

OPERATIONAL EXPERIENCE IN W7-AS DISCHARGES WITH ROTATIONAL TRANSFORM FROM BOOTSTRAP CURRENT

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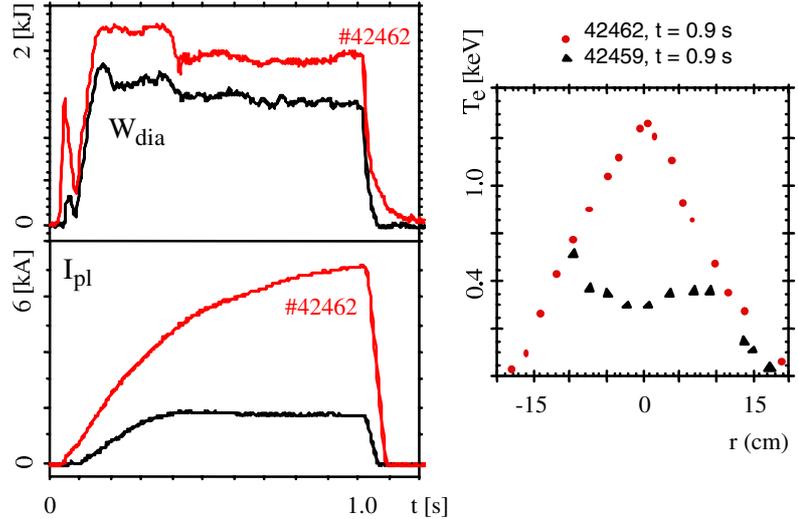
1. Introduction

The rotational transform in helical systems is usually produced by external coils - coils with lateral excursions in the case of W7-AS. In addition, a pressure driven bootstrap current, I_{BT} , develops in the plasma which increases the external rotational transform. With considerable bootstrap current the steady state characteristics of the helical system is still maintained, whereas the technical complexity of the non-planar coils could be reduced. On the other hand, the discharge development is more complex because the plasma current changes important quantities like the rotational transform, the magnetic shear and the shape of the flux surfaces which are linked to stability and confinement. This paper summarizes experimental results on the bootstrap current in W7-AS. Measured or calculated I_{BT} values are given for various discharge scenarios with respect to magnetic field, B , density, n , temperature, T , and heating power, P . Examples for the influence of larger bootstrap currents on confinement and plasma stability are shown. Usually the bootstrap currents in W7-AS are too small to drive substantial instabilities. Therefore also a discharge is presented where the current is further increased beyond the bootstrap current level by an additional loop voltage up to the limit where the plasma is strongly disturbed by MHD.

2. Bootstrap currents in W7-AS

The neoclassical bootstrap current is driven by finite plasma pressure and flows off axis in the pressure gradient region. In the plateau and long mean free path regime it is a complicated function of temperature, T , collisionality, ν , and the magnetic field configuration. Therefore, calculations have to be performed with the DKES code [1] which takes into account the three dimensional shape of the flux surfaces. In W7-AS only the electron bootstrap current has to be considered. It can be measured in several ways. The simplest method is the stellarator operation proper, where the bootstrap current freely develops. However, within a discharge time of 1 to 2 s a stationary state is reached only in cases with low T_e and consequently small I_{BT} (Fig. 1). A stationary state is obtained much faster by preprogramming a net plasma current with the aid of the OH transformer. In net current free discharges, the compensating ohmic current component is opposite to I_{BT} and both currents have to be calculated. For finite net currents, the OH component is negligible if the loop voltage approaches 0. Generally reasonable agreement is found between calculated and measured bootstrap currents [2] especially when the uncertainty of Z_{eff} is taken into account. The current rise time is essentially given by the L/R time constant and can be modelled by time dependent codes like ASTRA.

Fig. 1. The two discharges shown differ by the toroidal field. In the case of on axis ECRH the electron temperature profile is peaked and a large bootstrap current develops. For B_0 increased by 5%, the ECRH is strongly off axis, the central electron temperature and the bootstrap current are significantly reduced (350 kW ECRH at 1.25T, $\langle n_e \rangle = 1.5 \times 10^{13} \text{cm}^{-3}$). The drop of W_{dia} at about 400ms is connected with the $\iota=1/3$ surface close to the plasma boundary in agreement with changes in the MHD behaviour.



