Neutral Gas Transport Simulations of Gas Puff Imaging Experiments on NSTX & Alcator C-Mod

D. P. Stotler, S. J. Zweben, R. J. Maqueda[1],
G. A. Wurden[1], M. E. Rensink[2], X. Q. Xu[2],
B. LaBombard[3], J. L. Terry[3], S. Wolfe[3]

Princeton Plasma Physics Laboratory
Princeton University
Princeton, NJ 08543

[1]Los Alamos National Laboratory
Los Alamos, NM 87545

[2]Lawrence Livermore National Laboratory
Livermore, CA 94551

[3]MIT Plasma Science and Fusion Center
Cambridge, MA 02139

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Note: This poster is available on the Web at:
`http://w3.pppl.gov/degas2/`

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Neutral Gas Transport Simulations of Gas Puff Imaging Experiments on NSTX and Alcator C-Mod[1] D.P. STOTLER, S.J. ZWEBEN, PPPL, R.J. MAQUEDA, G.A. WURDEN, LANL, M.E. RENSINK, X.Q. XU, LLNL, B. LABOMBARD, J.L. TERRY, S. WOLFE, PSFC, MIT — A series of experiments using visible imaging of gas puffs to characterize edge plasma turbulence has been carried out in the NSTX and Alcator C-Mod devices. Their objective was to provide data that can be compared with edge plasma turbulence codes. However, simulations of the transport of the puffed gas and the neutral atomic physics are needed to relate the observed light fluctuations to the local density (and perhaps temperature) fluctuations. The results would also permit an assessment of a "shadowing" effect in which a localized density peak near the outer edge of the emitting region sufficiently ionizes the puffed atoms to affect the light fluctuations at smaller radii. The DEGAS 2 Monte Carlo neutral code is used to generate radial emission profiles of the D_α or 5876 Å He line that can be matched against observations. Nominal plasma profiles for NSTX are taken from runs of the UEDGE code. Midplane reciprocating probe data from Alcator C-Mod directly specify the average plasma parameters in the region of interest. The sensitivity of the size and location of the emitting region to variations and these profiles will be assessed. Simulations of the view seen by the fast visible camera are also possible.

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☐ Prefer Oral Session
☒ Prefer Poster Session

Daren Stotler
dstotler@pppl.gov
Princeton Plasma Physics Lab

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INTRODUCTION

- Tokamak edge ideal for comprehensive study of turbulence,
  - Accessible with probes
    $\Rightarrow$ directly measure n_e, T_e, and other properties.
  - Relatively low T_e facilitates use of atomic physics as basis for diagnostics.
  - Potential payoff great because edge sets boundary conditions for core transport,
    - E.g., internal transport barriers, H-mode pedestal.
- Gas Puff Imaging (GPI) experiments designed to measure 2-D structure of edge turbulence,
  - Compare with turbulence measured by probes,
  - And with simulations.

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DESCRIPTION OF GPI EXPERIMENTS

- Puff neutral gas near outer wall,
- View with fast camera visible light resulting from electron impact excitation of that gas,
- Use sightline $\parallel \vec{B}$ to see radial & poloidal structure.
- Neutral transport analysis required:
  - Relate emission fluctuations to underlying n_e and T_e fluctuations,
    - Local emission rate, number of D$_\alpha$ photons / s:

$$S = n_0 f(n_e, T_e) A_{3\rightarrow 2},$$

    - where
      - $n_0 =$ ground-state atom density,
      - $f =$ ratio of $n = 3$ to $n = 1$ from collisional-radiative model,
      - $A_{3\rightarrow 2} = 4.41 \times 10^7 \text{s}^{-1} =$ decay rate of $n = 3$ to $n = 2$.
  - Compare size and location of emission cloud to validate measured n_e & T_e profiles.
  - $\Rightarrow$ use DEGAS 2.
- Related experimental presentations:

1. CO1.008 (Mon. PM) J. L. Terry et al.
2. KP1.024 (Wed. AM) S. J. Zweben et al.
3. QP1.027 (Thurs. AM) R. J. Maqueda et al.
4. UI1.004 (Fri. AM) S. J. Zweben et al.

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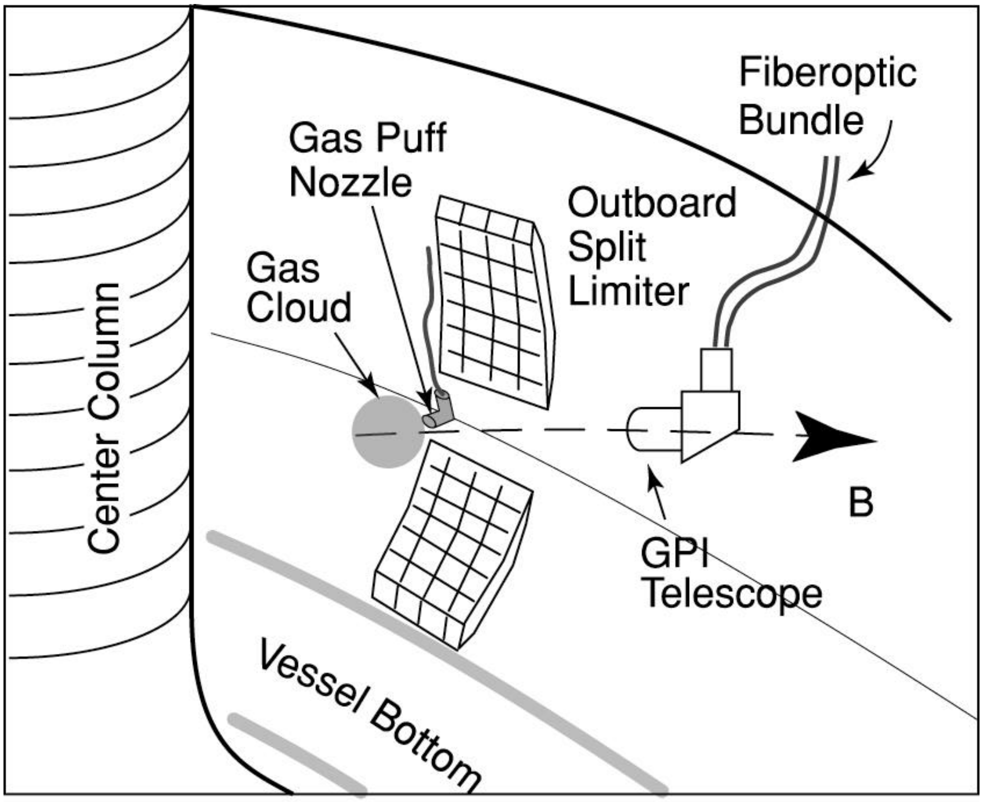

Fig. 1 - Zweben APS ‘01

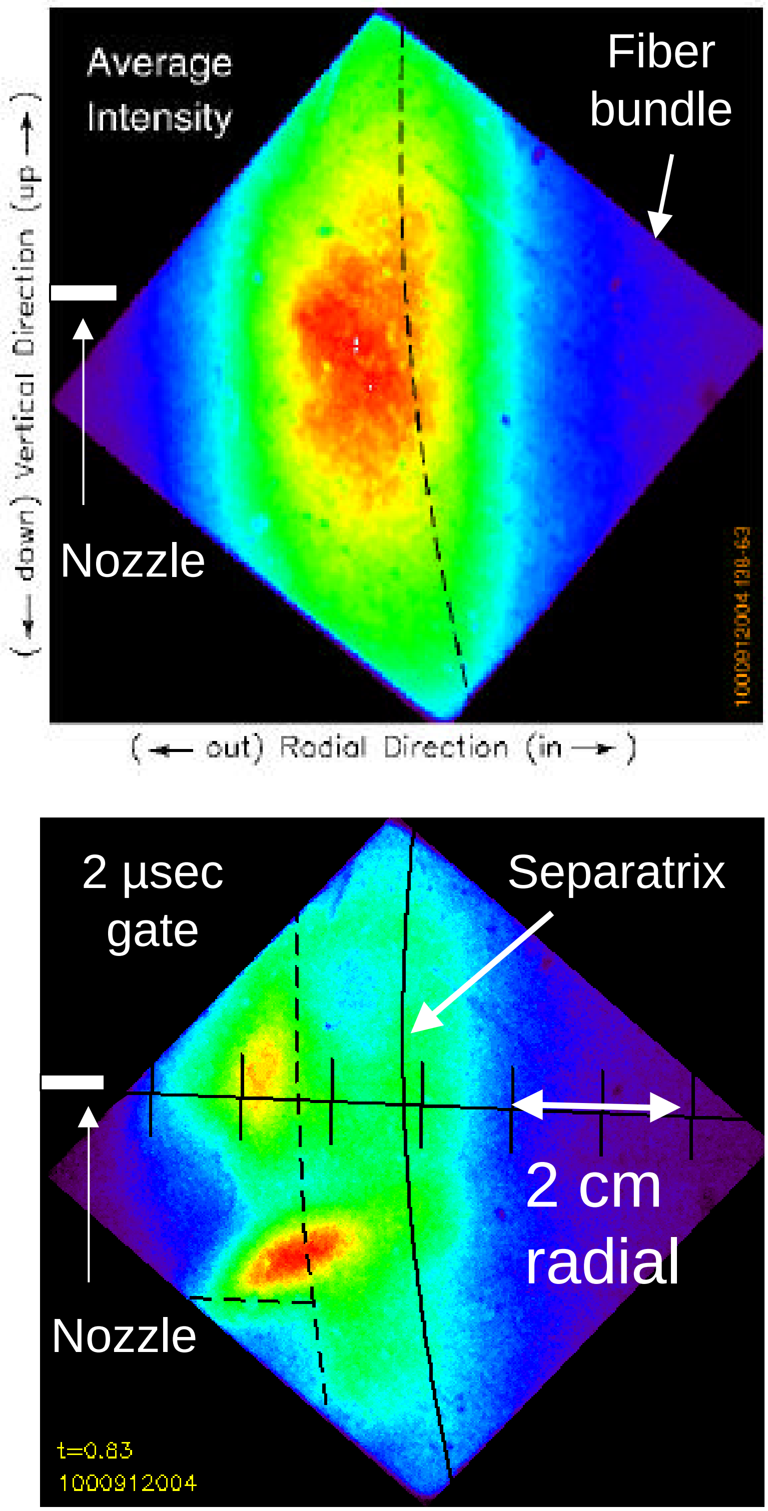

Fig. 2 - Zweben / APS ‘01

DESCRIPTION OF DEGAS 2 SIMULATIONS

- Simulate only the transport of the GPI gas puff,
  - Not simulating background recycling neutrals.
- 2-D axisymmetric for now,
  - E.g., limiter in C-Mod assumed to be axisymmetric.
  - Inside code, puff **is** toroidally localized & tracked in 3-D,
    - But, output is averaged over toroidal angle.
    - $\Rightarrow$ poloidal plane variation of photon emission rates.
  - Plan to add toroidal resolution $\Rightarrow$
    - Can directly simulate fast camera views,
    - And do quantitative comparisons.

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- Simulations assume steady-state.
  - Compare velocities:
    - * "Blob" velocities: $100 \rightarrow 1000$ m/s (C-Mod)
    - * D at 3 eV (dissociation): 2×10^4 m/s (C-Mod),
    - * He at 0.03 $\rightarrow$ 0.1 eV (wall + CX): $1 \rightarrow 2 \times 10^3$ m/s
  - Compare time scales:
    - * Autocorrelation time for turbulence = 10 μs (C-Mod), 30 μs (NSTX),
    - * Time for neutral to travel across cloud = 1 μs (C-Mod, 2 cm), $50 \rightarrow 100$ μs (NSTX, 10 cm),
    - * Timescale for emission of D_α photon $= 1/A_{3\rightarrow 2} = 0.02\ \mu$s,
    - * For emission of He 5877 Å photon $= 1/A_{3^3D\rightarrow 2^3P} = 0.01\ \mu$s.
    - * Note that camera exposure times = 2 μs (C-Mod, 60 frame/s), 4 μs (C-Mod, 5×10^6 frames / s), 10 μs (NSTX).
  - $\Rightarrow$ assumption of stationary plasma OK for C-Mod, questionable for NSTX.

