# Effects of a GPI deuterium gas puff on the edge plasma in NSTX

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# Overview and Outline of Poster

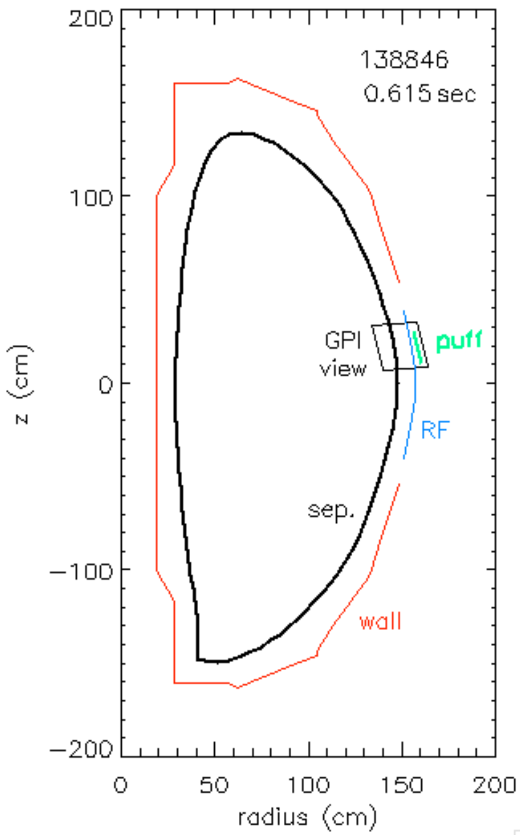
- **Does the $D_2$ gas puff used for the GPI diagnostic affect the edge plasma parameters or the edge turbulence ?**

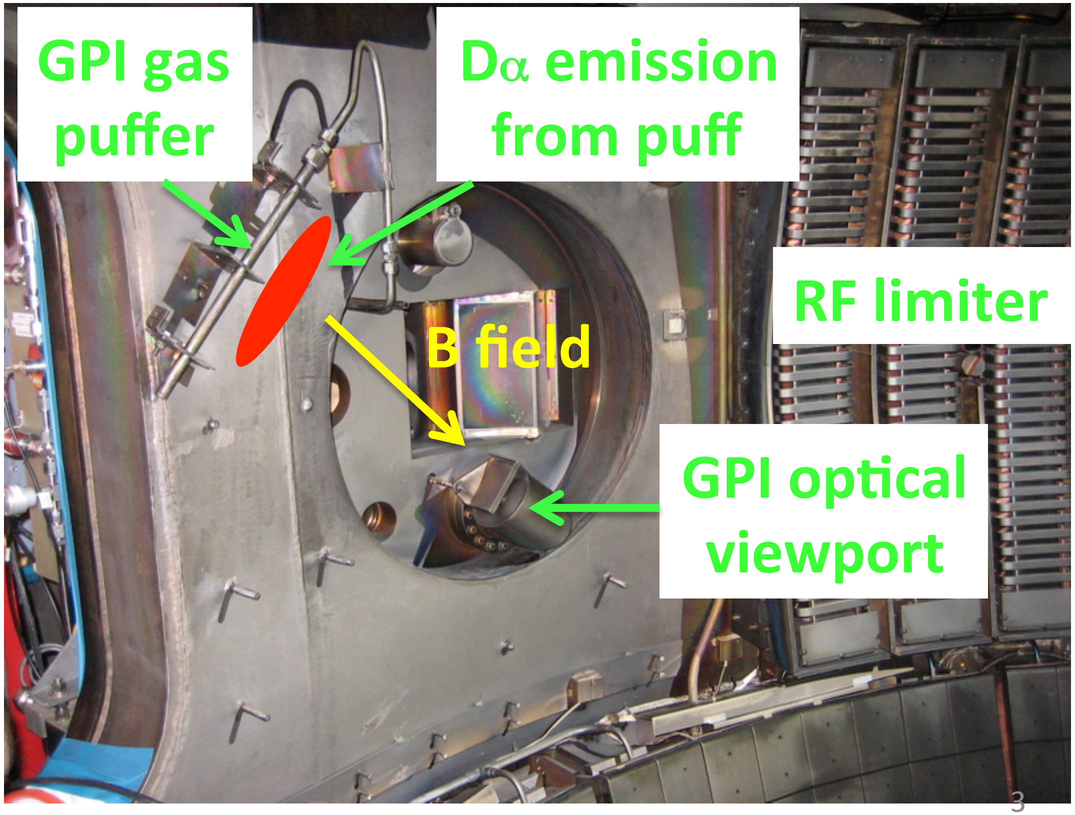
- This poster describes measurements of the edge plasma and turbulence with/without the GPI puff, and some modeling:

  - GPI gas puff and its effect on plasma parameters
  - time dependence of the GPI $D\alpha$ emission profiles
  - time dependence of GPI turbulence and its velocity
  - effects on other measurements (edge $T_i$, BES, high k)
  - theoretical estimates and modeling (DEGAS 2 and UEDGE)

# Deuterium Gas Puff Location

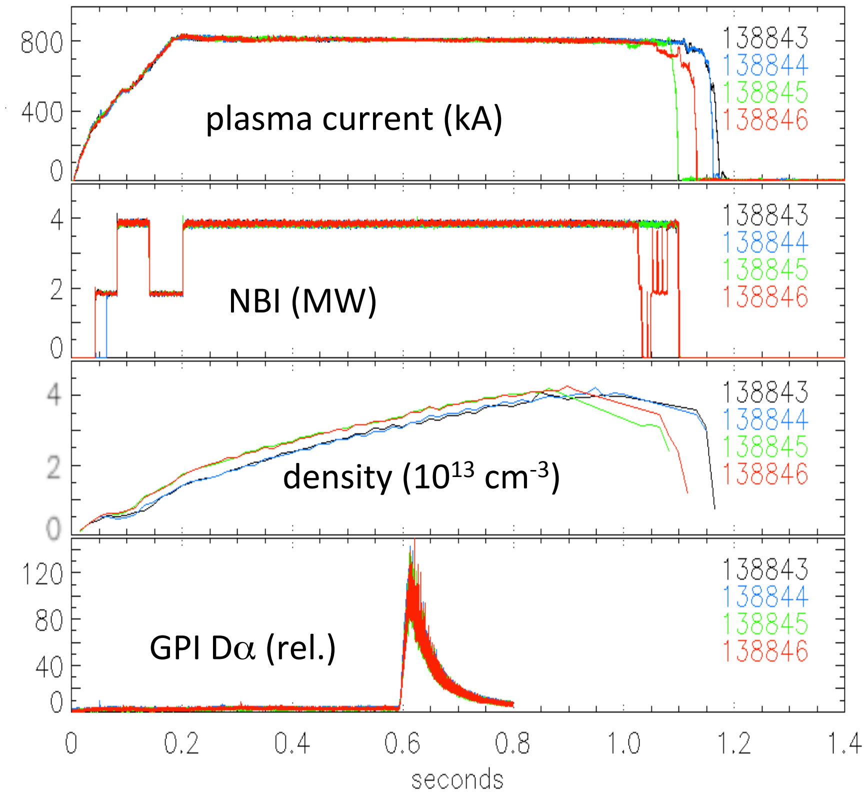
- $D_2$ gas puffed from GPI manifold on outer wall above midplane
- GPI gas puff manifold extends ~30 cm perpendicular to field line



# Timing and Strength of GPI Gas Puff

- GPI gas puffed during shot and monitored by local Dα emission
- Puff does *not* significantly increase line-average plasma density




| | |
|---|---|
| 138843 | no GPI puff |
| 138844 | 5.7 Torr-liters total $D_2$ puff |
| 138845 | 5.4 Torr-liters total $D_2$ puff |
| 138846 | 5.7 Torr-liters total $D_2$ puff |

total puff/shot = $3.8 \times 10^{20}$ D atoms
peak puff rate = $6.6 \times 10^{21}$ D atoms/sec
peak D puff ionization rate inside separatrix
~ $1.3 \times 10^{21}$/sec (~20% fueling efficiency)

electron source due to puff inside separatrix:
~ 3% of total electrons by peak of puff
~ 9% of total electrons by 70 msec of puff

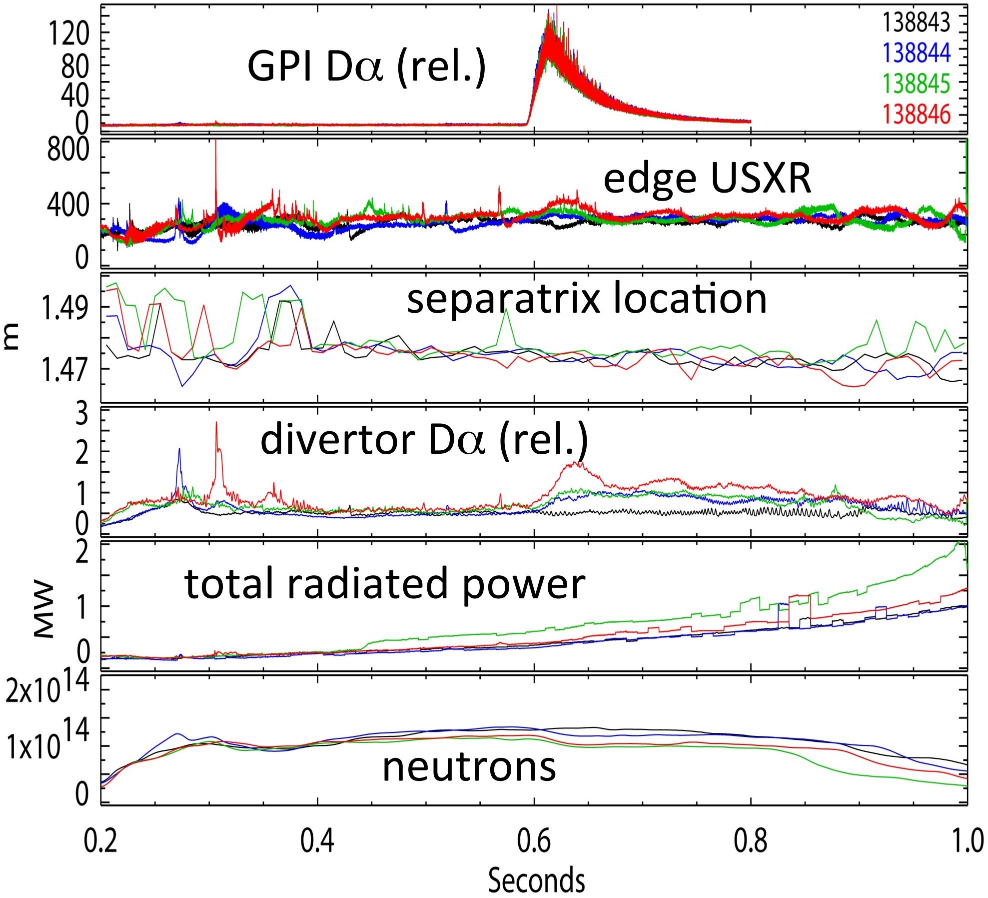
# Database of NSTX Shots for this Poster

