XP520: Divertor regimes and divertor detachment in NBI-heated plasmas

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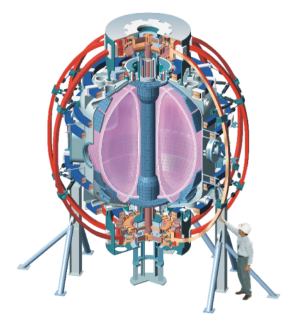

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Motivation for XP 520

- 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 complex interplay of parallel transport, atomic physics, plasma surface interactions
- Do ST magnetic geometry effects matter, or is it just the NSTX open divertor effect?
- Determine divertor regime mapping in the operational (P_{in}, n_e) space
- Obtain divertor data for ITPA participation

Scope of XP 520

• Aim of XP is a specific result - use two techniques to change density and edge rad. power 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

• Much improved diagnostic set for detachment studies in FY05:

tile Langmuir probes, D_{α}, D_{γ}, C III divertor cameras, high *n* Balmer series Stark broadening measurements (divertor T_e, n_e)

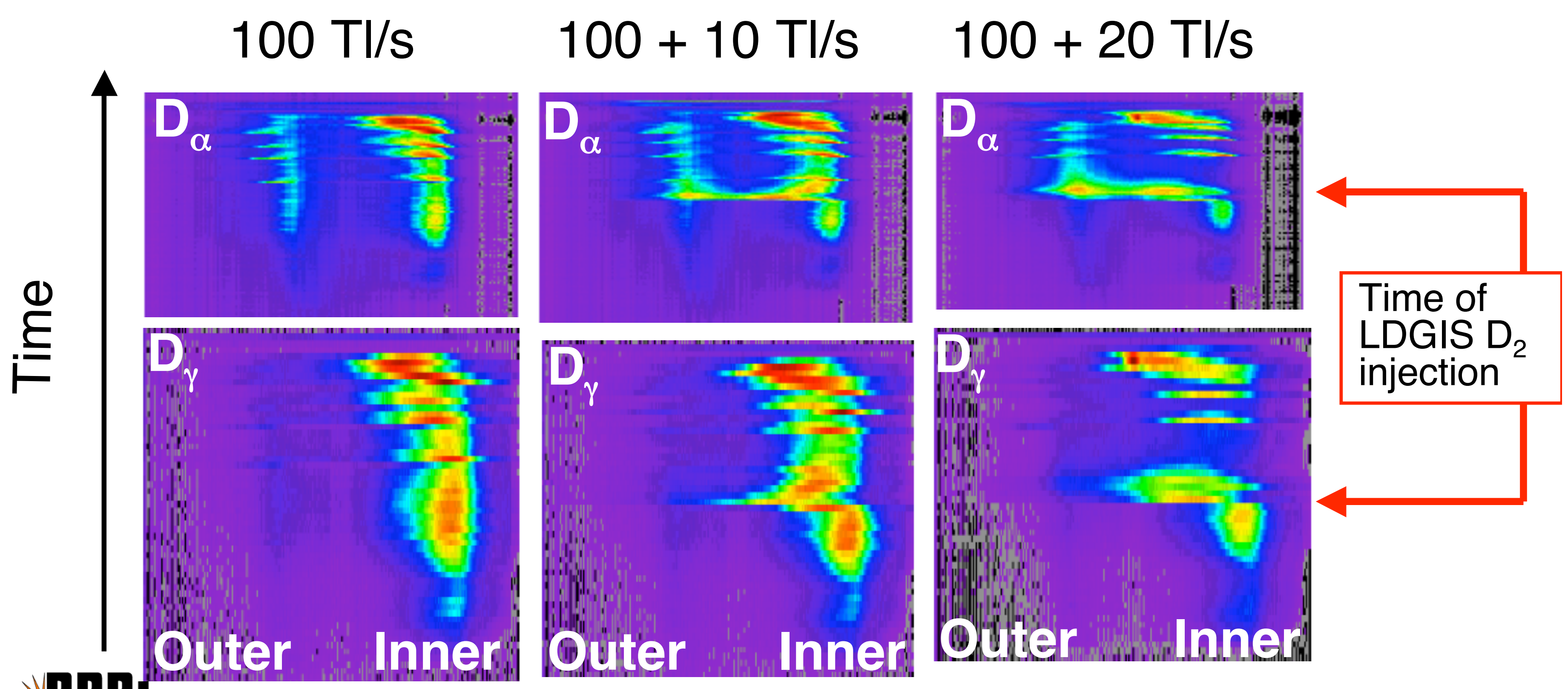
• XP 520 is a good candidate for reversed B_t campaign

FY'04 status

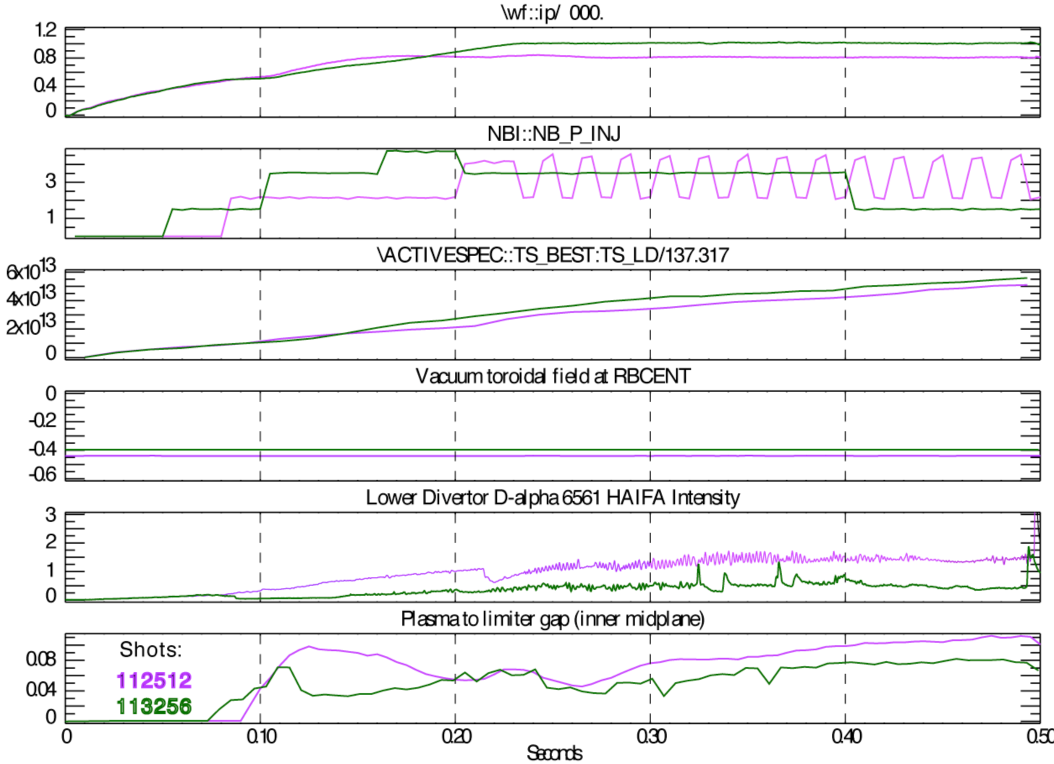
- XP-438 "Divertor regimes and divertor detachment in NSTX" was approved in FY04. Ran 8 shots.
- Due to TF coil safety restrictions, ran B_t=0.3 T, I_p= 0.6 MA short plasmas, suffered from IREs
- Reduced the scope of XP to a crude D_2 injection scan from 40 to 120 Torr l / s
- Despite P_{in}=2.5 MW (2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

Divertor detachment experiment started

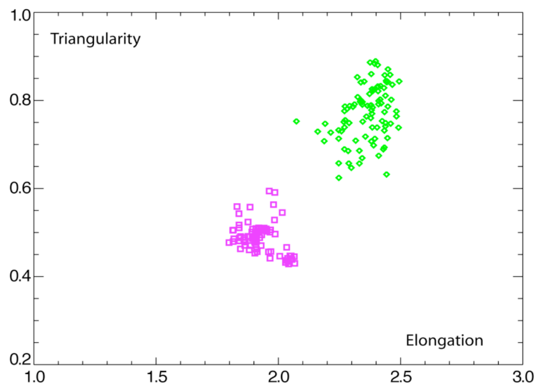
- Used PF2L shape, 4 MW NBI L-mode at $B_t = 0.3$ T
- Injected D_2 in LFS midplane and PFZ regions at 20 - 120 Torr l / s
- Concluded inner divertor detachment from D_γ/D_α ratio
- Inner divertor detachment threshold in $\langle n_e \rangle$, P_{in} is low
- No sign of volume recombination (D_γ/ D_α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



