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Flow measurements in the edge plasma of Tore Supra

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Abstract

In recent years, the measurement of flow velocity of the plasma in the edge of tokamaks has gained in importance. The determination of this parameter is often done using electrostatic probe systems such as Mach probes or Gundestrup probes. A Gundestrup system was recently commissioned in Tore Supra. The perpendicular ($U_\perp$) and parallel ($U_{//}$) components of the velocity are determined from the six ion saturation currents using a neural network. The neural network was trained using ion saturation currents obtained from a two-dimensional kinetic code developed at Tore Supra. We will describe the Gundestrup probe and the neural network training, validation and implementation. Preliminary measurements in ergodic divertor discharges show $U_{//}$ and $U_\perp$ profiles that exhibit small-scale spatial modulations similar to those reported for the temperature profiles.

Keywords: Ergodic divertor; Flow; Langmuir probe

1. Introduction

The past decade has seen a growing interest in measuring the plasma flow speed in the edge and SOL of fusion devices. This interest is motivated by the role that plasma flows are suspected to play in the control of impurities and in the advanced confinement scenarios in magnetic confinement devices. The understanding of the edge and divertor physics is incomplete without the knowledge of the plasma flows and the understanding of the physical mechanisms that drive them. It has been suggested that these flows may even explain some properties of the tritium retention in JET [1].

These flows can be measured using different techniques. For example, one way is to use spectroscopy to measure the Doppler shift of impurity radiation. This technique is an indirect measurement of the speed of the main plasma ions. Indeed, the result rests on the assumptions made on the slowing down time between main ions and the impurity ions [2]. Electrostatic probes have been extensively used to perform flow measurements. Referred to as Mach probes, they consist in a pair of collectors, usually flat, isolated or hidden from one another facing in opposite directions and aligned with the magnetic field [3,4]. With this collection geometry, Mach probes are capable of determining the flow parallel to the magnetic field but are insensitive to the presence of a perpendicular component.

More recently, a probe array called Gundestrup has been introduced to measure both components of the flow [5]. In the present paper, we describe a Gundestrup type probe that was designed, manufactured and used in Tore Supra. The probe head composed of six equally spaced graphite collectors encased in a carbon-covered boron nitride housing was installed on one of the existing fast scanning probe drives on top of the machine.

For this experiment the velocity components were deduced from the ion saturation currents of the collectors using a neural network trained using the predictions of a particle in cell (PIC) code developed at Tore Supra.

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2. The principle

The Gundestrup probe consists of an array of flat collectors distributed around a cylindrical insulating post. Two opposite collectors aligned with the magnetic field act as a standard Mach probe. All collectors are used to plot a polar diagram (Fig. 1) of the ion saturation current. Horizontal asymmetries are related to the parallel component while vertical asymmetries are a measure of the perpendicular component.

An intuitive model was proposed by MacLatchy et al. [5]. In this approach, it is assumed that for a flat collector at an angle with the magnetic field, the collected ion saturation current is a simple sum of three contributions: the parallel flux to the collector along the flux tube that it subtends, cross-field diffusion into the flux tube and a perpendicular flux due the perpendicular velocity. In more recent work, Van Goubergen et al. [6] have shown that the situation is in fact more complicated. In a 1D analytical model, an extension to Hutchinson's model, the authors show that the collected current becomes a measure of the perpendicular velocity through the modification of the boundary conditions at the sheath edge. A comparison of the ion saturation current obtained from the two models shows a good agreement for orientation of the collecting surface close to perpendicular to the magnetic field but a marked difference for orientations away from the perpendicular.

