Separatrix location in NSTX

F. Kelly[a], R. Maingi[b], R. Maqueda[c], J. Menard[a], B. LeBlanc[a], R. Bell[a], S. Paul[a]

[a]Princeton Plasma Physics Laboratory, Princeton, NJ USA
[b]Oak Ridge National Laboratory, Oak Ridge, TN USA
[c]Nova Photonics, Princeton, NJ USA

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Abstract

The separatrix location corresponding plasma parameters in NSTX were estimated for H-mode discharge 117125 containing both MARFEs and ELMs and for Type V ELMy H-mode discharge 128337. Since equilibrium reconstructions with LRDFIT did not accurately locate the LFS separatrix, method based on the strong electron parallel heat conductivity was used to map the LFS magnetic flux surfaces to the HFS since the innermost Thomson scattering measurement of $T_e(R)$ is the most accurate. During a MARFE or at MARFE onset in NSTX shot 117125, this method estimated the electron temperature at the LFS separatrix, $T_{e,sep}$, to vary between 31 and 41 eV in most cases. At times with no MARFE or ELM, $T_{e,sep}$ ranged between 41 and 101 eV. These $T_{e,sep}$ values compare well with $T_{e,sep}$ values (28-35 eV) in TEXTOR just before MARFE onset.[1] In NSTX shot 128337 late in the Type V ELMy phase, $T_{e,sep}$ was estimated to be ~100 eV. These separatrix locations place the E_r well outside the separatrix.

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

Introduction

Motivation

Plasma parameters (T_e, n_e, n_{carbon}, etc) needed at separatrix for MARFE and SOL width analysis

Problem

Equilibrium codes EFIT and LRDFIT do not uniquely or accurately locate the separatrix. Possible causes:

- Mode in which code is run
- Selection of magnetic and flux loop sensors
- Perturbations of sensors by ELMs
- 3D perturbations of magnetic surfaces (magnetic islands)
- Thomson scattering (TS) measurement of filament (blob, ELM)
- Spatial resolution of TS measurements in steep gradient region and fitting algorithm used

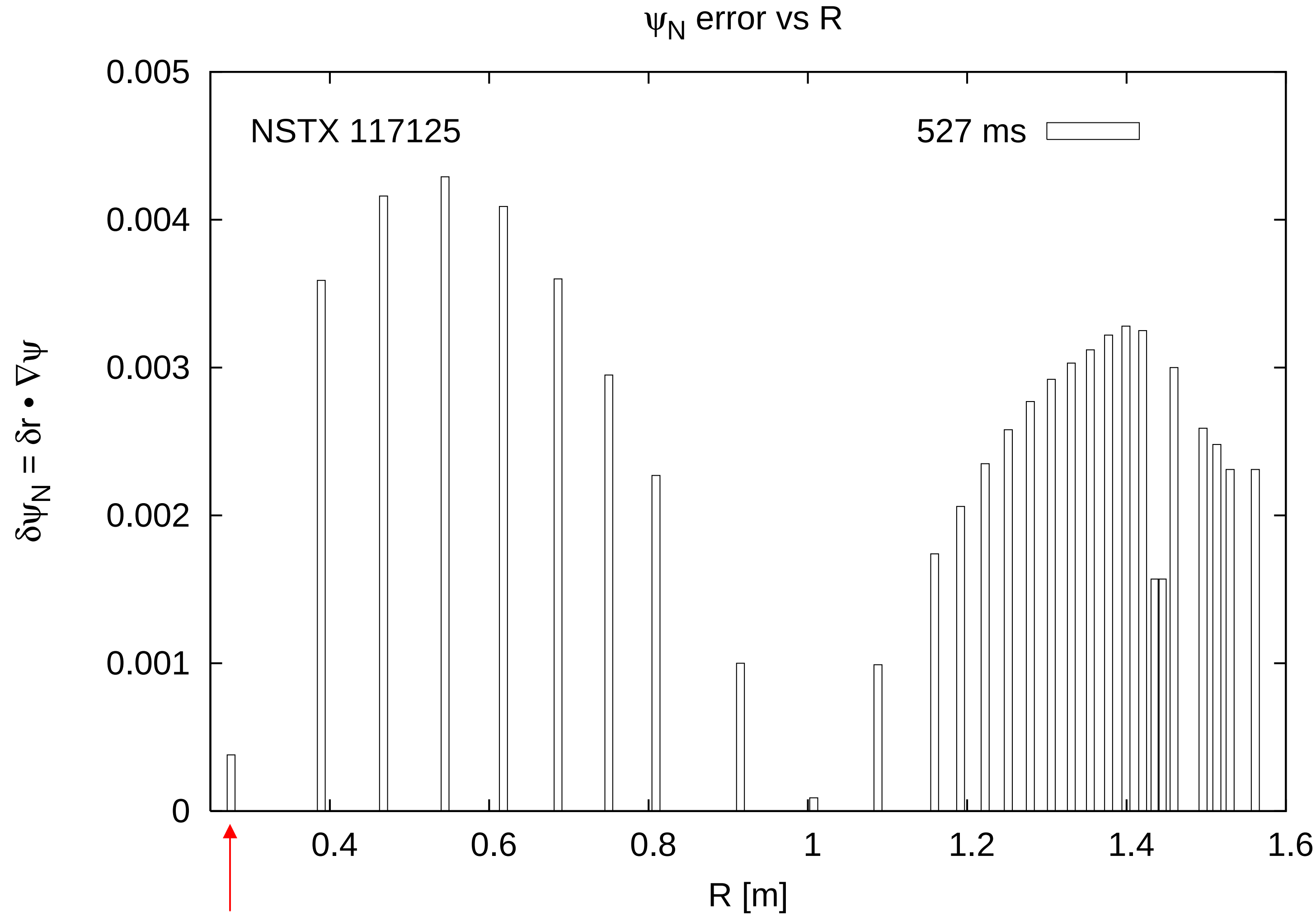
Introduction (2)

Approach

Enforce iso-T_e constraint on flux surfaces if T_e high enough

- Use (if possible) innermost TS channel since laser is tangent to flux surface here and results in ψ_N error is approximately an order of magnitude smaller than other edge TS channels
- Shift low field side (LFS) T_e profile to overlay innermost Thomson channel T_e

Small ψ_N error for innermost Thomson channel



NSTX 117125: I_p = 900 kA, P_{nbi} = 6.2 MW, LSN - Near DN, $\kappa \approx 2.4$

MARFE theory

Drake[2] found the MARFE to be a radiative condensation instability governed by

parallel and perpendicular conduction | radiative condensation

$$\frac{5}{2} n\gamma \tilde{T} + k_{\|}^{2} \kappa_{\|} \tilde{T} - \kappa_{\perp} \frac{\partial^{2} \tilde{T}}{\partial r^{2}} = n n_{z} \left(\frac{2L_{z}}{T} - \frac{\partial L_{z}}{\partial T} \right) \tilde{T} \qquad (1)$$

Wesson and Hender[3] observed that the most unstable mode $\tilde{T}$ varies as cos θ and wave number $k_{\|} = 1/qR$

$$\kappa_{\perp} \frac{\partial^{2} \tilde{T}}{\partial r^{2}} - k_{\|}^{2} \kappa_{\|} \tilde{T} = n n_{z} T^{2} \frac{\partial}{\partial T} \left(\frac{L_{z}(T)}{T^{2}} \right) \tilde{T} \qquad (2)$$

[2] Drake, PF **30** (1987) 2429.

[3] Wesson and Hender, NF **33** (1993) 1019.

MARFE density limit

Mahdavi[4], et al. and Maingi and Mahdavi[5], incorporated non-equilibrium radiation effect of neutrals in a uniform edge distribution to obtain

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

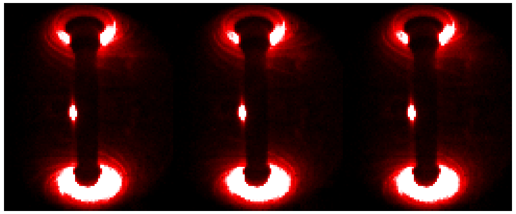
Defining the MARFE Index, MI

$$\mathrm{MI} \equiv \frac{\mathrm{n}_{e,sep}^{\exp}}{\mathrm{n}_{marfe}} \qquad (4)$$

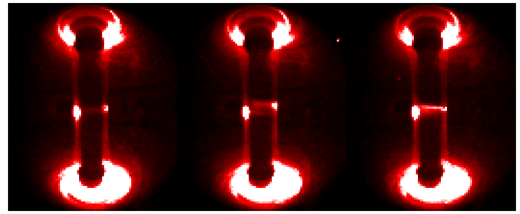
[4] Mahdavi, et al., in *Proc. 24th European Conf. on Controlled Fusion and Plasma Physics*, Berchtesgaden, Germany, 1997, Vol. **21A**, p. 1113.
[5] Maingi and Mahdavi, Fusion Sci. and Technol. **48** (2005) 1117.

