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HIGH- β STUDY IN JFT-2

September 1980

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High- β Study in JFT-2

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(Received August 11, 1980)

Characteristics of high- β tokamak plasmas of a circular cross-section are investigated experimentally and numerically with $q_a=2-4$, $R/a=3.5-4.75$ and NBI of 0.8-1.2 Mw. The observed maximum β value at the axis is 7 % due to the thermal component and 10 % including the beam component, and the volume average β is 2.6 % and 3 %, respectively. The observed β values including the beam component are much higher than the critical β values obtained from the ballooning analysis and the β values only due to the thermal component are slightly higher than the critical values. The mhd activities and impurity behavior are modified by NBI but the observed modifications are not due to a high- β effect. Ion and electron confinement characteristics are very similar to those in a low- β tokamak. Concluding the result, no new behavior is observed in the high- β tokamak plasma.

Keywords; JFT-2 Tokamak, High- β Tokamak Plasma, NBI Heating,
Critical β value, Ballooning Mode, MHD Activities, Impurities

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JFT-2における高ベータ研究

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(1980年8月11日受理)

円形断面トカマクの高ベータ・プラズマの性質を、 $q_a = 2 \sim 4$, $R/a = 3.5 \sim 4.75$, $0.8 \sim 1.2$ MW の中性粒子入射の条件下で、実験的および理論的に研究した。観測されたベータ値は、軸上で熱化成分7%ビーム成分を含めて10%, 熱化成分の体積平均値は2.6%ビーム成分を含めて3%であった。ビーム成分を含めたベータ値は、パレーニング解析より得られる臨界ベータ値よりも大幅に大きく、熱化成分は少し大きな値を示す。NBIは、MHDの性質および不純物のふるまいに影響を与えるが、これらの影響は高ベータによるものではない。イオンおよび電子の閉じ込め特性は低ベータの特性にきわめて近い。結果を総合すると、高ベータ・トカマク・プラズマにおいて新しい現象は観測されなかった。

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1. Introduction

A high- β plasma will be required in a future tokamak reactor. Therefore it is essential to obtain a high- β tokamak plasma and characteristics of the high- β plasma have to be investigated. These problems have been studied experimentally and numerically and the results on a circular tokamak are reported here.

In the experiment, circular tokamak plasmas with a wide range of plasma parameters, i.e. $R/a = 3.5 \div 4.75$, $q_a = 2.0 \div 4.2$, $n_{e0} = (2.5 \div 11) \times 10^{13} \text{ cm}^{-3}$ and $B_t = 0.95 \div 1.4 \text{ T}$, are heated by NBI of 0.8 - 1.2 MW. The NBI system which was installed to the modified JFT-2 [5] in March 1980 consists of a co-injector and a counter-injector (Fig.1). Each beam line injects a half of the total input into the torus. The experimental data are analyzed by using a tokamak code including NBI, neutral particle transport and the mhd activities [2, 3]. The critical β value from the ballooning analysis is very sensitive to a plasma profile. In this paper, the critical β value obtained by optimizing the plasma profile [1] is rather high, e.g. the average β value is 2.5% with $R/a = 3.5$ and $q_a = 2.5$ and the peak β value 7%. These values are compared with the experimental values.

In this paper, β values, ion and electron transport, impurity behavior, plasma-wall interactions and mhd activities in a high- β tokamak plasma are discussed.

2. β -value

The NBI heating of 0.8 - 1.2 MW is applied to an ohmic plasma. Typical time behaviors of plasma characteristics are shown in Fig.2. After starting NBI, loop voltage decreases, ion and electron temperatures increase and also plasma density increases because of an intense gas puffing (Fig.2-c). The line intensity from metallic ions increases during the first 25 ms and reduces. This behavior will be discussed in Section 4. The radiation loss power is mainly due to oxygen and is about 20% of the total input power during NBI heating. The peak β -value β_0 increases up to 7 % due to thermal component and up to 10% including the beam component. Plasma profiles at 25 ms after starting NBI are shown in Fig.3-a and the volume average β -values $\langle \beta \rangle$ is 2.6 % due to the thermal component and 3 % including the beam component.

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In Fig.4 observed β -values are compared with the critical β -values obtained from the ballooning analysis. An optimized pressure profile at the critical value is compared with the experimental data in Figs. 3-b and 3-c. The observed total β values including the beam component are higher than the critical β -values in many discharges, e.g. the maximum β_0 and the maximum $\langle\beta\rangle$ are 1.7 and 1.3 times higher than those critical values, respectively. No new behavior is observed in such a high- β plasma as discussed later. Therefore, it can be said that the high n ballooning mode does not limit the β value. However, it must be noted that the maximum thermal β values are only slightly higher than the theoretical values and, moreover, the β_p value measured by magnetic probes is equal to the thermal β_p within experimental errors. These results suggest the anisotropic feature of the beam component.

