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THE CURRENT PROFILE MODIFICATION IN JT-60 PELLET INJECTION EXPERIMENTS

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Japan Atomic Energy Research Institute

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The current profile modification by the pellet injection has been numerically investigated on JT-60 Tokamak using the diffusion equation of the poloidal magnetic field. The result suggests $q(0)<1$ during the sawtooth-free phase obtained by high power NB heating of pellet injected plasmas.

Keywords: JT-60, Pellet Injection, Current Profile, Sawtooth, Ideal m=1 Mode, m=1 Tearing Mode

ＪＴ－６０ペレット入射実験における電流分布変化

日本原子力研究所那珂研究所臨界プラズマ研究部
芳野　隆治

（１９８９年8月4日受理）

ＪＴ－６０におけるペレット入射による電流分布の変化をポロイダル磁場拡散方程式を用いて数値解析した。

その結果，$q(0)<1$ においても鋸歯状振動の発生しない状態が長時間維持されていることが分かった。

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Contents

目　　次

1. Introduction

Pellet injection is one of the promising methods to improve the energy confinement by making the peaked density profile[1-8]. Suppression of the η_i mode is generally considered to be the cause of this improvement.

In JT-60, high power NB heating of pellet injected plasmas has been studied, and the improvement in energy confinement compared with the gas fuelled plasma is also obtained even with 10MW NB heating[9,10], e.g. 40% improvement for Ip=1.8MA divertor plasma with P_{NB}=10MW, and 20% for Ip=2.1MA limiter plasma with P_{NB}=10MW. This improvement is obtained during the sawteeth-free phase and is degraded by the large sawteeth crashes. It becomes important to reinvestigate the mechanism of the sawtooth stabilization, that is generally considered to be caused by the accumulation of impurities to the plasma center. Strong electron temperature perturbations induced by the pellet injection is tolerated with the additional NBI heating, that enables the current profile (especially the q-values in the core plasma) modification by the pellet injection[11]. In JT-60, pellets are injected to plasmas with sawteeth, that makes easier for investigating the current profile after the pellet injection than to sawteeth-free plasmas.

The modification of the current profile by the pellet injection has been investigated using the diffusion equation of the poloidal magnetic field, that reproduces the time evolutions of plasma surface voltage and plasma internal inductance consistent with the experimental data. Then the stabilization of the sawteeth activity has been discussed using the simulated current profile.

2. Experimental Results

Figure 1 presents the typical experimental result of the pellet injection, which will be numerically simulated. Three hydrogen pellets of $2.7mm^{\phi}x2.7mm^{l}$(two small pellets) and $3.8mm^{\phi}x3.8mm^{l}$ (one large pellet) [illegible] about 1500m/sec[12] are injected starting at 5.77sec with 20msec interval to the 1.8MA lower X-point divertor plasma (q_{cyl}=2.4,) as presented in Fig.1(a). $\int n_e dl^{U6}$ is the line integrated density measured by the submilimeter interferometer at

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~2/3 of minor radius, path length of that is 1.1m. The first and second pellets are the small type, and are ablated outside the $q=1$ singular surface. The third large pellet penetrates to the plasma center and the usual reduction in Hα emission is observed at $q=1$ surface [13] as presented in Fig.2(a), that suggests $q(0)<1$ at this moment. NB heating power is raised from 1.7MW to 9MW just after the last pellet injection. The stored energy measured by the diamagnetic loop rises from 0.53MJ to 1.35MJ, and βp increases from 0.13 to 0.33. The line integrated ionic charge state($Z_{eff}{}^{U6}$) measured by the visible bremsstrahlung, that sights ~2/3 of minor radius, drops from 3.6 to 1.2 by the pellet injection.

The sawteeth are observed before the pellet injection, and the last one is between the first pellet and the second pellet at t=5.773, but is suppressed for ~400msec during the rise of the stored energy as shown in Fig.1(b), where Ch.13 sights near the plasma center. The maximum point of soft X-ray emission shifts from ch.13.5 to ch.14 during 6.19sec to 6.23sec. Then a large sawtooth crashes at t=6.23sec with degrading the stored energy. A well peaked soft X-ray emission profile is obtained during the rise of the stored energy inside the sawtooth inversion radius(at ch9.5, r~0.3m) of the pre-pellet injection phase as shown in Fig.2(a).