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

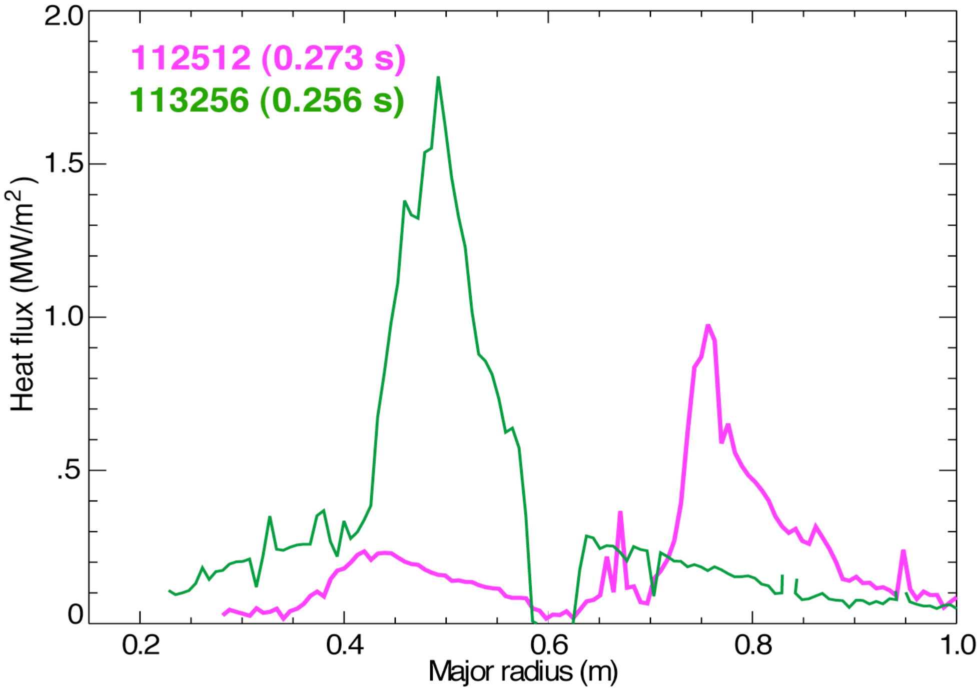


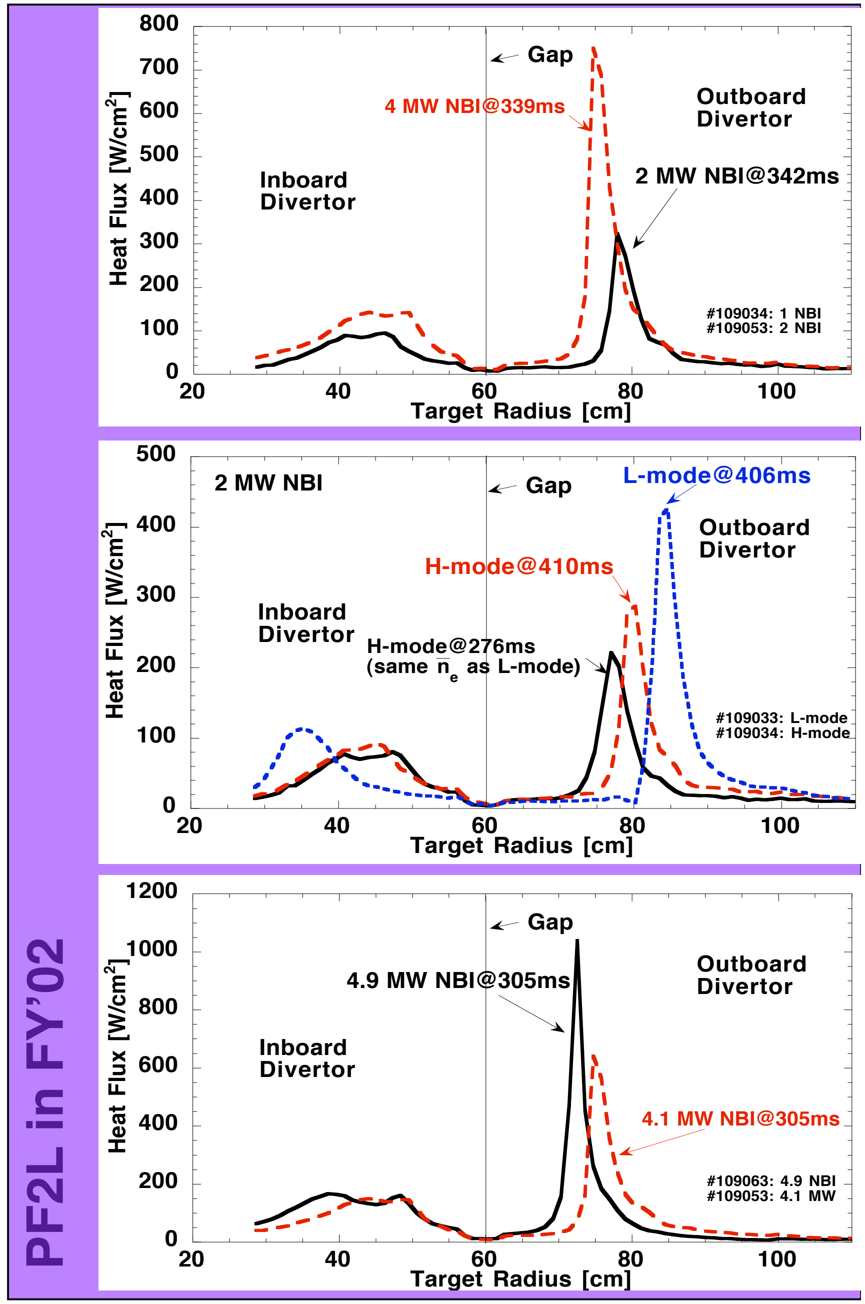
	109033 (PF2L)	113256 (PF1B)
κ	1.85	2.40
δ	0.47	0.74
Drsep (cm)	-1.8	-1.0*
q_{edge}	13	9.5
$L_{\|\|}$, inner (m)	16.4	19.5
$L_{\|\|}$, outer (m)	10.0	12.5
M (Mirror ratio)	5.0	4.2
f inner (Flux expansion)	2.1	5.0
f outer (Flux expansion)	3.2	2.1



- 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

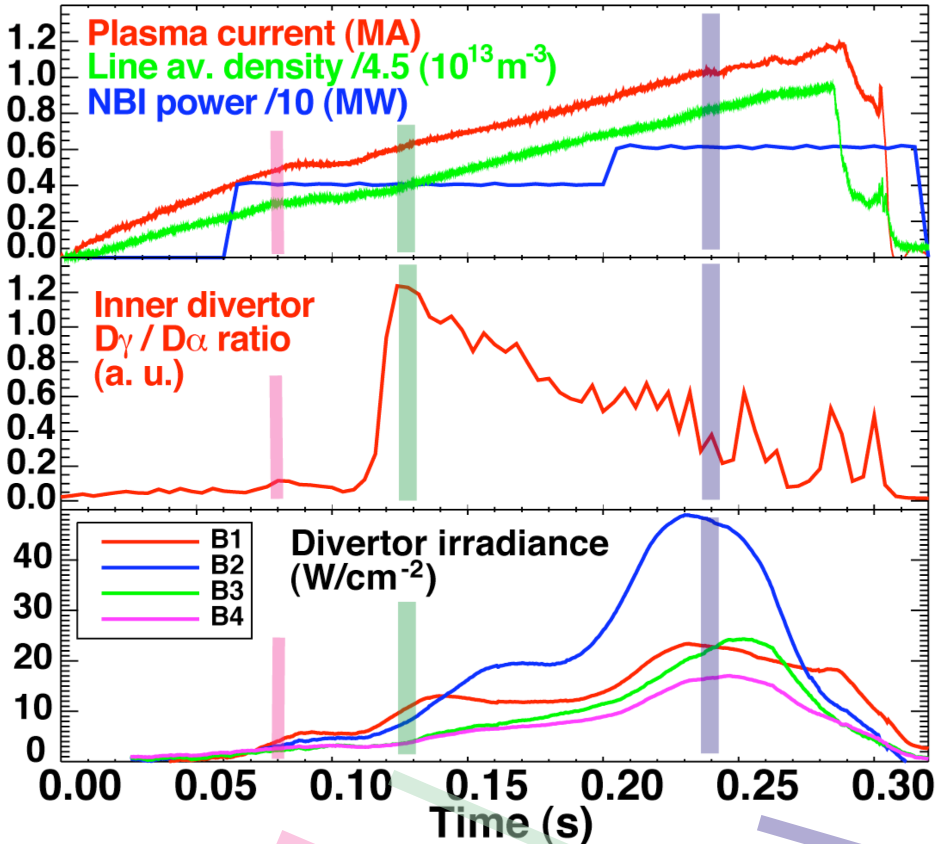




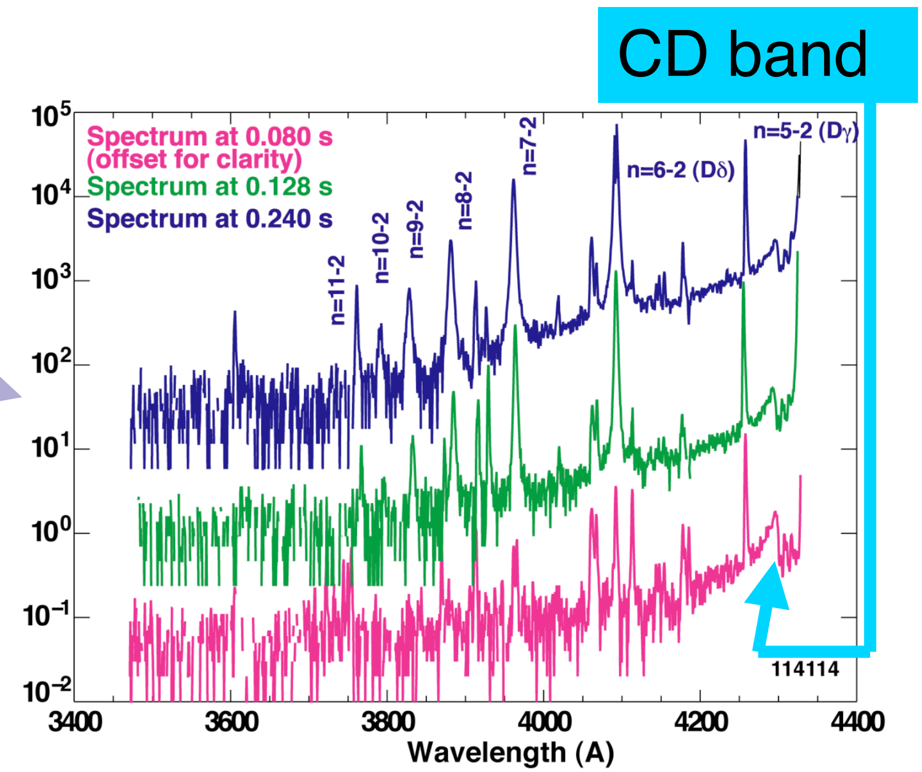
In PF2L plasmas:

