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Calculation of PETS Using Dielectrics for CLIC type TBA Applications

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Abstract: In this note we examine a new approach for the CLIC PETS (Power Extraction and Transfer Structure] by replacing the conventional metal structure with a thin layer of high dielectric constant material. We found that the use dielectric materials with high ε can be very competitive in comparison with the current CLIC design. In one particular configuration, we can obtain R/Q=100 ohms and βg=0.5 with much smaller transverse wakefield effects.

Introduction

In the current design of the compact linear collider (CLIC) [1], the scheme for the drive beam decelerator uses 4,6, or 8 channel-type slow wave structures to extract rf power from an intense drive beam passing through. One criteria for a "good" decelerator is that it has a low group velocity but relatively low R/Q. Another feature I think is also very important is the uniformity of the deceleration field across the gap to ensure that no wakefield focusing forces exists.

Dielectric loaded waveguides have long been considered as a power extraction device for wakefield accelerators [2]. The dielectric loaded waveguide has significant advantages:

- Effective transverse mode damping. The deflection modes HEM_{mn} can be easily canceled by using Chojnacki's scheme [3].
- The deceleration field across the gap is uniform for relativistic beams, which is exactly what needed for CLIC type TBA design.
- By adjusting varying the dielectric constant, one indeed can achieve low βg with low R/Q as shown below.

A typical dielectric loaded structure is shown in Figure 1.

Based on the above arguments, we have made a few sets of calulation to explore the possiblities of using dielectric materials for PETS structures.

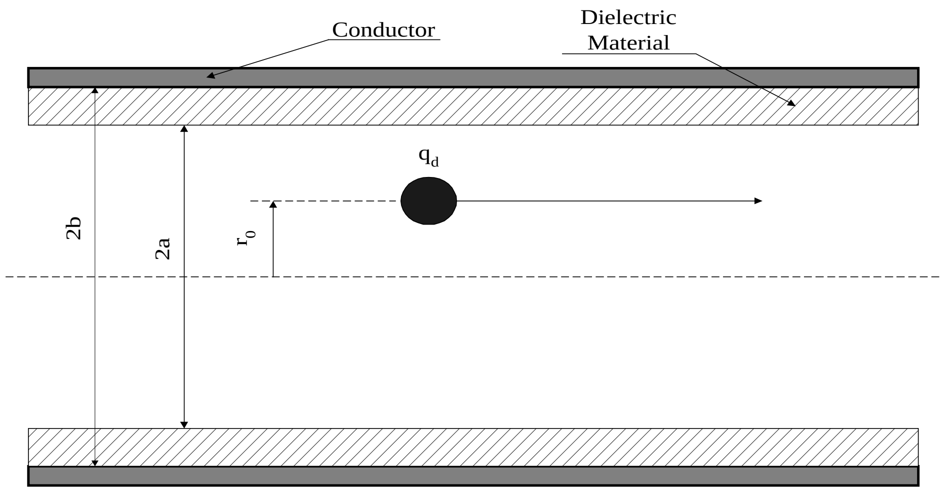

Figure 1. Schematic of dielectric loaded waveguide as a potential CLIC PETS.

Formulation

1. Deceleration field

A relativistic charged particle bunch (q_d) passes through a partially loaded dielectric (ε) waveguide with inner radius *a* and outer radius *b* will radiate according to the Cherenkov condtion. The radiated field can be expressed as

$$E_z(r,z) = \frac{4q_d}{\varepsilon a}\sum_n \left\{ \frac{R_0(sa)I_0(kr)}{\frac{d}{ds}\left[R_0'(sa) - \frac{sa}{2\varepsilon}R_0(sa)\right]} \right\}_{s=s_n} \cos(k_z Z_0) \qquad (1)$$
$$= \sum_n E_{zn} I_0(kr)\cos(k_z z)$$

where s_n satisfies the condition

$$R_0'(sa) - \frac{sa}{2\varepsilon}R_0(sa) = 0$$

and

$$s = \frac{\varpi}{v_p}\sqrt{\varepsilon - 1}$$

$$k_z = \frac{\varpi}{v_p}$$

$$R_0(sa) = N_0(sb)J_0(sa) - J_0(sb)N_0(sa)$$
$$R_0^{'}(sa) = N_0(sb)J_0^{'}(sa) - J_0(sb)N_0^{'}(sa)$$

In the following discussion, the phase velocity of the wave is taken as $v_p = c$. One interesting feature is that in the relativistic limit, $k \to 0$, and $I_0(kr) \to 1$. Thus deceleration field across the vacuum gap is constant.

