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Divertor heat flux reduction and detachment in NSTX (XP 605)

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Acknowledgements:

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XP 605 motivation and scope

- Steady-state divertor heat load mitigation - one of the key Boundary Physics issues in Spherical Tori (ST)
- Study divertor regimes at low aspect ratio in NSTX (A = 1.35, $q_{out} < 10$ MW/m^2, P/R < 9)
- NSTX divertor (open, no active pumping): ISP is naturally detached at $P_{in} > 1$ MW, $n_e > 2\text{-}3 \times 10^{19}$ m^{-3}, outer SOL is in high-recycling regime
- XP 605 includes three parts - study divertor heat flux reduction and detachment
  - in LSN shape with $\delta \sim 0.5$, $\kappa = 1.8\text{-}2.0$ with D_2 puffing (DONE)
  - in LSN shape with $\delta \sim 0.7$, $\kappa = 2.2\text{-}2.5$ with D_2 puffing (NOT DONE)
  - in LSN shape with $\delta \sim 0.5$, $\kappa = 1.8\text{-}2.0$ with CD_4 puffing (NOT DONE)
- Divertor tile lithium coating introduces uncertainties in divertor heat flux measurements by IR camera. XP 605 had to be executed before the lithium campaign.

NSTX diagnostic set enables divertor studies

- **IRTV**: two Indigo Alpha 160 x 128 pixel microbolometer cameras, 7-13 μm range, 30 ms frame rate

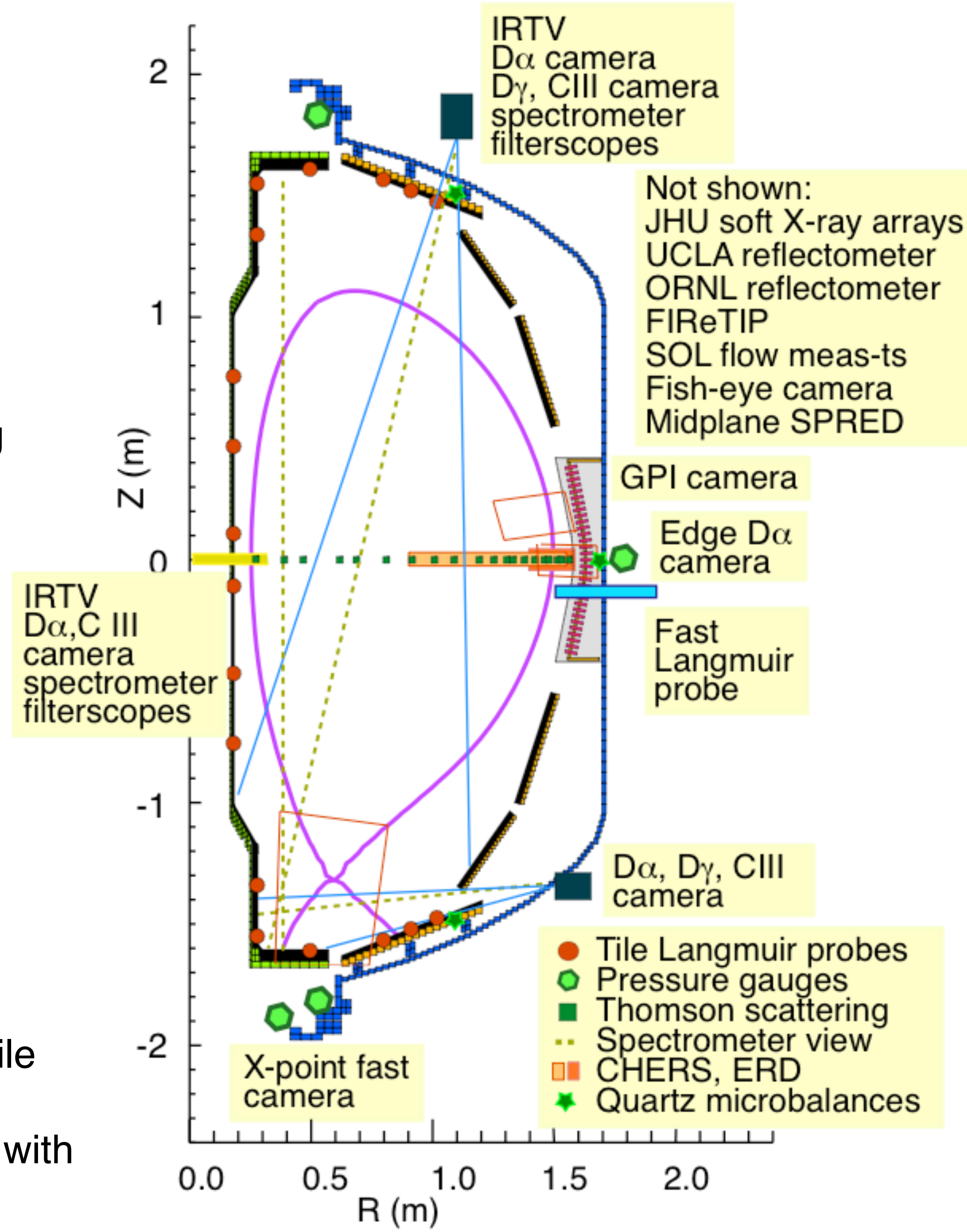
- **D_α, D_γ, C III filtered cameras**: four Dalsa 1 x 2048 pixel CCDs, filter FWHM 10-15 A, frame rate 0.2 - 1 ms

- **Neutral pressure gauges**: four micro-ion gauges on top and at midplane, two Penning gauges in lower and upper divertor, time response 5-10 ms

- **High-resolution spectrometer** ("VIPS 2"): ARC Spectro-Pro 500i, three input fibers (channels), time response 15-30 ms, FWHM > 0.6 A

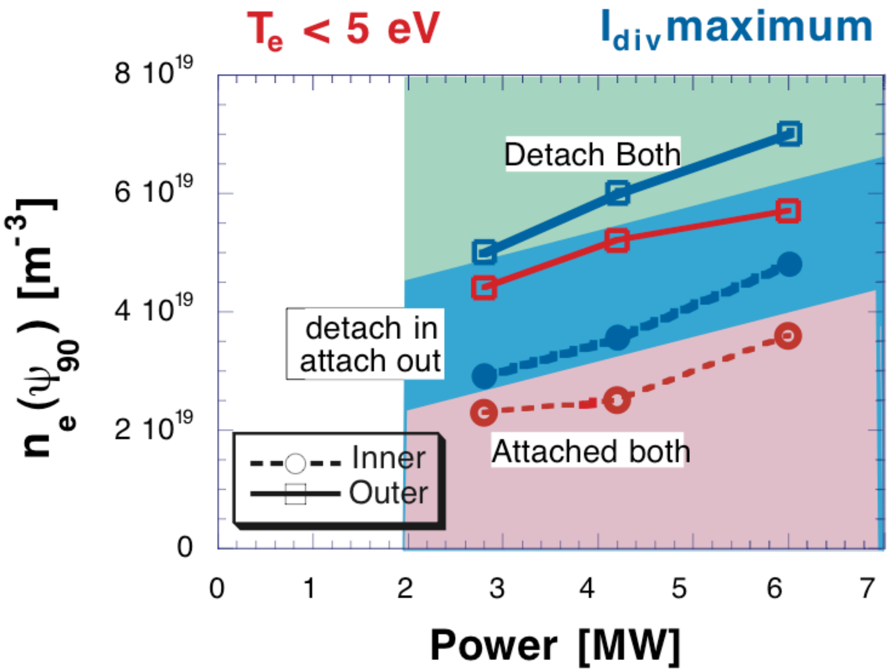
- **Bolometry**: midplane (AXUV radiometer array), divertor - ASDEX-type four channel bolometer, time response 20 ms

- **Langmuir probes**: midplane - fast probe, tile LPs - I_{sat}, T_e measurements
- Midplane **Multi-point Thomson** scattering with 2-4 points in SOL



UEDGE modeling guided detachment experiments

- Model divertor conditions *vs* P_{in}, n_{edge} for guiding purposes with UEDGE
- Generic H-mode LSN equilibrium used
- Diffusive transport model
- Impurities (carbon) included
- Outer midplane n_e, T_e profiles matched, D_α and IRTV not matched