| shot | B | I | P | n | gap(cm) | peak(s) | T-l | Type of shot |
|---|---|---|---|---|---|---|---|---|
| 138843 | 4.4 | 0.8 | 3.9 | 6.5 | 10.2 | 0.613 | 0 | NBI H-mode with no puff |
| 138844 | 4.4 | 0.8 | 3.9 | 6.5 | 10.1 | 0.613 | 5.7 | NBI H-mode |
| 138845 | 4.4 | 0.8 | 3.9 | 7.0 | 10.0 | 0.613 | 5.4 | NBI H-mode |
| 138846 | 4.4 | 0.8 | 3.9 | 7.1 | 10.1 | 0.613 | 5.7 | NBI H-mode |
| 139494 | 4.7 | 0.9 | 2.0 | 6.7 | 11.6 | 0.512 | 5.9 | NBI H-mode |
| 139495 | 4.7 | 0.9 | 2.0 | 6.1 | 11.5 | 0.512 | 0 | NBI H-mode with no puff |
| 139499 | 4.7 | 0.9 | 2.0 | 6.4 | 11.2 | 0.512 | 5.4 | NBI H-mode |
| 139500 | 4.7 | 0.9 | 2.0 | 6.3 | 11.4 | 0.512 | 5.5 | NBI H-mode |
| 139501 | 4.7 | 0.9 | 2.0 | 6.6 | 11.4 | 0.512 | 5.4 | NBI H-mode |
| 139044 | 4.9 | 1.0 | 6.0 | 5.7 | 10.3 | 0.412 | 5.4 | NBI H-mode |
| 139048 | 5.4 | 1.1 | 6.0 | 5.0 | 11.3 | 0.412 | 5.8 | NBI H-mode |
| 139286 | 4.9 | 0.8 | 3.0 | 3.7 | 10.9 | 0.314 | 5.7 | NBI H-mode |
| 139508 | 4.4 | 0.8 | 3.0 | 5.1 | 11.4 | 0.412 | 4.6 | NBI H-mode |
| 139509 | 4.4 | 0.8 | 3.0 | 4.5 | 11.8 | 0.412 | 4.3 | NBI H-mode |
| 139510 | 4.4 | 0.8 | 2.0 | 5.1 | 11.6 | 0.412 | 4.3 | NBI H-mode |
| 139443 | 5.4 | 1.1 | 0 | 2.9 | 9.9 | 0.287 | 4.8 | Ohmic |
| 141911 | 4.4 | 0.9 | 0 | 3.0 | 6.3 | 0.285 | 3.5 | Ohmic |
| 141912 | 4.4 | 0.9 | 0 | 3.0 | 6.5 | 0.285 | 3.5 | Ohmic |
| 141740 | 4.4 | 0.8 | 0 | 1.7 | 8.9 | 0.213 | 5.9 | Ohmic |
| 141741 | 4.0 | 0.7 | 0 | 1.9 | 9.3 | 0.213 | 5.7 | Ohmic |
| 141742 | 4.4 | 0.8 | 0 | 1.7 | 8.3 | 0.213 | 6.0 | Ohmic |
| 141754 | 3.6 | 0.8 | 0 | 2.0 | 8.6 | 0.213 | 5.7 | Ohmic |
| 141756 | 3.6 | 0.8 | 0 | 2.0 | 8.7 | 0.213 | 5.9 | Ohmic |
| 139441 | 5.4 | 1.1 | 2.0 | 2.5 | 10.1 | 0.287 | 5.4 | NBI L-mode |
| 139442 | 5.4 | 1.1 | 2.0 | 2.7 | 10.0 | 0.287 | 5.7 | NBI L-mode |
| 141984 | 4.4 | 0.9 | 1.1 | 2.5 | 2.8 | 0.224 | 3.7 | RF L-mode |
| 141985 | 4.4 | 0.9 | 1.1 | 2.5 | 3.1 | 0.224 | 3.5 | RF L-mode |

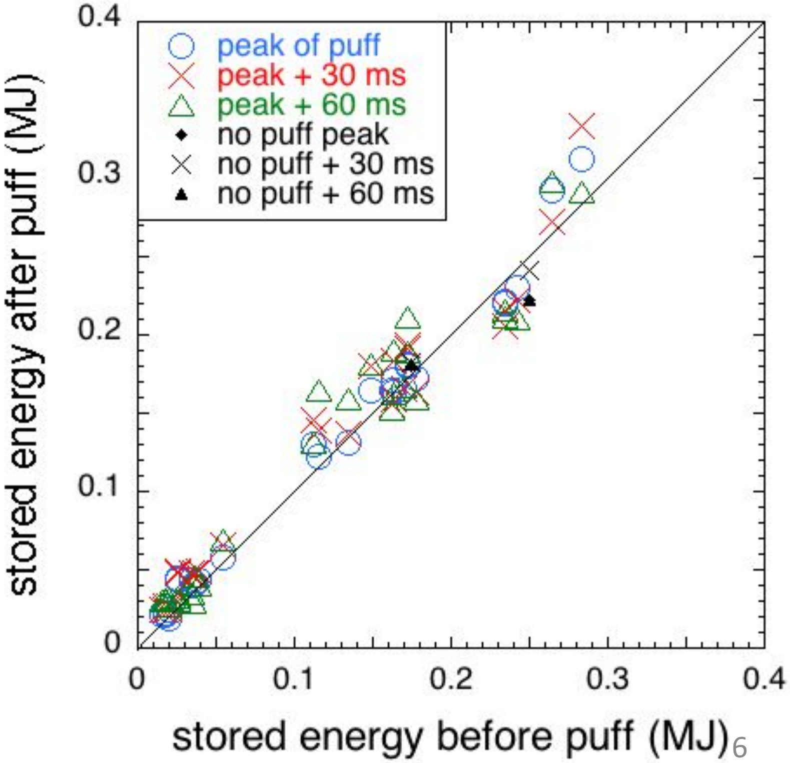
no “no puff” comparisons (shots 139044 through 141985)

# Global Effects of GPI Gas Puff (5 Torr-liters)

- No significant effect on total stored energy or radiated power
- No effect on separatrix position, slight effect on neutron rate

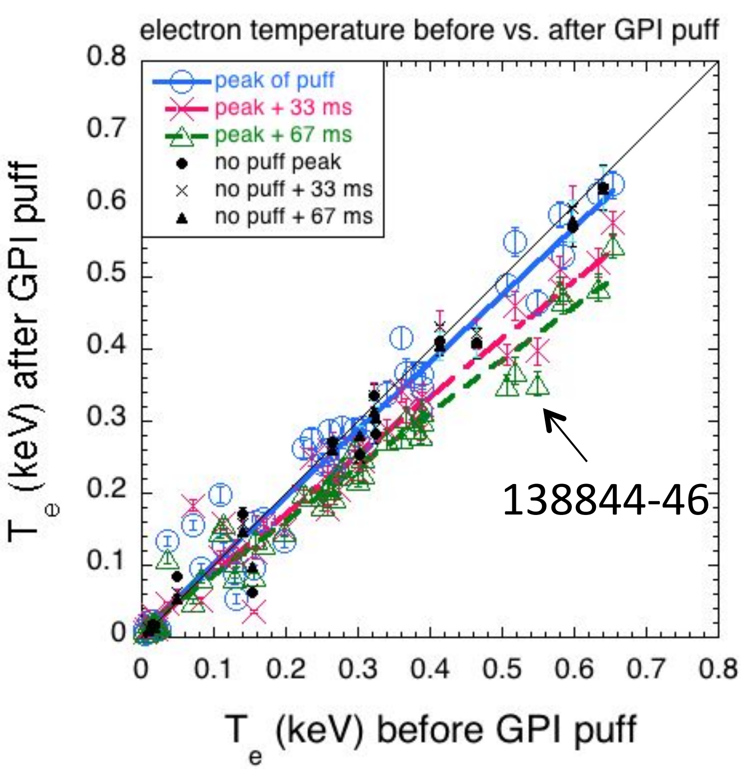


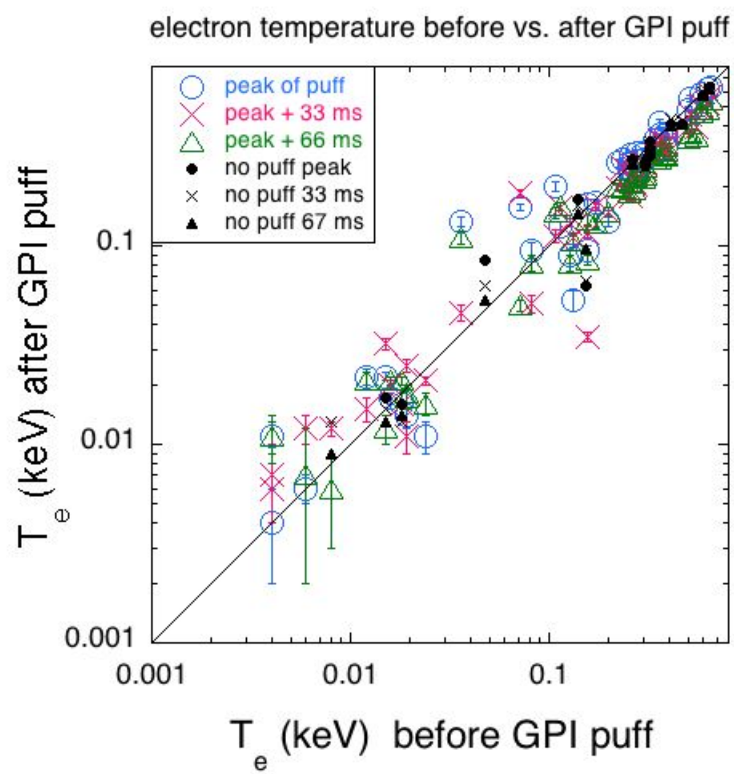

shots with GPI puff (colored points)
shot with no GPI puff (black points)



# Edge Electron Temperature with/without Puff

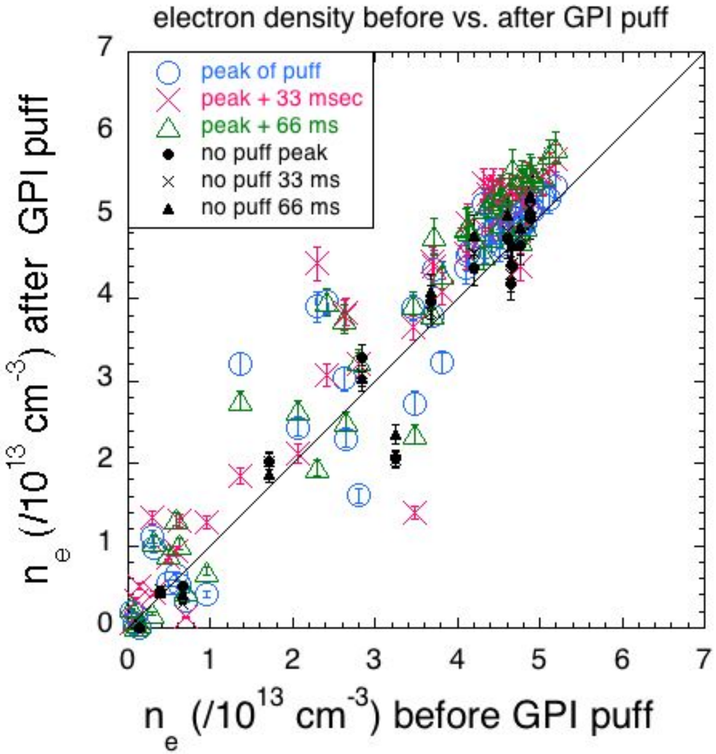
- These shots are H-mode cases with "no puff" comparison shots
- Average $T_e$ decreases by 10-25% with puff where $T_e \geq 100$ eV
- Little or no systematic $T_e$ decrease in edge where $T_e \leq 100$ eV