- 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

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

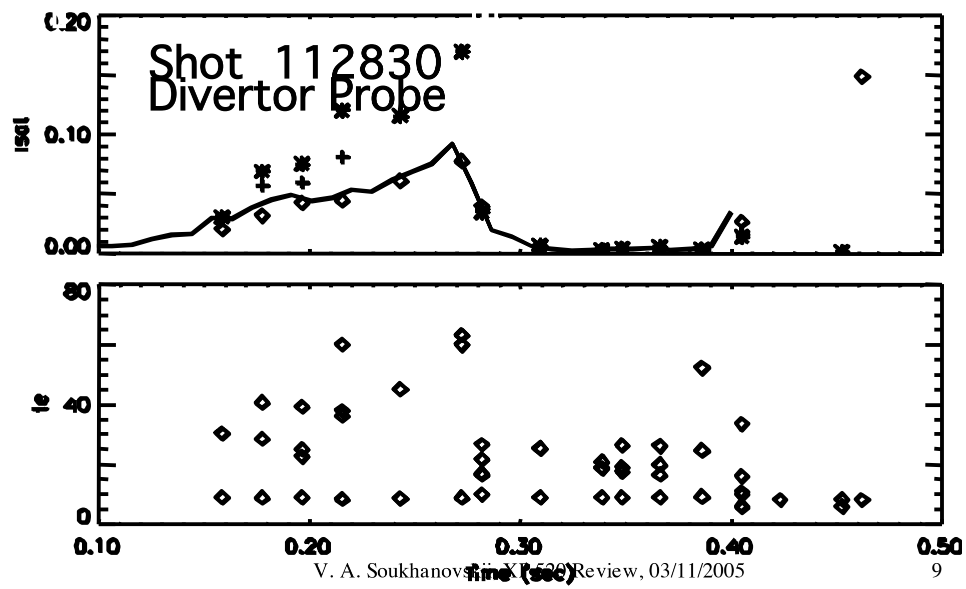


Appearance of Stark broadened high n Balmer series lines indicate:

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

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 - 40 eV
  - SOL collisionality ν^* = 0.5 - 100 (mostly 10 - 60)
- Divertor T_e = 5 - 40 eV
- If midplane T_e = 5 - 20 eV then the very weak $dT_e/dx_{||}$ raises 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)

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Experiment plan

- Use PF2L LSN discharge with I_p = 0.8 MA, B_t=0.45 T, 2 NBI src, LFS fueling from Injector # 2 (for density control), LDGIS, Injector # 3 for neon
- High flow diagnostic injector (Bay B) will be used for edge turbulence measurements in “radiative mantle” plasmas (R. Maqueda)
- Setup an L-mode NBI-heated discharge, Elongation κ = 2.0, Triangularity δ = 0.5 (2 shots)
- Inject D_2 in increasing quantities from Injector # 2: 40-100 Torr l / s (5 shots)
- Attempt to raise density further by adding LDGIS, Injector 1 and/or CS injector (10-15 shots)
- Use an intermediate density (3-5 x 10^{19} m^{-3}) good shot from above and add injections of neon in increasing quantities (1 - 20 Torr l / s, duration 50 - 200 ms) to obtain P_{rad} / P_{in} = 0.5 (10-15 shots)
- SGI may be used instead of Inj # 2 if adequate results come from XP516

Future work

- Reversed B_t experiments - role of drifts and flows
- 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
- Radiative divertor scenarios in long high power density H-mode plasmas

Backup

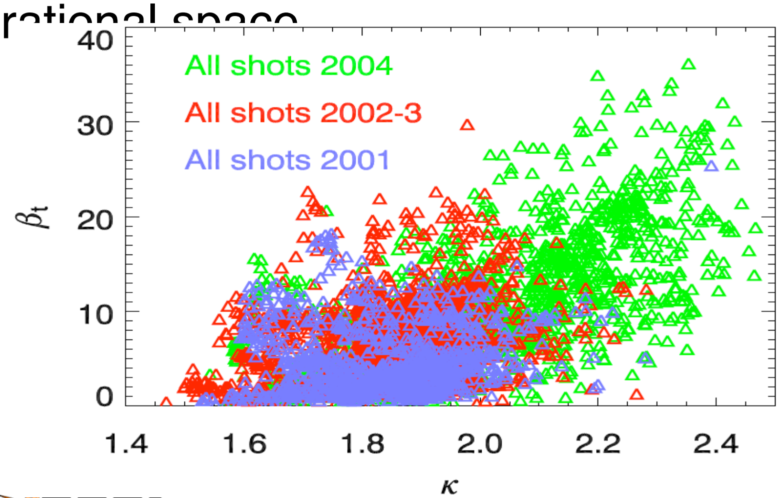
- Slides from APS 2004 poster

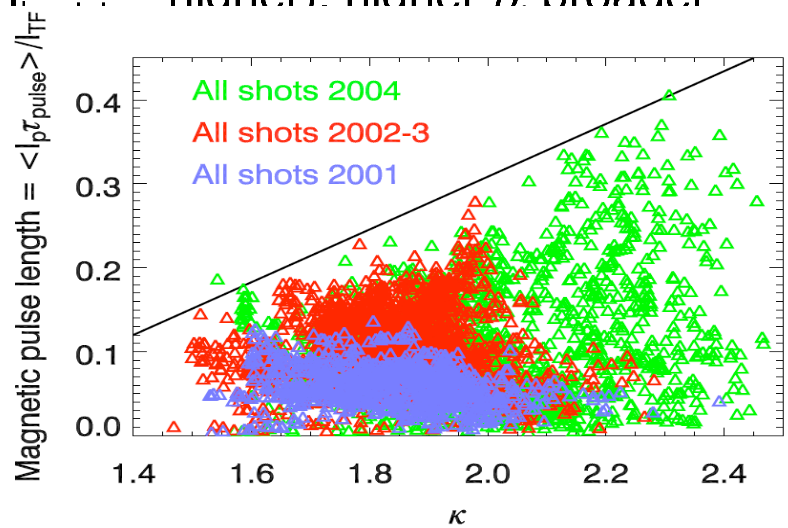
Analyze SOL / divertor properties in ST plasmas

- 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

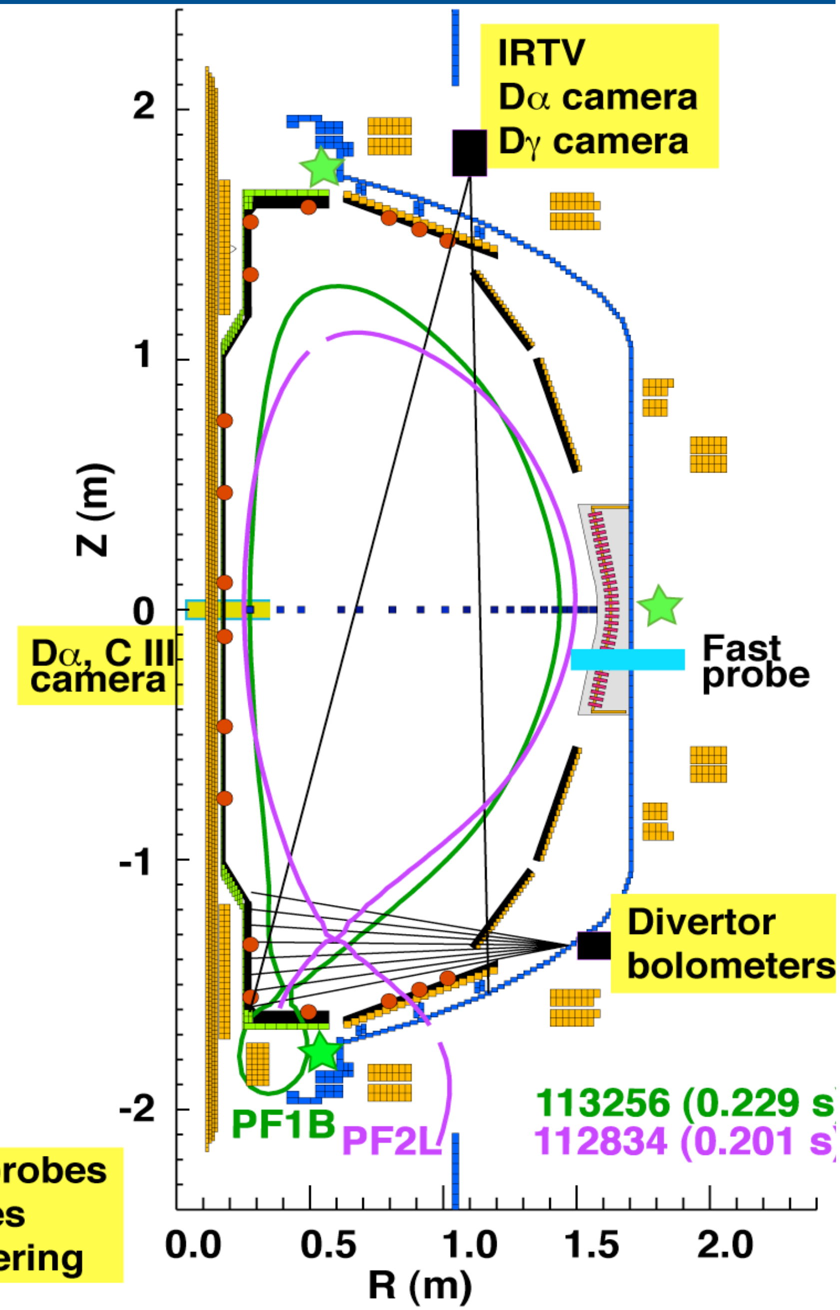
- Analyze SOL / divertor properties in plasmas with two common magnetic equilibria:
  - **PF2L** shape - H-mode physics (access, threshold), transport
  - **PF1B** shape - high β high performance long pulse, transport and H-mode
- NSTX has developed sustained high elongation high triangularity H-mode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





