第12卷 第4期 强 激 光 与 粒 子 束 Vol. 12, No. 4
2000年8月 HIGH POWER LASER AND PARTICLE BEAMS Aug., 2000

Article ID: 1001—4322(2000)04—0442—05

The Design and Test of a Compact Hydrogen Plasma Gun System*

YANG Jian-hua, ZHANG Ya-zhou, LIU Jin-liang

(Department of Applied Physics of National University of Defence Technology, Changsha 410073, China)

ABSTRACT: A compact hydrogen plasma gun system was designed and tested. There are two rings of graphite and two rings of Ti hydride between coaxial electrodes. Ti hydride is utilized as a reservoir of hydrogen. The surface flashover is taken advantage to produce plasma. The produced plasma density is $10^{10}cm^{-3}\sim10^{12}cm^{-3}$ in a volume of a column with radius 1～2cm and length of 60～80cm. The plasma existing time is over 400μs.

KEY WORDS: plasma gun; Ti hydride; surface flashover; high power plasma microwave

CLC number: O53 **Document code**: A

The presence of a controlled amount background plasma inside microwave tubes can lead to the improvement of generated microwave characteristics beyond what is available in evacuated devices. Many experimental results demonstrated clearly that the presence of background plasma can enable operation at very low magnetic fields, efficiency enhancement, frequency tunabilty by varying the background plasma density, and allow the injection of larger e-beam currents[1~3]. The introducing of plasma in microwave tubes enriches the physical process between e-beam and electromagnetic wave. There are many challenges in the development of plasma loaded high power microwave tubes both in theory and experiment. One of the challenges is to provide a suitable plasma source with easily controlled parameters[2].

The paper presents the design and test of a compact coaxial hydrogen plasma gun with a diameter of 3cm. The surface flashover is taken advantage to produce plasma. Ti hydride is utilized as a reservoir of hydrogen because of abundant hydrogen storage in it. Two rings of graphite between the electrodes are used to decrease the creeping distance and so as to reduce the applied voltage in the same diameter condition. The graphite rings also keep the path of arc current near to the surface so that the produced plasma can leave the surface along the axis. This type of plasma gun has been applied successfully in the experiment of plasma loaded relativistic backward wave oscillators (RBWO) by Y. Carmel and his colleagues in University of Maryland[1,4]. This small and coaxial plasma gun is also suitable for gyrotron, traveling wave tubes and dielectric plasma maser or plasma maser devices.

1 The Plasma Gun

Ti hydride was used as the hydrogen reservoir because hydrogen density in Ti hydride can be up to 9.2×10^{22}atom/cm^3. It is higher than liquid hydrogen density of 4.2×10^{22}atom/cm^3 and solid hydrogen density of 5.2×10^{22}atom/cm^3[5]. Ti hydride also has some other valuable characters e.g.: it doesn't desorb hydrogen under the room temperature, but releases much hydrogen at 600℃ or over

* 国防科技基础研究基金资助课题
2000年1月13日收到原稿，2000年5月24日收到修改稿。
杨建华，男，1974年2月出生，博士生，从事微波源及微波等离子体电子等方面的研究。

and in very low pressure. The surface flashover is taken advantage to produce plasma. The electrodes of the plasma gun are coaxial. Therefore the plasma can be jeted from the muzzle in the axis symmetry. When a high voltage pulse with several tens of microseconds duration is impacted on the two electrodes, the surface flashover process will develop after several nanoseconds. The surface layer of Ti hydride is heated by arc current, the temperature in surface layer would go up to the extent that the hydrogen is released . The released hydrogen is ionized by arc current and the plasma is produced. The produced plasma is pushed forward along the axis from the muzzle by $\boldsymbol{j}\times\boldsymbol{B}$ force of the self-magnetic field of arc current. Two rings of graphite are laid between the electrodes to keep the arc current near the surface so that more hydrogen is released as the Ti hydride would obtain more energy from the arc. The graphite rings between the two electrodes can also decrease the creeping distance. The diameter of surface of the plasma gun can be made larger in order to produce the plasma column with larger radius under the same applied voltage.

