Abstract*

The Gas Puff Imaging (GPI) diagnostic operated on NSTX uses a small puff of neutral gas at the edge of the torus to allow plasma fluctuations to be visualized and recorded with a fast camera. We will describe progress made towards validation of the DEGAS 2 neutral transport code against GPI experiments carried out during the 2004 NSTX run campaign. Rigorous geometric calibration of the GPI camera prior to and during these experiments resolved a previously noted misalignment of the simulated and observed clouds†. A discrepancy in the width of the simulated and observed clouds was eliminated once the nonlinear response of the GPI camera was taken into account. The resulting simulation cloud widths and peak locations then agreed to within the error bars associated with the GPI camera's geometric calibration and the Thomson scattering data used to provide the plasma density and temperature.

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

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†D. P. Stotler et al., Contrib. Plasma Phys. **44**, 294 (2004).

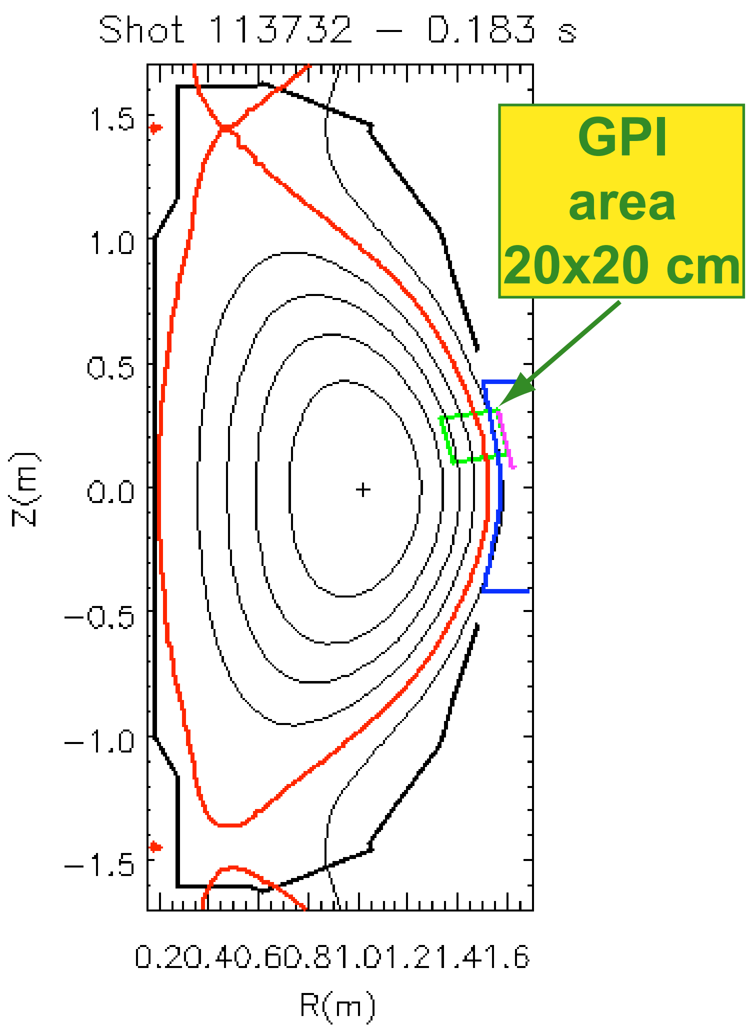
Helium Gas Puff Imaging (GPI) Experiments Provide Excellent Opportunity to Validate DEGAS 2

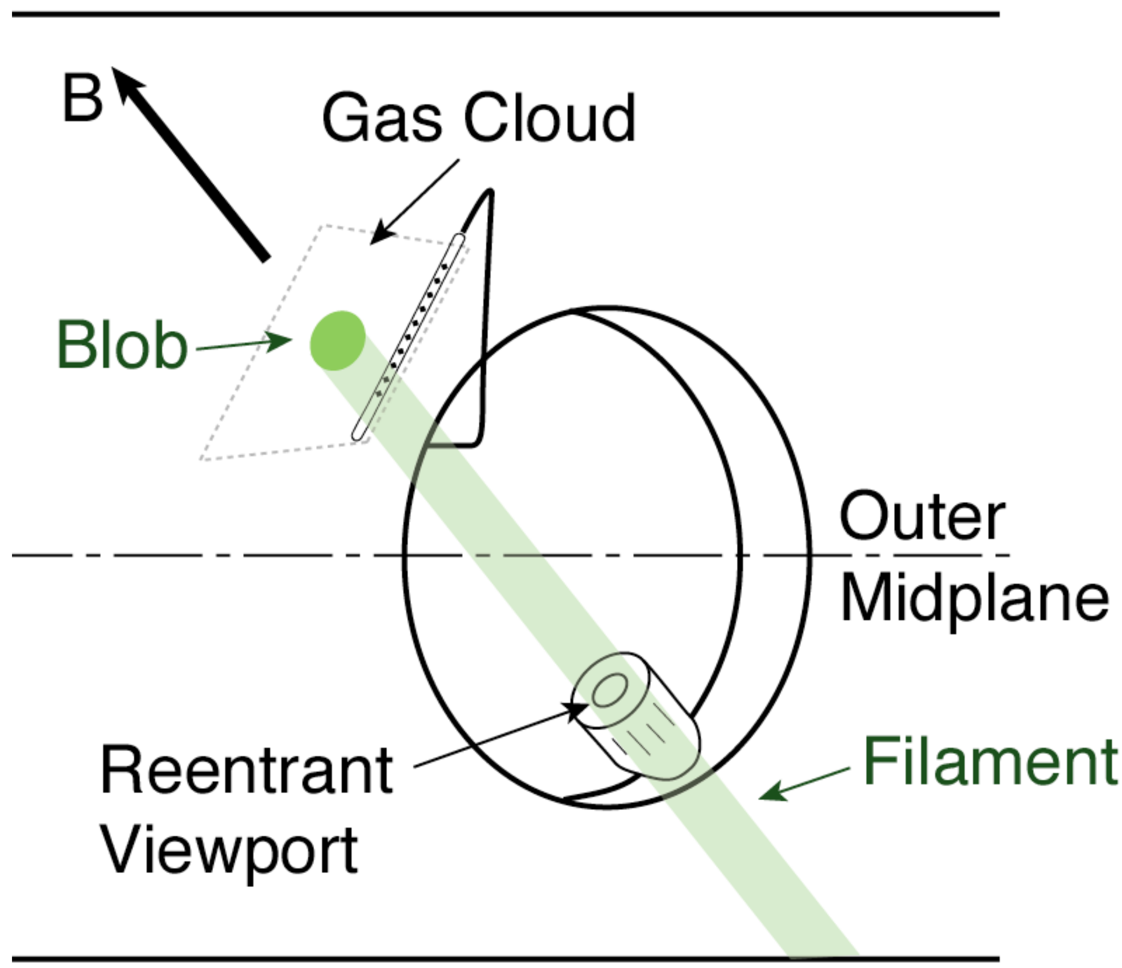
- Simulations require few assumptions, and uncertainties are modest,
- Input to DEGAS 2 well characterized:
  - Plasma data obtained from measurement plus plausible assumption,
  - Neutral source is a gas puff.
- Require only relatively simple physics models:
  - Use of helium puff $\Rightarrow$ atomic physics straightforward,
  - Recycling & plasma-material interactions play no role.
- Will, in effect, also be validating methods used to analyze GPI data.