MARFE Conditions observed in NSTX discharge 117125

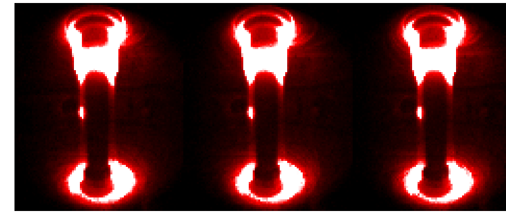
no marfe; t = 0.326662 s



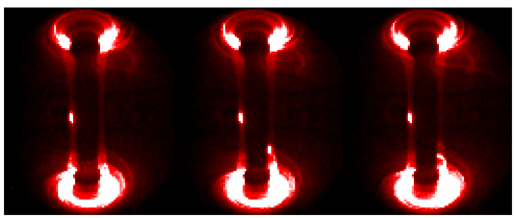
stagnation; 0.493322 s



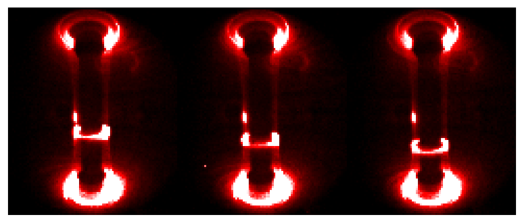
stable at top; 0.676685 s



marfe onset; 0.726662 s

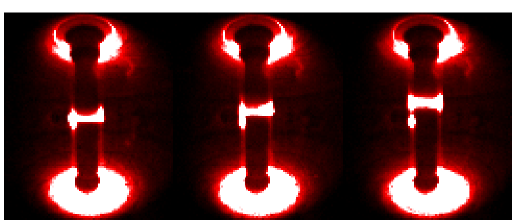


move down; 0.660002 s



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

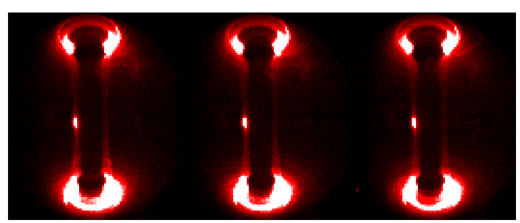


Table 1 Unshifted Maqueda LRDFIT04 separatrix data and MARFE condition for NSTX shot 117125 at TS times and calculation of MARFE Index when $t_{TS} \approx t_{CHERS}$.

t_{TS} (s)	Condition	t_{CHERS} +1.4 ms	T_e [eV]	n_e [10^{19} m^{-3}]	f_C[%]	MI
326.662	no marfe	326.65	11	0.86	7.2	2.57
343.345	no marfe	346.65	26	2.0		
359.992	no marfe	356.65	15	1.4		
376.685	upward move	376.65	12	0.88	6.4	2.36
393.332	no marfe	396.65	11	0.87		
410.015	no marfe	406.65	12	0.67		
426.662	no marfe	426.65	5	2.6	5.2	3.90
443.345	no marfe	446.65	10	1.2		
459.992	no marfe	456.65	13	0.72		
476.685	onset	476.65	20	1.1	6.2	1.29
493.322	stagnation	496.65	16	1.0		
510.025	stagnation	506.65	13	1.1		
526.662	no marfe	526.65	6	0.86	4.9	1.81
543.345	onset	546.65	17	0.53		
559.992	no marfe	556.65	11	0.50		
576.685	onset	576.65	14	0.99	6.8	2.33
593.332	onset	596.65	10	0.56		
610.025	no marfe	606.65	10	0.52		
626.662	burn	626.65	12	0.56	10.7	2.12
643.355	stagnation	646.65	8	0.71		
660.002	move down	656.65	7	0.12		
676.685	stable at top	676.65	25	1.7	4.5	1.10
693.332	no marfe	696.65	12	0.60		
710.015	onset	706.65	8	0.66		
726.662	onset	726.65	14	1.1	4.8	2.06
743.355	no marfe	746.65	8	0.56		
759.992	no marfe	756.65	24	2.1		
776.685	no marfe	776.65	21	1.2	5.9	1.22
793.332	no marfe	796.65	13	1.2		
810.015	stagnation	806.65	11	0.92		

