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OBSERVATION OF VERY DENSE AND COLD DIVERTOR PLASMA IN BEAM HEATED DOUBLET III TOKAMAK WITH SINGLE-NULL POLOIDAL DIVERTOR

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A very dense and cold divertor plasma associated with strong remote radiative cooling has been observed by a Langmuir probe array installed in the Doublet III divertor plates with beam-heated diverted discharges (injected power of up to 1.2 MW). The divertor plasma becomes denser and colder as the line-averaged electron density of the main plasma $\bar{n}_e$ is increased. The maximum electron density obtained is $n_{ed} = 2.8 \times 10^{14}$ cm^{-3} at the divertor plate when $\bar{n}_e = 3.4 \times 10^{13}$ cm^{-3}. The electron temperature at the divertor plate is $T_{ed} = 3.5$ eV at the same condition. This result indicates that dense and cold plasma obtained in a single-null poloidal divertor provides the solution for the wall erosion problem.

Keywords: Doublet III, Poloidal Divertor, Very Dense Plasma, Cold Divertor Plasma, Langmuir Probe, Remote Radiative Cooling, Wall Erosion

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NBI 加熱時のシングルヌルポロイダルダイバー付ダブレットⅢトカマクにおける高密度低温度ダイバータプラズマの観測

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（1983年1月20日受理）

強い遠隔放射冷却を伴なう，高密度，低温度のダイバータプラズマが中性粒子入射加熱時(1.2 MW)のダブレットⅢトカマクで観測された。測定は，ダイバータプレートに配列されたラングミュアープローブ群によった。ダイバータプレート近傍での最高の電子密度n_{ed}，最低の電子温度T_{ed}は，主プラズマの平均電子密度が$\bar{n}_e = 3.4 \times 10^{13} cm^{-3}$のときそれぞれ$n_{ed} = 2.8 \times 10^{14} cm^{-3}$，$T_{ed} = 3.5$ eVであった。ダイバータプラズマは，$\bar{n}_e$を増加するに従い，高密度，低温度になった。シングルヌルポロイダルダイバータで得られたこの様な高密度低温度プラズマの系は，壁の浸食の問題解決に一つの見通しを与える。

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Introduction

Strong remote radiative cooling in a single-null poloidal open divertor was observed in Doublet III and reported elsewhere [1]. Dense and cold divertor plasmas with electron density and temperature of $n_e > 5x10^{13}$ cm^{-3} and $T_e \leq 7eV$ were also observed. These measurements were, however, based on line-integrated techniques and therefore prone to ambiguity in interpretation. Besides, previous results were obtained with only joule heated discharges. It is important to study the divertor plasma with beam heated discharges. Similar phenomena were also observed in ASDEX which has divertor throats [2] but not in a small device such as DIVA [3,4]. Such a dense and cold divertor plasma provides the following advantages:

1. due to strong density build-up, the divertor plasma can radiate considerably high-power which leads to a reduction of the heat load onto the divertor plate without deleterious effects to the main plasma,

2. this sort of divertor is feasible for effective particle exhaust [5], i.e., the exhaust of unused fuel particles, helium ash and other impurities.

3. due to sufficiently low temperature, the erosion of the divertor plates caused by ion sputtering becomes negligibly small.

In order to make direct measurements of the profiles of the divertor plasma parameters, a Langmuir probe array and a thermocouple array were installed in the divertor plates. In this paper, we report on the observation of dense and cold divertor plasmas with neutral beam injection of P_{NB} ~ 1.2MW.

Experiment

Doublet III is a tokamak, which is capable of making D-shape and single-null poloidal divertor configurations with a Ti-gettered open divertor chamber [6]. In this divertor experiment, the deuterium plasma is heated with a neutral beam injection of P_{NB} ~1.2MW, beam duration time τ_{NB} ~ 200ms, at a toroidal field of B_T = 2T and a plasma current of I_p = 290kA. The central electron temperature is $T_e(0)$ = 1.2~0.7keV, the range of the line-averaged electron density of the main plasma of $\bar{n}_e$ = $(1.0\sim3.4)\times10^{13}$ cm^{-3} at 100 ms after the start of the beam injection (t=700ms).

