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Comparative studies on the bootstrap current in the standard and inward-shifted LHD configurations in the $1/\nu$ and plateau regimes

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Abstract

While a tokamak has a plasma current disruption, a helical system is much safer because the current-less operation is in principle possible. However, a bootstrap (BS) current due to the pressure gradient could be one of the concerns because the rotational transform could be increased. We have made experiments of BS current in the Large Helical Device (LHD) in the $1/\nu$ and plateau regime using three magnetic axis configurations of $R_{ax} = 3.75$ m, 3.6 m and 3.53 m with the completely balanced NBI (neutral beam injection). As a reference we use the standard configuration of $R_{ax} = 3.75$ m, we made the inward-shifted configuration of $R_{ax} = 3.6$ m, and the further inward-shifted configuration of $R_{ax} = 3.53$ m which is called the neoclassically optimized configuration [1]. It was clearly demonstrated that reduction of the BS current is observed for $R_{ax} = 3.53$ m configuration in LHD than that for $R_{ax} = 3.75$ m together with the confinement improvement. Based on these experimental results, the BS current coefficient has been derived capable of predicting the BS current in a helical fusion reactors.

1. Introduction

While a tokamak has a plasma current disruption, a helical system is much safer because the current-less operation is in principle possible. As a BS current due to the pressure gradient could alter the rotational transform profile in LHD, which leads to the decrease in the magnetic shear, it is still concerning from the viewpoint of a helical reactor design. Therefore, it is quite important to demonstrate how we can reduce the BS current in a helical system.

The BS current in a stellarator had been studied theoretically in terms of geometric factor using the Hamada coordinate [2][3], and using the Boozer coordinate together with ATF experiments [4]. And then the BS current in a large helical system of the heliotron type had been evaluated in a

banana and plateau regimes using the Boozer coordinate [5]. After that, a theoretical estimation of the BS current has been studied by the 3-D equilibrium calculation for LHD and showed that the BS current is sensitive to the magnetic configurations through the geometrical factor [6]. It showed that shifting the magnetic axis to the outboard side reduces the BS current. Furthermore, dependence of BS current on the collisionality parameter have been studied using the connection formula from the collisionless $1/\nu$ to the Pfirsch-Schlüter regime [7]. The collisionality dependence of the geometric factor provides that BS current is lower in the high-density plateau regime (high collisionality) than in the low density $1/\nu$ regime (low collisionality). On the other hand, it was shown that the geometric factor is positive in the $1/\nu$ regime and almost negative in the plateau regime, and then the reduction of the BS current is shown due to the reverse of the BS current direction [8].

In the reference [9], it is also pointed out that the BS current in the inward-shifted configuration originates from the toroidally oscillating trapped particles, and one in the outward-shifted configuration is from the poloidally oscillating trapped particles. Thus, in the BS current studies in LHD so far conducted, the larger magnetic axis effect was mainly studied together with the geometrical factor and collisionality.

On the other hand, it is theoretically shown in Fig. 2(a) in Reference [6] and in Fig. 1 in Reference [9] that the geometrical factor of the BS current in the inward-shifted configuration for $R_{ax} = 3.6$ m is smaller than that for $R_{ax} = 3.75$ m. While this tendency was experimentally seen in Fig. 3 in the reference [10], the BS current in the inward-shifted configuration was not intensively studied theoretically and experimentally. Looking widely, in the inward-shifted configuration (σ -optimization) in stellarators, it is well known that a single particle does not drift radially and stays on the magnetic surface (Omnigenity) [11][12]. Also, the inward-shifted configuration provided better confinement as demonstrated in the LHD experiments [13][14] and theoretical studies [15-18] which is suitable for reactor operation due to a small radial drift. If we take a different view, suppression of the radial drift motion could lead to the BS current reduction because the BS current is originated from the radial drift motion of the toroidally oscillating trapped electrons, namely the trapped banana particles (or blocked particles) with bounce motion. Based on this concept, we have conducted BS current experiments in LHD with inward-shifted configurations in the $1/\nu$ and plateau regimes. This concept was also pointed out by Helander and Nührenberg [19] that the bootstrap current and neoclassical transport are simultaneously minimized in a stellarator optimization.

So far, we have made experiments of BS current in LHD in the $1/\nu$ regime corresponding to the high temperature and low-density regime, and in the plateau regime to the low temperature and high-density regime, for various parameters under the two or three NBI injectors. To compare the BS

current in the different configurations, experiments were performed on the same day to reduce the uncertainty. Therefore, we conducted comparative experiments using the same magnetic field with the completely balanced NBI injection power for the different magnetic axis configurations. Here, we present the experimental results on the BS currents for comparison with the case of $R_{ax} = 3.75$ m and $R_{ax} = 3.53$ m. Finally, BS current experiments for $R_{ax} = 3.6$ m, which were conducted in a different year but the under the completely balanced NBI injection, are also presented for comparison.

In Section 2, experimental conditions are described. In Section 3, the method of experimental data analysis, such as estimation method of the bootstrap current, the definition of the collisionality parameter ν^* and the coefficient of the BS current are presented. In Section 4, observed discharge waveforms for $R_{ax} = 3.75$ m, 3.53 m, and 3.6 m configurations are presented. In Section 5, various plasma parameters vs collisionality parameter obtained in experiments are shown for the inward-shifted configuration with $R_{ax} = 3.6$ m, standard configuration with $R_{ax} = 3.75$ m and neoclassically optimized configuration with $R_{ax} = 3.53$ m. In Section 6, a comparison of the confinement times for the two configurations is presented. In Section 7, comparison of BS current coefficients for three configurations are described. In Section 8, the $1/\nu$ and plateau regimes on Plasma Operating Contour Map (POPCON) [20] is presented for the FFHR helical fusion reactor [21]. Finally, the discussion and summary are presented in Section 9.

2. Experimental conditions

Operation parameters used in LHD experiments are the negative toroidal field polarity with $B_t = -2.64$ T, the plasma shape parameter of $B_q = 100$ % means the circular average cross-section of the flux surface over one field period, and the helical pitch parameter is $\gamma = (m/\ell)(a_c/R) = 1.254$ for $R_{ax} = 3.75$ m, 3.6 m and 3.53 m. Hydrogen gas was used as the working gas, and experiments were done at the end of the experimental campaign. Tangentially injected NBI-2 (Clock-Wise/CW) and NBI-3 (Counter Clock Wise/ CCW) (detailed is shown in Fig. 1) have been used for balanced injection with NBI duration time more than 3 sec, which is needed to estimate the steady state BS current at least. Density and NBI power are scanned during experiments. The plateau regime ($\nu^* > 1$) needs the central density of more than $2 \sim 3 \times 10^{19} \text{ m}^{-3}$. Here ν^* is the so-called the collisionality parameter, where $\nu^* = 1$ corresponds to the normalized collision frequency at the boundary between the $1/\nu$ and the plateau regimes.

Three NBI and ECRH (electron cyclotron resonance heating) power injection patterns are prepared as

- (A group) NBI-2 (~ 1.5 MW) + NBI-3 (~ 1.5 MW),
- (B group) NBI-2 (~ 3 MW) + NBI-3 (~ 3 MW),
- (C group) NBI-2 (~ 1.5 MW) + NBI-3 (~ 1.5 MW) + ECRH.

This is because that the BS current depends on the injection power through the pressure gradient , which is roughly proportional to the injection power. Experimental conditions and shot numbers are described in Table 1.

Table 1 Experimental condition and shot number

Configuration	Shot number
$R_{ax} = 3.60$ m, $B_t = +2.75$ T, $B_q = 100$ %, and $\gamma = 1.254$	#177820 ~ #177837
$R_{ax} = 3.53$ m, $B_t = -2.64$ T, $B_q = 100$ %, and $\gamma = 1.254$	#186833 ~ #186858
$R_{ax} = 3.75$ m, $B_t = -2.64$ T, $B_q = 100$ %, and $\gamma = 1.254$	#186862 ~ #186895

We note that we omit the cases of off normal events such as NBI injection failure and so on. We briefly describe NBI injection geometry and define the direction of B_t and plasma current in Fig. 1. Negative polarity of $B_t = -2.75$ T and $I_p = -10$ kA indicate the CW direction of B_t and the plasma current, respectively. As NBI-2 drives the CW plasma current and NBI-3 drives the CCW plasma current, balanced injection makes zero plasma current driven by NBIs.

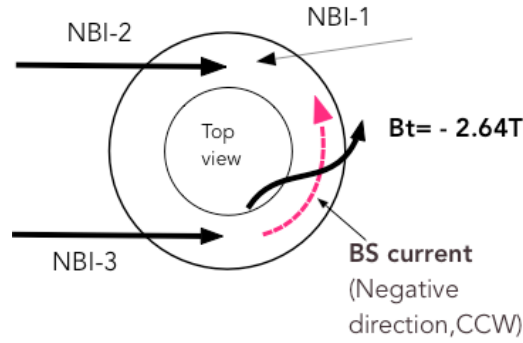


Fig. 1. NBI-2 and NBI-3 layout and definition of the polarity of B_t and the BS plasma current for the negative toroidal field of $B_t = -2.64$ T

3. Method of experimental data analysis

3.1. Estimation of Bootstrap current

As the measured plasma current is not a bootstrap current, the bootstrap current should be estimated by the following plasma circuit equation (Eq. (1)) without the induction effect by the Poloidal Field (PF) coils. Even when the constant BS current flows, the measured plasma current slowly increases with the decay time of $\tau = L_p/R_p$ due to the shielding current in the plasma.

Therefore, the plasma current eventually reflects the BS current after a long time for example ~ 3 s in LHD, which needs a long pulse of NBI injection.

$$L_p \frac{dI_p}{dt} + R_p (I_p - I_{BS}) = 0 \quad (1)$$

where I_p is the measured plasma current, I_{BS} is the assumed bootstrap current, L_p is the plasma self-inductance and R_p is the plasma resistance which is calculated from the measured T_e . The plasma inductance L_p is given by

$$L_p = \mu_o R \left(\log \frac{8R}{a_o} + \frac{\ell_i}{2} - 2 \right)$$

The internal inductance of $\ell_i = 0.5$ is assumed [10] and the average plasma minor radius is $a_o = 0.6$ m, and the major radius is $R = R_{ax}$ [22]. The plasma resistance R_p is estimated by the neoclassical plasma resistivity,

$$\eta = A_\eta \eta_\parallel = \frac{1 + 0.471\sqrt{\varepsilon}}{(1 - \sqrt{\varepsilon})(1 + 0.039\sqrt{\varepsilon})} \eta_\parallel$$

where the coefficient A_η is from the reference [10] and the Spitzer resistivity $\eta_\parallel$ is expressed as

$$\eta_\parallel = 1.65 \times 10^{-9} \frac{Z_{eff} \ln \Lambda}{T_e [\text{keV}]^{1.5}} [\Omega\text{m}]$$

For the assumed temperature profile throughout this paper

$$T_e(r) = T_e(0)(1 - (r/a_o)^2)^{\alpha_r}$$

the neoclassical plasma resistivity is now simply given by

$$\eta = A_\eta \eta_\parallel = \frac{A_{\eta 0}}{T_e(r)^{1.5}} \quad \text{with} \quad A_{\eta 0} = \frac{1 + 0.471\sqrt{\varepsilon}}{(1 - \sqrt{\varepsilon})(1 + 0.039\sqrt{\varepsilon})} 1.65 \times 10^{-9} Z_{eff} \ln \Lambda$$

Then, the plasma resistance is

$$R_p = \frac{2\pi R}{\int \frac{2\pi r}{\eta(r)} dr} = \frac{2\pi R}{\int \frac{2\pi r}{A_{\eta 0}} T_e(r)^{1.5} dr} = \frac{A_{\eta 0} 2\pi R}{T_e(0)^{1.5} \pi a_o^2 \int_0^1 (1 - x^2)^{1.5\alpha_r} 2x dx} = \frac{(1 + 1.5\alpha_r) A_{\eta 0}}{T_e(0)^{1.5}} \frac{2\pi R}{\pi a_o^2}$$

We have used two type of methods to derive the BS current. The first one is the direct method obtained by Eq. (1) as with the experimental results.

$$I_{BS} = \frac{L_p}{R_p} \frac{dI_p}{dt} + I_p \quad (2)$$

Here, the differential value of dI_p/dt is calculated from the measured plasma current I_p , which is filtered to smooth the waveform.

The second method is the iterative method. For the assumed bootstrap current, the plasma current is calculated using Eq. (1). When the calculated plasma current waveform is fitted with the measured plasma current, iteration is finished.

