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Divertor heat flux reduction in high performance H-mode discharges*

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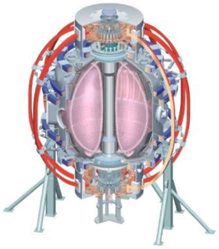
50th Annual Meeting of the APS Division of Plasma Physics
Dallas, TX
November 17, 2008



*Supported by the U.S. DOE under Contracts DE-AC52-07NA27344, DE-AC02-76CH03073, DE-AC05-00OR22725, and W-7405-ENG-36

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Spherical torus scrape-off layer geometry leads to challenges in handling divertor heat flux

	NSTX	Tokamak
▪ In-out plasma surface area ratio	1:3	2:3
➢ Power flows mostly into outer SOL / divertor		
▪ Magnetic field line angle at target (deg.)	2-5	1-2
➢ High divertor q for similar SOL $q_{\|\|}$		

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➢ High divertor q for similar SOL $q_{\|\|}$		
▪ Parallel connection length, X-point to target (m)	5-7	10-20
▪ Poloidal length, X-point to target (m)	< 0.15	< 0.25
▪ High SOL magnetic shear		

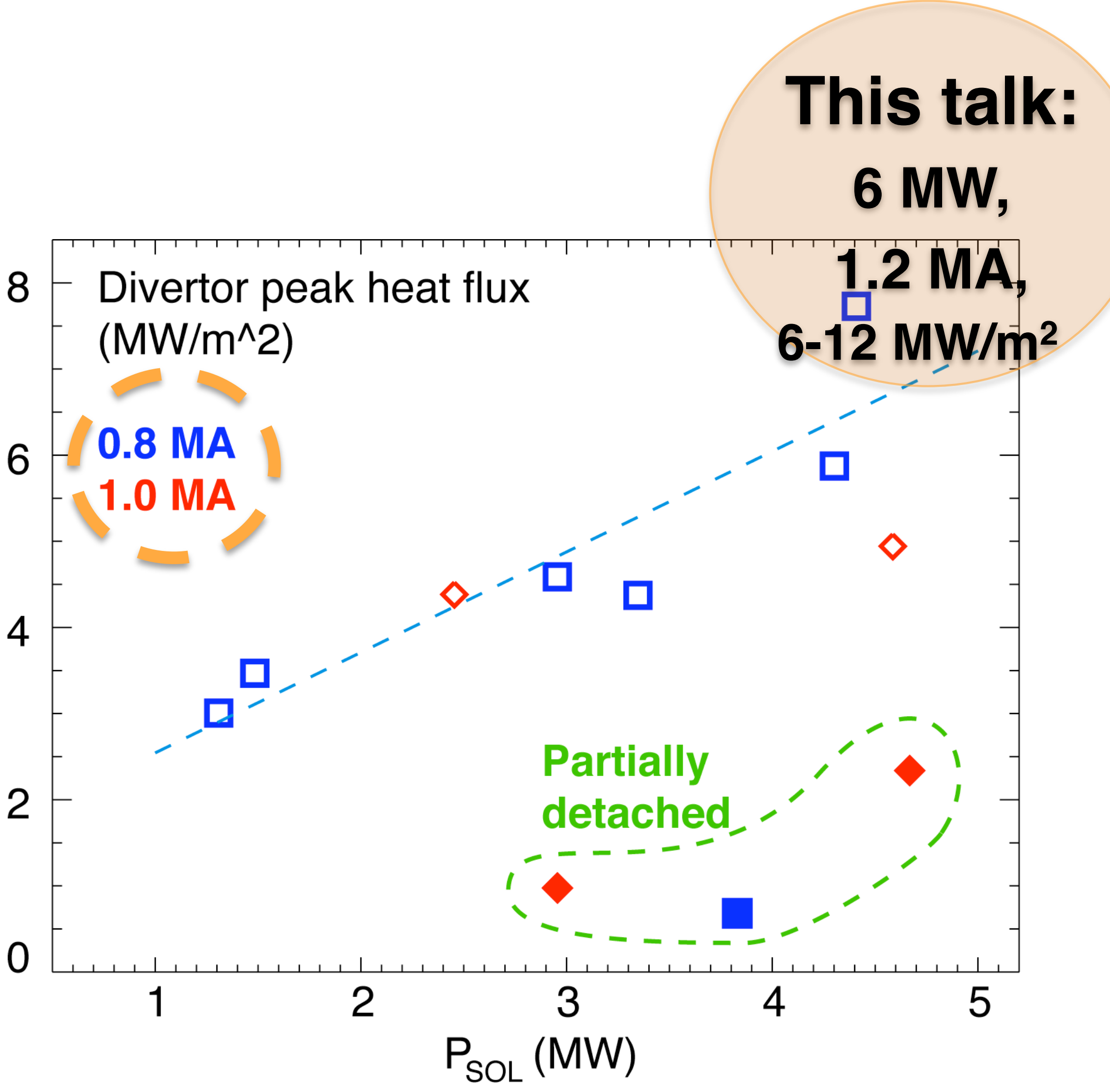
- ➢ Reduced ability to dissipate heat and momentum through radiated power, charge exchange and elastic collisions

High core plasma performance and reduced divertor heat flux are obtained in highly-shaped configuration

- High performance H-mode
  - κ=2.3-2.4, δ=0.7-0.8
  - I_p=0.7-1.0 MA, P_{NBI}=4-6 MW
  - H89P ~ 2.0
  - β_t = 15 - 25 %
  - f_{bs} = 45 - 50 %
  - longer pulses ~50 x τ_E
  - smaller ELM size
- Divertor peak heat flux reduction is achieved with
  - high poloidal magnetic flux (area) expansion (20-25)

$$f_m = \frac{(B_\theta/B_{tot})^{MP}}{(B_\theta/B_{tot})^{OSP}}$$

  - radiative divertor (partial OSP detachment)

