ECCD system design activities for JA DEMO

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Abstract. ECCD system design activities for JA DEMO is in progress. Activities contains physical analysis, launcher design, and RF power plant design. The physical analysis activity explores various approaches to enhance ECCD efficiency. The RF power plant design activity produced a conceptual design of a 100 MW class RF power plant. The launcher design activity presented the upper and equatorial launcher port of the JA DEMO tokamak vacuum vessel and analyzed the ECCD operation of each launcher. The result is the achievement of RF power deposition at the core of plasma for ECCD by selecting the proper injection angle and frequency.

1 INTRODUCTION

JA DEMO is planned as an electric power-generating fusion reactor that demonstrates the steady and stable operation of the tokamak system. The output electric power of JA DEMO is defined as several hundreds of MW class, and the design of the fusion plasma operation scenario and engineering study of the subsystem is underway.

Currently the JA DEMO tokamak is designed to have a major radius of 8.5 m, a minor radius of 2.42 m, a plasma current of 12.3 MA and an axial magnetic field of 5.94 T. When the reactor is operated at a fusion power of approximately 1.5 GW, the gross electric power generated is estimated to be 630 MW.[1] The primary scope of the JA DEMO design is to demonstrate steady and stable power generation beyond several hundreds of MW. For this purpose, a special team has been formed, comprising institutes, universities, and industries in Japan, and is actively working on various subsystems and scopes.

For the steady operation of the JA DEMO tokamak plasma, the electron cyclotron current drive (ECCD) is expected to be a promising current drive method because of its injection port size, a radial controllability of the driven current, efficient power absorption less dependent on plasma density, and so forth. A JA DEMO design group for the ECCD system design has been formed. Our group aims at physics and engineering approaches with work scopes, including physical analysis of ECCD, launcher design, technology development, and RF power plant design.[2]

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The primary aim of the physical analysis of ECCD is to improve the current drive efficiency. The efficiency of ECCD is critical to reduce internal electric power consumption in a fusion power plant site for steady-state operation of tokamak plasma. With a low-efficiency current drive, most of the produced fusion power is utilized for plasma current driving, and very limited output power from the power plant will be obtained. JA DEMO is designed to drive the plasma current of 12.3 MA with the bootstrap current of 7.5 MA (61%) and an external current drive of 4.8 MA (39%). The power required for the external current drive is estimated to be 87.3 MW in the case of NBI. [3] Since the current drive efficiency of ECCD is lower than that of NBI, a higher injection power will be required for ECCD compared to NBI. Nevertheless, regarding the required plug-in power, ECCD is likely to be comparable to NBI in that ECCD is anticipated to have superior system efficiency. Exploitation of efficient ECCD conditions is one of the purposes of this study. A survey of the injection port and injection condition uses several analysis codes to determine more efficient current drive operation conditions. The survey analysis found that avoiding unexpected absorption by the second harmonic resonance occurring in the edge plasma area is critical to improve the efficiency at various injection ports. [4,5]

A current drive scheme utilizing dual-frequency injection is considered to find an improved method of current drive efficiency. The TASK [6] code is applied to JA DEMO plasma configuration for this purpose. The basic idea of dual-frequency injection is explained as follows: one wave interacts with bulk electrons and accelerates those near the resonance curve in

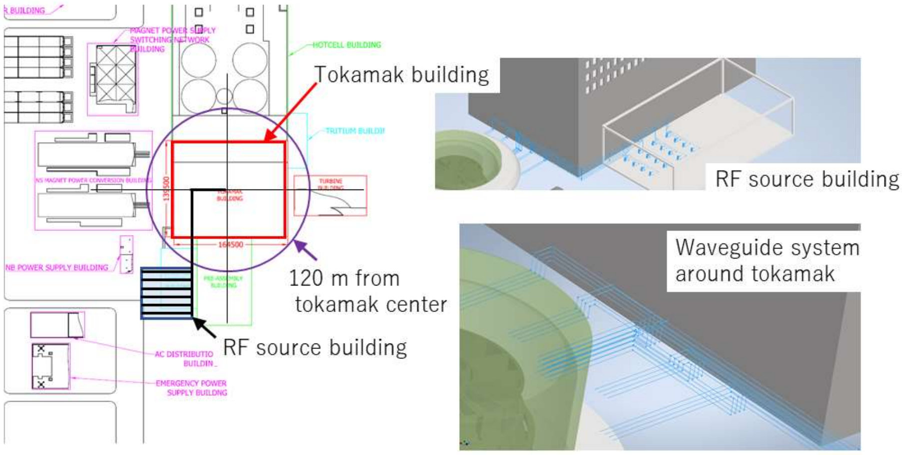

Fig. 1. Location and scale of RF power source building compared to tokamak building and CAD model of TL system.