In this divertor experiment, the separatrix surface intersects the divertor plates on the inner wall of the vacuum vessel as shown in Fig. 1 (the ratio of the divertor current to plasma current I_D/I_p = 0.55). Arrays of 21 channels of Langmuir probes and 28 channels of thermocouples are installed in the divertor plates in order to measure the vertical profiles of the plasma parameters (the location is also shown in Fig. 1). A horizontally scannable Langmuir probe is also installed in the mid-plane (Z=0) port.

The Langmuir probe array projects outward ~0.5mm from the divertor surface; the thermocouples are imbedded 5mm in the divertor plates. The single-probe characteristic curves are obtained by applying sinusoidal single-pulse voltages with a time period of 0.77ms. The projected area is employed as the effective probe area since the probe size is large enough compared with both the ion Larmor radius and the Debye length. The accuracy of the density evaluation is, however, within a factor of two because the ion collection theory is affected by the strong magnetic field. As the time-response of the thermocouple is long compared with the discharge duration, thermocouples provide time-integrated heat deposition during the discharge.

Dependences of the electron density n_{ed}, temperature T_{ed} and the heat flux on the divertor plate on $\overline{n}_e$ are studied.

Results

Well-saturated characteristic curves of the single-probes are obtained throughout the density range investigated. Vertical profiles of n_{ed} and T_{ed} at the divertor plates are shown in Fig. 2 for discharges of low ($\overline{n}_e$=1.0x10^{13} cm^{-3}), medium (2.2x10^{13} cm^{-3}), and high (3.4x10^{13} cm^{-3}) average electron density ('low', 'medium' and 'high' are used here in a relative sense). Two peaks of each profile correspond to the upper (electron drifting side) and lower (ion drifting side) separatrix. The profiles of n_{ed} become broader as $\overline{n}_e$ is increased. In the high density case, the electron temperature is cooled down and the peak of T_{ed} near the peak of n_{ed} profile disappears but is rather high in both outside of the divertor channel, presumably due to the low density or less radiation.

The electron density n_{ed} and temperature T_{ed} at the peak of the density profile on the ion drifting side are shown in Fig. 3 as strong functions of $\overline{n}_e$, or gas puffing. The electron density n_{ed} increases nonlinearly from 6x10^{12} cm^{-3} up to 2.8x10^{14} cm^{-3} with $\overline{n}_e$ increasing only by a factor of 3.4. At the same time, T_{ed} is cooled from 30eV down to 3.5eV. The measurements by the Langmuir probes at the mid-plane and the divertor plates show that the temperature gradient along the magnetic field line near the divertor plates is also found to be very steep (T_e = 36eV at Z=0, R≈102cm and 8eV at the divertor plate when $\overline{n}_e$ = 3x10^{13} cm^{-3}; the connection length between these two points is 380cm). The total particle flux across the mid-plane, which is deduced from

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Figure 4 shows the profiles of the heat flux onto the divertor plates meausred with the thermocouples and the product of the ion saturation currents and electron temperature, $j_s \cdot T_{ed}$ which is responsible for the heat flux [7], for the high density case. The heat flux during the neutral beam injection is deduced by dividing the increment due to the beam by the beam duration time and added to the value of other wise similar discharges with no beam. Both profiles coincide with each other and have broad half-width d_h in the high density case ($d_h = 15$ cm) in comparison with the low density case ($d_h = 5$ cm).

Strong remote radiative cooling is observed with a bolometer array. Total radiative and charge exchange loss powers increase with increasing $\bar{n}_e$: $P_{r,cx} \sim 0.45$ MW in the main plasma region (less than 10% of total input power is radiated in the bulk plasma) and $P_{rr,cx} \sim 0.45$ MW in the divertor region in the high density case; $P_{r,cx} \sim 0.45$ MW and $P_{rr,cx} \sim 0.2$ MW in the medium density case. The collimator of the bolometer array is located at ($Z = 88$ cm, $R = 196$ cm) and has radial lines of sight. In the upper divertor channel, $P_{rr,cx}$ is found to be localized near the divertor plate.

