EXPERIMENTAL AND NUMERICAL STUDIES OF DIELECTRIC WAKE FIELD ACCELERATION DEVICES*

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Abstract

Results are reported from experiments, and numerical analysis of wake fields set up by electron bunches passing through a cylindrical dielectric liner made of alumina. The bunches excite many TM- modes, and the *Ez* component of wake field is sharply localized on the axis periodically behind the bunches. The experiment is at ATF Brookhaven, and uses up to three 50 MeV bunches spaced by one wake field period (*21* cm) to study the superposition of wake fields by measuring the energy loss of each bunch after it passes through the 53-cm long dielectric element. The millimeter-wave spectrum of radiation excited by the passage of bunches is of interest too. The numerical analysis was aimed not only to simulate the behaviour of our device, but in general to predict dielectric wake field accelerator (DWA) parameters. It is shown that one needs to match the radius of dielectric channel with the bunch longitudinal rms-length to achieve optimal performance.

INTRODUCTION

In a dielectric wake field accelerator, a dielectric loaded waveguide supports wake fields radiated by the passage of an electron bunch (e-bunch), which travels at a speed exceeding that of light in the structure. Our studies here relate to a cylindrical structure, consisting of a thick cylindrical shell of alumina (high dielectric constant $\kappa\sim 9.6$) having a small bore hole (radius $A = 1.5$ mm) and an outer radius ($R = 1.9$ cm), all contained within a close-fitting conducting cylinder, which serves as a vacuum wall. The waveguide dimensions and dispersion free dielectric with large κ will favour the coherent superposition of many waveguide modes [1,2,3]. In this, we describe a multi-bunch experiment, with the purpose to measure the energy loss of a short drive bunch train. Very short bunches will be employed to favour wake fields of high amplitude, also shown by micrometer scale rectangular structures excited by fsec driving bunches [4,5].

A variety of numerical studies having to do with DWA performance is presented. We assume that the wake fields interact with Gaussian- shaped bunches (commonly produced by RF- guns) with the head- half width σ_1, tail half- width σ_2, and negligible (mostly) transversal features. If not specified otherwise, κ=9.65, $A = 1.5$ mm, $R= 1.931$ cm, $\sigma_1 = 1$ ps, $\sigma_2 = 2.5$ ps, initial energy = 50 MeV.

NUMERICAL STUDIES

Many recently conducted theoretical studies consider only the interaction between wake fields and infinitely thin electron bunches, but only by taking into account the real longitudinal features of an electron beam, can one predict the efficiency, energy spread, and acting accelerating gradient on a test bunch, which comes after the train of N driving bunches. Describing the wake fields inside of a circular waveguide through the decomposition into the normal eigen-modes [3], and advancing this approach toward computation of the energy exchange between electron bunches and the electromagnetic fields one finds that the power radiated by a train of e-bunches is:

$$P=\frac{Q_0^2\cdot\beta\cdot c}{16\pi\cdot\varepsilon_0\cdot A^2}\sum_m\left(\Omega_m\cdot\sum_{i,j}q_i\cdot q_j\cdot\cos\left(\frac{\omega_m\cdot(z_i-z_j)}{\beta\cdot c}\right)\right)$$

where Q_0 – reference charge; $q_i=Q_i/Q_0$ with Q_i - charge of i[th] bunch; ω_m – eigen frequencies of the structure;

$$\Omega_m=\frac{f_m^2(0)}{\alpha_m}\cdot\left(\left(\Gamma_c^m\right)^2+\left(\frac{\Gamma_s^m}{2}\right)^2\right)$$

with f_m – eigen functions, α_m – normalization coefficients, and Γ_c^m, Γ_s^m are given by:

