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Divertor heat flux reduction and detachment in NSTX

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Abstract

Abstract: We report the first successful experiments at achieving significant divertor outer strike point (OSP) peak heat flux reduction in H-mode plasmas with high auxiliary heating in a large spherical torus NSTX. Two approaches have been investigated in 1-6 MW NBI-heated L- and H-mode plasmas with elongation 1.8-2.4 and triangularity 0.45-0.75. One approach - a naturally obtained high poloidal flux expansion of up to 25 at the OSP in a strongly shaped configuration (high elongation and triangularity) - led to a moderate peak heat flux of 2-4 MW/m^2 in extended pulse small ELM H-mode plasmas. Another approach - a dissipative divertor scenario with D_2 puffing - was employed for plasma shapes with low elongation and triangularity where typical reference OSP steady-state peak heat flux was measured to be 4-6 MW/m^2 in the 4 MW NBI-heated H-mode phase. Using midplane or divertor D_2 injections at rates R=$(1.4 - 11) \times 10^{21}$ particles/s the OSP peak heat flux was reduced by up to 80 % in the radiative high-recycling divertor regime. A further increase in gas puffing rate to 3×10^{22} particles/s produced a partial OSP detachment and an X-point MARFE which degraded the core plasma confinement. On the basis of the two point model arguments the open divertor geometry and short connection length are identified as factors leading to reduced radiative and momentum losses in the NSTX divertor.

Acknowledgements

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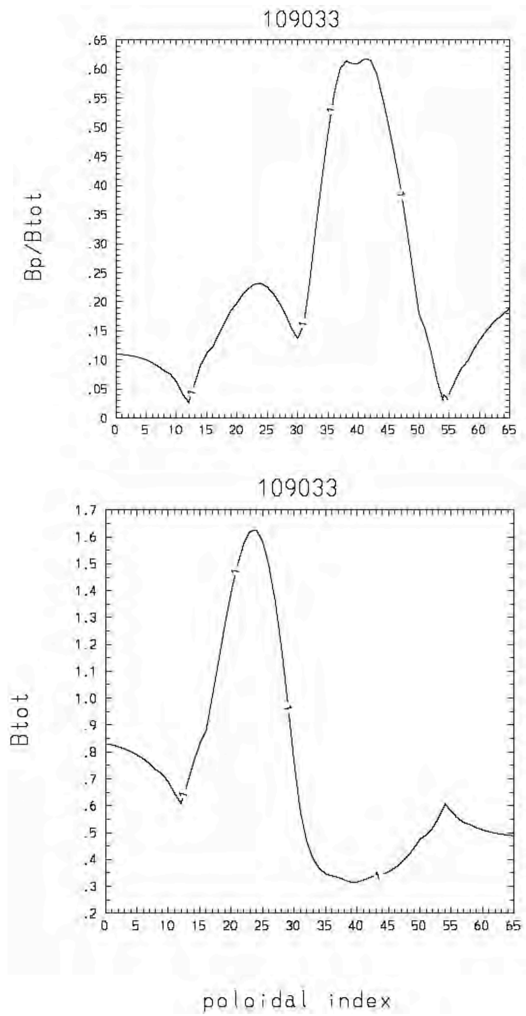
Goal - develop steady-state divertor heat load mitigation scenarios in a large Spherical Torus

- **Steady-state divertor heat load mitigation - one of the key Boundary Physics issues in Spherical Tori (ST)**



- **Low aspect ratio magnetic configuration leads to**
  - small divertor volume
  - small plasma wetted area
  - high q_{II}
  - short connection length L_{II}
  - High SOL mirror ratio $M=|B_{min}| / |B_{max}|$
  - SOL area factor: $A_{out} > A_{in}$
- **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)

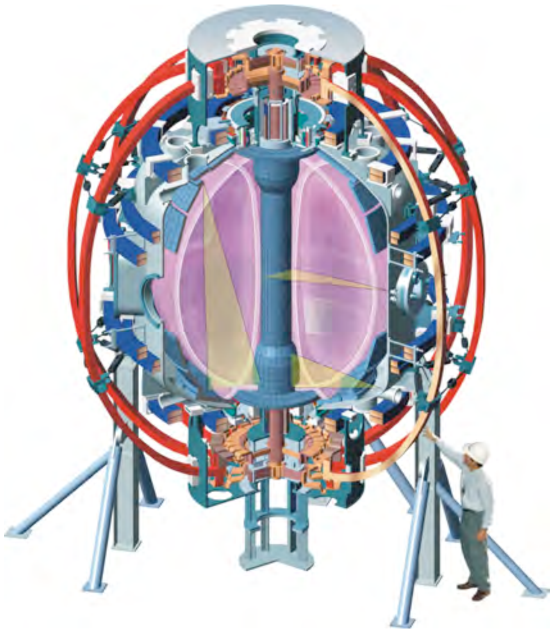
- **These scenarios must be compatible with good core plasma performance (H-mode confinement, MHD, ELM regime, density)**

Outline

- NSTX background: parameters, divertor heat and particle fluxes, divertor asymmetries

- Naturally occurring divertor regimes in NSTX

- Study of outer strike point (OSP) heat flux reduction and detachment with D_2 injection
  - ✓ radiative divertor (RD) regime compatible with high performance H-mode plasmas
  - ✓ partially detached divertor (PDD) regime
- ✓ OSP heat flux reduction by flux expansion

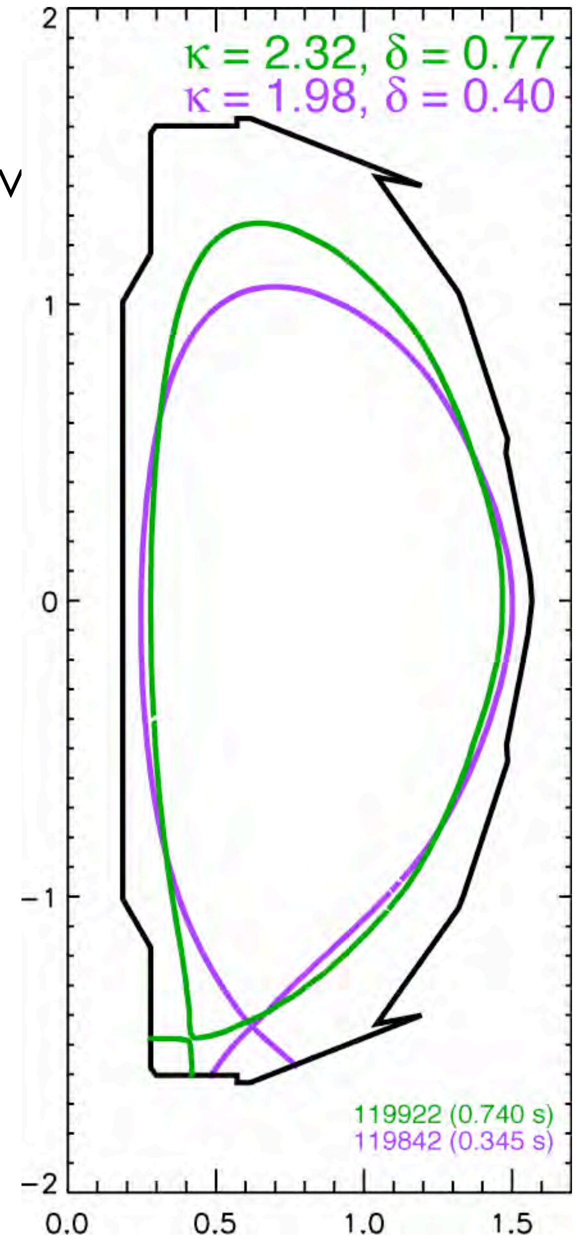


- Summary

Divertor heat flux mitigation in NSTX: background

- **NSTX divertor**
  - open, horizontal targets, graphite tiles, no activ pumping
  - 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 solutions
  - q_{out} < 10 MW/m^2, P/R < 9

- **Goal - study divertor heat flux reduction and detachment**
  - in lower single null **δ = 0.4-0.5, κ = 1.8-2.0** configuration with **D_2 puffing**
  - in lower single null **δ = 0.7-0.8, κ = 2.2-2.5** configuration by **flux expansion**



NSTX reference data

NSTX eng. and plasma parameters

$R = 0.85$ m, $a = 0.67$ m, $A = R/a > 1.27$, $P_{NBI} < 7$ MW, $P_{HHFW} < 6$ MW, $B_t < 0.6$ T

NSTX fueling

* 1 Torr l/s = 7e19 s^{-1}

- Gas injection: low field side (LFS, top + side) and high field side (HFS, midplane + shoulder). D_2, He, injected at S = 20 - 80 Torr l /s.
- Neutral beam injection system: three beams, 80 - 100 keV, 0.8-7 MW, fueling rate: S < 4 Torr l / s
- Supersonic gas injection: S = 30 - 65 Torr l / s

NSTX wall conditioning

- Between shots He GDC, He conditioning plasmas
- TMB and Plasma TMB
- Bake out at 350o C
- Li coatings deposited by Li evaporator

