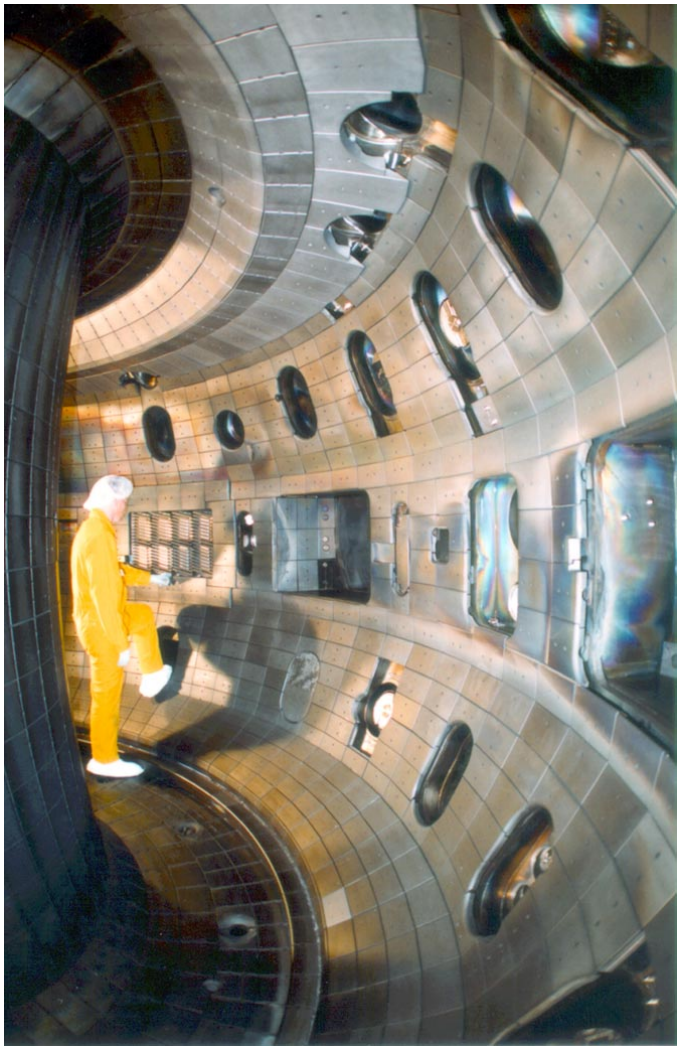

Poloidal Profile of CIV Emission in the DIII-D Divertor During PDD Operation

N. Jalufka, Q. Boney (Hampton University)

M.E. Fenstermacher (LLNL), W.H. Meyer (LLNL), A.W. Leonard (GA), G.D. Porter (LLNL) and the DIII-D Divertor Team

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Hampton University

Background

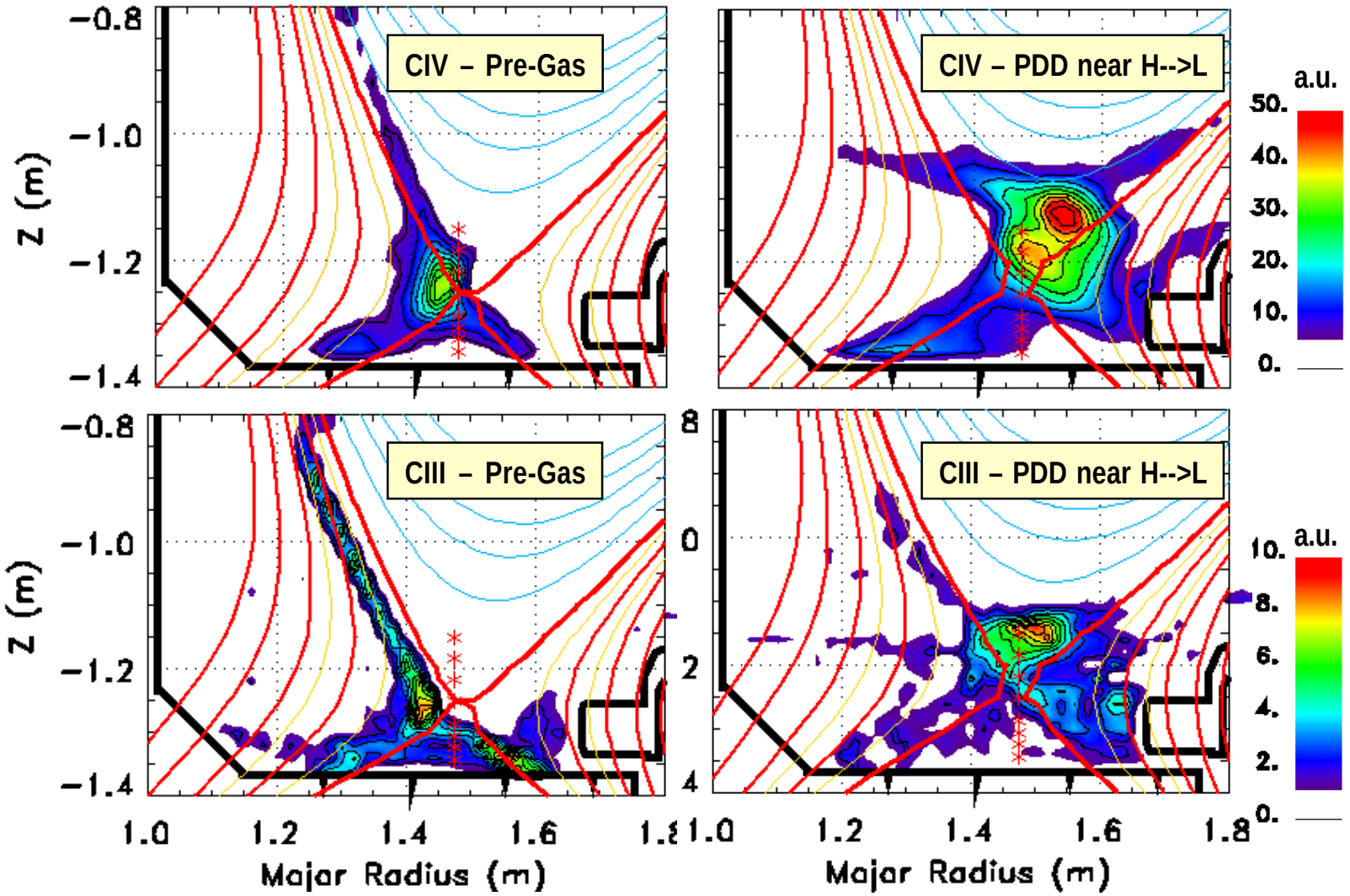
- The VUV-TTV[1] has been used to study the spatial distribution of CIV emission in the divertor region of DIII-D during Partially Detached Divertor (PDD) operation. This device records images of the 155nm radiation from the CIV ion using a tangential view. The 3-D images are then inverted assuming toroidal symmetry to produce 2-D profiles in a poloidal plane. The CIV emission in H-mode before gas injection appears in a localized zone in the inner SOL at the height of the X–point. It then moves to the outer SOL above the X–point during PDD. Finally, near the H—L density limit, the radiation moves into the closed flux region above the X–point. The radiation during high density operation is concentrated in a single peak which is fairly stable in time for most discharges. For some discharges however, a double peak is observed near the X–point. These profiles of CIV radiated power will be compared to reconstructions of the total radiated power from bolometers. Evolution of the 2–D profiles throughout the discharge will be compared with time histories of relevant discharge parameters.

  - *Work supported by U.S. DOE Grant DE-FG02-97ER54451 and Contractss DE-AC03-89ER51114 and W-7405-ENG-48.

  - D.G. Nilson, et al., Rev. Sci. Instrum., 70, 1999, pp.738-741.

Summary of Results

2D profile of high radiated power VUV CIV emission measured for the first time on any tokamak; visible CIII profile is similar.



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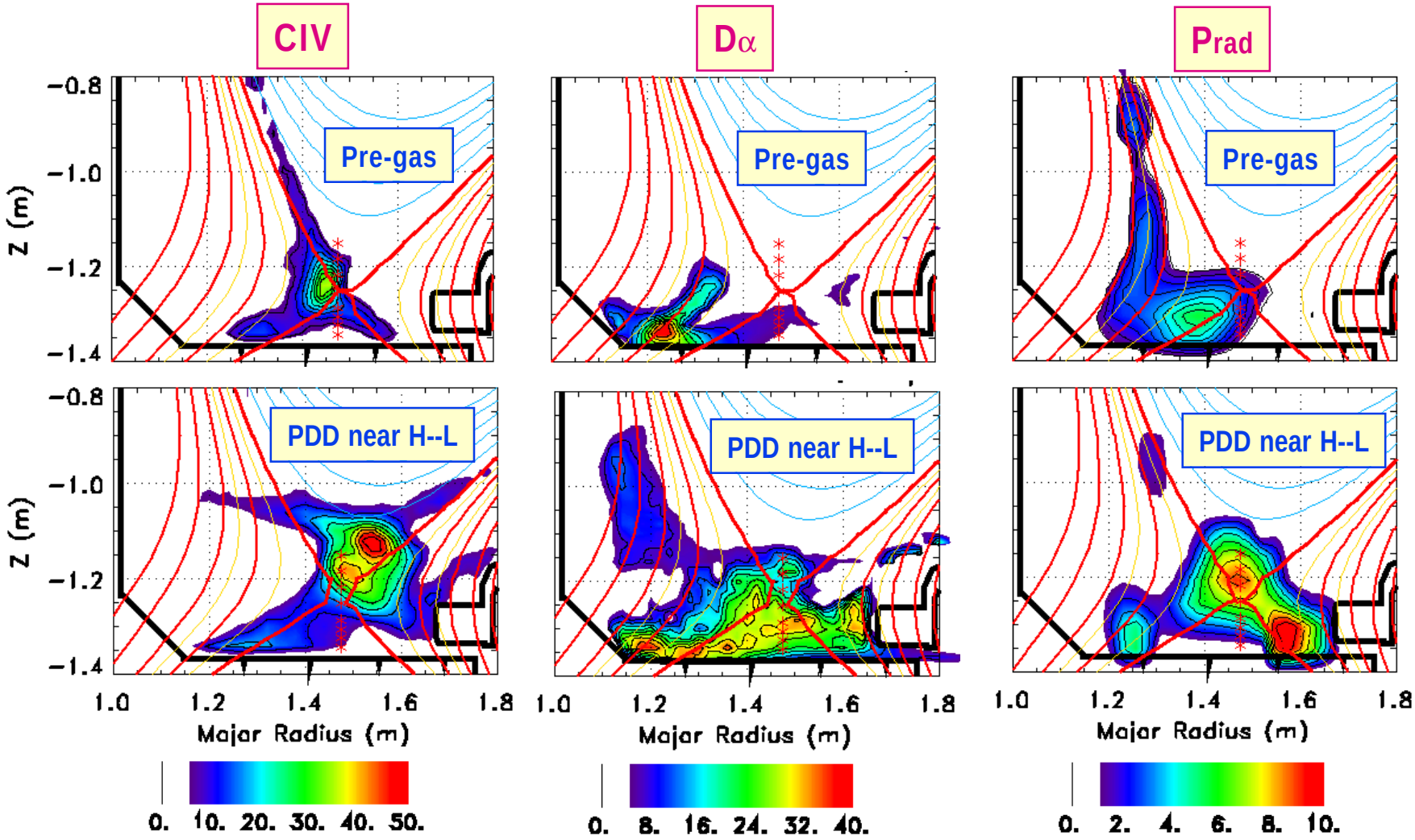
Spatial profiles of CIV plus deuterium radiation zones consistent with profile of total radiated power from bolometer reconstructions.



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Calibrated 2D profiles of divertor CIV emission provide important information for benchmarking computer models of carbon transport.

- VUV camera system has obtained the only images of CIV emission from a tokamak divertor.
  - MgF2 refractive and metalic reflective elements plus P1 phosphor and CID camera
  - 2D poloidal profiles reconstructed from tangential 3D data.
- 2D VUV CIV images were calibrated against Div. SPRED data. Quantitative comparison with UEDGE simulations is in progress.
- Poloidal profile of VUV CIV (main carbon radiated power) similar to visible CIII profile in the DIII-D divertor.
- Spatial profile of CIV plus deuterium radiation zones consistent with bolometer Prad.
- Locations of radiation peaks from CIV, CIII, Dα are consistent with Te and ne profiles measured with divertor Thomson scattering.
  - CIV appears where Te ~ 8 - 11 eV, CIII appears where Te ~ 5 - 8 eV consistent with SPRED spectrometer measurements.
  - Dα appears close to divertor targets (Te <~ 1 - 5 eV),

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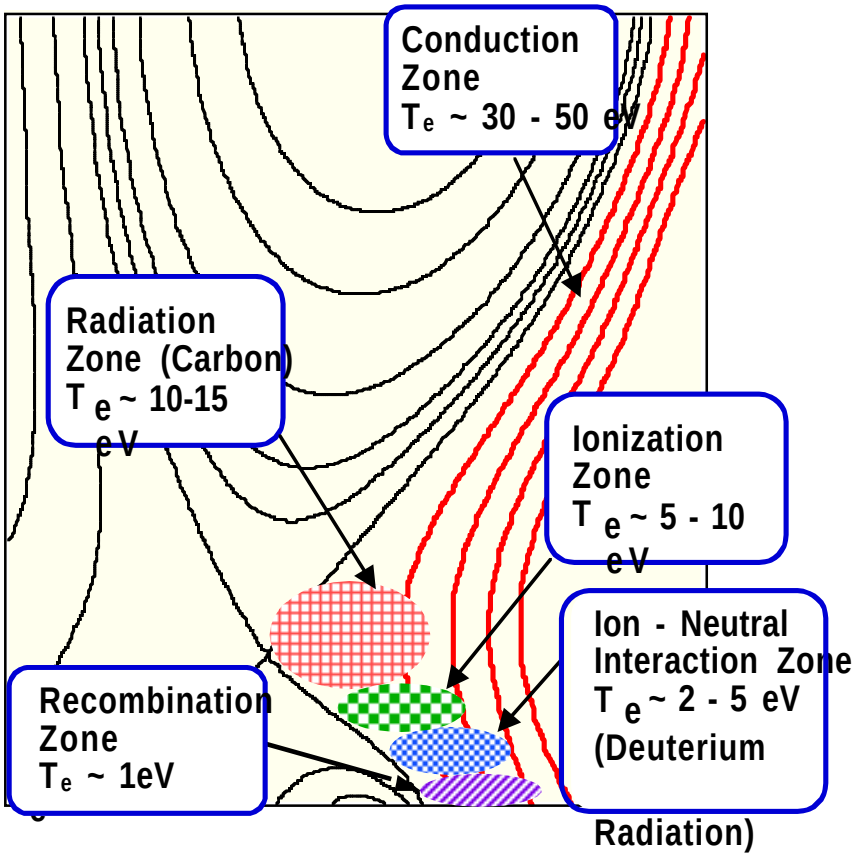
Motivation

Radiation, ion-neutral interactions and recombination at different locations in outer leg contribute to heat and particle flux reduction.

