Cherenkov Radiation and Dielectric Based Accelerating Structures: Wakefield Generation, Power Extraction and Energy Transfer Efficiency.

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Abstract. We present here our recent results of the Euclid Techlabs LLC/Argonne National Laboratory/St.Petersburg Electrotechnical University "LETI" collaboration on wakefield high energy acceleration of electron bunches in dielectric based accelerating structures. This program concentrates primarily on Cherenkov radiation studies providing efficient high energy generation aimed at a future 1 TeV collider. We report here on recent experiments in high power Cherenkov radiation and corresponding dielectric material developments and characterizations. Progress in diamond, quartz and microwave low-loss ceramic structure development in GHz and THz frequency ranges is presented. Beam Breakup effects and transverse bunch stability are discussed as well. We report on recent progress on tunable dielectric based structure development. A special subject of our paper is transformer ratio enhancement schemes providing energy transfer efficiency for the dielectric based wakefield acceleration.

1. Introduction
Since the invention and implementation of a photomultiplier general properties of Cherenkov radiation such as energy and momentum angular dependence [1,2] have become a well known and widely used analytical methods for particle diagnostics in high energy physics [1,3]. Threshold Cherenkov counters and Differential and RICH (Ring Imaging Cherenkov) or CRID (Cherenkov Ring Imaging) detectors have been developed and successfully applied for identifying the type of particles in nuclear physics and elementary particle science [3]. It should be note that IR and light emissions of charged particle are primarily used in Cherenkov detectors of high energy physics application.

At the same time, a new application of microwave and THz Cherenkov radiation has been proposed and studied in last decade to be used for linear accelerators and colliders in high energy physics as well [4-8]. It is a Dielectric Loaded Accelerator, or DLA concepts [4]. With this paper, we describe an experimental DLA program and present our latest results obtained by the Argonne National Laboratory/Euclid Techlabs LLC/St.Petersburg Electrotechnical University “LETI” collaboration [4-8,10,12-15].

2. Dielectric Based Accelerator
Dielectric loaded accelerator (DLA) structures using low-loss microwave ceramics or quartz and excited by a high current electron beam or an external high frequency high power RF source have been under extensive study recently [4-8]. The basic wakefield RF structure is very simple - a
cylindrical, dielectric loaded waveguide with an axial vacuum channel is inserted into a conductive sleeve, Fig.1. A high charge, (typically 20 – 40 nC), short, (1 – 4 mm) electron drive beam generates TM₀₁ mode electromagnetic Cherenkov radiation (wakefields) while propagating down the vacuum channel [4,10]. Following at a delay adjusted to catch the accelerating phase of the wakefield is a second electron (witness) beam. The witness beam is accelerated to high energy by the wakefield produced by the drive beam. A series of proof of principle experiments have been successfully performed in microwave frequency range at Argonne’s Advanced Accelerator [4-8]. THz range wakefields have been successfully generated by the UCLA-SLAC collaboration [11].

The advantages and potential problems of using dielectric for loading an accelerating structure are discussed in the above references [4-8] and are only summarized here. The advantages are: (1) Simplicity of fabrication: The device is simply a tube of dielectric surrounded by a conducting cylinder. This is a great advantage for high frequency (> 30 GHz) structures compared to conventional structures where extremely tight fabrication tolerances are required. The relatively small diameter of these devices also facilitates placement of quadrupole lenses around the structures. (2) Dielectrics can potentially exhibit high breakdown thresholds relative to copper, and high shunt impedance. (3) Reduced sensitivity to the single bunch beam break-up (BBU) instability: The frequency of the lowest lying HEM₀₁ deflecting mode is lower than that of the TM₀₁ accelerating mode. (4) Easy parasitic mode damping.

Potential challenges of using dielectric materials in a high power RF environment are breakdown and thermal heating, same as for all-metal conventional accelerating structures. Microwave DLA required high brightness high charge drive beam providing >200 MV/m accelerating gradient that has to be sustained by the dielectric material of the structure loading [10]. Currently we consider fused silica and CVD diamond as our primarily candidates for the high gradient DLA structure loadings [10,12].

\[
\sigma_r = \left( \frac{\varepsilon_N}{\gamma} \right)^{\frac{1}{2}} \quad W_z(z) = \frac{Q}{a_z^2} \exp \left[ -2 \left( \frac{\pi \sigma_z}{\lambda_n} \right)^2 \right] \cos(kz) \quad (1)
\]

Formula (1) presenting longitudinal wake function below clearly shows that the high gradient can be reached by using the small aperture structure (~ a') that, in turn, requires low emittance \( \varepsilon_N \), high charge Q drive beam (or bunch train) to be generated and transferred through the DLA structure [9,10]. The power extraction has to be provided for the two-beam accelerator design. 26 GHz wakefield power extractor has been successfully demonstrated in 2009 [13], and 30 MW power level has been reached for the ~ 10 ns pulse [13]. Beam handling is always a special issue for the decelerating section of a high charge wakefield accelerator [14]. We also proposed an original method of DLA structure tuning based on additional ferroelectric layer [15] introduce into the DLA loading.

