Recent Studies of NSTX Edge Plasmas: XGC0 Modeling, MARFE Analysis and Separatrix Location

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Modeling of NSTX with XGC0

NSTX

Equations of ion polarization drift and continuity[1],

$$\mathrm{v_p} = -\left(m_i c^2 / e B^2\right) \partial \nabla_\perp \phi / \partial t$$

$$\partial n_p / \partial t = \nabla \cdot n_i \mathrm{v_p} = 0$$

can be combined

$$e n_p = \nabla \cdot \frac{\omega_{pi}^2}{4\pi \Omega_i^2} \nabla_\perp \phi \qquad (1)$$

The ion polarization density is then proportional to

$$n_p \propto \frac{d}{dR}\left(\frac{1}{V_A^2}\frac{d\phi}{dR}\right) \propto \frac{d}{dR}\left(\frac{n_i m_i}{B^2}\frac{d\phi}{dR}\right) \qquad (2)$$

[1] C.S. Chang, S. Ku, H. Weitzner, Phys. Plasmas **11** (2004) 2649.

Modeling of NSTX with XGC0 (2)

Ion polarization density is proportional to density gradient and to gradient of $1/B^2$. In NSTX, magnetic field is a factor of 4 smaller than in DIII-D and hence polarization density is roughly a factor of 16 larger.

Using measured T_e , T_i and n_e profiles with NSTX 127533 equilibrium in XGC0 resulted in simulations with very large ion polarization densities after 40 ITTTs. Combination of low magnetic field and low temperature leads to a fast growth rate of the ion polarization density in XGC0.

Other problems: ion and electron transport are neoclassical and no capability to model impurities.

