Diagnosis of the inner SOL in DIII-D using a tangentially viewing CID camera

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DIII–D NATIONAL FUSION FACILITY SAN DIEGO

GENERAL ATOMICS

Objective: How significant is mainchamber recycling in low-aspect ratio tokamaks?

– Recent reports from C-Mod [LaBombard] and DIII-D [Whyte] postulate significant contribution of mainchamber recycling to core plasma fuelling
  - » Mainchamber wall = dominant impurity source?
  - » Significant heat flux onto the mainchamber wall?
  - » Degree of toroidal and poloidal symmetry of the ion flux onto the mainchamber wall?

– Limited diagnostic coverage of mainchamber wall in DIIID, view outer wall at midplane:
  - » Array of fast D_α detectors (8 radial channels ~ 4cm)
  - » Reciprocating Langmuir probes (15cm radial plunge)
  - » Beam emission spectroscopy (5x6cm array)
  - » Edge charge exchange recombination spectroscopy (20 radial channels ~ 10cm)

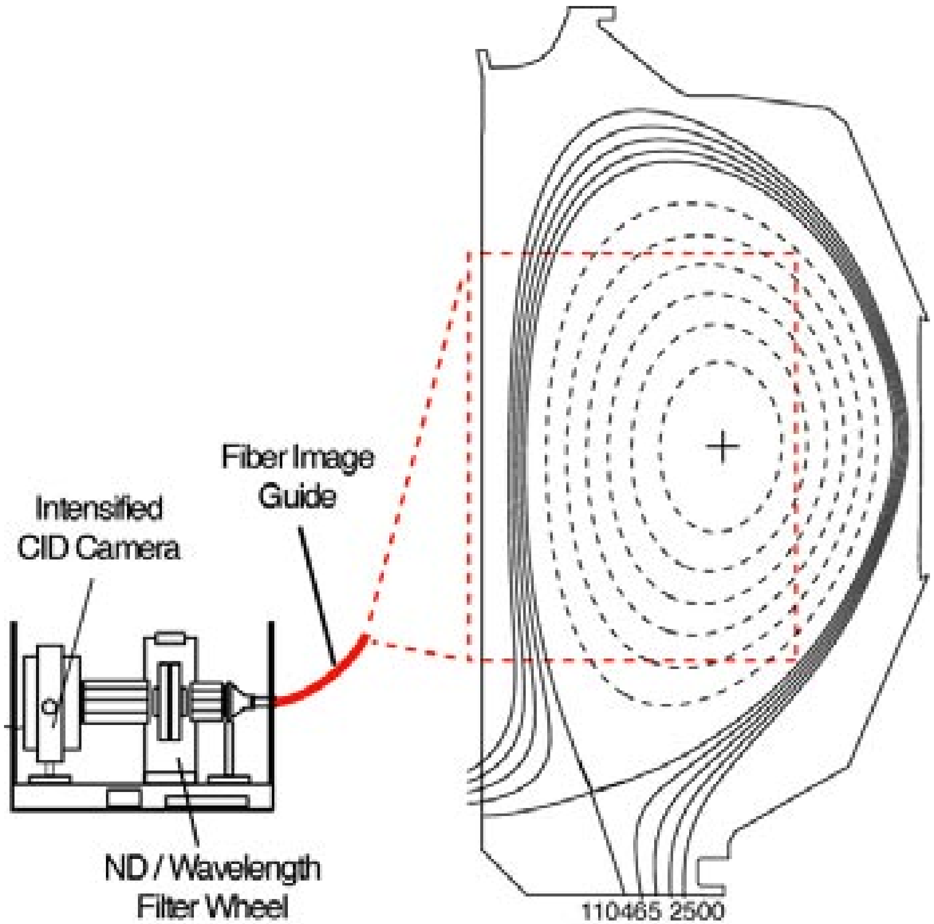
Preliminary analysis of SAPPs using a CID camera with midplane view

- Latest added diagnostic capability in DIII-D (2002):
  - Tangentially viewing (intensified) charge-injected device (CID) camera,
  - View: 1mx1.5m of the inner SOL
  - Measurement of deuterium (D_α) and carbon (CII 516nm / CIII 465nm) emission profiles
  - Reconstruction of 2D profiles using Abel inversion and tomographic reconstruction techniques; both methods agree well
- Preliminary analysis emission profiles in Simple-As-Possible-Plasmas (SAPP)
  - SAPP = quiescent L-mode plasmas; here low density $\langle n_e \rangle \sim 2 \times 10^{19} m^{-3}$
  - Compare experimental profiles with simulated profiles from 2D fluid code UEDGE

Summary and Conclusions

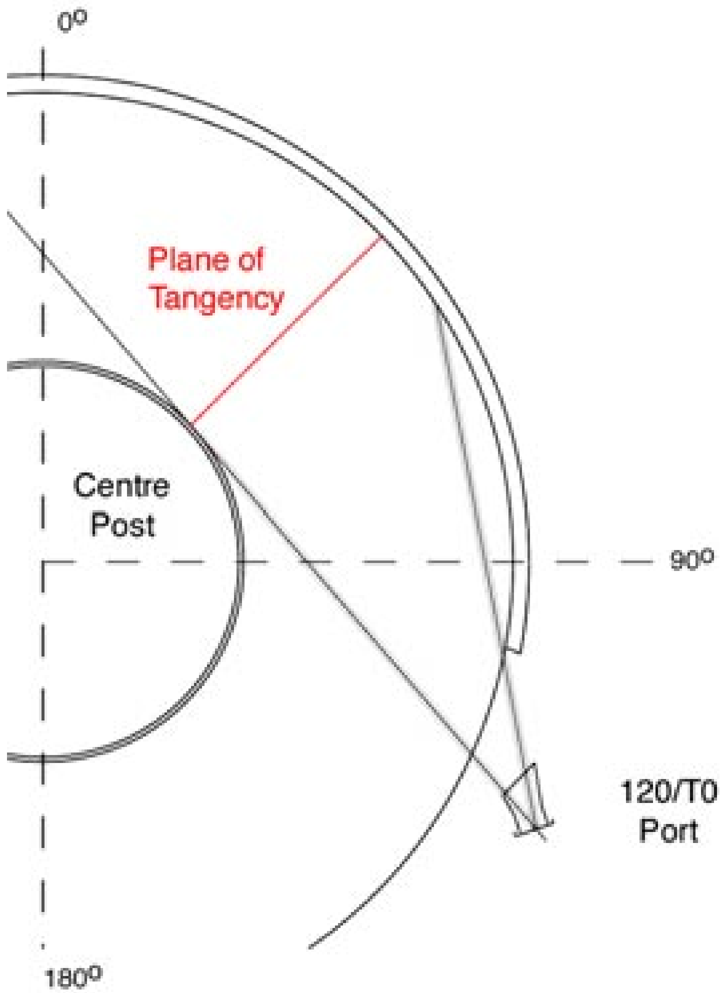
- Experiment: D-alpha $\rightarrow$ CII $\rightarrow$ CIII emission profiles narrow and extend poloidally upstream along the inner SOL
- Experimental D-alpha profiles suggest deuterium atoms leaking out of the divertor
- Remarkably good agreement between experimentally obtained 2D profiles and UEDGE simulation
  - » Simulation based on purely diffusive radial transport; carbon originated at target and mainchamber wall
  - » Significant ion leakage from divertor, but also chemical sputtering of carbon by hydrogen atoms at the mainchamber wall, causing emission profile as measured
- Yet another contribution to SAPP's objective: Understanding edge transport!
- Justifies further experimental and numerical investigations
  - » Higher densities, L-mode vs. H-mode, magnetic balance, closed vs. open divertor

New spectroscopic tool: XYBION intensified CID camera with midplane view

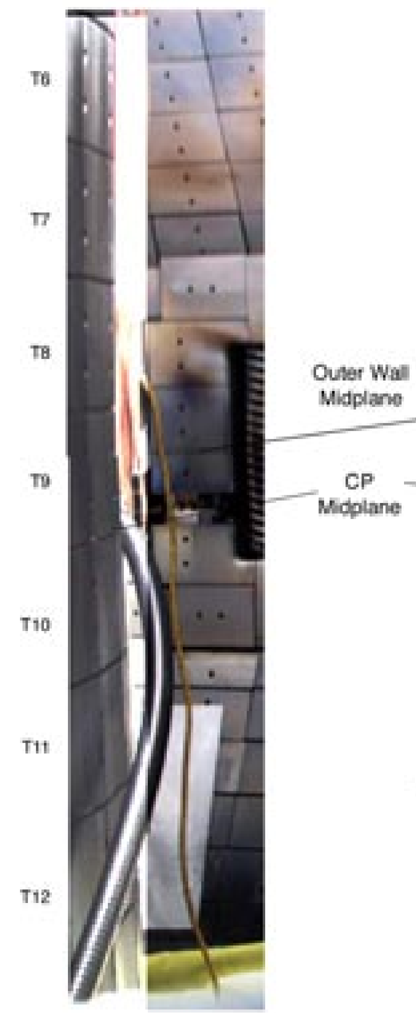


- Radiation hardened CID camera (CIDTEC Model D3710D)
- DEP GEN II intensifier
  - » **Max. gain ~ 10.000 (adjust.)**
  - » **Microsecond gates possible**
- Measurement of line emission profiles using interference filters
  - » **D_α 656 nm / CII 515 nm / CIII 465 nm**
- SCHOTT glass fiber image guide (400x400 pixel elements) connecting port optics with filter/ camera assembly

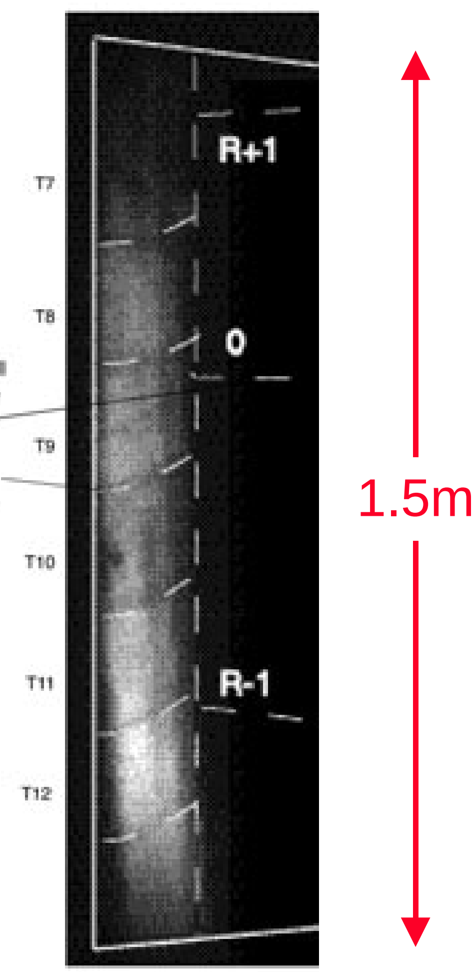
Viewing geometry I: Tangent at inner wall ~ 45º toroidally, 0.75m above and below midplane



Standard camera

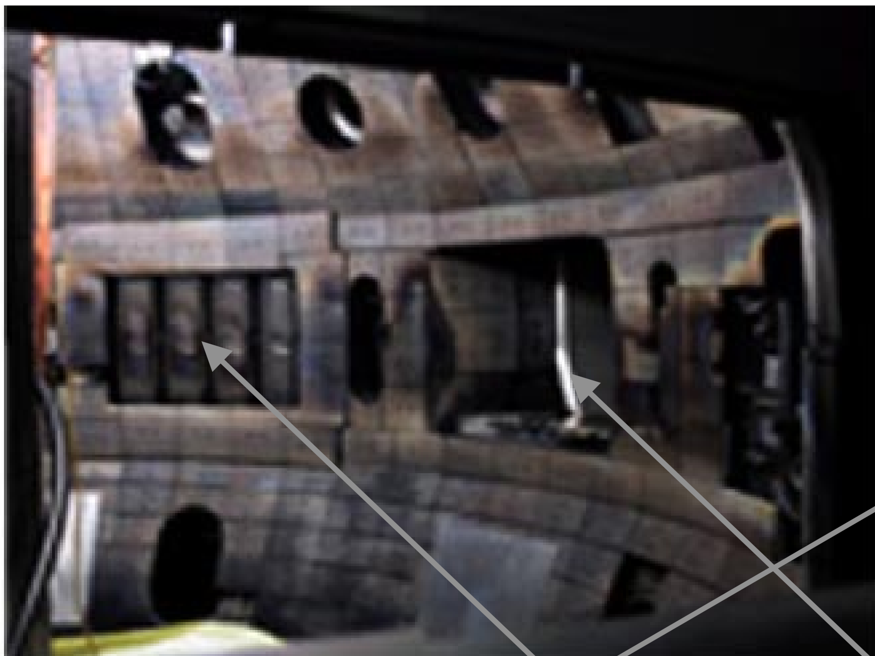


CID

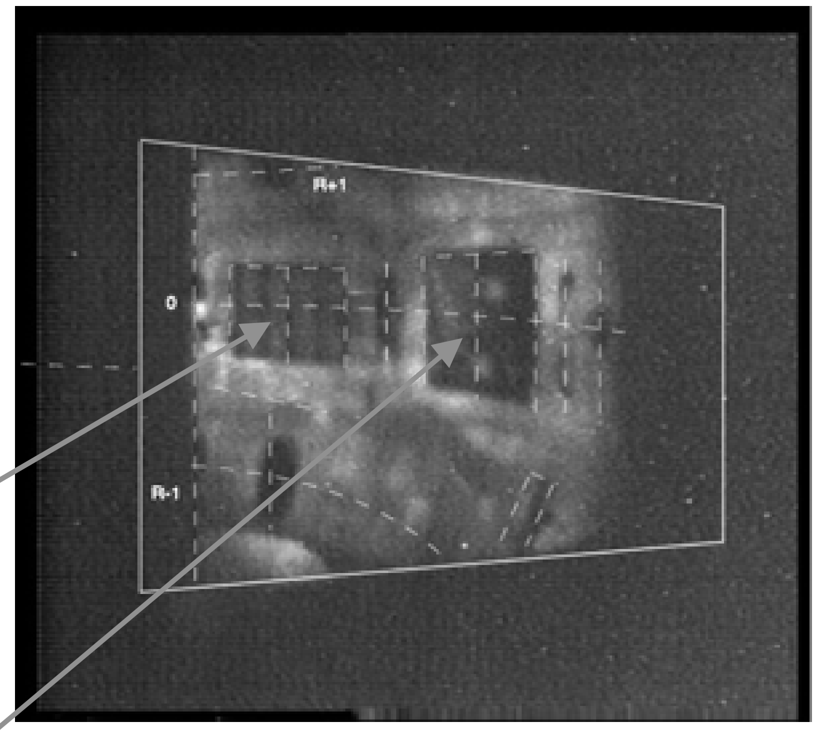


Viewing geometry II: Outer wall coverage ~ 60^o, ~ R-1 $\rightarrow$ R+1 ports at plane of tangency

