Divertor regimes and divertor detachment in NBI-heated plasmas

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Boundary Physics ET Meeting

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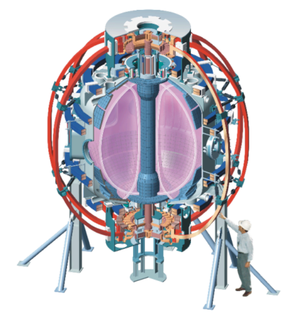


Motivation and Scope of proposed XP

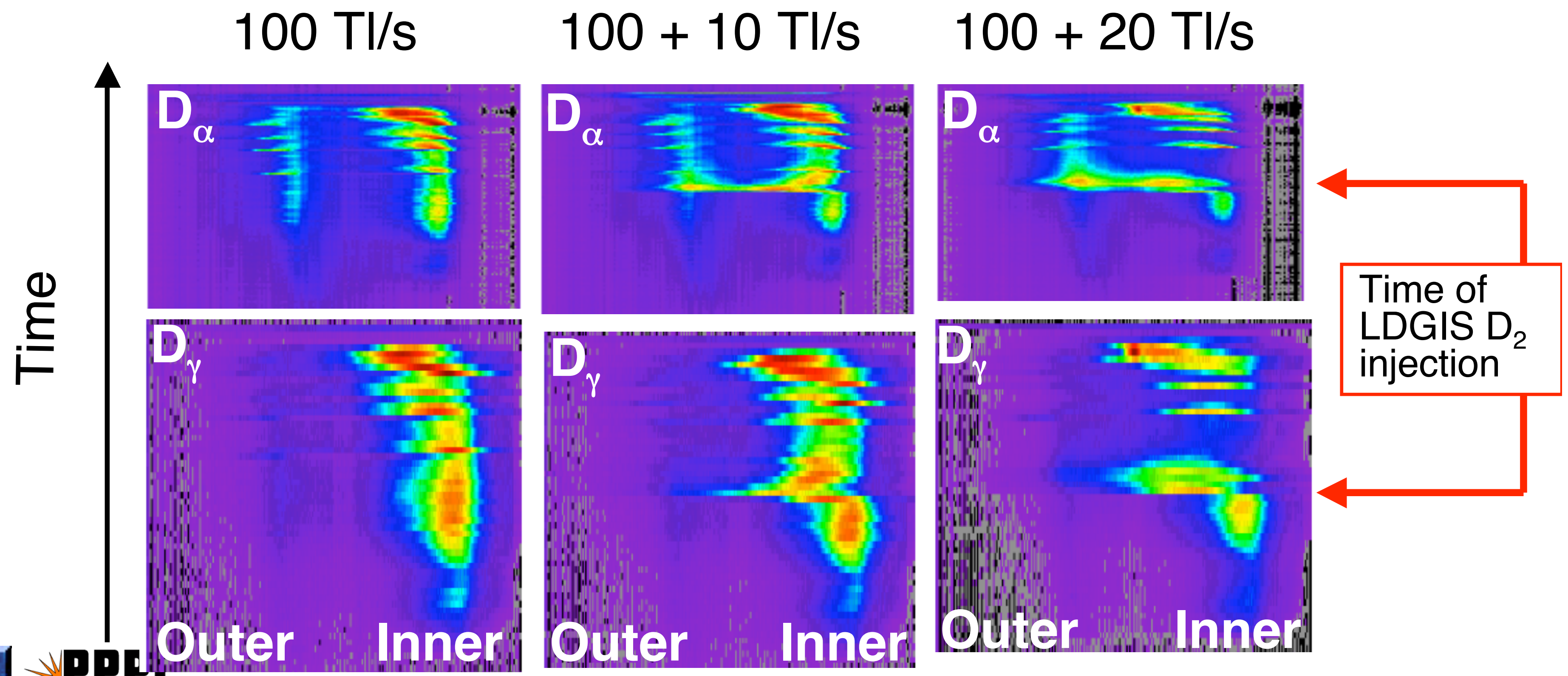
- Need to develop heat flux mitigation techniques for high-performance long pulse NSTX plasmas (strike point sweep, radiative divertor)
- Need to characterize divertor regimes to understand physics
- Do ST magnetic geometry effects matter?
- Aim of XP is a specific result - use two techniques to obtain outer target detachment
- Useful edge database as by-product
- Density limit scan as by-product
- First use of neon injection in non-trace quantities - useful "radiative mantle" experience
- Good candidate for reversed B_t campaign

FY'04 status

- XP-438 "Divertor regimes and divertor detachment in NSTX" was approved in FY04. Ran 8 shots.
- Due to TF coil safety restrictions, ran B_t=0.3 T, I_p= 0.6 MA short plasmas, suffered from IREs
- Reduced the scope of XP to a crude D_2 injection scan from 40 to 120 Torr l / s
- Despite P_{in}=2.5 MW (2 NBI sources) managed to stay in L-mode through most of shots
- Did not see outer divertor detachment
- Obtained experience with multiple LGDIS injectors

Divertor detachment experiment started

- Used PF2L shape, 4 MW NBI L-mode at $B_t = 0.3$ T
- Injected D_2 in LFS midplane and PFZ regions at 20 - 120 Torr l / s
- Concluded inner divertor detachment from D_γ/D_α ratio
- Inner divertor detachment threshold in $<n_e>$, P_{in} is low
- No sign of volume recombination (D_γ) in outer divertor even at 120 Torr l / s, $n_e = 4 \times 10^{19}$ m^{-3}

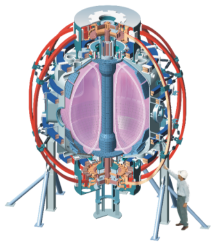


Experiment plan

- Use PF2L LSN discharge with I_p = 0.8 MA, B_t=0.45 T, 2 NBI src, LFS fueling from Injector # 1, 2 (for density control), LDGIS, High Flow diagnostic injector for neon
- Setup an L-mode NBI-heated discharge (2 shots)
- Inject D_2 in increasing quantities from Injector # 2: 40-150 Torr l / s (5 shots)
- Attempt to raise density further by adding LDGIS, Injector 1 and/or CS injector (10 shots)
- Use an intermediate density (4-6 x 10^{19} m^{-3}) good shot from above and add injections of neon in increasing quantities (2 - 30 Torr l / s) to obtain P_{rad} / P_{in} = 0.5 (10 shots)
- SGI may be used instead of Inj # 2 if adequate results come from XP516

Future work

- Reversed B_t experiments
- ST geometry effects on commonly observed divertor regimes
- Detachment in DN divertor
- Detachment in Helium plasmas
- Correlation of turbulence in inboard and outboard SOL and divertor detachment
- Divertor detachment in HHFW-heated plasmas
- Detachment in long high power density H-mode plasmas



Divertor regimes in NSTX

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Abstract

The identification of divertor regimes is a starting point for the deuterium and carbon particle balance analysis and understanding of low aspect ratio geometry implications for edge radial and parallel transport in NSTX. Main chamber and divertor recycling, impurity, radiated power, heat flux, temperature, density and neutral pressure measurements in NBI heated lower single null and double null discharges with elongation ranging from 1.8 to 2.5, input power from 1.8 to 7 MW, ne(0) = $(2.5-8)\times 10^{19}$ m^{-3}, and D_2 feed rate up to 8 $\times 10^{21}$ s^{-1} will be presented. Volume recombination signatures from D , D profiles and Stark-broadened high n Balmer series transitions, as well as the measured heat flux under 1 MW/m^2 and recycling dynamics in ELMy H-mode plasmas suggest that the inner divertor is detached. The outer divertor is in the sheath-limited and high-recycling regimes. Predictions of the analytical two point model and the UEDGE multi-fluid code will be compared to the data. The implications of the divertor regimes for carbon production and core fueling in NSTX will be discussed.

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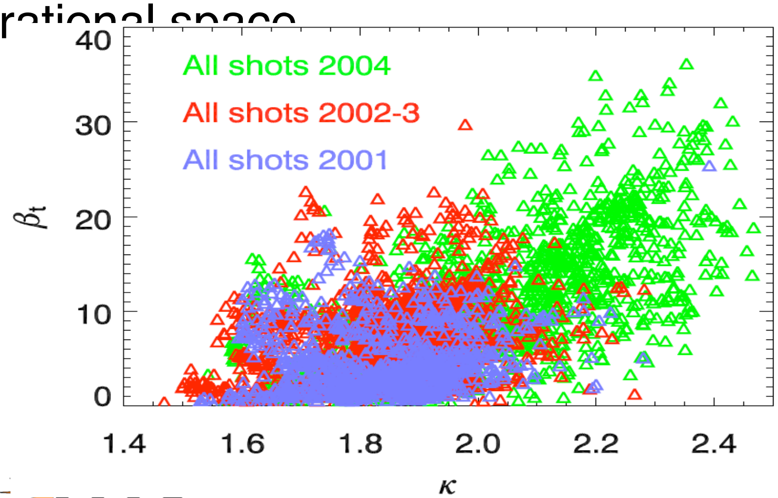
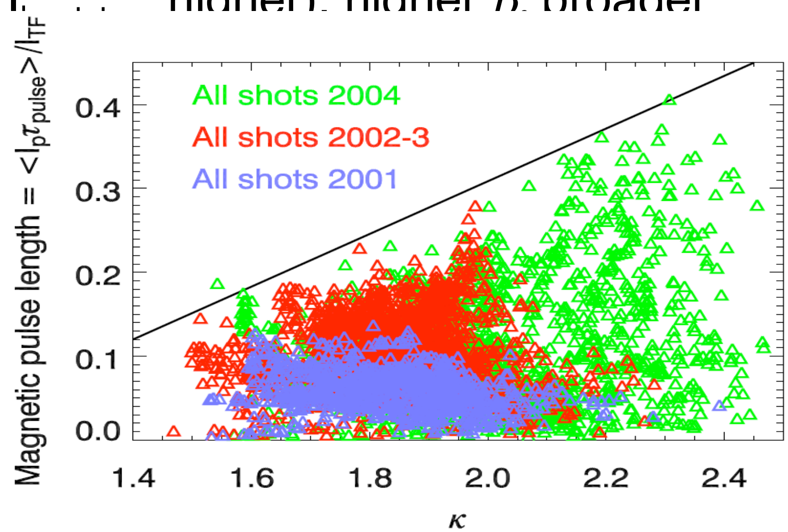
Analyze SOL / divertor properties in ST plasmas

- NSTX has made significant progress toward high performance plasmas:

  τ_{pulse} = *several* τ_E, β_T up to 40 %, routine H-mode access
- Analyze ST effects in SOL / divertor as well as divertor geometry effects
- Document SOL / divertor conditions, compare to tokamaks, 2D codes
- Develop radiative divertor regime compatible with high performance H-mode plasmas

