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Investigation of RF-enhanced Plasma Potentials on Alcator C-Mod

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Abstract

Radio frequency (RF) sheath rectification is a leading mechanism suspected of causing anomalously high erosion of plasma facing materials in RF-heated plasmas on Alcator C-Mod. An extensive experimental survey of the plasma potential (Φ_P) in RF-heated discharges on C-Mod reveals that significant Φ_P enhancement (>100 V) is found on outboard limiter surfaces, both mapped and not mapped to active RF antennas. Surfaces that magnetically map to active RF antennas show Φ_P enhancement that is, in part, consistent with the recently proposed slow wave rectification mechanism. Surfaces that do not map to active RF antennas also experience significant Φ_P enhancement, which strongly correlates with the local fast wave intensity. In this case, fast wave rectification is a leading candidate mechanism responsible for the observed enhancement.

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JNM keywords: Plasma Properties (includes Plasma Disruption)

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1. Introduction

Ion cyclotron resonance frequency (ICRF) heating is a common technique to heat tokamak plasmas to fusion-relevant temperatures, ≥10 keV. Alcator C-Mod, a compact (major radius R_o = 0.67 m, minor radius a = 0.22 m), high field (B_T = 5.4 T) tokamak with all high-Z (molybdenum or Mo) plasma facing components relies exclusively on ICRF power for plasma heating [1]. Extensive experimental campaigns on Alcator C-Mod reveal that, depending on the operating scenarios, ICRF-heated plasmas can suffer from prohibitively high levels of Mo impurities in the plasma core [2-4]. Coating of Alcator C-Mod's plasma facing materials with a thin (~1 μm) low-Z (boron) film, through boronization, temporarily reduces core Mo contents [2, 3, 5]. However, the positive boronization effects wear out after ~20-40 ICRF-heated discharges and require a new layer of boron to achieve high performance plasmas [5]. Anomalously high net erosion rates of both Mo surfaces [6] and boron coatings [3], coupled with high Mo core contents, point at enhancement of sputtering, net erosion, and transport of sputtered plasma facing materials ions in ICRF-heated discharges on Alcator C-Mod.

RF rectification of the plasma sheath is a leading proposed mechanism that is responsible for enhanced erosion of plasma facing surfaces on Alcator C-Mod [7]. The mechanism requires an oscillating electric field, normal to the sheath surface, and is driven by the large difference in the mobility between electrons and ions [8]. The net effect is the appearance of a DC voltage across the sheath that repels excess electrons and attracts ions to achieve the ambipolarity condition at the material surface [8]. Previous studies on Alcator C-Mod, using emissive probes, show that ICRF heating does enhance the plasma potential (Φ_P) above 100 V [4, 7] and the enhancement varies with ICRF power and magnetic mapping between the probes and the active antennas [4, 7]. Deleterious effects of ICRF power on plasma-wall interactions are not unique to

Alcator C-Mod and are also observed on Tore Supra [9], ASDEX Upgrade [10] and JET [11]. However, it remains uncertain what aspects of the ICRF – heating, RF waves, fast ions, etc. – are responsible for the observed Φ_P enhancement.

The goal of this study is to perform an extensive experimental survey of Φ_P enhancement on Alcator C-Mod in the presence of ICRF power, deduce the mechanism(s) responsible for Φ_P enhancement, and compare the results with proposed theories on RF sheath rectification in tokamaks [12, 13].

2. Experimental Setup

In order to carry out the proposed survey we installed emissive probes (to measure local Φ_P), Langmuir probes (to measure local plasma density n_e and electron temperature T_e), ion sensitive probes (to measure Φ_P and n_e, calibrated against a Langmuir probe), and dB/dt probes (to measure local RF fields). These were installed on fixed and scanning probe stations. An emissive and two Langmuir probes were installed on the outer midplane A-port Scanning Probe (ASP [14]). Emissive, Langmuir, and ion sensitive probes were installed on the scanning Surface Science Station below the midplane (S^3 [15]). An emissive, ion sensitive and field-aligned 3-directional dB/dt probes were installed on a probe station on a fixed limiter between A and B ports (lower edge on the side facing B-port) [4, 7]. The signal from the dB/dt coil the surface normal of which is oriented parallel to the background magnetic field is taken as an indication of the fast wave intensity. The locations of the probe stations in Alcator C-Mod are shown in Figure 1. Note from Figure 1 that the S^3 probes are the only set of probes that directly connect along a magnetic flux tube to an ICRF antenna limiter (centered at J-port). The ICRF antennas were operated in the dipole phasing (0, π) and the heating scheme was H-minority heating in D^+ plasma with H/(H+D) ~5-10%. The operating frequencies were 80.5, 80.0 and 78.0 MHz for the D, E and J antennas, respectively. A typical launched parallel index of refraction ($n_{//}$) was 10.

