Supported by Office of Science

Recycling and particle fluxes in NBI-heated H-mode plasmas

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Acknowledgements:

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NSTX Liquid Lithium Divertor Design Meetings
24 April 2007
2 May 2007
Princeton, NJ

Motivation

Based on measurements available in NSTX…

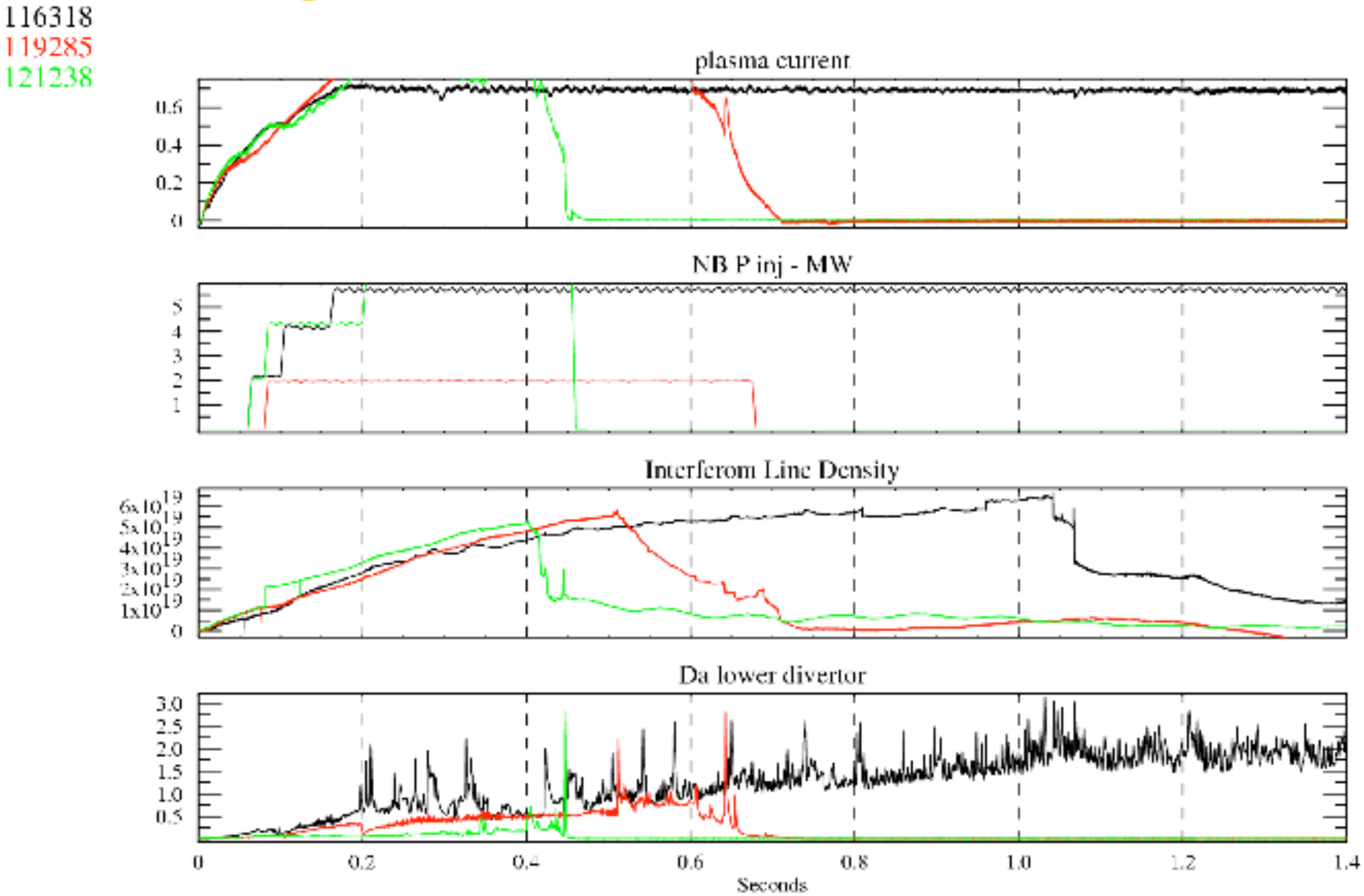
- Assess poloidal distribution of fueling sources
- Assess relative role of lower, upper divertor and "main chamber" recycling

- Provide input in liquid lithium divertor (LLD) module design
  - ✓ Input for 0D modeling
  - ✓ Assess optimal LLD module location and size
  - ✓ Assess expected impact of LLD on particle inventory

- Apply developed analysis to FY2006 LITER lithium evaporator experiments
  - ✓ Analyze ion source change in LITER experiments
  - ✓ Assess particle balance

Large effort!

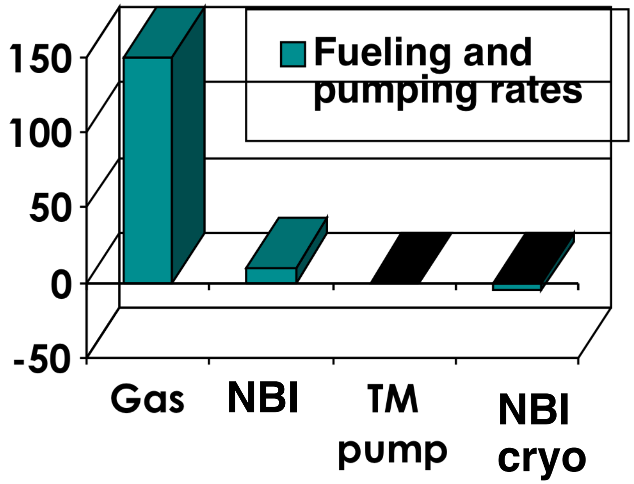
Three typical high-performance configurations are selected for analysis



Assess fueling sources in

- LSN shot 119285, 0.8 MA, 2 MW NBI, small ELMs, κ~2.0, δ=0.4 - "**Lower κ, δ LSN**"
- LSN shot 116318, 0.7 MA, 6 MW NBI, large ELMs, κ=2.2, δ=0.74 - "**Higher κ, δ LSN**"
- DN shot 121238, 0.8 MA, 6 MW NBI, small ELMs, κ=2.56, δ=0.8 - "**DN**"

External particle sources and sinks in NSTX



NSTX fueling source

- Gas injection: low field side (LFS, top + side) and high field side (HFS, midplane + shoulder), divertor. D_2, He, injected at S = 20 - 100 Torr l /s.
- Neutral beam injection system: three beams, 60 - 100 keV, 6-7 MW, fueling rate: S < 4 Torr l / s
- Supersonic gas injection S = 30 - 130 Torr l / s
- Wall (and divertor)