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

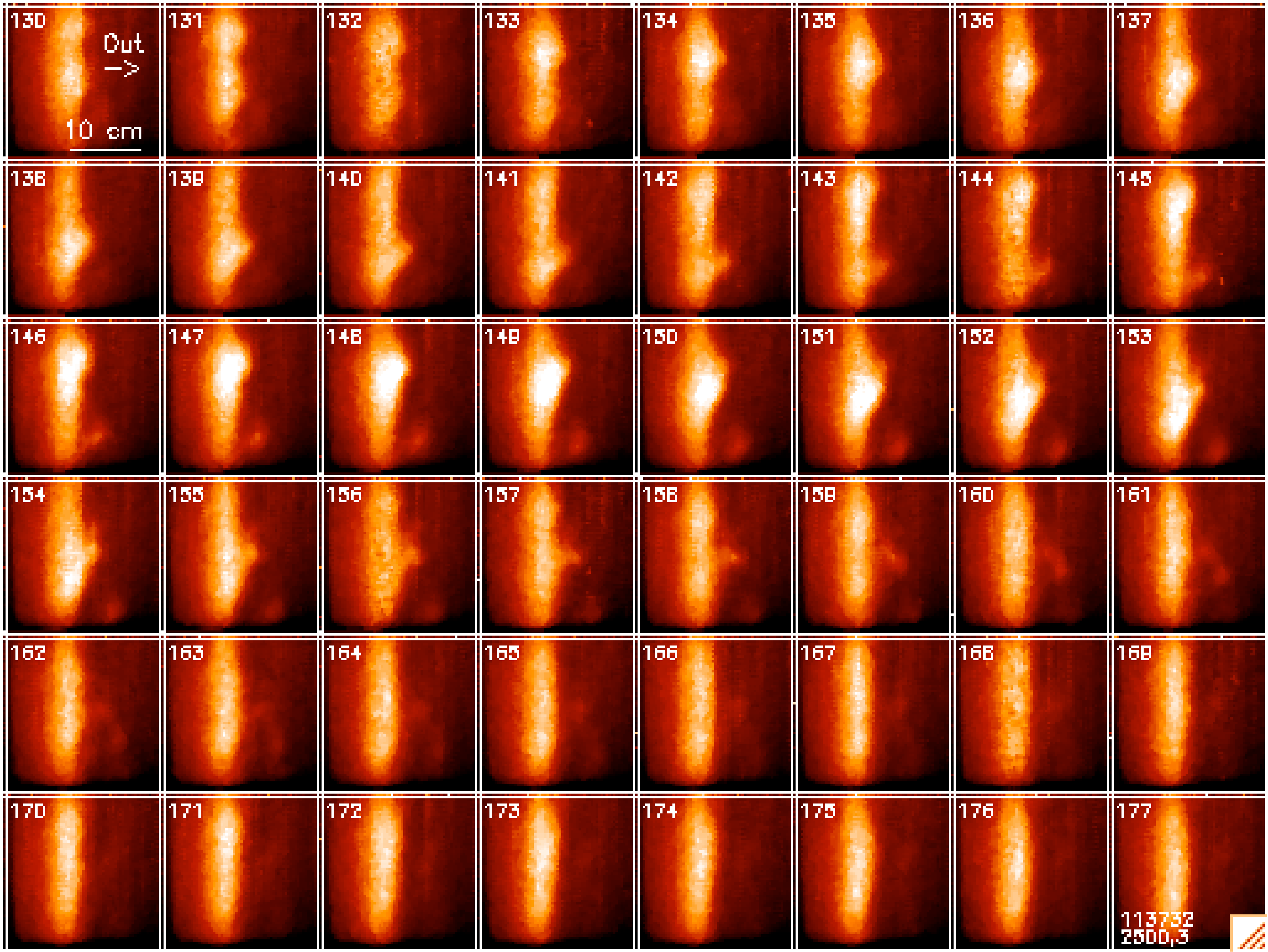
- NSTX GPI He gas puff generated by 30 holes in 30 cm tube $\perp \vec{B}$,
  - $\Rightarrow$ sheet of neutral gas (ideal).
- Camera views 587.6 nm He I line in direction $\perp$ to sheet & $\| \vec{B}$.
- Assumes plasma turbulence extended along $\vec{B}$,
  - Shorter scale lengths $\perp \vec{B}$,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