NSTX pumping

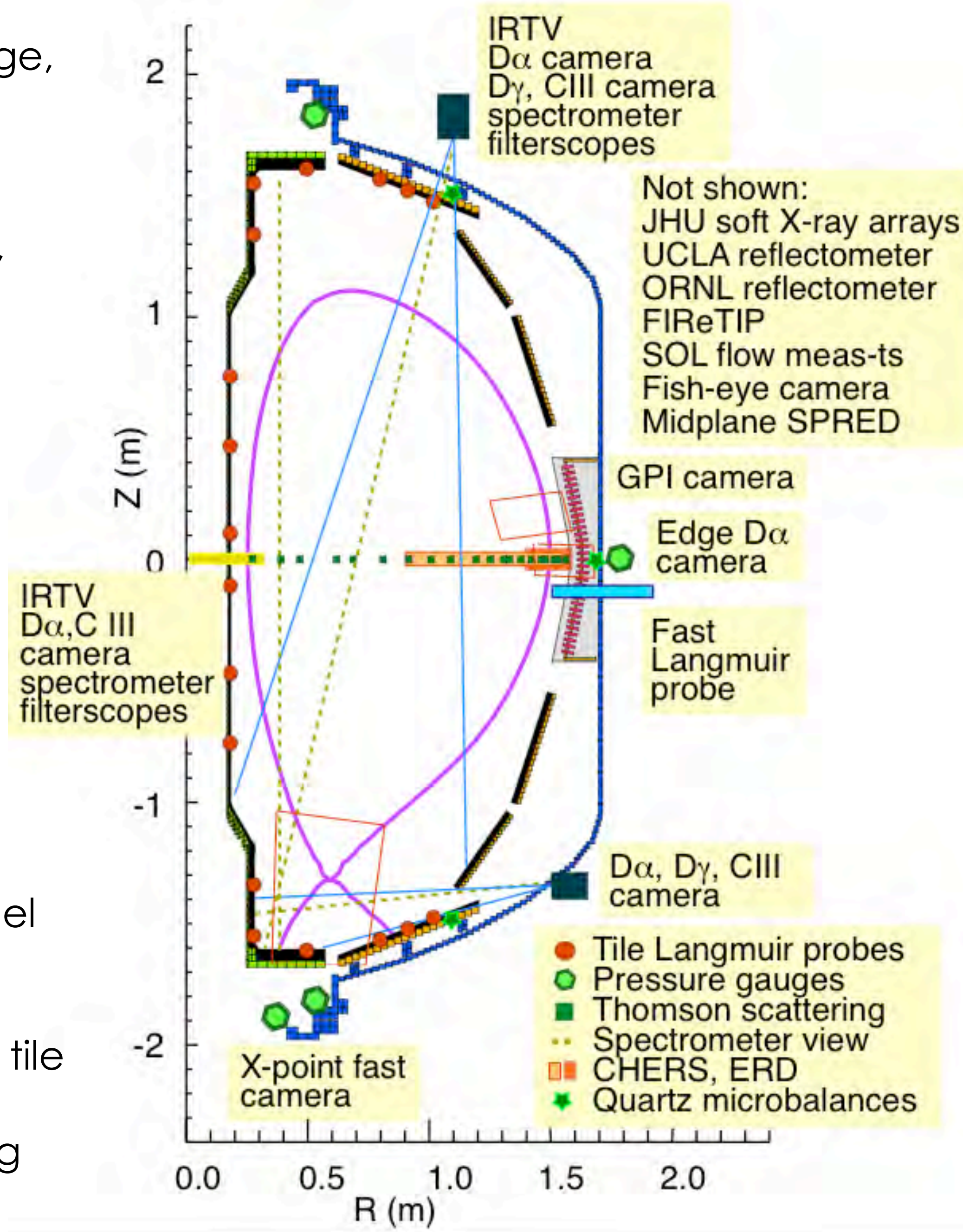
- Turbomolecular pump (3400 l / s)
- NBI cryopump (50000 l / s, in NBI plasmas only)
- Conditioned walls, Li coatings

Plasma Facing Components

- ATJ graphite tiles on divertor and passive plates
- ATJ and CFC tiles on center stack
- Thickness 1” and 2”

NSTX diagnostic set enables divertor studies

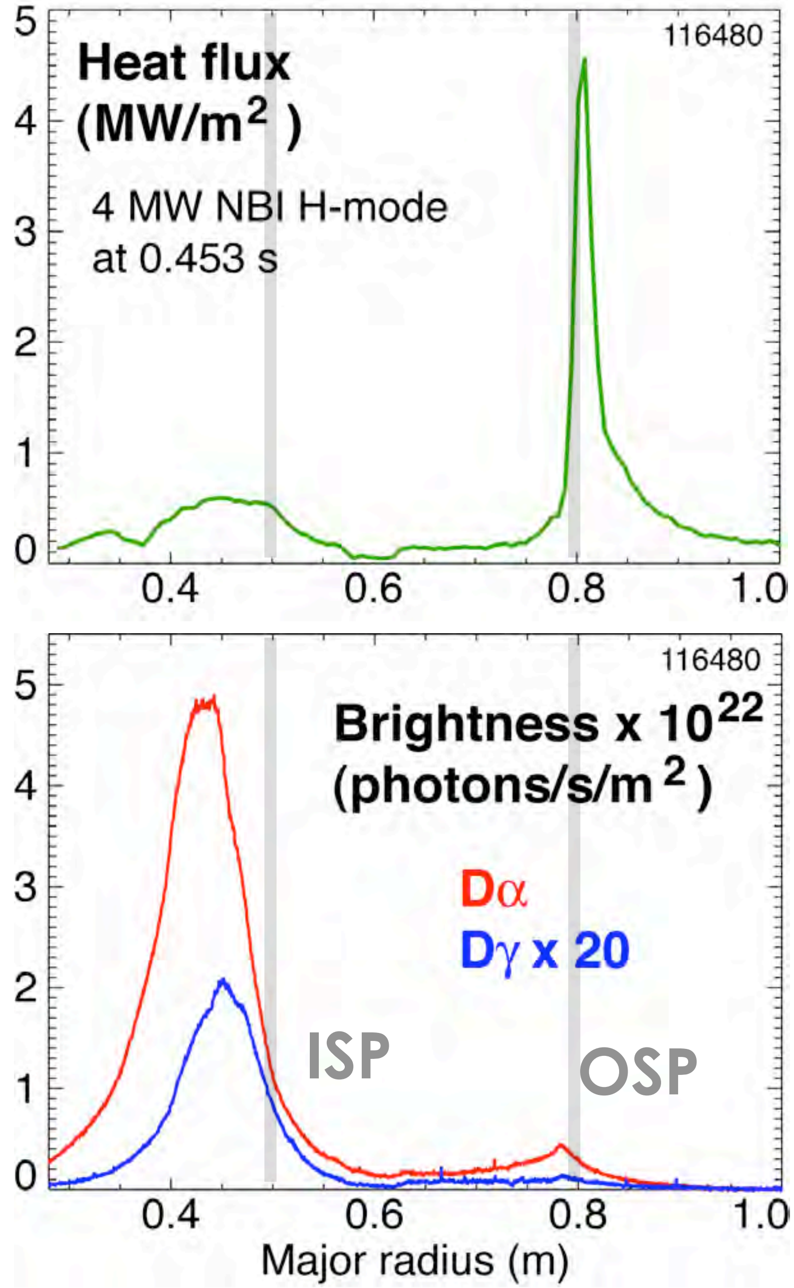
- **IRTV**: two Indigo Alpha 160 x 128 pixel microbolometer cameras, 7-13 mm range, 30 ms frame rate
- **Dα, Dγ, C III filtered cameras**: four Dalsa 1 x 2048 pixel CCDs, filter FWHM 10-15 A, frame rate 0.2 - 1 ms
- **Neutral pressure gauges**: four micro-ion gauges on top and at midplane, two Penning 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



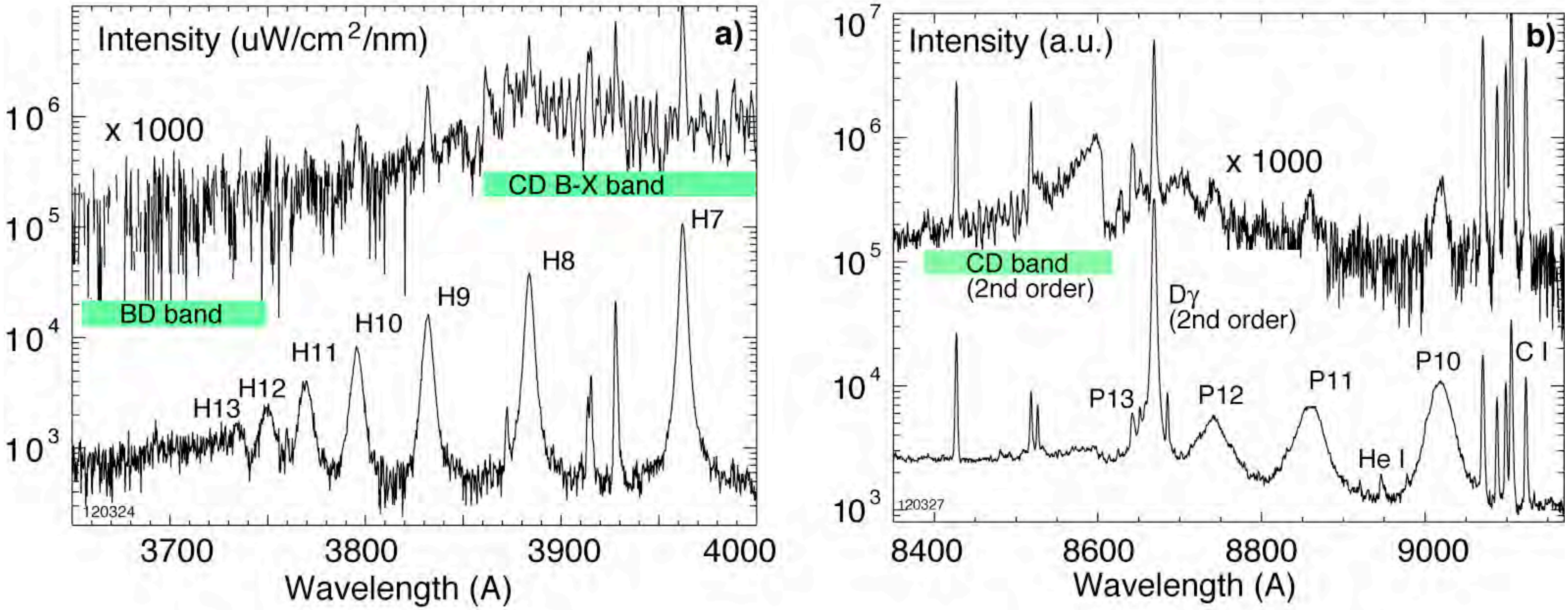
NSTX divertor regimes

- 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, $q_{out} <$ 2-7 MW/m^2 in 2-6 MW NBI-heated plasmas
- Recycling in-out asymmetry up to 15 from divertor Dα profiles
- Divertor Dγ observed in inner divertor only, typical ratio Dγ/ Dα about 0.020 - 0.12 - 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 $n_e < n_G$



