A Negative Biasing Experiment to Test Numerical Calculations Based on a Neoclassical L-H Transition Model in Stellarators

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Abstract—Numerical calculations based on Shaing's L-H transition theory in stellarators [1] and performed by Dahi *et al.* [2] determine viscosity as a function of ion flow speed in the interchangeable module stellarator (IMS) [3]. The calculations predict local maximums in viscosity at flows corresponding to Mach numbers −2 and −10, but not elsewhere. The local peaks manifest themselves as jumps in flow speed, and as regions of high radial electric field (E_r) shear. By inducting flows swept between Mach numbers ±5, an electron injection biasing probe revealed a jump at −2, but none at +2, in agreement with the numerical results. A series of flow profiles at constant bias confirmed this result. Altogether, these data agree well with the numerical calculations and provide support for Shaing's L-H transition model as applied to stellarators.

I. INTRODUCTION

THE L-H transition [4] has been induced through biasing of an electrode in the continuous current tokamak (CCT) [5], Textor [6], and Tuman-3 [7] tokamaks. It has been brought on by both positive and negative biasing, but the results are not identical. Negative biasing produced better confinement parameters in CCT and Tuman-3, while positive biasing proved better in Textor. An understanding of the role that biasing plays in the L-H transition may be important to the design of future fusion devices.

H-mode occurs when shear in radial electric field, E_r, creates a barrier to particle transport, thus improving confinement properties. As ion flows are varied, with a bias probe for example, nonlinear plasma viscosity can cause a jump in E_r and in ion flow. Since viscosity varies from magnetic surface to magnetic surface, a shear in E_r is created as the flows at different radii undergo somewhat different jumps in E_r and ion flow.

Shaing's model of the L-H transition predicts the nonlinear effect of viscosity on plasma flows, and has recently been extended to stellarators [1]. Numerical calculations for the interchangeable module stellarator (IMS) [3], based on Shaing's model, predict two regions of increased shear corresponding to a helical and toroidal peak in viscosity. The second peak appears only in stellarators, because it is caused by a lack of

torodal symmetry. A description of the calculations and the application of Shaing's model to IMS can be found in [2].

Nonlinearity of viscosity with respect to flow speed is related to resonances with toroidal and helical variations in B. In IMS, numerical calculations predict local viscosity maximums for negative ion flows of Mach number (M_p) −2 and −10, but predict linear viscosity for positive flows [2]. (Here, M_p is the poloidal flow velocity normalized with respect to ion thermal velocity, $M_p = -cE_r/B_p\nu_t$, with B_p being poloidal magnetic field and ν_t the thermal velocity.) The local peaks are not expected to appear for negative biasing (positive flows), as they might be expected to in a larger machine, because of the effect of the normalized ion temperature and pressure gradients, V_{pt} and V_{pp} [2].

$$V_{pp} = -\frac{c}{eNB_p\nu_t}\frac{dp}{dr}, \quad V_{pt} = -\frac{c}{eB_p\nu_t}\frac{dT}{dt}. \quad (1)$$

Density and ion temperature gradients induce flows in the same direction as a positively biased probe, and in doing so cause asymmetry for positive/negative flow inducement. These gradients might be ~0.1 and 0.2 in a large machine, producing only a small asymmetry, but are in the range of 1.1–1.3 in IMS, where the asymmetry is more pronounced.

The presence of the two local viscosity maximums at $M_p =$ −2 and −10 has been confirmed for positive biasing by Dahi *et al.* [2], both through sweep shots, where the bias is swept during a shot, and constant bias shots, where the bias is held constant during a shot, but changed from shot to shot.

The purpose of this paper is to determine whether such local peaks in plasma viscosity are seen for negative ion flows, or as the model predicts, they are not. An observation of linear viscosity for flows induced by negative biasing will confirm the numerical calculations, and in so doing, will provide support for the model on which those calculations are based. This model (Shaing's) might then be applied to other machines, helping either to explain current experimental results, or to predict the results of future experiments.

