Details of Neutral Transport in Gas Puff Imaging Experiments

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

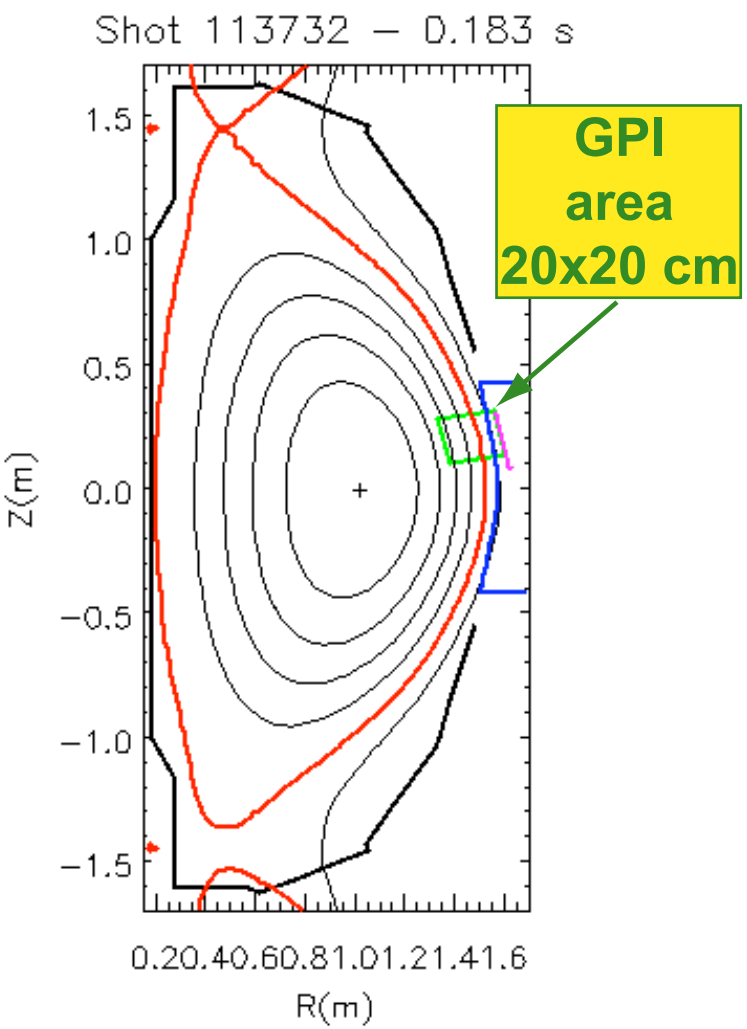
Gas Puff Imaging (GPI) Experiments Designed to Measure 2-D Structure of Edge Turbulence