3. Experimental Results & Discussion

According to a recently proposed theory, the RF enhancement of Φ_P is due to a slow wave (parallel electric field component $E_{//} \neq 0$, // refers to the local magnetic field direction) rectification by the plasma sheath [12]. One mechanism capable of generating slow waves is due to the misalignment between the active ICRF antenna straps and the magnetic field lines [16]. The generated slow waves propagate only in the low n_e ($\leq 1x10^{17}$ m^{-3} on Alcator C-Mod) region of the tokamak plasmas, typically found behind the main protection limiters (R > 0.910 m on Alcator C-Mod, all R distances on a flux surface are mapped to the midplane). Due to the strong evanescence of the slow wave in the region where n_e is above the lower hybrid (LH) resonance ($n_{e\_LH\_res}$ ~1-3x10^{17} m^{-3} on Alcator C-Mod), the propagating slow waves are localized to magnetic field lines that intercept the active RF antennas – the slow wave rectification is, therefore, a phenomenon localized to surfaces with direct magnetic connection to the antenna. Note that the slow wave theory [12] makes an explicit “tenuous plasma" assumption and, hence, needs to be modified to be applicable in the high density, evanescent regions of the plasma. Figure 2 shows the Φ_P values as a function of the local n_e obtained with the S^3 on the field lines that map directly to the active RF antenna (J antenna, oriented with vertical straps, operated at 70.0 MHz for this experiment). The local n_e was varied by scanning the core n_e, while keeping all other plasma parameters constant. The theoretical Φ_P estimate is equal to $3*T_e + V_{sh}$, where T_e = 10 eV is assumed and the enhanced sheath voltage V_{sh} is estimated for Alcator C-Mod parameters, in particular using parallel scale a = 0.1 m [12]. Φ_P values above 100 V are predicted by the model and measured (data averaged in time for a given radius), implying that incident deuterium ions have enough energy to sputter Mo surfaces. For comparison, measured Φ_P’s in Ohmic discharges are ≤10 V. We observe a threshold behavior of Φ_P with the local n_e, $n_{e\_threshold}$

~1×10^{16} m^{-3} and the threshold behavior of Φ_P with local n_e is expected from the slow wave theory [12]. However, the value of the threshold density and the saturation of Φ_P (~150-200 V) for $n_e > 1 \times 10^{16}$ m^{-3} appear to be almost independent of the RF power, contrary to the theory.

Surprisingly, we observe Φ_P above 100 V in discharges where the active RF antennas do not magnetically map to the probes, see Figure 3. In fact, the behavior of Φ_P with local n_e in the "not mapped" case is opposite to the slow wave picture. The data in Figure 3 suggests that the slow wave rectification may not be the only mechanism that enhances Φ_P in ICRF-heated discharges on Alcator C-Mod.

It is also possible to induce RF sheath rectification with a fast wave field if the plasma facing surface is not perfectly tangential to the background magnetic field: in order to satisfy the tangential electric field boundary condition at a conducting surface, $\Sigma(E_{tangential}) = 0$, in the most general geometry it is necessary to introduce both reflected fast and slow wave fields [13]. Unlike the slow wave rectification mechanism, which is local to active RF antennas, the fast wave rectification is expected to be a global effect that would depend on the local fast wave field intensity. Figure 4 shows Φ_P and relative fast wave intensity values obtained with the fixed A-B limiter probes in an ICRF-heated discharge. The large changes in the Φ_P and fast wave intensity values correlate with the saw tooth amplitude. The correlations between Φ_P and the fast wave intensity for two different antennas are plotted in Figure 5. The D antenna, which is toroidally nearest, yet not magnetically mapped, to the A-B limiter probes, induces the largest Φ_P and fast wave intensity changes, for a given RF power. This result is in agreement with recent studies of ICRF wave absorption on Alcator C-Mod [17]: the fast wave distribution for H-minority heating with H/(H+D) ~6%, applicable to our studies, is the strongest in the vicinity of the active ICRF antenna and rapidly decreases in the toroidal direction away from the antenna. Our measurements also suggest that it is not the T_e or n_e fluctuations during saw tooth events that enhance Φ_P, as these are similar for the two antennas. We also observe that Φ_P changes have a threshold-like behavior as a function of the local fast wave intensity: it suggests that it is beneficial to utilize ICRF heating in a high single-pass absorption regime to minimize the fast wave fields in the scrape-off layer (SOL) and thus this global RF rectification mechanism. The asymmetric Φ_P response to the change in the ICRF resonance location (see Figure 5 (a)), which was varied by changing the toroidal field strength, suggests that the path taken by the fast wave between the RF source and the plasma facing surfaces influences the strength of the resulting RF enhancement of Φ_P. This result again favors a high single-pass absorption regime to minimize the fast wave field intensity that reaches plasma facing components.