Standard camera



CID camera through image guide

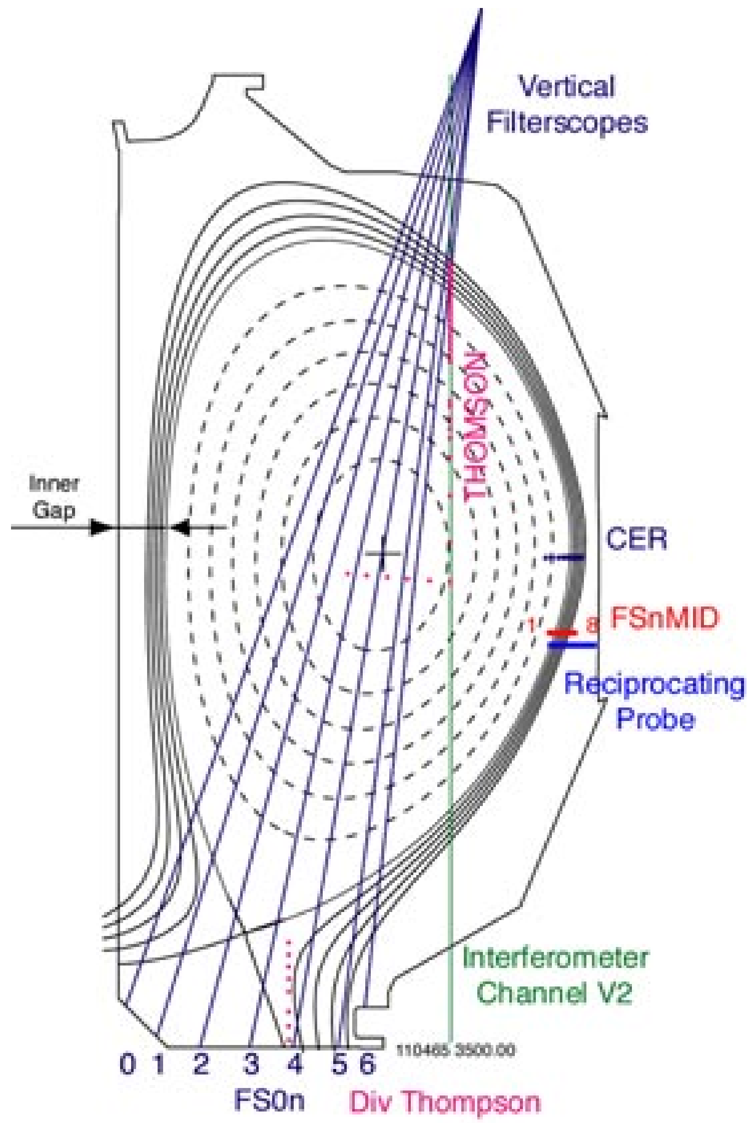


0^o ICRF Antenna

30^o NBI duct

Simple-As-Possible-Plasmas (SAPP) = quiescent L-mode plasmas, i.e no ELMs

P.C. Stangeby RP 1.050

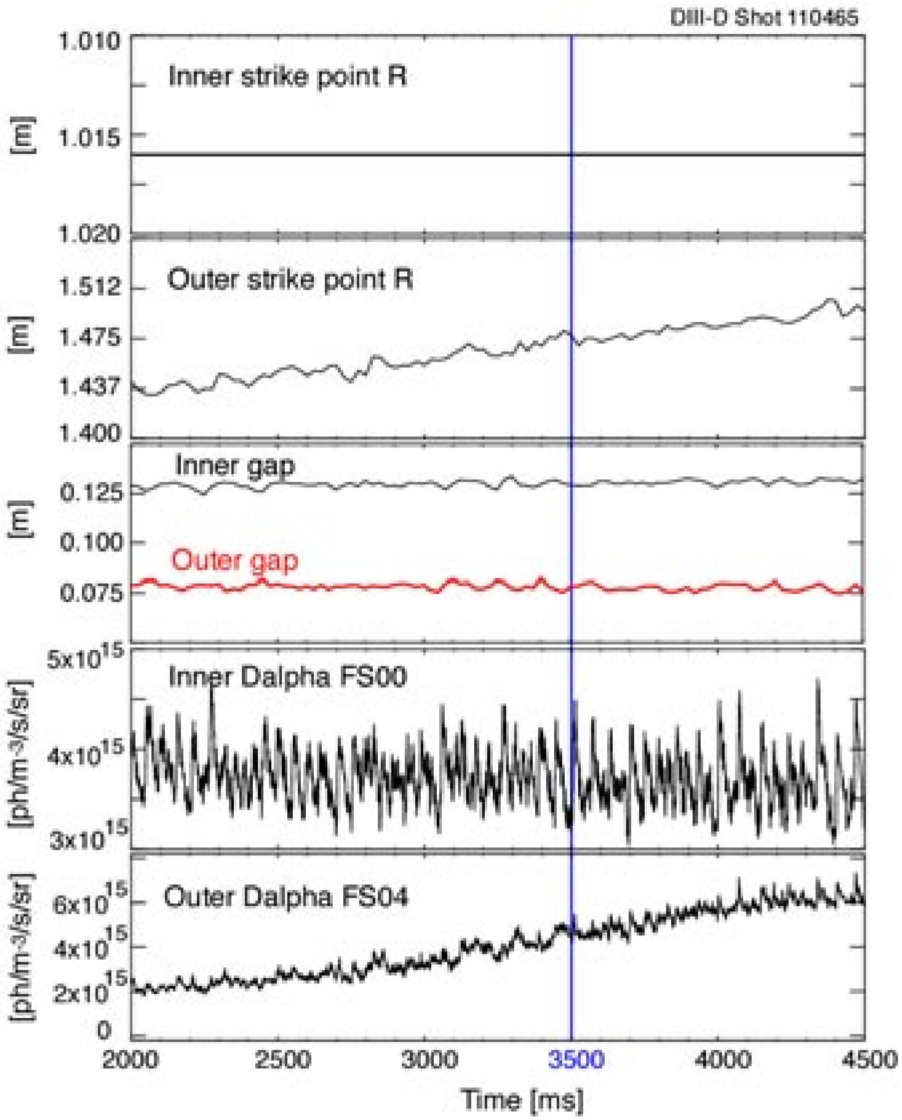


- Lower single null configuration; optimized for diagnosis of outer divertor leg; relatively high x-point, inner strike point on the center post
- Repeat of identical discharges at various core densities; here $\langle n_e \rangle \sim 2\times10^{19} m^{-3}$, attached divertor plasma
- Bring results from edge codes (OEDGE, UEDGE) in mutual comparison with measurements

Low density, L-mode plasma with low neutral beam heating

Basic Discharge Parameter	
I_P	1.1 MA
B_T	2.0 T
P_{beam}	450 kW
P_{ohmic}	450 kW
$P_{rad,\ core+SOL}$	177 kW
$P_{rad,\ div}$	367 kW
P_{plate}	x
$\int n_e dl$	$2.1 \times 10^{19}\ m^{-3}$

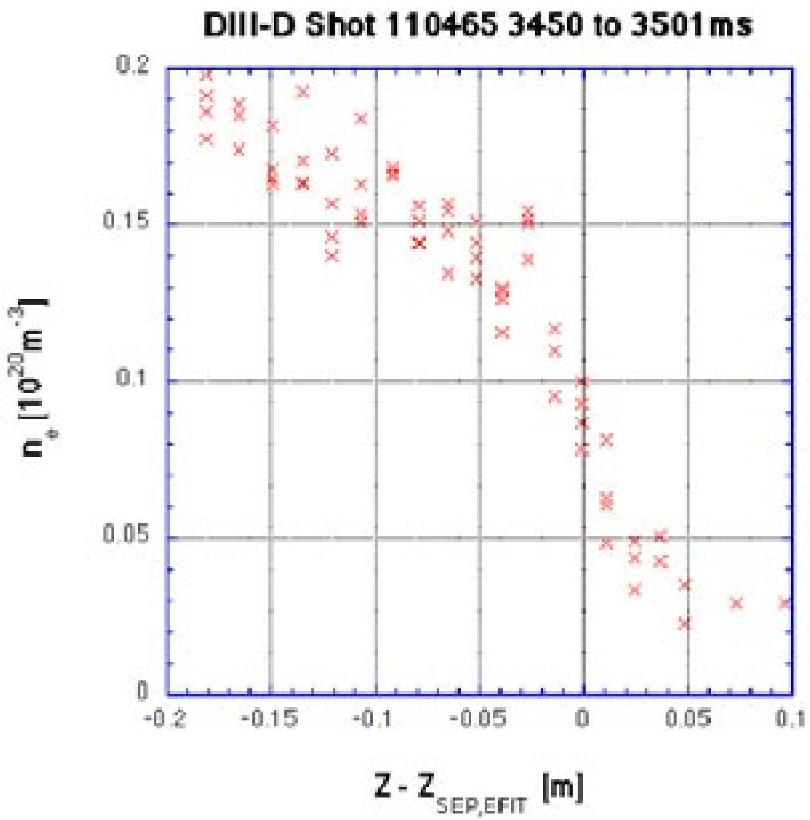
Slow sweep of outer strike point for divertor density and temperature measurement

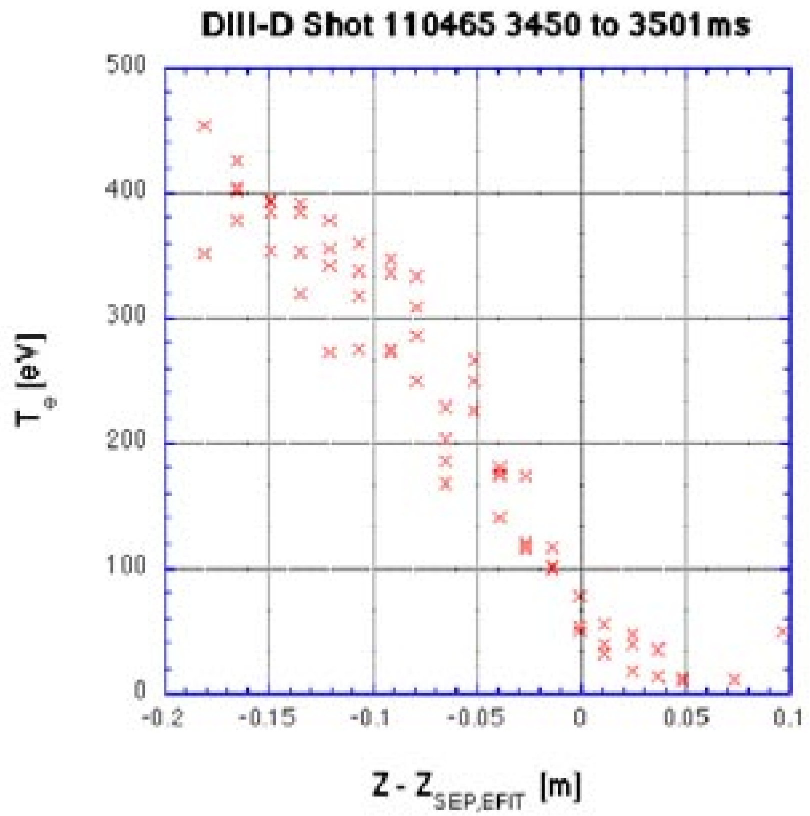


- Slow sweep of outer strike point to scan divertor plasma over Divertor Thompson scattering view cords → 2D $n_{e,div}$ and $T_{e,div}$
- Inner strike point fixed, but slightly increasing inner gap
- As plasma swept over filterscope line-of-sights, outer D-alpha (and CIII) increase; inner fixed

→ Combination of data over sweep to obtain emission profile with better radial resolution

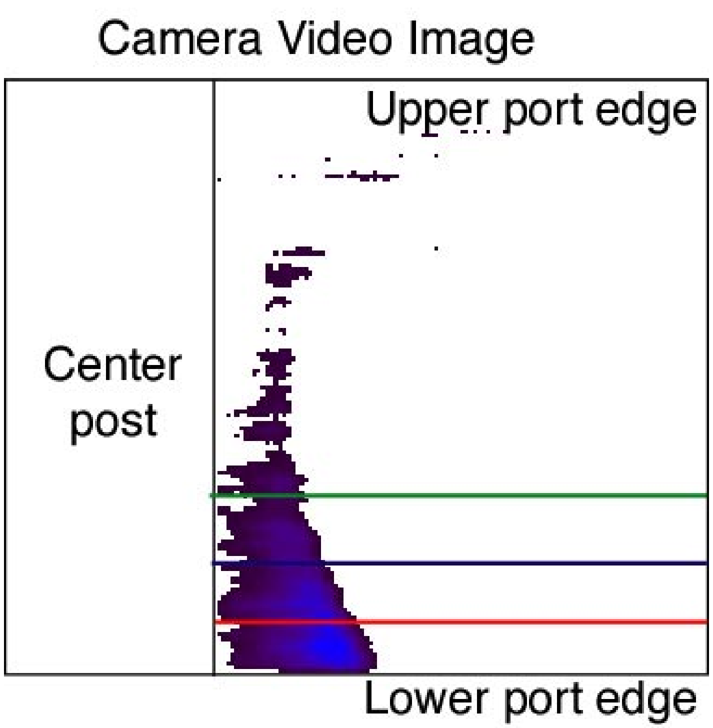
L-mode radial density and temperature profile at core/edge interface

