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By

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A description is given of the experimental shell-less Tokamak NOVA. This apparatus is designed to investigate the stabilization of plasmas in a shell-less Tokamak device, first by the program- and the feedback-control of the vertical magnetic field, and then by controlling the radial distribution of the longitudinal plasma current.

The basic concepts of design and the constructional data of the principal components are shown, together with some results of preliminary experiments.

1. Introduction

A small torus apparatus named "NOVA", which is essentially of the Tokamak-type except that it has no conductive shell, has been designed and constructed to investigate the stabilization of plasma equilibrium in a shell-less Tokamak (1) by the program- and the feedback-control of the vertical magnetic field, and (2) by controlling the radial distribution of plasma current density. The conceptual drawing and a photograph of the apparatus are shown in Fig. 1 and Fig. 2, respectively.

One of the characteristic features of the original Tokamak devices is the stabilization of plasma by means of the conductive shell. The equilibrium is primarily maintained by an externally applied longitudinal (toroidal) magnetic field, the azimuthal

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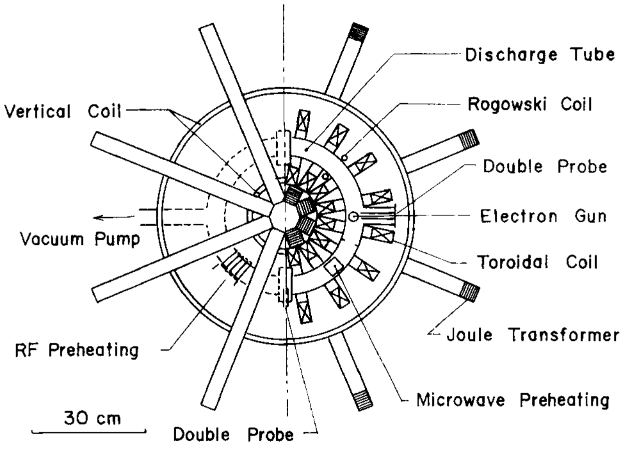


Fig. 1. A conceptual drawing of the shell-less Tokamak "NOVA".

(poloidal) magnetic field due to the longitudinal plasma current, and the repulsion exerted on both the toroidal and poloidal lines of force by the image currents induced in the conductive shell[1],[2].

To have an effective suppression of plasma displacement, the shell must have a thickness larger than the skin-depth, and the plasma must be extended to the vicinity of the shell surface. Unfortunately, however, a thick shell leads to large radii of all the reactor components outside the shell such as lithium-blanket, heat-exchanger, toroidal-field winding and so on. In addition, the shell is so close to the plasma that its surface would suffer from a heavy bombardment of neutrons and fast neutral particles.

Since the image currents in the shell can only be induced by rapid plasma displacements, the centering effect of the shell is absolutely ineffectual for slow displacements which may obstruct the long plasma confinement in a torus machine. Such slow displacements can successfully be suppressed, as suggested by Artsimovich and Kartashev[3], by giving programmed values to the vertical magnetic field. To investigate the possibility of stabilizing the plasma equilibrium in a shell-less Tokamak by both the programmed- and the feedback-control of the vertical field, is one of the major purposes of the experimental device NOVA.

In the original Tokamak devices, particle energy is unduly lost by the anomalous heat conduction by electrons[4]. Such an abnormal energy loss appears in the form of various types of instabilities which cannot be suppressed even with the highly conductive shell. These instabilities are strongly correlated with the radial distribution of the plasma current density. If the current is concentrated on the surface region of the plasma column due to the skin-effect, the herical instability may occur. On the contrary, concentration of the current on the central part of the column cross-section