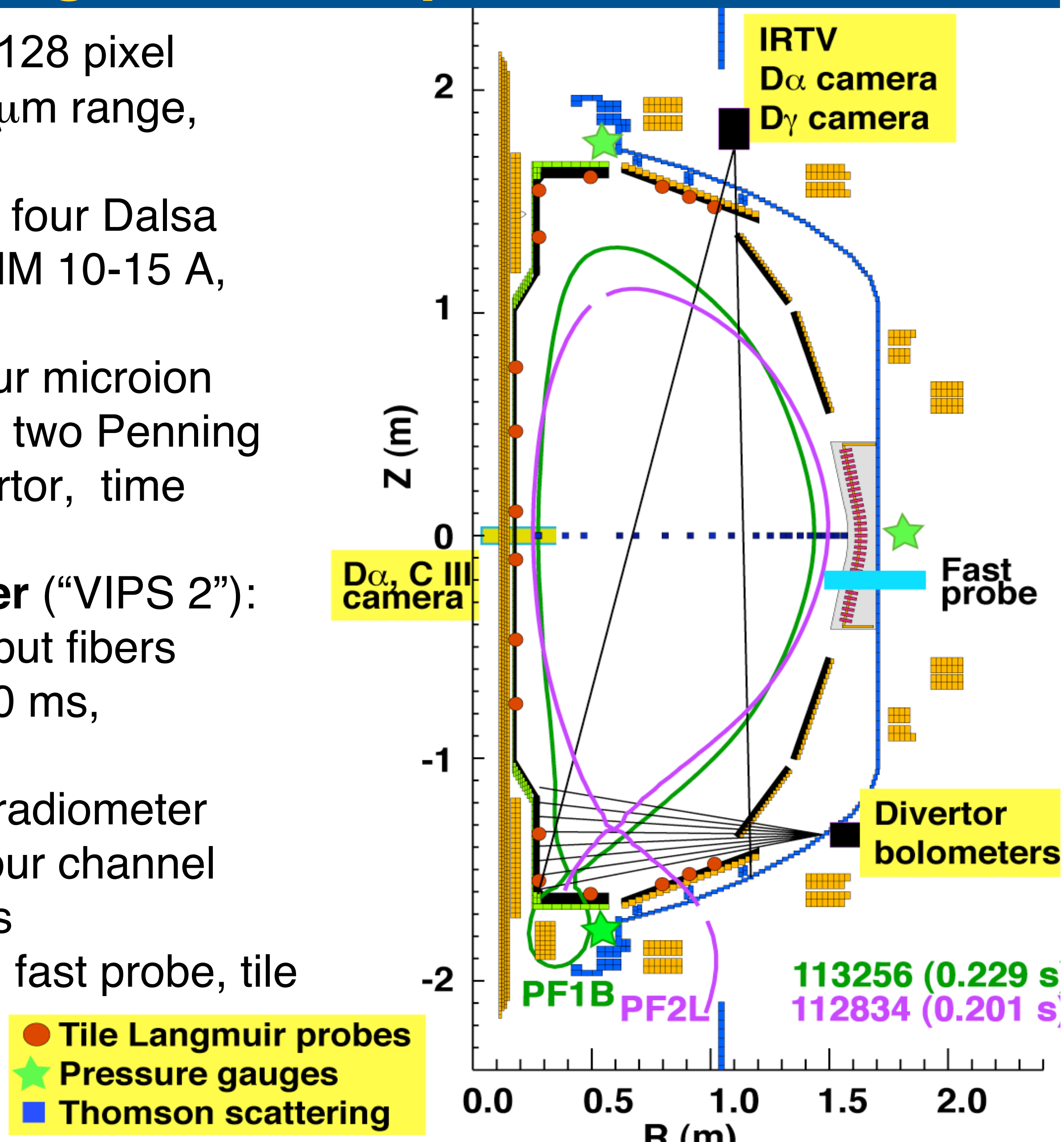
- Analyze SOL / divertor properties in plasmas with two common magnetic equilibria:
  - **PF2L** shape - H-mode physics (access, threshold), transport
  - **PF1B** shape - high β high performance long pulse, transport and H-mode
- NSTX has developed sustained high elongation high triangularity H-mode plasmas scenarios (D. Gates oral CO3.002)
- Higher elongation leads to longer pulse length (I ... higher), higher β, broader operational space





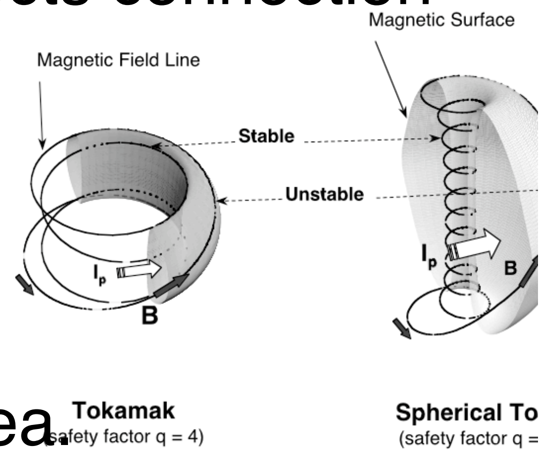
SOL / divertor diagnostics improved in FY'04

- **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



ST effects in SOL and divertor may lead to different physics

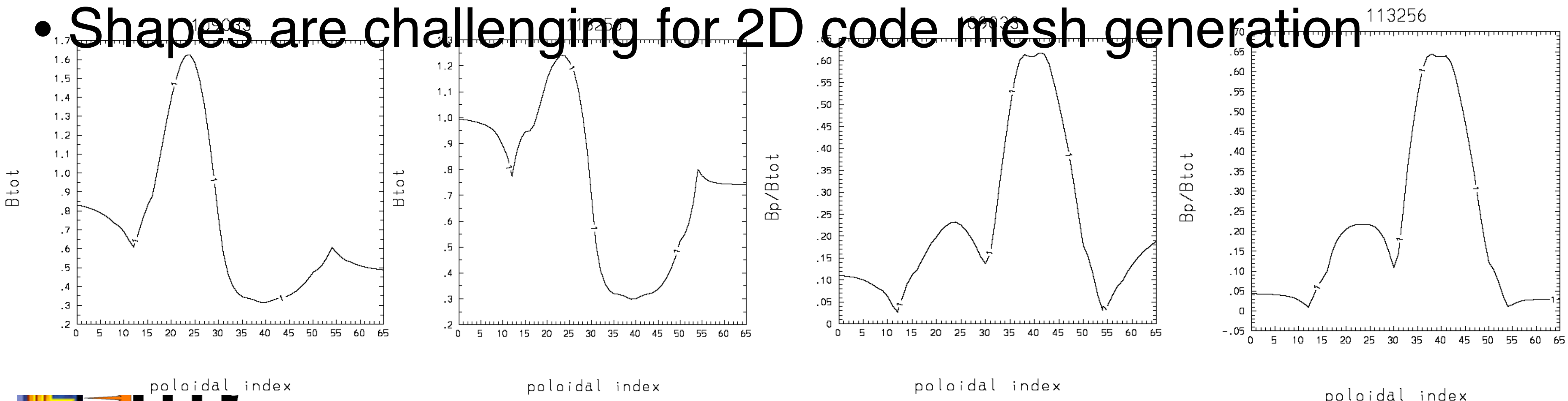
- High SOL mirror ratio $M=|B_{min}| / |B_{max}|$ - affects connection length $L_{||}$, fraction of trapped particles *f*, etc
- Large flux expansion ratio $f = \frac{(B_\theta / B)_u}{(B_\theta / B)_t}$:
  - Heat and particle in-out asymmetries
  - Parallel transport, divertor regimes



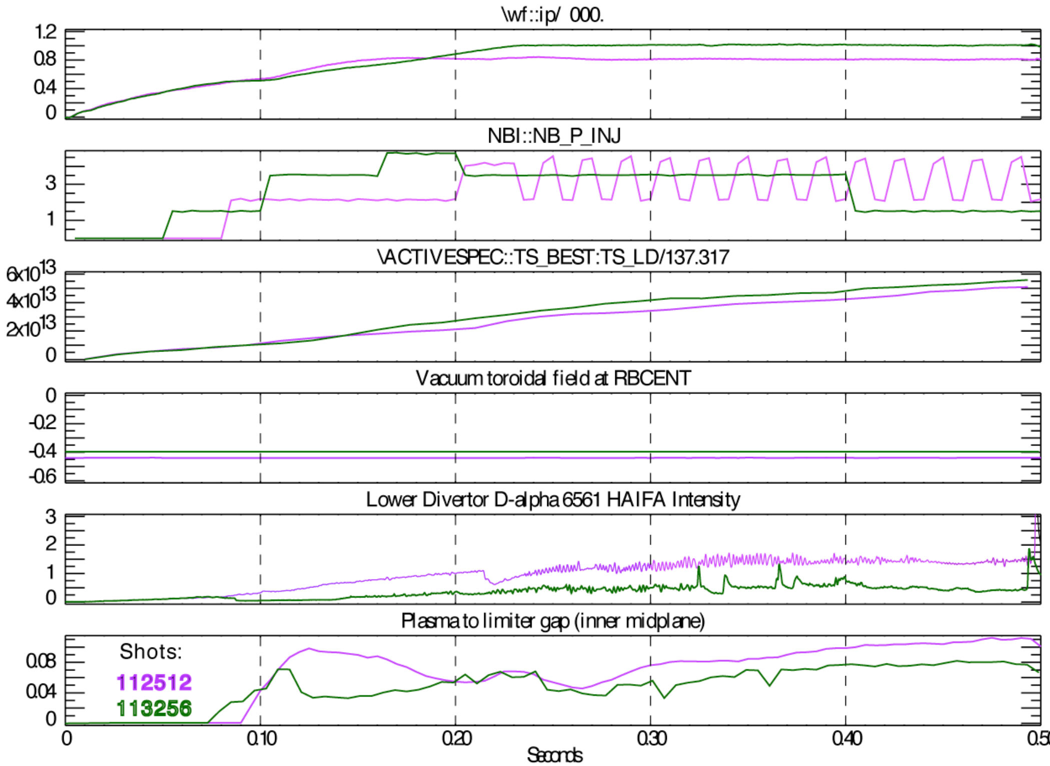
- Compact divertor - divertor volume, PFC area.