If the fast wave rectification determines the global RF enhancement of Φ_P, then we expect to see an exponentially decaying radial Φ_P profile in the shadow of the limiter (R > 0.910 m): the plasma density is low enough (<1e18 m^{-3}) that the fast wave dispersion relation becomes vacuum-like and the fast wave field intensity decay length is determined by its perpendicular wavenumber ($k_\perp$) [13]. The radial Φ_P profiles in ICRF-heated and Ohmic plasmas obtained with the ASP probes are shown in Figure 6 (a). We observe that RF-enhanced Φ_P does have an exponentially decaying radial profile (which peaks near R = 0.910-0.915 m) with the characteristic decay length of ~3.5 cm, compared to the inverse of the fast wave perpendicular wavenumber ($1/|k_\perp|$) of ~6 cm, as estimated from the cold plasma dispersion relation. Note, that there are no field lines that directly connect the ASP probes and the ICRF limiters of the J antenna. The corresponding radial electric field profiles, $E_r = -\nabla_R\Phi_P$, are shown in Figure 6 (b). For comparison, we also show the E_r profiles obtained with the gas puff imaging (GPI) diagnostic [18]. We see that the RF enhancement of Φ_P is confined not just to the shadow of the limiter (R > 0.910 m), but affects the entire SOL of Alcator C-Mod. The resulting $E_r x B_{Tor}$ flows are capable of transporting sputtered wall material in the SOL and may be responsible for anomalously high erosion of plasma facing materials on Alcator C-Mod.

4. Conclusion

We carried out an extensive survey of Φ_P enhancement in ICRF-heated discharges on Alcator C-Mod. Our results show that significant Φ_P enhancement (>100 V) is present on outboard limiter surfaces. The surfaces that magnetically map to active RF antennas experience Φ_P enhancement that is in partial agreement with the slow wave rectification theory: Φ_P enhancement has a density threshold, but does not scale with the RF power as predicted. The slow wave rectification is an effect local to the active antennas and can be minimized by controlling the n_e profile in the SOL. We also observe global Φ_P enhancement on surfaces that do not map to the active RF antennas. This enhancement correlates with the local fast wave intensity and may be driven by the fast wave rectification mechanism. GPI measurements show that Φ_P enhancement extends radially beyond the limiter structures into the SOL and the resulting E_r fields generate strong $E_r x B_{Tor}$ flows.

5. Acknowledgements

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6. References

[1] I.H. Hutchinson, R. Boivin, F. Bombarda et al., Phys. Plasmas, **1**, 1511 (1994).

[2] B. Lipschultz, Y. Lin, M.L. Reinke et al., Phys. Plasmas, **13**, 056117 (2006).

[3] E. Marmar, Y. Lin, B. Lipschultz et al., 33rd EPS Conf. on Plasma Phys., Vol. **30I**, O-2.005 (2006).

[4] B. Lipschultz, D.A. Pappas, B. LaBombard et al., Nuclear Fusion, Vol. **41**, No. 5 (2001) 585.

[5] B. Lipschultz, Y. Lin, E.S. Marmar et al., JNM, **363-365** (2007) 1110-1118.

[6] W.R. Wampler, B. LaBombard, B. Lipschultz et al., JNM, **266-269** (1999) 217-221.

[7] S.J. Wukitch, B. LaBombard, Y. Lin et al., JNM, **390-391** (2009) 951-954.

[8] H.S. Butler and G.S. Kino, Phys. Fluids, **6** (9) (1963).

