# ANALYSIS OF HIGH REPETITION RATE EFFECTS IN DIELECTRIC WAKEFIELD ACCELERATORS*

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*Abstract*

Recently the question has arisen of whether dielectric charging might become a significant limiting effect on the performance of the DLAs (dielectric loaded accelerators), leading either to deflection of the beam by the static electric field generated, or to breakdown of the structure. In experiments to date this has not been problematic with appropriate choice of dielectric material. However, given the high repetition rate that would be required, the device would be subjected to essentially a dc bombardment from the beam halo and thus be vulnerable to these effects because there is no time between machine pulses for discharge of the dielectric. We have begun re-examining this problem, emphasizing the expected charging rate and charge distribution in a thin walled dielectric device and the physics of conductivity and discharge phenomena in a dielectric medium. Simulations of the charging process will be presented. We will review early work on beam-induced charging of dielectric structures and also results from deep charging of satellite components by cosmic rays. Ageing and induced conductivity under large radiation doses are also to be investigated.

## IRRADIATION EFFECTS ON DLAS

The physical processes involved with the unwanted interception of beam electrons by a dielectric accelerating structure are complex and interacting:

- Asymmetric charging of the dielectric, leading to beam deflection;
- Breakdown (with structure damage). Although breakdown thresholds ~14 GV/m have been demonstrated for very short (<330 fs) pulses [1], maximum DC fields that can be supported are considerably lower;
- Changes in material properties with absorbed dose and repeated DC breakdowns;
- Dynamics of the charging/discharge process in the presence of high dose rates. Table 1 lists the characteristic discharge times for a number of dielectric materials used in DLAs, nearly all of which do not reflect the observed resistance to charging. This seems to suggest that other effects are compensating, for example ionization induced conductivity.

Charging effects were studied by the Argonne group as an incidental part of the first dielectric wakefield acceleration tests in 1988 [2]. In these experiments the charging originated from missteering of the drive beam through the dielectric structure. Transverse deflection of the beam through large angles by the induced DC field was sufficiently large as to deflect the beam outside the acceptance of the spectrometer focal plane detector. The initial tests used dielectric tubes made from plastics. Rexolite and Nylon dielectrics showed rather different behaviors under charging.

Table 1: Characteristic discharge times $\tau_c=\varepsilon/\sigma$ for commonly used dielectrics [6]. Here $\sigma$ is the dc conductivity and $\varepsilon$ is the (SI) permittivity.

| *Material* | $\tau_c$ |
|---|---|
| Alumina | >0.78 s |
| Delrin ® | 310 s |
| Kapton ® | 3.5 d |
| Mylar ® | 3.1 d |
| Polystyrene | 37 min |
| Fused Quartz | >38 d |
| Borosilicate glass | 0.41 s (variable) [7] |
| Teflon ® | 2.1 d |

Rexolite was found to charge until the beam was deflected and to hold its charge (and maintain the dc electrostatic field) for an extended time (~ 1 hr). No breakdowns were seen under the test conditions. Nylon would charge up and deflect the beam until breakdown occurred, snapping the beam back to its nominal undeflected position. The charge-discharge period was found to be ~ 30 s. It is worth noting that no permanent damage to the nylon structure was observed (based on repeated longitudinal wakefield measurements) despite being subjected to many charge-discharge cycles.

The rexolite structure was field-modified by depositing a thin layer of graphite powder on the interior surface of the tube. A thin conducting layer can short out the static field but be thin enough (<< 1 skin depth) to allow the rf fields of the structure to penetrate into the vacuum channel as before. It was determined that the graphite layer did in fact have the desired effect, although some trial and error was necessary to obtain a sufficiently thin layer. While use of graphite in this fashion is impractical for high energy acceleration, the principle of using an interior conductive coating was demonstrated. Ultimately the best approach was found to be tuning the beam through an electrically isolated aluminum tube in place of the dielectric, minimizing the intercepted beam current, and then swapping in the dielectric under test for the aluminum tube.