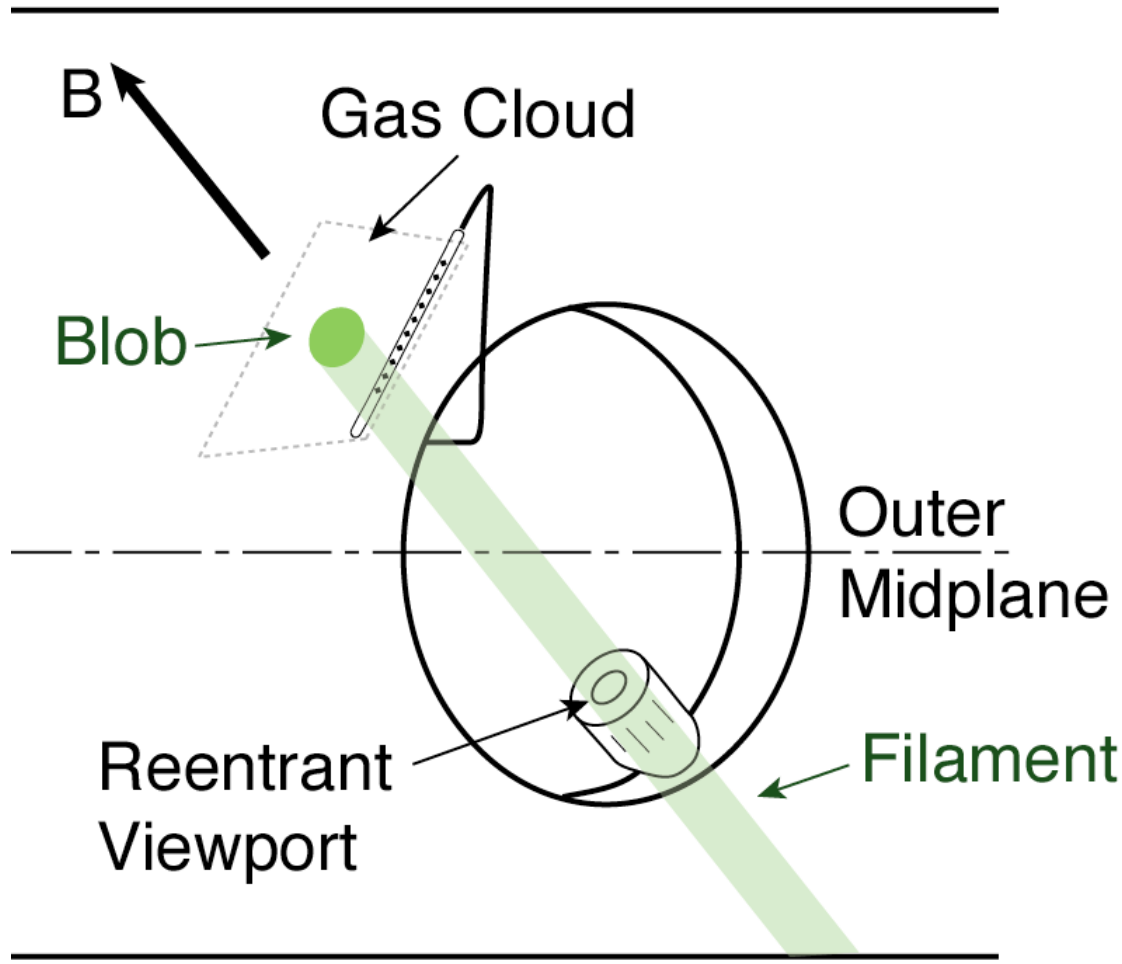
- Puff neutral gas near outer wall,
- View with fast camera fluctuating visible emission resulting from electron impact excitation of that gas,
  - Compare with 3-D nonlinear plasma simulation codes,
  - Reduced theoretical turbulence models,
  - And with turbulence measured by probes.
  - See also: [Maqueda 2002, Zweben 2004, Zweben 2006]
- How accurate are assumptions underlying interpretation of GPI?
- Can we infer plasma parameters from GPI images?

OUTLINE

1. Describe GPI experiments,
2. Time Dependent Response of Helium Atomic Physics Models,
3. 3-D DEGAS 2 Simulations,
4. Conclusions.