The electron temperature profile measured by ECE Fourier spectrometer is very flattened in the plasma core as presented in Fig.2(b), the error bar of that at the plasma center is ±10%. Density profile measured by Thomson scattering at t=6.1sec is shown in Fig.2(c) by x, where the plasma center is not diagnosed because of the off-axis sight-line. Time evolution of the density profile is not measured directly. Hence the density profile is estimated using the following function;

$$n_e(r)=(n_e^0-n_e(a))(1-(r/a)^2)^{\alpha}+n_{add}\exp(-(r/r_c)^2)+n_e(a)$$

Parameter of $n_e{}^0$ $n_e(a)$, α, r_c and n_{add} are selected to fit the density profile measured by Thomson scattering at t=6.1sec keeping the consistency with $\int n_e dl^{U6}$, soft X-ray emission profile and the stored energy measured by the diamagnetic loop. Then $n_e(r)$ of the other time points are estimated with the assumption of the same central plasma density($=n_e{}^0+n_{add}$) of $2.5\times10^{20}/m^3$ as at t=6.1sec keeping the consistency with experimental data. The obtained density profiles are presented in Fig.2(c), that with radially constant Z_{eff} well reproduce the soft X-ray emission profiles.

3. Numerical Simulation

Current profile is simulated by the diffusion equation of the poloidal magnetic field, where the neoclassical resistivity is adopted and the bootstrap current is estimated using the Hinton-Hazeltine model[14]. Sawteeth are simulated by setting q=1 artificially inside the q=1 singular surface at each sawtooth crash like the Kadomstev manner.

Figure 3(a)(b) presents the simulated time evolutions of plasma surface voltage(V_S) and plasma internal inductance(l_i) with dotted lines, that are compared with the experimental results with solid lines. Good agreement is obtained between them with the assumption of the radially constant Zeff, where both of them are smoothed with 20msec filter. The increase in l_i by the first two small pellets, that are ablated at the plasma periphery, is 0.02 during 40msec. The simulated q(0) drops largely from 1.0 to ~0.95 by this fast rise in li until the third pellet injection as presented in Fig.3(c) where q(0) is set 1.0 at t=5.773sec because of the sawtooth crash. This decrease in q(0) is consistent with the reduction observed in Hα emission of the third pellet at q=1 surface, that suggests q(0)<1. The current density at the plasma center decreases a little after the third pellet because of the flattened electron temperature profile. So q(0) rises a little, but is <1.0. In the case of joule plasma q(0) rises larger than 1.0 with the decrease in l_i. This difference in q(0) is caused by the rise speed of electron temperature at the plasma center. In the case of high power NB heating after the pellet injection, the increase rate of electron temperature becomes so fast that the current density at the plasma center has no time to decrease. The broad electron temperature profile and the bootstrap current, that flows off-axis inside the q=1 surface for the sake of the large density gradient as shown in Fig.3(d), makes a little hollow current profile inside the q=1 surface as presented in Fig.3(d).

The bootstrap current is only 10% of the total plasma (~150kA) , and the decrease in l_i by that is little. However the effect of bootstrap current to q(0) cannot be neglected. The broken line in Fig.3(c) is the case of without bootstrap current, where q(0) with bootstrap current is larger than without bootstrap current by ~0.05 at 6.2sec.

It is necessary to check the possibility of $q(0)<1$ during the sawteeth-free phase within the parameter ambiguity. (1)If Zeff is high inside the q=1 surface just after the pellet injection[4], q(0) rises higher than 1.0. The very flattened soft X-ray emission profile at t=5.85sec as presented in Fig.2(a) cannot be explained by the peaked Z_{eff} profile, and hollow Z_{eff} profile is more possible because of the large increase in plasma density. On the other hand the peaked Zeff profile cannot be denied in the latter phase(t=6.1~6.2sec). Zeff profile has been scanned adding $Z_{add}*\exp(-(r/0.2)^2)$ to the radially constant Zeff from 5.9sec, and $q(0)<1$ is obtained with $Z_{add}<0.5$. Sensitivity of Z_{add} to the soft X-ray emission profile is checked, and $Z_{add}<0.5$ is found out to be possible within the ambiguity. (2) The ambiguity in plasma density is large inside the q=1 singular surface(<0.3m), so that is scanned to increase q(0) within the ambiguity of stored energy of ±10%. Density is raised to decrease the resistivity(by suppressing the trapped particle effect) and to increase the bootstrap current. However these changes in density profile have little effect on the value of q(0).

