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3-D Hybrid PIC Code to Model the Tilt Mode in FRCs*

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The results from QN3D are presented. QN3D is a 3-dimensional hybrid particle-in-cell code designed to run efficiently on the Cray-2 Multiprocessor. The chief application has been to the tilt mode instability in FRCs.

QN3D accepts as input, the magnetic field, the ion particle density and the ion temperature on a two-dimensional r-z grid. These quantities are interpolated to the rest of the cartesian grid under the assumption of azimuthal symmetry. The particles are initialized with random numbers chosen according to the particle distributions input from the equilibrium code. The runs done here used equilibria computed by EQV, a kinetic equilibrium code developed by Dan Shumaker.

In general we would assume that the if the plasma containment vessel were far from the plasma boundary then the shape of the vessel would be of little consequence [1]. However, to facilitate modelling devices with passive mirrors we actually modelled the cylindrical wall as closely as possible.

We expect the tilt mode to be unstable when the ion gyroradius becomes small with respect to the size of the plasma. A convenient measure of this relative size is s, which is a measure of the number of ion gyroradii between the o-point and and the seperatrix. Analytically [2]

$$s \doteq \int_{R}^{r_s} \frac{r}{r_s} \frac{dr}{\rho_i(r)},$$

where R is the o-point radius, r_s is the seperatrix radius and ρ_i is the ion gyroradius. We investigated two cases, one with $s = 1.6$ and another with $s = 12$.

One easy method of viewing plasma behavior is to plot contours of constant particle density. This showed very clearly that one case tilted while the other did not (see figure 1).

Note that the tilt mode instability observed here grew out of noise introduced by the random nature of the particle intialization. *No* initial perturbation was employed to help the plasma develop the tilt.

For a quantitative diagnostic, we simulated an experimental method suggested by Michel Tuszewski of the Los Alamos National Laboratory. He suggested that we measure the Faraday rotation of a light beam shot through the plasma. The Faraday rotation of such a beam is proportional to the integral of the density multiplied by the magnetic field [3], i.e.

$$\Theta_F \propto \int n_i \mathbf{B} \cdot d\mathbf{l}, \tag{1}$$

where the integral is along the beam. From symmetry, it is clear that Θ_F is initially zero in an FRC. However, as the tilt mode develops, some rotation should be noticable. In fact, we should be able to recognize the tilt mode by the signature in a plot of Θ_F as a function of z (figure 2).

In order to pick the tilt mode signature out of the noise we fitted the simulated Faraday rotation data to a polynomial with the same signature. In particular, we used a least-squares fit to

$$f_x(z) = (Az^4 - Bz^8)e^{-(z/L)^4}$$

where L is predetermined and A and B are found by the fitting procedure. f_x is the polynomial that fits the data found from the Faraday rotation dignostic done in the x-z plane. A similar function, $f_y(z)$, was found for the y-z plane data. To get a magnitude from these functions we simply integrated the sum of the square of these functions, and then took the root, i.e.

$$|\Theta_F| \doteq \left[\int_{zmin}^{zmax} \left(f_x^2(z) + f_y^2(z)\right) dz\right]^{1/2}.$$

$|\Theta_F|$ gives us a magnitude as function of time from which we can get a growth rate. Again, The results are quite clear. The high-s case shows the tilt growing with a growth rate close to MHD predictions ($\gamma = 1.24\gamma_{MHD}$). The low-$s$ case shows only slight growth if any at all ($\gamma = .07\gamma_{MHD}$). Note that comparing the magnitudes of these numbers is not possible since in the density and magnetic fields are orders of magnitude different.

Our results compare favorably with preliminary results from Barnes, et al. [4] (see figure 3). We would not expect exact agreement since their equilibria are different and they are measuring the displacement of the flux surfaces rather than the Faraday rotation. However, the general agreement is very encouraging.

Quite fortunately, we have been able to give strong credence to our initial hypothesis that the tilt mode will exist in regimes of higher s. This result, by itself, is important for those planning to build larger FRC experiments. But, in addition, QN3D has a major advantage in that it should be able to model the nonlinear regime of the tilt mode which will be even more crucial to the future of FRC experiments.

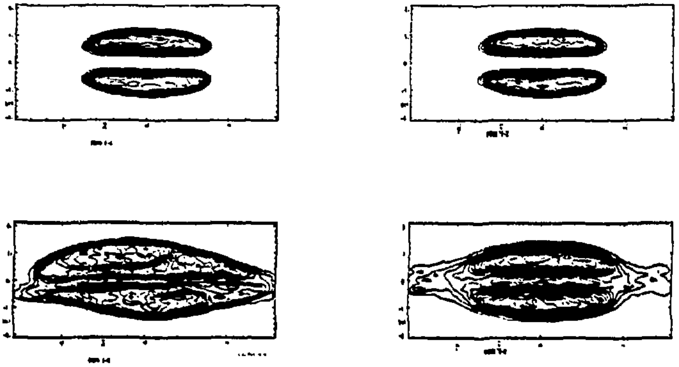

Figure 1: Surfaces of Constant Density

Top: $0\mu s$ *Bottom:* $3\mu s$

Left: $s = 12$ *Right:* $s = 1.6$

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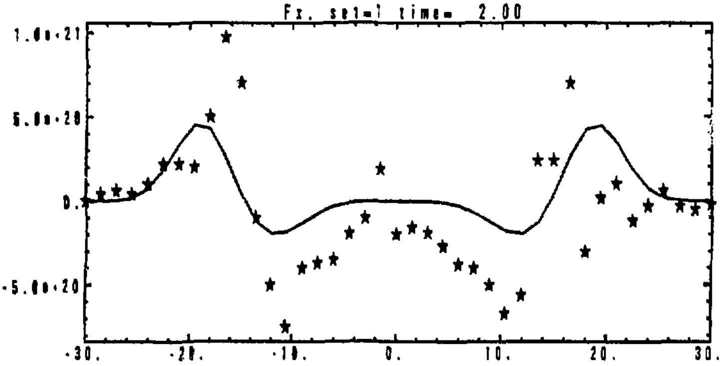

Figure 2: Expected Tilt Mode Signature from Faraday Rotation Diagnostic
Θ_F is plotted as a function of z. The stars indicate the simulation results and the curve is the polynomial fit.

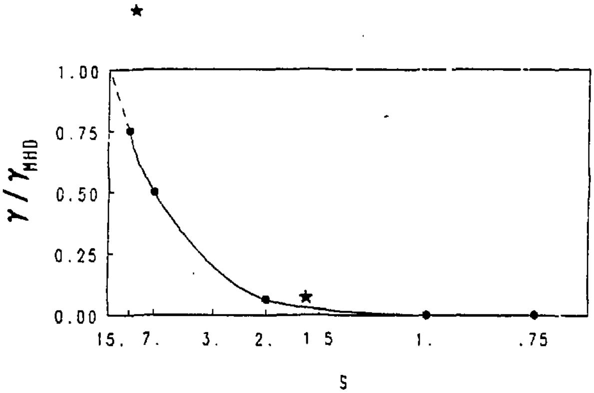

Figure 3: Barnes' Results
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