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RF pulse heating of the accelerating structures used in the proposed 3TeV ANL Flexible Linear Collider

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Abstract: AWA recently proposed a high energy (3TeV) linear collider based on a short rf pulse (~22ns flat top), high gradient (~267MV/m of the loaded gradient), high frequency (26GHz) two beam accelerator scheme [1]. This article concentrates on rf pulse heating calculation of the accelerating structures used in the conceptual collider design. Although none of the parameters in [1] is fixed, we like to have this 'might-be' rf breakdown related parameter estimated as a continuation work of ref [1].

Intensive rf breakdown studies in the recent years indicate that RF pulse heating might be one of main factors to cause rf breakdowns in metallic accelerating structures [2]. Unlike the average thermal effect that is a volume temperature rise due to the rf power dissipation in the accelerating structure (it can be cured by cooling system), the rf pulse heating is an instant phenomenon occurring in the skin depth of metallic surface. Contraction and expansion of the metal surface due to the local temperature variation by the rf pulse heating will cause the metal fatigue on the surface, which might lead to a rf breakdown.

The rf pulse heating can be calculated by [3, 4]

$$\Delta T = H_{\max}^2 \sqrt{T_p} \frac{R_s}{\sqrt{\pi \rho C k}}, \tag{1}$$

where ΔT--- local surface temperature rise (°C), H_{max}--- maximum magnetic field under the average unloaded gradient (A/m), T_p--- rf pulse length (Sec), R_s--- metal surface resistance (ohm), ρ---metal mass density (kg/m^3), C---metal specific heat capacity (J/(kg· °C), and k--- metal thermal conductivity (W/(m· °C)). We can see that, other than the thermal properties of the metal material, magnetic field on the structure surface plays the most important role in the pulse heating mitigation.

Rf pulse heating in DLA structures

The single layer DLA structure intrinsically has a low electric field (Es/Ea<<1 in a general case) but high magnetic field on the metal surface [5]. Multilayered DLA structure can reduce the magnetic field on the metal surface but may sacrifice other parameter, like R/Q, since the Q improvement is more rapid than the shunt impedance [6]. Here we just concentrate on the conventional single layer DLA structure (refer Fig. 1 for the general geometry and magnetic field profile). Plugging the parameters from ref. [1] into Eqn. (1), we can estimate the rf pulse heating for dielectric based 26GHz short

pulse power extractor and accelerator. Results are summarized in Table 1. Note the pulse heating temperatures shown in Table 1 are significantly higher than that of the conventional metallic structure, where temperature rise from the pulse heating is usually less than 60 degrees. However, unlike the metallic structure, there is no high electric field appears at the surface of a DLA structure. It is still debatable if the breakdown will occur at this level of pulse heating. Nevertheless, it generates a concern.

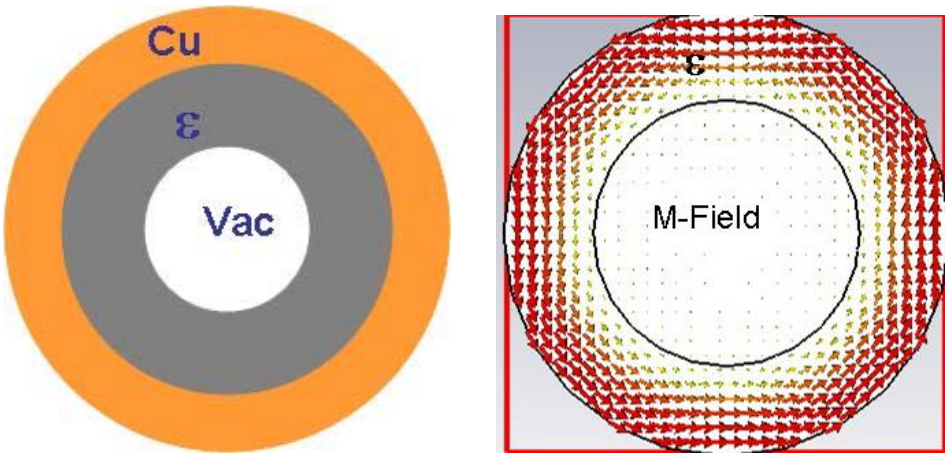

Figure 1. The transverse geometry and the typical magnetic field profile of a conventional single layer DLA structure.

