Design of C Band High Power Teflon Water Load

Dingzhen Li[1,2], Lianmin Zhao[1], Fukun Liu[1]

[1] Institute of Plasma Physics, Chinese Academy of Sciences, 230031, Hefei, China
[2] University of Science and Technology of China, 230026, Hefei, China

E-mail: lmzh@ipp.ac.cn

Abstract. A C band Teflon water load is designed for the 4.6 GHz lower hybrid current drive (LHCD) system in the experimental advanced superconducting tokamak (EAST) to absorb the high power microwave reflected from the circulator, Teflon is used to substitute traditional ceramics to isolate the air and the water, which is cheaper and easier to processed. The simulation result carried out by CST microwave studio shows that the return loss reaches -64 dB at 4.6 GHz, and the power loss density was fitted by Origin software to calculate the thermal distribution of the Teflon and the water. Besides, the thermal analysis carried out by ANSYS indicates that this water load can work under 5 kW CW, with the maximum temperature of Teflon less than 71 ℃, and the maximum thermal deformation and stress are no more than 0.14 mm and 3.2 MPa.

1. Introduction

Water load can be used to absorb high power microwave generated by many different high power microwave sources such as klystrons [1-3], magnetrons [4], gyrotrons [5-7], accelerator [8] and some other devices [9-11]. Traditional water loads used to adopt special ceramics, alumina (Al2O3), beryllium oxide (BeO) and aluminum nitride (AlN), to isolate the air and the water or keep the vacuum environment. Compared to these ceramics, Teflon has the similarly excellent microwave performance with low loss tangent (at 25℃). Besides, Teflon is a mature plastic material which is easy to produce and process, its price is only nearly 10 percent of alumina's price and less than 1 percent of beryllium's or aluminum nitride's price, which shows potential value in microwave engineering. While the coefficient of thermal conductivity and the melting point of Teflon are only 0.25 W/m and 327 ℃, respectively. As a result, it can just work under several kilowatts steady state or at megawatt level for several microseconds.

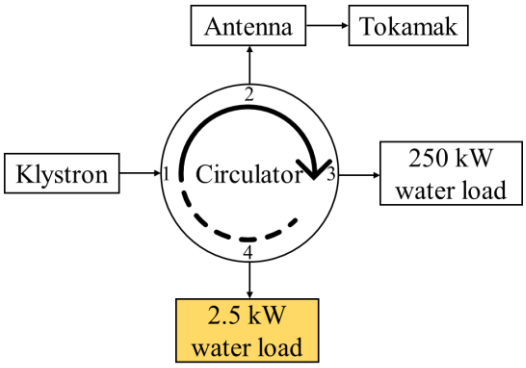


Figure 1. The diagram of 4.6 GHz LHCD system in EAST.

As shown in Fig.1, in the 4.6 GHz 250kW LHCD system of EAST, each transmission line has 2 water loads connected with the circulator to protect the klystron from the high power reflecting microwave. In the port 3 of the circulator, this water load must have the ability to absorb more than 99 percent reflecting energy, and the rest of the energy (less than 2.5 kW) can be absorbed by water load at port 4. Above all, Teflon water load would be a more affordable structure to be adopted at port 4.
In section II, this work aim to calculate the physical size and the simulate the return loss, power loss density by CST microwave studio. In section III, the power loss density was fitted by Origin to analysis the thermal distribution in the Teflon and the water with * functions. Section IV indicates the thermal analysis results carried out by ANSYS Fluent, which show that the Teflon water load can work under 5 kW CW. Finally, a brief conclusion is given.