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- Physics:
  - D_2 puff (C-Mod)
    - D_2, D_2^+ dissociation,
    - D + D^+ elastic scattering (i.e., charge exchange),
    - D_2 + D^+ elastic scattering,
    - e + D ionization (includes D_α emission).
    - **Note:** Prompt D_α from D_2, D_2^+ dissociation not included yet,
      - D_2 density relatively large $\Rightarrow$ cannot ignore,
      - Initial estimate indicates only quantitative change in results.
  - He puff (NSTX)
    - He + D^+ elastic scattering,
    - e + He ionization,
      - Simplified collisional radiative model (1 transported state) by Fujimoto,
      - Includes 5877 Å emission.
  - Ignore neutral-neutral collisions,
    - Neutral densities should be small enough,
    - Can treat properly only in 3-D model.
  - All puffs are 300 K with cosine distribution,
    - Sensitivity examined,
    - Source strength realistic, but quantitative comparisons not possible.

- Geometry:
  - Based on EFIT equilibrium for time of interest,
  - With actual hardware locations.
  - 2-D plasma mesh set up using `DG` & `Carre`,
    - Bunch surfaces & grid points to get resolution 3 mm or smaller in region of interest.
  - Divide puff region into ~ 3 mm triangles using `Triangle`.
- Plasma profiles:
  - All are taken from measured data mapped to midplane,
  - Assume constant on a flux surface,
    - Extend to triangulated region in approximate fashion.
  - Assume $n_i = n_e$, $T_i = T_e$.

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C-MOD RESULTS

- Primary focus on shot 1010622006 at 700 ms.
- Briefly consider 1000912008 at 698 ms,
  - Interesting because observed GPI emission is significantly broader,
  - Even though n_e, T_e profiles not very different.

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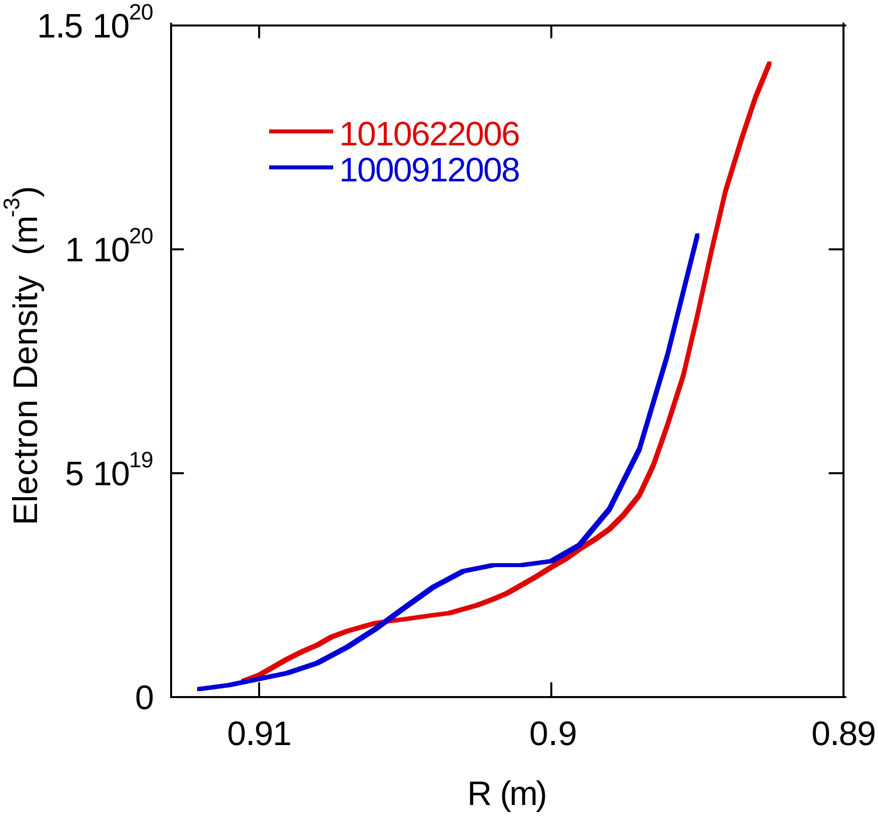
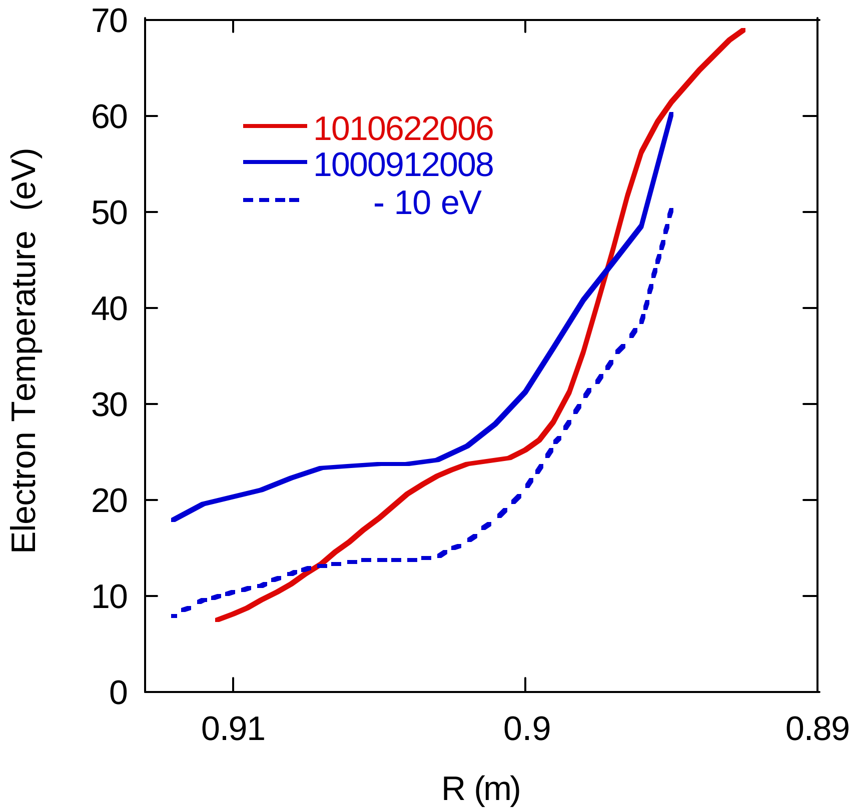
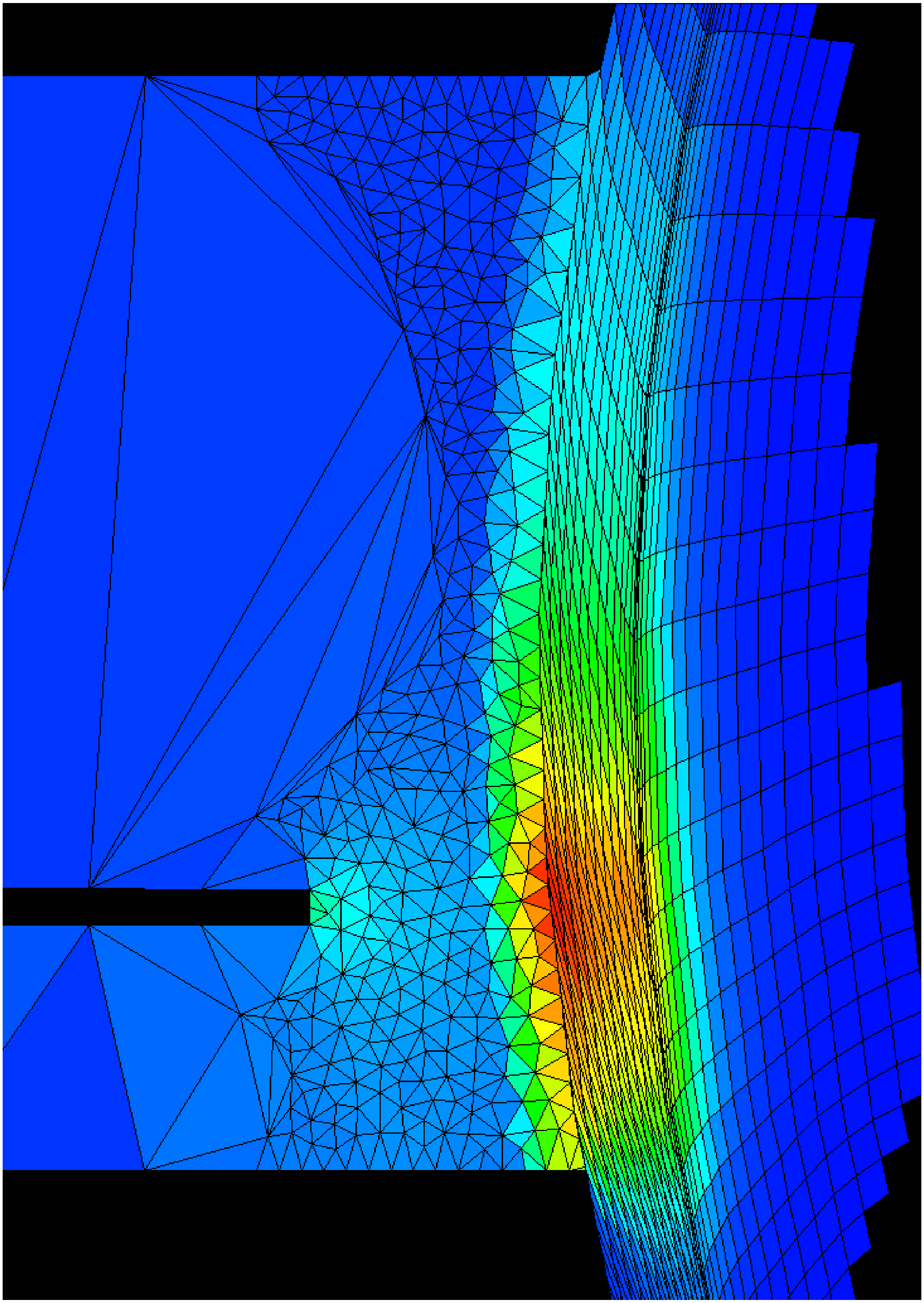
C-Mod Scanning Probe Data