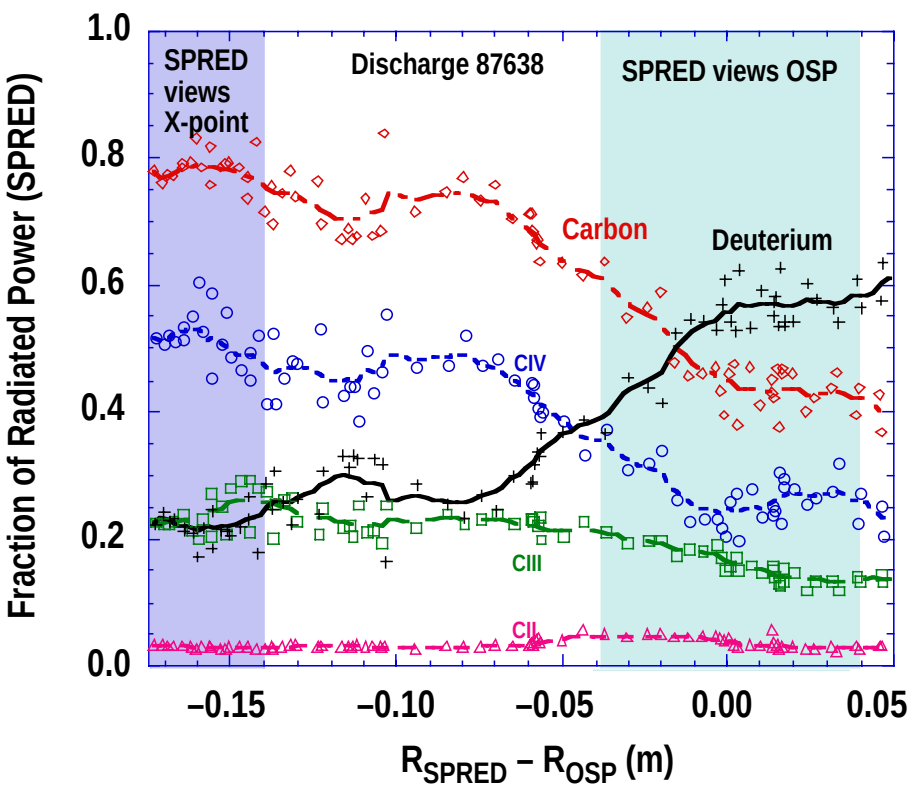
- Carbon radiation near the X-point lowers SOL temperature.
- Neutral ionization in Te = 5 - 10 eV zone produces poloidal flow.
- Ion-neutral interactions remove parallel momentum by cross field neutral transport.
- Cold, dense, slowly flowing plasma recombines before striking target surfaces.

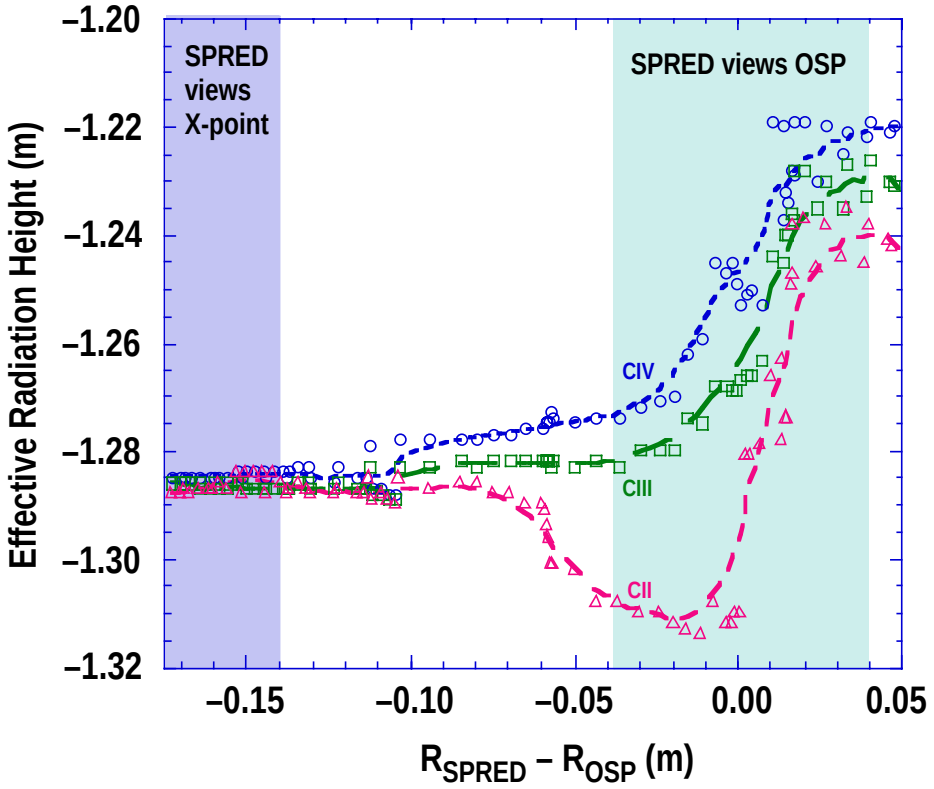


CIV is the dominant radiator in the DIII-D PDD near the X–point; deuterium dominates near the outer strike point.

R.D.Wood
APS97

- CIV dominates divertor SPRED line integrated spectrum near X–point.
- Temperatures from spectrum and divertor Thomson Te vertical profile imply CIV emission within 1 cm of CIII emission





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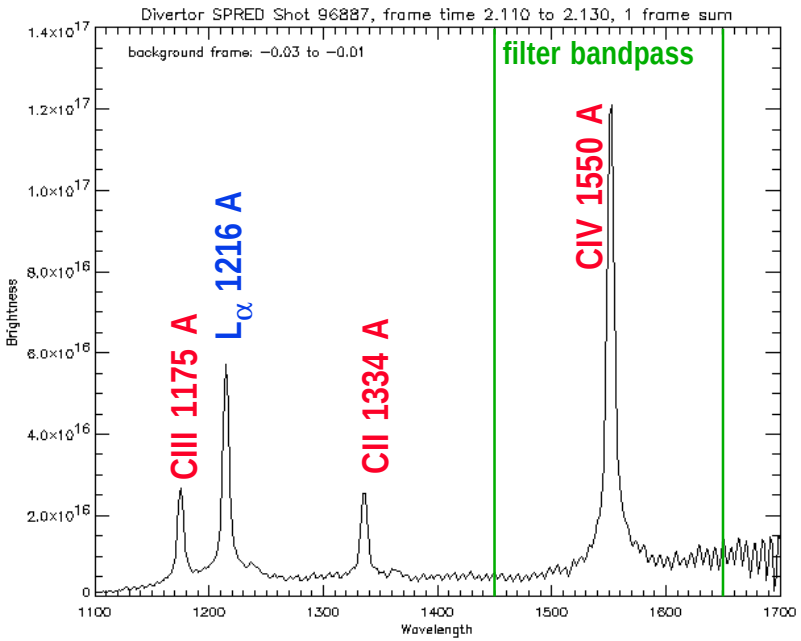
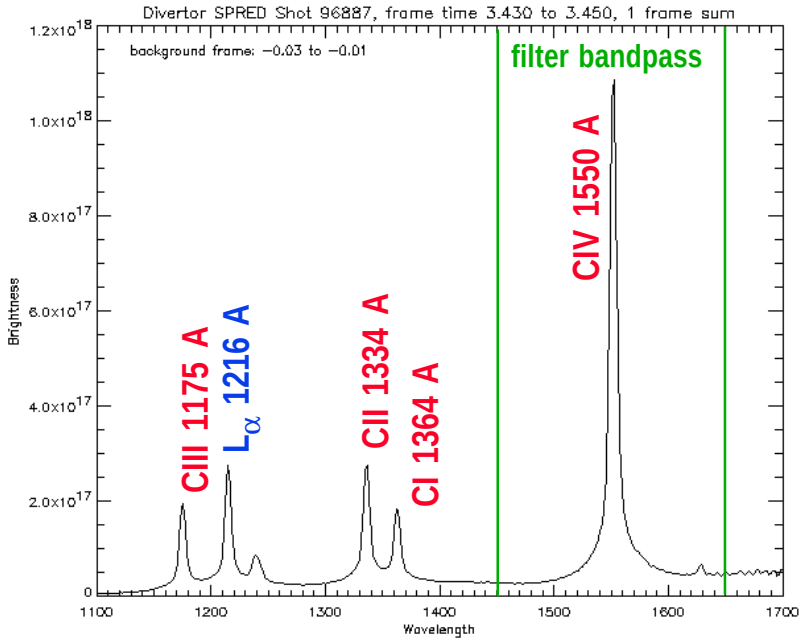
Divertor SPRED confirms that 155 nm CIV emission line is isolated from other strong emission lines.

- VUV TTV wavelength filter has +- 100 A bandpass. CIV emission at 1550 A is isolated within 1450 - 1650 bandpass.

Pre-Puff H-mode phase



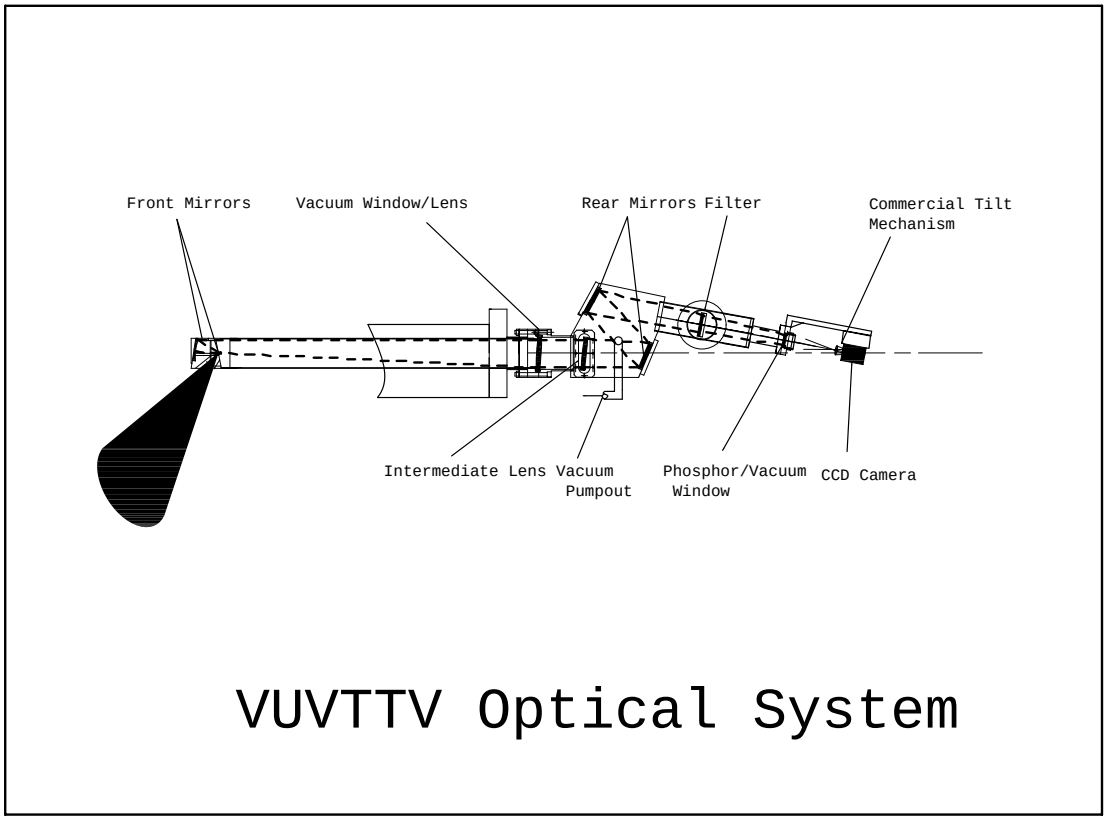
PDD Phase



Diagnostic Description

VUV TTV optical system is a catadioptric design with a inverse Cassegrain form.