The functional form of viscosity can be investigated through measurements of ion flows as torque, induced through a bias probe, is varied. To see this we start with the steady-state surface-averaged poloidal momentum balance equation (see [2] for a more complete derivation)

$$\langle B_p \cdot \nabla \cdot \overleftrightarrow{\pi} \rangle + \upsilon_{\text{eff}} NM \langle B_p \cdot V \rangle + \frac{B^\theta B^\zeta}{c}\langle J \cdot \nabla V \rangle = 0. \quad (2)$$

Here, $\overset{\leftrightarrow}{\pi}$ is the viscous stress tensor, B_p is the poloidal magnetic field, V is the fluid mass flow, J is the plasma current density, N and M are ion density and mass, respectively, V is the volume, ν_{eff} is the effective ion–neutral collision frequency (charge exchange), and B^θ and B^ζ are poloidal and toroidal contravariant components of the magnetic field, respectively. The third term in (2) is the drive term (torque due to ion orbit loss or external bias current). The first and the second terms are damping terms due to viscosity and ion–neutral collisions. In the Hamada coordinate system [8], these two terms are given by

$$\frac{\langle B_p \cdot \nabla \cdot \overset{\leftrightarrow}{\pi} \rangle}{NM\nu_t^2\chi'} + \nu_{\text{eff}}\frac{\langle B_p \cdot V \rangle}{\nu_t^2\chi'}$$

$$= \sqrt{\pi} \sum_{\substack{m,n=-\infty \\ m \neq 0}}^{\infty} \epsilon_{mn}^2 m^2 [I_{mn}(M_p - V_{pp}) + L_{mn}V_{pt}]$$

$$+ \nu_{\text{eff}}\frac{R_0\epsilon^2}{q\nu_t}(1 + 2q^2)(M_p - V_{pp}) \tag{3}$$

where

$$\left\{\begin{matrix} I_{mn} \\ L_{mn} \end{matrix}\right\} = \frac{1}{4\pi(m - nq)} \int_0^\infty dx\, x^2 \exp(-x)\left\{\begin{matrix} 1 \\ x - 25 \end{matrix}\right\}$$

$$\cdot \int_{-1}^1 dy(1 - 3y^2)^2 \frac{c_1'}{y - c_2')^2 + c_1'^2}$$

and

$$c_1' = \frac{\nu_T}{(m - nq)\nu\chi'/B}, \qquad c_2' = \frac{mM_p}{(m - nq)\sqrt{x}}$$

m and n are the poloidal and toroidal mode numbers, $y = \nu_\parallel/\nu$, $x = \nu^2/\nu_t^2$, and $q = \epsilon_t(B/B_p)$.

By inspecting (2) and (3) we can see that we have an equation relating a driving term, bias current, with viscosity, which is given as a function of M_p. By measuring flow at different biases, we determine the relation of flow (M_p) to bias, and by extension the dependence of viscosity on M_p.

II. EXPERIMENTAL SETUP

A. General Experimental Description

IMS [3] is a seven-field period, $m = 7, \ell = 3$ modular stellarator (major radius (R) = 0.4 m, minor radius (a) = 0.04 m, $\iota_0 = 0.0, \iota_a = 0.6$) with typical electron cyclotron heating (ECH) discharge parameters: $n_e = 2$–2.5×10^{11} cm^{-3}, $T_e \sim$ 18 eV, $T_i \sim 6$ eV, $B_0 = 0.3$ T, ECH power (P_{ECH}) up to 5.5 kW at 9.31 GHz with a 10-ms pulse length. We used hydrogen gas puff pressures of 18, 40, and 164 μtorr. Preionization was necessary at 18 μtorr to produce plasma. Measurements of plasma electron temperature and density, plasma potential, ion temperature, and poloidal and toroidal ion flow velocities were made using a Langmuir probe, grided energy analyzer (GEA), and Mach probe, respectively. A 28-GHz microwave interferometer provided line average densities.