Discussion and Conclusions

Strong buidup of the electron density with cold plasma near the divertor plates is observed. This result can be explained by the following factors:

1) a large amount of particle source from the open divertor chamber [8]; this experiment reveals that the electron temperature is still high enough ($T_e = 36$ eV), and has a broad enough profile (FWHM $\sim$ 9 cm) to ionize on the mid-plane (the ionization mean-free-path $\lambda_{ion} < 1$cm).

2) strong enhancement of particle recycling near the divertor plates [9,10]; the particle gain between the mid-plane and the divertor plates is found to be $\Gamma_p = \Gamma_p^d - \Gamma_p^m \simeq (0.9 \sim 1.3) \times 10^{22}$ particles/sec when $\bar{n}_e = 3 \times 10^{13}$cm^{-3} and $P_{rr,cx}$ at the upper separatrix is localized near the peak of the particle flux at the divertor plate.

3) strong remote radiative cooling [1]; ($P_{rr,cx} \sim 0.45$ MW for the total input power of $P_{IN} = 1.5$ MW).

4) broadening of the thickness of the divertor channel; the thickness increases up to FWHM $\sim$ 11 cm.

The situation of a large amount of particle flux together with maintaining a rather high temperature at the midway of the divertor channel presumably occurs only in a large-sized device. Analytical studies of these processes are under investigation.

The heat flux density q can be deduced from $q = \gamma\, j_s\, T_{ed}$ [7,11], whree γ is the heat transmission rate across the sheath (a function of T_{ed}) and is estimated here to be 7 in the high density case [11, 12].

By integrating q over the entire divertor plates, the conduction-convection loss power P_{cc} is evaluated to be ~0.5MW in the high density case. A rough estimation by the measurement of the heat flux with the thermocouple $q_{T/C}$ also gives $P_{cc} \sim 0.5MW$. The heat transmission rate is found to be enhanced by a factor of 2.5 in low density discharges by comparing $q_{T/C}$ with $j_s\ T_e$, which may be ascribed to a contribution of non-Maxwellian electrons [11].

If the divertor plasma in a fusion reactor can be made dense and cold as in the divertor plasma investigated here, the erosion of the divertor plate due to ion sputtering would be negligibly small because of sufficiently low T_{ed} and thus low sheath potential. The threshold energy for ion sputtering is approximately several tens eV for materials such as titanium, iron, nickel, carbon, etc. [13].

The conclusions are summarized as follows:

1) A dense and cold divertor plasma (n_{ed}=2.8x10^{14}cm^{-3} and T_{ed}=3.5eV) is observed in a beam-heated throatless divertor plasma with Langmuir probe measurements at the divertor plate.

2) The electron temperature measured at the mid-plane is still high enough to ionize the incoming neutral particles (T_e = 36eV) and thus a large amount of ionization in the divertor region can be expected.

3) The particle gain between the mid-plane and the divertor plate is found to be very large (Γ_p = (0.9~1.3)x10^{22} particles/sec).

4) Global power balance is roughly obtained as: $P_{IN} \approx P_{r,cx}+P_{rr,cx}+P_{cc}$ where $P_{IN} \sim 1.5MW$, $P_{r,cx} \sim 0.45MW$, $P_{rr,cx} \sim 0.45MW$ and $P_{cc} \sim 0.5MW$ at $\overline{n}_e = 3.4 \times 10^{13} cm^{-3}$.

Because of its simplicity, these results with a simple open divertor are very encouraging for the design of a divertor in future tokamaks. Further investigations with a wide parameter range, i.e., higher in both $\overline{n}_e$ and P_{IN}, are necessary and are now under investigation.

