Study of Beam-Material Interaction by Using Hydrogen Ion Beam

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Abstract. In this research, the effect of beam convergence with magnetic field of GAMMA 10/PDX has been investigated. The hydrogen ion beam is injected to the tungsten target under the various strength of magnetic field. The spatial distribution of emission light and rising temperature of the target are measured with a fast camera and a calorimeter, respectively. Effectiveness of beam convergence due to the magnetic field expansion is evaluated from the viewpoint of beam-material Interaction studies.

INTRODUCTION

In order to realize nuclear fusion reactors, it is one of the most important issues that the development of plasma facing materials. For example, the materials used in the divertor are exposed to high heat plasma-flow and are significantly damaged. Heat-load characteristics of the materials have been researched in all over the world by using various heat sources such as particle beams and laser light. We constructed ion beam injection system and installed this system at the west end-cell to inject beam in an axial direction of GAMMA 10/PDX. GAMMA 10/PDX is the largest tandem mirror device in the world and the structure of the magnetic field of GAMMA 10/PDX has opening end at the end-cell. Due to this magnetic field gradient, the ion beam is converged toward the mirror throat and the beam intensity become stronger as the beam approaches the mirror throat.

Our goal is to study beam-material interaction to reveal the physical mechanism of beam facing materials under the circumstances with converging magnetic field configuration. We choose the materials which are going to be used in ITER such as tungsten. In order to investigate the beam characteristics, calorimeters, high-speed video cameras and tungsten targets are prepared. Calorimeters are mainly used for measuring beam intensity. Spatial distribution of light emission from beam-material interaction can be captured by high-speed video camera. In the present experiment, tungsten is used for target material.

EXPERIMENTAL SETUP

GAMMA 10/PDX

The magnetic field of GAMMA 10/PDX has open ended at west and east end-cells. The strongest magnetic field is generated at the end-mirror throat and the magnetic field strength reaches 30 kG.

The z-axis corresponds to the axial direction of GAMMA 10/PDX with the origin at the center of the device. The distance between ion source and the origin is about 1,600 cm .The coordinates of the end-mirror throat is z=1,000 cm. The position of the calorimeter we installed to measure the temperature increase due to the beam injection is z=1,030 cm. And the rotating target is installed at z=1,070 cm. The magnetic field strength at z=1,030 cm and z=1,070 cm are 13.7 kG and 2.82 kG, respectively when the magnetic field strength is 0.91 PU (Power Unit) which is the standard magnetic field strength in GAMMA 10/PDX. This unit is proportional to the coil current intensity. When 1 PU is applied, the magnetic field strength at the end-mirror throat, the calorimeter, the rotating target are 30 kG, 15 kG, 3.1 kG, respectively.

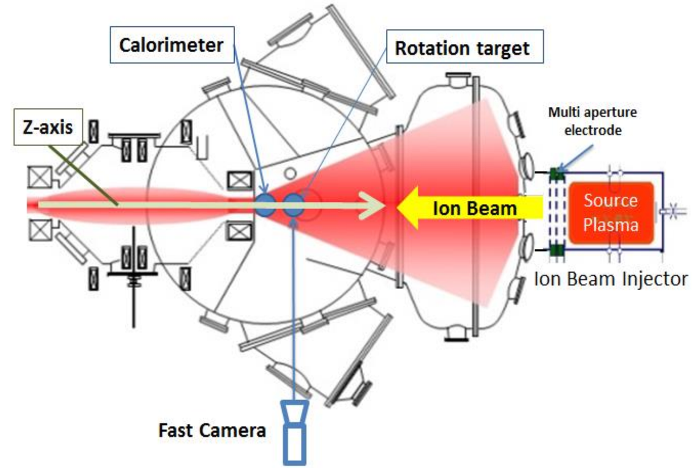

FIGURE 1. View of the west end-cell of GAMMA 10/PDX

Beam System

In order to inject the ion beam in GAMMA 10/PDX, recently, the ion beam injection system is installed on west end-cell (Fig. 1). The beam injection system is composed of power supplies and ion source and measuring apparatus. There are four power supplies. Twenty filaments installed in ion source are usually supplied 500 A by a filament power supply. In order to generate arc discharge current, about 100-180 V and are supplied by the arc power supply. Acceleration and deceleration electrodes are usually supplied ~15 kV and ~ -2 kV, respectively from another two power supplies.

The bucket-type ion source with cusp field is utilized to inject hydrogen positive ion beam. Multi-aperture type electrodes are installed in the ion source. In order to make moderate arc current density for obtaining good parameter beam, the various timings are controlled by a delay pulse generator which controls timings of turning on and off timing of electromagnetic valve to introduce hydrogen gas, the timing of applying arc voltage, and the timing of turning on the filaments. The values such as beam current, arc discharge current and voltage, filament current, acceleration and deceleration voltage are checked on oscilloscopes.