NSTX pumping

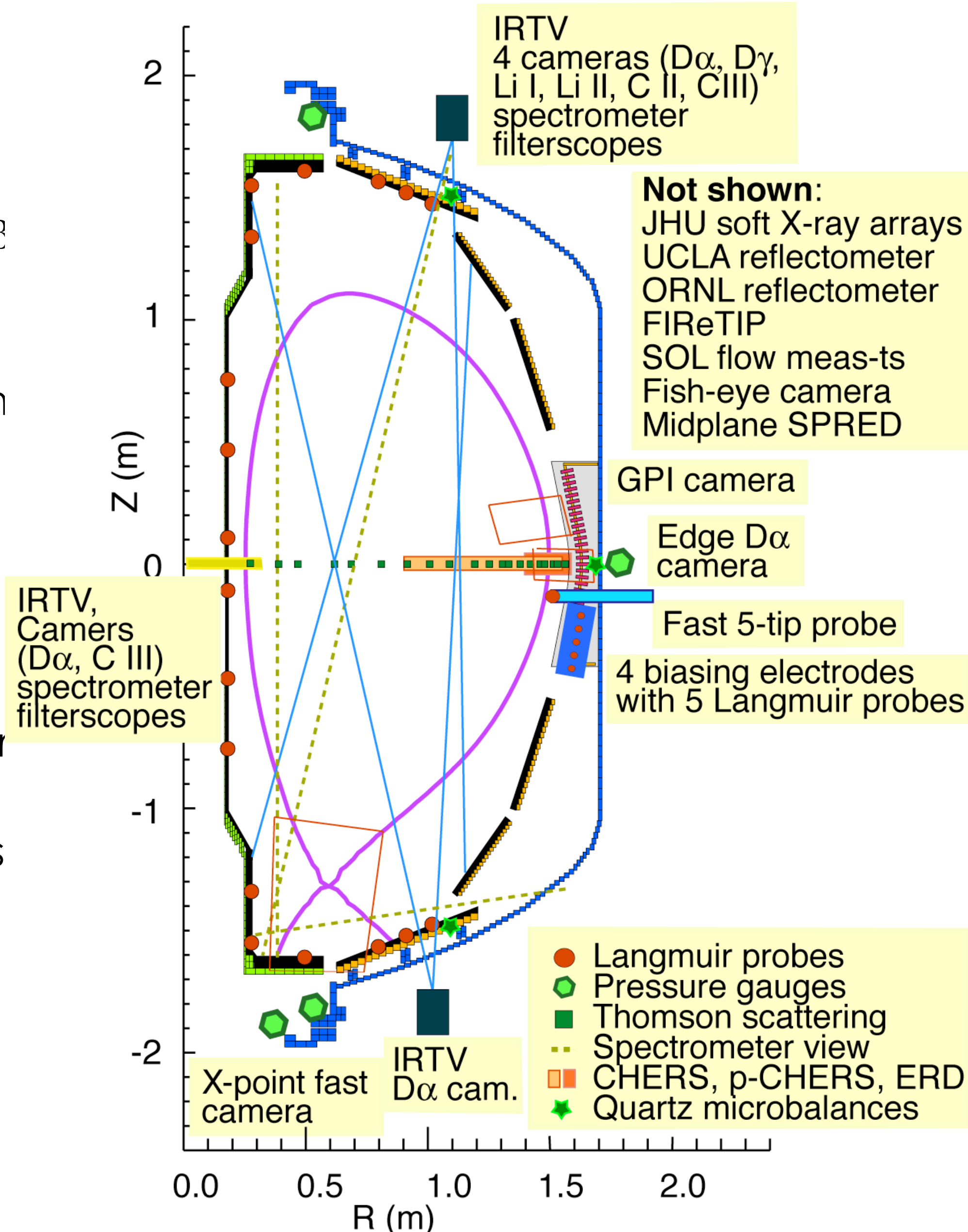
- Turbomolecular pump (S = 3400 l / s)
- NBI cryopump (S = 50000 l / s, in NBI-heated plasmas only)
- Conditioned walls

PFC

- ATJ graphite tiles on divertor and passive plates
- ATJ and CFC tiles on center stack

Spectroscopy, Langmuir probe and pressure gauges measurements are

- Deuterium emission
  - Lower divertor Dα camera
  - Lower divertor Dγ camera
  - Center stack midplane Dβ camera
  - Outer edge midplane 4-channel Dβ EIES (PMT) array
  - One channel tangential Dα EIES
  - Calibrated *in-situ* before/after each run year with a LabSphere radiometric standard
- Neutral pressure gauges
  - Not conductance limited
  - Penning gauges in lower and upper divertors
  - Several midplane micro-ion gauges
  - One top micro-ion gauge
- Plasma-wall interaction: 18 tile Langmuir probes
  - I_{sat} routinely available with few ms resolution



S/XB ratio technique is used to infer ionization source from spectroscopic Dα, Dβ measurements

$$\Gamma_{ph} = \int_{x_1}^{x_2} n_i\, n_e\, X\ B\, dx$$

- Technique originally developed by L. C. Johnson & E. Hinnov, and further by A. Kallenbach
- Used for deuterium and impurities

$$\frac{\partial n_i}{\partial t} + \frac{\partial}{\partial x}(v_i\, n_i) = S^{i-1}\, n_e\, n_{i-1} - S^i\, n_e\, n_i$$

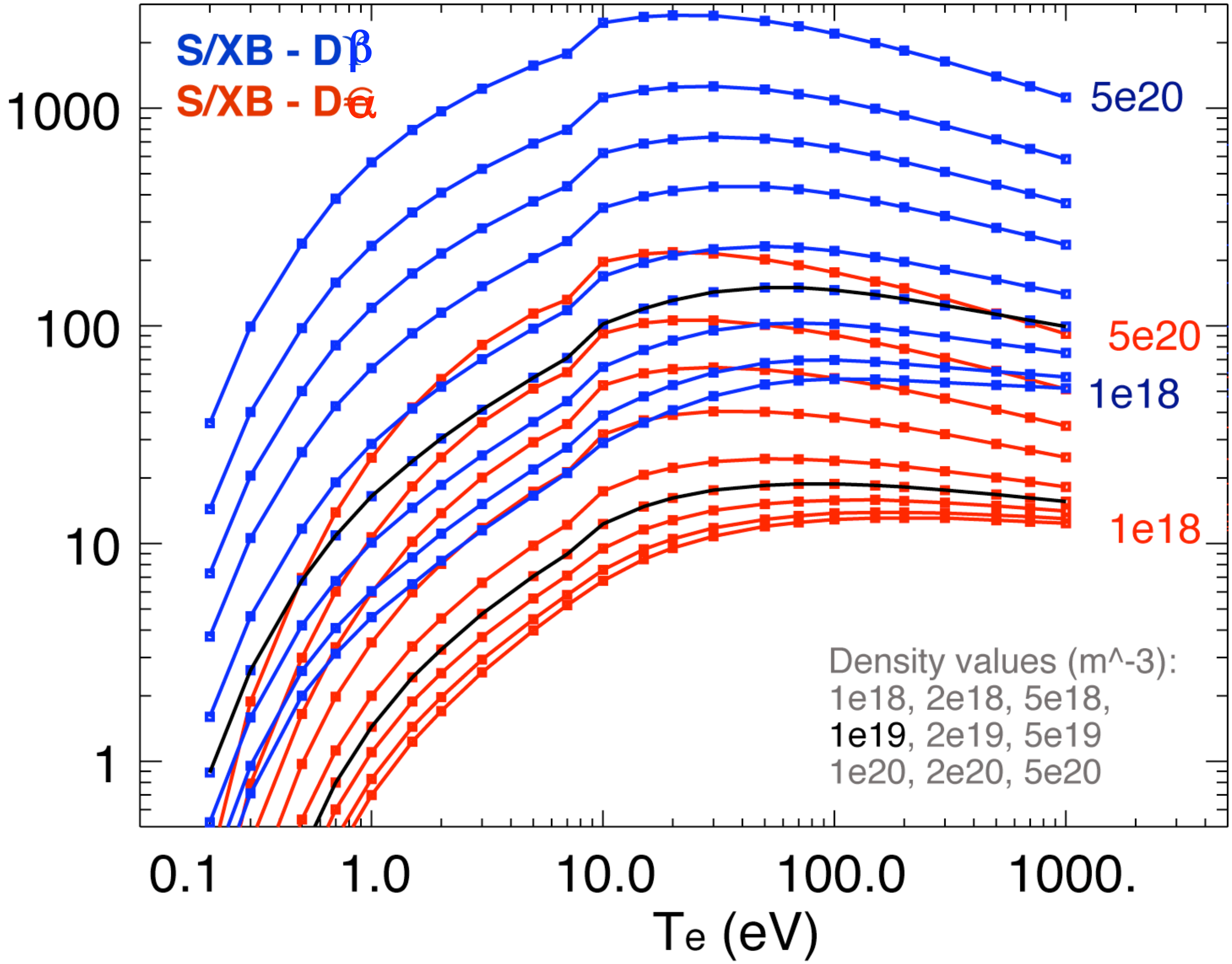
$$\Gamma_{ph} = -\frac{X\ B}{S^i}\left(v_i\, n_i|_{x_1}^{x_2} - \int_{x_1}^{x_2} S^{i-1} n_{i-1}\, n_e\, dx + \int_{x_1}^{x_2} \frac{\partial n_i}{\partial t}\, dx\right)$$