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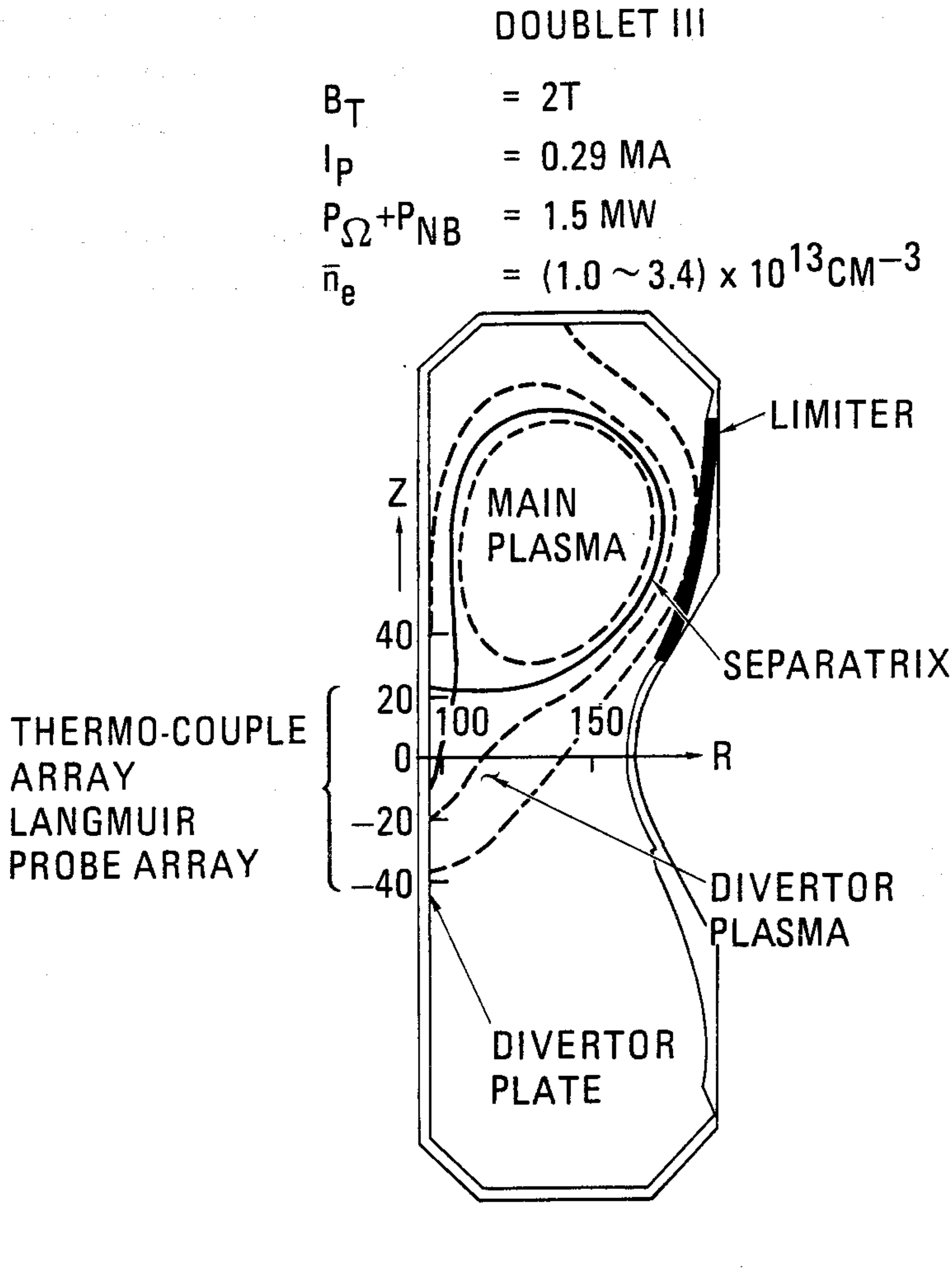

FIG. 1 Cross-sectional view of Doublet-III with magnetic flux surfaces obtained by an MHD equilibrium calculation at high density case. Operation parameters are also shown.

