Real-time diagnostic for charging and damage of dielectrics in accelerators

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Abstract:

We report on the progress made during the initial stage of our research to study charging rate and charge distribution in a thin walled dielectric wakefield accelerator (DWA) from a passing charge bunch and the physics of conductivity and discharge phenomena in dielectric materials useful in accelerator applications. The issue is the role played by the beam halo and intense wakefields in charging the dielectric, possibly leading to undesired deflection of charge bunches and degradation of the dielectric material: the effects that may grow over many pulses, albeit perhaps differently at different repetition rates. During the initial stage of development, a microwave apparatus was built and signal processing was developed to observe time-dependent charging of dielectric surfaces and/or plasmas located on or near the inner surface of a thin-wall hollow dielectric tube. Three frequencies were employed to improve the data handling rate and the signal-to-noise. The test and performance results for a plasma test case are presented; in particular, the performance of the test unit shows capability to detect small changes $\sim 0.1\%$ of a dielectric constant, which would correspond to the scraping-off of only 0.3 nC to the walls of the dielectric liner inside the cavity from the passing charge bunch.

Keywords: Dielectric Wakefield Accelerator, Beam Halo, Charging Effects, Real Time Diagnostic

Introduction:

Dielectric Wakefield Accelerators (DWAs) have received a considerable attention lately as candidates to deliver high-gradient acceleration for both electron and positrons. The interest has been fueled by a finding that some dielectrics can withstand very high fields, e.g. in excess of 100 MV/m in the upper GHz frequency range [1], and a few GV/m in the THz frequency range [2]. DWAs offer many favorable properties. In particular, dielectric loaded structures offer simpler geometries and easier fabrication as compared to conventional metal structures. It is believed that difficulties associated with generating and distributing RF-power by conventional means will be avoided because in the case of DWAs a relativistic beam transports the energy directly into an accelerating structure. The generated wakefields themselves constitute RF pulses that are short in duration and of high-peak intensity and, thus, are ideally suited to accelerate a high-current, sub psec-long bunch of charged particles. It is also possible to have the accelerating field nearly-uniform across the transverse cross-section where the accelerated bunch moves (to achieve thus more uniform acceleration), where there are no geometrical features that promote field enhancement. Single-channel and multi-channel structures have been studied in which a single drive bunch or a drive bunch train sets up a wakefield in a dielectric-lined hollow cylindrical tube and is followed by a witness bunch which is accelerated by the wakefield. The problems with breakup of a high charge drive bunch [3] have been studied in single-channel structures. The concept of ramped bunch train has been studied to boost the transformer ratio [4, 5]. More complicated structures, e.g. two-channel coaxial configurations [6] that naturally give a high-transformer ratio have been extensively studied also.

While particular dielectric materials have been used in different DWA experiments (as e.g. summarized in [7]), there however, has been no systematic investigation of dielectrics for long-term

practical use in the DWA. This we deem to be a serious omission and it is the aim of the present investigation to develop apparatus and methods to investigate dielectric damage that can occur in an accelerator environment. Herein, we describe the performance of diagnostic hardware and procedures that were developed for the study of charging effects, damage, and conductivity changes resulting from the passage of one or more charged bunches, e.g. because of the deposition of the halo particles on the dielectric material, or effects caused by intense fields –as set up by the drive bunches - on the dielectric material.

Approach and method:

Our approach and method can be summarized in a few steps as follows:

