# Study of Fueling by Supersonic Molecular Beam Injection in the GAMMA 10 Tandem Mirror

数理物質科学研究科　博士論文の要約

# Study of Fueling by Supersonic Molecular Beam Injection in the GAMMA 10 Tandem Mirror (GAMMA 10 タンデムミラーにおける超音速分子性ビームによる燃料補給に関する研究)

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## Abstract

### 1. Background and Objectives of the Research

Fueling is very important issue for the future thermonuclear fusion reactor. Supersonic molecular beam injection (SMBI) has been developed as a new fueling system that can combine both advances of the pellet injection and the conventional gas puffing system. SMBI is very simple and economically feasible to develop. In this system high pressure gas is injected through a fast solenoid valve which is equipped with the Laval nozzle. The purpose of this study is to investigate the detailed fueling characteristics by SMBI with Laval nozzle in GAMMA 10 tandem mirror device with simplified configurations in magnetic field. Furthermore, 3-dimentional neutral transport simulation code (DEGAS) is employed in order to clarify the neutral particle behavior during SMBI. These results enable us to contribute the study of neutral particle for the complicated devices such as helical type devices, or tokamak devices as represented by ITER.

### 2. SMBI Experiments in the central-cell in GAMMA 10

In the central-cell of GAMMA 10, SMBI experiments is carried out in ion cyclotron range of frequency (ICRF) heated plasmas and those with simultaneous injection of ECRH by using a Laval nozzle. The pulse width is usually 0.5 ms and plenum pressure is varying from 0.3 MPa to 2.0 MPa throughout experiments. In the case of only ICRF heated plasma, the response of gas fueling by SMBI to the electron line-density and Hα line emission is investigated by changing the SMBI plenum pressure. At high plenum pressure (~2MPa), the increase in electron line-line density is almost doubled. Since both the change in electron line-density (ΔNLcc) and Hα-line emission intensity ($\Delta I_{H\alpha}$) increase to SMBI plenum pressure, the particle fueling rate by SMBI is proportional to the plenum pressure in this operation range. The

directivity of the gas fueling by SMBI is evaluated by the 2-D image captured by the high-speed camera. The directivity of injected neutral particles with the Laval nozzle is better than those with the straight nozzle that was used before the installation of the Laval nozzle.

The gas puffing (GP) experiment is also performed to compare with the SMBI results. The experimental results show that the electron line-density is higher during SMBI than that of the gas puffing. On the other hand, the Hα intensity is low and become steeper during SMBI than the gas puffing. It means SMBI with Laval nozzle is more efficient than gas puffing.

Since SMBI inputs a large amount of gas within a short period of time, the plasma density is increased in the central-cell and more ions flow into the end-cells. In GAMMA 10, electron cyclotron resonance heating (ECRH) is applied at plug/barrier-cells in order to form the axial confinement potential. Therefore, to plug the particles escaped from central-cell to end-cells, P/B-ECRH is applied to ICRF heated plasma. From the experimental results, it is observed that the increase in electron line-density is higher than that of without P/B-ECRH in all plenum pressure cases. It implies that the particles are confined in the central-cell due to the potential formation by the P/B-ECRH injection in the plug/barrier region. Hα-line emission intensity is also increased due to the enhancement of ionization during SMBI with P/B-ECRH. The end-loss ion current is measured during SMBI by end loss ion energy analyzer (ELIEA) which is installed on both end sides in GAMMA 10. The end-loss ion current is increased during SMBI. When P/B-ECRH is used during SMBI the end-loss ion current is suppressed and increases the plasma density in the central-cell. It might be due to the formation of plug and thermal barrier potential by P/B-ECRH in the plug/barrier region.

The fueling efficiency, η during SMBI experiments is defined as the ratio of the increase in plasma electron contents to the injected particles by SMBI. The fueling efficiency during SMBI is about 23% and SMBI with ECRH is about 31%. The electron temperature is increased during ECRH injection and high Hα emission intensity is observed during SMBI due to the enhancement of ionization. It is also observed that the electron line-density in the central-cell is higher in the case of ECRH injection due to potential formation by ECRH. Therefore, the fueling efficiency is increased during SMBI with ECRH. In this calculation considerable ambiguities is remaining. The obtained fueling efficiency in GAMMA 10 is almost near to the value of other devices like LHD, JT-60U, Tore Supra, ASDEX-U, EAST tokamak etc.