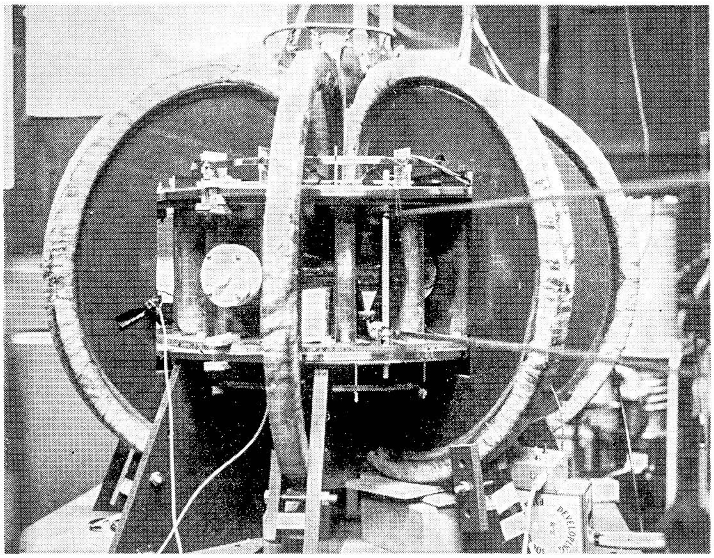


Fig. 2. A side-view of NOVA.

due to the bone-effect may result in the interchange- and the tearing-mode-instability through cooling of the plasma due to impurities, as well as to the anomaly in the electron-component of heat conductivity. Thus, some inherently stable current distribution may be found between the above two extremes, although the optimum condition has not yet been found theoretically nor experimentally.

To produce the desirable current distribution in a Tokamak plasma, it seems to be expected to heat the plasma surface (1) by means of absorption of the radio-frequency power into the lower-hybrid resonance layer,[5,6] and (2) by applying a travelling wave electric field along the plasma column[7]. NOVA is so designed that it is feasible for such experimental trials.

2. Fundamental Concepts of Design

2.1 Equilibrium of Plasmas in Shell-less Tokamak

For future development of the Tokamak-type machines of long confinement time, it is expected that the conductive shell will be removed even at the sacrifice of losing its admirable capability of suppressing the high frequency plasma fluctuations.

The scaling law obtained empirically with Tokamaks can be expressed in the form[8]

$$\tau_E \approx 5.47\times 10^3 a^2 \frac{a}{R}\cdot\frac{B_t}{q}\ [\mathrm{ms}], \qquad (1)$$

where a is the minor radius, R the major radius, B_t the toroidal magnetic field, τ_E the energy confinement time, while q is the safety factor which should be as large as from 2 to 3. According to this scaling law, in order to realize long energy confinement, it is required that (1) the aspect ratio $\gamma=R/a$ must be small, and (2) B_t/q must be as large as possible. In the present program of our experiments, however, a long confinement time is not expected. The experimental apparatus should be as small as possible in order to minimize the cost. An aspect ratio as large as 5 to 6 may be tolerable in these circumstances.

In a shell-less apparatus, equilibrium is to be maintained by controlling the vertical field B_v. It is known that a displaced plasma column is automatically restored to the central position if the vertical magnetic field satisfies the condition[1)]

$$\frac{3}{2}>n>0, \quad n=-\frac{R}{B_v}\cdot\frac{\partial B_v}{\partial R}, \tag{2}$$

which was originally derived in 1953 by Osovets.[9)] Therefore, the spatial distribution of the vertical field should be so determined that this condition is met everywhere inside the plasma region.

The vertical field B_v should also be controlled according to the variation of the plasma current during the period of discharge. For this purpose, the following control-modes are applicable.

(1) Programmed control of B_v based on the ideal wave-form of the plasma current $I_p(t)$.

(2) Feedback control with reference to the required functional relation between the plasma current I_p and the vertical field B_v.

2.2 Electric Field for Joule Heating

The whole cycle of plasma discharge consists of (1) pre-ionization, (2) breakdown, (3) heating and (4) maintenance of plasma current. From the breakdown to the end of this cycle, a longitudinal (toroidal) electric field is applied to the plasma loop for heating. This electric field is usually produced by discharging a capacitor bank through the transformer primary winding, whose secondary circuit is the plasma loop.

For a breakdown and a successive rapid build-up of plasma current, a strong electric field is necessary. After the attainment of a sufficient amount of ionization, however, the electron temperature is so raised that the electric resistivity of the plasma column is much reduced. In this period of high electric conductivity, a very weak electric field is enough to accelerate the electrons and maintain the plasma current, if the plasma column is not damaged by distortion or cooling. The electric field for Joule-heating should, therefore, be the combination of a high but short pulse for the breakdown, and a low but long pulse for the maintenance of the plasma current.

Because of the shell-less configuration, the breakdown is very sensitive to the ripple of the longitudinal electric field. The Joule-heating core should, therefore, be equi-divided and distributed along the torus to produce a sufficiently uniform electric field.