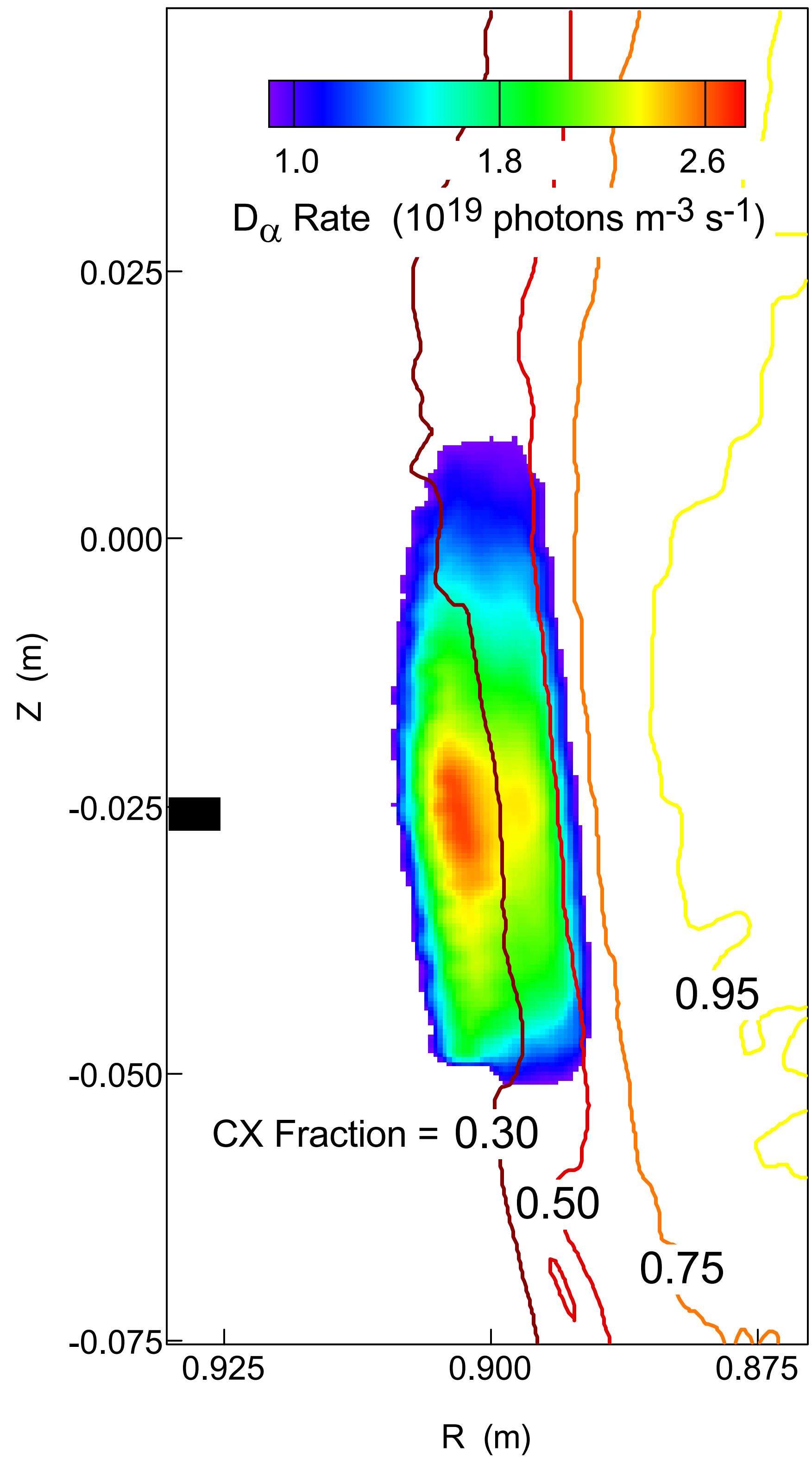
Separate Simulation Examines
Effect of Reducing T_e in 1000912008 by 10 eV



DEGAS 2 Geometry for C-Mod Shot 1010622



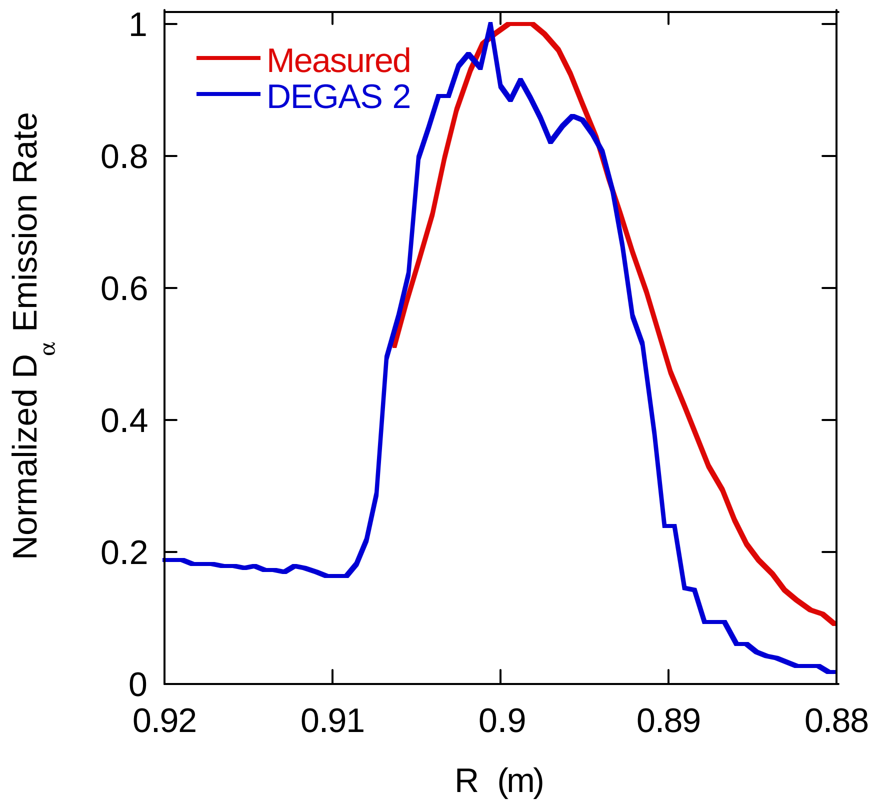
Shot 1010622006 @ 700 ms
DEGAS 2 Baseline



1. Note that:

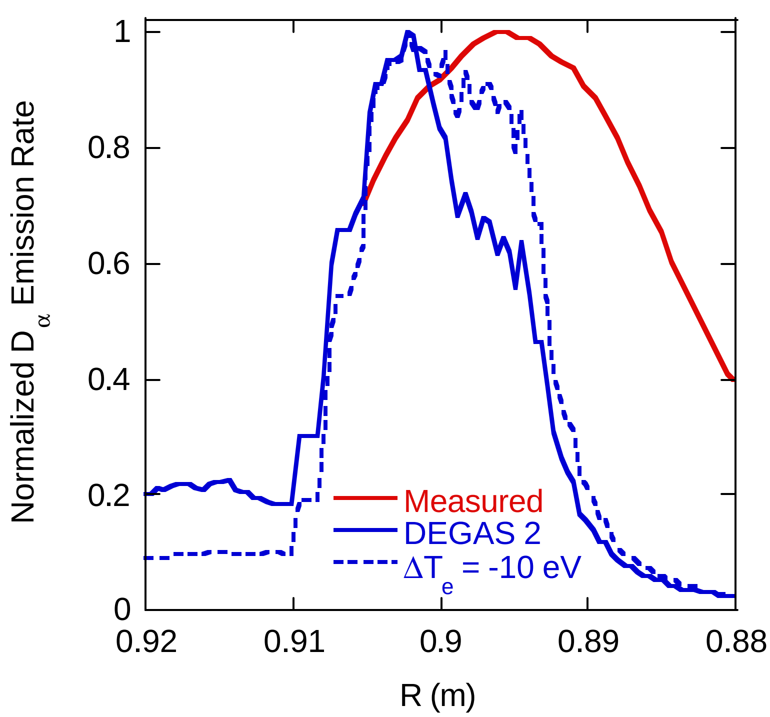
- D_2 density falls off with 0.5 cm scale length,
  - Dissociated into atoms,
  - Charge exchange dominates closer to core plasma.
- Shot 1010622006 qualitatively similar to experiment,
- But, 1000912008 significantly narrower than observed.

Radial Profile of Measured & Simulated Emissions Agree Well for 1010622006



Measured Profile for 1000912008 Wider Than Simulation

Lowering T_e Broadens Simulated Emission Slightly



2. Sensitivity studies:

- Shift temperature profile.
- Vary velocity distribution of D_2 puff,
- Change radial location of gas nozzle.

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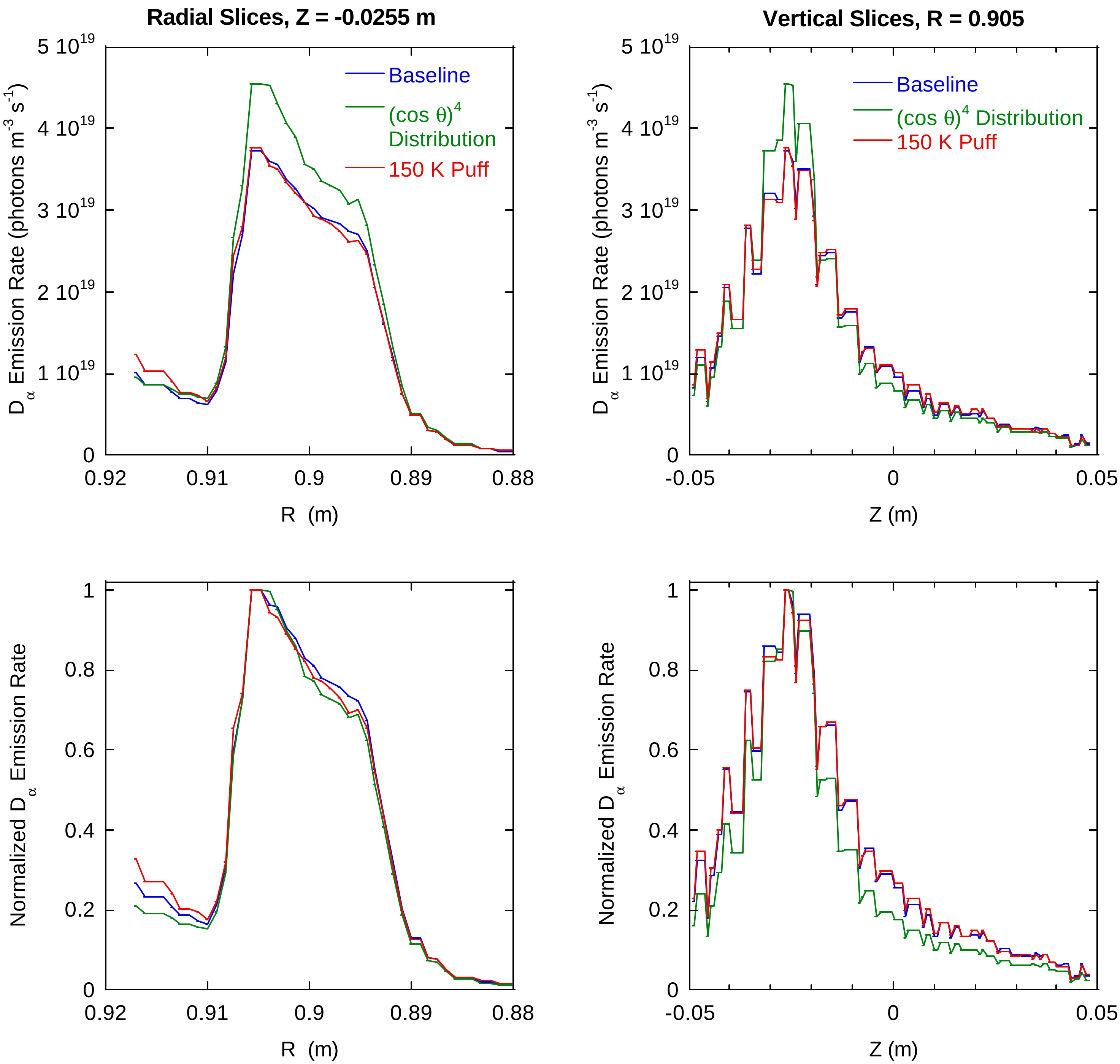
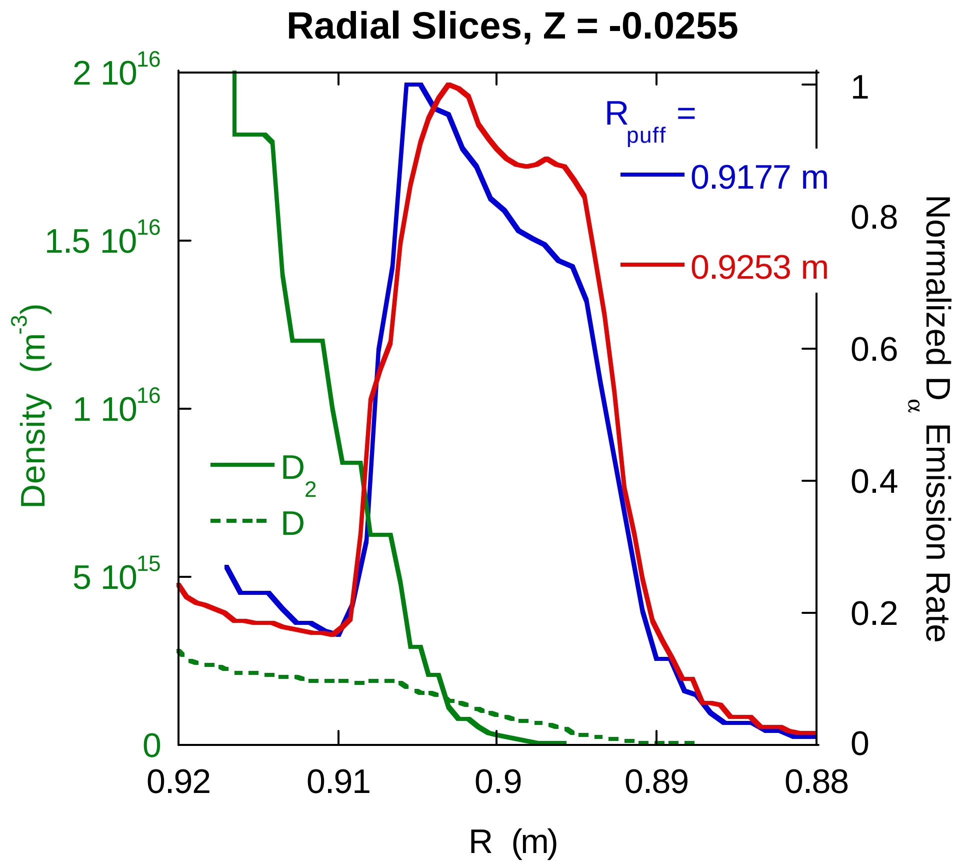
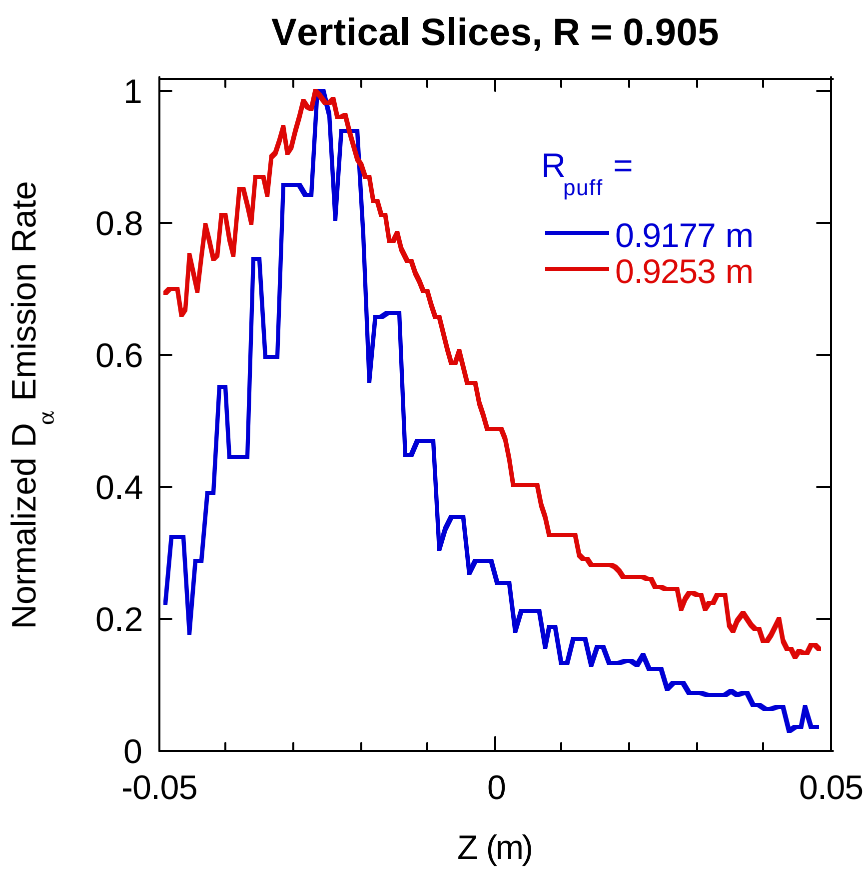
Peak Location & Width of Simulated Emission Insensitive to Details of D_2 Distribution