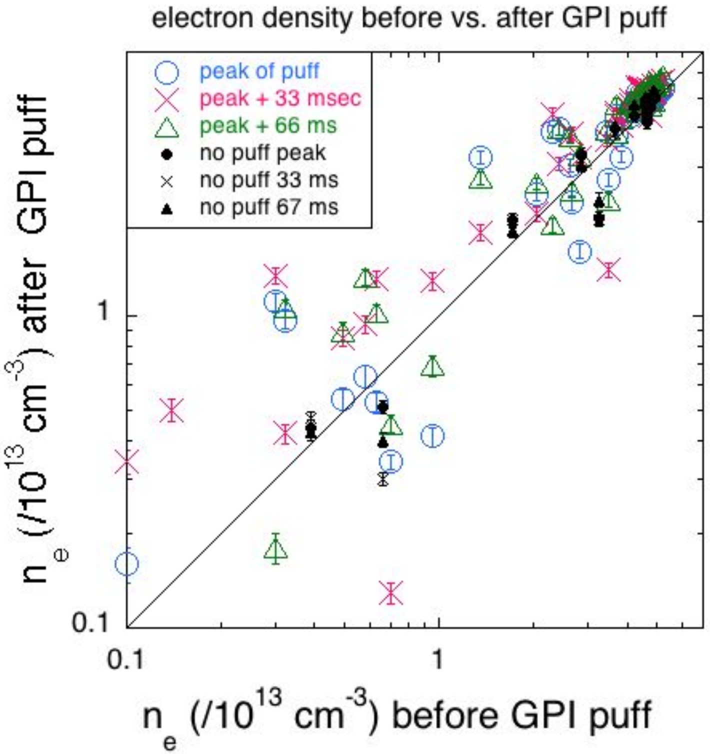


# Edge Electron Density with/without Puff

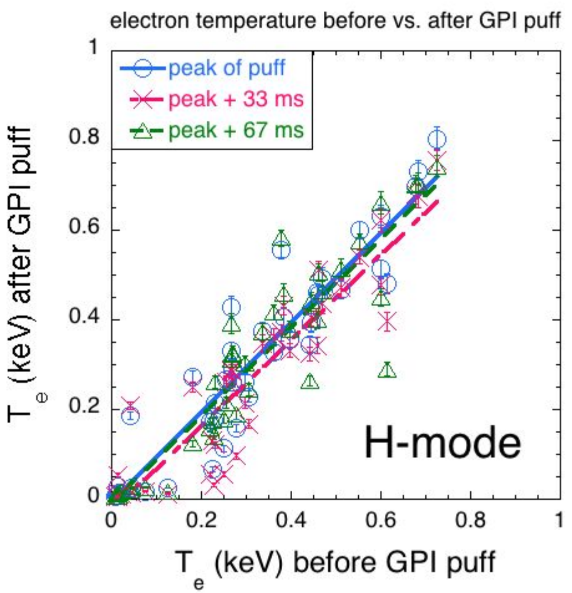
- These shots are NBI H-mode cases with “no puff” comparisons
- Edge $n_e$ increases by 10-20% with puff where $n_e \geq 3x10^{13}$ $cm^{-3}$
- Little or no systematic $n_e$ decrease in edge where $n_e \leq 3x10^{13}$ $cm^{-3}$

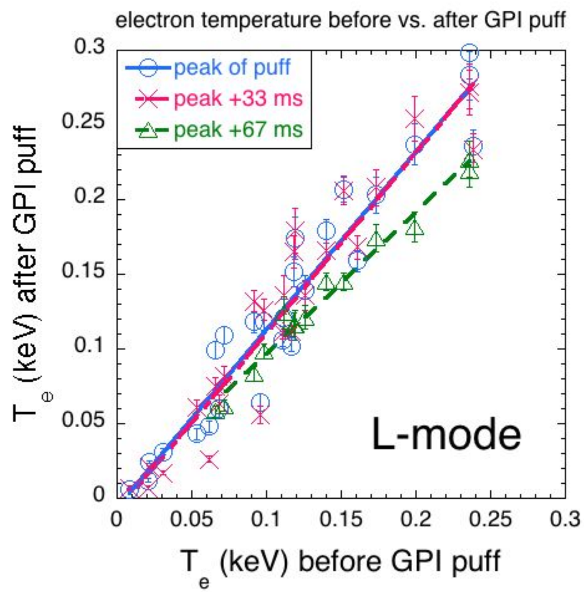


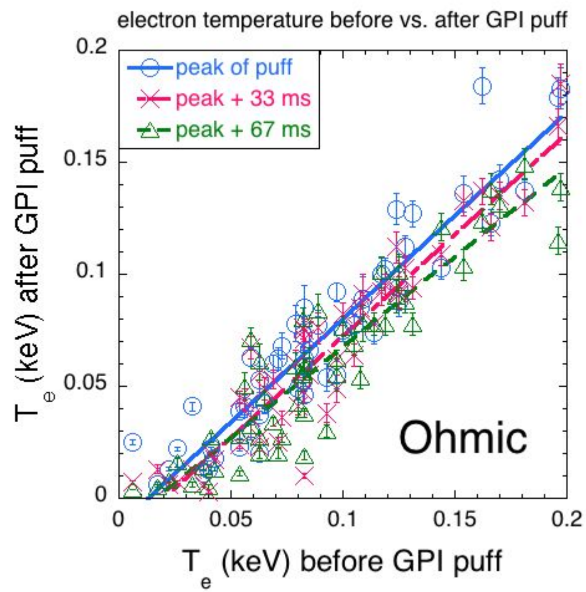



# Wider Database of Temperature Effects

- These shots do not have any “no puff” comparison shots
- H-mode and L-mode data show relatively small $T_e$ effects
- Ohmic plasmas show somewhat larger $T_e$ effects
- Lines are linear fits to the data for each time during puff

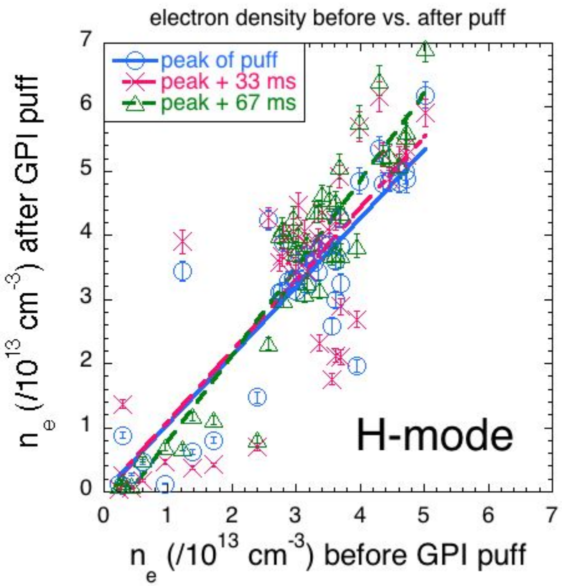


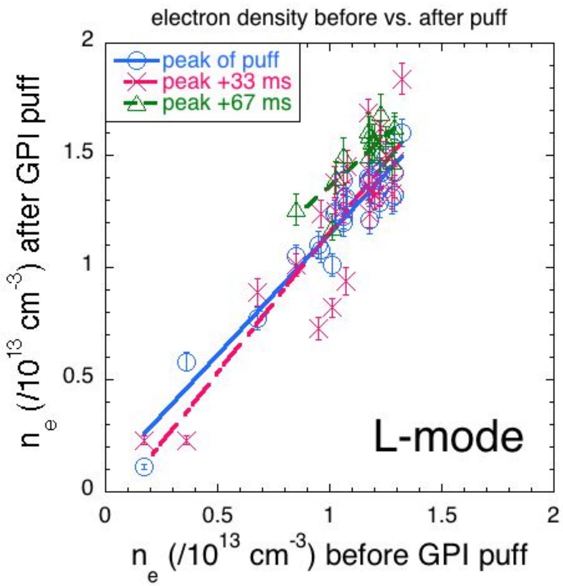



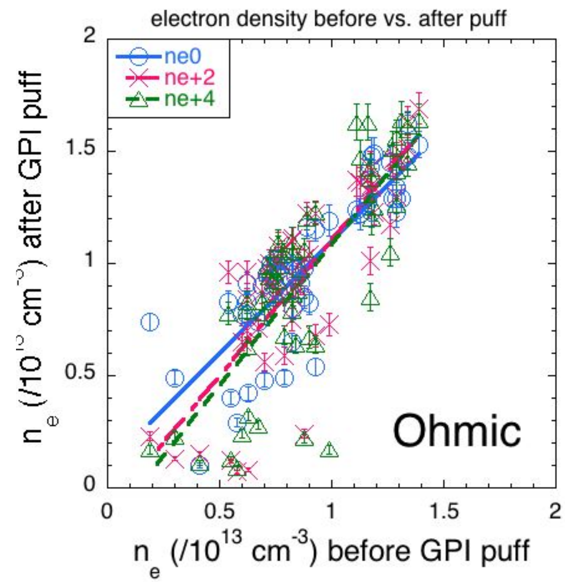



# Wider Database of Density Effects

- These shots do not have any “no puff” comparison shots
- H-mode and L-mode data show relatively small $n_e$ increases
- Ohmic plasmas show relatively wide scatter in $n_e$ effects
- Lines are linear fits to the data for each time during puff