Gas Puff Imaging Hardware Configuration in NSTX





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



L-mode

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H-mode

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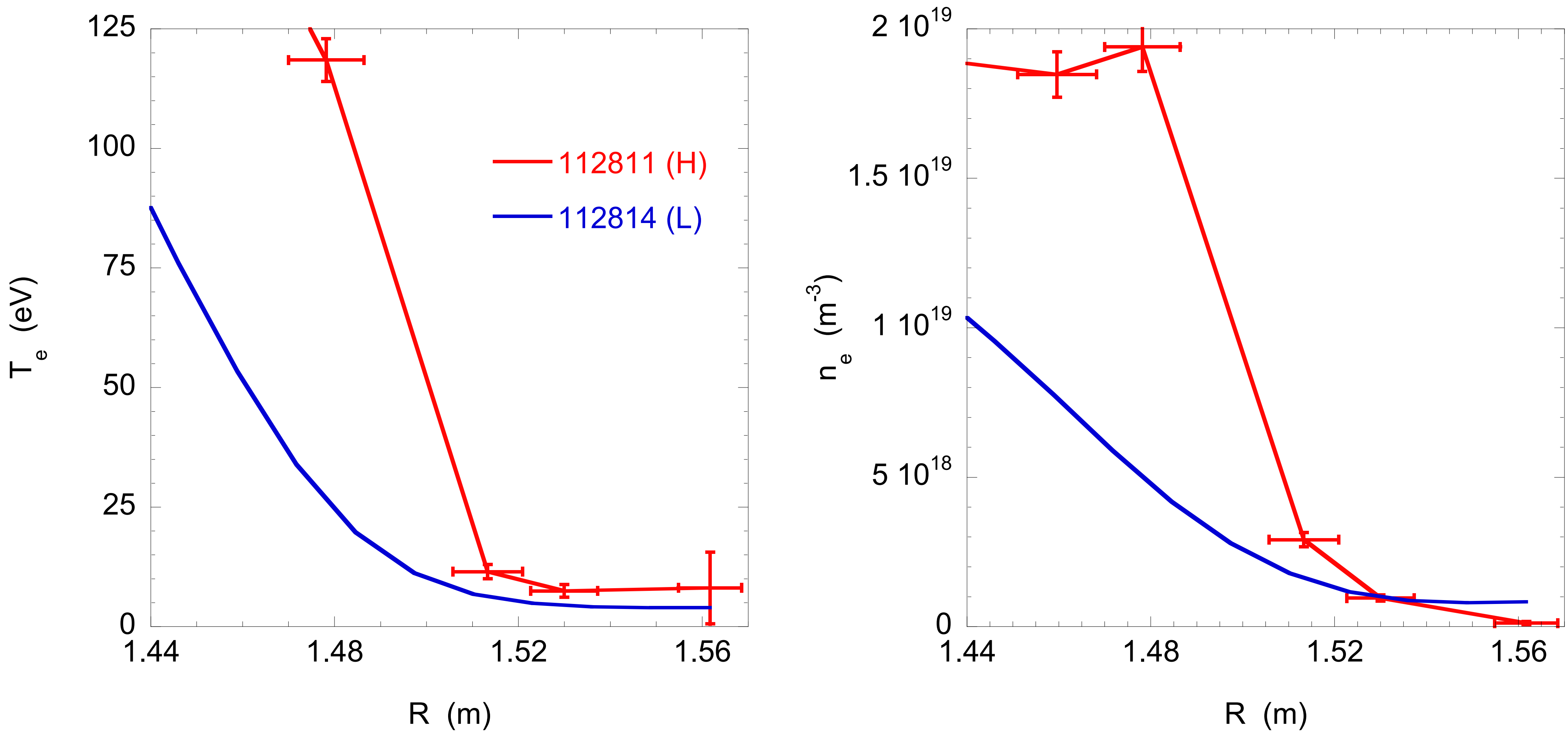
Three-Dimensional DEGAS 2 Simulations of GPI Experiments

- 3-D $n_{\mathrm{He}}(\vec{x})$ result of atoms propagating across SOL,
  - Temporally & spatially averaging over turbulent structures.
  - $\Rightarrow n_{\mathrm{He}}(\vec{x})$ from steady state simulation similar to actual profile.
- Procedure similar to Stotler et al. [Contrib. Plasma Phys. **44** (2004) 294],
- 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 $n_e(R_{\mathrm{mid}})$, $T_e(R_{\mathrm{mid}})$ from Thomson scattering,
  - Assume $n_i = n_e(\psi)$, $T_i = T_e(\psi)$ only.
  - Assume representative of quiescent or “average” plasma conditions.
  - $\Rightarrow$ Choose shots with profiles showing no obvious effects from passing blobs.
- Emulate 64×64 pixel camera view,
  - Record helium 587.6 nm emission.