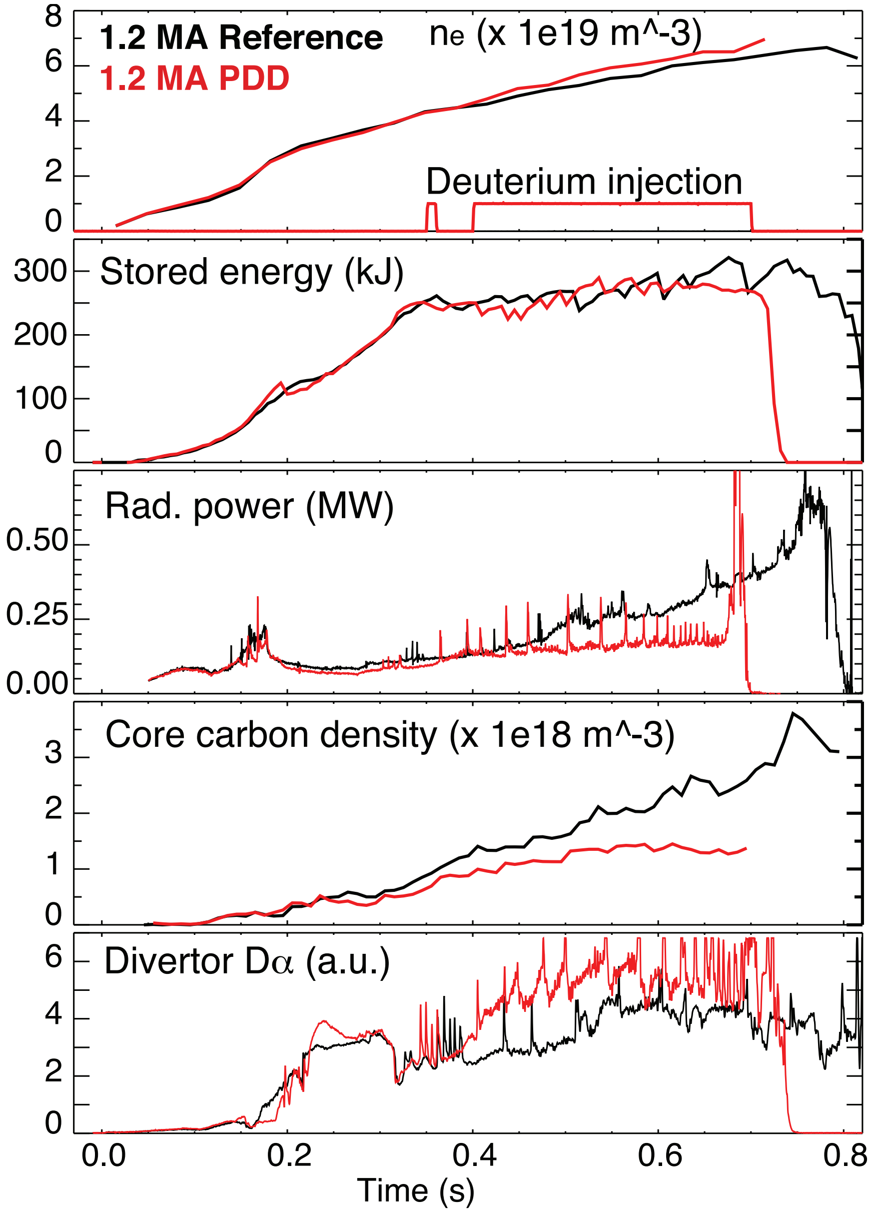


This talk:
6 MW,
1.2 MA,
6-12 MW/m²

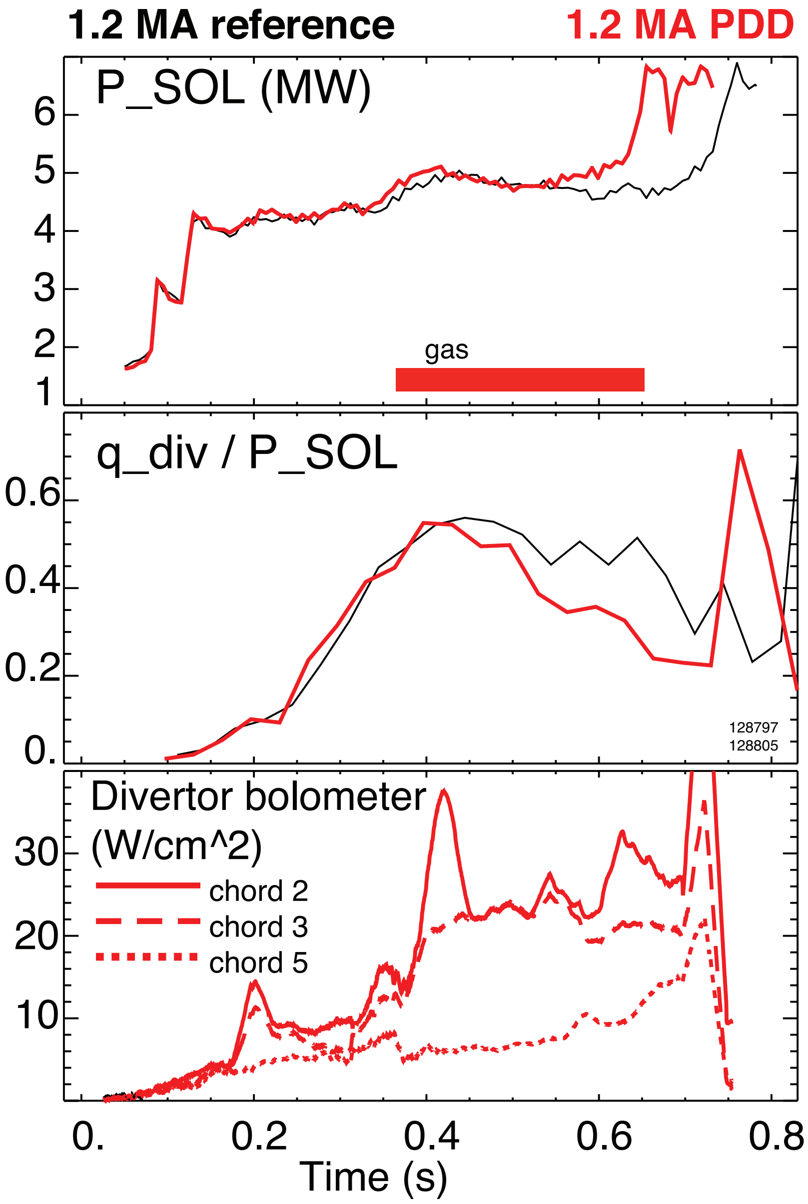
Soukhanovskii et. al., APS DPP 2007

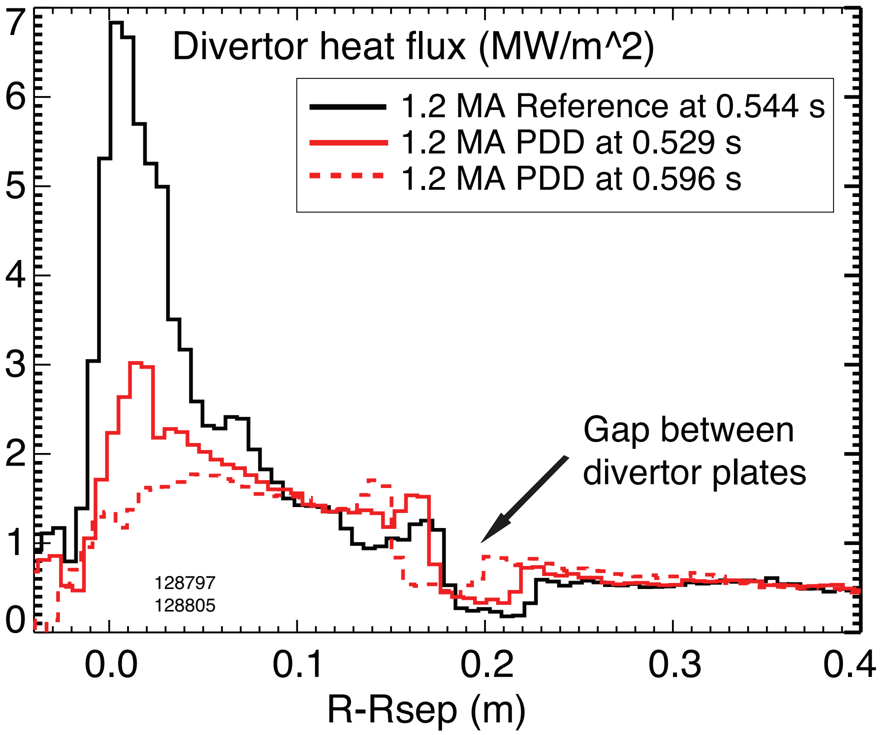
High core and pedestal plasma performance are maintained during partially detached divertor (PDD) phase

- These experiments
  - **I_p = 1.0-1.2 MA**
  - **P_{NBI} = 6 MW**
  - $q_{||}$= 50-80 MW/m^2
  - **Carbon is main impurity**