momentum space. The other wave is chosen so that it interacts with the accelerated electrons on the same magnetic surface and further accelerates to higher velocity to reduce the collisional drag force. There are several choices of the resonance curve of the second wave. One choice is to use the backward second-harmonic wave. The centre of the second resonance curve is far away from that of the first one and the resonance curve is almost perpendicular near the resonance region of the first one. Therefore efficient acceleration to the higher velocity is expected. The modification of the momentum distribution function was described by the 3D Fokker-Planck module of the TASK code with quasi-linear diffusion and the collisional relaxation. Slight improvement of the current drive efficiency has been obtained [7] and further optimization is under way.

As another physical analysis field, ECCD operation during an initial start-up of the JA DEMO tokamak is also analyzed [8]. The same frequency (210GHz) as the wave for ECCD on the burning plasma is employed but the X-mode is used to drive current efficiently in a low temperature and density start-up plasma [7]. The start-up plasma is initially generated in front of the ECR layer near the inboard wall (see Fig.4) and expands toward the lower field side as the current and temperature increases. The current ramps up from 0.1 to 3 MA by 2.5 to 15 MW EC power during 20 seconds, during which the self-induction (-2 Volt) is cancelled out by the positive loop voltage from central solenoid; thus a fast ramp-up is realized.

To realize the ECCD operation analyzed above, enormous RF power is needed in JA DEMO. To start the design activities for the RF power plant design, a preliminary plant specification is defined as the total output of the RF power level, which is assumed to be 100 MW class. The frequency is at range > 200 GHz. Such a vast RF power source of the ECCD system consists of hundreds of gyrotrons, high-voltage power supplies, transmission systems, and various auxiliaries.[9] JA DEMO RF power plant becomes a cluster of 1 MW class gyrotrons. To avoid interference with the stray magnetic field of the tokamak and gyrotron magnet system, the location of the RF power plant in the JA DEMO site was determined as shown in Fig. 1. The length of TL from the RF power plant to the tokamak becomes longer than 200 m [2,5].

The long-distance TL in the JA DEMO ECCD system operates in a steady-state condition. The mode purity degradation caused by the waveguide system's thermal deformation during RF operation must be avoided. A mechanical control system to suppress the thermal deformation of the TL waveguide system is studied using a servomotor driving system with feedback control. A mockup test was carried out, and its successful operation was demonstrated.

The RF launcher system design for ECCD operation is the leading engineering part of integrating the ECCD system into the JA DEMO tokamak. This paper presents a launcher design based on outcomes from physical analysis and analyses its ECCD operation.

2 STATUS OF LAUNCHER DESIGNS FOR ECCD

To develop an integrated design of the ECCD launcher in JA DEMO tokamak, launcher port spaces in a tokamak vacuum vessel are evaluated for upper and equatorial port directions. The port space for the upper launcher is determined by avoiding interference with the toroidal field coils, poloidal field coils, support structures of both coil systems, and various feeding components around the tokamak. The equatorial port is already settled in the vacuum vessel and utilized for the equatorial launcher. The locations of both ports are shown in Fig. 2.

The determined port size and angle of port direction of the upper port are severely restricted due to interference with the poloidal field coil and the surrounding vacuum vessel components. Compared to equatorial port, the size of the upper port is less than half in height and width. Even with such limited space, a cluster of several tens of waveguides has to be implemented in each port to provide the necessary RF power. A detailed RF waveguide setup and auxiliary system design in the launcher port are on-going.

Since the JA DEMO's launcher system is in a very severe radiation environment, front mirror steering technology has difficulty in operation and maintenance.