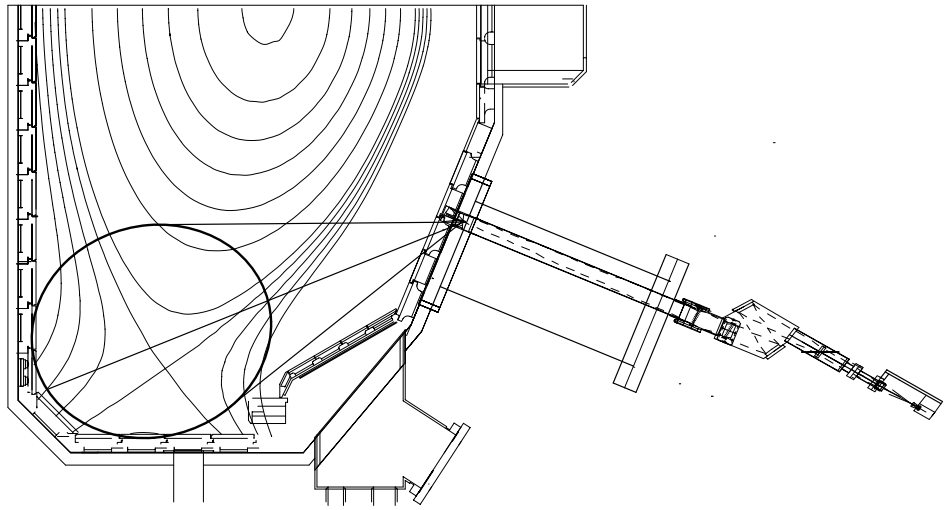
- Three mirror WALRUS configuration (Wide Angle Large Reflective Unobscured System)
  - Entrance mirror is aperature stop (4.5 mm)
  - Magnification = .023, f/8.9
- Vacuum window is MgF2 lens
- Secondary chamber pumped during operation.
- Image formed on P1 phosphor.
- Image plane fixed by lens in secondary (MgF2 or Bk7 for alignment).



VUVTTV Optical System

VUV TTV system installed in a radial port above the height of the X-point with a view of the entire divertor.

- Approximately 90 degrees of toroidal angle are viewed
- Large depth of field ~ 2 - 3 m



Vacuum Ultraviolet Tangential TV

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Discharge Description

All discharges in this paper obtained a PDD phase by deuterium injection into the SOL of an ELMing H-mode plasma.

- Common shot characteristics:
  - Lower single null configuration
  - I_p = 1.68 MA, B_T = 2.1 T, κ = 1.89, δ = 0.37, q_{95} = 3.2, P_{inj} = 8.4 MW
  - Deuterium gas injection rate = 18 Pa m^3/s (135 Tl / s)
  - Reduction in peak heat flux = Factor of 4
- Divertor SPRED shows CIV radiation at 155 nm dominates carbon radiated power near the X-point during PDD.
- Divertor Thomson scattering shows a steep Te gradient in the region of maximum CIV radiation. Te is in the range 3 - 40 eV
- Simultaneous VUV and visible emission data obtained at 17 ms framing rate, animations available for:
  - CIV - 155 nm VUV
  - CIII - 465 nm visible
  - Dα - 656 nm visible

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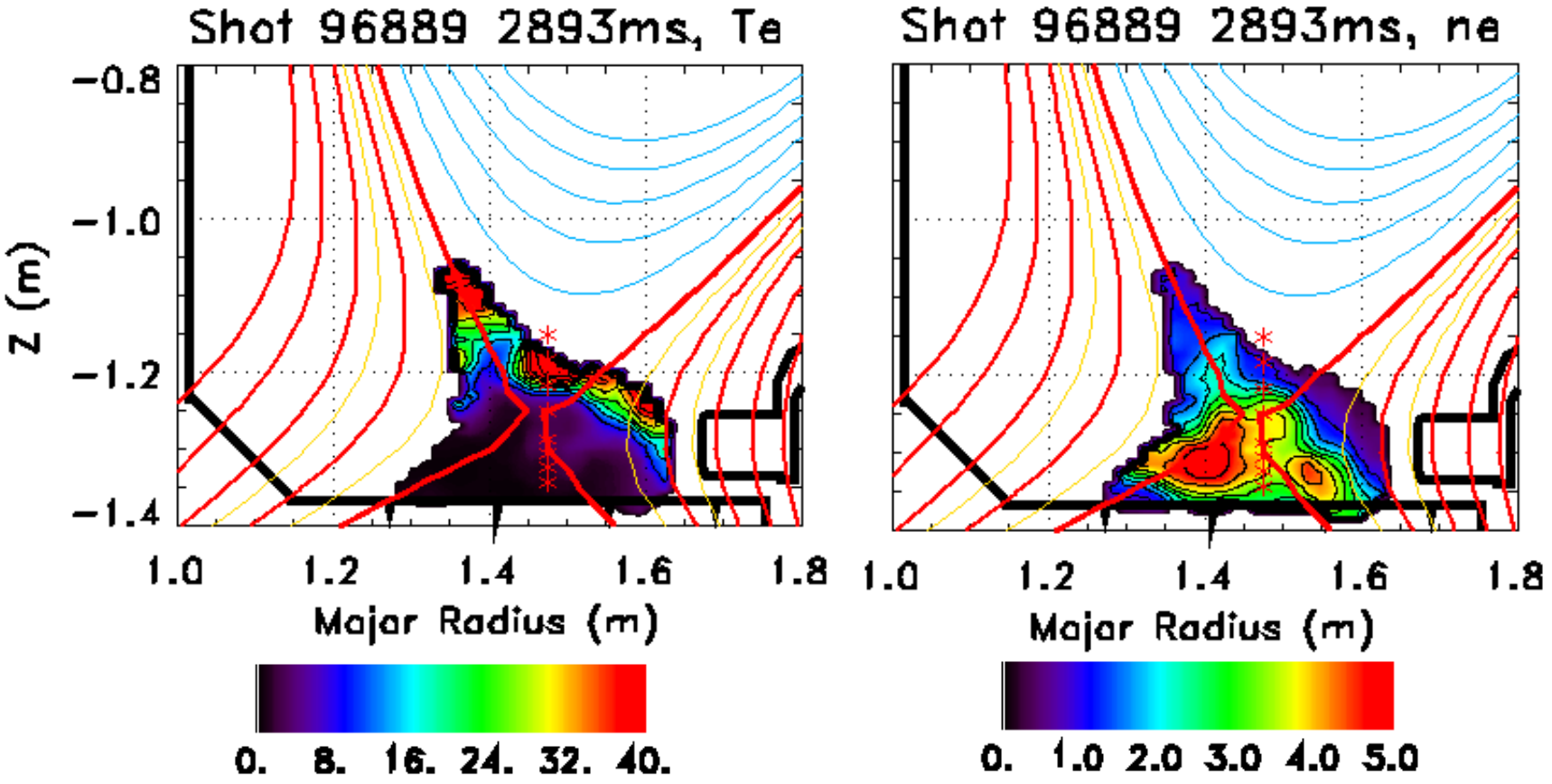
Time histories of discharge parameters show changes due to deuterium gas injection.

Time Histories of divertor parameters show evolution of detachment.

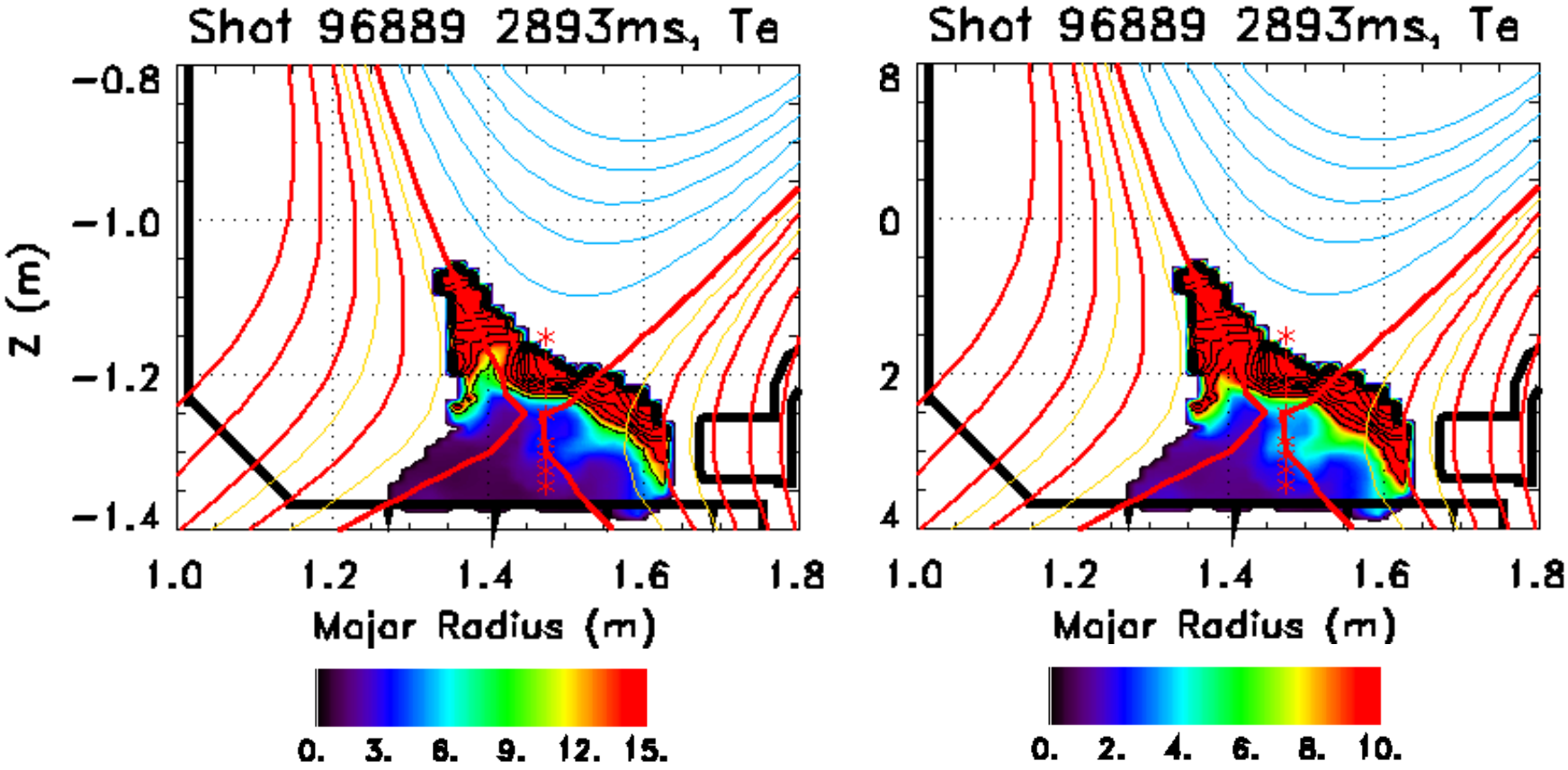
Reconstructions of T_e and n_e profiles during PDD from Divertor Thomson Scattering show steep gradients near the X–point.

- DTS data from PDD phase of a shot with radial divertor sweep is remapped onto equilibrium of shots with CIV image data.



Reconstructions of T_e profiles during PDD from Divertor Thomson Scattering show steep gradients near the X–point.

- DTS data from PDD phase of a shot with radial divertor sweep is remapped onto equilibrium of shots with CIV image data.



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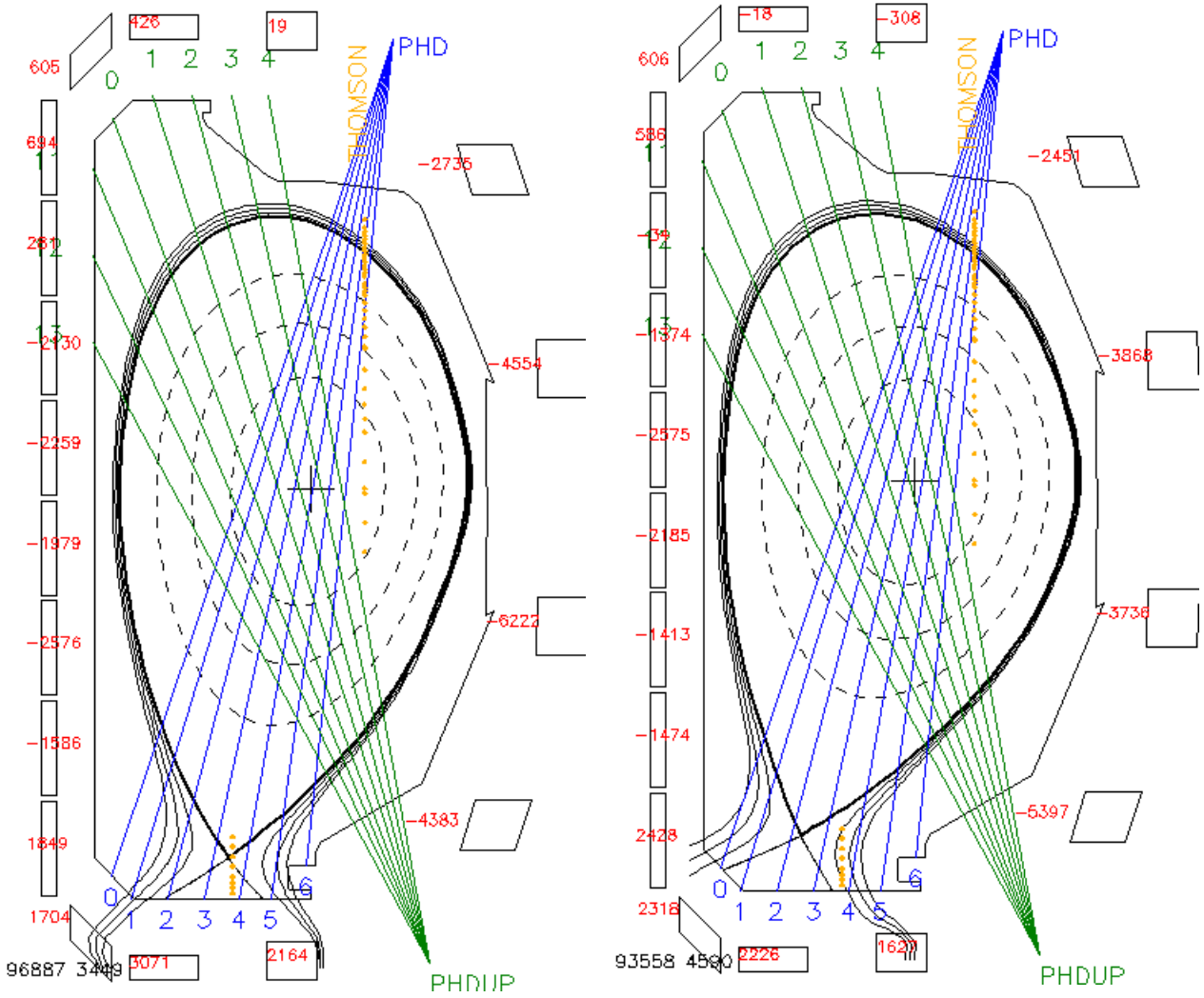
EFIT equilibrium reconstructions for the two discharge shapes in this paper show LSN configurations with varying triangularity.