The Langmuir probe was used to measure both T_e and n_e and the plasma and floating potentials, V_p and V_f, which in turn allow E_r, and by extension M_p, to be calculated. The choice between the V_p and V_f was determined by whether or not the bias on the bias probe was held constant during a shot or swept during the shot. To provide accurate readings of V_p, we swept the bias of the Langmuir over a range of 160 V at 1 KHz. The current and voltage signals were sorted and smoothed over a period of 3–8 ms so that an average I versus V curve could be produced. T_e, N_e, and V_p could then be found by fitting an exponent and line to the curve [9]. The standard deviation of repeated measurements indicated that this method was accurate to about ± 1 V, leading to an error in derived Mach number of ± 0.8.

Poloidal and toroidal flows were also determined using a Mach probe. Two shots were taken with the probe rotated by 180° in-between shots. The flows could then be derived using routines based on the equations described by Peterson et al. [10]. We found these values to be less accurate than the flow values derived from V_p, so we used the Mach probe mainly to confirm the qualitative shape of flow profiles derived from V_p and to look for changes in flow in the dynamic signals produced during swept bias shots. By noting the location of jumps during bias sweeps, we determined the choice of biases for constant bias shots.

Ion temperature measurements, which were necessary to run the numerical models, were performed using a grided energy analyzer (GEA). The GEA [11] consisted of four grids biased to different voltages in order to first repel electrons and then repel ions with a swept voltage. When the current measured on the last grid is compared with the repelling voltage, the energy distribution of the ions can be determined. The error in ion temperature determination was low (~ 1 eV) for the outer 2 cm of plasma, but much higher inside where the signal became very weak.

B. The Biasing Probe

We used a biasing probe located at the plasma edge to induce both positive and negative radial electric currents, and to preionize the plasma. The probe was capable of inducing both positive and negative biasing in the same shot, allowing comparison of the two flow directions without the effect of shot to shot differences. Preionization was necessary at low neutral densities (18 μtorr) in order to make plasma. The probe, pictured in Fig. 1, consisted of a 2 $\times$ 10 mm iridium filament coated with thorium oxide and clamped between graphite holders which were in turn mated to copper feedthroughs. The graphite was necessary to prevent the copper feedthroughs from melting at the filament temperature. The whole assembly, except the filament, was coated with boron nitride paint to isolate it from the plasma.

A constant current, generally about 9 A, was run through the filament to preheat it. Three seconds before a shot was taken this was increased by about 15% to bring the probe to emission temperature. The heating circuit floated relative to the machine ground, allowing the net filament bias to be controlled separately. The biasing circuit either added a constant dc bias during a shot, or was swept during the shot. The bias ranged from ± 300 V for <1 A emission, to ± 200 V for <2 A emission. We maintained the heating current for both positive and negative biases to provide uniform data.
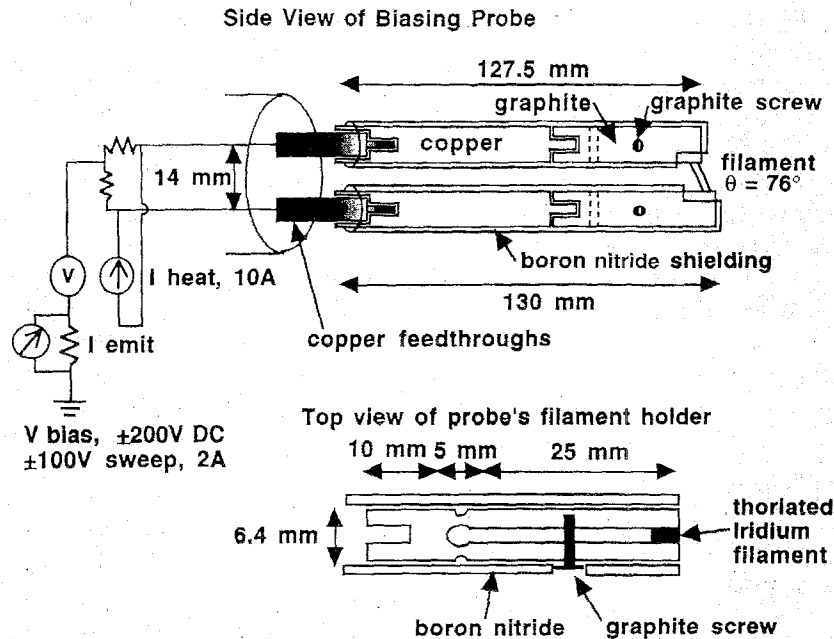
Fig. 1. The biasing probe, capable of delivering a positive or negative current of about 1 A and of sweeping from positive to negative during a single shot.