[9] L. Colas, A. Argouarch, S. Brémond et al., these proceedings.

[10] Vl. Bobkov, F. Braun, L. Colas et al., JNM, **415** (2011) S1005-S1008.

[11] Vl. Bobkov and JET EFDA contributors, these proceedings.

[12] J.R. Myra and D.A. D'Ippolito, Phys. Rev. Lett. **101**, 195004 (2008).

[13] D.A. D'Ippolito, J.R. Myra, E.F. Jaeger, and L.A. Berry, Phys. Plasmas, **15**, 102501 (2008).

[14] J. Reardon, "RF Edge Physics on the Alcator C-Mod Tokamak", PhD thesis, PSFC RR 99 8, MIT (1999).

[15] R. Ochoukov, D.G. Whyte, B. Lipschultz et al., JNM **415** (2011) S1143-S1146.

[16] M.L. Garrett, S.J. Wukitch, P. Koert, D.G. Whyte, 19^{th} RF Topical Conference, Newport, RI, USA (2011).

[17] N. Tsujii, M. Porkolab, P.T. Bonoli et al., 19^{th} RF Topical Conference, Newport, RI, USA (2011).

[18] I. Cziegler, J.L. Terry, S.J. Wukitch et al., Plasma Phys. Control. Fusion, **54**, 105019 (2012).

Figure Captions

Figure 1: View of Alcator C-Mod outer wall. Dashed red arrows show field lines intersected by the probe stations.

Figure 2: Estimate of the local Φ_P from theory and the time-averaged Φ_P as a function of the local n_e obtained with S^3 probes. R refers to the location of S^3 emissive probe. J antenna is active and magnetically maps to S^3 probe. USN: upper single null plasma configuration.

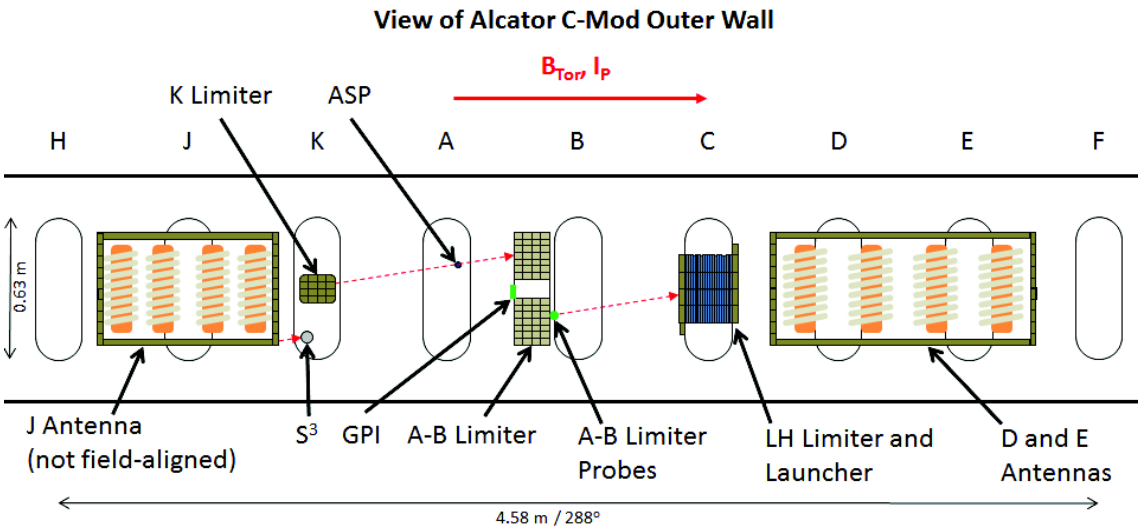
Figure 3: Average Φ_P as a function of the local n_e obtained with S^3 probes. R refers to the location of the S^3 emissive probe. E antenna is active and not does not magnetically map to S^3 probe.

Figure 4: Example of Φ_P and local fast wave intensity data in an ICRF-heated discharge (D antenna only) obtained with the fixed A-B limiter probes. The RF power and the core T_e are also shown. D antenna is not mapped to A-B limiter probes. IWL: inner wall limited plasma configuration.