2. Calculation of the physical size and microwave simulation

The foremost challenge of the design of the Teflon water load is that Teflon cannot stand high temperature compared with ceramics, and enlarging the propagating cutting plane is a common method to reduce the power loss density. In the 4.6 GHz LHCD system in EAST, all the microwave structures are connected by WR229 rectangular waveguides (58.2 mm × 29.1mm), and the water load cutting plane was expanded to a circle with a radius of 50 mm (see Fig. 2). while the effect is that the microwave would propagate in several different modes.
The cutting wavelengths [12] of circular waveguide can be calculated by

$$\lambda_{c\mathrm{TE}_{nm}} = 2\pi R / p'_{nm} \tag{1}$$

$$\lambda_{c\mathrm{TM}_{nm}} = 2\pi R / p_{nm} \tag{2}$$

where the R is the radius of the circular waveguide and p'_{nm}, p_{nm} refer to the extrema, zeros of the Bessel function of first kind. For 4.6 GHz electromagnetic microwave, it can be calculated that there are 5 different propagation modes: TE_{11}, TM_{01}, TE_{21}, TE_{01} and TE_{31} (arranged in order of the increasing waveguide wavelength λ_g). According to the transmission line theory, the length of the Teflon should be integer multiple of the $\lambda_g/2$, and λ_g can be calculated by

$$\lambda_g = \frac{1}{\sqrt{1/\lambda^2 - 1/\lambda_c^2}} \tag{3}$$

As a result, the minimum waveguide wavelength $\lambda_{g\mathrm{TE}_{11}}$ is 70.6 mm, and the maximum waveguide wavelength $\lambda_{g\mathrm{TE}_{31}}$ is 132 mm. Considering the relative permittivity of the Teflon $\varepsilon_r = 2.08$, so the length of the Teflon should be between 24.48 mm and 45.76 mm. The height and the thickness after optimizing are 26 mm and 41.5 mm, respectively. As shown in Fig. 3, the return loss could reach -64 dB at 4.6 GHz.

3. Fitting power loss density distribution functions

3.1. Power loss density of water

The power loss density of water under the input power of 0.5 W (default) simulated by CST microwave studio is shown in Fig. 4, and the X direction is the propagating direction. It is clear that the power loss density obeys Gauss2D function in YOZ cutting plane, the equal phase plane (shown in x=25mm). And according to the skin effect, it would obey exponential function along the transmission direction. The power loss density of the water was fitted with these functions by Origin software, and the fitted results are reported in Fig. 5. Compared with the central area, power loss densities in other areas are less than one forth, which would be ignored in fitted functions.

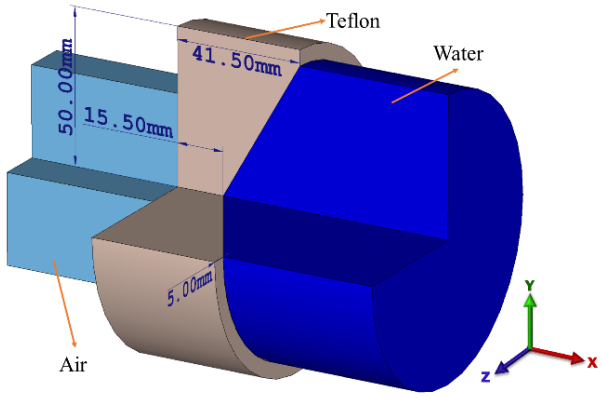


Figure 2. The physical model of Teflon water load (3/4 part).

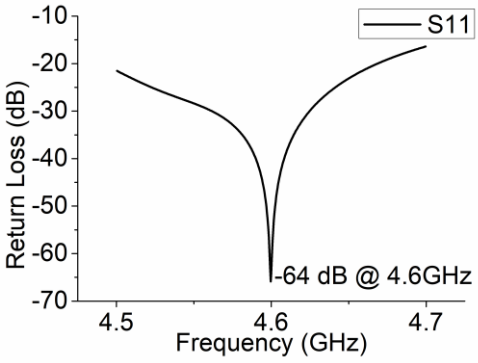


Figure 3. Return loss simulated by CST.

