Zonal Flow measurements using an HIBP

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Abstract:
Zonal flows were detected on TEXT and TEXT-U using a Heavy Ion Beam Probe, (HIBP.) These were not understood at the time but are now. The zonal flows are characterized by radial electric field fluctuations with poloidal and toroidal mode numbers or zero, m=n=0. The measured fluctuating radial electric field is of the same order of magnitude as the profile electric field. The fluctuations are found to exist at the Geodesic Acoustic Mode (GAM) frequency. These GAM fluctuations are shown to have nonlinear coupling with the broadband driftwave fluctuations, and there are some indications of a weaker linear coupling to density fluctuations as would be expected. Zonal flows can couple power into an f = 0 radial electric field variation which has not been detected. The sensitivity of the diagnostic to the f = 0 component is presented. Also presented are a) the radial dependence of the zonal flows, and b) a discussion of why the HIBP is sensitive to the zonal flows.

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Characteristics of Zonal Flows

Radial electric fields

- With m=0 poloidal and n=0 toroidal structure
- Radial correlations are relatively short
- Electric field fluctuations occur at ω=0 and maybe at the Geodesic Acoustic Mode (GAM)
- Density fluctuations have weak (at best) linear correlation with the electric fields
- Drift wave density fluctuations are non-linearly coupled to the zonal flow electric field.

A. Why not direct measurements of E_r?

The HIBP measures the potential simultaneously at more than one location. The electric field can be determined by taking the gradient of the potential, $\vec{E} = -\nabla \Phi$ But for the TEXT HIBP, the sample volume size is the order of, or larger than, the zonal flow radial correlation length, so direct measurements of E_r, are not practical.

The HIBP has the demonstrated ability measure the plasma potential, Φ, in hot magnetically confined plasma and has been a diagnostic on many devices, (ISX-B, ATF, TEXT, MST, JIPPTII-U, T-10, and others.) For most systems, the measurements are made at 2 or more sample locations simultaneously. The sample locations can be scanned by steering the beam using electrostatic sweep plates external to the plasma, or by changing the beam energy. Ideally one would calculate E_r by locating 2 sample volumes close to each other and use $\vec{E} = -\nabla \Phi$. For zonal flows, this requires that the sample spacing be smaller than both the zonal flow correlation length, $l_c(zf)$, and the radial wavelength, $\lambda_r = 2\pi / k_r$, where k_r is the radial wavenumber. Past and present HIBP systems generally have spacing greater than a simple estimate of these terms. Using TEXT as an example, the sample spacing was the order of 2cm and the largest dimension of the sample volume was about 1cm, as shown in figure 1. $l_c(zf)$ is crudely estimated to be $5r_s$, which was the order of 0.4cm at the half radius for TEXT. The sample size and spacing make the direct measurement of E_r impractical, though an estimate could be made by using conditions where the radial separation of the sample volumes is the order of $l_c(zf)$. Even it these cases, the shape of the sample volume complicates the interpretation. Future designs can address this issue and be optimized for direct measurements.

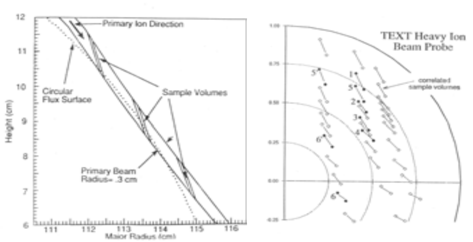


Figure 1 Sample volume size and orientation for the TEXT HIBP. Note that sample size and spacing are large compared to a crudely estimated 0.4cm zonal flow correlation length.

Why the indirect measurement works:

Despite the sample volume size issue, the HIBP is able to measure the integral of the zonal flow electric field. The integral is of direct interest if

a) the zonal flow correlation length is small compared to the zonal flow radial wave length, $l_c(ZF) < \pi / k_r(ZF)$

b) or zonal flow radial mode number is small, $k_r(ZF) \approx 0$

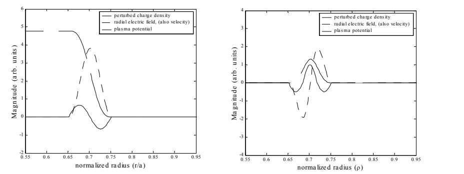
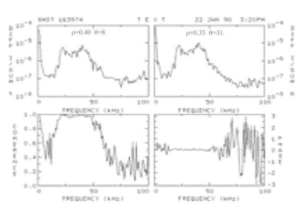


Figure 2 Model of a zonal flow. Poloidal direction is vertical, toroidal direction is into poster. Assume a simple perturbed charge distribution which is uniform in the poloidal and toroidal directions and oscillates. This creates a radial electric field (zonal flow.) The associated electric field can be calculated as well as the potential as a function of radius. Vacuum vessel used as the ground reference. The left figure shows case were internal measurements of the potential will accurately integrate the zonal flow radial electric field. Figure on right is for a case where there aren't any internal potential fluctuations from the zonal flow. The critical factor is the relation between the radial correlation length and the radial mode structure. Zonal flows form many such layers. Internal measurements of the potential will be the rms sum of the zonal flow layers.