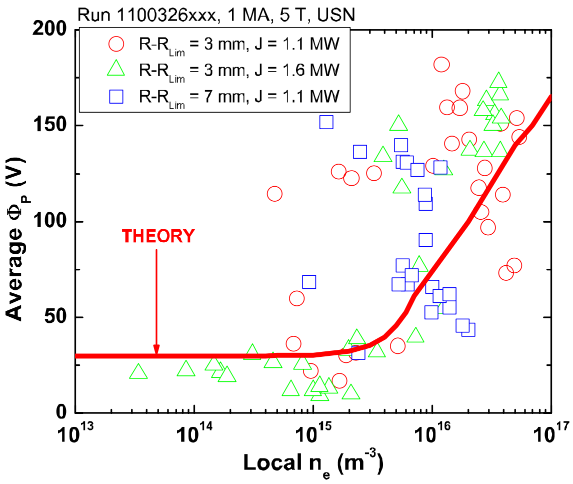
Figure 5: Correlations between Φ_P and fast wave intensity changes in ICRF-heated discharges ((a) D antenna or (b) E antenna only) for various ICRF resonance positions. $\Delta_{res} \equiv R_{ICRF\ resonance} - R_o$. Each data point is time-averaged over 0.02 s.

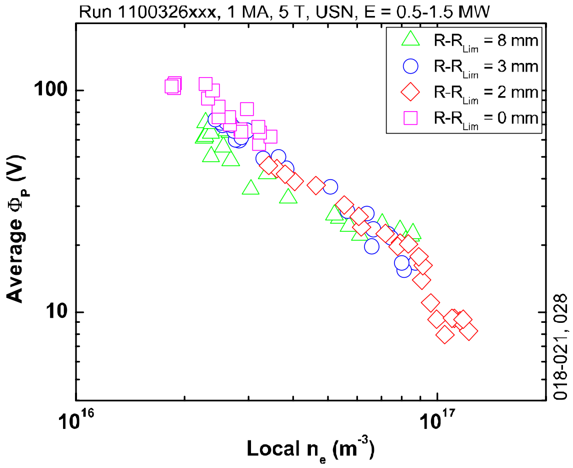
Figure 6: (a) Radial profile of Φ_P and floating Langmuir probe voltage V_F measured with ASP in ICRF-heated and Ohmic plasmas. (b) The corresponding E_r profiles are also shown. GPI refers to the gas puff imaging diagnostic measurements.