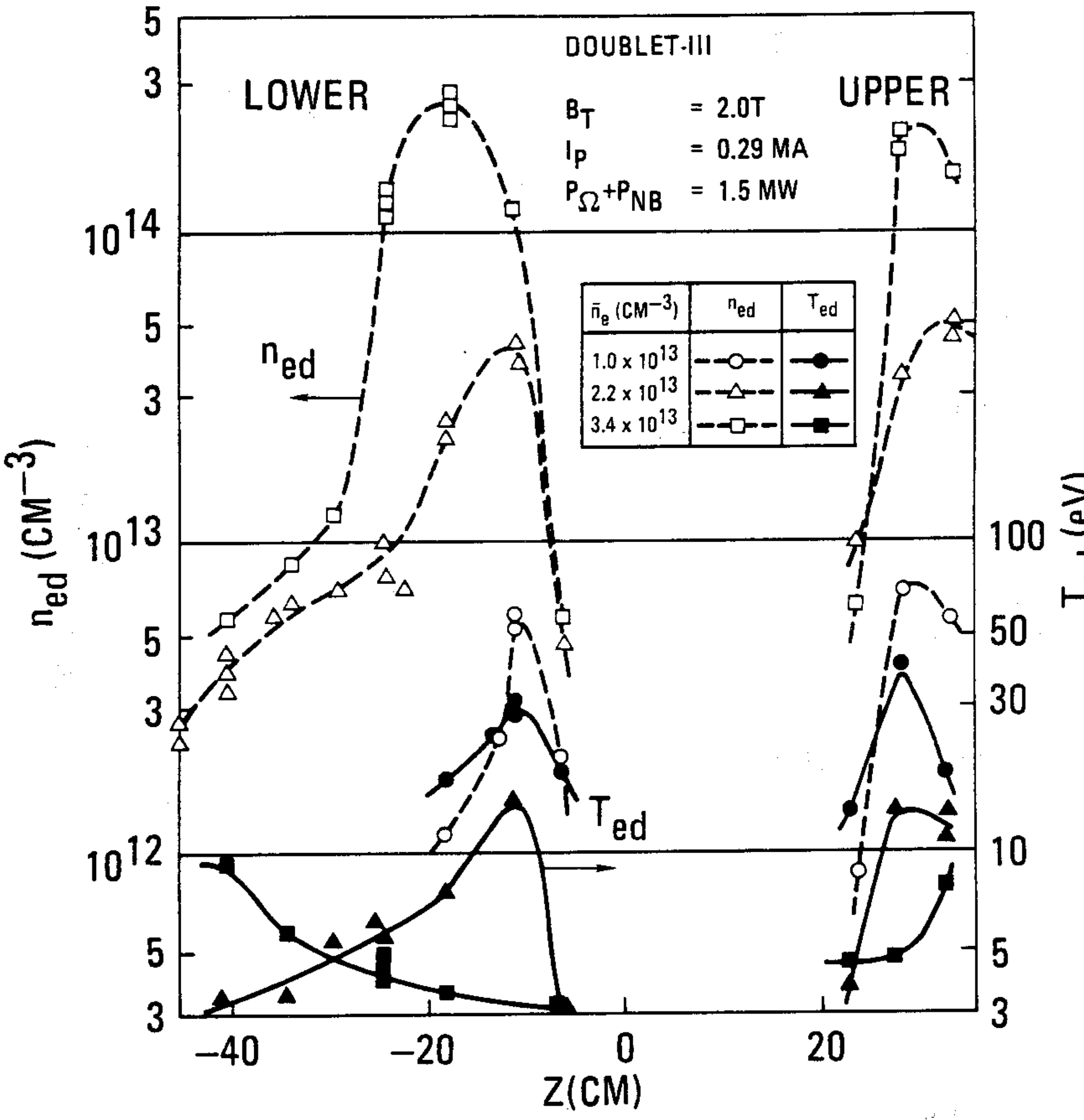

FIG. 2 Measured electron density n_{ed} and temperature T_{ed} profiles on the divertor plates when the average electron density of the main plasma $\overline{n}_e$ = $1.0\times10^{13}cm^{-3}$, $2.2\times10^{13}cm^{-3}$ and $3.4\times10^{13}cm^{-3}$ at t = 700ms. "UPPER" and "LOWER" in this figure correspond to the upper and lower separatrix.