Gas Puff Imaging Hardware Configuration in NSTX

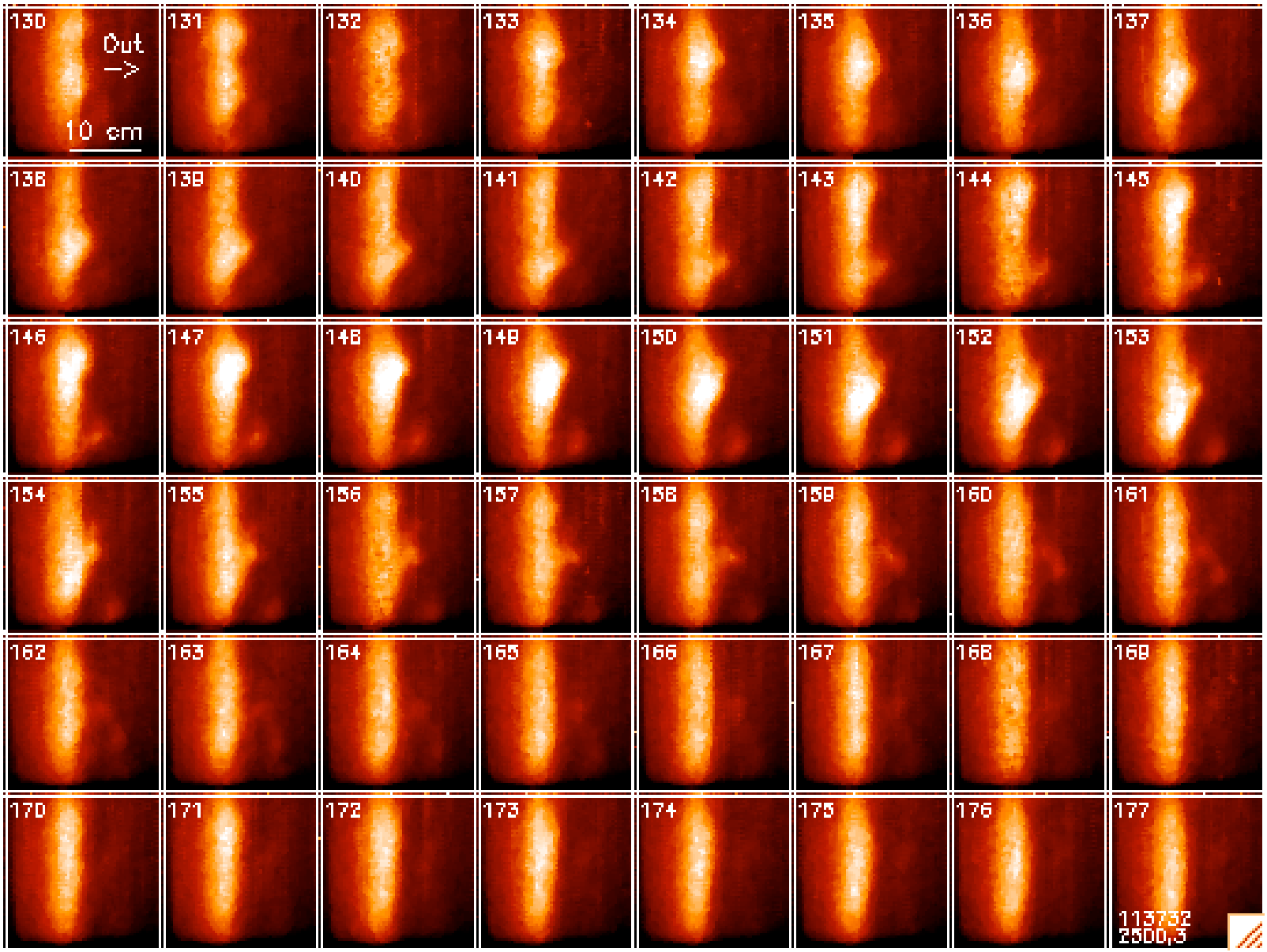




Experimental Arrangement

- NSTX GPI gas puff generated by 30 holes in 30 cm tube $\perp \vec{B}$,
  - $\Rightarrow$ sheet of neutral gas (ideal).
- Camera views 587.6 nm He I line in direction $\perp$ to sheet & $\parallel \vec{B}$.
- Assumes plasma turbulence extended along $\vec{B}$,
  - Shorter scale lengths $\perp \vec{B}$,
  - Supported by theory & observations.

Camera Records Fluctuating Emission for 300 Frames @ 4 μs/frame



L-mode

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H-mode

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Time-Dependent Response of Helium Atomic Physics Models

- GPI assumes light emission instantaneous compared with time scales of interest, $\gtrsim 1\ \mu$s,

- May not always be true,
  - E.g., helium has 2^1S and 2^3S metastable states.
  - If not, temporal & spatial characteristics of turbulence could be affected.

- Find that the simple model conventionally used is valid & provides adequate time resolution.

General Description of Excited Atomic States Requires Solving $N \gg 1$ Equations

- Full equations:

$$\frac{dn(i)}{dt} = -\left[\sum_{j\neq i}^{N} C(i,j)n_e + \sum_{j<i}^{N} A(i,j) + S(i)n_e\right] n(i)$$
$$+ \sum_{j\neq i}^{N} \left[C(j,i)n_e + A(j,i)\right] n(j) + \left[\alpha(i)n_e + \beta(i) + \beta_d(i)\right] n_i n_e,$$

- Where for helium, $i = 1 \rightarrow 1^1$S, $2 \rightarrow 2^1$S, $3 \rightarrow 2^3S$, $4 \rightarrow 2^1$P, $5 \rightarrow 2^3$P, $6 \rightarrow 3^1S$, ..., and $N = 59$ [Fujimoto 1979, Goto 2003]

- Write in matrix form as:

$$\dot{\mathbf{n}} = \mathbf{M}\mathbf{n} + \mathbf{\Gamma}.$$

Collisional Radiative Models Intended to Simplify Treatment of Excited Atomic States

- Split N states into sets P (N_P) and Q (N_Q) [Greenland 2001],

$$\begin{bmatrix} \dot{\mathbf{n}}_P \\ \dot{\mathbf{n}}_Q \end{bmatrix} = \begin{bmatrix} \mathbf{M}_P & \mathbf{H} \\ \mathbf{V} & \mathbf{M}_Q \end{bmatrix} \begin{bmatrix} \mathbf{n}_P \\ \mathbf{n}_Q \end{bmatrix} + \begin{bmatrix} \mathbf{\Gamma}_P \\ \mathbf{\Gamma}_Q \end{bmatrix}$$