Time integral of the electric field is equal to the total change of the magnetic induction multiplied by the cross-sectional area of the transformer core. Consequently, duration of the toroidal electric field is limited both by the magnetic saturation of the core and by the cross-sectional area. For further extending the duration of the plasma current, it has been proposed to reduce the plasma resistivity, hence the required intensity of the electric field, by a radio-frequency field travelling along the plasma column.7)

2.3 Radial Distribution of Plasma Current Density

The instabilities arising in Tokamak devices seem to be strongly correlated with the radial distribution of the plasma current density. Therefore, in order to suppress the instabilities and to attain a long confinement of Tokamak plasma, it is almost inevitable that an ingenious method for improving the current distribution will have to be introduced. Fortunately, it has been theoretically predicted that the higher mode oscillations can be suppressed by heating the surface region of the plasma column.10)

The following two possibilities are being considered for the control of the radial distribution of longitudinal plasma current.

(1) Heating of the desired region of the plasma column through excitation of the lower-hybrid resonance.

(2) Heating a surface layer of plasma by means of radio frequency fields travelling along the plasma column.

3. Description of Components

3.1 Vacuum Vessel

The vacuum vessel is made of Pyrex glass. It is equipped with six experimental ports and two observation windows. The major radius R is 18 cm, the minor radius a 2.7 cm, the aspect ratio of the vessel being about 6.6. The limiter is also made of Pyrex glass, the diameter of whose aperture is 3 cm. Consequently, the aspect ratio of the plasma column is 12. The joints of the vacuum components are sealed with rubber O-rings. The vessel is evacuated by a 4-inch oil-diffusion pump with a rotary pump. The highest vacuum attained with this pump-system is 2×10^{-6} mmHg without baking. In ordinary experiments, helium gas is diffused back from the throat of the diffusion pump, to avoid the occurence of a gas-flow inside the vessel.

3.2 Toroidal Coil

The toroidal magnetic field winding is designed to meet the following requirements.

(1) The uniformity of the magnetic field is realized within the range of plus-minus 1%.
(2) The maximum intensity is not less than 10 kG (1 Wb/m^2).
(3) Enough space is to be guaranteed for measurements.
(4) Construction, assembly and disassembly of the coils are as easy as possible.
(5) The winding has sufficient mechanical strength.

For realizing a uniform toroidal field, the cross-section of the winding should be thick in radius, rather than wide in longitude. For the convenience of connecting the winding with the current feeder, a double-layer winding is desirable. This configuration secures at the same time the toroidal field from being perturbed by the current feeder. The number of turns per coil unit should be odd, as one of the turns is used for connecting one layer of the winding to the other. This gradual bridging reduces localized horizontal components of the magnetic field and ensures the required uniformity for the toroidal magnetic field. The uniformly distributed horizontal component can be eliminated by a method which will be described later.

The total ampere-turn AT of the toroidal field is estimated from the relation

$$B_t \approx \frac{\mu_0 AT}{2\pi R} > 1 \ [\mathrm{Wb/m^2}] \tag{3}$$

Assuming that the major radius R is 18 cm and that the maximum magnetizing current available is 10^3A, the total number of turns required is given by $N > 900$.

The specifications of the final design, which are determined in concordance with all the considerable requirements, are as listed below.

number of coil units: 16
number of turns per unit: 75
size of conductor: 1 mm × 10 mm copper strip
resistance per unit: 0.048 Ohms at 20°C
weight per unit: 3.3 kg
total inductance in toroidal: about 20 mH
temperature rise: 0.9°C/kJ
externals: 200 mm × 200 mm × 30 mm
bore diameter: 100 mm

The winding was fixed with glass tape and glass wool, and in addition, it was molded with epoxy resin in a vacuum environment. A pair of coils in the Helmholtz connection has been tested by applying current pulses from a 20 kJ capacitor bank, and the mold around the fixing nuts was broken by applying 1350A pulses. Neither a breakdown among the winding layers nor a thermal damage of the insulation were observed.

3.3 Current-Transformer for Joule-Heating

The transformer is designed to meet the following requirements.

(1) A strong longitudinal (toroidal) electric field is to be produced with a long period of duration.

(2) Any significant leakage flux should not be produced.