  - n_e=(0.7-0.8) x n_G
  - Highly shaped LSN, B grad B down
  - Divertor D_2 injection (100-150 T l / s)
- High core plasma performance maintained in PDD phase
  - Minimal effect on W_{MHD} or pedestal
  - Core P_{rad} and n_c decreased
  - Small ELMs ($\Delta W_{MHD}/W_{MHD} \leq$ 1%) and mixed ELMs



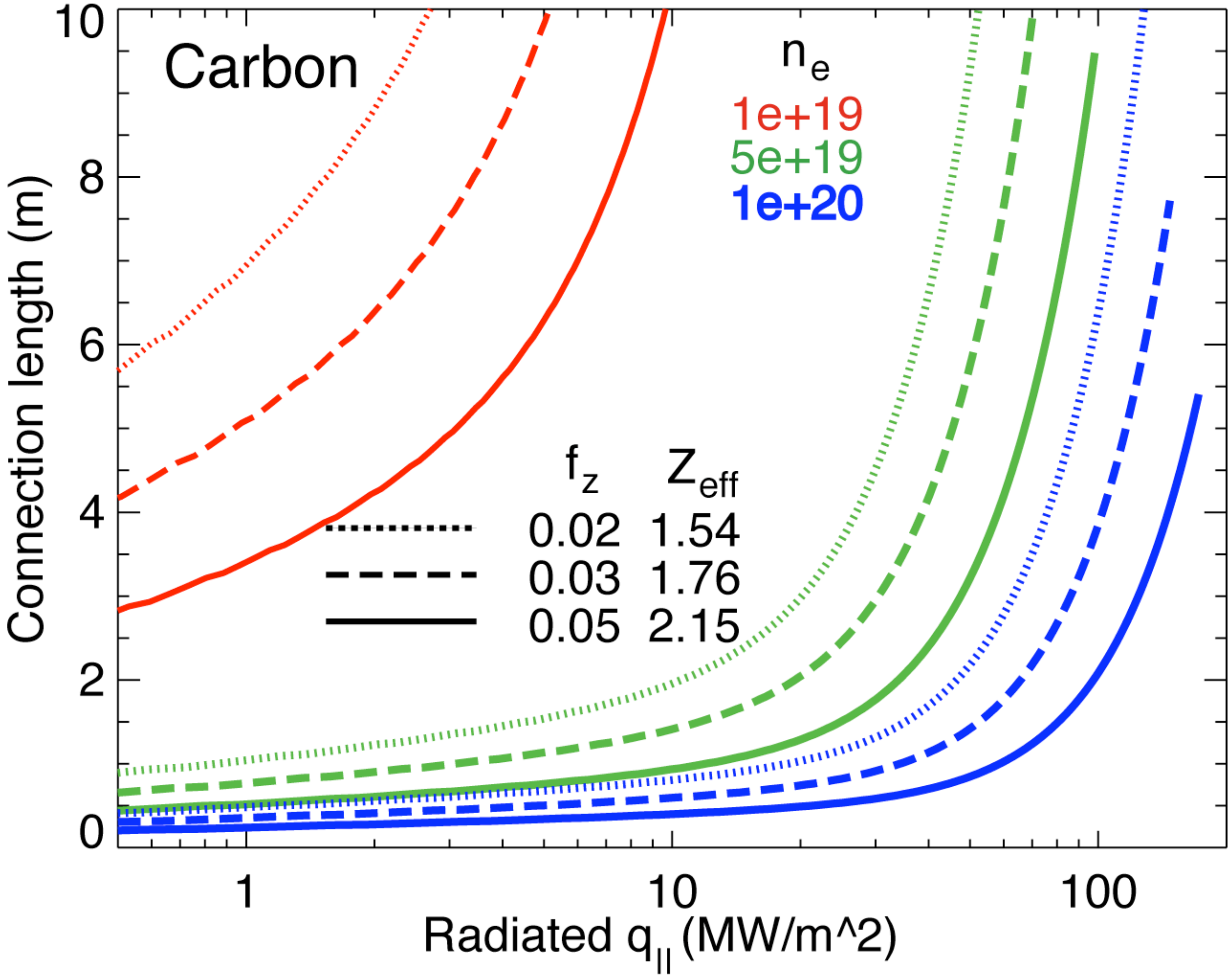
Divertor peak heat flux reduced by up to 60 % as a result of outer strike point partial detachment