Example of typical discharge waveforms for $R_{ax} = 3.75$ m is shown in Fig. 2. Figure 2(a), (b), (c), (d), (e), (f), (g) and (h) show the plasma current, the port through heating power, the dI_p/dt , the line averaged electron density by FIR, the L_p/R_p evaluated using the expressions as shown in this section, the central electron temperature by the Thomson scattering system, the electron temperature and the electron density profiles by the Thomson scattering system. The plasma current increases to the negative direction, the NBI injected power is a total of 3 MW, the line density is close to $4 \times 10^{19} \text{ m}^{-3}$, the peak electron temperature is around 1.5 keV, the L_p/R_p time is 3 sec, which is comparable to the NBI injection pulse. As dI_p/dt is actually fluctuating as shown in Fig. 2(c), the low pass filter is used to derive the bootstrap current. After filtering, the BS current estimated by the first method is obtained as shown in Fig. 2(i). The BS current estimated by the second method is shown in Fig. 2(j). As those two methods provide similar results (Fig. 2(j)), we use the second method which can provide a constant value. Note that in the discharge #186864, one NB injector is shortly broken down before $t = 6.0$ s, then the estimated BS current changes before and after $t \sim 6.0$ s. However, as the electron temperature and the density profile are almost constant between $t = 4.2$ s, and 5.9 s, the BS current at $t = 5.9$ s is evaluated as the BS current of this discharge.

Rax=3.75 m , Bt=-2.64 T #186864

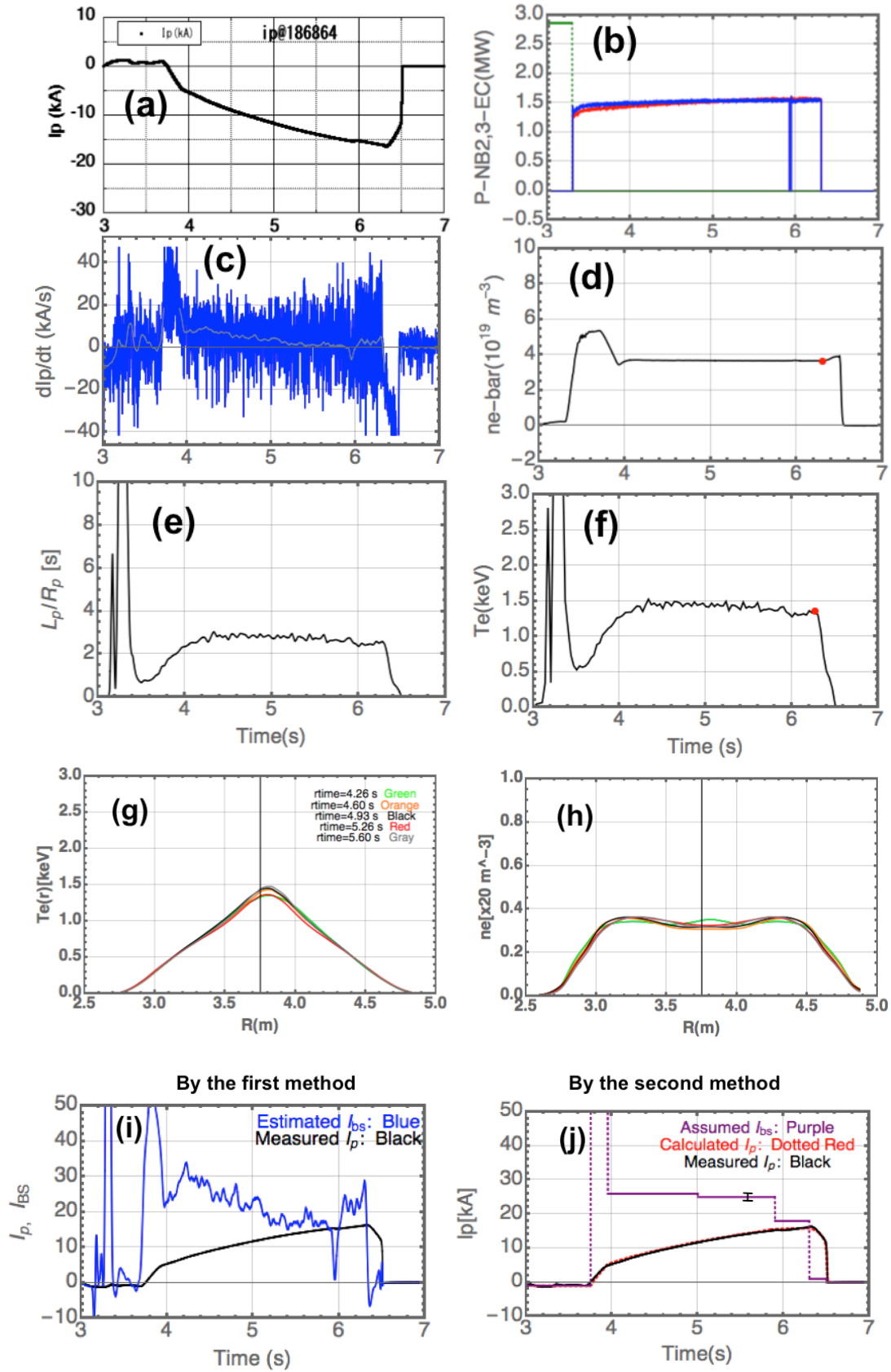


Fig. 2 Discharge waveforms in LHD experiments for derivation of the bootstrap current. (a) The measured plasma current by the Rogowskii coil, (b) NBI-2 (Red), NBI-3 (Blue), ECH (Green) injection power, (c) dI_p/dt derived from I_p waveform, (d) line density measured by FIR interferometer, (e) L_p/R_p calculated by device parameters, and (f) peak electron temperature T_e measured by Thomson scattering, (g) temperature profile by the Thomson scattering, provided by fitting results for Thomson data by neural network variational bayes method. (h) density profile by the Thomson scattering, the measured time is the same as (g), (i) BS current derived by the first method, and (j) BS current estimated by the second method. Error bar of the BS current estimation is shown by " $\pm$ " on the BS current trace.

We note that the difference between the calculated and measured plasma current is within ± 0.2 kA, leading to the final estimation error of the BS current less than ± 1 kA at most. The error bar is shown in Fig. 2(j).

3.2. Collisionality parameter ν^*

The regimes, such as the $1/\nu$ and plateau regimes, can be defined by the collisionality parameter ν^* , which depends on the density, temperature, helical ripple and rotational transform.

For the parallel electron velocity along the magnetic field $V_{e\parallel}(r)$, the half-bounce frequency of the trapped electron bouncing between the connection length $L = R_o / \iota = qR_o$ is given by

$$\nu_p(r) = \frac{V_{e\parallel}(r)}{L} = \frac{\iota V_{e\parallel}(r)}{R_o} = \frac{V_{e\parallel}(r)}{qR_o}$$

where ι is the normalized rotational transform and q is the safety factor. If the helical ripple ε_h is larger than the inverse aspect ratio ε_i , the trapped electron changes the direction more frequently, leading to the larger effective collision frequency $\nu_{eff} = \nu / \varepsilon_h$. Here, ν is a collision frequency. If this larger effective collision frequency is smaller than the bounce frequency,

$$\nu_{eff} = \frac{\nu}{\varepsilon_h} < \nu_p = \frac{V_{e\parallel}}{qR_o} < \frac{\sqrt{\varepsilon_h} V_{e\perp}}{qR_o}$$

where the trapped particles satisfy the condition of $V_{e\parallel} < \sqrt{\varepsilon_h} V_{e\perp}$ with $V_{e\perp}$ being the perpendicular velocity, particles can bounce in the banana regime. To take the wider banana regime, we use the larger value V_e in this inequality, as commonly used

$$\frac{\nu}{\varepsilon_h} < \frac{\sqrt{\varepsilon_h} V_e}{qR_o}$$

Note that $V_e = \sqrt{V_{e\perp}^2 + V_{e\parallel}^2} \geq V_{e\parallel}$ for $V_{e\parallel}^2 / V_{e\perp}^2 < \varepsilon_h$. The frequency boundary between the $1/\nu$ and the plateau regimes is now given by

$$\nu_{eq} = \nu = \frac{\varepsilon_h^{1.5} V_e}{qR_o} = \frac{\varepsilon_h^{1.5} \iota V_e}{R_o}$$

The collisionality parameter is thus defined by the ratio of electron-ion collision frequency ν_{ei} to ν_{eq}

$$v^* = \frac{v_{ei}}{v_{eq}} \quad (3)$$

Its denominator including the profile effect is given by

$$v_{eq}(r) = \varepsilon_h(r)^{1.5} v_p(r) = \varepsilon_h(r)^{1.5} \frac{\tau(r)}{R_o} V_e(r) \quad (4)$$

Here, as the normalized rotational transform depends on the magnetic axis as described below which is given by HSD code [23].

$$\tau_{3.53}(r) = 0.410735 + 0.380345(r/a_o) - 0.98015(r/a_o)^2 + 1.543451(r/a_o)^3 \quad (5-1)$$

$$\tau_{3.60}(r) = 0.362731 + 0.332291(r/a_o) - 0.783479(r/a_o)^2 + 1.40294(r/a_o)^3 \quad (5-2)$$

$$\tau_{3.75}(r) = 0.320147 + 0.329512(r/a_o) - 0.706686(r/a_o)^2 + 1.33925(r/a_o)^3 \quad (5-3)$$

with a_o being the effective minor radius. The rotational transform gets larger when the magnetic axis is shifted inwardly from $R_{ax} = 3.75$ m to $R_{ax} = 3.53$ m.

The helical ripple profile is given by VMEC (NEWBOZ) [24, 25] as follows.

$$\varepsilon_{h3.53}(r) = 0.030131(r/a_o) + 0.16341(r/a_o)^2 + 0.078243(r/a_o)^3 \quad (6-1)$$

$$\varepsilon_{h3.60}(r) = 0.041189(r/a_o) + 0.094354(r/a_o)^2 + 0.17858(r/a_o)^3 \quad (6-2)$$

$$\varepsilon_{h3.75}(r) = 0.026726(r/a_o) + 0.085387(r/a_o)^2 + 0.15026(r/a_o)^3 \quad (6-3)$$

The helical ripple at $r/a_o = 1$ is largest as $\varepsilon_h = 0.27$ for $R_{ax} = 3.53$ m, $\varepsilon_h = 0.31$ for $R_{ax} = 3.60$ m and $\varepsilon_h = 0.26$ for $R_{ax} = 3.75$ m.

The numerator is given by [26]

$$v_{ei}(r) = 2.90117 \times 10^{-12} \frac{n_e(r) Z_{eff} \ln \Lambda(r)}{T_e(r)^{1.5}} \quad (7)$$

with

$$\ln \Lambda(r) = \log \left[\frac{1.552 \times 10^{13} T_e(r)^{1.5}}{\sqrt{n_e(r)}} \right]$$

As the collisionality parameter depends on the radius r , Eqs. (4) and (7) are combined as

$$v^*(r) = \frac{v_{ei}(r)}{v_{eq}(r)} \quad (3')$$

we take the minimum value as shown in Fig. 3(f). $Z_{eff} = 2$ was used throughout this paper.

The density profiles are assumed as

$$n_e(r) = n_e(0) \left(1 - (r/a_o)^8 \right) = \frac{9}{8} \bar{n}_e \left(1 - (r/a_o)^8 \right) \quad (8)$$

where $\bar{n}$ is the line averaged density. For example of #186864 shot, in the case of the temperature profile $\alpha_T = 1$ and the line density $\bar{n} = 3.67 \times 10^{19} \text{m}^{-3}$, in Fig. 3 are shown the temperature profile $T(r)$, the density profile $n(r)$, the iota profile for $R_{ax} = 3.75$ m, the helical ripple for $R_{ax} = 3.75$ m, the pressure gradient profile dp/dr together with collisionality parameter $\nu^*(r)$ profile. The radial point of the maximum pressure gradient, where the bootstrap current could be maximum, is around $r = 0.5$ m, which is close to the point of the minimum collisionality parameter ν^* . Although the maximum BS current may also depend on the geometric factor, we use the collisionality parameter at the minimum point near 0.45 m for simplicity of the analysis.