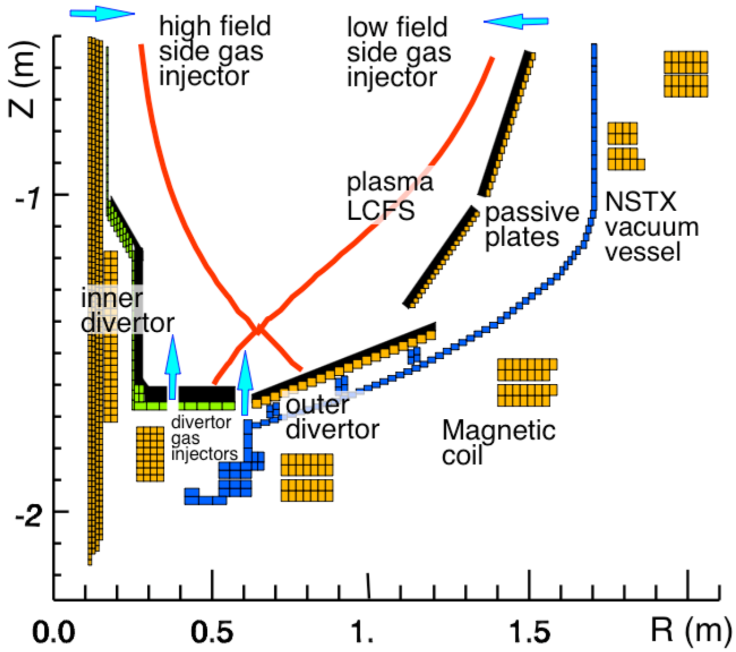
G. Porter, N. Wolf

Attempt to change parallel momentum and power balance:

$$\frac{d}{ds}(m_i n v^2 + p_i + p_e) = -m_i(v_i - v_n)S_{i-n} + m_i v S_R$$

$$\frac{d}{ds}((-\kappa T_e^{5/2}\frac{dT_e}{ds}) + n v_{||}(\frac{5}{2}(T_i + T_e) + \frac{1}{2}m_i v_{||}^2 + I_0)) = S_E$$

Radiative and partially detached divertors in NSTX have achieved OSP peak heat flux reduction by 3-4

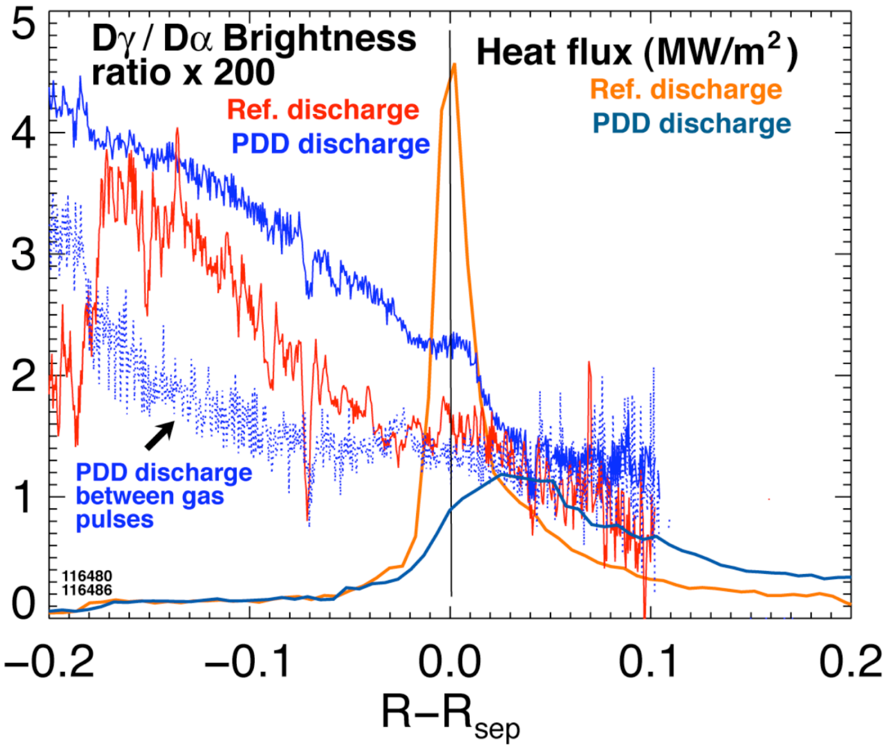


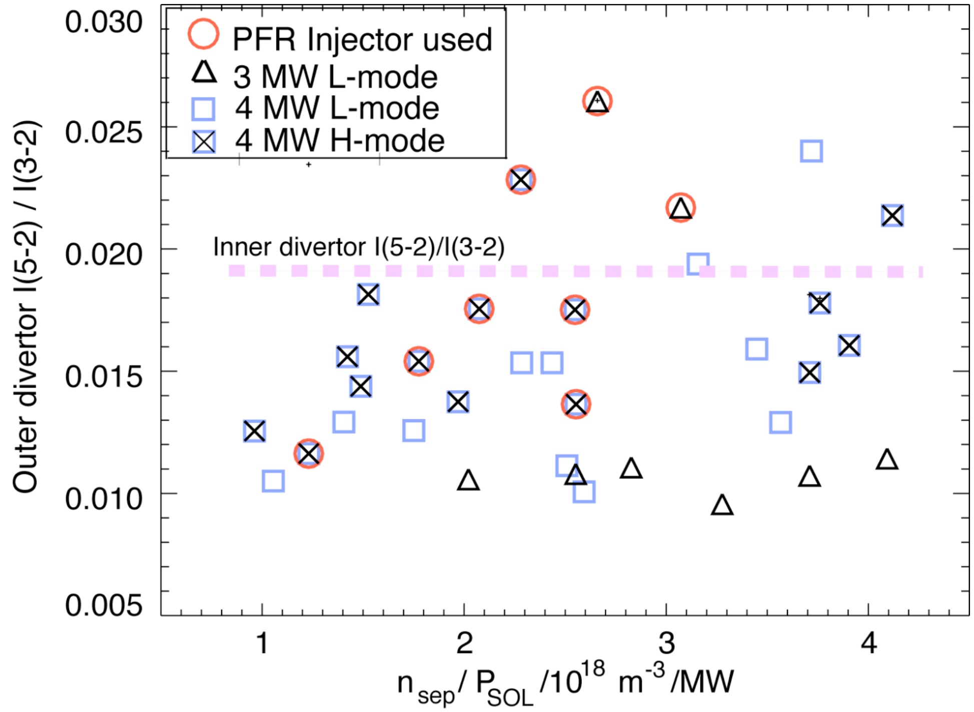
κ	1.85
δ	0.4
Drsep (cm)	1.0-1.5
q_{edge}	13
L_{II}, inner (m)	8.0
L_{II}, outer (m)	6.0
M (Mirror ratio)	5.0
f inner (Flux expansion)	2-3
f outer	2-3

- **Partially detached regime (D_2 at > 200 T l /s at ISP)**
  - OSP heat flux reduced by 3-4
  - Obtained by pulsed D_2 injection
  - ISP heat flux did not change
  - Volume recombination at OSP
  - Detachment extent: 2-3 cm at OSP
  - Divertor bolometer signal increases from 10-15 W/m^2 to 15-20 W/m^2
  - Generally compatible with H-mode (?) - H-L transition within 100 ms

- **Radiative divertor regime (D_2 at 100-160 T l /s in PFR or at ISP)**
  - OSP heat flux reduced by 3-4
  - Obtained by steady-state D_2 injection
  - ISP heat flux did not change
  - No clear signs of volume recombination at OSP
  - Compatible with H-mode
  - Divertor bolometer signal increases from 10-15 W/m^2 to 20-30 W/m^2

Outer leg partial detachment evident from peak q_{out} reduction and onset of volume recombination