- Total P_{SOL} = 4.5 - 5 MW
  - $Q_{out.div.}$= 2-3 MW (ref. discharge)
  - $Q_{out.div.}$= 1-2 MW (PDD discharge)
- Outer leg radiated power estimate:
  - Total P_{rad}~0.25-0.4 MW (ref. discharge)
  - Total P_{rad}~0.5 MW (PDD discharge)

Post model shows that high (however reasonable) divertor n_e and n_C are needed for high divertor P_{rad}

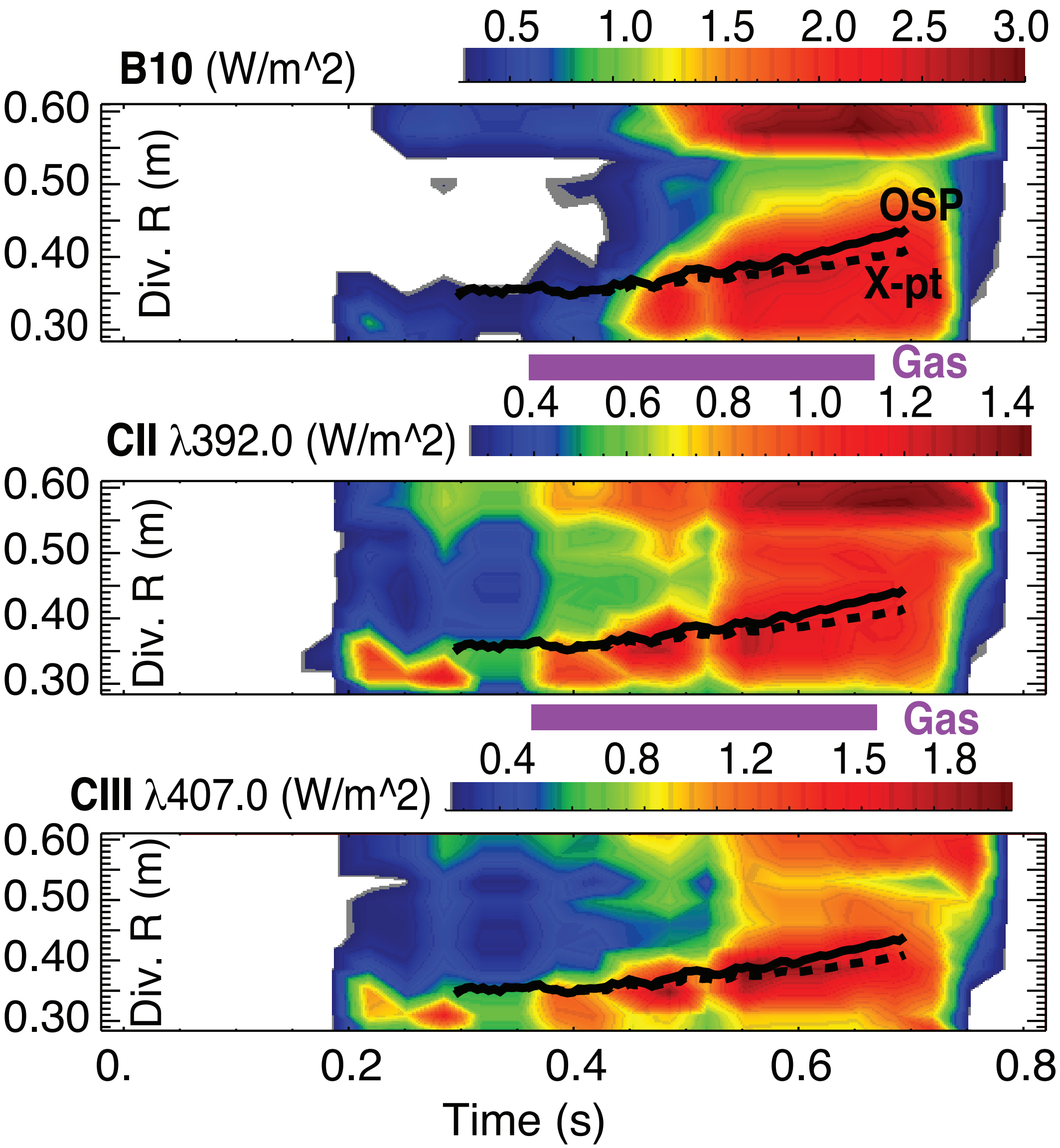


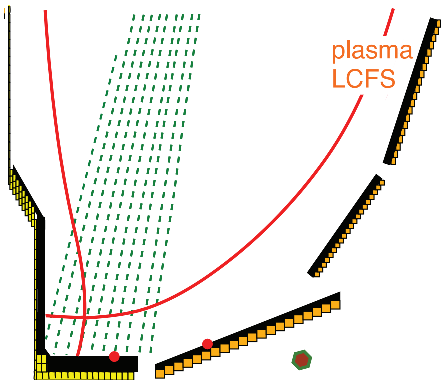
$$q_{\|} = -\kappa_0 T_e^{5/2} \frac{\partial T_e}{\partial x}$$

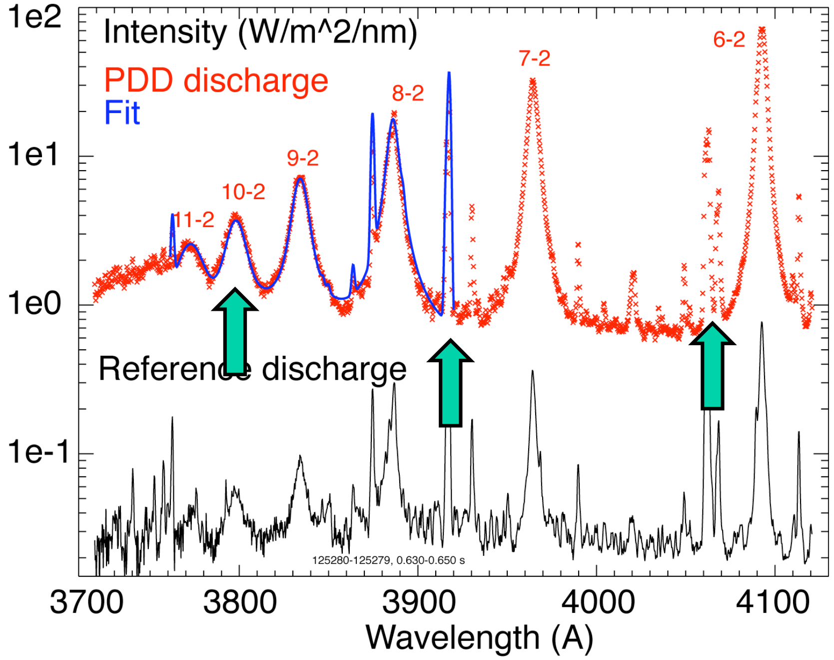
$$\frac{\partial q_{\|}}{\partial x} = -n_e n_z L_Z(T_e)$$