These numerical simulation suggests q(0) is <1.0, that is consistent with the experimental observation of the peaked Soft X-ray emission inside the sawteeth inversion radius of the pre-pellet injection phase still during the sawteeth-free phase.

4. Discussions

Therefore possible mechanism of the sawtooth stabilization with $q(0)<1$ is necessary to be discussed. First one is the stabilization of the m=1 tearing mode with the diamagnetic effect[15]. The growth rate γ of that at the post-pellet injection phase is found out to be lower than at the pre-pellet injection phase for the sake of the large density gradient as presented in Fig.4(a). The absolute value of γ is still high, however the toroidal effect effectively reduces the growth rate and the lower shear possibly exists at q=1 surface[16]. Therefore the suppression of the resistive tearing mode is the one explanation. As another possible candidate Nave and Wesson's model of ideal m=1 model[17] is tested, where quasi-interchange is proposed with the flattened current profile inside the q=1 surface. The simulated q(0) is 0.95~1.0 and βp defined inside the q=1 surface is 0.35~0.55, that is a little larger than the threshold value estimated in ref.[17] as presented in Fig.4(b). The modeled current profile in this reference is not the same as our

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simulated results, so that precise investigation based on the simulated current profile is now under going using the ERATO-J code.

5. Conclusions

The modification of the current profile by the pellet injection has been numerically investigated in the case of sawteeth-free shot, where stored energy increases just after the pellet injection for ~400msec without the saturation and sawteeth. The simulation, that reproduces plasma surface voltage and plasma internal inductance experimentally observed, suggests q(0) is kept <1.0 during the sawteeth-free phase because of the fast recovery of electron temperature caused by 10MW NB heating.

The mechanism of the sawteeth suppression with q(0)<1 is discussed. The lowered growth rate of the resistive m=1 tearing mode suggests the one explanation of this stabilization. The ideal m=1 mode is also investigated, however βp defined inside the q=1 surface is higher than the theoretical prediction. However the referred current profile is not the same as the simulated one. Therefore more quantitative investigation is now going using ERATO-J code.

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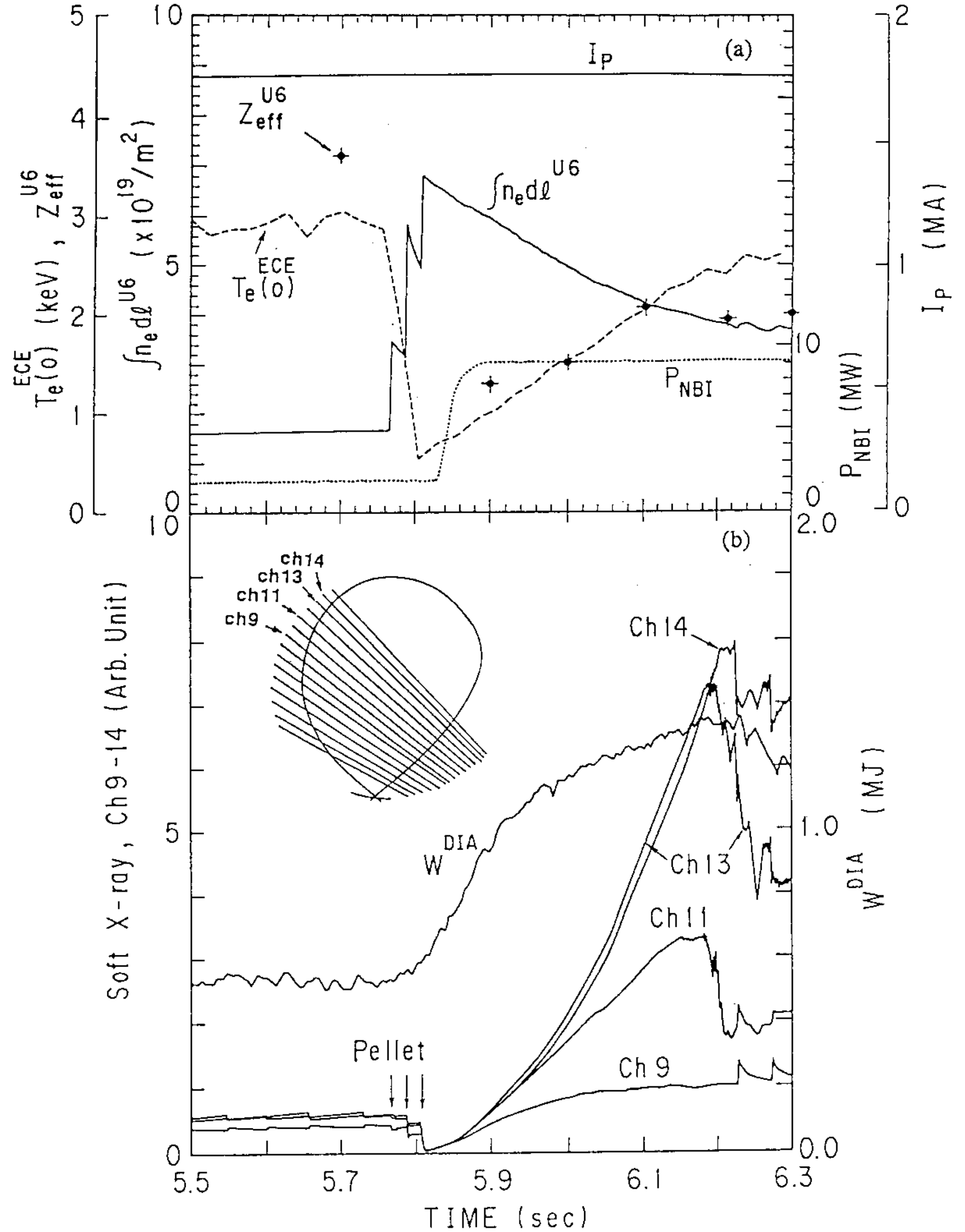