Poor agreement between theory and experiment

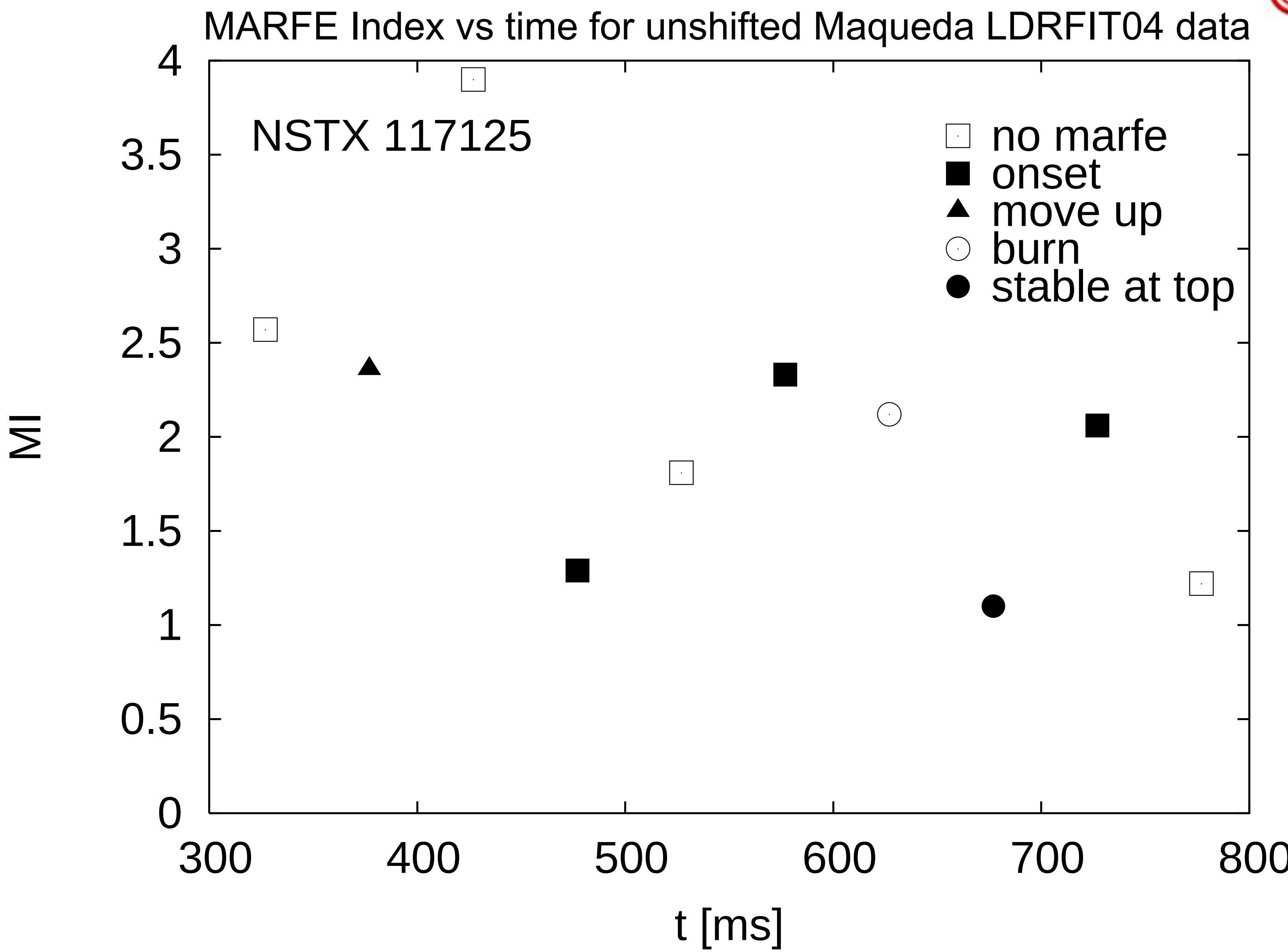


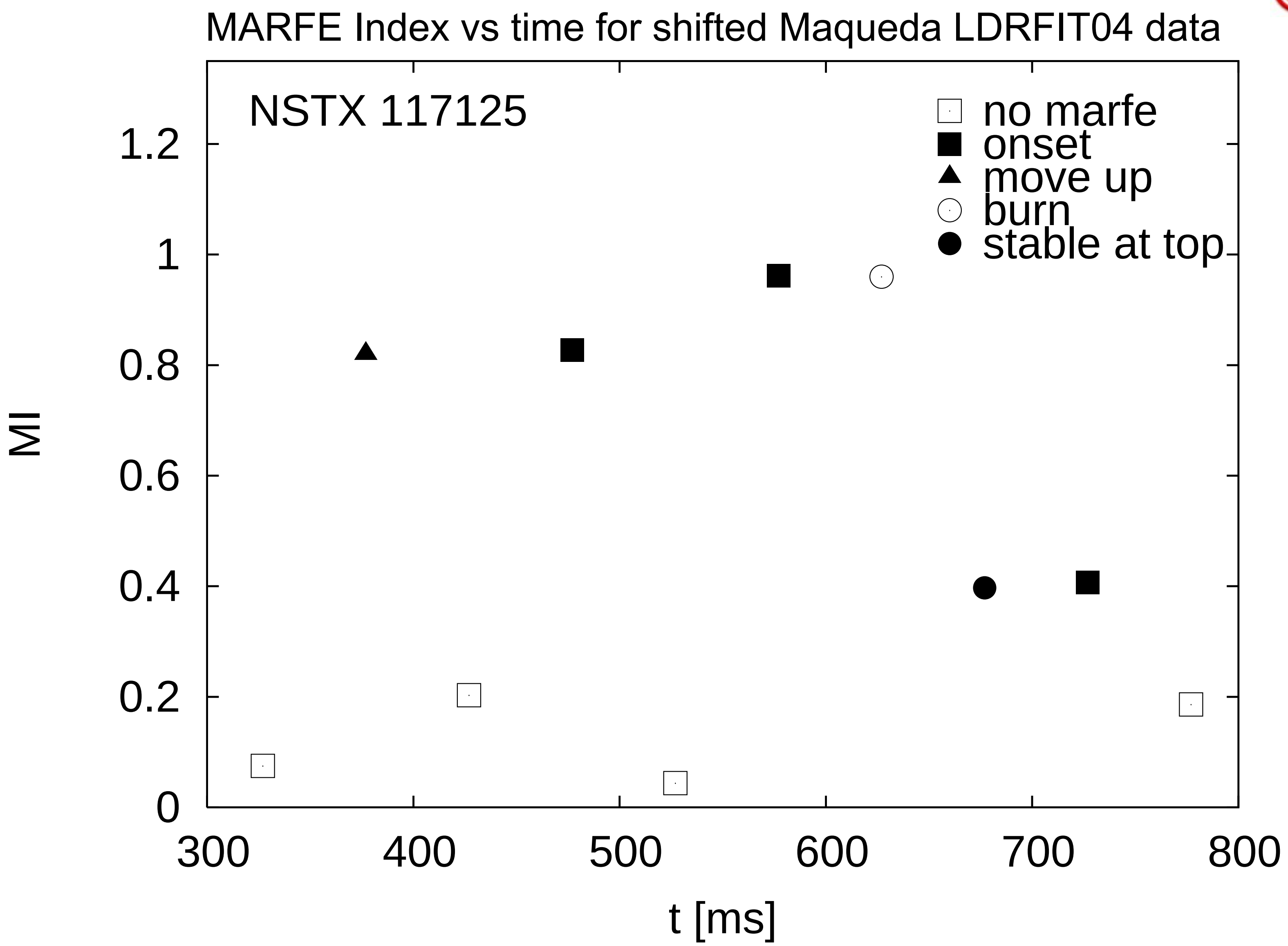
Table 2 Shifted Maqueda LRDFIT04 separatrix data and MARFE condition for NSTX shot 117125 at TS times and calculation of MARFE Index when $t_{TS} \approx t_{CHERS}$.

NSTX

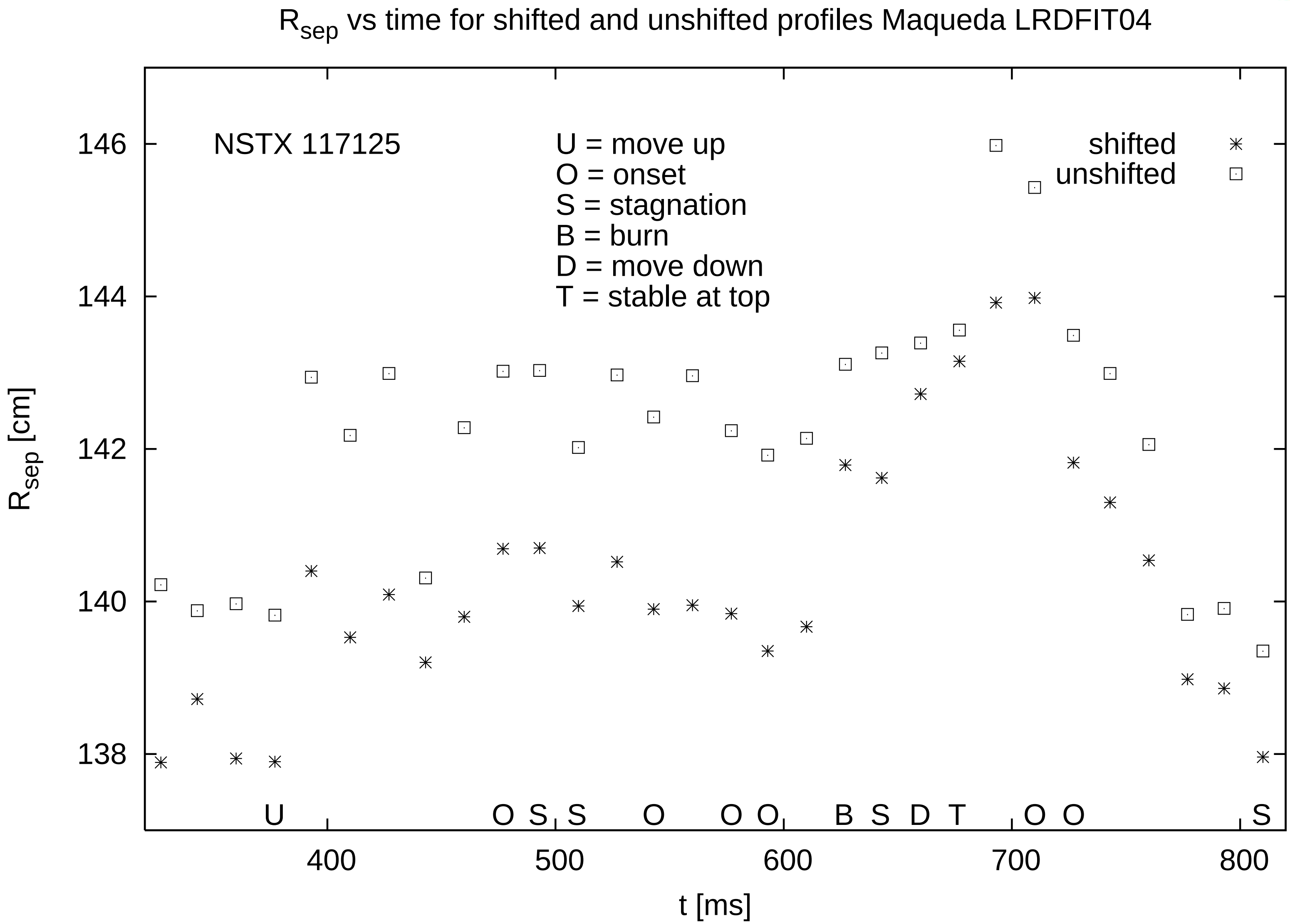
Align	t_{TS} (ms)	Condition	t_{CHERS} +1.4 ms	T_e [eV]	n_e [10^{19} m^{-3}]	f_C[%]	MI
1	326.662	no marfe	326.65	93	2.5	7.2	0.07
1	343.345	no marfe	346.65	101	2.9		
1	359.992	no marfe	356.65	71	2.6		
1	376.685	upward move	376.65	34	2.2	6.4	0.82
1	393.332	no marfe	396.65	99	2.4		
2/v	410.015	no marfe	406.65	61/94	1.5/1.9		
1	426.662	no marfe	426.65	51	1.8	5.2	0.20
1	443.345	no marfe	446.65	64	2.2		
1	459.992	no marfe	456.65	53	2.1		
1	476.685	onset	476.65	38	3.0	6.2	0.83
1	493.322	stagnation	496.65	35	2.1		
1	510.025	stagnation	506.65	33	1.9		
1	526.662	no marfe	526.65	147	3.4	4.9	0.04
1/v	543.345	onset	546.65	24/35	1.2/1.4		
1	559.992	no marfe	556.65	53	2.1		
1	576.685	onset	576.65	31	1.9	6.8	0.96
1	593.332	onset	596.65	58	2.7		
1	610.025	no marfe	606.65	41	1.9		
1	626.662	burn	626.65	34	1.8	10.7	0.96
2/v	643.355	stagnation	646.65	58/35	2.4/1.9		
2/v	660.002	move down	656.65	17/32	0.3/1.5		
2/v	676.685	stable at top	676.65	41/41	2.2/2.2	4.5	0.40
1	693.332	no marfe	696.65	41	2.3		
2/v	710.015	onset	706.65	63/35	3.5/2.2		
1	726.662	onset	726.65	41	2.2	4.8	0.41
1	743.355	no marfe	746.65	50	1.6		
1	759.992	no marfe	756.65	68	2.8		
1	776.685	no marfe	776.65	61	2.5	5.9	0.19
1	793.332	no marfe	796.65	75	2.5		
1	810.015	stagnation	806.65	60	2.6		

