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# DESIGN OF A HIGH GRADIENT 60 GHz DIELECTRIC ACCELERATING STRUCTURE

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*Abstract*

RF breakdown are the main limitation for the application of high gradient structures. Higher frequencies and shorter pulse length benefit the design of accelerating structure for the breakdown threshold of surface field is $E_s = f^{1/2}\tau^{-1/4}$. Power source which generates very short V-band pulse with nearly hundred megawatt is now available. The paper presents the analysis of a V-band dielectric acceleration structure and power source. Future plan about RF transmission and power coupling of the whole structure will be discussed.

## INTRODUCTION

Large scale accelerator facilities are strongly essential for extremely conditions research, such as high energy and high brightness physics. Higher gradient accelerator will be economically feasible in the future since shortening the required accelerating length

The study of high gradient accelerating over X-band is on the progress such as THz acceleration in dielectric material [1]. Theoretical and experimental results show that GV/m accelerating grading is possible in dielectric structure.

In 2001, electron beam accelerating experiment has been processed in X-band at the Naval Research Lab [2]. With the 30 MW providing and up to 1us duration pulses, gradient is ~40MV/m in dielectric tube. The schematic of dielectric structure is shown in Fig. 1.

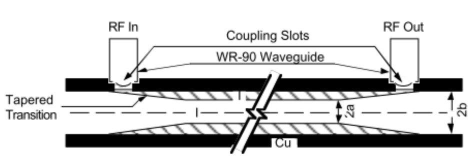


Figure 1: Schematic diagram of the dielectric-loaded traveling-wave accelerating structure.

With the appearance of microwave source in high power and short pulse length nearly 60GHz, high gradient electron acceleration in dielectric structure is possible.

New V-band traveling tube of dielectric tube working in $TM_{01}$ mode is analysed to purse higher gradient value in norm temperature. The following section we will present electromagnetic analysis procedure of field components in structure and introduce the microwave source. Full structure simulation and mechanical design will be present in the future.

## ELECTROMAGNETIC FIELD IN DIELECTRIC STRUCTURE

Completely procedure of designing the acceleration structure starts with field component analysis [3]. The Helmholtz function simplified describe transmission of microwave.

$$\left(\nabla^2 + \omega^2 \mu\varepsilon\right)\begin{Bmatrix}\vec{E}\\ \vec{B}\end{Bmatrix} = 0 \quad (1)$$

Focusing on $E$ component of electromagnetic in analysis procedure in transmitting mode, since symmetric of electric and magnetic field. Using separate variables method to solve the Eq.1 in cylinder coordinate, formulas of longitudinal and transverse are shown in Eq.2.

$$\begin{cases}\vec{E}(x,y,z) = \vec{E}(x,y)Z(z)\\ \nabla^2 = \nabla_T^{\ 2} + \dfrac{\partial^2}{\partial z^2} = \left(\dfrac{\partial^2}{\partial r^2} + \dfrac{1}{r}\dfrac{\partial}{\partial r} + \dfrac{1}{r^2}\dfrac{\partial^2}{\partial^2\varphi}\right) + \dfrac{\partial^2}{\partial z^2}\end{cases} \quad (2)$$

$$\Rightarrow \quad Z(z) = A^+ e^{-k_z z} + A^- e^{+k_z z} \quad (3)$$

Since the transverse-longitudinal relationship, solving the longitudinal component of electric field $E_z$ in Eq.3* and separate functions and solved longitudinal electric field are shown in Eq.4 and Eq.5.

$$\left[\left(\frac{\partial^2}{r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{{}^2\varphi}\right) + \left(k_z^{\ 2} + \omega^2\mu\varepsilon\right)\right]\vec{E}_z(x,y) = 0 \quad (3^*)$$

$$\Rightarrow \begin{cases} r^2\dfrac{d^2R(r)}{dr^2} + r\dfrac{dR(r)}{dr} + \left(k_c^{\ 2}r^2 - n^2\right)R(r) = 0\\ \dfrac{d^2\Phi(\varphi)}{d\varphi^2} + n^2\Phi(\varphi) = 0\end{cases} \quad (4)$$

$$E_z(r,\varphi) = \left[B_1 J_n(k_c r) + B_2 N_n(k_c r)\right]\cos(n\varphi - \varphi_0) \quad (5)$$

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Where $E_z = R(r)\Phi(\varphi)$, $k_c^{\,2} = k_z^{\,2} + \omega^2\mu\epsilon$, $B_1$, $B_2$ and $\varphi_0$ are the integral constant.

### *Accelerating Gradient in Cylinder Dielectric Tube*

Through transverse-longitudinal relationship and boundary conditions, electromagnetic fields components of $TM_{01}$ mode are solved in Eq.6 in cylinder dielectric tube shown as Fig. 2.

