ELECTRON BERNSTEIN WAVE HEATING FOR THE TJ-II STELLARATOR

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Abstract

Electron Bernstein waves (EBW) have been successfully used to heat overdense plasmas in W7-AS and H-J stellarators [1,2], having the advantage of overcoming the cut-off density limit of usual electron cyclotron heating (ECH) methods. The feasibility of plasma heating using EBW has been examined in the TJ-II flexible heliac. The complicated TJ-II geometry together with the difficulty of access from the High Field Side (HFS) pose specific problems for using this heating method in this device and a special consideration is given to those problems related to the hardware design. In this paper the theoretical calculations are summarized and the layout and the main features of the new system are described.

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Introduction

The electron Bernstein wave (EBW) is a longitudinal electrostatic wave, which can propagate in plasmas without any cut-off density in contrast to electromagnetic waves . The Bernstein wave is absorbed at the electron cyclotron resonance layer. The excitation of the B-mode is based on the so called O-X-B conversion, in which the O-mode is converted into de slow X-mode, which is transformed in the upper hybrid resonance (UHR) into B-mode, or on direct X-B conversion. The higher densities allow to reach a higher collisionality physics and to get a good plasma target for neutral beam injection. EBWs can also be used to drive currents in these high density plasmas and to perform perturbative experiments.

The ray and beam tracing code TRUBA has been developed in order to study the properties of conversion, propagation and absorption of EC waves [3].

The magnetic field in TJ-II is B < 1 T and the plasma is heated by two 53.2 GHz - 300 kW- 1s - gyrotrons in the X polarization mode. The typical electron temperatures are above 1 keV and the density is about 1 x 10^{19} m^{-3}. This two gyrotrons create the target plasma to launch later the 28 GHz power.

Calculations

The Clemmov-Mullaly-Allis (CMA) diagram for the EC frequency range in TJ-II [4] shows that the X-B2 heating scheme (X to EBW conversion at second harmonic) is unfeasible in TJ-II, since the magnetic field variation inside plasma does not exceed 30–35% (must be >100%). Then, the O-X-B schemes at first and second harmonics are not practicable in low-density plasmas with $n_{max}<n_{O\text{-}X}$. The central densities for O-X conversion in TJ-II are: ~ 1.1 x 10^{19} m^{-3} for O-X-B1 (f =28 GHz) and ~ 3.8 x 10^{19} m^{-3} for O-X-B2 (f = 53.2 GHz). Therefore, the only heating schemes that can be used in the present days are X-B1 and O-X-B1. The X-B1 may be troubled in high density plasmas with $n_{max}>1.3$ x 10^{19} m^{-3} because the central region is opaque for X-mode, while peripheral propagation suffers from strong refraction. One should note that when n_{e0} drops below 1.1 x 10^{13} cm^{-3}, O-X conversion fails with the subsequent total loss of efficiency of this scheme. Therefore, ECH must be used to get high densities and an extra gas puffing is needed to achieve the necessary density.

Although both scenarios: X-B and O-X-B in the first harmonic are feasible in the TJ-II from the theoretical point of view, the O-X-B1 has been chosen to carry out the experiments due to accesibility restrictions of the launching position inside the TJ-II vacuum vessel. The optimum launching direction has been determined by single ray tracing calculations. Several positions on the O-mode cut-off surface, with total transmission efficiency (T=1) and covering a wide range around the injection port, have been considered. The chosen position has the most centered (closest to the plasma center) and localized power deposition. (The calculations have been carried out with the magnetic field configuration optimized for present ECRH) An example of ray tracing calculations for this heating scheme with off-axis absorption is presented in figure 1.