Fig.1 Time evolutions of pellet injection.

(a) $\int n_e dl^{U6}$;line integrated plasma density at 2/3 of minor radius(line length is ~1.0m), P_{NB};NB heating power, Te(0);central electron temperature, and Z_{eff}^{U6};line averaged effective ionic charge state measured at ~2/3 of minor radius. b)stored energy and soft X-ray emission.

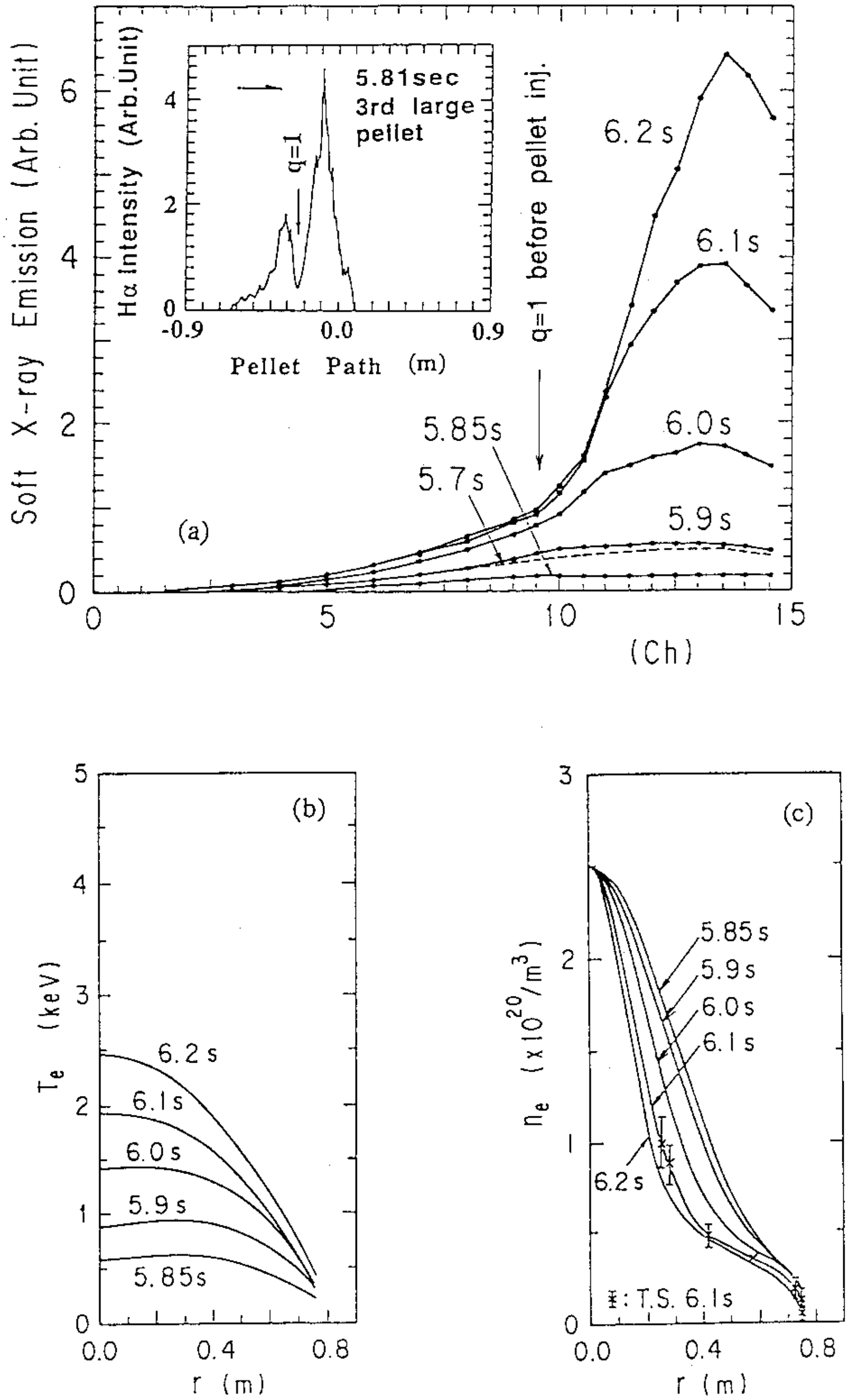

Fig.2 Time evolutions of profiles.
(a)soft X-ray emission profile and the Hα emission of the third large pellet, (b)electron temperature profile measured by ECE spectrometer, (c) electron density assumed to be consistent with the experiment data. x; Thomson scattering data at t=6.1sec.