⇒ Vertical extent can be affected

Peak Location & Width of Simulated Emission Insensitive to Location of Gas Nozzle





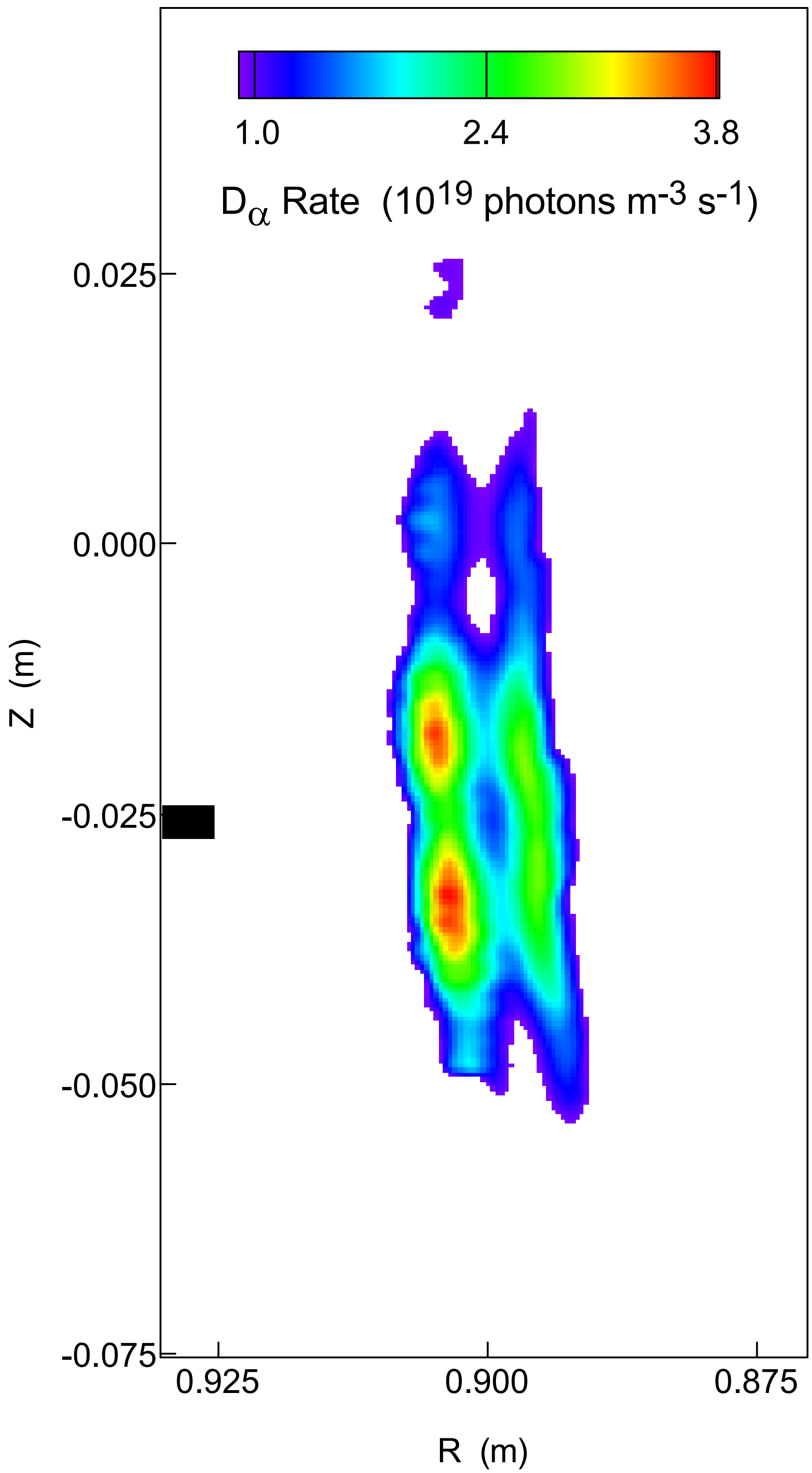
3. Impose 2-D perturbation on n_e,

- Important to understand relation between spatial variation in emission & underlying plasma fluctuations,
- Probably enough to verify that the two have same spatial frequencies,
- Subsequently consider possibility for inferring plasma parameters from emission patterns.
- Consider ad hoc n_e perturbation:

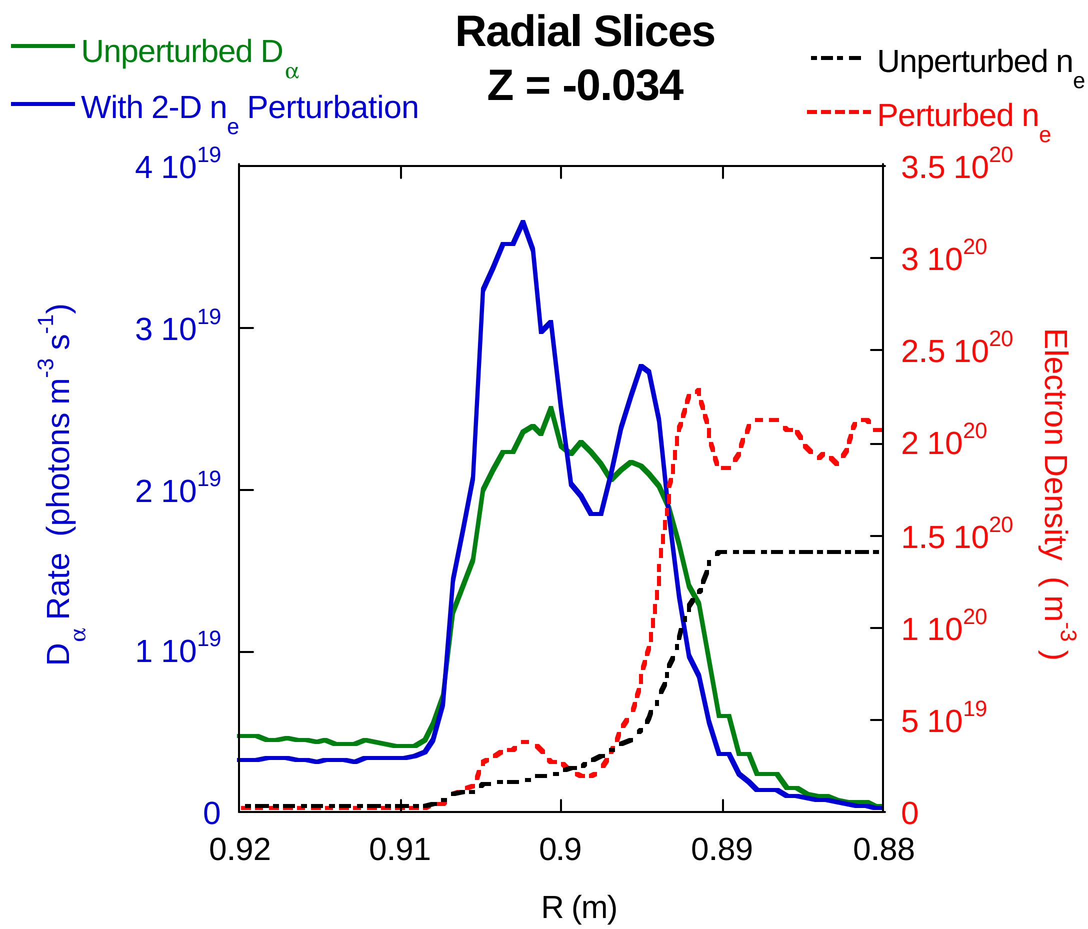
$$\begin{aligned} n'_e(R, Z) &= n_e(R, Z)[1 + \frac{1}{2}\sin(\frac{\pi Z}{0.01})] \\ &\times \{1 + \frac{1}{2}\sin[\frac{\pi(R - R_{\rm sep} + 0.0035)}{0.005}]\}, \end{aligned}$$