Figure 1 MARFE evolution in NSTX shot #117125

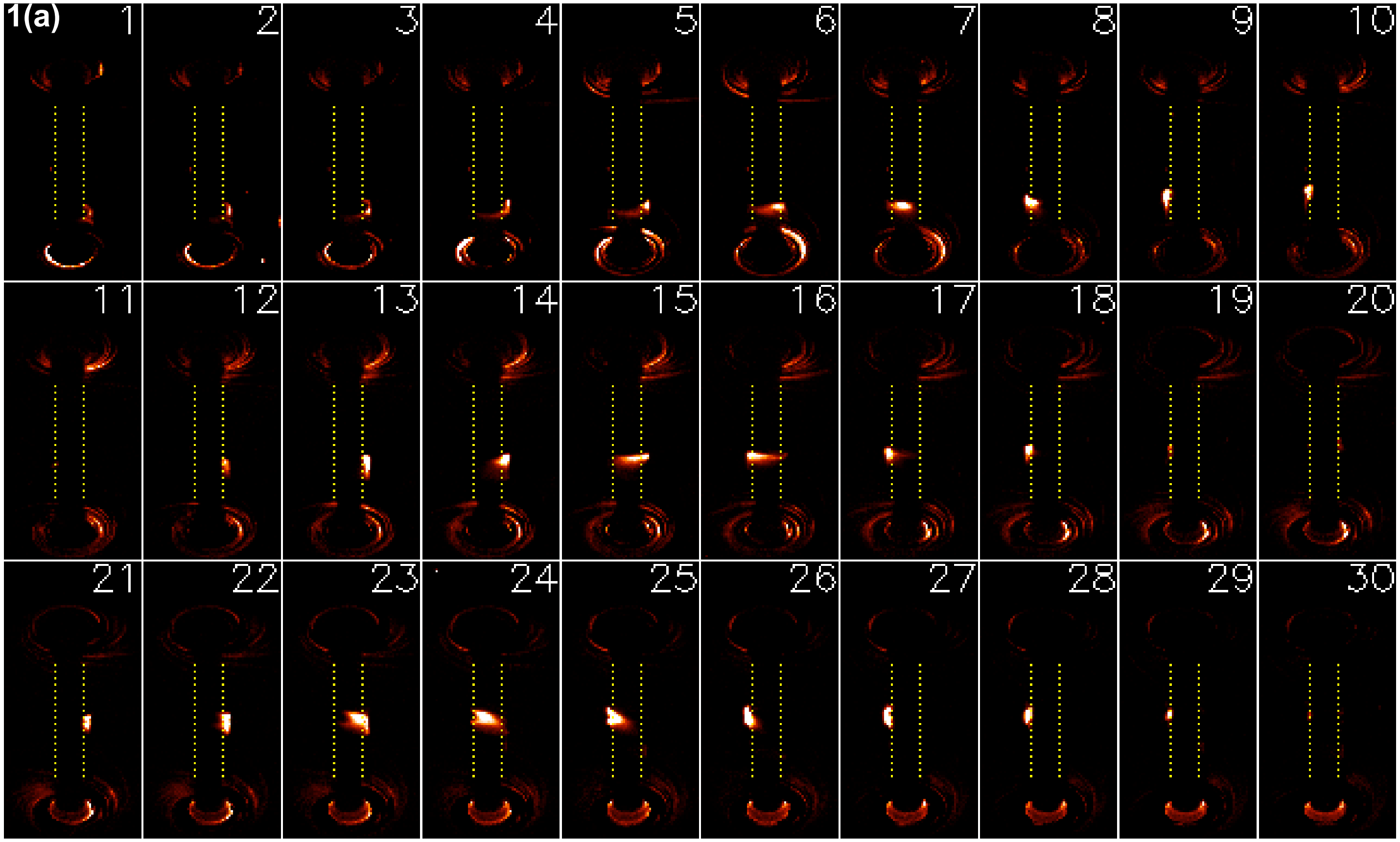
NSTX

660.458 ms

'average frame' subtracted to enhance contrast

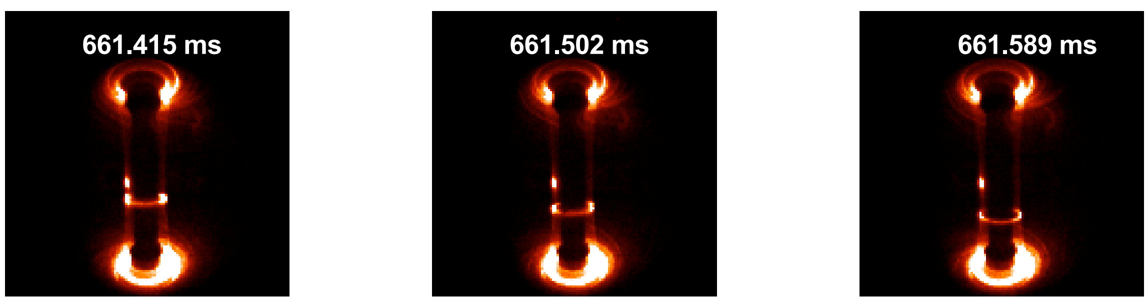
68000 frames/s or ~14.7 s between frames with a D_α-line bandpass filter

1(a)



660.879 ms

1(b)