$$\Gamma_i = -v_i\, n_i|_{x_1}^{x_2} + \int_{x_1}^{x_2} S^{i-1} n_{i-1}\, n_e\, dx$$

$$\Gamma_i = \frac{S}{X\ B}\,\Gamma_{ph}$$

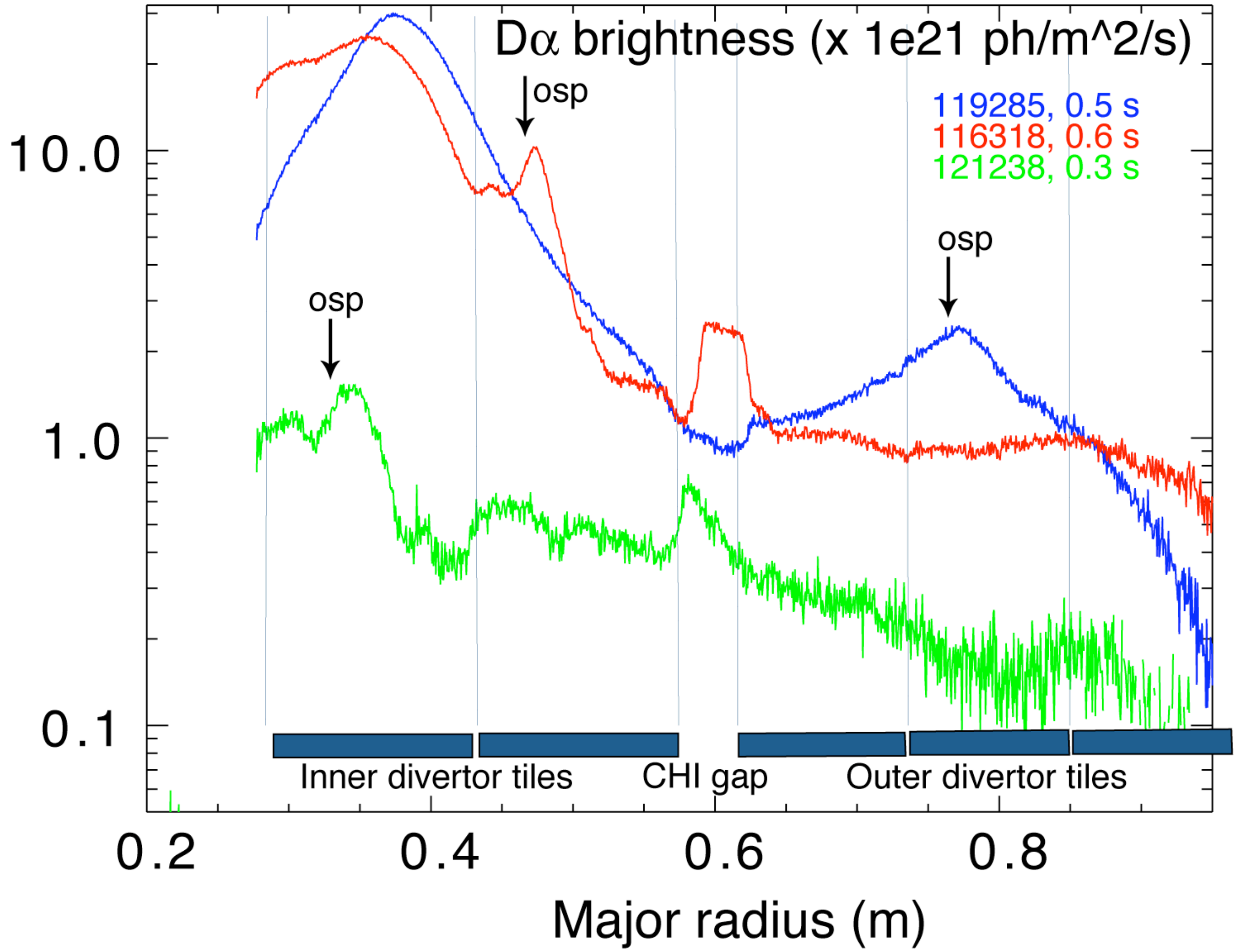
- 1D viewing geometry
- x_1- recycling / erosion boundary, x_2 - detector location
- Recombination neglected
- Excitation and ionization occur in the same volume
- Steady-state condition

S/XB ratio technique is used to infer ionization source from spectroscopic Dα, Dβ measurements



- From ADAS database (courtesy of ORNL Controlled Fusion Atomic Data Center (CFADC))

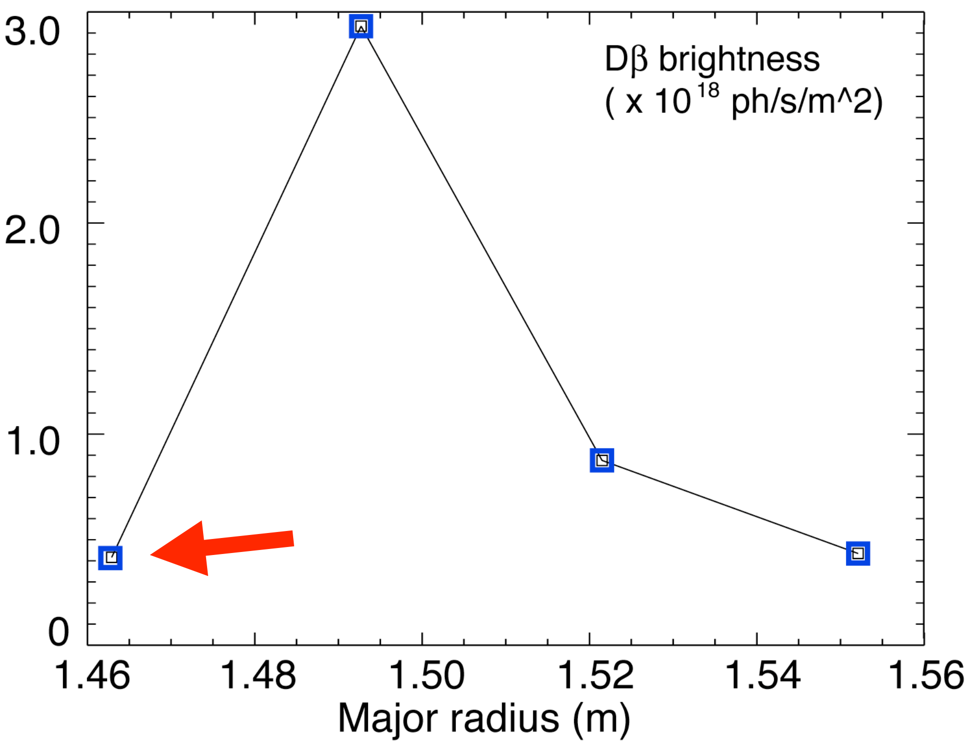
Lower divertor sources and sinks are inferred from deuterium emission profiles