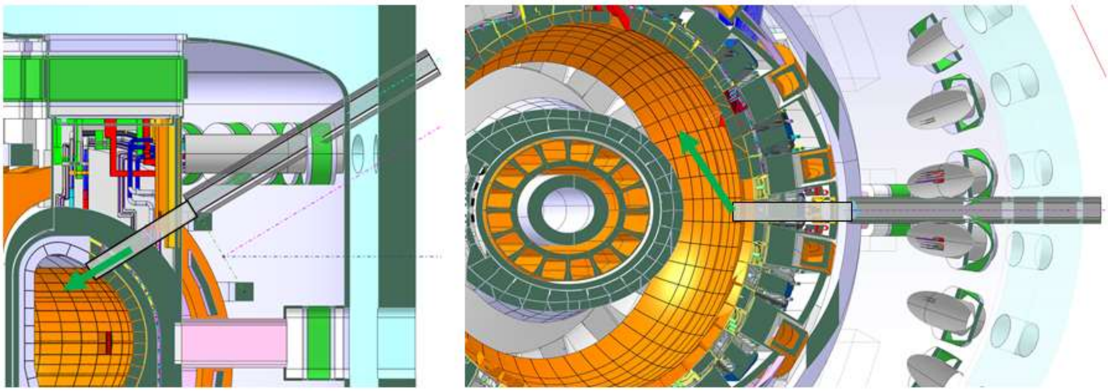

Fig. 2. Example of launcher port location for upper injection in the tokamak vacuum vessel.

Therefore remote steering launcher technology is expected to be promising. To produce large angle injection angle, different methods are under survey, such as high order branch operation technology of remote steering system, combined optics with a remote steering mechanism and a fixed quasi-optical mirror, and etc. A detailed optical design based on each method is in progress to provide an RF beam with a proper injection angle.

Apart from launcher design process in vessel, basic research of remote steering technology itself is another scope of launcher design activities of the design group. A large oblique angle injection is demanded for ECCD operation, and simulation and low-power experiments examine the possibility of a sizeable oblique angle injection. Apart from a typical remote steering control with a steering angle of around 0 degrees [10], an extended operational range has been proposed and confirmed at the low-power test. The extended operating range of the remote steering antenna will be surveyed for the JA DEMO application [2,5].

3 PHYSICAL ANALYSIS FOR ECCD EFFICIENCY IMPROVEMENT

To evaluate the ECCD performance with designed launcher locations, TRAVIS [11] and PARADE [12-13] codes are applied to the JA DEMO configuration. Fig. 3 shows the injection ray trace of various injection angles from the upper launcher at 210 GHz. By selecting the proper injection angle and frequency, RF power from the launcher can access the plasma core for the plasma current drive. Fig.4 shows the injection ray trace from the equatorial launcher at 210 GHz. As with upper port injection, RF power deposition occurs at the plasma's core by selecting the proper injection angle and frequency. (See ref. [4] for a mechanism that can effectively avoid higher-order resonances even from the equatorial launcher.) The current drive efficiency was estimated as almost 0.04 A/W at both injection condition configurations. As a result, this evaluation represented that the launcher port design was suitable for ECCD operation.

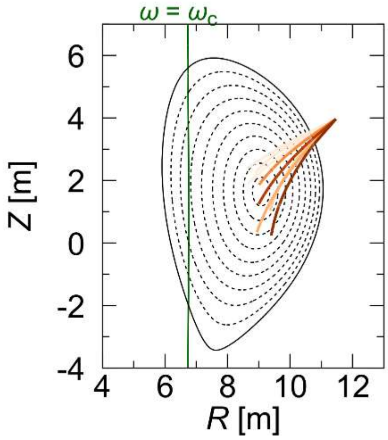

Fig. 3. RF power injection ray trace from the upper launcher.

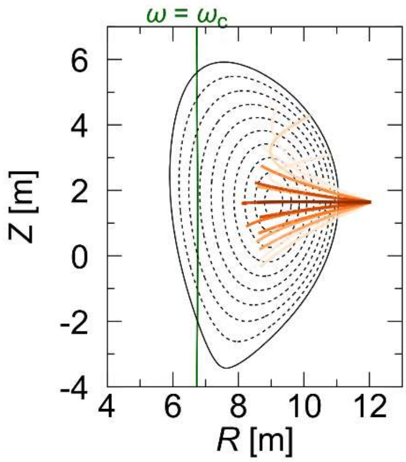

Fig. 4. RF power injection ray trace from the equatorial launcher.

4 Summary

ECCD system design activities for JA DEMO are reported. Activities contain physical analysis, launcher design, and RF power plant design. Physical analysis covers various topics for improving ECCD efficiency, namely survey of injection conditions for higher current drive efficiency, dual-frequency injection method, initial current driving operation analysis, etc. RF power plant design activity produced a conceptual design of a 100 MW class RF power plant. The launcher design activity presented the upper and equatorial launcher port design of the JA DEMO tokamak vacuum vessel, which avoids interference with toroidal and poloidal field coils and support structures. For both launcher ports, physical analysis of ECCD operation demonstrated excellent RF power deposition at the plasma core by selecting the optimal injection angle and frequency. As further steps of ECCD system design, detailed mechanical and optical design of launchers, reliability, and maintenance studies are planned.

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