Scale lengths of current flow in magnetized plasmas

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I. INTRODUCTION

When a current is driven from an electrode into a plasma, part of the voltage will drop across the sheath, the rest in the bulk. It is not uncommon in the ASDEX Upgrade divertor for an I–V characteristic to show a slope near floating of $I_{\rm sat}/(1\,{\rm V})$, even at densities as high as $10^{20}\,{\rm m}^{-3}$. The slope expected if all the voltage were dropped in the sheath is $I_{\rm sat}/(k_B T_e/e)$, so the electron temperature cannot then be higher than 1 eV. This puts an upper limit of about $\lambda_{\rm resist} = (\sigma_\| k_B T_e)/(n_e e^2 c_s) \approx 13\,{\rm mm}$ on the length of the current path, since otherwise more than the full voltage would have to be dropped in the bulk. For typical 1 mm probe dimensions, we see that the cross field current density can be no more than one order of magnitude smaller than the parallel current density. Current flowing across a magnetic field produces a force, which must be compensated by an equal and opposite force or an acceleration. If we can identify the nature of this compensating force, we may also find out whether and how Langmuir probe analysis needs to be modified to take the voltage drop in the bulk into account.

There are a number of approaches to these questions. Although it would be difficult to measure directly, the parallel path is certainly shorter than the connection length if all the current from a probe returns to the surrounding surface. Another indirect indication of the parallel path is the perpendicular distribution of the return current, which can be measured directly with passive probes or indirectly through the ratio of electron to ion saturation current. The connection between the parallel and perpendicular scales can be understood by considering a small perturbation on a uniform background plasma. Expressing the solution in terms of Fourier modes, larger $k_\|$ will be associated with larger $k_\perp$, although the exact relationship will depend on the details of the physics. Modes with a parallel scale longer than $\lambda_{\rm resist}$ will be dominated by the bulk resistance. Probes larger than the corresponding perpendicular scale will thus be affected by the bulk resistivity, although they will seek to minimize the cost by giving more weight to smaller scales, so that most of the current will flow near the edges of the probe. Probes smaller than this scale will be dominated by the sheath resistance and may be evaluated using the classical formulas. Since modes up to the characteristic scale are associated with little bulk resistance, the probe will use these to minimize the sheath resistance of the return current, spreading it over a distance given by the characteristic perpendicular scale. These ideas can be formulated and solved within the framework of magnetohydrodynamics (MHD) since the ion gyroradius is small compared to the perpendicular scale and the parallel mean free path is about $\sqrt{m_i/m_e}$ times smaller than λ_{resist}. Comparison with experimental results on the current distribution and saturation current ratio will help determine what force balances $j \times B$.

II. MEASUREMENT OF RETURN CURRENTS

The first study [1] to measure the pattern of current flow from Langmuir probes in a tokamak used the divertor plate probe arrays in ASDEX Upgrade. One element was driven actively, and a passive current was looked for on elements in the surrounding and the opposing target plates. At most a few percent of the current was found to reach the opposing surface. The bulk of the current returned to the surrounding surface within about 2 mm as measured perpendicular to the magnetic field. A later study used a specially constructed Checkerboard Probe (CBP) [2] on a manipulator in the midplane of ASDEX Upgrade. This probe consisted of several elements which could optionally be driven together to vary the active area. The surrounding elements were maintained at vessel potential to measure the magnitude and distribution of the return current. In addition, the assembly could be rotated to vary the angle relative to the field and consequently the projected area. Within the experimental accuracy of about 10%, all of the current was found to return to the surrounding surface (Fig. 1) despite the relatively short connection length of $L_c = 3\,\text{m} \approx 10\lambda_{e,mfp} \approx 1/5\lambda_{\text{resist}}$. The distribution of current as a function of angle varied in a way that suggests that the width of the return area does not follow the width of the active area but is characteristic of the plasma conditions.

III. MEASUREMENT OF CURRENT RATIOS

The first investigation [3] of the ratio of electron to ion saturation current as a function of probe size was performed with the Tilting Probe Array (TPA) on DITE. A tendency of the current ratio to rise with projected probe size was found. A study done with the CBP on ASDEX Upgrade showed similar results where the projected areas were the same, but with larger projected areas, the reverse tendency was found (Fig. 2). The transition between small and large probes in this sense was found to occur when the projected length was a few ion gyroradii or a few tens of local Debye lengths. We note here that no promising ansatz has been found to explain a rise of the current ratio with probe size, and potential orbit and kinetic effects make this branch more difficult to handle theoretically. If we concentrate on the large probe branch, which is e.g. valid for the target plate probes at ASDEX Upgrade, we see that the current ratio is inversely proportional to the projected probe size (Fig. 2). If the saturation of the electron current is caused by ion saturation in the return area, then the current ratio can be taken as a measure of the ratio of the return area to the probe area. These results are again consistent with a 2 mm return current scale which is a characteristic of the plasma.