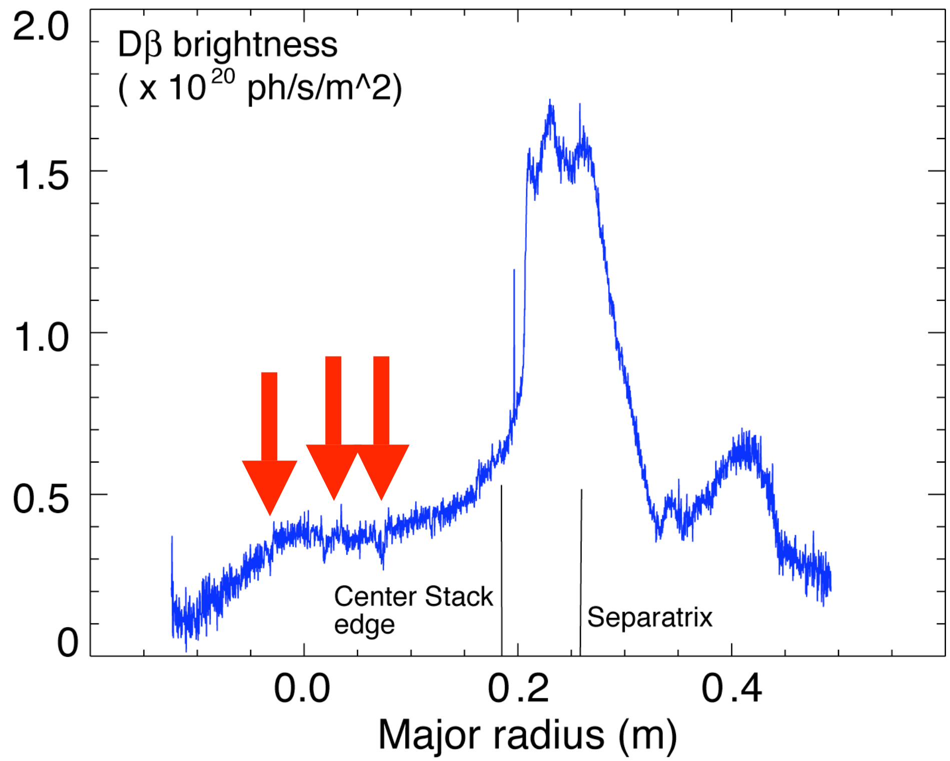


- Reflections in outer divertor small (<10 %), in inner divertor higher
- Private flux region fluxes not presently considered
- Future work: use Dγ profile to infer inner divertor sink using recombinations / Dγ photon

- Outer strike point attached - use S/XB ratio of 20 ionizations / Dα photon
- Inner strike point detached, use S/XB ratio of 1-2 ionizations / Dα photon

Midplane center stack recycling is much higher than outer midplane edge recycling





- Outer SOL Dβ EIES array
  - Too few points for Abel inversion, typically all outside separatrix
  - Take innermost point and use as "radial" view

- Inner SOL Dβ profile from 1D CCD camera
  - Inversion difficult due to reflections / poor background coverage
  - No T_e and n_e measurements in inner SOL
  - Use values of emission in tile gaps to reduce effects due to reflections

Atomic and molecular fluxes are inferred from neutral pressure measurements

$$\Gamma_{D_2} = \frac{1}{4} n_{D_2} \bar{v} \qquad \bar{v} = \sqrt{\frac{8kT}{\pi m}} \qquad P = n\, kT$$

$$\Gamma_D = 2 \times \frac{1}{2} \times \Gamma_{D_2} = \frac{1}{4} \frac{P}{kT} \sqrt{\frac{8kT}{\pi m}}$$

- "Standard" way to estimate molecular / atomic fluxes from neutral pressure measurements
- Might be about factor of 2-3 overestimated (comes from comparisons to MC simulations and / or kinetic simulations)
- Typical midplane pressure $P < 0.1$ mTorr, lower divertor $P < 1$ mTorr
- Inferred midplane Γ_d in agreement within factor of 1 -5 with Γ_i from midplane Dβ measurements

Plasma ion out-flux is inferred from tile Langmuir probes

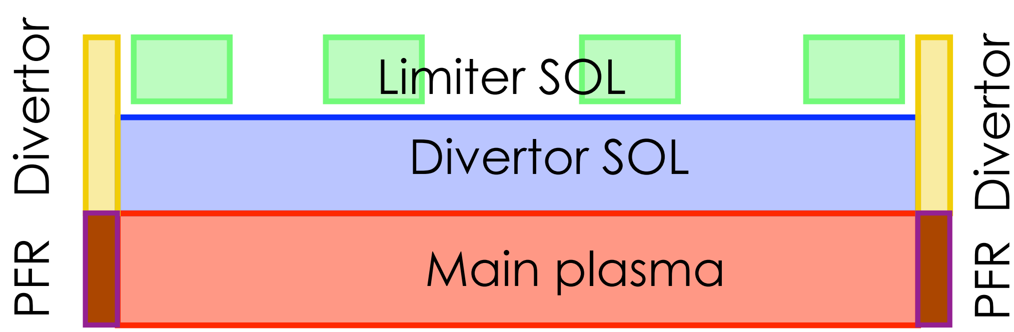
- I_{sat} data available for nearly all 2005 - 2007 shots

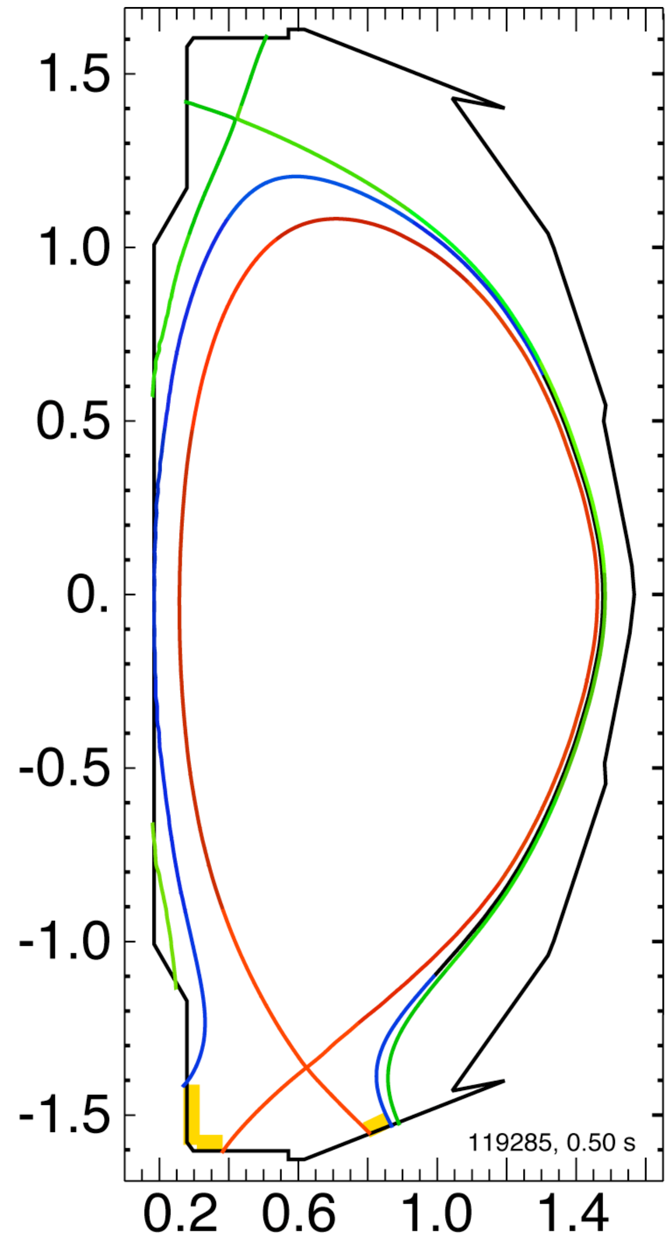
$$j_{sat} = \frac{I_{sat}}{A_{pr} \sin \alpha} \qquad \Gamma_i = j_{sat}/e$$