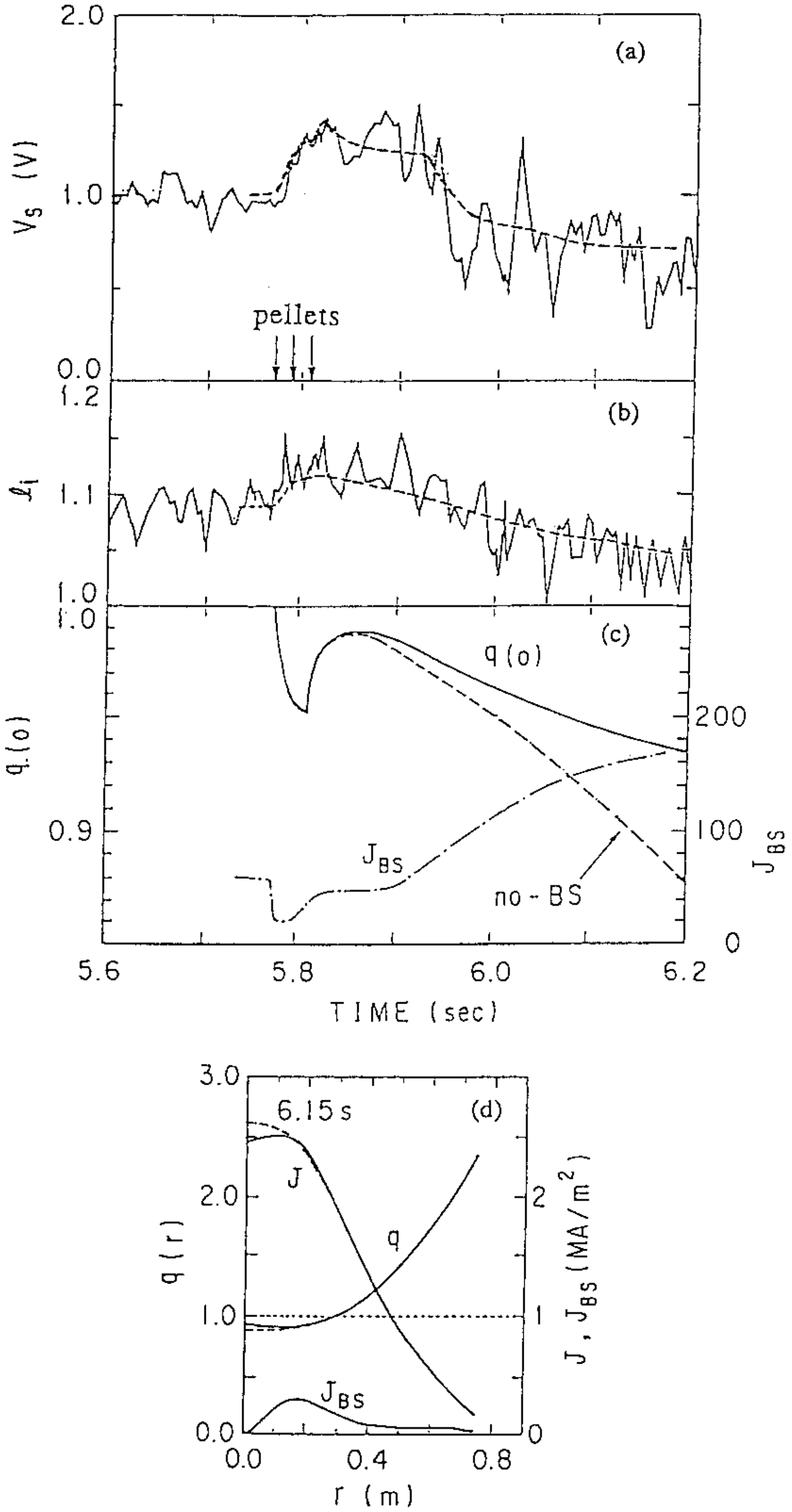

Fig.3 The simulated results.

(a)Vs;plasma surface voltage, (b) l_i; plasma internal inductance, where solid lines are the experimental results and dotted lines are the simulated ones, (c)q(0) and total bootstrap current J_{BS}, dotted line of q(0) is without bootstrap