## 3. SMBI experiments in the east anchor inner-transition region in GAMMA 10

In order to investigate the fueling characteristics, a short size Laval nozzle is newly designed and the SMBI system with this new type Laval nozzle is installed in the east-anchor inner-transition region (EA-SMBI) of GAMMA 10. The dependence of the plenum pressure and the pulse width on the plasma behavior is investigated in the EA-SMBI experiment. The experimental results show that the change in electron line density and Hα-line emission intensity increases linearly with plenum pressure (0.3

MPa~2.0MPa). By comparing with CC-SMBI results it is observed that the change in electron density is slightly high in the case of CC-SMMBI than that of EA-SMBI. On the other hand, the pulse width dependence of EA-SMBI results shows that the line density as well as Hα-line emission intensity increases with SMBI pulse width. However at high pulse width the line-density and Hα emission is saturated.

In the central-cell SMBI experiment, the diamagnetism (DMcc) is decreased during SMBI. The bottom value of DMcc during SMBI almost constant in all plenum pressure (0.3 MPa~2.0 MPa). This is due to the increase in the charge exchange (CX) energy loss of the hot ions produced by ICRF. On the hand, in the EA-SMBI, the diamagnetism is decreases gradually with the increase of plenum pressure. I may be due to the degradation of ICRF heating efficiency because during EA-SMBI there is no increase of Hα emission is observed in the central-cell.

**4. Analysis of neutral transport during SMBI by Monte-Carlo simulation**

The DEGAS code is a 3-dimensional numerical simulation code which simulates the transport of neutral particles in the plasmas by using the Monte-Carlo technique. The neutral transport simulation is successfully applied to GAMMA 10 in order to investigate precisely the spatial distribution of neutral particle behavior during SMBI.

In order to simulate the molecular beam injected by SMBI, $\sigma_{div}$ is introduced as an index the divergence angle of the initial particle. If the angular profile of launched particles has a cosine distribution, it is defined to be unity ($\sigma_{div}$=1.0). The axial and radial profile of neutral transport is investigated for different value of divergence angle index. When the value of divergence angle index is less than unity, the divergence of launched particles is reduced. The perpendicular velocity component of the initially injected particle is reduced in the case of $\sigma_{div}$<1.0. The parallel component of the velocity along the fueling direction is newly considered and the code is modified to conserve the energy. The obtained results are compared after velocity modification. The simulation results well explains the GAMMA 10 SMBI experimental results with Laval nozzle at divergence angle index 0.33. It is found that the particles are suppressed and localized in the injection point according to the reduction of divergence angle index. The neutral particles behavior have been shown a clear dependence on the initial particle source. When the value of initial particle source is reduced, the simulation results are mostly similar with the experimental results. We also evaluated the penetration depth of SMBI-induced particles and it is clarified that the penetration depth has no dependence on the directivity of the particles from the radial distribution of Hα emissivity in the plasma cross-section.

The simulation is also carried out in the different profiles of electron temperature in order to check the sensitivity of the background plasma parameter. The simulation results indicates that the penetration depth depended on the background plasma parameter, electron temperature. The penetration depth increases with the decrease of electron temperature. The radial and axial distribution of Hα emission area shifts towards the core region in the case of low electron temperature. The FWHM value decreases with increase of background electron temperature. This results well explains the SMBI experimental results with additional heating by ECRH.

## 5. Conclusion

The fueling characteristics by SMBI is investigated by both experiments and simulations. Better directivity is clarified in the case of SMBI with Laval nozzle. The enhancement of ionization and confinements of particles during SMBI with additional heating ECRH leads to the improvement of the fueling efficiency.

In the simulation, the code is modified in order to conserve the energy of the initial particles. SMBI experimental results with Laval nozzle is well agreed with the simulation results after energy conservation. It is also observed that the penetration depth depends on the background plasma parameter.

From the above results, the fueling characteristics by SMBI with Laval nozzle obtained in experiments and neutral transport simulations during SMBI will be useful for developing the fueling study. These results also enable us to analyze in detail the neutral particle behavior without dependence of the fueling method. The beneficial knowledge obtained from this study may contribute for the optimization of fueling in future plasma confinement devices such as ITER and DEMO.