- Tile Langmuir probes are flush-mounted
- Main computational effort is to calculate α's accurately
- For very shallow angles ($\alpha < 1\text{–}2^o$) will use Gunn's probe sheath expansion model. At present uncorrected j_{sat} are used
- Inferred fluxes will be used to assess main wall flux according to the "window frame" technique

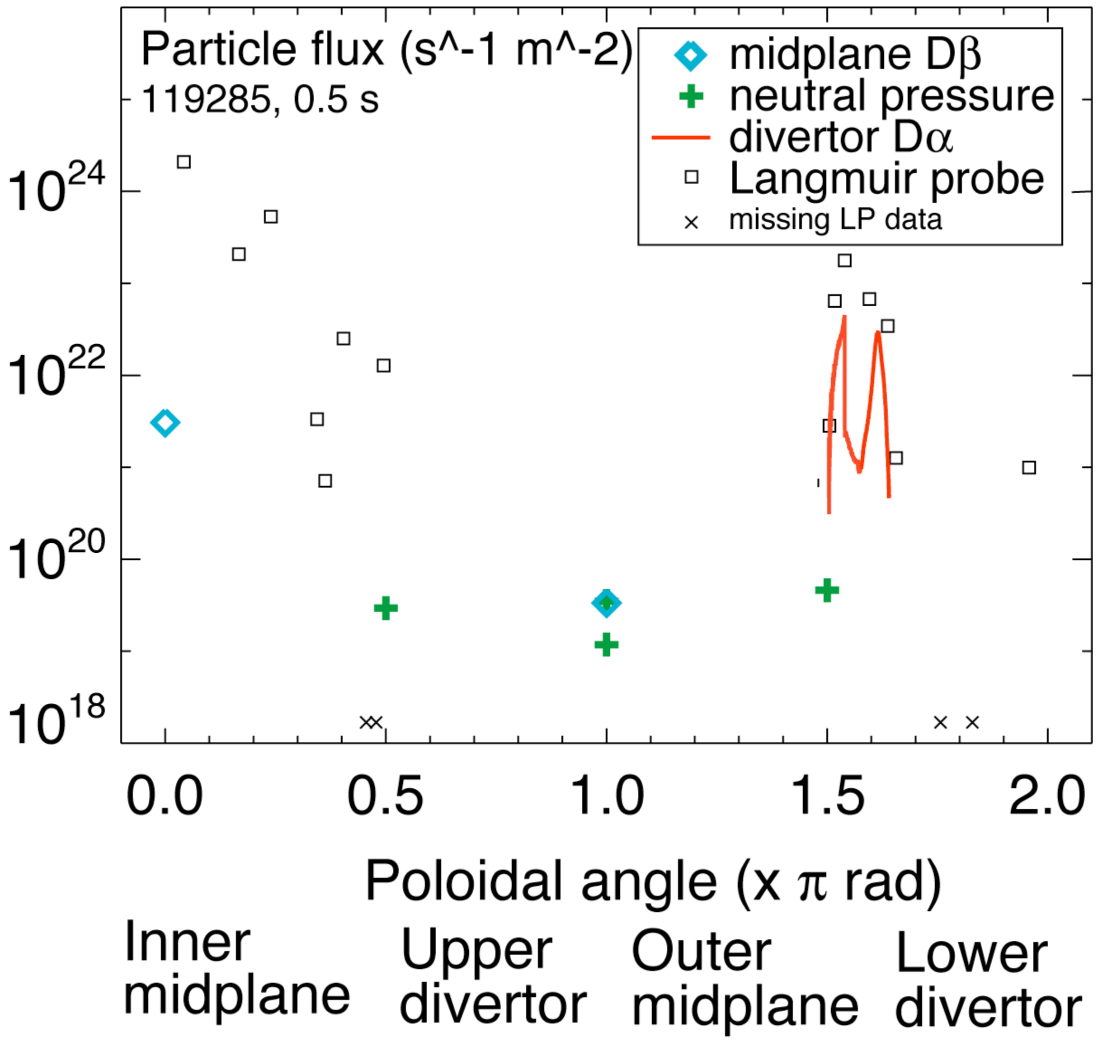
“Window frame” technique will be used for main chamber particle flux estimate

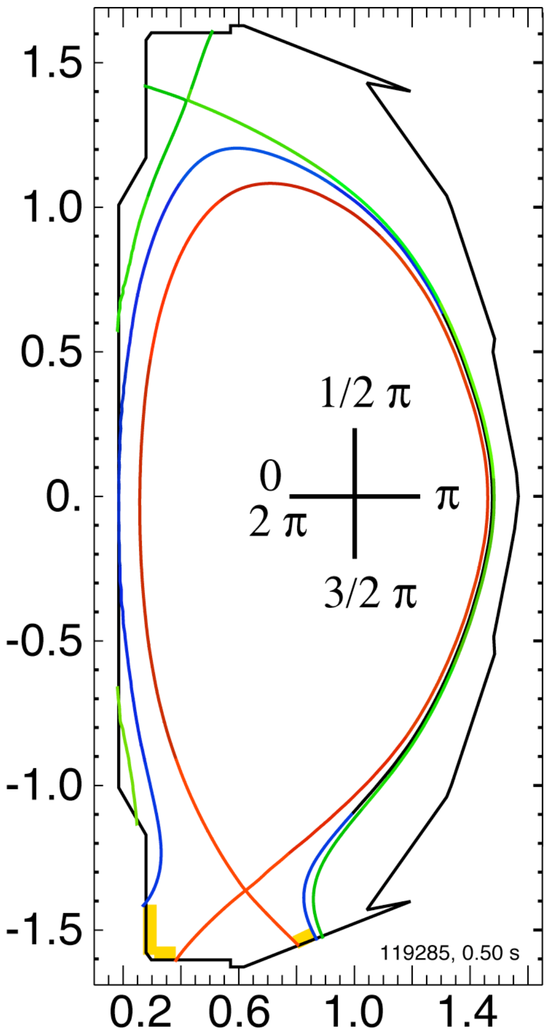
- “Window frame” technique developed by P. C. Stangeby, D. G. Whyte et. al.
- Define “divertor SOL” as region between | | (full line connection from plate to plate)
- Define “main chamber wall” at DivSOL boundary | where connection length abruptly decreases
- Use Langmuir probes to infer plasma flux $\Gamma_{//}$ on “window pane”, then convert to Γ_{perp} through “window frame” (future work)
- At present, use less accurate method - use spectroscopy and neutral pressure measurements to infer recycling / neutral fluxes from main wall at 3 locations:
  - Inner wall (CS) - from Dβ
  - Upper divertor / top - from pressure gauge
  - Outer wall - from Dβ and pressure gauge
- Prescribe smooth poloidal profile for “main wall” based on three point measurements and top stagnation point