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Later AATF and AWA experiments used borosilicate glass as the dielectric [3]. This material exhibits a large temperature dependent electrical conductivity. Measurements on wakefield structures made of this material showed no detectable charging and no apparent degradation in the magnitude of the wakefield excitation. While borosilicate glass does indeed possess a short discharge time, fused quartz has a discharge time longer than 30 days, while repeated experiments at the AWA and elsewhere have not observed DC charging effects with this material.

Euclid and ANL have begun a systematic study of radiation effects in dielectric wakefield accelerators, with the goal of understanding both acute (charging, dose rate, electric field) and long term (material damage) effects. This project involves both experimental and computational aspects; here we focus on the status of the simulation effort.

## COMPUTATIONAL APPROACH

A complete model of DLA irradiation effects needs to include

- characteristics of the halo (energy spectrum, angular distribution) either determined experimentally or from a simulation of the accelerator;
- interaction of the halo particles with the dielectric structure (spatial distribution of stopped charges and energy deposited in the dielectric);
- computation of the electric field in the dielectric from the trapped charge distribution using a self-consistent determination of the conductivity. This will give the dependence of the equilibrium electric field on the halo current.

### *Dielectric Irradiation by Halo Electrons*

The Geant4 Monte-Carlo code [4] will be used to transport the halo electrons through the dielectric structure, simulating their electromagnetic interactions with the material and scoring the distribution of charges injected into the material. User-written C++ routines are used to code the geometry and material of the target structure, and a Tcl/Tk interface is used to input parameters to control the execution of the program. While originally designed for high energy physics applications, a number of authors ([5], e.g.) have used Geant4 for the study of dielectric charging in spacecraft.

We have begun looking at some test problems to study charging in dielectric structures. Fig. 1 shows a Geant4 simulation of 100 MeV electrons striking the interior of a quartz wakefield structure at glancing incidence to simulate beam halo. The user code we developed flags the location of each stopping electron and also the location where an effective positive charge is created (for example where an electron is removed by a Compton scattering event). In this way the distribution of charge internal to the dielectric induced by the halo is computed (Fig. 2-3). At the same time, the energy deposited in the dielectric and any induced temperature rise is also calculated. The charge and energy deposition results are then input to a field calculator.

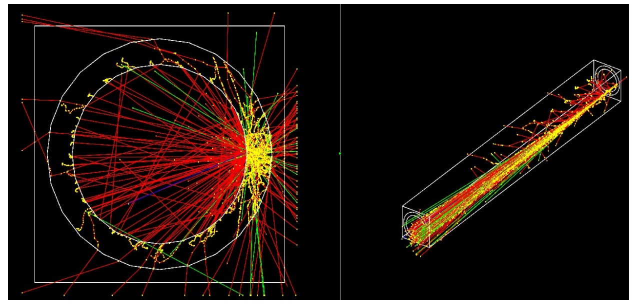

Figure 1: Geant4 simulation of 100 MeV electrons striking a quartz tube (0.35 mm inner radius, 0.45 mm outer radius, 10 mm long, 336 GHz fundamental $TM_{01}$ mode) at glancing incidence to a point on the inner surface. The plots are a sum of 100 events. Red tracks: photons; green: $e^+$ and $e^-$. The yellow rectangles indicate the segmentation of the tracks.

This part of the simulation code will use the spatial dependence of the stopped charges from Geant4 and a Poisson solver to compute the dc field inside the dielectric. Using the electric field and the energy deposited in the dielectric, the conductivity can be determined as a function of position. Finally, the trapped charges can be updated using Ohm's law. The procedure is iterated to obtain the time dependence of the field and charges in the dielectric.

An assumption is made here that the quasistatic electric field and its effect on the conductivity are independent of the rf fields induced by the beam. If needed, rf effects could be incorporated through the use of a FDTD EM solver.