Table 1. rf pulse heating of the dielectric structures used in 3TeV LC design [1]. Values are estimated based on the unloaded gradient of 316MV/m, 22ns pulse length.

Structures for 3TeV LC design	H_{max}	Pulse heating
26GHz DLA	1.853 MA/m	329 °C
26GHz DWPE	1.064 MA/m	108 °C

Conventional metallic structure

Since the pulse heating temperature looks like severe based on the best knowledge from the rf breakdown test of metallic structures (although it is unnecessary to lead to the same scenario for DLA structures for the reason mentioned above), we did a simple alternative case study---replace the DLA accelerators with the metallic counterparts. A basic 26GHz 2pi/3 mode traveling wave disk-loaded structure is designed. Parameters is tuned close to those of the DLA structure. Figure 2-4 show the electric field profile, group velocity, and phase velocity. And some other parameters are summarized in Table 2. The simulation was done using CST MicrowaveStudio®. It should point out that, at this moment, the simulation is just for a coarse estimate (mesh study was not performed in the simulation.).

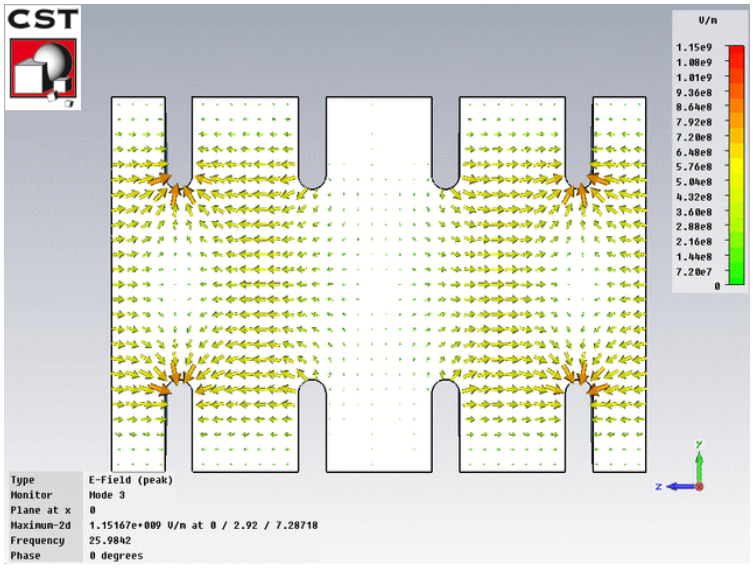

Figure 2. Electric field profile of a high group velocity 2pi/3 mode disk-loaded accelerator, which serves as an alternative to the 26GHz DLA structure in the 3 TeV short pulse collider design.

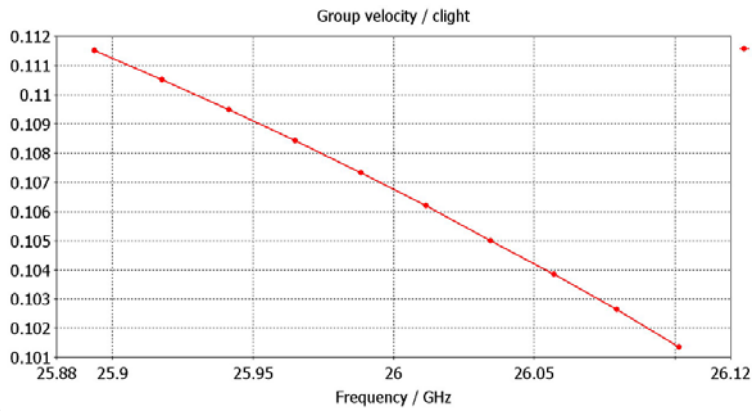

Figure 3. Simulated group velocity of the structure presented in Fig.2.