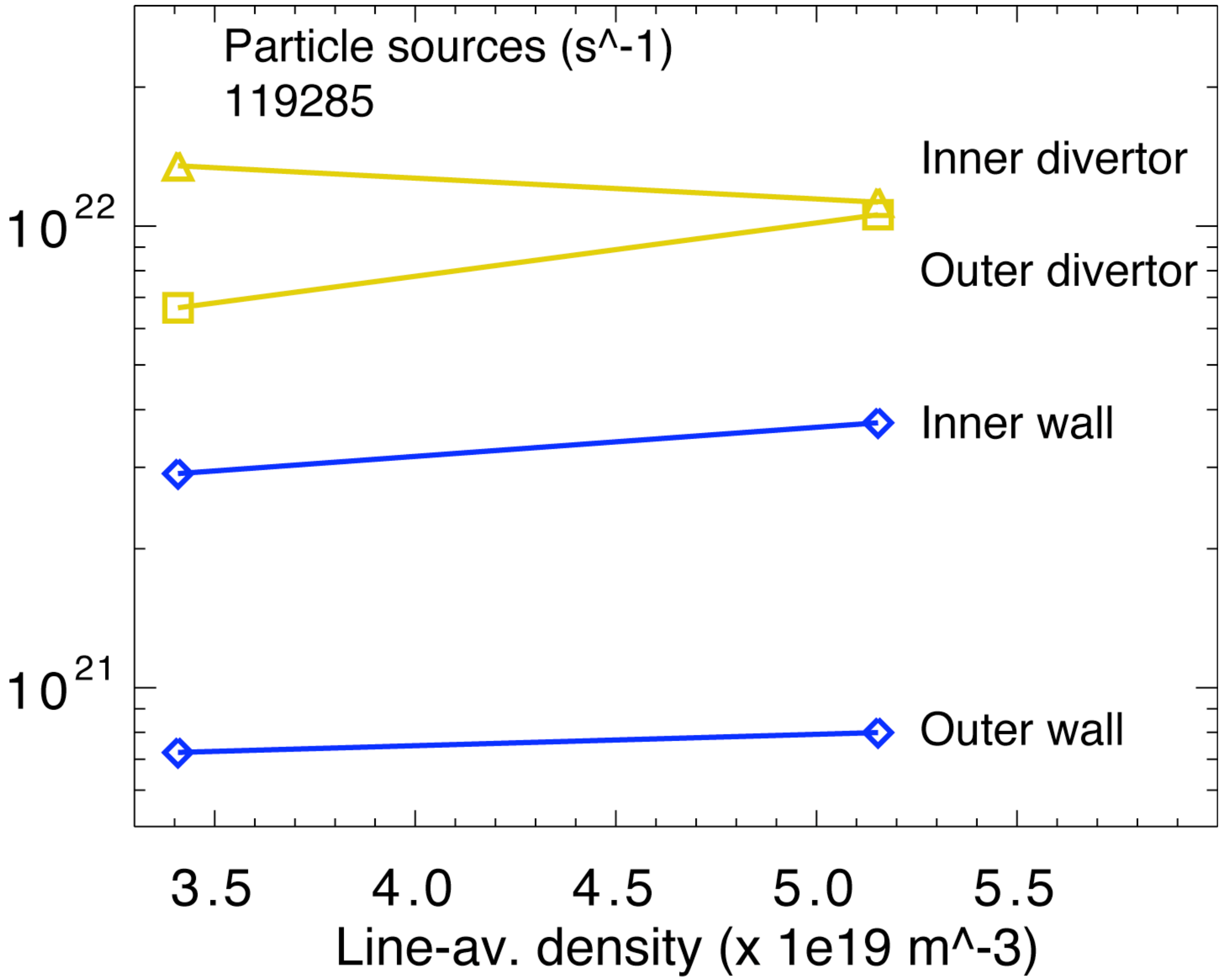
Poloidal distribution of particle flux measurements, shot 119285 (low κ, δ)

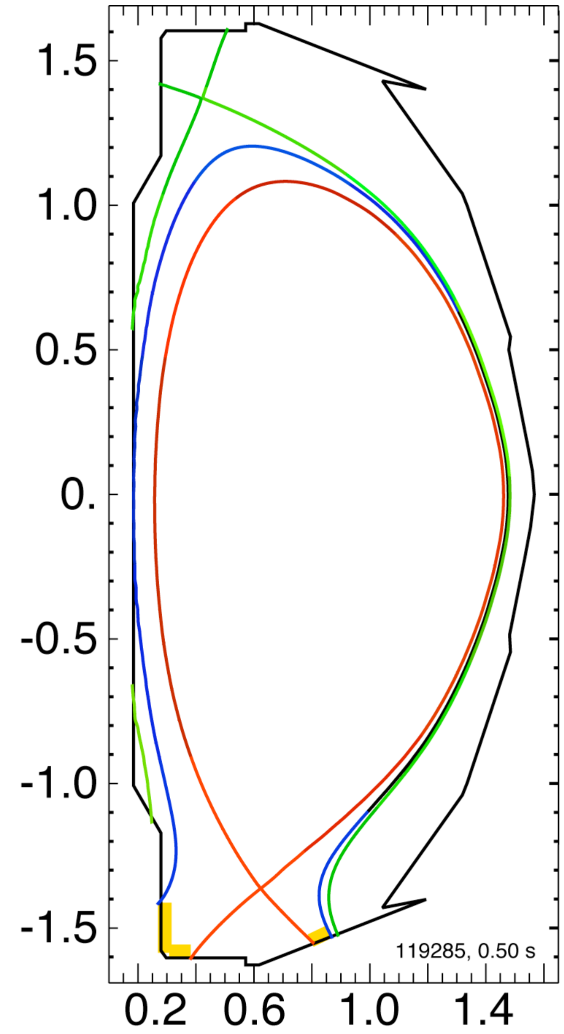




- Main "wall" particle flux similar at upper divertor, outer midplane
- Langmuir probe - uncorrected j_{sat} shown
- Need to reconcile LP flux measurements with other diagnostics

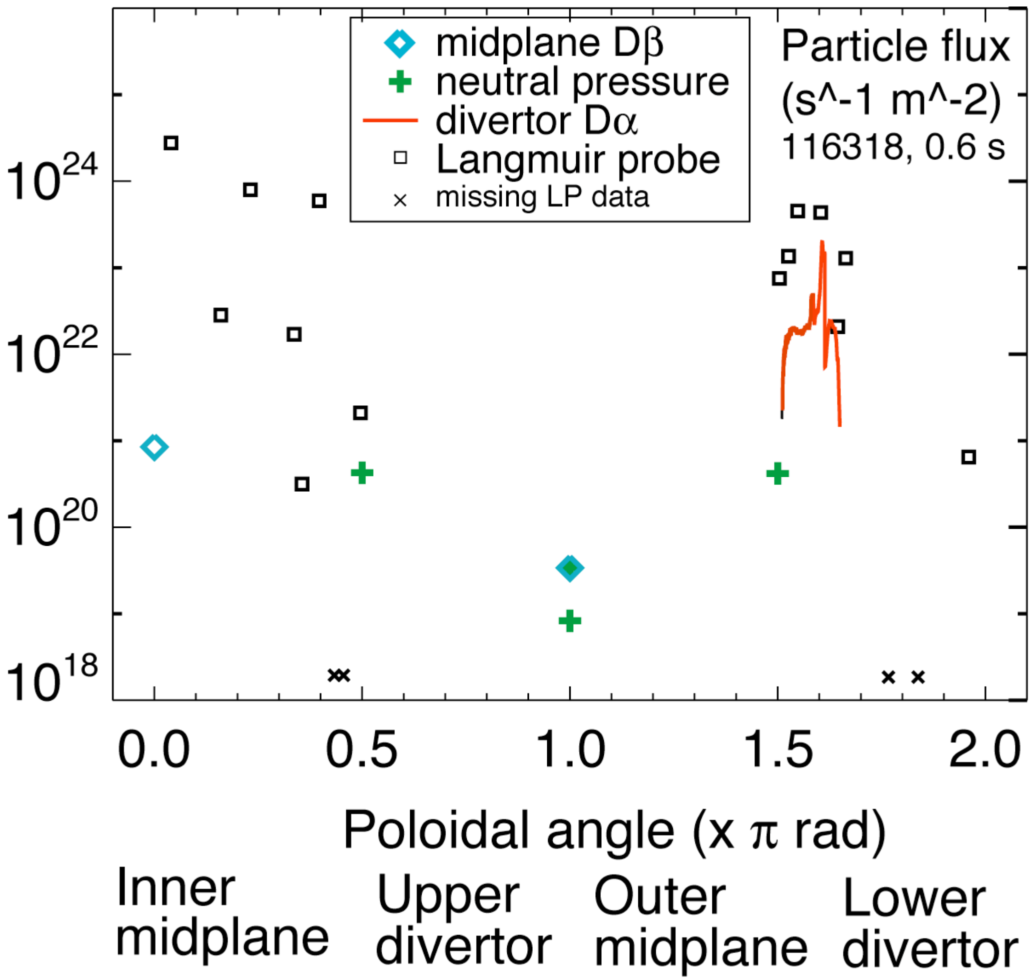
Particle sources, shot 119285 (low κ, δ) at 0.3 s and at 0.5 s

