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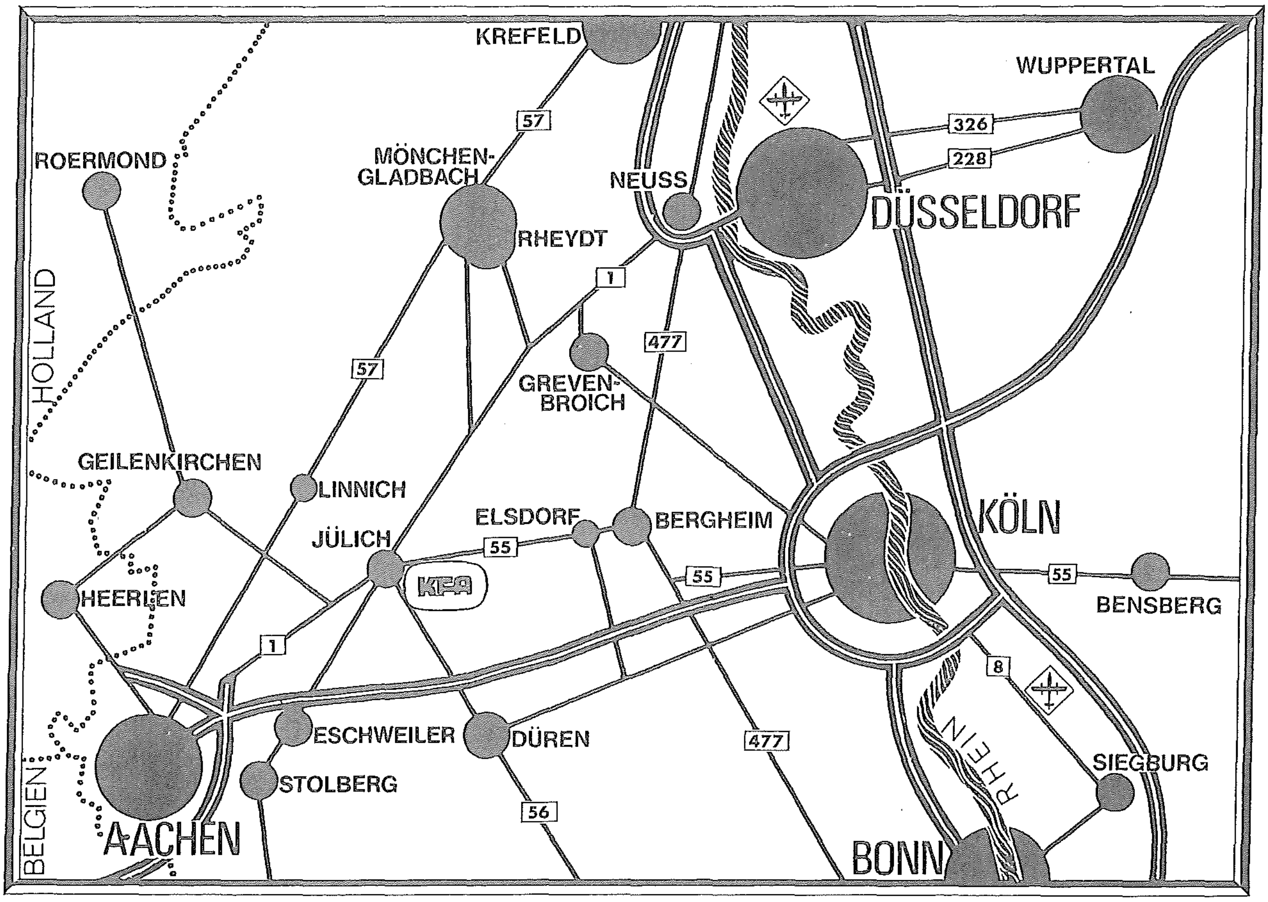

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H. Gratzl

ON PLASMA SCRAPE-OFF IN AXIALSYMMETRIC DIVERTOR

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In a toroidal guiding center plasma with hot ions and cold electrons at surface, the plasma scrape-off layer is computed from the drift orbits of magnetically untrapped ions that do not reach the collector plates of an axialsymmetric divertor. The scrape-off thickness is of the poloidal Larmor radius (R_p) order.