- VUV CIV data is compared with visible CIII and Da in shot 96887.
- Da due to recombination and due to ionization is calculated for shot 93558.



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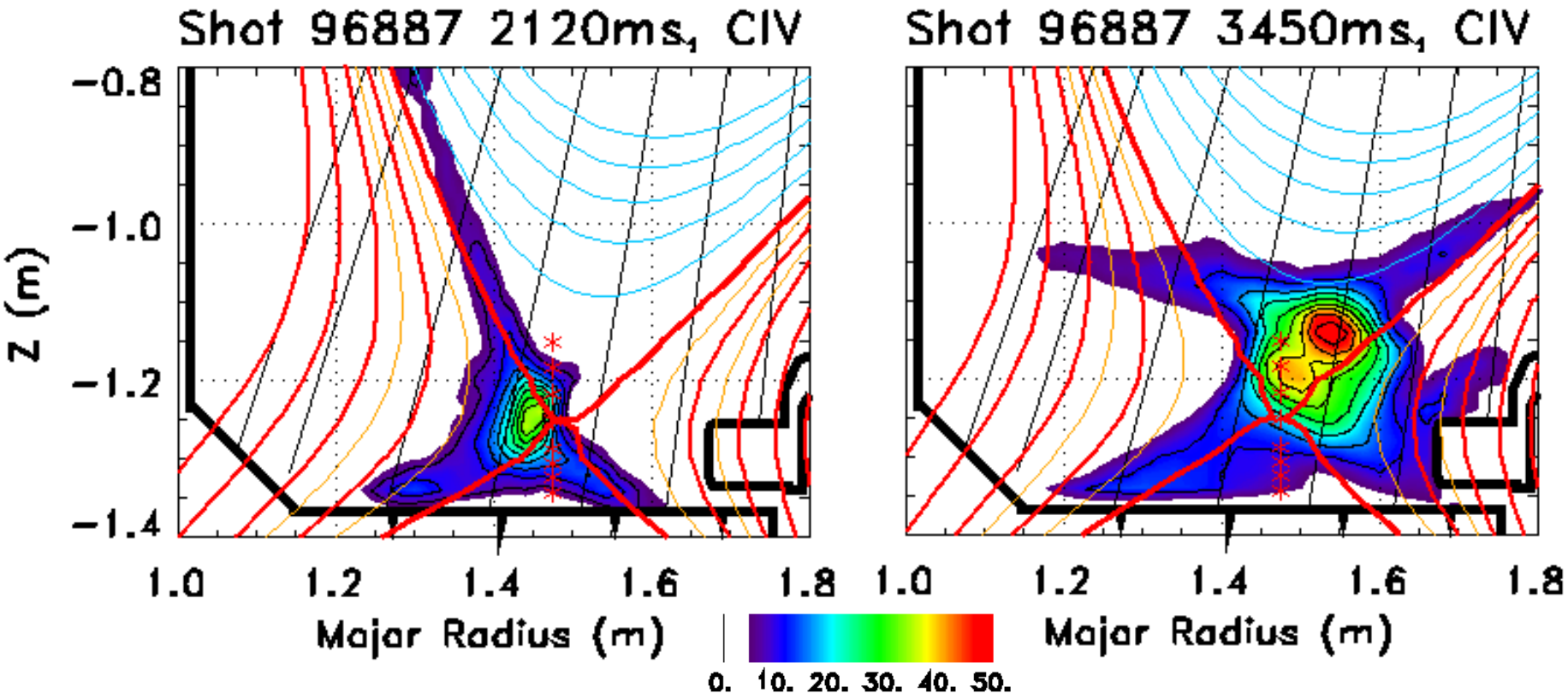
Comparison of Profiles

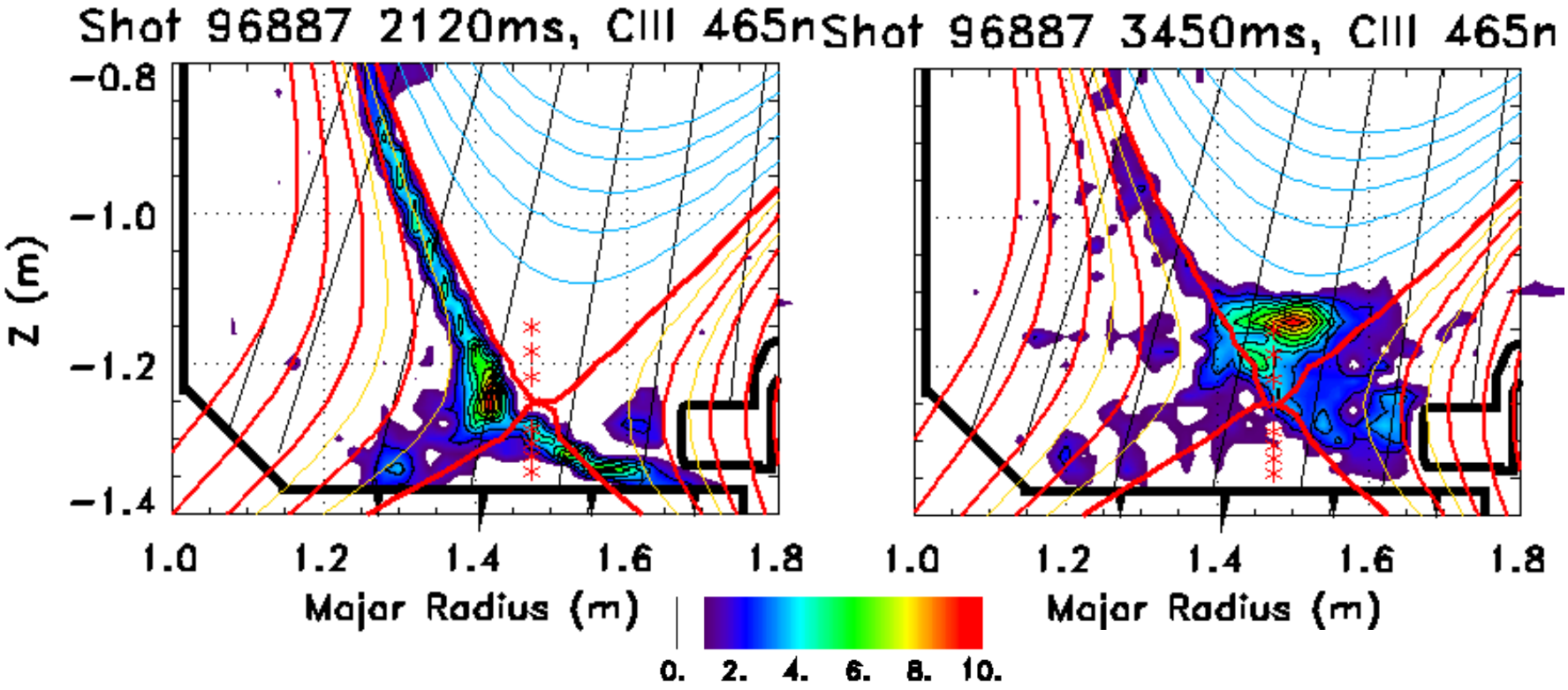
VUV CIV shows shift from pre-gas peak in inner SOL at X–point height to inside LCFS above X–point near H--L density limit.

- Animations show intermediate phases of PDD operation with CIV peaked in outer SOL along outer leg or localized at the X–point height.



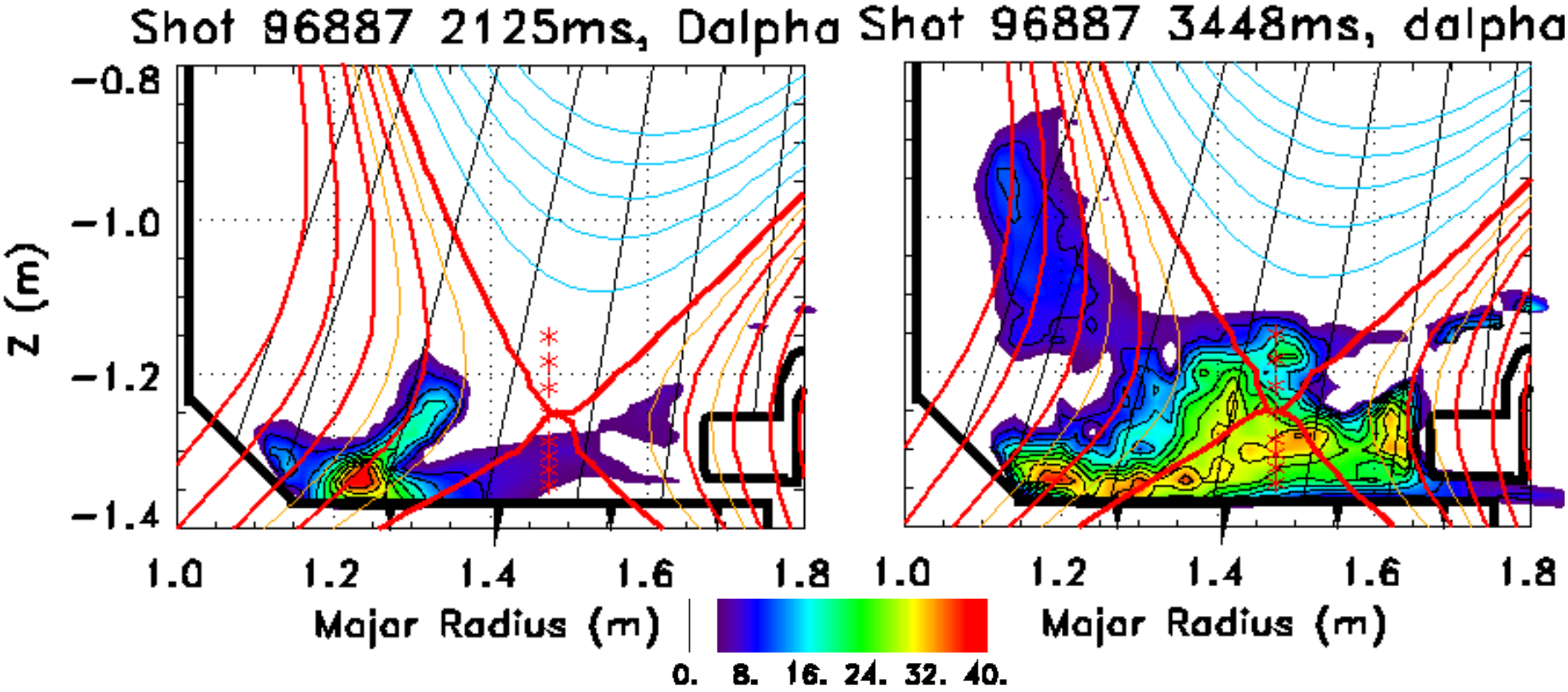
Visible CIII reconstructions show emission profiles which are similar to those from VUV CIV.

- CIII emission peaks occur in regions of slightly lower Te than the corresponding peaks from CIV.



Deuterium emission contributes to total Prad near the target regions and, during PDD, in the private flux region.

- Animations show rapid transition from inner target emission to distributed emission throughout divertor legs and PF region when transition to PDD occurs (about 200 ms after gas injection).