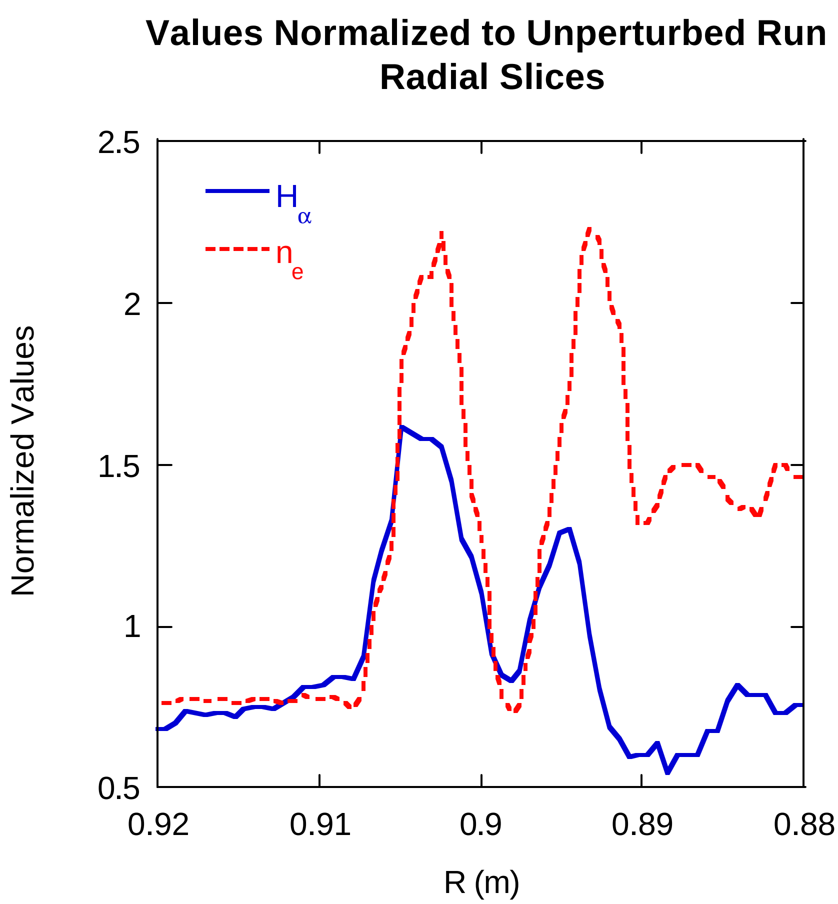
- where:
  - The $1/2$ factors make this a 50% perturbation,
    * Factor ranges from 0.25 to 2.25.
  - 2 cm wavelength for poloidal ($\sim Z$) variation,
    * Typical size of observed emission structures.
  - Used only 1 cm in R because of limited radial width,
    * 0.0035 shift so innermost data point unchanged.
- Simulated emission shows same 2-D structure,
  - Divide out unperturbed ("average") emission,
  - Resulting ratio does not equal n_e perturbation factor because $f(n_e, T_e)$ scales less than linearly with n_e,
  - Incremental ionization ("shadowing") can also reduce relative emission strength at smaller R,
    * Would need to study impact of varying perturbation magnitude.

Shot 1010622006 @ 700 ms
2-D Perturbation to Electron Density

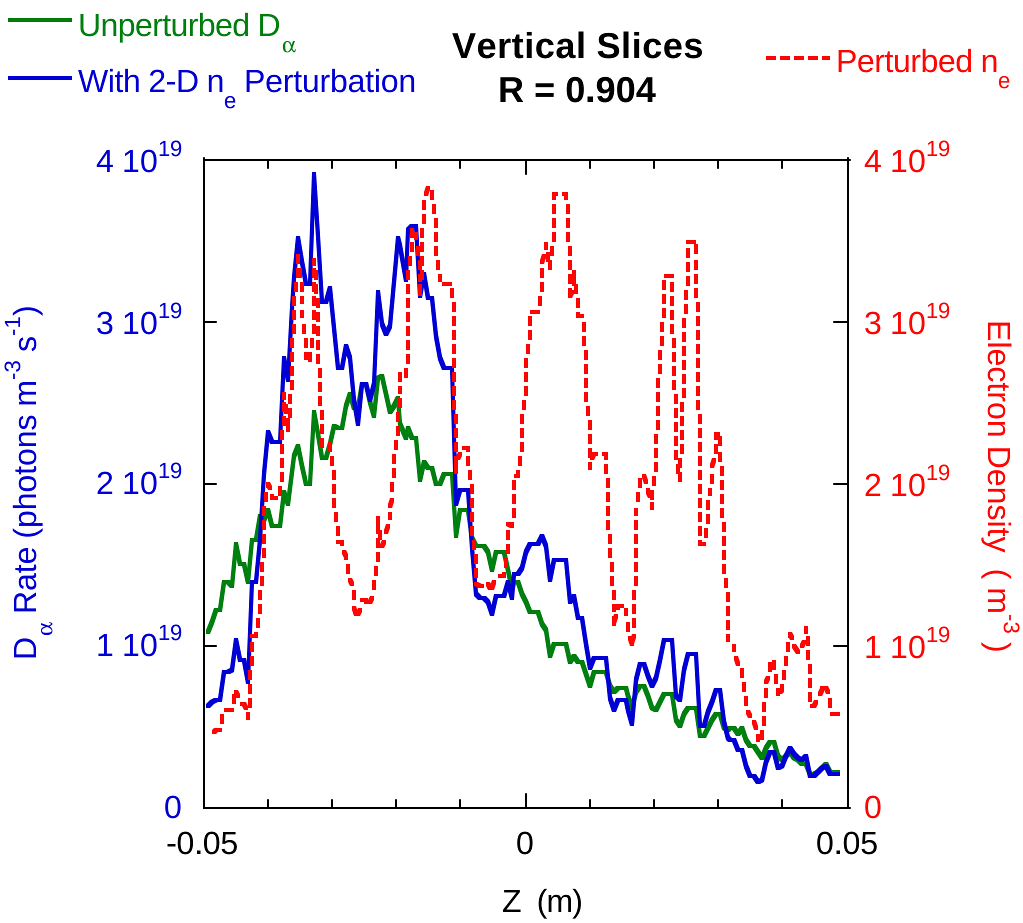


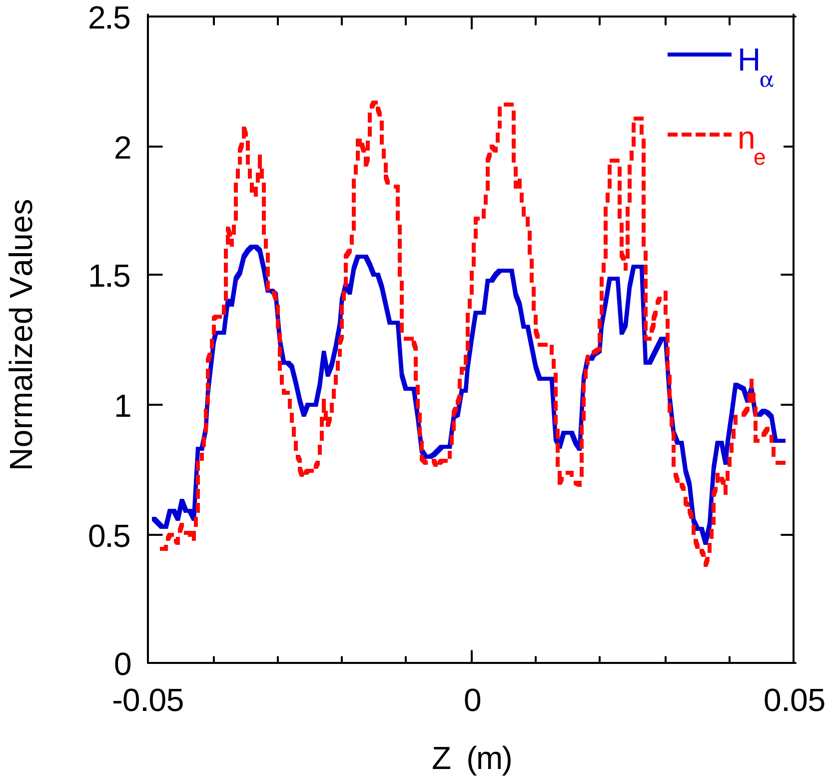
Shot 1010622006 @ 700 ms
Effect of 2-D Electron Density Perturbation



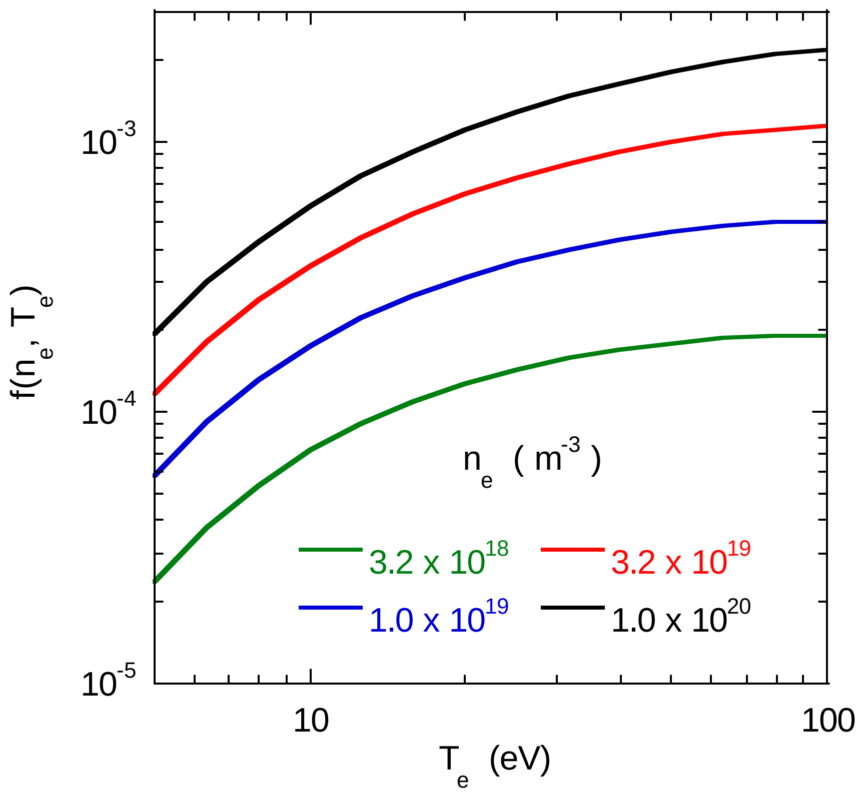


Shot 1010622006 @ 700 ms
Effect of 2-D Electron Density Perturbation

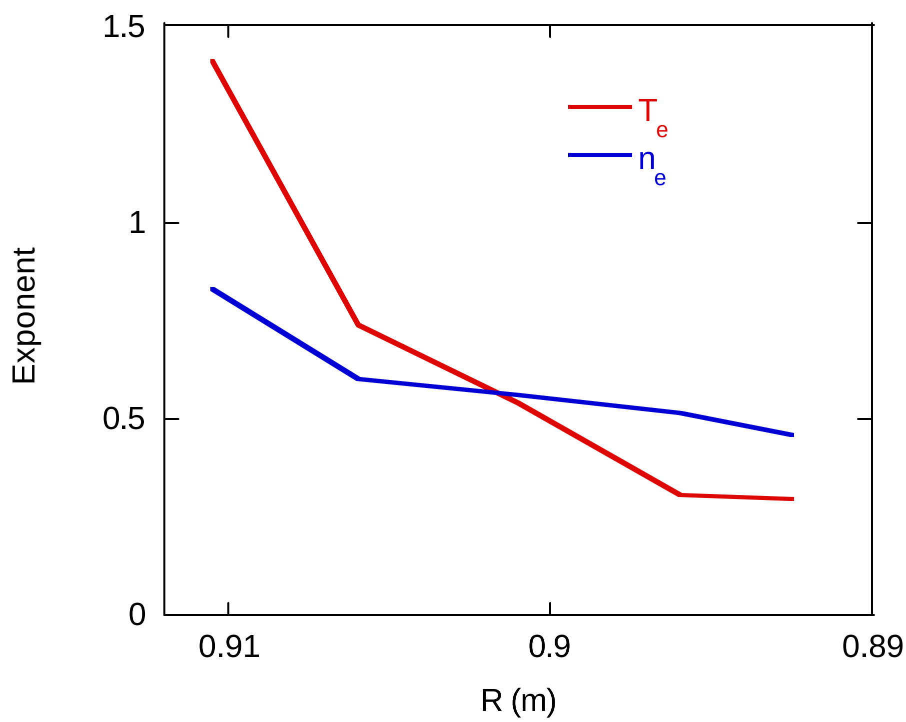




n_e, T_e Dependence of D_a Emission Rate Contained in Ratio of n=3 Density to n=1



Scaling of $f(n_e, T_e)$ Varies Across Radial Profiles of 1010622



4. Try same perturbation on T_e,

- Only difference is that T_e bound between 5 and 100 eV.
- Resulting emission profiles qualitatively similar to those obtained with n_e perturbation,
  - Because T_e and n_e dependence of $f(n_e, T_e)$ so similar for these parameters.
- Makes unfolding underlying perturbation difficult,
  - Would help if knew relation between perturbed n_e, T_e, e.g., perturbation on p_e.
  - Could unfold by viewing multiple spectral lines.