The parameter dependence of the observed β -values on the safety factor q_a seems similar to those of theoretical values (Fig.4). This parameter dependence, however, is due to the characteristics of the conventional tokamak discharges and not due to the high β characteristics, i.e. a higher- β plasma is easily obtained in a lower- q plasma. From these results, it can be said that a higher β -value may be obtained by increasing the heating power.

3. Transport

The observed temperature and β -value are analyzed by using a tokamak code including, NBI heating, neutral particle transport and the sawtooth effect. The density and temperature profiles and the parameter dependence on plasma density and toroidal magnetic field B_t are well explained by the tokamak code with the same heat conductivities as in ohmic plasmas; $\chi_e = 2.0 \times 10^{17} / n_e \text{ cm}^2 \text{ s}^{-1}$ and $\chi_i = 1.5 \chi_{\text{neo}}$ where n_e is plasma density in cm^{-3} and χ_{neo} the neoclassical value.

The density clamp as observed in ISX-B with the NBI heating [4] and in JFT-2 with the LHR heating [5] is also observed in this experiment. In a helium discharge, however, the density clamping is not observed (Fig.6). The phenomena is related to particle recycling at the first walls, rather than the enhancement of the particle transport.

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The transport analysis with $D_e = 8 \times 10^{16}/n_e \text{ cm}^2/\text{s}$, which is the same value in an ohmic plasma, supports this explanation.

Therefore, we can conclude that the particle and heat transport coefficients are not changed in a high- β plasma.

4. Impurities

In usual cases, the metal impurities such as Ti, Fe and Mo increase with a high-power heating. This increment can be suppressed by an intense gas puffing. The edge cooling is observed with the intense gas puffing. And the metal impurities decrease during the NBI heating phase in the optimized condition as shown in Fig.7. Therefore, it is reasonable to consider that this reduction of metal impurities during the NBI phase is due to the reduction of influx rather than the change of transport.

Arcing is not observed during the NBI heating as in a stable ohmic plasma. In a helium operation, the increment of the metal impurities are higher than those in a hydrogen operation. These results show that the ion sputtering is also the dominant metal impurity source as in an ohmic plasma [6].

5. MHD activities

The mhd activities are modified by the NBI heating as shown in Fig. 5. The larger amplitude and longer repetition time of sawtooth oscillations are observed (Fig. 8-b) but can be explained by the same mechanism in an ohmic plasma. The sawtooth oscillations are strongly deformed (Fig. 8-c, d, e) and completely disappear in an extreme case (Fig. 8-f). In these cases, a large $m=1/n=1$ mode is observed. These phenomena are not well understood but are observed in a low- β plasma in some cases [7]. Therefore, these phenomena are not due to a high- β effect.

The $m=2/n=1$ tearing mode can be suppressed by the heating (Fig. 9). This effect is explained by the profile change due to NBI heating.

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6. Summary

High- β plasma up to $\beta_0 = 10\%$ and $\langle\beta\rangle = 3\%$ are stably obtained. These values are higher than the critical β values from the ballooning mode analysis. No new adverse effect on plasma confinement is observed. Therefore a higher β value may be obtained by optimizing the heating conditions.