Edge Thomson Scattering Midplane Profiles for H- & L-Mode Shots

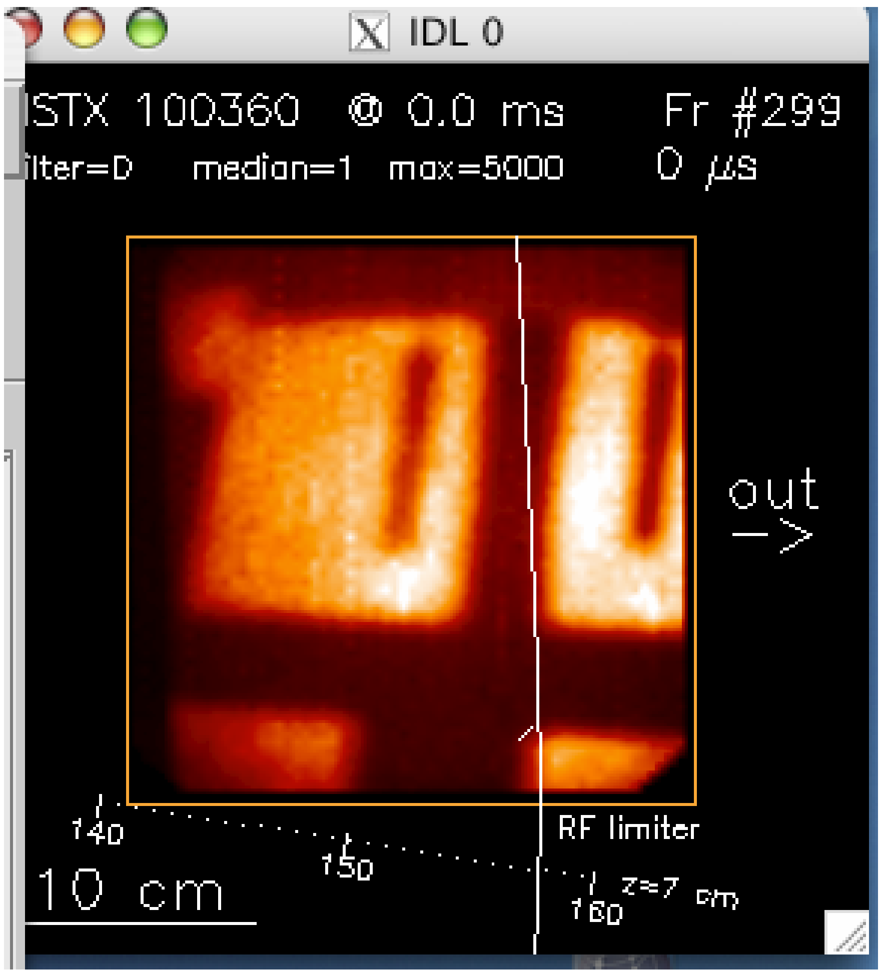


Agreement Improved by Careful Examination of GPI Diagnostic Details

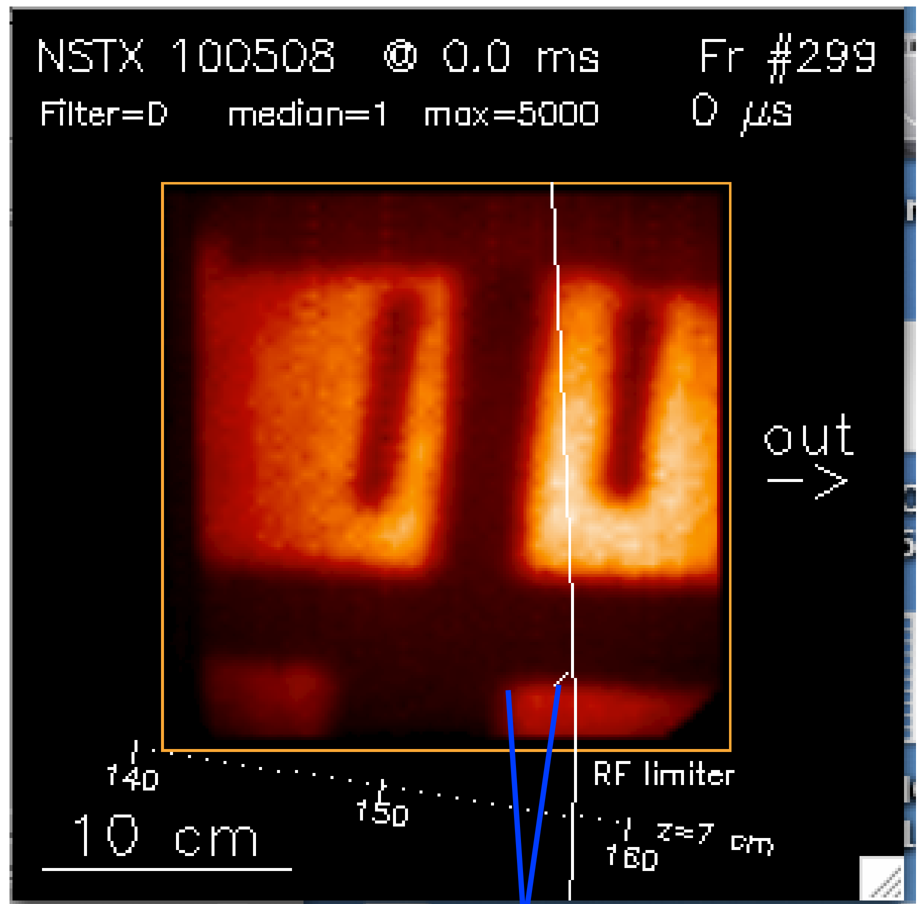
- Calibration of GPI camera geometry,
  - Absolutely calibrated with fixed “target plate” & measuring arm before & after 2004 NSTX run campaign,
    - Uncertainty in these calibrations: ± 1 pixel.
  - Calibrations differ by 6 pixel radial shift due to discrete change in optics,
  - Do not know when shift occurred $\Rightarrow$ not sure which to use.
  - Opt for “pre-run” calibration,
    - “Post-run” puts emission cloud peaks at locations with $T_e = 6 - 8$ eV, $\ll 24.6$ eV ionization energy of He.
    - “Pre-run” calibration shows peaks at $T_e = 15 - 18$ eV,
    - And $T_e \gg 24.6$ eV on inner half of cloud where emission $\rightarrow 0$.