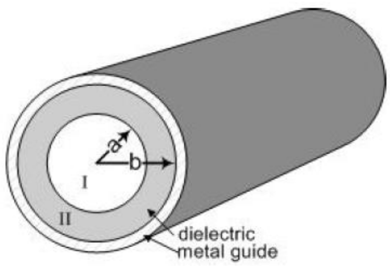


Figure 2: Typically cylinder dielectric tube model.

$$\begin{cases} E\ (r,\varphi) = B_1, E_r(r,\varphi) = B_1 \dfrac{\beta r}{2} \\ H_\varphi(r,\varphi) = B_1 \omega \varepsilon_0 \dfrac{r}{2} \end{cases} \qquad 0 < r \le a$$

$$\begin{cases} E_z(r,\varphi) = B_1 \mathrm{K}(r), E_r(r,\varphi) = -B_1 \dfrac{\beta}{k_c} \mathrm{K}'(r) \\ H_\varphi(r,\varphi) = -B_1 \dfrac{\omega \varepsilon_0 \varepsilon_r}{k_c} \mathrm{K}'(r) \end{cases} \qquad a < r \le b$$

$$E_\varphi(r,\varphi) = H_r(r,\varphi) = H_z(r,\varphi) = 0 \qquad 0 < r \le b$$

Where $B_1$ is the constant and

$$\mathrm{K}(r) = \frac{\lfloor N_0(k_c b) J_0(k_c r) - J_0(k_c b) N_0(k_c r) \rfloor}{N_0(k_c b) J_0(k_c a) - J_0(k_c b) N_0(k_c a) \rceil}$$

$$'(r) = \frac{\lfloor N_0(k_c b) J_0'(k_c r) - J_0(k_c b) N_0'(k_c r) \rceil}{N_0(k_c b) J_0(k_c a) - J_0(k_c b) N_0(k_c a) \rceil}$$

Certainly parameters of *a, b, ε* define the microwave frequency in cylinder dielectric tube and transferring mode.

Assuming microwave power will be transfer into electromagnetic field totally, accelerating gradient of $TM_{01}$ mode along the axis can be calculated with 100MW outer source power. Some calculated results of working frequency in 60GHz and its gradient are listed in Table.1.

Table 1: Calculated Results of Dielectric Tube in 60GHz

| Parameters | 1# | 2# | 3# | 4# |
|---|---|---|---|---|
| a/mm | 0.1 | 0.1 | 1 | 10 |
| b/mm | 1.158 | 0.524 | 1.717 | 10.17 |
| epsilon | 3.78 | 16 | 3.78 | 3.78 |
| Group velocity ($v_g$/c) | 0.265 | 0.063 | 0.293 | 0.952 |
| Accelerating gradient(MV/m) | 178 | 378 | 106 | 11 |

Theoretical results over 350MV/m in dielectric tube provide the potential to pursue higher gradient in structures.

Verifying the excited mode is $TM_{01}$ by establishing the model and simulating the electromagnetic field [4]. The magnetic field distribution is shown in Fig. 3.

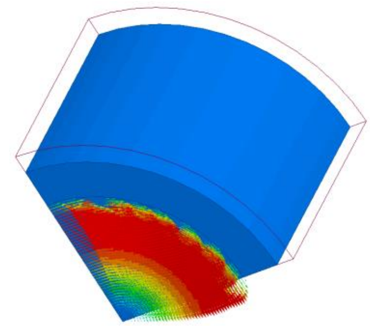

Figure 3: $TM_{01}$ mode in cylinder dielectric tube.

With high power exciting microwave source nearly or more than 100MW working in proper frequency such as 60GHz, electron beam can be accelerated at high gradient over 300MV/m in single shoot of short microwave pulse in ns scale, attempting to avoid the breakdown and multipacking effects.

## MICROWAVE SOURCE

Based on the PhD thesis of Tsinghua university [5], high power microwave source working in pulse mode has been designed in 60.6GHz. Optimistic parameters of current, voltage and induced magnetic field in numerical simulation are higher than 500MW in energy level.

High power experimental platform and mechanical assembly drawing of power source are shown in Fig. 4.

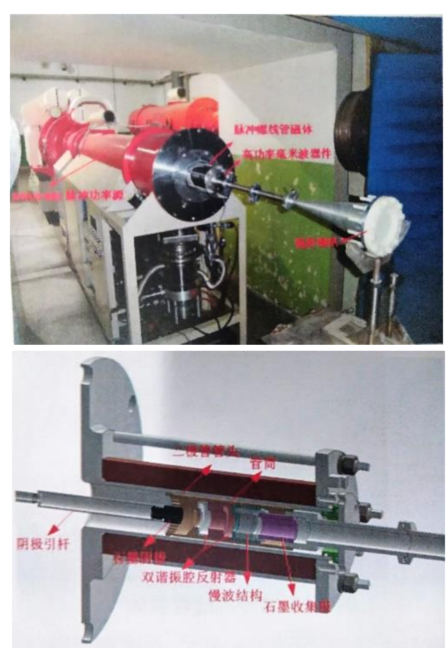


Figure 4: Experimental platform and power source.

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Results of high power test and energy collection are listed in the Table 2, compared with the numerical simulation [5].

Table 2: Experimental and Numerical Results

| Parameters | Experimental | Numerical |
|---|---|---|
| Dioxide voltage/kV | 445 | 465 |
| Current/kA | 4.45 | 3.7 |
| Induced magnetic field/T | 1.45 | 1.2 |
| Frequency/GHz | 61.5 | 60.6 |
| Power/MW | 120 | 537 |
| Pulse width/ns | 7 | 12 |
| Transfer efficiency | 6% | 31.2% |

From the experimental results, high power microwave source product short pulse in ns scale nearly 60GHz. With the analysis process in cylinder dielectric tube, high gradient acceleration is possible not only typically dielectric tube such as cylinder structure.

## CONCLUSION

This paper analyses the electromagnetic field in cylinder dielectric tube and calculates gradient in main accelerating mode $TM_{01}$. With available high power source in shorter pulse length, acceleration gradient are estimates over 300MV/m and break the limitation of norm-temperature acceleration gradient. Thus electron beam can be accelerated to higher energy within shorter length.

In the future, rf transmission and full electromagnetic structure will be in the progress. Mechanical manufacturing and high power test are in the time schedule next two years.

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