Diagnostics

In order to check beam parameter and experimental values, there are various measuring apparatus are installed. Three-type calorimeters are used to measure experimental values. One of them is for researching beam intensity profile, being installed at z=1,030 cm. Another one is installed at 150 cm downstream from the acceleration electrode for researching beam divergence angle. Last one is installed at rotating target (z=1,070 cm) for measuring beam intensity distribution. All of the calorimeter has heat-receiving body made of Cu. And the target we called rotating target is installed at z=1,070 cm for investigating beam-material interaction. The beam is injected to the rotating target and the emission light of beam-material interaction occurred around the target surface. The emission light is measured by a fast camera, which is able to capture image 100,000 fps at maximum. In this experiment, the flame ratio is set 100~1,000 fps. Rotating target is able to rotate due to change experimental conditions. The circular target shown in Fig. 2 is facing to plasma for measuring plasma parameter. This target is not used on this experiment but the target shown in red square is used. The various target material can be installed. In this experiment, tungsten is installed. Figure 2 (a) is the side view of the rotating target, which corresponds to the camera image.

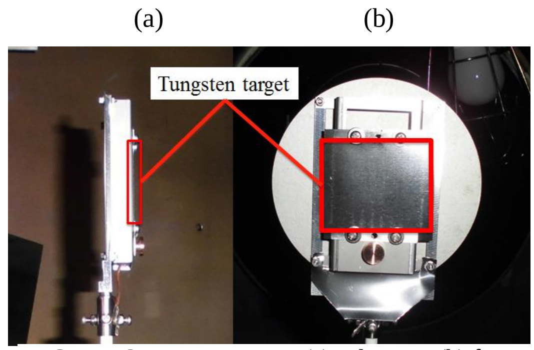

FIGURE 2. Rotating target, (a) side view, (b) front view.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Measurement of Light Emission

The beam divergence angle is measured by moving up and down the calorimeter installed near the ion source. The angle is measured to be about 2.6 degrees in FWHM angle. In this experiment, the beam current and the arc discharge current are measured to be about 4~5 A and ~400 A, respectively.

The profile of the emission light and beam intensity are investigated as follows. At first, the beam is injected to the rotating target with applying various magnetic field strength, then the light emission distribution is measured. This experiment is performed twice by changing the distance from the ion source to the rotating target. At the first experiment, the distance L between the ion source and rotating target is about L=600 cm and the second experiment is carried out about at L=500 cm. Figure 3 shows the two-dimensional image of the light intensity obtained in the first experiment with (0.91 PU) and without (0 PU) magnetic field. In camera images, the approximate length of per pixel is estimated to be 0.5 cm from the size of the light emission around the surface of the target.

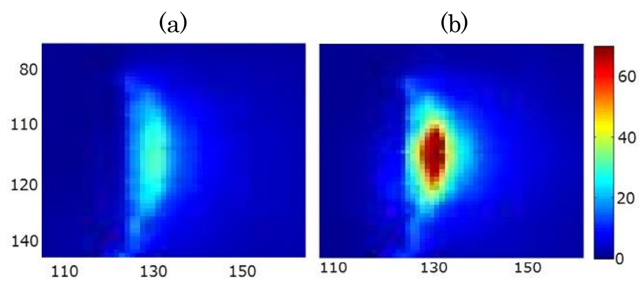

FIGURE 3. Two-dimensional image of the Emission light of the rotating target, (a) 0 PU, (b) 0.91 PU.

The captured images shown in Figs. 3 (a) and (b) represent the condition of the magnetic field strength of 0 PU and 0.91 PU, respectively. It is clear that the light emission around the target depends on the magnetic field strength. It indicates that the ion beam is converged by the magnetic field. In order to investigate the beam convergence effect, the spatial distribution of the emission light on the target is analyzed.

The data of light emission are fitted by Gaussian function and the HWHM value is calculated. As magnetic field becomes stronger, the HWHM of the light emission distribution becomes narrower and the maximum brightness also becomes stronger except 0.78 PU. Possible cause why the brightness is small at 0.78 PU is that an appropriate beam condition was lost at that time. However, as a whole, the brightness increases linearly. Note that the distribution in Fig. 4 (a) is not the beam distribution itself, since this light emission results from the beam material interaction and the target thin film is smaller than the beam diameter.

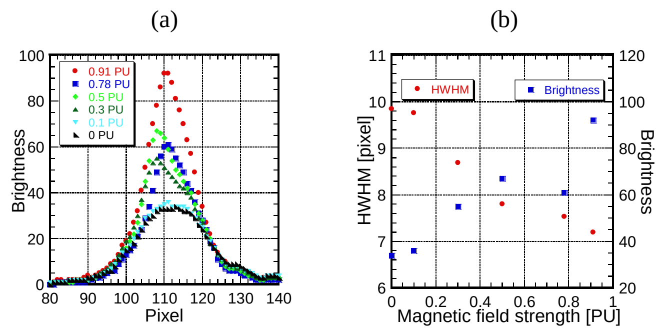

FIGURE 4. (a) Spatial distribution the light emission on the target, (b) HWHM value as a function of the magnetic field.