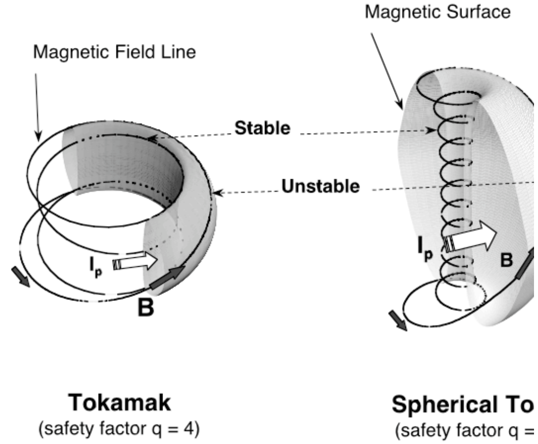
SOL / divertor diagnostics improved in FY'04

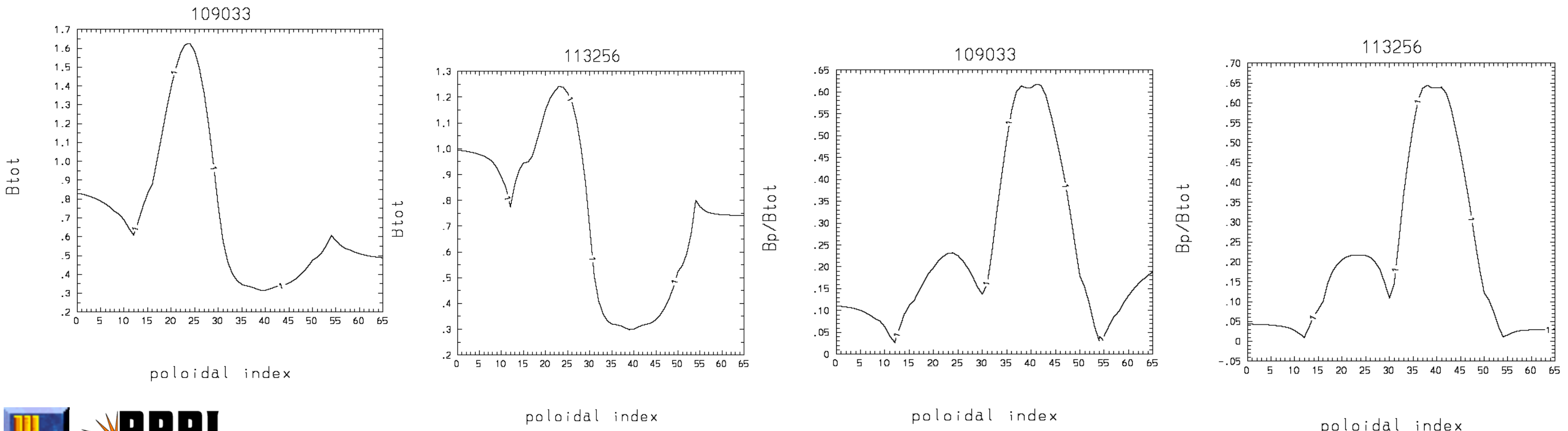
- **IRTV**: two Indigo Alpha 160 x 128 pixel microbolometer cameras, 7-13 μm range, 30 ms frame rate
- **D_α, D_γ, C III filtered cameras**: four Dalsa 1 x 2048 pixel CCDs, filter FWHM 10-15 A, frame rate 0.2 - 1 ms
- **Neutral pressure gauges**: four microion gauges on top and at midplane, two Penning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



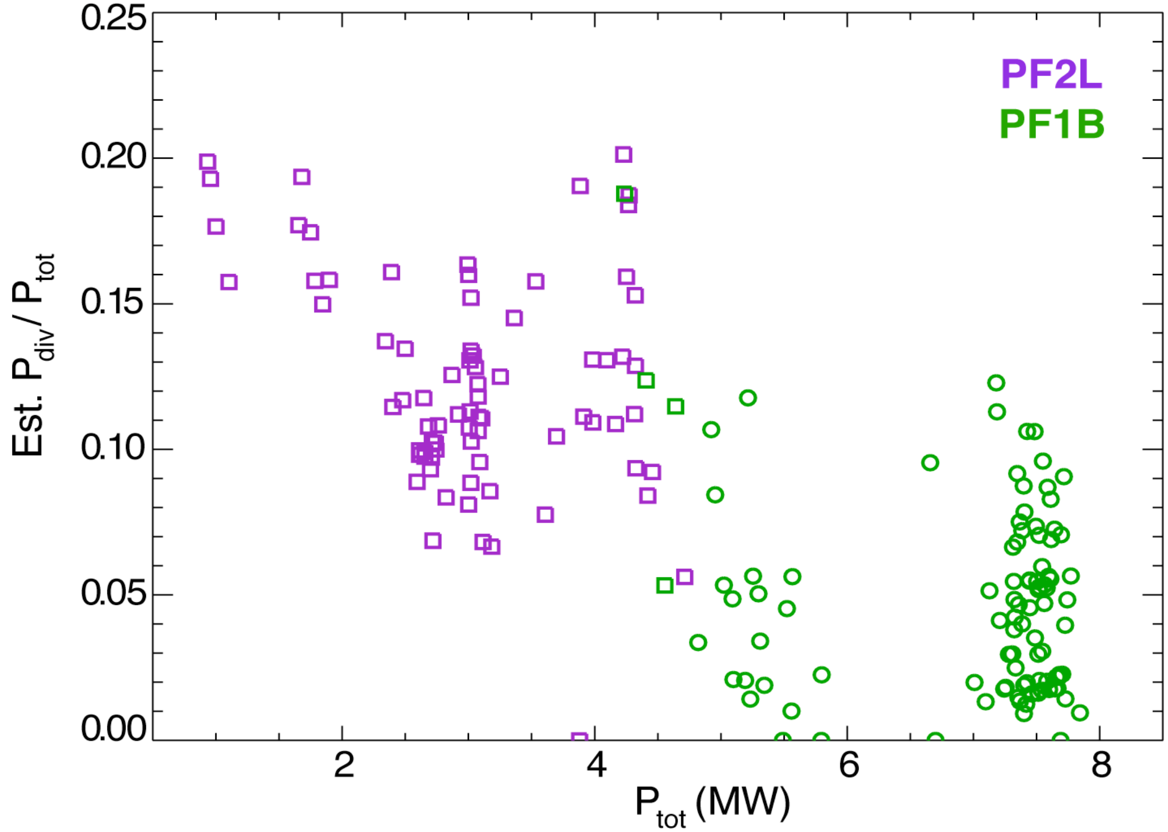
ST effects in SOL and divertor may lead to different physics