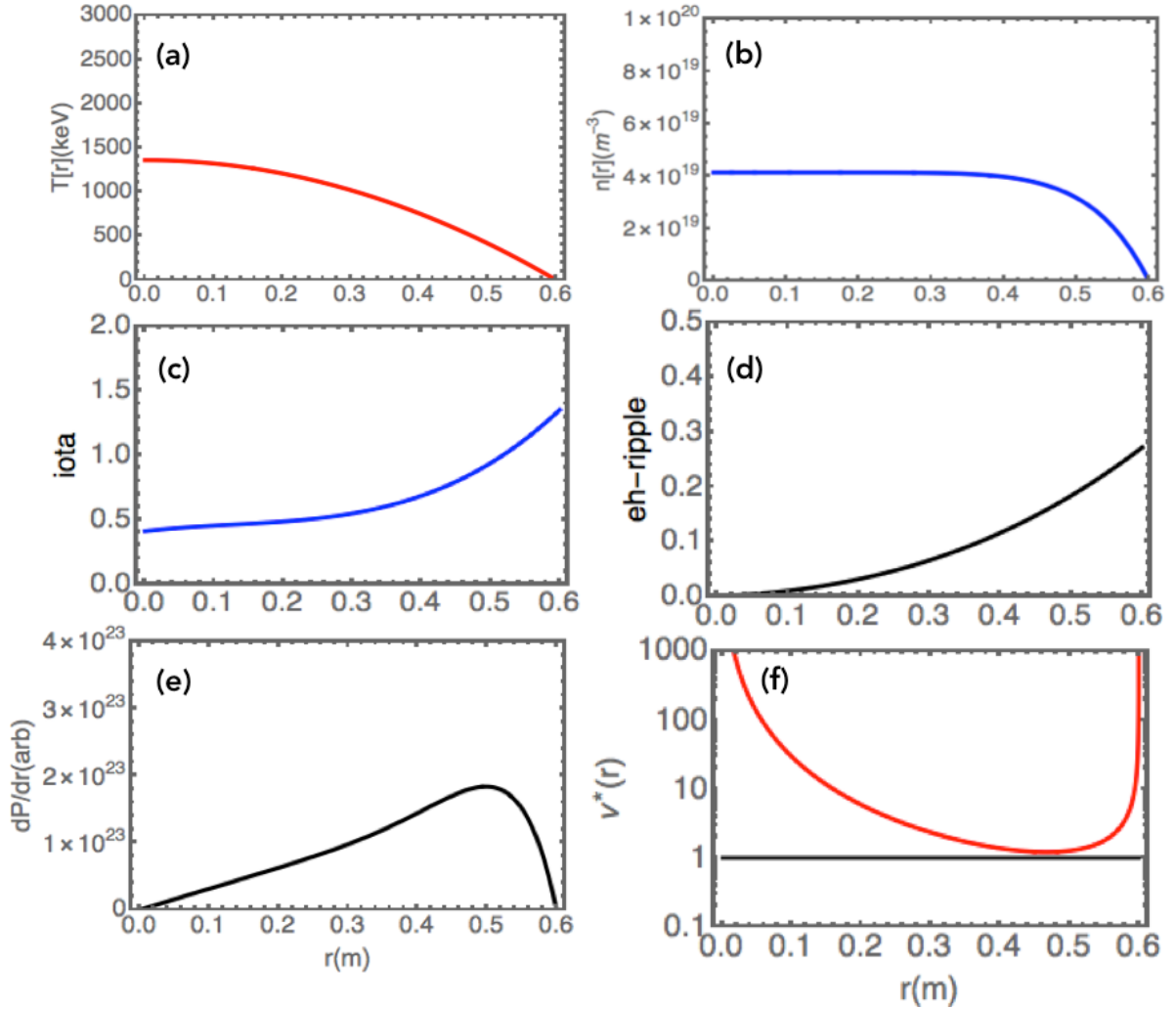


Fig. 3 Parameter profiles used for analysis. (a) The temperature profile, (b) the density profile, (c) the iota profile for $R_{ax} = 3.75$ m, (d) the helical ripple profile for $R_{ax} = 3.75$ m, (e) the pressure gradient profile, and (f) the collisionality parameter ν^* profile for #186864.

3.3. The coefficient of the BS current

The bootstrap current inside the flux surface in the Boozer coordinate $(\psi, \theta_B, \zeta_B)$ is given by Eq. (5) of reference [6]

$$I_{BS} = 2\pi \int \frac{\langle j_{BS} B \rangle}{\langle B^2 \rangle} d\psi \sim \frac{2\pi}{B_t^2} \int \langle j_{BS} B \rangle d\psi \quad (9)$$

As the BS current density J_{BS} is simply expressed by the pressure gradient with the geometric factor G_{bs} , Eq.(1) of reference [6] provides

$$\langle J_{BS} B \rangle = -G_{bs} \frac{dp}{d\psi} \quad (10)$$

where G_{bs} is the geometric factor, which has a dimension of [Weber/m], p is the plasma pressure, which is the driving force of the BS current. To compare the geometric factor in the BS current for various LHD configurations, we normalize the geometric factor by the tokamaks (axisymmetric) one [9][18] as given by

$$G_{BS-Tok} = \frac{\mu_o I_{pol}}{2\pi \mathfrak{r}} \quad (11)$$

where μ_o is the vacuum magnetic permeability, and I_{pol} is the poloidal current outside of a magnetic surface given by

$$B_t = \frac{\mu_o I_{pol}}{2\pi R}$$

Using the non-dimensional geometric factor $\widehat{G}_{bs}$, the BS current density is expressed by

$$\langle J_{BS} B \rangle = -G_{BS-Tok} \widehat{G}_{bs} \frac{dp}{d\psi} = -\frac{\mu_o I_{pol}}{2\pi \mathfrak{r}} \widehat{G}_{bs} \frac{dp}{d\psi} \quad (10')$$

With this expression, the total BS current in the helical system (Eq. (9)) is

$$\begin{aligned} I_{BS} &= -\frac{2\pi}{B_t^2} \int \frac{\mu_o I_{pol}}{2\pi \mathfrak{r}} \widehat{G}_{bs} \frac{dp}{d\psi} d\psi = -\frac{\mu_o I_{pol}}{B_t^2} \int_{p(0)}^{p(a)} \left(\frac{\widehat{G}_{bs}}{\mathfrak{r}} \right) dp = \frac{2\pi R B_t}{B_t^2} \left(\frac{\widehat{G}_{bs}}{\mathfrak{r}} \right)_{int_p} p(0) \\ &= \frac{0.5 p(0)}{(B_t^2 / 2\mu_o)} \left(\frac{2\pi R B_t}{\mu_o} \right) \left(\frac{\widehat{G}_{bs}}{\mathfrak{r}} \right)_{int_p} = 0.5 \beta_t(0) I_{pol} \left(\frac{\widehat{G}_{bs}}{\mathfrak{r}} \right)_{int_p} \end{aligned} \quad (12)$$

where the BS current coefficient is defined by

$$\left(\frac{\widehat{G}_{bs}}{\mathfrak{r}} \right)_{int_p} \equiv \int_{p(0)}^{p(a)} \left(\frac{\widehat{G}_{bs}}{\mathfrak{r}} \right) dp / \int_{p(0)}^{p(a)} dp = - \int_{p(0)}^{p(a)} \left(\frac{\widehat{G}_{bs}}{\mathfrak{r}} \right) dp / p(0)$$

with $p(0)$ being the peak pressure and the peak beta value given by $\beta_t(0) \equiv p(0) / (B_t^2 / 2\mu_o)$. The non-dimensional BS current coefficient is now obtained as [9]

$$\left(\frac{\widehat{G}_{bs}}{\mathfrak{r}} \right)_{int_p} = \frac{I_{BS}}{0.5 \beta_t(0) I_{pol}} = \frac{\mu_o I_{BS}}{0.5 \beta_t(0) (2\pi R B_t)} \quad (13)$$

This BS current coefficient is calculated using experimental data for comparison of the BS currents among the LHD different configurations. Here, to use the experimentally obtained volume averaged beta β_t (diamagnetic beta value β_t), the profile factor $f_p = 2.142$ in the relation $\beta(0) = f_p \langle \beta \rangle$ was used for conversion. This is obtained by integration of the product Eq. (9) and the parabolic temperature profile. We expect that this coefficient is a decreasing function with collisionality parameters.

4. Discharge waveforms for three configurations

To see the difference in the BS current for $R_{ax} = 3.75$ m, 3.53 m, and 3.6 m configurations, typical discharge waveforms are shown here. Two tangential injectors of NBI are completely balanced.

4.1. Higher density case for $R_{ax} = 3.75$ m and $R_{ax} = 3.53$ m configurations

Discharge waveforms for higher density of $n \sim 5 \times 10^{19} \text{ m}^{-3}$ are shown in Fig. 4 for $R_{ax} = 3.75$ m and in Fig. 5 for $R_{ax} = 3.53$ m. The peak electron temperature $T_e \sim 1.2$ keV, the toroidal beta $\beta_t \sim 0.4$ % (plasma energy $W_p \sim 400$ kJ), and the total NBI injection power of ~ 3 MW, which are almost the same range as shown in Figs. 4 and 5. Although the peak pressures (Fig. 4(f) and Fig 5(f)) are also the same, it is clearly seen that the observed plasma current at the end of NBI injection is 11.7 kA for $R_{ax} = 3.75$ m and 2.93 kA for $R_{ax} = 3.53$ m. The estimated BS currents differ as $I_{BS} \sim 16$ kA for $R_{ax} = 3.75$ m and $I_{BS} \sim 5$ kA for $R_{ax} = 3.53$ m. Thus, the inward-shifted plasma configuration clearly shows the lower BS current. We note that although ECRH power is applied after shutdown of NBI for further study, it does not affect the results.

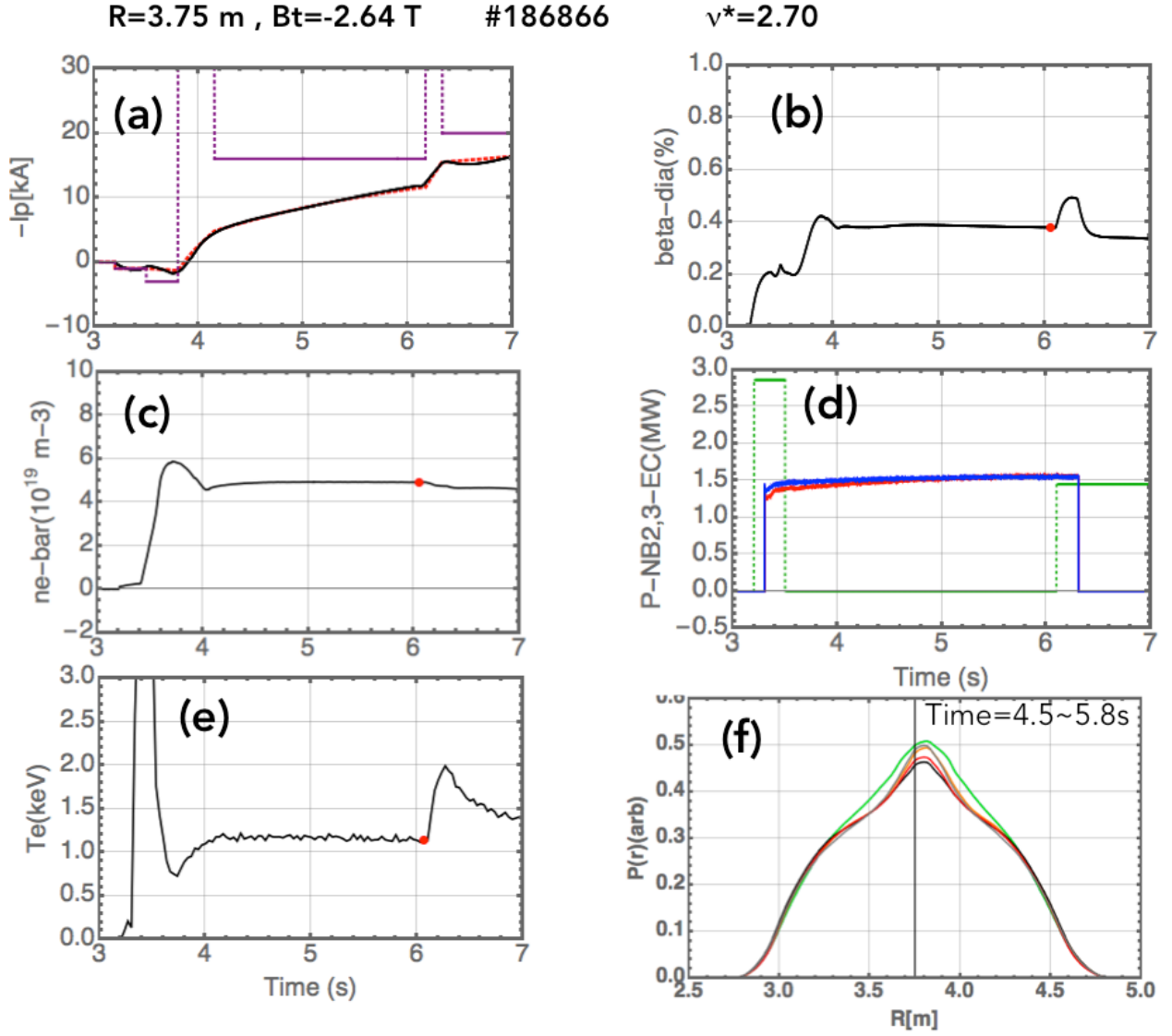


Fig. 4 Discharge behavior for $R_{ax}=3.75\text{ m}$ configuration with the higher density. ν^* value is at the end of the NBI injection indicated by the small red circle. (a) Observed plasma current waveform (Black) and estimated BS current (Purple), (b) diamagnetic beta value, (c) line-averaged density, (d) NBI-2 (Red), NBI-3 (Blue), ECH (Green) injection power, (e) peak electron temperature, and (f) Pressure profile.