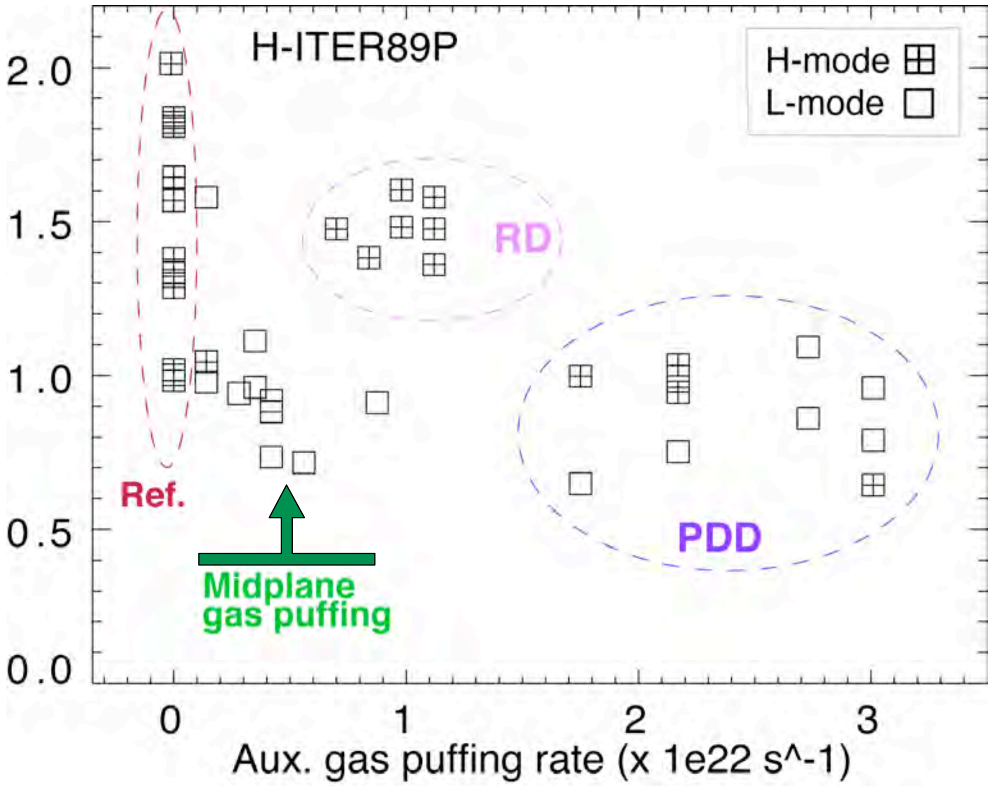
High $n_{e,}$ low T_e inferred from Balmer and Paschen emission lines measured in inner divertor leg

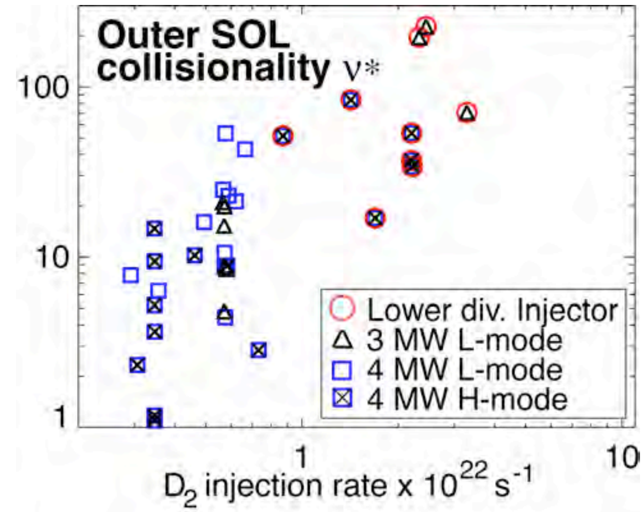


Upper traces - attached, lower traces - detached

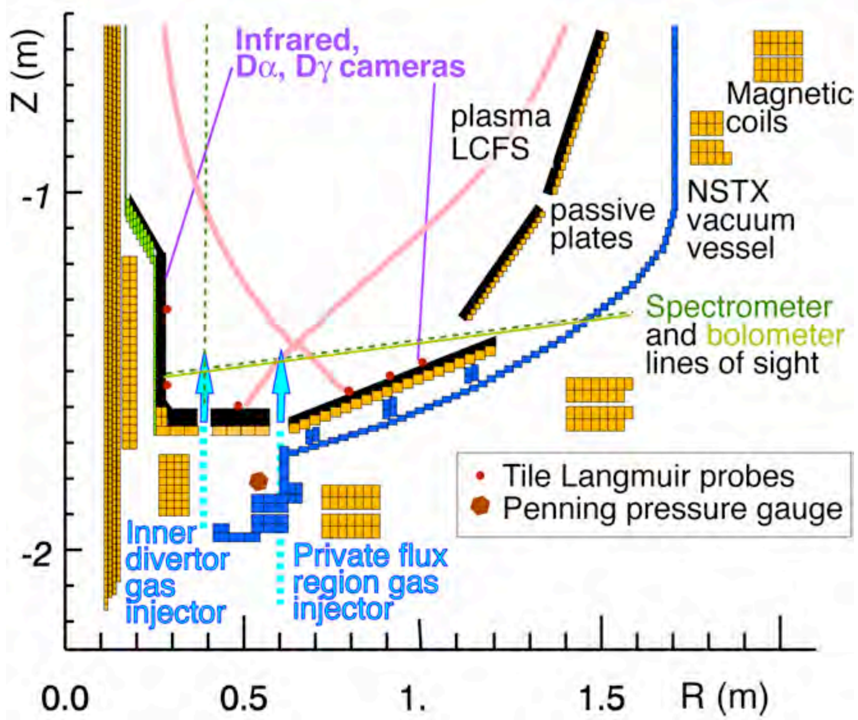
- In dense low temperature plasmas 3-body recombination rate is high - Lyman (FUV), Balmer (UV), Paschen (NIR) series lines are prominent
- Stark broadening due to plasma electron and ion statistical microfield
- n_e = 0.6-6 x 10^{20} m^{-3} from Stark broadening (Model Microfield Method calculations) **Soukhanovskii et. al., Rev. Sci. Instrum. 77, 10F127 (2006)**
- T_e = 0.3-1.3 eV from line intensity ratios (Saha-Boltzman population distribution, ADAS data)

A range of core and divertor conditions obtained at various divertor D_2 puffing rates





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

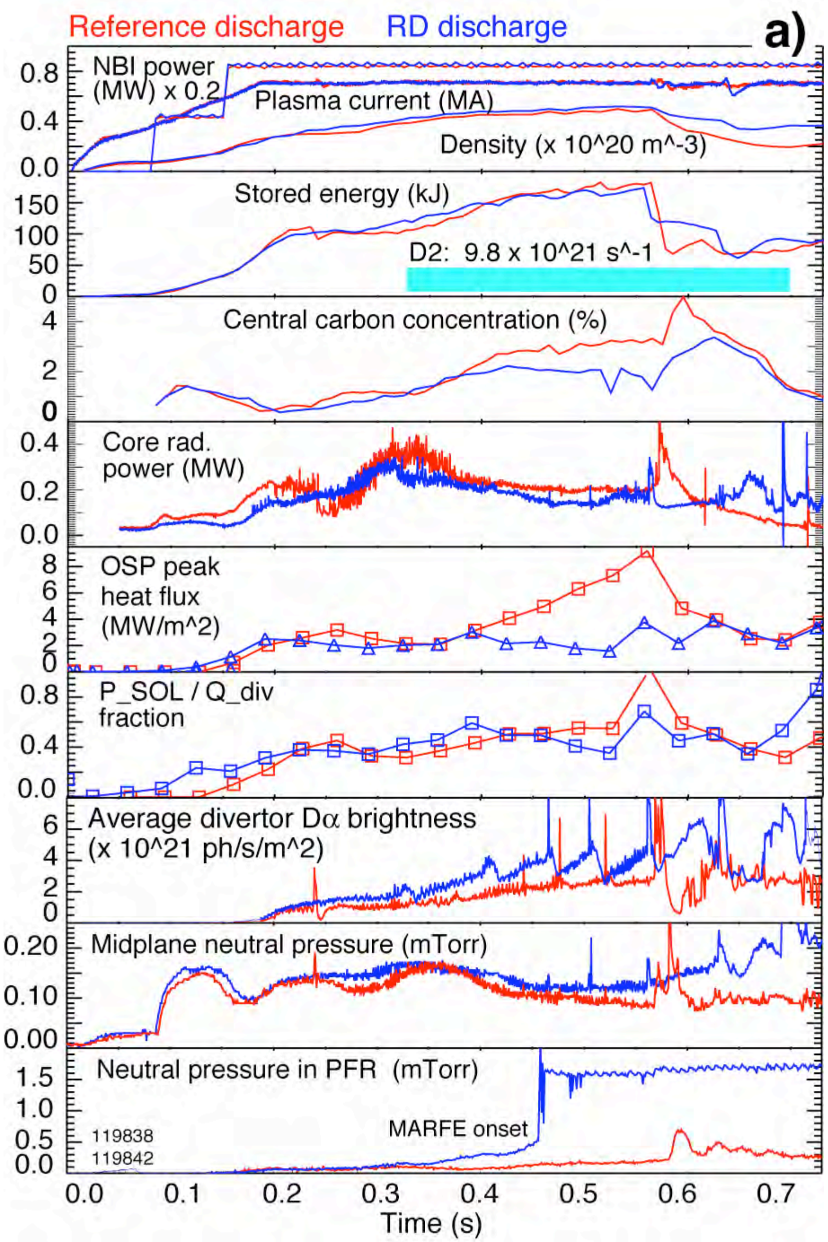


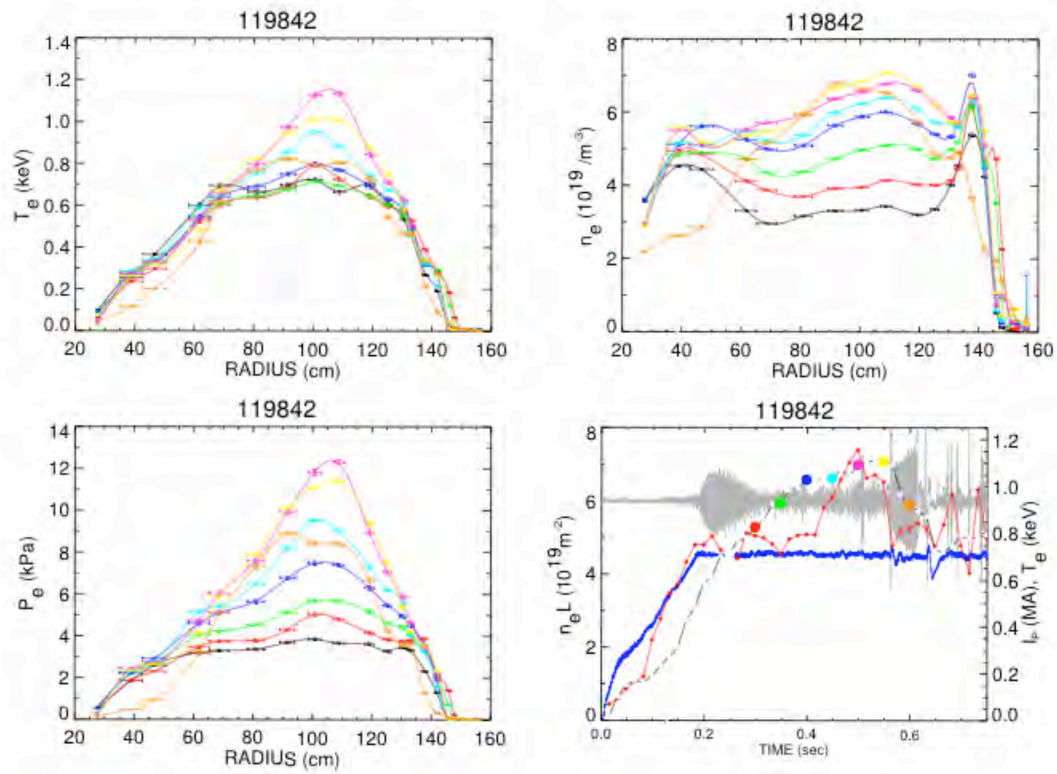
Radiative divertor obtained using moderate rate divertor gas puffing; OSP peak heat flux reduced