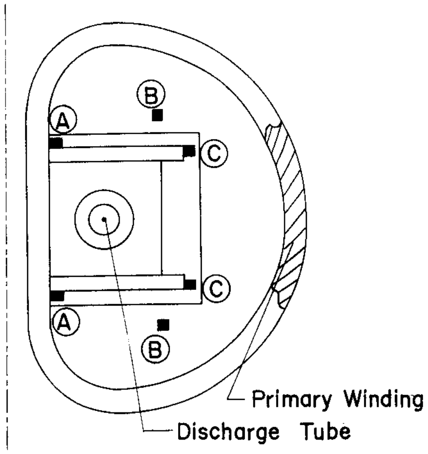
(3) The toroidal electric field should be as uniform as possible along the torus tube.

(4) Enough space is left for measurements.

(5) Neither the toroidal nor the vertical magnetic field is appreciably disturbed by the transformer.

(6) Construction, assembly and disassembly of the coils are all as easy as possible.

For realizing the strong electric field, a high-permeability cold-milled steel belt 0.1 mm thick is wound. To make certain of a long period, the cross section of the core should be as large as possible. It was not easy for us to make a wound core with a large cross-sectional area. However, the merits of high permeability and low leakage were appreciated in spite of all the other demerits. To minimize the leakage



Joule Transformer

Fig. 3. Arrangement of the windings for the vertical field and for the compensation of stray field. Combination of a A with B satisfies the Osovets condition, while A with C does not. The compensation windings are fixed on A and C.

of magnetic flux from the core, a long steel belt is wound tightly in a D-like shape fo a large diameter without any butt joint or sharp folding at corners. In order to minimize the leakage flux through coil intersects, the primary winding is wound tightly with braided wire and distributed over the whole surface of the transformer core. The transformer consists of eight cores with individual windings. Periodical arrangement of the cores along the torus tube promises a uniform electric field. Such an arrangement also ensures a wide space for measurements.

The specifications of the final design are as listed below.

number of cores: 8
cross-sectional area of core unit: 3 cm × 3 cm
total magnetic capacity of cores: 0.02 Vsec
number of turns of primary winding: 25

The core is pre-magnetized to the redisual magnetization in the reverse direction before starting the primary current, so that the flux can be changed to about twice as large as the saturation flux.

3.4 Vertical Field Windings

The vertical field is determined according to the Osovets condition of Eq.(2). The apparatus NOVA is equipped with two independent vertical field windings; one satisfies the Osovets condition, while the other does not. The position of the windings and the field intensity required have been determined from the results of numerical analyses of the Osovets condition (See Fig. 3).

Each of the windings has ten turns of copper strip with a 1 mm × 10 mm cross section. Reverse windings are wound around the legs of the Joule-transformer cores so as to cancel the electromotive force induced in the vertical windings by the primary current of the transformer.

3.5 Power Supplies

The toroidal field windings, the vertical field windings and the primary windings of the Joule-transformer are supplied from the respective condenser-banks. The specifications of the capacitor banks are listed below.

	toroidal	vertical	Joule
capacity:	640 μF	4 μF	160 μF
charging voltage:	max 5 kV	0–1 kV	max 5 kV
energy stored:	max 15 kJ	0–2 J	max 2 kJ
rise time to first peak:	6 ms	20–50 μs	—
max. field intensity:	10 kG	25 G	1.78 V/cm
switch:	ignitron	SCR	ignitron
crowbaring:	ignitron	diodes	diodes

