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Particle and power exhaust in NBI-heated plasmas in NSTX

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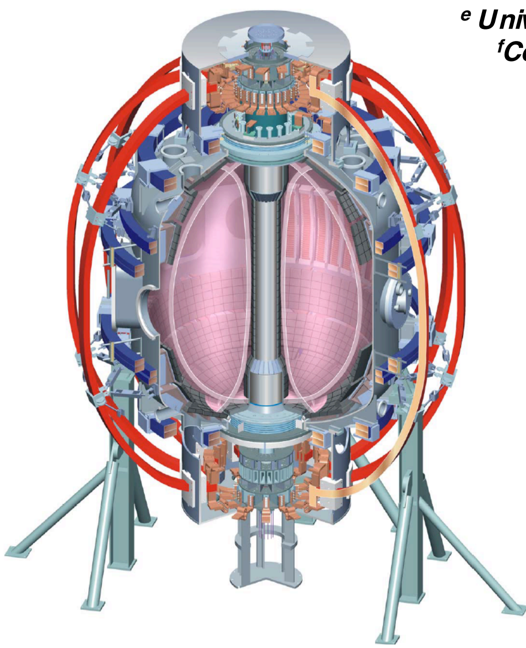

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Abstract

Particle and power exhaust in high-performance NSTX plasmas*

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Recent NSTX progress toward long-pulse high-performance operation highlighted heat and particle exhaust trends and features both similar to conventional devices and apparently unique to the spherical torus due to its magnetic geometry. A variety of lower single null L-mode, ELMy and ELM-free H-mode plasmas with elongation ranging from 1.8 to 2.5, triangularity from 0.4 to 0.9, NBI power from 0.8 to 6 MW, $n_e(0) \simeq (2.5-8) \times 10^{19}$ m^{-3}, and B_t from 0.3 to 0.45 T has been used to analyze the scrape-off layer (SOL) and divertor properties. In these plasmas up to 70 % of the input power dissipated in the divertor as heat on the targets and 10 - 15 % as radiation from ionized carbon and neutral deuterium. Evidence of volume recombination from D_α, D_γ divertor profiles and Stark-broadened high-n Balmer series transitions, observations of a molecular CD spectral band emission, and the measured inner target heat flux under 1 MW/m^2 suggest that the inner target is detached at $P_{NBI} \geq 0.8$ MW, $\bar{n}_e \geq (2-3) \times 10^{19}$ m^{-3}. The outer target, with the typical measured peak heat flux ranging from 2 to 6 MW/m^2, remains attached at $\bar{n}_e$ up to $0.9 \times n_G$, the Greenwald density, and the D_2 gas feed rate up to 8×10^{21} particles/s Mid-plane separatrix temperature is in the range 10 - 50 eV, suggesting that the outer divertor operates in the sheath-limited and high-recycling regimes with a low parallel T_e gradient. Dedicated experiments aimed at radiative divertor development using D_2 and neon injections are planned. Recycling and neutral pressure trends with P_{in} and n_e point to the need of active or passive divertor pumping for density control. The continuous and non-disruptive density increase at $dN/dt < 2 \times 10^{21}$ s^{-1} is observed in NBI-heated plasmas, with an estimated divertor source contribution up to 4×10^{23} ionizations/s, the main chamber source up to 2×10^{22} ionizations/s under the assumption of poloidal uniformity, and the outer SOL neutral compression ratio in the range 5 to 10. A recently commissioned supersonic gas injector may provide an interim solution with more efficient gas fueling and reduced gas-wall interaction.

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Thesis

- Divertor heat load mitigation - one of the key Boundary Physics issues in large aspect ratio tokamaks, more so in Spherical Tori (ST)
- Study divertor regimes at low aspect ratio in NSTX (A = 1.35, $q_{out} < 10$ MW/m^2)
- NSTX divertor (open, no active pumping): inner leg is naturally detached at $P_{in} > 1$ MW, $n_e > 2\text{-}3 \times 10^{19}$ m^{-3}, outer leg is never detached
- In a dedicated experiment D_2 injection from private flux region produced outer leg detachment in 4 MW NBI-heated H-mode
- Neon injections did not result in outer leg detachment

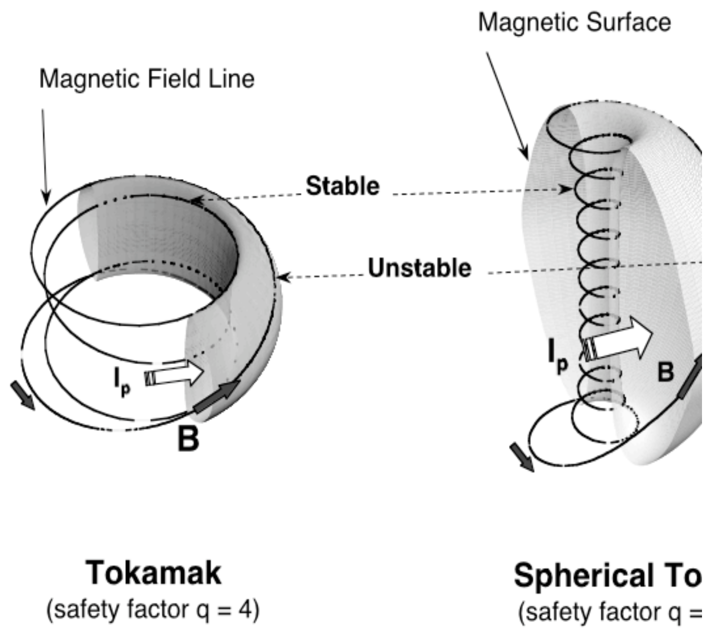
Outline

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

- Naturally occurring divertor regimes in NSTX

- Dedicated D_2 and neon injection experiments to develop and study dissipative divertor regime compatible with high performance H-mode plasmas

- Summary



NSTX reference data

NSTX fueling

- Gas injection: low field side (LFS, top + side), high field side (HFS, midplane + shoulder), private flux region. D_2, He, injected at S = 20 - 120 Torr l /s.
- Neutral beam injection system: three beams, 80 - 100 keV, 6 MW, fueling rate: S < 4 Torr l / s
- Supersonic gas injection: S = 60 Torr l / s

NSTX wall conditioning

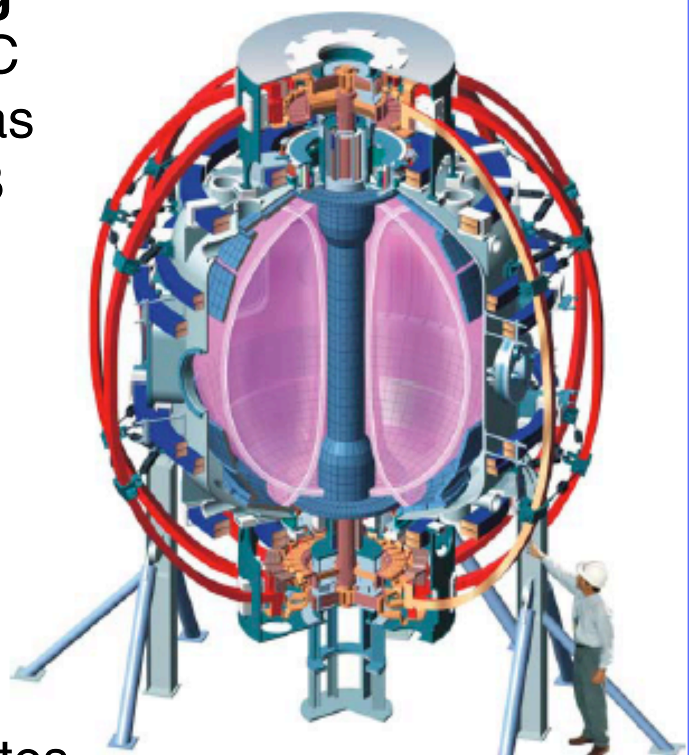
- Between shots He GDC
- He conditioning plasmas
- TMB and Plasma TMB

NSTX pumping

- Turbomolecular pump (3400 l / s)
- NBI cryopump (50000 l / s)
- Conditioned walls

PFC

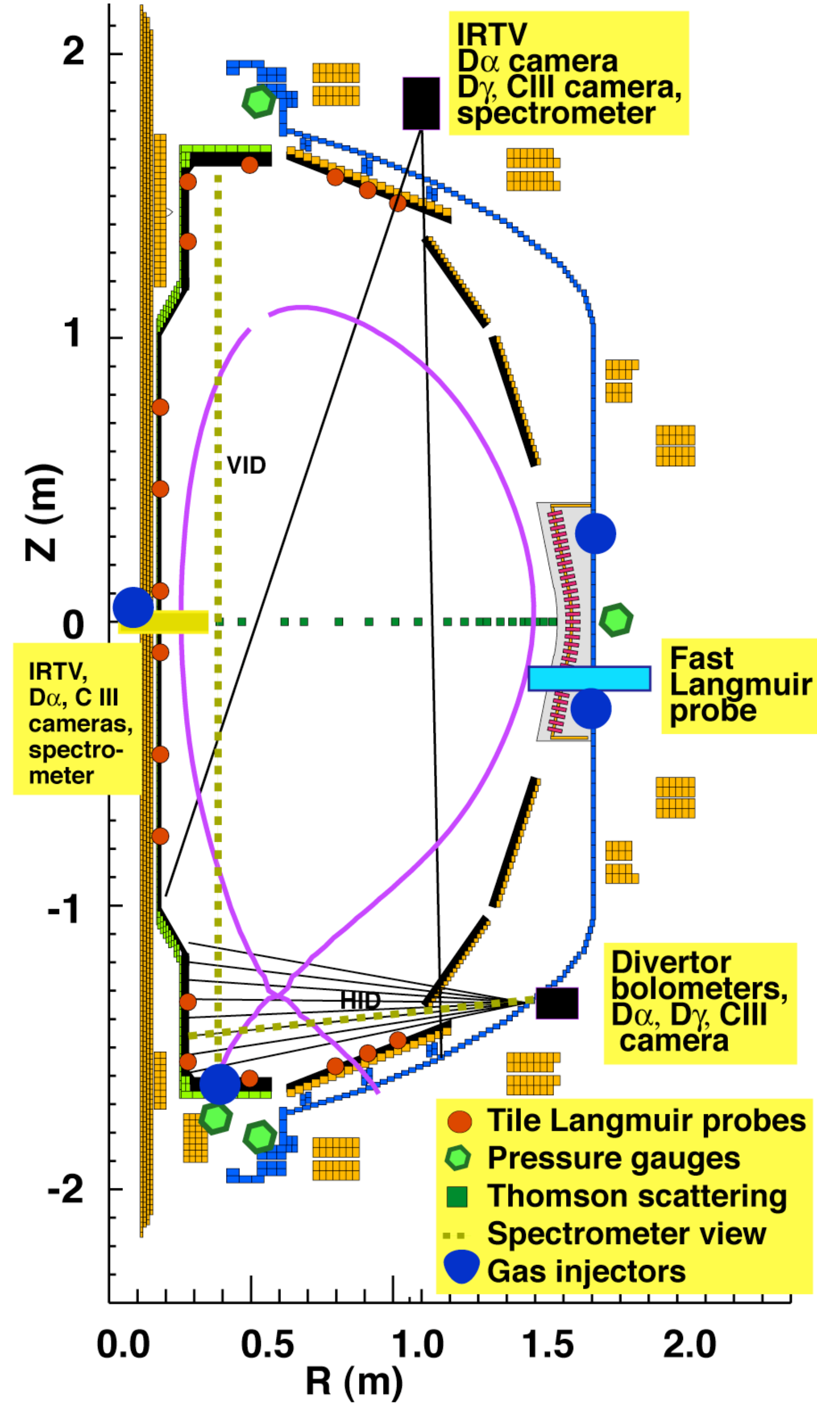
- ATJ graphite tiles on divertor and passive plates
- ATJ and CFC tiles on center stack
- Thickness 1” and 2”