1. (*step 1*) The dielectric material (a sample of dielectric thin-wall tubing) is to be positioned inside a cylindrical microwave cavity. The cavity is manufactured to work at the TM_{010} mode whose frequency (via appropriate choice of cavity dimensions) is chosen to be in a low GHz frequency range (e.g. < 20 GHz). The fundamental mode is recommended here since it is situated far away from the nearest higher-order mode.
2. (*step 2*) The changes in transmission through the cavity are to be measured at pre-defined frequencies, f_m . The measurements are done in the real time, at micro-second time-scales or greater. The set of frequencies is chosen so that each is relatively close to the resonant frequency, F_ξ , of the chosen cavity mode. For instance, if the cavity bandwidth is BW_ξ , the recommended frequency choice is $f_m = F_\xi \pm BW_\xi \cdot N_m / 2$, where $N_m = 0, \pm 1, \pm 2$, etc
3. (*step 3*) The information obtained at *step #2* is to be used to infer the changes in the cavity resonant frequency, F , and quality-factor, Q . This is done by application of a set of pre-derived procedures and formulas, which will be given below. In particular, at this point, an already developed and tested noise-rejection and filtering algorithm is to be applied to boost the signal-to-noise ratio.
4. (*step 4*) The corresponding changes are to be found in the dielectric constant and loss-tan of the dielectric thin-walled tubing and its enclosed contents. To perform this, one inputs the known dielectric material geometrical configuration into HFSS (or similar software), and runs the code to find what the dielectric constant and loss-tan should be at each given time-instant to cause the observed changes in the cavity resonant frequency and Q-factor. Note that this will allow one to monitor/detect both transient effects as well as permanent ones.
5. (*step 5*) The numerical/ analytical models are to be used to find the corresponding density of free electrons/ charges (n_e), collision frequency (F_{coll}), and any other relevant parameters of the region enclosed by the dielectric tubing.
6. (*step 6*) Lastly, the data from above are to be used to predict changes in the dielectric constant and loss-tan of the dielectric material in GHz- or other-frequency ranges. Again, by the nature of the techniques, both transient changes on the microsecond time scale or greater as well as permanent ones can be inferred.

The principal measurement diagram that follows the principles described in (*step 2*) is presented in Fig. 1. A particular implementation is shown in Fig 2. This one is envisioned to be used when working with dielectric tubing samples used for accelerator applications and thereby exposed to electron beams and intense wakefields; it includes a fast microwave switch that can suppress radiation emitted by the passing relativistic charge bunch [8].

(...Figure 1 goes here...)

(...Figure 2 goes here...)

Let F_ξ and Q_ξ be the resonant frequency and the quality-factor respectively of the cavity when the inserted dielectric tubing sample is not exposed to wakefields and/or the beam halo (no deposited/free electrons are present), and ξ be the linear ratio of the transmitted to incident power at the resonant frequency F_ξ . Let F and Q be the resonant frequency and Q-factor respectively of the cavity when the dielectric sample is being exposed to the beam halo and/or wakefields. Note that these two values will change as the time passes and the exposure varies. Lastly, let T_m be the linear ratio (time-dependent value) of the transmitted to incident power at the observer frequency f_m when the dielectric sample is being exposed. One finds that:

$$F = \frac{f_m + f_k}{2} + \frac{F_\xi^2}{f_m - f_k} \frac{T_m - T_k}{\xi} \frac{\xi^2}{T_m T_k} \frac{1}{8Q_\xi^2} \quad (1a)$$

$$\frac{1}{Q^2} = \frac{\xi}{T_k} \frac{1}{Q_\xi^2} - \left(\frac{f_m - f_k}{F_\xi} + \frac{F_\xi}{f_m - f_k} \frac{T_m - T_k}{\xi} \frac{\xi^2}{T_m T_k} \frac{1}{4Q_\xi^2} \right)^2 \quad (1b)$$

One sees that at least two external frequencies are required to find the changing resonant frequency and Q-factor. Having more than two observer frequencies allows one to have an effective means to filter noise and reject erroneous signal values.

To find the changes in the sample dielectric constant and loss-tan as per (step 4) one uses:

$$\frac{\Delta \epsilon}{\epsilon} = 1 + A \frac{F - F_\xi}{F_\xi} + B \left(\frac{F - F_\xi}{F_\xi} \right)^2 + \dots \quad (2a)$$

$$\Delta(\text{loss tan}) = C \left(\frac{1}{Q} - \frac{1}{Q_\xi} \right) \left(1 + D \frac{F - F_\xi}{F_\xi} + E \left(\frac{F - F_\xi}{F_\xi} \right)^2 + \dots \right) \quad (2b)$$

where the coefficients A, B, C, D and E are dependent on the geometry and found after numerical simulations in e.g. HFSS.