Radiative divertor regime

- ✓ Obtained by steady-state D_2 injection in PFR or at ISP at 80-160 Torr l /s
- ✓ OSP heat flux reduced by 2-5
- ✓ ISP heat flux practically unaffected
- ✓ X-point ("divertor") MARFE developed during gas puffing
- ✓ No sign of volume recombination at OSP until later phase of gas injection
- ✓ Divertor bolometer signal increased from 10-15 W/m^2 to 20-30 W/m^2
- ✓ Generally compatible with H-mode
- ✓ Gas puffing eventually caused confinement degradation, locked mode, large MHD modes and low *m,n* modes
- ✓ RD is suitable for heat flux reduction in long high-performance H-mode plasmas

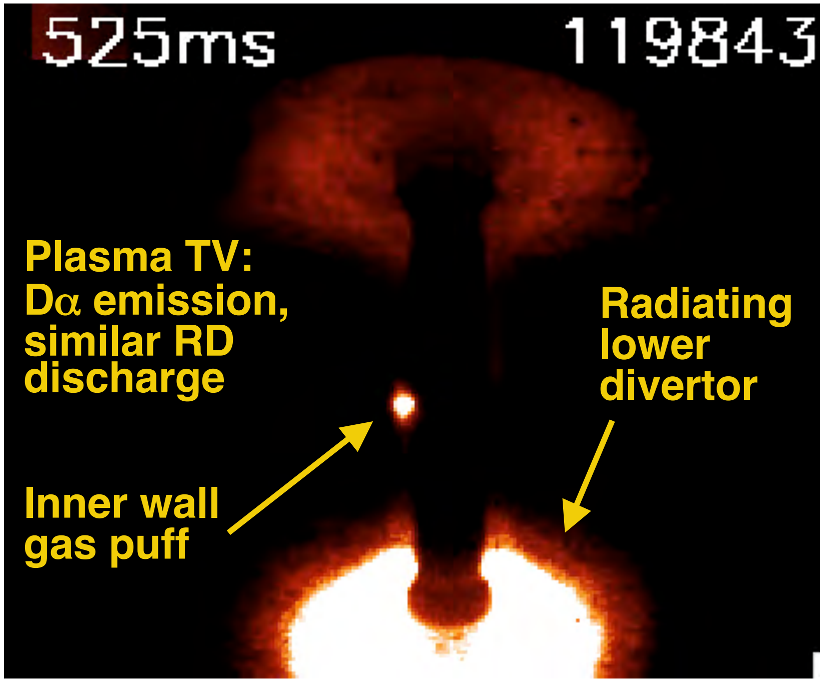
Core confinement properties are unaffected by moderate flow rate divertor D_2 injection

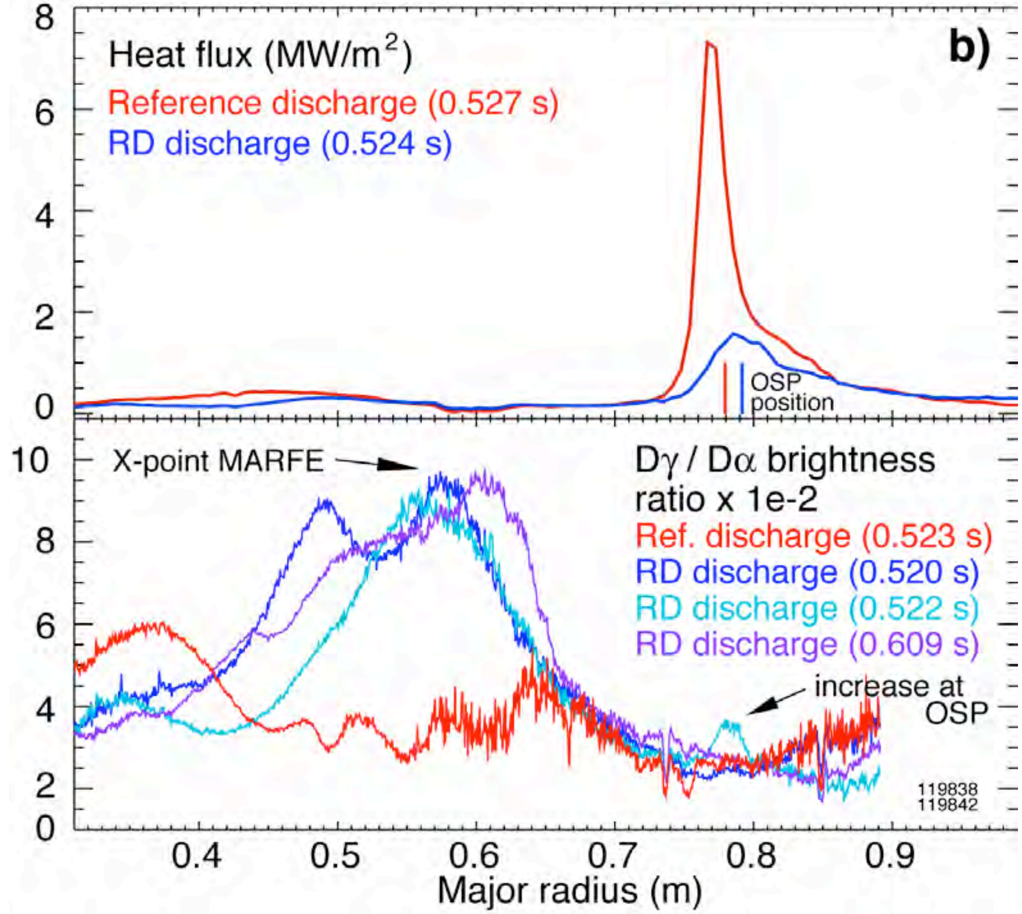




- Core plasma parameters practically unaffected
- Gas puffing eventually leads X-point MARFE onset
- Discharge duration is limited by β-limiting instability (both reference and RD)

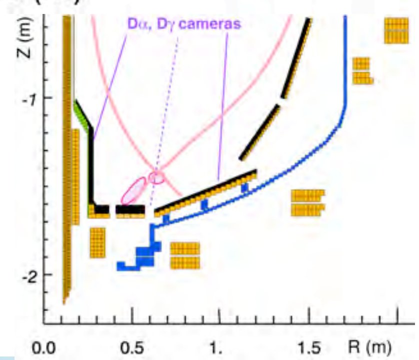
Radiative Divertor leads to OSP peak heat flux reduction by 2-5, development of X-point MARFE





- Outer peak heat flux reduced by x 2-5, but no sign of recombination
- X-point MARFE develops during gas puffing
- At highest D_2 puffing rate Dγ/Dα ratio at OSP transiently increases