Aspect ratio A	1.27
Elongation κ	2.5
Triangularity δ	0.8
Major radius R_0	0.85m
Plasma Current I_p	1.5MA
Toroidal Field B_{T0}	0.6T
Pulse Length	1s
Auxiliary heating:	
NBI (100kV)	7 MW
RF (30MHz)	6 MW
Central temperature	1 – 3 keV

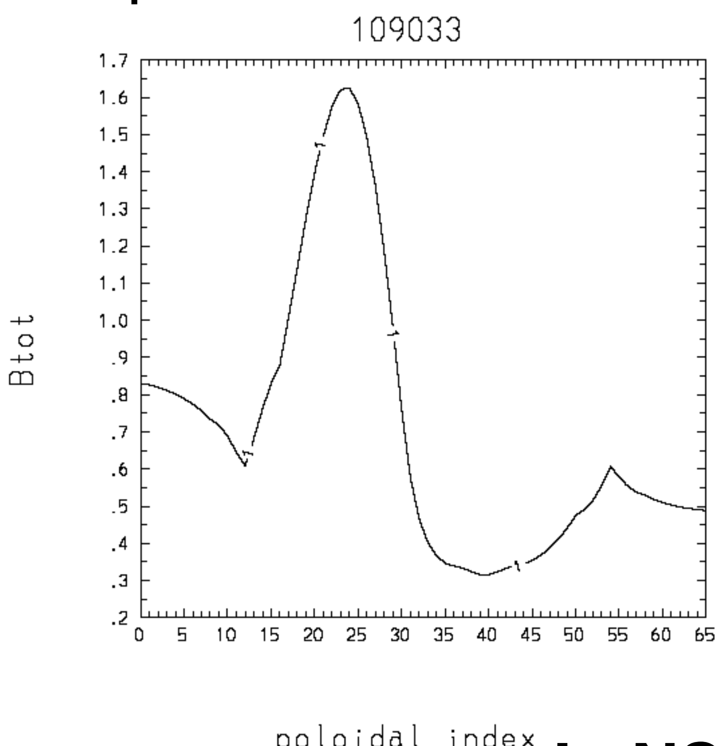
Many useful diagnostics to study SOL and divertor

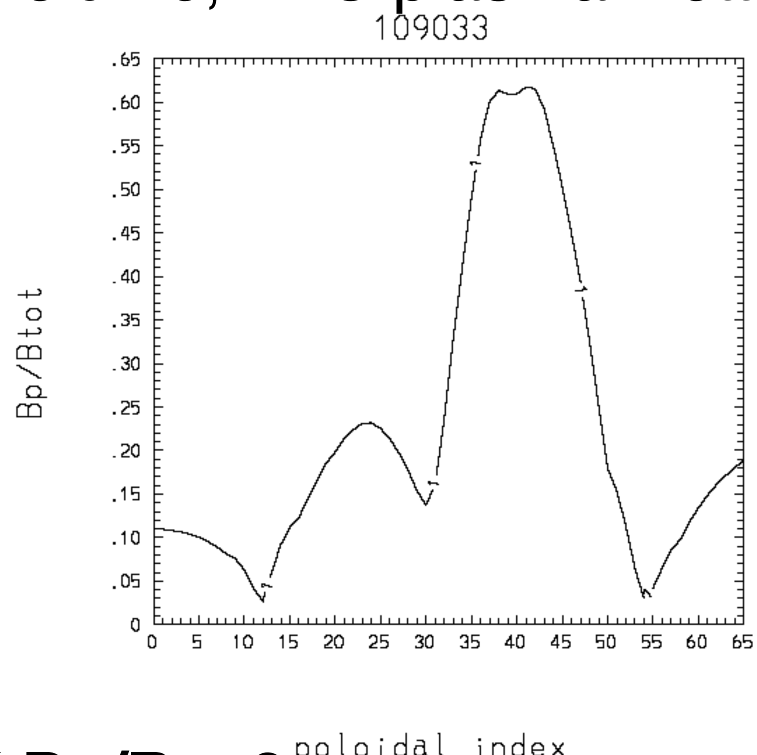
- **IRTV**: two Indigo Alpha 160 x 128 pixel microbolometer cameras, 7-13 μm range, 30 ms frame rate
- **D_α, D_γ, C III filtered cameras**: four Dalsa 1 x 2048 pixel CCDs, filter FWHM 10-15 A, frame rate 0.2 - 1 ms
- **Neutral pressure gauges**: four microion gauges on top and at midplane, two Penning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



Impact of ST geometry effects on SOL and divertor physics is studied in NSTX

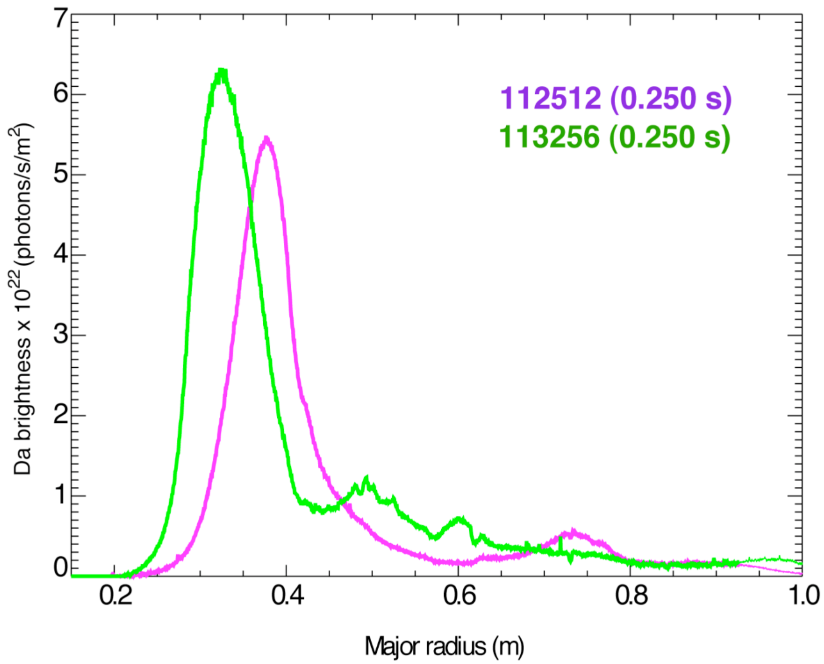
- High SOL mirror ratio $M=|B_{min}| / |B_{max}|$ - affects connection length $L_{||}$, fraction of trapped particles f, etc
- Large flux expansion ratio $f = \frac{(B_\theta / B)_u}{(B_\theta / B)_t}$:
  - Heat and particle in-out asymmetries
  - Parallel transport, divertor regimes
- Compact divertor - divertor volume, PFC plasma-wetted area





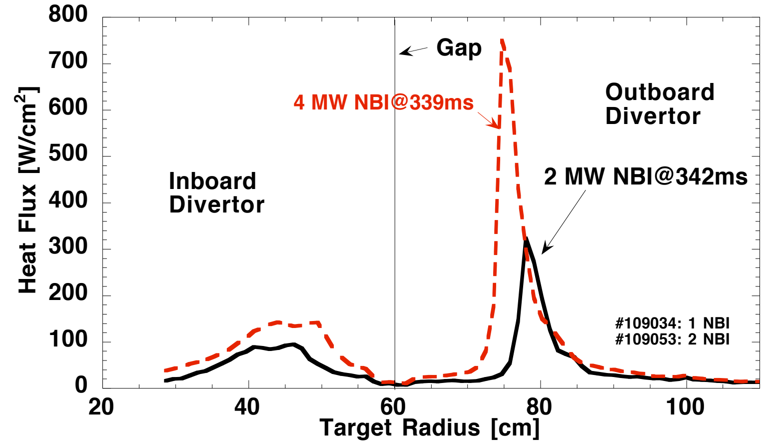
In NSTX $P_{in}/R < 9$

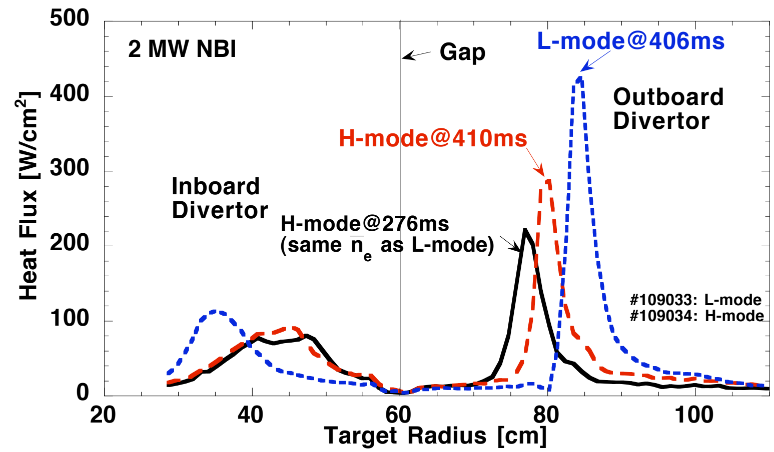
Heat flux, recycling, impurity divertor profiles