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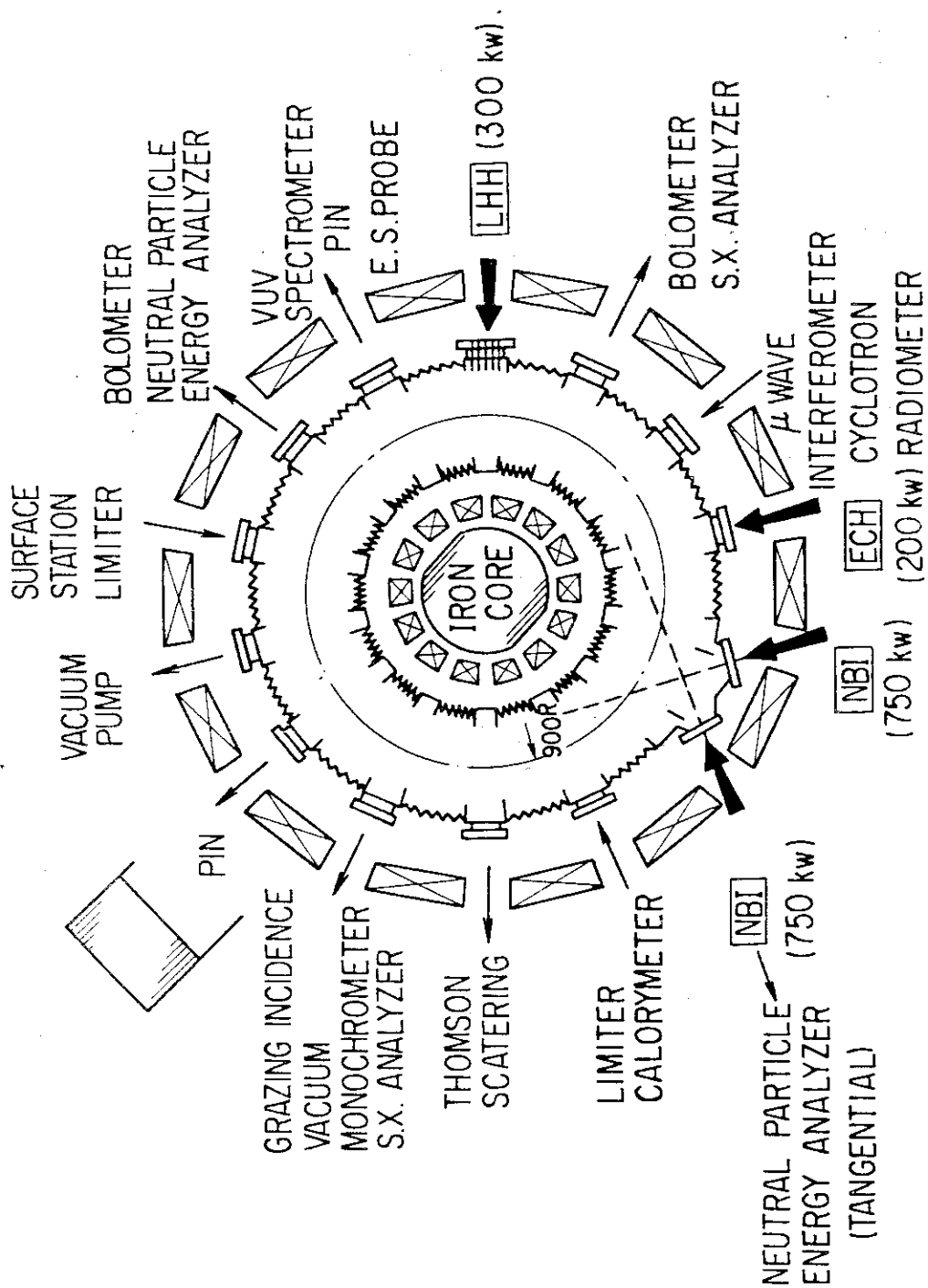