**Figure 1.** Partially Dielectric Loaded Accelerating structure excited by the drive beam. Inner region is vacuum; outer layer is dielectric; and the outermost layer is metal.
It should be also noted that expected problems with dielectric charging are easily mitigated by using a dielectric with a small dc conductivity.

3. Dielectric Based Accelerator Development.

3.1. Diamond DLA Structure.
Quartz and cordierite structures have been recently beam tested, and accelerating gradient exceeding 100 MV/m has been demonstrated [10]. Low-loss (tan $\sim 1\times 10^{-4}$) fine microwave ceramics have been high power tested recently at 1.9 MW power with the gradient corresponding to surface field more than 100 MV/m at the coupler joints [10]. Amorphous dielectrics, such as glass, are known to exhibit high breakdown limits (~100’s of MV/m), but most have a loss tangent that is too high for high-gradient accelerator applications.

Figure 2. Photographs of CVD diamond tube developed: (a) top view; (b) axial view. Tube parameters are: 5 mm inner diameter, 2.5 cm long and ~ 500 µm thick. Light reflects off the naturally smooth individual facets of diamond crystals comprising the polycrystalline aggregate.

Low-loss microwave ceramics and quartz are not the only materials that are being intensively studied as potential DLA loading. An alternative is to use polycrystalline artificial diamond produced by CVD [12], which shows promise for use in a high-gradient, dielectric-loaded accelerator (DLA) structure. It has a very high breakdown field up to 2 GV/m at DC field (no data available for RF frequency range yet), low loss tangent (<10^{-4}), and the highest known thermal conductivity ($2\times 10^3$ W/m°K) [12].

In Ref. [16], a diamond-based rectangular DLA was discussed and all-metal and dielectric-based accelerating structures were compared. For cm- and mm-wavelength linear accelerators with normal-conducting structures as studied by the NLC/JLC collaboration and the CLIC study group [16], the main limitation to the achievement of high accelerating gradient is rf breakdown. It is known that the field limit is proportional to an inverse fractional power of the pulse length, and will vary with material and surface processing. Recent experiments on 30GHz accelerating structures at the CLIC Test Facility with an rf pulse width of 16 ns showed the usable average gradient is lower than these values; e.g. <130 MeV/m for molybdenum [17]. Therefore, a clear objective is to increase acceleration gradient without incurring an unacceptable rate of breakdown events in the accelerating structure.

A DLA structure, unlike a conventional metallic one, admits the unique possibility of sustaining extremely high gradients by using a diamond-based material as the dielectric loading of the guiding structure [12,16]. These structures are based on cylindrical diamond dielectric tubes that are manufactured via a relatively simple and inexpensive chemical vapor deposition (CVD) process, plasma assisted CVD. Use of the CVD process is a much simpler method to achieve high quality rf microcavities compared to other microfabrication techniques. Our initial work was based on 100 µm
scale tubes with fundamental frequencies in the 0.1–1.0 THz range; promising results were obtained using the plasma assisted and hot-filament CVD process. For the larger structures required for Ka band (34 GHz) and longer wavelength applications, the use of microwave plasma-enhanced CVD (PECVD) was determined to have a greater likelihood of success based on its larger rate of diamond deposition and the ability to control surface temperatures on the substrate during deposition. The 5 mm inner diameter, 2.5 cm long and 500 µm thick diamond tube has been fabricated and characterized with SEM, micro-Raman and micro-photoluminescence spectrum analysis. Fig.2 shows the finished free standing diamond tube.

| Inner Diameter | no vacuum gap |
|----------------|---------------|
| 1.5 mm         | 0.19          |
| 3 mm           | 0.24          |
| \(P_{\text{amp}}\), dB/m | -4.7          |
| \(r_s\), MΩ/m | 152           |
| \(E_{z,\text{dielectric}}/E_{z,\text{accel}}\) | 1              |
| \(E_{x,\text{metal}}/E_{z,\text{accel}}\) | 0.17           |
| \(E_{x,\text{metal}}/E_{z,\text{accel}}\) | 0.25           |

**Figure 3.** (a) diamond-based cylindrical DLA structure parameters in case of, no vacuum gap. Surface field ratio \(E_{\text{metal}}/E_{\text{acc}} > 0.17\) for a 1.5 mm beam channel aperture; (b) longitudinal (red) and transverse (blue) electric field profiles normalized to the acceleration gradient \(E_{\text{acc}}\) for the structure parameters: (a) - inner diameter \(2a = 1.5\) mm, outer diameter \(2b = 3.79\) mm, diamond thickness is 1.15 mm.