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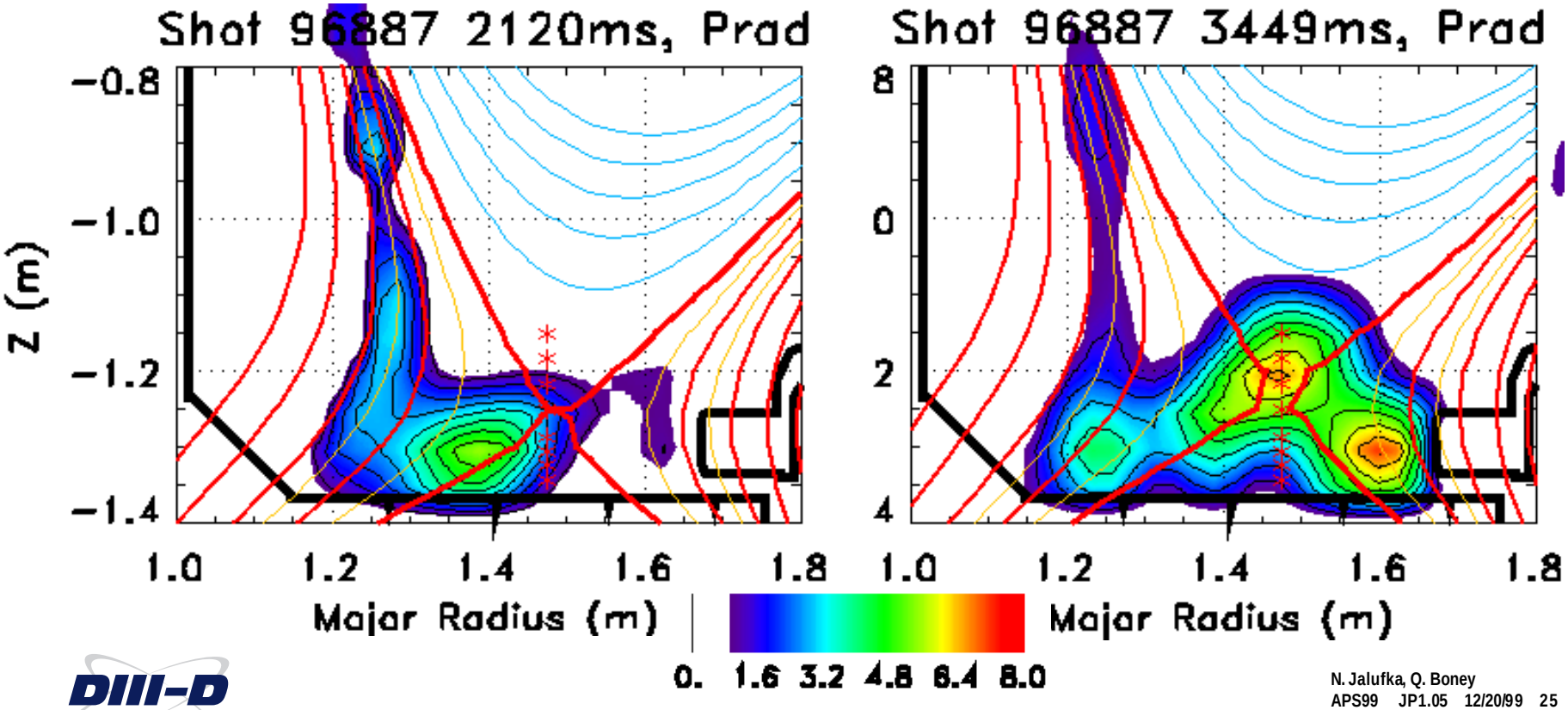
Reconstruction profiles of Prad from bolometers show contributions corresponding to peaks in CIV and D_α emission.

- Pre-gas Prad is combination of Da near ISP and CIV in inner SOL near X-point smoothed because bolometer inner leg chords are sparse for this divertor geometry.
- PDD Prad near H–L transition shows maximum inside X-point from carbon and local maxima at strikepoints from deuterium.



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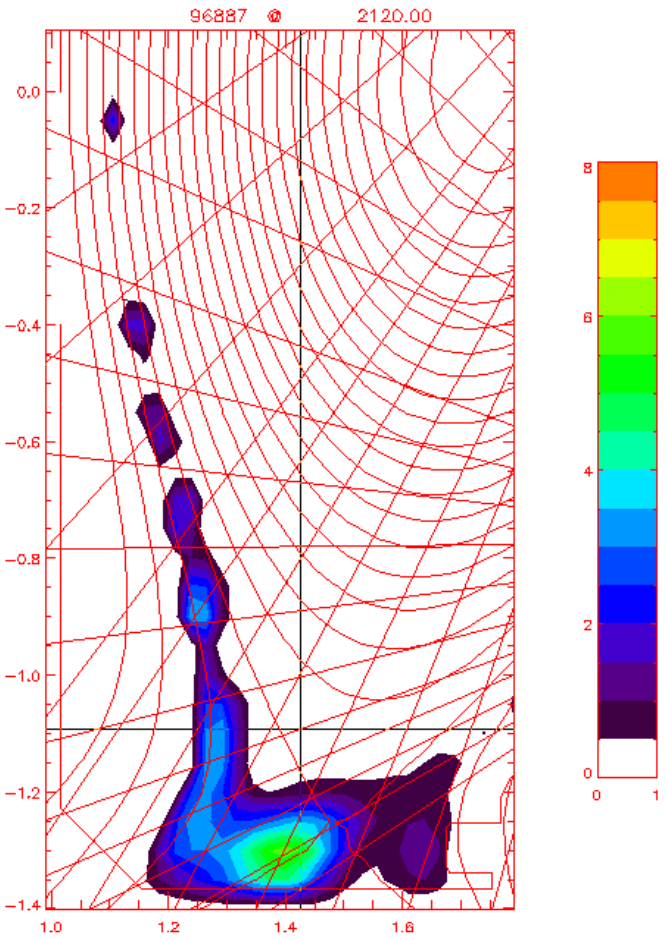
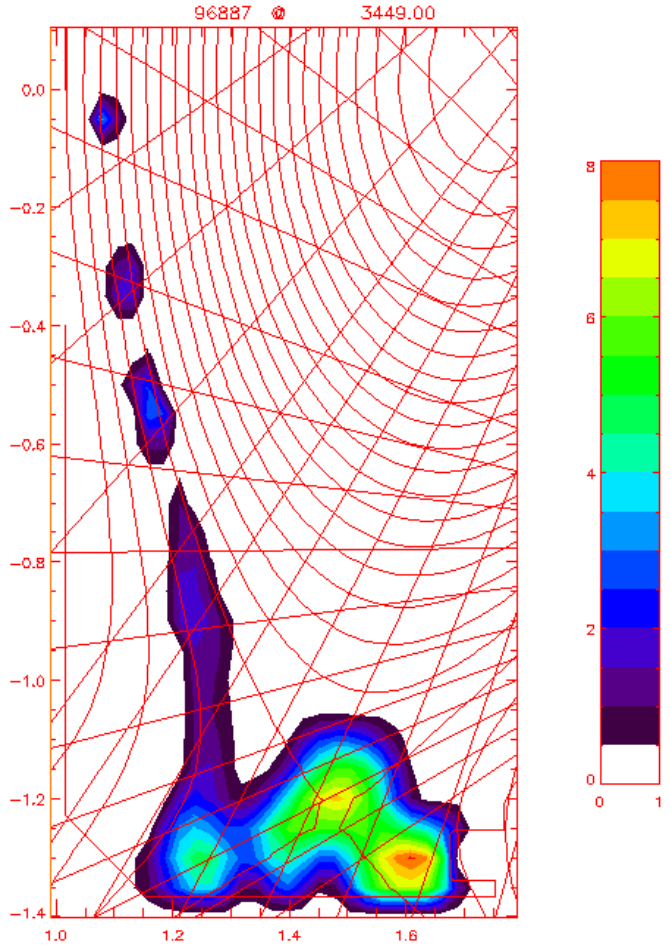
Spatial resolution of Prad profile in divertor legs is limited for this low X-point height discharge .

- Reconstruction for inner leg from nearly parallel chord views and one crossed chord.
- Outer leg target region viewed by only one bolometer chord.





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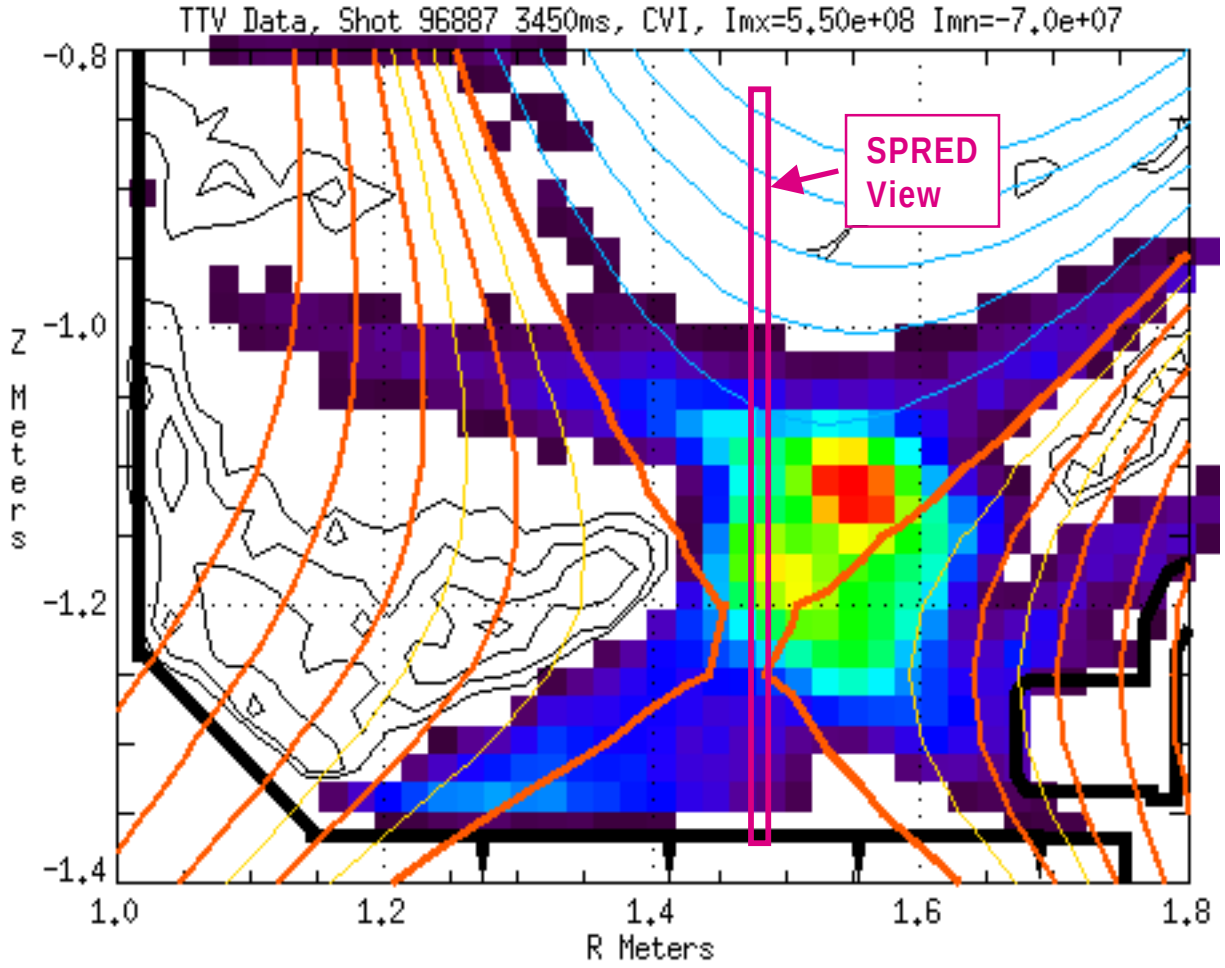
Calibration to Div. SPRED

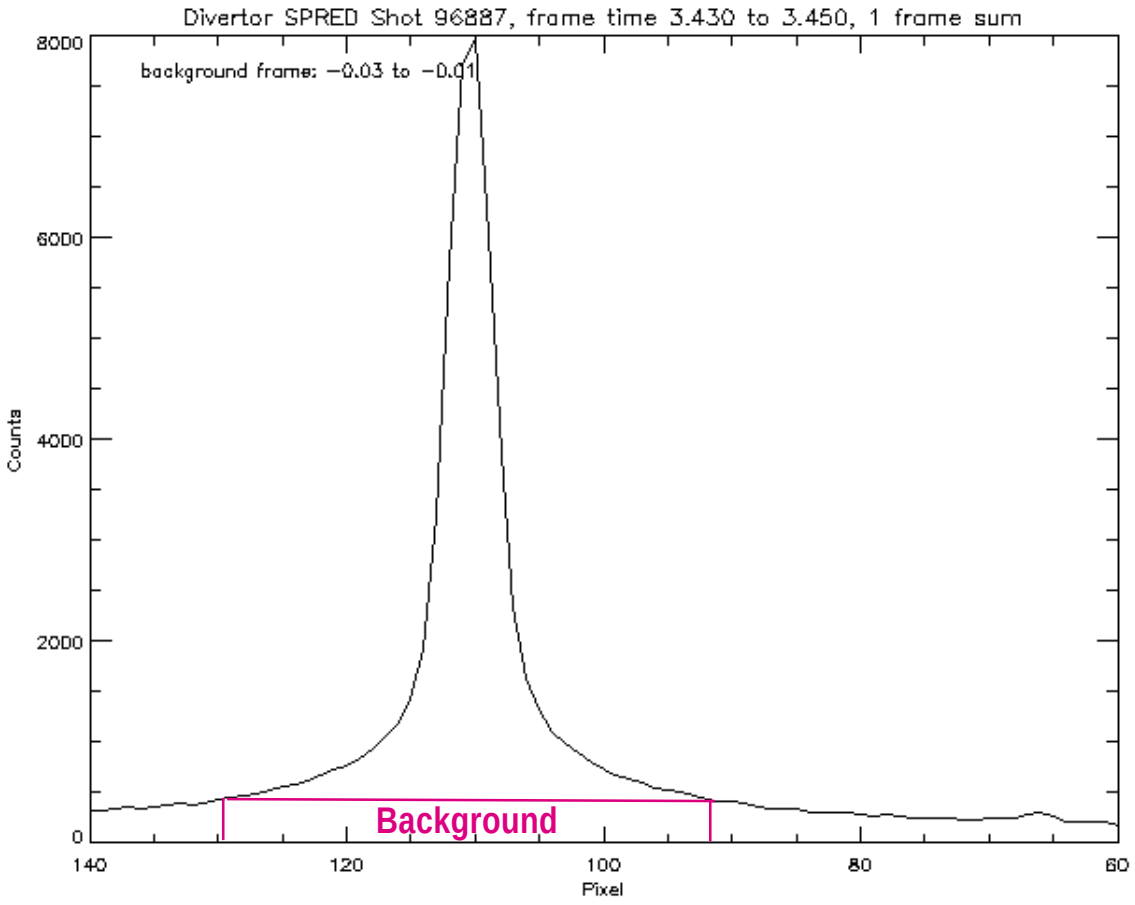
2D Reconstruction Integrated Along SPRED Vertical View Yields VUVTV Calibration Factor

- Pixel resolution of 2D reconstruction image is 2 cm x 2cm.
- Divertor SPRED viewspot is 1.1 cm radially, 5.3 cm toroidally.
- Emission data integrated from vessel floor, Z = -1.366m to Z = -0.8m only.