1D CCD camera viewing geometry

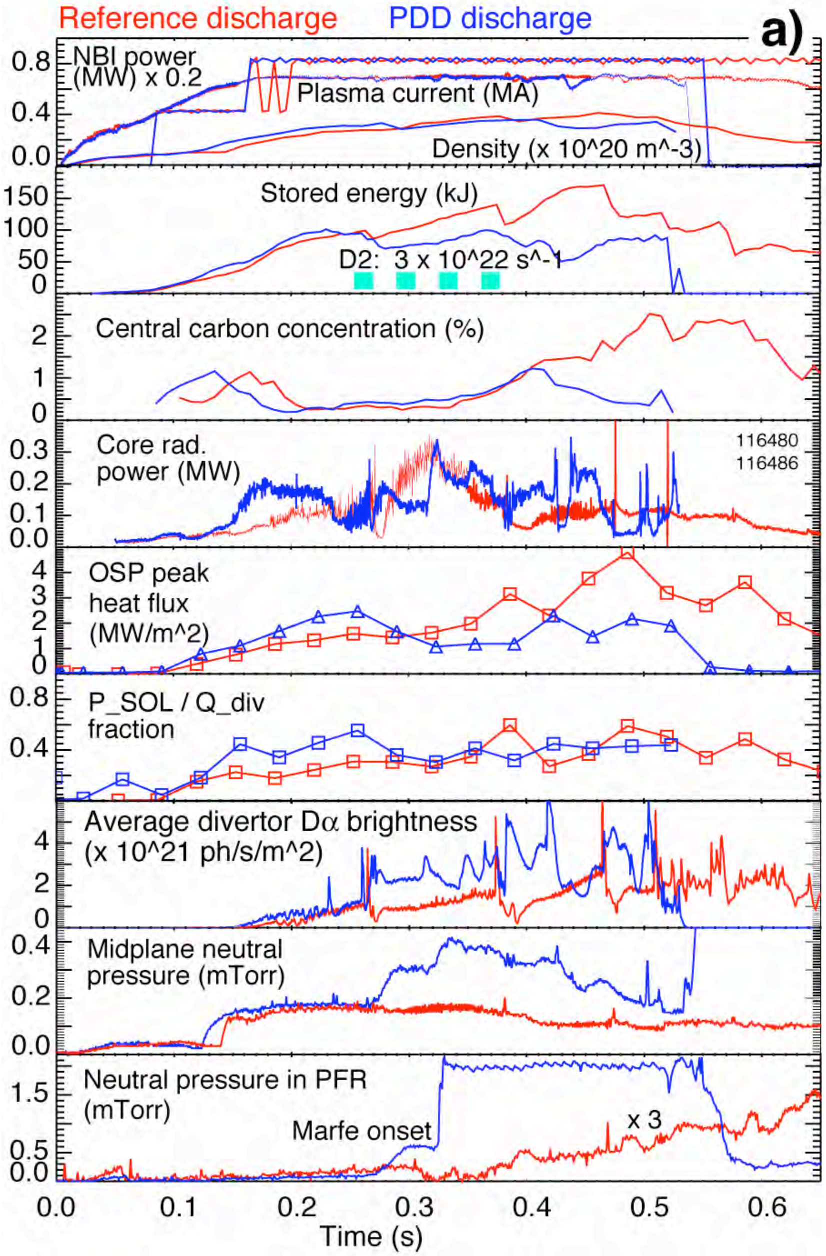


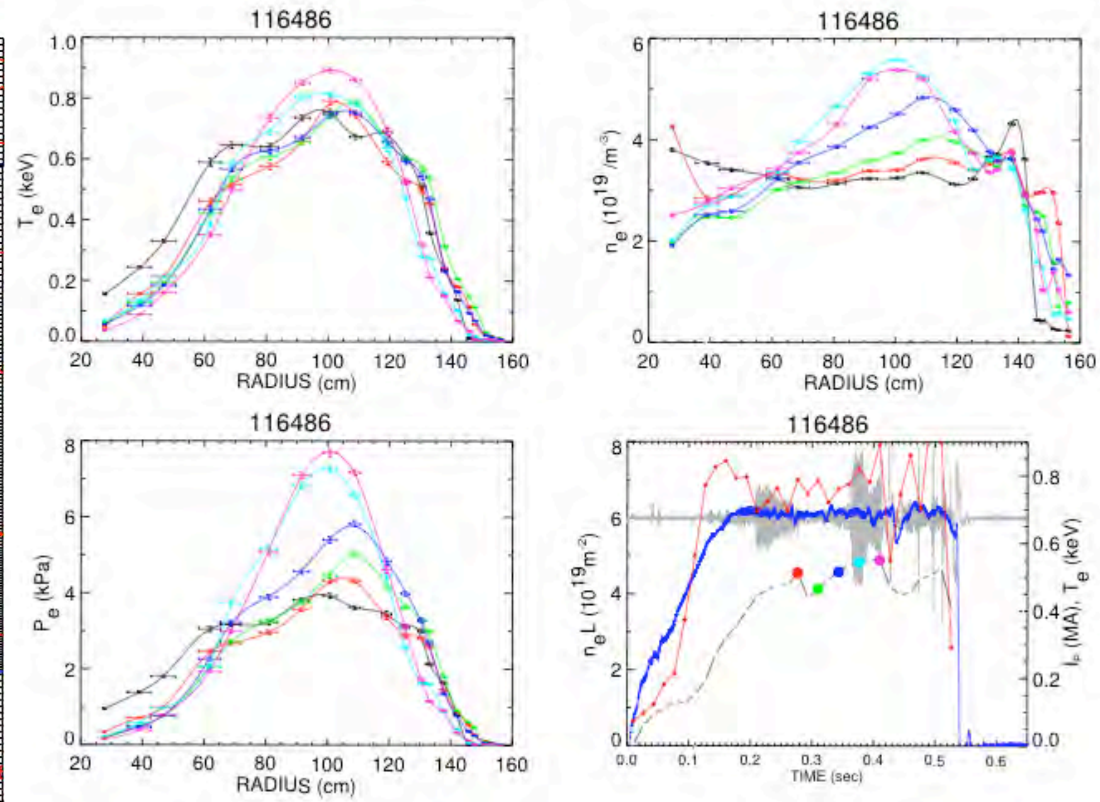
OSP partial detachment obtained using pulsed divertor D_2 injection at high flow rates

Partially detached divertor regime (OSP detached, outer SOL attached)

- ✓ Obtained by pulsed D_2 injection at > 200 T l /s at ISP
- ✓ OSP heat flux reduced by 4-5
- ✓ ISP heat flux did not change
- ✓ Broadened Dα and Dγ brightness profiles, increases outer leg Dγ / Dα ratio - volume recombination at OSP
- ✓ Divertor bolometer signal increased from 10-15 W/m^2 to 15-20 W/m^2
- ✓ Correlation of I_{sat} drop in Langmuir Probe close to OSP and Dγ / Dα increase in OSP region
- ✓ Detachment extent: 2-3 cm at OSP, detached only during gas pulse
- ✓ H-L transition within 20-100 ms

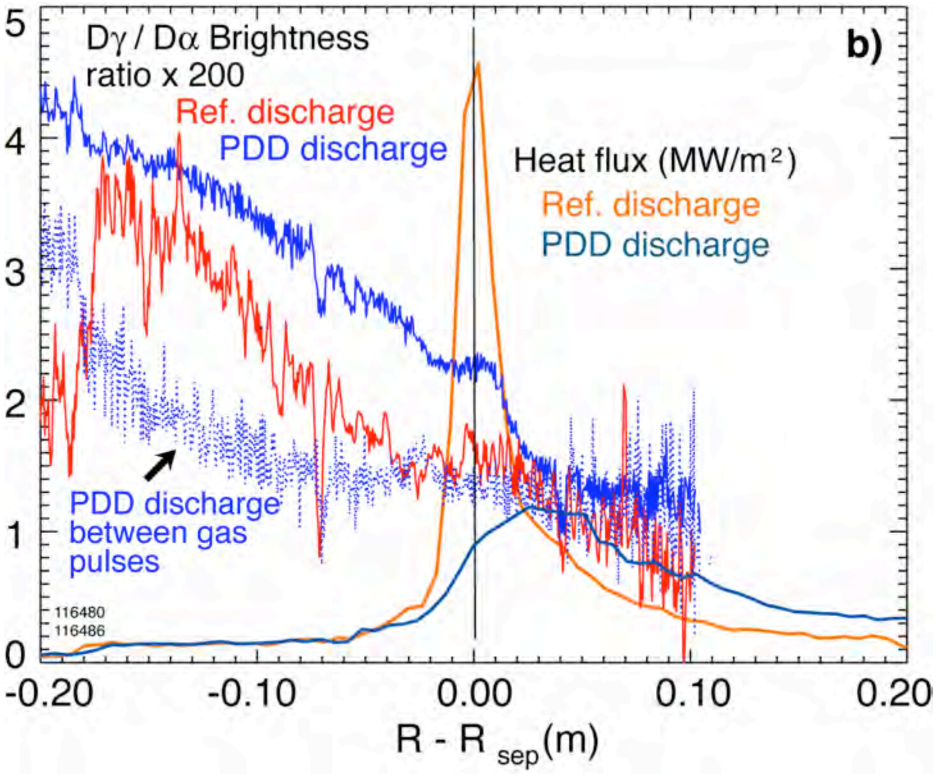
Core confinement properties are affected by high flow rate deuterium injection in PDD

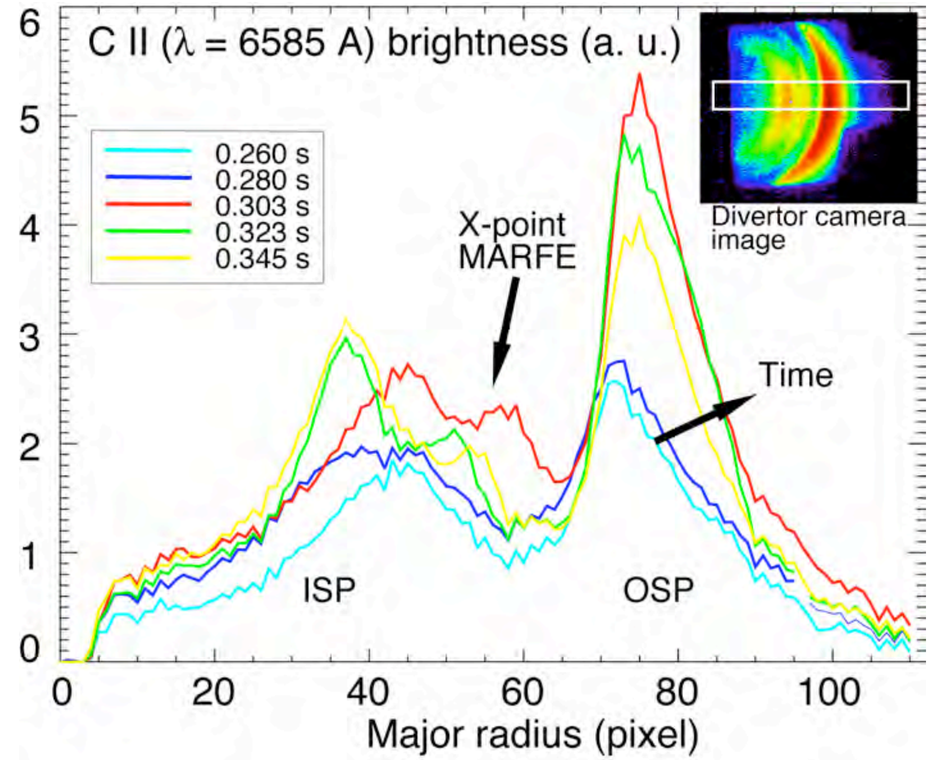


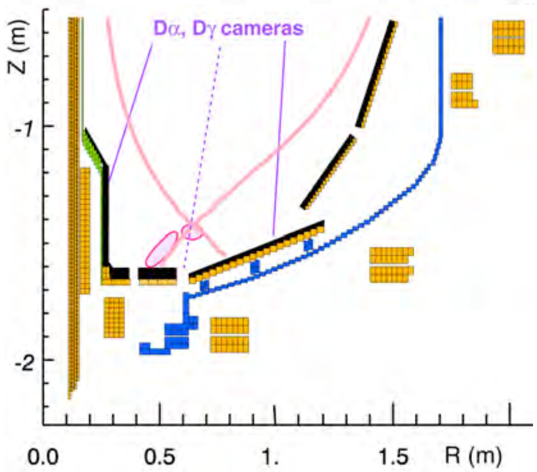


- Core plasma parameters degrade quickly
- X-point MARFE develops within 20-30 ms
- Discharge duration is limited by large MHD modes, confinement degradation