- Post JNM 220-222, 1014 (1995)
- Hulse-Post non-coronal carbon radiative cooling curves for n_0/n_e, n_e-τ_{recy}

UV spectroscopy shows large increase in n_e, C II and CIII emission during the PDD phase







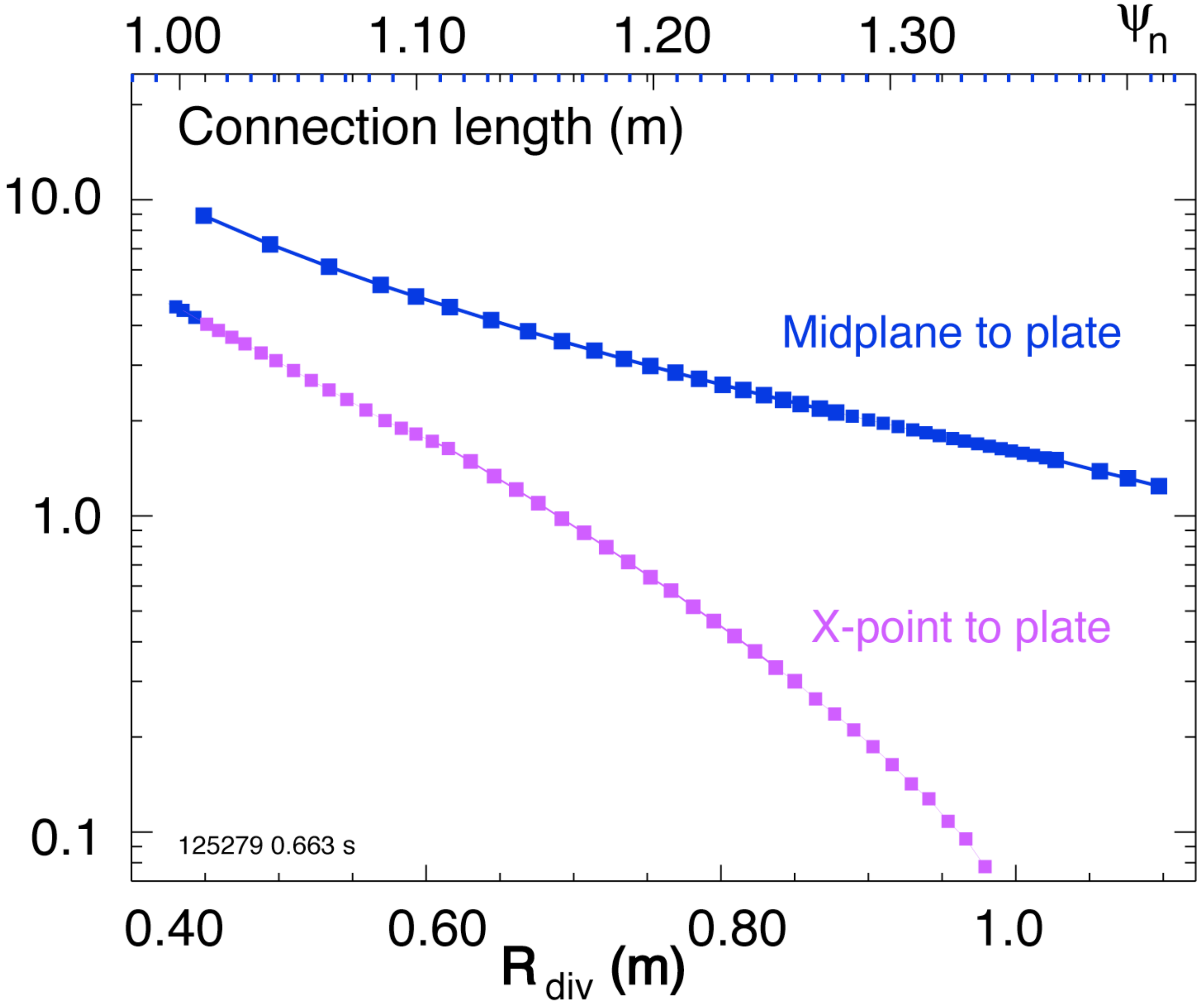
- Inferred from D I Balmer spectra (8…11 – 2)
  - T_e < 0.7-1.2 eV
  - n_e ~ 2-6 x 10^{20} m^{-3}

Summary

- Significant divertor **peak heat flux reduction** has been demonstrated in highly shaped high-performance H-mode discharges in NSTX using **divertor magnetic flux expansion and radiative divertor** simultaneously with **high core plasma performance**
  - Good synergy of high performance H-mode regime with partially detached divertor
  - Open geometry un-pumped divertor with additional D_2 injection
  - Radiation due to intrinsic carbon and deuterium

- Divertor performance in a high power density spherical torus
  - consistent with our expectations based on conventional tokamak divertor physics
  - determined to a large degree by SOL geometry effects

