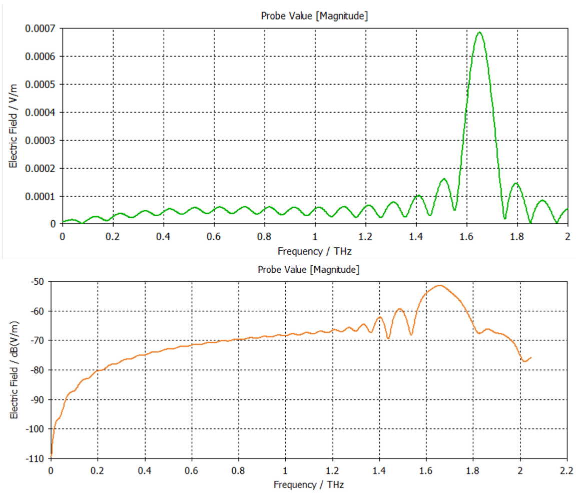

Figure 6: Frequency generated in cylindrical and slab dielectric structure using wakefield solver.

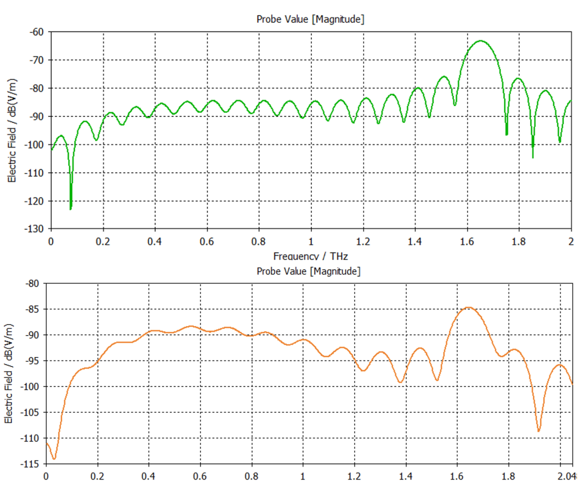

Figure 7: Frequency generated in cylindrical and slab dielectric structure using PIC solver.

is evidence of the beam propagating off-axis down the structure. It is important to first efficiently outcouple the modes from within the structure to free space, so that the radiation can be transported to relevant diagnostics. Recent DWA experiments at FACET have taken advantage of Vlasov antennas, where an asymmetry in the exit boundary causes the modes to be converted and launched at an angle into free space. An advantage to using a Vlasov antenna instead

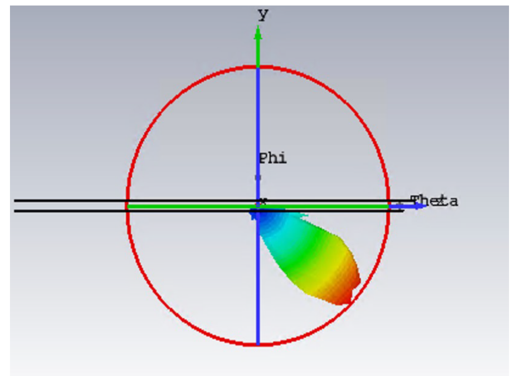

Figure 8: Out-coupling radiation using Vlasov cut dielectric structure using a metal horn.

of a traditional impedance-matching transition into, e.g. a horn, is that the radiation and collection optics are removed from the beam axis, where a high amount of background THz radiation exists due to coherent radiation generated by the ultrashort electron beam. Efficient, low noise transport of CCR has been accomplished with cylindrical structures, but we are currently engaged in studies for optimization in planar-symmetric structures.

CONCLUSIONS

We will have beam positioning monitors and coherent Cerenkov radiation measurement [12] capabilities that use an optimized Vlasov antenna [13] launching approach. This is discussed further in [14], also in these proceedings. Designs for DWA experiments at MITHRA lab is underway, with the layout understood. We did CST simulations to determine which structure will be easy to manufacture and will generates modes in the THz frequency. Then CCR radiation of suitable frequency will be outcoupled into free space using a Vlasov antenna which will reduce background noise and allow for clean measurement of modes generated inside the dielectric structures.

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