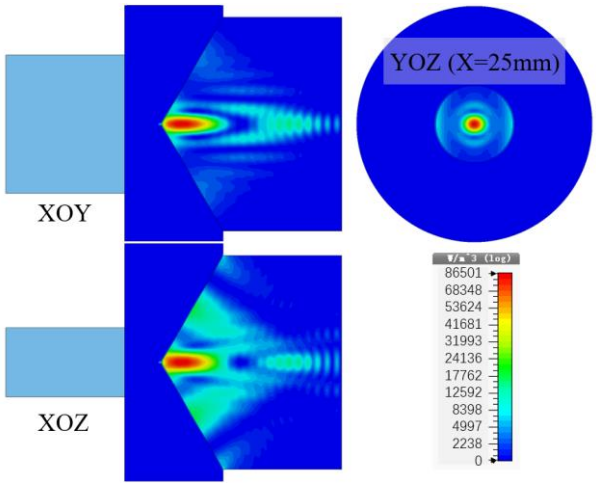
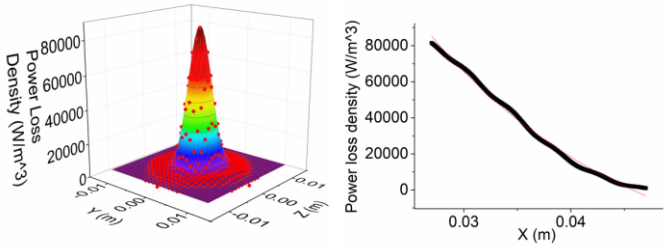


Figure 4. Power loss density of water.



YOZ plane
(x=25mm)
GAUSS2D FITTED

Propagating direction
(25mm<x<55mm)
EXPDEC FITTED

Figure 5. Power loss density functions fitted results.

It is indicated that the Adj. R-Square are 0.99385 and 0.99453 separately, which means that the fitting results are extremely successful. The fitted functions are reported in Table 1.

3.2. Power loss density of the Teflon

Since the power loss density in the Teflon is less than 0.1 percent compared to it in the water, it is hard to observe the distribution functions in the Teflon. So E-field distribution is used to calculated the power loss density distribution in the Teflon. The power loss can be calculated by

$$P = \omega \varepsilon_0 \varepsilon_r' \tan\delta |E|^2 / 2 \quad (4)$$

where the $\varepsilon_0, \tan\delta$ are the permittivity of vacuum and loss tangent of the Teflon, and $\omega = 2\pi \times 4.6 \times 10^9$ rad/s,

Table 1. Power Loss Density Fitted Functions

Area	Function type	Expression	Adj. R-Square
YOZ plane (X=25mm)	GAUSS2D	$P_1=z_1+A_1*\exp(-0.5*((Y-x_{c1})/w_1)^2-0.5*((Z-y_{c1})/u_1)^2)$	0.99385
Propagating direction (Y=0,Z=0)	EXPDEC	$P_2=A_2*\exp(-X/t_2)+b_2$	0.99453
Parameter values	z_1=4154.29856; A_1=83799.42159; x_{c1}=3.23448e-19; w_1=0.00202; y_{c1}=4.60423e-8; w_2=0.00251		
	A_2=541119.31483; t_2=0.01995; b_2=-54617.74196		

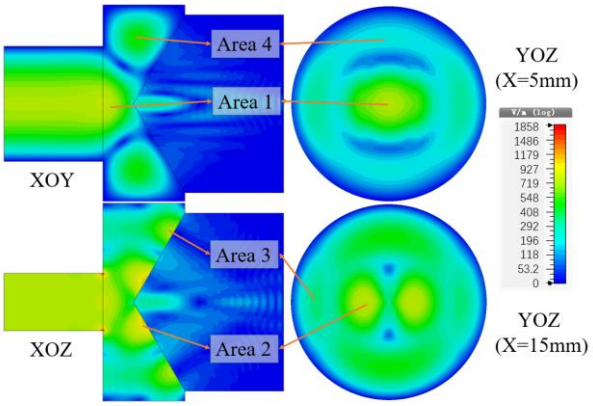


Figure 6. E-field distribution of the Teflon.