Relative Calibration of GPI Camera Geometry

Before



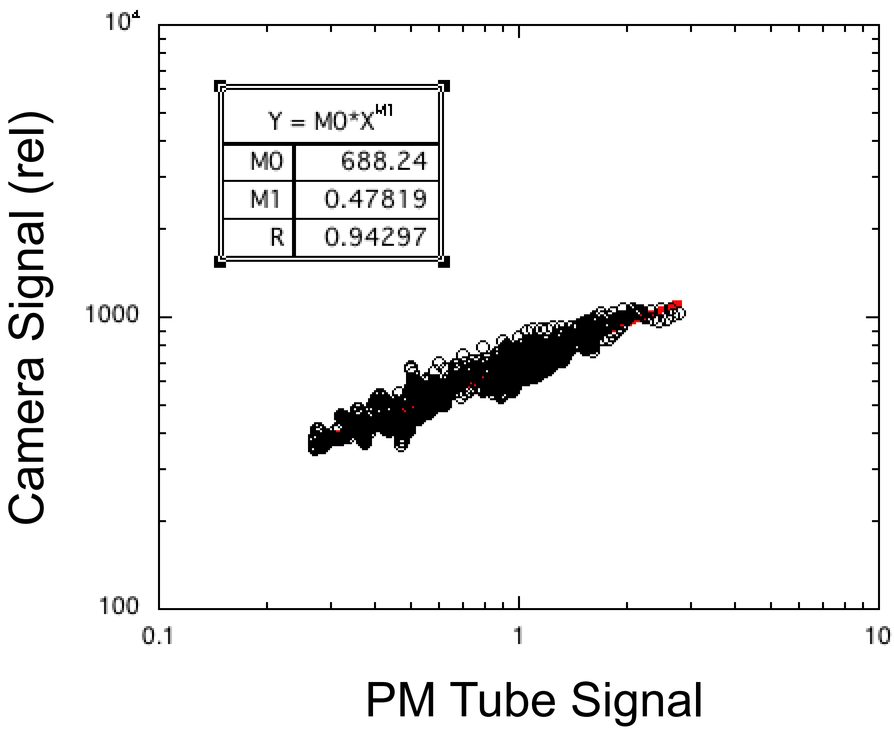
After



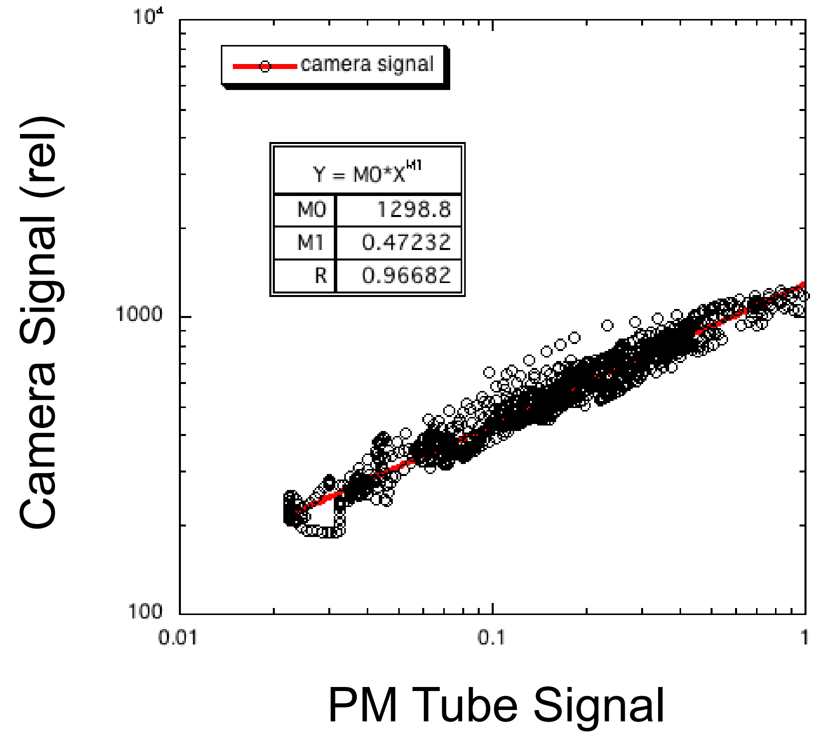
6 pixel shift

Calibrate PSI-5 Camera Nonlinear Response Against Photomultiplier Tube

112811

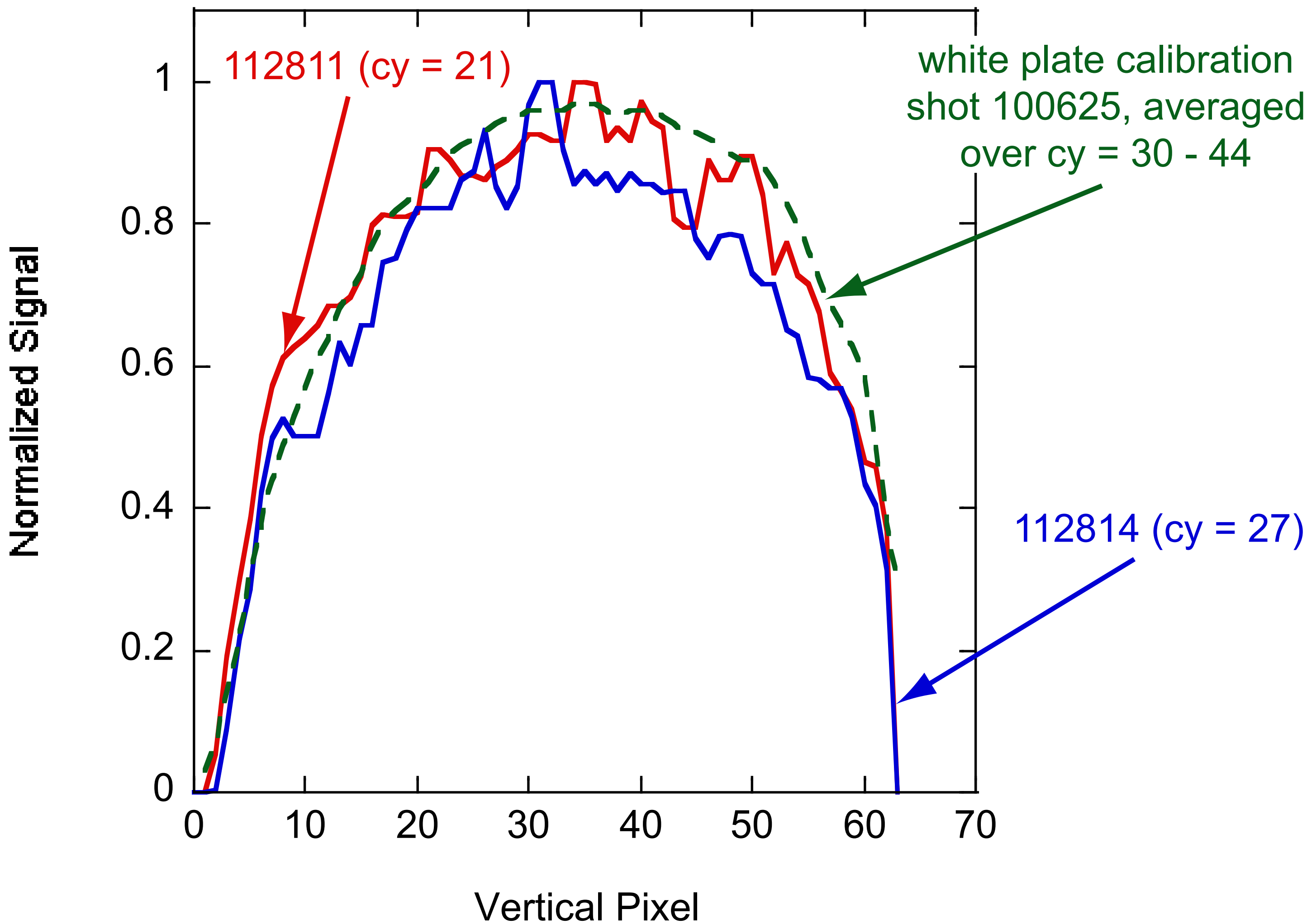


112814



- Apply *inverse* to GPI data to get something $\propto$ photons / (m^2 s st).