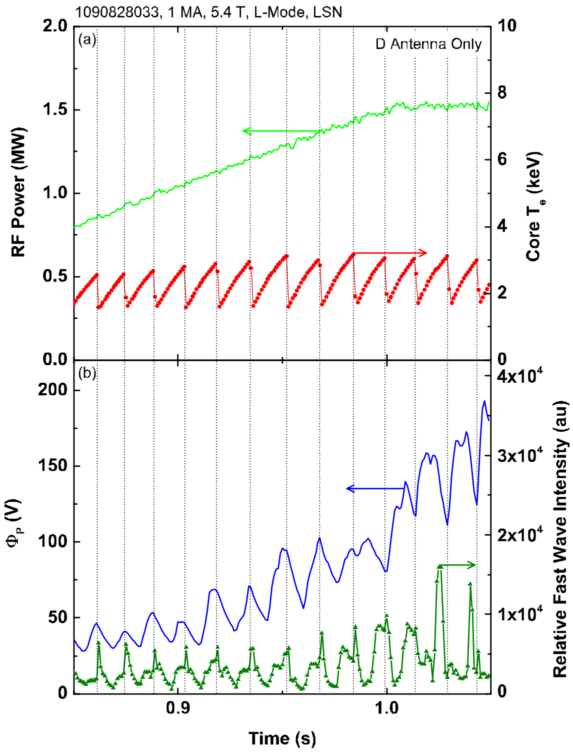
Figures



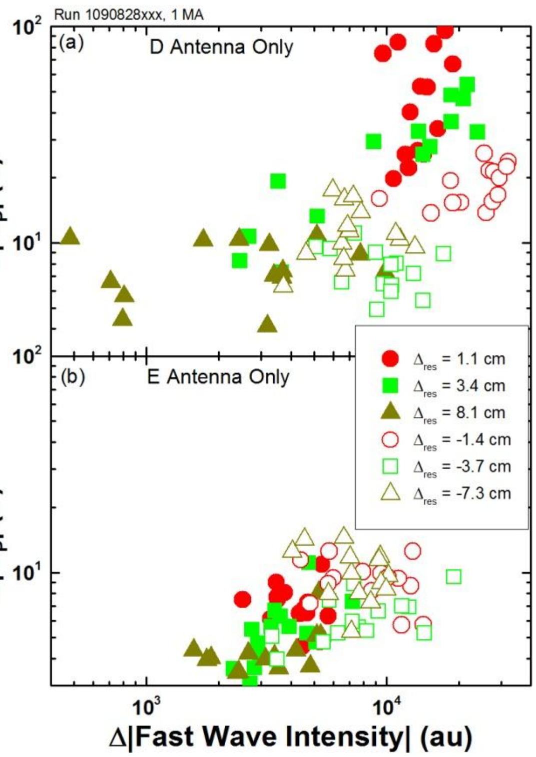
View of Alcator C-Mod Outer Wall
B_Tor, I_P
K Limiter
ASP
H
J
K
A
B
C
D
E
F
0.63 m
J Antenna
(not field-aligned)
S3
GPI
A-B Limiter
A-B Limiter
Probes
LH Limiter and
Launcher
D and E
Antennas
4.58 m / 288°


Run 1100326xxx, 1 MA, 5 T, USN
R-R$_{Lim}$ = 3 mm, J = 1.1 MW
R-R$_{Lim}$ = 3 mm, J = 1.6 MW
R-R$_{Lim}$ = 7 mm, J = 1.1 MW
THEORY
Average Φ_P (V)
Local n_e (m^{-3})
0
50
100
150
200
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}

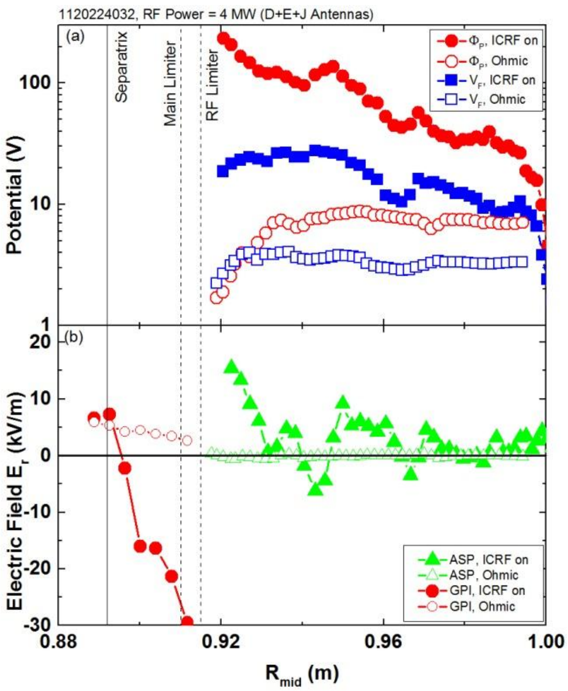

Run 1100326xxx, 1 MA, 5 T, USN, E = 0.5-1.5 MW
R-R_Lim = 8 mm
R-R_Lim = 3 mm
R-R_Lim = 2 mm
R-R_Lim = 0 mm
Average Φ_p (V)
100
10
10^16
10^17
Local n_e (m^-3)
018-021, 028



1090828033, 1 MA, 5.4 T, L-Mode, LSN
(a)
D Antenna Only
RF Power (MW)
Core T$_e$ (keV)
(b)
Φ_P (V)
Relative Fast Wave Intensity (au)
Time (s)



Run 1090828xxx, 1 MA
(a)
D Antenna Only
(b)
E Antenna Only
Δ_{res} = 1.1 cm
Δ_{res} = 3.4 cm
Δ_{res} = 8.1 cm
Δ_{res} = -1.4 cm
Δ_{res} = -3.7 cm
Δ_{res} = -7.3 cm
$\Delta|\Phi_P|$ (V)
$\Delta|\Phi_P|$ (V)
10^2
10^1
10^2
10^1
10^3
10^4
Δ|Fast Wave Intensity| (au)


1120224032, RF Power = 4 MW (D+E+J Antennas)
(a)
Separatrix
Main Limiter
RF Limiter
Φ_P, ICRF on
Φ_P, Ohmic
V_F, ICRF on
V_F, Ohmic
Potential (V)
100
10
1
(b)
Electric Field E_r (kV/m)
20
10
0
-10
-20
-30
ASP, ICRF on
ASP, Ohmic
GPI, ICRF on
GPI, Ohmic
0.88
0.92
0.96
1.00
R_mid (m)