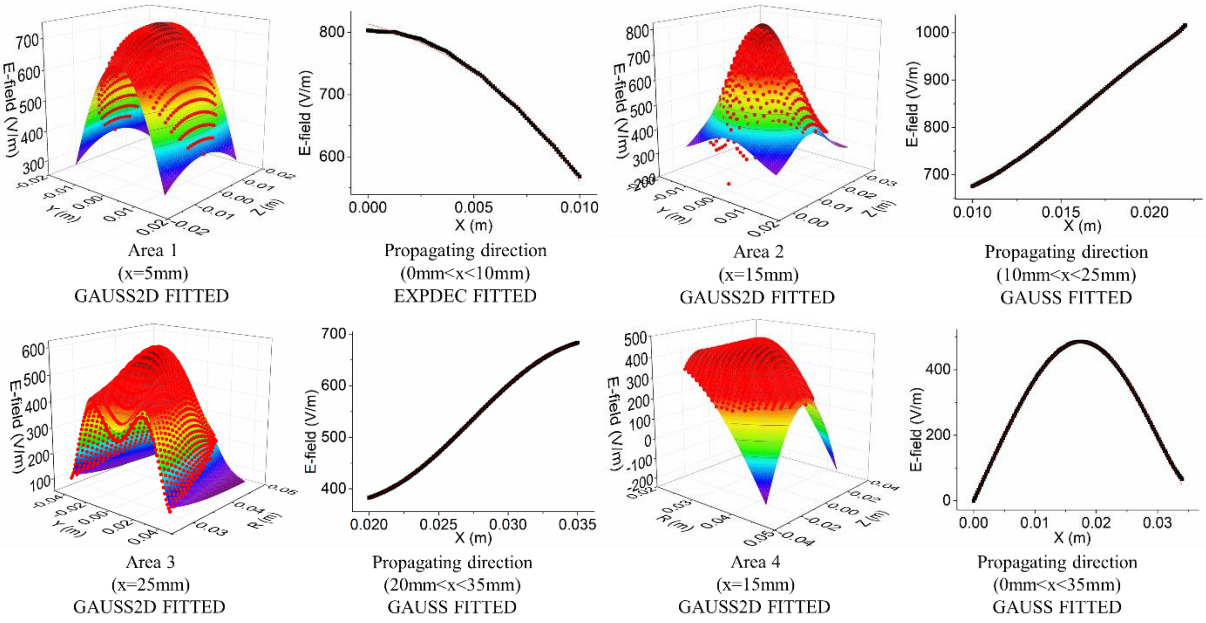


Figure 7. E-field distribution functions fitted results.