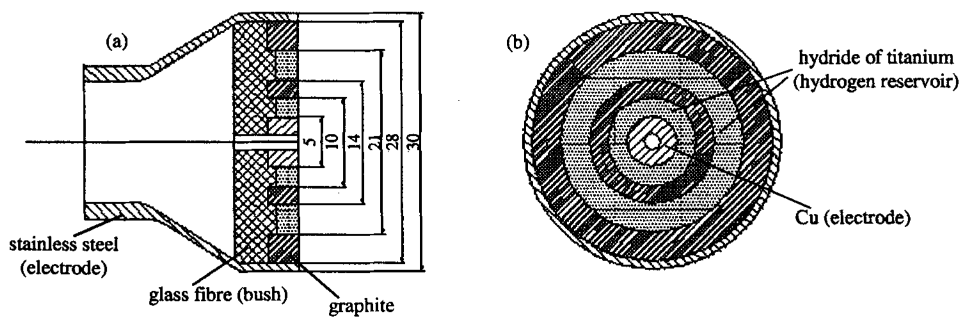


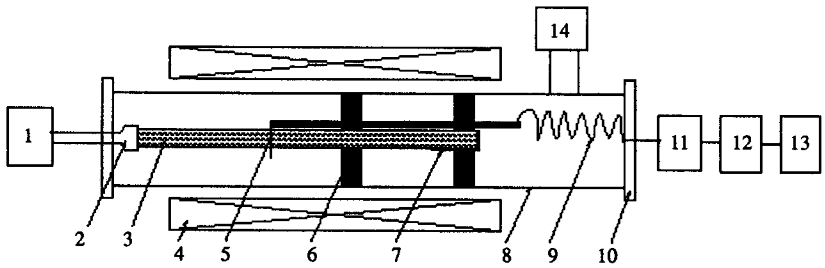
Fig. 1 The structure of the plasma gun(unit: mm). (a)cutway view; (b)elevation

The structure and main dimensions of the plasma gun are illustrated in Fig. 1. There is a hole with a diameter of 5mm in the center of the central electrode for fixing the feed cable and the gun. The stainless steel outer electrode, glass fiber and graphite rings were made first. Some sodium silicate solution was put into Ti hydride powder to make them uniform wet mixture. The mixture was then filled in the grooves between the two graphite rings and between graphite ring and Cu electrode. The mixture should be pressed in the process of filling. After the filling, the plasma gun was heated for about 12hours at 45℃ in an oven. There may be some white powder on the surface after heating. It implies that the solution of sodium silicate is excessive. Get rid of the white power, then permeate some water into the mixture and let it dry again.

2 The Plasma Generation Experiment

The schematic diagram of experimental setup is showed in Fig. 2. The inner radius of drift tube is 4. 5cm and its length is 1m. The pressure in the drift tube is $2\sim4\times10^{-3}$ Pa in the experiments. Langmuir probe was utilized to measure the parameters of the generated plasma. The Langmuir probe is a thin (0. 15cm in diameter) tungsten wire of 5cm collective length and perpendicular to the axis of the drift tube. The other part of the probe is isolated by ceramics and epoxy. There are two regions called saturate electron current region and saturate ion current region respectively in the V-I curve of the probe. The probe current changes little with the bias voltage. So fixed bias voltage (40～60V) from the batteries is provided for the probe to measure the waveform of temporal dependence of the saturate probe current. The saturate ion current is measured with negative bias voltage. The sampling resistor is 5Ω.

According to theory[6], the saturate ion current I_{io} is



1. driving circuit; 2. plasma gun; 3. plasma column; 4. magnet system; 5. Langmuir probe; 6. bracket of probe; 7. brass sheath; 8. drift tube; 9. cable; 10. flange; 11. batteries, 12. sampling resistor; 13. oscillator; 14. vacuum system

Fig. 2 The experimental setup and diagnosis system of plasma

$$I_{io} = 2 \times 10^{-13} n_i \sqrt{kT_e} S \qquad (A) \tag{1}$$

where S is the plasma collective area of the probe in cm^2; kT_e is electron temperature in eV. The electron temperature varies little with different plasma gun voltage. The value of kT_e is about 1eV according to the paper[5]. The measured typical saturate ion current is showed in Fig. 3 when the probe was put 50cm down stream from the plasma gun , the guiding magnetic field is 0. 59T, the capacitor charged voltage is 10 kV. The plasma density is high at the axis of the plasma column, there is no signal away from the axis over 2cm, so the radius of the plasma column is considered to be about 2cm. The collective area of the probe is $S = 1.88 cm^2$, from formula (1) and Fig. 3 it could be got that the peak plasma density was $n_i = 6.05 \times 10^{12} cm^{-3}$ with existing time over $400 \mu s$.

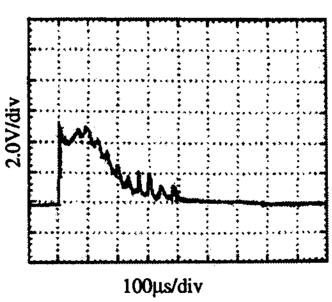


Fig. 3 A typical temporal dependence of saturate probe ion current

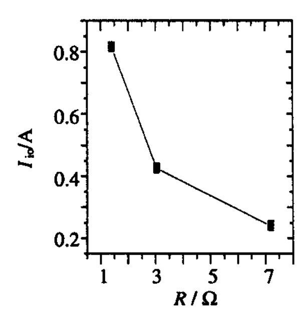


Fig. 4 The saturate probe ion current I_{io} *vs* the limiting current resistor R

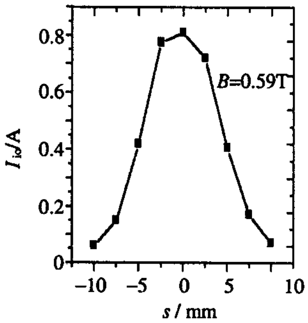


Fig. 5 The radial profile of the plasma in the tube. s is distance frome the axis of tube to the probe

