SOURCES OF TOROIDAL CURRENT IN THE WENDELSTEIN VII-AS STELLARATOR

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INTRODUCTION - The nearly shearless modular stellarator Wendelstein VII-AS (major radius $R = 2\ m$, averaged minor radius $< a > = 0.2\ m$) started plasma operation in October '88. As in W VII-A, also in W VII-AS a strong correlation between the global confinement properties and the value of the rotational transform ι has been observed in "net-current-free" plasmas. Apart from the confinement degradation at values of ι corresponding to low order rational values, already observed in W VII-A, broader intervals of degraded confinement are also found at values of $\iota = \frac{5}{m}$ (m integer) where, due to the five field period structure of the machine, the vacuum field configuration presents natural magnetic islands /1/. In the first months of operation particular attention has been paid to the investigation of 2^{nd} harmonic Electron Cyclotron Resonance Heating (ECRH) in the ι-region $\frac{1}{2} \leq \iota \leq \frac{5}{9}$. The vacuum ι-profile can be affected by toroidal currents. At $B_0 \simeq 1.25\ T$ (2^{nd} harmonic heating) a current I_P causes a change $\Delta\iota_a \simeq 0.014 \cdot I_P(kA)$ at the boundary value ι_a or the rotational transform ($\Delta\iota_a \propto \frac{I_P}{B_0}$). For the ranges of B_0 and ι currently under examination, the maximum tolerable I_P for operation in the good confinement ι-interval is about 1 kA. Within neoclassical theory radial diffusion drives a net current ("bootstrap-current") peaked in the pressure gradient region. The existence of this current component is experimentally supported. Since the magnitude of this current is related to plasma energy, the existence of a critical current I_P can influence the maximum achievable energy. Operation at values of ι corresponding to good confinement properties during the whole duration of the discharge could require an external ι-profile control acting on the current profile itself and not merely obtained by having two channels of current of different sign at different radii. Due to the possibility of controlling the profiles of the absorbed power and of the driven current, electron cyclotron waves are a natural candidate for current profile control. The strong dependence of global confinement properties on the ι-profile puts a particular interest in the investigation of the toroidal current sources. Furthermore, the "net-current-free" regime of operation of most Stellarator-devices gives the opportunity of observing and studying non inductive currents without the presence of an "obscuring" Ohmic current. The results of the analysis of the toroidal current in W VII-A /2/ are reconfirmed.

AUXILIARY HEATING SOURCES - Three different auxiliary heating systems will be used in W VII-AS: Neutral Beams Injection (H^0, 1.5 MW, tangential injection) Electron Cyclotron Resonance Heating (70 GHz, 1.0 MW), and Ion Cyclotron Resonance Heating

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1.0 MW). So far, the neutral beam lines have only been tested, while ECRH has routinely been used (up to three gyrotrons). During the neutral beam lines testing discharges (unbalanced injection) some beam induced current has been observed. The W VII-AS ECRH system consists of four 200 kW , 70 GHz , 3 s pulse-length gyrotrons, highly oversized circular waveguide transmission lines and quasi-optical wave launch antenna. Before reaching the plasma the Gaussian beam is reflected by focusing movable mirrors. After reflection a microwave beam of parallel plane phase-fronts (bringing to a lower beam divergence in a refractive plasma) with an half width radius $\simeq 1.5$ cm is obtained. The plasma column is not axisymmetric with respect to the injection plane also for exactly perpendicular injection the toroidal angle of the ray will be affected, in a finite density plasma, by refractive effects. The mirrors can be tilted in both toroidal and poloidal direction, so that the sign and the magnitude of the toroidal angle of injection, as well as the vertical position at which the beam reaches the resonant layer, can be choosen. After a description of the theoretical model, results obtained in a single shot analysis and by scanning the toroidal ECRH injection angle will be presented.

THEORETICAL MODEL - Within neoclassical theory, electron transport is related to the deviation of the electron distribution function from the Maxwellian, a theoretically consistent description of transport (including the influence of auxiliary heating) would require the solution of the related Fokker-Planck equation in full phase space. This is not possible at present time. With respect to the toroidal current the problem can be simplified if the bootstrap current and the auxiliary heating driven current are described as independent processes. Through the comparison of a set of discharges it will be also experimentally possible to distinguish between the two sources (while on a single shot data analysis only the total contribution can be measured).