The probe proved capable of emitting up to about 900 mA with a bias of -230 V and accepting 1300 mA at $+200$ V. We did not use higher biases in order to prevent arcing between the filament and the grounded coils or vacuum vessel. With available power supplies the probe was capable of sweeping from an emission of $+450$ mA to -450 mA in a single shot.

The initial probe design was based on lanthanum hexaboride filaments, but while LaB_6 emits nicely in relatively high pressure environments (mtorr range), it did not emit at all at our working pressures (~ 40 μtorr), even with plasma present. Thoriated iridium filaments proved not only capable of emission at low neutral density, but were also easier to work with, being less brittle.

III. RESULTS

A. Ion Temperature

In order to use numerical models to predict the form of viscosity in IMS, the plasma ion temperature (T_i) and density (n_i) edge gradients must be known. $dn_i(r)/dr$ was previously measured to be 7×10^{16} m^{-4} [12]. To determine $T_i(r)$ we took several profiles at eight points covering the outer 3 cm of plasma. These were all taken at 40 μtorr, with RF powers of 5.3, 3.5, and 2.0 kW. The profiles show a gradient of almost 2 eV/cm at the edge with an experimental error of about ± 1 eV. Ion temperature approximately doubled (from 3 to 7 eV) as RF power was raised from 2 to 5 kW. For the numerical calculations, we set $T_{i\ average}$ to 6.5 eV and dT_i/dr to 2 eV/cm at the edge. This choice leads to normalized temperature and density gradients of 1.2 and 1.3, respectively.

B. Flow Versus Bias

Before looking for nonlinear jumps in flow, it was important to ascertain that we were indeed able to obtain large enough

flows in both directions to be in the regions where such jumps might be expected to occur. We took a series of shots (at 40 μtorr, RF = 4 kW) while varying emission current in small increments in order to determine the relationship between flow speed and emission (negative biasing) or absorption (positive biasing) current. The biasing probe was left at a constant $r = 41.2$ cm and the flows were measured with a Mach probe 1 mm outside of the bias probe, and by taking Langmuir probe measurements of the plasma potential at 41.0 and 41.6 cm, allowing us to estimate the radial electric field and thus determine flow speed.

Flow speed versus emission current measurements are depicted in Fig. 2. The graphs show an approximately linear dependence of flow on current between -500 and $+100$ mA. Between $+100$ and $+300$ mA there appears to be a local maximum. The flows range from Mach number -5 to $+5$, demonstrating that we should be able to see the jump at $M_p - 2$ and $+2$ if the latter exists. It is interesting to note that the flow's absolute magnitude actually decreases from $+200$ to $+400$ mA. This might seem to reflect experimental error, but it is a real effect that also appears in the Mach probe data. It can be explained by looking at flow profiles (presented later) which show that flows can decrease with increasing bias current at certain radii and for ranges of bias current corresponding to a local viscosity maximum. At the radius where the data were taken, flow actually decreases in the jump region corresponding to currents between $+100$ and $+300$ mA. We would expect flows to increase again beyond $+400$ mA, unfortunately we do not have data in that region to confirm this.