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



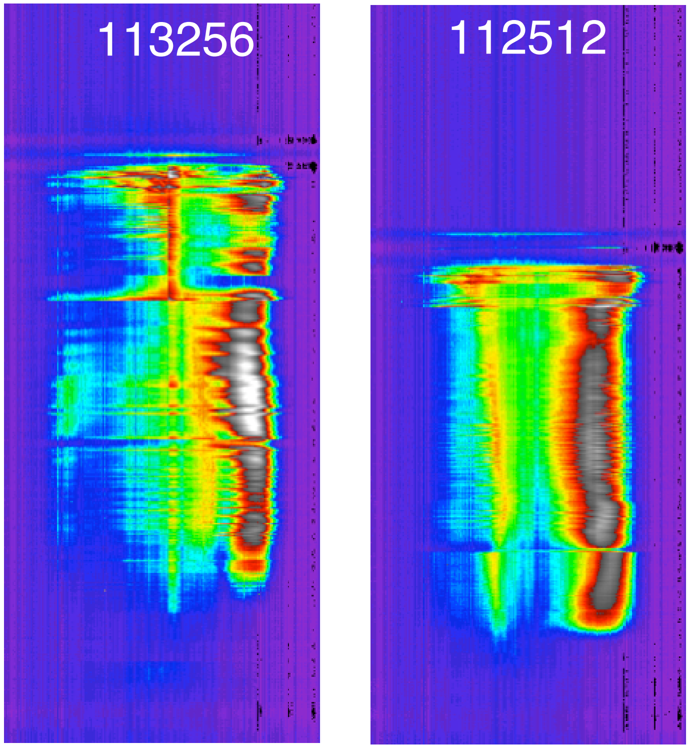


Divertor P_{rad} is similar in PF2L and PF1B shapes

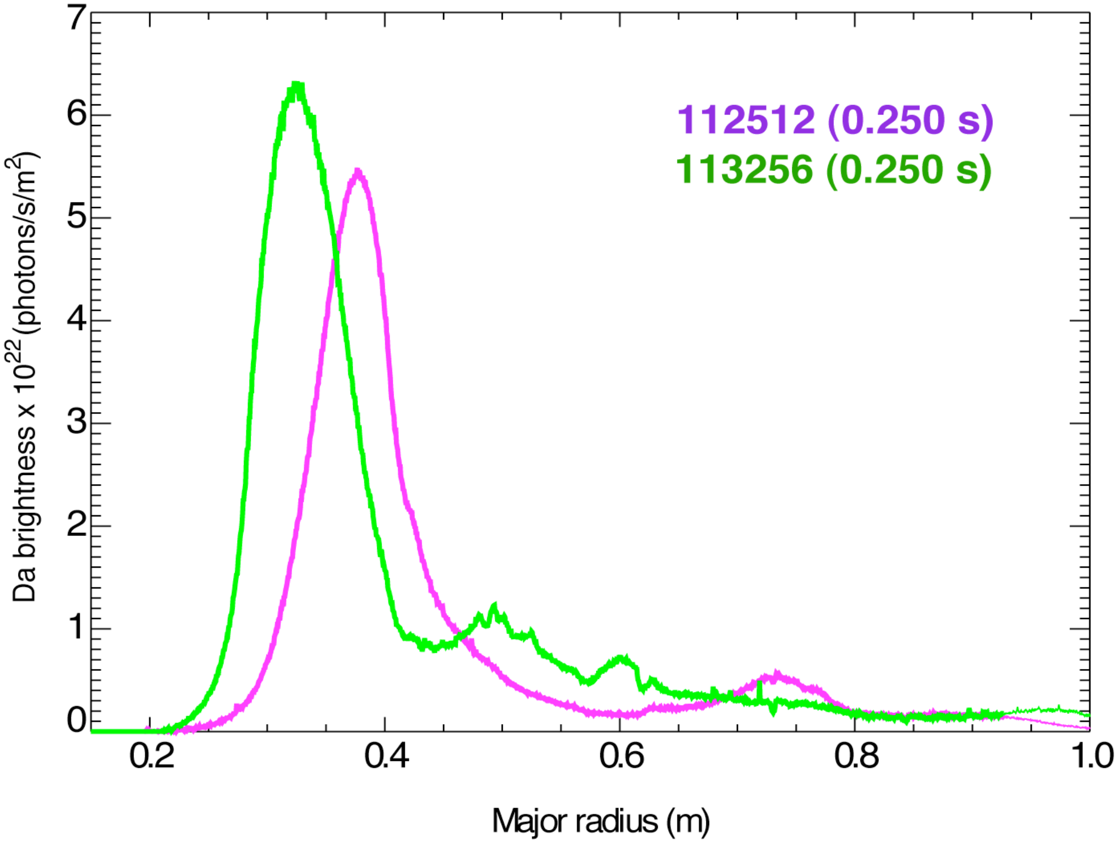


- Analyses is based on plasma emissivity estimate from divertor bolometers
- Effective divertor volume in PF2L shape is 3-5 higher than in PF1B
- Accurate comparison and power accounting is only possible through 2D modeling
- Power balance studies in NSTX - S. F. Paul et. al., Poster JP1.010

Divertor D_α in-out asymmetry is high



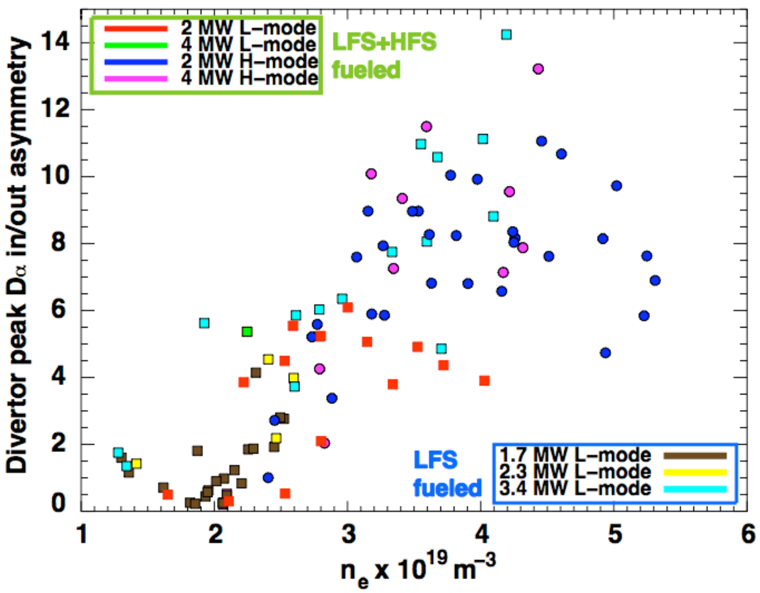
Divertor D_α - space vs time



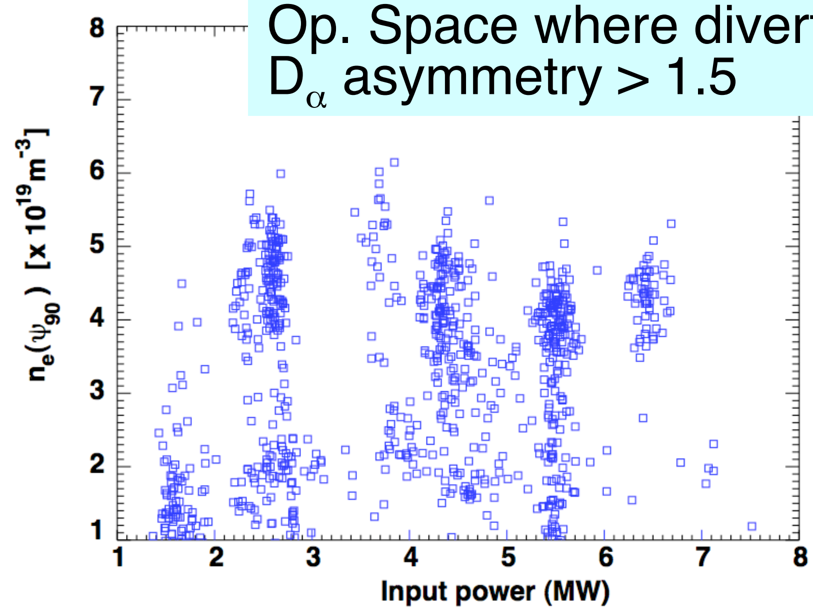
- Recycling in PF2L and PF1B occurs in different div. regions
- Asymmetry is weakly dependent on R_{Xpt}
- Both inner and outer D_α brightness are line-av. n_e dependent

Divertor in-out asymmetries

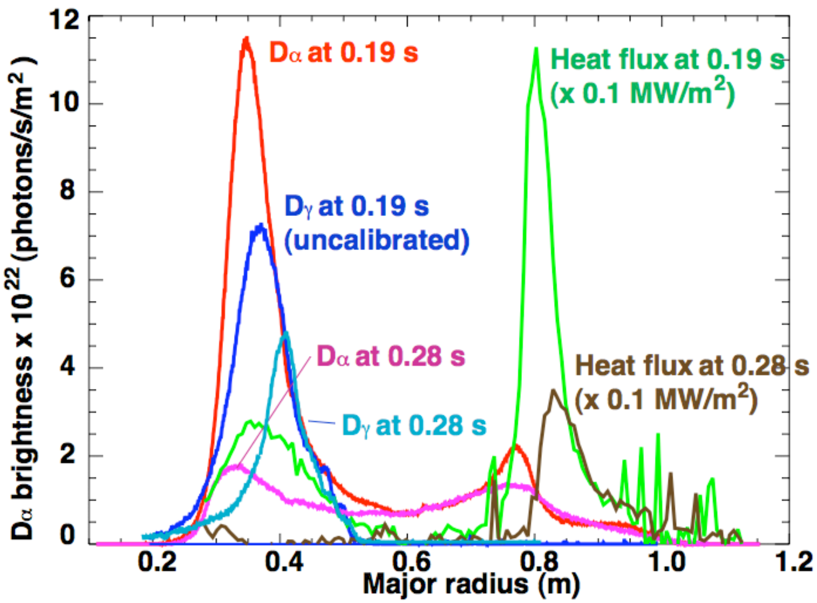
- Heat flux asymmetry always $q_{out}/q_{in} > 1$, consistent with
  - SOL area factor: $A_{out} = (4.0 - 4.5)\ A_{in}$
  - Magnetic flux expansion factor (mid/div): $f_{in} > f_{out}$
- D_{α} asymmetry (particle flux / recycling) is observed through most of op. space
  - Density and power dependent
  - 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)