Fig.1 JFT-2

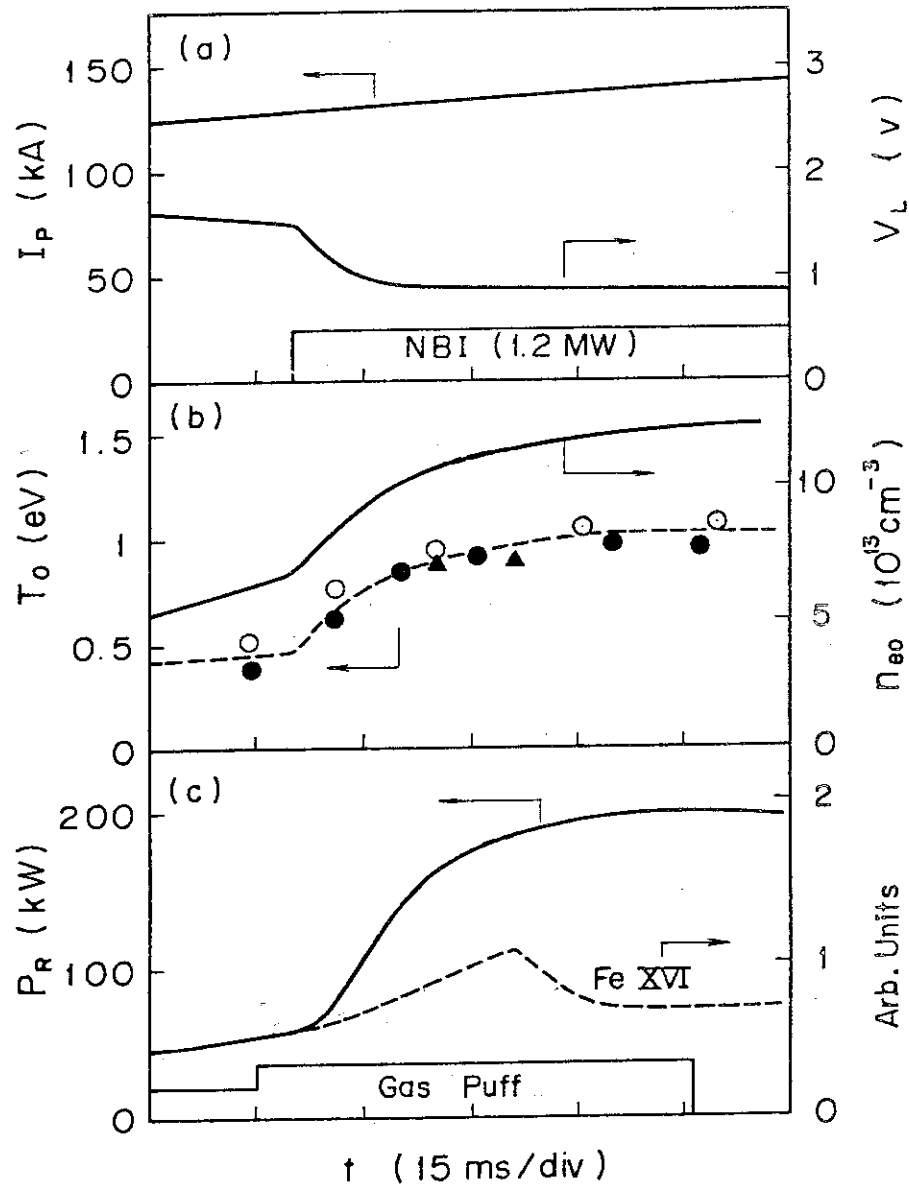


Fig. 2 Time behaviour of plasma current I_p , loop voltage V_L , central density n_{e0} , ion temperature, electron temperature, radiation loss power P_R , line intensity of Fe XVI 361.0 Å and gas influx. $B_t = 1.1$ T and $a_p = 21$ cm. The plasma radius is defined by the rail limiters.

- : Ion temperature measured by a cx analyser.
- ▲ : Ion temperature measured by doppler broadening of titanium line emitted from a central part of the plasma column.
- : Electron temperature measured by Thomson scattering (relativistic effect is not included) and measured by a soft x-ray energy analysis.

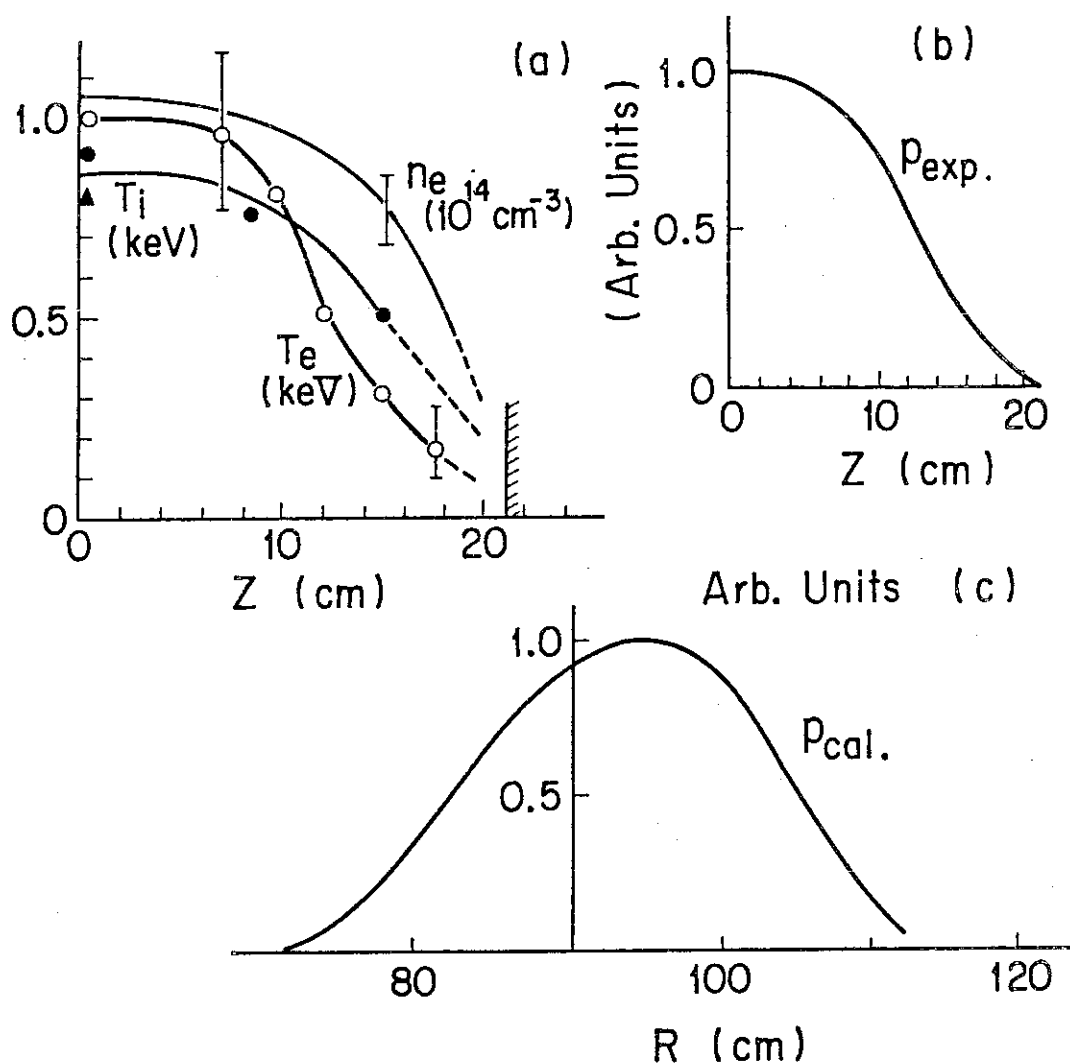


Fig. 3 Plasma profile.