Table 2. E-field Distribution Fitted Functions

Area	Function type	Expression	Adj. R-Square
YOZ plane Area 1 (X=5mm)	GAUSS 2D	$E_3=z_3+A_3*\exp(-0.5*((Y-x_{c3})/w_3)^2-0.5*((Z-y_{c3})/u_3)^2)$	0.99699
Propagating direction 1 (Y=0,Z=0)	EXPDEC	$E_4=A_4*\exp(-X/t_4)+b_4$	0.99652
YOZ plane Area 2 (X=15mm)	GAUSS 2D	$E_5=z_5+A_5*\exp(-0.5*((Y-x_{c5})/w_5)^2-0.5*((Z-y_{c5})/u_5)^2)$	0.9701
Propagating direction 2 (Y=0,Z=0)	GAUSS	$E_6=b_6+(A_6/(w_6*\mathrm{sqrt}(pi/2)))*\exp(-2*((X-x_{c6})/w_6)^2)$	0.99994
YOZ plane Area 3 (X=25mm)	GAUSS *GAUSS	$E_7=(b_7+(A_7/(w_7*\mathrm{sqrt}(pi/2)))*\exp(-2*((\mathrm{sqrt}(Y^2+Z^2)-x_{c7})/w_7)^2)*(c_7+(k_7/(u_7*\mathrm{sqrt}(pi/2)))*\exp(-2*((Y-y_{c7})/u_7)^2))/600$	0.99169
Propagating direction 3 (Y=0,Z=37mm)	GAUSS	$E_8=b_8+(A_8/(w_8*\mathrm{sqrt}(pi/2)))*\exp(-2*((X-x_{c8})/w_8)^2)$	0.99989
YOZ plane Area 4 (X=15mm)	GAUSS *GAUSS	$E_9=(b_9+(A_9/(w_9*\mathrm{sqrt}(pi/2)))*\exp(-2*((\mathrm{sqrt}(Y^2+Z^2)-x_{c9})/w_9)^2)*(c_9+(k_9/(u_9*\mathrm{sqrt}(pi/2)))*\exp(-2*((Z-y_{c9})/u_9)^2))/470$	0.99831
Propagating direction 4 (Y=33mm,Z=0)	GAUSS	$E_{10}=b_{10}+(A_{10}/(w_{10}*\mathrm{sqrt}(pi/2)))*\exp(-2*((X-x_{c10})/w_{10})^2)$	0.99938
Parameter values		z_3=-615.14344; A_3=1360.83596; x_{c3}=4.6789e-19; w_3=0.01824; yc_3=0.58908e-7; u_3=0.03783	
		A_4=-58.85349; t_4=-0.00598; b_4=872.69072	
		z_5=295.13611; A_5=527.65302; x_{c5}=-3.28815e-19; w_5=0.00907; y_{c5}=0.01279; u_5=0.00731	
		b_6=1182.21655; A_6=-14.13536; w_6=0.02083; x_{c6}=0.00622	
		b_7=137.92733; A_7=7.20801; w_7=0.01457; x_{c7}=0.03693; c_7=233.24537; k_7=24.77161; u_7=0.0448; y_{c7}=-7.75368e-10	
		b_8=331.0194; A_8=6.99422; w_8=0.01588; x_{c8}=0.03579	
		b_9=-627.41772; A_9=45.64531; w_9=0.04405; x_{c9}=0.0332; c_9=912.70274; k_9=8.19763; u_9=0.03381; y_{c9}=3.13092e-6	
		b_{10}=-402.68034; A_{10}=31.47404; w_{10}=0.02828; x_{c10}=0.0175	

4. Fluid and thermal analysis

In the actual engineering design, it is necessary to preserve the margin to ensure the safety situation. For 4.6 GHz LHCD system in EAST, the power capacity of the water load must reach 5 kW at the port 4 of the circulator. Taking the requirements of the 4.6 GHz LHCD water system in EAST into consideration, the radius of the water pipe is 10 mm, and the velocity of the water at the inlet should be less than 2 m/s to reduce the mechanical noise. According to formula

$$\Delta T = \frac{P}{c \cdot S \cdot v \cdot \rho} \tag{5}$$

the temperature increase ΔT would be only 2 ℃ under the 5 kW input power, where P is the input power, c is the specific heat capacity of water, S is the cross-sectional area of pipe, v is the velocity of the water, and ρ is the density of water. However, the thermal conductivity of Teflon is only 0.25 W/m, which would cause there is a huge temperature difference between the Teflon and the water, since that the heat generated in the Teflon can hardly be transferred to the water.