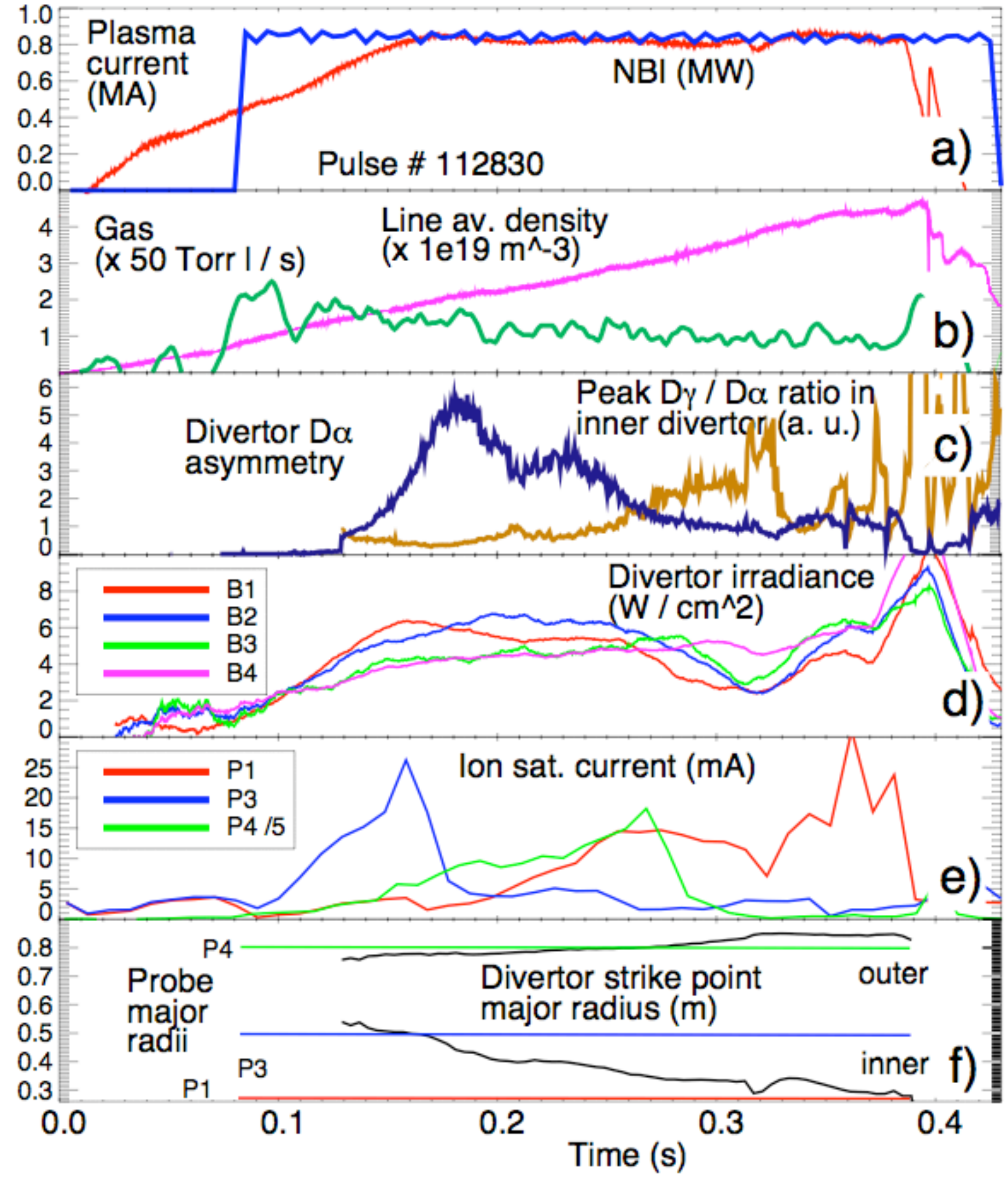


Op. Space where divertor D_{α} asymmetry > 1.5



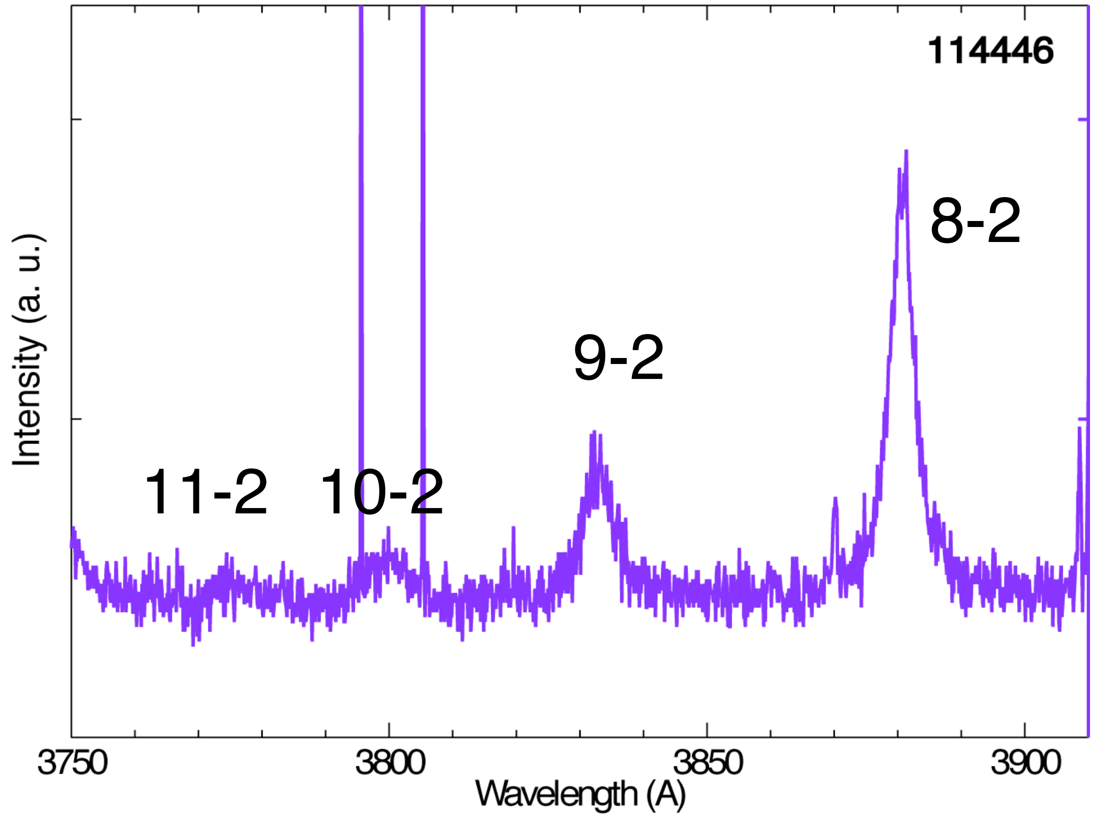
Inner divertor cold / detached in PF2L shots

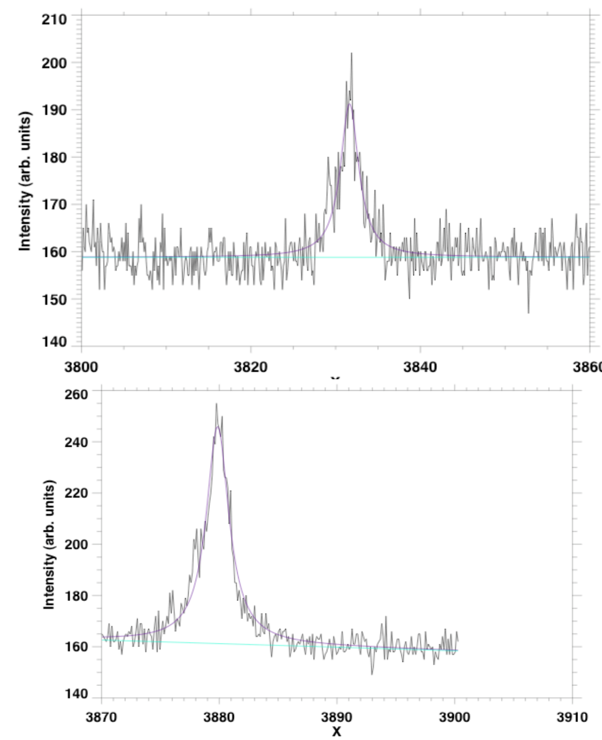




- 1 NBI src L-mode
- Inner divertor detached at $\langle n_e \rangle$ = 2.5-3 x 10^{19} m^{-3}