Substantial bootstrap currents can be expected at high T_e . At low densities, where T_e stays rather constant, I_{BT} increases with density and finally saturates (Fig. 2). At very high densities ($\langle n_e \rangle > 10^{14} \text{cm}^{-3}$, neutral beam (NBI) heated high β plasmas at 1.25T) I_{BT} is restricted to about 3 kA in W7-AS. The largest free-running I_{BT} of 8.5 kA has been measured with 800 kW ECRH at 2.5T ($\langle n_e \rangle \approx 3 \times 10^{13} \text{cm}^{-3}$) and $T_e(0) \approx 3.5$ keV where after 1.4s the current was still increasing. For 400 kW ECRH at 1.25 T bootstrap currents up to 10 kA can be extrapolated from discharges with zero loop voltage. A preliminary analysis indicates that even values of the order of $I_{BT} = 20$ kA can be expected for net current free discharges with 1.5 MW ECRH at 2.5T, rather low density ($\langle n_e \rangle \approx 2 \times 10^{13} \text{cm}^{-3}$) and $T_e(0) \approx 5$ keV and also for discharges with combined ECRH and NBI (700 + 750 kW) and very good energy confinement (factor two above ISS95 scaling [3]) resulting in $T_e(0) \approx 1.7$ keV at $\langle n_e \rangle \approx 5 \times 10^{13} \text{cm}^{-3}$. In this case also the influence of negative radial electric fields on the particle orbits (which increase the electron and decrease the ion bootstrap component) seems to be important [4].

3. Increase of rotational transform

As mentioned above, the largest free-running bootstrap current was found at 2.5T. Although I_{BT} scales with $1/B$, almost the same value of $I_{BT} = 8.3$ kA was achieved at 1.25T with only 350 kW ECRH at $t=1$ s. This occurs because the confinement in W7-AS improves almost linearly with B and thus higher electron temperatures are achieved at higher magnetic fields. Because of $\Delta \tau \propto I_{pl}/B$, the largest increase of the rotational transform was therefore achieved

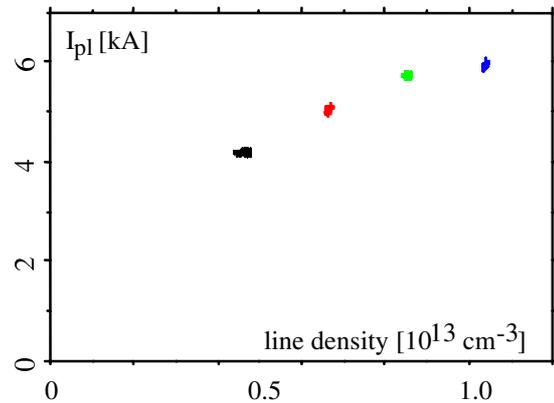


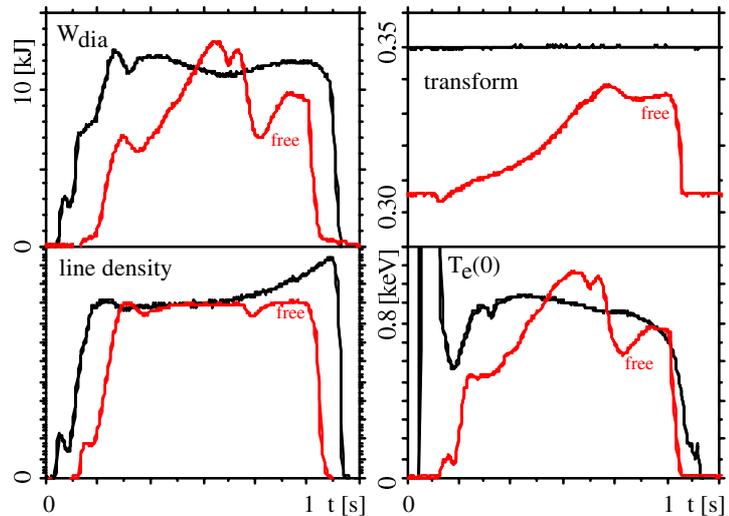
Fig. 2. Density dependence of the non-stationary bootstrap current at $t = 1$ s for 350 kW ECRH at 1.25T. The maximum density is about $\langle n_e \rangle = 1.5 \times 10^{13} \text{cm}^{-3}$.

at the lower field with a $\Delta\tau \approx 0.10$ for a plasma radius $a \approx 16$ cm and a major radius of 2 m.