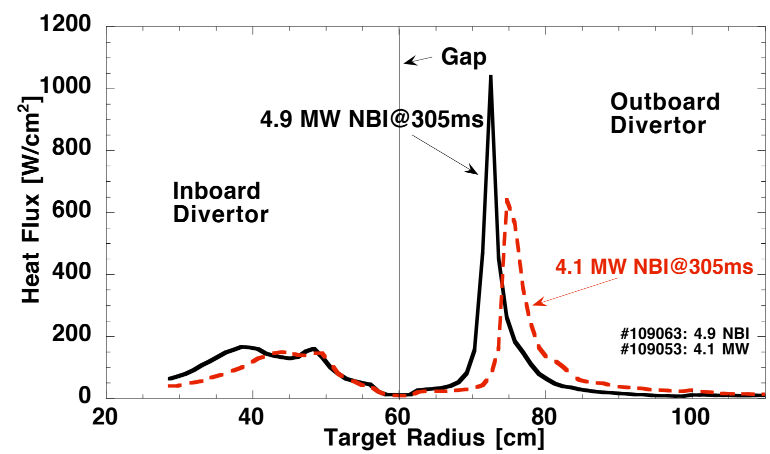


In lower single null plasmas:

- Heat flux increases non-linearly with P_{in}
- q_{in}/q_{out}= 2-3
- Heat flux equilibration time τ_{eq}~ 100 ms
- Recycling strong in divertor
- High neutral pressure (0.1-0.2 mTorr)
- Neutral compression ratio is 5-10

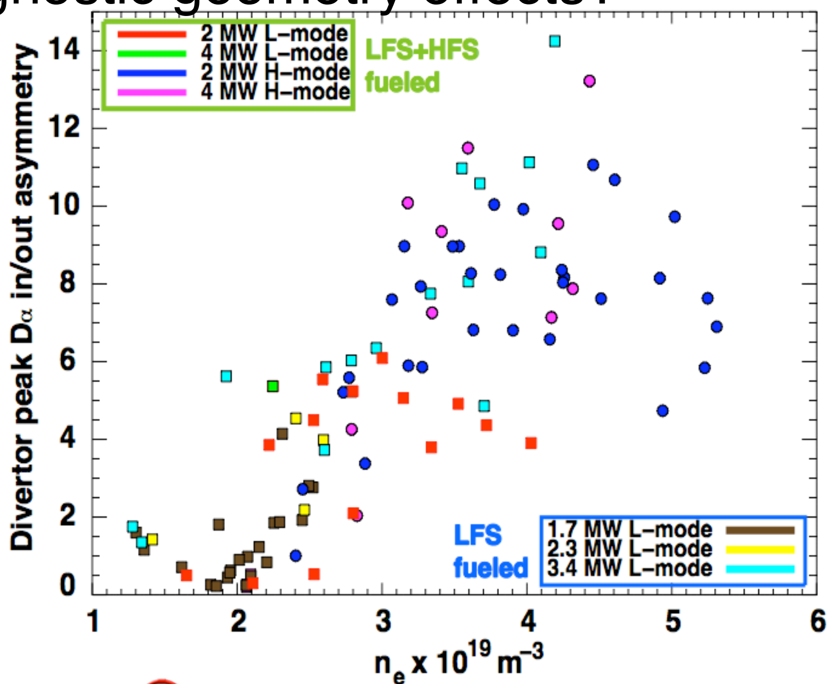


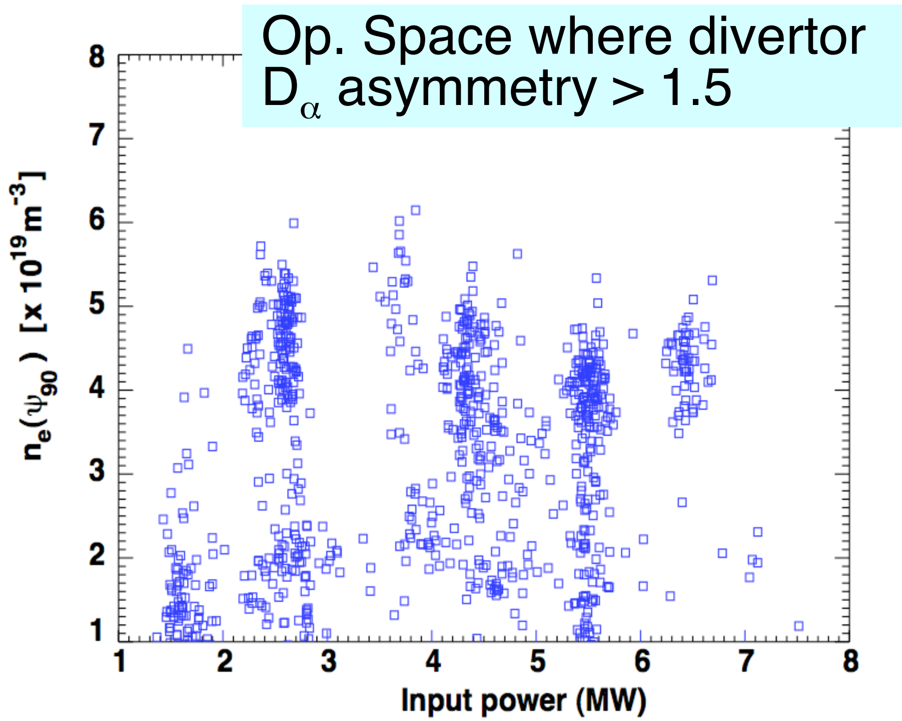




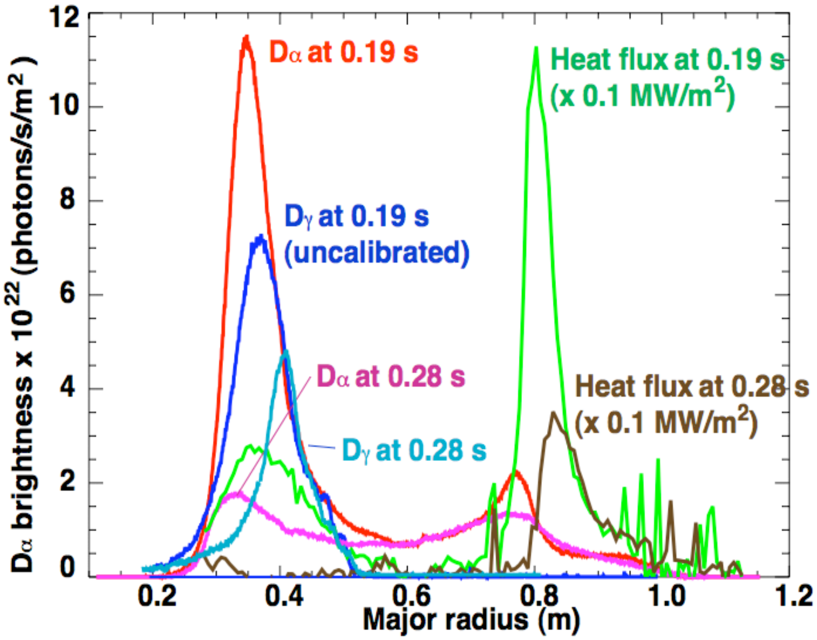
Divertor in-out asymmetries observed

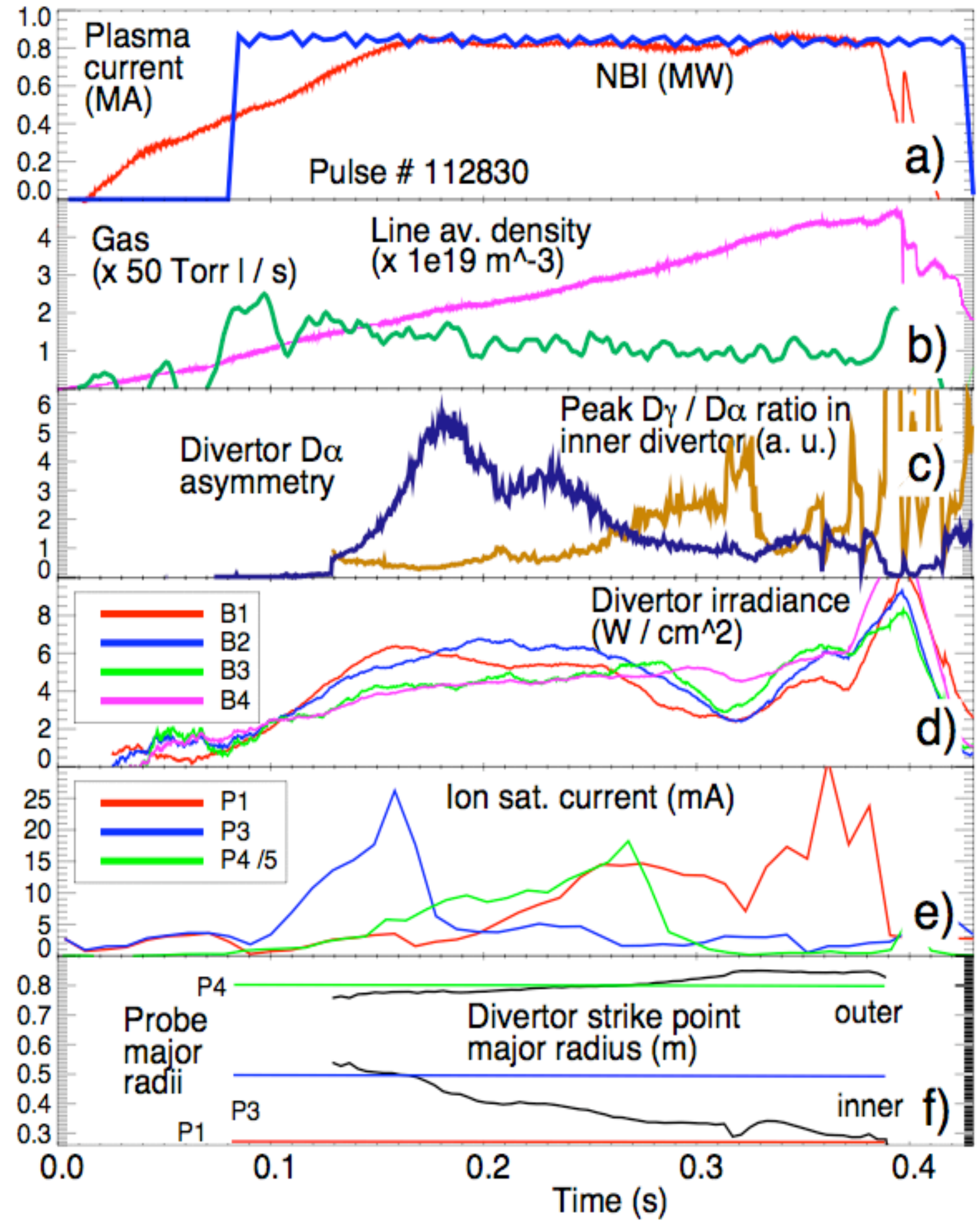
- Heat flux asymmetry always $q_{out}/q_{in} > 1$, consistent with
  - SOL area factor: $A_{out} = 3 \times A_{in}$
  - Magnetic flux expansion factor (mid/div): $f_{in} > f_{out}$
    - Large Shafranov shift
  - Core / edge in-out transport asymmetry
- D_α asymmetry (particle flux / recycling) through most of op. space
  - Density and power dependent
  - Not always correlated with volume recombination onset
  - Complex interplay of cold dense opaque detached 3D plasma and diagnostic geometry effects?