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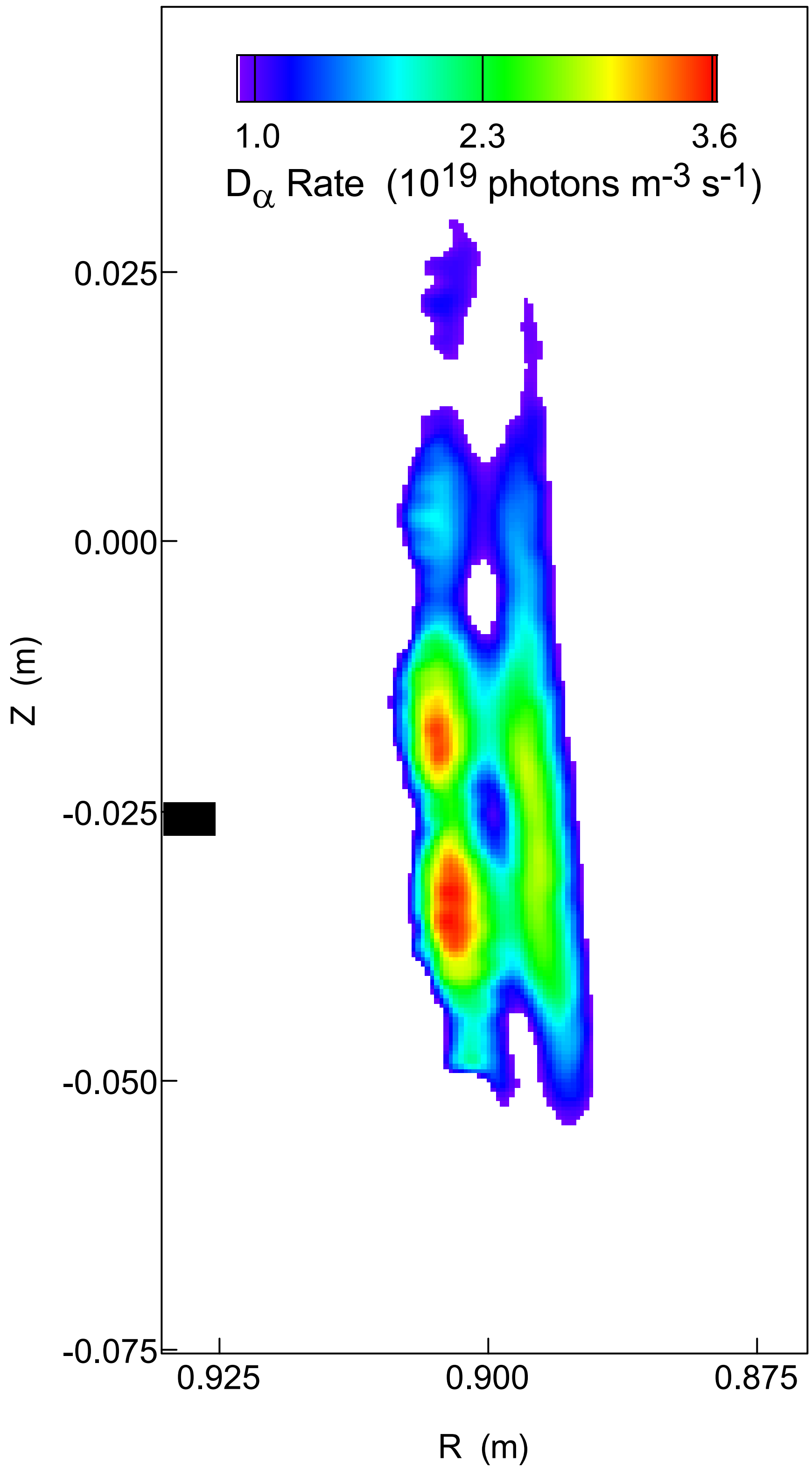
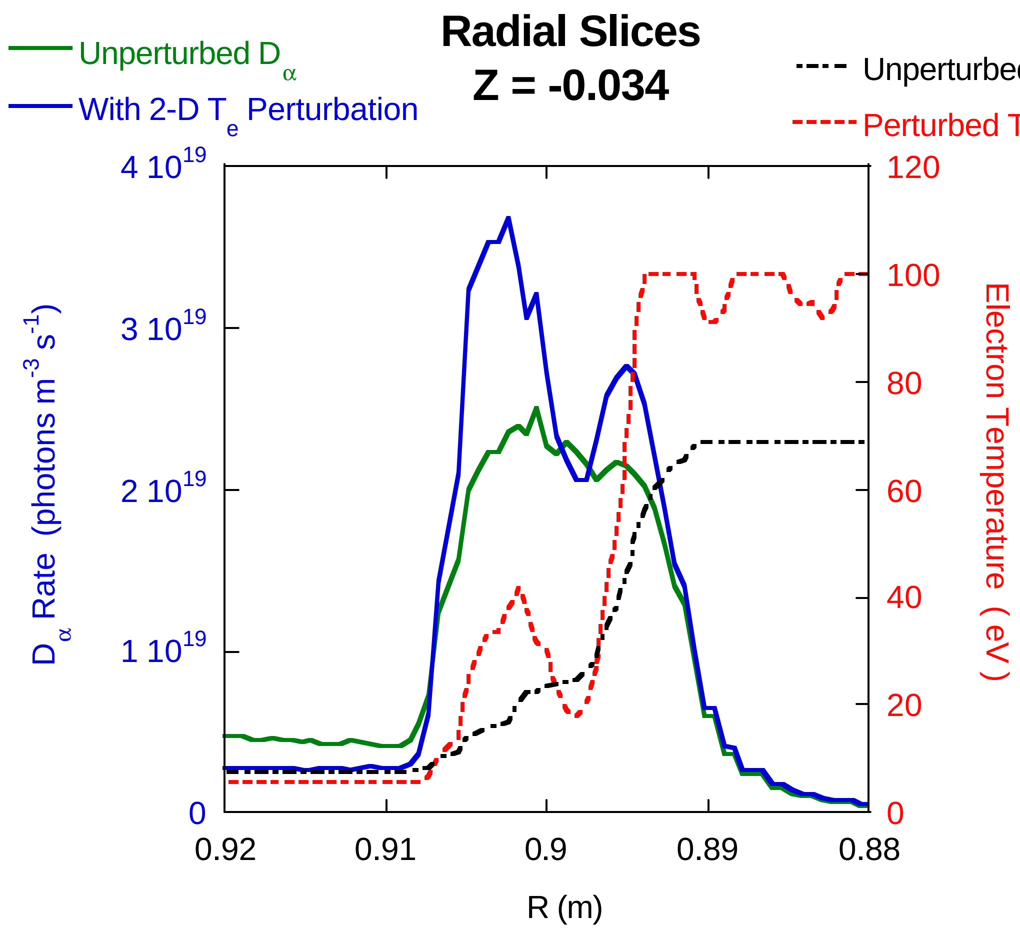
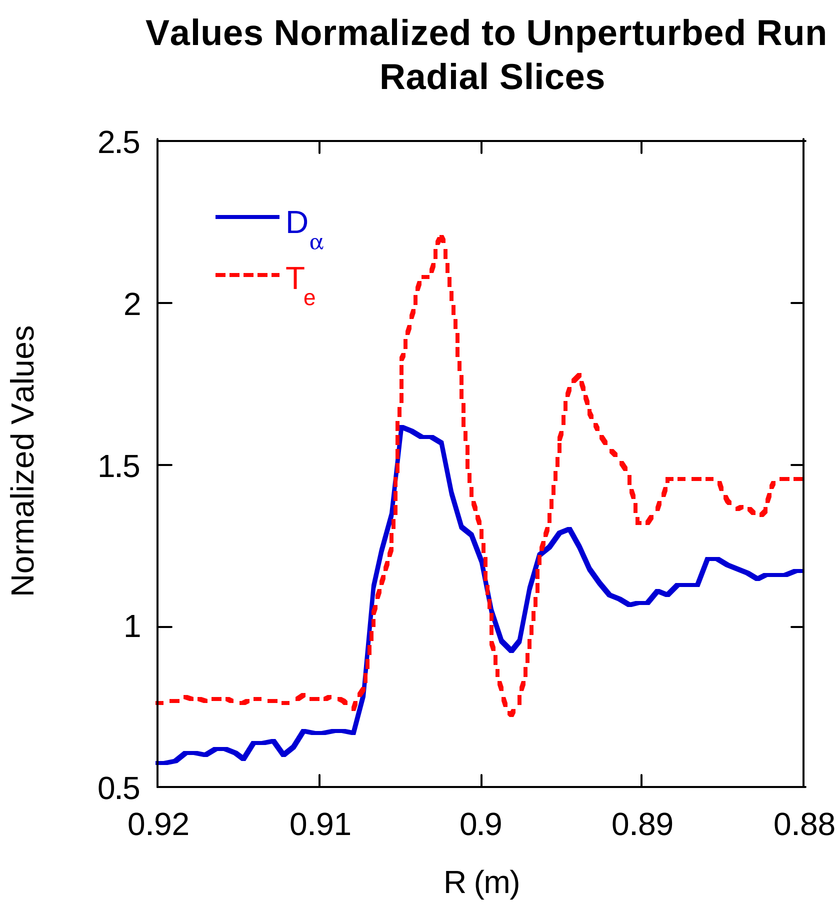
Shot 1010622006 @ 700 ms
2-D Perturbation to Electron Temperature