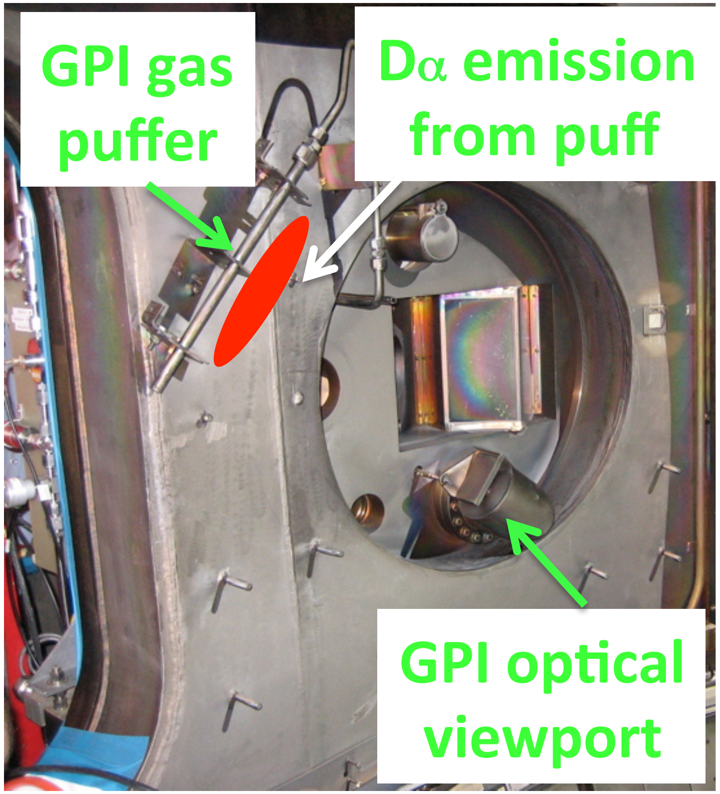
# Linear Fits to the Wider Database

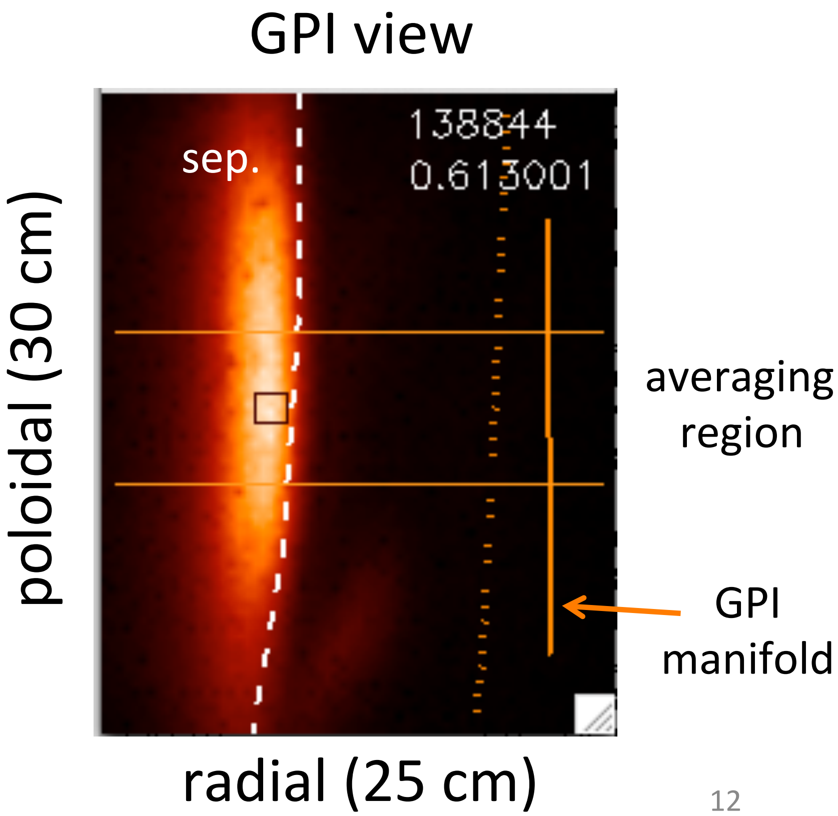
- These are the slopes of the linear fits to the previous figures
- Most fits show ≤25% average change in $T_e$ or $n_e$ with gas puff

| | GPI peak | peak + 33 ms | peak + 67 ms |
|---|---|---|---|
| $T_e$ (138844-6) | 0.93 | 0.80 | 0.74 |
| $T_e$ (H-mode) | 1.00 | 0.95 | 0.98 |
| $T_e$ (L-mode) | 1.19 | 1.20 | 0.95 |
| $T_e$ (Ohmic) | 0.92 | 0.90 | 0.81 |
| | | | |
| $n_e$ (138844-6) | 1.00 | 1.04 | 1.07 |
| $n_e$ (H-mode) | 1.07 | 1.11 | 1.33 |
| $n_e$ (L-mode) | 1.08 | 1.25 | 0.88 |
| $n_e$ (Ohmic) | 1.00 | 1.20 | 1.26 |

# Effect of Gas Puff on GPI Profiles

- Best local diagnostic for GPI puff changes is GPI Dα emission
- Radial profile of Dα should respond to local $T_e$ & $n_e$ profiles

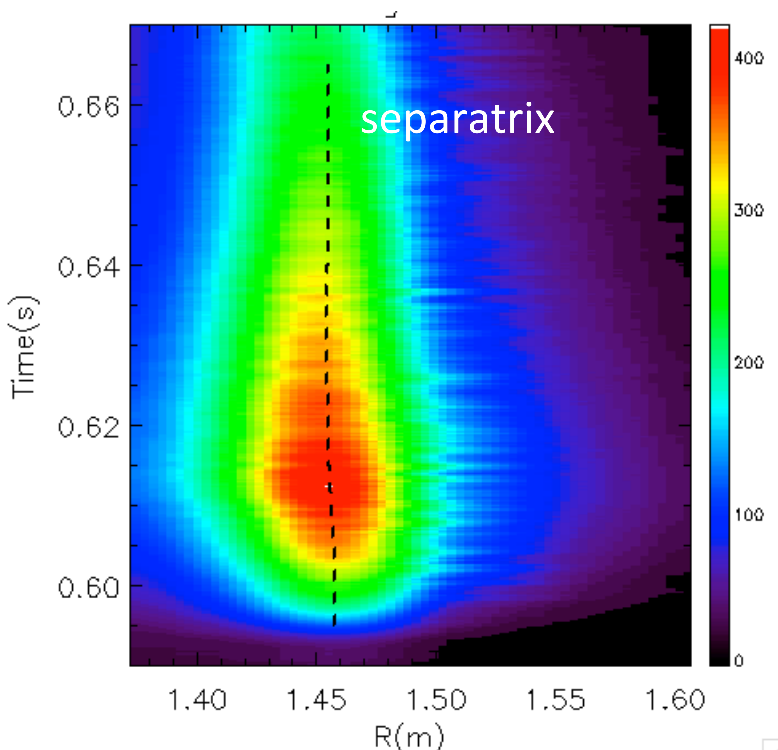


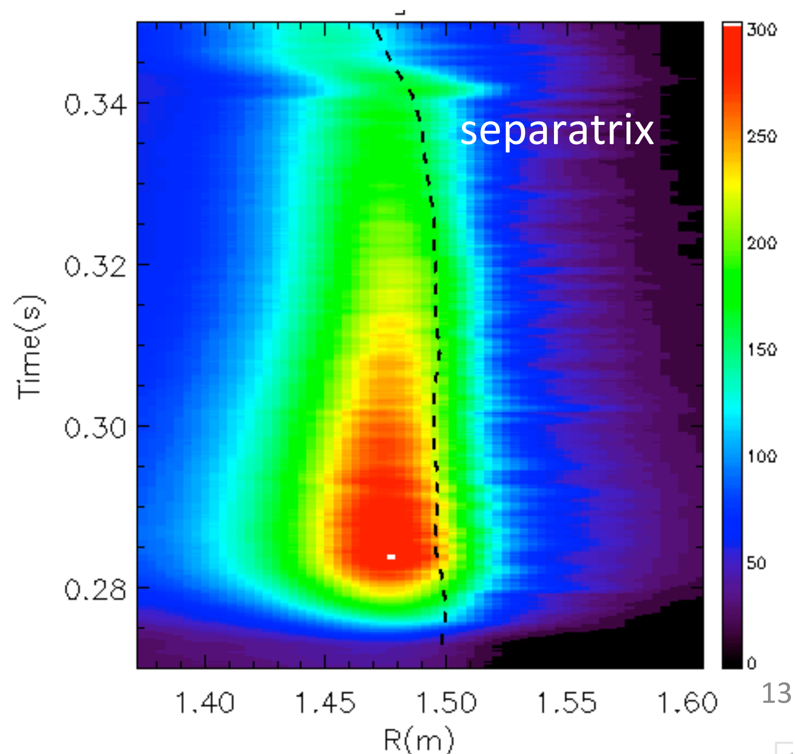
# Typical GPI Dα Radial Profiles vs. Time

- GPI radial profile shapes do not vary significantly during puff
- This is consistent with a small variation in $T_e$ and $n_e$ profiles
- GPI profiles do move radially with separatrix movement

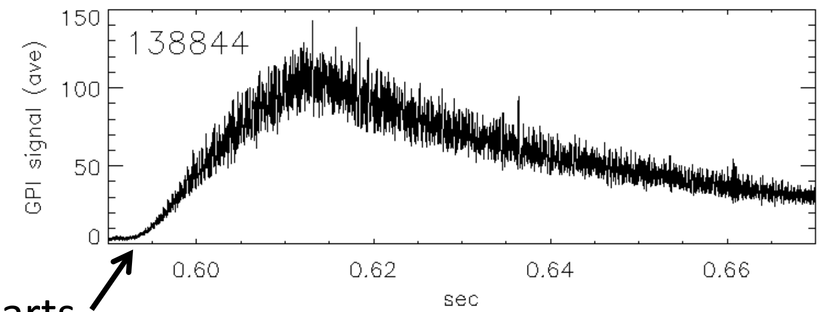
#133844 – 4 MW NBI H-mode




#141912 – Ohmic

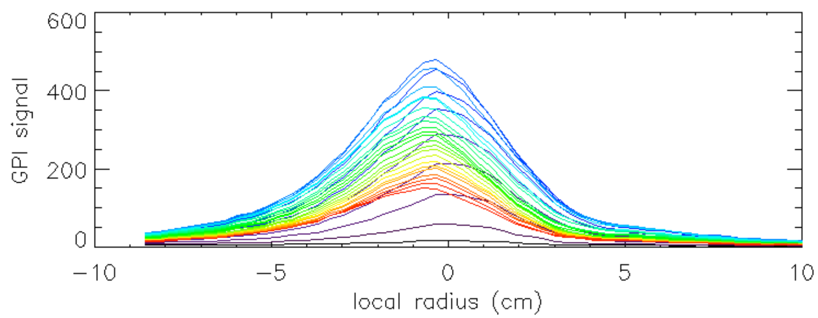


# Example of GPI Dα Profile vs. Time

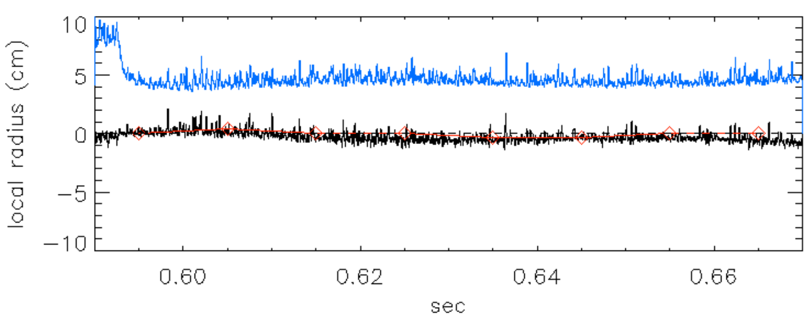



puff starts

GPI Dα signal vs. time




Radial profile of Dα vs. time




FWHM of GPI profile (blue)

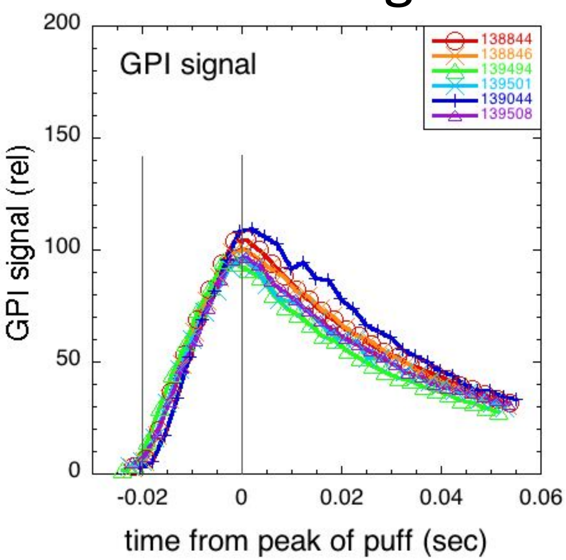
Peak of GPI profile (black)

Separatrix position (red)

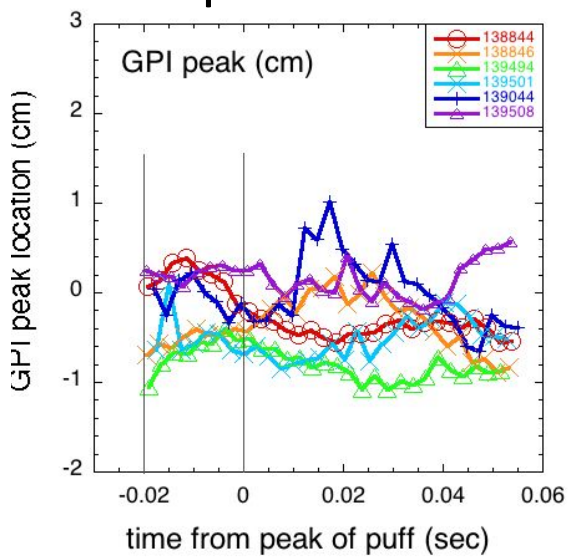
# GPI Profile Variation for H-mode Shots

