Zonal Flow measurements using an HIBP

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Zonal flows are of keen interest in efforts to understand transport in magnetically confined plasma. Of the well-developed diagnostics, the Heavy Ion Beam Probe, HIBP, is most suited to measure the radial electric field, E_r, associated with the flows in present medium to large devices. This paper discusses why the HIBP is capable of measuring E_r and how to design an HIBP to optimize zonal flow measurements. The TEXT HIBP is used as an example of a typical system. The NSTX spherical torus is used in a design study for future work with emphasis on zonal flow measurements. The key diagnostic considerations are 1) sample volume size, 2) sample volume orientation, and 3) the ability to rapidly scan the sample volume in the radial direction. The measurement of principal interest here is E_r but there is additional information in a nonlinear analysis of the fluctuations.

I. Introduction:

Recent publications have noted the likely importance of zonal flows as the mechanism that controls turbulence and transport in magnetically confined plasma.[1,2,3] Zonal flows have been generated in simulation codes.[4] Experimental evidence has been presented, for example from Langmuir probe measurements on H-1[5], BES measurements on DIII-D[6], and other experiments. Zonal flows in a toroidal geometry generate fluctuating radial electric fields that are uniform in the poloidal and toroidal direction, with mode numbers m=n=0. Zonal flows can't directly tap the free energy of the plasma gradients, rather they are driven by nonlinear coupling of driftwave turbulence. The flows cause shear decorrelation of the driftwaves resulting in a feedback loop that ultimately limits transport. The flows have relatively short radial correlation lengths, perhaps $5\rho_s$, and finite radial wave numbers. The nonlinear coupling predicts poloidal and toroidal wavenumbers of zero, $k_\theta=k_{||}=0$ and also predicts a frequency of zero (average frequency is zero but there is a frequency spread). For toroidal geometries, the flows will also drive an E_r fluctuation at the Geodesic Acoustic Mode frequency, GAM. This paper discusses how data from an HIBP can be used to measure these quantities associated with zonal flows, and how to optimize specifically for zonal flow measurements.

II. Capabilities of present and past HIBPs

A. Why not direct measurements of E_r?

The HIBP has the demonstrated ability measure the plasma potential, Φ, in hot magnetically confined plasma and has been a diagnostic on many devices[7], (ISX-B, ATF, TEXT, MST, JIPPTII-U, T-10[8], 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 $5\rho_s$, 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 in these cases, the shape of the sample volume complicates the interpretation. Future designs can address this issue and be optimized for direct measurements.

B. Why the indirect measurement works:

Despite the sample volume size issue, the HIBP is able to measure the fluctuations of potential due to the zonal flows and accurately do so if $l_c(zf) << \lambda_r$ or more specifically if $l_c(zf) < \pi / k_r$. This result is due to the nature of the zonal flows. 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 to 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 closely spaced shells this is nearly uniform. Figure 2 is a cartoon of this situation. In this figure it is assumed that the perturbed charge density has a sinusoidal radial dependence distributed across a flux surface and is uniform along a flux surface. For simplicity, the DC electric field profile has been subtracted and this is a slab model. For short spacing, the slab model is a good approximation to the toroidal geometry.

The charge distribution in figure 2 is very arbitrary, but for this distribution one can see that by measuring the potential at an interior location, the HIBP will detect the effect of zonal flows at larger minor radii. If there are many zonal flow layers that are decorrelated, an interior measurement will have the rms sum of the layers.

This ability of the HIBP to indirectly measure zonal flows depends on the radial wave structure of the flow itself. Figure 3 shows a flow structure that doesn't result in an interior potential fluctuation and would not be measured. For this case, the effective radial wavelength is shorter than the effective correlation length. (The effective correlation length for this example it the total length with perturbed charge.)

The profiles used for figures 2 and 3 are constrained by the need to conserve charge. This constraint is generalized to say that total charge must be conserved within a correlation length. For 2 regions to be decorrelated, the regions cannot have a net charge fluctuating between them. This limits the charge distribution models that can be used and the result is that the HIBP interior potential measurements will accurately be the integral of the zonal flow radial electric fields if $l_c(zf) < \pi / k_r$, as was stated above. For TEXT, this requires $k_r < 8cm^{-1}$. The radial wavenumbers for zonal flows have not been measured, but given that zonal flows are low frequency fluctuations, it seems reasonable to expect this condition to be satisfied. If one models the plasma as many zonal flow layers, each layer represented by a correlation length, and the interior potential measurements will be the rms sum of the integrated E_r in each layer.