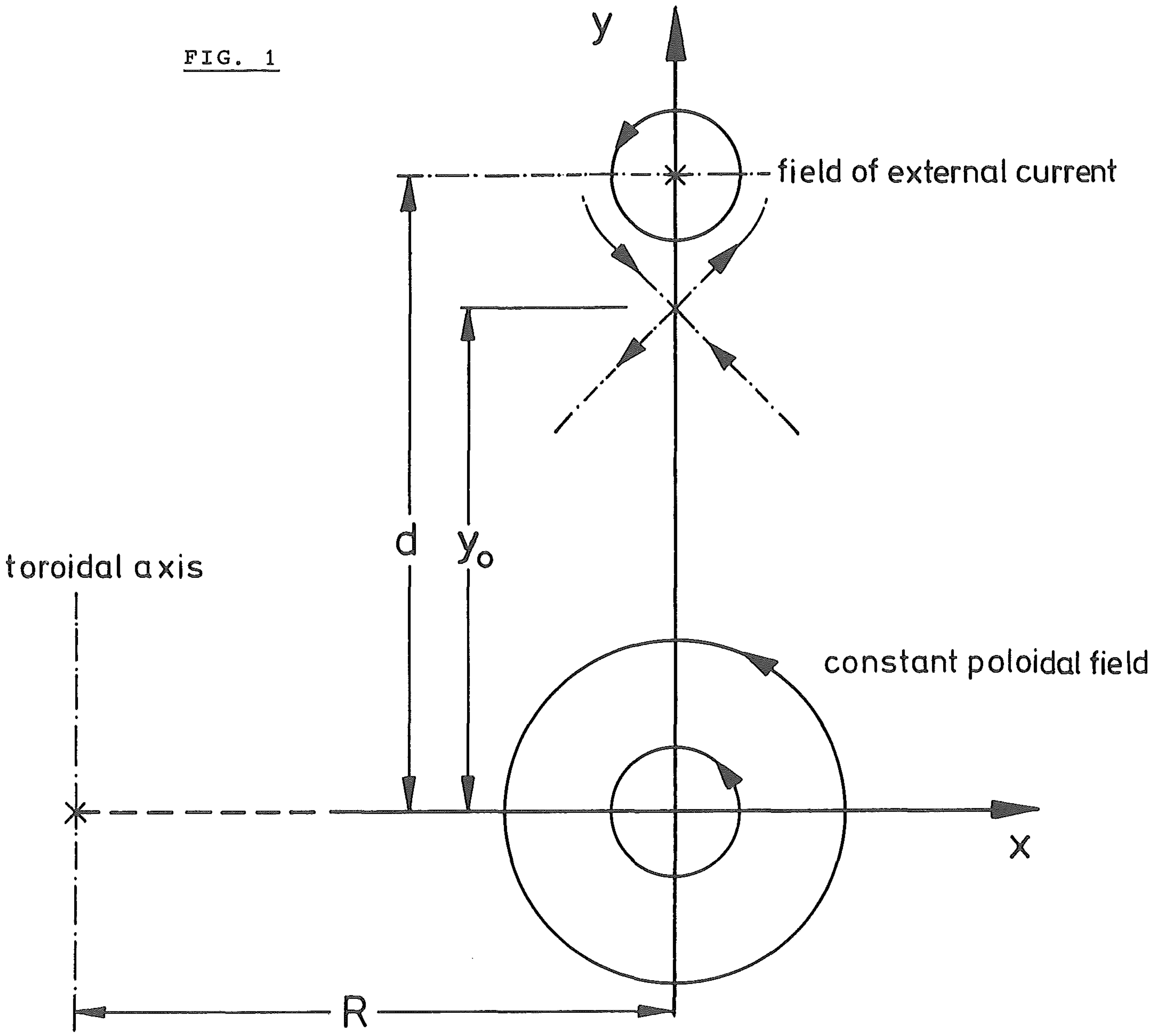
INTRODUCTION

The divertor should reduce the impurities in toroidal plasmas. The surface then is limited by magnetic field lines guiding to the collector plates of the divertor chambers, the separatrix dividing these and the interior magnetic field lines which are confocal, deformed circles in the projection into the poloidal plane. The thickness of the plasma surface layer along the separatrix can in a fairly wide range be obtained by the guiding center theory as will be shown.

If the ions can be assumed hot and collisionless and the electrons cold and collisional, the ions do not move strictly along the field lines, because of the toroidal drift. The electron distribution is obtained from quasi-neutrality [1].

Whereas for a constant poloidal field component the orbits of the untrapped ions are obtained easily [1,2], the motion close to the neutral point is to be evaluated numerically as in the following example.