Vertical Variation Dominated by Vignetting in Optical System

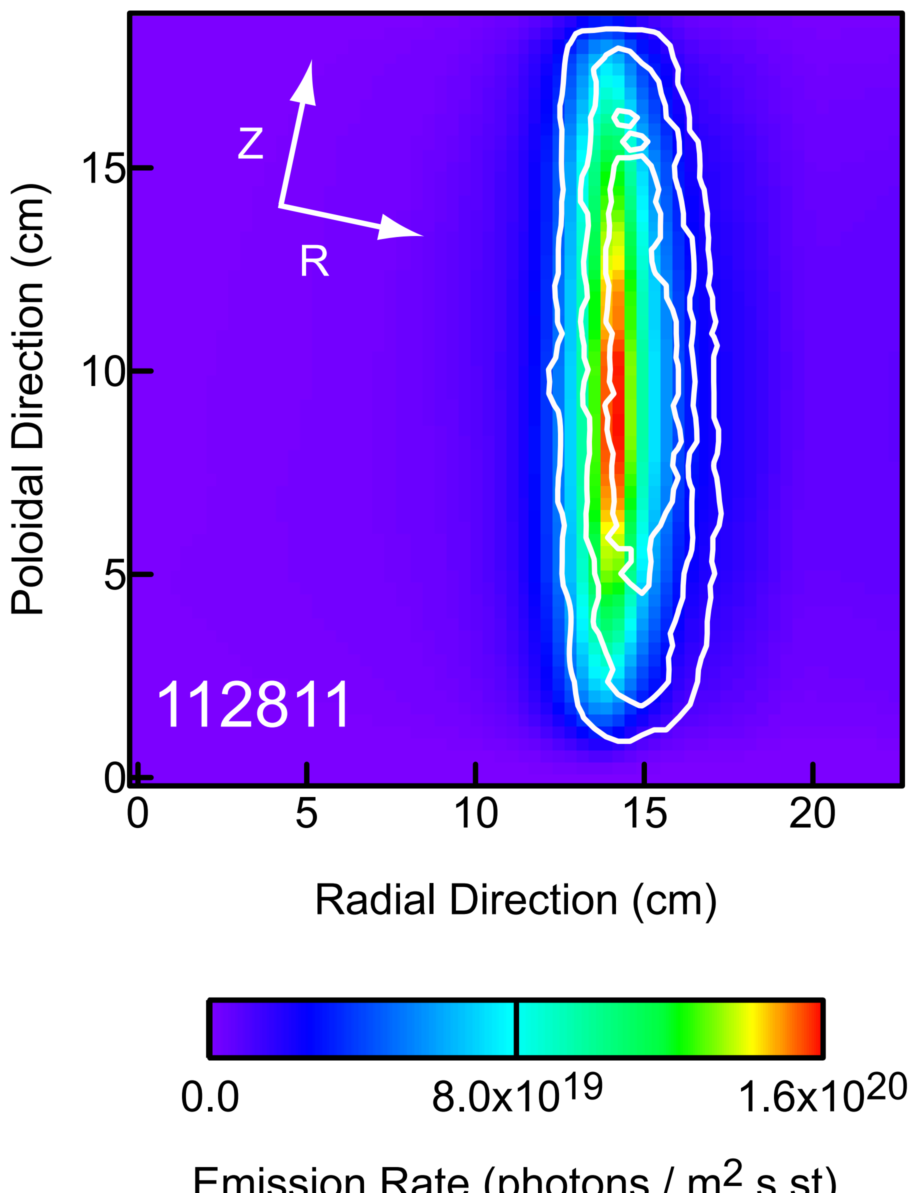


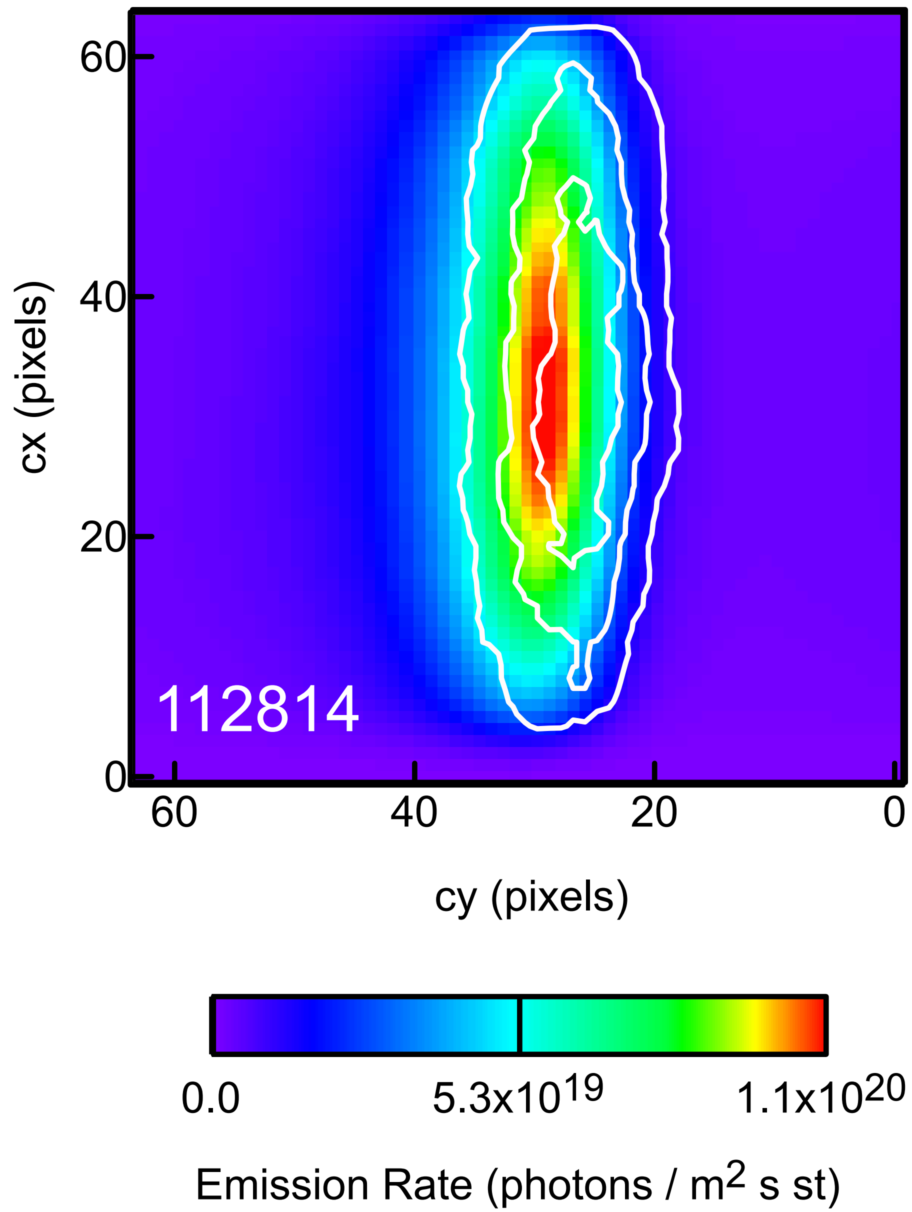
- Vertical variation of “white plate” calibration similar to that of GPI experiments,
- Use to define filter function & apply to simulated camera image.

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





Can We Quantify How Well Simulation & Experiment Agree?

