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(post-deadline paper)

NATIONAL INSTITUTE FOR FUSION SCIENCE

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ABSTRACT

Control of rotational transform profile with a small ohmic heating (OH-) current to increase the rotational transform has led to a continuous rise in the line-averaged electron density with reduction of Hα-lights around the torus, in a heliotron/torsatron plasma heated by neutral beams. During the density rise, the transport barrier with steep temperature and density gradients near the plasma edge has been formed. Edge localized modes (ELM)-like activity is also observed. Incoherent magnetic fluctuations in the frequency range f > 20 kHz are clearly suppressed during the density rise phase, while low frequency coherent part remains almost unchanged. Global energy confinement time in the density rise phase is improved by ~ 15 %, compared with that of the discharge without the OH-current. These experimental observations are very similar to the H-mode in tokamaks. There is a threshold of the current for the transition, where the increment of rotational transform by the threshold current corresponds to ~ 0.1 at the edge. No obvious increase in the edge poloidal rotation velocity, however, is observed during the density rise phase, that is, at most ~ 3 km/s.

keywords: H-mode, transport barrier, heliotron/torsatron, rotational transform, confinement improvement, edge localized modes, threshold plasma current, edge poloidal rotation

1 INTRODUCTION

The global energy confinement time of net current-free plasmas produced in heliotrons, torsatrons or stellarators is well-expressed by the so-called LHD-scaling[1] or its slight modifications [2,3]. The scalings indicate an obvious improvement with electron density and toroidal magnetic field, while the power degradation is very similar to the L-mode or H-mode ITER-scaling in tokamaks [4]. Study on difference and similarity between the respective scaling law for tokamak and helical plasmas may improve understandings of anomalous transport in toroidal confined plasmas, and may elucidate roles of net plasma current and magnetic field ripple on the plasma confinement. Recently, many confinement studies in tokamaks are addressed to the improved confinement regime, i.e., H-mode. Experimental and theoretical studies on H-modes discuss the effect of edge radial electric field Er and its shear Er' on the L-H transition and confinement improvement [5,6]. However, a cause and effect relationships between Er or Er' and L-H transition are not yet established. To search for the H-mode in helical devices is very significant to extend the parameter range in helical plasmas and also helpful to understand the physical mechanism of H-modes. In ATF [7], a trial for getting H-mode with a biased electrode is carried out, but the results are obscure so far. In CHS [8], perpendicular neutral beam injection does change Er and Er' near the edge, but no confinement improvement is observed. Another promising way to trigger the H-mode is a control of the rotational transform profile by introducing toroidal plasma currents. This is motivated from the H-mode experiments based on a control of edge toroidal current density profile in the JIPP T-IIU tokamak [9,10,11]. We have achieved, for the first time, the H-mode like transition in the low aspect ratio heliotron /torsatron type device CHS[12] with the control of rotational transform profile.

2. Experimental Results and Discussions

At the toroidal magnetic field B_t~0.94 T and 1.56 T, hydrogen plasmas initiated by electron cyclotron heating(53 GHz) are heated by co-injected hydrogen beams (NBI) of about 600 - 900 kW (through a port) with beam energy 32 - 36 keV. Line averaged electron density $\overline{n}_e$ is adjusted to be less than ~ 4 x 10^{13} cm^{-3} by gas puffing . The ohmic heating (OH -) current is generated during NBI heating by induction of small loop voltage less than ~2 volts using a set of poloidal field coils[13]. In this experiment, the position of magnetic axis in vacuum field is adjusted to be R_{ax} = 92 - 94 cm. Radial profiles of electron temperature T_e and density n_e are obtained by Thomson scattering, and those of ion temperature T_i and poloidal rotation velocity v_θ are measured with ~ 16 ms time resolution by charge exchange recombination (CXR-) spectroscopy[14]. Particle recycling is monitored by 11-channel poloidal fan array[15] and by a single channel H_α-detector at 8 toroidal locations.