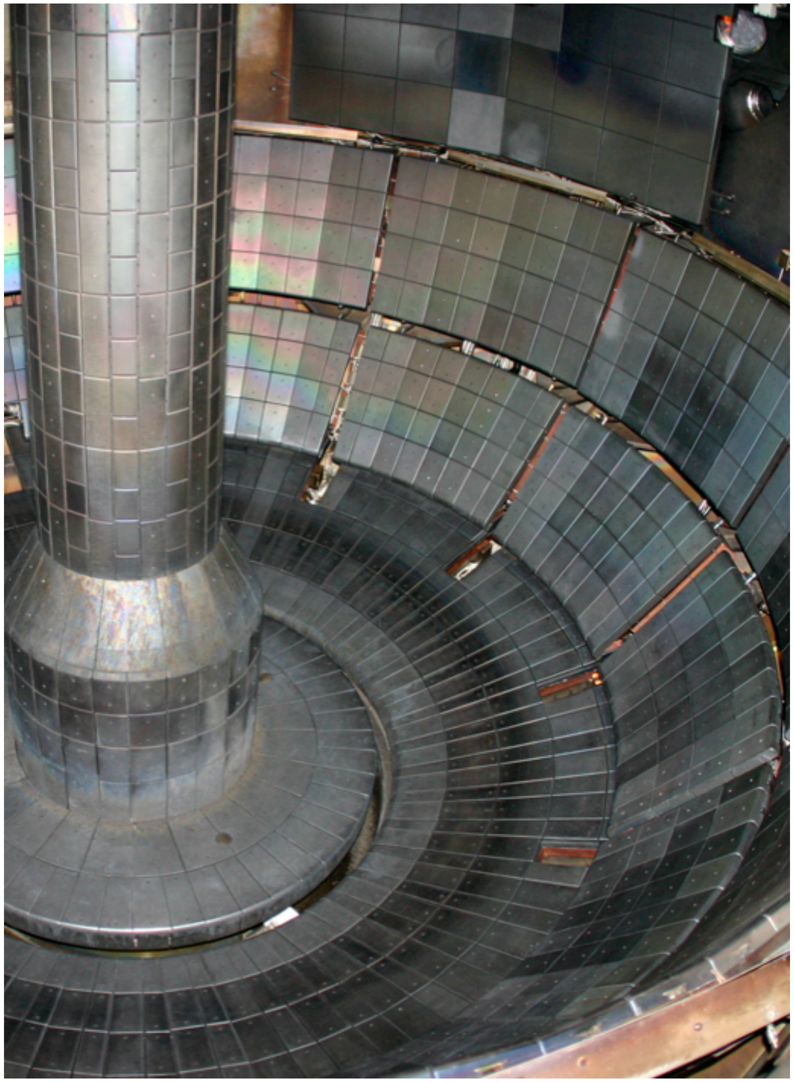
Backup slides



Open geometry NSTX divertor enables flexibility in plasma shaping

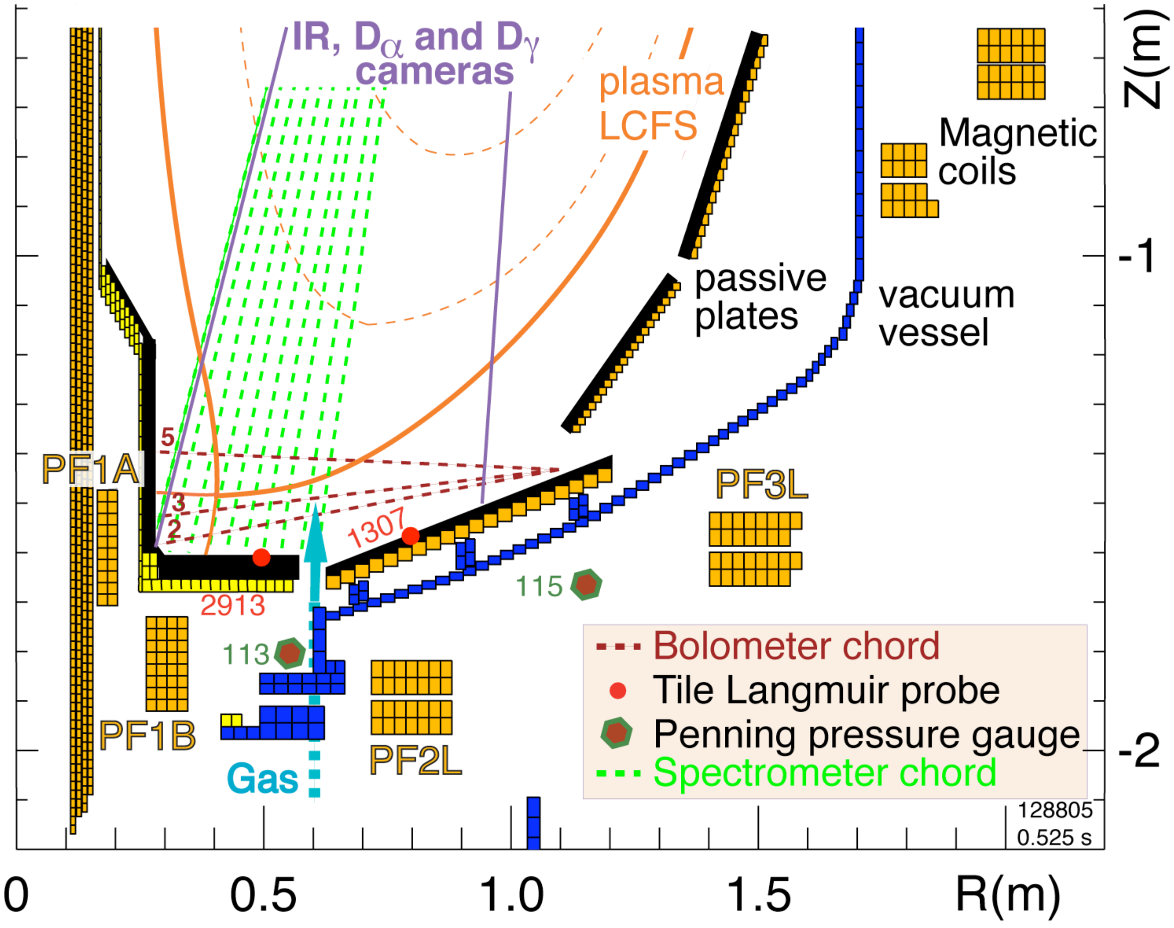
- Plasma facing components
  - ATJ and CFC tiles
  - Carbon - erosion, sputtering
  - Max P_{rad} fraction limited by carbon radiation efficiency
  - Typical divertor tile temperature in 1 s pulses $T < 500$ C ($q_{peak} \leq 10$ MW/m^2)

- No active divertor pumping
  - Experiments with lithium coatings for reduced recycling