Alignment: 1 – 1st TS ch.; 2 – 2nd TS ch.; v - visual

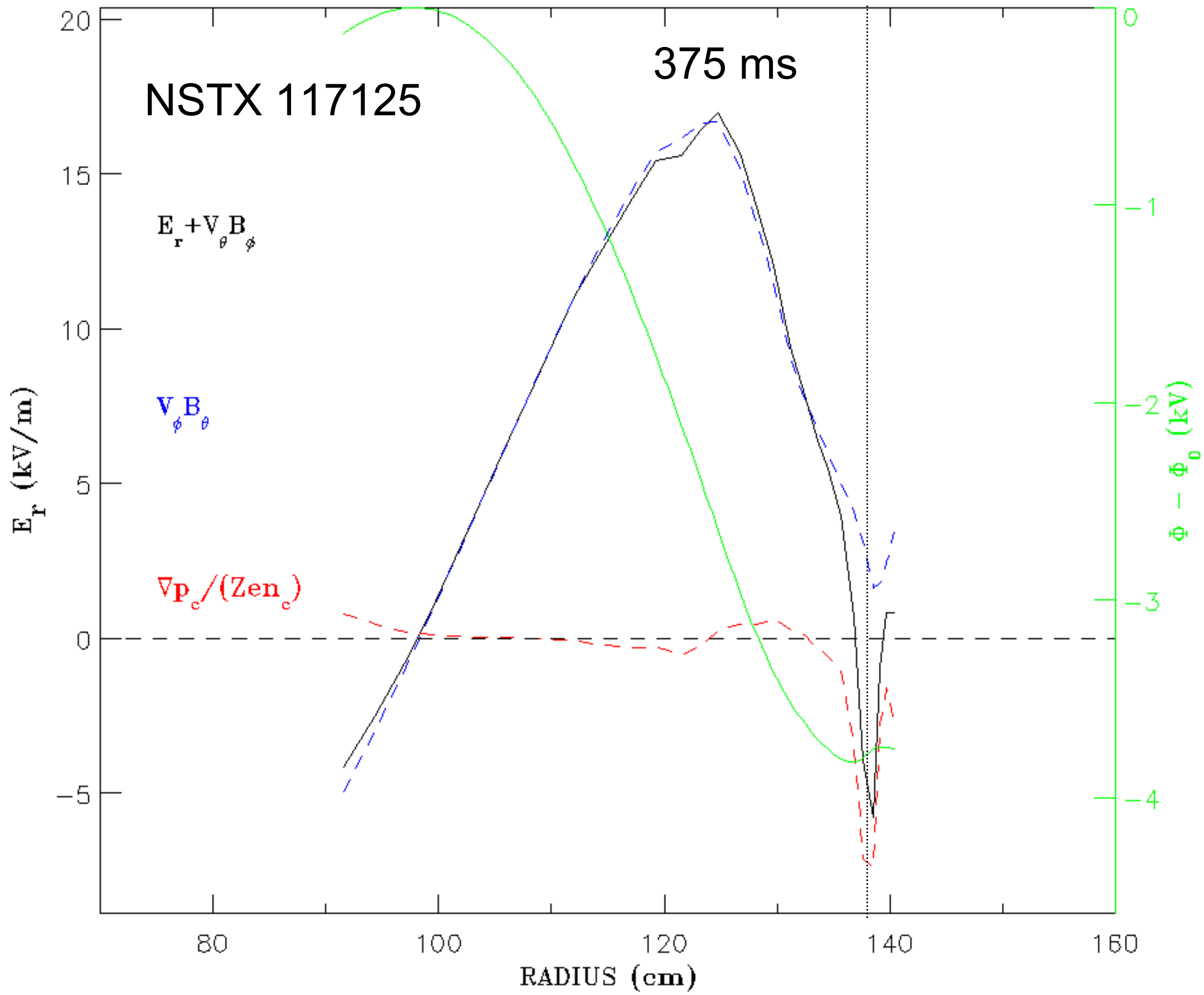
Shifted T_e profiles improve theory/experiment agreement



LFS separatrix shifted inward between 0.4 to 3.0 cm



E_r well appears mostly outside separatrix



Shifted Maqueda LRDFIT04 R_{sep} = 137.90 cm.

Can theory/experiment agreement be improved?

Attempt to run LRDFIT (J. E. Menard) in different modes with JEM recommended magnetic and flux loop sensor selection:

- B_2DMIBDV* excluded, influenced by OHxTF error field
- B_L1DM*PPG** excluded, not corrected for local eddy current effects
- B_L1DM*PPG**_AXEQ included, corrected for local eddy current effects
- F_FLEVVL7, B_1DMCSCU6, B_2DMCSCU1N excluded, sensor failure
- B_2DMOBD*** included

Varied p' and FF' node definitions and grid resolutions.

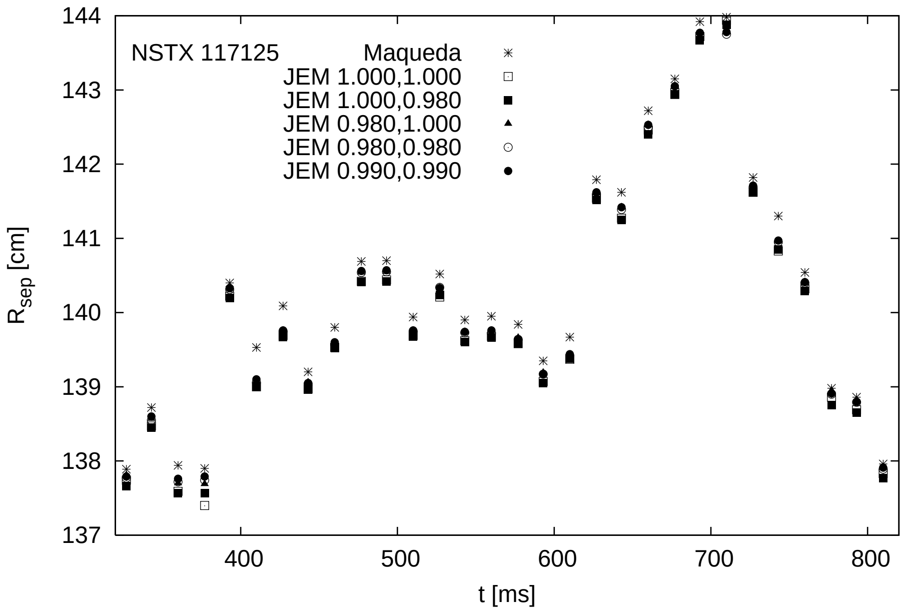
First, use 4 nodes each and vary last node location with default 41x41 grid resolution and run LRDFIT in 04 mode (Magnetics and T_e-iso):

p' = [0.0 0.300 0.920 x.xxx] for the pairs x.xxx,y.yyy
FF' = [0.0 0.500 0.750 y.yyy]

