S2-2 Application of Plasma Heating Technology for Frontier Science

核融合プラズマ加熱技術のフロンティア科学への展開

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Abstract
The plasma heating technology developed for fusion research, in particular power source for electron cyclotron heating (gyrotron), and its application are discussed. Recent progress of gyrotron and related technology accelerated the application to other field of science and technology. Some examples of application are introduced.

1. Introduction

In a fusion research, many technologies have been newly developed. As for a plasma heating, both neutral beam and RF technologies have contributed to the heating and current drive experiment on fusion devices. In particular, a gyrotron, a high power mm wave source for electron cyclotron heating, has been and realized a stable power output at various frequency range from 28GHz to sub-millimeter region. A feature of the mm wave is: (a) loss tangent of dielectric of most materials increase with frequency *f*, and ohmic loss on the metal surface increase with $f^{0.5}$, (b) cut-off density in the un-magnetized plasma is high, which increase as f^{2}, (c) power distribution of the mm wave beam can be controlled using a combination of phase correction mirrors, which will be a merit for plasma processing.

Previously, the gyrotron has been used only for fusion research. However, the gyrotron technology has been progressing and the new applications of the mm wave are proposed. In this paper, the gyrotron and its new application to the various areas except the plasma heating are introduced.

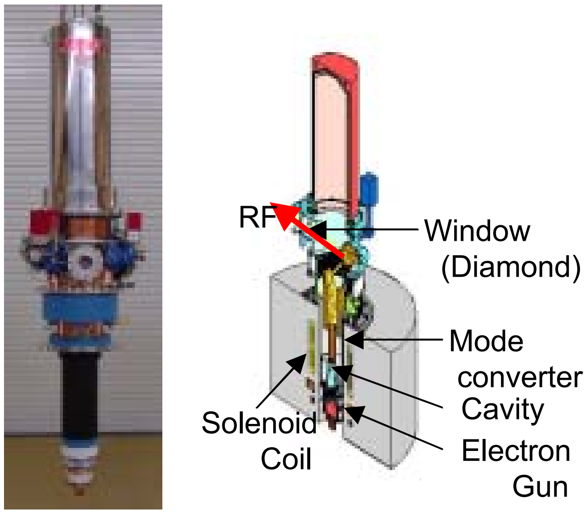

Fig.1 Picture and cross section of 170GHz gyrotron for ITER. Hight of the gyrotron is ~3m.

2. High power mm wave source (Gyrotron)

In 1990's, major progress on the gyrotron research was made. In JAERI, the 170GHz and 110GHz gyrotrons with synthetic diamond window and a depressed collector have been developed for ITER and JT-60U application, respectively [1]. In JT-60U, the 4MW system is under operation with four-1MW/110GHz gyrotron, and demonstrated the electron heating (~26keV), suppression of instability (neoclassical tearing mode), current drive. Also, a 28GHz gyrotron has been developed with Plasma research center, Univ. of Tsukuba. Up to now, the power output of 0.5MW, and maximum efficiency of 50% was obtained without depressed collector.

In Fig.1, a picture and a configuration of the recent gyrotron are shown. The gyrotron is installed in the solenoid coil. A rotational electron beam is injected into a cavity, where the high power oscillation occurs with a mechanism of electron cyclotron resonance maser. The magnetic field at the cavity B_c should be set as $f(GHz) \geq 28B_c/\gamma$. Here, f an oscillation frequency, γ a relativistic factor of the electron beam. For example, B_c~1.08T at 28GHz operation.

The oscillation mode is usually high order mode that has a complex configuration of electromagnetic field, which is converted to the parallel beam mode using a quasi-optical mode converter and outputted through the window. Inner surface of the converter has a small periodic perturbation. During passing through the converter, the many modes are excited. These modes overlap at the end of the converter, and the single peaked power distribution is formed at the end of the converter to suppress the diffraction loss. The RF beam can be reformed to arbitrary shape such as Gaussian, flat distribution, multi-beams [2] with a combination of phase correction mirrors.