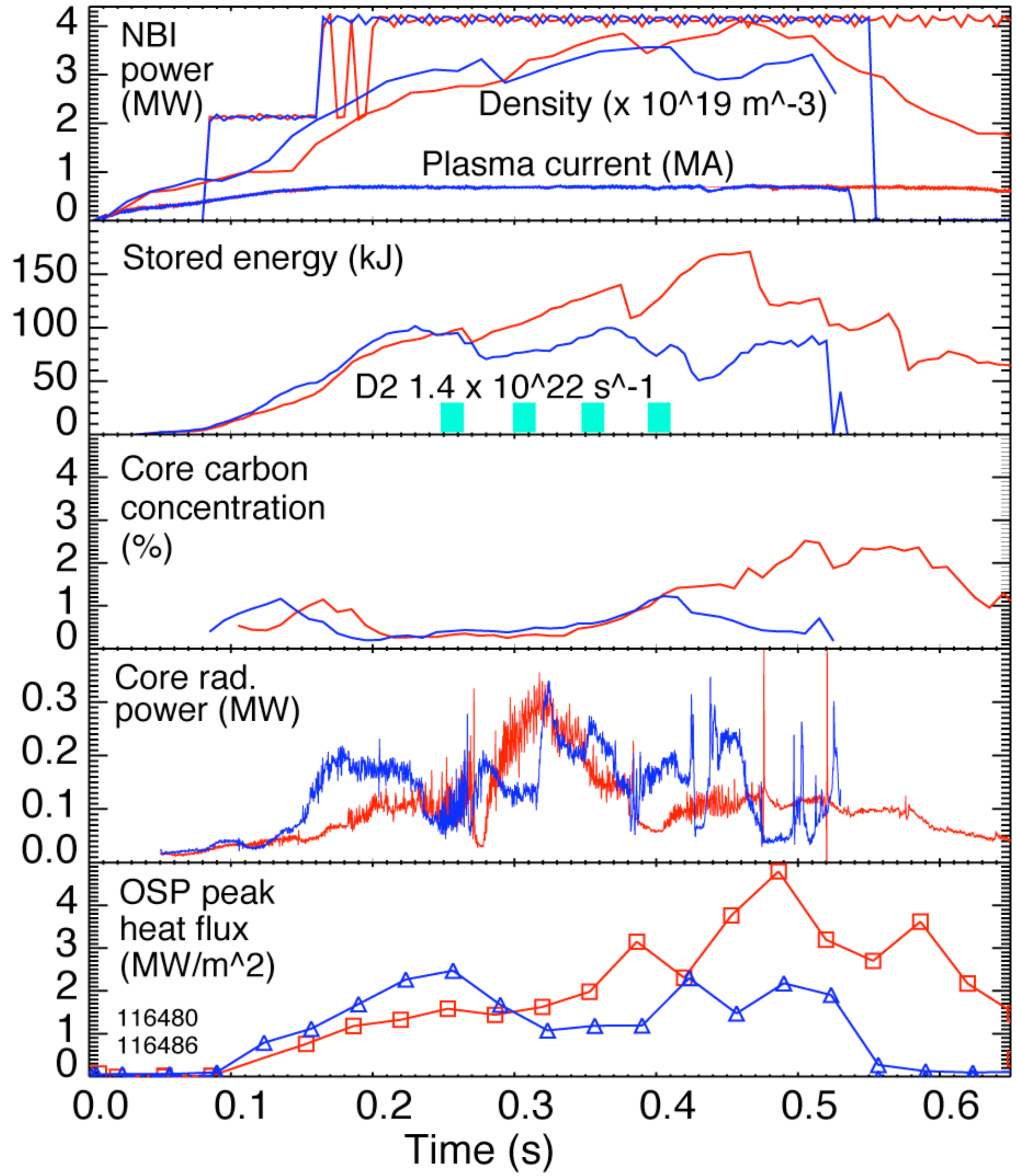




- D_2 puffing from lower divertor
  - Decreases peak q_{out} by 4-5, with peak shift outward by up to 3 cm
  - Broadens D_α and D_γ brightness profiles, increases outer leg D_γ / D_α ratio
  - No change in detached inner divertor - $q_{in} < 0.5$ MW/m², $D_\gamma/D_\alpha = 2\text{-}3 \times 10^{-2}$

- Langmuir probe data analysis in progress

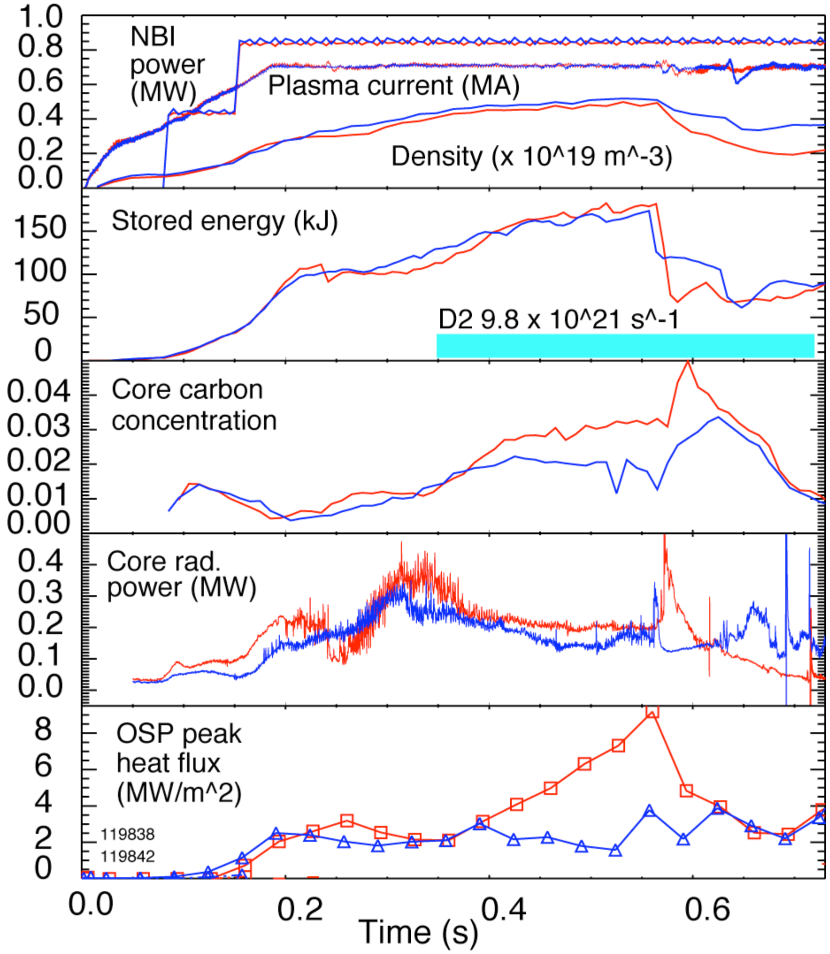
Core confinement properties are affected by high flow rate deuterium injection in PDD

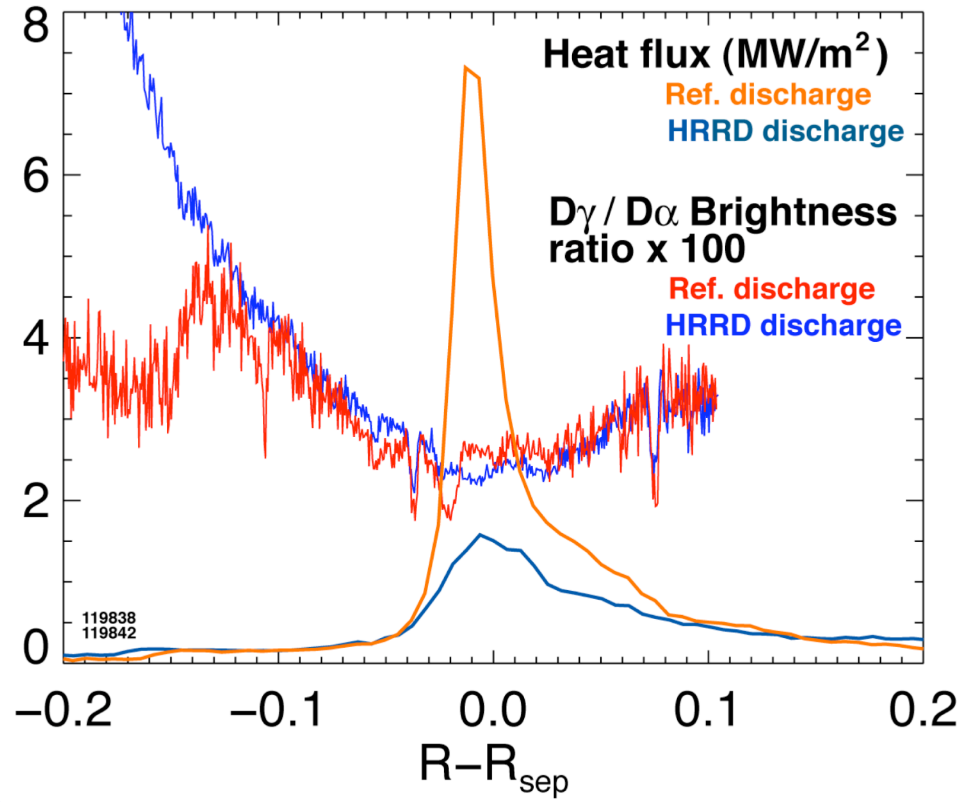


PDD discharge

Ref. discharge

Radiative divertor effective in reducing heat flux; H-mode confinement unaffected