- Define effective rates $\mathbf{M}_{\text{eff}}$ such that entire system described as [Bates 1962, Johnson 1973]:

$$\dot{\mathbf{n}}_P = \mathbf{M}_{\text{eff}} \mathbf{n}_P + \mathbf{\Gamma}'_P.$$

- And Q state evolution computed from $\mathbf{n}_P$:

$$\mathbf{n}_Q = \mathbf{\Omega} \mathbf{n}_P - \mathbf{M}_Q^{-1} \mathbf{\Gamma}_Q.$$

- [Greenland 2001] gives criteria for testing particular choice of P and Q states,
  - And gives time scales that choice can resolve.

[Greenland 2001] Criteria Based on Eigenvectors of Rate Matrix

- Use normalized eigenvectors of $\mathbf{M}$ to form $\mathbf{T}$,
  - Columns ordered by increasing eigenvalue $\lambda^{(i)}$.
- Then, break up into submatrices:

$$\mathbf{T} = \begin{bmatrix} \mathbf{T}_P & \boldsymbol{\Delta} \\ \boldsymbol{\delta} & \mathbf{T}_Q \end{bmatrix}.$$

- For CR model to be valid [Greenland 2001], $\|\boldsymbol{\delta}\| \ll 1$ and $\|\mathbf{T}_Q^{-1}\boldsymbol{\delta}\| \ll 1$.
- And phenomena faster than $\tau_Q \equiv 1/|\lambda_Q|$ are *not* resolved,
  - $\lambda_Q =$ smallest eigenvalue in Q.

Do Helium CR Models Adhere to These Requirements?

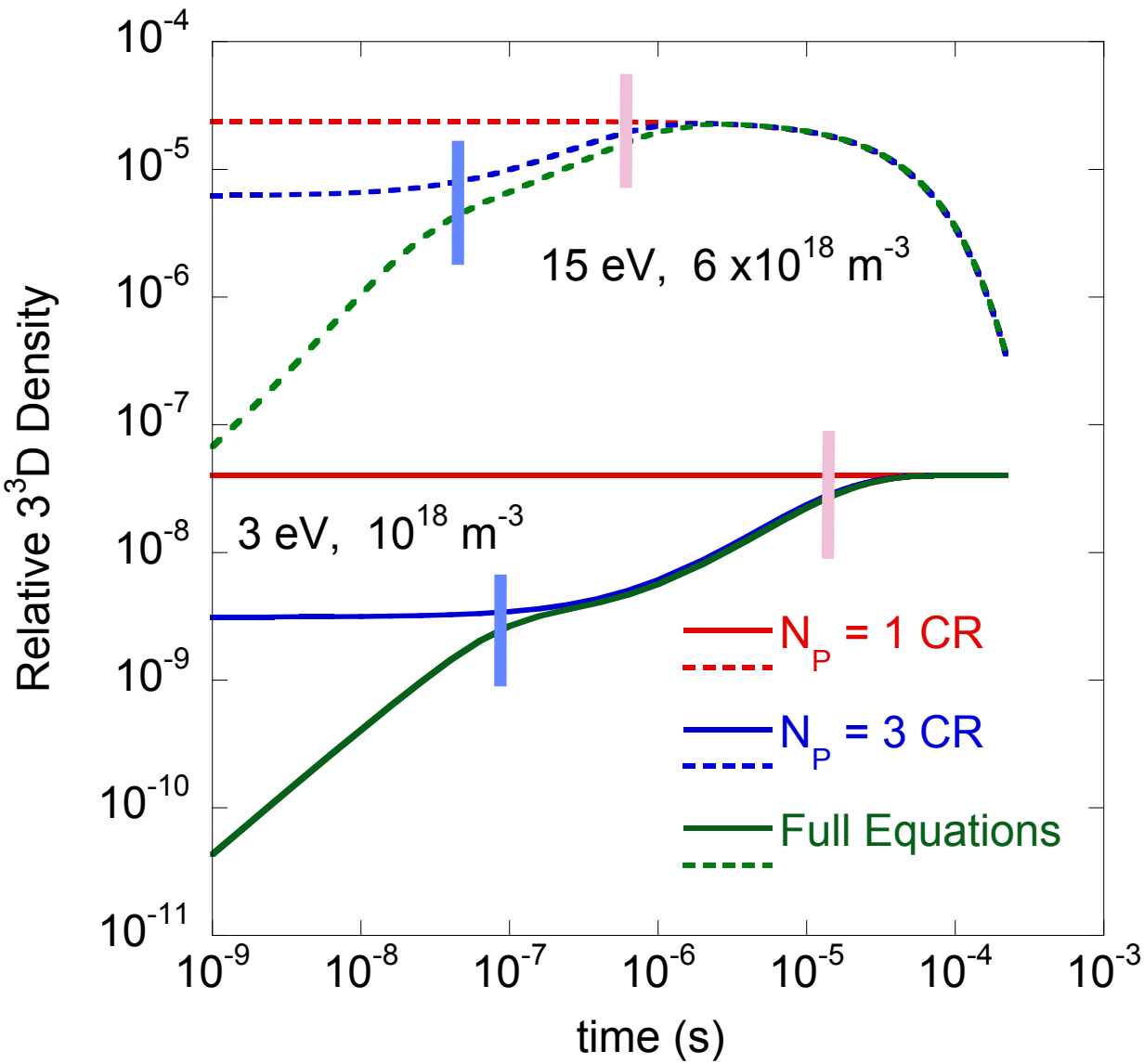
- [Fujimoto 1979, Goto 2003] describe one (N_P = 1) and three ($N_P = 3$) state CR models,
  - 3 state model requires explicit modeling of 1^1S, 2^1S, and 2^3S states.
- Do these models provide $\sim \mu$s time resolution required by GPI experiments?
- Is 3 state model enough of an improvement over 1 state to offset additional overhead (12 reactions vs. 2)?