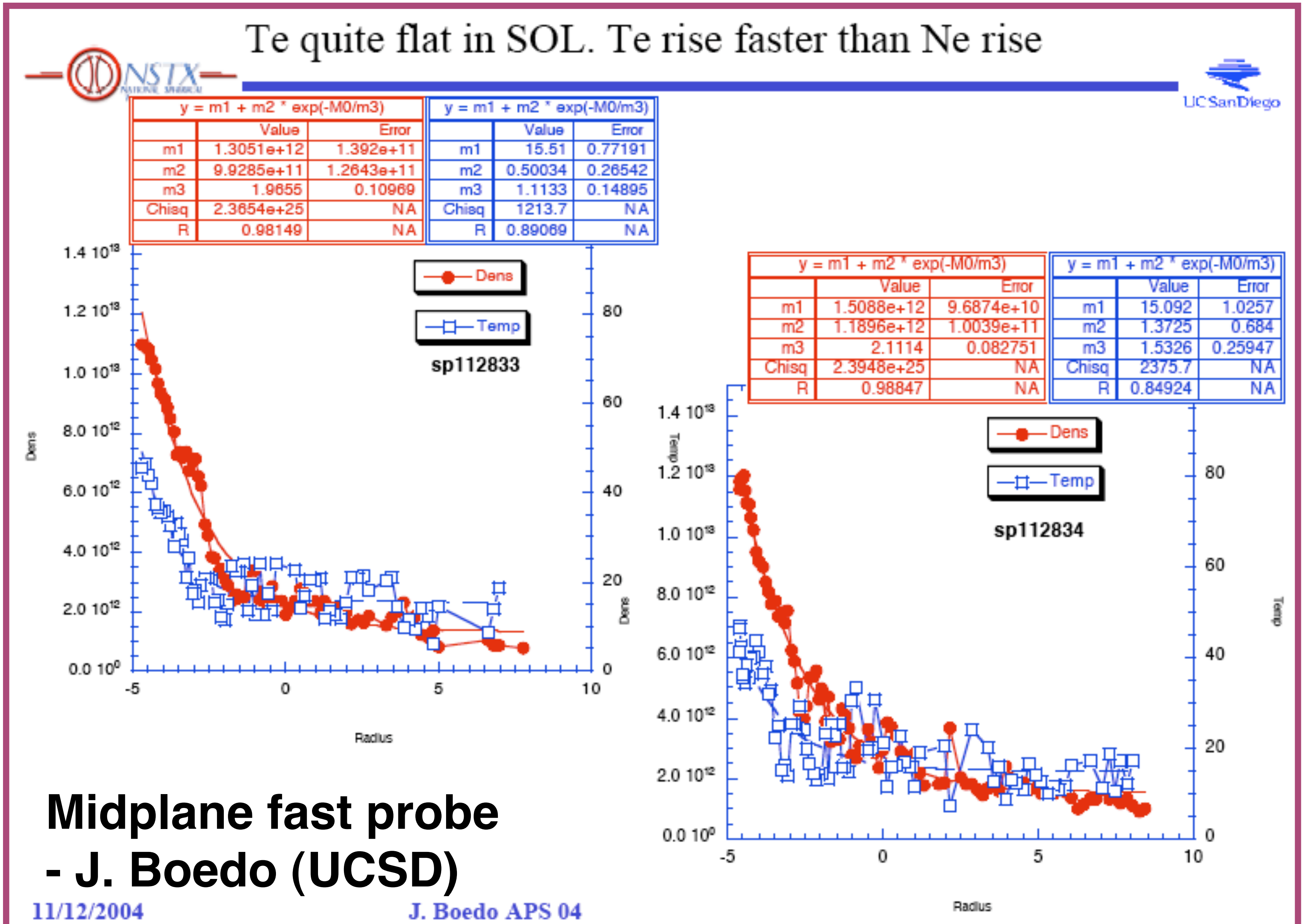
Stark broadening of Balmer lines yelds high n_e





- Do not observe photorecombination continuum edge - probably due to high core bremstralung background and spectrometer/fiber sensitivity fall-off
- 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

Flat T_e, n_e in outer midplane SOL in PF2L shots



sp112833 (density fit):

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

sp112833 (temperature fit):

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

sp112834 (density fit):

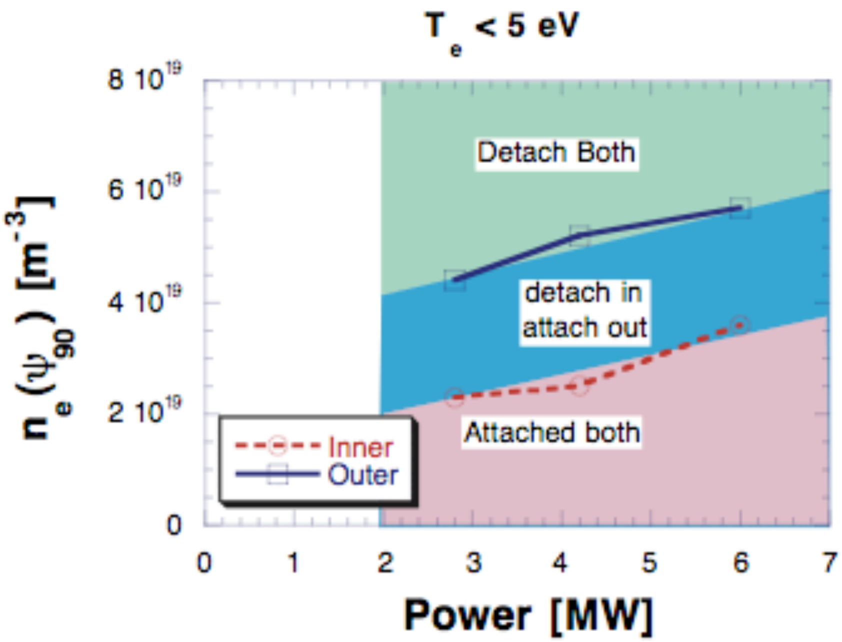
y = m1 + m2 * exp(-M0/m3)	Value	Error
m1	1.5088e+12	9.6874e+10
m2	1.1896e+12	1.0039e+11
m3	2.1114	0.082751
Chisq	2.3948e+25	NA
R	0.98847	NA

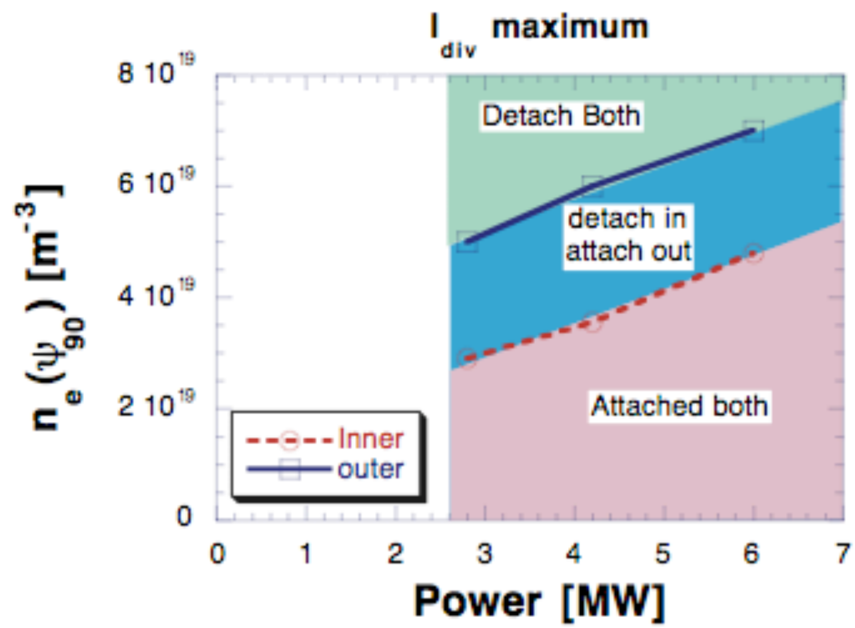
sp112834 (temperature fit):

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)

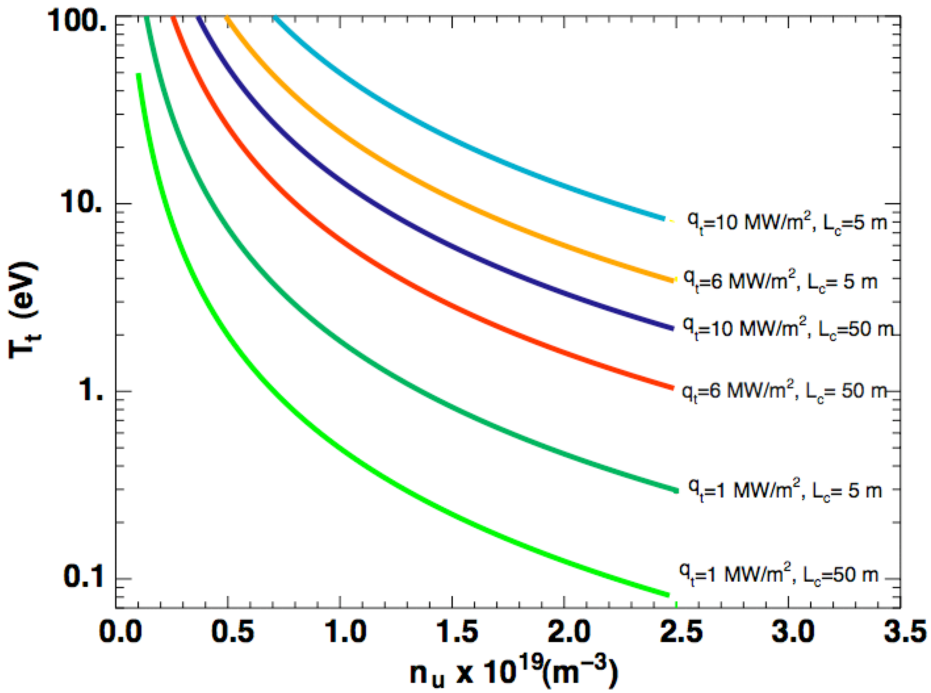
UEDGE detachment space is close to the observed