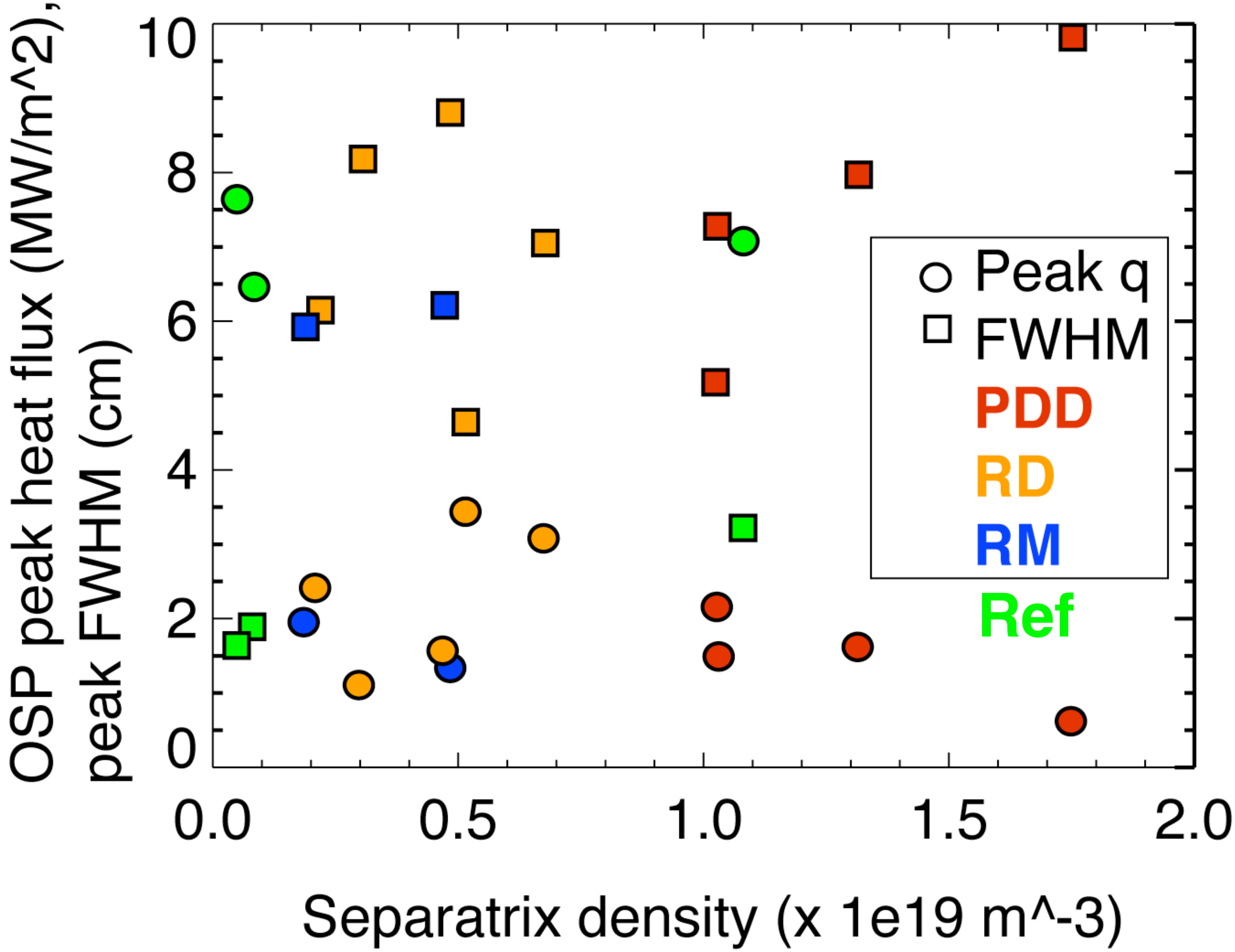


RD discharge

Ref. discharge

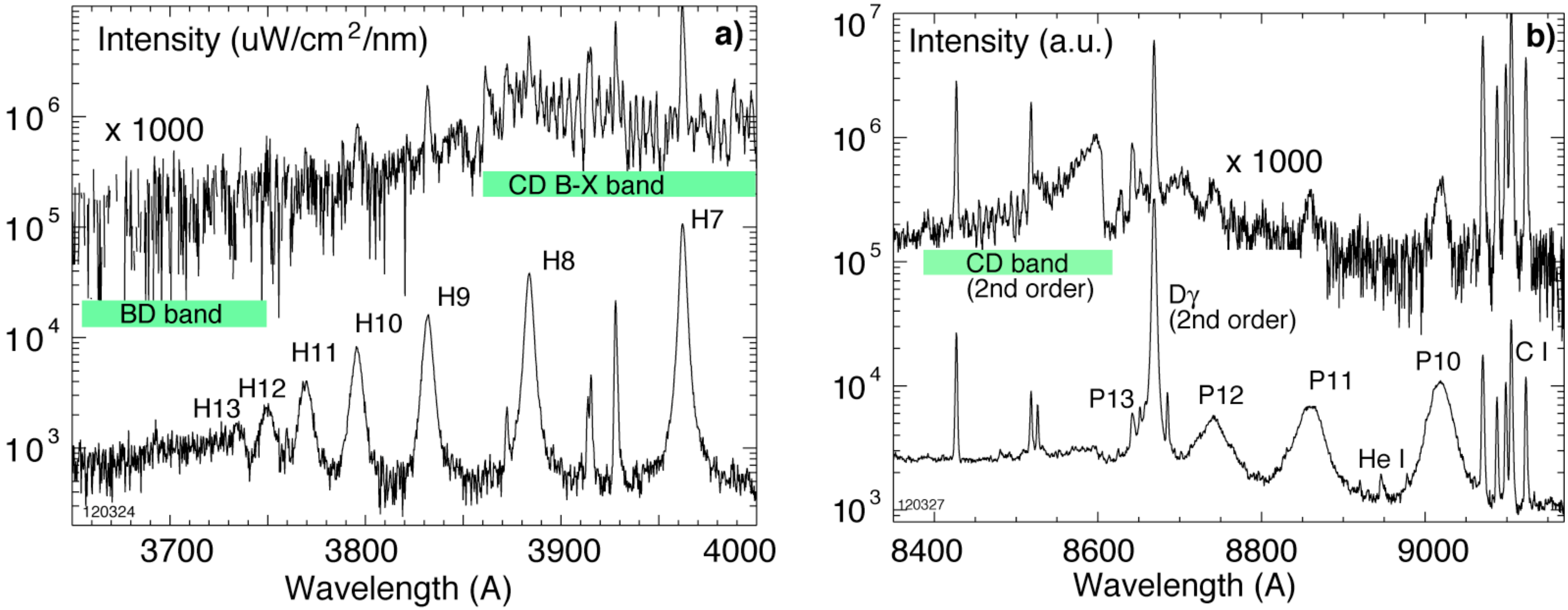
- D_2 puffed into 3-4 MW L and H-mode
- Gas puffing eventually causes confinement degradation, locked mode, large MHD modes and low *m,n* modes
- Outer peak heat flux reduced x 2-5, but no sign of recombination

PDD, RD, RM regimes separated in n_{sep}- q space



$\nu^* \sim n_e L / T_e$

High n_e, low T_e inferred from Balmer and Paschen emission lines measured in inner divertor



- In dense low temperature plasmas 3-body recombination rate is high - Lyman (FUV), Balmer (UV), Paschen (NIR) series lines are prominent
- Stark broadening due to plasma electron and ion statistical microfield
- n_e = 0.6-6 x 10^{20} m^{-3} from Stark broadening (Model Microfield Method calculations)
- T_e = 0.3-1.3 eV from line intensity ratios (Saha-Boltzman population distribution, ADAS data)
- **Diagnostic advance: can IR spectroscopy replace UV/VIS spectroscopy in BP plasma devices? (V. A. Soukhanovskii et.al, RSI 77(10), 2006)**

Summary and Future work

- D_2 injections were used to obtain the high recycling radiative divertor and partially detached divertor regimes in low δ, κ LSN H-mode plasmas in NSTX

- OSP peak heat flux was reduced x 3-4 in these regimes

- Partially Detached Divertor was obtained at high D_2 injection rates (~ 1.4×10^{22} s^{-1})

- Radiative Divertor is less perturbing and looks more promising for long pulse H-mode RD scenarios

- Future work will focus on
  - further characterization of NSTX divertor regimes
  - dissipative divertor regime with CD_4 puffing
  - dissipative or radiative divertor regime for high δ, κ H-mode CTF-relevant plasmas