Shot	112811	112814
Simulated Peak	23	29
Observed Peak	21	27
Simulated FWHM	6.2	12
Observed FWHM	9.0	12

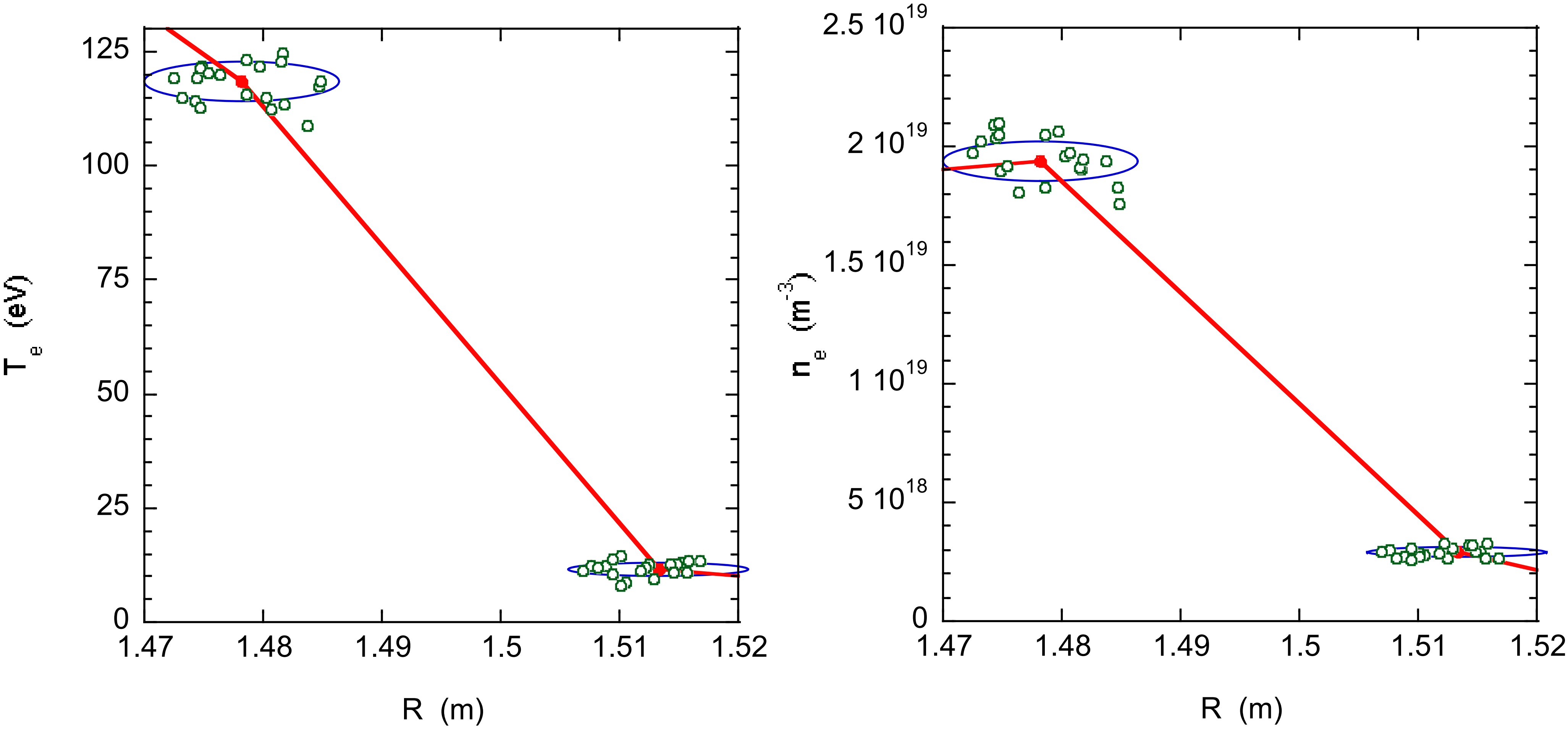
- One pixel corresponds to distance of 0.36 cm at location of emission cloud.
- $\Rightarrow$ looks pretty good, but what are the errors on each quantity?
- Some can be estimated:
  - Geometry calibration: ± 1 pixel (peak location only),
  - Finite size of DEGAS 2 “zones”: < 1 pixel,
  - Plasma profile uncertainties????

Simulation Errors Associated with Thomson Scattering Profiles

- TS error bars on T_e and n_e large enough to affect comparison,
  - $\Rightarrow$ Need to estimate corresponding uncertainty in simulation results.

- Use "ensemble computing"
  [Oberkampf & Trucano, Prog. in Aero. Sci. 38 (2002) 209],
  - Sample ensemble of 20 T_e, n_e profiles,
  - Radial error indicative of sampling volume $\Rightarrow$ use uniform distribution,
  - Parameter errors statistical & independent
    $\Rightarrow$ Gaussian distribution with error bars giving 1σ.

Sample 20 T_e and n_e Profiles Using Thomson Scattering Error Bars



- Do 20 DEGAS 2 simulations analogous to baseline,

- Do "uncertainty quantification of output" [Oberkampf 2002],

  - Get distribution of location & width of emission peak (at cx = 32) during post-processing,

  - Characterize with mean & standard deviation
    $\Rightarrow$ desired estimate of uncertainty.

  - $\Rightarrow$ peak at $\mathrm{cy} = 23 \pm 1$ pixel,

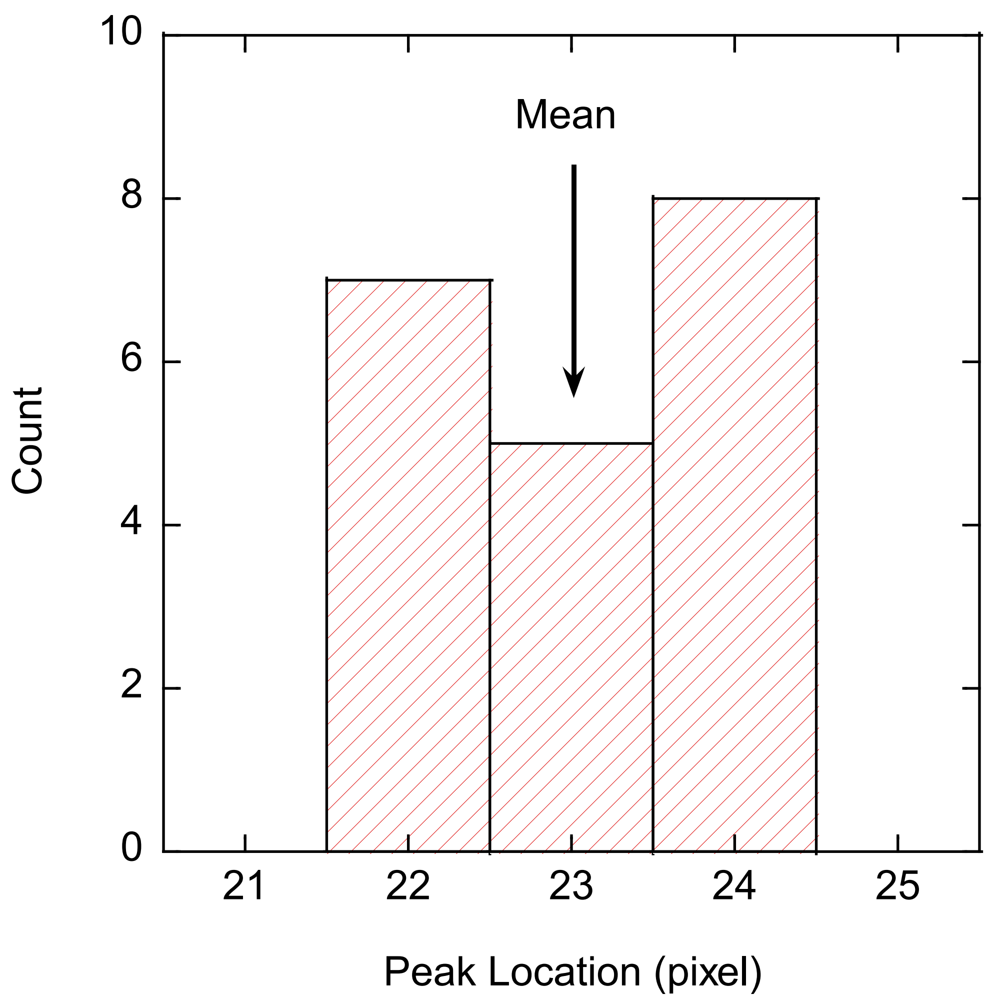
  - FWHM = 6.5 pixels ± 1 pixel.