4. Influence on confinement

The influence of a free running bootstrap currents on confinement follows roughly the results which were obtained for net current free discharges and which are only partly understood [5]. For small to medium currents, just the change of the boundary transform τ (a) and of the shear have to be taken into account. Similar to the current ramp-up phase in tokamaks a modulation of the energy content W_{dia} is observed which is probably related to field line resonances close to the plasma boundary (Fig. 1). In cases with a pronounced dependence of W_{dia} on τ (a), the discharge can follow that dependence with increasing current. A discharge with optimum confinement [6] is compared in Fig. 3 with a discharge with free I_{BT} but lower external rotational transform. The rising current contributes at first to the rotational transform missing for optimum confinement and the energy content W_{dia} reaches values comparable to the net current free discharge. Later on, the plasma confinement deteriorates with increasing current in this case. In discharges with large ohmic currents, such a deterioration is usually not observed [5]. For discharges with large shear (substantial internal currents at low density, high β or large net currents) no significant dependence of the confinement on τ (a) or the bootstrap current is observed or has to be expected.

Fig. 3. A net current free discharge with optimum confinement ($2.5T$, $P_{\text{NBI}} = 350$ kW, $\langle ne \rangle \approx 1.0 \times 10^{14} \text{cm}^{-3}$) is compared with a similar discharge with free running bootstrap current starting at lower external rotational transform at the plasma boundary.

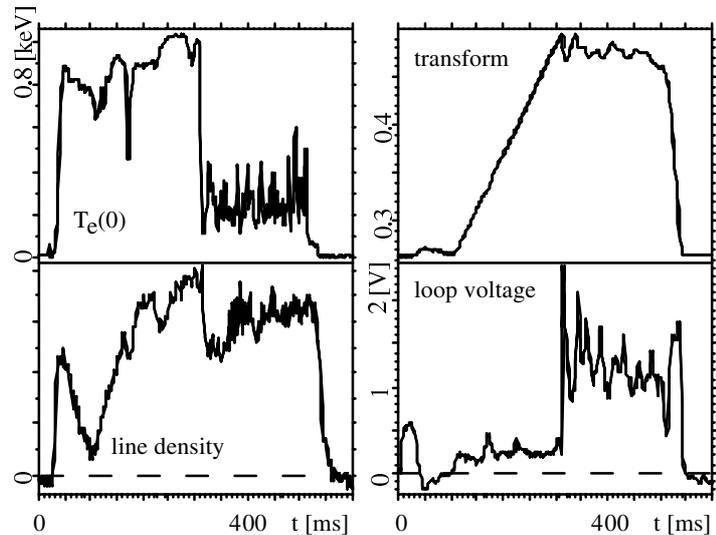


5. Development of Instabilities

Within the limitation of the pulse length to 1 to 2 s, bootstrap currents remain too small to drive significant instabilities. An example where fluctuations driven by I_{BT} alone were clearly visible is presented in Ref. [7]. They could at least partly identified as $m=2$ tearing modes. To demonstrate the stability behaviour of stellarators with non negligible external rotational transform [8] at still larger currents the bootstrap current can be further increased by applying an external loop voltage. A result is shown in Fig.4 (see also [7]). Similar to tokamaks large amplitude $m=2$ tearing modes develop when τ (a) approaches $1/2$ and the $\tau = 1/2$ (or $q=2$) is close to the plasma boundary and T_e drops considerably. However, due to the improved positional stability by the external poloidal field no disruption occurs. The density and the

plasma current stay almost constant and the discharge terminates only when the OH transformer can no longer supply the necessary large loop voltage.

Fig. 4. A low density discharge (1.25T, $P_{ECRH} = 350$ kW, $\langle ne \rangle = 1.0 \times 10^{13}$ cm^{-3}) where the bootstrap current has been increased by applying an external loop voltage. At about 300ms the rotational transform at the plasma boundary approaches 1/2 and large amplitude $m=2$ tearing modes develop, which cool down the central electron temperature to about 300eV.



6. Conclusions

In W7-AS bootstrap currents up to 10 kA have been measured and currents up to 20 kA are estimated for net current free discharges at 2.5T. To obtain large bootstrap currents high electron temperatures are mandatory and this can be achieved in W7-AS only by ECRH. Depending on the electron temperature and the aspect ratio, pulse lengths of several seconds are necessary to reach a stationary maximum current. The largest increase of the external rotational transform, $\Delta \tau \approx 0.10$, was found at a reduced toroidal field of 1.25 T. In cases where the plasma confinement depends on τ (a) and on the magnetic shear, the confinement follows on the whole the modifications introduced by the bootstrap current. Plasma stability is no serious problem in stellarators with sufficient external rotational transform even at very large plasma currents. Nevertheless major resonances like $\tau=1/2$ close to the plasma boundary should be avoided since in these cases current driven instabilities deteriorate the plasma confinement considerably.

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