Backup slides

Understand and control divertor heat and particle fluxes at low aspect ratio

- XP 605 includes three parts - study divertor heat flux reduction and detachment
  - in LSN shape with $\delta \sim 0.5$, $\kappa = 1.8\text{-}2.0$ with D_2 puffing
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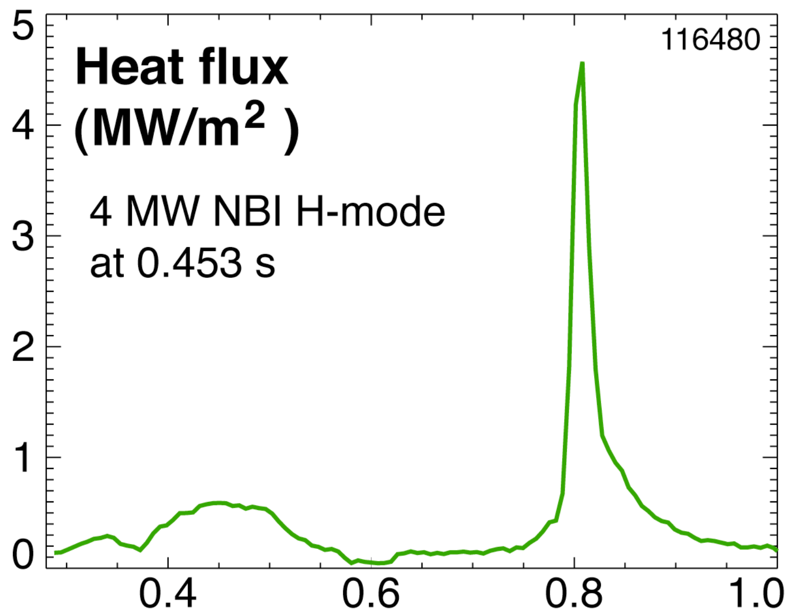
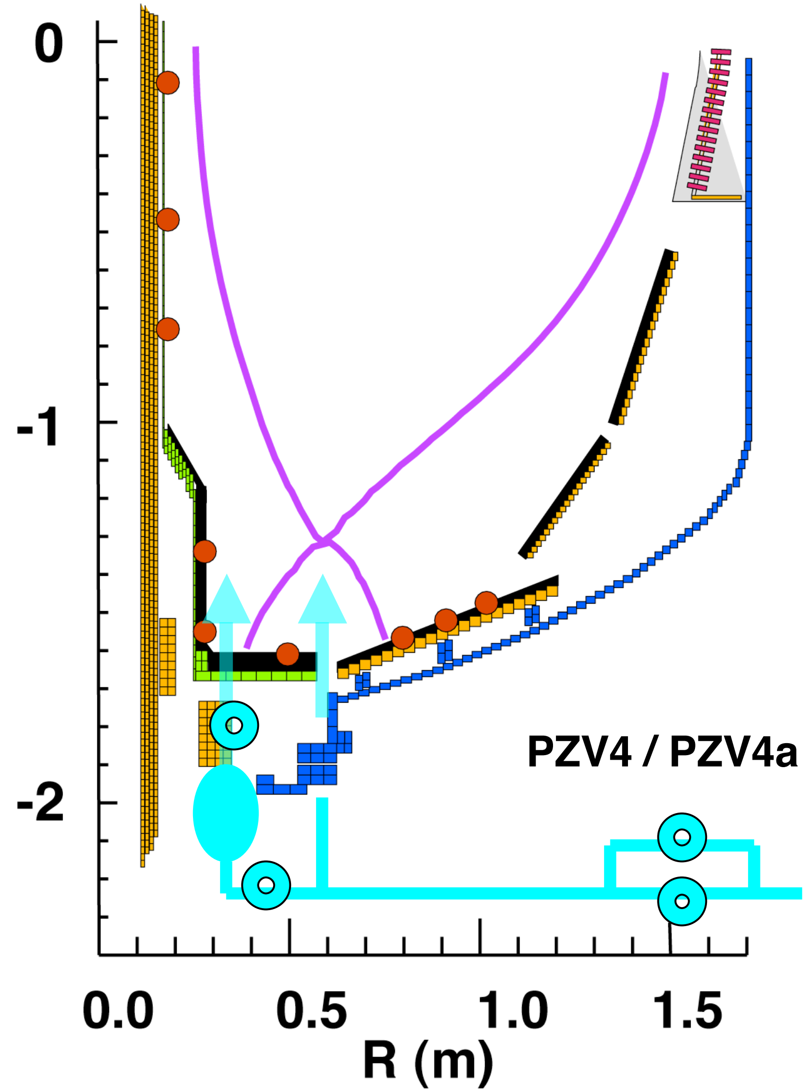
  - in LSN shape with $\delta \sim 0.5$, $\kappa = 1.8\text{-}2.0$ with CD_4 puffing

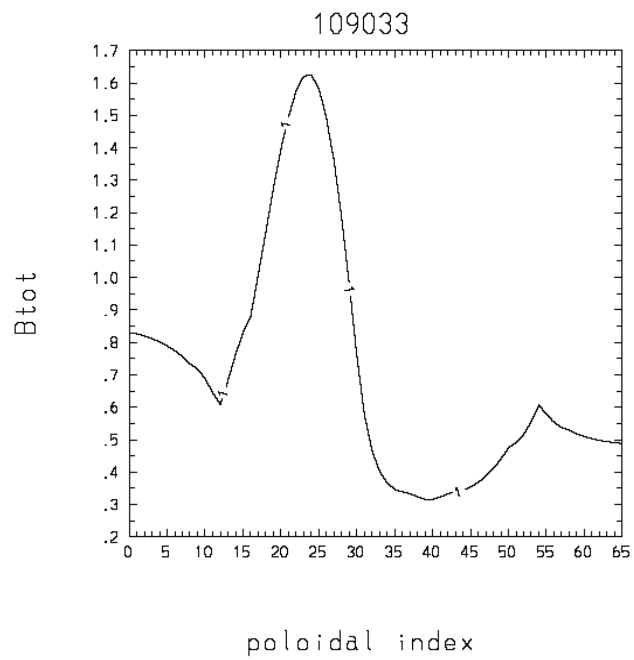


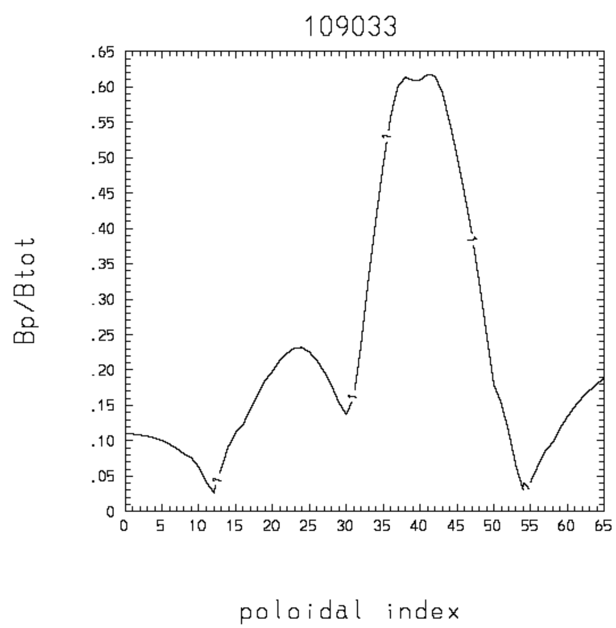


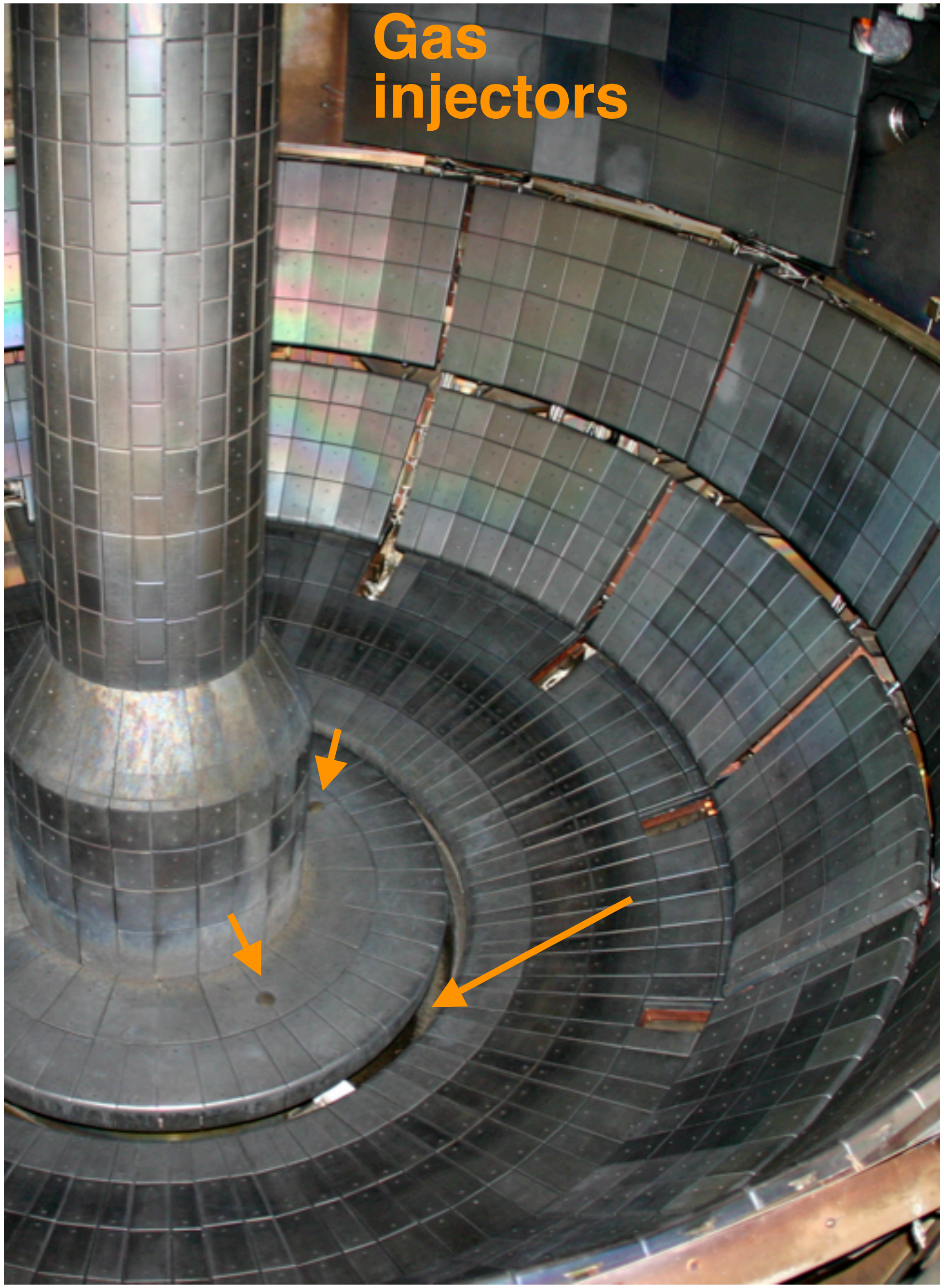
Divertor heat flux mitigation in NSTX: which route?