IV. ANALYTICAL SOLUTION OF MHD EQUATIONS

The linearized MHD equations reveal three candidates for the effect opposing $j \times B$: Braginskii viscosity [4], convective acceleration [5], and interaction with neutrals [6,7]. Viscosity turns out to be too weak to explain most of the I–V characteristics seen in the ASDEX Upgrade divertor. A convection of plasma across the probe, as would be produced by turbulence, can be thought of as the polarization drift of the ions, which see a changing electric field as they move across the probe. This mechanism is much stronger than viscosity, but is not able to explain measurements at the lowest temperatures and highest densities. In this regime the most powerful mechanism turns out to be interaction with neutrals. Under most conditions the dominant process is charge exchange with atoms, but under certain circumstances elastic collisions with molecules and ionization can be of a similar magnitude. Analysis of the MHD equations coupled with estimates of the neutral interaction obtained from Monte Carlo simulations yield a characteristic perpendicular scale of about 1 mm for electron temperatures below 5 eV. This is consistent with the observation in the ASDEX Upgrade divertor of I–V characteristics with slopes of $I_{\mathrm{sat}}/(1\,\mathrm{V})$ at all densities and a 2 mm return current perpendicular scale length.

It is important to point out that no "anomalous" diffusion was added to the MHD equations, as has been done in some other analyses [4,6,7]. Tokamak scrape-off layers are known to exhibit strong turbulence with a scale length of about 1 cm, which can be understood in terms of nonlinear solutions of the MHD equations. On a scale larger than 1 cm, the effects of this turbulence may well be described by an anomalous diffusivity. A Langmuir probe with a perpendicular dimension of only 1 mm, on the other hand, does not see turbulence, but only a more or less uniform convection of the plasma which changes its direction with time.

V. IMPLICATIONS FOR ANALYSIS OF PROBE DATA

Whether a correction is necessary to account for bulk resistivity is closely related to the question of whether the perpendicular extent of the probe is larger or smaller than a characteristic scale determined by plasma parameters. We have estimated that probes used in tokamaks are typically smaller than this scale, but not necessarily by a large factor, so moderate corrections may be necessary. We have also suggested that the ratio of electron to ion saturation current may be an indication of the ratio of characteristic scale to probe size. If this is so, then the temperature determined from the slope near floating and the saturation current might have to corrected downward more strongly when the current ratio is low. If the I–V characteristic is evaluated as that of an asymmetric double probe [8], this will occur automatically. In fact, where they showed lower current ratios, the measurements made with the TPA and the CBP both showed higher apparent temperatures as determined by a traditional analysis using the data below or near floating. A double probe analysis shows a constant temperature (Fig. 3) in both data sets, regardless of whether the data are taken from the small probe or large probe branch. Whether or not the fluid analysis above is the entirely correct explanation, this establishes empirically that the double probe analysis is a necessary and adequate procedure for I–V characteristics with low electron current.

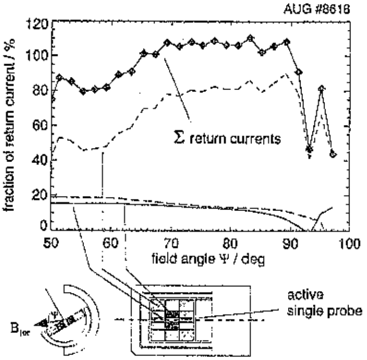

Fig. 1: *measurement of return currents*

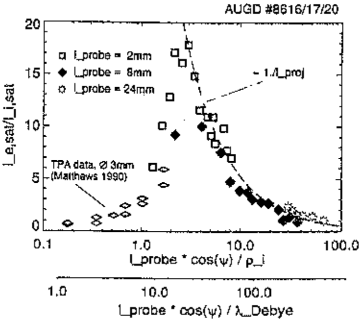

Fig. 2: *current ratios at different projected probe sizes*

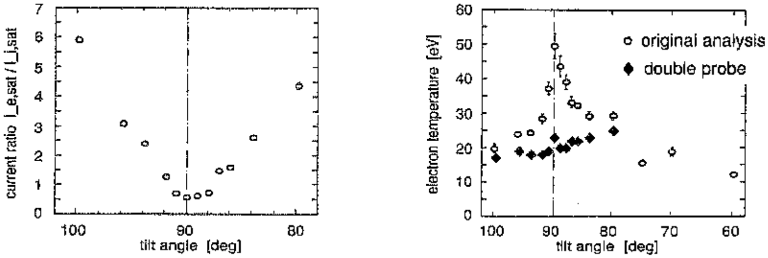

Fig. 3: *small current ratios require a double probe analysis to reproduce constant plasma parameters (TPA data points marked with open circles are out of [3]).*

[1] WEINLICH, M., report IPP V/64 (1995), Max-Planck-Institut für Plasmaphysik.
[2] CARLSON, A. et al., Journal of Nuclear Materials (1996), Proceedings of the 12th International Conference on Plasma Surface Interaction, to be published.
[3] MATTHEWS, G. et al., Plasma Physics and Controlled Fusion **32** (1990) 1301.
[4] ROZHANSKY, V. et al., Contributions to Plasma Physics **36** (1996) 391.
[5] CARLSON, A. et al., in *Europhysics Conference Abstracts* (1993) 17C/III, pp 1103.
[6] GÜNTHER, K. et al., Contributions to Plasma Physics **34** (1994) 484.
[7] GÜNTHER, K., in *Europhysics Conference Abstracts* (1995) 19C/I, pp 433.
[8] WEINLICH, M. et al., Physics of Plasmas **4** (1997) 2151.