C. Sweep Shots

With the next series of shots, we sought to identify any jumps in flow as the bias was varied continuously through a range of values. Jumps should appear as spikes in the Mach
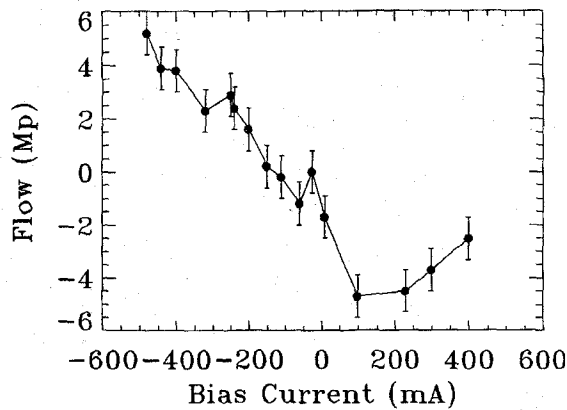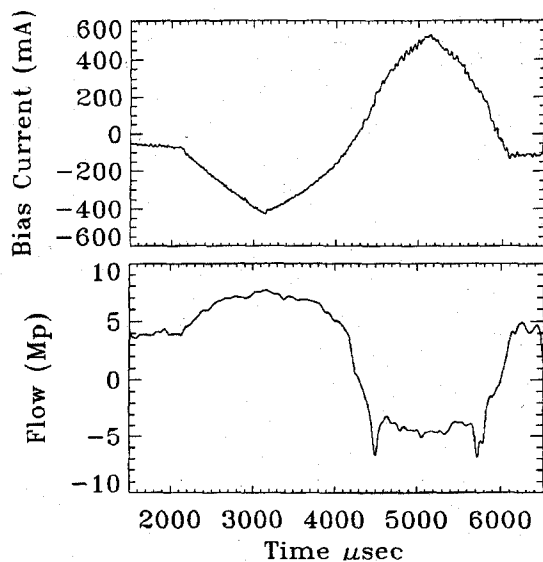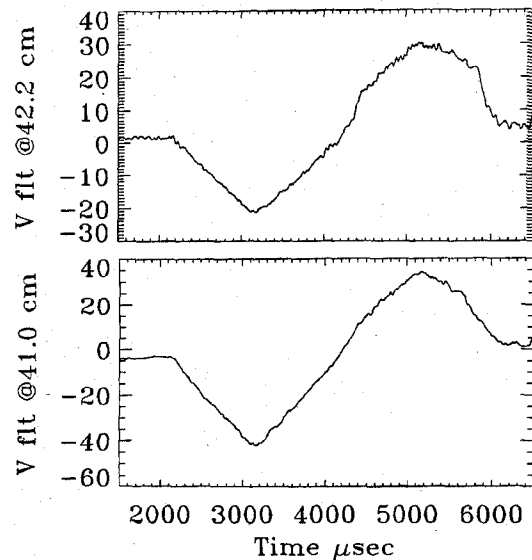
Fig. 2. Poloidal flow (M_p derived from E_r) versus bias probe current.

Fig. 3. Mach probe signal and bias current. Note spikes in the Mach signal beginning and ending at times corresponding to bias currents of $+100$ mA and $+300$ mA.

Fig. 4. Floating potentials from a Langmuir probe at two radii during a ±450 mA sweep. Subtracting the two signals gives E_r and thus flow. Spikes can be seen for the positive part of the sweep, but the negative half is linear.
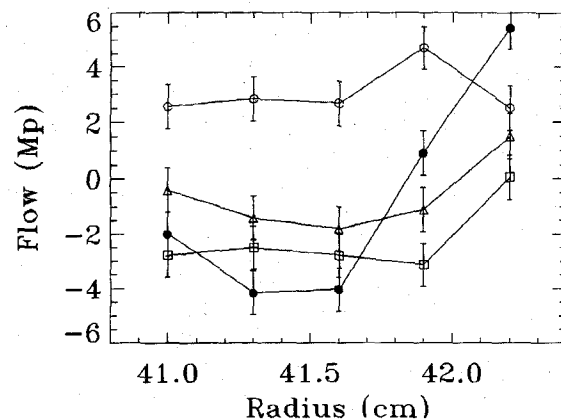
Fig. 5. Flow profiles at four different biases. Only one, corresponding to the jump at -2, shows high shear. Filled circles represent $+200$ mA bias, squares $+400$ mA, triangles 0 bias, and empty circles -200 mA.