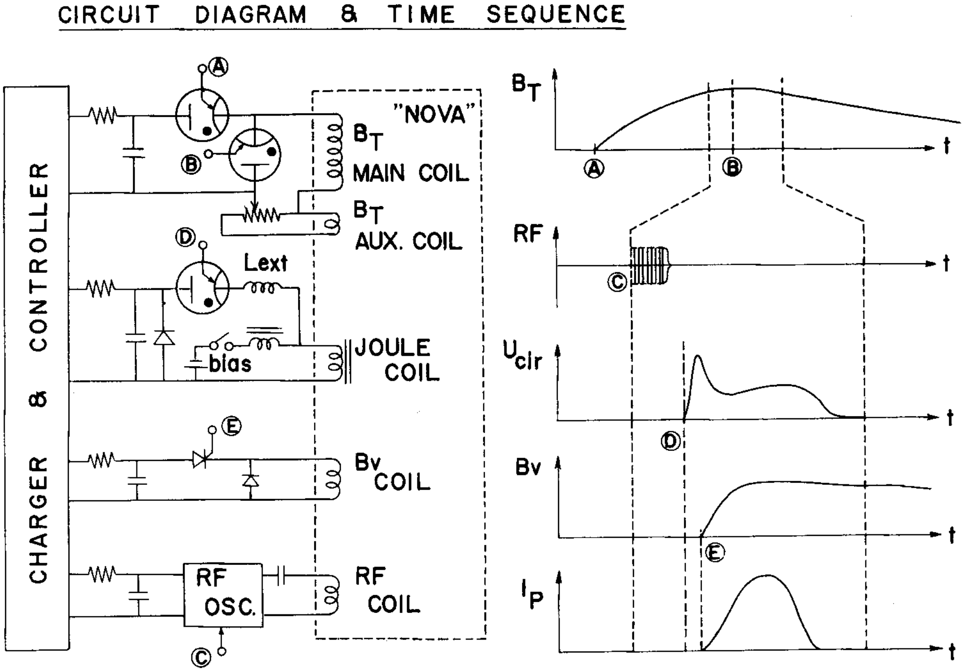


Fig. 4. Circuit diagram and time sequence. U_{cir} is the one-turn voltage.

The circuit diagram and the time sequence are shown in Fig. 4. The time sequence is previously arranged. The circuit is triggered by a special order-made pulser.

To secure the breakdown at the beginning of Joule-heating period, the vertical field is started shortly after the ignition of the plasma. An adequate pre-ionization with an RF-oscillator of 10 MHz and 2 kW ensures good reproducibility of plasma discharge.

3.6 Miscellaneous

In order to compensate stray magnetic fields due to wiring among the toroidal coil units, and also due to irregularity in the arrangement of the components, the toroidal field current is branched into an auxiliary coil which consists of a pair of one-turn windings fixed beside the vertical field windings. A manganin strip is used for the shunt resistor. By careful adjustment of the branching ratio, the sway of plasma column is effectually suppressed and reproducibility of plasma discharge is considerably improved.

Lower-hybrid resonance heating is under preparation. RF power of about 150 MHz and 10 kW will be coupled into the Joule-heated plasma through antenna coils.

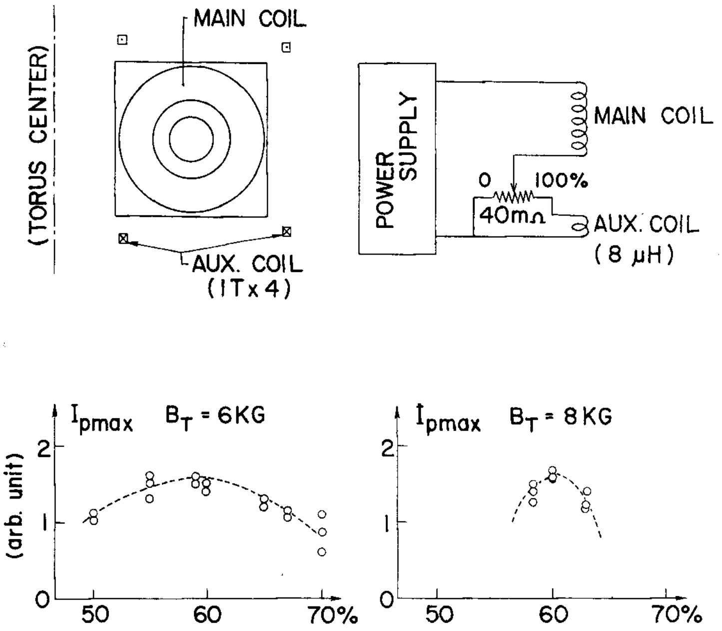


Fig. 5. The maximum plasma current as a function of the branching ratio. The auxiliary coils are energized by a certain fraction of the toroidal current to compensate the horizontal stray fileld.