(a) Density and temperature profiles. (b) Thermal pressure profile in experiment. (c) Pressure profile in ballooning analysis. The discharge conditions are shown in Fig. 1. The average β -value is 2.6% due to thermal component and 3% including beam component.

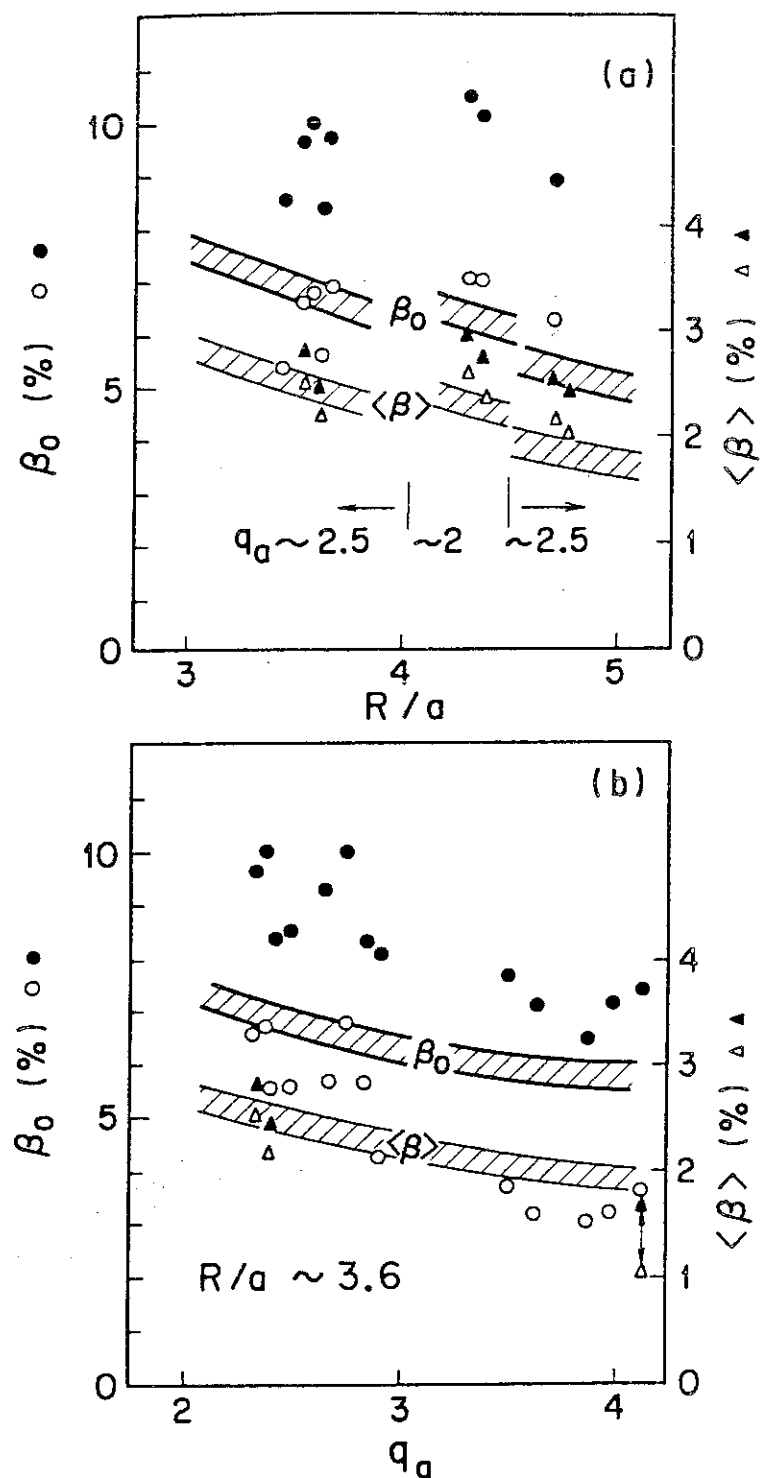


Fig. 4 Critical β values obtained from the ballooning analysis and observed β values. R/a : aspect ratio, q_a : safety factor, β_0 : peak β and $\langle \beta \rangle$: average β . $\circ \Delta$ due to thermal component and $\bullet \blacktriangle$: including the beam component in experiment. hatched line : critical peak β value from the analysis and hatched line : critical average β value. The lower lines indicate the critical values for $q_0 = 1$ and the upper lines for $q_0 = 0.9$.