Figure 1 shows temporal behaviour of various plasma parameters in NBI heated plasma with the OH-current (I_p ~ 27 kA), where a beam driven current is estimated to be less than ~ 5 kA. The OH-current is driven to increase the external rotational transform. The plasma confinement is obviously degraded in the opposite driven case. The rotational transform by the current at the last closed flux surface (LCFS) is ~0.18 for I_p ~ 27 kA and B_t = 0.94 T, and that by vacuum magnetic field ~0.9. At t ~ 95 ms line averaged electron density begins to increase continuously in the course of the ramping phase of the OH-current, while the gas puff rate is kept constant . During the density rise phase, H_α-lights observed around the torus are reduced. This behavior suggests the reduction of outward particle loss flux and improvement of the particle confinement. In the discharge shown in Fig.1, the reverse transition, so-called H-L transition, is not clearly seen. Radial profiles of T_e, n_e and T_i just before the density rise phase (at t=80 ms for T_e- and n_e-measurement , or 67-83 ms for Ti-measurement) and during the rise phase (at t=120 ms or 117-133 ms) are shown in Fig.2, together with the profiles for the discharge without the OH-current. Just before the density rise, the profiles are nearly parabolic. After entering the density rise-phase, n_e-profile evolves to a hollow profile with very steep gradient just inside LCFS, and T_e-profile also evolves to the profile with a steep gradient there. Also T_i-profile becomes broader during the phase. All of T_e, n_e and T_i profiles in the density rise phase are broader than those in OH current-free discharge with the similar $\bar{n}_e$. Figure 2 clearly shows the formation of edge transport barrier very similar to the H-modes observed in tokamaks. As shown in Fig.1, reduction of the H_α-lights is not significant as observed in tokamak H-modes. This phenomenon may be caused by an enhanced orbit loss of beam ions due to a broad n_e-profile. During the density rise phase (t ~ 120 ms), a deposited NBI power is estimated to be ~ 540 kW which much higher than ohmic heating power ~ 40 kW, and to be ~ 740 kW for the discharge without the OH-current. Global energy confinement time in the H-mode type discharge is improved by about 15 %, compared with the L-mode type discharge without the OH-current. In contrast to the tokamak H-modes, no obvious increase in the edge poloidal rotation velocity is observed (at most ~ 3 km/s) during the density rise phase, where the rotation is in the electron diamagnetic direction. This result seems to indicate that the connection between the formation of the edge transport barrier and edge poloidal rotation or edge radial electric field is weak. The ELM-like spike is sometimes observed in H_α-

lights during the density rise phase. The ELM-like spike ceases the continuous density-rise, exhibiting a small dip in $\bar{n}_e$. In the density rise phase, incoherent part of poloidal magnetic fluctuations (f > 20 kHz) detected by magnetic probes are suppressed by more than a factor of two, compared with that without the OH-current. But, the low frequency part (f ~ 3 - 10 kHz), which dominates the amplitude of magnetic probe signals, remains unchanged for both cases.

We have studied the relationship between this H-mode like transition and a required plasma current for two cases of different toroidal magnetic field, changing the OH-current. The transition which is defined by a large change in the density rise rate is triggered at I_p = 13 - 23 kA for B_t = 0.94 T , and 25 - 29 kA for B_t = 1.56 T (Fig.3). For both toroidal magnetic fields, the transition occurs at the almost same value of edge rotational transform by I_p (i.e., $\iota_I(a)/(2\pi)$ ~ 0.1), although a fine structure of the rotational transform or magnetic shear may be more important factor for the transition [16]. Existence of the threshold in I_p for the transition suggests that the control of magnetic field structure near the edge is most essential for triggering the H-mode like transition.

3. Conclusion

The H-mode like transition has been discovered in the heliotron/torsatron type device CHS, through a control of the rotational transform profile with a small ohmic heating current. Observed phenomena are very similar to H-modes in tokamaks except that no obvious increase in edge poloidal rotation is observed. In a future helical device, the attractive confinement regime can be extended under condition with intense plasma heating, by the combination of smaller OH-current with non-inductive currents.