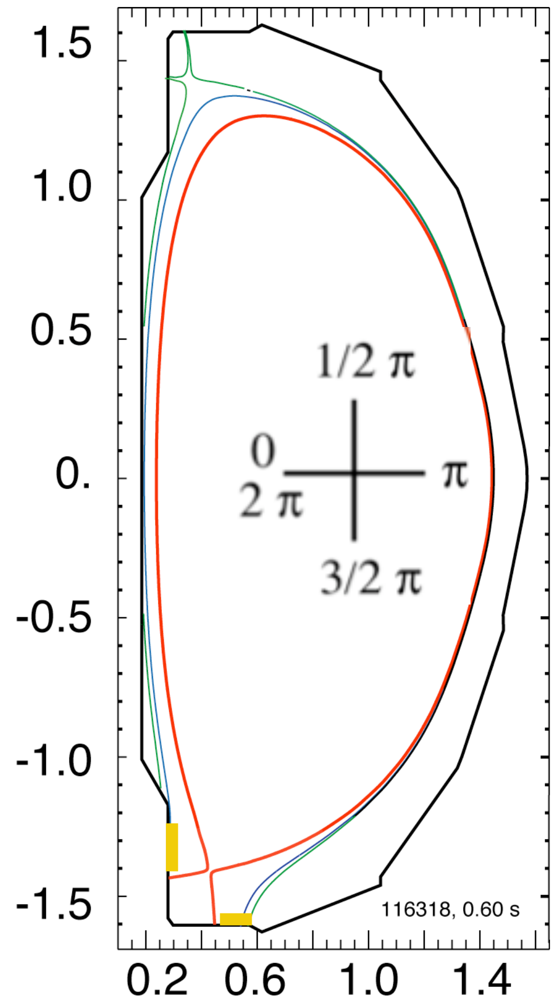




- Main particle source is (outer) divertor
- As inner divertor is detached (high n_e, low T_e) - fueling efficiency is low
- Total particle inventory is 3.17e20 and 5.08e20

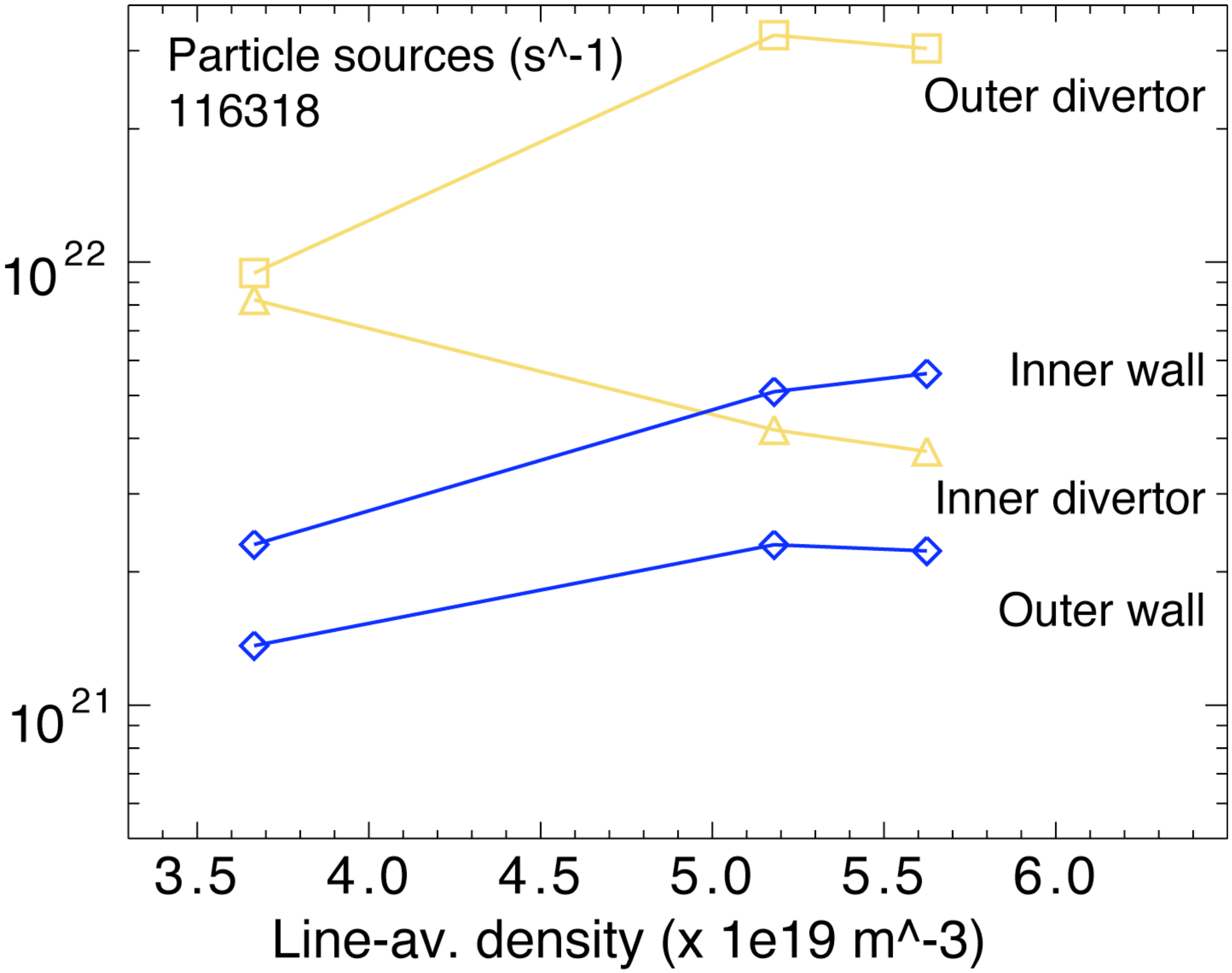
Poloidal distribution of particle flux measurements, shot 116318 (high κ, δ)

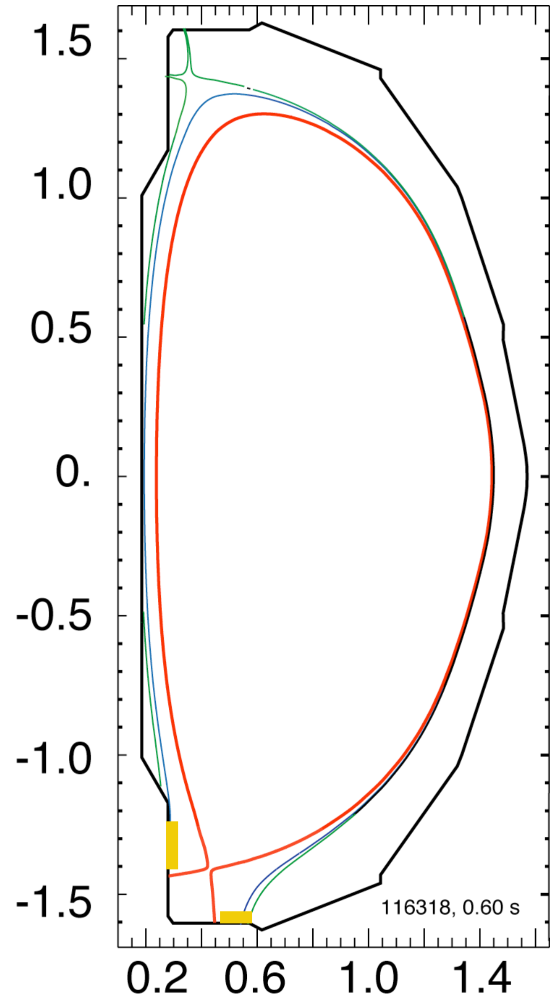




- Main "wall" particle flux high at lower and upper divertors
- Langmuir probe - uncorrected j_{sat} shown
- Need to reconcile LP flux measurements with other diagnostics