$R_{ax}=3.53 \text{ m}$, $B_t=-2.64 \text{ T}$

#186836

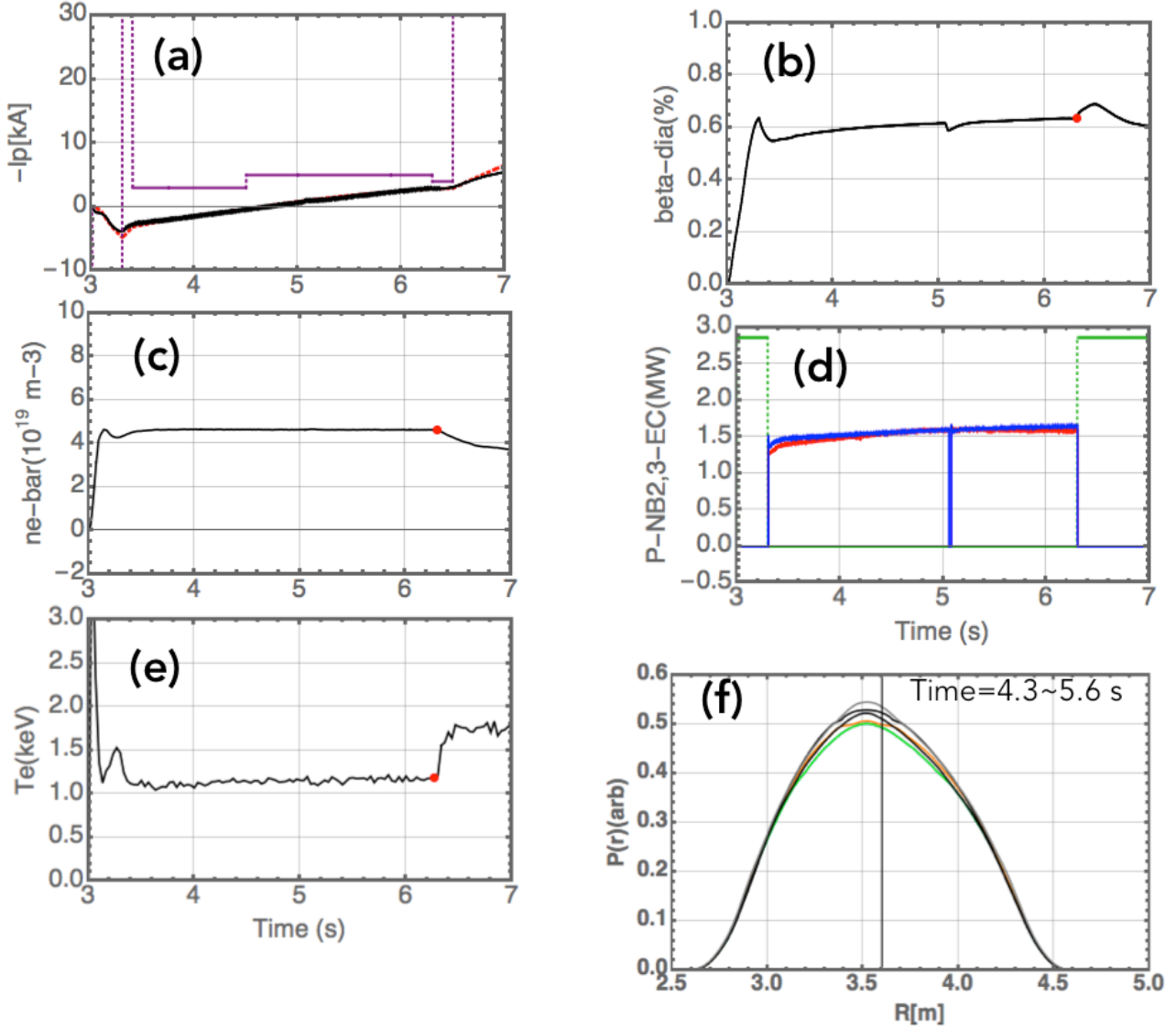
 $\nu^*=1.85$


Fig. 5 Discharge behavior for $R_{ax} = 3.53 \text{ m}$ configuration with the higher density. (a) -(f) are the same as in Fig. 4.

We note that the initial plasma current direction for $R_{ax} = 3.53 \text{ m}$ is clearly opposite to the later phase and as large as -4 kA larger than that for $R_{ax} = 3.75 \text{ m}$ in Fig. 4, which may be caused by the initial ECRH power of 2.8 MW during the low-density phase [6+1][26+1]. This tendency has been remarkably observed in the inward-shifted configuration.

4.2. Lower density case for $R_{ax} = 3.75 \text{ m}$ and $R_{ax} = 3.53 \text{ m}$ configurations

The discharge waveforms in the lower-density regime $n \sim 2 \times 10^{19} \text{ m}^{-3}$ are shown in Fig. 6 for $R_{ax} = 3.75 \text{ m}$ and in Fig. 7 for $R_{ax} = 3.53 \text{ m}$. Corresponding parameters are the peak electron temperature $T_e = 1.7 \text{ keV}$ and 1.3 keV , the toroidal beta $\beta_t = 0.22 \%$ and 0.4% (plasma energy $W_p = 200 \text{ kJ}$ and 300 kJ), respectively, for the same total NBI injection power of $\sim 2.6 \text{ MW}$. The observed plasma

currents at the end of the NBI injection phase are 14.0 kA for $R_{ax} = 3.75$ m and 4.2 kA for $R_{ax} = 3.53$ m, respectively. Thus, the estimated BS currents are $I_{BS} \sim 25$ kA for $R_{ax} = 3.75$ m and $I_{BS} \sim 8$ kA for $R_{ax} = 3.53$ m. Both currents are increased compared to higher density. Thus, the in the same density discharges, the BS currents I_{BS} for $R_{ax} = 3.53$ m are much smaller than those for $R_{ax} = 3.75$ m configuration.

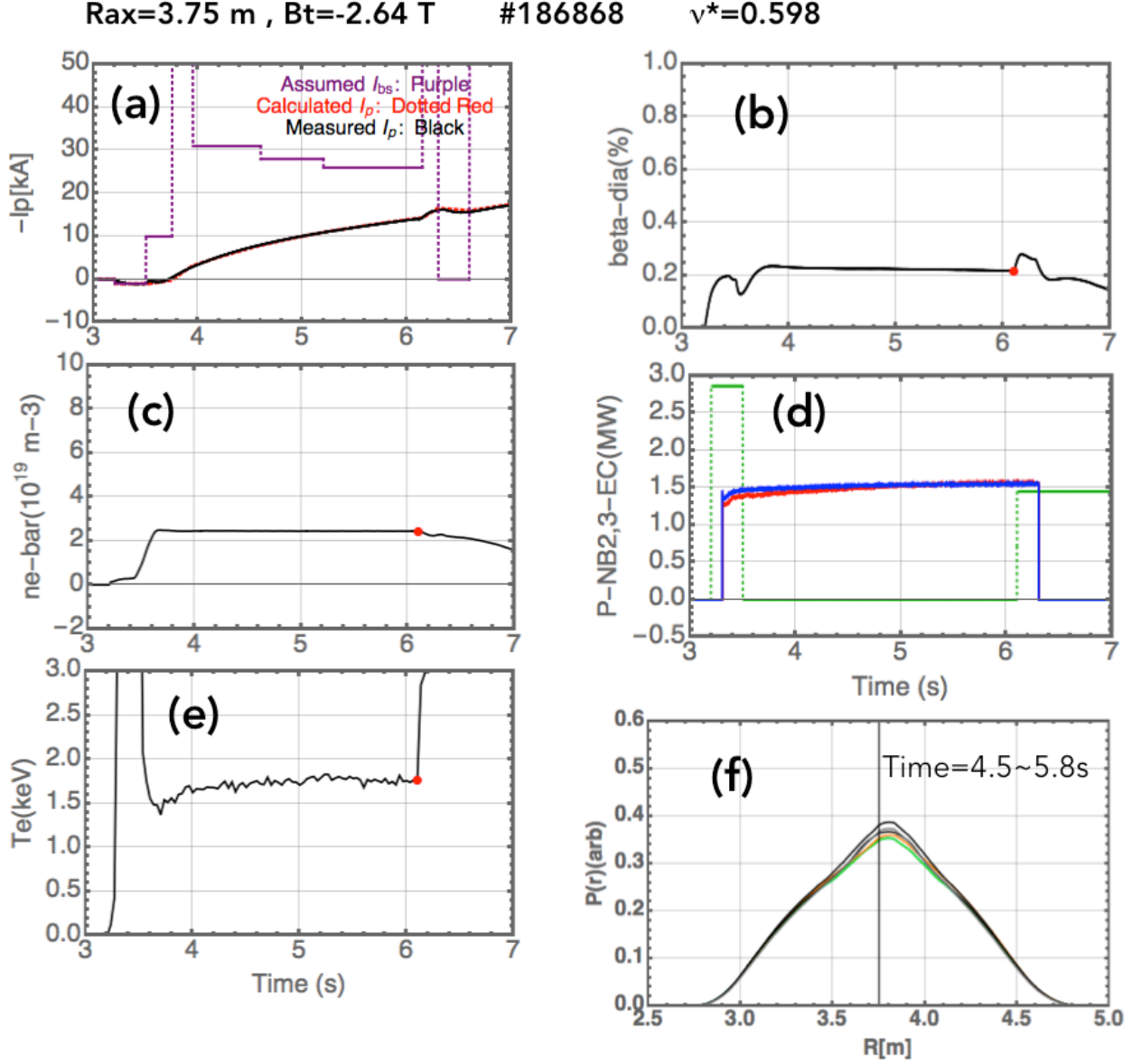


Fig. 6 Discharge behavior for $R_{ax} = 3.75$ m configuration with lower density. (a) -(f) are the same as in Fig. 4.

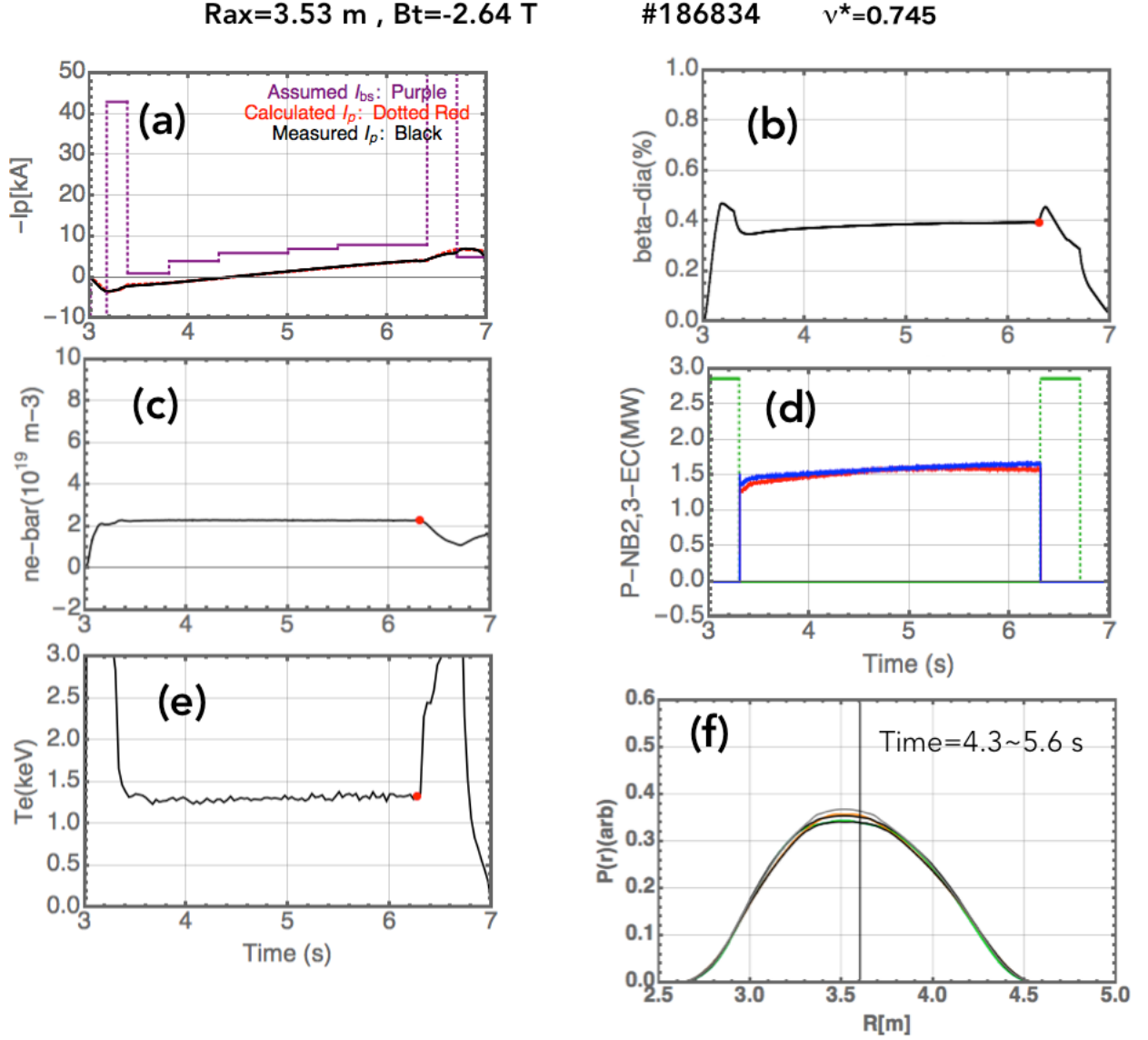


Fig. 7 Discharge behavior for $R_{ax} = 3.53 \text{ m}$ configuration with lower density. (a) -(f) are the same as in Fig. 4.