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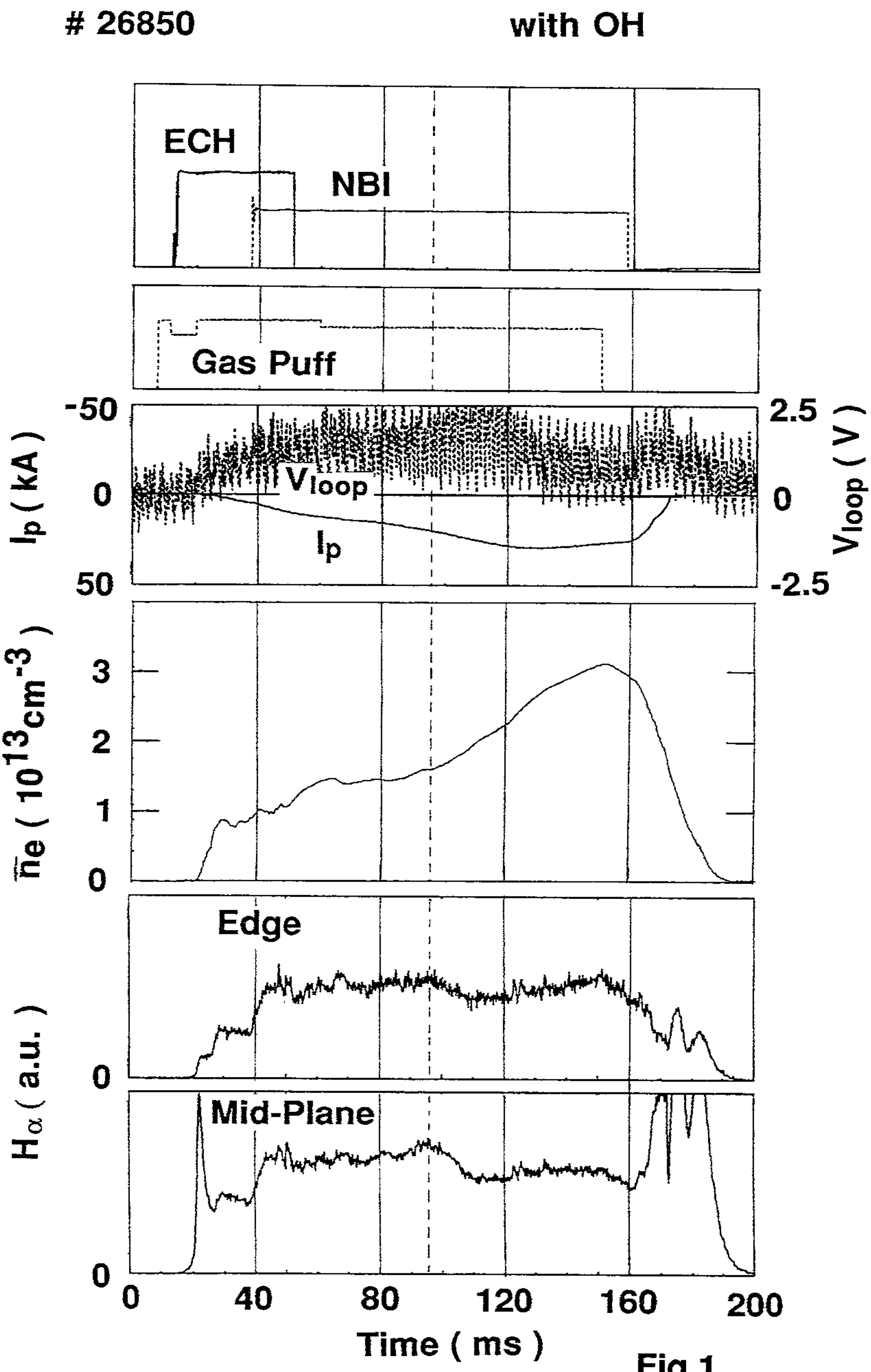
Figure Captions

Fig.1 Temporal evolution of plasma parameters in the case with the OH-current. Plasma current rises up to 27 kA with ~ 100 ms time scale at B_t = 0.94 T, where a beam driven current is estimated to be less than ~ 5 kA. Total NBI power injected through a port is ~ 900 kW with the beam energy of E = 36 kV. The H-mode like transition occurs at t ~ 95 ms, when $\overline{n}_e$ begins to rise continuously with reduction of H_α-light. Gas puff rate is kept constant before and after the transition .