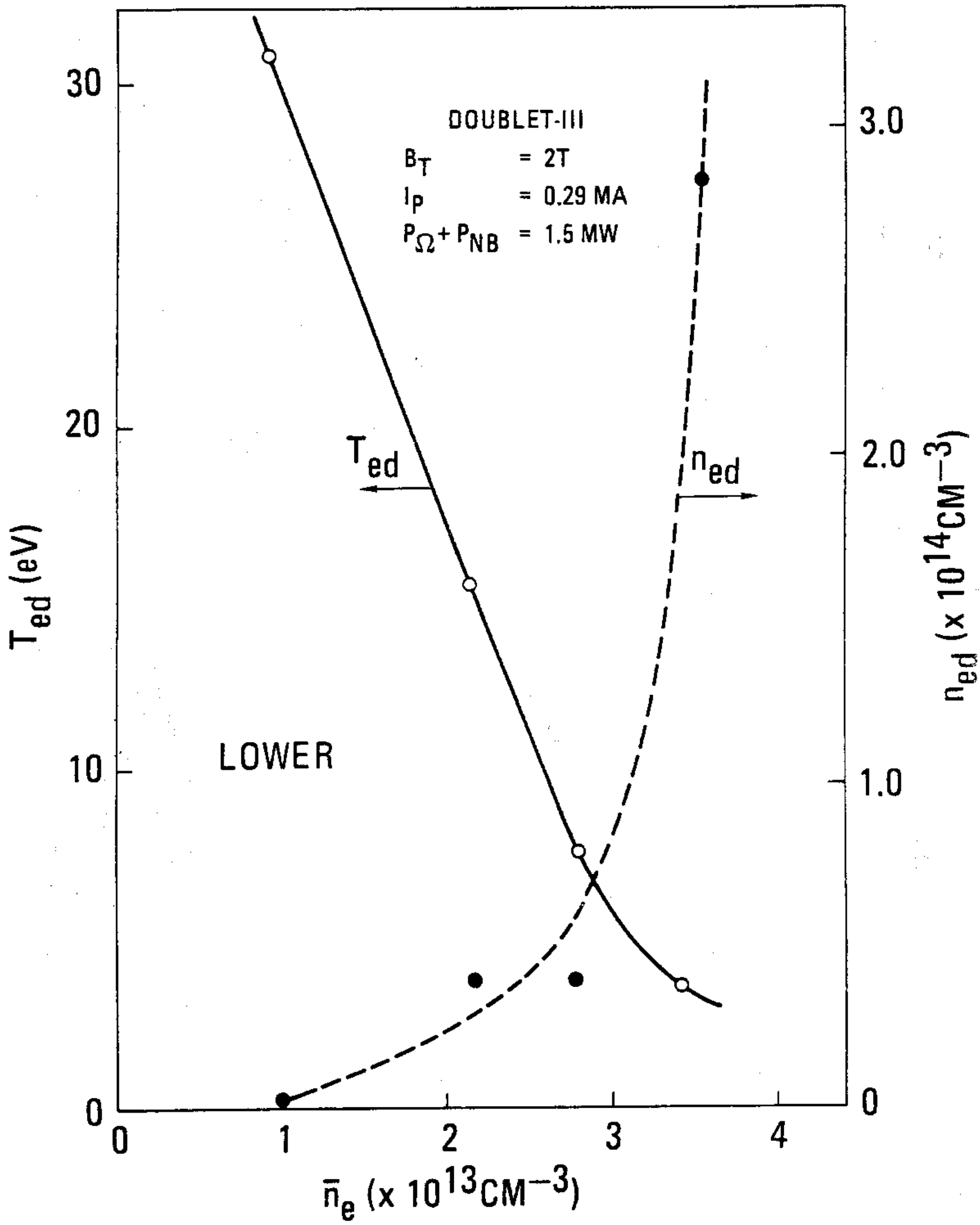

FIG. 3 Electron density n_{ed} (--●--) and temperature T_{ed} (-o-) at the peaks of density profile on the divertor plates as a function of the average electron density of the main plasma $\bar{n}_e$.