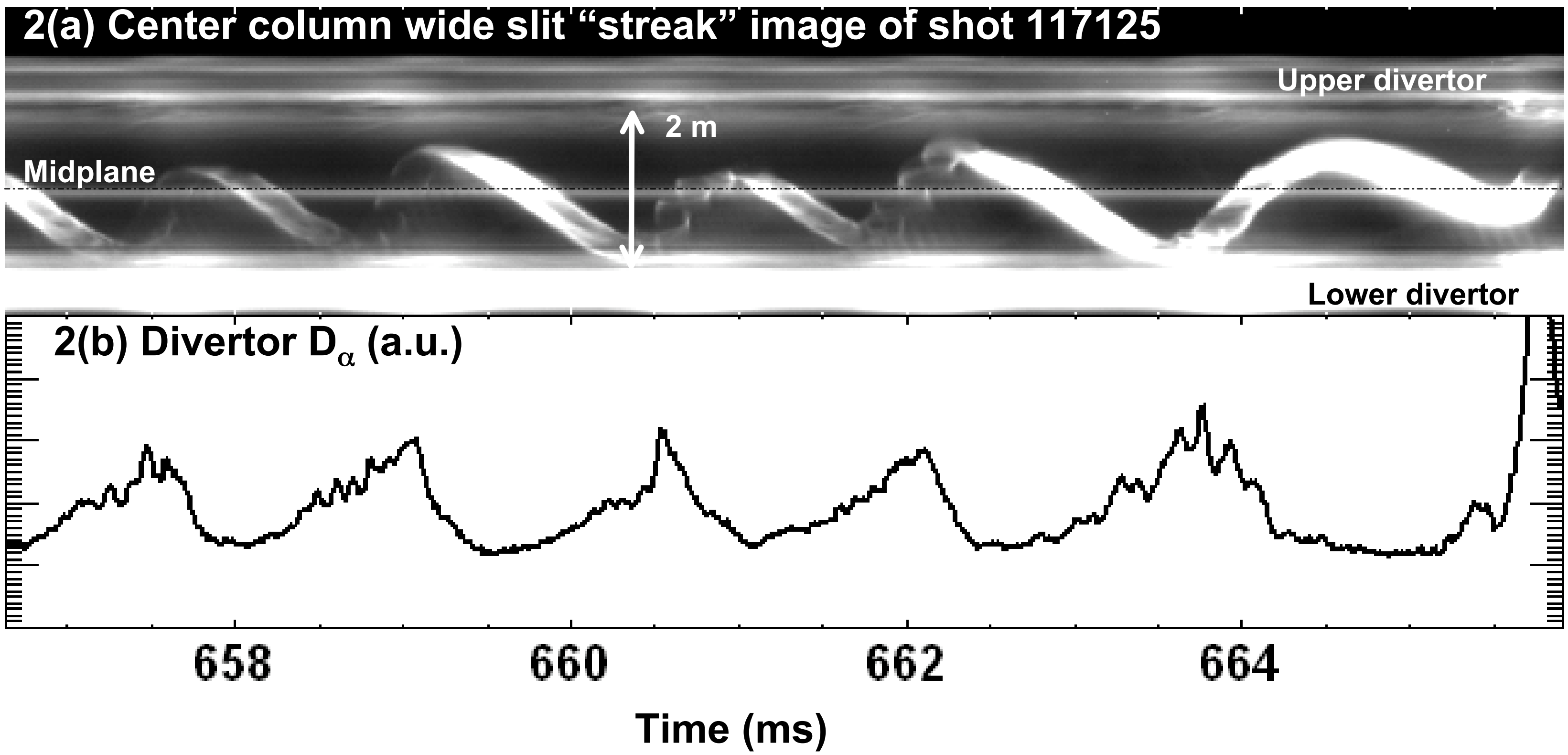
MARFE/ELM cycle in NSTX shot #117125 (900 kA, 6.2 MW, Double Null, ~ 656-665 ms)

- Poloidally and toroidally localized MARFE remnant (plasmoid) moves upward following magnetic field line
- Plasmoid (MARFE precursor) upward movement stagnates and expands into a toroidally symmetric ring
- MARFE ring moves downward in ion ∇B drift direction
- ELM activity in divertor region coincides with burn through of most of MARFE
- Type I ELM (at ~665.5 ms) burns through MARFE

Downward drift in ion grad-B direction places stable MARFE position near lower divertor.[2] Velocity of background plasma (poloidal ExB drift) is equal to the MARFE velocity.[3]

[2] Asakura, et al., NF **36** (1996) 795.
[3] Chankin, Phys. Plasmas **11** (2004) 1484.

Figure 2 ELM cycle drives dynamics of MARFE



ELM cycle and MARFE cycle are directly linked. Precursor of Type I ELM slows, then reverses MARFE movement and then ELM burns through MARFE[4].

[4] Maqueda, et al., JNM 363-366, 1000 (2007).