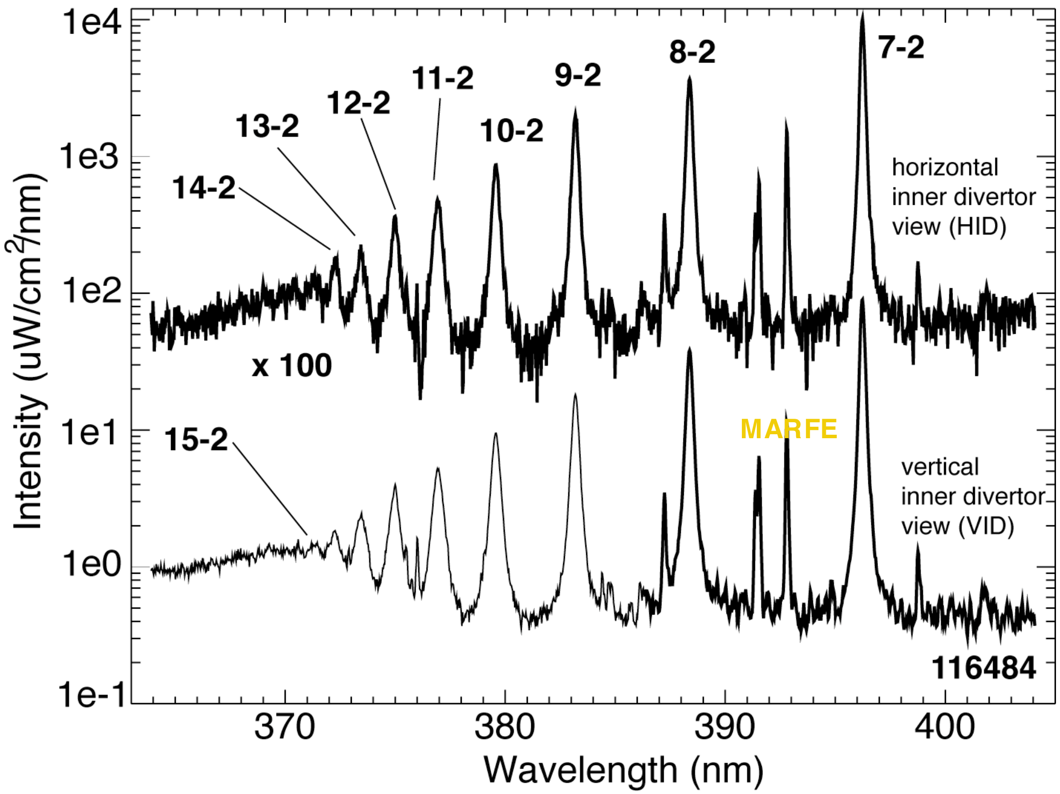
Inner divertor detached in NBI-heated plasmas

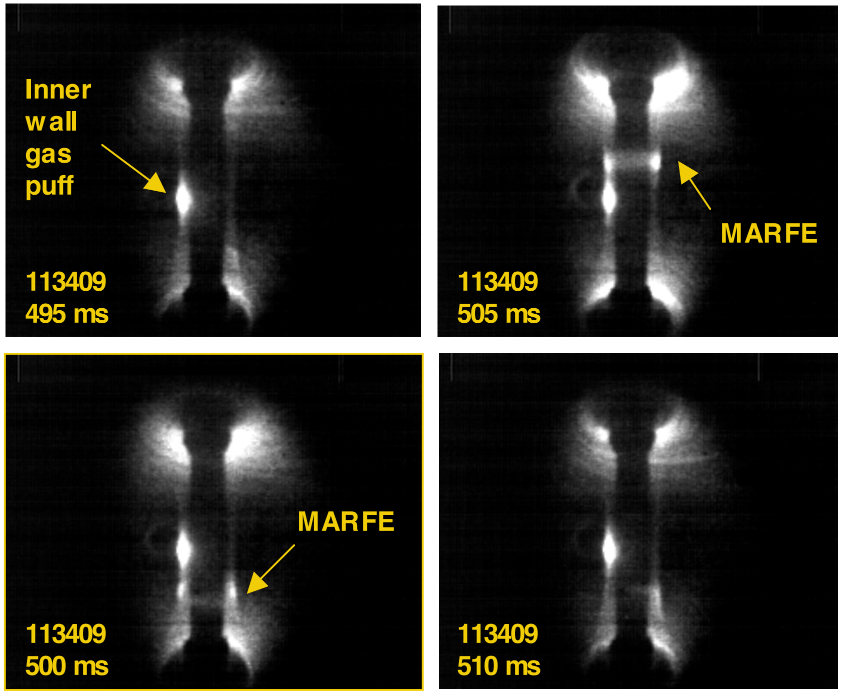




- Inner divertor detached naturally at $\langle n_e \rangle = 2.5\text{-}3 \times 10^{19}\ \mathrm{m}^{-3}$

High n_e, low T_e inferred from Balmer series lines measured in inner divertor



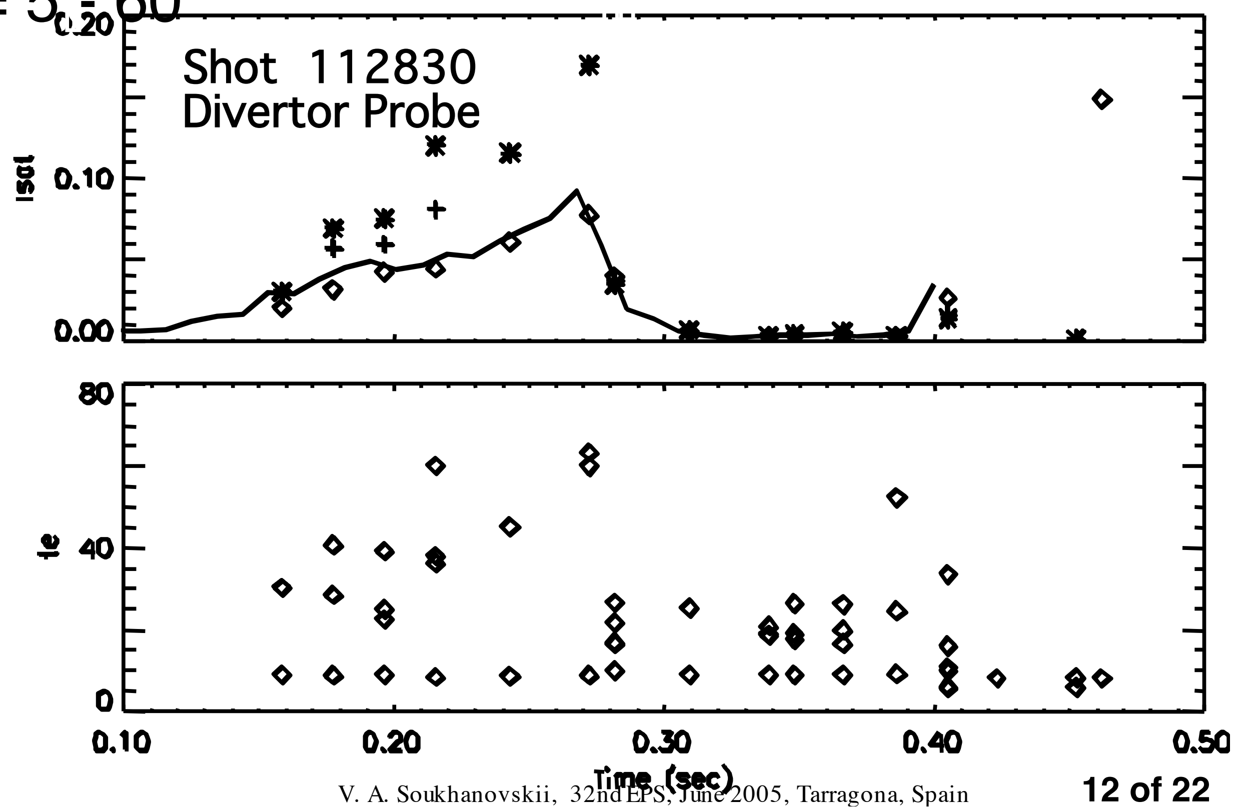


Fish-eye view of NSTX plasma

- FWHM increases with n, Voigt line profile shape
- Inglis-Teller limit for n=14 yields $n_e=10^{21}$ m^{-3} (too high!)
- Stark broadening of 8-2 line yields n_e= 1-5 x 10^{20} m^{-3}
- Analysis with LLNL radiation transport code CRETIN in progress
- From line intensities (Saha-Boltzman population distribution): T_e = 0.3-1.0 eV
- Inner SOL MARFE oscillating between midplane and divertor often observed