3.2. Numerical Simulations.

Numerical simulations of completed and planned experiments with these structures have been reported in [5,7,9,12-15]. Field analysis for diamond-based DLA structures has been carried out analytically [9]. The dispersion equation solutions and field magnitude expressions for TM\(_{0n}\) modes of the cylindrical dielectric loaded waveguides can be found in [9]. Parameters of the diamond-based DLA structures with the 1.5 mm and 3 mm apertures presented in Fig. 3(a) [12]. The structure operates at the TM\(_{01}\) mode in the Ka band frequency range where its axial wave number corresponds to a phase velocity of \(c\); the diamond has dielectric constant of 5.7 and loss tangent tan<sub>δ</sub> < 1×10\(^{-4}\).

The radial field profiles normalized to the accelerating gradient for the 34 GHz diamond-based structure are presented in Fig. 3(b). The accelerating gradient is equal to the maximum \(E_z\) field magnitude on the inner dielectric (diamond) surface. The transverse \(E_x/E_{\text{acc}}\) ratio on this surface does not exceed 0.37. If the dielectric breakdown limit is indeed in the range of 0.5-1.0 GV/m [32, 33], the maximum acceleration gradient also would exceed 500 MV/m, if dielectric breakdown is the ultimate limitation. It should be noticed that for relatively short RF pulse length, the accelerating gradients to be available with the diamond-based DLA structure are evidently well in excess of those for iris-loaded all-metal accelerating structures [12,16].

From Fig. 3(a), the shunt impedance is equal \(R = 152\) MV/m for an aperture of 1.5 mm. Fig. 5b shows the calculated shunt impedance \(R\) vs. the vacuum beam channel radius as it was calculated for the cylindrical diamond-loaded traveling-wave (TW) structure, Fig.3a. Simulations showed that the maximum shunt impedance \(R_{\text{max}}\) increases with \(1/R\) along with the accelerating gradient. Note that for the rectangular DLA structure the larger aperture decreases the shunt impedance [16], another advantage of the cylindrical design presented in this paper.
3.3. Beam Break-Up.
The dynamics of the beam in structure-based wakefield accelerators leads to beam stability issues not ordinarily found in other machines [5,14]. In particular, the high current drive beam in an efficient wakefield accelerator loses a large fraction of its energy in the decelerator structure, resulting in physical emittance growth, increased energy spread, and the possibility of head-tail instability for an off axis beam, all of which can lead to severe reduction of beam intensity. Beam breakup effects resulting from parasitic wakefields provide a potentially serious limitation to the performance of dielectric structure based wakefield accelerators as well.

![Wakefields (longitudinal: blue, transverse: green) and beam profile for the Ka band dielectric wakefield experiment (diamond based DLA). The beam at the time of this snapshot has been propagating for ~430 ps (13 cm). The bunch tail has been deflected by the transverse wakefield almost to the inner radius of the vacuum channel [14].](image)

**Figure 4.** Wakefields (longitudinal: blue, transverse: green) and beam profile for the Ka band dielectric wakefield experiment (diamond based DLA). The beam at the time of this snapshot has been propagating for ~430 ps (13 cm). The bunch tail has been deflected by the transverse wakefield almost to the inner radius of the vacuum channel [14].

We used a dielectric structure BBU code derived from the software described in Ref. [5]. The longitudinal and transverse wakefields of a bunch of macroparticles (1000 in this case) are propagated down a dielectric structure using the analytic Green’s functions [14]. For this calculation the first 5 TM and HEM modes were used to compute the wakefields of the bunch. The magnitude of the longitudinal single bunch wakefield is ~70 MV/m, while the transverse force magnitude for the initial offset as given is ~20 MV/m. The bunch propagates about 13 cm through the structure before particle losses from deflection of the tail begin to occur, adequate for measurement of the signal without using external focusing to control the beam, Fig.4 [14]. The wakefield signal can be detected using radial field probes inserted into the copper sleeve of the diamond structure.