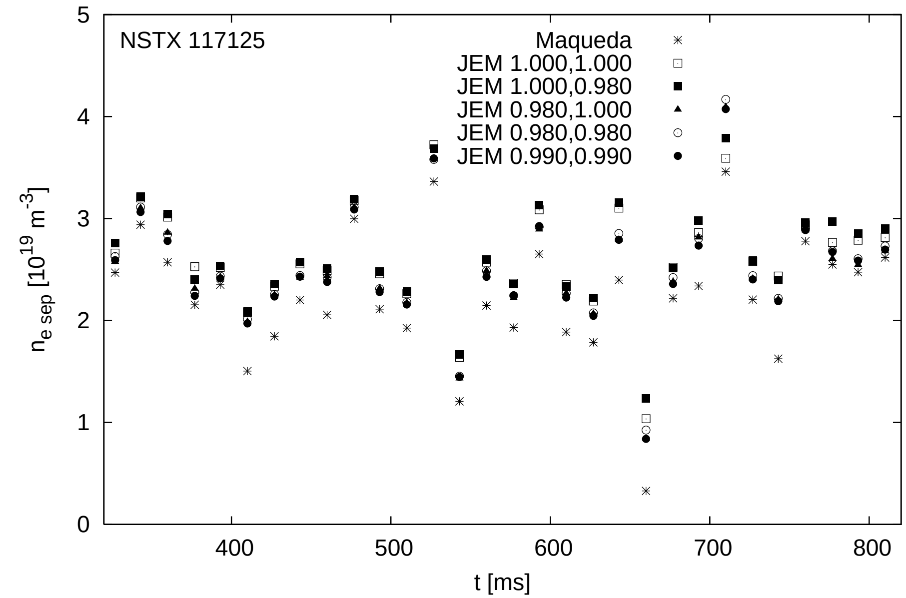
1.000,0.980
1.000,1.000
0.980,1.000
0.980,0.980
0.990,0.990

Position of last nodes of p' and FF' affect LFS separatrix

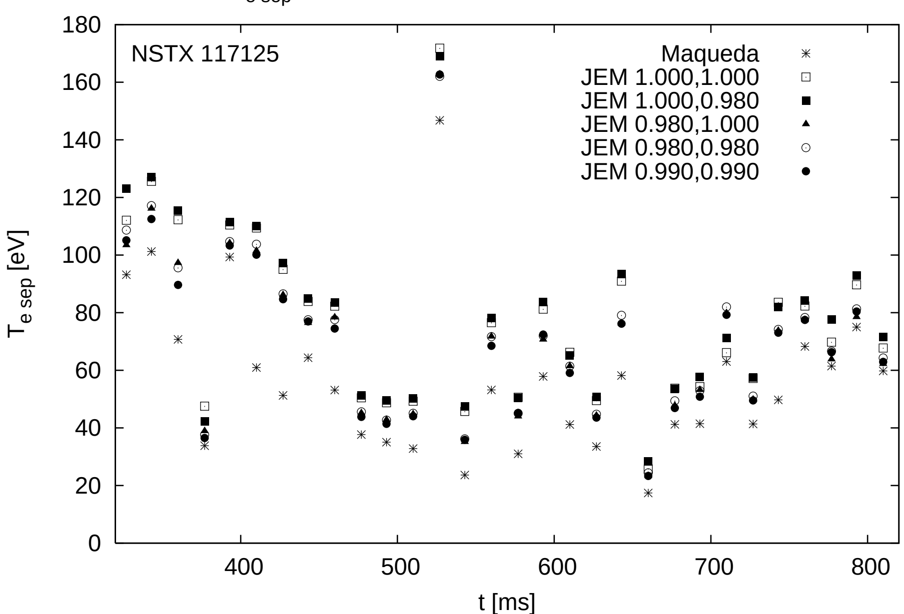
R_{sep} vs time for varied last node location LRDFIT04



$n_{e\ sep}$ vs time for varied last node location LRDFIT04



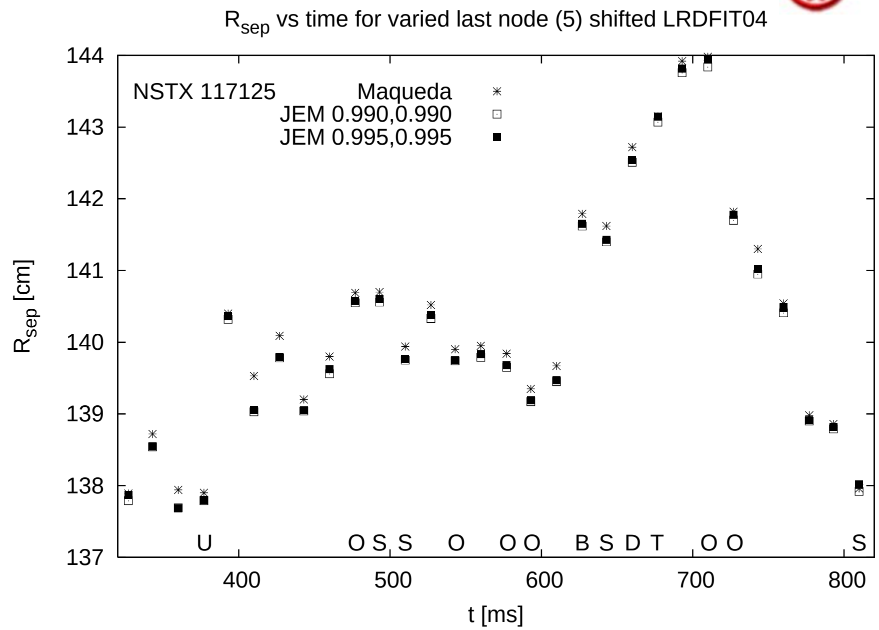
$T_{e\ sep}$ vs time for varied last node location LRDFIT04



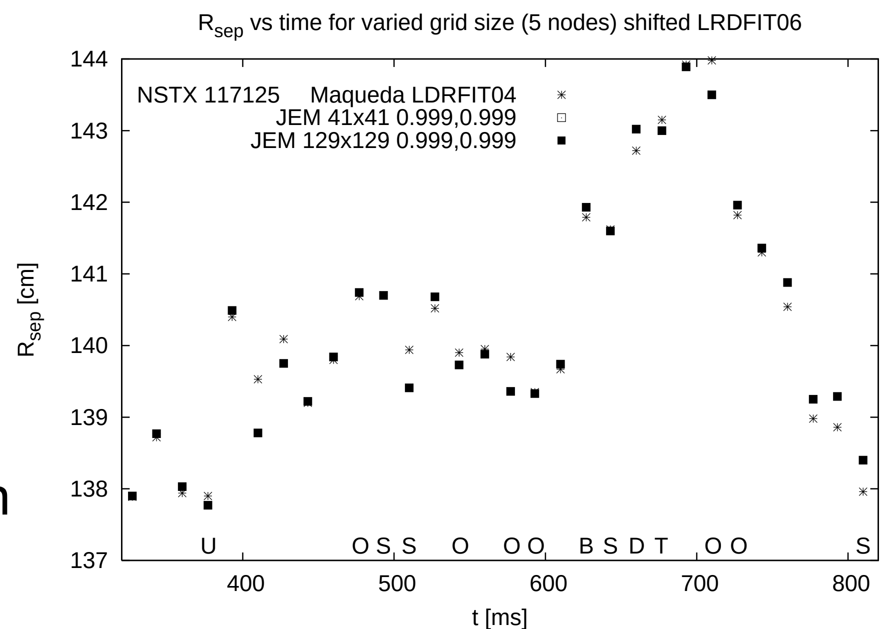
Last p' node at 1.000 moves separatrix deepest into plasma which seems unrealistic. Shifted Maqueda equilibrium generally furthest out and 0.990,0.990 usually furthest out of JEM equilibria.