$$\Gamma_c^m=\frac{\sigma_1}{\sigma_1+\sigma_2}\exp\left(-\left(\frac{\omega_m\cdot\sigma_1}{2\cdot\beta\cdot c}\right)^2\right)+\frac{\sigma_2}{\sigma_1+\sigma_2}\exp\left(-\left(\frac{\omega_m\cdot\sigma_2}{2\cdot\beta\cdot c}\right)^2\right)$$

$$\Gamma_s^m=\frac{\sigma_1}{\sigma_1+\sigma_2}\exp\left(-\left(\frac{\omega_m\cdot\sigma_1}{2\cdot\beta\cdot c}\right)^2\right)-\frac{\sigma_2}{\sigma_1+\sigma_2}\exp\left(-\left(\frac{\omega_m\cdot\sigma_2}{2\cdot\beta\cdot c}\right)^2\right)$$

Every bunch is located along the z- axis at z_i, moves at the speed of $\beta\cdot c$, and has the same shape, but different charge.

Deploying this expression for the case where the first N- bunches, spaced at $z_i=L\cdot(1-i)$, pump energy into the wake, and the very last bunch, located at $z_T=L\cdot(1-N-1/2)$ is accelerated, one derives the expressions for the set of parameters which should be used to describe a wake field apparatus as an accelerator device (L = wake field period):

- enhancement of the wake field due to its amplification by the train of N bunches:

$$\xi=\left(\sum_{m,i,j}^{\infty,N,N}\Omega_m\cdot\cos\left(\frac{\omega_m\cdot L\cdot(i-j)}{\beta\cdot c}\right)\right)\Big/\sum_m^{\infty}\Omega_m$$

- structural ratio (we are introducing now as)

$$\chi_\rho=-\left(\sum_m\Omega_m\cdot\sum_i^N\cos\left(\frac{\omega_m\cdot L(N-i+1/2)}{\beta\cdot c}\right)\right)\Big/\sum_m\Omega_m$$

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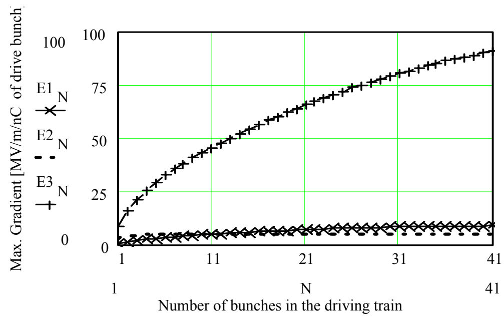
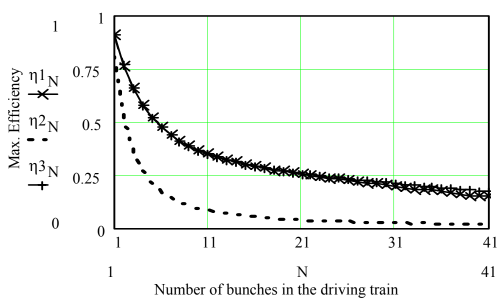
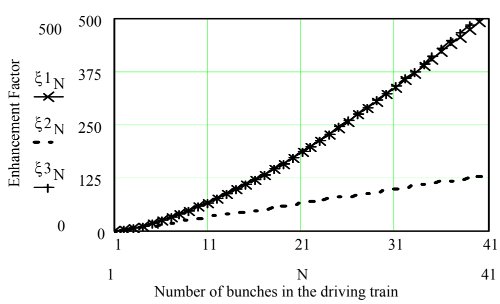