4.3. Discharge waveforms for $R_{ax} = 3.6 \text{ m}$

While the data of inward-shifted configuration of $R_{ax} = 3.6 \text{ m}$ were taken in an earlier year, the injection powers of NBI-2 ($\sim 1.5 \text{ MW}$) and NBI-3 ($\sim 1.5 \text{ MW}$) were completely balanced and categorized as A-group. The toroidal field is slightly larger as $B_t = +2.75 \text{ T}$ compared to $R_{ax} = 3.75 \text{ m}$ and $R_{ax} = 3.53 \text{ m}$ cases.

Typical discharge waveforms are shown for higher density and lower density in Fig. 8 (left column) and (right column), respectively. Discharge behavior of the high-density (#177825) for $R_{ax} = 3.6 \text{ m}$ in Fig. 8 (left column) is not much different from the high-density discharge (#186866) for $R_{ax} = 3.75 \text{ m}$ in Fig. 4. The BS currents are $I_{BS} \sim 20 \text{ kA}$ ($R_{ax} = 3.6 \text{ m}$) and $I_{BS} \sim 16 \text{ kA}$ ($R_{ax} = 3.75$), respectively.

However, in the lower density discharge, behavior (#177830) for $R_{ax} = 3.6$ m in Fig. 8 (right column) is different from #186868 for $R_{ax} = 3.75$ m in Fig. 6 in spite of similar density. While the electron temperature is as low as 1.7 keV and the beta value is as low as $\beta_t \sim 0.2$ % (the plasma energy ~ 200 kJ) for $R_{ax} = 3.75$ m, the electron temperature is as high as $T_e(0) \sim 2.34$ keV and beta value is as high as $\beta_t \sim 0.3$ % (the plasma energy ~ 300 kJ) for $R_{ax} = 3.6$ m. This is caused by the better confinement time for the $R_{ax}=3.6$ m configuration. A detailed description is given later in Section 5.1.

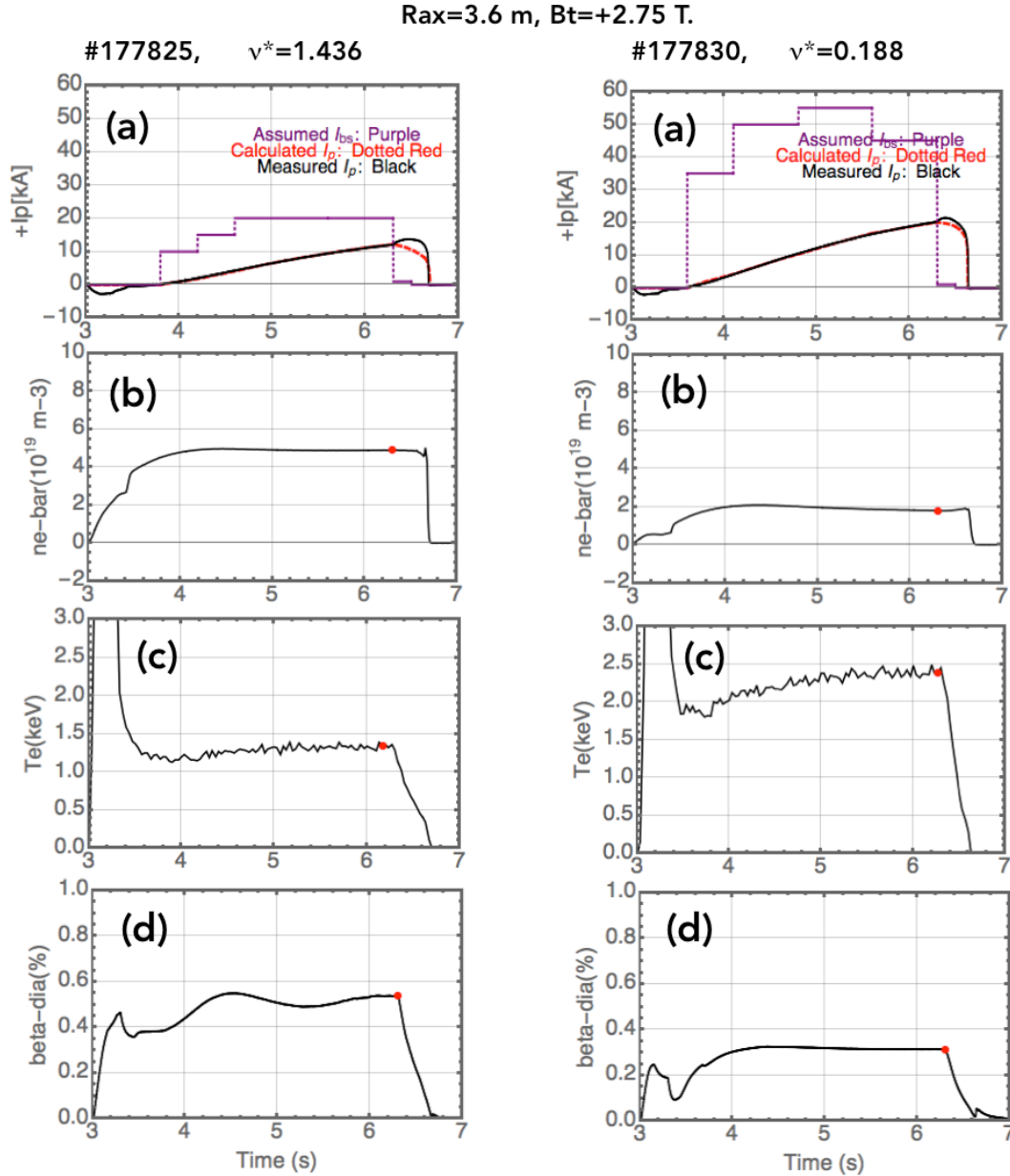


Fig. 8 Discharge behavior for $R_{ax} = 3.6$ m configuration for (Left column) higher density and (Right column) lower density. (a) Observed plasma current waveform (Black) and estimated BS current (Purple), (b) line-averaged density, (c) peak electron temperature, and (d) diamagnetic beta value. ν^* value is at the time indicated by the small red circle.

5. Various plasma parameters vs collisionality parameter

As a reference for the discharge, we have conducted BS current experiments in the standard configuration with $R_{ax} = 3.75$ m, whose discharge waveforms are already shown in Figs. 4 and 6. And on the same day, experiments for $R_{ax} = 3.53$ m were conducted for comparison. However, to understand the logic of experimental analysis, we first show data for $R_{ax} = 3.6$ m together with $R_{ax} = 3.75$ m, which was conducted in an earlier year under the completely balanced injection up to 3 MW. The following shows the data associated with the BS current phenomena.

5.1. The inward-shifted configuration with $R_{ax} = 3.6$ m

Various parameter dependencies for $R_{ax} = 3.6$ m (black triangle) on collisionality parameters ν^* are shown in Fig. 9 together with $R_{ax} = 3.75$ m (red triangle) for quick comparison. Figure (a) shows the observed plasma current just before the NBI stop, (b) the BS current estimated by the 2nd method as shown in Section 3.1, (c) the total absorbed power (P), (d) the volume averaged beta measured by a diamagnetic flux loop, (e) the energy confinement time and (f) the line averaged electron density. Both data are categorized as A-group (~ 3 MW) as shown in Section 2. This comparison leads to a clear understanding of the BS current behaviors. We should note that lower density data less than $n < 2 \times 10^{19} \text{ m}^{-3}$ are omitted in this study as shown in Fig.9(f) because NBI absorbed power is not accurately estimated due to the shine through and prompt loss of beam ions, and it is difficult to estimate the plasma energy consisting of the beam energy.

The BS current estimated in the $1/\nu$ regime is several times larger than the observed plasma current and a few times in the plateau regime, as shown in Fig. 9(a) and (b). While Eq. (12) shows that the BS current is proportional to β_t value, which is equivalent to the plasma pressure, Fig. 9(b) and (d) show the anti-proportionality each other. This fact means the BS current coefficient $\left(\hat{G}/\tau\right)_{int_p}$ in Eq.(12) is a decreasing function with respect to the collisionality parameter ν^* . It is remarkable that β_t value (plasma energy W_p) for $R_{ax} = 3.6$ m is much larger than that for $R_{ax} = 3.75$ m as seen in Fig. 9(d) in the whole regime.

As the total NBI absorbed powers P_{in} are almost the same for both cases (Fig. 9(c)), the confinement times simply estimated by W_p/P_{in} are different and the $R_{ax} = 3.6$ m case has much longer confinement time than that for $R_{ax} = 3.75$ m case in the whole regime as seen in Fig. 9(e). We also see the increase in the electron density with the collisionality parameter ν^* as shown in Fig.9(f).

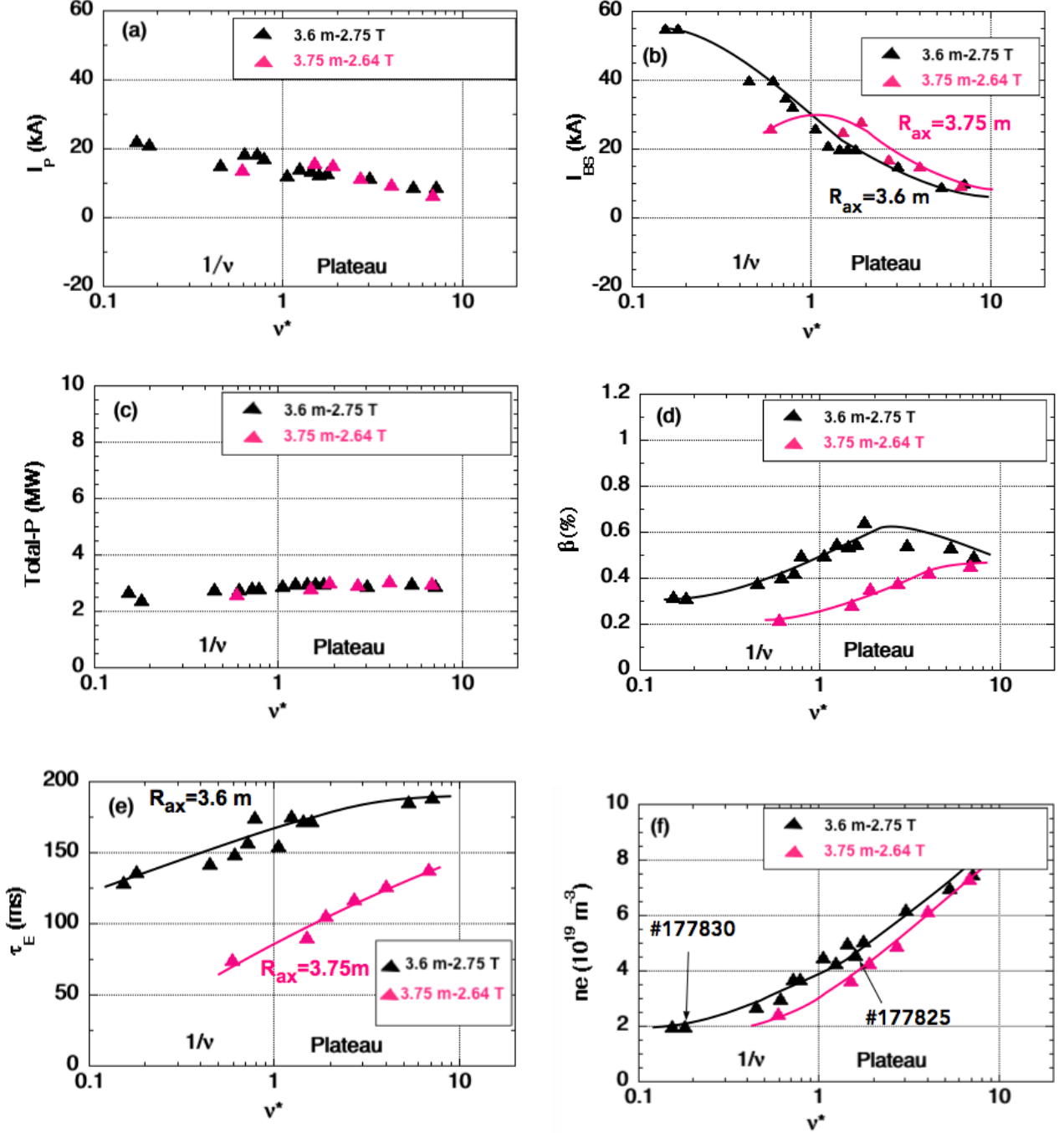


Fig. 9 Dependencies of the plasma parameters on collisionality parameter v^* for $R_{ax} = 3.6$ m (black triangle) together with $R_{ax} = 3.75$ m (red triangle). (a) Observed plasma current I_p just before the NBI stop, (b) estimated bootstrap currents I_{BS} at the end of the NBI heating by the second method shown in Section 3.1, (c) total absorbed power TOTAL-P, (d) the diamagnetic beta value β , (e) estimated confinement time by W_p/P_{in} , and (f) line density n_e with the shot number of Fig 8.