Outer divertor is in linear and high-recy. regime

- Outer divertor is always attached, heat flux typically 2-5 MW/m^2, max measured q =10 MW/m^2
- **Outer divertor is in sheath-limited and high-recycling regime**
- **Short connection length + L_c (carbon) = not detached at high n_e**
- Uncertainty in LCFS position 1-2 cm:
  - MPTS midplane T_e = 5 - 40 eV
  - Fast midplane probe T_e = 10 - 30 eV
  - SOL collisionality ν^* = 5 - 60
- Divertor T_e = 5 - 40 eV
- Very weak $dT_e/dx_{||}$ (e-i partition, heat transport mechanism)
- Carbon radiation "zone" is 10 eV

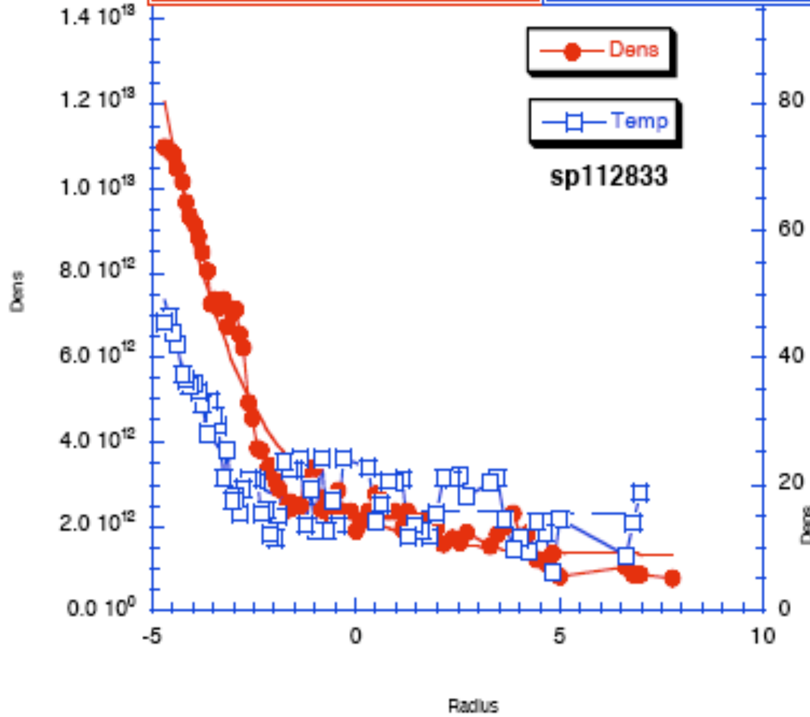


Flat T_e, n_e in outer midplane SOL

Te quite flat in SOL. Te rise faster than Ne rise

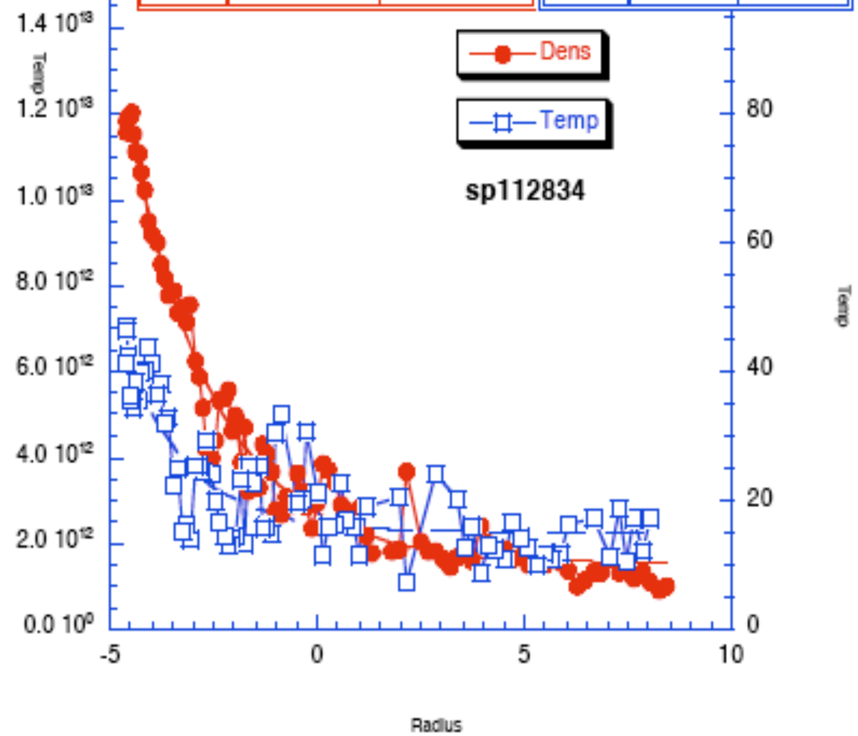
y = m1 + m2 * exp(-M0/m3)	Value	Error
m1	1.3051e+12	1.392e+11
m2	9.9285e+11	1.2643e+11
m3	1.9655	0.10969
Chisq	2.3654e+25	NA
R	0.98149	NA

y = m1 + m2 * exp(-M0/m3)	Value	Error
m1	15.51	0.77191
m2	0.50034	0.26542
m3	1.1133	0.14895
Chisq	1213.7	NA
R	0.89069	NA



y = m1 + m2 * exp(-M0/m3)	Value	Error
m1	1.5088e+12	9.6874e+10
m2	1.1896e+12	1.0039e+11
m3	2.1114	0.082751
Chisq	2.3948e+25	NA
R	0.98847	NA

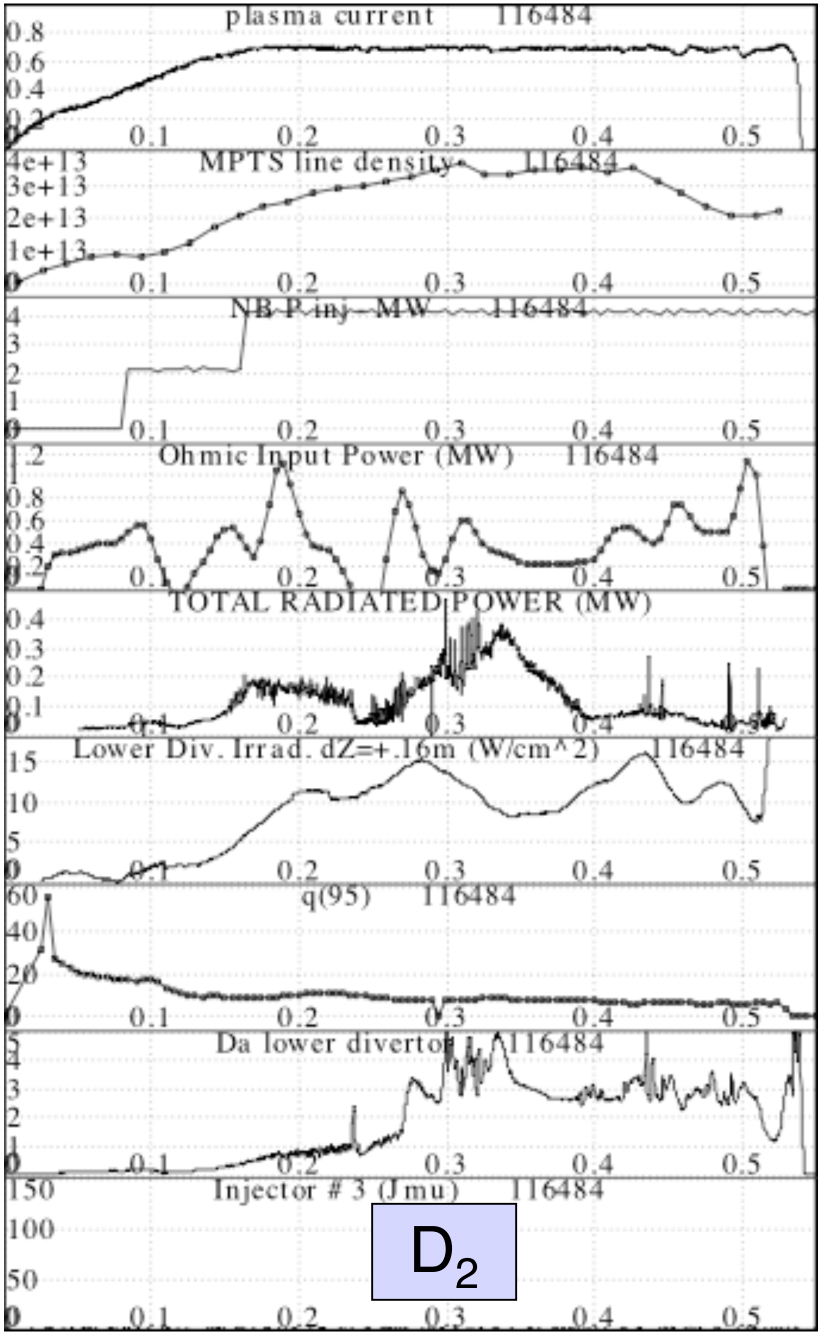
y = m1 + m2 * exp(-M0/m3)	Value	Error
m1	15.092	1.0257
m2	1.3725	0.684
m3	1.5326	0.25947
Chisq	2375.7	NA
R	0.84924	NA

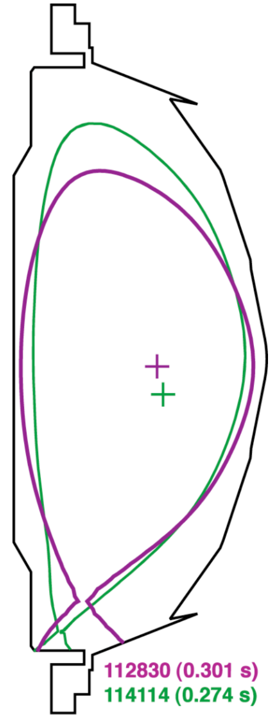


Midplane fast probe
- J. Boedo (UCSD)