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



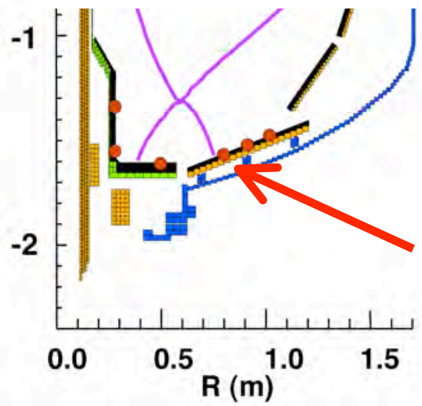


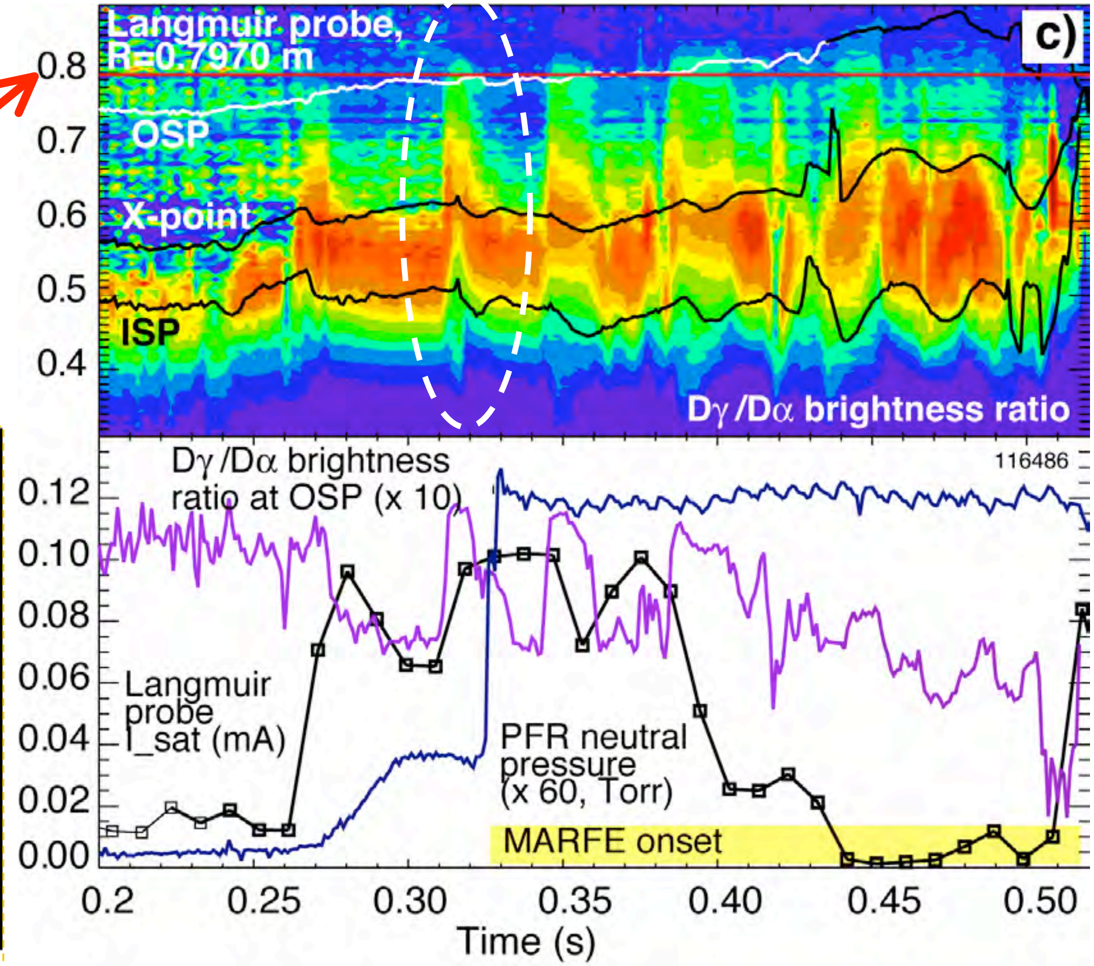


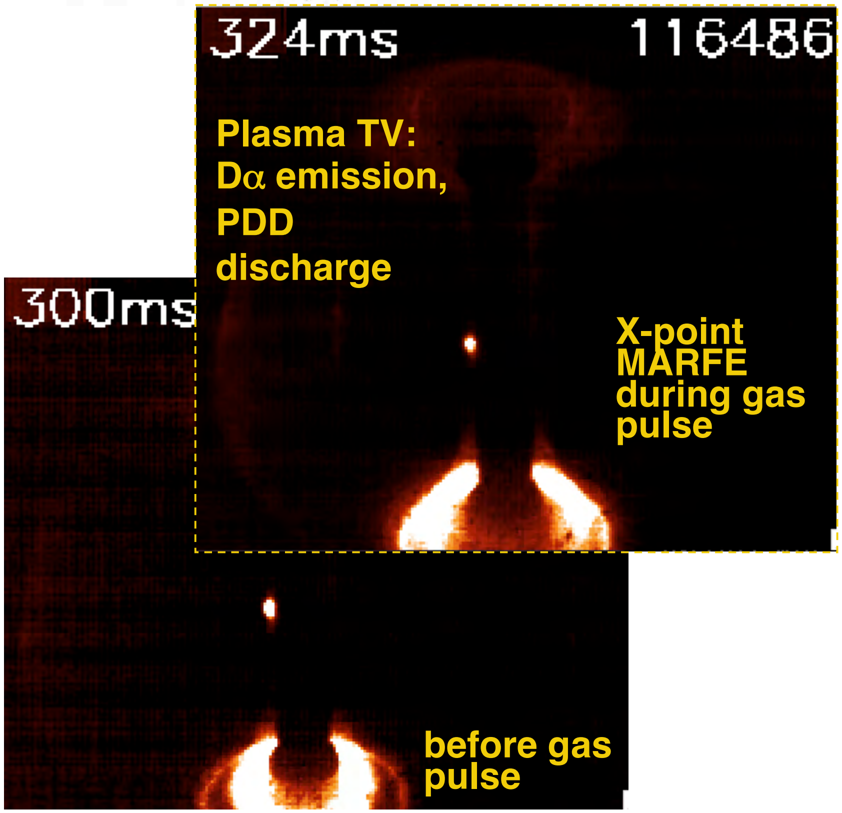
Pulsed D_2 injection from ISP divertor region

- Decreased peak q_{out} by 4-5, with peak shift outward by up to 3 cm
- Broadened Dα and Dγ brightness profiles, increased outer leg Dγ / Dα ratio at OSP
- Divertor C II profile also broadened during gas pulses
- X-point MARFE onset during gas pulses

Langmuir probe I_{sat} and Dγ/Dα brightness ratio at OSP indicative of partial detachment

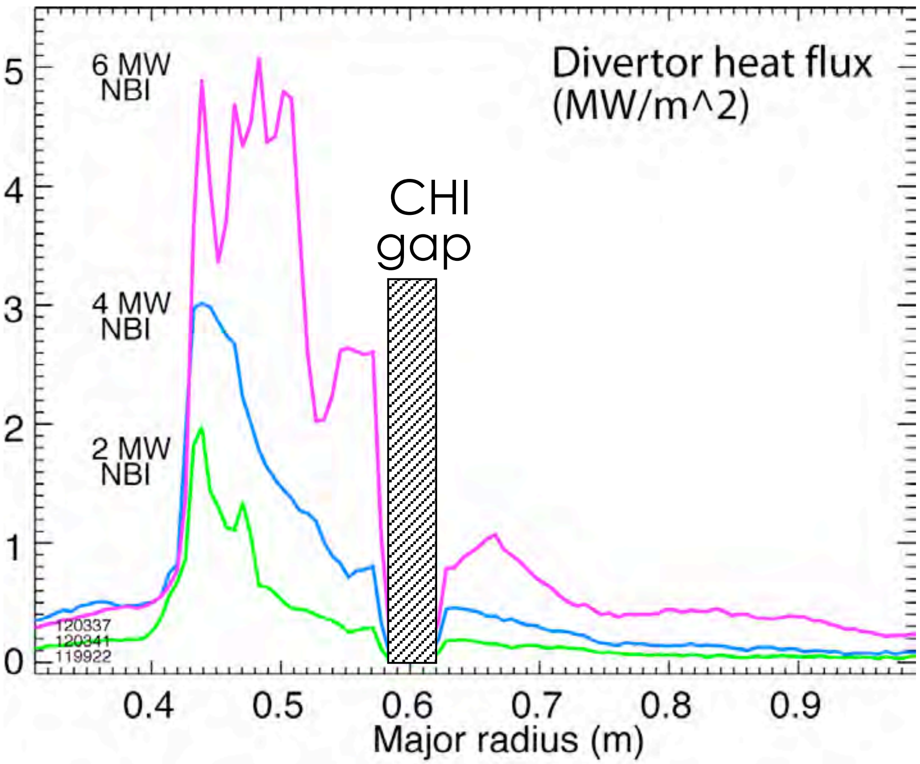


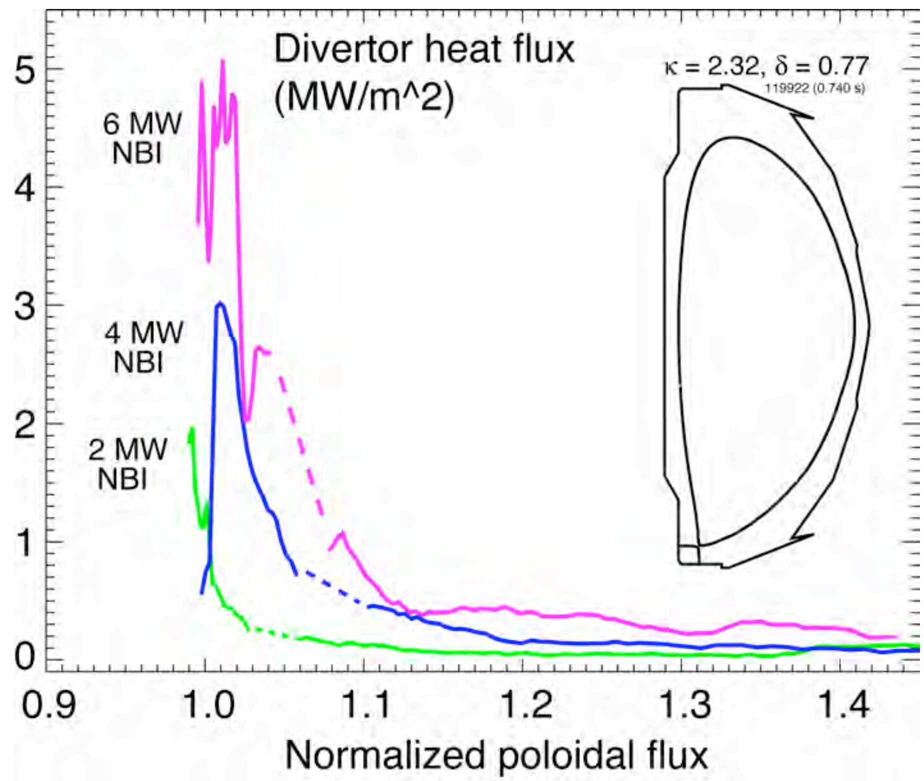




- Langmuir Probe I_{sat} drop correlates with Dγ /Dα increase at separatrix
- X-point MARFE develops during gas pulses, disappears in between