- GPI Dα radial profile widths and peak locations during puff
- This is consistent with a small variation in $T_e$ and $n_e$ profiles
- Ohmic and L-mode shots have more separatrix movement

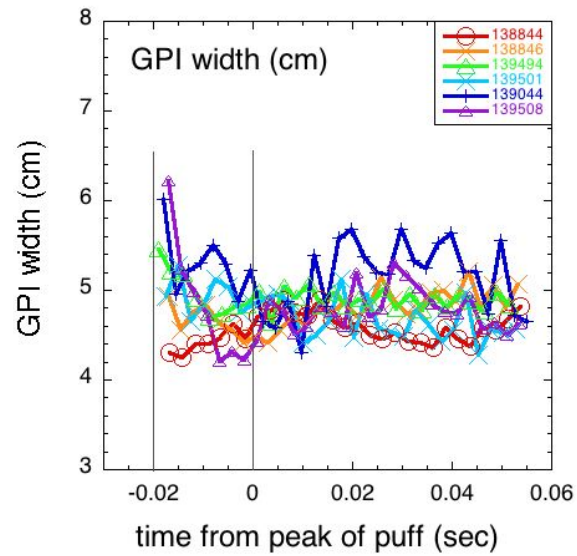
GPI Dα signal




GPI peak location

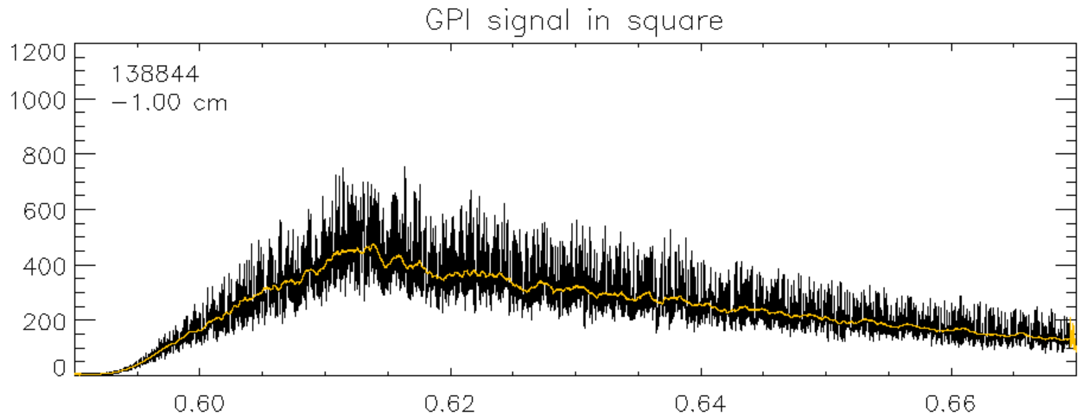



GPI width

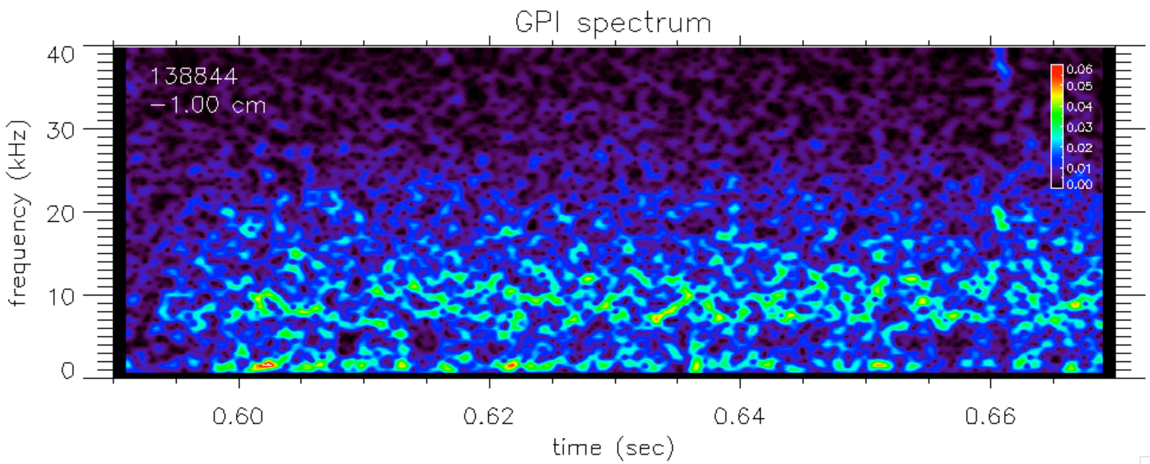


# GPI Turbulence Analysis vs. Time

- Turbulence in GPI signal evaluated in 1.5 cm square (see image)
- Look for any systematic variations with puff strength vs. time



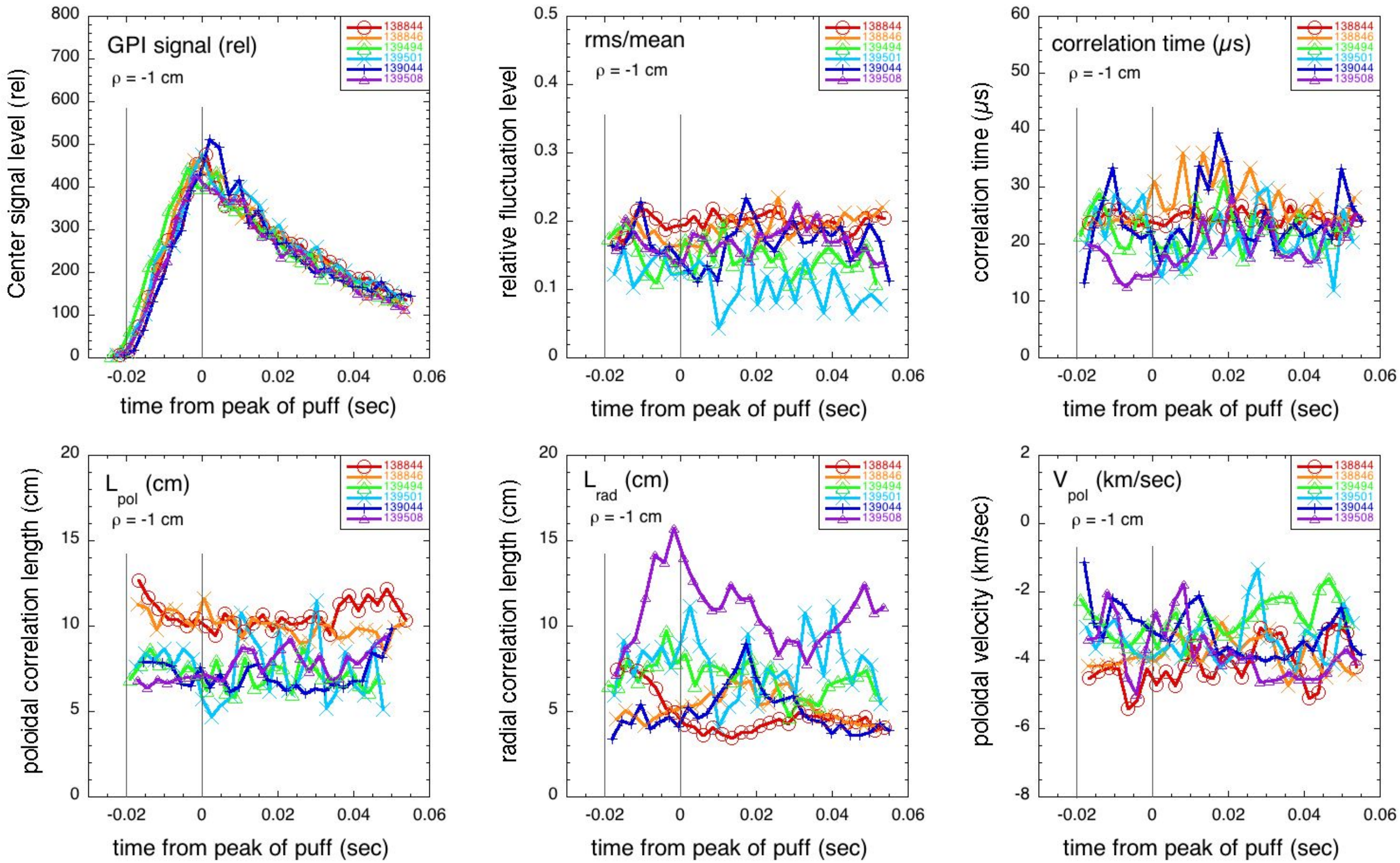

GPI Dα signal in 1.5 cm square at 1 cm inside separatrix




Frequency spectrum of GPI Dα signal in this square vs. time

# GPI Turbulence Analysis vs. Time

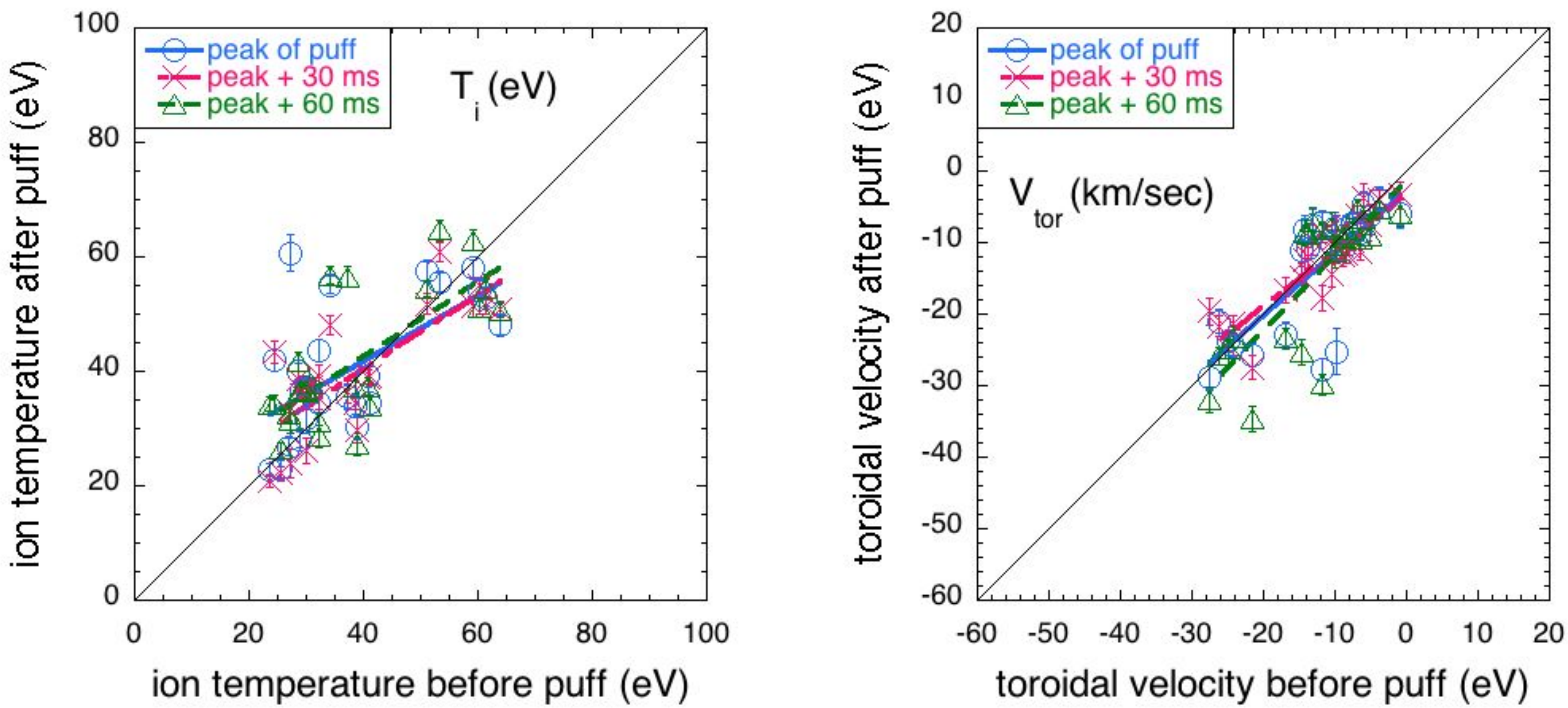
- No systematic variations of turbulence or turbulence velocity with puff strength vs. time, i.e. puff is not affecting turbulence