$$n_e = 1.7(1-\psi^{1.375})^{1.5} \quad 10^{13}\ \text{cm}^{-1}$$

$$T_e = 0.7(1-\psi^{1.125})^{1.25} \quad \text{KeV}$$

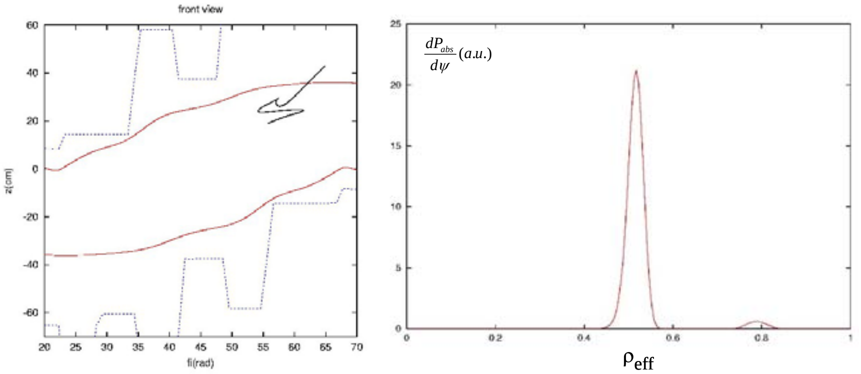

Figure 1. Ray trajectory for O-X-B1 and power deposition.

The high voltage power supply

The 28 GHz- 300kW -100ms - gyrotron was previously used for ECR plasma heating in the TJ-IU stellarator. The main parameters of this gyrotron are as follows:

- cathode voltage: 60-70 kV
- current: 13-25 A
- pulse length: 100 ms
- power: 300-350 kW

A new high voltage power supply unit, which provides the formation of a stabilized negative voltage pulse up to 70 kV and a maximum current of 25A, is designed for this gyrotron. It is intended for the formation of negative pulses at the cathode of the two-electrode gyrotron with a duration specified by an external driving generator. It must ensure 100% modulation of the output microwave power with a given pulse duration and also must provide the high-speed protection of the gyrotron from damages caused by internal breakdowns by limiting the energy deposited at the electrodes.

The figure 2 shows the block diagram of the previously used HVPM.

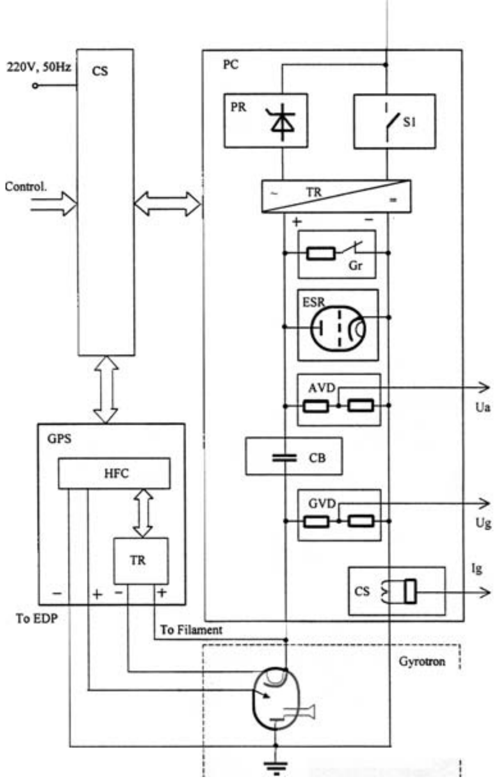

Figure 2. Block diagram of the HVPM

It includes the following units:

- primary regulator (PR)
- transformer-rectifier (TR)
- capacitor bank (CB),
- electronic switch regulator (ESR)
- controlled power supply for the gyrotron filament circuit (GFPS)
- power source for a built-in-electric-discharge pump (EDP) with a vacuum gauge for permanent vacuum monitoring
- the monitoring system
- auxiliary system (AUX)
- control system.

The supply voltage feeds through a power switch the primary regulator and the transformer-rectifier. The controlled direct current from the output of the TR charges the CB up to the required output voltage. After triggering the electronic switch regulator, the stabilized pulse voltage supplies the gyrotron. Stored in capacitors energy limited the pulse length only at 40 ms value.

The primary regulator maintains a given voltage at the input of the transformer rectifier stabilizes it against the variations in the circuit and load parameters and also switches off the power supply in emergency regimes.