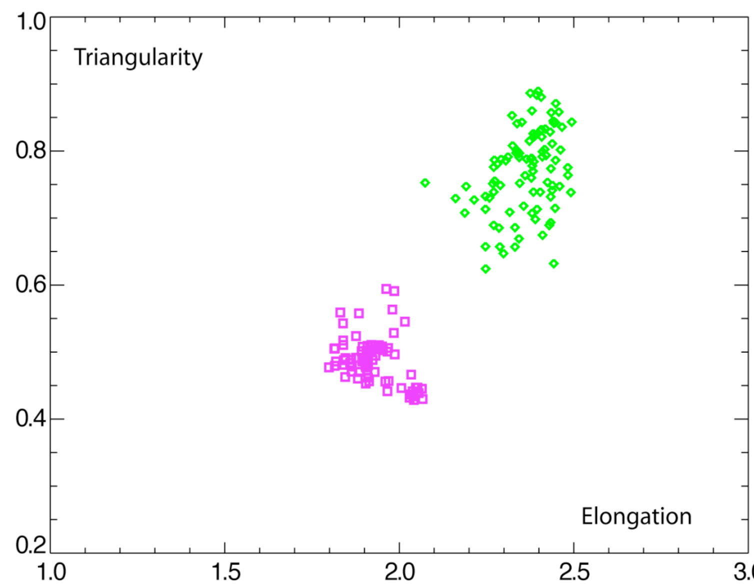
11/12/2004 J. Boedo APS 04

Moderate κ, δ plasma used for detachment studies





κ	1.85
δ	0.4
Drsep (cm)	1.0-1.5
q_{edge}	13
$L_{\|\|}$, inner (m)	8.3
$L_{\|\|}$, outer (m)	6.0
M (Mirror ratio)	5.0
f inner (Flux expansion)	2-3
f outer (Flux expansion)	2-3



Detach outer divertor by injecting D_2

- Used PF2L shape, 4 MW NBI at $B_t = 0.45$ T
- Injected D_2 in LFS midplane at 20 - 120 Torr l / s
  PFR at 0 - 15 Torr l / s, HFS at 40-65 Torr l /s
- Concluded divertor detachment from D_γ/D_α ratio, peak heat flux reduction
- Sign of volume recombination (D_γ/ D_α) in outer divertor at 100 Torr l / s, or with HFS+PFR injector at 65 Torr l / s
- D_2 puffing from midplane injectors brings outer outer SOL close to detachment threshold, however plasma hits operational limits (locked modes, large low m,n MHD modes, confinement degrdation)

Scan outer SOL collisionality by gas puffing

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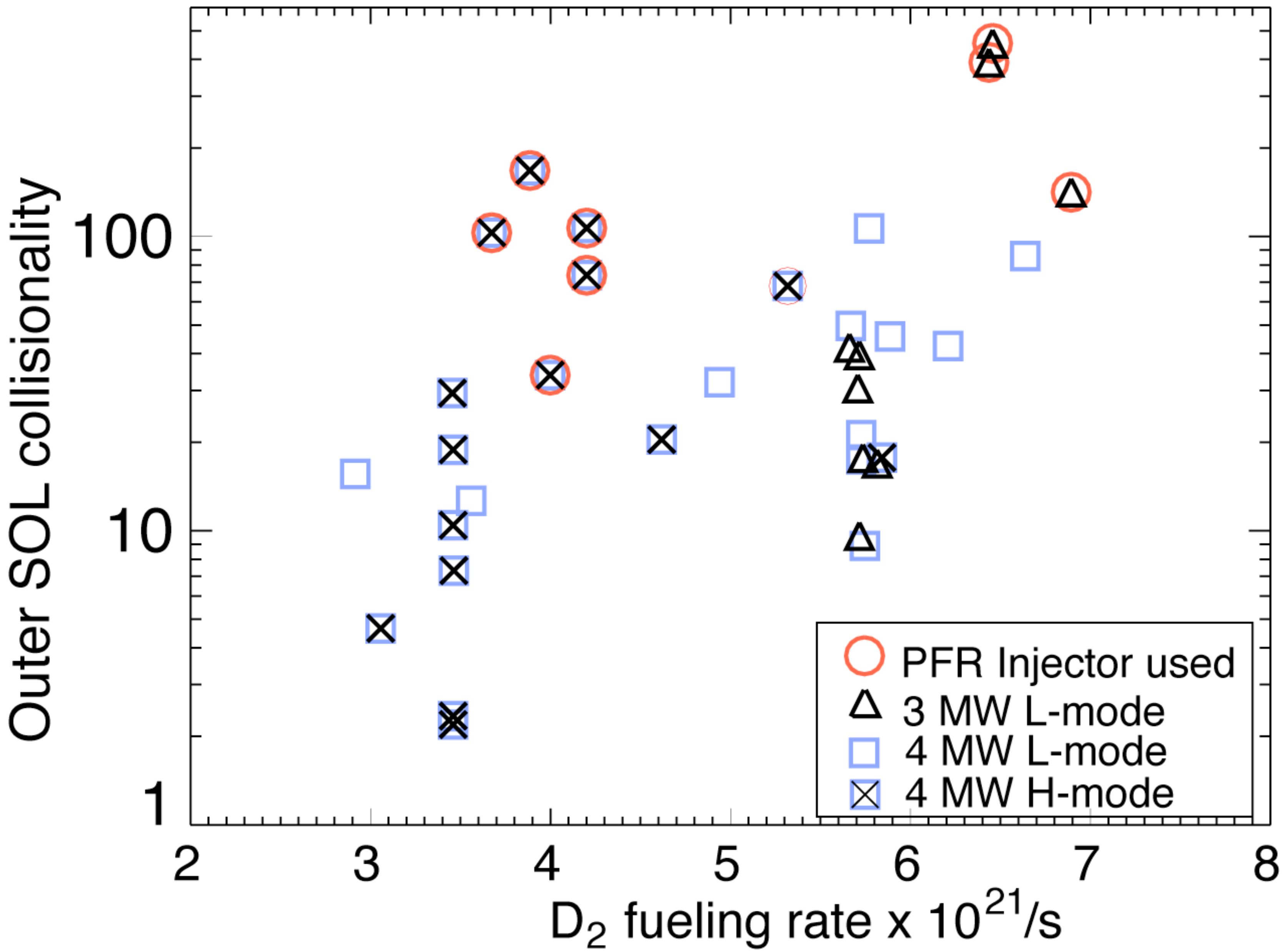
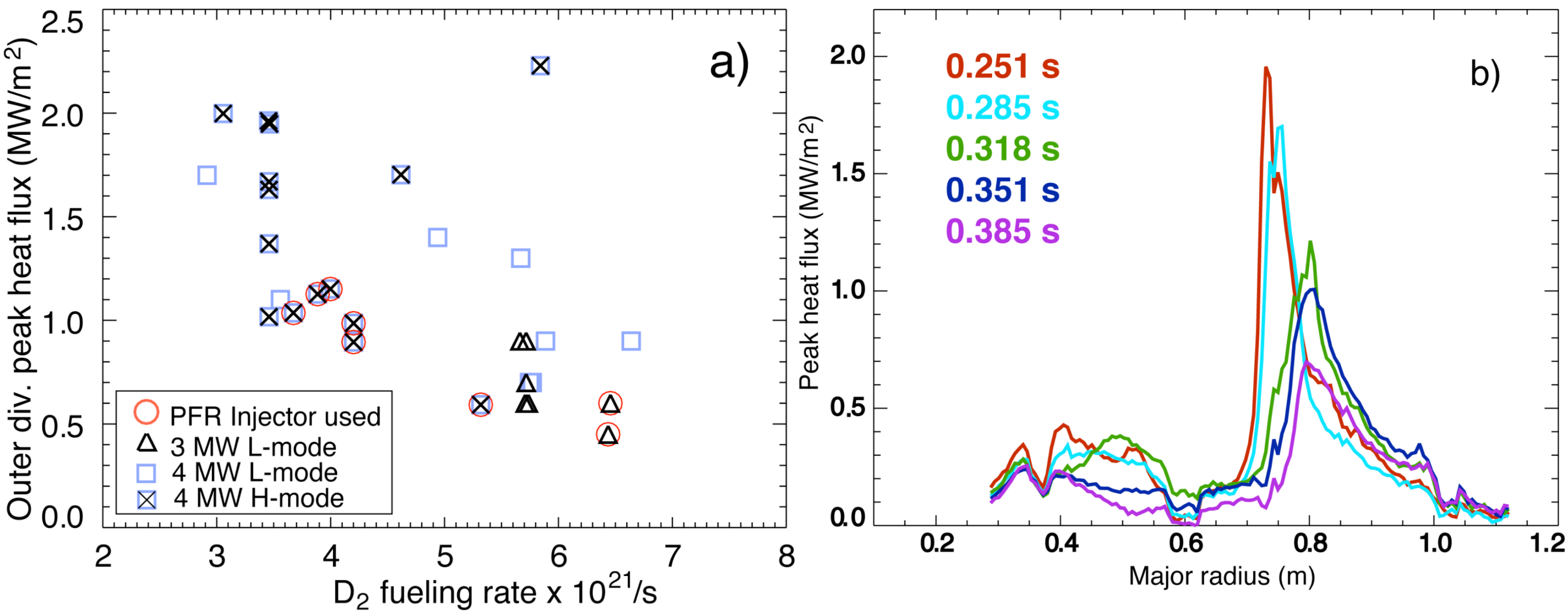
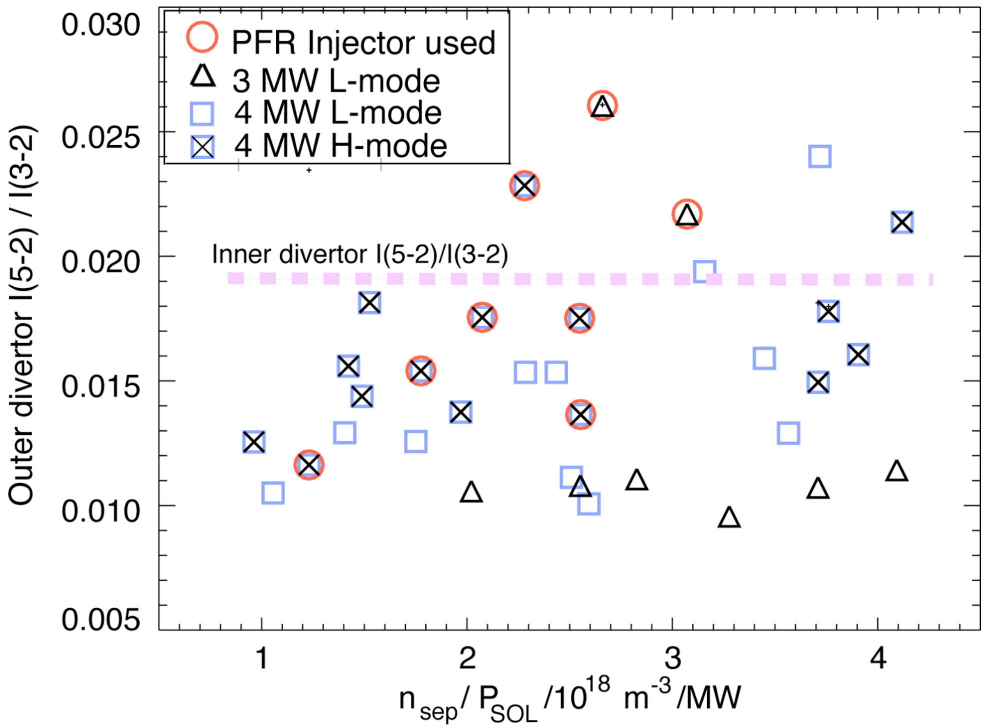