  In NSTX P_{in}/R = 8 MW/ 0.85 m = 9.5

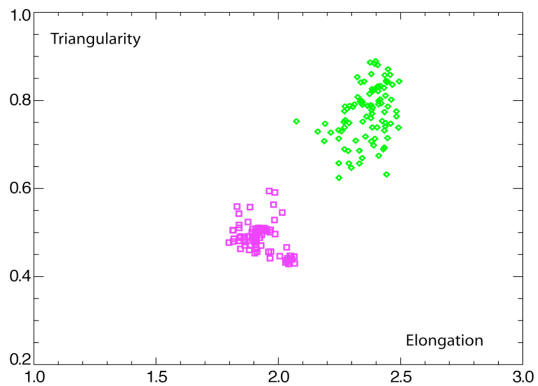
- Toroidicity effects - drifts (not addressed here)
- Shapes are challenging for 2D code mesh generation



Plasma shapes obtained with PF2L and PF1B divertor coils dominate operational space

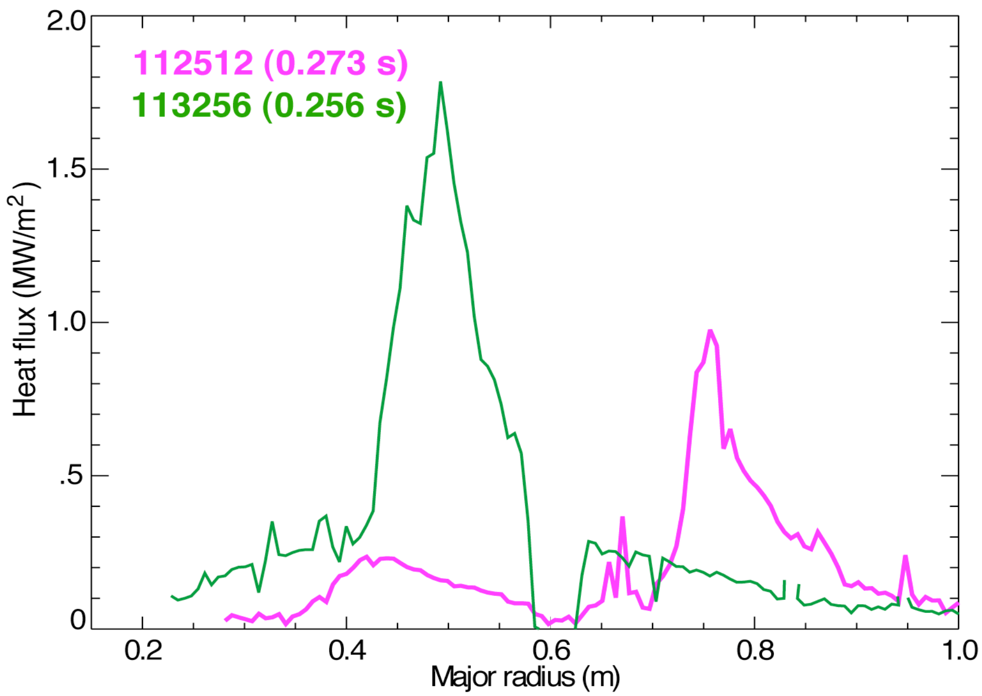


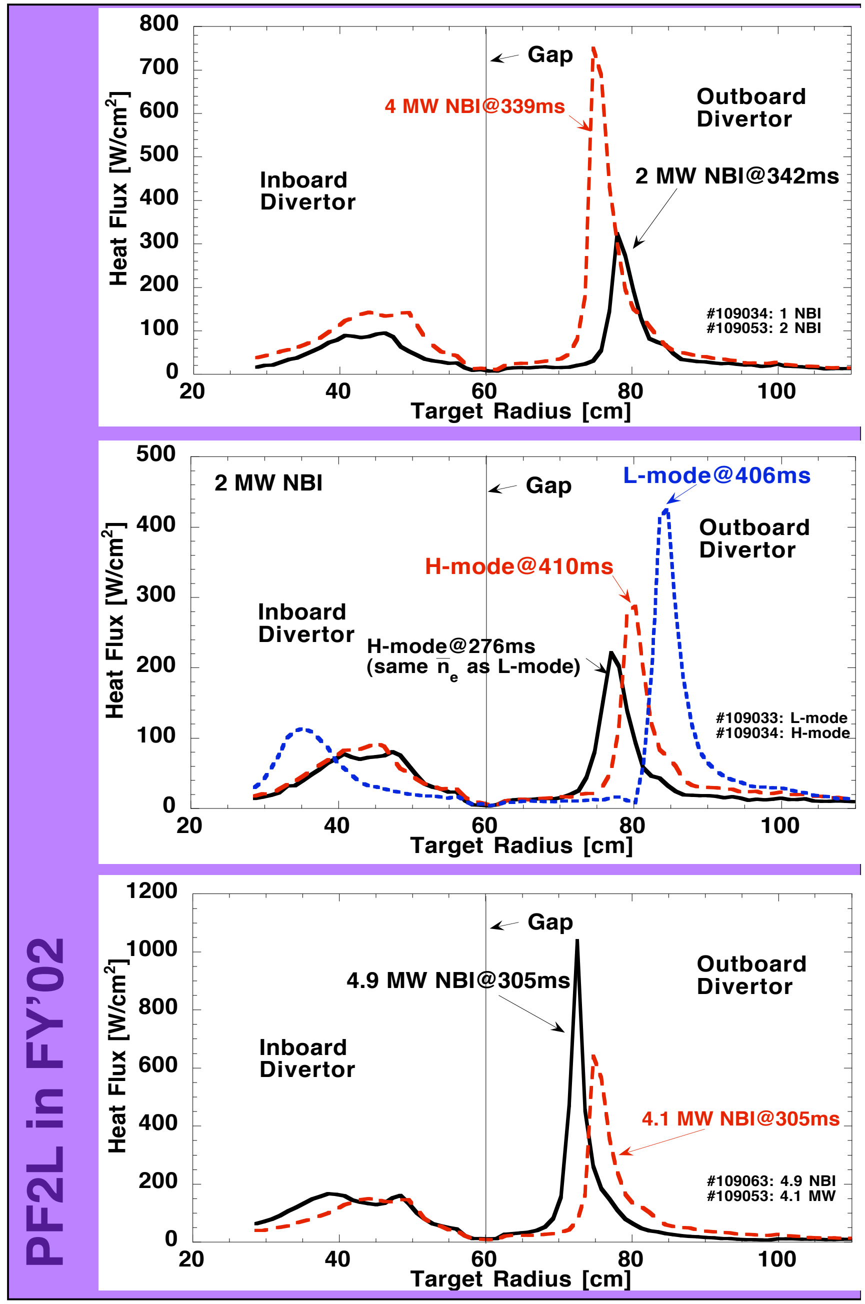
	109033 (PF2L)	113256 (PF1B)
κ	1.85	2.40
δ	0.47	0.74
Drsep (cm)	-1.8	-1.0*
q_{edge}	13	9.5
$L_{\|\|}$, inner (m)	16.4	19.5
$L_{\|\|}$, outer (m)	10.0	12.5
M (Mirror ratio)	5.0	4.2
f inner (Flux expansion)	2.1	5.0
f outer (Flux expansion)	3.2	2.1



- Because of diagnostic constraints only LSN divertor can be studied at present
- Properties of DN divertor will be studied in FY’05 - FY’06

$q_{||}$ profiles are different in PF2L and PF1B shapes

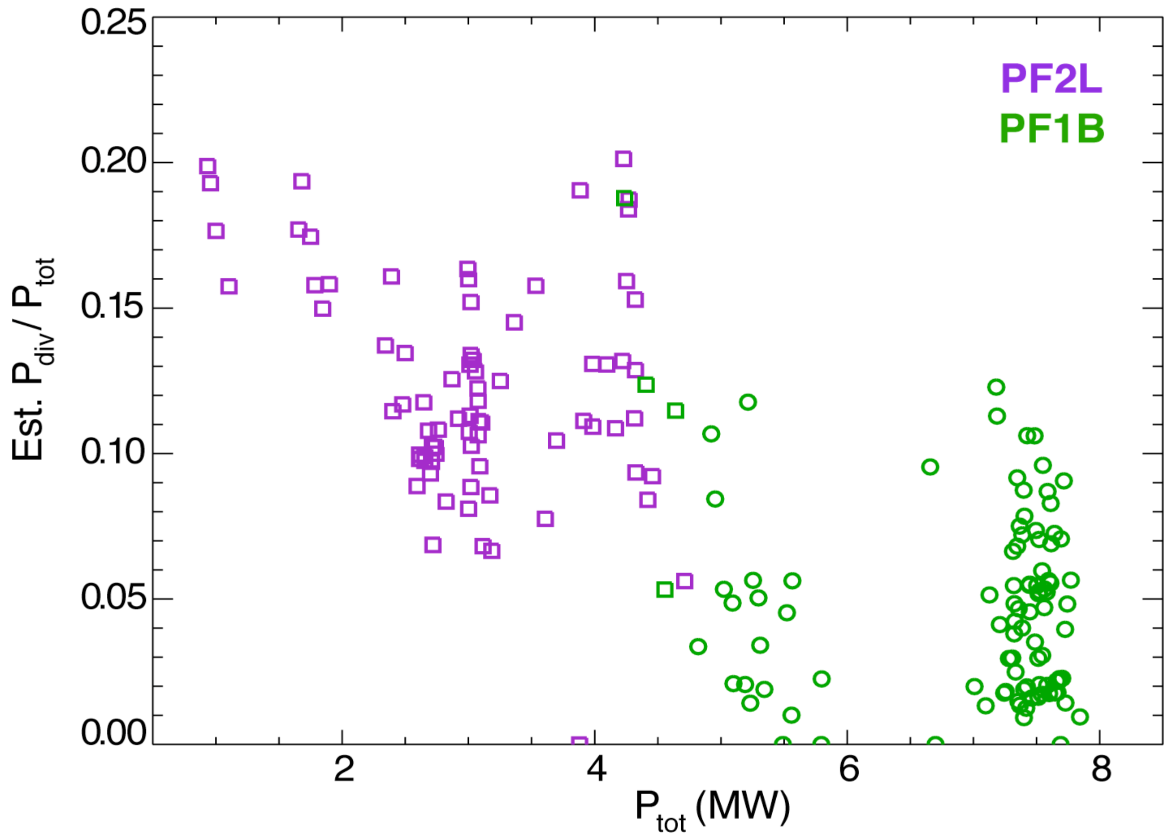




In PF2L plasmas:

- Heat flux increases non-linearly with P_{in}
- q_{in}/q_{out}= 2-3
- Heat flux equilibration time τ_{eq}~ 100 ms
- Power accountability: up to 70 % of P_{NBI} measured in divertor
- Divertor heat flux independent of gas injection location

Divertor P_{rad} is similar in PF2L and PF1B shapes



- Analyses is based on plasma emissivity estimate from divertor bolometers
- Effective divertor volume in PF2L shape is 3-5 higher than in PF1B
- Accurate comparison and power accounting is only possible through 2D modeling
- Power balance studies in NSTX - S. F. Paul et. al., Poster JP1.010