By using equation (1), all other field components can be obtained easily. In general, we are only interested in the lowest excited mode. It is a pure TM_{01} mode.

2. Definition of R/Q

Here we use the same definition as in the CLIC note 364.

$$\frac{R}{Q} = \frac{4E_{z0}}{q_d \varpi}$$

Since we can obtain E_{z0} by simply evaluating equation (1), calculating R/Q is straightforward.

3. Transverse Wakefield.

When a beam passing through the dielectric loaded structure with an offset r0, it will generate transverse wakefields as

$$W\perp(r_0, z) = \frac{8q_d r_0}{a^2} \sum_n \frac{E_{1n}}{k_z} \sin(k_z z) \qquad (2)$$

where

$$E1n = \left| s \frac{d}{ds} \left\{ \frac{\varepsilon + 1}{s^2 a^2} - \frac{1}{2} - \frac{1}{sa} \left[\frac{S_1^{'}(sa)}{S_1(sa)} + \varepsilon \frac{R_1^{'}(sa)}{R_1(sa)} \right] \right\} \right|_{s=s_n}$$

similar to the longitudinal case, the s_n satisfy

$$\frac{\varepsilon + 1}{s^2 a^2} - \frac{1}{2} - \frac{1}{sa} \left[\frac{S_1^{'}(sa)}{S_1(sa)} + \varepsilon \frac{R_1^{'}(sa)}{R_1(sa)} \right] = 0$$

and

$$R_1(sa) = N_1(sb)J_1(sa) - J_1(sb)N_1(sa)$$
$$R_1^{'}(sa) = N_1(sb)J_1^{'}(sa) - J_1(sb)N_1^{'}(sa)$$
$$S_1(sa) = N_1^{'}(sb)J_1(sa) - J_1^{'}(sb)N_1(sa)$$
$$S_1^{'}(sa) = N_1^{'}(sb)J_1^{'}(sa) - J_1^{'}(sb)N_1^{'}(sa)$$

Now we have the complete formulation for dielectric wakefield calculations.

Design of the PETS using a dielectric tube and numerical results.

In this section we discuss a reference design for CLIC PETS. The free parameter in our calculation is the dielectric constant for a given 30 GHz structure. The inner diameters are fixed at 2, 2.2,2.4 cm as in the CLIC note 364. By using above formulas, we give our calculated results below. The content of the table is self explanatory.

Case 1 a=1 cm

Dielectric constant	a (cm)	b (cm)	βg	R/Q (Ω)	Wz(MV/ m/nC)	W⊥(V/pc /mm/m)	f (GHz) W⊥
20	1	1.03585	0.764	4933.45	0.233365	7.005	29.512
50	1	1.02649	0.705	3672.82	0.17299	5.364	29.632
100	1	1.02038	0.645	2789.40	0.131381	4.023	29.742
200	1	1.01531	0.572	2055.88	0.096832	3.011	29.796
500	1	1.01022	0.464	1336.62	0.062955	1.985	29.854
1000	1	1.007418	0.382	955.37	0.044998	1.422	29.906
5000	1	1.003436	0.218	431.21	0.02031	0.644	29.957
10000	1	1.0024497	0.165	305.32	0.01438	0.457	29.978
25000	1	1.0015606	0.111	194.05	0.00914	0.289	29.981