- Typical divertor tile temperature in ~1 s NSTX pulses $T < 300$ C. Engineering limit is $T = 1200$ C. Long pulses will require steady-state heat flux mitigation solution
- Divertor heat flux mitigation solutions:
  - Poloidal flux expansion at outer strike point (OSP)
  - Strike point sweeping
  - Radiative divertor: outer SOL in high-recycling regime with enhanced radiation at divertor plate
  - Dissipative divertor (detachment)
  - Radiative mantle (exhaust power before it reaches divertor)
- These scenarios must be compatible with good core plasma performance
- Present focus is on divertor regime characterization and development of heat flux mitigation scenarios for plasmas with κ=1.8 - 2.5, δ=0.4 - 0.9, at low aspect ratio A = 1.35, $q_{out} < 6$ MW/m^2, $P_{in}/R < 9$

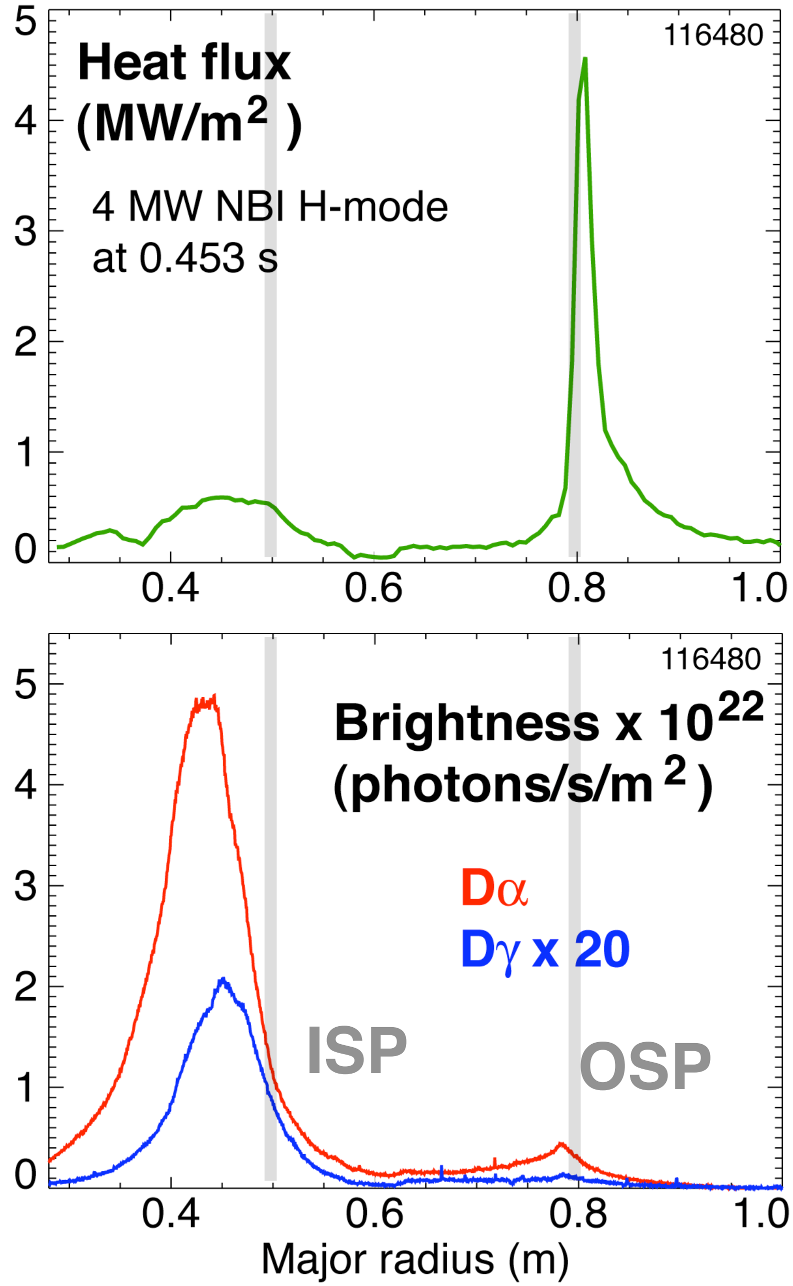
NSTX reference data





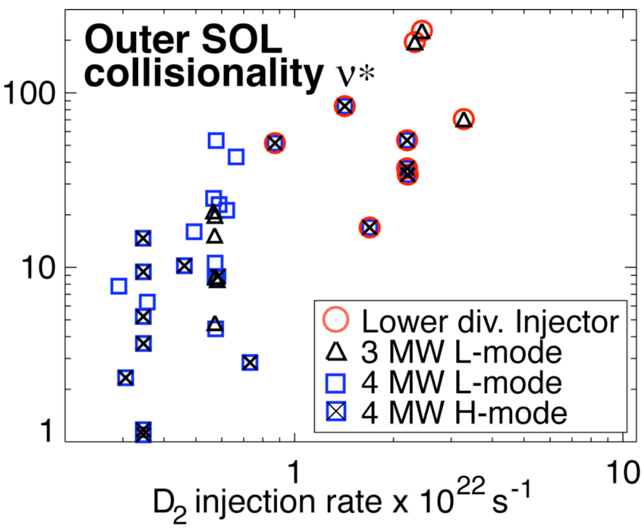


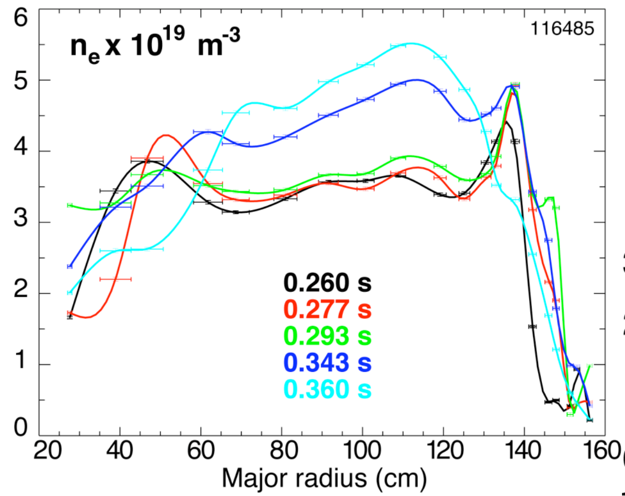
- Observations and measurements:
  - Heat flux asymmetry always $q_{out}/q_{in} > 1$, typically q_{out}/q_{in}= 2-4. Typical peak heat flux $q_{in} <$ 0.5-1.0 MW/m^2, $q_{out} <$ 2-6 MW/m^2 in 2-6 MW NBI-heated plasmas
  - Recycling in-out asymmetry up to 15 from divertor D_α profiles
  - Divertor D_γ observed in inner divertor only, typical ratio D_γ / D_α about 0.020 - 0.030 - sign of volume recombination
  - High divertor neutral pressure (0.1-0.2 mTorr), neutral compression ratio is 5-10 (open divertor)