Figure 4 shows data from the TEXT HIBP. It shows the autospectra of potential fluctuations from 3 sample volumes. The data is collected simaltanously and the samples are displaced both radially and poloidally. The figure shows the characteristics predicted in this section, namely that a sample location detects zonal flows at all larger radii. The sample location at the largest minor radius detects the fewest fluctuations. A location more interior detects all the fluctuations measured at the larger minor radius plus additional fluctuations that are from zonal flows that occur in the intermediate radii. The fact that the interior measurements include higher frequencies is due the radial dependence of the GAM.

C. Separating the zonal flow potential fluctuations from the driftwave potential fluctuations:

Interior measurements of fluctuations of potential will have signal from both the zonal flows at larger minor radii and from the local driftwave fluctuations. Experimental measurements have already shown that for TEXT, the zonal flow fluctuations dominate those of the driftwaves in certain frequency range.[9] Additional checks can be made of the data. 1) The zonal flows have an m=0 mode structure, while driftwaves have a finite poloidal wave number. Data from 2 detector sets can be used to determine the poloidal mode structure of the potential fluctuations. 2) Zonal flows result in internal potential fluctuations without internal density fluctuations. The density and potential fluctuations can be compared.

D. Frequency range of zonal flow fluctuations:

Theory predicts the electric field due to zonal flows 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[9]. 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, and each layer has a characteristic GAM frequency

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. If there are many zonal flow layers, each with building and decaying f = 0Hz 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 = 0Hz component.

III. Design issues to improve zonal flow measurements:

A. Sample volumes

A HIBP can be designed to allow improved measurements of zonal flows. Two issues are considered here 1) designing for small closely spaced sample volumes to be able to directly measure the zonal flow E_r and 2) design to sweep the sample volume over a radial range to detect the f = 0Hz component.

Many HIBP experiments have multiple detector sets to allow simultaneous measurements at 2 or more sample locations. The sample locations are using the same primary ion beam, therefore they are measuring signal from different parts of that primary. The spacing between samples is set by the entrance openings to the energy analyzer and in principle can be arbitrarily close. In practice there must be some separation so that the energy analyzer has a reasonable dynamic range, but the spacing could be 0.4cm with only simple modifications to previous systems. Closer spacing can be achieved by adding ion optics to spread the spray of secondary ions; in this case the optics would be used to defocus the spray. The optics could be either electrostatic or magnetic.

Simply decreasing the sample volume spacing is not sufficient, as can be seen in figure 1. The sample volumes look like curved disks that usually have a significant radial length. Closely spaced sample volumes will in general have significant radial overlap, complicating the determination of E_r. Therefore it is also necessary to minimize the radial overlap.

Minimizing the radial overlap can be done by either picking the sample locations where the long dimension of the sample volume falls nearly on a flux surface, or by optimizing the HIBP design so as to keep the sample volume small. Figure 5 shows some relatively small sample volumes that could be achieved with an HIBP on NSTX.

In combination with reducing the sample volume size and spacing, there is the option to look for devices with larger correlation lengths. Again assuming that the correlation length goes something like $5\rho_s$, then a machine with high temperatures and weak magnetic fields might allow direct measurements of the radial electric field. Spherical Torus devices and RFPs may be of interest. NSTX is good example, for a 1keV, 0.35Tesla deuterium discharge in NSTX, $5\rho_s$ is about 6cm. The sample volumes shown in figure 4 are significantly smaller than this estimate of the zonal flow correlation length. The samples have a spacing of about 2 cm and could be used to directly calculate radial electric fields by using 2 detectors. There is an HIBP on the MST RFP, but the measurement is complicated in the RPF because there are m=0 MHD modes resident in the plasma. Frequency analysis may allow for isolating the zonal flow m=0 fluctuations from the MHD.

B. Radial scans of the sample location:

If the sample location is modulated radially faster than the frequency of the zonal flow fluctuations, then the flow electric field will appear as a slow variation of the potential vs. position. The zonal fluctuations will effectively be modulated by the sweep frequency. This is useful to measure the $f = 0$Hz component of the flows.