4. Characteristics of Plasma in NOVA

Some fundamental characteristics of plasma in NOVA have been investigated. Firstly, it has been found that the horizontal stray field due to the connection and the bridging among toroidal coils strongly affects the breakdown and the build-up of the plasma current. To compensate the stray magnetic field, a fraction of the toroidal field current is branched into an auxiliary coil. The characteristics of the plasma discharge is exceedingly improved by this method. The optimum value of the branching ratio can easily be determined, as shown in Fig. 5. These data show that the discharge can occur in a limited range of branching ratio and that this range becomes narrower for a stronger toroidal field. Secondly, a violent oscillation of plasma current is observed when the condenser bank is directly connected to the primary winding of the Joule-transformer. As the primary winding is closely coupled with the plasma loop through the transformer cores, the primary circuit acts as a low-impedance power source to the plasma current. Consequently, the plasma current can reach an extremely high value, unless the transformer core is saturated. With such an excessive growth of plasma current, however, the condition for equilibrium is no more satisfied with a

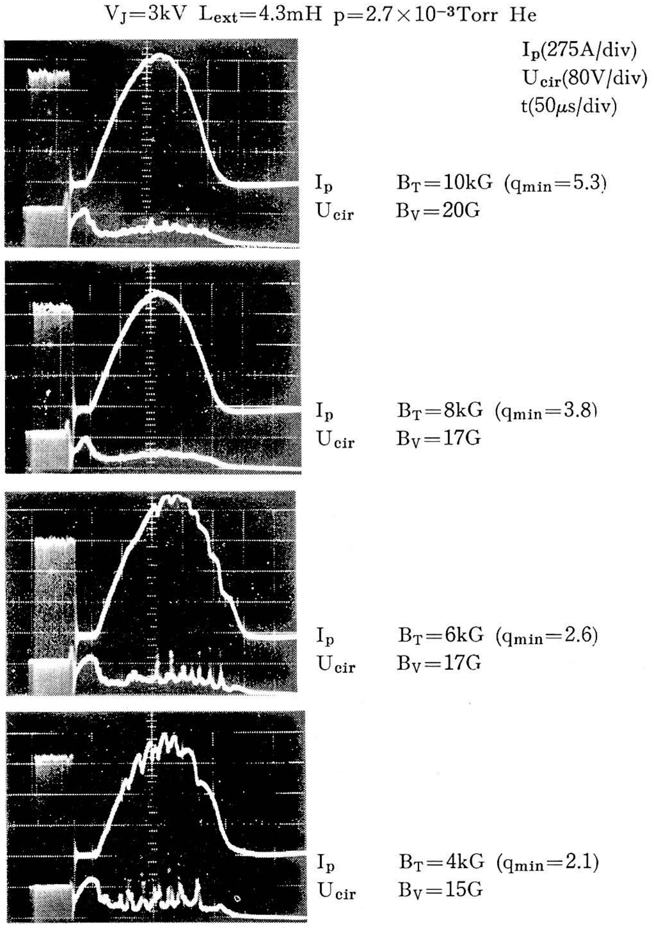


Fig. 6. Waveforms of plasma current and one-turn voltage. The upper is for a stable equibrium, while the lower is for an unstable equilibrium.

finite intensity of the vertical field. The plasma column, therefore, sways until the increase of plasma current finally ends by crashing the column onto the edge of the limiter. This phenomenon is considerably suppressed by increasing the primary impedance by inserting a series inductance.

Typical waveforms obtained with NOVA are shown in Fig. 6 together with the experimental conditions. The data show that the plasma current is quite smooth for B_t=10 kG, the peak value being larger than 1.2 kA. If the parabolic distribution of the plasma current is assumed, the available minimum of the safety factor q is 7, the safety factor being given by

$$q=\frac{2a^2B_t}{\mu_0 R(I_p)_{\max}}. \tag{4}$$

For a more reduced toroidal field, there appear oscillations in the plasma current with sharp spikes in the one-turn voltage U_{cir}. They are the symptoms of the fact that either the equilibrium of plasma can no more exist in those experimental conditions, or that some instability appears when the safety factor q becomes less than 5. To suppress the oscillations, a more careful arrangement of the vertical field, and a control or modification of the radial distribution of the plasma current may be required.

The electron density in the optimum condition is estimated to be in the order of $10^{14}\,\mathrm{cm}^{-3}$ by transmission measurement of a 6 mm wave-length microwave. The electron temperature of the same plasma is also estimated to be 14 eV using Spitzer's formula.11)

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