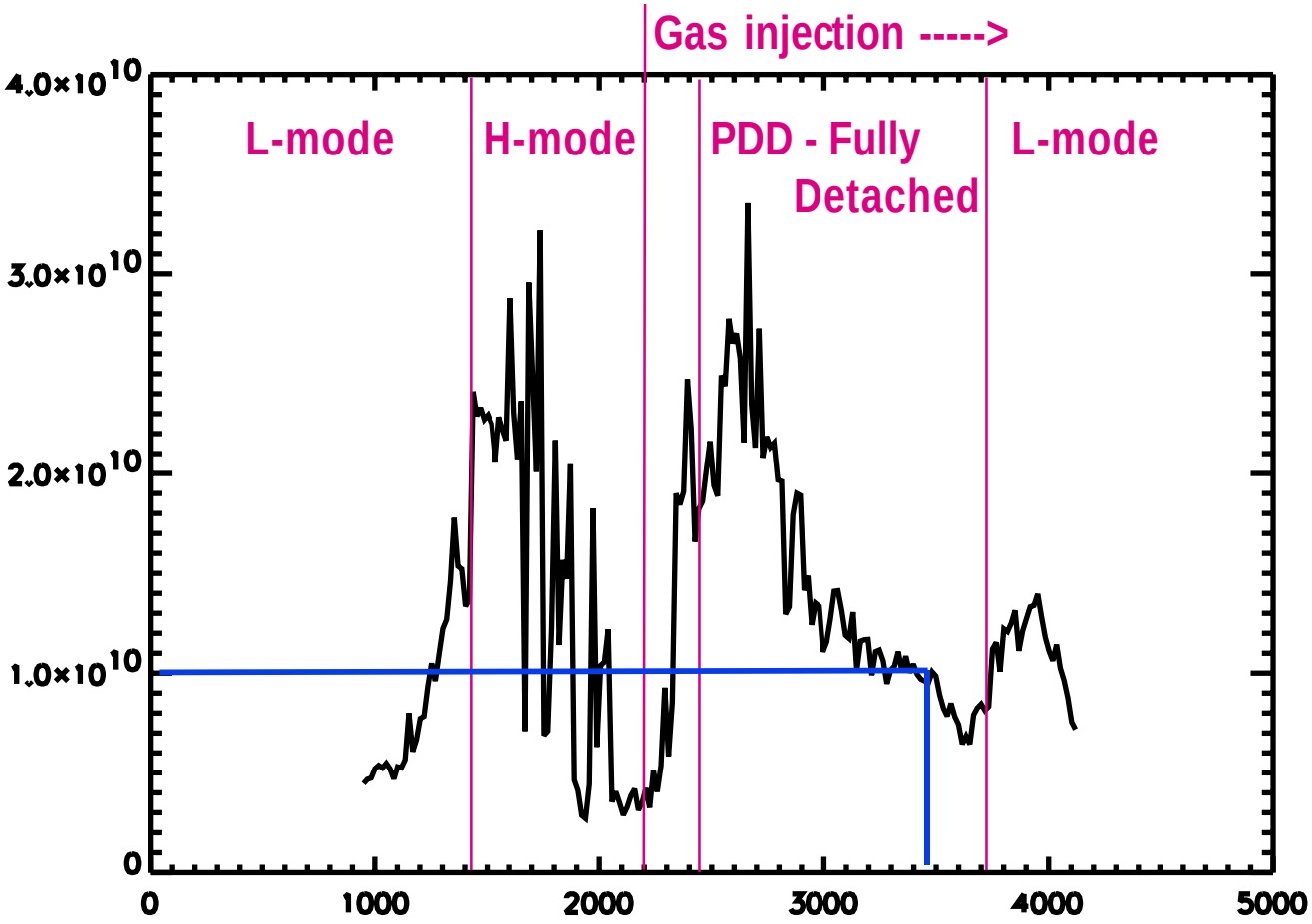
Divertor SPRED spectrum integrated under 155 nm peak.

- CIV 155nm line shape unperturbed by neighboring lines.
- Linear background continuum subtraction included.



Calibration factor varies substantially during typical PDD shot.

- Calibration coefficient shows sharp changes at mode transitions:
  - L -- H before gas
  - Gas injection and PDD formation
  - H -- L at high density

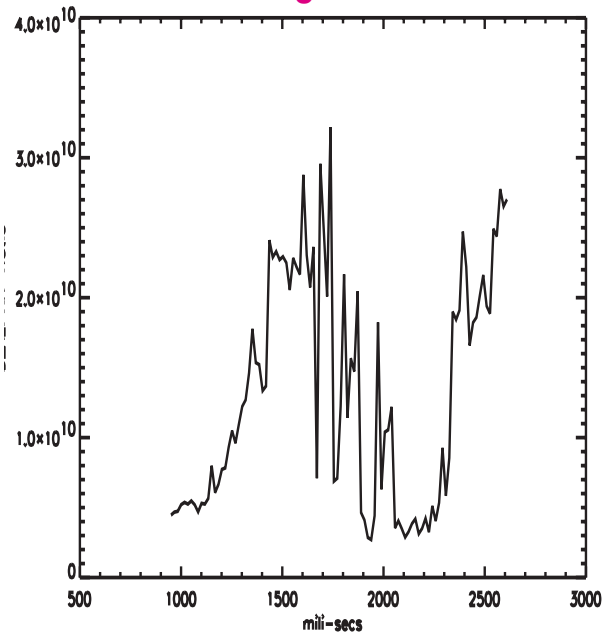


Calibration factor varies less when the radius of the integration path through the TV image is moved outward.

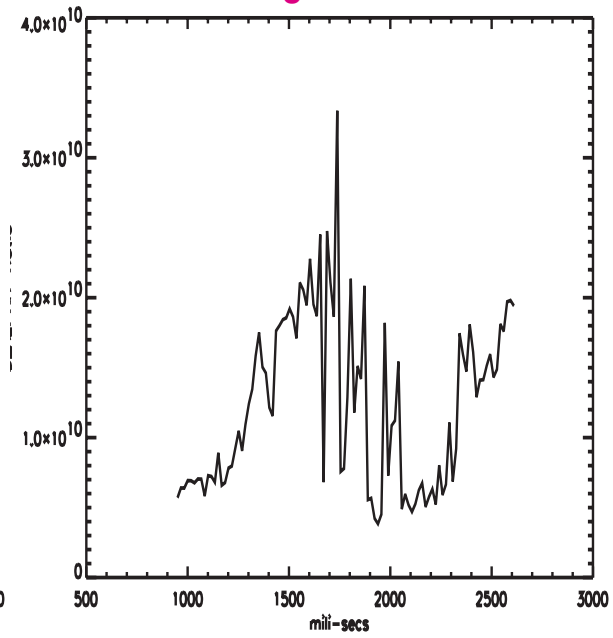
- Reduction in variation of calibration coefficient implies either:
  - CIV reconstruction is shifted outward 2 - 4 cm from true radiation position - possible given alignment techniques, or

or
  - Divertor SPRED diagnostic line of sight is 2 - 4 cm outboard of design specification - unlikely given past spatial calibration work on SPRED.