Neoclassical transport in the non-axisymmetrical geometry of W VII-AS has been investigated by means of the DKES-code /3/. The induced bootstrap current as well as the radial transport has been obtained as a function of the local plasma parameters for several magnetic surfaces.

The Electron Cyclotron Current Drive efficiency is estimated by means of a Hamiltonian 3-D ray tracing code based on the cold plasma dispersion relation and an absorption coefficient for general angle of propagation (relativistic Doppler shifted resonance relation) based on a Maxwellian distribution function. The self-adjoint approach is used. It is to be noticed that the angle of injection experimentally determined by the orientation of the reflecting mirror, is usually slightly different from the angle formed by the rays and the magnetic field at the resonant layer. This last angle is the physically important one and can only be theoretically evaluated by determining the ray trajectories under the hypothesis of geometrical optics of the ray tracing. This causes an uncertainty in the evaluation of the current drive efficiency for small angles of injection, where the dependence of the efficiency on the angle is very strong. With the increase of the injection angle this uncertainty becomes negligible. Quasi-linear and trapped particle effects are outside the present description. Heating of electrons trapped in the field ripple of the 3-D magnetic field topology of W VII-AS /3/ and quasi-linear effects can contribute to a degradation of the current drive efficiency. The linear model used in the ray-tracing is expected to give an upper limit for current drive efficiency.

FREE CURRENT, SINGLE SHOT ANALYSIS - In some set of discharges the current was left free to evolve, no loop voltage being externally applied. Under stationary condition the loop voltage (V_{loop}) would be zero and the total driven current value can be directly measured removing the uncertainty coming from the evaluation of the plasma conductivity (strongly dependent on temperature profile and Z_{eff}) generally required to determine the current I_P from the measured V_{loop}. In the series #906 $\div$ 923 two gyrotrons were applied (X-mode 2^{nd} harmonic, total injected power $P_{inj} \simeq 350$ kW). The microwave radiation was launched nearly perpendicularly to the magnetic field, this should minimize its contribution to the total current (see next paragraph). During the second gyrotron pulse (200 ms) the toroidal current saturated at a value $I_P = +1.5\ kA$ in the resistive time scale $\frac{L}{R} \simeq 100 \div 150\ ms$. This value is of the order of the electron bootstrap current $I_B = +1.4 \div 0.95\ kA$ (for $Z_{eff} = 2 \div 4$, respectively) theoretically calculated using the measured Thomson profiles (central density $n_{e,0} = 1.9 \cdot 10^{19}\ m^{-3}$, central temperature $T_{e,0} = 0.8\ keV$). The ion bootstrap current (ion temperature $T_{i,0} \simeq 0.2\ keV$) and ECRH driven current (ray-tracing calculation evaluates total absorption with an efficiency of $\eta = +1\ A/kW$, see next paragraph) are also expected to give a smaller positive contribution to the measured current.