# Effects on GPI Puff on $T_i$ and $V_{tor}$

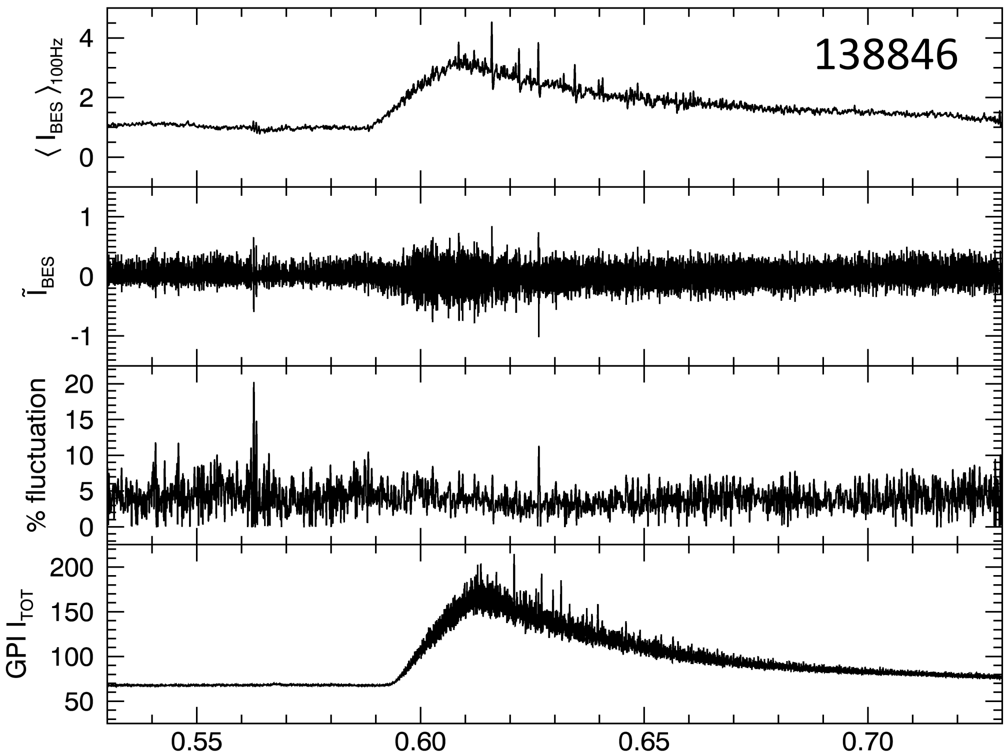
- Ion temperature and toroidal velocity is measured at peak of CIII line emission from passive "edge rotation diagnostic" (active CHERS data not available due to the effect of the GPI gas puff on its CX signal level)

- No clear systematic change in $T_i$ or $V_{tor}$ (or $V_{pol}$) between before GPI puff and during first 60 msec of GPI puff



# Effect on GPI Puff on BES Diagnostic

- Beam emission spectroscopy (BES) diagnostic measures edge turbulence near to GPI puff (~38 cm away)
- BES signal level increased by GPI puff, but relative fluctuation level and spectrum not changed 3 cm inside separatrix




BES signal 3 cm inside sep.

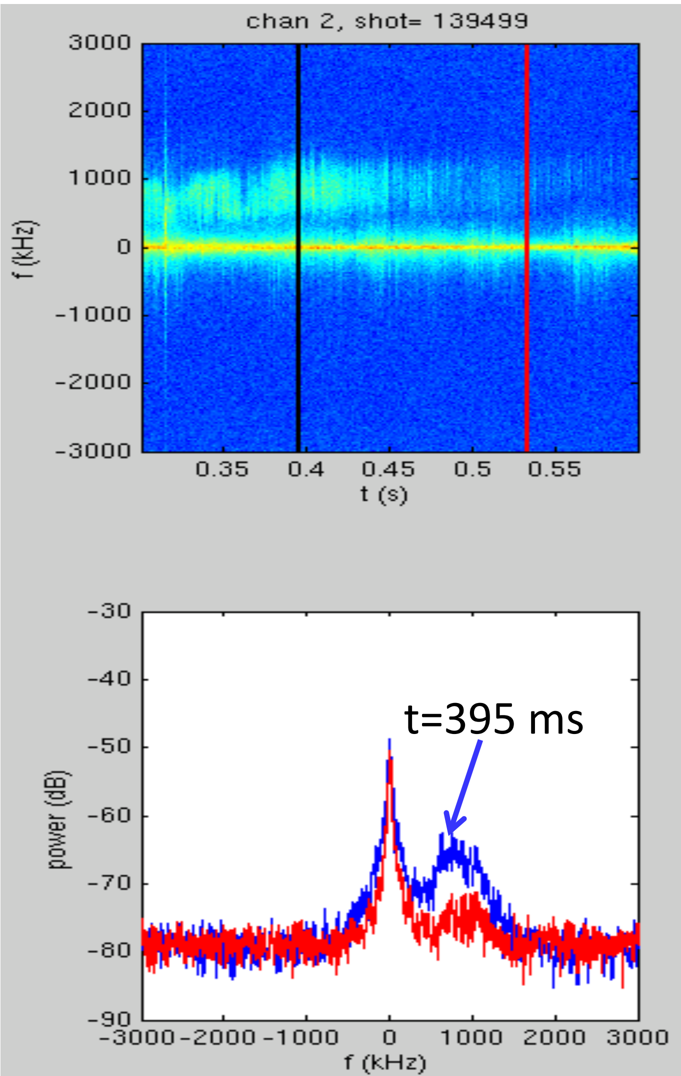
BES fluctuation level

relative fluctuation level

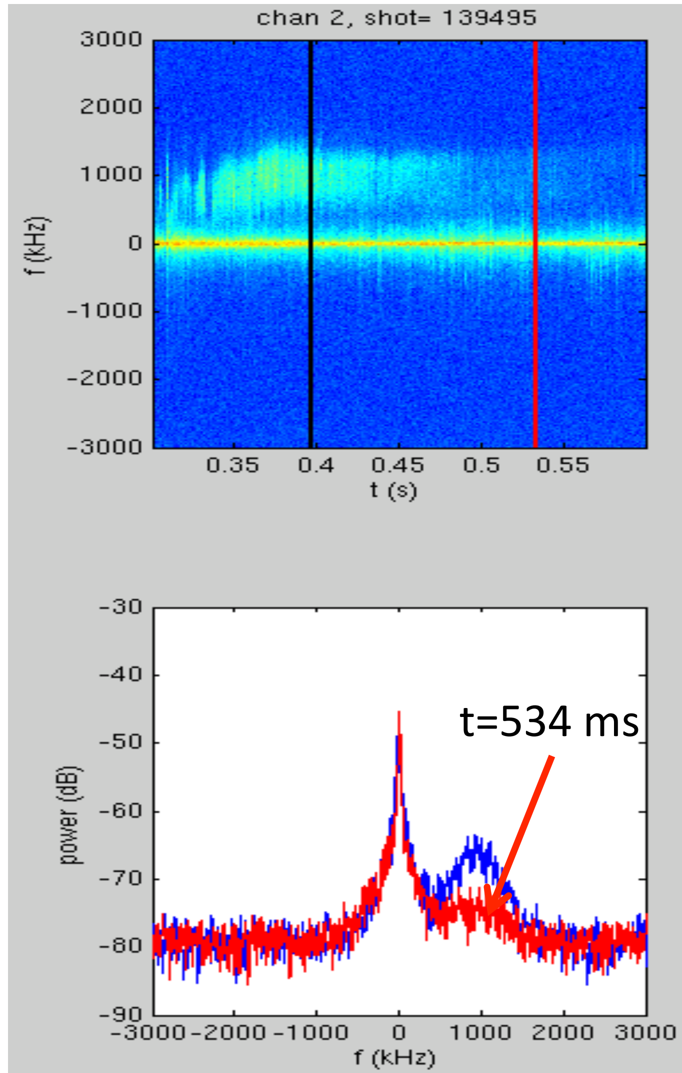
GPI gas puff D$\alpha$ signal

# No Qualitative Change in High-k Turbulence Evolution is Observed with GPI Gas Puff

With GPI gas puff




Without GPI gas puff




- One channel from high-k scattering system, $k_{\perp}\rho_s$~ 16
- Measurement location: r/a~ 0.64-0.73 (R~138-142 cm)

# Expected Effects of Puff on Edge Temperature

- Expected electron energy loss from $D^o$ radiation ~ 25 eV/neutral
  => peak power loss $P_{rad}$ ~ 5 kW from radiation inside separatrix
- Expected ion energy loss from CX ≤ $T_i$/neutral ~ 230 eV/neutral
  => peak power loss $P_{cx} \leq$ 50 kW from CX inside separatrix
- Thus $(P_{rad} + P_{cx}) << P_{edge}$ ~ 1-6 MW (power into edge from plasma)
- Without puff, $\tau_{E,edge} = W_{edge}/P_{edge}$ ~ 0.5 msec (0-6 cm inside sep.)
- With puff, => $W_{edge} \sim \tau_{E,edge}*(P_{edge}-P_{rad}-P_{cx})$ ~ unchanged by puff

  => edge temperature should change only with density increase

# Expected Effects of Puff on Edge Density

Locally within ionization volume of $V_o$ with length $L_o$ along B field:

$\delta n \sim (\Gamma_{o,in}/V_o)/(L_o/c_s)$
$\delta n \sim 0.4 \times 10^{13}$ cm$^{-3}$
$\delta n \sim$ 10% of n @ -3 cm

$\Gamma_{o,in} \sim 1.3 \times 10^{21}$ atoms/sec (max)
$c_s \sim 7 \times 10^6$ cm/sec @ $T_e \sim 100$ eV
$V_o \sim 700$ cm$^3$, $L_o \sim 15$ cm

Within flux surface inside separatrix:

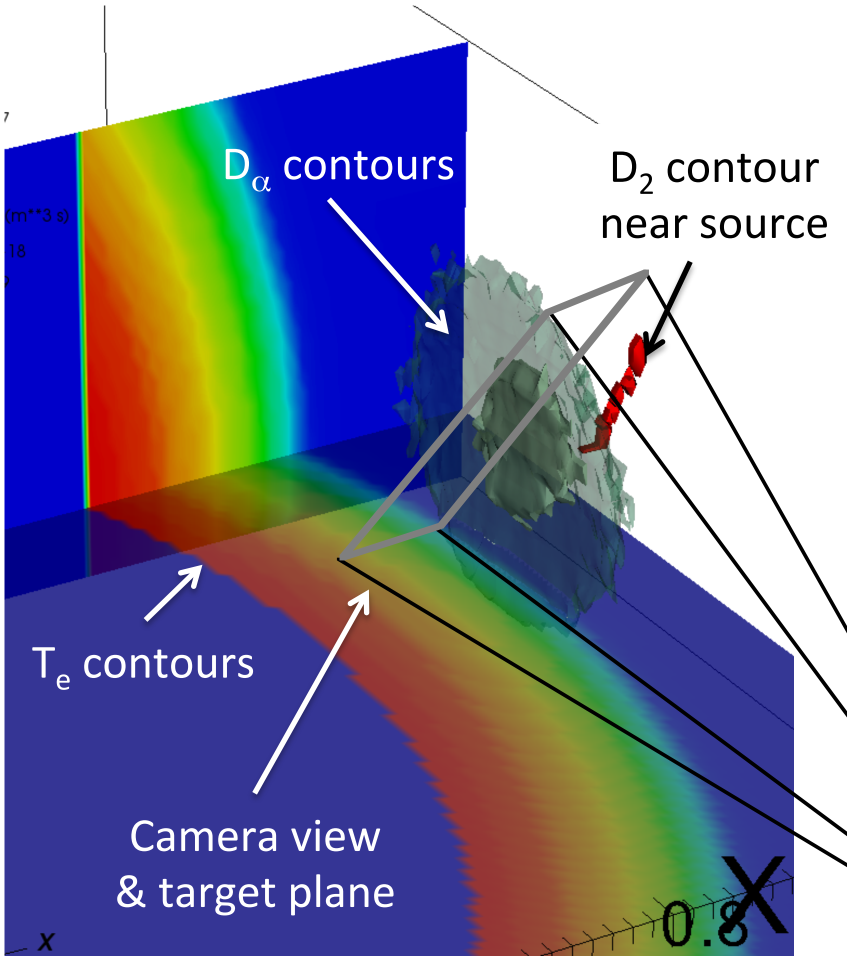
$\delta n \sim 1.5 \times 10^{13}$ cm$^{-3}$ by peak of GPI puff (no radial transport)
$\delta n \sim 5 \times 10^{13}$ cm$^{-3}$ by 70 msec after start of puff (no transport)
$\delta n \sim (\Gamma_{o,in}\, \tau_{p,edge})/V_o \sim 10^{11}$ cm$^{-3}$ (assuming $\tau_{p,edge} \sim 1$ msec)

Outside separatrix:

no prompt effect at Thomson since not on same B field line
if 100% recycled at divertor $\delta n \sim 0.7 \times 10^{13}$ cm$^{-3}$ (w/ no ion loss)

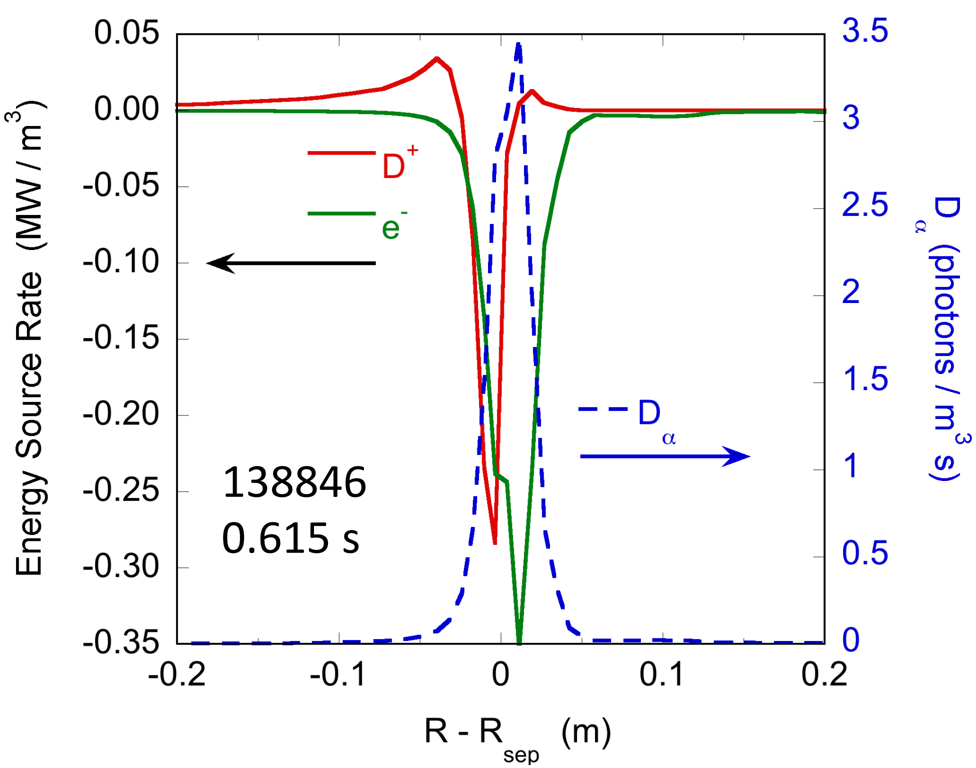
# DEGAS 2 Modeling of NSTX GPI

- 3-D, steady state neutral transport simulations [Cao et al, FST(2013)].
- $D_2$ source: small squares aligned with pitch of GPI manifold.
- $D_2$ undergo dissociation, ionization, elastic scattering as they penetrate,
  - ⇒ atoms, undergo ionization & CX.
  - Compute $D_\alpha$ light using same atomic physics data.
  - Integrate light along GPI camera chords to simulate its view.
- Input data:
  - EFIT ⇒ flux surface shapes,
  - Thomson scattering ⇒ $n_e$, $T_e$,
  - CHERS ⇒ $n_{D+}/n_e$ ratio & $T_i \cong T_e$
    - All constant on flux surface.



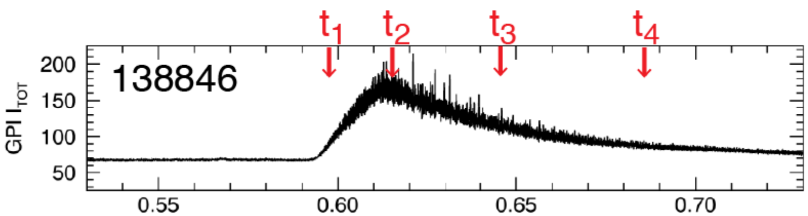
# Power Loss Due To Puff Much Less Than $P_{NBI}$ = 4 MW

- Integrate power losses & emission rate along flux surfaces,
- Plot as function of flux surface R at midplane:

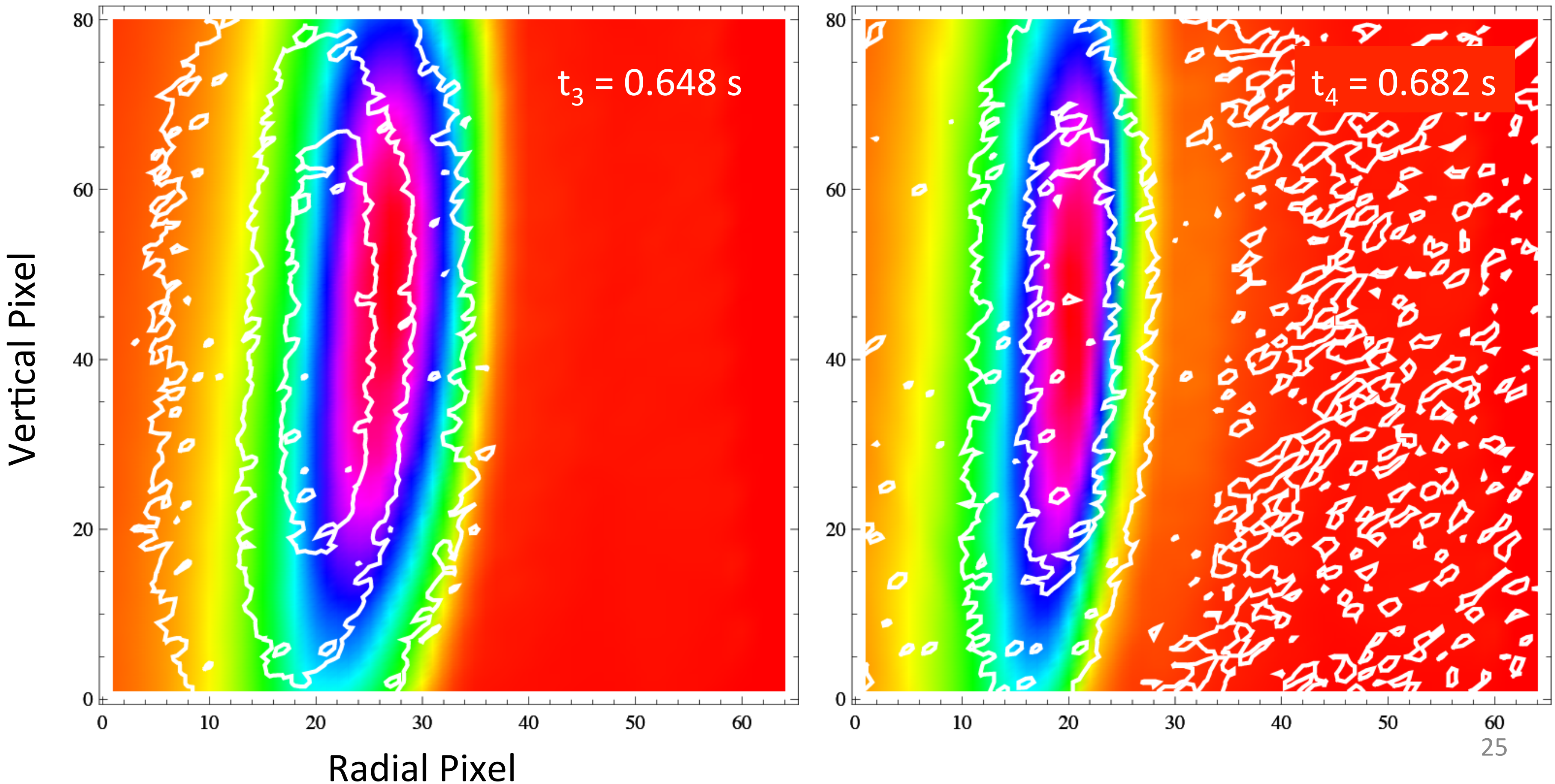



- For #138846, with source rate $6.6\text{x}10^{21}$ D/s.
- Electrons lose: 21 kW
  - 11 kW to D ionization & line radiation.
  - 10 kW to $D_2$ dissociation & ionization.
- Ions lose: 4 kW
  - Lose 18 kW heating D via CX,
  - But, gain 13 kW back when those D are ionized.
  - 1 kW gain from $D_2$ processes.