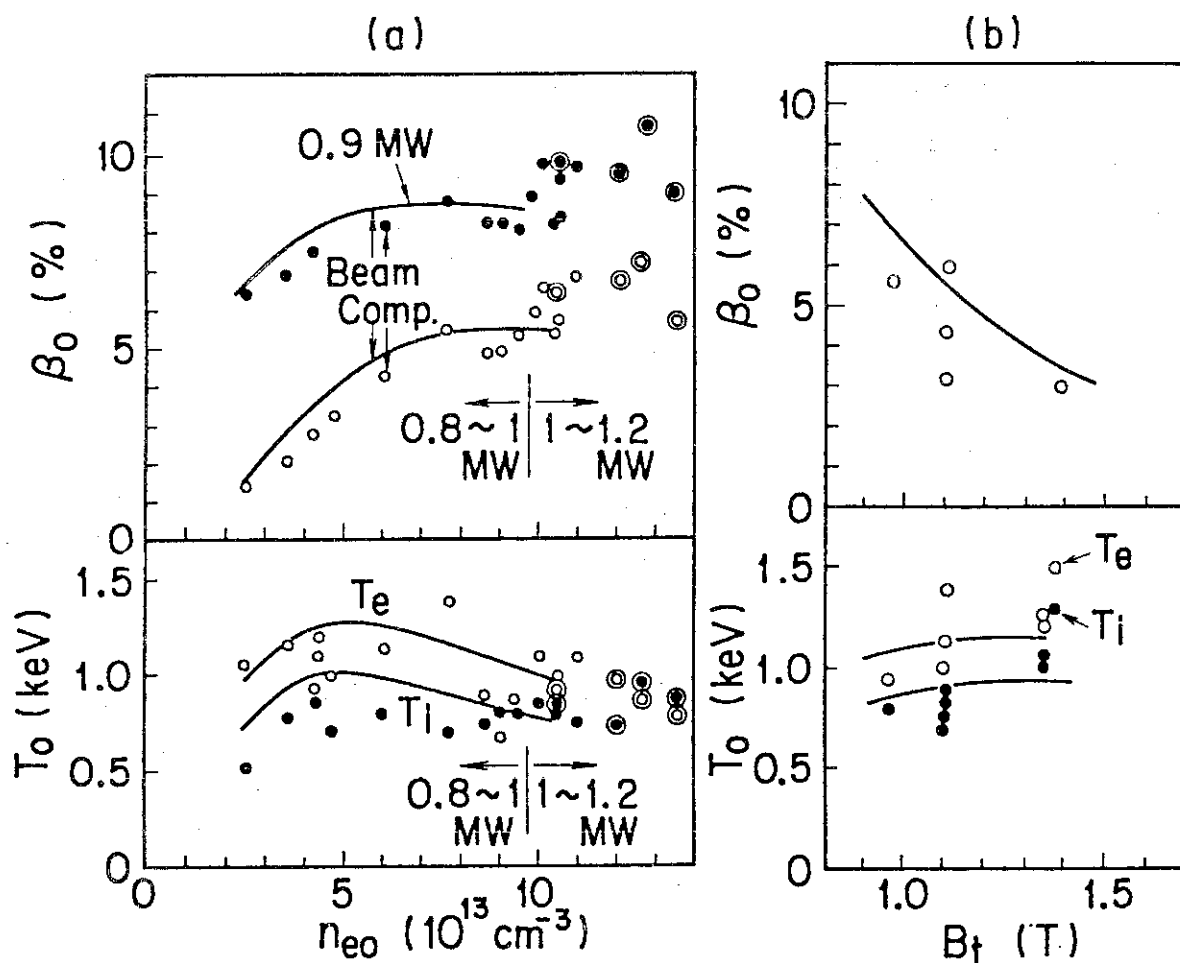


Fig. 5(a) The peak β values and the peak temperatures. Solid lines indicate numerical results with $\chi_e = 2 \times 10^{17}/n_e (\text{cm}^{-3}) \text{ cm}^2 \text{ s}^{-1}$, $\chi_i = 1.5 \chi_{ne0}$, $D_e = 8 \times 10^{16}/n_{e0} (\text{cm}^{-3}) \text{ cm}^2 \text{ s}^{-1}$, $a = 25 \text{ cm}$, $I_p = 130 \text{ kA}$, $B_t = 1.1 \text{ T}$. Experiment is done with $B_t \approx 1.1 \text{ T}$, $I_p = 120 \sim 150 \text{ kA}$, and $a \approx 25 \text{ cm}$ ($\bigcirc \bullet$) and $a \approx 21 \text{ cm}$ ($\odot \odot$).

(b) The thermal peak β values and temperatures. Solid lines indicate the numerical result. Numerical and experimental conditions are the same in Fig. 4-a except B_t , $a \approx 25 \text{ cm}$ and $n_{e0} \approx (5 \div 7) \times 10^{13} \text{ cm}^{-3}$.