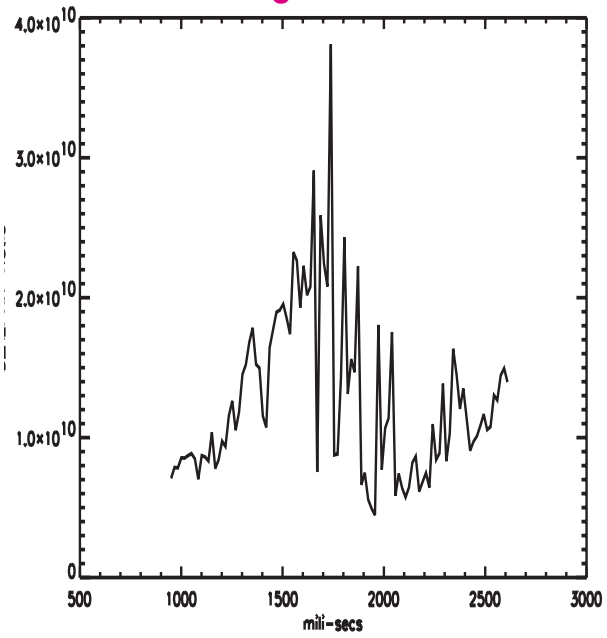
R_integral = 1.48 m



R_integral = 1.50 m



R_integral = 1.52 m



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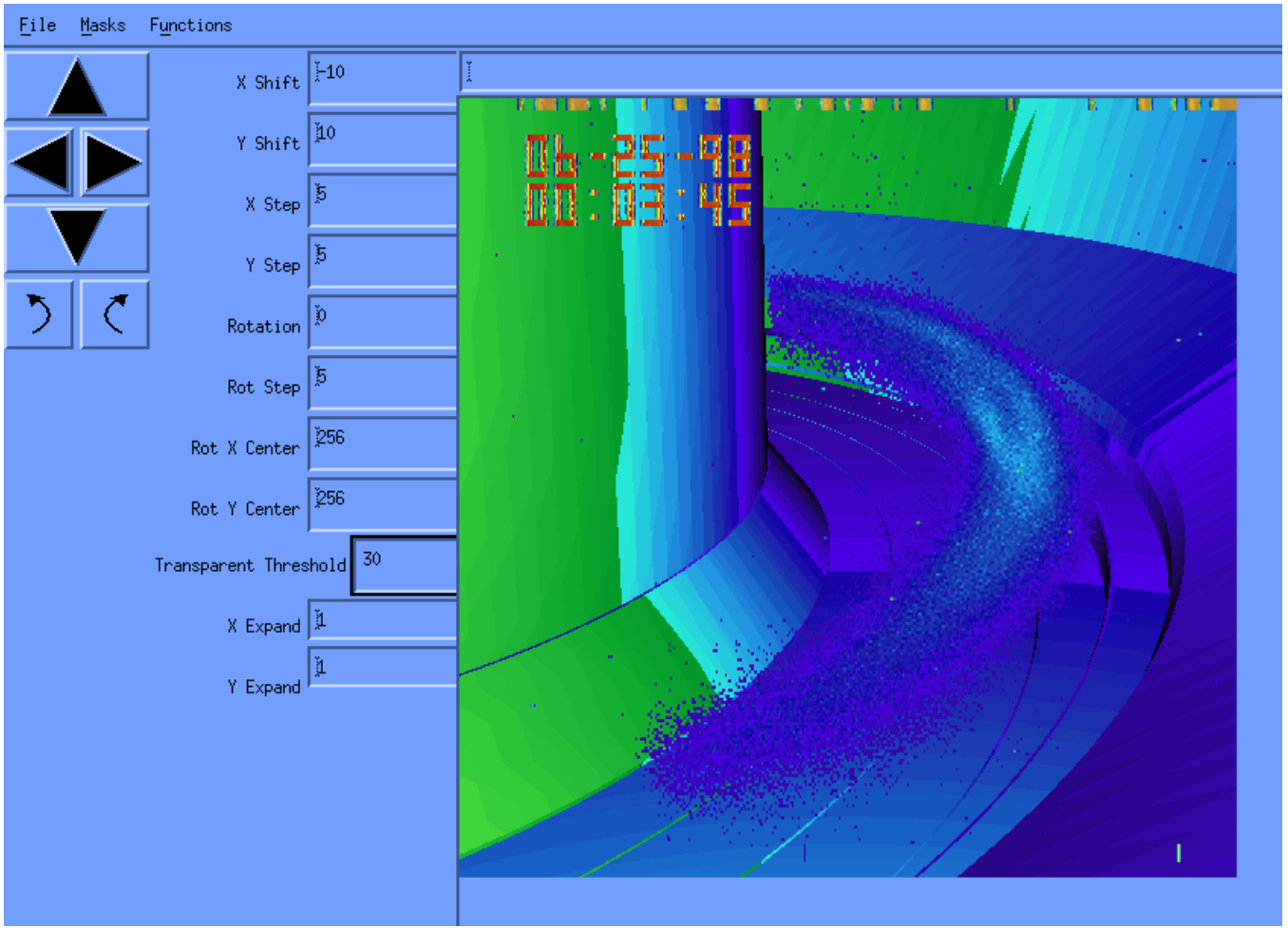
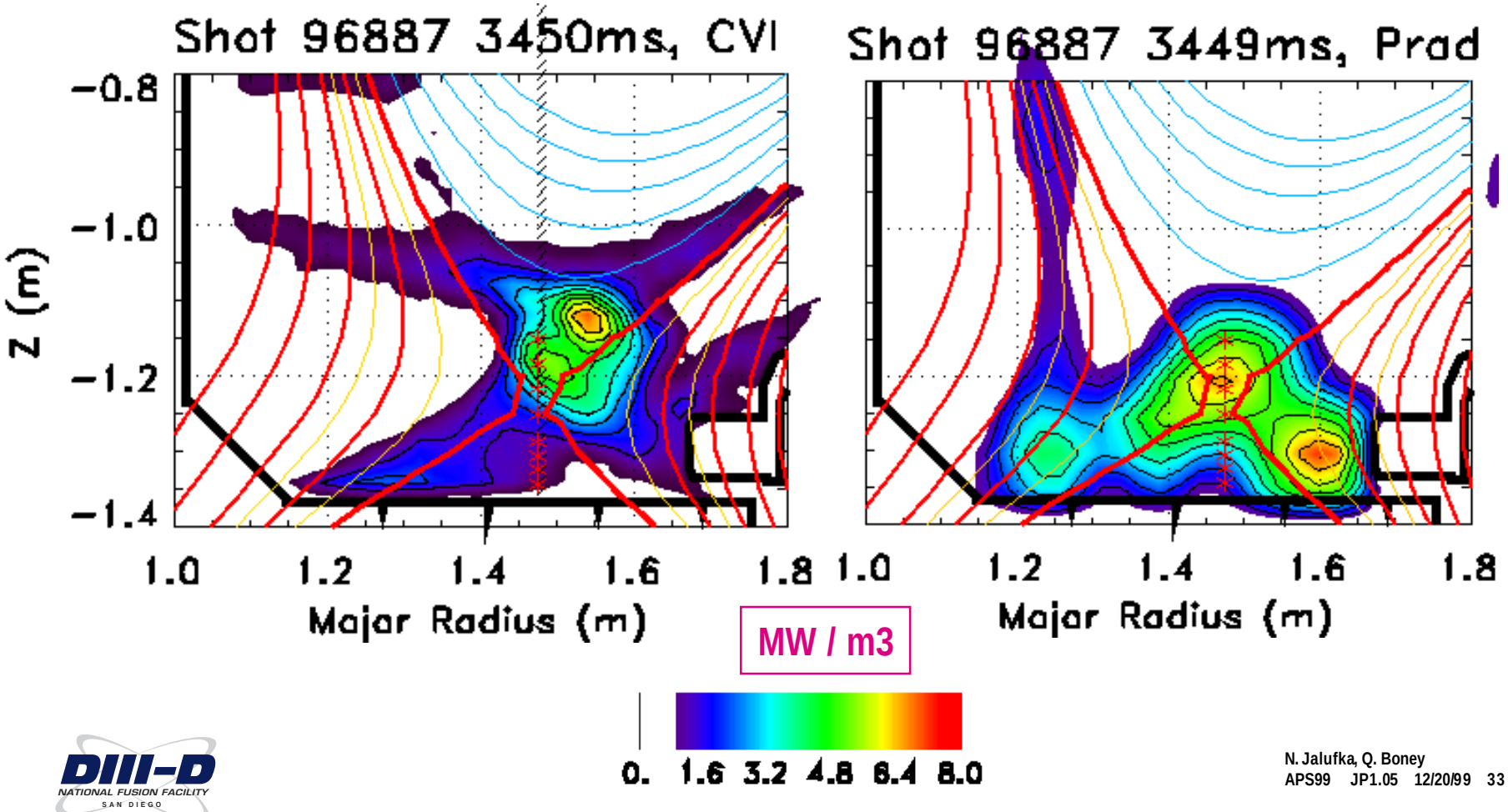
Raw VUV data is “aligned” to 3D rendering of DIII-D vessel created from VUV geometry matrix.

- Alignment is required if the camera position changes between in-vessel spatial calibrations.



Estimate of calibrated CIV emission power is a substantial fraction of radiated power measured by bolometers.

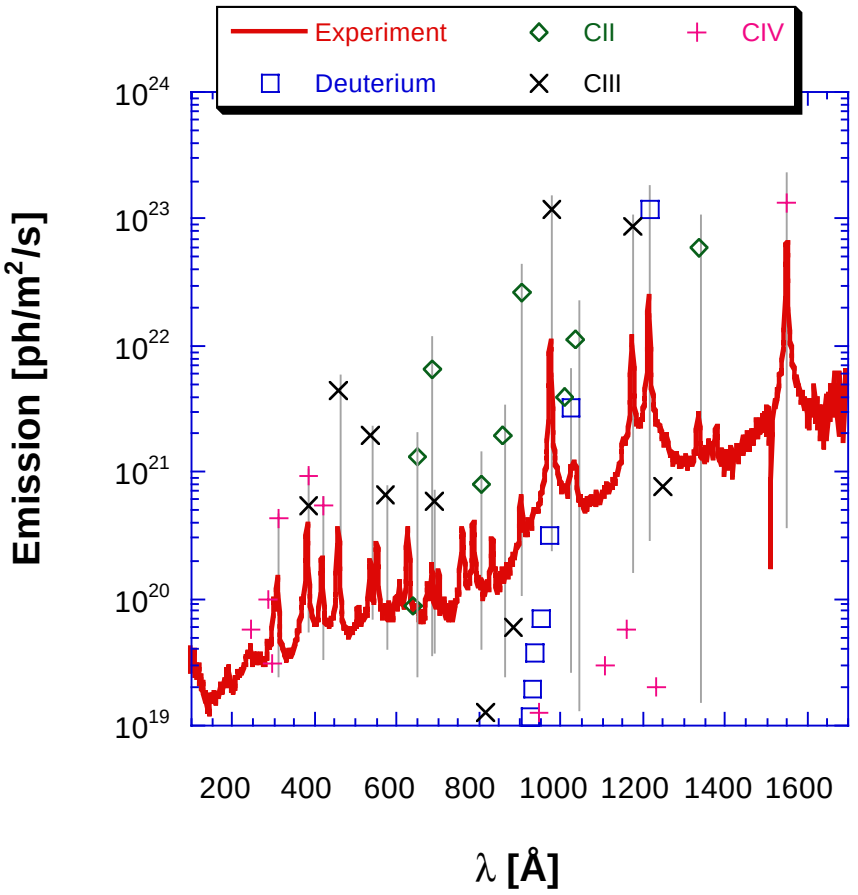
- At 3450 ms, calibration factor is 1.e10 photons/count.
- For 155 nm emission (8 eV), peak of 2D CIV profile at X–point is comparable to Prad.



Comparison to Modeling

UEDGE Simulation Compares Well with Many Diagnostics from shot 94002 including Carbon and Deuterium Lines from Div. SPRED.

- Input parameters (D, Xe, Xi, Rdiv, a_walls) adjusted to give best match to:
  - Midplane density and temperature profiles
  - Divertor heat and particle flux profiles
  - Divertor line integrated Da emission
  - Total radiated power and divertor radiated power
- Carbon model used the full Haasz model sputtering coefficients for deuterium on carbon surfaces.
- Best model available for CX rate of carbon on deuterium used.
- Good agreement of UEDGE integrated intensity along SPRED view and spectrum from SPRED.



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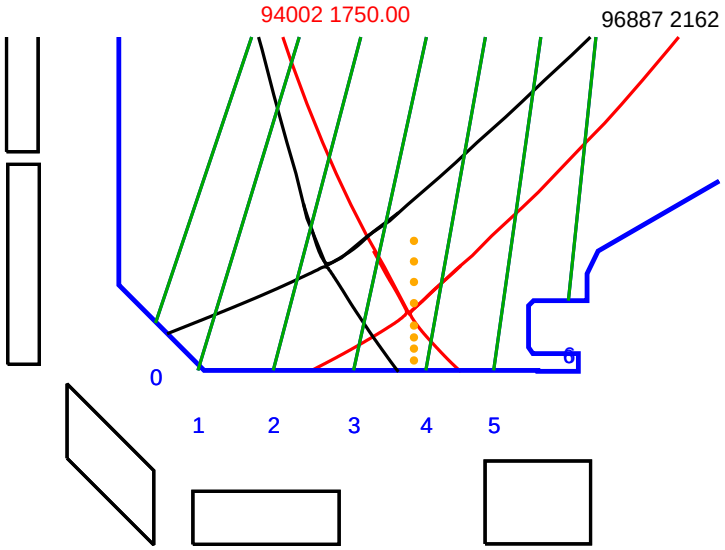
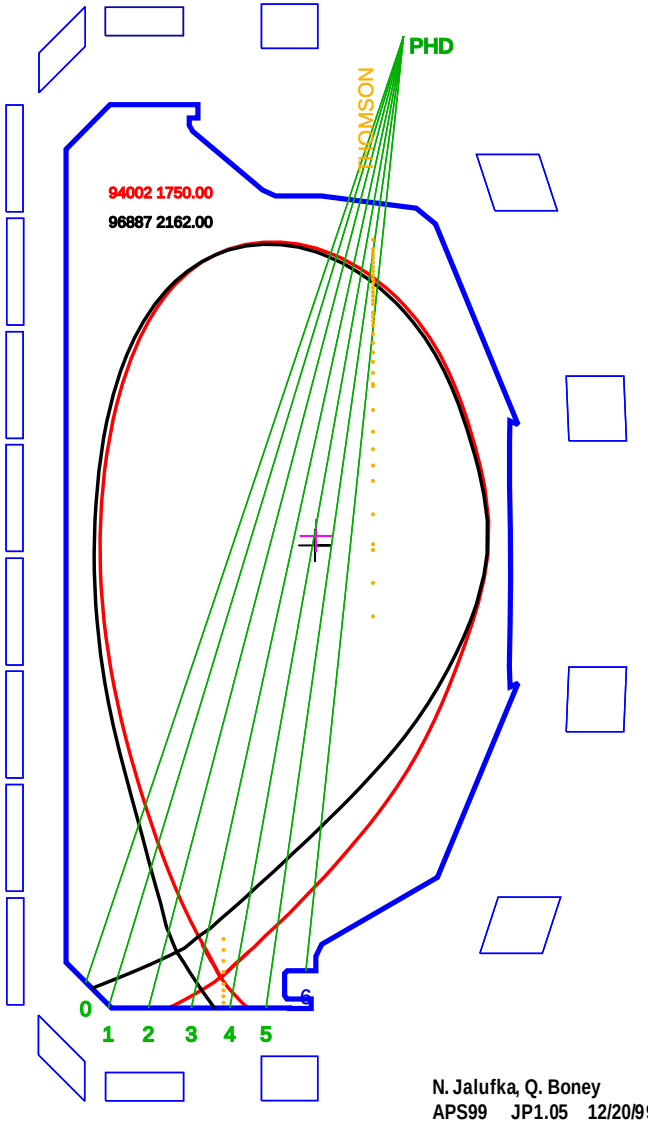
Discharge with best UEDGE simulation of carbon (94002) is a substantially different shape from VUV data shot (96887)

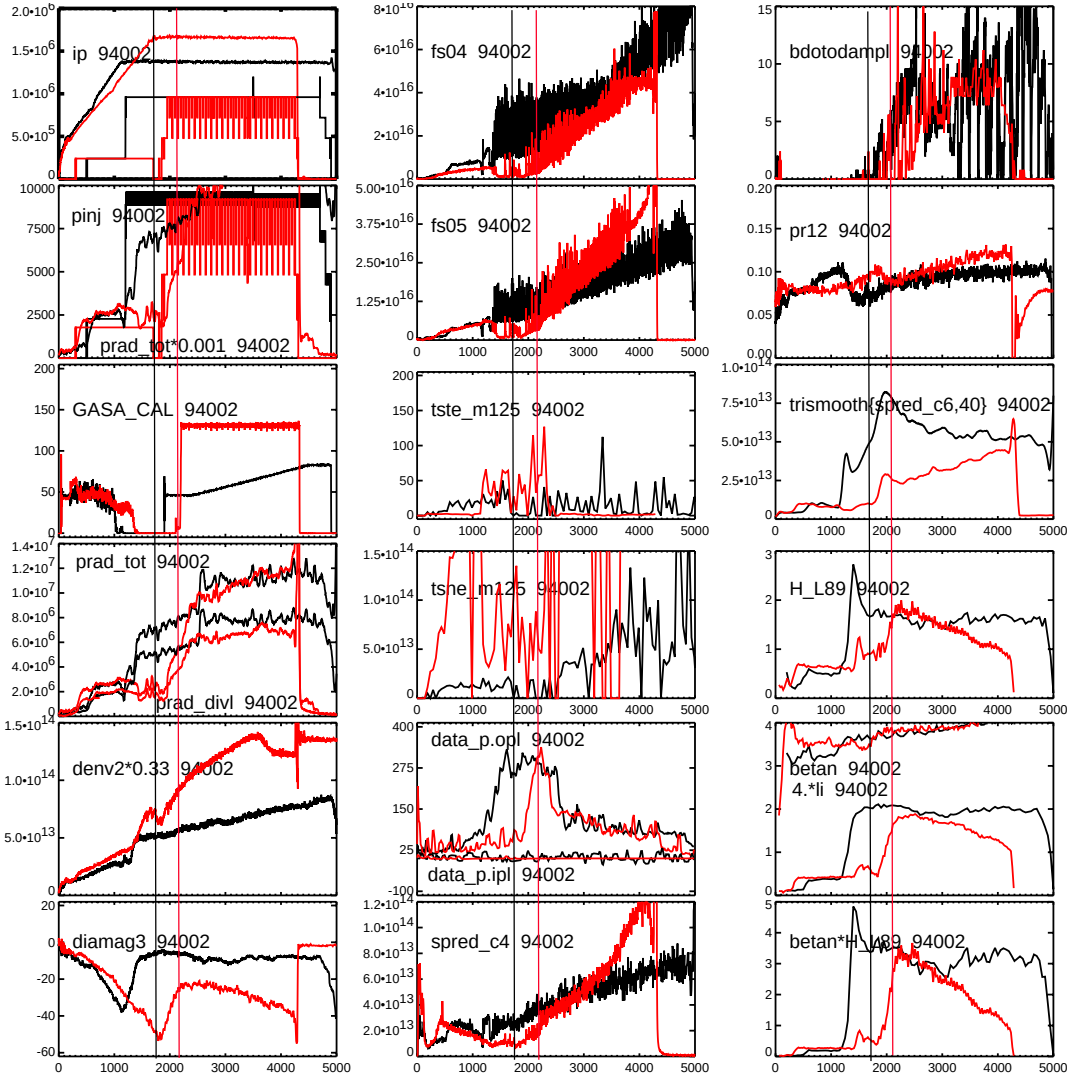
- UEDGE simulation results are therefore only representative of LSN discharge in attached ELMing H-mode.
- Full carbon simulation of shot 96887 is in progress.