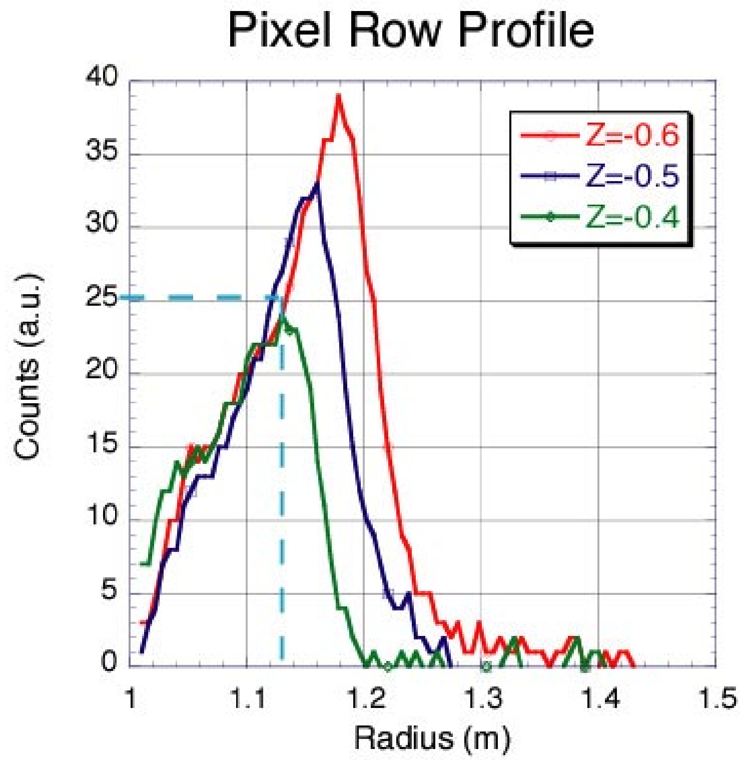




Midplane image data inversion - Method 1: Abel inversion of image pixel rows

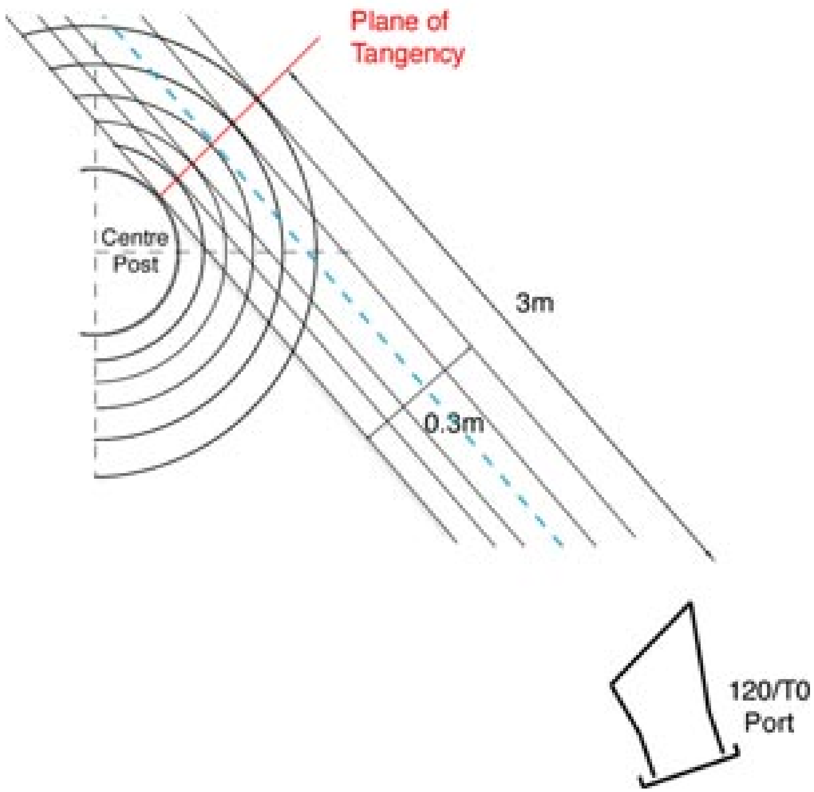
- Treat each camera pixel row as an individual horizontal slice of the image
- Measured brightness line-integrated; depends on radial and vertical position
- Selected image size: 50x100 pixels → Resolution: 0.6cm x 1.1cm per pixel



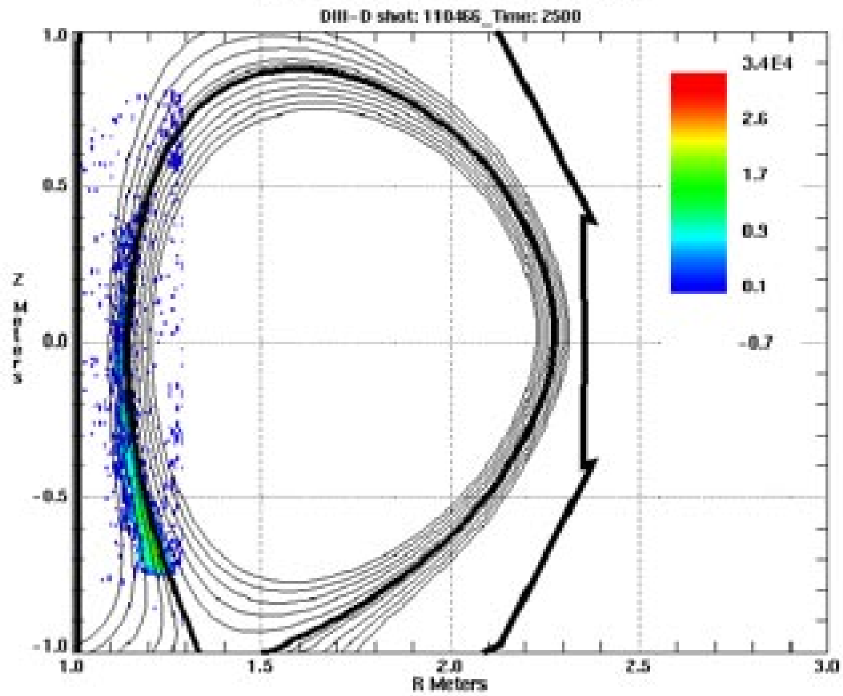


Method 1, Slide 2

Geometry: Top view



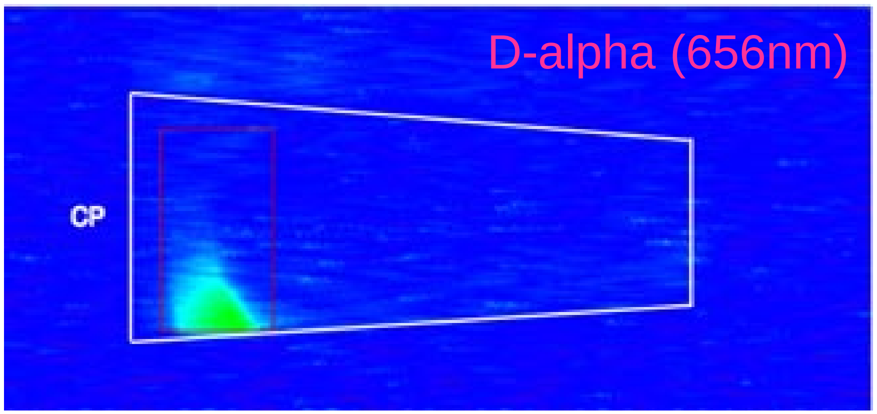
Abel inverted image

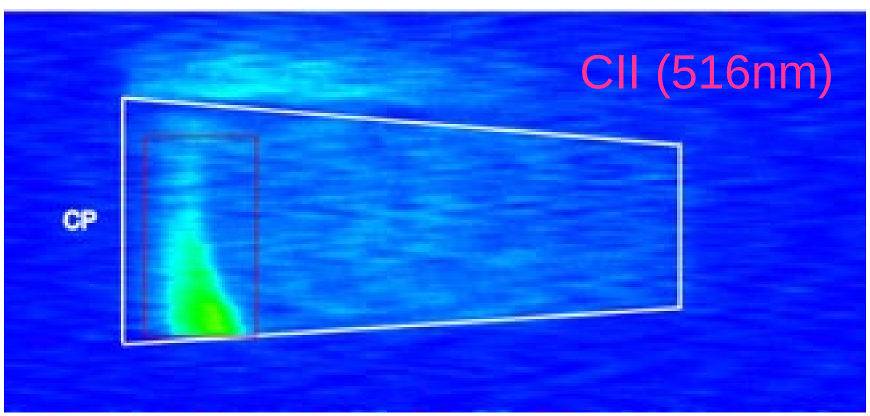


- Obtain local emissivity from recursive Abel inversion method, starting outermost radial channel (user-defined) using geometry as shown
- At Z=0 (equatorial plane), horizontal divergence of view ~ 6^o

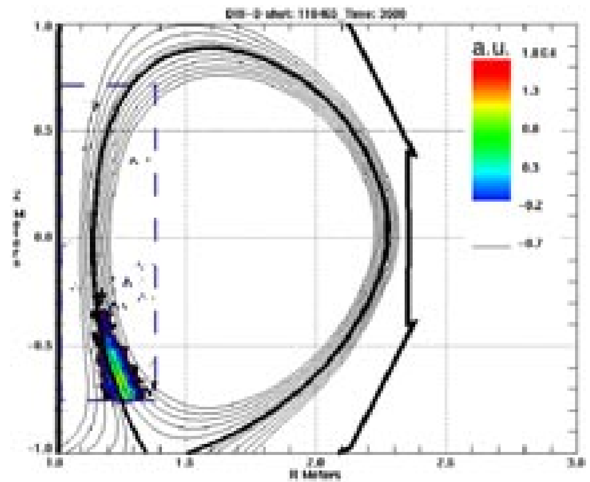
Deuterium-alpha, Carbon II and CIII emission profiles in low density SAPP (Method1)