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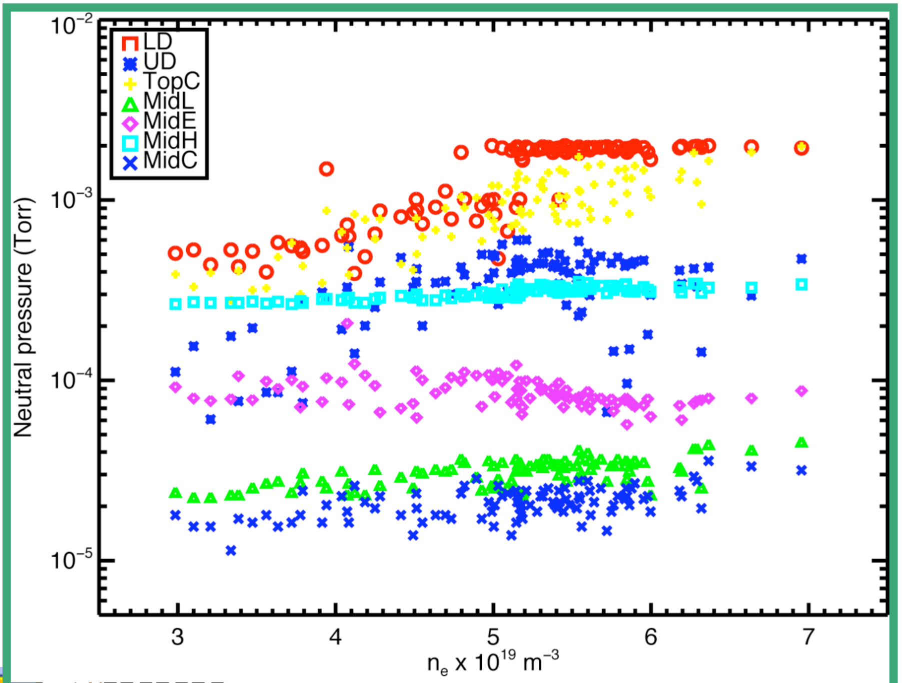
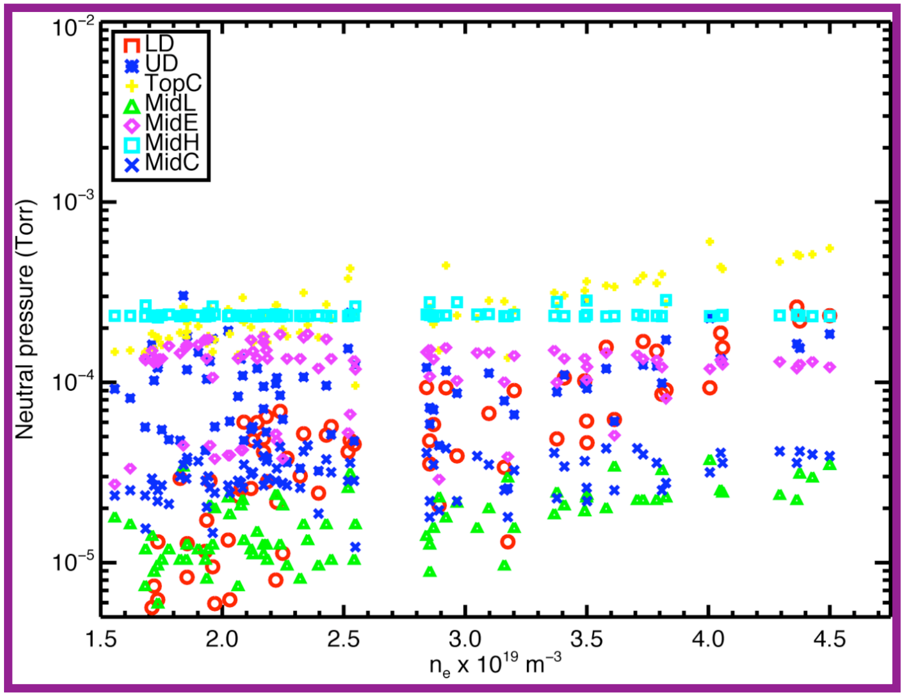
Divertor neutral pressure is high

- High pressure measured in divertor and mid-plane
- Measurements are not conduction limited
- In PF1B shots, pressure mesured in outer SOL;
  in PF2L shots, pressure is measured in PFZ
- Compression ratio is 5-10 for PF1B shots
- Midplane pressure is similar in PF2L and PF1B
- Gas fueling similar for both types





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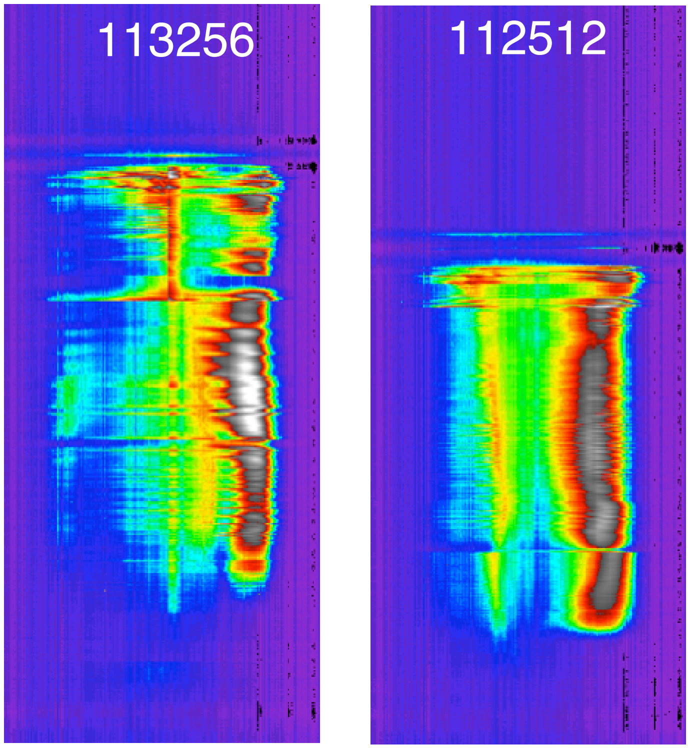
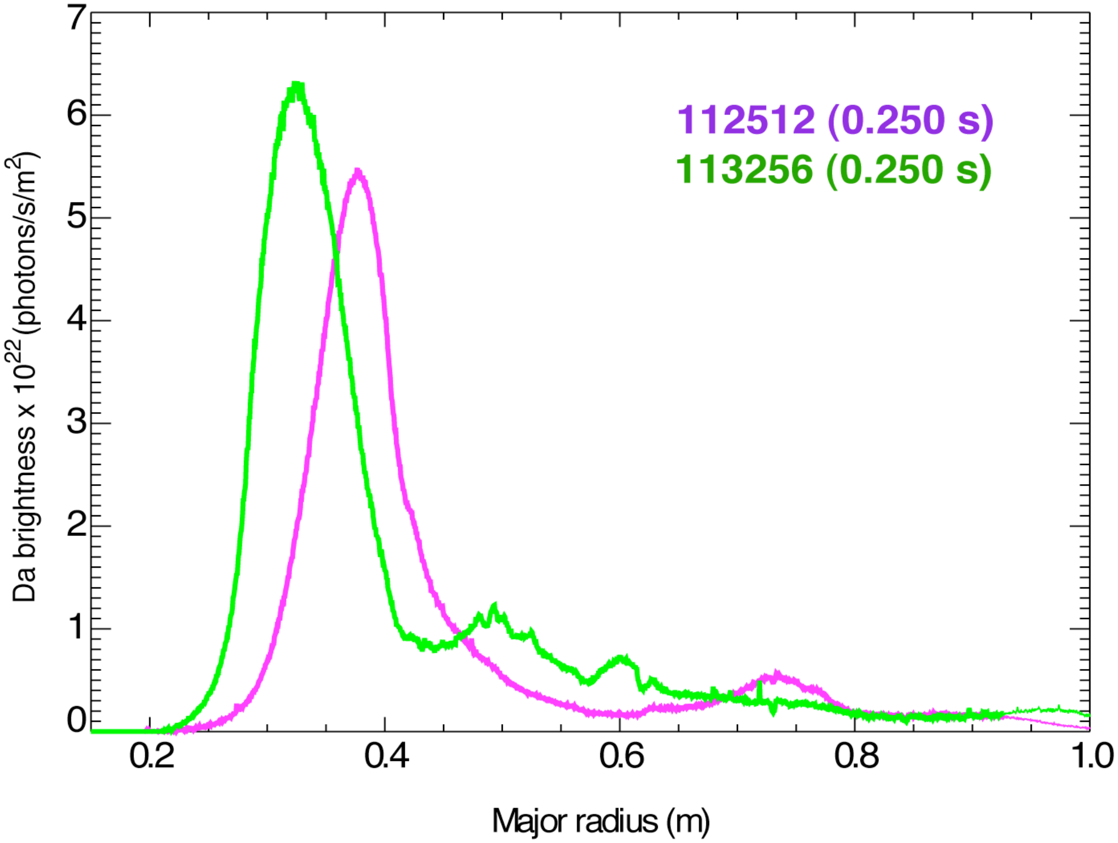
Divertor D_α in-out asymmetry is high



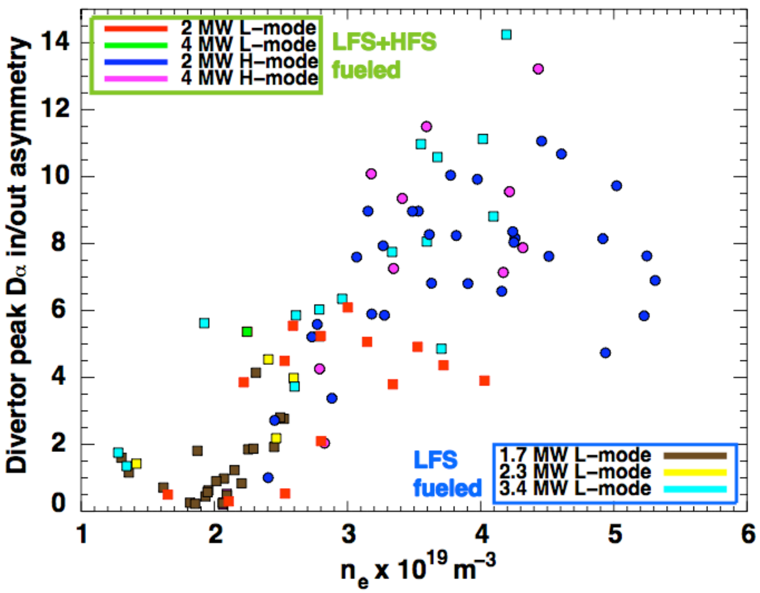
Divertor D_α - space vs time

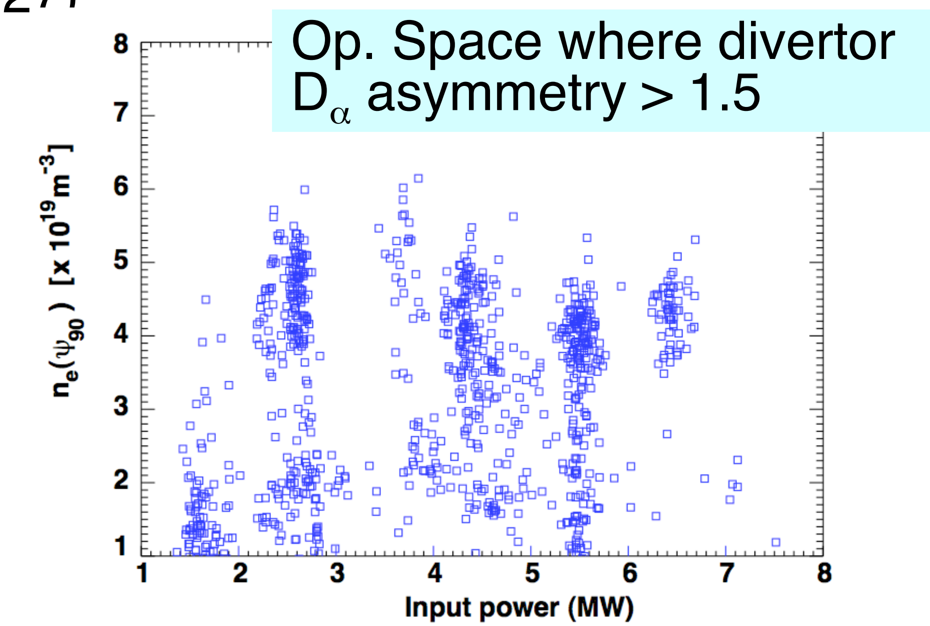


- Recycling in PF2L and PF1B occurs in different div. regions
- Asymmetry is weakly dependent on R_{Xpt}
- Both inner and outer D_α brightness are line-av. n_e dependent