The BS current and β_t value as shown in Fig. 9(b) and (d) provide the BS current coefficient $\left(\widehat{G}/\tau\right)_{int_p}$ using Eq. (13) as shown in Fig. 10. It is seen that the $\left(\widehat{G}/\tau\right)_{int_p}$ is a decreasing function with respect to v^* in both the $1/v$ and plateau regimes for $R_{ax} = 3.6$ m as for $R_{ax} = 3.75$ m.

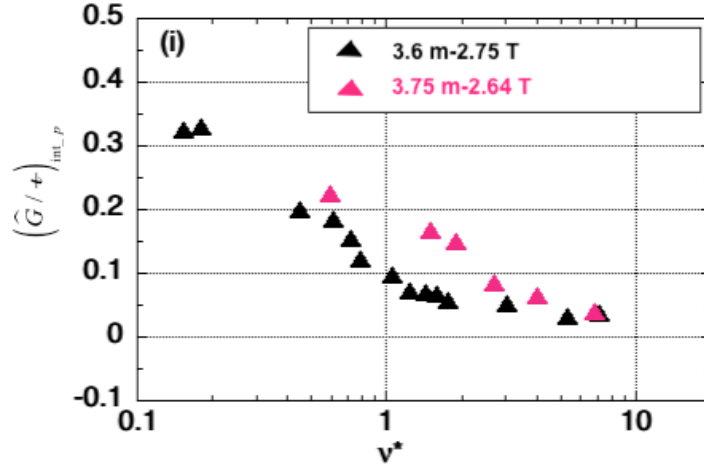
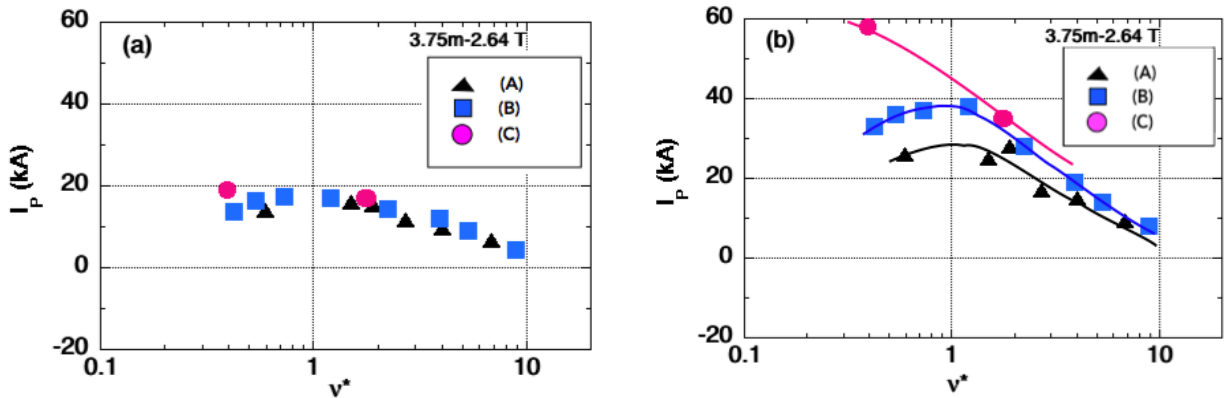


Fig. 10 The coefficient $\left(\hat{G}/\tau\right)_{\text{int},p}$ for the BS current vs collisionality parameter ν^* for $R_{\text{ax}} = 3.6$ m (black triangle) and $R_{\text{ax}} = 3.75$ m (red triangle). Injection power pattern is in A-group.

5.2. Standard configuration with $R_{\text{ax}} = 3.75$ m

As a reference of the discharge, we have made BS current experiments in the standard configuration with $R_{\text{ax}} = 3.75$ m and group (A) whose discharge waveforms are already shown in Figs. 4 and 6. Here we show the data related with the BS current for the NBI heating conditions of group A, B and C (see Section 2).

In Fig. 11(a) and (b), the observed plasma current and the estimated BS current at the end of the NBI heating phase are shown as a function of the collisionality parameter ν^* . The estimated BS current reaches ~ 60 kA in the $1/\nu$ regime. In this standard configuration, the diamagnetic beta values, confinement time, and the electron density increase with the collisionality parameter.



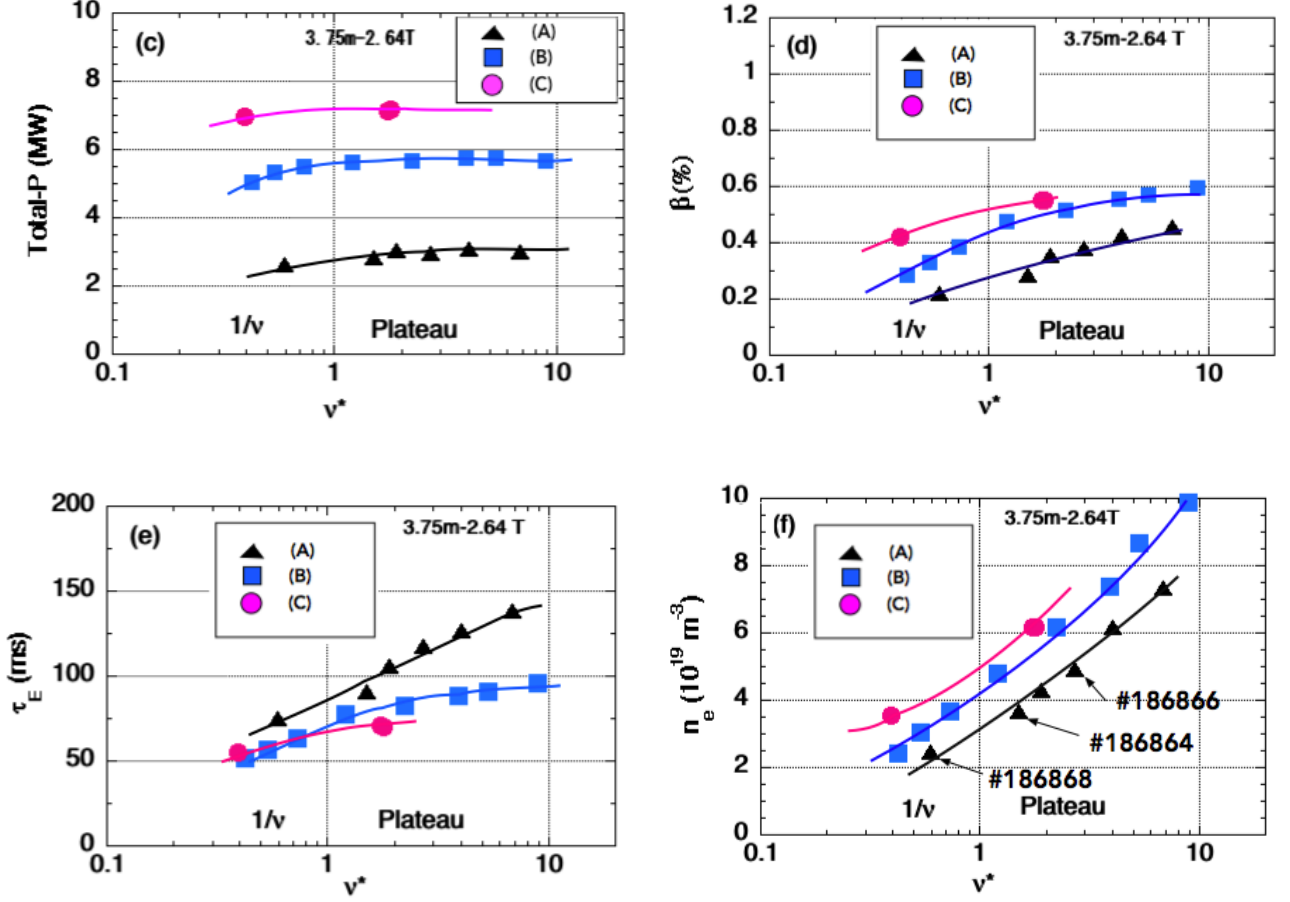


Fig. 11 Various parameter dependencies on collisionality parameter for $R_{ax} = 3.75$ m. (a) Observed plasma current and (b) estimated bootstrap currents and the plasma energy at the end of the NBI heating (c) total absorbed power, (d) the diamagnetic beta, (e) simply estimated confinement time by W_p/P_{in} , and (f) line-density the shot number of Fig. 4 and Fig. 6. Injection power pattern is distinguished by black triangle: A: blue square: B: red circle: C.

Data of the BS current coefficient $\left(\hat{G}/\tau\right)_{int_p}$ is now gathering on a single curve despite the different heating power groups for the range of $v^* > 0.3$ as shown in Fig. 12. Although beta values and bootstrap current are scattered, it is remarkable to find that the coefficient $\left(\hat{G}/\tau\right)_{int_p}$ lies on the single curve in the $1/v$ regime and plateau regime.

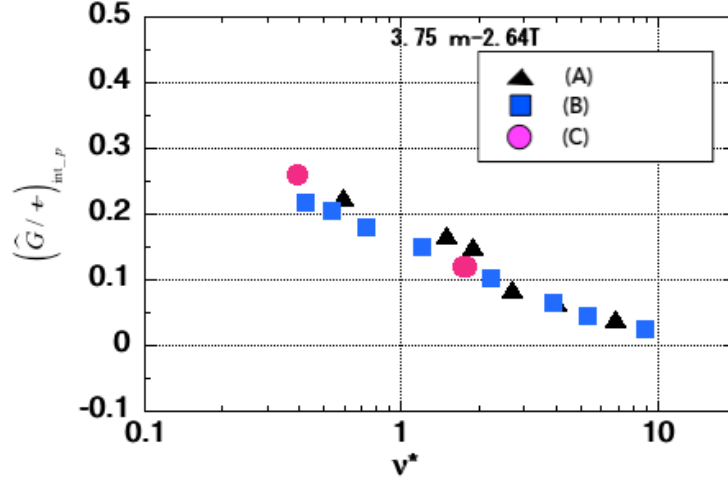
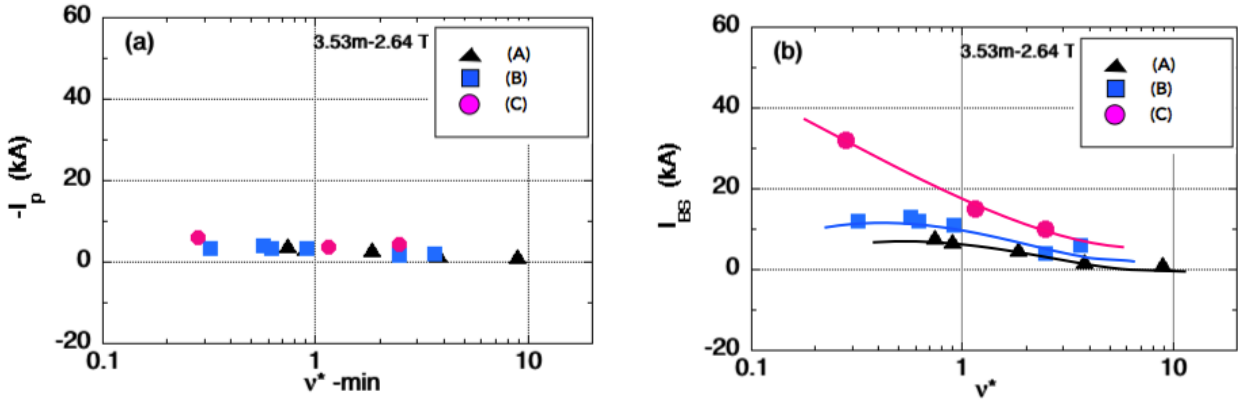


Fig. 12 The coefficient $\left(\hat{G}/+\right)_{int,p}$ for the BS current derived from $R_{ax} = 3.75$ m data vs collisionality parameter. Data encircled by dotted purple circle are discarded for further analysis. Injection power pattern is the same as in Fig. 11.

