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High-Speed Gas Injection to RELAX to Attain High-Density, High-Beta Plasmas
高速ガス入射による低アスペクト比RFPプラズマの高密度化

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Reversed-field pinch (RFP) is one of the toroidal magnetic confinement systems for high-β plasmas. Relatively weak external magnetic field is enough for confinement. In low-aspect-ratio RFP, neoclassical effect becomes to play important roles. In RELAX with A = 2, equilibrium calculation shows existence of the RFP equilibrium with neoclassical bootstrap current fraction of ~ 30% at poloidal beta β_p～0.2-0.3, depending on the pressure profile. Experimentally, the maximum electron poloidal beta ~15% is achieved in RELAX. The more density profile peaks, the more the fraction of Bootstrap current increases. Nozzle design is need to produce high speed gas, because the higher gas speed become, the higher central density can be. Desirable shape is laval nozzle which make gas speed supersonic speed.

1. Reversed-field pinch (RFP)

Reversed-field pinch (RFP) is one of torus magnetic plasma confinement systems, High temperature and high beta Plasma can be confined by weak external toroidal magnetic field. As the aspect ratio (A) of a machine is lowered, the self-induced bootstrap current tends to increase, which may lead to a reduction of the external source for current drive. In addition, in a low-A RFP, an increase in the self-induced bootstrap current may result in a neoclassical equilibrium [1].

RELAX (Reversed-field pinch low-aspect-ratio eXperiment) is a low-A machine with major radius R = 0.508 m, minor radius a = 0.25 m and aspect ratio $A = R/a$ = 2 [2]. We are researching RFP configuration of low-aspect-ratio.

2. Neoclassical equilibrium in RELAX and need for high density operation

Equilibrium analysis shows that there exists an RFP equilibrium with the bootstrap current fraction of~20-30 % at poloidal beta β_p~-0.2-0.3, depending on the pressure profilein RELAX. β_p ~ 0.3 corresponds to T_e~200 eV and n_e~ 3×10^{19} m^{-3} at I_p ~100 kA. In the experiment, the parameters achieved in RELAX are as follows: n_e~ 10^{19} m^{-3} , T_e~100-200eV at I_p ~50-80 kA. The maximum electron poloidal beta is ~15%, close to the region where we may expect sizable fraction of the bootstrap current. [3].

In RELAX, it is shown that the electron poloidal beta increases with density normalized to the Greenwald density n_G ($\propto$ j/n). It is required therefore to achieve higher density operation at higher current in order to attain to higher beta value. Since the electron temperature increases with plasma current, it becomes more difficult for neutral particles to penetrate deep into the plasma in higher current discharges. High-speed gas injection is therefore necessary to achieve higher density regime in RELAX experiment.

3. Gas puffing system

We are developing a high-speed gas injection system in RELAX to achieve higher density regime and to control the pressure profile. The injection system consists of a fast-acting electromagnetic gas valve and a nozzle to produce directed supersonic gas flow. It is quite important to design optimum nozzle structure to attain gas speed high enough to penetrate deep into the target plasma. On the contrary, we may be able to control the gas deposition (ionization) profile by controlling the gas speed using appropriate nozzle design. An ideal structure is the laval nozzle by which we can obtain supersonic gas flow. Figure 1 shows an example of the design of the laval nozzle. Using this corn-shaped nozzle, Mach number of 5 (M = 5) is obtained.

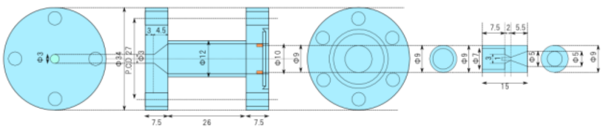

Fig.1. the design of the laval nozzle (M=5)

Figure 2 shows connecting the nozzle to vertical port.

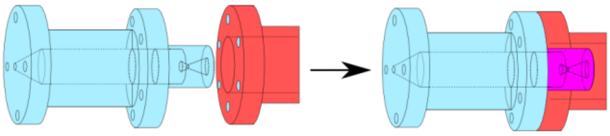

Fig.2.Connecting the nozzle to vertical port.

4. 140 GHz Interferometer system

We measured electron density by 104 GHz interferometer (on loan from the University of Tokyo) in RELAX. The measured electron density n_e varied from 0.3×10^{19} m^{-3} to 3×10^{19} m^{-3}, depending upon the discharge conditions [4].

A 140-GHz interferometer has been developed for higher-density operation in RELAX. Figure 3 shows the block diagram of the heterodyne interferometer. It uses two oscillators whose oscillation frequencies have 70 MHz difference. The two signals, one through the plasma and the other through the reference chord, are mixed at the IQ detector, whose output provides the sine and cosine component of the phase difference. The upper bound of the density measurement is estimated to be cut-off frequency of the 140 GHz. The system has been attached to the RELAX machine and initial test operation is in progress.

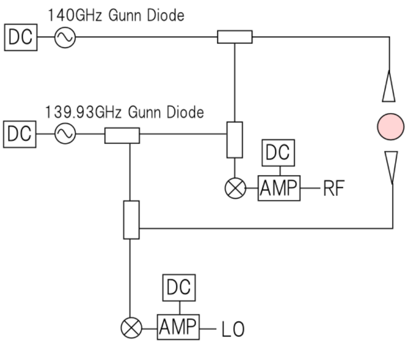

Fig.3. 140 GHz Interferometer system

5. Result of Experiment

High-speed-gas injection by use of the laval nozzle is performed in RELAX. The gas is injected into an RFP discharge with duration of ~2.5ms. The gas pressure is chosen so that the gas injection brings about no degradation of the discharge. A high-speed camera with frame rate of 10^7 fps is used to observe the time evolution of the visible light (mainly from H_α line emission) near the gas injection port.

The back pressure is 0.6 MPa, valve open time is 600 μs, and pressure is 40 mPa in plasma chamber. Figure 4 shows a visible light image taken with the high-speed camera through a horizontal port. A bright spot in the right hand side is the location of the port for gas injection. We can identify a jet structure from the port into the plasma. It is an indication of injection of the hydrogen gas with directed speed. Since the time interval between the frames is 10 micro-sec, we may be able to identify the gas speed from the pictures. Such effort is in progress.

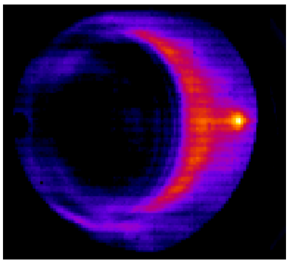

Fig.4.fast camera image of H_α as seen from a tangential port with gas puffing from the right side vertical port

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