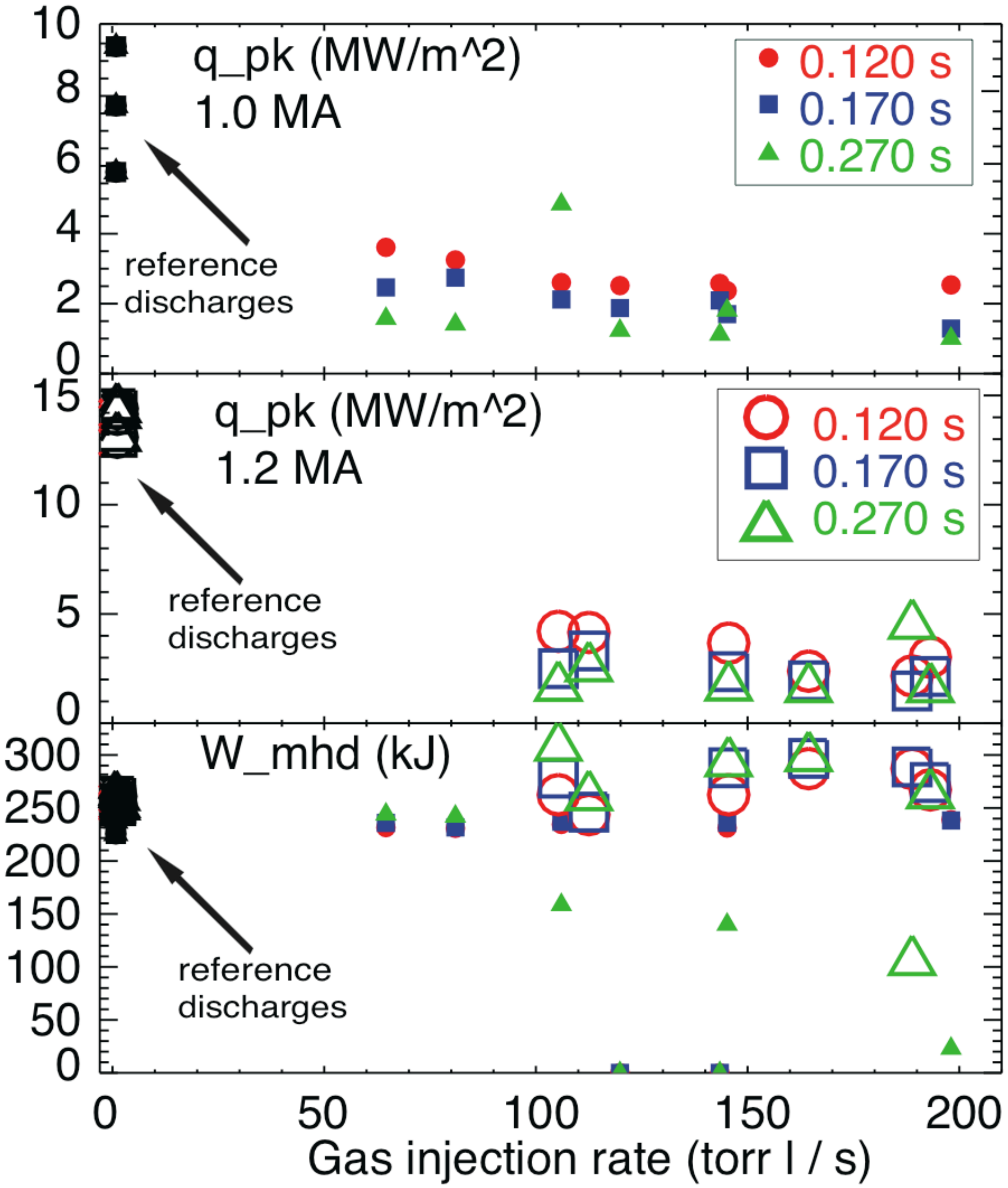
Multiple diagnostic measurements are analyzed to elucidate on radiative divertor physics in NSTX

- Diagnostic set for divertor studies:
    - IR cameras
    - Bolometers
    - Neutral pressure gauges
    - Tile Langmuir probes
    - D_α, D_γ filtered CCD arrays
    - UV-VIS spectrometer (10 divertor chords)
- Midplane Thomson scattering and CHERS systems
- Divertor gas injector
  Γ_{gas} = 20-200 Torr l / s