5.3. The neoclassically optimized configuration with $R_{ax} = 3.53$ m

Among the inward-shifted magnetic axis configurations in LHD, the neoclassically optimized configuration shows the best performance for high energy particle confinement [1][16]. In the neoclassically optimized configuration, the drift surface and magnetic surface almost overlap.

In all discharges with $R_{ax} = 3.53$ m, the observed plasma current at the end of NBI heating phase is less than 6 kA, as shown in Fig. 13-(a), and the corresponding BS current is less than ~ 30 kA as shown in Fig. 13(b). It is clearly shown that the BS current with $R_{ax} = 3.53$ m configuration is smaller. In the plateau regime, the maximum diamagnetic beta is ~ 1.1 % as shown in Fig 13(d), which is clearly larger than maximum value of $\beta_t \sim 0.6\%$ in the $R_{ax} = 3.75$ m case. Therefore, the confinement time in the whole range of v^* tends to be larger in this inward-shifted configuration as shown in Fig 13(c), compared to the standard configuration shown in Fig. 11(e).



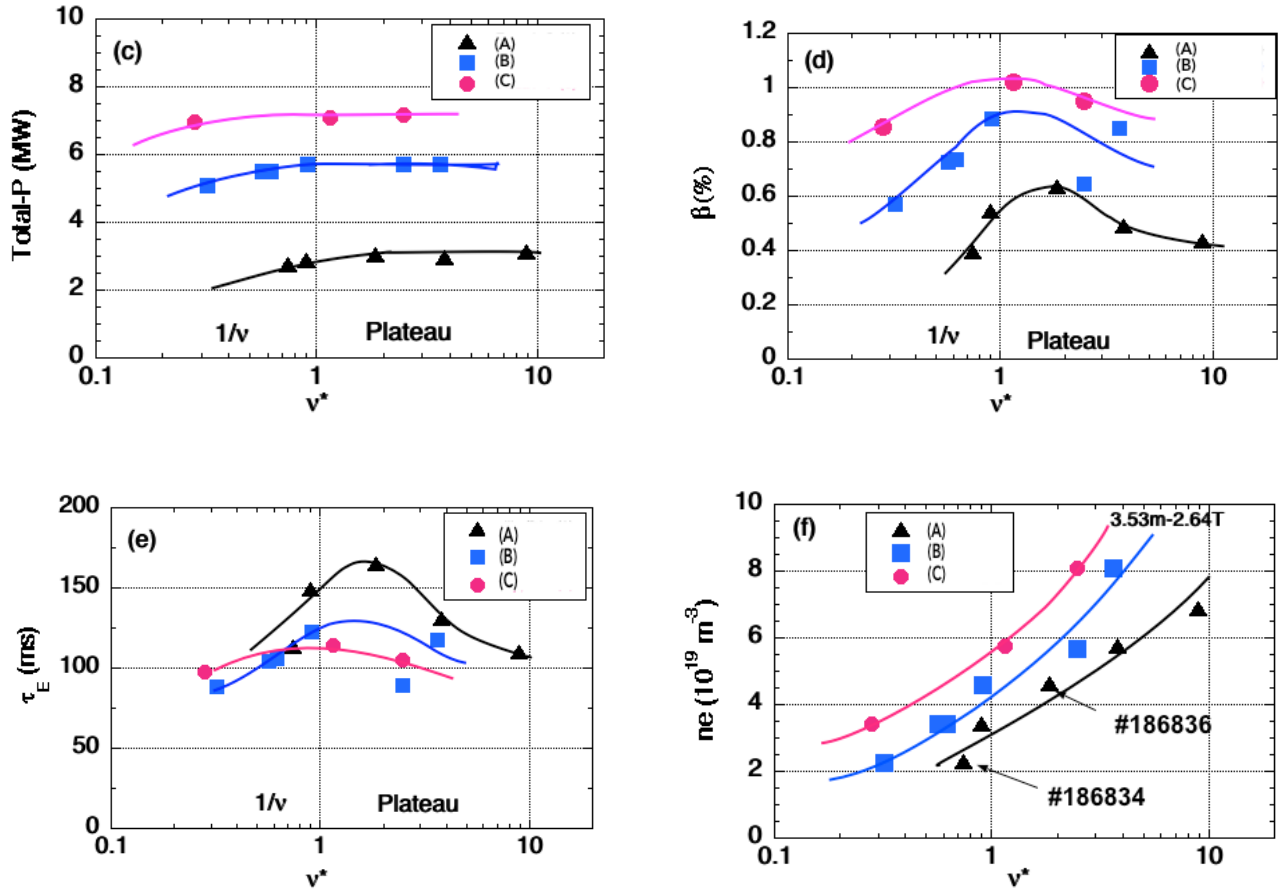


Fig. 13 Various parameter dependencies on collisionality parameter for $R_{ax} = 3.53$ m. (a) Observed plasma current and (b) estimated bootstrap currents and the plasma energy at the end of the NBI heating (c) total absorbed power, (d) the diamagnetic beta, (e) confinement time and (f) line-density with the shot number of Fig. 2, Fig. 4, and Fig. 6. Injection NBI power pattern is the same as in Fig. 11.

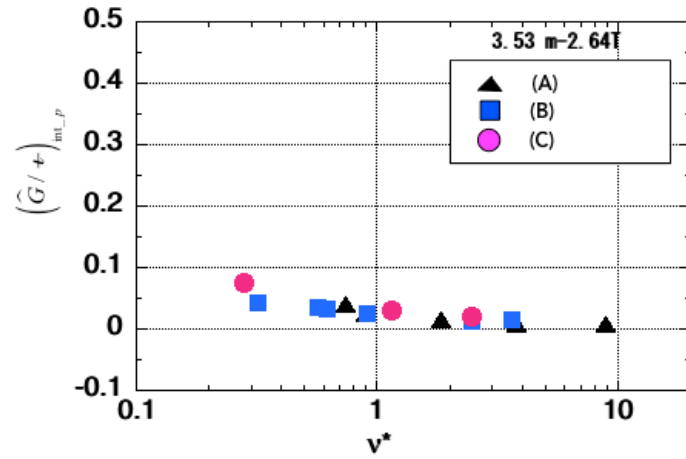


Fig.14 The coefficient $(\hat{G}/\tau)_{int_p}$ for the BS current vs collisionality parameter v^* for $R_{ax} = 3.53$ m.

The BS current coefficient $\left(\widehat{G}/\tau\right)_{\text{int}_p}$ composed of data with three different heating powers is plotted in Fig. 14, which yields a single curve. In the $1/\nu$ regime and plateau regimes, the coefficient $\left(\widehat{G}/\tau\right)_{\text{int}_p}$ shows the decreasing function with collisionality parameter ν^* as in other cases.

6. Comparison of the confinement time for two configurations

It is already demonstrated in LHD that the inward-shifted configuration has a better confinement time [13][14]. As the bootstrap current and neoclassical transport are simultaneously minimized in a stellarator optimization [19], this statement could also be true in the LHD heliotron configuration, as confirmed in these BS current experiments.

The confinement time τ_E is given by the following plasma energy equation

$$\frac{dW_p}{dt} = P_{\text{in}} - \frac{W_p}{\tau_E}$$

which is simply estimated by the plasma stored energy W_p divided by the total absorbed power P_{in} ($\tau_E = W_p/P_{\text{in}}$) when the term dW_p/dt is small. Actually, in these long pulse discharge experiments, $dW_p/dt \sim 0$ is obtained from the β_t data as shown in Fig. 4(b). In Fig. 15, the plasma stored energy W_p vs the total input power P_{in} (Total-P) is shown for each magnetic axis configuration. The confinement time for $R_{\text{ax}} = 3.53$ m is roughly improved by the factor of $W_p = 850$ kJ/580 kJ = 1.46 at $P_{\text{in}} = 8$ MW compared to $R_{\text{ax}} = 3.75$ m. This tendency confirms the previous results in LHD [13], where the inward-shifted configuration has a better confinement time.

If we look at the lower heating power case (A group) ($<$ total power 3 MW) as shown by the black triangle in Fig. 15, it is seen that the plasma energy W_p increases quickly with the density, leading to the confinement time improvement with density. This shows that the confinement scaling has a good density dependence [28].

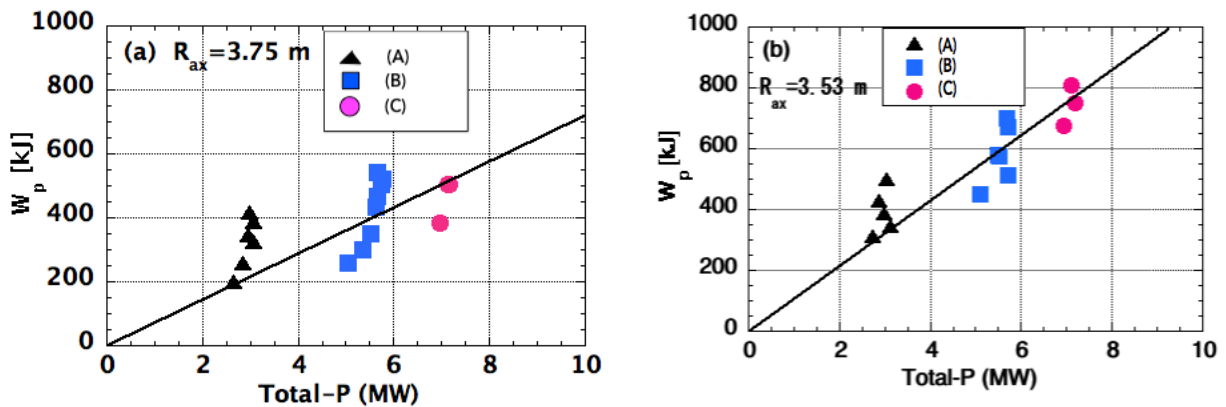


Fig. 15 The plasma energy W_p vs total absorbed NBI power P_{in} for the confinement time estimation. (a) $R_{ax} = 3.75$ m, and (b) $R_{ax} = 3.53$ m. Injection power pattern is distinguished by A group (black triangle), B group (blue square), and C-group (red circle).

7. Comparison of BS current coefficient for three configurations

To compare the BS current coefficient $\left(\hat{G}/\tau\right)_{int_p}$ in the standard and inward-shifted configurations, Fig. 10, Fig. 12 and Fig. 14 are combined in the same figure as in Fig. 16. To obtain the fitting function, we use the data fitting method "FindFit" function in Mathematica V12.2 program [29]. This finds numerical values of the parameters that make the expression of ax^{-b} a best fit to the data as a function of variable x . Thus, the coefficient $\left(\hat{G}/\tau\right)_{int_p}$ is expressed as $\left(\hat{G}/\tau\right)_{int_p}(3.75m) = 0.16\nu^{*-0.52}$, $\left(\hat{G}/\tau\right)_{int_p}(3.6m) = 0.11\nu^{*-0.62}$ and $\left(\hat{G}/\tau\right)_{int_p}(3.53m) = 0.026\nu^{*-0.66}$, which are indicated by dotted lines in Fig.16.

The BS current coefficient for $R_{ax} = 3.53$ m is clearly smaller than that for $R_{ax} = 3.75$ m by the factor of ~ 5.8 at $\nu^* = 1$. The BS current coefficient for $R_{ax} = 3.53$ m is also smaller than that for $R_{ax} = 3.6$ m by a factor of ~ 4.1 . On the other hand, as the BS current coefficients for $R_{ax} = 3.75$ and $R_{ax} = 3.6$ m do not look much different, as shown in Fig. 16, we check them in detail. We also notice that the dependence of the BS current coefficient on the collisionality parameter is very small for $R_{ax} = 3.53$ m.