FIG. 1



Model of the poloidal magnetic field, vanishing at y_o.

1) The ion orbits in the magnetic field model

In the poloidal plane, a constant basic magnetic field is chosen. The magnetic field of a toroidal line current at $y = d$ ($x = o$) is added, so that the poloidal magnetic field vanishes at $y = y_o$ ($x = o$). The poloidal field line through this neutral point will be called 'separatrix', with rectangular branches through the neutral point.

The parallel velocity in the poloidal projection is

$$\frac{B_p}{B_t} V_{\parallel} \left\{ = \frac{\iota}{2\pi} \frac{r}{R} V_{\parallel} \right\},$$

$V_{\parallel}$ being approximately constant under the assumption $B_p^2 \ll B_t^2$. In the following equation (1), the toroidal field quantity B_t does not appear.

Since the toroidal drift from the $(R + x)^{-1}$ dependence of B_t is

$$W_g = - (\Omega_p R)^{-1} \left(V_{\parallel}^2 + \frac{V_{\perp}^2}{2}\right) \frac{B_p}{B_t},$$

the ion trajectory is

$$\frac{d_y}{d_x} = \frac{B_y + \frac{W_g}{V_{\parallel}} B_t}{B_x}, \qquad (1)$$

$\Omega_p = \frac{eB_p}{M}$ being the poloidal Larmor frequency.

Equation (1) is used to calculate the ion orbits near the separatrix in order to obtain the scrape-off thickness. In the case of a constant poloidal field $B_p = \sqrt{B_x^2 + B_y^2}$, the solution is, using polar coordinates,

$$r(\vartheta) - r_o = -a \frac{W_g B_t}{V_{\parallel} B_p} \cos\vartheta, \qquad (2)$$

where the radius is assumed (along the separatrix) to be approximately a. Furthermore, $r(\vartheta) = r_o$ at $\vartheta = \frac{\pi}{2}$, i.e., for x = o.

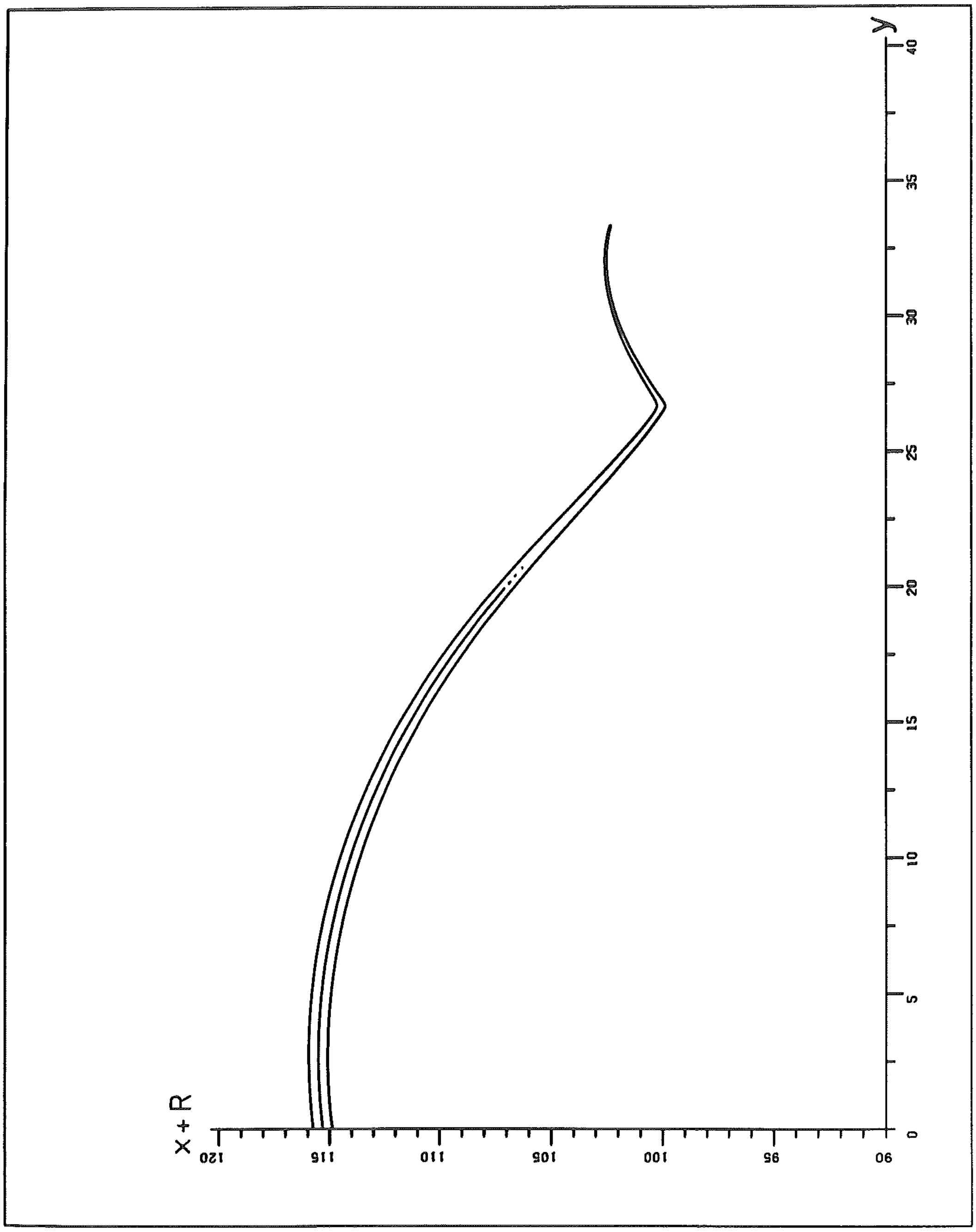
In a model with the orbits (2), the collector plate at x = o is hitting the plasma surface at the very point where the marginal trajectories (2) converge which divide the phase space region of confined and lost ions. At this singular point, collisions broaden the sharp transition to a finite scrape-off width [1].