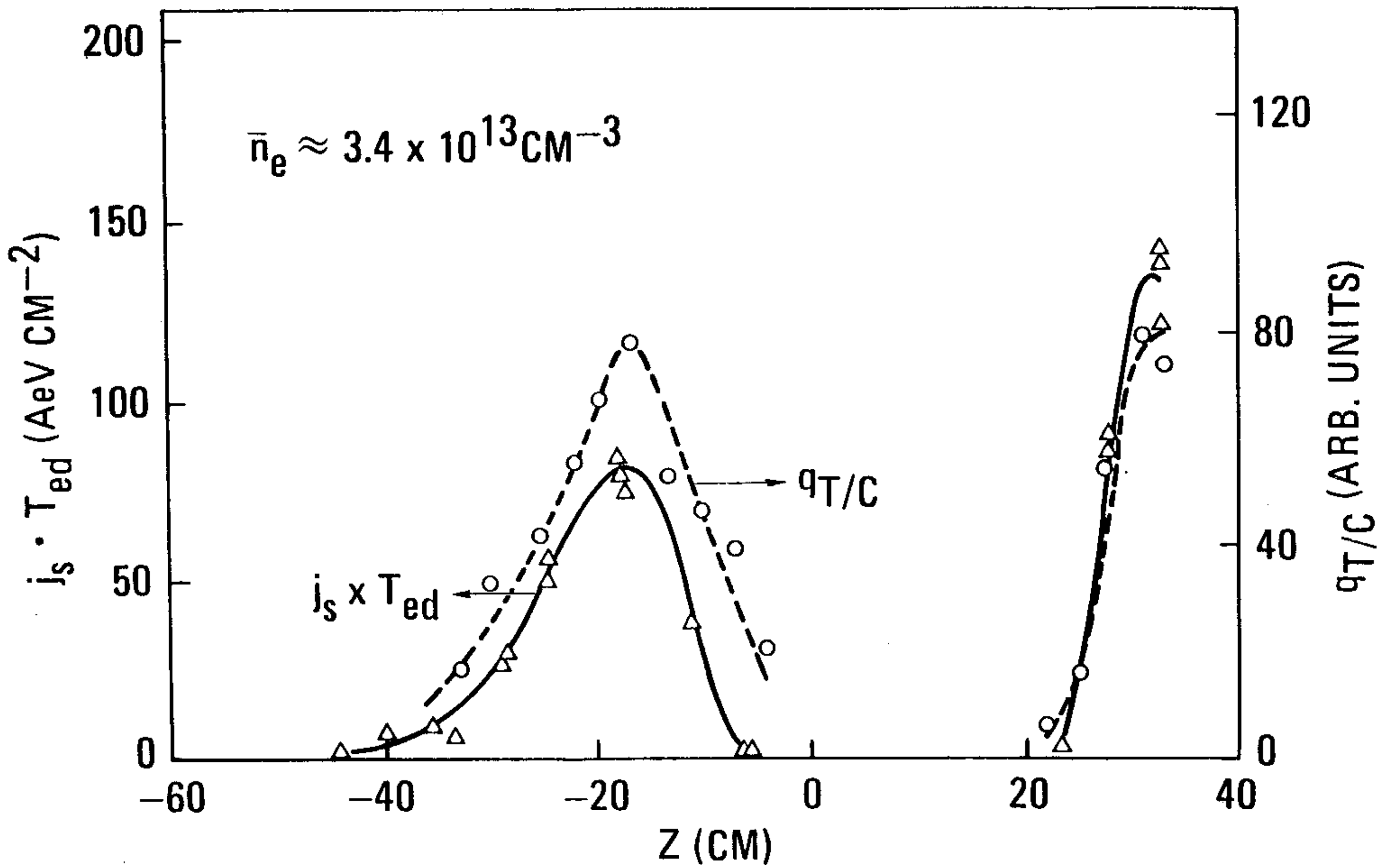

FIG. 4 Profiles of heat flux density measured by the thermocouple array $q_{T/C}$ (--o--) and the product of j_s T_{ed} (-Δ-) for $\overline{n}_e=3.4\times10^{13}cm^{-3}$ at t=700ms.