

Design of auxiliary ECR heating system for the Gas Dynamic Trap

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The mirror device Gas Dynamic Trap (GDT) in Budker Institute of Nuclear Physics, Novosibirsk is proposed as a fusion neutron source to test and validate inner wall components of ITER and future thermonuclear fusion reactors [1]. Relative to previous magnetic mirror neutron sources, the GDT facility uses simpler axisymmetric magnetic coils and consumes less tritium providing about 2MW/m² neutron flux. Recent results with high $\beta=0.6$ provide a firm basis for extrapolating to a fusion relevant high-flux neutron source [2]. Another important application of the GDT neutron source is nuclear waste processing based on fusion driven burning of minor actinides [3]. In this paper we discuss physics and design of a new system for electron cyclotron resonance heating (ECRH) presently under construction for the GDT device which is aimed at increasing the bulk electron temperature in the trap volume and in the long run the efficiency of the neutron source.

The main part of the GDT setup is an axially symmetric magnetic mirror with high mirror ratio. Plasma in the trap consists of two ion components: the background ions with a temperature of about 200 eV and density $2 \cdot 10^{19} \text{ m}^{-3}$ confined in a gas-dynamic regime, and the hot ions, which are produced as a result of oblique injection of high-power (up to 5 MW) hydrogen or deuterium beams into plasma. The distribution function of the hot component is essentially anisotropic in the velocity space; therefore the density and pressure of hot ions are peaked in the mirror points providing conditions for the fusion reactions. Presently the mean energy of the hot ions is about 9 keV, and their density near the mirror points reaches $5 \cdot 10^{19} \text{ m}^{-3}$. Energy confinement times of hot ions as well as their velocity spread are determined basically by the collisional slowing-down on the bulk electrons. Since $\tau_{ei} \propto T_e^{3/2}$ the electron drag force is rapidly decreasing with the electron temperature increase. This makes the electron temperature to be the most important parameter which determines the efficiency of the neutron source.

One of the possibilities to increase the electron temperature in the GDT is provided by the auxiliary ECRH system discussed in the present paper. This system based on two 450 kW / 54.5 GHz gyrotrons has a pulse duration longer than the typical NBI-driven discharge (about 5 ms). Evident and attractive feature of ECRH is direct power transfer into the electron component which may be comparable to the power transmitted to electrons due to the ion slowing-down (1.5 MW). Power balance analysis shows that the auxiliary ECRH can provide essential enhancement of electron temperature: up to 350 eV (in case of full absorption) instead of 200 eV achieved in present-day experiments with 5 MW NBI heating. This corresponds to enhancement of the hot-ion confinement time from 2.3 ms to 5 ms what drastically increases the efficiency of neutron-flux production.

The key physical issue of the GDT conditions is that all conventional and widely used ECRH geometries are not accessible. The so-called transverse launch of the gyrotron radiation with respect to the ambient magnetic field shows low efficiency for GDT plasmas even at the fundamental harmonic due to relatively low electron temperature and small scales of the device. Indeed, the total optical depth for the ordinary (O) mode may be estimated as

$$\tau^{\text{O-mode}} = \int 2 \text{Im} \mathbf{k} \cdot d\mathbf{l} \approx \pi \beta_e^2 q k L_B \ll 1,$$

where $\beta_e = (T_e / m_e c^2)^{1/2} \sim 0.02$, $q = \omega_{pe}^2 / \omega_{ce}^2 \sim 1$ is the ratio between the electron plasma and cyclotron frequencies, $k = \omega_{ce} / c$ is the vacuum wave number corresponding to 54.5 GHz, and $L_B \sim 10$ cm is the magnetic field inhomogeneity scale. Quasi-transverse launch of the extraordinary (X) mode is impossible at the fundamental harmonics due to plasma refraction and poses the same low efficiency at the second harmonic as the fundamental O-mode. Fortunately, the fundamental X-mode may be effectively absorbed while propagating quasi-longitudinally along the magnetic field at large enough longitudinal refractive index $N_{\parallel} \sim \beta_e^{-1/3}$, the total optical depth is then [4]

$$\tau_0^{\text{X-mode}} \approx \frac{8}{\sqrt{\pi}} \beta_e^{1/3} q^{2/3} (1-q)^{3/2} k L_B \sim 10.$$

However, the quasi-longitudinal launch of waves with high-enough N_{\parallel} is physically impossible at the GDT conditions. The solution proposed is based on a peculiar effect of radiation trapping in an inhomogeneous magnetized plasma column. Under specific conditions *oblique* launch of gyrotron radiation results in X-mode propagating longitudinally in the vicinity of the cyclotron resonance, what provides effective single-path absorption of

the injected RF power. The physics of the radiation trapping may be understood as following. A wave beam injected obliquely from a vacuum passes $N_{\parallel} < 1$ which is nearly constant of the plasma-vacuum boundary. During propagation in plasma the longitudinal refractive index increases as

$$\Delta N_{\parallel}^2 \approx \Delta \varepsilon_{-} \left[(\cos^2 \theta + \varepsilon_{\parallel}) / (\varepsilon_{-} + \varepsilon_{\parallel}) \right]_{\text{at injection point}},$$