To find corresponding changes in the density of free electrons, one uses a reasonable assumption about our medium under test. In the case of the dielectric thin-wall tubing, the model is yet to be fully developed. However, the proposed method can be used, in principle, to investigate any medium, for instance a plasma discharge, as we will demonstrate in the next section. For uniform plasma discharges, we can use well known relationships between the density of free electrons, n_e , and their collision frequency, F_{coll} and the plasma dielectric constant $\epsilon_0(\epsilon_{\text{Re}} + j\epsilon_{\text{Im}})$.

$$\epsilon_{\text{Re}} = 1 - \frac{n_e \cdot e^2}{m_e \epsilon_0 (2\pi F_\xi)^2} \frac{1}{1 + (F_{\text{coll}} / F_\xi)^2} \quad (3a)$$

$$\epsilon_{\text{Im}} = \frac{n_e \cdot e^2}{m_e \epsilon_0 (2\pi F_\xi)^2} \frac{F_{\text{coll}} / F_\xi}{1 + (F_{\text{coll}} / F_\xi)^2} \quad (3b)$$

where e , and m_e are the electron charge and mass respectively, and $\epsilon_{\text{Im}} = \epsilon_{\text{Re}} \cdot \text{loss-tan}$.

Knowing ϵ_{Re} and loss-tan and solving the equations above one can find the free electron density and collision frequency. In this particular case (uniform plasma discharge, and $A \approx -D$), the free electron density is given rather by a simple formula

$$n_e[cm^{-3}] = 10^6 \frac{F_\xi^2[MHz]}{80.6} (-A) \frac{F - F_\xi}{F_\xi} \left(1 + \left(F_\xi \frac{1/Q - 1/Q_\xi}{(F - F_\xi)} \frac{C}{A} \right)^2 \right) \quad (4)$$

where the coefficients A and C are those that appear in Formulas 2.

In the case of the dielectric thin-wall tubing, the model might be different (it is beyond the scope of this article to describe it) but the principles remain the same.

Proof- of – principle experiment to validate the technique:

For the proof-of-principle experiment, we applied our technique to the case of a plasma discharge contained within a quartz tube (the dielectric here), since it is well known how it behaves [9-11]. This choice was also required by not having access to a suitable beam-line that would provide a dielectric wakefield accelerator, namely a relativistic charge bunch that passes through a hollow dielectric tube.

Figure 3 shows the diagram of the setup, which is another particular implementation of the generic diagram shown earlier in Fig. 1. The discharge tube was located along the axis of the cavity that has a resonant frequency $F_\xi = 2479.157\text{MHz}$, and $Q_\xi = 1175$ (corresponding to $BW_\xi = 2.11\text{ MHz}$). The values are denoted with the subscript ξ to indicate that they are found when there is no discharge or deposited/free electrons present. The changes in transmission were monitored at 3 different frequencies: $f_1 \approx F_\xi$; $f_2 \approx F_\xi + (BW_\xi/2)$ and $f_3 \approx F_\xi + BW_\xi$, (the other choice was to monitor at $f_1 \approx F_\xi - (BW_\xi/2)$; $f_2 \approx F_\xi$ and $f_3 \approx F_\xi + BW_\xi/2$).

(...Figure 3 goes here...)

(...Figure 4 goes here...)

An example of recorded traces of the microwave signal vs. time, as obtained in our proof-of-principle runs with plasma-discharge columns, is shown in Fig 5. The corresponding current behavior is shown in Fig 6.

(...Figure 5 goes here...)

(...Figure 6 goes here...)

Figure 7 shows an example of the resulting changes in the cavity resonant frequency. An example of the found changes in the dielectric constant (by applying formulas 2) is shown in Fig. 8. For the geometry as shown in Fig. 9, the coefficients were found to be:

$$A = -22.558, \quad B = -5.4 \times 10^{-4}, \quad C = 11.305, \quad D = 22.581, \quad \text{and} \quad E = 648.776.$$

Figure 10 gives an example of the resulting free electron density.

(...Figure 7 goes here...)

(...Figure 8 goes here...)

(...Figure 9 goes here...)

(...Figure 10 goes here...)

Discussion and conclusions:

One observes that the method dynamic range is $\sim 20\text{dB}$, and the detected minimum electron density is about 10^8 cm^{-3} .

The upper limit is dictated here by the limited number of observer frequencies (only 3). If there is a high density of free electrons, the frequency shift is significant, and is out of the coverage range of the comb of the observer frequencies: this brings the signal-to-noise ratio down and beyond detection. If however, the frequency comb can cover a wide range, the dynamic range can be increased (in principle by tens of dB).