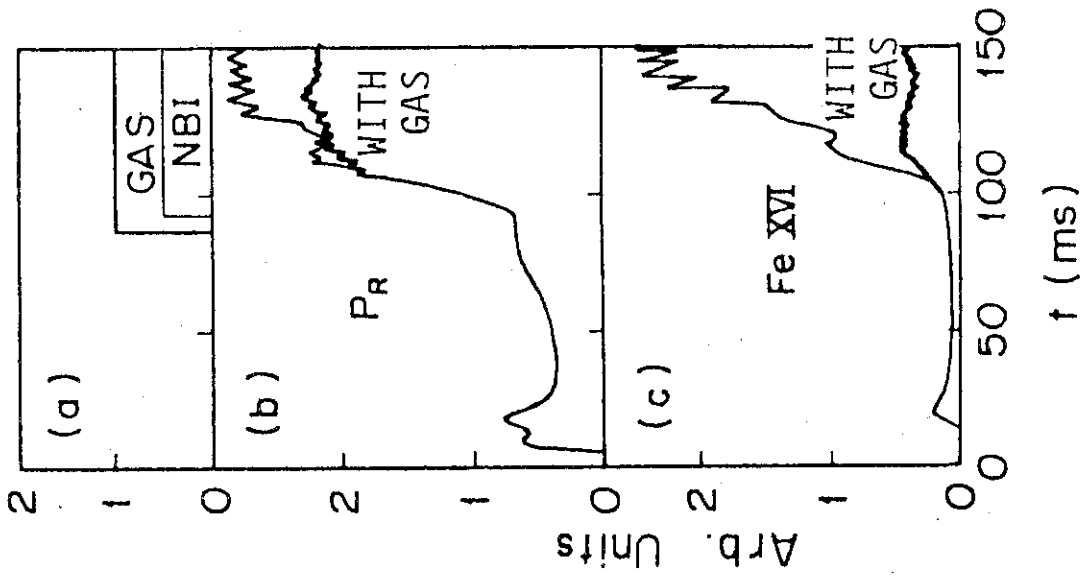


Fig. 7 High-z impurity influx during NBI heating. The NBI heating induces a large influx because of enhanced ion sputtering due to a higher edge temperature. The influx is strongly reduced by cooling the edge plasma with an intense gas puffing.

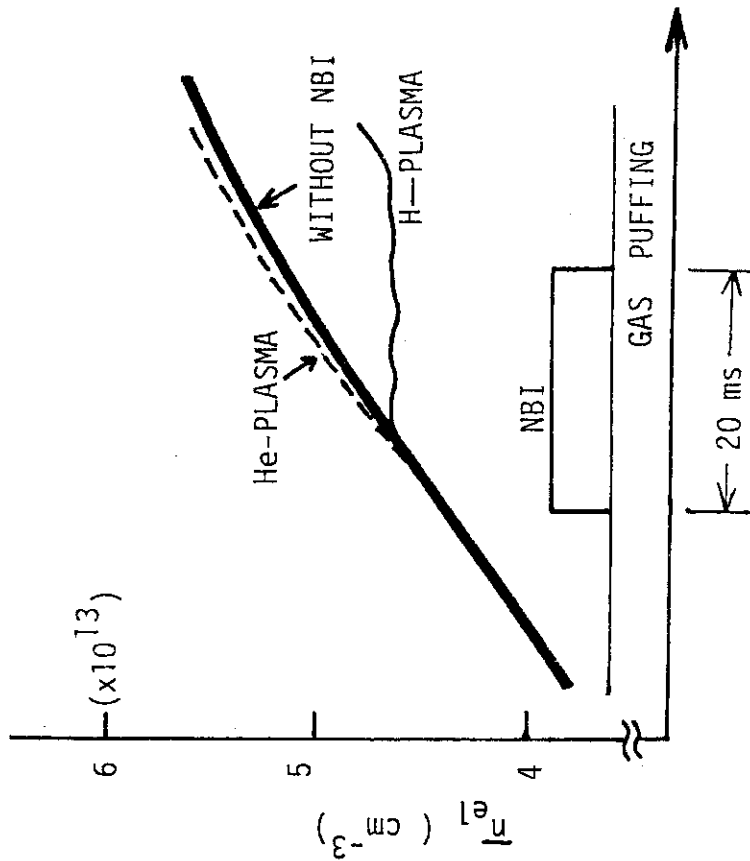


Fig. 6 Density clamp during NBI heating. The density clamp is not observed in He plasma and is observed in H plasma.