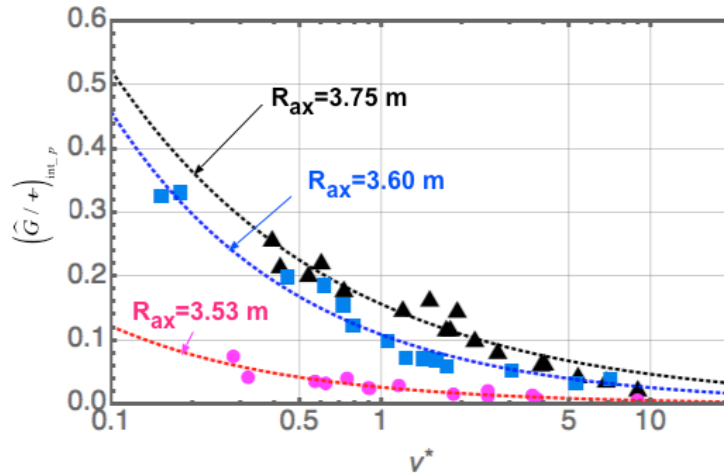


Fig. 16 Dependence of the coefficient of BS current $\left(\hat{G}/\tau\right)_{int_p}$ on collisionality parameter for $R_{ax} = 3.75$ m (black triangle), $R_{ax} = 3.6$ m (blue square) and $R_{ax} = 3.53$ m (red circle).

The BS current is now estimated using Eq.(12) and experimentally obtained BS current coefficients $\left(\hat{G}/\tau\right)_{int_p}$. For example, the BS currents at $\nu^* = 0.5, 1$ and 2 are estimated for $B_t = 2.64$ T, $a = 0.6$ m, $W_p = 400$ kJ corresponding to the volume averaged beta value $\beta_t = 0.0054, 0.0056$,

0.0058 for $R_{ax} = 3.75$ m, 3.6 m and 3.53 m, respectively. The peak beta values are then obtained using the profile factor. The results are shown in Fig. 17. The BS current is slightly decreased at $R_{ax} = 3.6$ m than at $R_{ax} = 3.75$ m, and then abruptly reduced at $R_{ax} = 3.53$ m. It is interesting to see that while confinement is linearly improved at $R_{ax} = 3.53$ m from $R_{ax} = 3.75$ m as shown in Fig. 1 in the reference [14], the BS current is drastically decreased between $R_{ax} = 3.6$ m and $R_{ax} = 3.53$ m as shown in Fig. 17. In the same configuration of $R_{ax} = 3.6$ m, the BS current is reduced by a factor of ~ 2.4 from 48 kA ($\nu^* = 0.5$) to 20 kA ($\nu^* = 2$), if the higher collisional operation is employed. Thus, it is found that shifting the magnetic axis to $R_{ax} = 3.53$ m (the neoclassically optimized configuration) is most effective in reducing BS current together and improving confinement, which is favorable for a helical reactor operation. It is also seen that the dependence of BS current on the collisionality parameters is quite small for the $R_{ax} = 3.53$ m configuration.

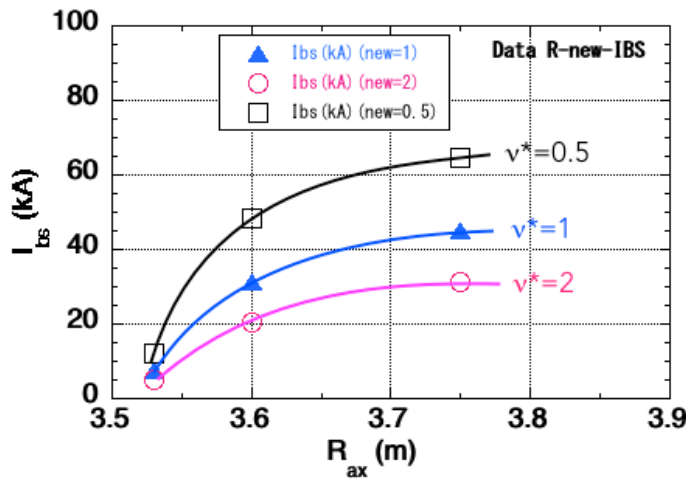


Fig. 17 Dependence of the BS current on the magnetic axis for collisionality parameter of $\nu^* = 0.5$ (open circle), $\nu^* = 1$ (solid triangle) and $\nu^* = 2$ (open square).

8. The $1/\nu$ and plateau regimes on POPCON in the helical fusion reactor

It is thus found in this study that the BS current depends on the plasma major radius and collisionality parameter. Based on these data, the BS current could be estimated in the design of a commercial helical fusion reactor such as FFHR, where we propose the ignited operation in the thermally unstable regime with the low temperature and high-density [30]-[32] together with a stable control method. We estimate that the BS current and the map of collisionality parameter on POPCON in FFHR-d1, based on the plasma major radius of $R_{ax} = 3.53$ m, which provided the minimum BS current. Here, we note that POPCON diagram is describing the ignition regime and the trace of the operating point from the start up to the final steady state ignition point on the T_i - n

plane. Although the operating point of this FFHR-d1 reactor is located at the thermally unstable ignition boundary, the newly invented control algorithm to stabilize the operating point has made this type of operation possible [30][31].

As the BS current depends on the pressure profile $p(r)$, it could have a maximum value at the peak point of the pressure gradient of $dp(r)/dr$. The temperature and density profiles are assumed for a reactor ignition analysis as

$$\begin{cases} T(x) = T(0)(1-x^2)^{\alpha_T} \\ n(x) = n(0)(1-x^2)^{\alpha_n} \end{cases}$$

where $x = r/a_o$. As the pressure gradient $dp(r)/dr$ is obtained as

$$\frac{dp(x)}{dx} = -p(0)2(\alpha_T + \alpha_n)(1-x^2)^{\alpha_T + \alpha_n - 1} x$$

where $p(0) = n(0)T(0)$ and its peak point is calculated by the further differentiation as $d^2p(x)/dx^2=0$. Thus, the relation

$$\begin{aligned} p'(x) &= -p(0)2(\alpha_T + \alpha_n)(\alpha_T + \alpha_n - 1)(1-x^2)^{\alpha_T + \alpha_n - 2}(-2x)(x) \\ &\quad - p(0)2(\alpha_T + \alpha_n)(1-x^2)^{\alpha_T + \alpha_n - 1} = 0 \end{aligned}$$

yields the point

$$x = \frac{r}{a_o} = \frac{1}{\sqrt{2(\alpha_T + \alpha_n) - 1}} \quad (15)$$

As the BS current could be maximum at this point, we estimate the collisionality parameter there.

In Fig. 18, POPCON is shown for FFHR-d1 ($R = 15.7$ m, $a = 2.5$ m, $B_t = 4.5$ T, $P_f = 3$ GW and $\beta_t = 0.058$) with the density profile of $\alpha_n = 0.5$ and temperature profile of $\alpha_T = 1$, with the operation path to the thermally unstable ignition point [33]. The ISS04 scaling with the enhancement factor of 1.1 has been used [34]. Alpha particle confinement is better for the broader density profile of $\alpha_n = 0.5$.

For this density and temperature profile, the pressure gradient peak point is $r/a = 0.71$, providing the collisionality parameter of $\nu^* = 0.98$. Based on the $R_{ax} = 3.53$ m configuration, as the steady state operating point at $T_i = 8.5$ keV and $n = 4.6 \times 10^{20} \text{ m}^{-3}$ has the average beta value of $\beta_t = 0.058$ and peak beta value of $\beta(0) = (\alpha_n + \alpha_T + 1)\beta_t = 0.146$, the BS current could be estimated by the direct extrapolation as 697 kA for $\nu^* = 0.98$ by Eq.(12) and Fig. 16. We note as the BS current changes the rotational transform, its effect should be taken into account by iteration, which is beyond this work.

Although we have expected to use higher density operation in the plateau regime for reducing the BS current so far [7][8] as discussed in introduction, we have found in this study that the magnetic configuration (the neoclassically optimized configuration with $R_{ax} = 3.53$ m) is more effective for reducing the BS current than a collisionality parameter adjustment. POPCON for the neoclassically optimized configuration with $R_{ax} = 3.53$ m in Fig. 18(a) shows that the operation point has $\nu^* \sim 1$. In the case of $R_{ax} = 3.75$ m, the operation point has $\nu^* \sim 2$ as shown in Fig. 18(b).

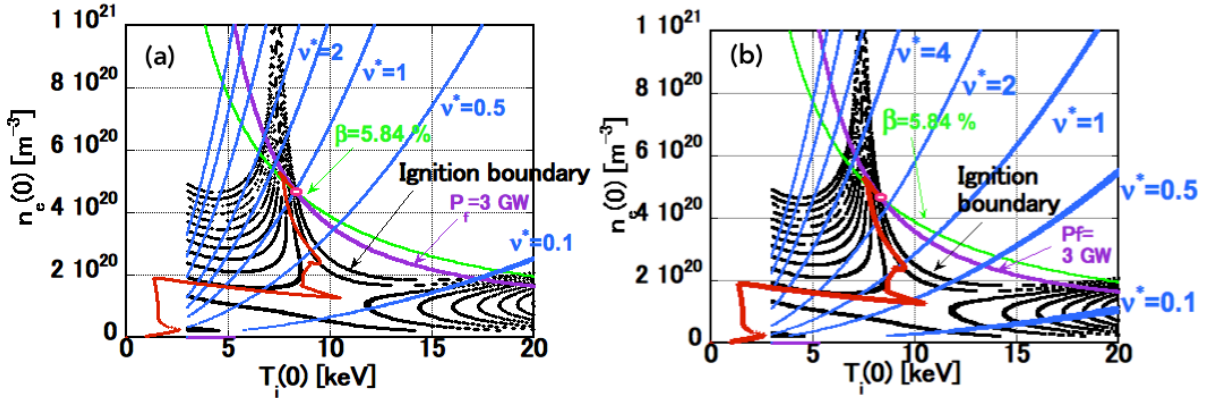


Fig. 18 The $1/\nu$ and plateau regimes on POPCON for FFHR-d1 reactor with the fusion power of $P_f = 3$ GW based on (a) $R_{ax} = 3.53$ m and (b) $R_{ax} = 3.75$ m configurations. The solid red line indicates the operation path to the ignition. Blue lines show the collisionality parameters.

9. Discussion and summary

So far, to know about the physical mechanism of reduced diffusion in an inward-shifted configuration, a detailed theoretical study on the ripple diffusion in LHD has been conducted for the various configurations with $R_{ax} = 3.45$ m, 3.5 m, 3.53 m, 3.55 m, 3.6 m, and so on [35]. They have found that the effective ripple is a minimum around $R_{ax} = 3.53$ m. On the other hand, we have conducted the BS current experiments for only three configurations with $R_{ax} = 3.53$ m, 3.6 m, and 3.75 m in LHD. Although the $R_{ax} = 3.53$ m configuration provided the minimum BS current among the experiments with $R_{ax} = 3.53$ m, 3.6 m and 3.75 m, it is interesting to know the relationships between BS current and neoclassical transport properties in the other configurations such as $R_{ax} = 3.45$ m, 3.5 m, and 3.55 m. The above experiments would make clear whether the bootstrap current and neoclassical transport are simultaneously minimized in a heliotron type device [19].

In the FFHR reactor design study, the inward-shifted configuration has been employed and the BS current is evaluated by the PENTA code [36]. Their study provided the BS current of 550 kA for the $Q = 10$ operation [37]. In the same paper, the reversal of the BS current profile near the plasma edge is obtained, leading to a small effect of the BS current on the rotational transform profile. Unfortunately, in this LHD experiment the current density profile was not measured by Motional Stark Effect (MSE) system because we concentrated on the comparison experiments and it could also be difficult to measure it due to the small BS current itself. Although we consider the reason of

small BS current is due to the small particle drift, further theoretical consideration is necessary to explain their result.

In this paper, we have demonstrated how to reduce the BS current in LHD. However, in an actual situation of reactor operation, as the BS current may suppress the plasma shift due to the higher beta value with the help of the vertical field, the optimum magnetic axis could be determined by optimization of the confinement time, allowable BS current, the plasma shift, and the rotational transform. As the rotational transform has a shear in the heliotron type device LHD which can suppress the turbulent transport, and the large built-in helical divertor which is different from Wendelstein 7/X [38], it is still worth pursuing it for achieving a fusion reactor.

We have experimentally demonstrated in the heliotron type device LHD device that the inward-shifted configuration, especially the neoclassically-optimized configuration, provides a smaller BS current than that in the standard configuration, in addition to the better confinement characteristics. It is also experimentally demonstrated that the BS current gets smaller in the plateau regime than $1/\nu$ regime. Although those experimental results are in the limited plasma parameter range, we believe this experimental result would provide a promising feature for a heliotron type fusion reactor.

As a result, it is clearly demonstrated in LHD that the inward-shifted configuration provides a reduced BS current, especially the neoclassically optimized configuration of $R_{ax} = 3.53$ m shows a remarkably lower BS current than that in $R_{ax} = 3.75$ m standard configuration. At the same time, it is confirmed that the inward-shifted configuration also improves confinement.

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