However, collisions need not be considered for the scrape-off thickness if the trajectories are calculated with the slightly more realistic poloidal field of figure 1. Here the scrape-off layer becomes thinner at the neutral point of the poloidal magnetic field at $y = y_o$ only by a factor of about 1/2 (compared with the thickness at x = o), but the adjacent flow in the divertor chamber becomes thinner (in its center by a factor 1/1o).

Therefore, collisions would first change the width of this flow in the vicinity of the divertor plates.

However, only untrapped ions are considered for the scrape-off layer and the intercept is calculated for ions moving parallel or antiparallel to the sepåratrix. This scrape-off layer is important for the divertor flow which is generated by collisioned scattering of the ions of this layer [1] . But the density gradient in the scrape-off layer may be modified by trapped ions.

FIG. 2



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y =	o	26,65	32,oo	33,35
separatrix	15,31	oo,11	o2,63	o2,41
x_1	14,88	- oo,o7	o2,59	o2,39
x_2	15,74	oo,31	o2,67	o2,44

2) Scrape-off in a numerical model

The marginal ion trajectories are computed from eq. (1) with the values $V_\perp^2 = V_\parallel^2 = V_{th}^2$ and $R \cdot R_p^{-1} = \Omega_p(o) R\, V_{th}^{-1} = 5o$ and for the magnetic field depicted in figure 1, with the values $d = R/3$ and with the point of vanishing poloidal field at $y_o = \frac{4}{15} R$, the major radius R of the plasma torus being normalized to unity times 1oo, in figure 2.

Since for simplicity only one divertor chamber, in the upper half-plane ($y > o$), is added to the constant poloidal magnetic field, the field is slightly unsymmetric close to $y = o$.

The ion trajectories in figure 2, for both signs of $V_\parallel$, end at the divertor plates, but are almost marginal: nearly all trajectories closer to the coordinate axis $x = o$ are not remaining in their half-plane after passage through the area around y_o, since they are confined. The marginal trajectory is split into branches as is the separatrix, but not quite mirror symmetric (as is the separatrix) to $x = o$ (see also Appendix).

The marginal trajectories of figure 2 are o,22 R_p away from the separatrix at $x = o$ (R_p = 2,o being the maximum poloidal Larmor radius). At the neutral point $y = y_o$, this distance (for both signs of $V_\parallel$) is o,1 R_p, becoming smaller in the divertor chamber. The value o,1 R_p is also obtained analytically (Appendix).

Whereas the overall scrape-off thickness agrees thus with the model of Ref. 1 derived from the orbits (2), the details differ:

At $y = o$ the layer is slightly thinner, but differing only by an order $1o^{-1}$. However, due to the parallel velocity depending on the toroidal radius, the layer becomes thicker to this order (see Appendix) in any model that considers this dependence. Close to $y = y_o$, but not in the divertor chamber, the thickness is also of the poloidal Larmor radius order. Such a flow in the divertor chamber is only present due to collisional scattering (into the loss cone), of course.