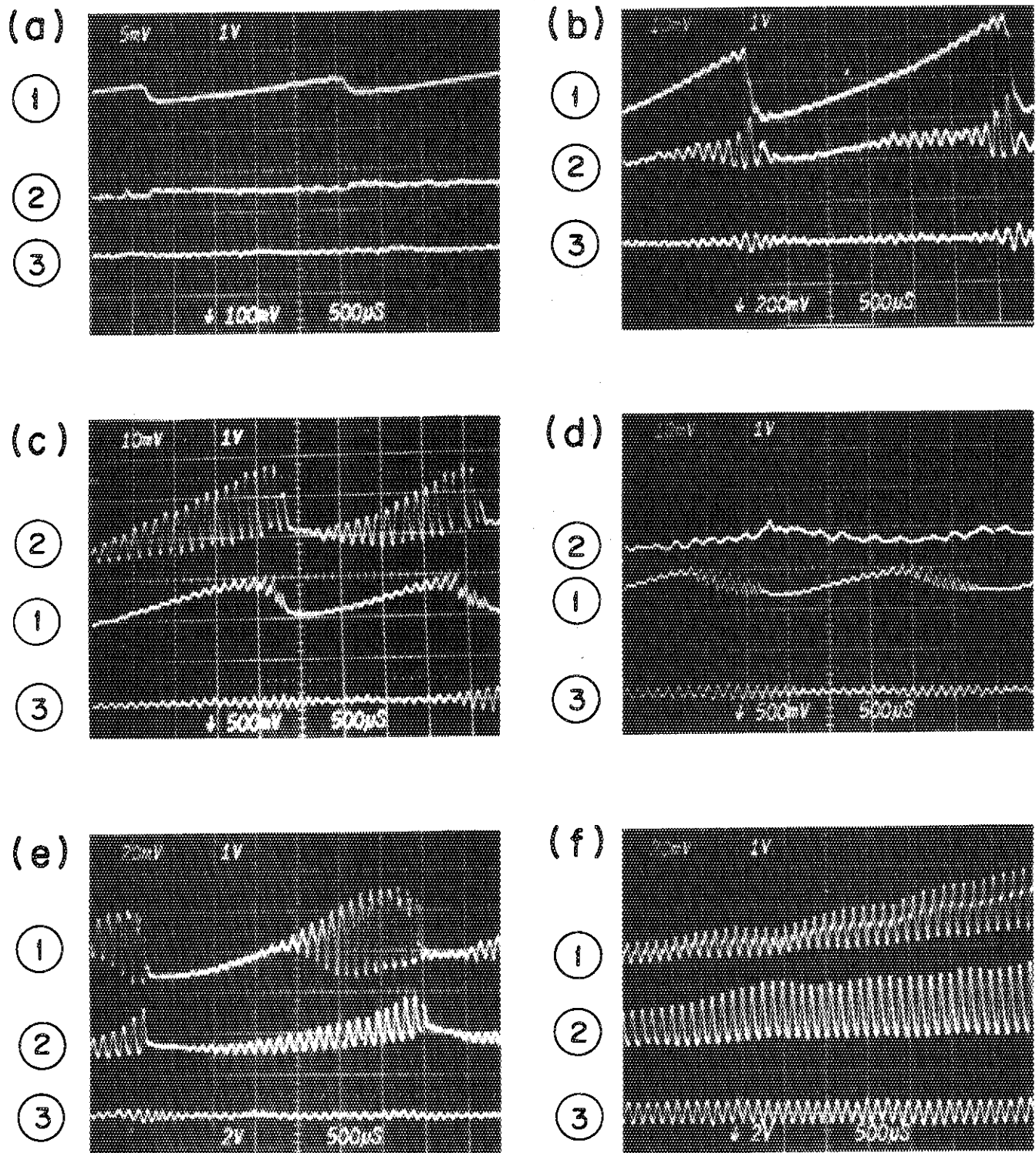


Fig. 8 Fluctuations. ①: PIN diode signals from the central chord, ②: PIN diode signals from the off central chord, ③: Poloidal field fluctuations. (a) ohmic plasma, (b)-(f) with NBI and almost the same operation conditions.

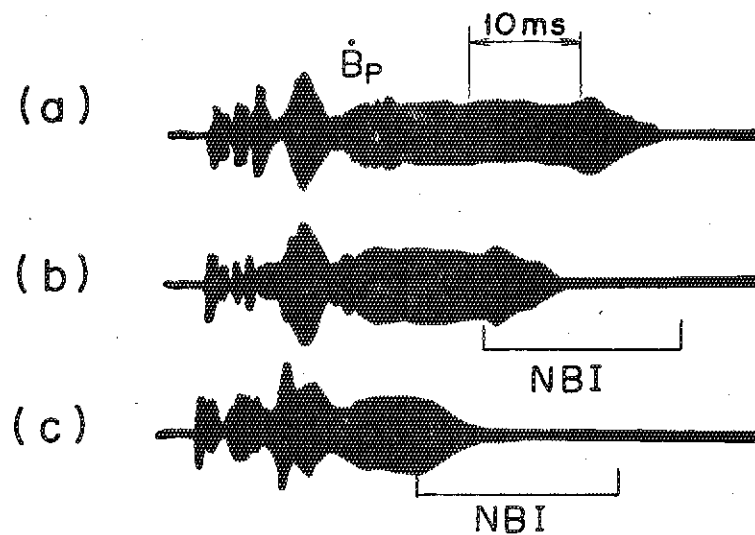


Fig. 9 Suppression of $m = 2/n = 1$ mode by NBI.