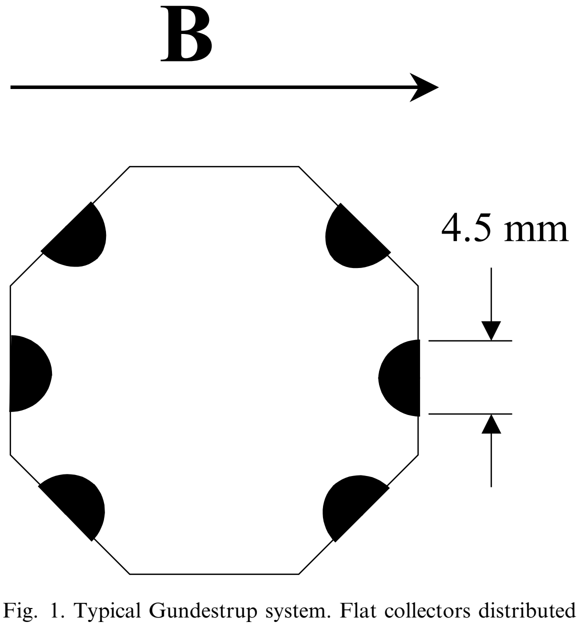

Fig. 1. Typical Gundestrup system. Flat collectors distributed around a post with two opposite collectors aligned with the magnetic field and acting as a Mach probe. In the case of the Tore Supra system, the collectors are 4.5 mm wide by 6 mm long.

Interpretation of the data obtained by a Gundestrup probe requires a non-linear fitting of the current from several collectors. Such algorithms require rather long computation time given the large amount of data and can therefore pose a problem in situations where real time calculations must be performed as is the case for long shots (at least several minutes) in Tore Supra. In what follows, we describe the use of the results of a PIC simulation to train a neural network to extract the values of the velocity components from the shape of the polar diagrams.

3. The PIC code

The PIC code used was described in [7]. The code supposes that the Larmor radius of the ions are small compared to the probe dimensions such that only the collisionless motion of the guiding centres needs to be considered. The parallel electric field is determined from the electron parallel momentum equation in which the electron density is replaced by the ion density to ensure quasineutrality [8]. The further assumption that the electron temperature does not vary in the vicinity of the probe ensures that electrons need not be included in the simulation. Along with the parallel motion of the ions, two types of perpendicular or cross-field motions are considered. First, diffusion is included in the form of a random walk and second, a constant perpendicular velocity $U_\perp$ is imposed on all the ions to simulate the effect of an $E \times B$ drift. The perpendicular diffusion coefficient used is 1 m^2/s although the results are rather insensitive to this value because the cross-field motion is dominated by convection. The modified Bohm criterion [9] arises naturally in the PIC simulation, confirming the fluid model of Van Goubergen. The cylindrical collector is segmented into 360 collectors. When an ion reaches one of the segments, it is assumed to be neutralized and the current is calculated. A continuous polar diagram results and is illustrated by the continuous line in Fig. 2. The PIC code was validated by comparing the results for zero perpendicular drift with classical mach probe theory (Fig. 3).

4. The neural network

The polar diagram for a specific probe assembly is determined from the continuous diagram by averaging at the positions of the collectors over their angular extent. In the case of the device used on Tore Supra, polar diagrams for six equally spaced collectors with an angular offset of 7° to account for the typical edge safety factor at the probe location were generated.

A detailed description of neural networks is beyond the scope of this presentation, we refer the reader to a

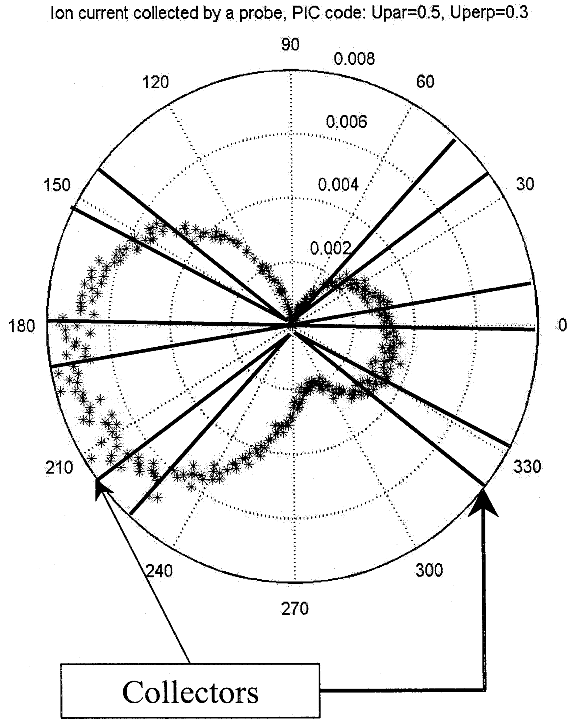

Fig. 2. The discrete polar diagrams are calculated using continuous diagrams obtained from the PIC code.