The lower electron density limit can be improved by increasing the cavity Q-factor. This follows from the fact that, at low densities of free electrons, $n_e \sim BW_\xi$. In our present setup, $Q \sim 1000$, and the minimum density $n_{e, \min} \sim 10^8 \text{ cm}^{-3}$; If one works, however, with $Q \sim 3000-5000$, this will still allow us to capture the processes on the *micro*-sec time-scale, yet to detect $n_{e, \min} 2 \div 4 \times 10^7 \text{ cm}^{-3}$.

Lastly we would like to draw an attention to the cited in literature values for the dielectric constant and loss-tan of certain materials like quartz and alumina. To find the dielectric constant of Quartz (SiO_2 or fused silica) and Alumina (Al_2O_3 , 99.6% pure), a set of samples were ordered from two manufacturers: <http://technicalglass.com> and <http://advaluetech.com>. The quartz samples were either $13 \times 15 \text{ mm}$ or $12 \times 16 \text{ mm}$ (ID $\times$ OD); the alumina samples were either $9.51 \times 13.02 \text{ mm}$ or $9.585 \times 12.91 \text{ mm}$. We denote these samples by following code-names: Q13:15, Q12:16, A9.51:13.02, and A9.59:12.91. To find the properties of interest, the samples were placed in the cavity with a high Q-factor ($\sim 10,000$), operating near 2.5 GHz. The changes in the resonant frequency and Q-factor were recorded. HFSS simulations were run in which one adjusted the loss-tangent and dielectric constant of the material under test to achieve the frequency shifts and changes in Q-factor as had been observed in the experiments. All the samples were thoroughly washed with Acetone. Certain samples (Alumina) were sanded to skim a thin outer layer: for these no changes – within the measurement accuracy - were found between the same (processed and not-processed) samples. The results are tabulated in Table 1.

Table 1: Raw data and inferred dielectric constant and loss-tangent near 2.5 GHz

Sample	Material	Changes in Frequency (MHz)	Changes in 1/Q	Dielectric constant**	Loss-tan***
Q13:15	Quartz	-83.57	*	3.408	$< 1 \times 10^{-5}$
Q12:16	Quartz	-162.67	*	3.391	$< 1 \times 10^{-5}$
A9.51:13.02	Alumina	-313.06	3.86×10^{-4}	8.731	1.38×10^{-3}
A9.59:12.91	Alumina	-289.28	2.85×10^{-4}	8.023	1.09×10^{-3}

* cannot be measured within the measurement accuracy; ** $\Delta\epsilon = 6 \times 10^{-3}$; *** $\Delta(\text{loss-tan}) \leq 1 \cdot 10^{-5}$ (for Quartz); and $\Delta(\text{loss-tan}) \leq 5 \cdot 10^{-5}$ (for Alumina)

One observes that extreme care must be taken when designing a DWA apparatus: the numbers for the loss-tan and dielectric constant as found in the literature cannot always be used. Thorough measurements on sample batches (certification) must be performed to find the values of the parameters of the interest.

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Figures and Captions:

Figure 1: the principal diagram of generic measurement system, whose particular implementations are as shown in Figures 2 and 3

Figure 2: Diagram of a detector to install at an accelerator: 1 – tunable frequency generators; 2 - circulators; 3 – variable amplifier; 4 – power combiners; 5 – fast RF switches; 6 – cavity with samples under test; 7 – high frequency output amplifier; 8 – local oscillator; 9 – mixer; 10 – band-pass frequency filters; 11 – crystal detectors; 12- low frequency amplifiers; 13 – oscilloscope; 14 – GPIB/USB-Ethernet/USB adapter; 15- computer.

Figure 3: the schematic of the experimental setup used in the proof-of-principle experiments.

Figure 4: Photo of the setup used in the proof-of-principle experiments

Traces were recorded at three observer frequencies:

f1 = 2479.1936 MHz ($\approx$ resonant frequency) (RED, #1)

f2 = 2480.276 MHz (BLUE, #2)

f3 = 2481.141 MHz (BROWN, #3)

*Input power stays the same

This "jump" in the traces data points will give us our sensitivity

Figure 5: Microwave signals transmitted through the resonator which is loaded with plasma, using three different frequencies.

Figure 6: Current behavior during the time of discharge.

Figure7: Changes in the resonant Frequency (2 MHz/div) vs. time (100msec/div).

Figure 8: Changes in Real part of dielectric constant vs. time (msec)

Figure 9: geometry of the used sample.

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Figure 10: Electron density ($\times 10^9 \text{ cm}^{-3}$) vs. time (msec)