Five p' and FF' nodes, mode 06 and grid size

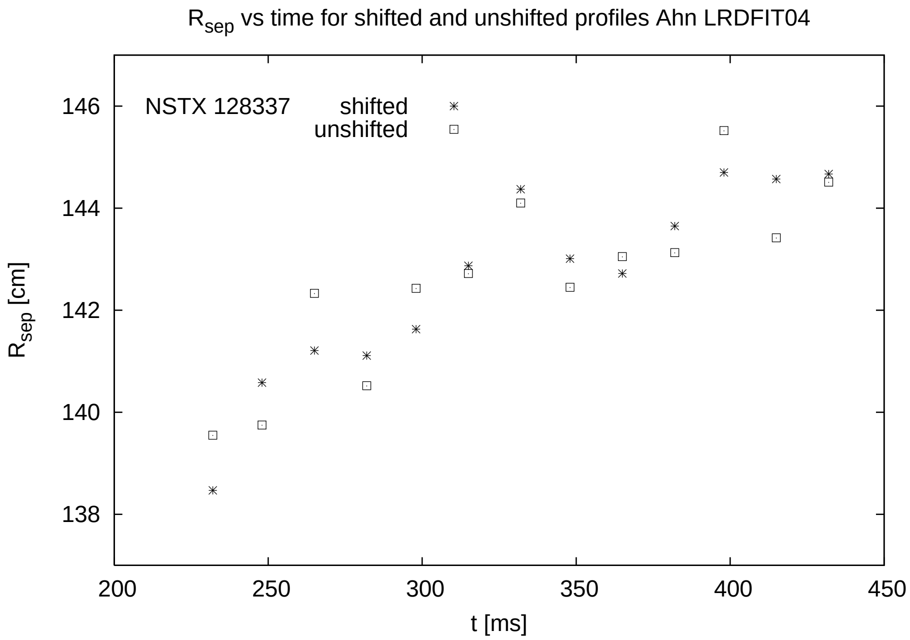
Runs with LRDFIT04
Magnetics and T_e-iso
with
p' = 0.0 0.250 0.700 0.970 x.xxx
FF' = 0.0 0.400 0.800 0.980 y.yyy

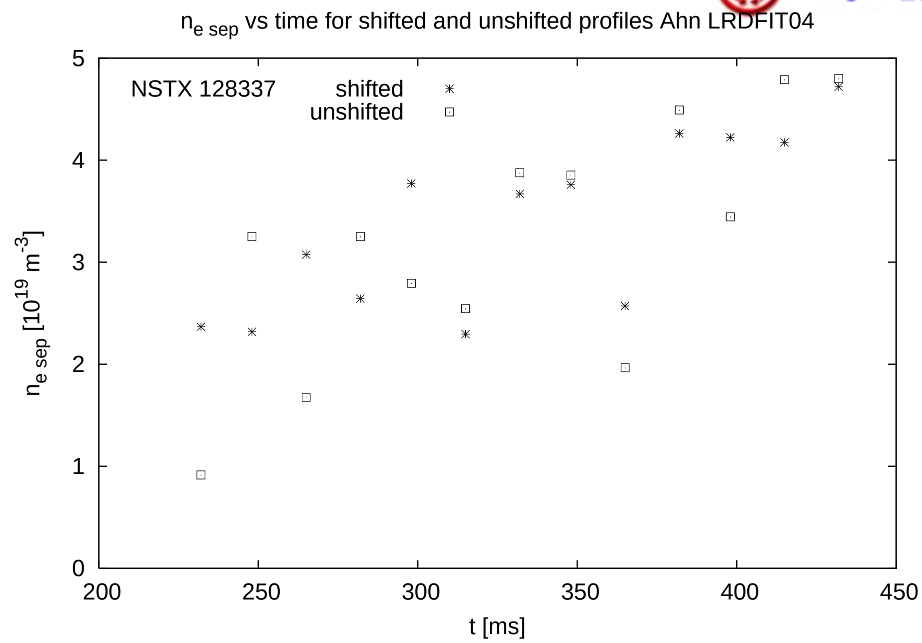


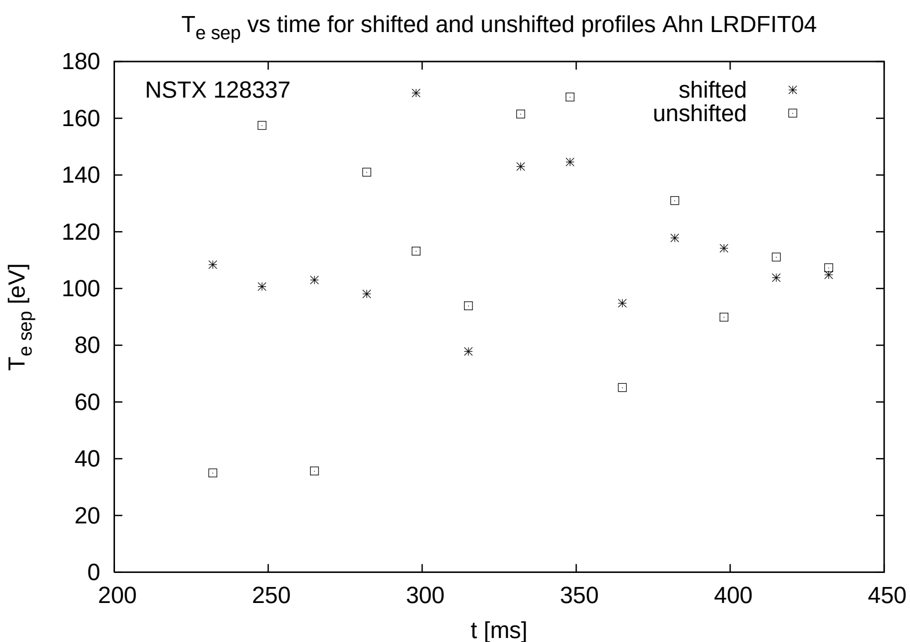
Runs with LRDFIT06
Magnetics, T_e-iso,
Pitch Angle Data (error wt = 0.4)
and E_r correction
with
p' = 0.0 0.250 0.700 0.970 0.999
FF' = 0.0 0.400 0.800 0.980 0.999
41x41 and 129x129 grid resolution



Separatrix location for Type V ELMy shot 128337







Both shifted and unshifted flux surfaces can result in separatrix position deep in plasma with remarkably high T_e and n_e for discharge 128337

P_{nbi} = 2 MW for t < 320 ms,

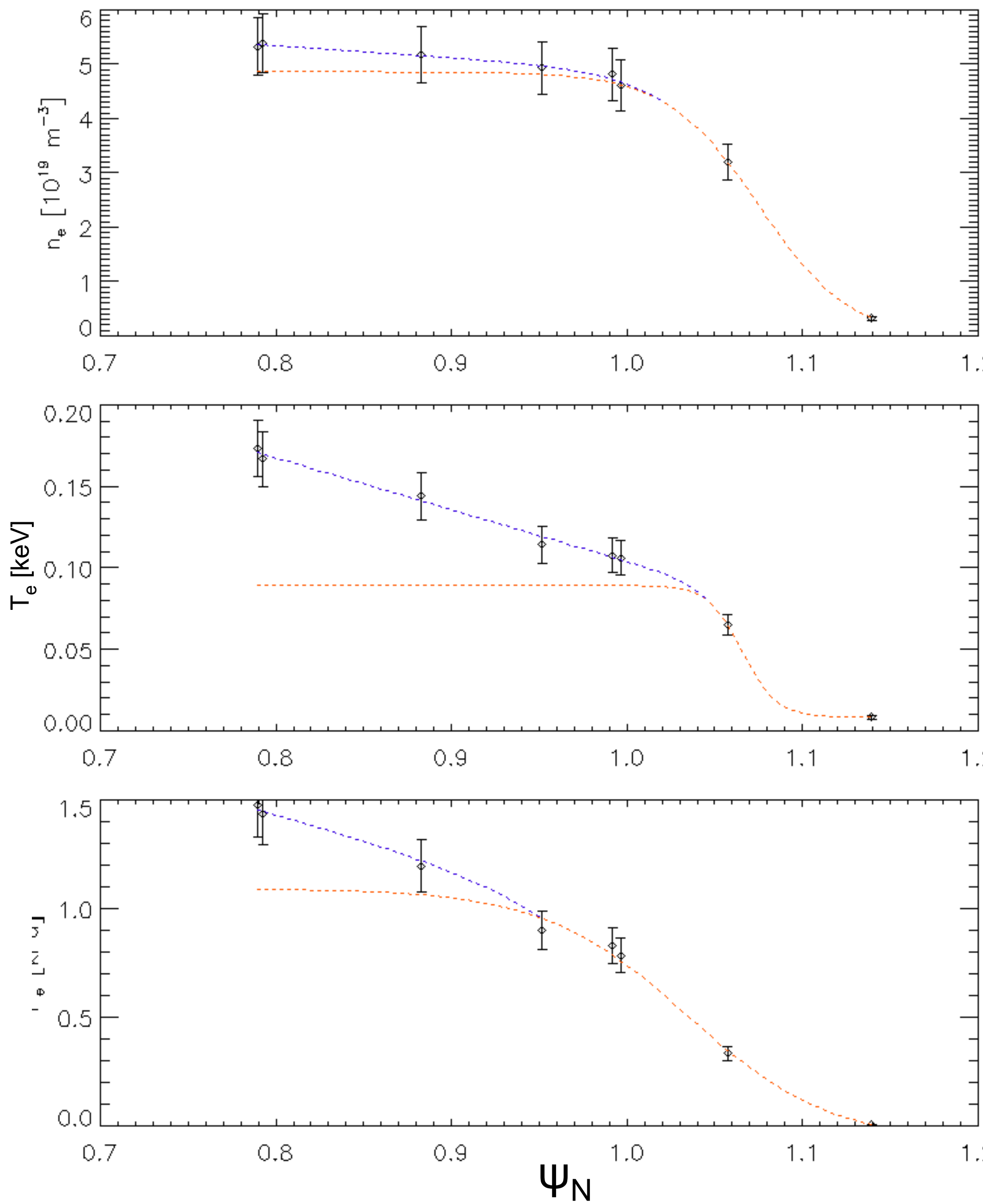
P_{nbi} = 1 MW for t > 330 ms and I_p = 1 MA.