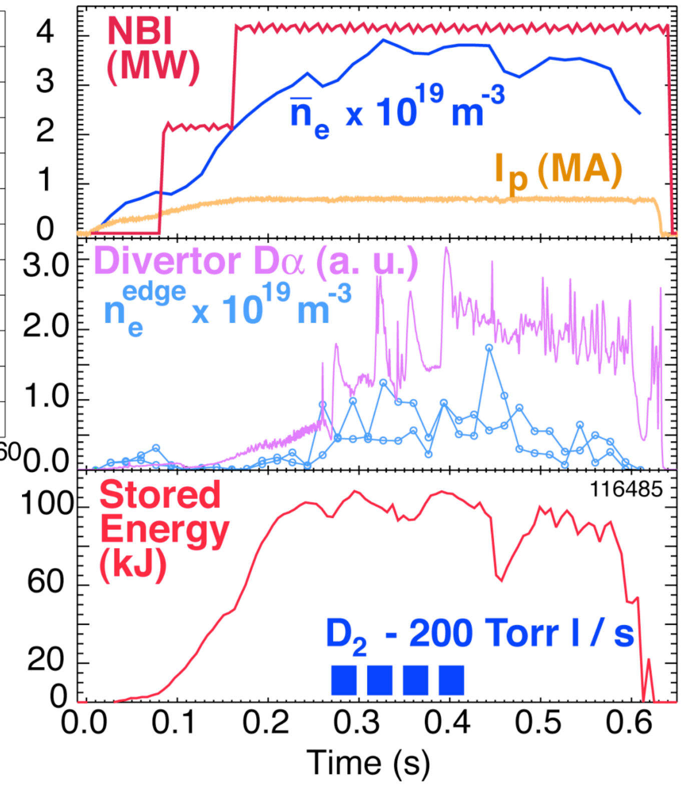


- **Inner divertor** leg is naturally **detached** throughout most of operational space, similarly to conventional tokamak divertors operating w/o pumping. **Outer divertor** leg is always attached, being **in sheath-limited and high-recycling regime** up to $n_e \sim n_G$

Pulsed injection leads to OSP partial detachment



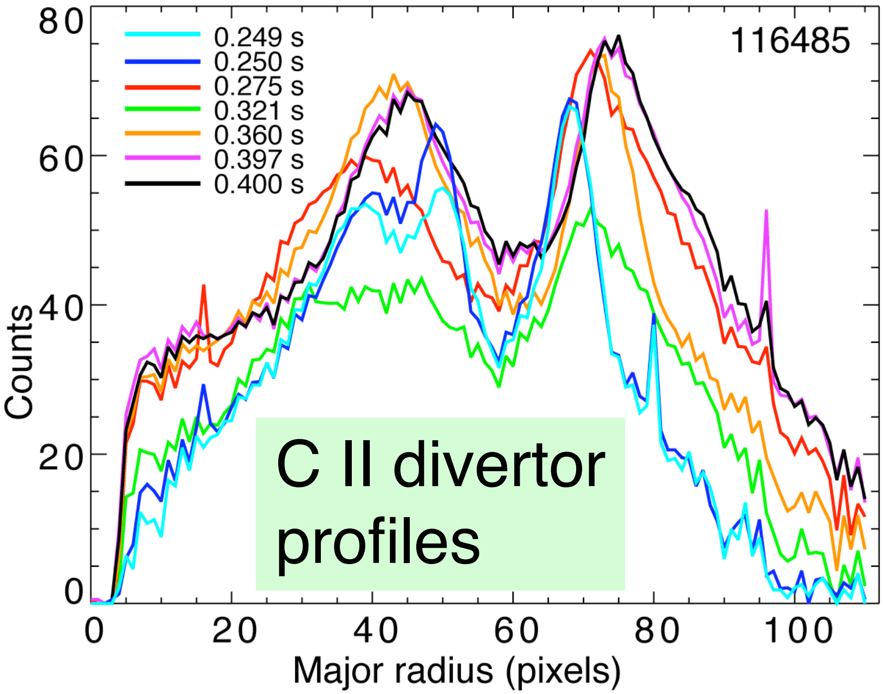


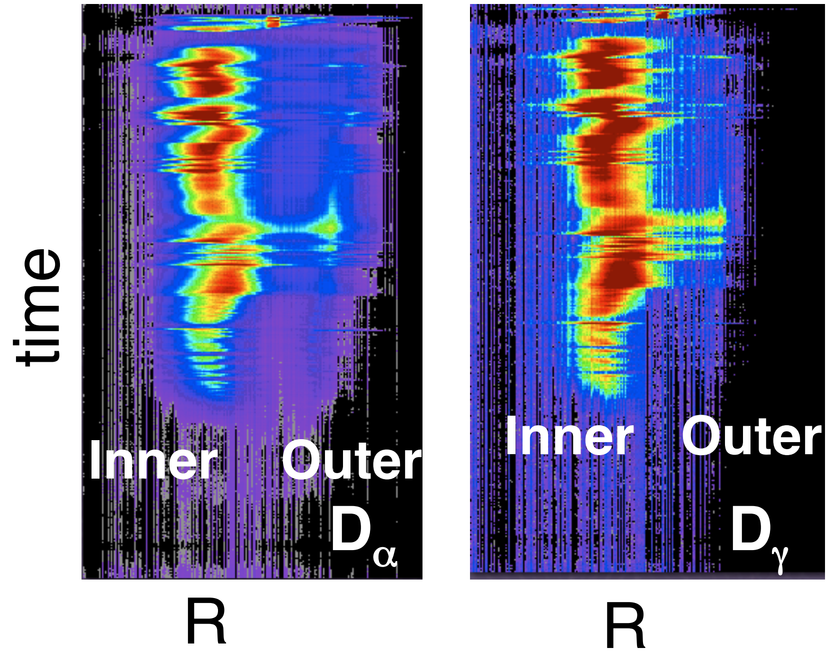


- Target plasma: ELM-free H-mode, LSN, 0.7 MA, $B_t = 0.45$ T , 4 MW NBI, ∇B down, q_{edge} = 12 - 20, central Z_{eff}= 1.2-1.3, fueled by HFS Inj. at 40-65 Torr l /s

- Injected D_2 at LFS midplane at 20 - 120 Torr l / s and / or lower divertor (LD) at 0 - 200 Torr l / s
- Retained H-mode for 5 x τ_E and detached outer leg with LD injection only
- Concluded outer leg *partial* detachment from peak heat flux reduction, radial peak shift, and volume recombination onset (D_γ/D_α ratio)

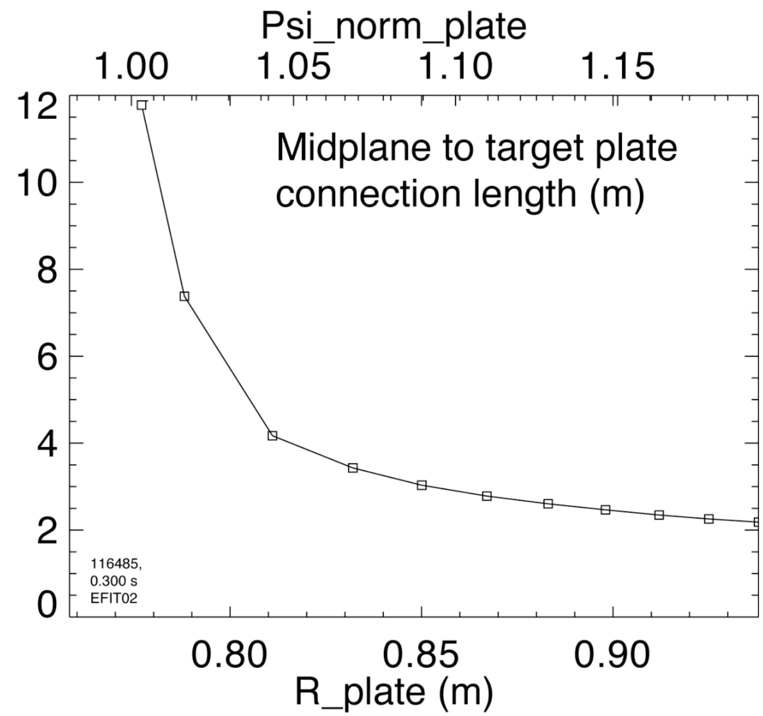
Volume recombination is observed only during gas puff, CII profile broadens during gas puff

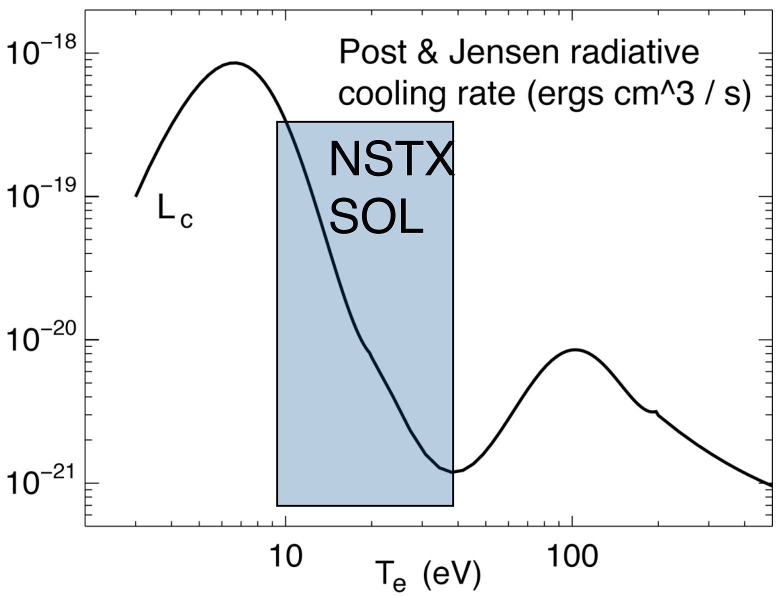




- Profiles obtained from cameras
- During pulsed D_2 injection OSP peak D_α and D_γ increase
- D_α , D_γ brightnesses return to background levels without gas flow
- C II profile broadens during D_2 gas pulses

Why is it difficult to obtain OSP detachment?