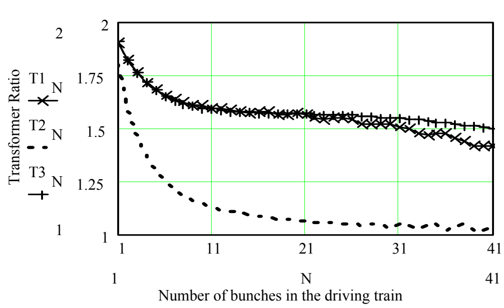
a) maximum possible accelerating gradient acting on a test bunch (given per [nC] of a driving bunch); the upper ($E3_N$) curve corresponds to the narrow bunch + small channel radius in the dielectric slab



b) maximum possible efficiency of energy transfer



c) enhancement of the wake field due to its coherent amplification by the train of N bunches



d) transformer ratio

Figure 1: Parameters of DWA are shown for the different bunch length and dielectric hole radius (σ_1, σ_2, A).
#1 – (1 ps, 2.5 ps, 1.5 mm) – solid, marked by “X”,
#2 – (1 ps, 2.5 ps, 0.5 mm) – “dot”,
#3 – (0.33 ps, 0.83 ps, 0.5 mm) – “dash”, marked by “+”

- efficiency of energy transfer from the N- bunch train to a test bunch of charge $Q_T = q_T \cdot Q_0$

$$\eta = \frac{2 \cdot q_T \cdot \chi_\rho - q_T^2}{\xi}$$

with its maximum value of

$$\eta_{MAX} = \frac{\chi_\rho^2}{\xi}$$

- acceleration gradient acting on the test bunch:

$$E_T = \frac{Q_0}{16 \cdot \pi \cdot \varepsilon_0 \cdot A^2} \sum_m \Omega_m \cdot \left(2 \cdot \chi_\rho - q_T\right)$$

- customarily used transformer ratio [2] is expressed as:

$$TR_N = 2 \cdot \eta_{MAX} \frac{N}{\chi_\rho}$$

One sees that maximum efficiency occurs when a test charge equals χ_ρ, while the accelerating gradient drops down by 2 times from its possible maximum. Only a test charge less than $2 \cdot \chi_\rho$ can experience acceleration.

Fig. 1 gives examples of performances for several cases. The maximum gradient of 256 MV/m will be achieved after 20 narrow driving bunches each with charge Q_0 = 4 nC (see the #3 case.) One can increase significantly the accelerating gradient by reducing the channel radius in a dielectric only if it is accompanied by bunch shortening. The reason for this is that both the wake field peak where acceleration/ deceleration occurs and an e-bunch are features of almost the same longitudinal dimensions. When one reduces the channel radius the wake field can become narrower than the bunch, which leads to reduction of all performances (see the case #2 in Fig. 1, b), c), d). Fig. 2 demonstrates that when mismatching between the bunch length and the channel radius happens, almost all driving bunches (N≥ 4) cannot lose energy above some limit.

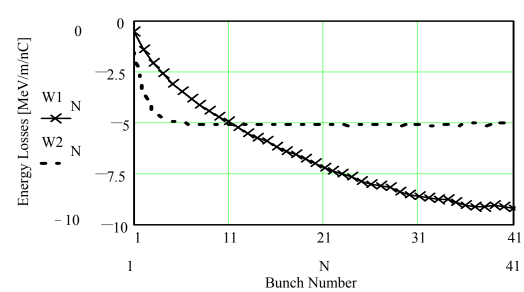


Figure 2: Energy lost by every consecutive driving bunch for different (σ_1, σ_2, A):
#1 – (1 ps, 2.5 ps, 1.5 mm) – solid, marked by “X”;
#2 – (1 ps,2.5 ps, 0.5 mm) – “dot”

In considering narrowing the driving bunches to improve performance, one should keep in mind that excessive narrowing may lead to an increment in the test bunch energy spread when a few drive bunches are used. The only reliable way to prevent it is to narrow the test bunch. For drive (σ_1, σ_2) ≈ (1 ps; 2.5ps), and test (σ_1, σ_2) ≈ (0.3 ps; 0.8ps) the energy spread does not exceed 15 %.

The accuracy of bunch spacing (between any bunch and the reference bunch) must be better than 425 μm to avoid any performance decrease larger than 15 %. This also means that our model is valid when the time slippage of a bunch is within this range after interaction with the wake field. Thus, the DWA length must not exceed some limit, or, equivalently the acceleration gradient should be sufficiently high.