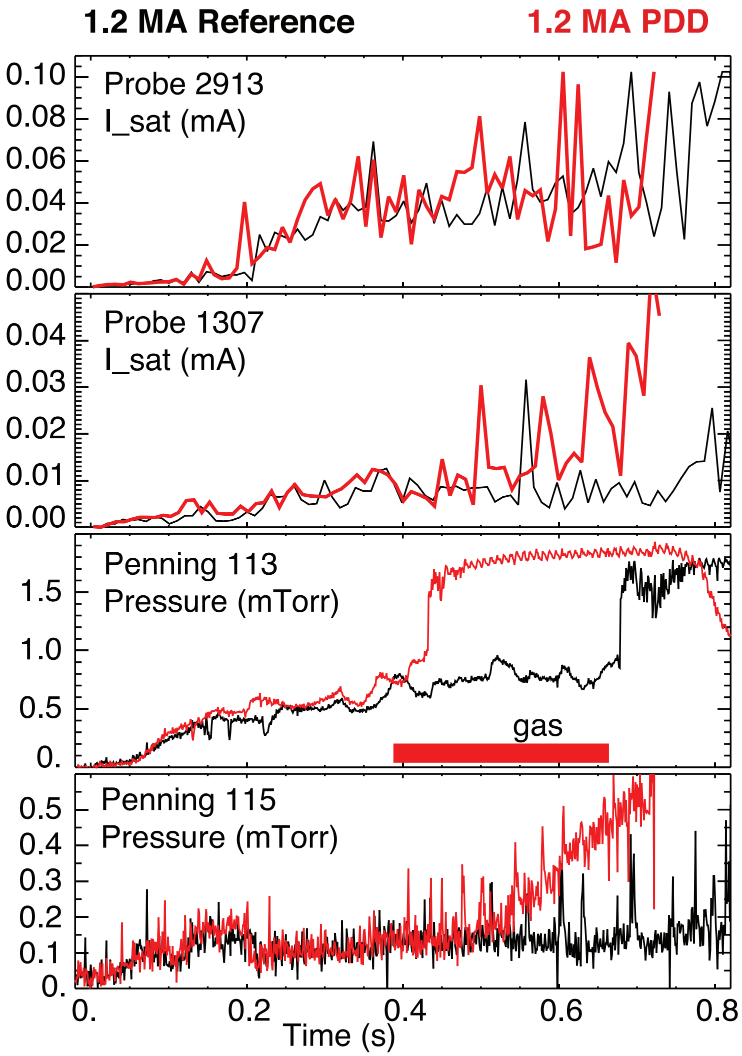


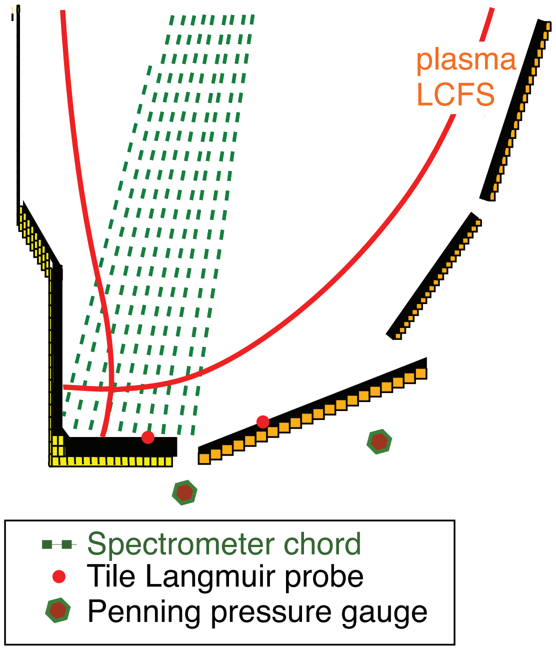
Radiative divertor conditions were optimized in 1.0 MA and 1.2 MA 6 MW H-mode discharges

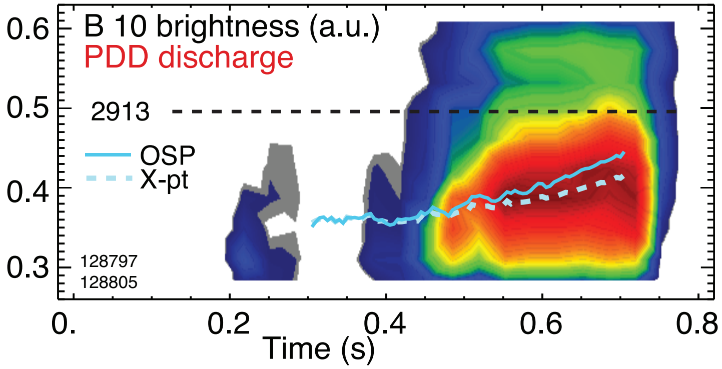
- Criteria of optimization - find gas injection rate to obtain PDD with minimal confinement degradation
- $q_{||}$ was higher in 1.2 MA discharges thus more gas was needed to reduce q_{pk}
- After 0.250-0.270 ms peak heat flux reached low steady-state level
- Optimal gas injection found (used 300 ms pulses)
    - 50-100 Torr l /s for 1.0 MA discharges
    - 110-160 Torr l /s for 1.2 MA discharges



Momentum loss was evidenced by particle flux decrease and divertor neutral pressure increase





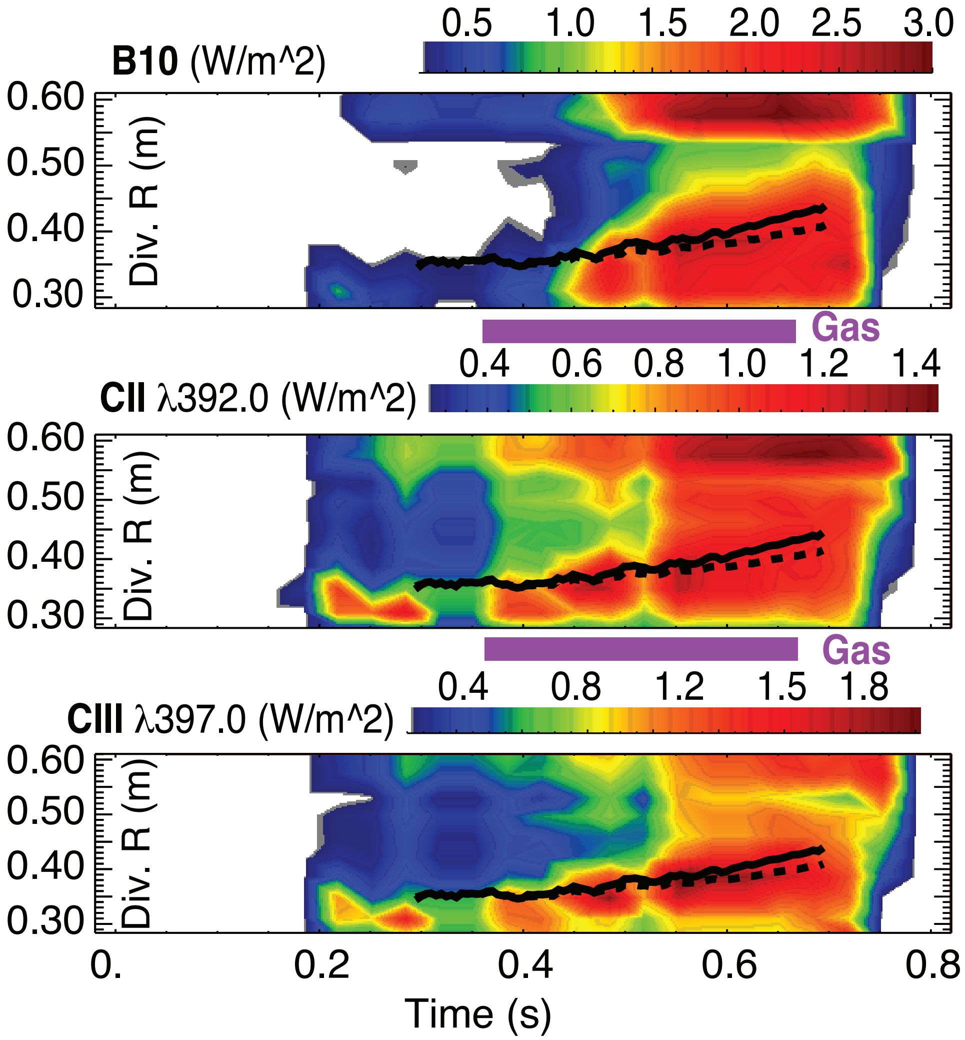


- Neutral pressure of 2-3 mTorr is required to explain plasma pressure drop of *dp/dx* = 10 Pa/m

$$\frac{dp}{dx} = m\Gamma_i n_n \langle \sigma v \rangle_{cx+el} + m n^2 \langle \sigma v \rangle_{rec}$$

UV spectroscopy shows large increase in recombination, n_e, and C II, CIII emission during the PDD phase

- PDD discharge



Reference discharge