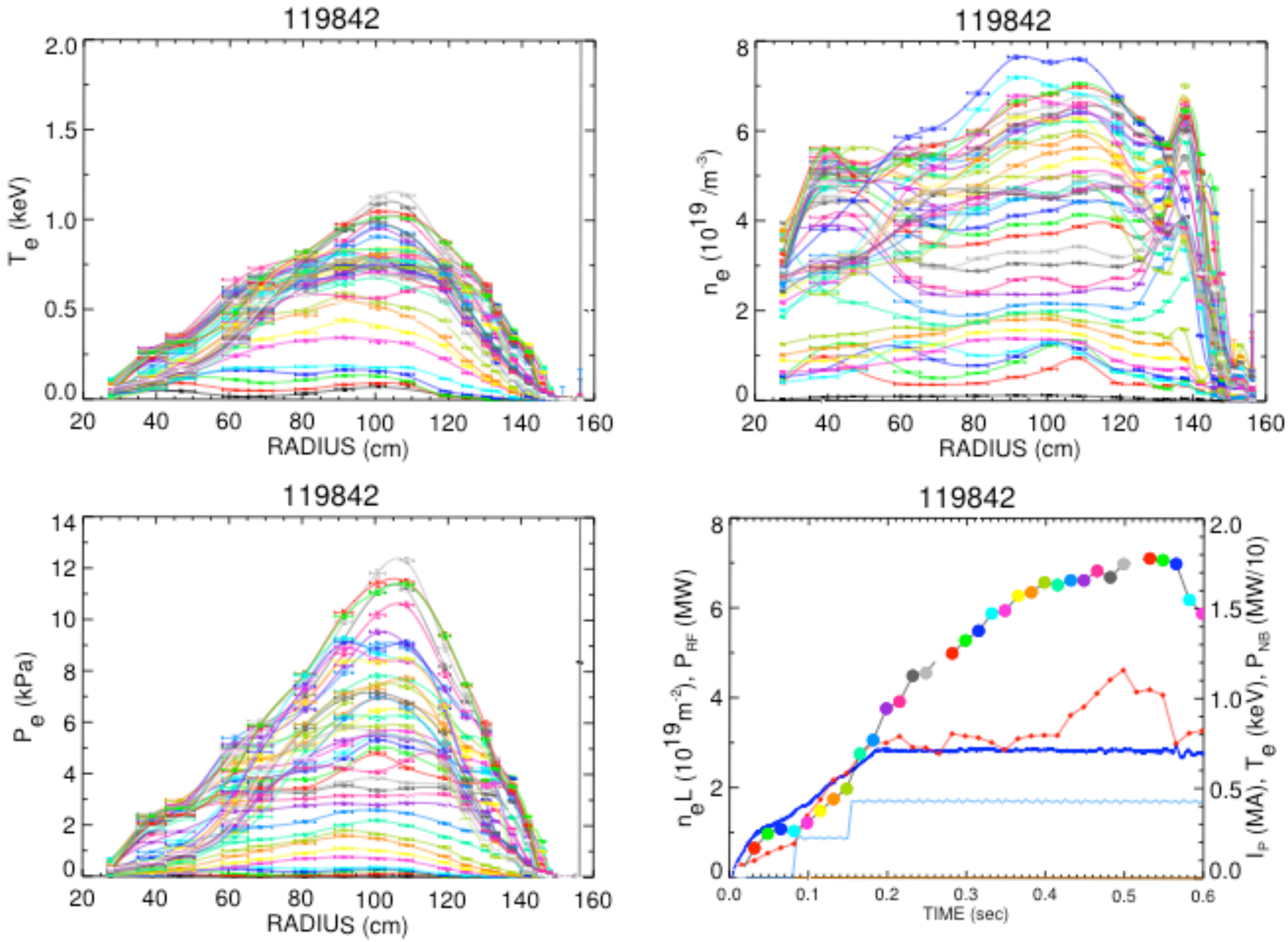


- Connection length drops to very short values within 1-3 cm (both midplane to plate and X-point to plate)

- SOL temperature 10-40 eV (rather low)
- Weak $dT_e/dx_{||}$ in high-recycling outer SOL
- Carbon cooling rate max at $T_e < 10$ eV

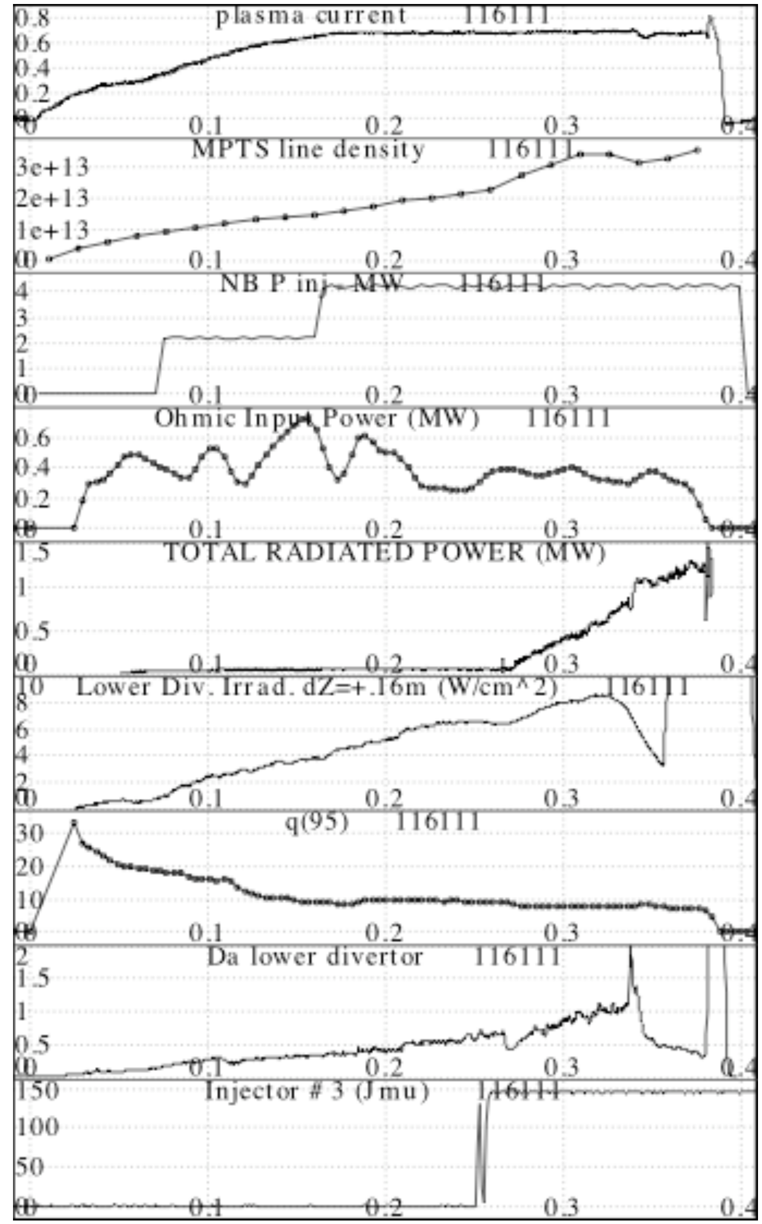
- Open divertor geometry - high detachment threshold is expected
- Neutral compression ratio is 5-10 (low)
- Midplane pressure (density?) is practically independent of plasma density

H-mode confinement and radiative high recy. divertor are compatible



Radiative mantle plasmas with neon puffing

- Two similar conditions were obtained with D_2 and D_2+neon injection, both at midplane location
- Neon puffed into 4 MW NBI 0.7 MA H-mode plasma
- Caused H-L transition within 5 x τ_E
- Puffing rate 1.5 x 10^{20} s^{-1}
- P_{rad} = 0.3 x P_{in}
- Peak heat flux reduced by 50-75 % as a result of P_{SOL} reduction
- Divertor radiation did not increase (divertor plasma too cold)
- No sign of volume recombination



P_{SOL} and OSP peak heat flux are reduced in neon radiative mantle plasmas