LFS Separatrix location for Type V ELMy shot 128337

Both shifted and unshifted equilibrium fits place separatrix on top of pedestal at 432 ms with $T_{e,sep}$ > 100 eV.

Way in which LRDFIT04 was run may not be correct.

Examine p' and FF' node locations “basis functions”, magnetic and flux loop sensor selection used by Maqueda and Ahn.

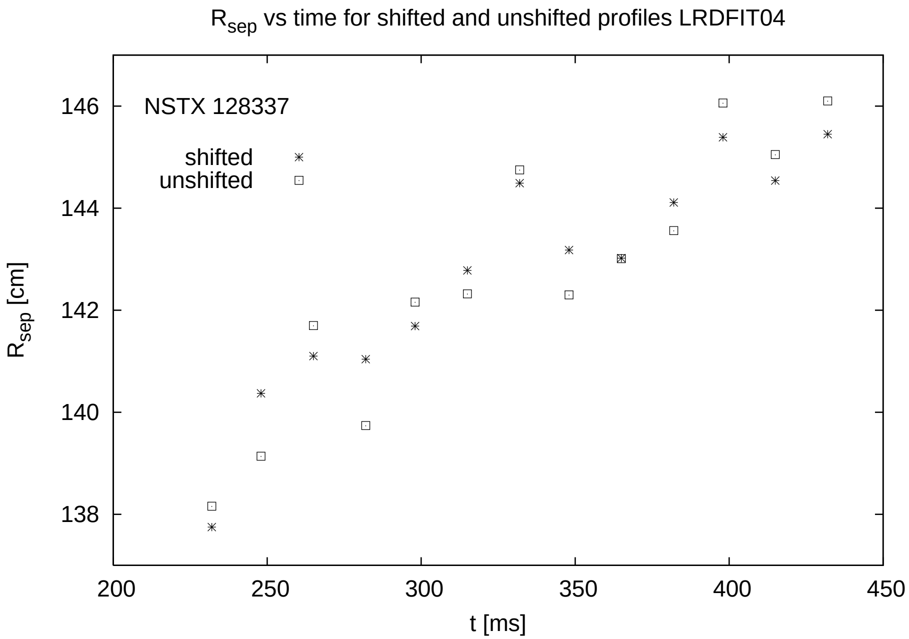


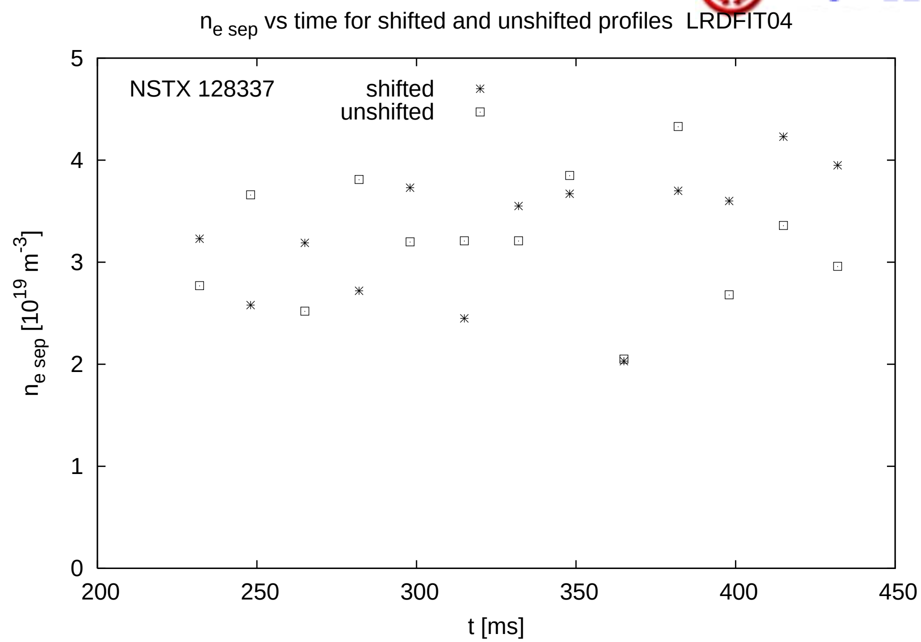
LRDFIT04 basis functions, magnetic and flux loop sensors

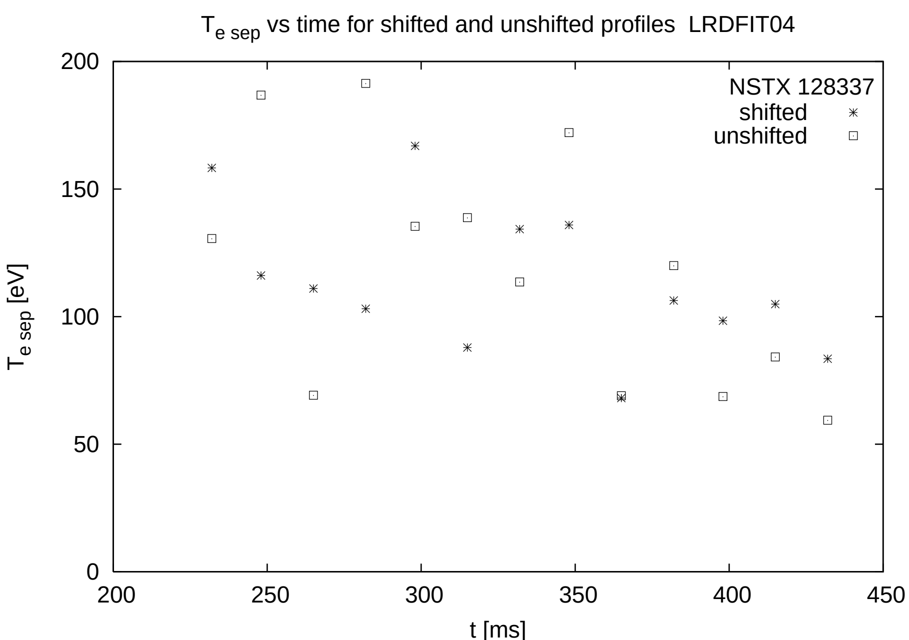
Maqueda LRDFIT04 117125	Ahn LRDFIT04 128377
p' = 0.0 0.980	p' = 0.0 0.980
FF' = 0.0 0.600 1.0	FF' = 0.0 0.600 1.0
B_2DMIBDV* excluded	B_2DMIBDV* excluded
B_L1DM*PPG** excluded	B_L1DM*PPG** excluded
B_L1DM*PPG**_AXEQ included	B_L1DM*PPG**_AXEQ 10/12 excluded!
B_1DMCSCU6 excluded	B_1DMCSC** 10/12 excluded!
B_2DMCSCU1N excluded	B_2DMCSC*** 3/3 excluded!
B_2DMOBD*** included	B_2DMOBD*** 11/12 excluded!
F_FLEVVL6, F_FLEVVL7 excluded	F_FL***** 32/46 excluded!