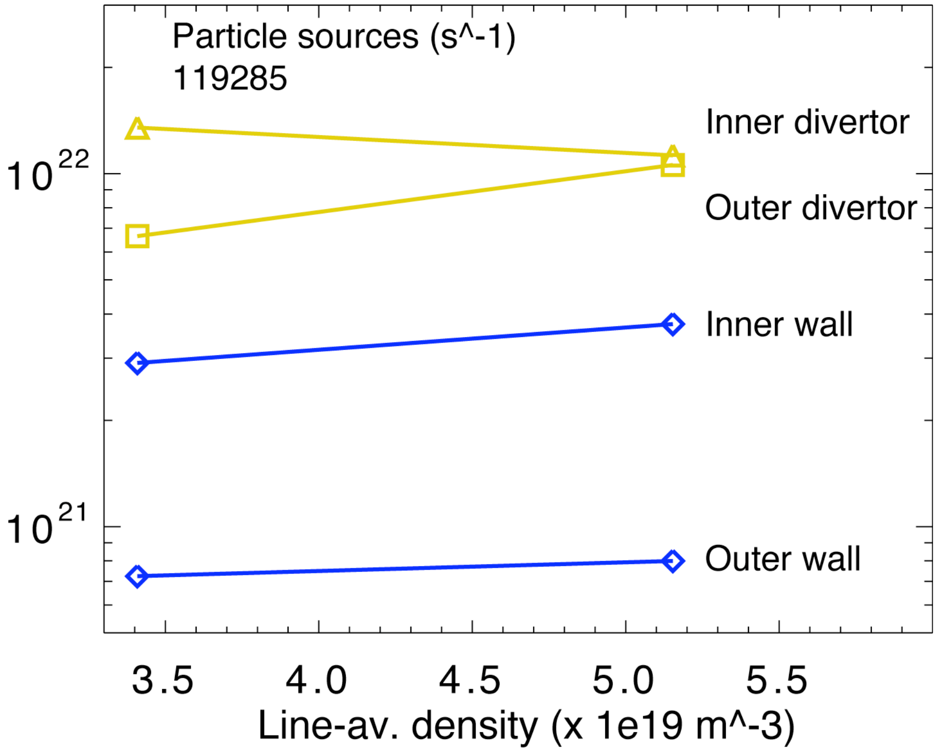
Particle sources, shot 116318 (high κ, δ) at 0.275 s, 0.600 s and at 0.750 s

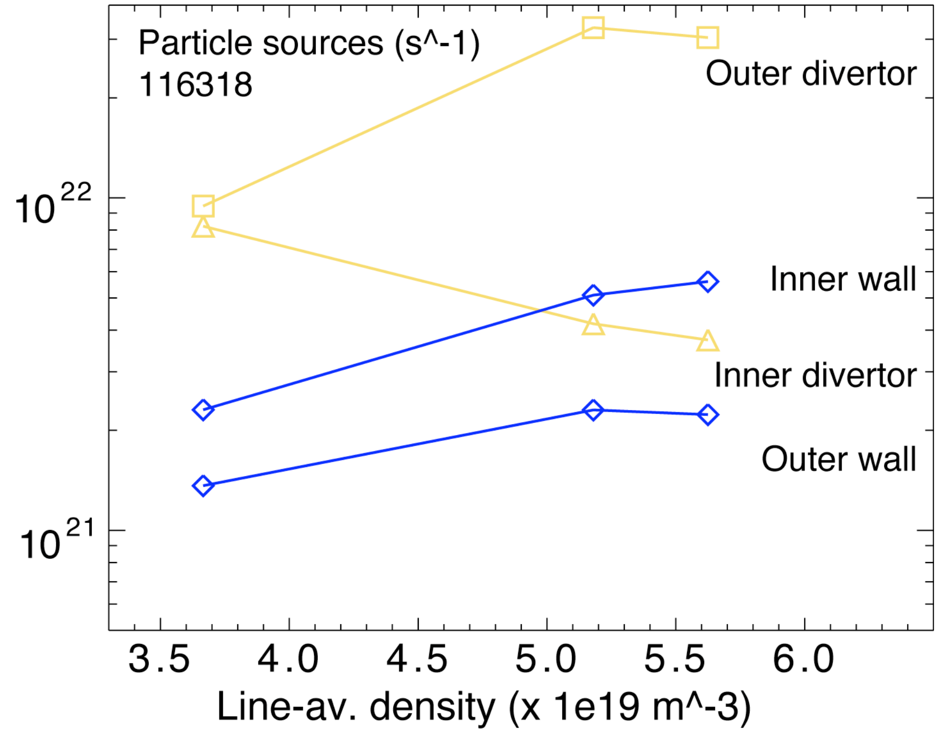


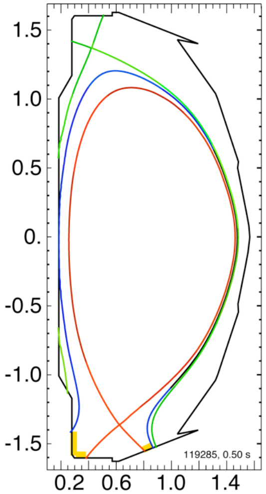


- Main particle source is still (outer) divertor
- Small inner divertor volume leads to reduced inner div. source strength
- Total particle inventory is 4.1e20, 5.63e20, and 6.1e20

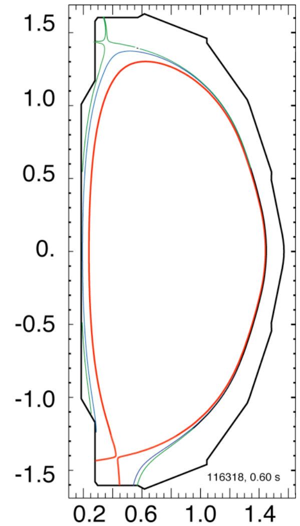
In both configurations divertor appears to be largest particle source







- Differences are though to be due to upper divertor volume, inner gap, etc
- Still in both configurations divertor appears to be dominant particle source



Conclusions

- In both LSN configurations
  - ✓ Lower divertor *appears* to be dominant ionization source (x 5-10) over "main wall" source
  - ✓ Upper X-point may induce substantial plasma-wall interaction and particle fluxes
- Implications for LLD design
  - ✓ LLD should be where ***outer divertor SOL*** intersects the divertor plate
  - ✓ LLD tray **width** should be approx. ***drsep x flux expansion*** at OSP
  - ✓ In lower κ,δ LSN configuration, **OSP control** is an issue - OSP drift due to control by PF2L only
  - ✓ In lower κ,δ LSN configuration, LLD area as largest
  - ✓ In lower κ,δ LSN configuration, LLD placement at OSP is least interfering with plasma operations

Given technical complexity of LLD, suggest initial LLD placement outboard of CHI gap ("outer divertor plate")