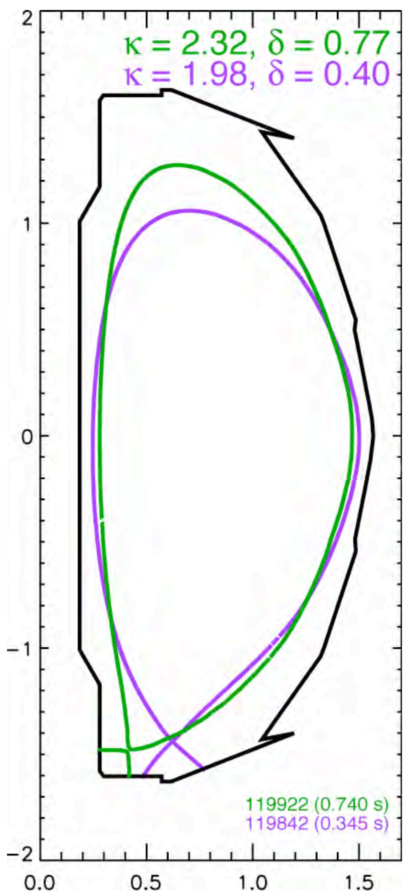
Significant OSP peak heat flux reduction can be achieved by poloidal flux expansion

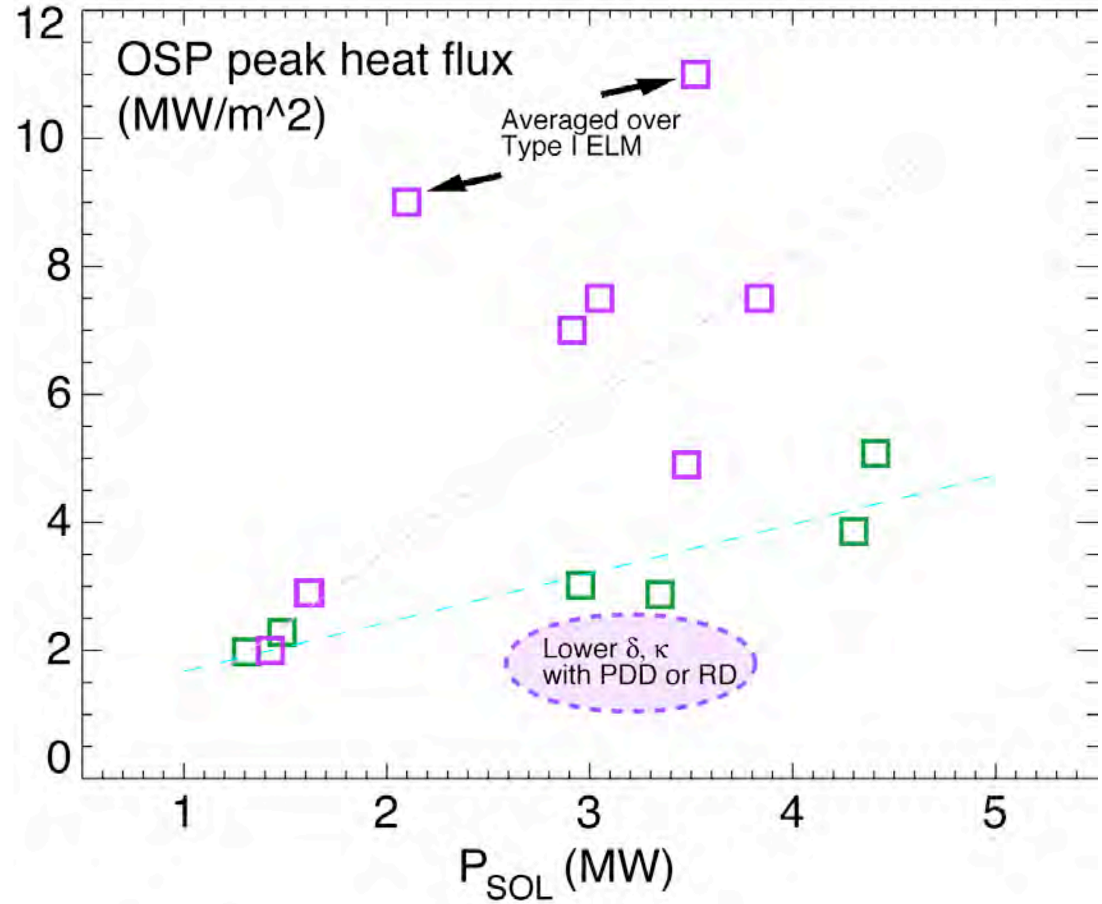




- High-performance long-pulse H-mode plasmas (Menard OV-2-4)
- Poloidal flux expansion at OSP 20-25
- ISP on vertical target (detached), OSP on horizontal target
- OSP detachment threshold to be investigated

More favorable scaling of peak OSP heat flux with input power is obtained in higher κ, δ plasmas



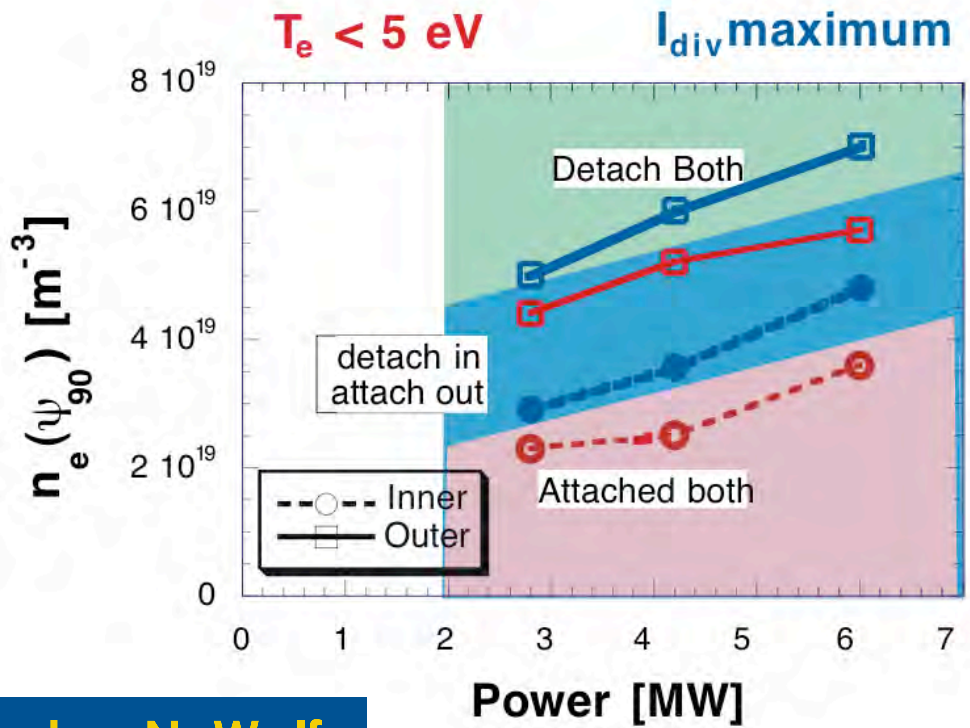


- Scaling depends on fueling location and gas injection rate
- P_{SOL} is determined from measured and TRANSP-calcualted quantities as

$$P_{SOL} = P_{NBI} + P_{OH} - dW_{MHD}/dt - P_{rad}^{core} - P_{fast\ ion}^{loss}$$

UEDGE modeling guided detachment experiments

- Model divertor conditions *vs* P_{in}, n_{edge} with UEDGE to guide experiment
- Generic low κ,δ 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

Parallel momentum and power balance:

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

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

Large momentum and power losses are needed for divertor detachment according to 2PM-L

- Two point model with losses
- f_p, f_m scanned, f_{cond}=0.9
- n_u, $q_{||}$, L_c from experiment