MARFE theory

NSTX

Drake[4] found the MARFE to be a radiative condensation instability governed by

parallel and perpendicular conduction — radiative condensation

$$\frac{5}{2} n\gamma \tilde{T} + k_{\parallel}^{2} \kappa_{\parallel} \tilde{T} - \kappa_{\perp} \frac{\partial^2 \tilde{T}}{\partial r^2} = n n_z \left(\frac{2L_z}{T} - \frac{\partial L_z}{\partial T} \right) \tilde{T} \qquad (1)$$

Wesson and Hender[5] observed that the most unstable mode $\tilde{T}$ varies as cos _ and wave number $k_{\parallel} = 1/qR$

$$\kappa_{\perp} \frac{\partial^2 \tilde{T}}{\partial r^2} - k_{\parallel}^{2} \kappa_{\parallel} \tilde{T} = n n_z T^2 \frac{\partial}{\partial T} \left(\frac{L_z(T)}{T^2} \right) \tilde{T} \qquad (2)$$

[4] Drake, PF **30** (1987) 2429.
[5] Wesson and Hender, NF **33** (1993) 1019.

MARFE density limit

NSTX

Mahdavi[6], et al. and Maingi and Mahdavi[7], incorporated non-equilibrium radiation effect of neutrals in a uniform edge distribution to obtain

$$n_{marfe} = \sqrt{\frac{(\kappa_0 / Z_{eff}) T^{1/2} / (qR)^2}{-\sum_z f_z \frac{\partial}{\partial T}\left(\frac{L_z(T, f_0)}{T^2}\right)}} \tag{3}$$

Defining the MARFE Index, MI

$$\mathrm{MI} \equiv \frac{\mathrm{n}_{\mathrm{e,sep}}}{\mathrm{n}_{\mathrm{marfe}}} \tag{4}$$

[6] Mahdavi, et al., in *Proc. 24th European Conf. on Controlled Fusion and Plasma Physics*, Berchtesgaden, Germany, 1997, Vol. 21A, p. 1113.
[7] Maingi and Mahdavi, Fusion Sci. and technol. 48 (2005) 1117.

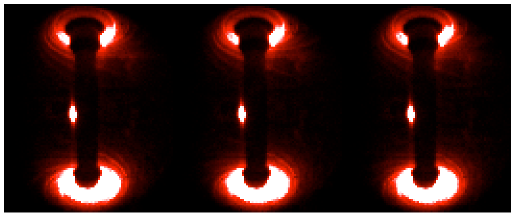
Table 1 MARFE condition for NSTX discharge 117125 at Thomson Scattering times and separatrix data used in calculation of MARFE Index if | t_{TS} – t_{CHERS} | < 1.5 ms.

NSTX

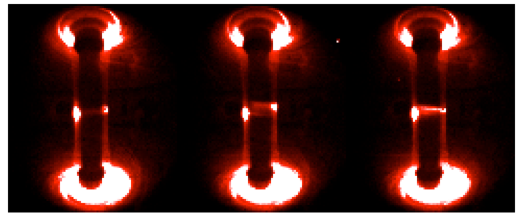
TS time (s)	Condition	CHERS time	$T_{e,sep}$[eV]	$n_{e,sep}$[m^{-3}]	f_C[%]	MI
0.326662	no marfe	0.32525	93	2.5E19	7.2	0.07
0.343345	no marfe	0.33525				
0.359992	no marfe	0.35525				
0.376685	upward move	0.37525	34	2.2E19	6.4	0.82
0.393332	no marfe	0.38525				
0.410015	no marfe	0.40525				
0.426662	no marfe	0.42525	51	1.8E19	5.2	0.20
0.443345	no marfe	0.43525				
0.459992	no marfe	0.45525				
0.476685	onset	0.47525	38	3.0E19	6.2	0.83
0.493322	stagnation	0.48525				
0.510025	stagnation	0.50525				
0.526662	no marfe	0.52525	147	3.4E19	4.9	0.04
0.543345	onset	0.53525				
0.559992	no marfe	0.55525				
0.576685	onset	0.57525	31	1.9E19	6.8	0.96
0.593332	onset	0.58525				
0.610025	no marfe	0.60525				
0.626662	burn	0.62525	34	1.8E19	10.7	0.96
0.643355	stagnation	0.63525				
0.660002	move down	0.65525				
0.676685	stable at top	0.67525	41	2.2E19	11.3	0.71
0.693332	no marfe	0.68525				
0.710015	onset	0.70525				
0.726662	onset	0.72525	41	2.2E19	4.8	0.41
0.743355	no marfe	0.73525				
0.759992	no marfe	0.75525				
0.776685	no marfe	0.77525	61	2.6E19	5.9	0.19
0.793332	no marfe	0.78525				
0.810015	stagnation	0.80525				