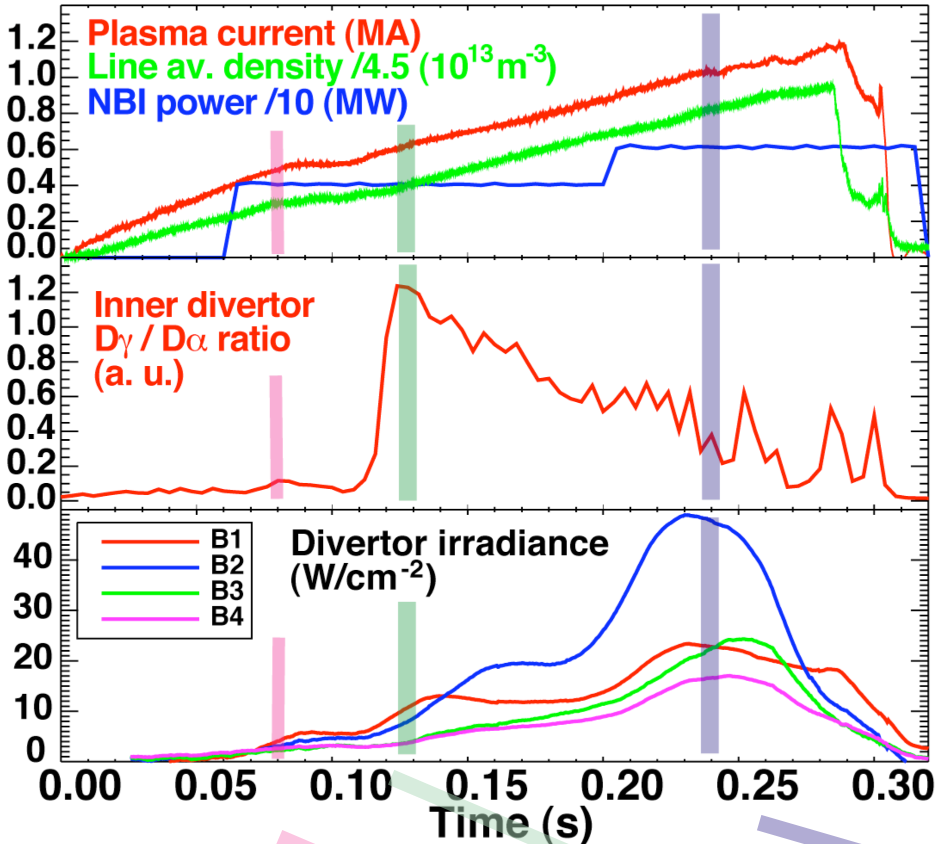
Divertor in-out asymmetries

- Heat flux asymmetry always $q_{out}/q_{in} > 1$, consistent with
  - SOL area factor: $A_{out} > A_{in}$
  - Magnetic flux expansion factor (mid/div): $f_{in} > f_{out}$
- D_α asymmetry (particle flux / recycling) is observed through most of op. space
  - Density and power dependent
  - Not always correlated with volume recombination onset
  - Complex interplay of cold dense detached plasma and diagnostic geometry effects?
  - Analysis in progress to address radiation opacity effects (A. Pigarov et. al. Poster JP1.027)

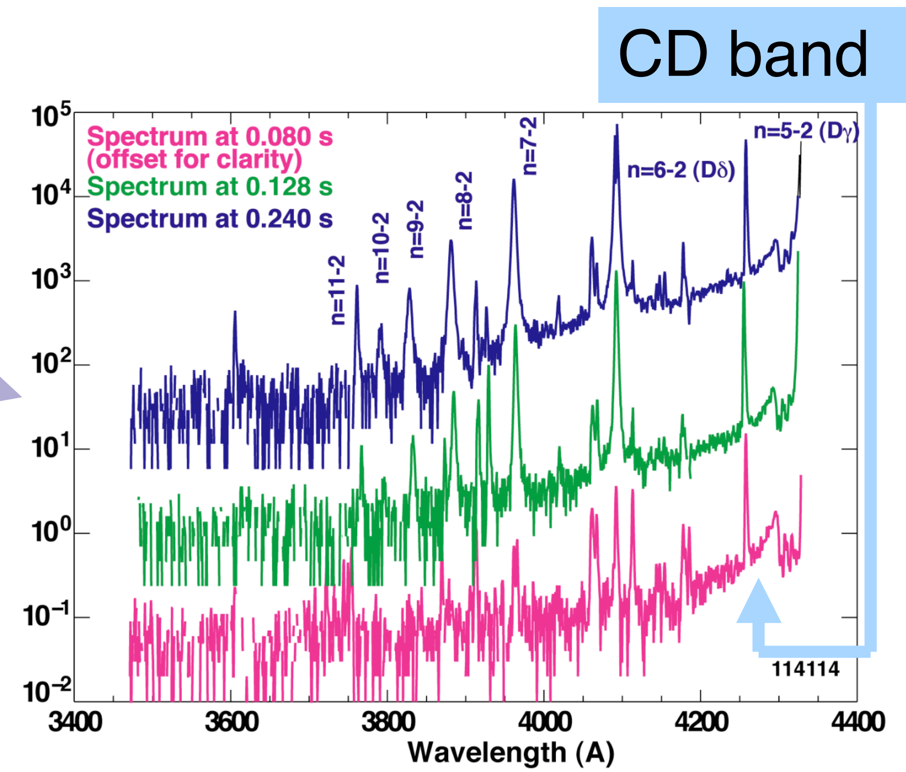




Inner divertor is cold / detached in PF1B shots



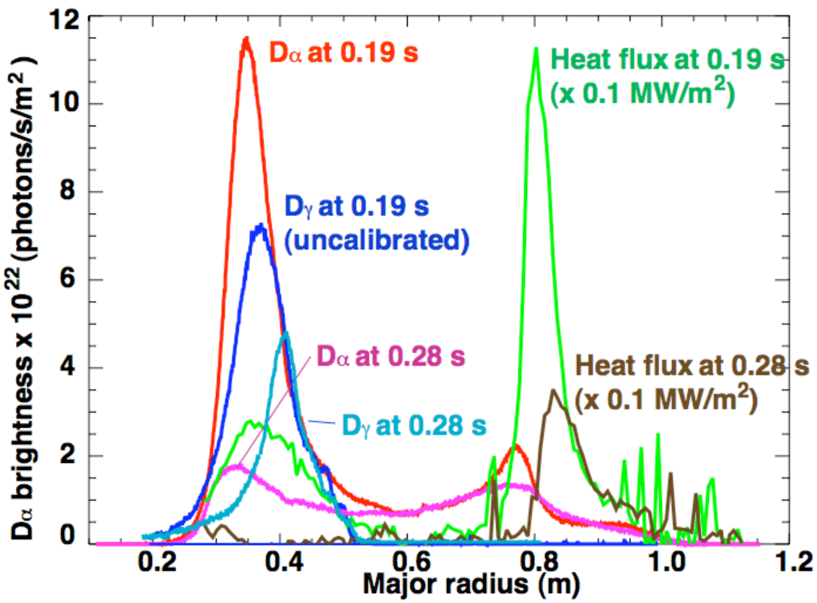
- Similar divertor behavior in L- and H-mode plasmas with $P_{NBI} < 6$ MW.
- Inner divertor is cold, often detached
- Heat flux $q < 1$ MW/m^2
- Sign of detachment: observed volume recombination (D_γ/D_α ratio increases), P_{rad} increase

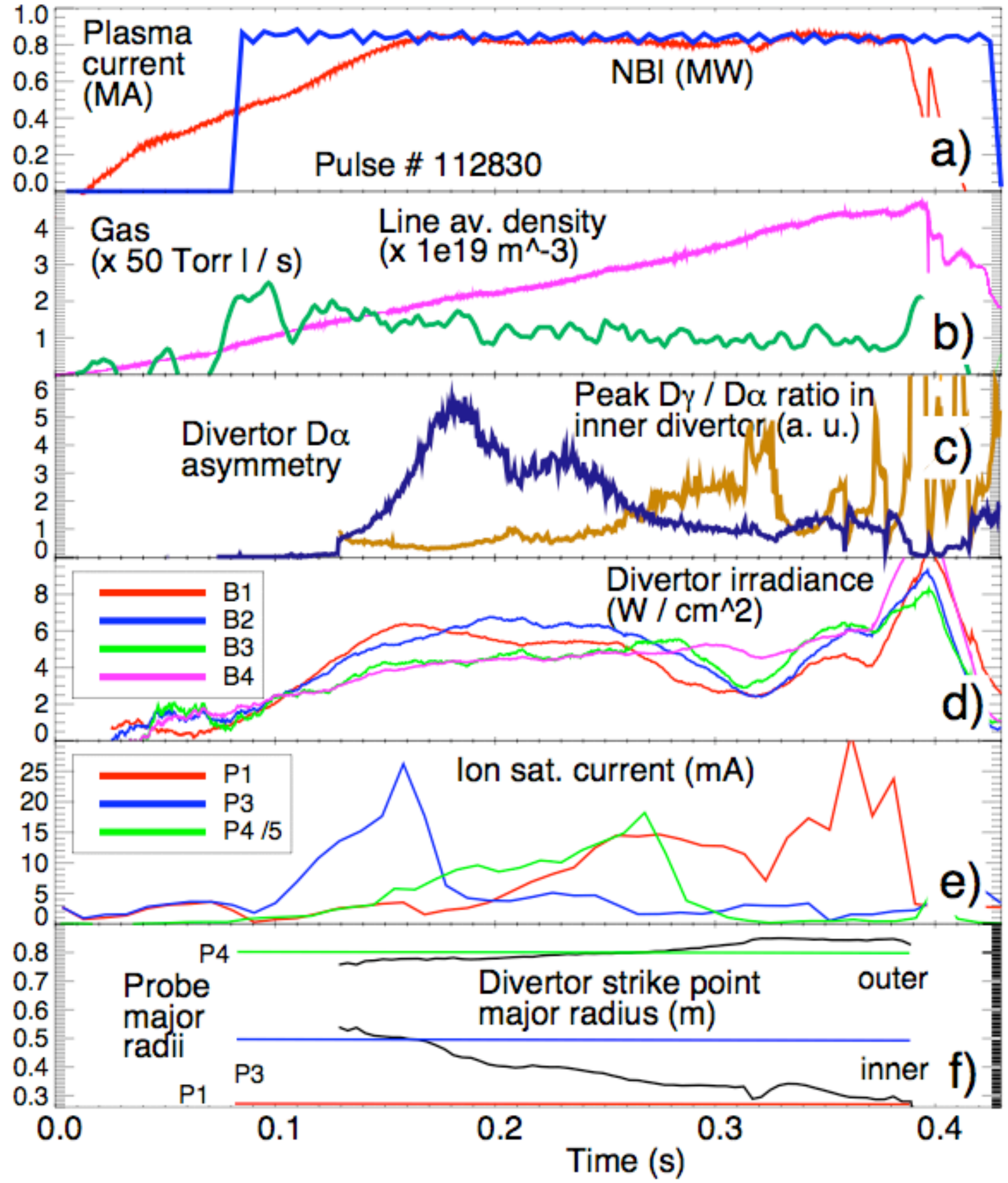


Appearance of Stark broadened high n Balmer series lines indicate:

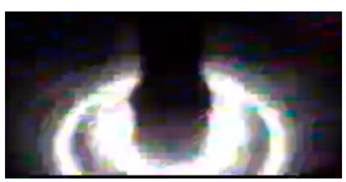
- Volume recombination
- Apparently high n_e, n_0, low T_e
- Possibly optically thick