Sweeping the sample location is easy and common with HIBP systems. Electrostatic steering plates can be used in either the primary or secondary ion beam systems. The sweep frequency limit is limited by the voltage and current requirements of the system. The voltage required goes directly as the ion beam energy and inversely as the length of the sweep plates. The current required is that necessary to charge and discharge the sweep plates, which can be modeled as a capacitor. The current therefore increases linearly with the frequency (dV/dt) and the sweep plate length (capacitance.) Previous systems were able to sweep the sample volume by 10cm with a 2kHz triangle waveform. This would be sufficient to allow measurements of the $f = 0$Hz component with improved sensitivity. Faster sweep systems have been proposed.[10]

IV. Conclusions

The HIBP is suitable to indirectly measure zonal flow electric fields by measuring internal fluctuations of potential. The ability to scan the sample volume across hot dense plasma and to make spatially and temporally measurements of the potential is unique to this diagnostic. There are several HIBP systems in the world that can pursue this research, most notable in Japan and Europe. In the US there is the MST HIBP, which faces the added complication of internal m=0 MHD modes, and there is the extensive database from the TEXT HIBP and the TEXT-U HIBP. New HIBPs could be designed, (or existing ones modified,) with the goal of making direct measurements of zonal flow fields. The key requirement is to reduce the sample volume size and spacing so that they are smaller than the correlation length of the zonal flow.

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Figure Captions:

Figure 1 (from reference 7) TEXT HIBP sample volume spacing and size for one region in the plasma. Two sample volumes shown, system made simultaneous measurements at 3 locations.

Figure 2 Solid line is a plot of the radial variation of the assumed charge distribution due to a zonal flow, short dash line shows the magnitude of the resultant radial electric field, and long dash line shows the resultant potential using the vacuum vessel as the ground reference. All quantities will oscillate together during the zonal flow fluctuation. For zonal flows, all quantities vary with radius and are uniform in the poloidal and toroidal directions.

Figure 3: Plot of magnitude of perturbed charge distribution (solid line), resultant radial electric field (short dashed line) and plasma potential (long dashed line) verses normalized radius for a model of a zonal flow.

Figure 4: Autopower spectra of potential for 3 sample locations. x symbol is for data taken at $\rho=0.85$ and $\theta=73^o$, diamonds for $\rho=0.76$ and $\theta=67^o$, and circles for $\rho=0.69$ and $\theta=61^o$. Potential fluctuations detect the zonal flows at larger minor radii, so measurements at smaller radii see a greater total autopower.

Figure 5: Sample volume size and spacing for a proposed NSTX HIBP. Detector spacing for figure is 1.5cm. Closer spacing is practical.