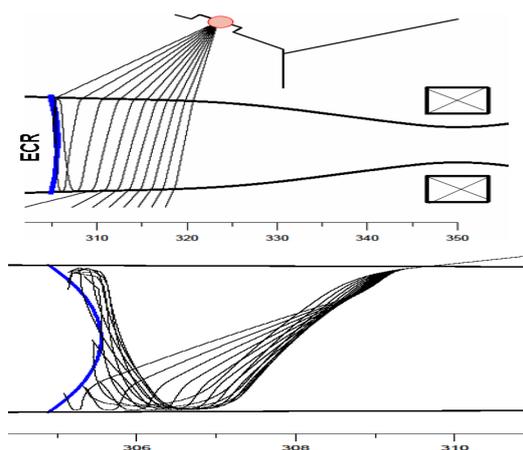


Fig. 1. Top – geometric-optical rays for a set of launching angles $15^{\circ} - 70^{\circ}$. Bulk plasma density is $1.5 \cdot 10^{19} \text{ m}^{-3}$. Bottom – rays launched with the same angle 55° for a set of plasma densities $0.5 - 2.5 \cdot 10^{19} \text{ m}^{-3}$.

where $\varepsilon_{-} = 1 - \omega_{pe}^2 / (\omega - \omega_{ce})$,

$\varepsilon_{\parallel} = 1 - \omega_{pe}^2 / \omega^2$, and $\Delta \varepsilon_{-}$ is variation of ε_{-} along the radiation path, θ is the wave propagation angle.

Evidently, if $|N_{\parallel}| > 1$ at a plasma border, then radiation cannot escape the plasma volume at least as a geometro-optical ray. A ray is reflected back to the plasma core, and propagates towards the electron cyclotron resonance (ECR) where both ε_{-} and N_{\parallel} are increasing.

Finally the ray reaches the vicinity of the ECR with $N_{\parallel} \sim \beta_e^{-1/3}$ sufficient for a single-pass absorption. Note that due to increasing ε_{-} the trapping does not occur if the injection port is close enough to the ECR surface.

In the present communication we investigate numerically a number of optimized ECRH scenarios based on the proposed mechanism. In the example shown in Fig. 1 we demonstrate how a set of rays may be splitted into trapped and untrapped fractions depending on the initial launching angle. All trapped rays are 100% absorbed. Also we show that trapping is still possible for various plasma densities. Calculations are summarized in Fig. 2 where the trapping regions are mapped in the plasma density – launching angle diagram. Here we consider three possible positions for the last mirror shown in the inset. After some discussion the “launch 1” point was chosen for the reference design presented below. Correspondingly, this geometry allows operating in the density range $0.5 - 2.5 \cdot 10^{19} \text{ m}^{-3}$ using a $50^{\circ} - 55^{\circ}$ angular window.

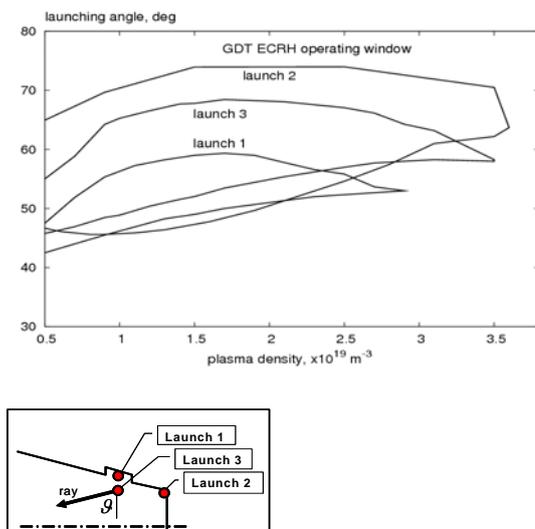


Fig. 2. Operating windows in angle—density plot for three positions for the ECRH launcher. Launch 1 has been selected for manufacturing

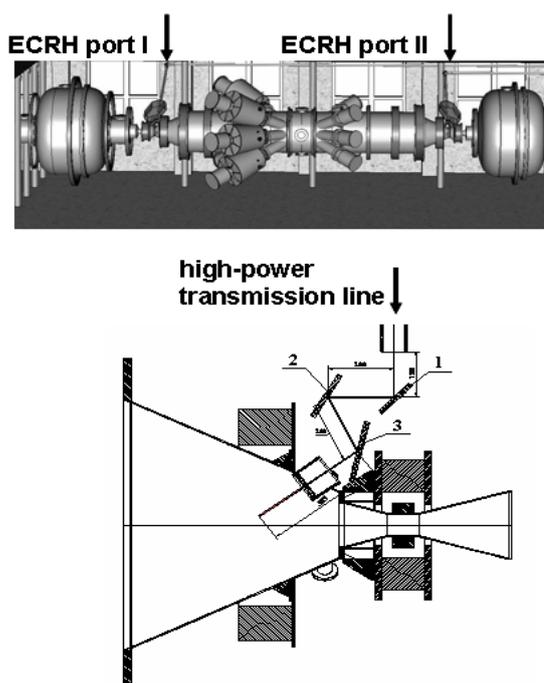


Fig. 3. Top – overview of the GDT facility and positions of the ECRH ports. Bottom – schematic of one of the ECRH launchers (currently under construction in Novosibirsk).

The auxiliary 450/900 kW 54.5 GHz ECRH system is now under construction at the GDT. Design of the proposed fundamental harmonic X mode ECRH launch system is shown in Fig.3. The start-up of the first gyrotron line is expected in Spring 2012. This system can provide essential enhancement of the electron temperature application up to 300 – 400 eV. According to computer simulations, in this temperature range the GDT neutron source is quite attractive in comparison with the accelerator based systems [1].

In conclusion we would mention another promising application of ECRH for creating a hot electron population for improved confinement, which is a matter of our future research.

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