Inner divertor cold / detached in PF2L shots

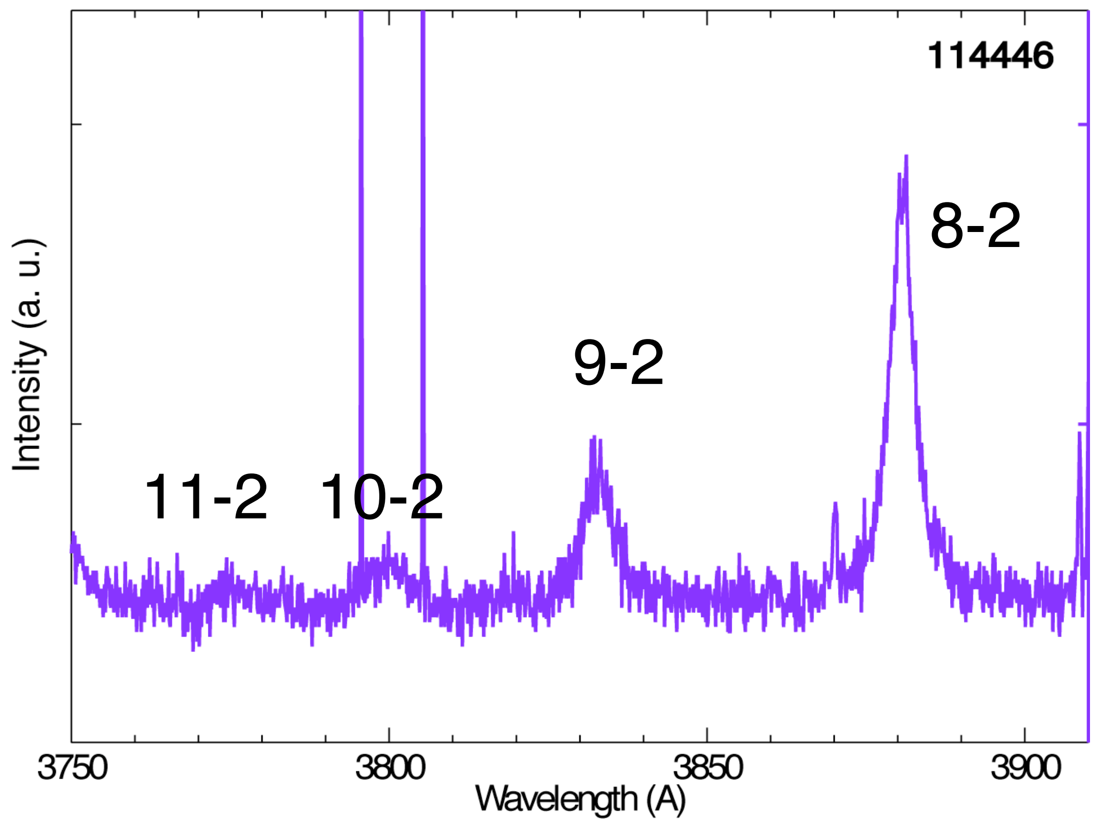


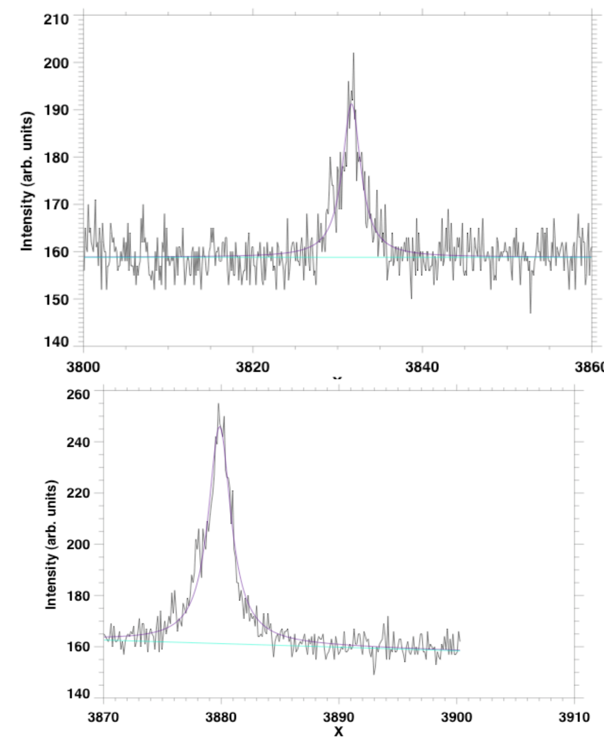


- 1 NBI src L-mode
- Inner divertor detached at $<n_e> =$ 2.5-3 x 10^{19} m^{-3}



Stark broadening of Balmer lines yelds high n_e



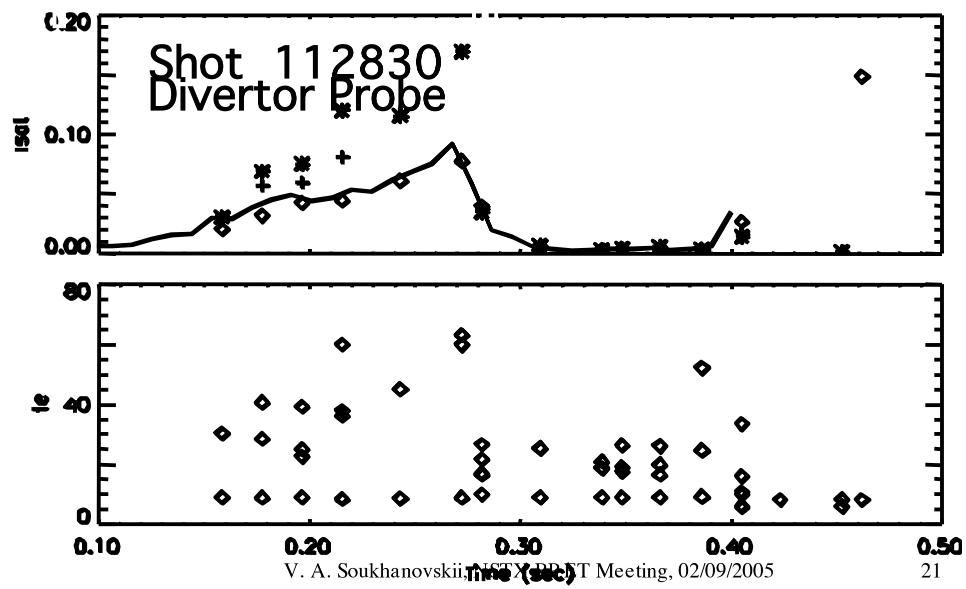


- Do not observe photorecombination continuum edge - probably due to high core bremstralung background
- FWHM increases with *n*, Voigt line profile shape
- Inglis-Teller limit for n=11 yeilds n_e=10^{15} cm^{-3} (too high!)
- Analysis with CRETIN in progress

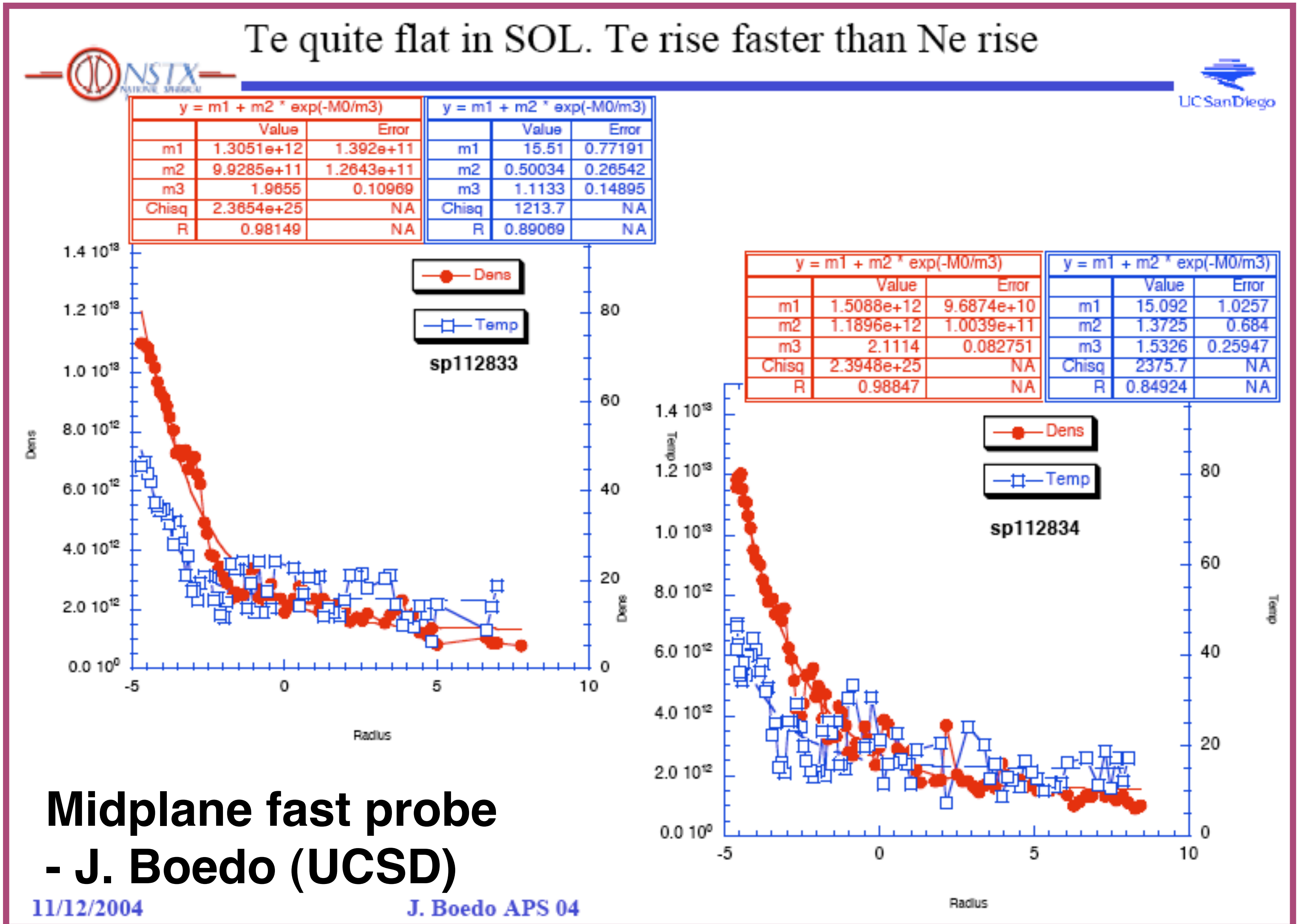
Outer divertor is in linear and high recy. regime

- Outer divertor is always attached, heat flux $q < 10\ MW/m^2$
- **Outer divertor is in sheath-limited and high-recycle regime**
- Uncertainty in LCFS position undermines analysis:
  - MPTS midplane $T_e = 5 - 40$ eV (5 - 15 eV or 20 - 40 eV?)
  - Fast probe midplane $T_e = 10 - 30$ eV
  - SOL collisionality $\nu^* = 0.5 - 100$ (mostly 10 - 60)
- Divertor $T_e = 5 - 40$ eV
- If midplane $T_e = 5 - 15$ eV then the very weak $dT_e/dx_{||}$ poses questions about heat flux measurements, e-i partition and the heat transport mechanism
  - Carbon radiation zone is 10 eV
- Difficult experimental issue