Figure 3 Conditions observed in NSTX discharge 117125

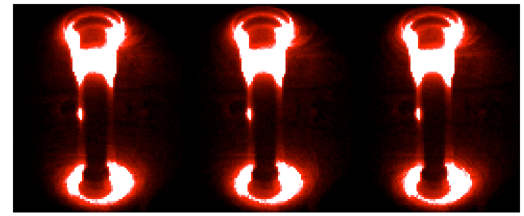
no marfe; t = 0.326662 s



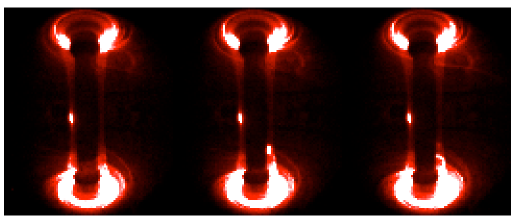
stagnation; 0.493322 s



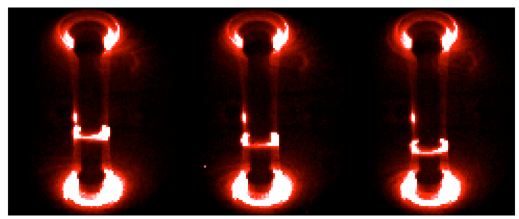
stable at top; 0.676685 s



marfe onset; 0.726662 s

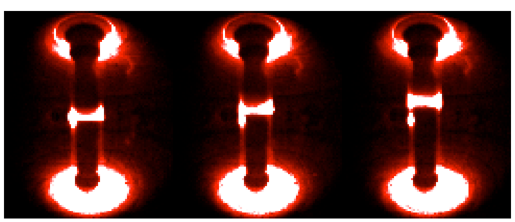


move down; 0.660002 s



Center image is nearest to TS time, left image -72.5 ms, right image +72.5 ms

move up; 0.376685 s



burn; 0.626662 s

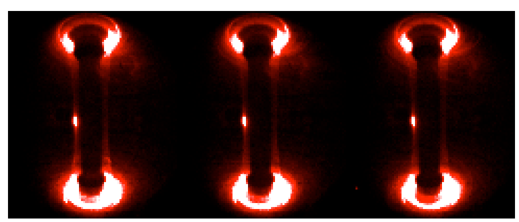
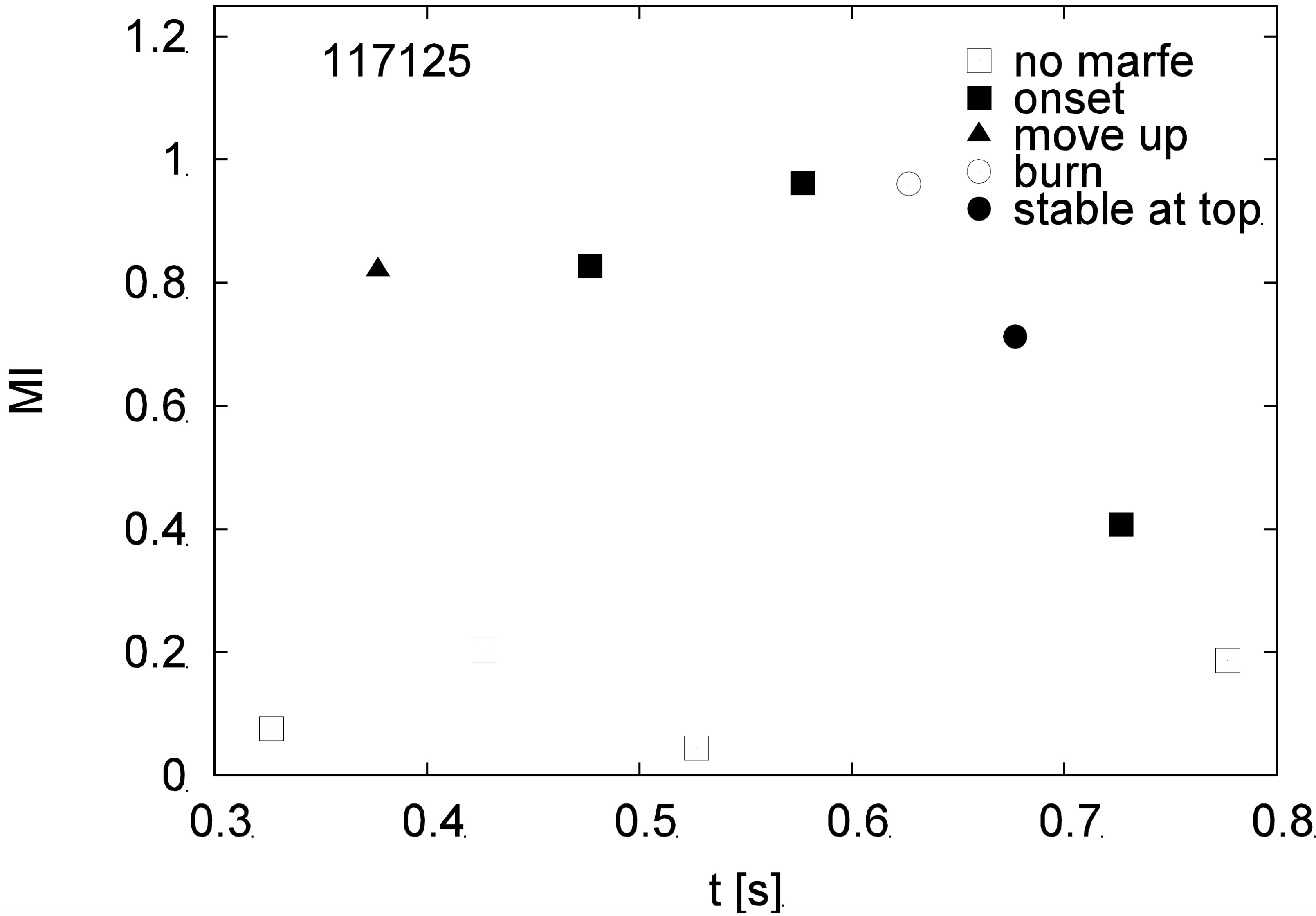


Figure 4 MARFE Index vs time for NSTX 117125



Experimental estimates and assumptions

- Shot 110077 of NSTX: DN, D fueled, $B_T(0) = -0.45$ T, $I_p = 1$ MA and P_{NBI} up to 5.1 MW during an H-mode edge during which the LFS radial electric field has been estimated[8] to be between 0 and -5 kV/m.

- From Fig. 2(a), ring MARFE at 660 ms has an experimental poloidal velocity of -1.54 km/s (downward). From Fig. 4 case 2, ring MARFE at 377 ms moves upward 0.273 m in 0.145 ms for an experimental poloidal velocity of 1.88 km/s (upward).

- Neutral fraction, n_0/n_e, was estimated to be 1×10^{-3}.

- Electron thermal diffusivity χ_e at separatrix was assumed to be 50 m^2/s and conductive fraction 0.5. Perpendicular thermal conductivity was calculated from

$$\kappa_{\perp e} = n_e \chi_{\perp e}$$

- Thomson scattering resolution insufficient to resolve pedestal. Assumed HFS separatrix accurately determined by LRDFIT04 with shifted LFS profiles to make HFS + LFS T_e profiles smooth.

[8] T. M. Biewer, et al., Rev. Sci. Instr. **75** (2004) 650.