### *Dielectric Conductivity*

There are a number of empirical relations used in the literature to parameterize the time, temperature and electric field and dose rate dependence [8-11] of the dielectric conductivity σ.

$$\sigma(t) = \frac{\sigma_1}{F(1+bt)} \qquad \text{(time)} \qquad (1)$$

$$\sigma(T) = \sigma_\infty \exp(-\frac{E_A}{kT}) \qquad \text{(temperature)} \qquad (2)$$

$$\sigma(E,T) = \frac{1}{3}\sigma(T)\times [2+\cosh(\frac{\beta_F E^{1/2}}{2kT})][\frac{2kT}{eE\delta}\sinh(\frac{eE\delta}{2kT})] \qquad \text{(electric field)} \qquad (3)$$

$$\sigma(\frac{dD}{dt}) = \sigma_0 + k_p(\frac{dD}{dt})^\Delta \qquad \text{(Dose rate)} \qquad (4)$$

here $\beta_F = \sqrt{e^3/\pi\varepsilon}$, $E$ is the electric field strength, and $D$ is the absorbed radiation dose (rads). $k_p$ and Δ are positive constants, with Δ in the range 0.6-1.0; these and the other free parameters in eq. (1)-(4) need to be determined experimentally. We note that the conductivity increases with increasing dose rate and electric field, leading to reduced discharge times of accumulated charge in an accelerator environment.

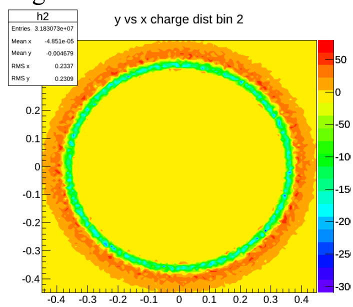


Figure 2: Trapped charge distribution in a 1 mm axial segment for 100 MeV electrons incident symmetrically around the circumference of the tube in Fig. 1. Note that regions with excess electrons and depleted in electrons both occur.

## *Modeling of Beam Halos*

Machine parameters (rf, optics, vacuum) are input to a halo simulation code. (Alternatively, if sufficient data from the accelerator exists, they could be parameterized and input directly to the particle transport code.) The tracking code Placet [12] incorporating the halo simulator htgen [13] has been chosen as a reference to perform the machine simulation. The accelerator lattice and other parameters are input via Tcl/Tk scripts.

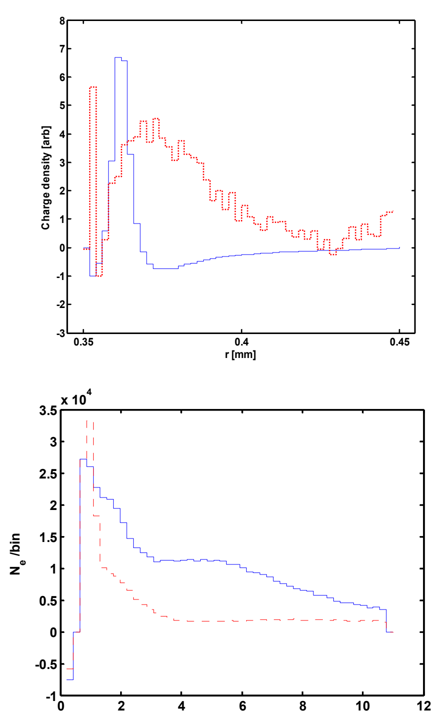


Figure 3: Trapped charge distribution as a function of (a) radial (b) axial position. in the geometry shown in Fig. 2. (Solid: 100 MeV $e^-$; dotted: 10 MeV $e^-$.)

Htgen models the effects of beam-gas scattering and bremsstrahlung from scraping on collimators and other beamline components, using the Placet components to model the beam and also transport the halo particles produced to the dielectric structure.

## SUMMARY

We have begun investigating the effects of irradiation on dielectric wakefield structures. We consider developing a simulation code to calculate the interaction of halo electrons with DLA structures. Because of the more complex geometry the problem presents challenges not treated in previous analyses.

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