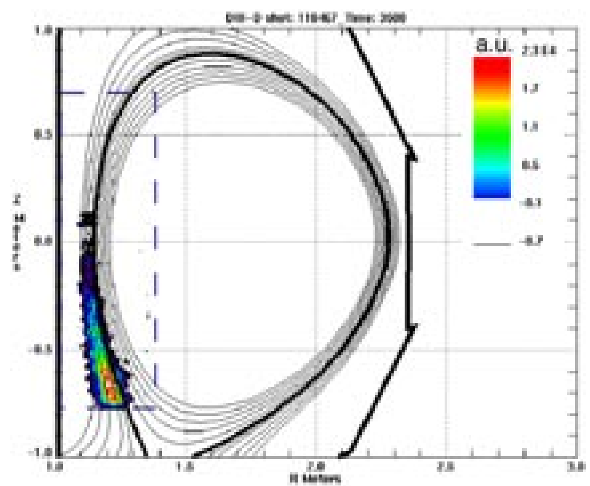
Raw image data

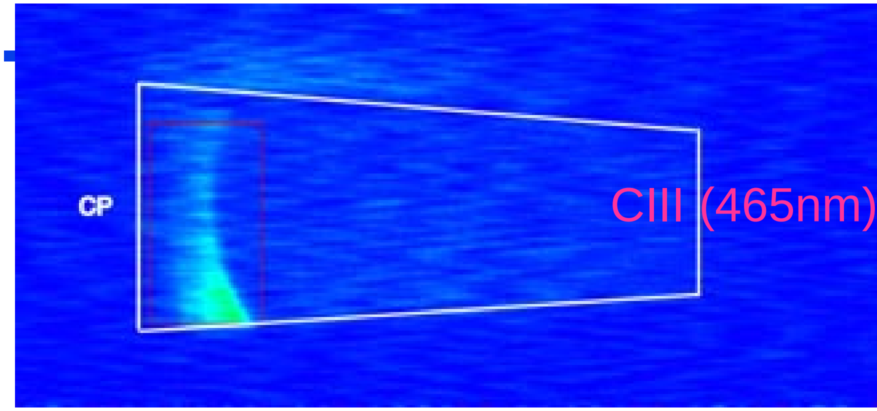


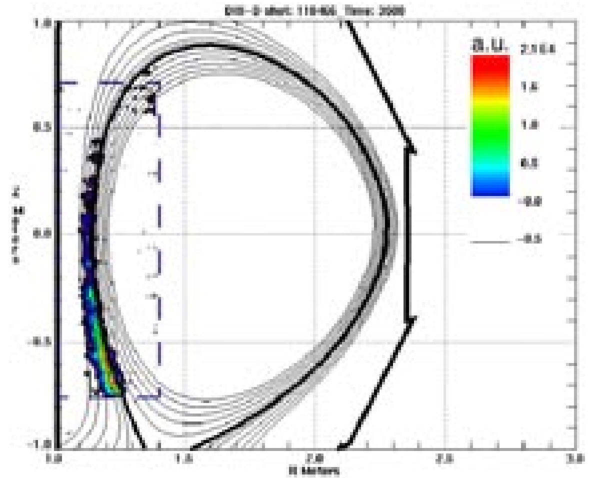


Abel inversion







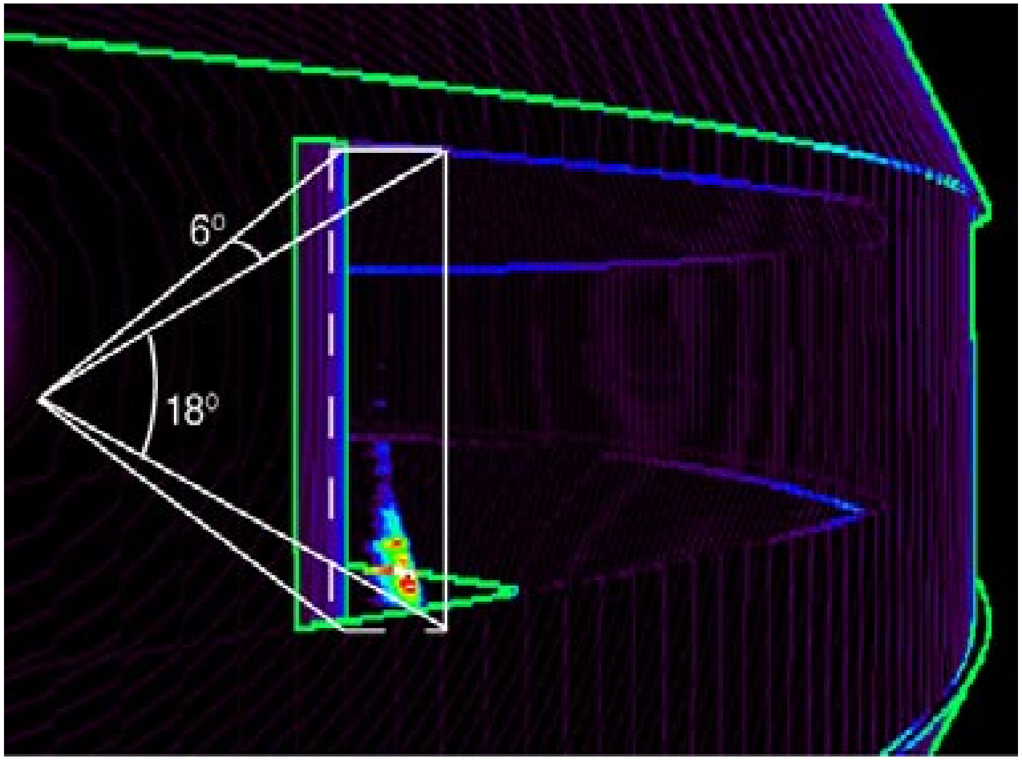


- Inversions produce narrow band of emission along separatrix
- D-alpha → CII → CIII: emission profiles narrow and extend further up poloidally along the inner SOL
- D-alpha emission found mostly inside separatrix; CII and CIII outside in SOL (whereby CIII closer to separatrix)

If mainchamber is the dominant source for deuterium, one would expect higher degree poloidal symmetry! Data suggest, however, that deuterium atoms escape from the divertor. Carbon requires more thought ...

How applicable is an Abel inversion ?

Viewing cone of midplane camera



– Camera = point observer, but parallel viewing cords required for Abel inversion

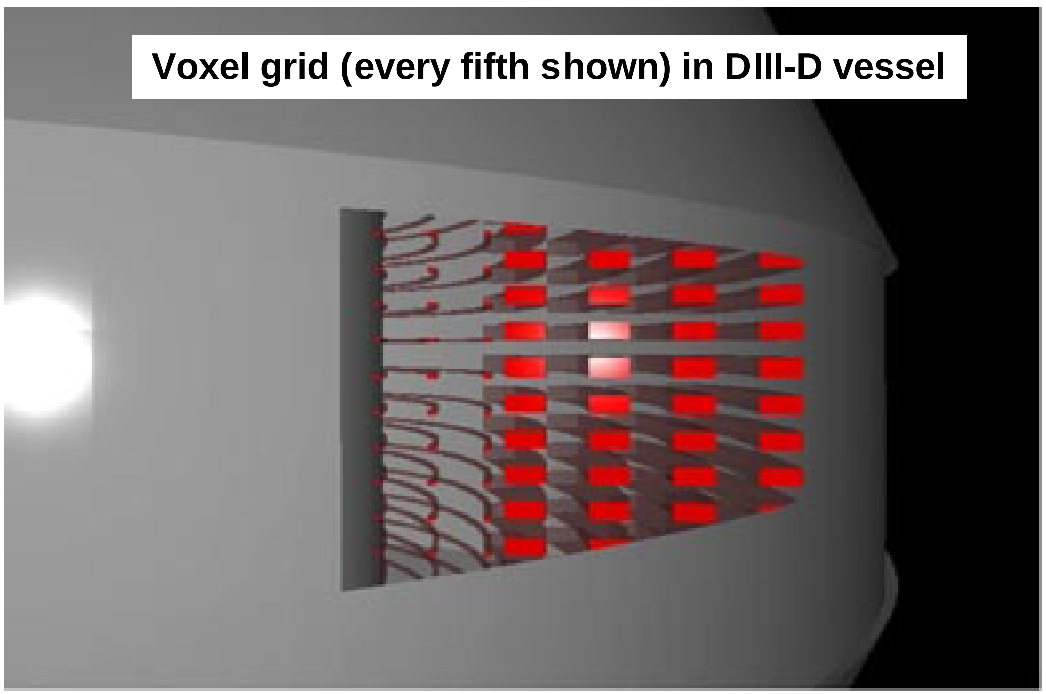
– Abel inversion approximation holds for horizontal cords near midplane

– In vertical direction, view cords span ~ 20° $\rightarrow$ intersect plasma that belong to various other horizontal planes

$\Rightarrow$ Appropriate analysis: Tomographic reconstruction

Midplane image data inversion - Method 2: Tomographic reconstruction

- DIII-D vessel and in-vessel spatial calibration → **POV-ray** (3D ray tracing code) → camera viewing geometry
- Geometry matrix elements = line-integrals taken from many points in space to each camera pixel

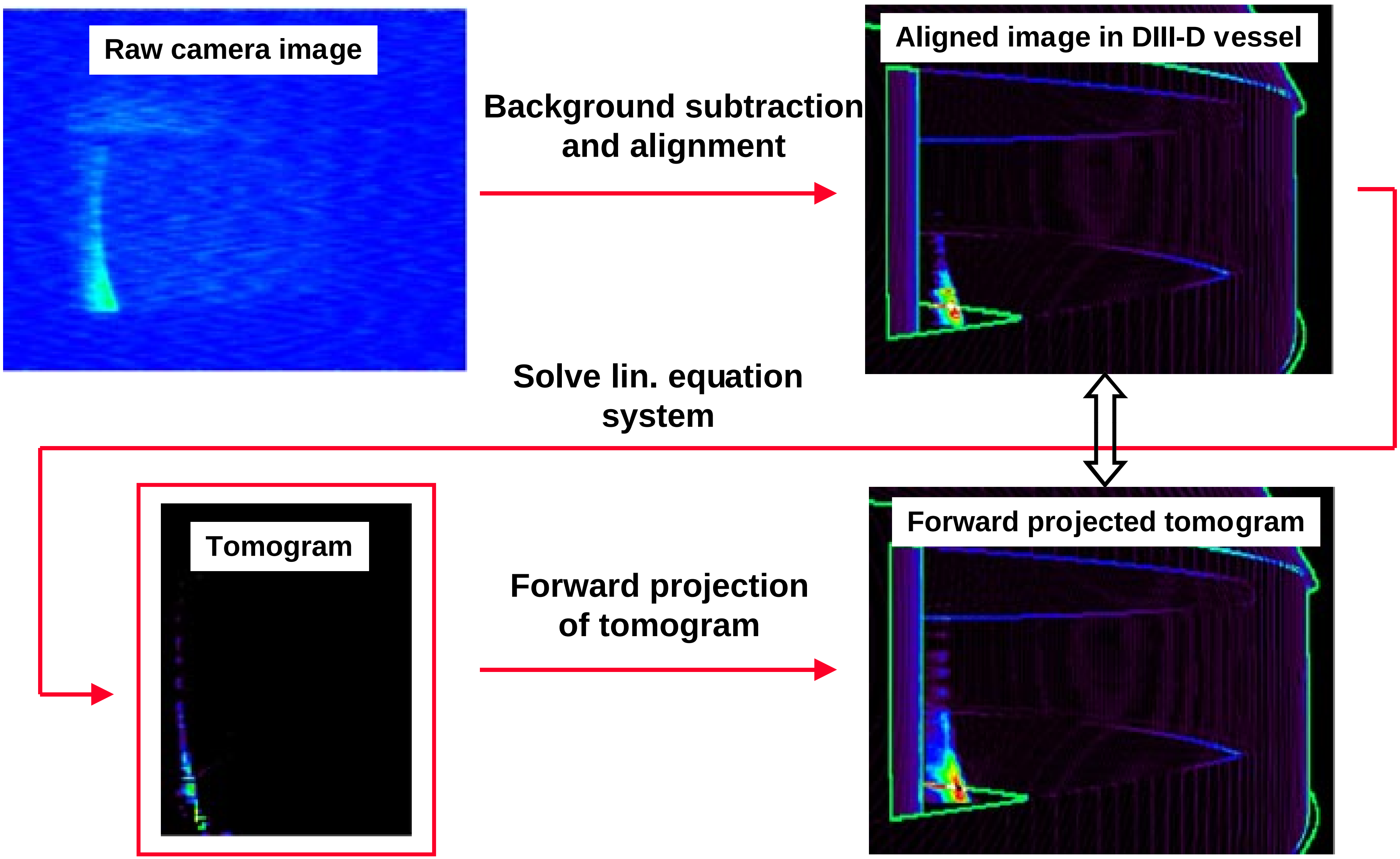


- Adaptive solution grid; fine resolution for inner SOL region (1.0m<x<1.3m), coarse grid for 1.3<x<2.4m

⇒ Pixel size for inner SOL region: 2cmx1.5cm, solved on 67x101 pixel grid

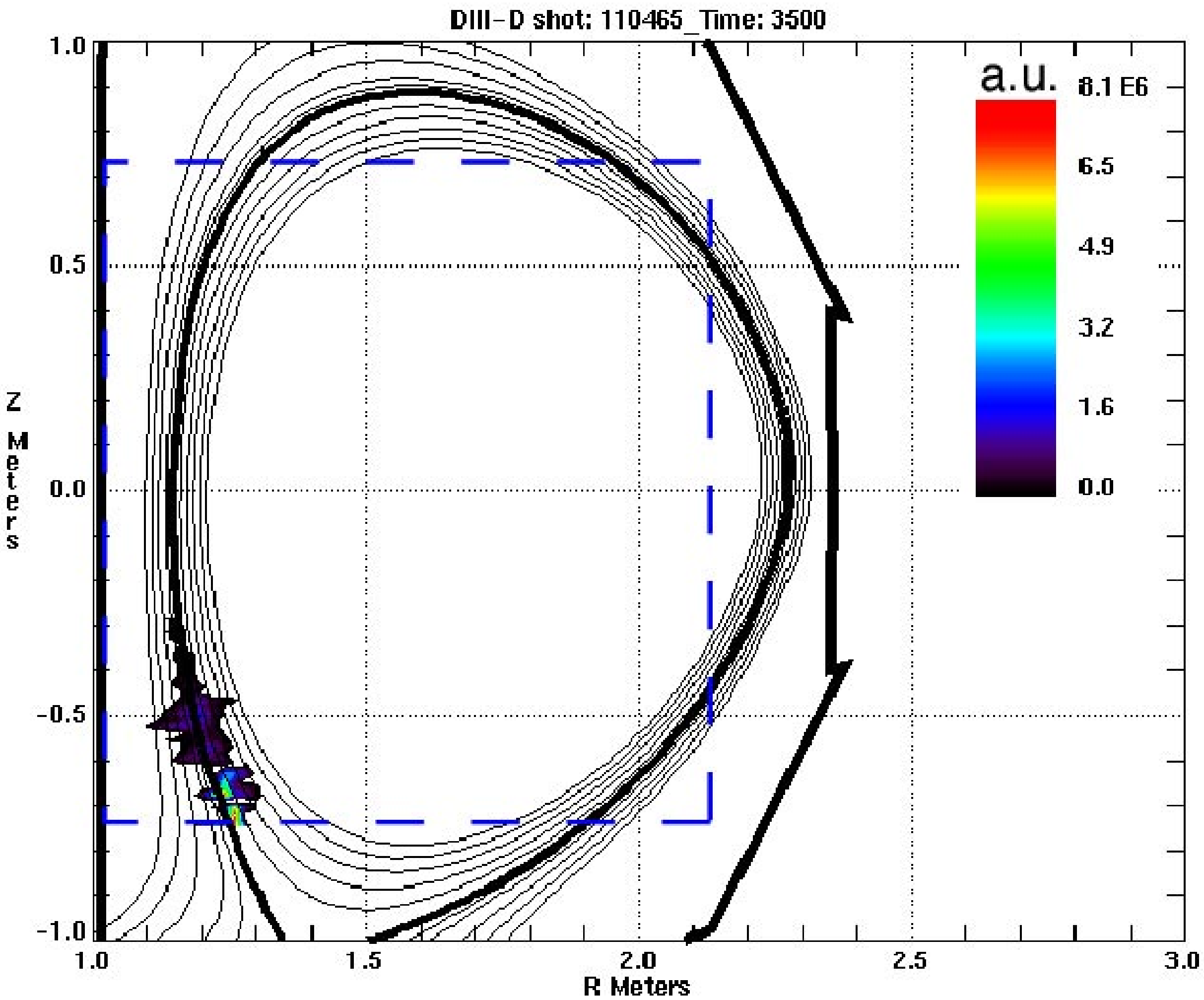
- Solve Ax=b; A=geometry matrix, b=image, x=solution
- SLATEC routines **SBOLS** and **WNNLS** to constrain solution to non-negative values
- Forward-project tomogram and compare with experimental image data