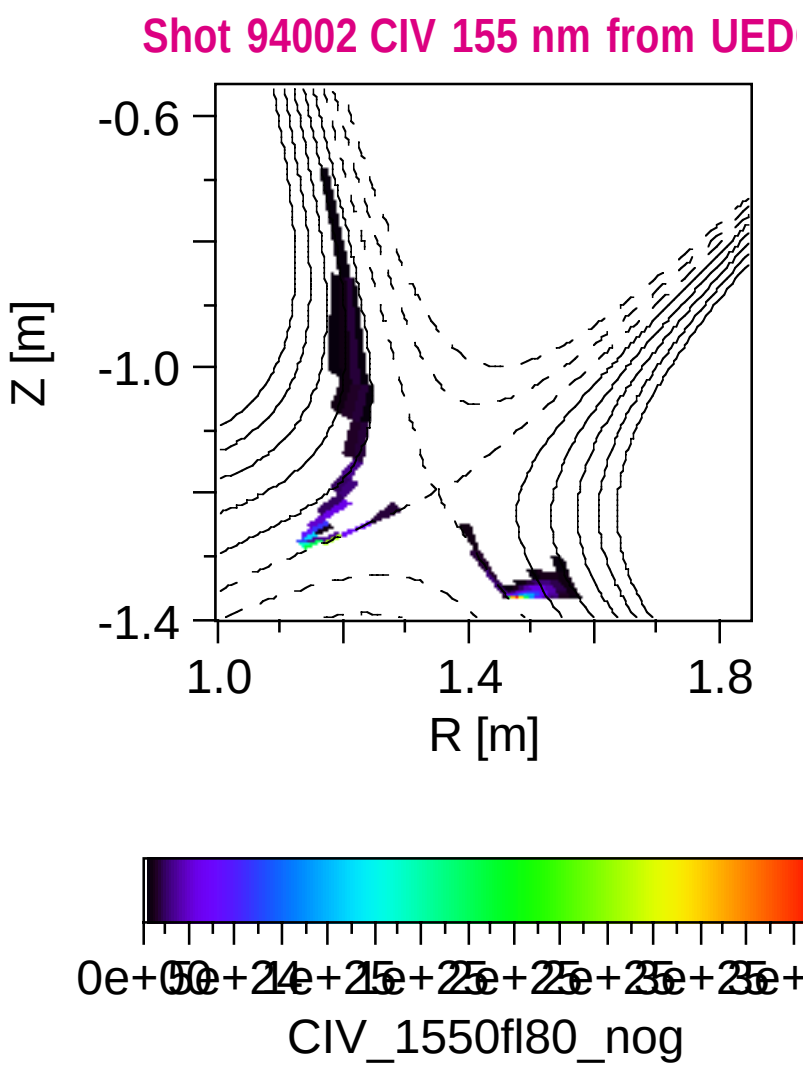


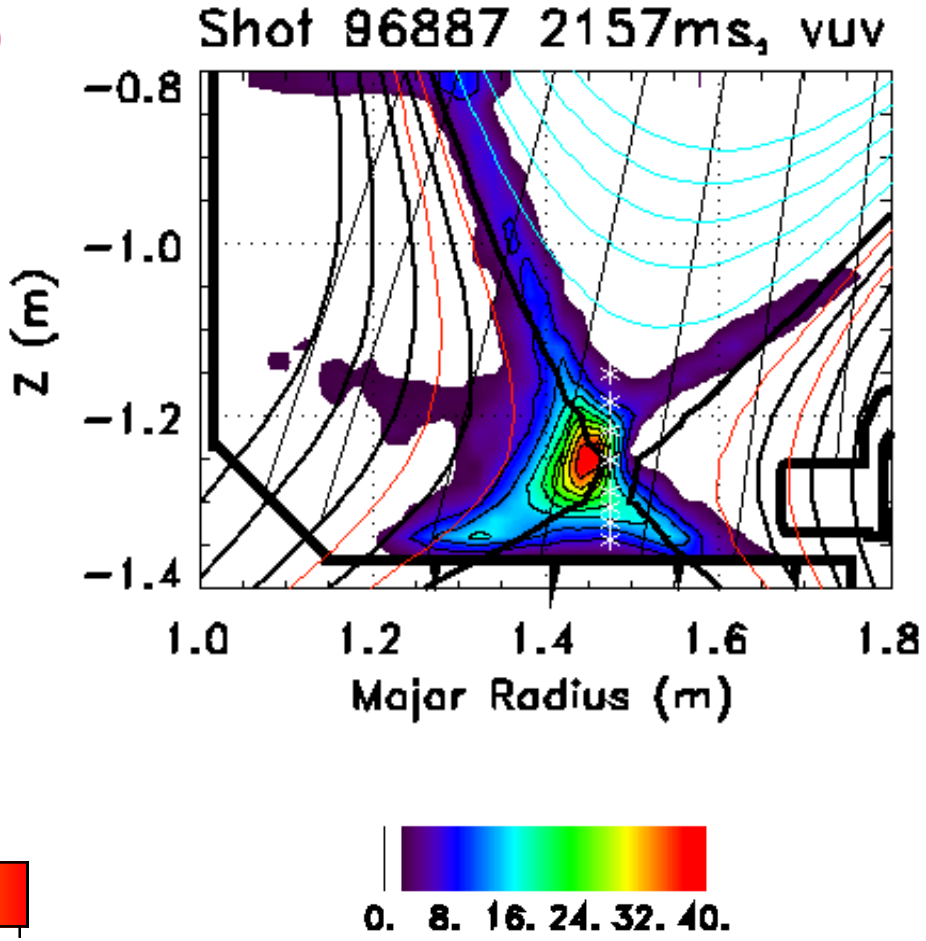
VUV CIV Discharge 96887 significantly different than UEDGE full Carbon Simulation Discharge 94002

- Discharges are not similar enough for quantitative comparison between simulation and VUV image data.
- Best comparison of simulation parameters (shot 94002 at 1750 ms) is in VUV data shot 96887 at 2150 ms, just before gas injection.



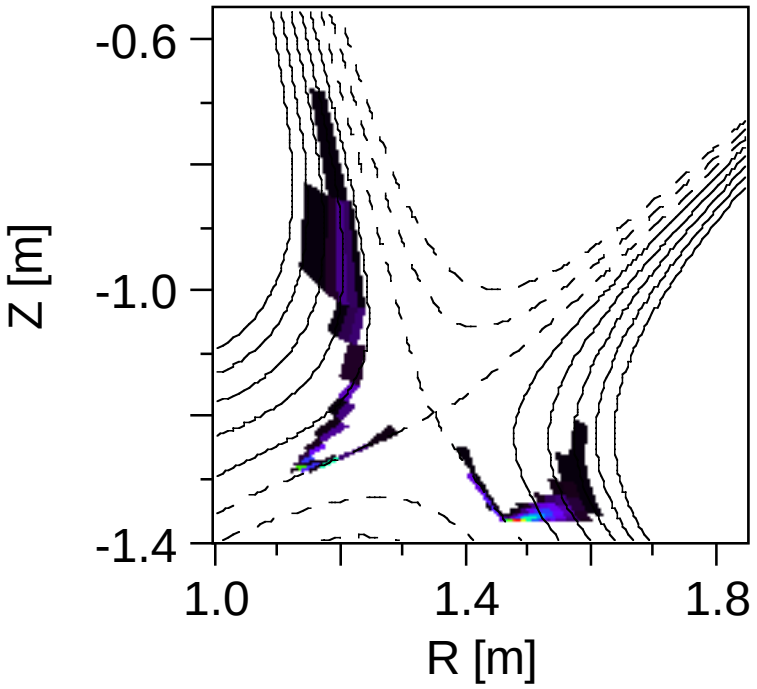
Carbon profiles from UEDGE simulation of attached H-mode show emission peaks along a "flame front" in the inner divertor leg.

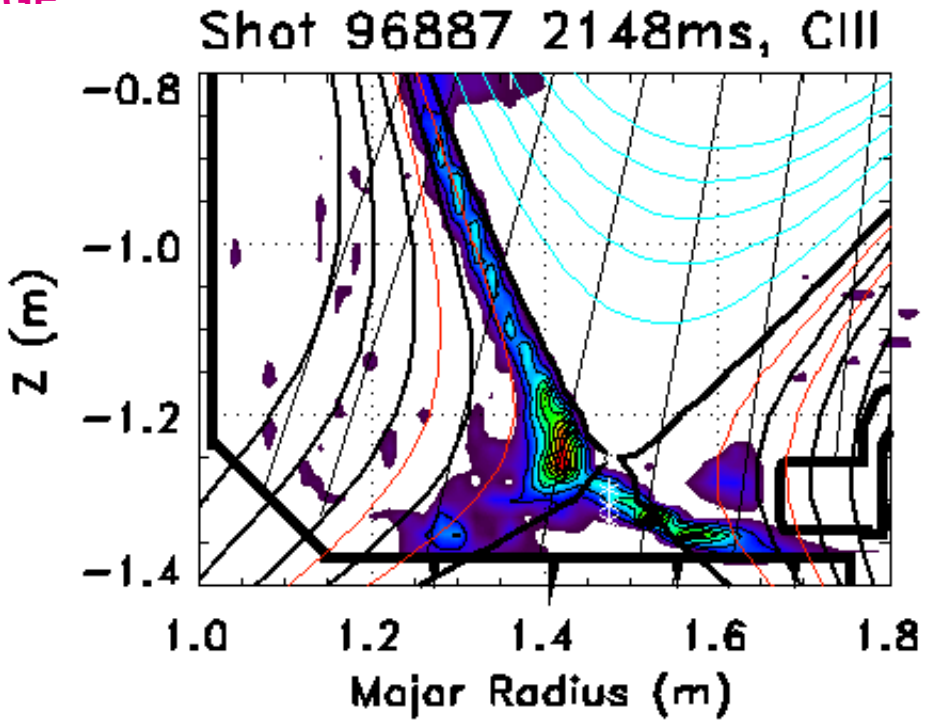


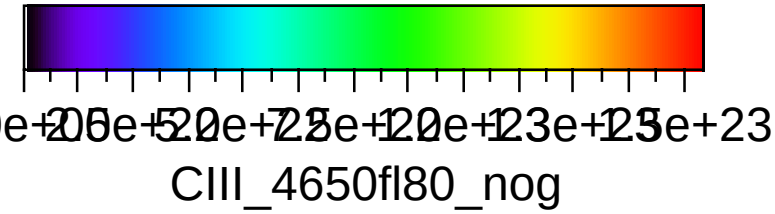


Carbon profiles from UEDGE simulation of attached H-mode show emission peaks along a "flame front" in the inner divertor leg.

Shot 94002 CIII 465 nm from UEDGE







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Summary / Conclusions

2D profiles of divertor CIV emission provide important information for understanding divertor physics and validating simulations.

- VUV camera system has obtained the only images of CIV emission from a tokamak divertor.
  - MgF2 refractive and metalic reflective elements plus P1 phosphor and CID camera
  - 2D poloidal profiles reconstructed from tangential 3D data.
- Poloidal profile of VUV CIV (main carbon radiated power) similar to visible CIII profile in the DIII-D divertor.
- Spatial profile of CIV plus deuterium radiation zones consistent with bolometer Prad.
- Locations of radiation peaks from CIV, CIII, Dα are consistent with Te and ne profiles measured with divertor Thomson scattering.
  - CIV appears where Te ~ 8 - 11 eV, CIII appears where Te ~ 5 - 8 eV consistent with SPRED spectrometer measurements.
  - Dα appears close to divertor targets (Te <~ 1 - 5 eV),
- 2D VUV CIV images can be calibrated against Div. SPRED data. Comparison with UEDGE simulations is in progress.

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