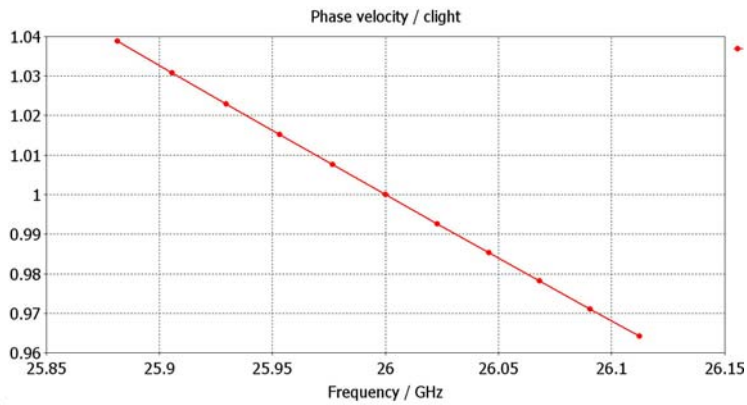

Figure 4. Simulated phase velocity of the structure presented in Fig.2.

Table 2. Major accelerating parameters of the structure presented in Fig.2.

parameters	**value**
a/λ	0.2255
Vg	10.67%c
R/Q	19.16 kΩ/m
Q	4910
Shunt impedance	94.08 MΩ/m

Both the magnetic field and electric field distributions are plotted in Figure 5, and the pulse heating temperature rise and maximum EM field strength are presented in Table 3. Those values are obtained under the condition of the structure operating at the same gradient as the DLA structures, 316MV/m, 22ns pulse width. It notes that the pulse heating now drops to an acceptable range due to the low magnetic field but the electric field around the iris becomes significantly high.

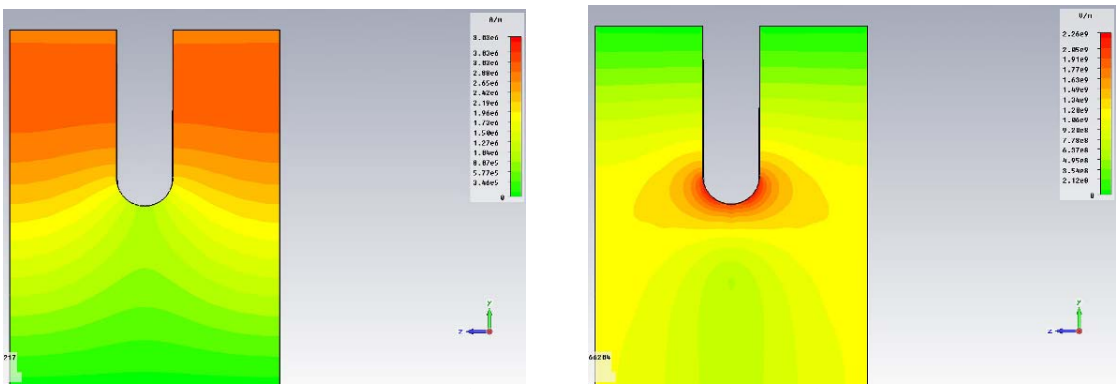

Figure 5. Amplitude of the magnetic (left) and electric (right) fields of the structure presented in Fig.2.

Table 3. Pulse heating and maximum electric field at the surface of the structure presented in Fig.2.

Structures	H_{max}	Pulse heating	Es-max
26GHz metal accelerating structure	875.4 KA/m	73.5 °C	663MV/m

References:

[1] C.Jing and W. Gai, WF-Note-239, http://www.hep.anl.gov/awa/wfnotes/wf-239.pdf

[2] Joint efforts from SLAC, CLIC, and KEK, etc. Numerous data have been presented in major related conferences and workshops, like PAC, IPAC, AAC, High Gradient Workshop, etc.

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[5] W. Gai and C. Jing, Chapter: “The Dielectric-Loaded Accelerating Structures”, Periodic Structures, 2006: ISBN: 81-308-0032-2, Editors: Maurizio Bozzi and Luca Perregrini.
[6] C. Jing, et al. *Nucl. Instr. Metho. in Phy. Research A*, **539**, Mar. 2005, pp.445-454.