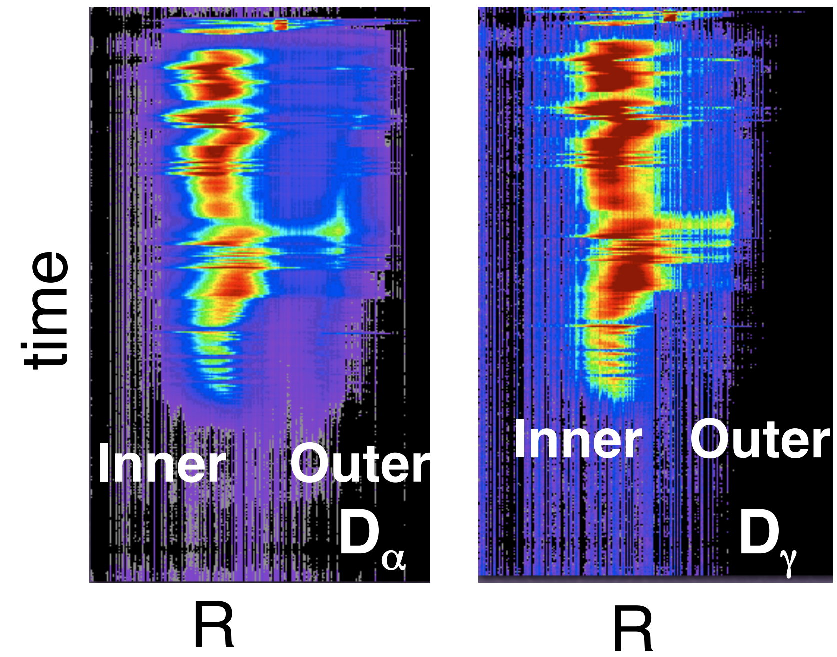
Outer divertor peak heat flux reduced x4 by D_2 injection in private flux region



- D_2 puffing from PFR reduces peak q_{out} four-fold
- No change in inner divertor - peak q_{in} = 0.5 MW/m^2
- Divertor radiation increases (difficult to quantify - poor bolometric coverage
- Interim IRTV calibration used

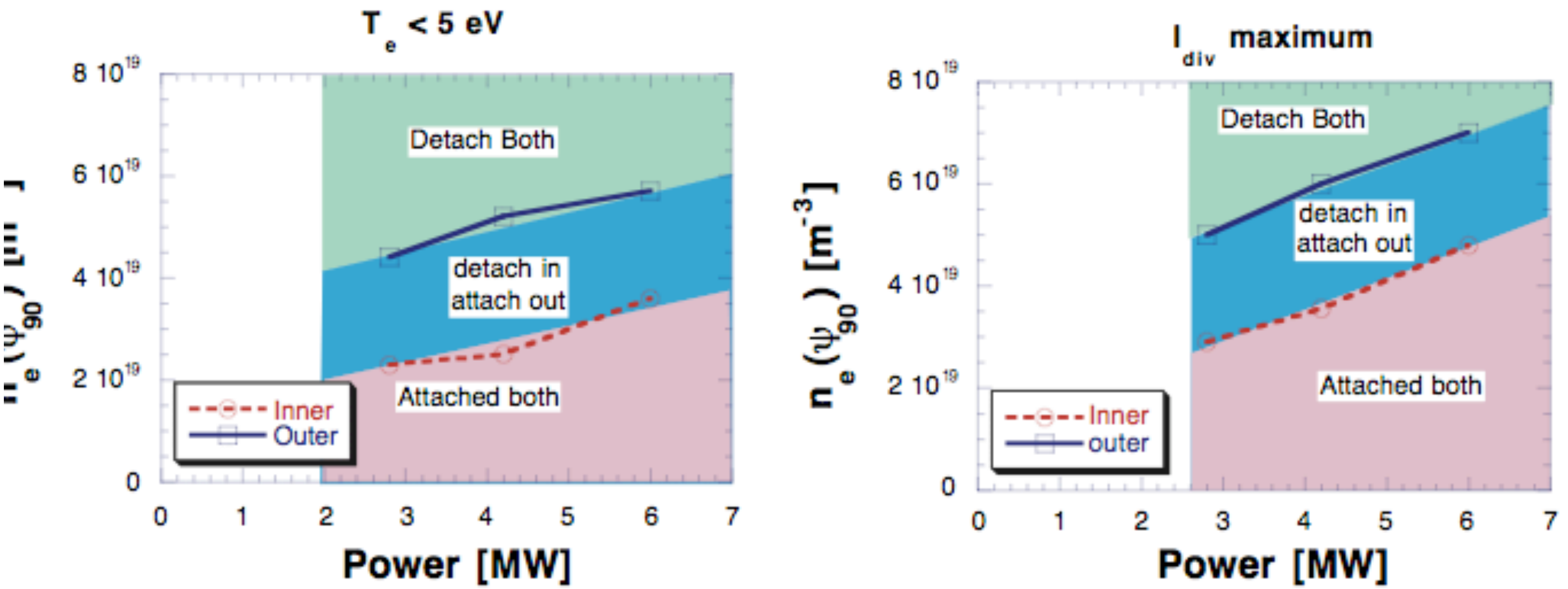
Inner divertor Dγ / Dα increases x2 during D_2 injection from PFR





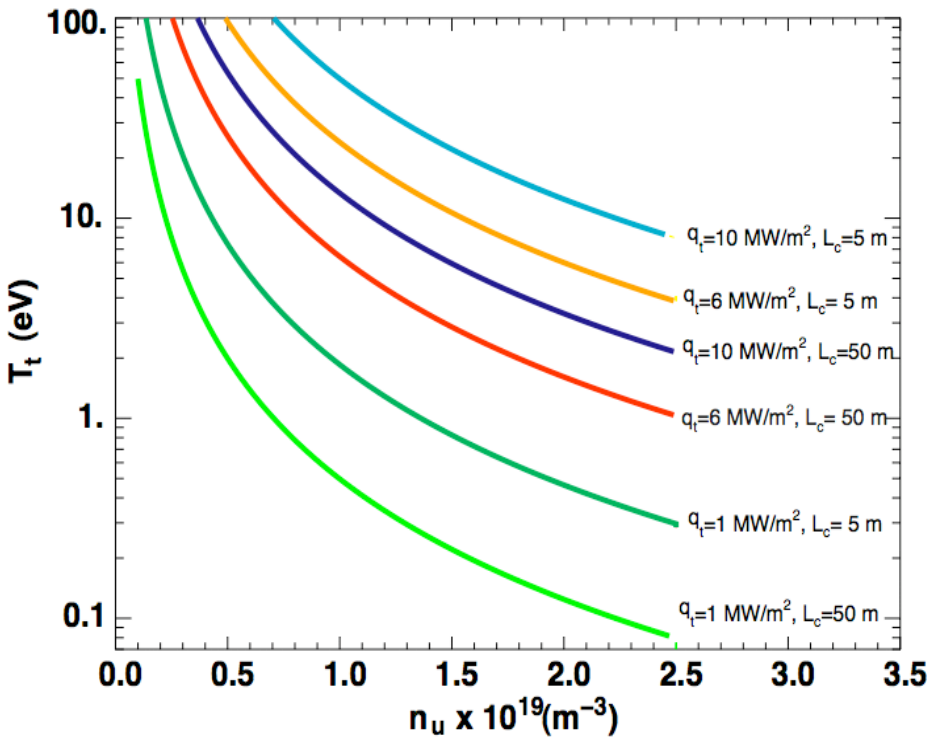
- D_2 puffing from PFR increases outer divertor D_γ / D_α two-fold
- No change in detached inner divertor - D_γ / D_α = 0.020 – 0.030
- Interim D_γ, D_α camera calibration used