Apply Analysis to Code from [Goto 2003]

(T_e eV, n_e m^{-3}) =	(3, 10^{18})	(15, 6×10^{18})	(30, 10^{16})
$N_P = 1$: $\|\boldsymbol{\delta}\|$	8.2×10^{-5}	2.5×10^{-3}	1.0×10^{-2}
$\|\mathbf{T}_Q^{-1}\boldsymbol{\delta}\|$	8.7×10^{-5}	1.9×10^{-3}	1.0×10^{-2}
τ_Q (μs)	14	0.61	980
$N_P = 3$: $\|\boldsymbol{\delta}\|$	7.3×10^{-2}	5.4×10^{-1}	1.6×10^{-3}
$\|\mathbf{T}_Q^{-1}\boldsymbol{\delta}\|$	1.1×10^{-1}	6.9×10^{-1}	2.7×10^{-3}
τ_Q (μs)	0.087	0.045	0.52

- Single state model valid for all three conditions,
- But, 3 state model valid only for lowest n_e!
- Confirm with time dependent integrations.

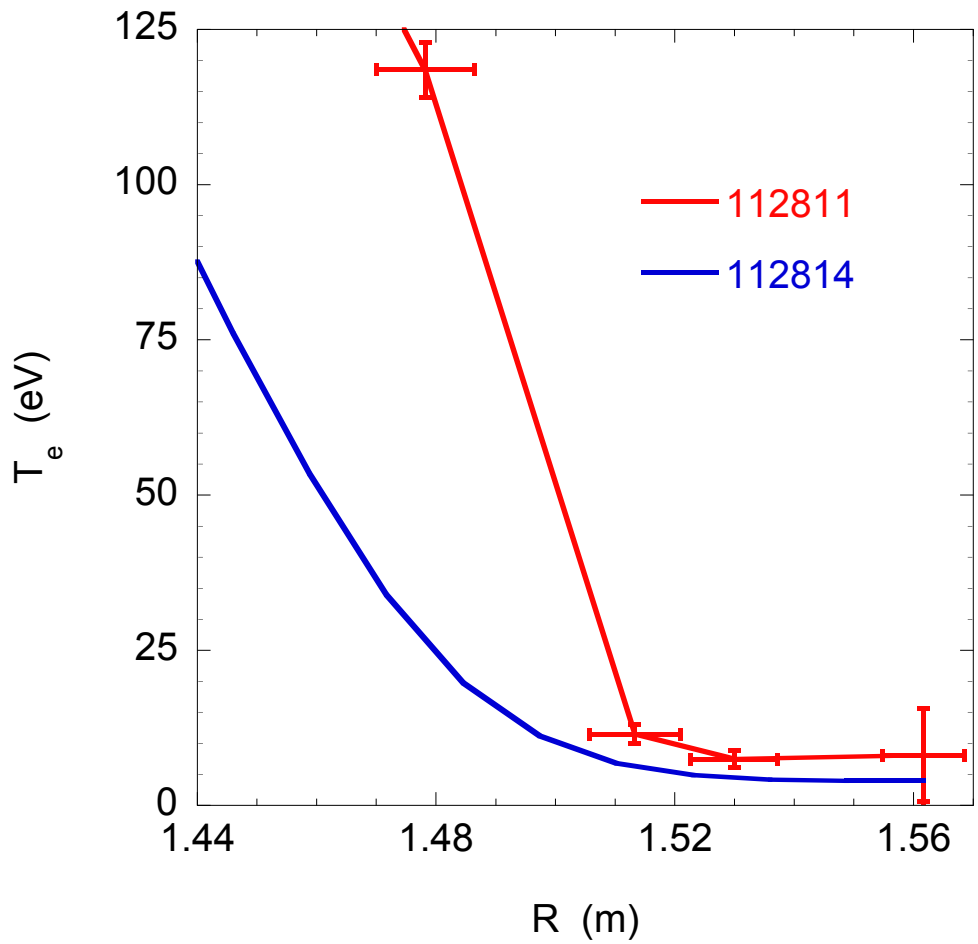
Time Dependent Integration Confirms Conclusions of Eigenvector & Eigenvalue Analysis