current. (d)profile of q and current J and J_{BS} at t=6.15sec. The solid lines of q and J are with bootstrap current, and broken lines are without bootstrap current.

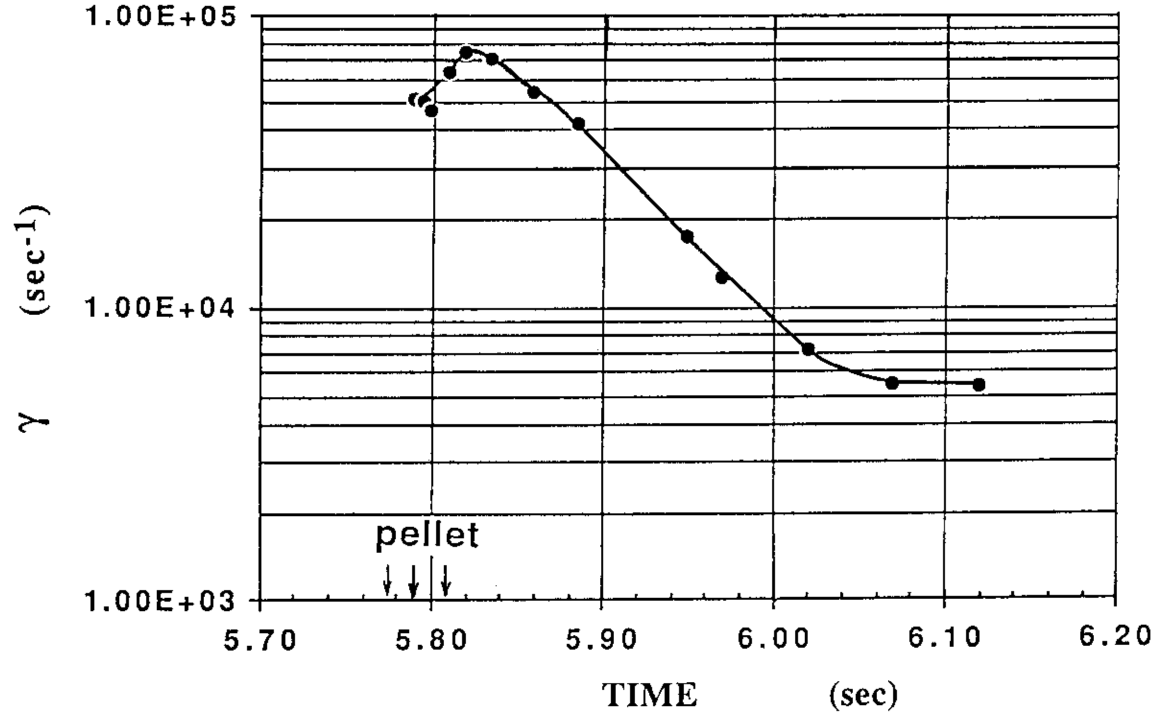

Fig.4(a) Time evolution of the growth rate of the m=1 resistive mode calculated according to Waddell et al.'s model[15].