SCAN IN THE ECRH ANGLE OF INJECTION - Two gyrotrons (X-mode 2^{nd}-harmonic, $P_{inj} = 180\ kW$ each) were used in a set of discharges dedicated to the investigation of electron cyclotron current drive. The first gyrotron (with an angle of injection nearly perpendicular, with respect to the external magnetic field) produced and mantained a target plasma over a pulse length of 500 ms. The second gyrotron with a pulse length of 150 ms, long enough to reach a second stationary state, was switched on $\simeq$ 190 ms later. The toroidal angle of injection of this second gyrotron was then scanned from a value corresponding to nearly perpendicular propagation to an angle nearly 40° from the perpendicular. To have similar plasma conditions during the angle scan the boundary value ι_a was fixed by a feed-back current control (during the scan the net current is kept under 50 A). Line density ($\simeq 4 \cdot 10^{18}\ m^{-2}$) is nearly stationary during the whole plasma discharge and highly reproducible from shot to shot. The diamagnetic energy W_P increases during the second pulse from $1.1 \pm 0.1\ kJ$ to $1.3 \pm 0.1\ kJ$ no correlation with $k_{\|}$ being noticeable. The measured loop voltage is clearly correlated with the angle of injection (see Fig. 1). This correlation is pointed out in Fig 2 where the loop voltage at the time $t = 300\ ms$ is reported as a function of the angle of injection (at the reflecting mirror) after having redefined as zero the V_{loop} observed during the shot with minimal $k_{\|}$. The behaviour of the observed loop voltage with the change of the injection angle is in very good agreement with the behaviour of the current drive efficiency evaluated theoretically by means of the ray tracing code (Fig. 3). The fact that the loop voltage remains clearly negative, also when the injection angle of the second gyrotron corresponds to optimal current drive efficiency, is an indirect proof of the existence of a further predominant positive current source. This component is theoretically identified with bootstrap current. Due to the observed very small dependence of plasma energy and density on the injection angle of the second gyrotron, the loop voltage relative to the boostrap current (and to the current driven by the first gyrotron, whose injection angle remain fixed) will be nearly independent on the $k_{\|}$ of the second gyrotron and would be responsible of a ΔV_{loop} contribution nearly constant for all the shots of the $k_{\|}$-scan. The different behaviour of V_{loop} at the change of the injection angle can be in this way brought back to a direct current drive of the second gyrotron. For a quantitative comparison with theoretical predictions the equivalent current must be determined from the observed ΔV_{loop}. Thomson profiles are missing for this series. A temperature profile with a central temperature $T_{e,0} \simeq 1.2\ keV$, supported by ECE and X-ray signals and in agreement with the observed diamagnetic energy is assumed. The density dependence of the result is much weaker than the temperature dependence and a density profile with central density of $n_{e,0} \simeq 1.4 \cdot 10^{19} m^{-3}$ reproducing the observed line density, is assumed. With these profiles the ray tracing evaluates strong absorption for injected X-mode polarized waves, but passing from perpendicular to oblique injection the absorbtion coefficient as well as the percentage of the injected X-mode polarized wave slightly decreases (10% effect). The maximal current drive efficiency is $\eta_{max} = -23\ A/kW$ (corresponding to an injection angle $\simeq 15°$), as reported in the ordinate of Fig. 3. A quantitative agreement with the observed loop voltage would require, for the second gyrotron, an absorbed power $P_{abs} = 150 \div 180\ kW$ assuming $Z_{eff} = 3 \div 4$, respectively.

CONCLUSIONS - In the advanced stellarator Wendelstein VII-AS net toroidal currents (of the order of few kA) are experimentally observed even in absence of externally driven ohmic currents. These currents must be the sum of (at least) two components of different physical origins. A theoretical description based on neoclassical bootstrap current and electron cyclotron driven current explains the observed behaviour. In particular, the theoretically predicted dependence of the ECRH driven current on the angle of injection has been experimentally observed. Due to the experimental uncertainties (especially for the strong dependence on Z_{eff} of the quantitative results) the substantial quantitative agreement found between theory and experiment should be judged with some care. More definite results are expected to be achievable for the next future.

REFERENCES

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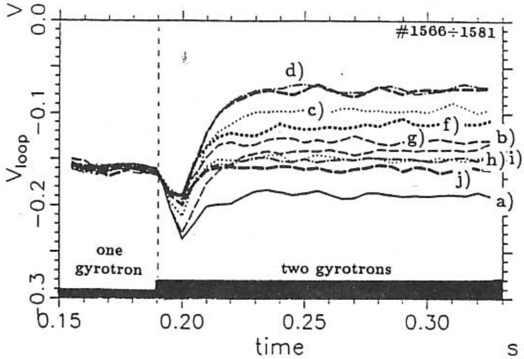
Fig. 1 *V_{loop} dependence on the angle of injection of the second gyrotron:*
a) → 2°
b) → 4.9°
c) → 9.7°
d) → 13.9°
e) → 18.2°
f) → 22.5°
g) → 26.8°
h) → 31.2°
i) → 36.2°
j) → 40.1°



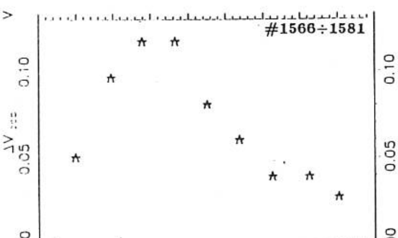


Fig. 2 *Same as Fig. 1, defining as $V_{loop} = 0$ the loop voltage relative to the smaller angle of injection.*

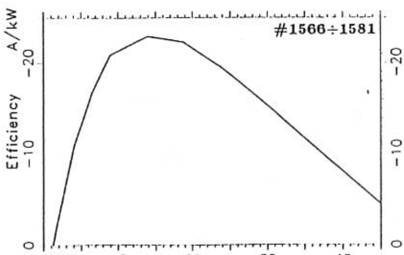


Fig. 3 *ECRH current drive efficiency evaluated from the ray tracing code. To be compared with Fig. 2.*