After this experiment, in order to get stronger beam intensity than it on the first experiment, the ion source is moved 1 m close to GAMMA 10/PDX end-tank. Due to the improvement of the beam line, as shown in Fig 5 (a), the intensity increased and the beam diameter becomes small. According to Fig. 5 (b), the differences of maximum brightness values in each magnetic field strength is about 2~2.5 times and the increase rate of the brightness is almost observed to be similar.

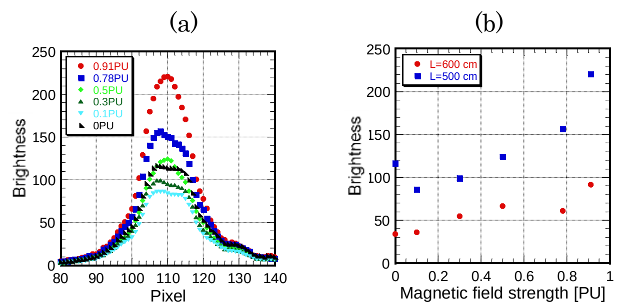

FIGURE 5. (a) Spatial distribution the light emission on the target, (b) HWHM value as a function of the magnetic field.

Beam Intensity Distribution

We investigated the beam intensity distribution at z=1,030 cm under the various magnetic field strength. The data is obtained by using one channel calorimeter. The distribution without magnetic field is flat, although the distribution with magnetic field reveals a Gaussian distribution. It is confirmed that the beam is converged and becomes strong by the magnetic field. The measuring point in Fig. 6 (b) is the maximum value of each distribution. As shown in the figure, it has become clear that the increase tendency of beam intensity is linearly in regard to the magnetic field strength. It is found that the temperature rise in the case of 0.78 PU becomes about ten times larger than that with 0 PU.

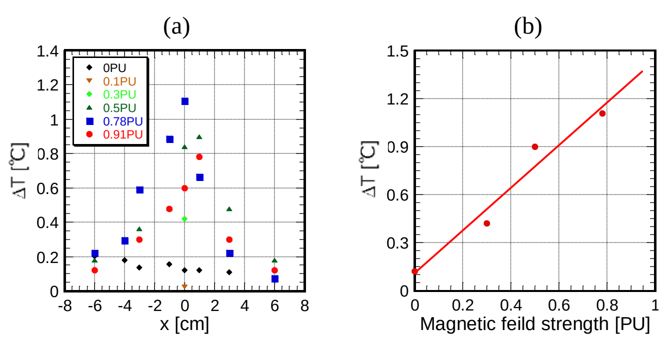

FIGURE 6. (a) Spatial profile of the rising temperature at z=1030cm, (b) ΔT as a function of the magnetic field strength.

At z=1,030 cm, the rising temperature under 0.91 PU is estimated to be 1.33 degrees by the extrapolation in Fig. 6 (b). The average rising temperature under 0 PU in Fig. 6 (a) is calculated to be 0.1 degrees. From the extrapolation of the dependence showed in Fig. 6 (b), the rising temperature under 0.91 PU becomes 13.3 times stronger than that under 0 PU.

In order to evaluate the applicability of the converging effect on the magnetic field strength for beam-material interaction studies, the heat multiplication factor is estimated. Here, in the case that a tungsten target of $10 \times 10 \times 1$ mm is installed at z= 1,030 cm, the temperature rise of the target is calculated under the condition of using the higher performance ion source installed in GAMMA 10/PDX. The rated values of the ion source are 25 kV, 70 A and the beam power is 1.75 MW. This beam intensity is about 30 times larger than that of the present ion source. It is found that the rising temperature of the tungsten target reaches 1500 degrees in 1 sec irradiation under 0.91 PU magnetic field strength. The obtained temperature is superior to DBTT Ductile-to-brittle transition temperature) of tungsten. It is confirmed that the ion beam injector system using the GAMMA 10/PDX end-cell is one of the effective methods for beam-material Interaction studies.

SUMMARY AND FUTURE PLAN

Beam convergence effect is investigated in the end region of GAMMA 10/PDX. It is found that the beam intensity under the magnetic field strength of 0.91 PU becomes more than 13 times stronger than 0 PU. It is confirmed that the ion beam injector system using the GAMMA 10/PDX end-cell is one of the effective methods for beam-material Interaction studies. In the future, we have a plan to study the damage on the surface of the target by using helium beam with more powerful ion source. The various target material not only tungsten but also other kinds of materials will be investigated from the view point of beam-material interaction under the strong magnetic field.

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