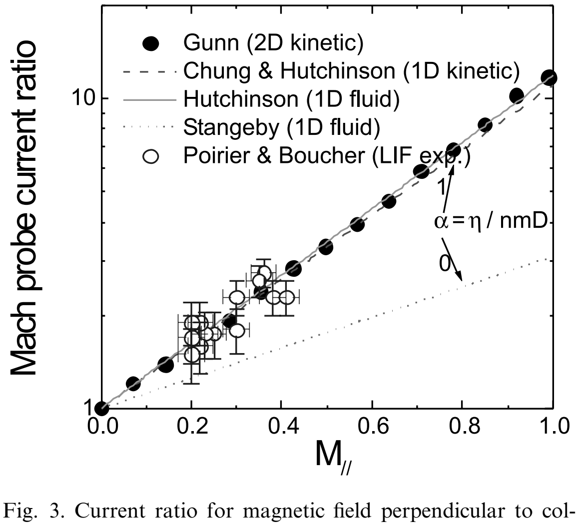

Fig. 3. Current ratio for magnetic field perpendicular to collector surface (classical Mach probe geometry) as predicted by several models and as measured [14].

complete presentation on the subject [10], however we will give in this section a brief description of the principle and the specific architecture used. It is well known that neural networks are especially useful for curve fitting when a large amount of data needs to be treated rapidly [11]. To analyse the Gundestrup diagrams, we used a multiplayer perceptron (MLP) with one hidden layer (Fig. 4) of 50 hidden units. The elements of the hidden layer are determined using the sigmoid function $f(x) = (1/(1 + e^{-x})) - (1/2)$. The neural network maps the six saturation current inputs to the two velocities ($U_{//}$ and $U_{\perp}$).

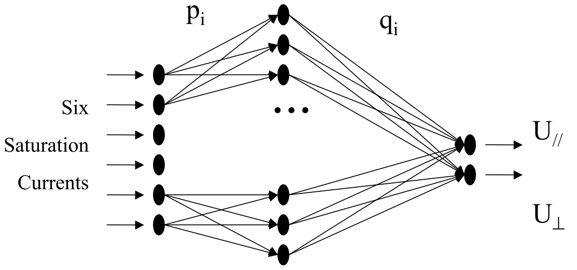

Fig. 4. Architecture of the neural network used. The coefficients p and q are the weights between the layers.

The training of the network involves determining the weights to optimize the accuracy of the mapping. This is done by minimizing the error between the output values obtained and the expected values for a given set of diagrams referred to as the training set. The error to minimize is given by:

$$E_{\rm net} = \sum_D \sum_c [U_c(I) - U_c]^2,$$

where $\sum_c$ is the sum over the two components of vector U and $\sum_D$ is the sum over the diagrams in the training set. In the above equation, $U_c(I)$ is the output of the neural network for a given set of currents I and U_c is the expected value of the components of U for these same values of currents according to the PIC code. The square of the difference between the output for a given set of weights and the expected values of the components of U are summed over all diagrams in the training set. Backpropagation was used to minimize $E_{\rm net}$ therefore determining the optimum weights for the network.

The resulting network is then validated using a different set of polar diagrams. The typical difference between the output of the neural network and the expected values for the velocity components as used with the PIC code is around 0.1, validating the capacity of the neural network to interpolate. Fig. 5 illustrates the accuracy of the values obtained using the neural network. Six values of current (squares) are given as input to the neural network and values of $U_{//} = 0.8387$ and $U_{\perp} = 0.0040$ are obtained. For comparison, the stars are the results of the PIC code for $U_{//} = 0.8$ and $U_{\perp} = 0.0$.

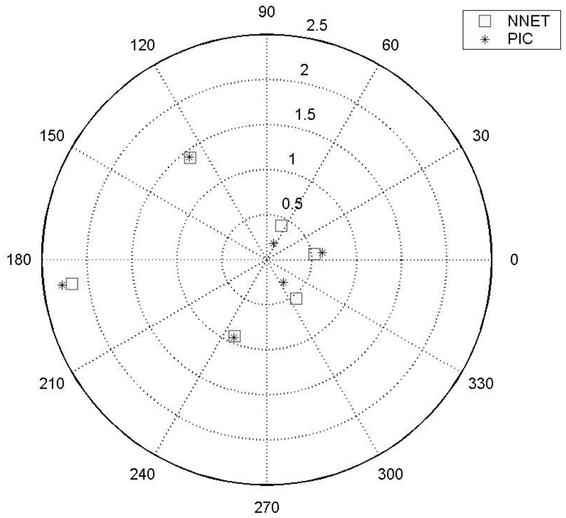

Fig. 5. The squares are the experimental current values for which the neural network gives $U_{//} = 0.8387$ and $U_{\perp} = 0.0040$. The stars are the output of the PIC code for $U_{//} = 0.8$ and $U_{\perp} = 0.00$.