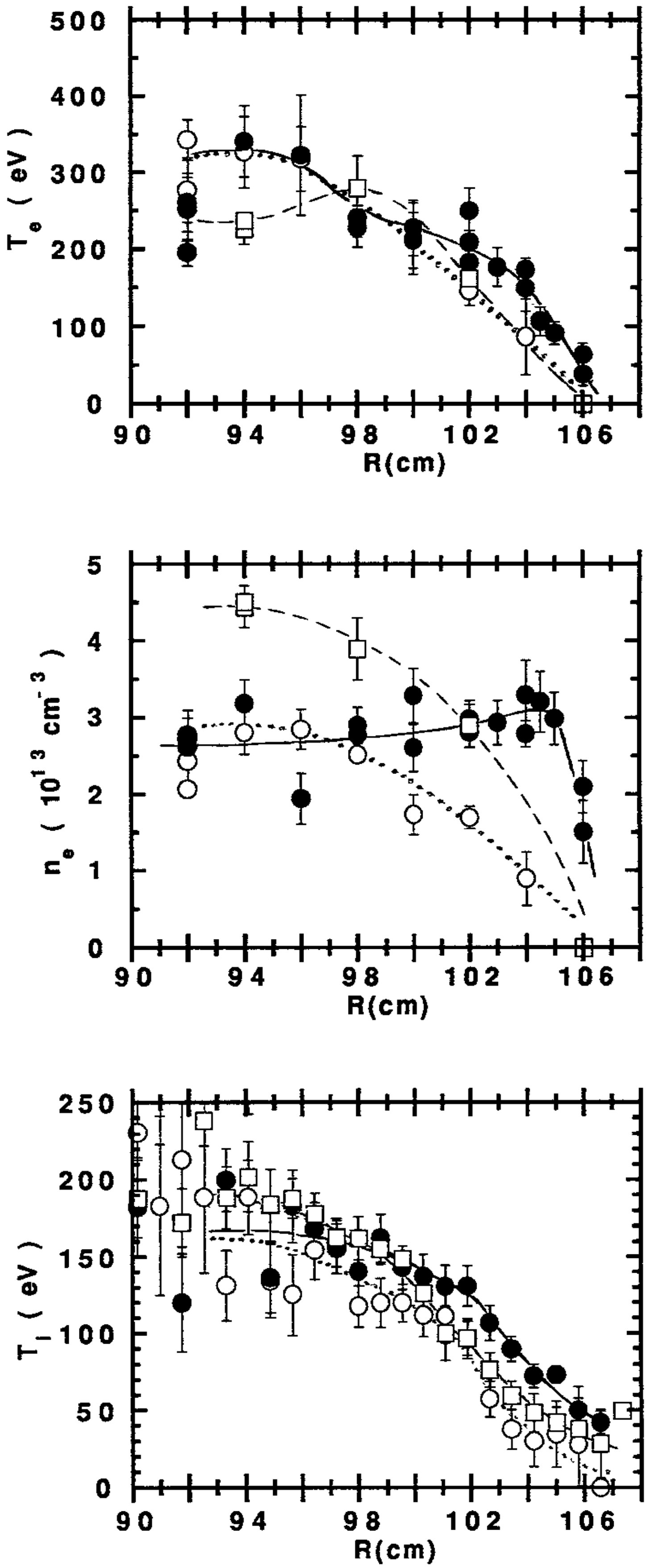
Fig.2 Radial profiles of electron temperature, electron density and ion temperature for three cases. Open circles and dotted curve denote the profiles just before the density rise (t = 80 ms for T_e and n_e-profiles or t= 67-83 ms for T_i-profile) in Fig.1. Solid circles and solid curve denote the profiles during the density rise phase (t = 120 ms or 117-133 ms) in Fig.1. The profiles at t=120 ms or 117-133 ms for the discharge without the OH-current are shown by open squares and broken curve. During the density rise phase, all of profiles have a pedestal or steep gradient near the edge.

Fig.3 Temporal evolution of several H-mode like discharges on a plane of a density rise rate and a plasma current for lower toroidal field case (B_t = 0.94 T) and higher one (B_t = 1.56 T).