The ESR provides the high-speed commutation and stabilization of the load voltage by a command from the control stand and ensures the fast switching-off of the load in the case of its breakdown. In the case of simultaneous breakdowns of the gyrotron and commutation tube, the protection of the load electrodes from damages is provided by the crowbar protection system. The maximum admissible energy deposited at the gyrotron electrodes is 10 J. The control unit is intended for matching a low-voltage control signal to the high voltage input circuit of the commutating tube. This unit includes control circuits, the power supply system of the high-power regulating triode, and the diagnostic elements of the main units.

A deep discharge of the capacitor bank and a power booster will be used to increase the pulse length up to 100 ms. Voltage decrease up to 50% at the CB allows using of 75% of stored energy. Such over drop in an input voltage at ESR should be compensated with pulse power booster. The booster consists of low voltage small power regulator, low voltage capacitor bank and high power converter with HV output rectifier connected in series to the CB to produce the boosting voltage. Thus we can conserve all advantages of previous HVPM concept and obtain new long pulse high power supply with low consumption from the mains.

Transmission and launching system

The microwave beam is transmitted by a corrugated waveguide and it is launched through the D6 port of TJ-II. A movable internal mirror is needed in order to focus the beam and to accomplish the restrictive launching angle conditions. The design of this mirror, the support and its handling is the hardest task due to the complicated TJ-II geometry and the lack of space inside the vacuum vessel. Due to this reason the O-X-B1 scenario has been chosen to carry out the experiments because the position of the mirror for the X-B1 scenario implies too many difficulties [5].

An oversized corrugated waveguide has been chosen to transmit the 300 kW- microwave power due to the lack of space next to the TJ-II launching port. The waveguide has an inner diameter of 45 mm and operates at atmospheric pressure. Two continuous curvature 90-degrees bends are needed and the losses are estimated in less than 0,5 %. The distance between the gyrotron and the launching TJ-II port is approximately 7 m.

The optimum coupling from the output Gaussian beam of the gyrotron into a straight corrugated waveguide with an internal diameter D requires that the beam waist parameter is equal to 0.32 D. The beam waist must be close to the aperture of the waveguide to insure that the beam wavefront is planar. To achieve this conditions two curvatures mirrors are designed to get the required electromagnetic field at the input of the waveguide. The quasi-optical part also includes two corrugated mirrors that actuate as an elliptical polarizer and as a polarization twister to get the optimal polarization of the launched beam.

The position and the curvature of the internal mirror is designed in order to get the better absorption as it is explained in [6]. A lateral view of the position of the internal mirror in the vacuum vessel of the TJ-II stellarator is shown in figure 3.

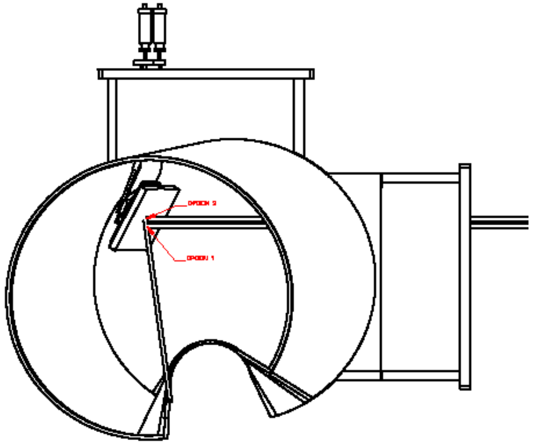

Figure 3. Port D6 and position of the internal mirror.

The power delivered to the plasma for a given shot will be measured by an in line monitor whose design is described in [7]. A calorimeter will be installed at the output of the gyrotron and the transmission losses along the line can be estimated.

Conclusions

To carry out experiments on plasma heating by Electron Bernstein waves in the TJ-II stellarator a new system has been designed. The EBW will be excited by the O-X-B conversion scenario in the first harmonic. The 28 GHz - 300 kW - 100 ms - gyrotron will be used for EBW plasma heating. A new high voltage power supply has been designed. The microwave power will be transmitted by an oversized corrugated waveguide. An internal movable mirror has to be used to launch the beam in the required position and with the optimal parameters.

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