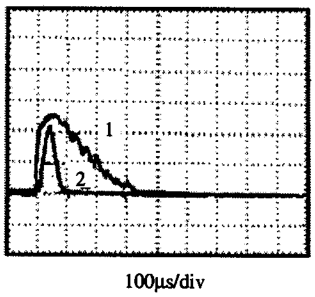


Fig. 6 The saturate probe ion current with (1. $B = 0.59T$) and without (2. $B = 0$) the guiding magnetic field

In the experiments, we mainly investigate the relation as follow: (1)The plasma density varying with the applied voltage and the limiting resistor in driving circuit, (2)The radial profile of the plasma column, (3)The difference of the plasma existing time with and without guiding magnetic field, (4) The plasma drifting velocity, (5). The variety of the plasma between shots. Some conclusions are drawn (because the plasma density is in direct proportion to the saturate ion current from formula (1), so the saturate ion current stands for the relative magnitude of the plasma density in figure):

1. The plasma density increases as the charged voltage increases. The plasma density also increases as the current limiting resistor drops within a certain range(see Fig. 4).

2. The radial profile of the plasma is about axis symmetry, which is shown in Fig. 5. The density is high near the axis and it drops as the distance away from the axis increases.

3. The plasma existing time is quite different when there is and there is not guiding magnetic field. The existing time of the plasma is 100μs without the guiding magnet, and is over 400μs with guiding magnet at 0.59T. Fig. 6 is the comparison of the plasma existing time with and without the guiding magnet.

4. The plasma expanding velocity is estimated by measuring the distance of the probe away from the plasma gun and the time interval between the front of the current wave of probe and the front of the current wave of the driving circuit. The experiment result showed that the expanding velocity is about 1cm/μs in the axial direction[7].

5. The probe current of the first 1~2 shot is larger than the latter, it keep about the same with a little difference from shot to shot under the same conditions after the first 1~2 shot .

In the experiments it was found that the resistance between electrodes varies with shots. At the first shot, the resistance was very high and dropped to about 100Ω. After 2~3 discharges it dropped further as the discharge continued. At last it was about 40Ω. These demonstrated that the hydrogen released from Ti hydride, and the material of the plasma gun had changed. It was also found that there was some black material left in the surface of the stainless steel electrode. It was the vaporized graphite. It implied that the temperature of the gun surface was high enough to vaporize the graphite.

4 Summary

The hydrogen plasma gun uses Ti hydride as a reservoir to store the hydrogen, instead of a complicated hydrogen gas storage system. The mechanism of the plasma initiation and process is due to the surface flashover. The coaxial structure of plasma gun can lead to the produced plasma symmetrized about the axis of the tube and make the gun small and compact. The produced plasma density is $10^{10}cm^{-3}$~$10^{12}cm^{-3}$in a volume of a column with radius 1~2cm and length of 60~80cm. The plasma existing time is over 400μs. The parameters of the produced plasma are related with the parameters of the driving circuit. They are also affected by the structure of the muzzle of plasma gun.

There is some potential to improve and optimize the plasma gun to increase plasma density. For example, improve the hydrogen ratio in Ti hydride, increase the diameter of the gun, raise the number of graphite rings, and change the structure of the surface of the plasma gun from planar structure to cone-shaped structure.

Reference:

1 Carmel Y, Minami K, et al. Demonstration of efficiency enhancement in a high-power backward-wave oscillator by plasma injection [J]. *Phys Rev Lett*, 1989, **62**:2389~2392.

2 Nusinovich Gregorg S, et al. Recent progress in the development of plasma-filled traveling-wave tubes and backward-wave oscillators [J]. *IEEE Trans on Plasma Sci*, 1998, **26**(3):628~645.

3 QIAN Bao-liang. Backward oscillator with plasma background or dielectric-lining[D]. Beijing: The doctoral dissertation of Tsinghua University, 1996.

4 Shkvarunets A G, et al. Electromagnetic properties of corrugated and smooth waveguides filled with radially inhomogeneous plasma [J]. *IEEE Trans on Plasma Sci*, 1996, **24**(3): 905～917.

5 DAJIAO Zhang-tai. The character and application of metal hydride[M]. Beijing:Chemical Industry Press.

6 XIANG Zhi-lin, YU Chang-xuan. The diagnosis of high temperature plasma[M]. Shanghai;Shanghai Science and Technology Press. 1982. **1**;27～36.

7 Yang Jian-hua. Study of a compact hydrogen plasma gun[D]. Changsha:The master dissertation of NUDT,1999.

紧凑型氢等离子体枪设计和实验

杨建华， 张亚洲， 刘金亮

（国防科技大学理学院，长沙，410073）

摘 要： 设计了一种紧凑型氢等离子体枪及驱动电路。这种枪采用同轴结构，电极之间有两层石墨环和两层氢化钛，利用氢化钛作为气源储存体，利用表面闪络机制产生等离子体。实验表明，等离子体枪能产生密度为 10^{10}～$10^{12}/cm^3$、半径为 1～2cm、长度为 60～80cm 的等离子体柱，它在磁场导引下存在时间大于 400μs。

关键词： 等离子体枪； 氢化钛； 表面闪络； 高功率微波器件