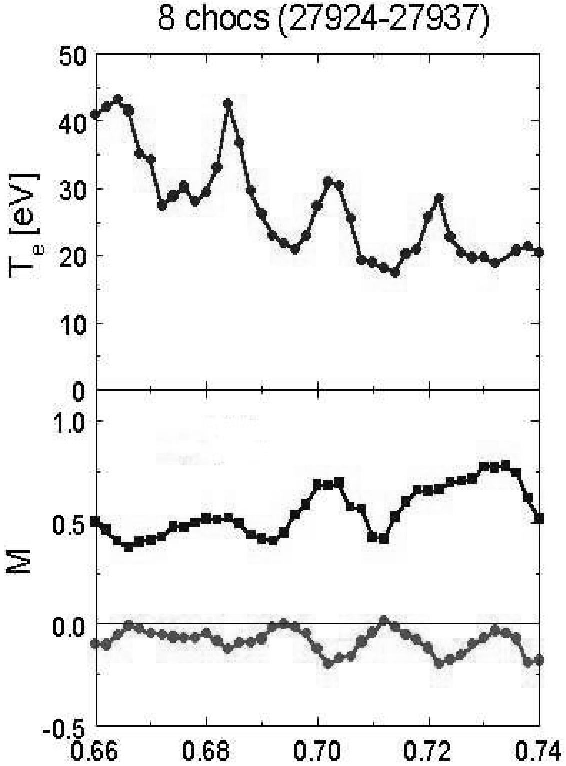

Fig. 6. Results obtained in the ergodic divertor of Tore Supra. Temperature, perpendicular and parallel Mach number profiles are given as a function of the radial position in meters. The profiles are the average of measurements taken during eight shots.

5. Some results

Fig. 6 illustrates a set of results obtained with the six pin Gundestrup used on top of Tore Supra, across the ergodic layer. The plasma parameters corresponded to the usual $q_a = 3$ resonant magnetic equilibrium adopted for ergodic divertor studies ($B_t = 3$ T, $I_p = 1.4$ MA, $I_{ED} = 45$ kA). There is an evident structure in the velocity profiles corresponding to the structure in the temperature profile. These peaks in the temperature profile were attributed to the property of the ergodic divertor that connects alternate plasma channels to successively hot (small minor radius, away from the wall) and cold (large minor radius, closer to the wall) plasma [12]. Fluctuation measurements resulting in profiles of the poloidal phase velocity exhibit similar structures [13]. This similarity in the profiles implies that the structures in the results are not caused by the variation of the connection length that would be associated with the local parallel loss time determined by the sound speed. One would have hoped to find the velocity modulations to be in phase with the slope of the temperature profile if the perpendicular velocity were given by the $E \times B$ drift. The absolute value of velocity is in fact rather low and may be within the error bars of the measurement. The principle uncertainty comes from the alignment of the pins with the magnetic field, and possible shadowing effects of the housing. In the present approach, the alignment of the pins with the magnetic field must be known to generate a discrete polar diagram from the continuous diagram calculated by the PIC code. If an offset angle different from the actual angle is taken, a different discrete polar diagram will result and the determination of the velocity components will be erroneous. A systematic analysis of possible pin misalignments needs to be performed to determine the sensitivity of the results on the angular offset. In principle, the algorithm could be modified to include the angle between a reference line through the probe array and the magnetic field so that the neural network would be trained to determine not only the velocity component but also the direction of the magnetic field. Strong $E \times B$ drifts are not expected in Tore Supra, so the fact that none were measured is not a surprise.

6. Conclusion

A Gundestrup probe was implemented in the edge of Tore Supra. The data were analyzed using a neural network that was trained using results of a PIC code to simulate the collection by the probe. This faster algorithm gave results that are consistent with the Hutchinson model for the parallel velocity component and an extended analytical model including the perpendicular component. Furthermore, the profile of the perpendicular component is consistent with the profile of the poloidal phase velocity of the fluctuations.

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