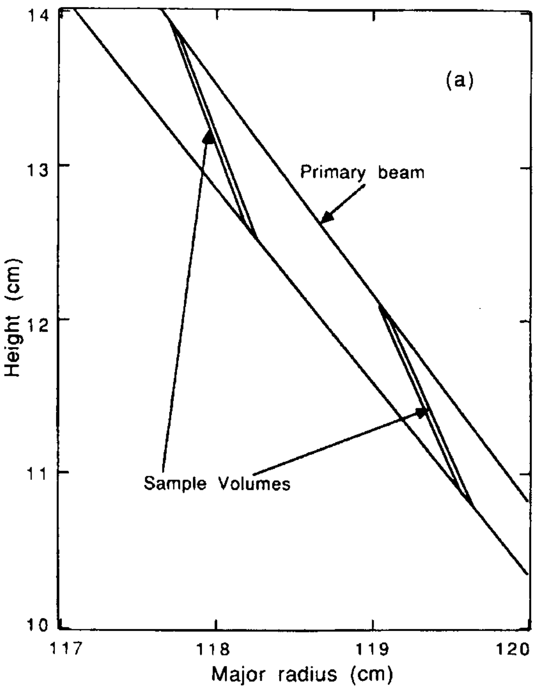


Figure 1 HTPD 2002 MS# DP02 Schoch

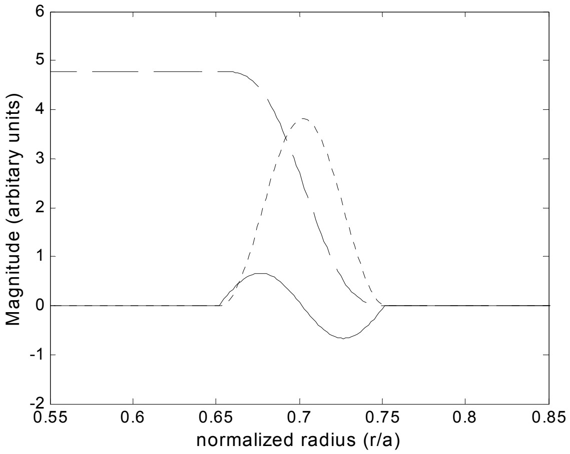
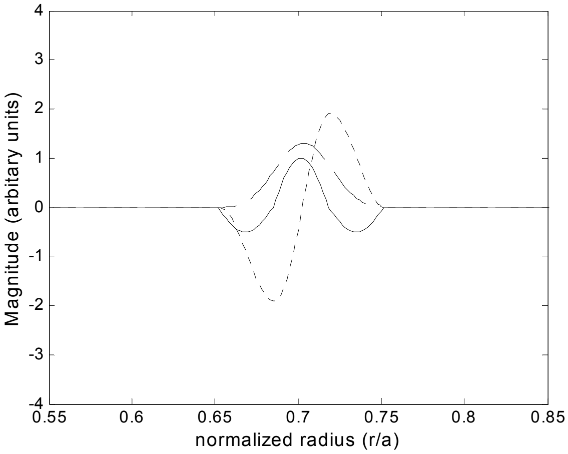


Figure 2 HTPD 2002 MS# DP02 Schoch



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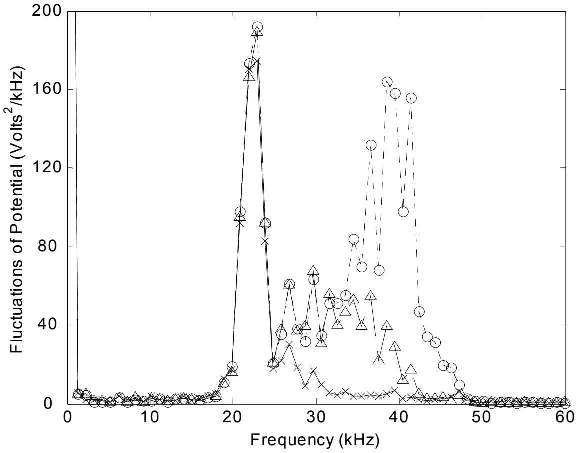

Figure 4 HTPD 2002 MS# DP02 Schoch

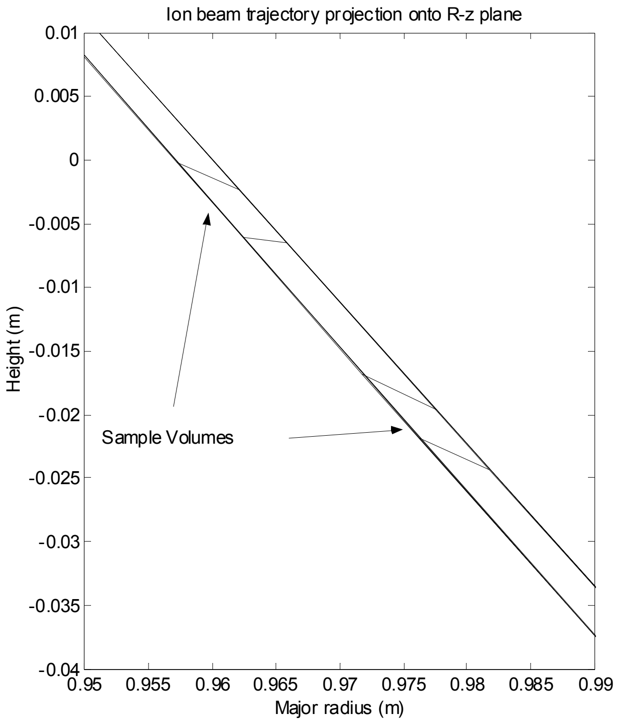

Figure 5 HTPD 2002 MS# DP02 Schoch