# DEGAS 2 Profiles at Peak Puff Rate Shift Radially by 1-2 cm in Shot #138846

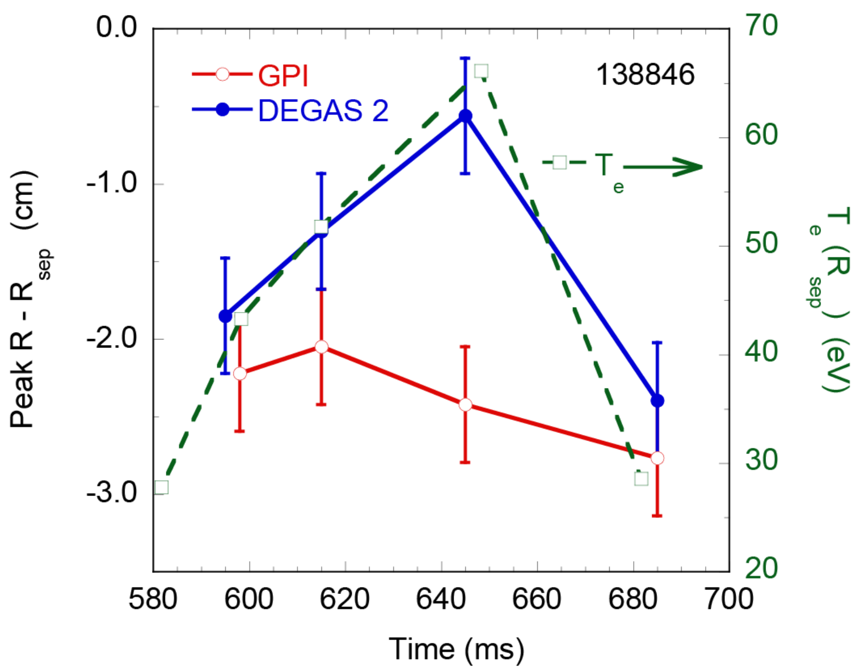



- Color: DEGAS 2 simulated camera.
- Contours: GPI signal averaged over 1 ms, 25%, 50%, & 75% of maximum.



# Variations in Location of Simulated Peak Due to Changes in $T_e$ & $n_e$ Profiles

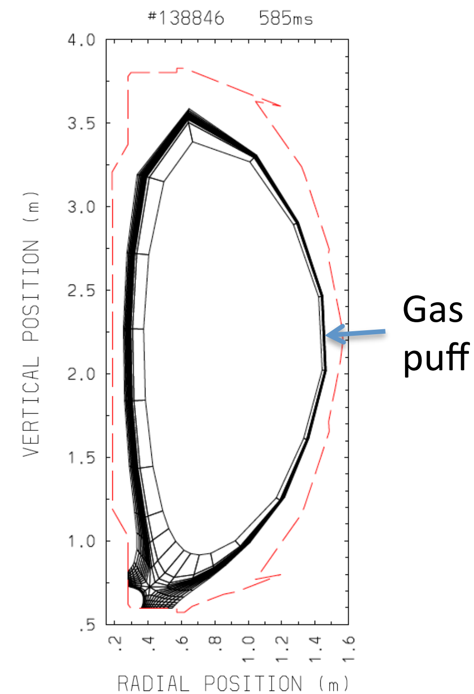
- Radial location of emission peak at $t_1$ & $t_4$ agree within uncertainties,
- But, near GPI puff maximum ($t_2$ & $t_3$) see larger differences.
- DEGAS 2 is just following increases in $T_e$ & $n_e$ at separatrix:




- Most likely explanation: profiles at $t_2$ & $t_3$ happened to catch blobs,
  - Thomson profiles in 138844, 138845 do NOT show similar pattern.
  - But, do display other blob effects.
- Motivation for simulating 4 times was to see if GPI puff is altering local $T_e$ & $n_e$ more than Thomson profiles,
  - E.g., Unterberg et al. (JNM 2005) showed $n_e$ ↑ & $T_e$ ↓ near puff relative to toroidally distant values.
  - Blobs obscure any effect in 138846.
  - Should look at lower power shots ⇒any effects of puff would be more pronounced.

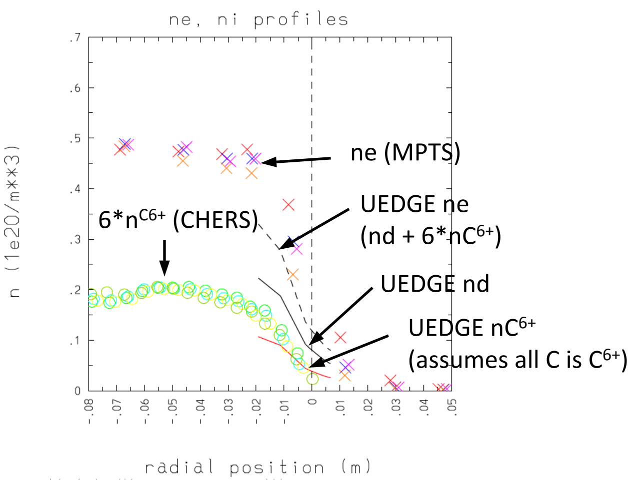
# Time-dependent GPI Simulation with UEDGE

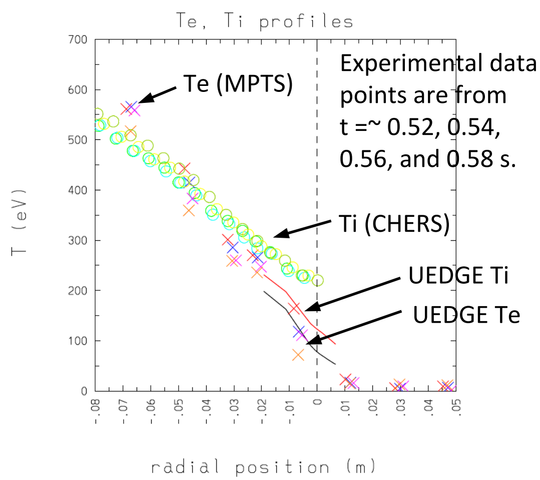
- **Axisymmetry is assumed.**
- **A steady-state solution is established based on diagnostic information before GPI gas puff.**
  - **Cross-field diffusivities (D, $\chi_{i,e}$) chosen to match MPTS and CHERS density/temperature outer midplane profiles.**
  - **D, $\chi_{i,e}$ are flat in SOL:**
    - **$D_{SOL}$=0.32 m²/s, $\chi_{i,e,SOL}$=12 m²/s.**
  - **D, $\chi_{i,e}$ are reduced in closed-flux region (transport barrier):**
    - **$D_{min}$=0.06 m²/s, $\chi_{i,e,min}$=5 m²/s.**
- **A time-dependent simulation of gas puff is performed.**
  - **Gas puff at grid edge ($\psi_n$ = 1.035) is based on DEGAS2 analysis of gas puff penetration.**
    - **UEDGE puff rises from 0 to peak puff rate of 2.6x10$^{21}$ over 20 ms.**
    - **Exponential decay with $\tau_{decay}$ = 0.05 s.**




Grid captures narrow slice of closed-flux region and SOL.

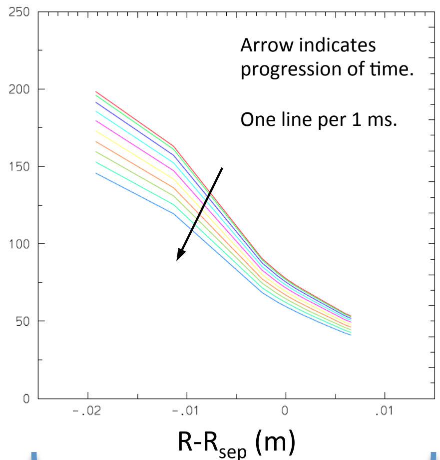
- R-$R_{sep}$ = -1.92 to 0.65 cm in outer midplane
- $\psi_n$ = 0.9 to 1.035



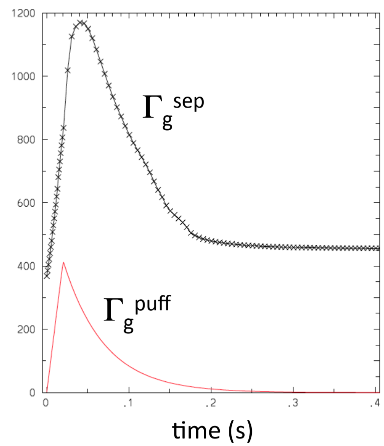



# UEDGE Shows ~30% Drop in Separatrix $T_e$

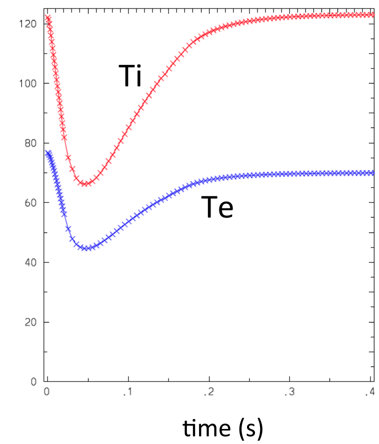
Outer midplane $T_e$ profile (eV)



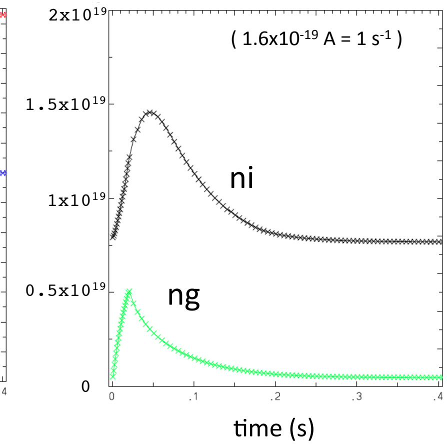

Separatrix gas flux (A)




Outer midplane sep. $T_{i,e}$ (eV)




Outer midplane sep. ni, ng ($m^{-3}$)




- Outer midplane $T_e$ drops ~30% and ne rises proportionally.
  - Thermal energy in the simulation changes <10%.
- Power transfer
  - If model extended deeper into the core, power transfer would likely increase across this surface.

- Gas puff peaks at 20 ms.
- Total separatrix gas flux continues to rise for another ~30 ms.
  - Divertor recycling process enhances separatrix gas flux.
  - Simulation shows outer divertor detachment, but divertor spectroscopy does not.
- Outer midplane temperature profiles recover as puff subsides.
- Gas density in outer midplane peaks at 20 ms (with peak gas puff) but main ion density rises for another ~30 ms.
  - Main ion density rises globally in SOL due to recycling/detachment.

These results are preliminary. Future work could include modeling deeper into core to allow energy transfer from higher $T_e/n_e$ regions with fixed cross-field diffusivities.

# Summary

- The GPI gas puff does not change measured edge $n_e$, $T_e$, $T_i$, or $V_{tor}$ in any systematic way, within uncertainties of about ±25%
- The GPI $D\alpha$ signals do not show any systematic variations over a factor of about x5 as the gas puff strength varies vs. time
- The edge turbulence as measured by BES and high-k scattering does not vary with vs. without the GPI gas puff
- DEGAS 2 modeling shows GPI $D\alpha$ profiles shift outward 1-2 cm during puff, slightly more than in measured $D\alpha$ during puff
- UEDGE modeling shows ~30% change in edge $n_e$ and $T_e$, close to consistent with measured changes in the edge

# Conclusions and Future Directions

- There is little or no perturbation of the edge turbulence by the GPI gas puff itself, at least at the levels in this experiment
- The GPI gas puff sometimes causes a decrease in edge $T_e$ after about 50 msec, which is not understood at present
- The power loss expected to the GPI puff itself is negligible
- DEGAS 2 and UEDGE modeling suggest some effects of the GPI puff on the edge for one shot which are not quite consistent with the measurements, so more shots should be modeled
- The local effects of the puff were estimated to be small, but should be more carefully modeled with a 3-D edge code