For zonal flows, a flux surface can be looked at as a conducting shell, $E_\theta=0$ and $E_{||}=0$, the only component of E is E_r which is normal to the flux surface as it is for a conductor. View the region of a zonal flow as 2 conducting shells (2 flux surfaces) and subtract off any dc radial electric field for convenience. If charges are transferred back and forth between these shells, then an electric field oscillation will exist between the shells and nowhere else. This is a zonal flow. If one measures the potential of this system as a function of radius, using the vacuum vessel as a ground reference, there are no potential fluctuations outside of the outer shell, the potential fluctuations vary with radius between the shells, and there will be a spatially uniform potential fluctuation everywhere inside of the inner shell. If the sample location is scanned in from the edge across multiple zonal flow layers, the measured potential fluctuations will carry information about all zonal flow layers at radii greater than the sample location. Assuming the flow layers are decorrelated, the interior measurements will be an rms sum of all zonal flow layers.

If charges move between 2 conducting shells, or between two flux surfaces, then the electric field between the shells is nearly uniform. In a cylindrical system, the field would have a 1/r fall off, and for closed spaced shells this is nearly uniform. Figure 2 is a cartoon of the case where the charges separate with a sinusoidal radial distribution across a flux surface and is uniform along a flux surface. For simplicity, the profile electric field has been subtracted, and this is a slab model. For short spacing the slab model is a good approximation to the toroidal geometry.

m=0 poloidal mode structure



The fluctuations have a m=0 mode structure. If the mode were m=1 there would be a 0.4 radial phase shift.

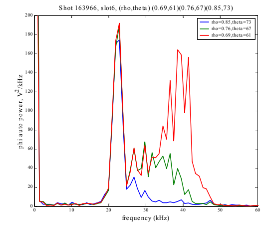
Frequency range of zonal flow fluctuations:

Theory predicts the zonal flow electric field will have 2 components, one with an average frequency of 0Hz, the other at the GAM frequency. The HIBP is capable of looking for both. **The GAM frequency has been seen, (APS 2001). The f=0Hz component has not.** The GAM frequency component lends itself to observation in machines such as TEXT because it is well above typical MHD frequencies and below the frequency of the bulk of the driftwave fluctuations.

The GAM frequency varies with radius, since it depends on the ion and electron temperature. This also aids in the mode identification, as the sample volume is scanned from large minor radius to smaller, the measured fluctuations spectra should broaden. The key point is that interior fluctuations of potential contain signal from all zonal flow layers at larger minor radii.

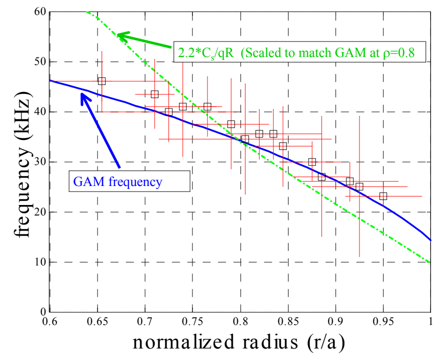
The f = 0Hz component is still measurable in that there is a frequency spread. The frequency spread can be viewed as a measure of the correlation time. There are many zonal flow layers, each with building and decaying f=0 fields, this will result in a spread of low frequency fluctuations in the interior measurements of potential. This component has not been detected looking at the TEXT data. It is suggested that future HIBP experiments be designed to allow more sensitive detection of the f=0 Hz component.

Data from the TEXT HIBP, fluctuations of potential



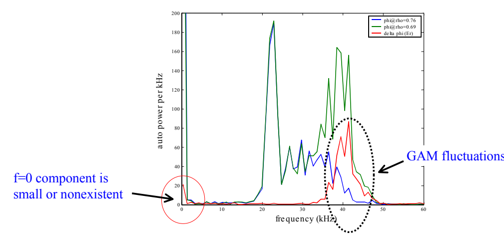
Auto power spectra of fluctuations of potential. Data from detectors are shown. As the sample location is moved radially inward, the fluctuations spectra broadens due to additional zonal flow layers. This fits the model presented.

Frequency of GAM, E_r, and MHD vs. Radius



- Frequency of measured electric field fluctuations matches the GAM frequency across the region.
- The frequency don't match that for modes associated with the parallel direction. The mismatch is both in absolute magnitude and in profile.

Determine the frequency of E_r by taking the difference between 2 sample locations



Red curve is auto power spectra of $\varphi_1 - \varphi_2$ This is measure of E_r fluctuations for radial range between two detectors, 0.69<ρ<0.76 in this case.