The Tab. 1 shows the lowest limit on gradient $E_{lim,min}$ when one plans to have gross energy losses/gain of W.

Table 1: Lowest gradient vs. planned energy gain/losses to use this numerical model

W [MeV]	0.1	1	10	50
$\boldsymbol{E_{lim,min}}$ **[KV/m]**	0.05	4.8	375	4600

For the structure at ATF- BNL with the drive (σ_1, σ_2) ≈(1ps; 2.5 ps), Q0 ≈300 pC the decelerating/accelerating gradient is at least 500 times larger than the limit. The energy losses are: 1st bunch – 78; 2nd – 212; and 3rd – 315 KeV. The maximum accelerating gradient is 716 KV/m (after N= 3 drive bunches), and the acting gradient on a test charge of 150 pC will be 537 KV/m.

Should another set of (σ_1, σ_2, Q_0, κ, A, etc) occur, the model allows the "quick-to-predict" computation of energy losses/gains and any other relevant parameters (ξ, η, E_T, etc)

EXPERIMENTAL STUDIES

Oversize alumina castings were obtained from LSP Industrial Ceramics (Lambertville, NJ). Since no sample 53 cm in length had the straightness of bore hole that was required, it was decided to use two selected shorter sections smoothly butted together and fitted into a metal-walled cylindrical vacuum jacket and waveguide. Initial measurements of the spectrum of TM_{0n} modes (after a single bunch) were made on a slightly oversized sample [6], which was then ground to the correct dimension (Fig. 3) for this experiment. A new measurement (Tab. 2) of the TM_{0N} frequencies shows that the wake field period is 21 cm.

The apparatus is installed on the 2nd beamline of the ATF- BNL, which was redesigned to meet the experimental (Fig. 4) requirements. New focusing triplets were introduced, together with beam profile monitors (BPMs) to produce the small e-beam transverse size and a suitable alignment to pass the bunch down the hole in the dielectric. The HeNe laser-and-optical system was employed to check the alignment on every assembling and operational step. The transport dynamics of the redesigned line has been studied intensely to insure matching between the ATF rf- linac and the apparatus.

The three driving bunches are obtained by splitting an optical pulse into three precisely delayed pulses, which impinge on the rf- photocathode gun within 30° of the peaks of 2.8 GHz field to generate the compressed electron bunches that are suitable for the excitation of multiple TM- mode wake fields. The spacing between drive bunches (equal to the wake field period L) will be adjusted to maximize energy losses of every individual bunch. Since in this test experiment no large bunch charge is available, the energy losses can be comparable with the energy jitter of the diagnostic apparatus, and a technique is being developed to maintain the same energy over a significant period of time.

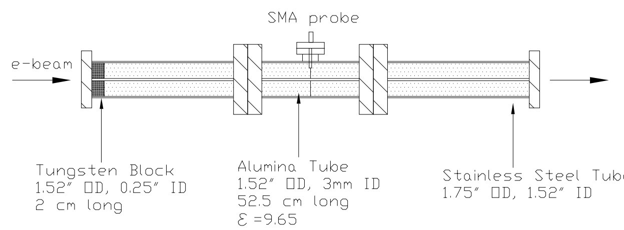


Figure 3: Apparatus drawing and dimensions

Table 2: Spectrum for TM_{01} – TM_{06}♣

M#	1	2	3	4	5	6
Exp.	2.04	4.70	7.45	10.14	12.99	15.68
Th.	2.03	4.72	7.45	10.21	13.02	15.83

♣ *(frequencies in [GHz], M# - mode number, Exp. – experimental data, Th. – theoretical prediction ± 1% which results from κ =9.65 + 1%, R= 19.31 mm ± 0.3%, A= 1.5 mm ± 1%·R (the best manufacturing accuracy)*

Figure 4: DWA experiment at ATF

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