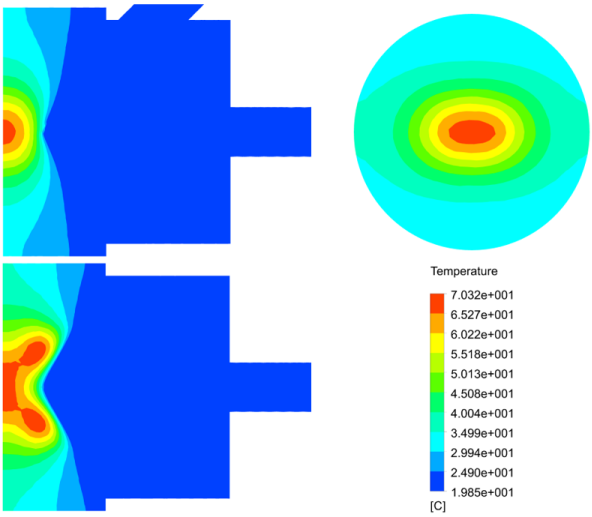
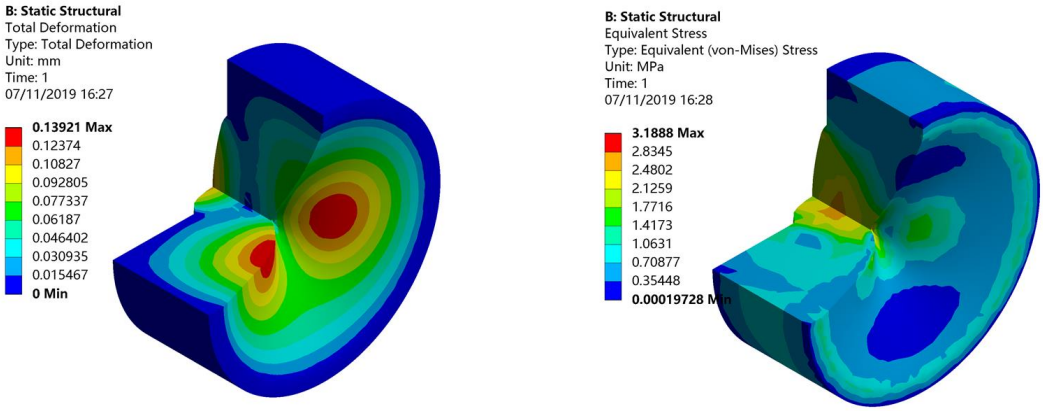


Figure 8. Heat distribution of Teflon water load under input power of 5 kW.



(a) (b)

Figure 9. Thermal analysis results carried out by ANSYS Static Structural. (a) Deformation; (b) Stress.

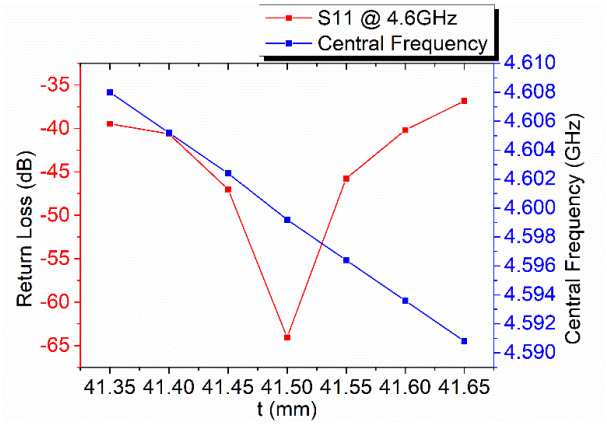


Figure 10. Return loss @ 4.6 GHz and the central frequency changing with the parameter "*t*"

Adjusting the angle of the input water pipe to make the water take the heat generated in the water away rapidly, setting the inlet velocity, outlet pressure and the room temperature to 2 m/s, 0.5MPa and 20 ℃ separately, multiplying the fitted functions by 10000 to get UDF (user defined function) under input power of 5 kW and compiling the UDF in ANSYS Fluent to simulate the heat distribution of the Teflon water load. Simulated result is given in Fig. 8. It is indicated that the maximum temperature of the water

load is 70.32 ℃, located at the center of the Teflon. Importing these results to ANSYS Static Structural Unit to get the thermal deformation and stress, it can be observed that maximum deformation and stress are only 0.139 mm and 3.19 MPa, respectively, see Fig. 9. The tensile yield strength of Teflon is 20 MPa [13], which means that the Teflon has the ability to stand the stress under input power of 5 kW. The parameter "*t*" (total thickness of the Teflon) sweeping result is given in Fig. 10, which shows that the microwave performance is almost unaffected by the error of 0.15 mm (maximum thermal deformation).