LP outer divertor data - C. Bush (ORNL)



Flat T_e, n_e in outer midplane SOL in PF2L shots



y = m1 + m2 * exp(-M0/m3) (sp112833, Dens)

	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) (sp112833, Temp)

	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) (sp112834, Dens)

	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

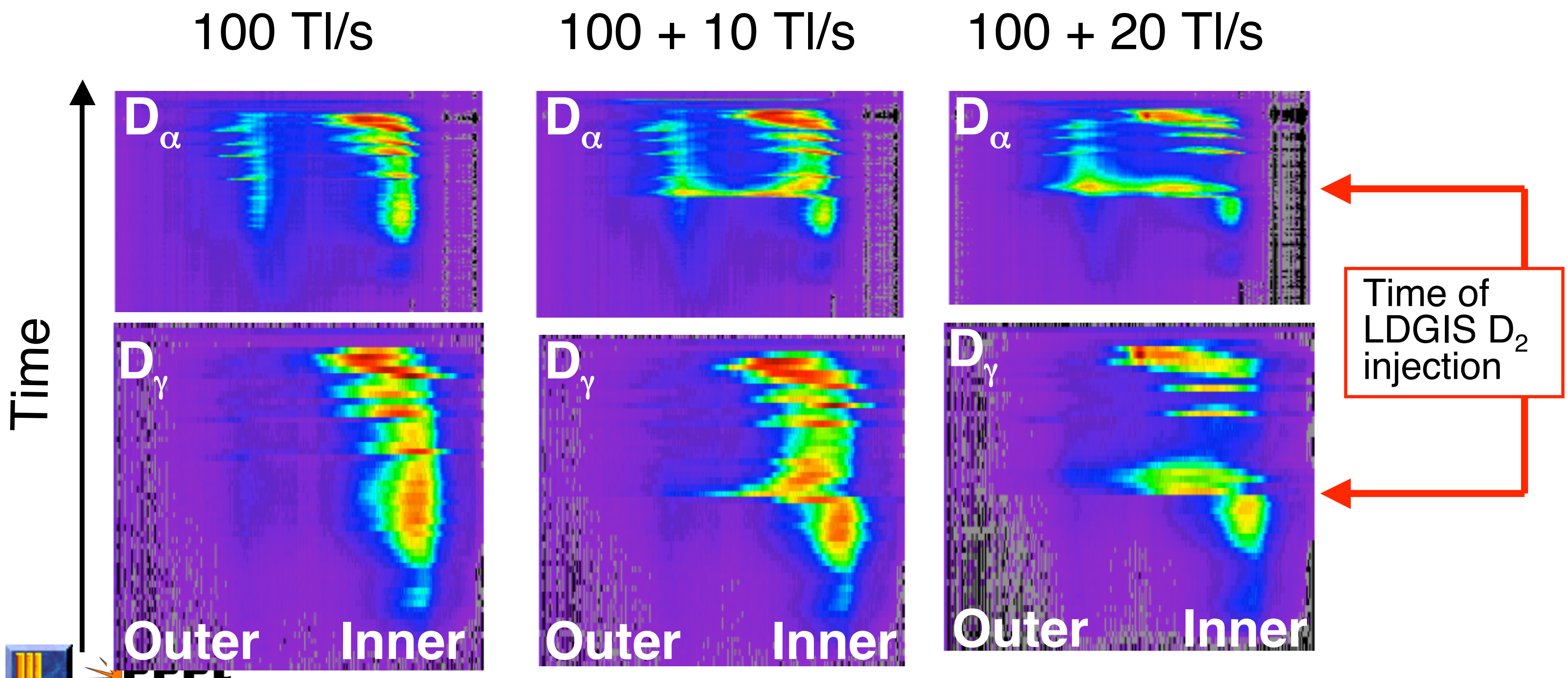
y = m1 + m2 * exp(-M0/m3) (sp112834, Temp)

	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

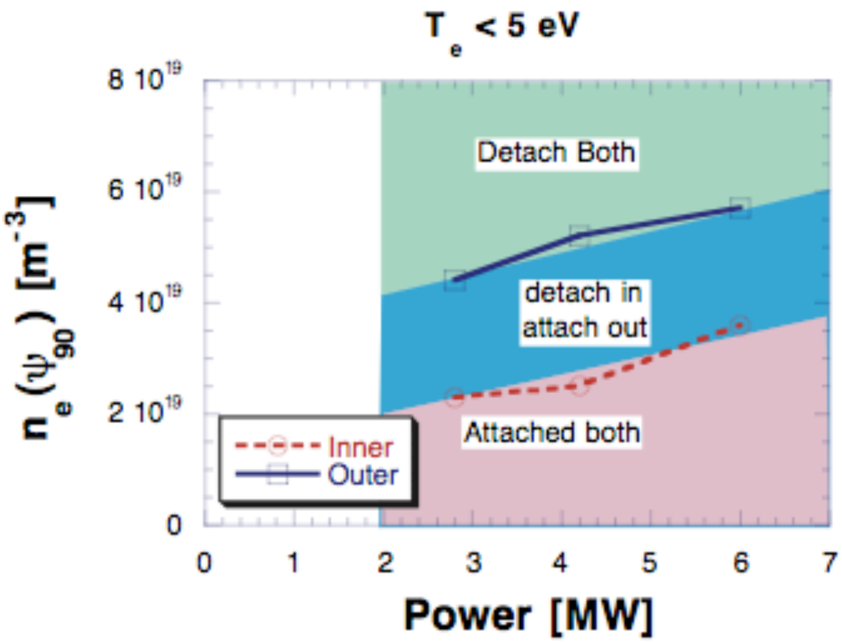
Midplane fast probe
- J. Boedo (UCSD)

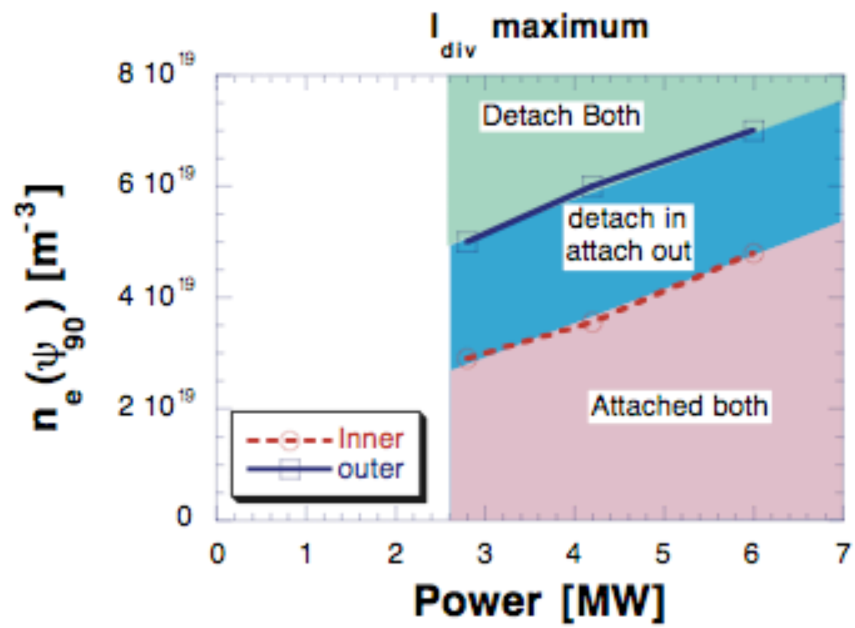
Divertor detachment experiment started

- Used PF2L shape, 4 MW NBI L-mode at $B_t = 0.3$ T
- Injected D_2 in LFS midplane and PFZ regions at 20 - 120 Torr l / s
- Concluded inner divertor detachment from D_γ/D_α ratio
- Inner divertor detachment threshold in $<n_e>$, P_{in} is low
- No sign of volume recombination (D_γ) in outer divertor even at 120 Torr l / s, $n_e = 4 \times 10^{19}$ m^{-3}



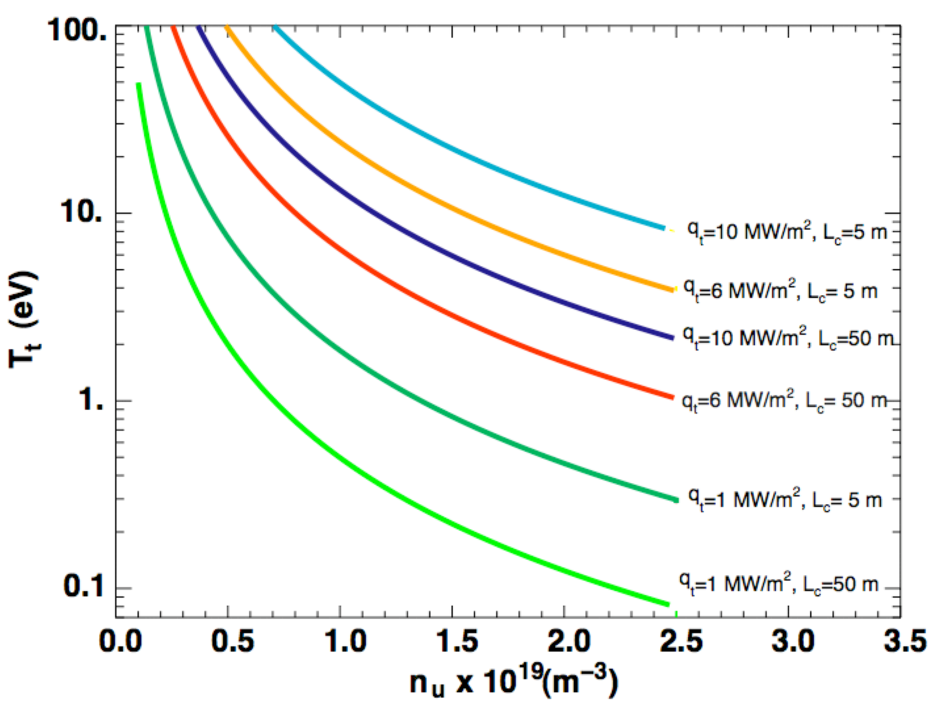
UEDGE detachment space is close to the observed