From the raw image data to the final tomographic reconstruction



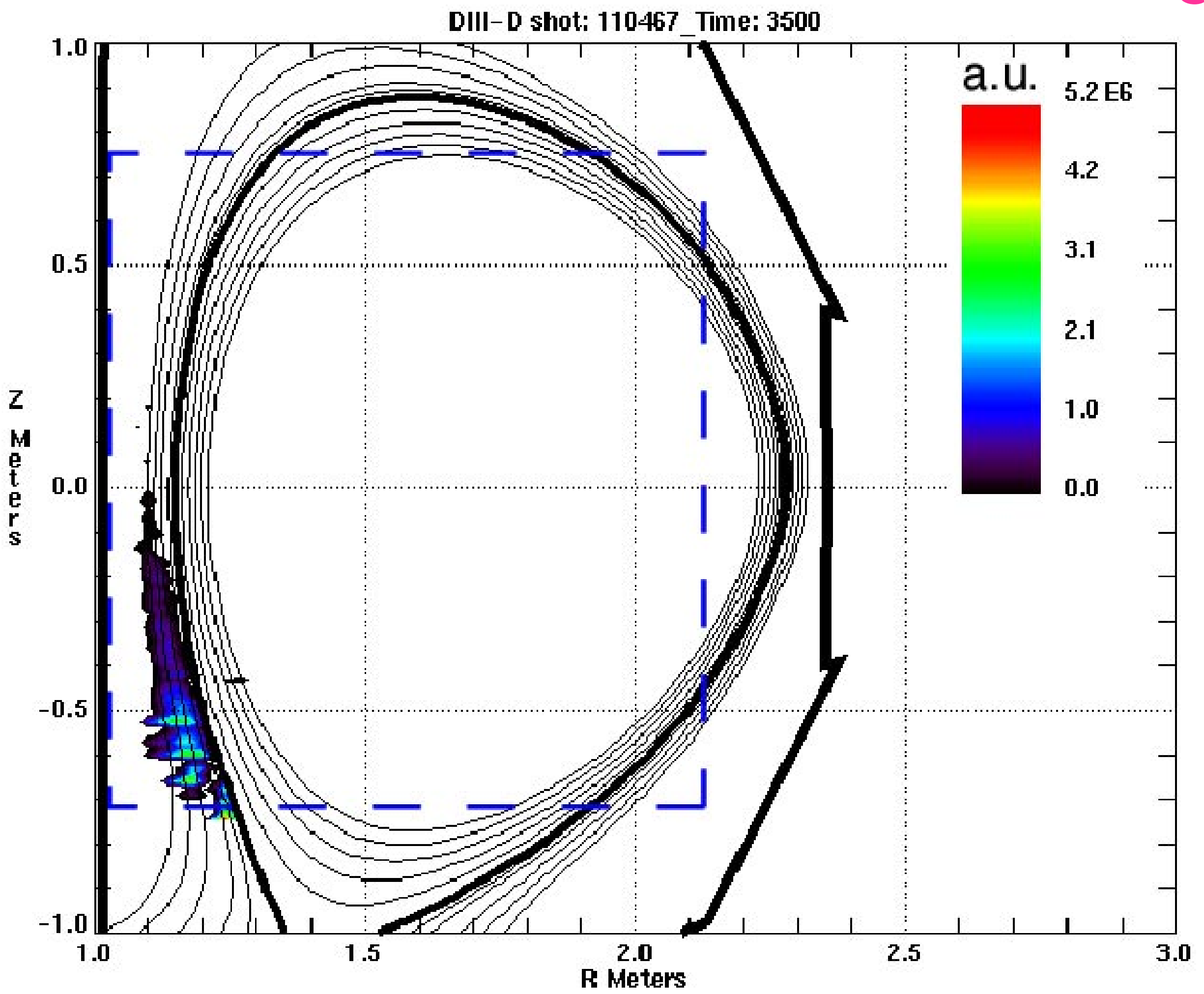
Tomographic reconstruction leads to similar conclusions as Abel inversions

D-alpha (656nm)



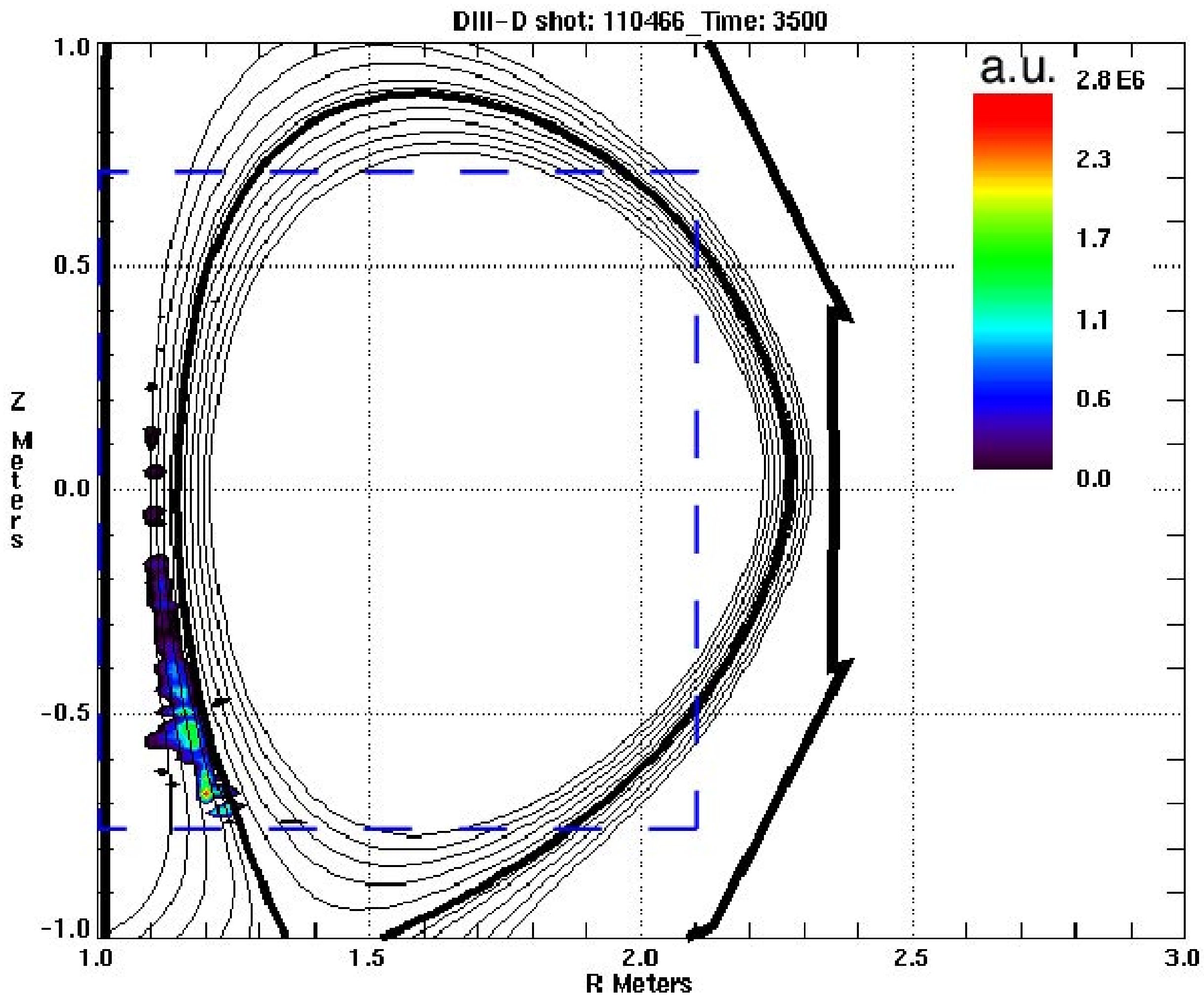
Deuterium-alpha, Carbon II and CIII emission profiles in low density SAPP (Method2)

CII (516nm)

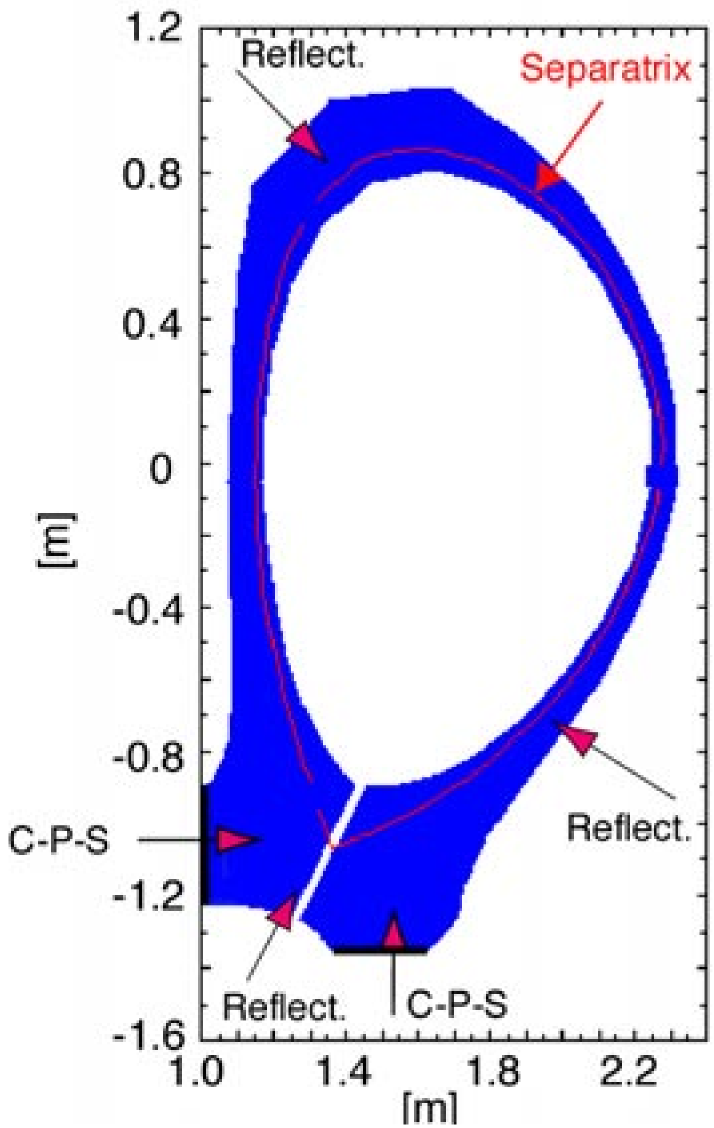


Deuterium-alpha, Carbon II and CIII emission profiles in low density SAPP (Method2)

CIII (465nm)



SAPP modeling of the SOL using UEDGE with purely diffusive radial transport prescription



- Classical parallel transport
- Diffusive radial transport, spatially constant diffusivities:
  - $D_\perp = 0.2 m^2/s$
  - $\chi_e = \chi_i = 0.8 m^2/s$
- Boundary conditions:
  - 100% hydrogen ion recycling at target
  - Neutrals reflected at wall surfaces; unity albedo in private flux region and divertor, above x-point albedo = 0.95

Force balance model for carbon impurities in parallel B-field direction

- Carbon origin
  - » Target plates: Physical and chemical sputtering (C-P-S) using Toronto database
  - » Chemical sputtering at outer grid boundary
- Carbon ions of each charge experience predominately friction force from deuterium ion flow into divertor and ∇T forces in opposite direction:

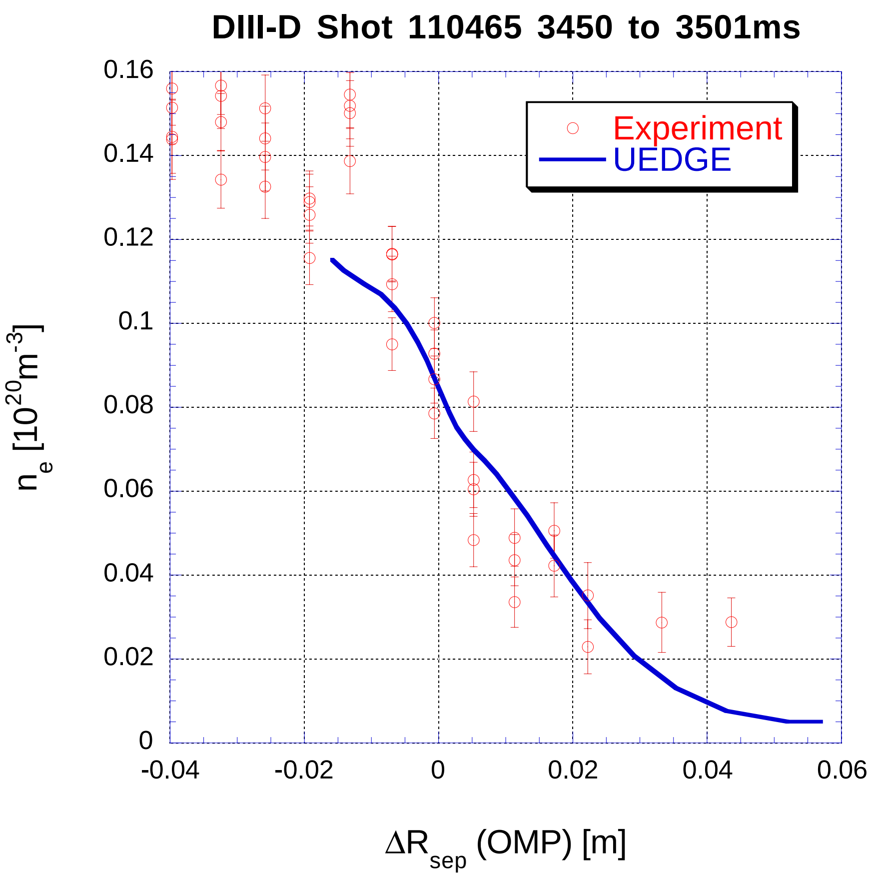
$$F_Z = -\frac{1}{n_Z}\frac{dp_Z}{ds} + \underbrace{m_Z\frac{(v_i - v_Z)}{\tau_{Spitzer}}}_{\text{Friction term}} + ZeE + \underbrace{\alpha_e\frac{d(kT_e)}{ds} + \beta_i\frac{d(kT_i)}{ds}}_{\nabla T\text{ term}}$$