A numerical uncertainty arises at the branching point of the computed trajectories near $y = y_o$. The exact branching point seems to be difficult to define numerically, unless some finite connection length, say by collisions, is considered. But this uncertainty is generally of smaller order und thus not of interest for the results obtained.

However, close to $y = y_o$ the field lines and the trajectories are much more spaced. Therefore, the rounding errors and/or the small distance from the exact marginal trajectory yield a larger numerical unaccuracy near $y = y_o$, but not elsewhere, as is found from varying the parameters involved.

From the analytic estimate of the Appendix, the x-values of the numerical trajectories near $y = y_o$ in figure 2 are believed to be too much on the negative side by about $1 \cdot 1o^{-1}$ (equal to $o{,}o5\ R_p$).

CONCLUSION

It was shown how the scrape-off layer is determined by the guiding center model. Around the neutral point, but not for the flow within the divertor chamber (which itself is to be induced by collisions), the boundary layer is of the poloidal Larmor radius order. The thickness of the divertor chamber flow is minimum close to the divertor plates, the detailed magnetic field configuration near the collector plates therefore is of interest.

However, also the stability of the scrape-off loss-cone distribution may be investigated, e.g., against Kelvin-Helmholtz instability [3]. Moreover, near the neutral point, an instability might change the collision induced flow to the convertor plates [1]. Our numerical evaluation did also indicate such an uncertainty, i.e., of the exact branching point between a contained and diverted ion trajectory, but this can possibly be remedied by introducing collisions which provide for a finite transition area (instead of a single point).

In figure 2, only the diverted branch is shown, but we checked also numerically that the scrape-off layer is symmetric with respect to x = o. A variation of the toroidal field is not taken into account, except for the gradient drift.

ACKNOWLEDGEMENT

G. Giesen computed the ion trajectories.

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APPENDIX

Scrape-off near the neutral line

As a result of the varying poloidal field, also the branching points of the marginal trajectories with different parallel velocities ly apart. In a constant poloidal field, these orbits have only different centers, according to equation (2).

In a distance from the neutral point $x = o$, $y = y_o$ which is smaller than a poloidal Larmor radius $R_p = V_{th} \Omega_p(o)^{-1}$, the expansion of equation (1) yields:

$$\frac{d_y}{d_x} = \frac{R + \Delta R \cdot o{,}16\, d - x}{y_o - y} \qquad \text{(A1)}$$

$$\Delta R = \frac{W_g}{V_{\parallel}} \; \frac{B_t}{B_p(o)} \;;$$

where the following poloidal magnetic field is used,

$$B_x = B_p(o) \cdot \left[\frac{y}{\sqrt{(x-R)^2 + y^2}} + \frac{1}{5} \; \frac{y - d}{(x-R)^2 + (y-d)^2} \right]$$

$$B_y = B_p(o) \cdot \left[\frac{R - x}{\sqrt{(x-R)^2 + y^2}} + \frac{1}{5} \; \frac{R - x}{(x-R)^2 + (y-d)^2} \right]$$

with $\qquad y_o = \frac{4}{5} d \;, \; d = \frac{R}{3} \;, \; R \equiv 1oo.$

The integration of (A1) yields for $W_g = o$ the separatrix (through the point of neutral poloidal field). The ion trajectories obtained for $W_g \neq o$ are parallel to the separatrix in a distance of $|\Delta x| = \frac{1}{625} R = o{,}o8\ R_p$, using the numerical values of section 2. Also from the numerical computations $1o^{-1} R_p$ is obtained for the distances, but with an x-coordinate shift of about $o{,}o5\ R_p$ due to the numerical problems close to $y = y_o$.

If the variation of the parallel velocity on the toroidal radius is considered, $V_{\parallel}^2 = V_{\parallel}^2\ (x = o) + V_{\perp}^2\ (x = o)\ \frac{x}{R}$, the excentricity ΔR of the orbits is increased to $\frac{7}{6} \Delta R$.

Furthermore, the tangent of the angle between the branches near $y = y_o$ is decreased to $1 - \frac{\Delta R}{6}$.

Although electric fields are small in the scrape-off layer [1], they shift the branching point of an ion trajectory, so that in the case of thermal velocities also equation (A1) is no longer valid around this point.