Too many magnetic and flux loop sensors excluded from LRDFIT04 128337 equilibrium reconstruction. Reran LRDFIT04 for shot 128337 with input parameters similar to those by Maqueda for shot 117125. Also compared with EFIT02 for shot 128337 on MDS tree.

LRDFIT04 for 128337 with revised input



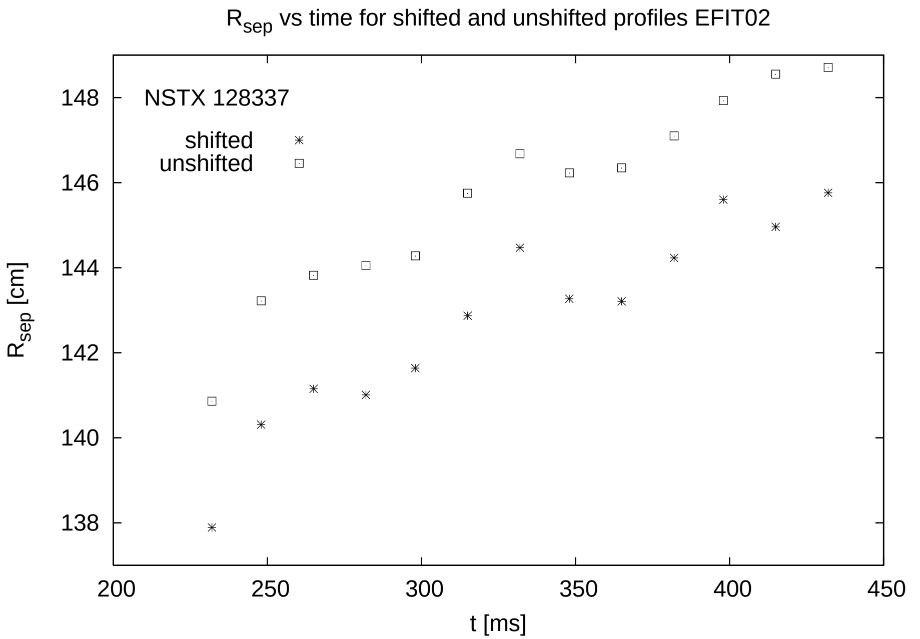


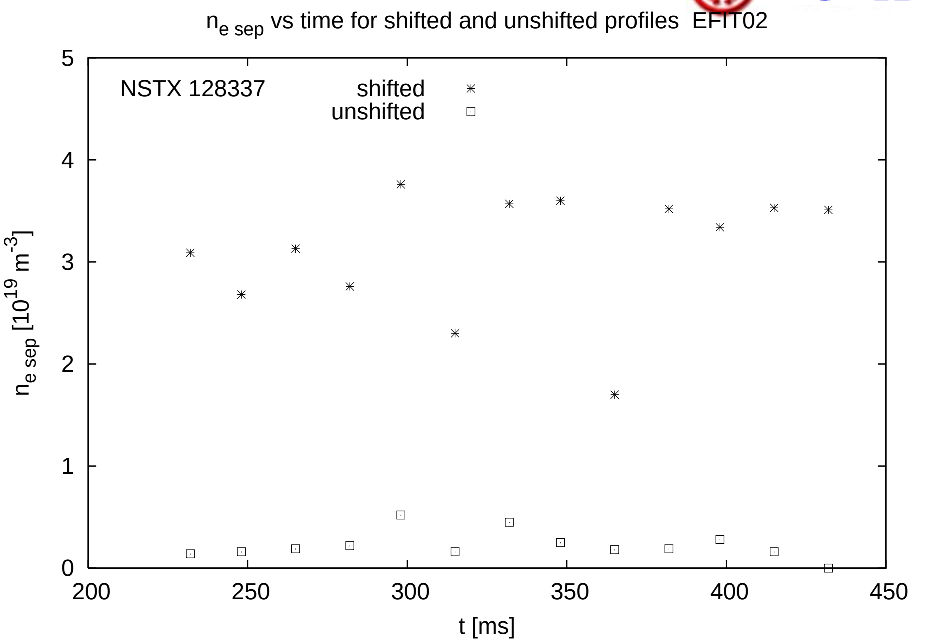


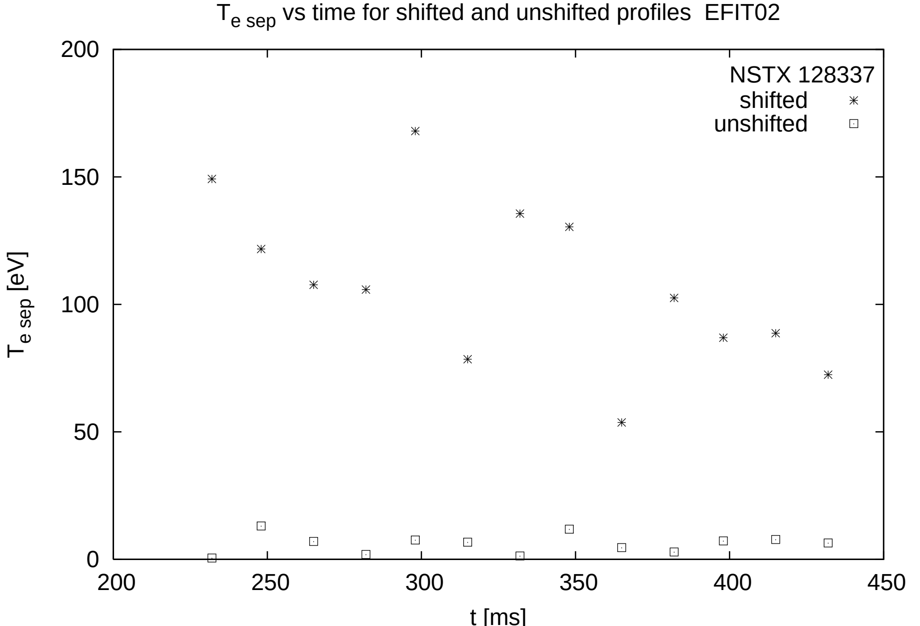
Separatrix locations are similar. Are they better? Suggests Type V ELMy H-mode has a separatrix near top of T_e pedestal.

Try using EFIT02 from MDSplus tree.

EFIT02 for 128337







Required large inward shifts!

Separatrix locations again are similar. Hard to say if they are better. EFIT02 seemed to have difficulty locating magnetic axis.

Discussion of Results

Seems possible to run LRDFIT to improve separatrix location, as calibrated by MARFE onset. Maqueda LRDFIT04 117125 equilibrium after flux surface shifting seem best, but problems still remain.

Method fails when MARFE in sightline of innermost TS channel.

Type I ELM occurred at 375 ms before upward moving MARFE at 377 ms without apparent effect on LRDFIT04 equilibrium fit. However, were ELMs near 527 and 543 ms cause of degradation of equilibrium fits or was degradation due to 3D perturbations (magnetic islands)?

Did magnetic islands cause a failure at 810 ms? What about 593 ms?

Way that LRDFIT is run affects separatrix position. Difficult to say which is best. Too many p' and FF' nodes can over constrain the equilibrium fit. Must include enough magnetic and flux loop sensors to place innermost Thomson channel near the correct flux surface. Separatrix placed too far inward by using last p' node at $\psi_N = 1.0$.

Iso-T_e shifted profile method tends to place E_r well mostly outside estimated separatrix in NSTX shot 117125.

Conclusions

- MARFE experiment/theory found useful to calibrate separatrix location

- LFS separatrix location depends on how the equilibrium code is run
  - p' and FF' node numbers and locations
  - Selection of magnetic sensors and flux loops
  - Grid size
  - Constraint set iso-Te, MSE, E_r correction, …

- Shifting LFS flux surfaces can improve separatrix location in some cases, however
  - Equilibrium fit is complex and difficult to know when correct
  - fast Thomson measurements catch blob and ELM filaments
  - 3D perturbations invalidate 2D-equilibria
  - MARFEs near sightline make innermost TS channel unusable

- Slower measurement with higher time and spatial resolution than Thomson scattering diagnostic (He-beam?) maybe useful for accurate equilibrium calculation. Problem of 3D perturbations remains.