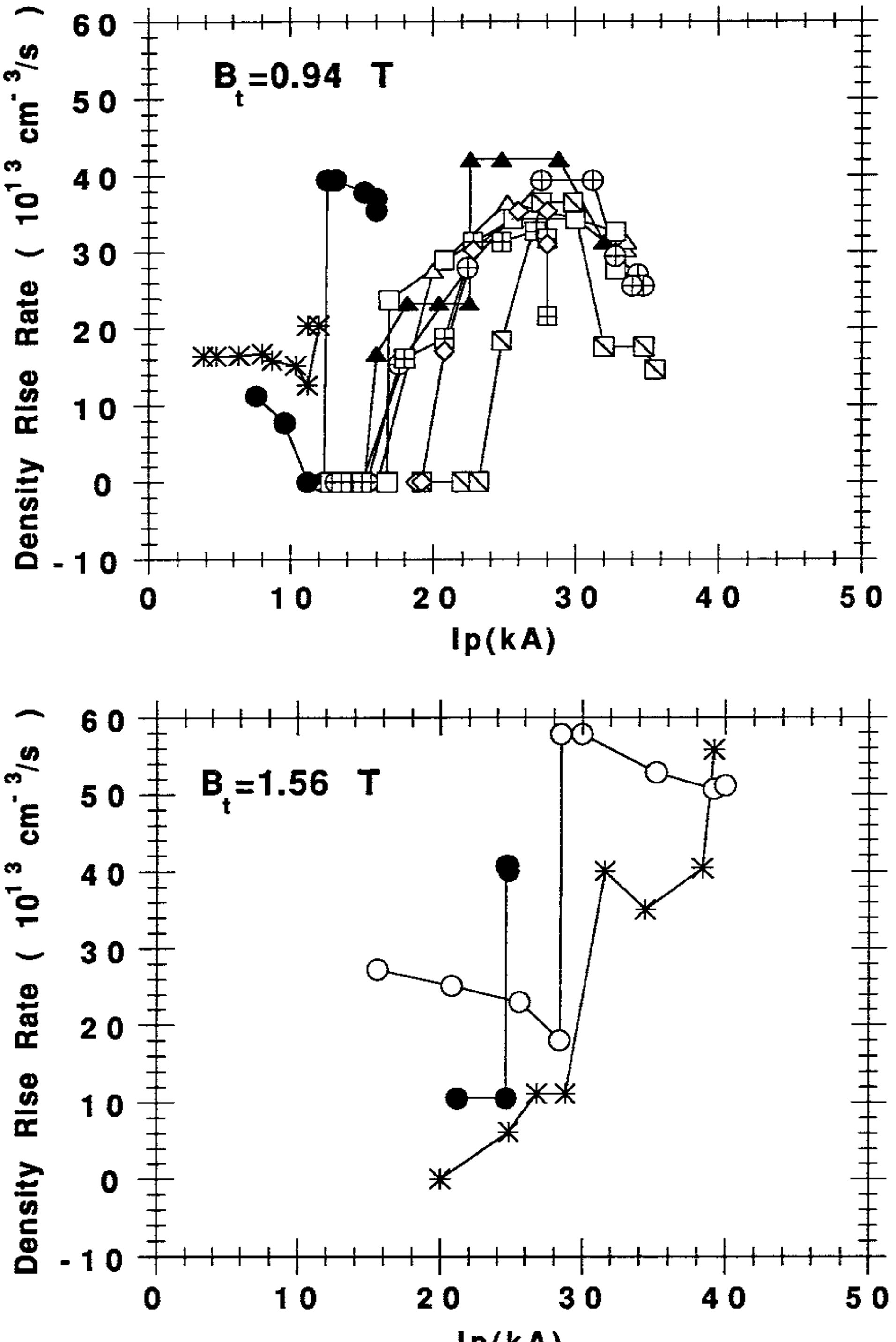
26850
with OH
ECH
NBI
Gas Puff
-50
0
50
Ip (kA)
Vloop
Ip
2.5
0
-2.5
Vloop (V)
$\bar{n}_e$ ($10^{13}cm^{-3}$)
3
2
1
0
Edge
Mid-Plane
H_α (a.u.)
0
0
0
40
80
120
160
200
Time (ms)

Fig.1



500
400
300
200
100
0
T_e (eV)
90
94
98
102
106
R(cm)
5
4
3
2
1
0
n_e (10^{13} cm^{-3})
90
94
98
102
106
R(cm)
250
200
150
100
50
0
T_i (eV)
90
94
98
102
106
R(cm)

Fig.2



B_t=0.94 T
Density Rise Rate (10^13 cm^-3/s)
Ip(kA)
B_t=1.56 T
Density Rise Rate (10^13 cm^-3/s)
Ip(kA)

Fig.3

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