probe signal, and as jumps in the dynamic floating potential signal. We swept the bias to vary the emission current from -900 to $+1300$ mA. Sample plots for the Mach probe signal, bias current, and floating potentials at two radii, focused on sweeps of ±450 mA, appear in Figs. 3 and 4. By noting the sudden spikes in the Mach probe signal and their location on the bias current signal below, we can see only one jump in flow beginning at about $+100$ mA and ending at $+300$ mA. This jump, which corresponds to the expected local viscosity maximum at $M_p = -2$, appears twice in the signal as the bias is swept through the range of nonlinear viscosity, reaches the sweep's maximum, and returns. The jump also appears in the floating potentials in Fig. 4. For positive biasing the outer floating potential is nonlinear with bias voltage while the inner is linear, indicating a jump in E_r, which is given by the difference between the potentials at two radii. Both floating potentials linearly follow the bias voltage for negative biasing, indicating no jumps for negative flows of at least Mach number $+5$. This is compatible with the numerical calculations which predicted nonlinear flow for positive biasing and linear

flow for negative biasing. We do not expect to see the toroidal viscosity peak at $M_p = -10$ because it is very weak at the neutral density used for these shots (40 μtorr), and because our maximum flow may not be large enough.

D. DC Profiles

We next took a series of flow profiles where the bias was held constant during a shot and varied only from profile to profile. Figs. 5 and 6 depict flows from $r = 41.0$ to $r = 42.6$ cm at RF $= 4$ kW and a pressure of 40 μtorr for a total of seven different bias currents. We note only one region with high shear in flow, i.e., a flow that changes rapidly with radius. This region (produced by bias currents of $+200$ and $+240$ mA) corresponds to the expected jump at $M_p = -2$. All of the other profiles are relatively flat, including the two taken at a point symmetric to the high shear region (-200 mA). The flatness of these profiles indicates linear flow for negative biasing, in agreement with the numerical work. If there was a jump in
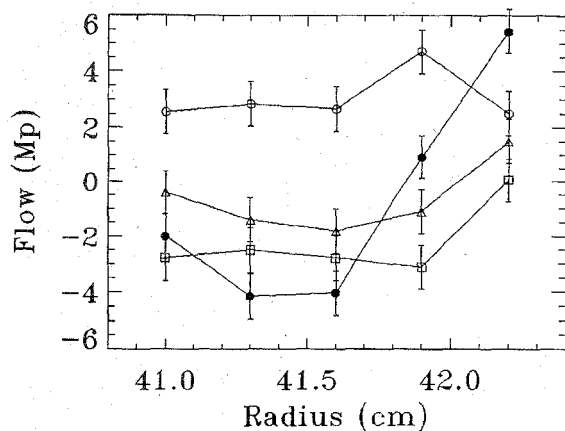
Fig. 6. Flow profiles at three other biases, confirming the result of Fig. 4. Filled circles represent +250 mA, empty circles −250 mA, and triangles 0 bias.

flow at mach number +2, it should have produced a region of high shear there.

It is also worth noting that at $r = 41.3$ cm, the flow is actually greater for a bias of +200 mA than it is for +400 mA. This is what caused the apparent decrease in flow with bias seen in Fig. 2 and described in the flow versus bias section. Had the flow versus bias measurements been taken at $r = 41.9$ cm for example, flow would have appeared more linear for positive biasing.

IV. CONCLUSION

Along with previously determined electron density profiles, new ion temperature gradient measurements allowed us to apply numerical models based on Shaing's L-H transition theory to IMS. Calculations performed by Dahi *et al.* show that viscosity should be linear in Mach number for positive flows (induced by negative biasing), and nonlinear for negative flows (induced by a positive bias), given the plasma parameters in IMS. A series of negative biasing experiments confirms this prediction. Mach probe signals recorded during swept bias shots show a single jump corresponding to the helical peak in viscosity for positive biasing. A corresponding peak is not found with negative biasing. Poloidal flow profiles, derived from plasma potentials measured with a Langmuir probe during constant bias shots, further confirm the model's predictions by revealing regions of high and low shear for positive biasing, and only low shear for negative biasing. Overall, these results agree with numerical calculations based on Shaing's L-H transition theory as applied to stellarators.

ACKNOWLEDGMENT

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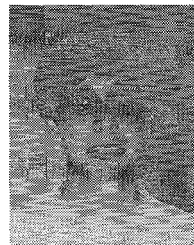
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