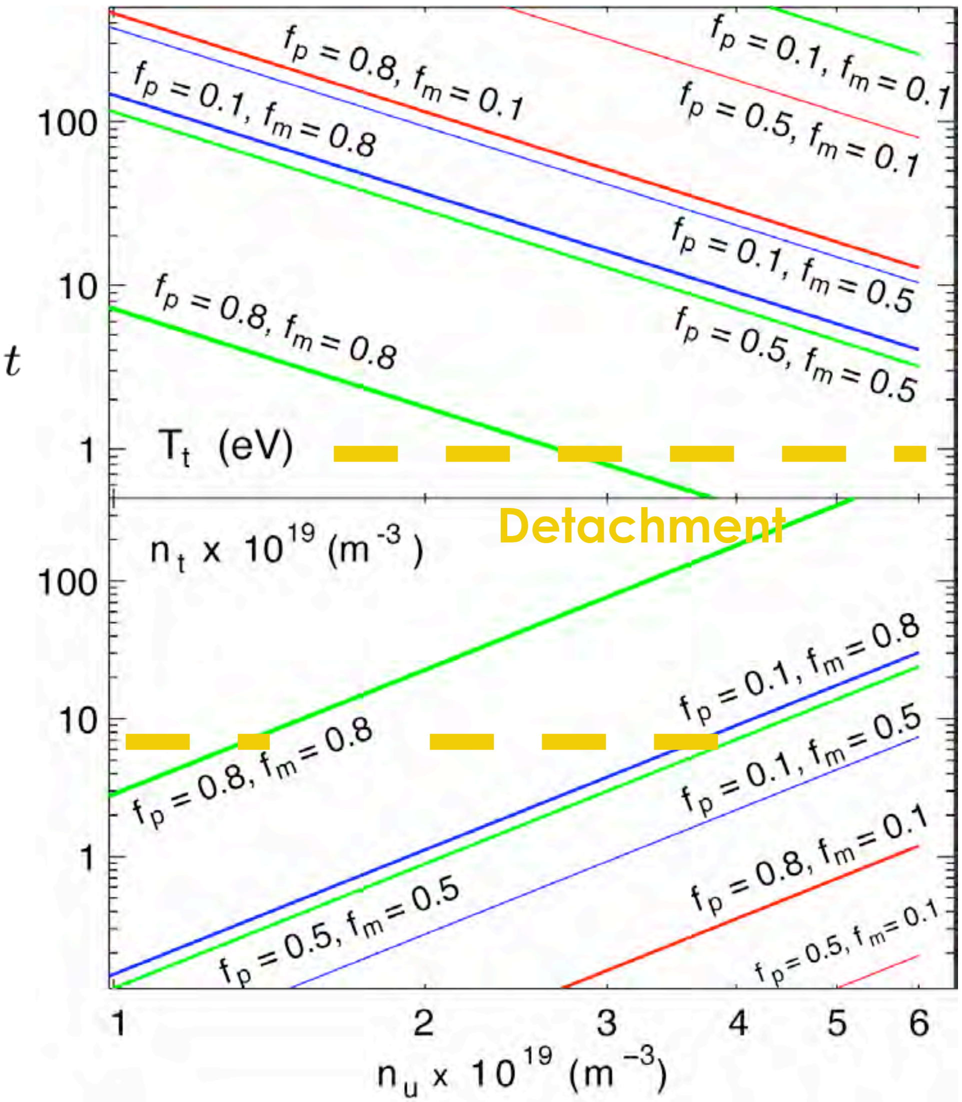
$$(1 - f_{power})\ q_{||} = q_t = \gamma\ T_t\ n_t\ c_{St}$$

$$2\ n_t\ T_t = f_{mom}\ n_u\ T_u$$

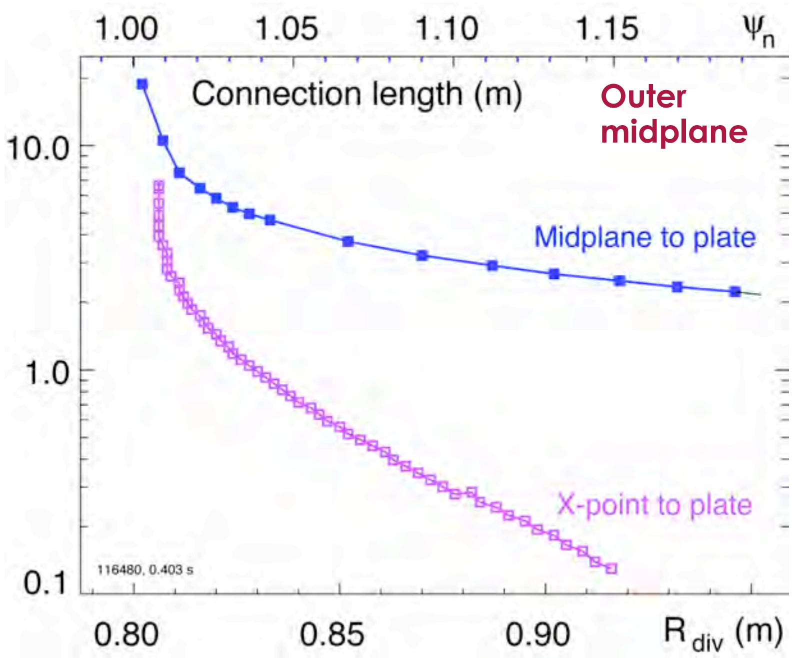
$$T_u^{7/2} = T_t^{7/2} + \frac{7}{2}\ \frac{f_{cond}\ q_{||}\ L_c}{\kappa_{0e}}$$

$$\Gamma_t \sim \frac{f_{mom}^2\ f_{cond}^{4/7}}{1 - f_{power}}$$

L_c =20 m, $q_{||}$ = 25-30 MW/m^2

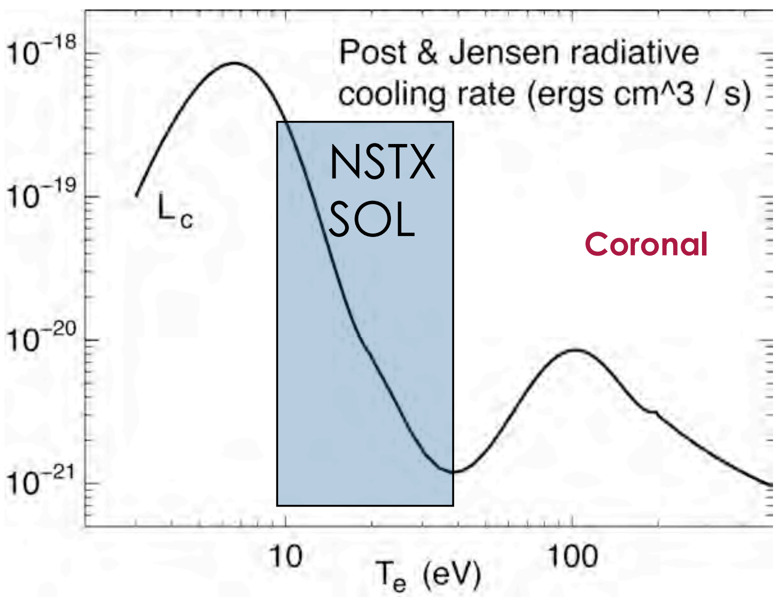


Why is it difficult to obtain OSP detachment?



- Connection length decreases to very short values within radial distance of 1-3 cm (both midplane to plate and X-point to plate)

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

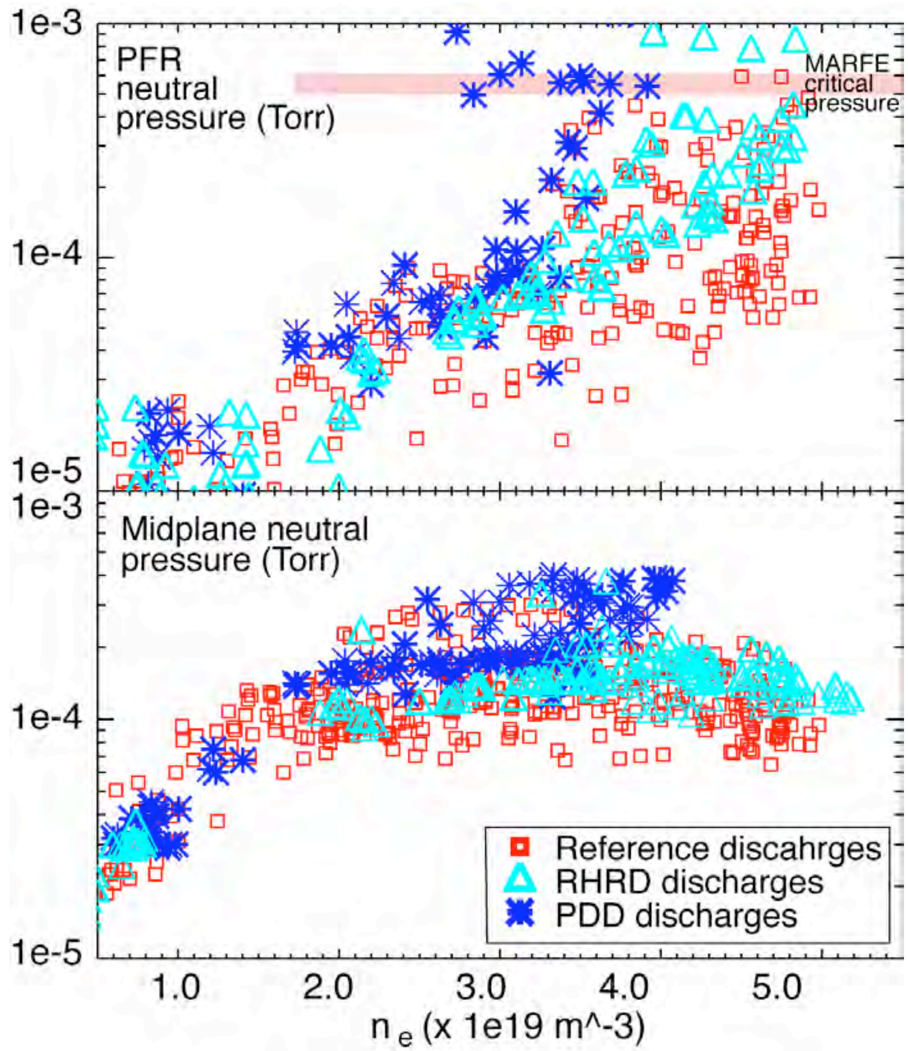


- Recombination time:
  $\tau_{rec} = 1./(n_e R_{rec}) \sim 1\text{–}10$ ms at T_e =1.3 eV
  Ion divertor residence time:
  $\tau_{ion} = L_d/v_{ion} \sim 0.8$ ms (with $v_{ion} \sim 10^4$ m/s)

- Open divertor geometry - high detachment threshold is expected
- Neutral compression ratio is 5-10 (low)

Observed midplane and PFR pressure trends are due to open divertor geometry

- In reference discharges, n_u independent of P_{mp}, but a strong linear function of P_{PFR}
- X-point MARFE critical PFR pressure is 0.5-0.6 mTorr
- Reference discharges never reach PFR critical pressure
- PDD discharges reach MARFE onset PFR pressure faster than RD discharges
- P_{mp} similar in ref. and RD discharges
- P_{mp} higher in PDD discharges (stronger gas puffing)



Summary and Future work

- Divertor heat flux reduction and detachment in low aspect ratio geometry are studied in high input power H-mode plasmas in NSTX
- OSP peak heat flux was reduced x 2-5 using high recycling radiative divertor and partially detached divertor regimes in low δ, κ LSN 4 MW H-mode plasmas with divertor D_2 puffing
- Significant (x 2-3) reduction in peak divertor heat flux has been achieved in 4 MW high δ, κ LSN configuration using high flux expansion
- Future work will focus on
  - dissipative divertor regimes with **CD_4 puffing**
  - dissipative or radiative divertor regimes in **high δ, κ** H-mode plasmas relevant to **Component Test Facility**

Sign-up sheet