3. Application of gyrotron to frontier science

1) Plasma processing

Research of plasma processing is currently carried out at a frequency of ~2.45GHz, or MHz band, and significant progress has been obtained. Up to now, example of mm wave application on plasma processing is small. However, mm wave has a merit that a uniform or arbitrary designed power distribution can be formed with phase correcting mirrors. This feature has a potential to make the large sized uniform or arbitrary shaped plasma.

2) ECR ion/plasma source

ECR (electron cyclotron resonance) ion source is commonly used for accelerator (ECRIS) using low frequency microwaves. Modern heavy ion accelerator such as LHC (Large Hadron Collider) at CERN, GSI in Darmstadt, MUSES at Riken, requires an intense heavy and multi-charged ion beam like Pb^{27+}, at ~1mA. For this purpose, 10kW level 28GHz gyrotron has been tested as a power source at CEA Grenoble (new generation ECRIS). The RF power is injected into the mirror configuration in parallel with the magnetic field, and presented higher performance than lower frequency. In next project, ion beams of U^{60+}, Cu^{29+} and Kr^{36+}(full ionized), are planned [3].

3) Gyrotron amplifier

Using a technology of gyrotron oscillator, a gyrotron amplifier (gyro-klystron) is under development. The gyro-amplifier is useful for high gradient accelerator, high-resolution radar, communication, etc. For next generation linear collider (TeV collider), gyro-amplifier is considered as a candidate of drivers. Some designs have conducted for short pulse but high power using a high voltage electron beam (~0.5MeV). Design values of power and frequency are 100MW/17GHz, 55MW/34GHz, 20MW/91GHz, etc [4].

4) ESR/NMR/Plasma scattering measurement

The gyrotron frequency is extended up to 889GHz with 3rd harmonic oscillation at Univ. of Fukui [5]. By controlling the magnetic field, the oscillation mode shifts. Consequently, the frequency changes in stepwise. The high frequency (sub-mm wave) gyrotrons are applied as a power source of spectroscopy for ESR (electron spin resonance) [6], NMR (nuclear magnetic resonance)[7], and plasma scattering measurement [8].

5) Microwave beaming propulsion

By focusing the mm wave power with a parabolic mirror, the air discharge arises. A picture of air discharge is shown in Fig.2. Shock wave at the discharge cause a driving force on the parabolic mirror. The experiment of microwave beaming propulsion was confirmed using 1MW/170GHz gyrotron under the collaboration between Univ. of Tokyo and JAERI. Short pulse RF (~0.1msec) is injected to the thruster. Momentum coupling coefficient of a conical thruster C_m defined as a ratio of propulsive impulse to the input power was 400N/MW, which is larger than that obtained at air discharge with laser [9].

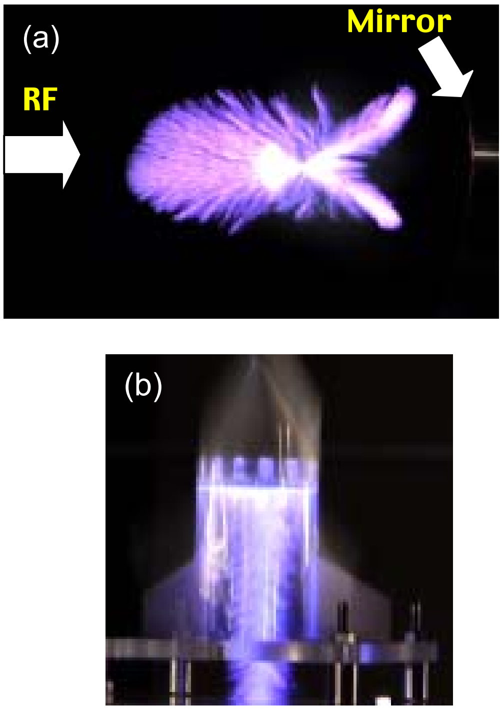

Fig.2: (a) Air discharge with RF beam(170GHz/0.5MW) focusing by parabolic mirror. (b) Experiment of microwave beaming propulsion by injection of mm wave (170GHz/0.5MW).

4. Conclusion

A major progress has been obtained in the development of ECH technologies in 1990's with the ITER and other fusion projects. The applications of mm wave to frontier science have increased with the gyrotron progress at wide range of frequencies. Because the technology of the mm wave is universal, new applications of high power mm wave will be proposed and accelerated further.

References

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