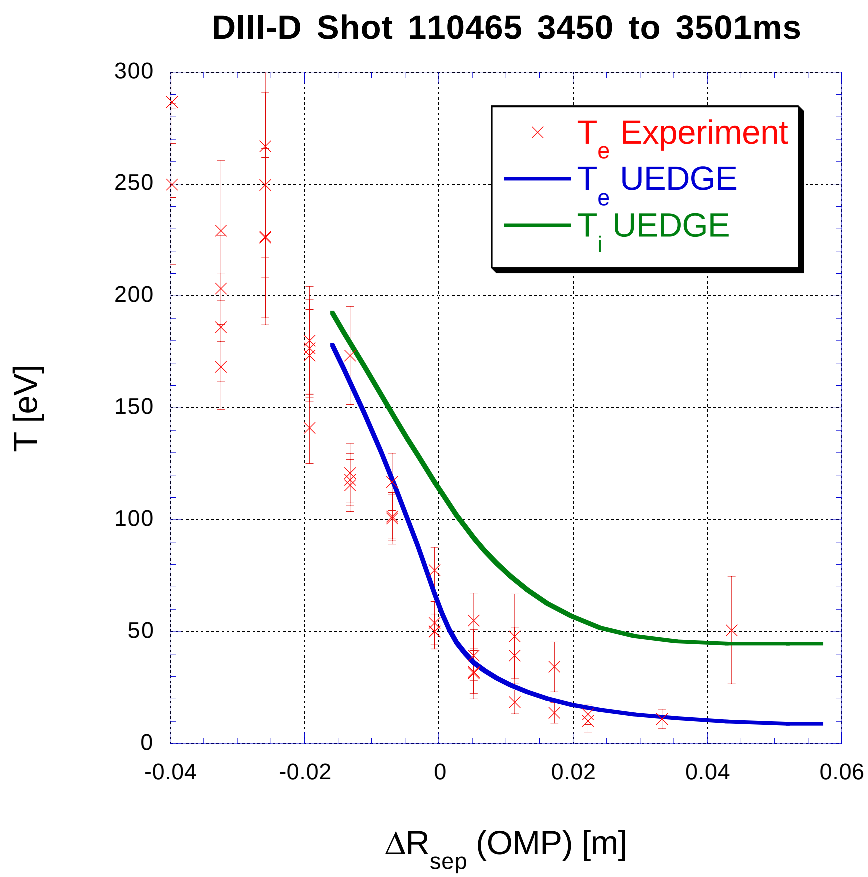
Comparison Experiment - UEDGE run MGa01
Global plasma parameter

	Experiment 110465	**UEDGE Run MGa01**
P_{sep}	781kW	764kW
$P_{rad,\ SOL+Div}$	426kW	200kW
$P_{plate,\ total}$	X	604kW
I_{plate}	X	0.55kA
N_{carbon} (MP)	$5x10^{16}\ m^{-3}$	$3.5x10^{16}\ m^{-3}$

Good match between the experiment and UEDGE upstream density and temperature profiles

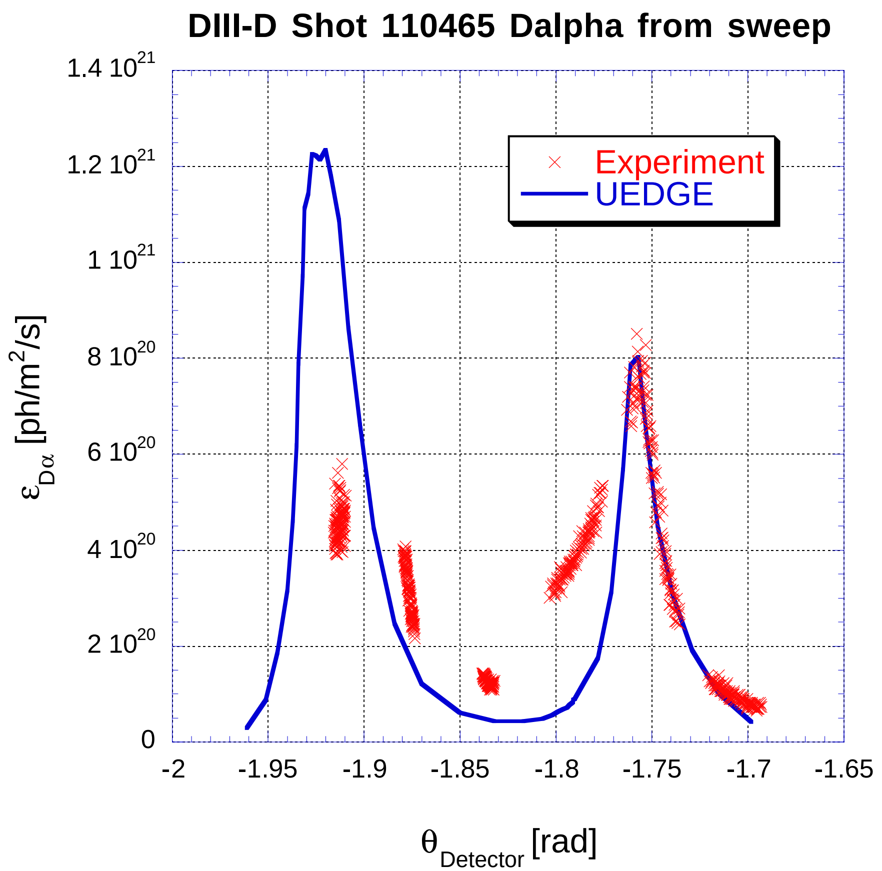
- UEDGE underestimates Far SOL upstream density by a factor of 6
- Better match of the temperature profile; $T_e < T_i$

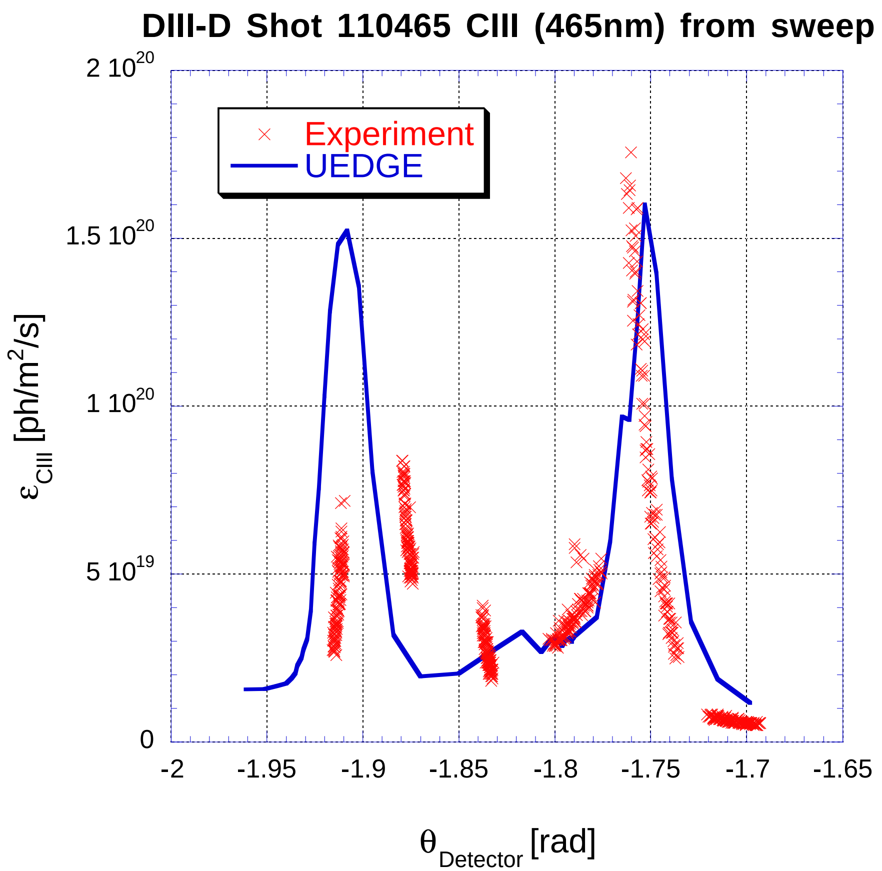




Vertical filterscope D-alpha and CIII profiles: UEDGE overestimates inner-leg emissivities

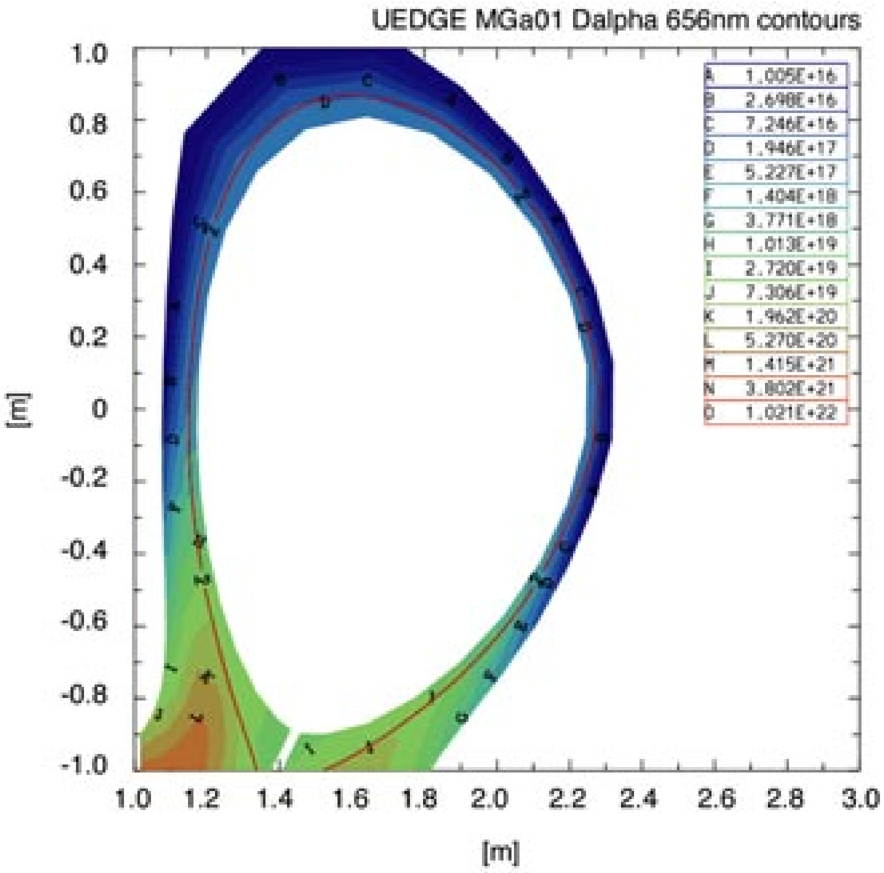
– Poor match of inner-leg D-alpha and CIII emissivities - Viewing geometry: Inner strike point position high up at the center post