5. Conclusion

A 5 kW Teflon water load is designed for the 4.6 GHz LHCD system in EAST, taking the microwave theory and fluid thermal analysis into consideration simultaneously. The UDF was written by fitting the distribution of the E-filed and the power loss density, final simulated results indicate that this water load can absorb more than 99 percent energy under 4.6 GHz 5 kW microwave with little thermal deformation and sustainable stress.

6. References

[1] Liu L, Liu F K, Shan J F and Kuang G L 2007 Design of a New Water Load for S-band 750 kW Continuous Wave High Power Klystron Used in EAST Tokamak Plasma Science and Technology 9 223-6

[2] Koert P, MacGibbon P, Beck W, Doody J and Gwinn D 2007 High Power Water Load for Lower Hybrid Current Drive at 4.6 GHz on Alcator C-Mod. In: Symposium on Fusion Engineering, pp 1-4

[3] Horan D, Kustom R and Ferguson M 1995 Performance of a 2-megawatt high voltage test load. In: Proceedings Particle Accelerator Conference, pp 1988-90

[4] Gao D P, Zhang R, Ding H B and Tang K 2015 Design of 100kW Water Load for P-band Continuous Wave Magnetron. In: International Vacuum Electronics Conference, (Beijing: IEEE) pp 27- 9

[5] Illy S, Gantenbein G, Schmid M and Weggen J 2011 Design, construction and first tests of a stainless steel load for high power MM-wave radiation. In: 2011 Abstracts IEEE International Conference on Plasma Science, pp 1

[6] Ives R L, Mizuhara M, Schumacher R and Pendleton R 1999 Development of a high power CW waterload for Gaussian mode gyrotrons IEEE Transactions on Plasma Science 27 531-7

[7] Ok J-W, Choi S, Lee B-S, Yoon J-H, Park J Y, Shin C S, Won M-S and Hong I-S 2015 Development of a water load for a Ka-band 10 kW continuous-wave gyrotron in an ECR ion source system Journal of the Korean Physical Society 66 349-52

[8] Gold S H and Gai W 2001 High-power testing of 11.424-GHz dielectric-loaded accelerating structures. In: Proceedings of the 2001 Particle Accelerator Conference pp 3984-6 vol.5

[9] Panahi M A, AbdollahRamezani S, Ebrahimzadeh Ardakani G and Safian R 2015 An Efficient High Power RF Dummy-Load IEEE Microwave and Wireless Components Letters 25 409-11

[10] Han J, Kim J-h, Park S-d, Yoon M, Park S Y, Choi D W, Shin J W and So J H 2009 Coaxial-type water load for measuring high voltage, high current and short pulse of a compact Marx system for a high power microwave source Physical Review Special Topics - Accelerators and Beams 12

[11] Matsumoto H, Iino Y, Fujiwara C, Kabeya Z and Onda T 1999 Experience on the high-power SiC microwave dummy-load using SiC absorber. In: Proceedings of the 1999 Particle Accelerator Conference, pp 842-4 vol.2

[12] Pozar D M 2005 Microwave Engineering vol 3 (USA: Wiley)

[13] Chin G Y, Nesbitt E A and Williams A J 1966 Anisotropy of strength in single crystals under plane strain compression Acta Metallurgica 14 467-76

Acknowledgments

This work was supported by National MCF Energy R&D Program of China under Grant 2018YFE0305100 and National Natural Science Foundation of China under Grant 11675212.

Authors' background

Name	*Prefix*	*Research Field*	*Email*	*Personal website*
Dingzhen Li	Master Student	High power microwave	dingzhen.li@ipp.ac.cn	
Lianmin Zhao	Associate Professor	Microwave transmission line	lmzh@ipp.ac.cn	
Fukun Liu	Full Professor	Plasma Physics	fkliu@ipp.ac.cn	

Note:

[1] **This form helps us to understand your paper better; the form itself will not be published.**

[2] *Prefix*: can be chosen from Master Student, PhD Candidate, Assistant Professor, Lecture, Senior Lecture, Associate Professor, Full Professor