Case 2 a=1.1 cm

Dielectric constant	a (cm)	b (cm)	βg	R/Q (Ω)	Wz(MV/ m/nC)	W⊥(V/pc /mm/m)	f (GHz) W⊥
20	1.1	1.134135	0.805	4300.38	0.202548	5.092	29.575
50	1.1	1.125637	0.756	3260.11	0.153551	3.914	29.676
100	1.1	1.119915	0.704	2500.27	0.117763	2.882	29.752
200	1.1	1.115067	0.638	1854.50	0.087347	2.135	29.816
500	1.1	1.110115	0.535	1211.64	0.057068	1.392	29.880
1000	1.1	1.107368	0.451	867.05	0.040838	0.995	29.913
5000	1.1	1.103426	0.271	391.89	0.018458	0.449	29.960
10000	1.1	1.102445	0.208	277.49	0.01307	0.318	29.967
25000	1.1	1.101559	0.143	175.67	0.008274	0.201	29.974

Case 3 a=1.2 cm

Dielectric constant	a (cm)	b (cm)	βg	R/Q (Ω)	Wz(MV/ m/nC)	W⊥(V/pc /mm/m)	f (GHz) W⊥
20	1.2	1.232538	0.837	3779.51	0.177968	3.702	29.626
50	1.2	1.224817	0.797	2914.43	0.13727	2.858	29.712
100	1.2	1.219462	0.752	2257.49	0.106328	2.212	29.776
200	1.2	1.214827	0.694	1686.03	0.079412	1.650	29.833
500	1.2	1.210015	0.598	1106.71	0.052126	1.081	29.892
1000	1.2	1.207317	0.516	793.39	0.037369	0.774	29.923
5000	1.2	1.203416	0.325	359.08	0.016913	0.350	29.961
10000	1.2	1.202439	0.254	254.44	0.011984	0.248	29.980
25000	1.2	1.201557	0.178	161.02	0.007484	0.157	29.975

Case 4 a=2.0 cm (large aperture)

Dielectric constant	a (cm)	b (cm)	βg	R/Q (Ω)	Wz(MV/ m/nC)	W⊥(V/pc /mm/m)	f (GHz) W⊥
1000	2.0	2.006931	0.828	465.64	0.021932	0.171	29.924
5000	2.0	2.003335	0.689	214.56	0.010106	0.078	29.981
10000	2.0	2.002399	0.612	152.31	0.007174	0.057	29.987
25000	2.0	2.00154	0.5	96.58	0.004549	0.035	29.997

Discussion

As we can see above, the βg and R/Q follows the same trend as we change the dielectric constant. One clear conclusion we can make is that we need much higher dielectric constant (in the range of 1000 – 25000) materials to compete with the existing CLIC PETS design. A few notable results are listed below:

- For almost the same R/Q and βg, the transverse wakefield amplitude is smaller, particularly in case 4.
- One can achieve low R/Q and low βg by increasing the dielectric constant and inner radius at the same time.
- The transverse wake field excitation frequencies are very close to that of the TM_{01} mode, but slightly lower (as in the current PETS design).

There are also a few practical issues need to be addressed:

- Availablity of the materials: There is a class of ceramic called Relaxor [4]. Its dielectric constant is in the range of 1000 – 30000, and can be tuned easily with temperature changes. High field and high frequency properties of these materials are presently unknown. Although tests at 1 MV/m (DC) show no breakdown.
- Thin layers of dielectric materials are needed, in some cases only a few tens of microns. But those thickness are considered to be “bulk” in the eyes of materials

scientists. There are no fundamental reasons not to expect that we achieve these design parameters.

In summary, we found that dielectric loaded structures are not only suitable as a decelerator for CLIC type TBA, but also have distinct advantages.

I would like to thank Ron Ruth for his suggestion on the subject of deceleration devices using the dielectrics.

Reference:

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4. J. Kelly et al, "Effect of composition on the electromechanical properties (1-x)Pb(Mg1/3Nb2/3)O3-xPbTiO3 Ceramics", J. America Ceramic Soc., 80 (4), p. 957