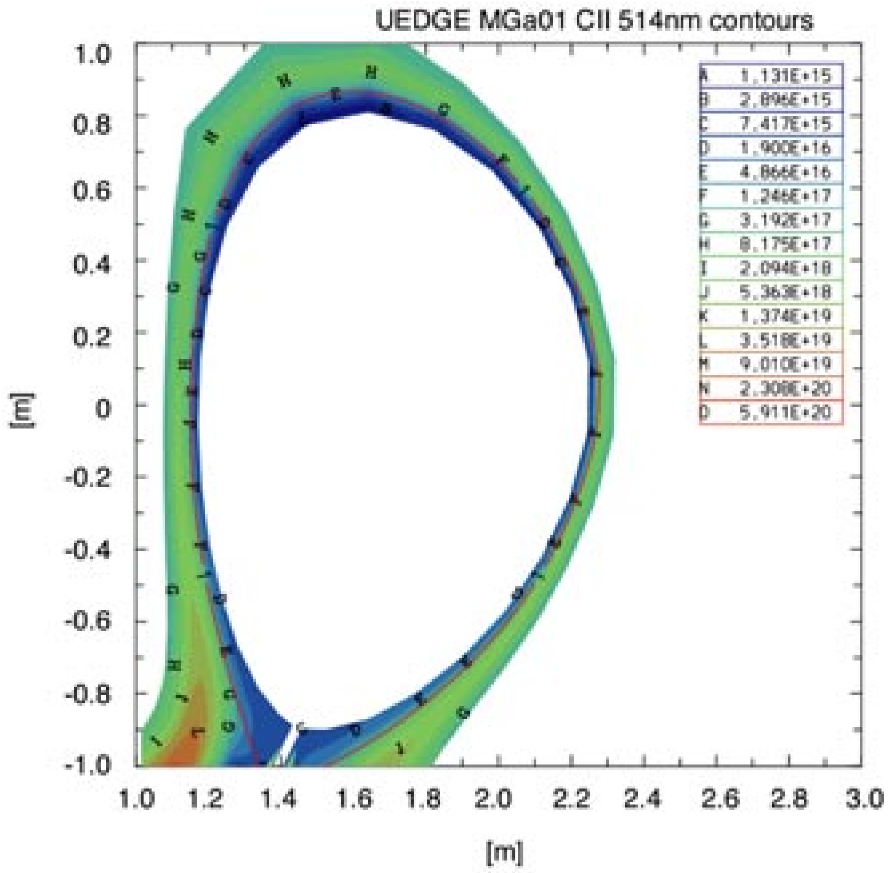


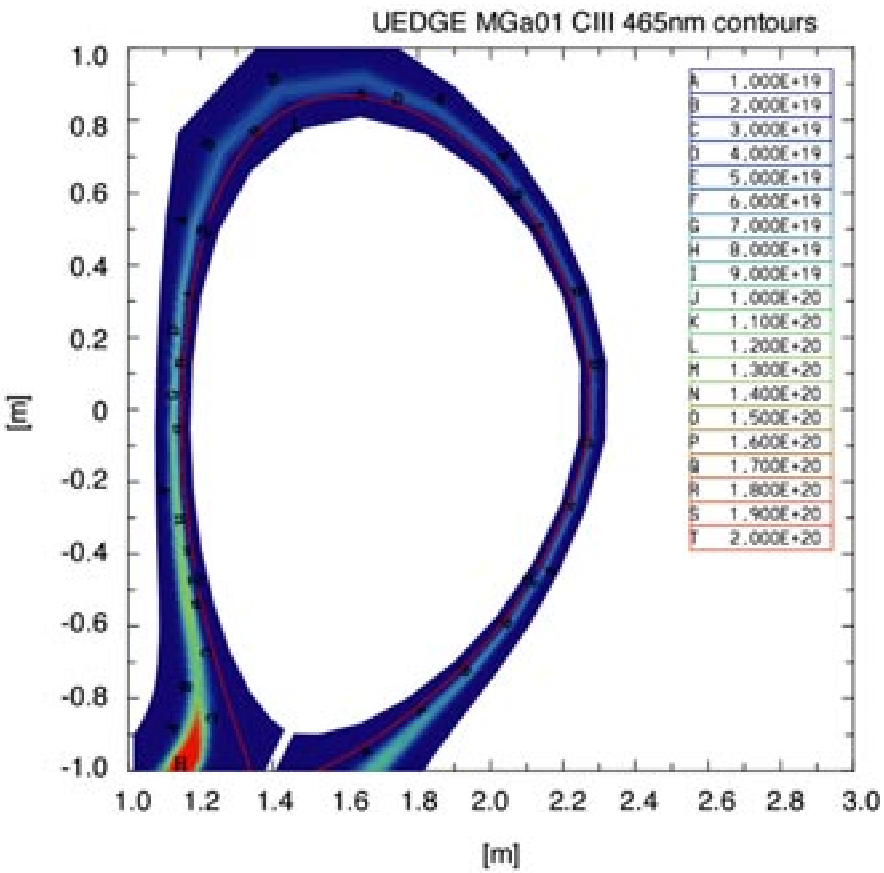


Well matched spatial distribution of observed and simulated D-alpha, CII, and CIII emission profiles

– Significant D-alpha emission occurs both inside and outside the separatrix, CII emission in the Far SOL







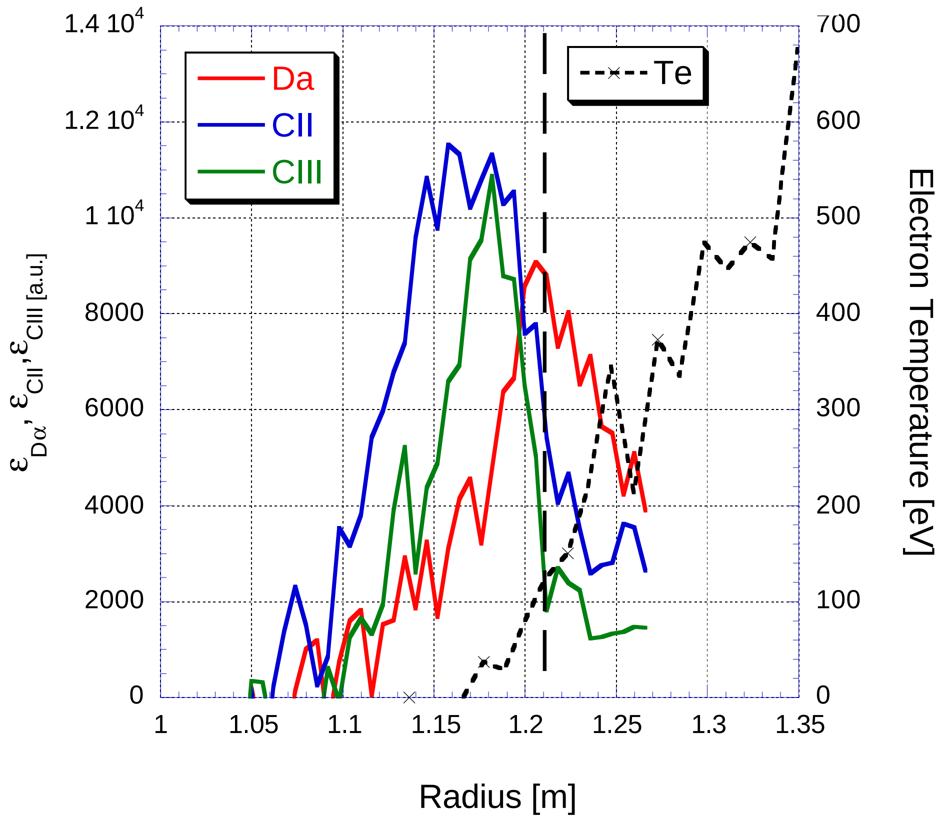
- CIII typically ‘maps’ Te=8-10eV contour
- D-alpha → CII → CIII: emission profiles narrow and extent poloidally along the inner SOL

Significant fraction of D-alpha emission from main plasma region

– Both reconstructed image data and UEDGE place D-alpha emission inside and outside the separatrix; CII and CIII outside