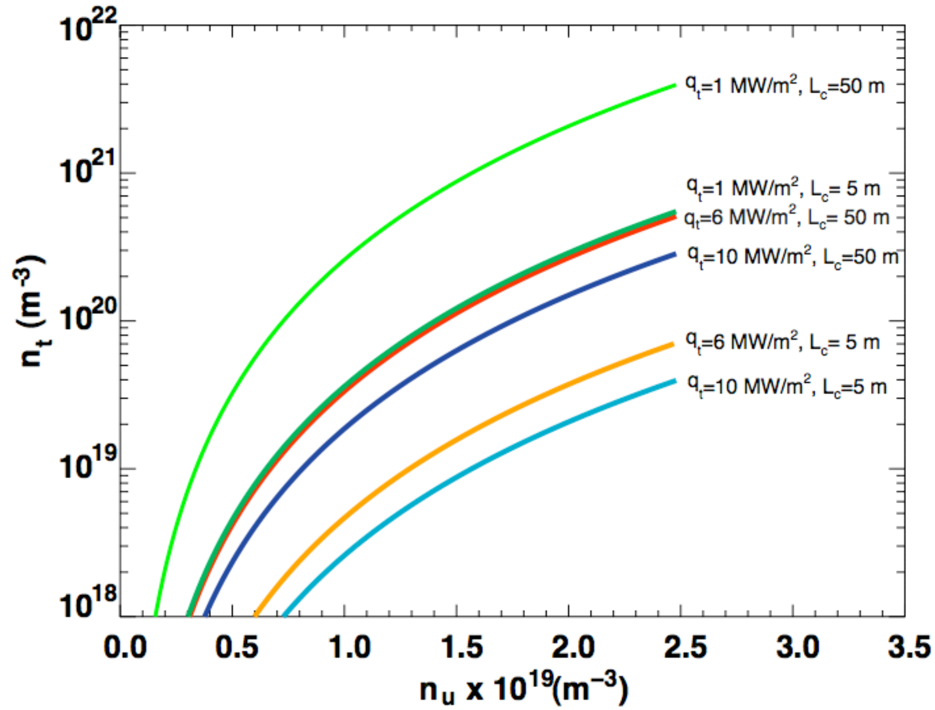




- H-mode LSN equilibrium used
- UEDGE diffusive transport model
- Impurities included
- Outer n_e, T_e profiles matched, Dα and IRTV not matched
- For guiding purposes only

2PM suggests detachment of inner divertor





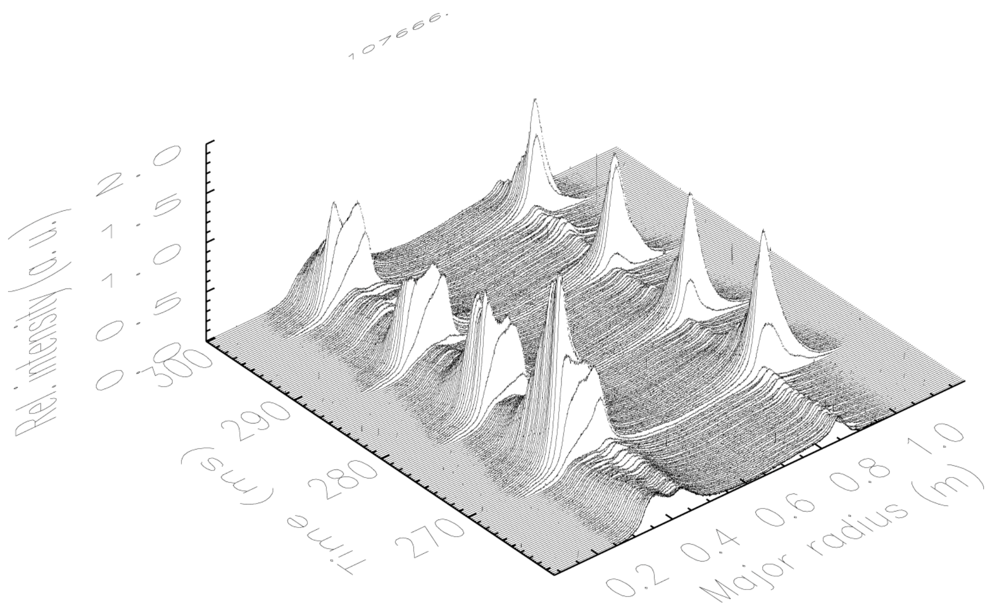
$$2\, n_t\, T_t = n_u\, T_u$$

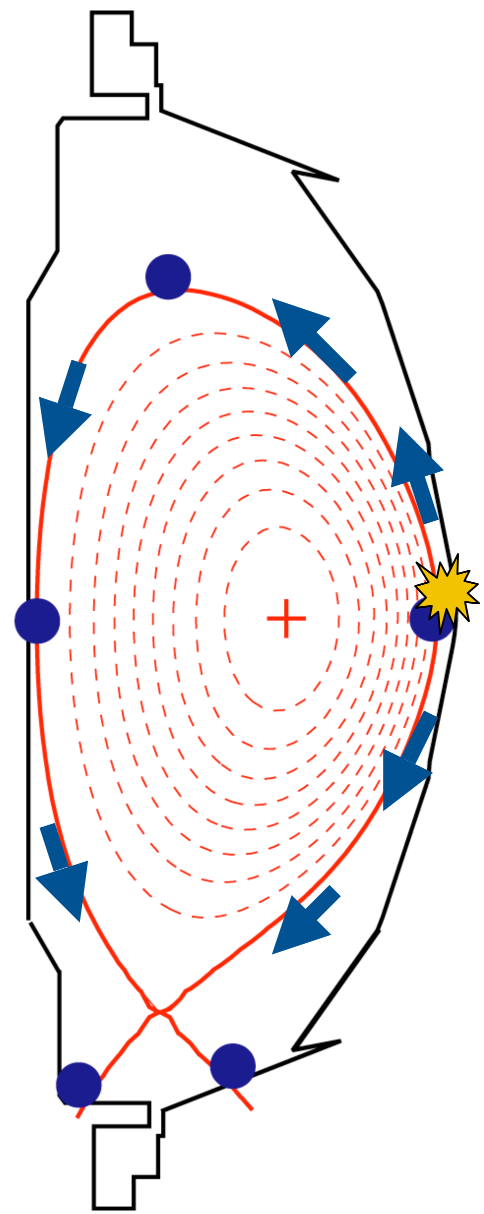
$$T_u^{7/2} = T_t^{7/2} + \frac{7}{2}\,\frac{q_{||}\, L_c}{\kappa_0}$$

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

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

SOL response to ELMs

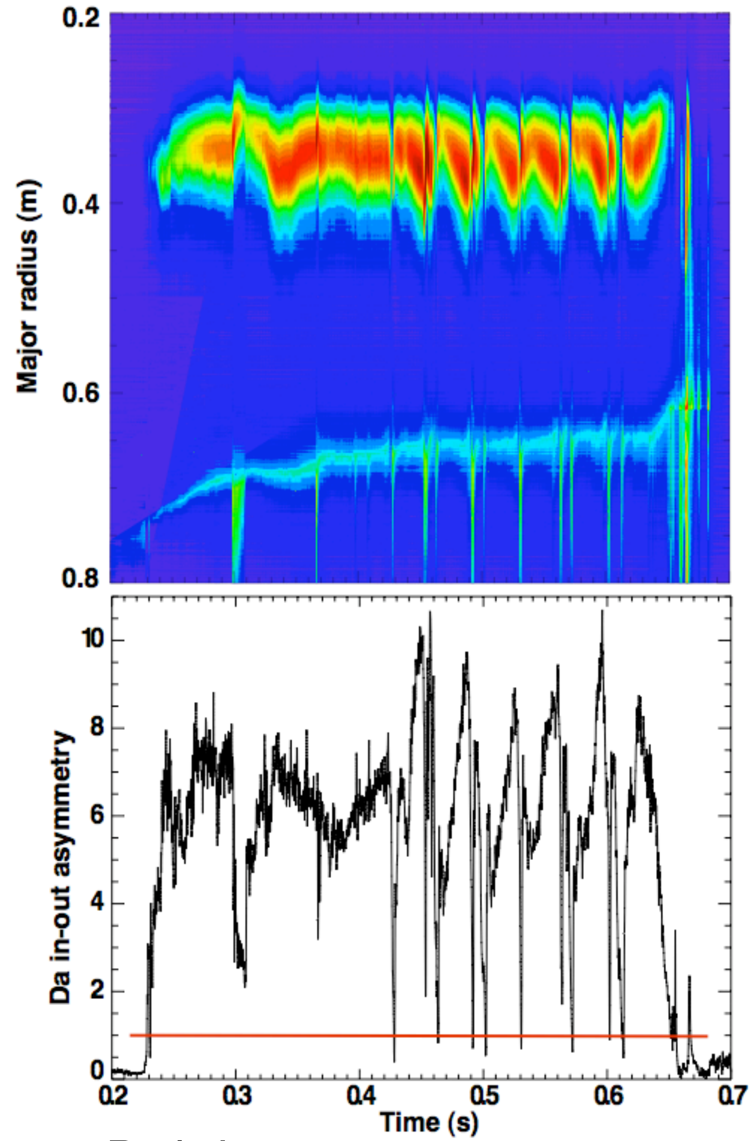




- *Attached* inner divertor D_α always lags behind outer divertor D_α by 200-400 μs
- Analysis in progress - look at many ELM arrival times at several locations ( ), develop self-consistent picture (n_e, n_i, ν^*, $L_{||}$)
- ELM Type I propagates from outboard at $c_s=(T_{e,ped}+T_{i,ped})^{1/2}/m_i$

Divertor response to ELMs

- In ELMy H-modes:
  - Inner divertor cold and dense, often detached
  - Outer divertor always attached
- Type I ELM heat pulse burns through inner leg plasma and causes transient inner leg re-attachment
- Type III, V ELMs do not change divertor state
- Need to correlate fast C III, D_α data with divertor and midplane probes



Lower divertor D_α brigtness

Summary

• Present analysis of heat and recycling fluxes in L- and H-mode plasmas suggests that the inner divertor operates in a detached state in $n_e > 2 - 3 \times 10^{19}$ m^{-3} ($0.2 < n_e/n_G < 0.9$), $P_{in} = 2 - 6$ MW LSN PF2L and PF1B plasmas, whereas the outer divertor is always attached

• The outer divertor is in the sheath-limited (linear) and flux-limited (high recy. regime) regime

• Inner divertor transiently re-attaches when Type I and Type III ELMs reach the divertor, and shows resiliency to Type V (small) ELMs

• Stationary heat loads up to 10 MW/m^2 measured in outer divertor, and about 1 MW/m^2 in inner divertor

• High in-out D_α asymmetry is observed as a result of complex interplay of proximity of vertical CS wall, cold dense recombining plasmas and opacity effects

• High neutral pressure is measured in divertor, divertor compression is 5 -10

• MARFEs are often observed on inboard side

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

NSTX fueling

- Gas injection: low field side (LFS, top + side) and high field side (HFS, midplane + shoulder). D_2, He, injected at S = 20 - 150 Torr l /s.
- Neutral beam injection system: three beams, 80 - 100 keV, 6 MW, fueling rate: S < 4 Torr l / s
- Supersonic gas injection (near future) S = 30 - 150 Torr l / s

NSTX wall conditioning

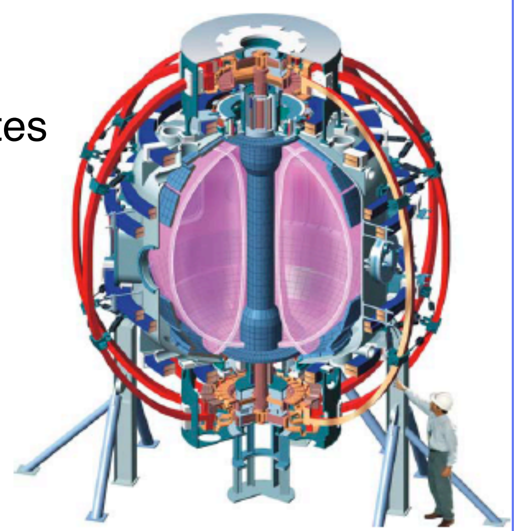
- Between shots He GDC, He conditioning plasmas
- TMB and Plasma TMB

NSTX pumping

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