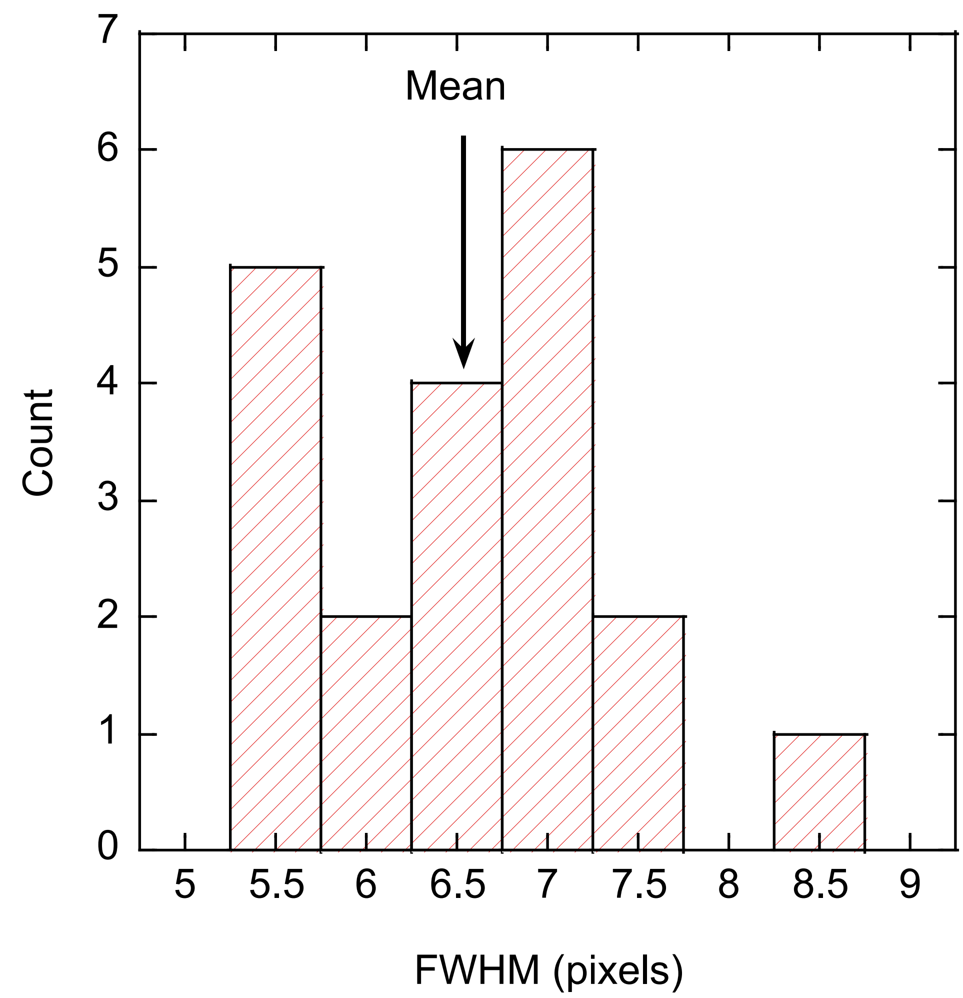
- Hard to quantify uncertainties:

  - Effect of passing blobs on T_e & n_e profiles,

  - Remnant impact of blobs on average GPI camera image.

Distribution of Simulated Emission Peak & FWHM with 20 Sampled T_e & n_e Profiles





Does This Constitute Validation?

- We can make qualitative statements:
  - Simulation & experiment agree, given uncertainties,
  - Or, difficult to do much better.
- But, validation should be quantitative [Oberkampf 2002].
- Because *really* want to ask: can we use code / model to predict outcome of experiment XYZ?
  - Conditions of XYZ presumably fall outside range of existing (validation) experiments $\Rightarrow$ no guarantees, only inferences!
- Bigger validation database $\Rightarrow$ greater confidence in making predictions,
- Moreover, not all validation exercises of equal value!

Can We Start Thinking About Validation Metrics?

- E.g., metric should increase with level of agreement,
- And with size of experimental dataset.
- Not so easy, though. Example [Oberkampf 2002]:

$$V = 1 - \frac{1}{L}\int_0^L \tanh\left[\left|\frac{y(x) - \bar{Y}(x)}{\bar{Y}(x)}\right| + \int_{-\infty}^{\infty} \frac{s(x)}{\sqrt{N}}\left|\frac{z}{\bar{Y}}\right| f(z)\,dz\right] dx.$$

- Analogy: do high performance computer users just say "my code runs well on computer ABC"?
  - No! Will quantify scaling or fraction of peak performance,
  - And repeat for various machines.

Future Possibilities

- Use absolute calibrations for GPI camera & gas source
  $\Rightarrow$ Compare absolute photon emission rates.

- D_2 puff experiments,

  - Dissociation of D_2 & D_2^+ also give D_α photons
    $\Rightarrow$ test DEGAS 2's treatment of those processes.

- Shot with probe and Thomson scattering data
  $\Rightarrow$ higher resolution $T_e(R)$, $n_e(R)$.

- Parameter scan experiments $\Rightarrow$ unlikely to reproduce observed trends with "fortuitous agreement".

- Repeated shot,

  - Decrease uncertainty in code inputs,

  - *May* permit reduction of effect of blobs on comparison.