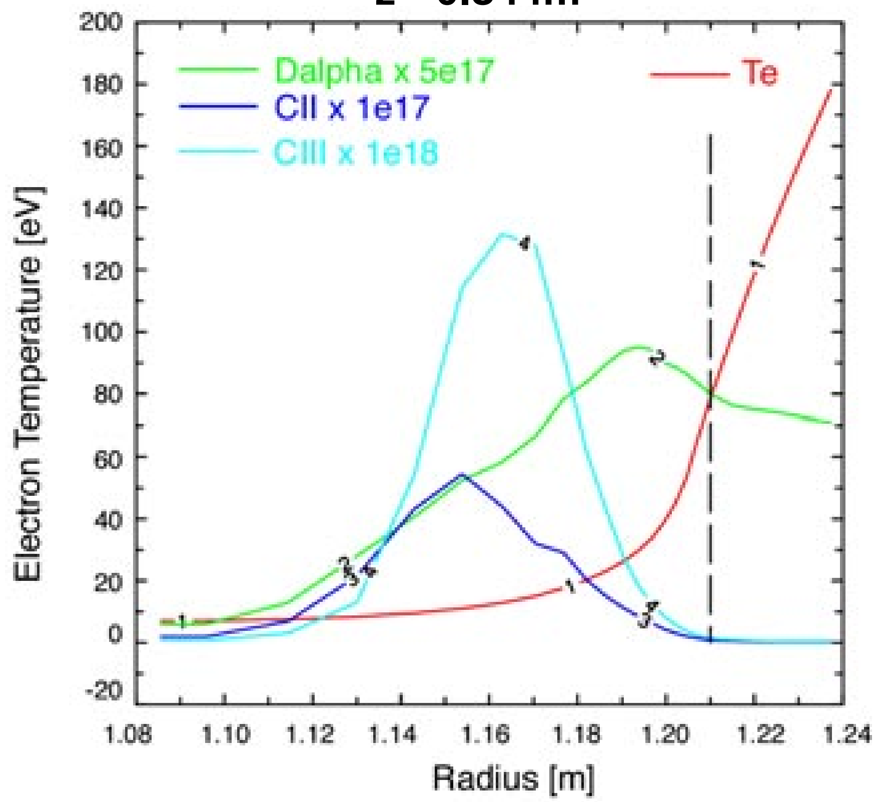
DIII-D Shot 110465/66/67

z=-0.54m



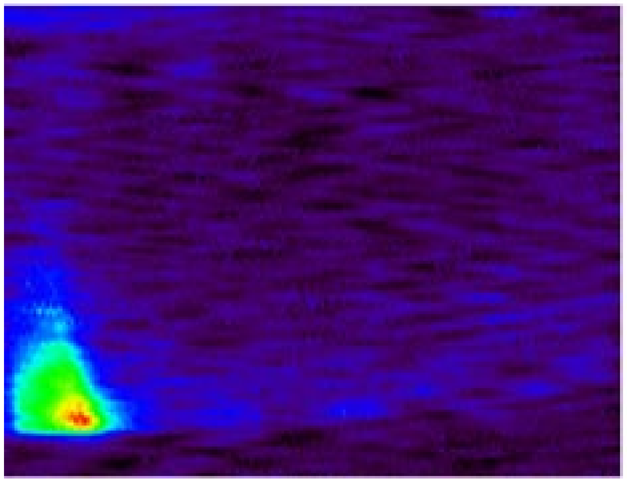
UEDGE Run MGa01

z=-0.544m

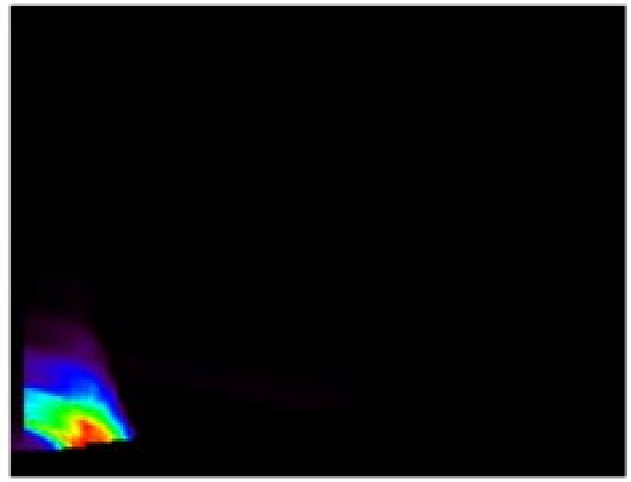


Simulated camera image from UEDGE agrees remarkably well with experimental data

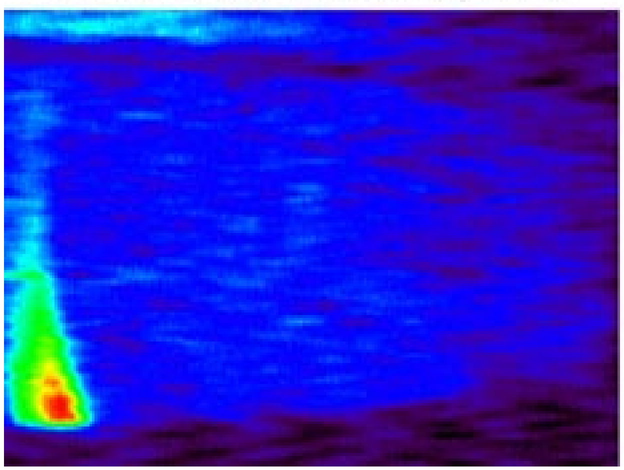
110465 Da 656nm Raw Image Data



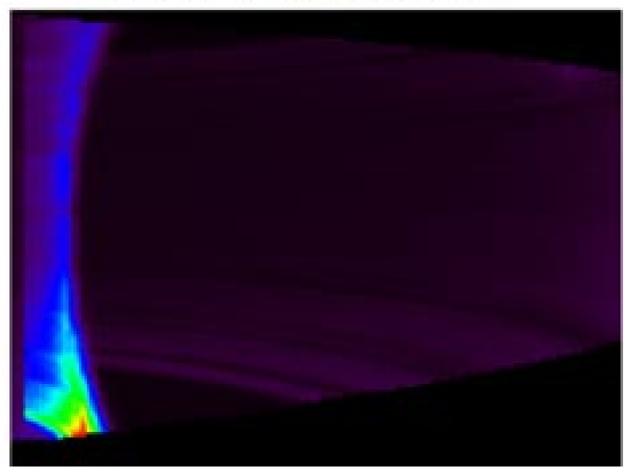
110465 Da 656nm UEDGE



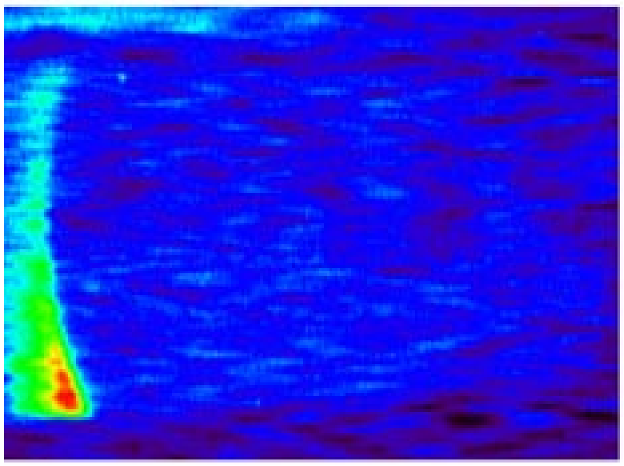
110467 CII 516nm Raw Image Data



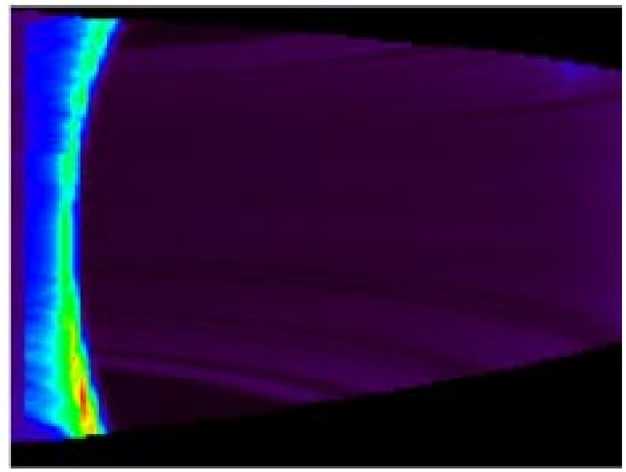
110467 CII 516nm UEDGE



110466 CIII 465nm Raw Image Data

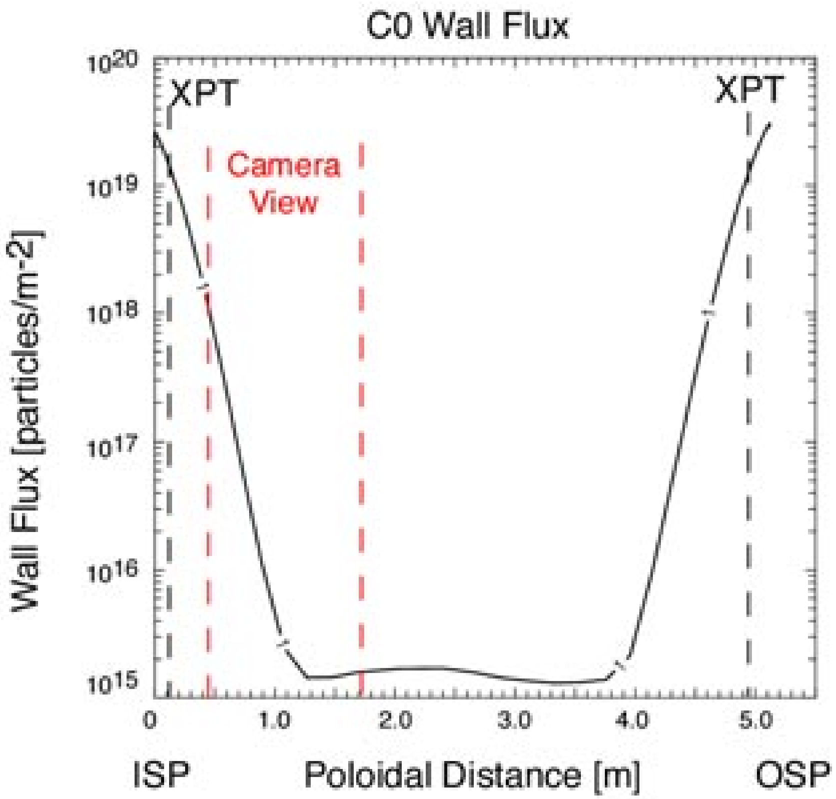


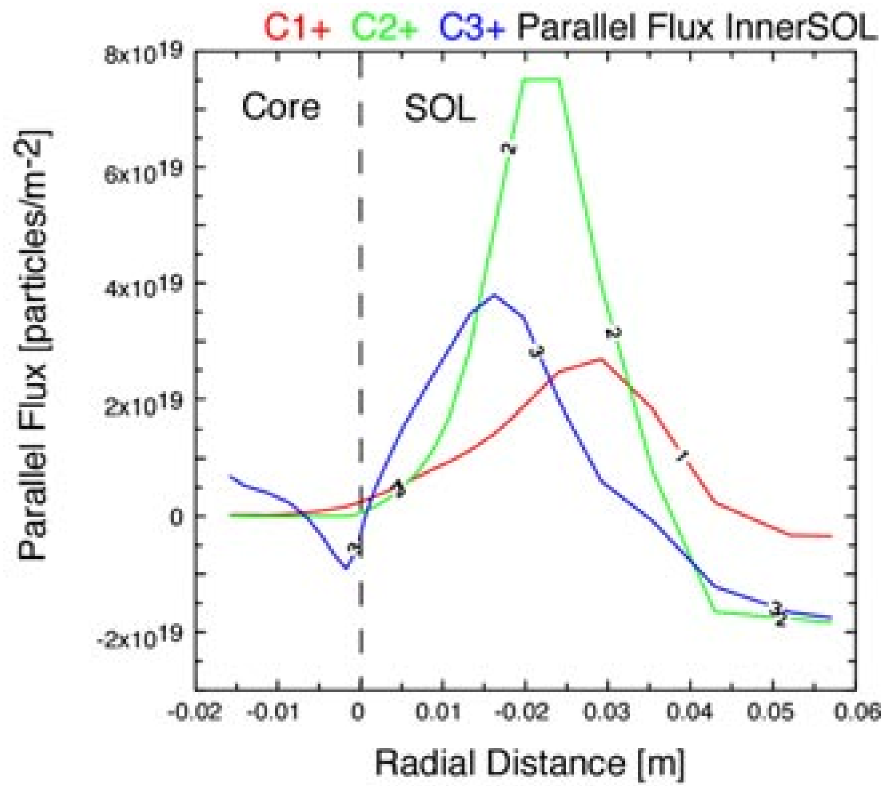
110466 CIII 465nm UEDGE



Carbon from the divertor and wall, transported into field-of-view by atomic and ionic leakage

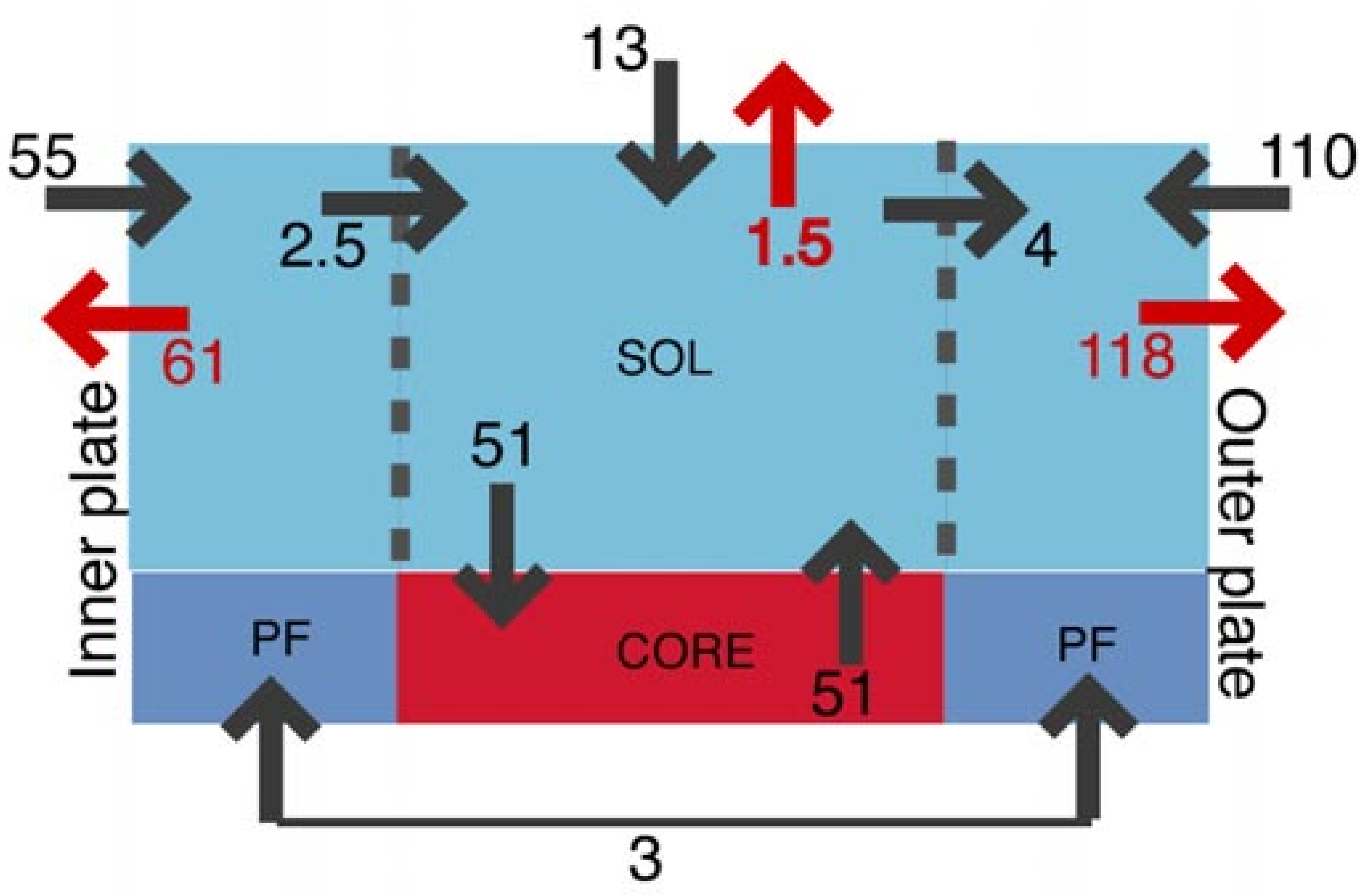
- In field-of-view, carbon neutral flux from inner wall is one order of magnitude lower than in divertor; still considerable source
- Carbon ion leakage from the divertor mainly in C^{2+} channel





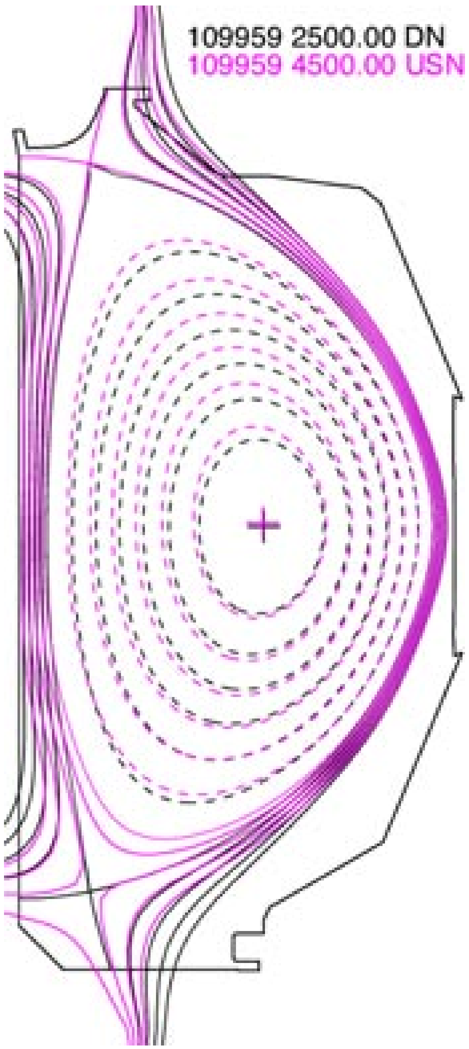
Carbon origin in camera field-of-view = mainchamber wall?

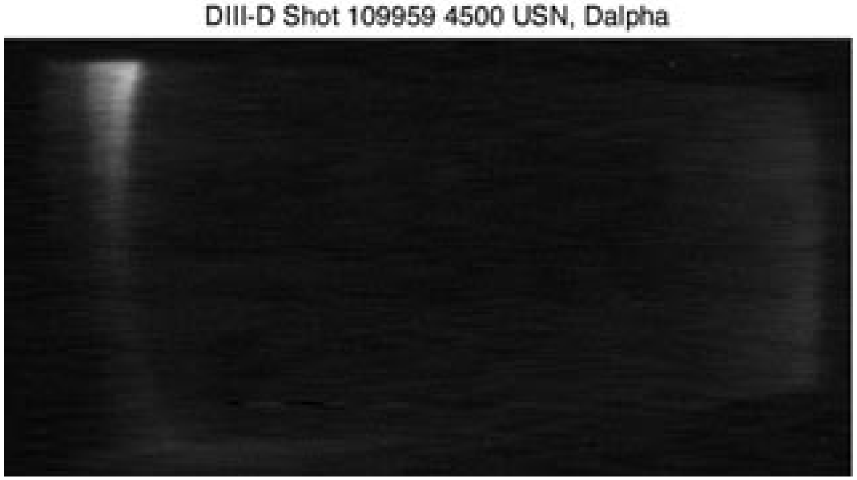
– Significant netflux of carbon into SOL from chemical sputtering of carbon by hydrogen atoms at mainchamber wall



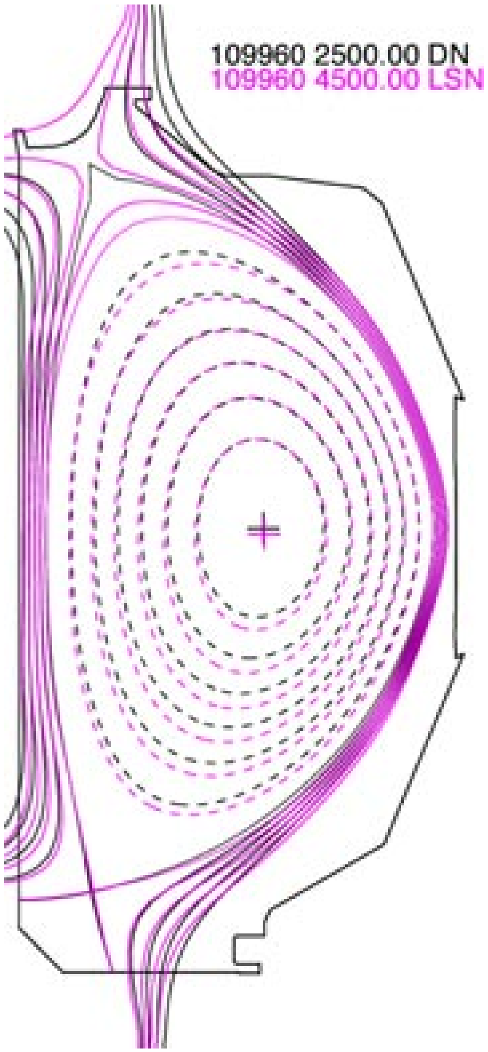
In mag. balance exp.: Shift of D-alpha emission profile towards primary divertor or ∇B direction ?

∇B ↑





$\nabla\mathbf{B}\uparrow$



DIII-D Shot 109959 2500 DN, Dalpha

DIII-D Shot 109959 4500 LSN, Dalpha