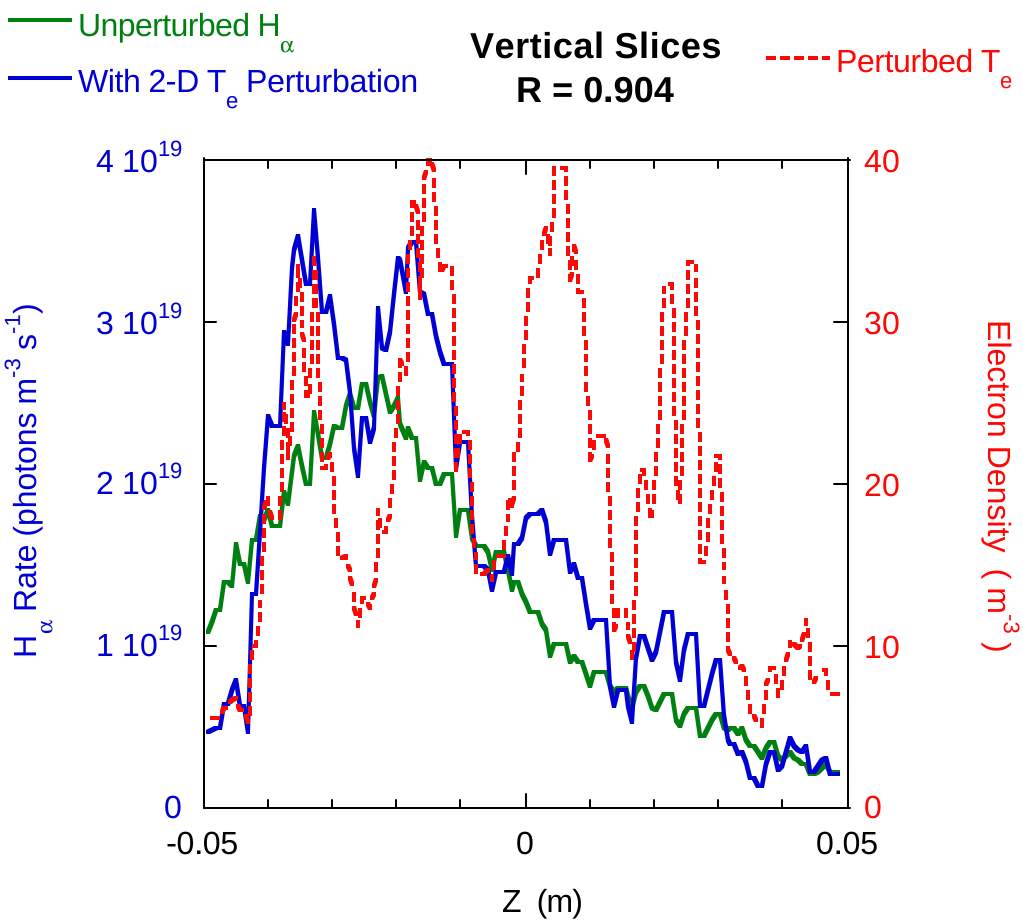


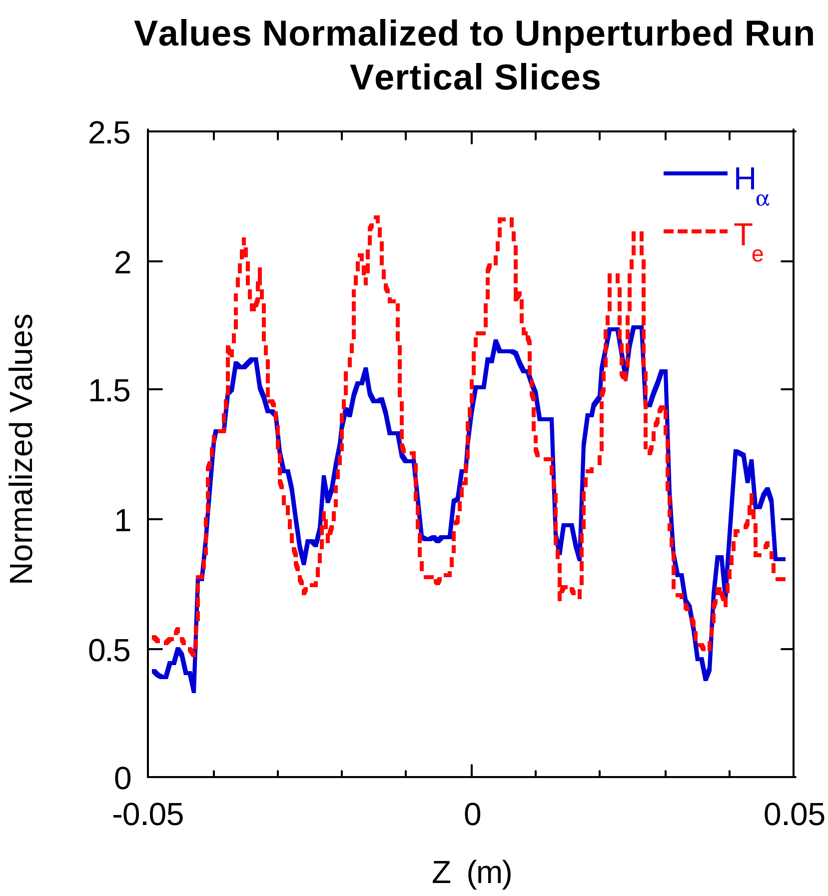
Shot 1010622006 @ 700 ms
Effect of 2-D Electron Temperature Perturbation





Shot 1010622006 @ 700 ms
Effect of 2-D Electron Temperature Perturbation





NSTX SIMULATIONS

- Experimental technique very similar to C-Mod,
- Differences:
  - Uses linear gas puff, 30 cm $\perp \vec{B}$,
  - Puff He into D plasma.
- Interesting because H-mode emission cloud much narrower than L-mode.
- But, plasma data sparser than C-Mod,
  - 3–4 Thomson scattering points in region of interest,
  - $\Rightarrow$ these are only “demonstration” runs.
- Plan to also utilize `UEDGE` simulations for n_e, T_e.
  - Results in hand not representative of this discharge,
  - Also, need plasma data over wider range in R.
- Results:
  - L-mode & H-mode n_e, T_e profiles very different,
    - $*$ Suspect actual H-mode gradients may be steeper than these.
  - Simulated emission profiles differ correspondingly,
    - $*$ L-mode cloud 2–3 $\times$ wider,
    - $*$ Probably governed by L_T & L_n.

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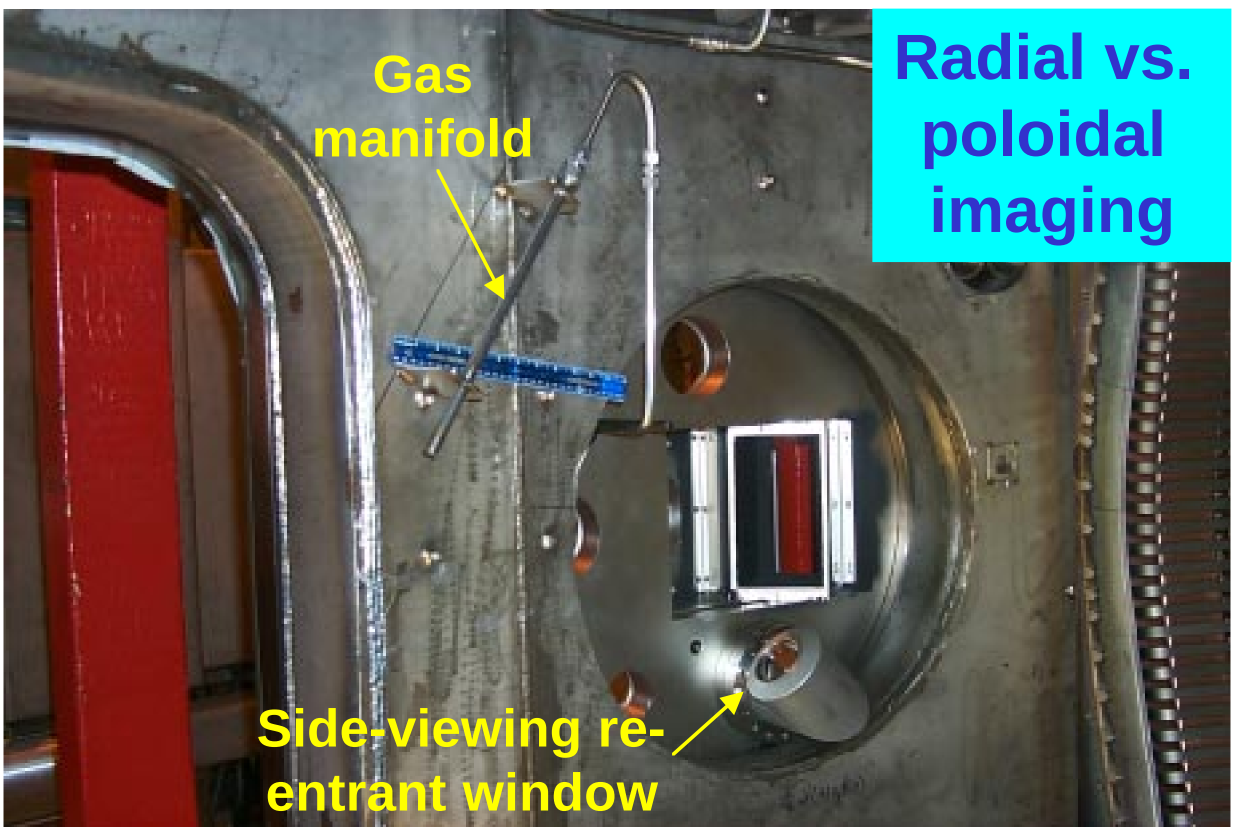
GPI Setup in NSTX (2000)

- **Radial vs. poloidal imaging:**

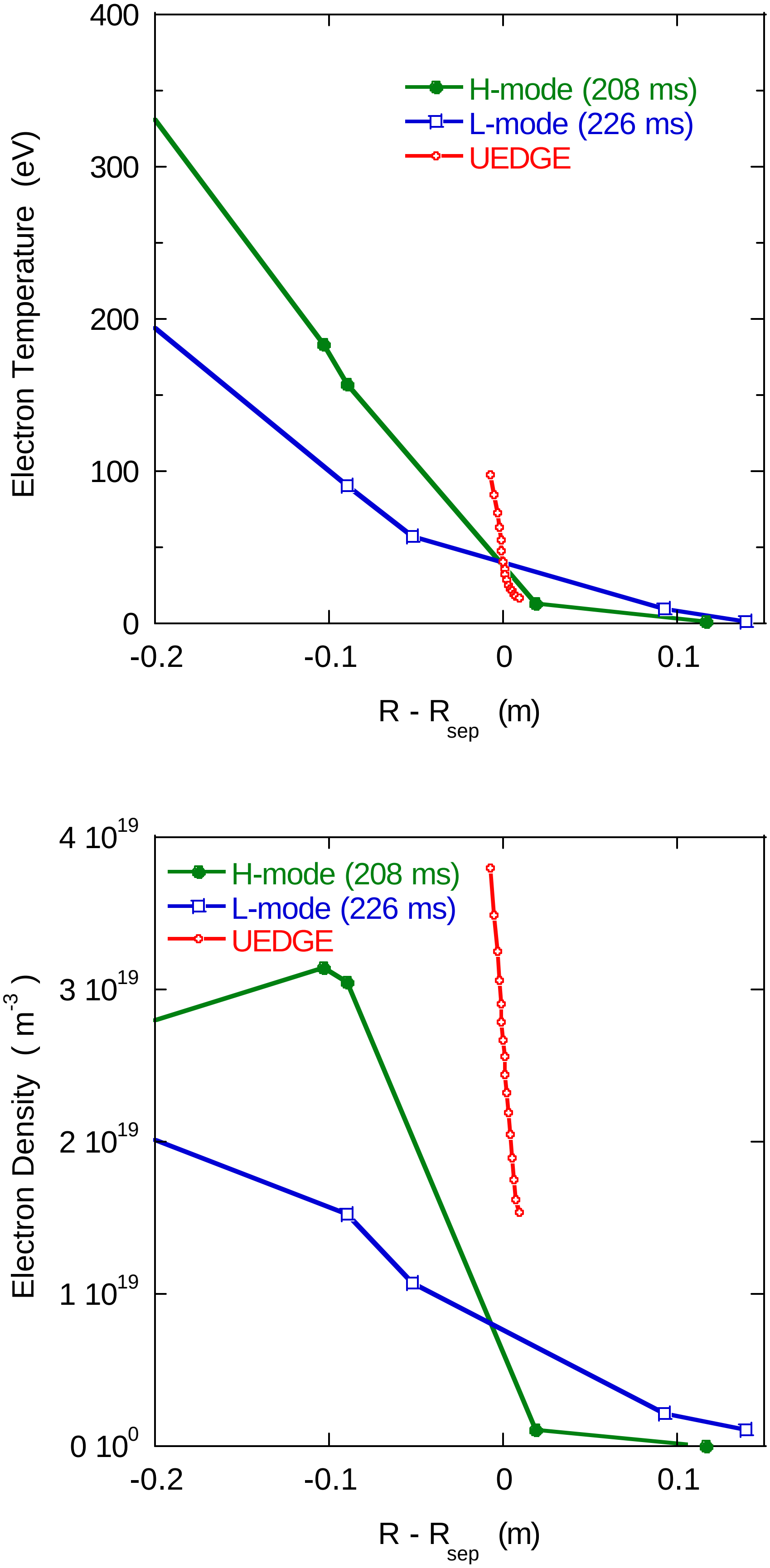
  Use “long” gas manifold to produce a 30-cm wide “linear” gas puff, with side-viewing re-entrant window to view puff