3.4. Frequency Tuning.
The frequency of a metallic accelerating structure is defined by its geometry. DLA structures, on the other hand, have another important parameter that determines the frequency spectrum -- the dielectric constant of the loading material. There are two classes of materials that can be tuned, in other words, materials with electromagnetic properties that can be controlled by external fields: ferrites, controlled by magnetic fields, and ferroelectrics, controlled by electric fields. Ferrites do not appear to be a practical solution for use in high frequency high gradient accelerators because of the high loss factor and also because a magnetic field could interfere with the electron beam optics. We proposed a new technique that allows control of the dielectric constant (and consequently the frequency spectrum) for dielectric waveguides by incorporating ferroelectric layers [15].

The most noteworthy feature of the tunable DLA is the replacement of a single ceramic by a composite of 2 layers as shown in Fig. 5a. The inner layer is ceramic, with permittivity typically in the range of 4 - 36 [15]. The outer layer is a film made of BST ferroelectric, of permittivity, placed...
between the ceramic layer and the copper sleeve. The DLA structure tuning is achieved by varying the permittivity, \( \varepsilon \), of the ferroelectric film by applying an external DC electric field across the ferroelectric. This allows us to control the effective dielectric constant of the composite system and therefore, to control the structure frequency during operation [15].

Using a combination of ferroelectric and ceramic layers permits tuning of a composite ceramic–ferroelectric waveguide while keeping the overall material loss factor in the (4 - 5)\times10^{-4} range. Two sets of dual layer waveguides were fabricated. The ferroelectric components had 400 and 800 \( \mu \)m thicknesses and dielectric constants of ~550 and ~450. The tunable DLA resonator with the double layer loading was assembled with the following parameters: inner layer made of forsterite ceramic, dielectric constant 6.8, inner diameter 6 mm, thickness 1.35 mm, length 25 mm; outer ferroelectric layer made of BST(M) ferroelectric, dielectric constant 450/550, thickness 400 \( \mu \)m, and length 34.7 mm. This double layer was inserted into a cylindrical copper sleeve. The geometry of the resonator is shown in Fig. 6 [15].

Unlike a simple copper jacketed resonator with dielectric loading, the ferroelectric based device showed a positive frequency response to temperature variation. In general, the ordinary ceramic material has very small thermal expansion and stable dielectric constant over a wide temperature range but the copper housing will expand and increase the volume so that the resonant frequency of a regular dielectric loaded resonator will shift down with increasing temperature. Here, since the dielectric constant of the ferroelectric tube will decrease significantly with a temperature increase that will lead to an increase of the resonance frequency, the overall effect is a positive slope over a rising temperature. The results from Fig. 4b show a very good linearity and sensitivity of the thermal tuning of this ferroelectric material: ~14MHz/\( ^\circ \)K has been measured for both materials, Fig. 7(a). We also applied a high dc voltage to the DLA resonator that we used for the thermal testing. In these measurements, a tuning range of 6 MHz at 25 kV/cm biasing dc field has been demonstrated [15].

3.5. Energy Transfer Efficiency.

One approach to future high energy particle accelerators is based on the wakefield principle: a leading high-charge drive bunch is used to excite fields in an accelerating structure or plasma that in turn accelerates a trailing low-charge witness bunch. Energy transfer efficiency for the driver-witness bunches is a critical issue for this type of accelerator technique. The transformer ratio \( R \) is defined as the ratio of the maximum energy gain of the witness bunch to the maximum energy loss of the drive
bunch. A number of techniques have been proposed to overcome the transformer ratio limitation. We reported recently the first experimental study of the ramped bunch train (RBT) technique in which a dielectric loaded waveguide was used as the accelerating structure. A single drive bunch was replaced by two bunches with charge ratio of 1:2.5 and a separation of 10.5 wavelengths of the fundamental mode. An average measured transformer ratio enhancement by a factor of 1.31 over the single drive bunch case was obtained in this experiment [8].

![Figure 6](image.png)

**Figure 6.** (a) Temperature dependence of the TM$_{012}$ mode of the dielectric loaded resonator with ferroelectric tunable layer; (b) the tunable DLA resonator with double layer loading. Inner layer (forsterite ceramic), dielectric constant is 6.8, inner diameter 6mm, thickness 1.35 mm, length is of 25 mm; outer ferroelectric layer made of BST(M) ferroelectric, dielectric constant 450/550, thickness 400 µm, length 34.7 mm.

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