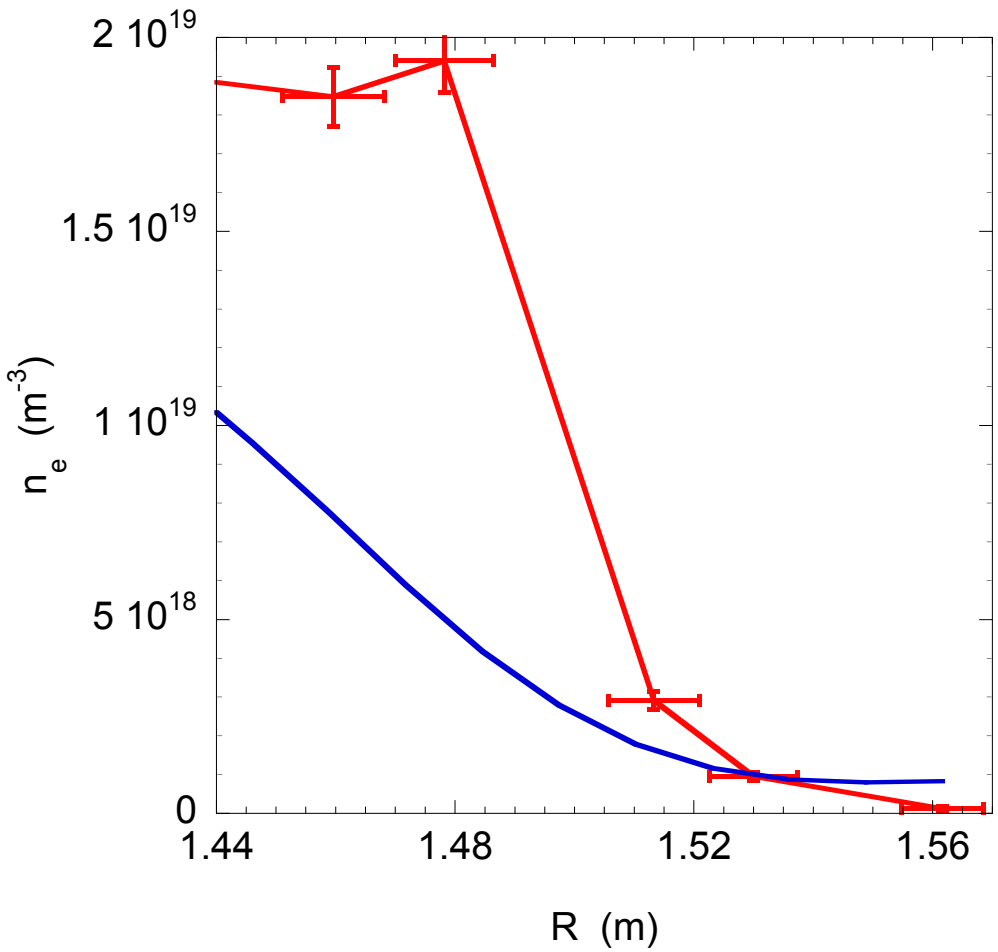


Three-Dimensional DEGAS 2 Simulations of GPI Experiments

- Procedure similar to [Stotler 2004],
- Begin with EFIT equilibrium at time of interest $\Rightarrow$ mesh,
- Incorporate geometry of vacuum vessel, including manifold,
  - Point sources along a line matching actual manifold.
- Single-time $n_e(R_{\text{mid}})$, $T_e(R_{\text{mid}})$ from Thomson scattering,
  - Assume $n_i = n_e(\psi)$, $T_i = T_e(\psi)$ only.
  - Simulations are time-independent.
- Emulate 64×64 pixel camera view,
  - Record helium 587.6 nm emission.