- **Poloidal vs. toroidal imaging:**

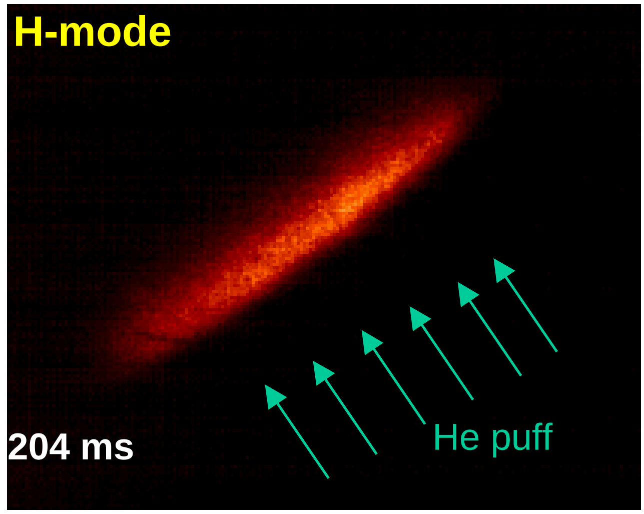
  Use puff from pumping port or natural recycling, viewing across machine from midplane window

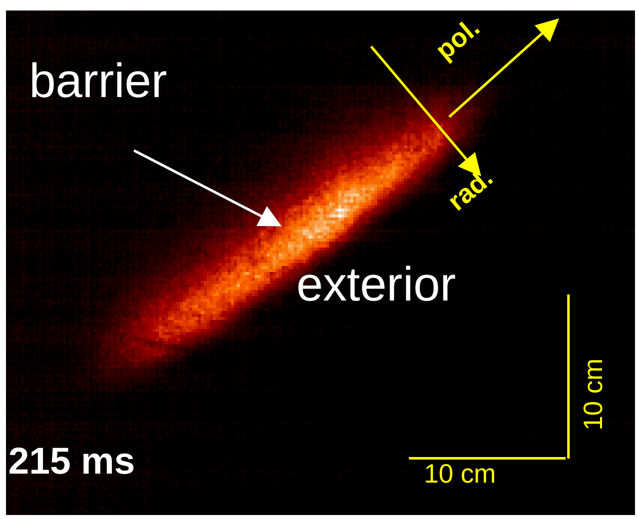


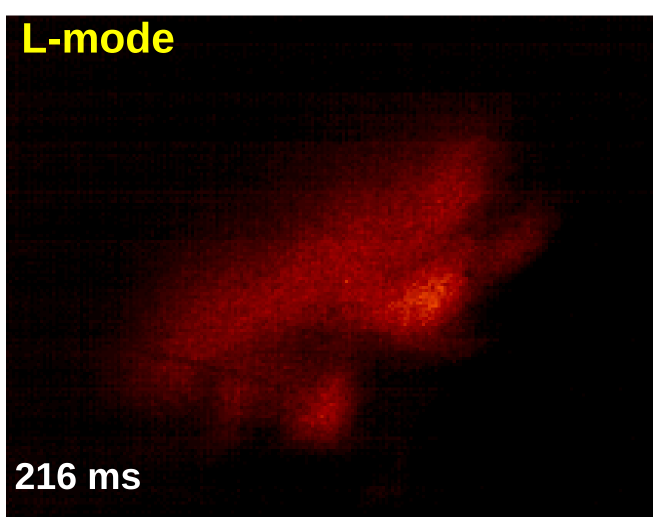
NSTX Shot 105710 Plasma Profiles
From Thomson Scattering Data
Note Smaller Radial Extent of Example UEDGE Data



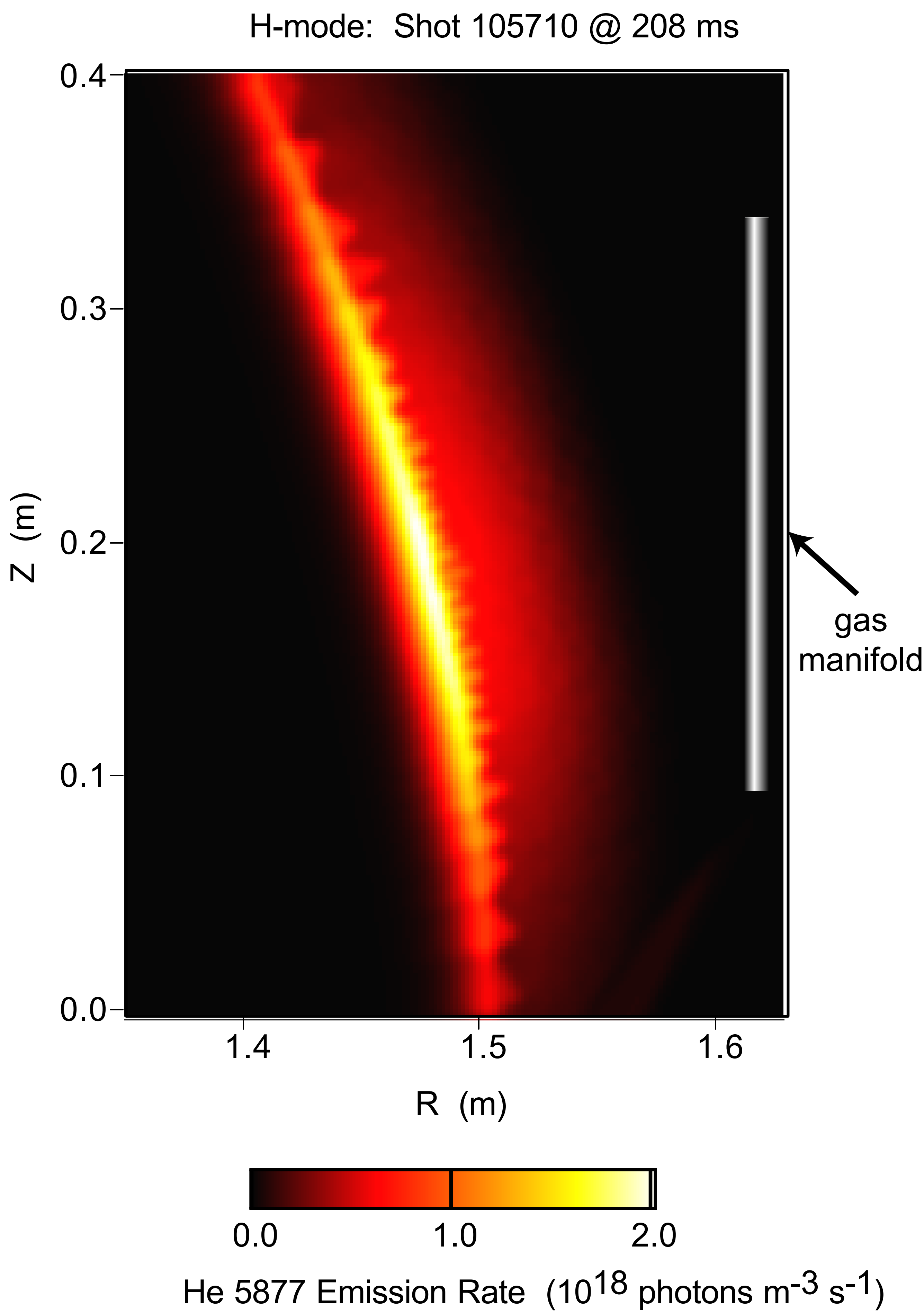
NSTX Shot 105710
Observed He 5877 Emissions

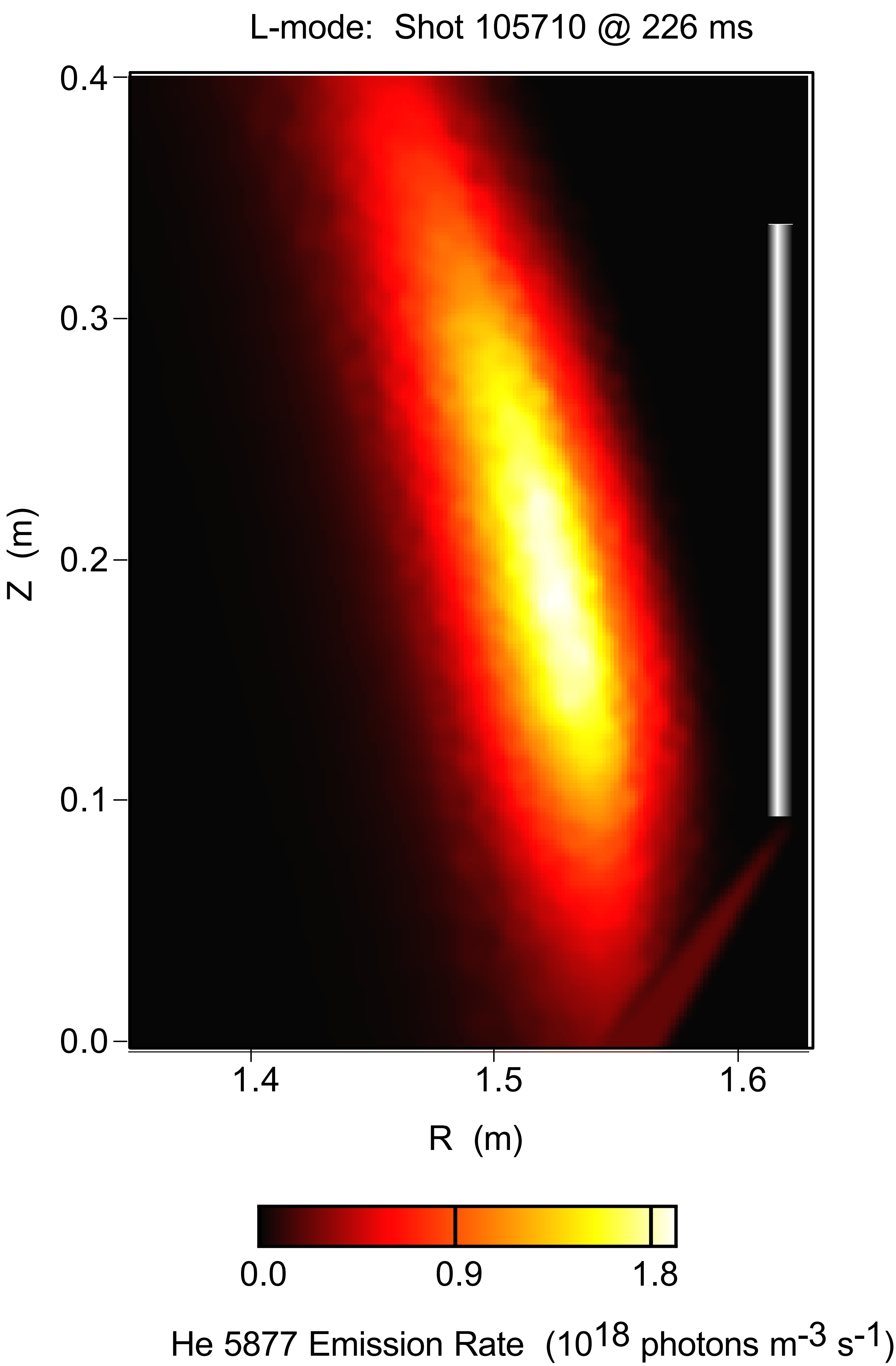






Shot 105710


H-mode: Shot 105710 @ 208 ms
0.4
0.3
0.2
0.1
0.0
Z (m)
1.4
1.5
1.6
R (m)
gas
manifold
0.0
1.0
2.0
He 5877 Emission Rate (10^18 photons m^-3 s^-1)


L-mode: Shot 105710 @ 226 ms
0.4
0.3
0.2
0.1
0.0
Z (m)
1.4
1.5
1.6
R (m)
0.0
0.9
1.8
He 5877 Emission Rate (10^18 photons m^-3 s^-1)

CONCLUSIONS

- DEGAS 2 simulations show that spatial variation of D_α emission same as that of n_e, T_e.
  - But, effects of n_e & T_e perturbations similar $\Rightarrow$ difficult to infer from emissions.
- Qualitative similarity to observed emissions is encouraging,
  - Diagnostics are absolutedly calibrated $\Rightarrow$ do quantitative comparisons with 3-D simulations.
- DEGAS 2 physics model can be improved,
  - Add prompt D_αs from D_2 dissociation,
  - Perhaps incorporate CR model for D_2.
  - Transport metastable He($n = 2$) states.
- Consider developing techniques for inferring n_e, T_e perturbations from emission patterns,
  - Use DEGAS 2 to develop an “inversion map”.