Heat flux driven Diamagnetic Drift

NSTX

- Tokar[9] - MARFE movement is due to one MARFE border cooled and the other heated by diamagnetic heat flows in the magnetic surface.

- Non-stationary heat balance equation with conductive diamagnetic heat flux and terms describing the dependencies of the pressure, P, on time, t, and poloidal angle, _, and assuming the other terms constant

$$\frac{3}{2}\frac{\partial P}{\partial t} + \frac{5}{2}\left(1 - \alpha_{\nabla T}\,\alpha_T\right)\frac{q_b}{eB\kappa_{\perp}a}\frac{\partial P}{\partial \theta} = C \qquad (5)$$

$q_b = \bar{q}_b(1 - \beta\cos\theta)$ conductive heat flux density through plasma edge

$\bar{q}_b = Q_b / A_p$ Q_b is conductive power transported through area A_p

$\alpha_{\nabla T} \equiv \nabla_r T_i / \nabla_r T_e$ and $\alpha_T \equiv T_i / T_e$

[9] M. Z. Tokar, Contrib. Plasma Phys. **32** (1992) 341.

MARFE Movement due to Diamagnetic heat flux drift

Taking perturbations of P of the form

$$\tilde{P} \propto \exp\left(V_{\vartheta d}\, t - a\theta\right) \qquad (6)$$

poloidal diamagnetic heat flux driven drift velocity is

$$V_{\theta d} = \frac{5}{3}\frac{q_b}{eB\kappa_\perp}\left(1 - \alpha_{\nabla T}\alpha_T\right) \qquad (7)$$

Using Thomson measurements of n_e and T_e and CHERS measurements of T_i at LFS separatrix we estimate for shot 117125

$\alpha_{\nabla T} = 0.85$ and $\alpha_T = 8.2$ at 660 ms => V_d = 1.0 km/s upward

$\alpha_{\nabla T} = 3.9$ and $\alpha_T = 9.4$ at 377 ms => V_d = 3.6 km/s upward

MARFE Movement = Diamagnetic heat flux + ExB Drift

- Total poloidal velocity of MARFE will be diamagnetic heat flux driven drift relative to the ExB drift.

- If MARFE velocity is due to the sum of the ExB and diamagnetic heat flux driven drifts, this implies ExB drift is

  -2.6 km/s (downward) => HFS E_r = -4.6 kV/m at 660 ms

  -1.7 km/s (downward) => HFS E_r = -3.3 kV/m at 377 ms

Discussion of Results

- CHERs measurements of carbon C6+ are averaged over ~7 ms and Thomson scattering measurements occur at 60 Hz. Temporal and spatial resolution of the data not quite sufficient. LFS separatrix location not accurately determined by equilibrium code. Experimental data was adjusted by assuming innermost HFS TS channel was placed on correct poloidal flux surface and shifting LFS Thomson T_e profiles to match HFS profiles.

- General tendency of MARFE threshold confirmed by NSTX experimental data.

- Theory strictly applies to conditions <u>before</u> MARFE formation and poloidal asymmetries not considered.

- Movement of MARFEs in NSTX consistent with the sum of diamagnetic heat flux and ExB drift, if conductive fraction is 0.5 and $_{e}$ is 50 m^2/s, then E_r is about -4 kV/m.

Conclusions

NSTX

• Modeling of NSTX by XGC0 limited by fast growth of ion polarization density at low magnetic fields and temperatures, neoclassical e-transport and no impurities.

• MARFE onset in NSTX is found to roughly agree with basic MARFE theory, but uncertainties in the data limit the comparison.

• MARFE movement in NSTX shot 117125 is consistent with diamagnetic heat flux driven motion relative to the background plasma velocity, i.e. ExB drift.

• Separatrix placement yielded separatrix T_e in the range 31 to 41 eV during MARFE activity, consistent with observations in TEXTOR at MARFE onset[10].

[10] F.A. Kelly, W.M. Stacey, J. Rapp and M. Brix, Phys. Plasmas **8** (2001) 3382.