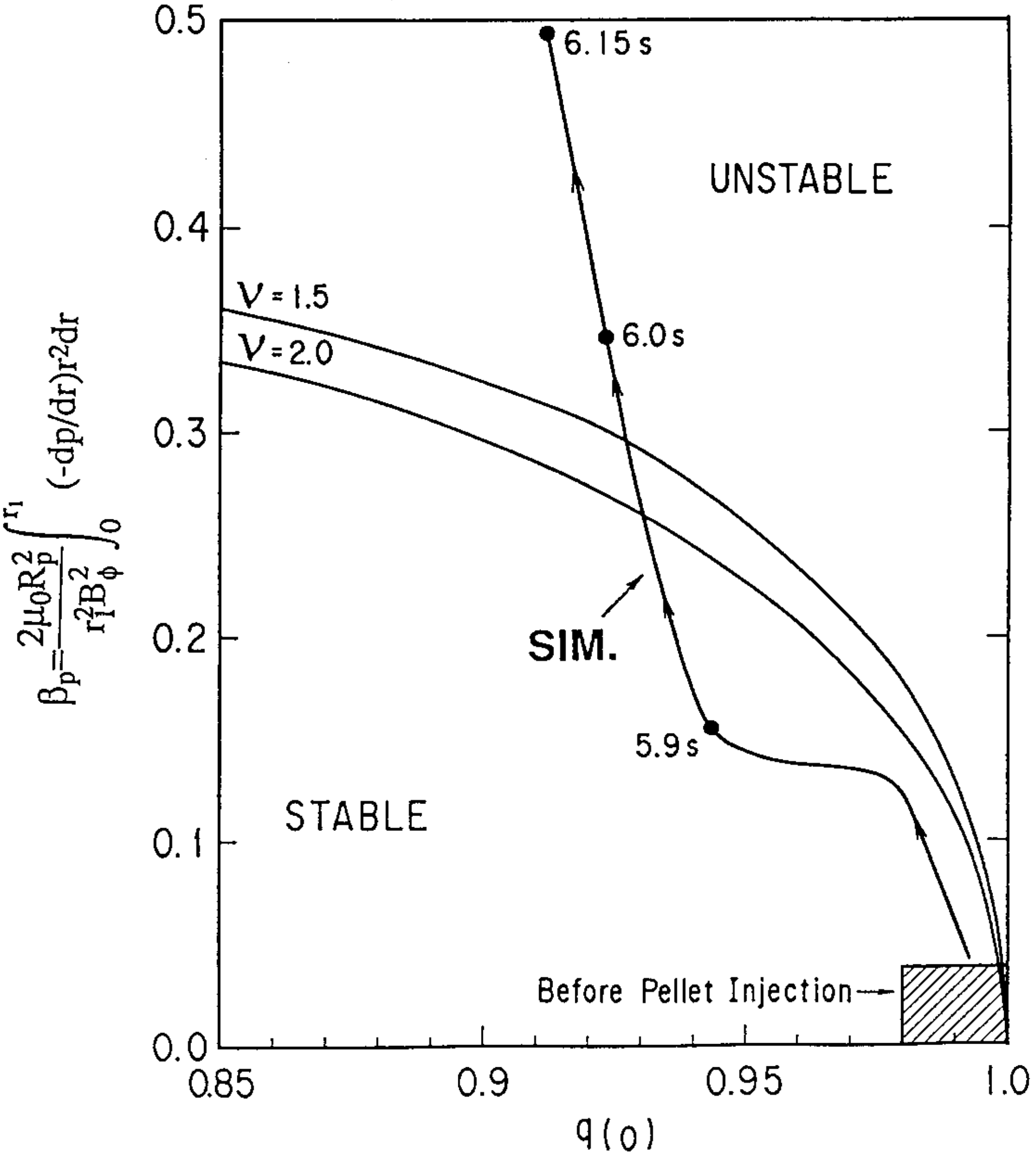

Fig.4(b)Stability diagram of m=1 ideal model in q(0) and βp plane proposed by Nave and Wesson [17], and the trace of the simulation results during the sawtooth-free phase. βp is defined inside the q=1 radius(r_1). V defines the current profile as $j=j_0(1-(r/a)^2)^V$.