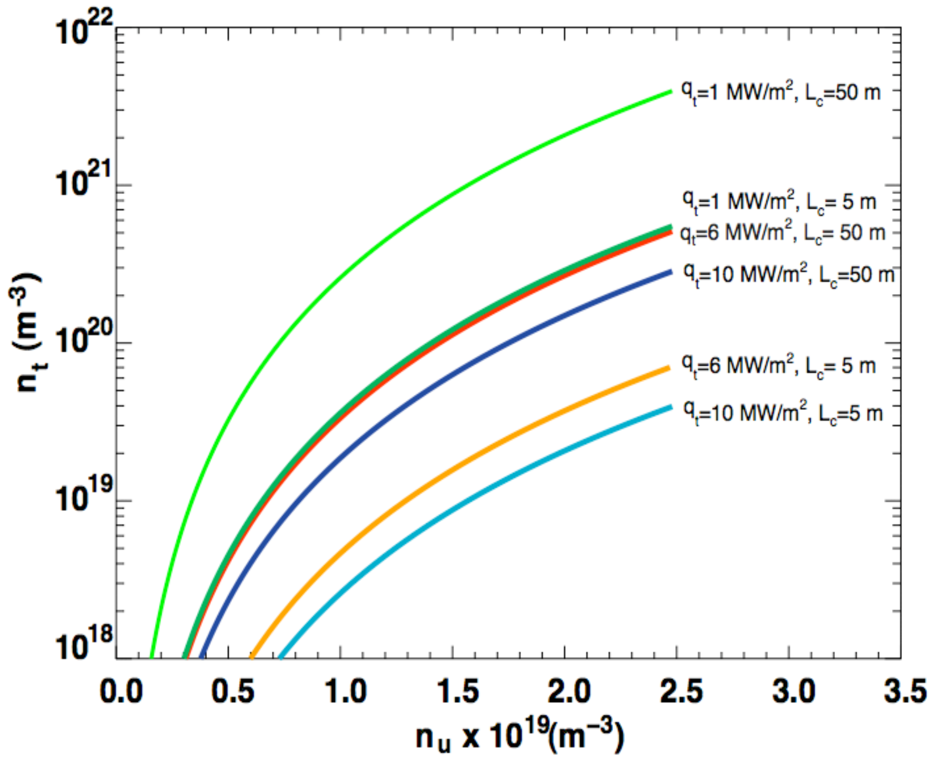
UEDGE detachment space is close to experiment



- H-mode LSN equilibrium used
- UEDGE diffusive transport model
- Impurities included
- Outer n_e, T_e profiles matched, Dα and IRTV not matched
- For guiding purposes only

Detachment observations consistent with 2PM





$$2\, n_t\, T_t = n_u\, T_u$$

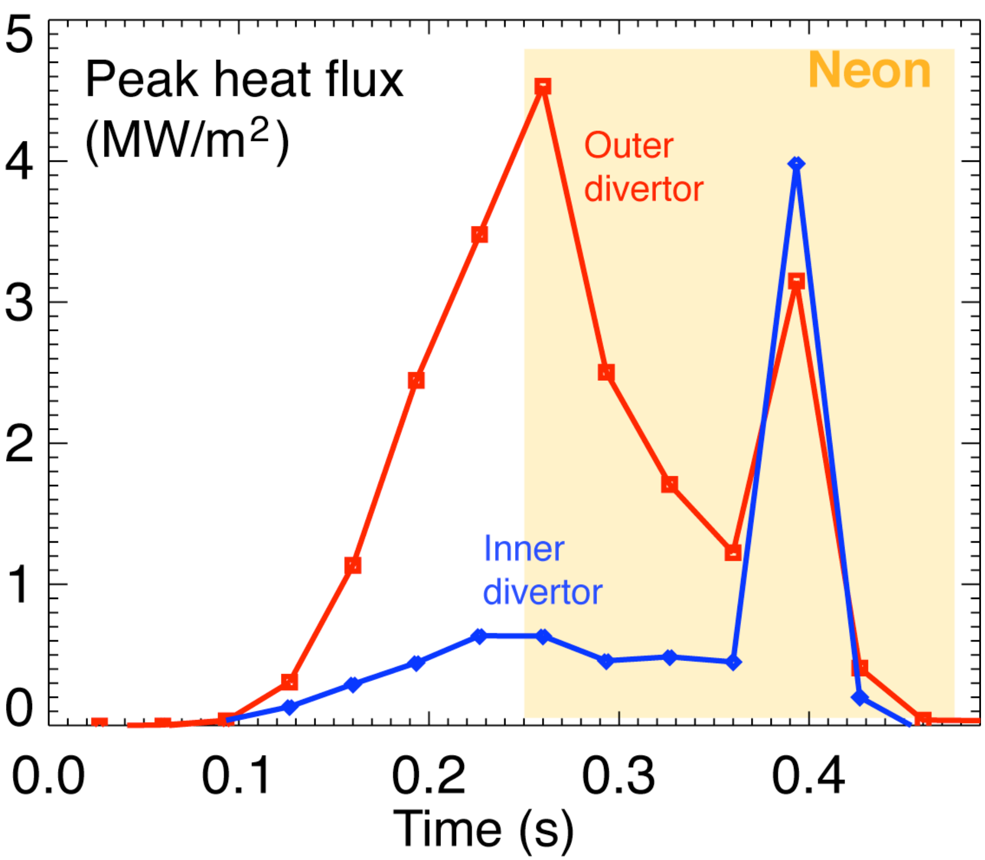
$$T_u^{7/2} = T_t^{7/2} + \frac{7}{2}\,\frac{q_{||}\, L_c}{\kappa_0}$$

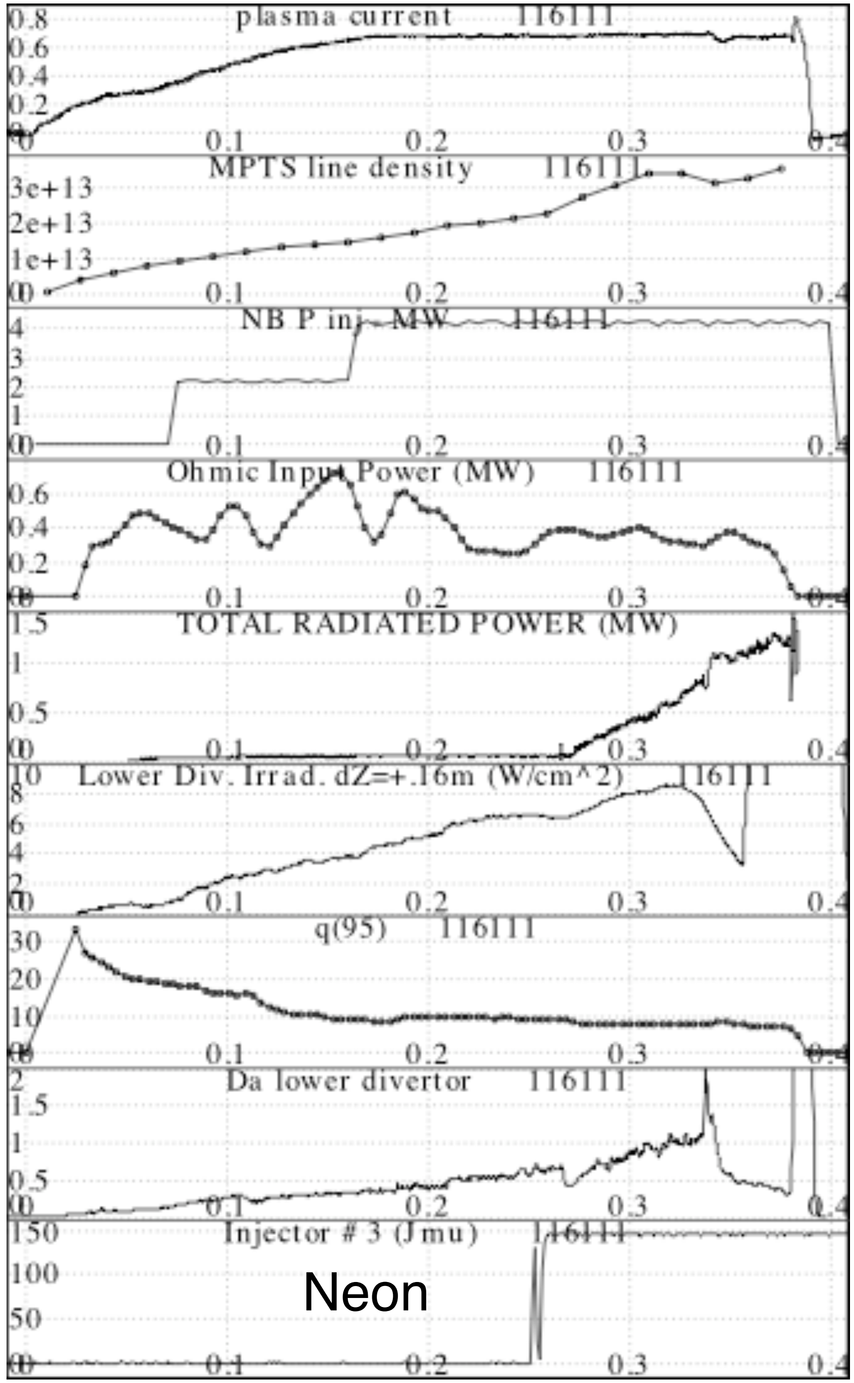
$$q_{||} = \gamma\, n_t\, T_t\, c_{St}$$

P. C. Stangeby, *The plasma boundary of Magnetic Fusion Devices*, IoP Publishing, Bristol & Philadelphia, 2000

Neon injections did not detach outer divertor

- Neon puffed into 4 MW H-mode
- Did not cause H-L transition
- Puffing rate 1.5 x 10^{20} s^{-1}
- P_{rad} = 0.3 x P_{in}
- Outer peak heat flux reduced x4





Summary

- D_2 and neon injections were used to attempt detachment of outer divertor leg in 3-4 MW NBI-heated L- and H-mode plasmas

- Clear signs of outer leg detachment were obtained in 4 MW H-mode plasmas with D_2 injections from the private flux region (PFR). Peak heat flux at the outer divertor target was reduced four-fold from 2 MW/m^2 to 0.5 MW/m^2. During D_2 injections from PFR spectroscopic diagnostics indicated the onset of volume recombination in the outer leg, where $D\gamma$ / $D\alpha$ ratio increased two-fold and approached the value measured in the detached inner divertor

- Midplane gas injectors alone with D_2 fueling rate up to 110 Torr l / s failed to produce SOL conditions necessary for outer divertor leg detachment

- Up to four-fold reduction of the peak heat flux on the outer target was measured in 4 MW NBI-heated H-mode and L-mode plasmas with Ne injections. Outer divertor leg remained attached. P_{rad} / P_{in} was > 30 %