Thomson Scattering Midplane Profiles





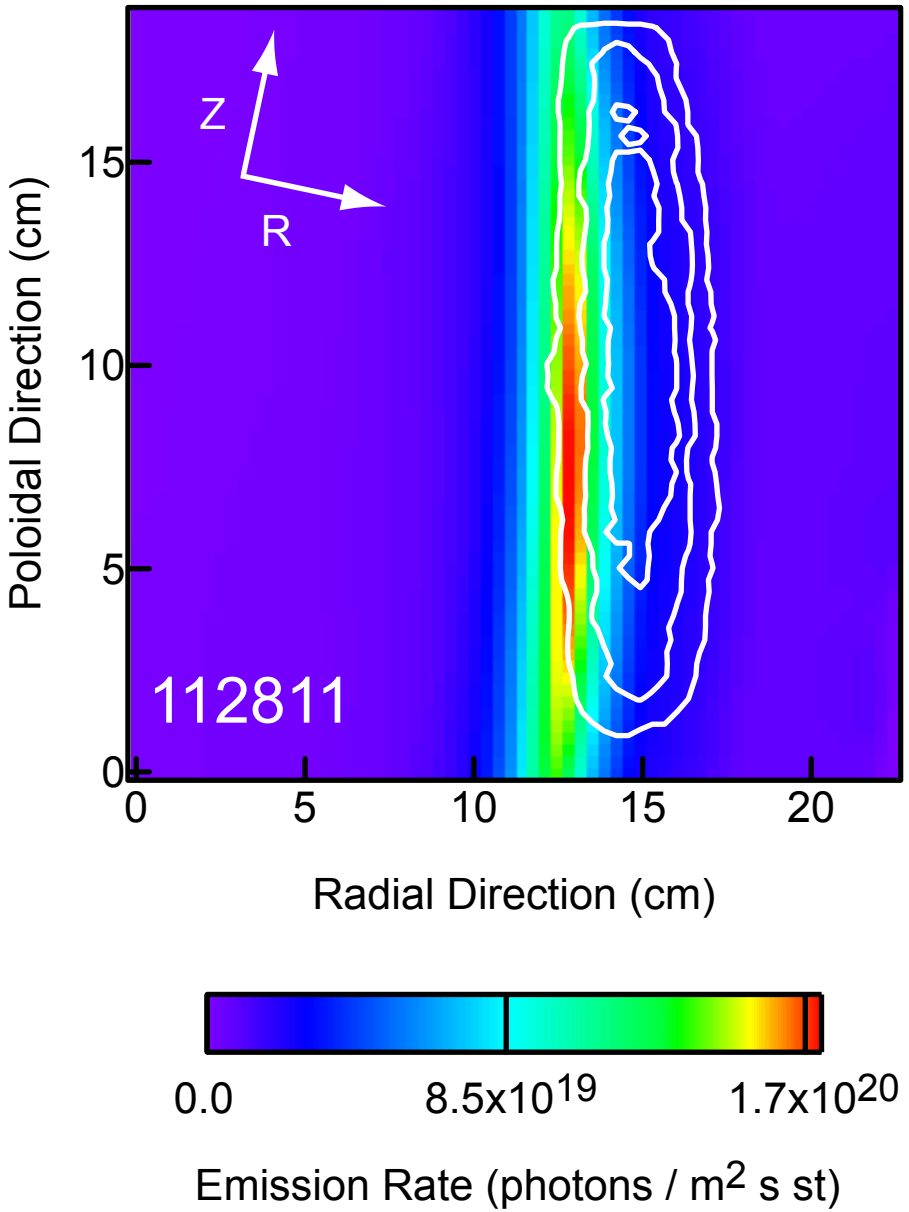
Compare With Experiment

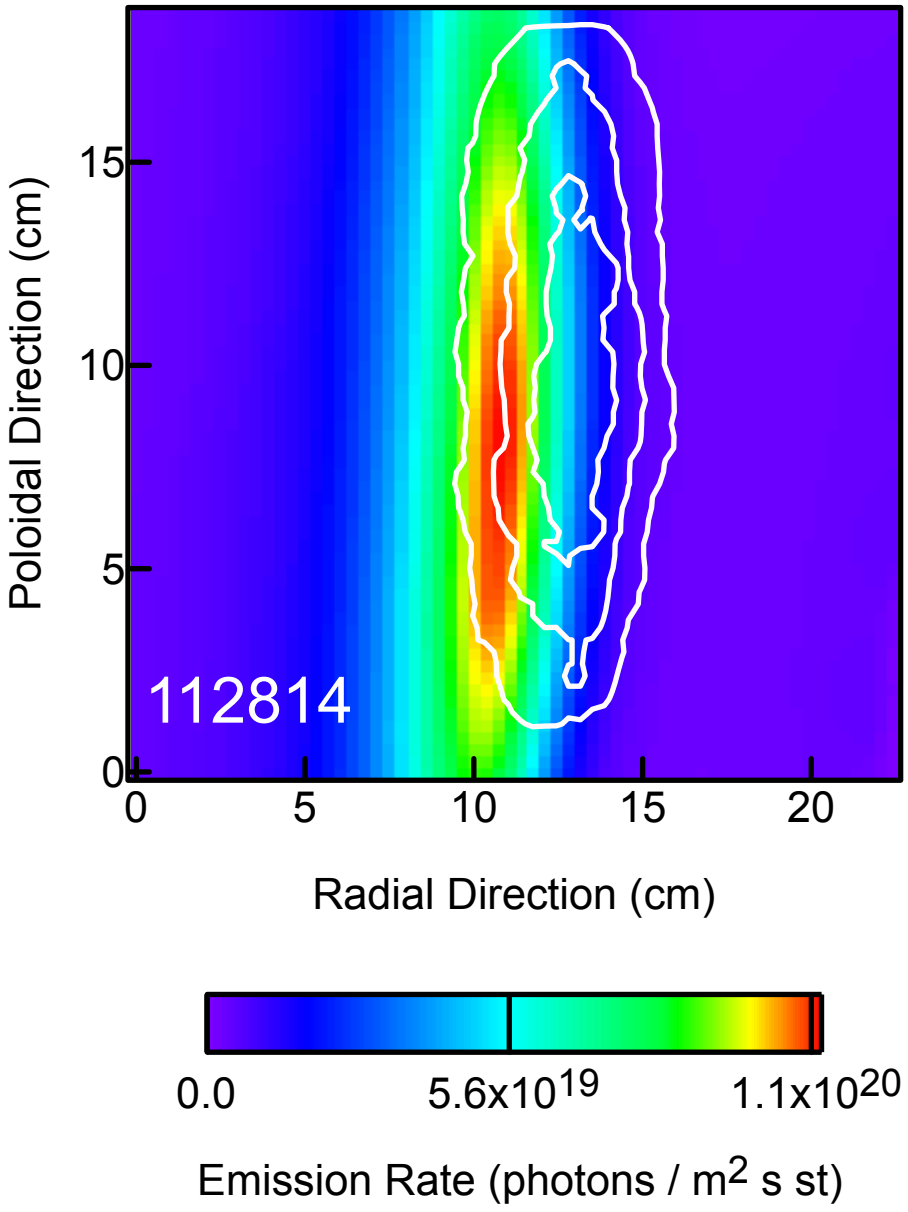
- Two shots: 112811 (H-mode), 112814 (L-mode),

- Overlay experimental data,
  - 3-D plasma used in DEGAS 2 *does not* correspond to a particular GPI frame,
  - $\Rightarrow$ compare with "averaged" frame,
  - Use median in time to minimze effect of blobs.

- Experimental contours at 25%, 50%, and 75% of peak.

Radial Width & Location of Simulated Emission Clouds Match Experiment to Within Estimated Error





Conclusions

- Single state atomic physics model valid for GPI conditions & provides adequate time resolution,
  - More complicated 3 state model does not provide greater time resolution,
  - Is not even valid for conditions at center of GPI emission cloud!
- Can then use simple relation between emission S & plasma parameters: $S = n_0 F(n_e, T_e)$ provided by this model,
  - $\Rightarrow$ can unfold 2-D, time-varying plasma parameters from GPI images if we know n_0,
- 3-D DEGAS 2 simulations give this n_0,
  - Satisfactory agreement with observed emission clouds confirms fidelity of n_0,
  - And of entire model of helium-based GPI diagnostic.

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