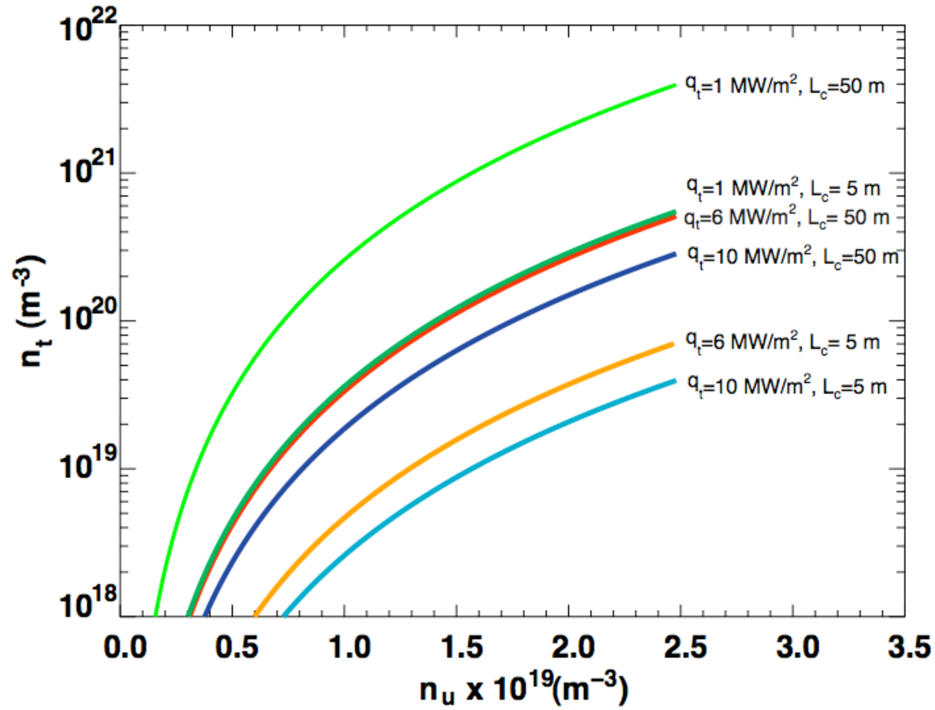




- H-mode LSN equilibrium used
- UEDGE diffusive transport model
- Impurities included
- Outer n_e, T_e profiles matched, Dα and IRTV not matched
- For guiding purposes only

2PM suggests detachment of inner divertor





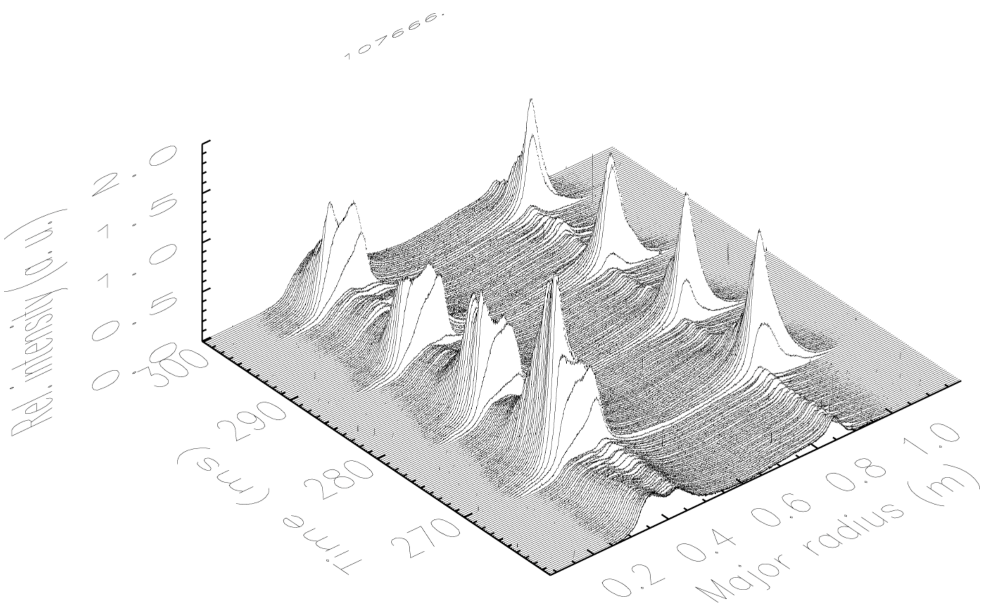
$$2\, n_t\, T_t = n_u\, T_u$$

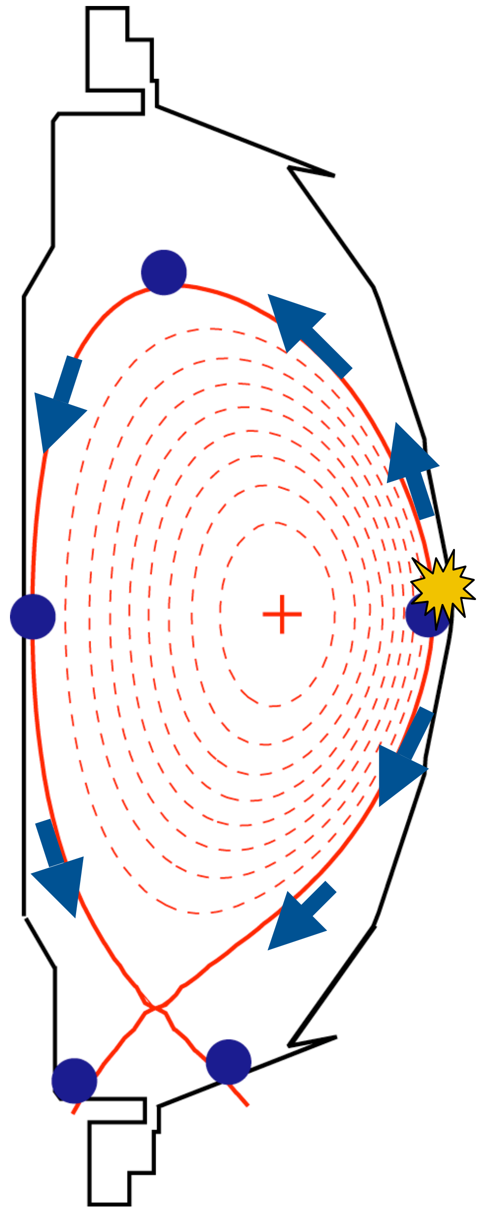
$$T_u^{7/2} = T_t^{7/2} + \frac{7}{2}\, \frac{q_{||}\, L_c}{\kappa_0}$$

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

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

SOL response to ELMs

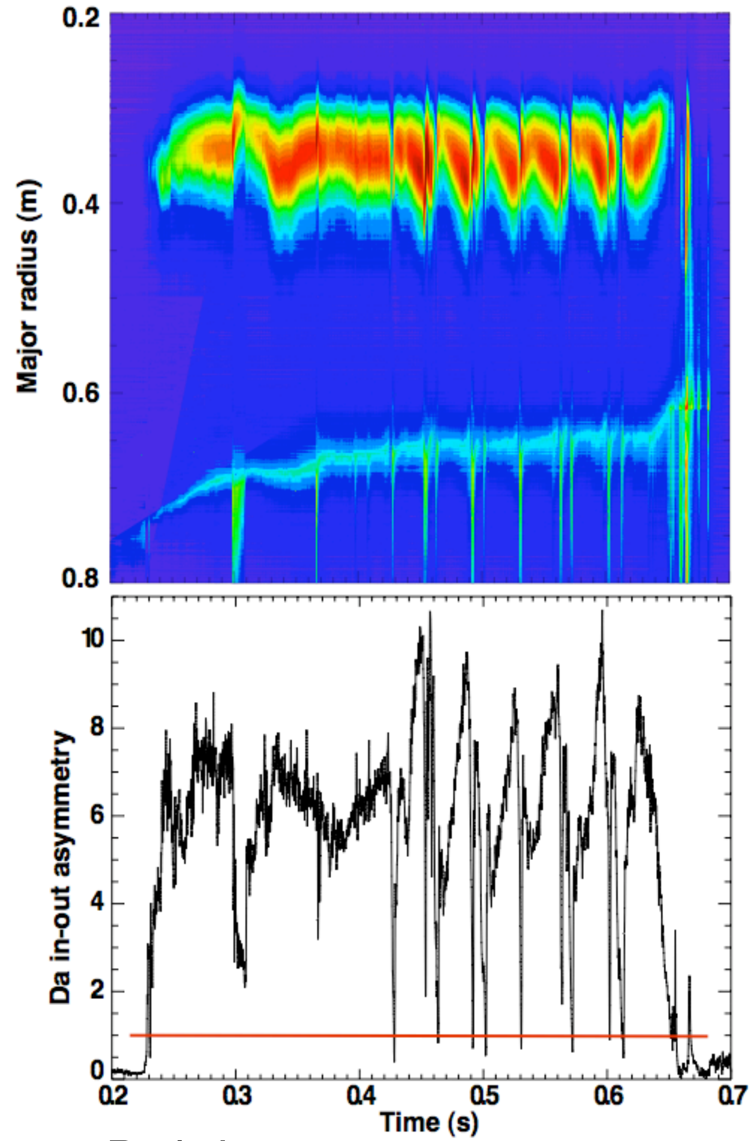




- *Attached* inner divertor D_α always lags behind outer divertor D_α by 200-400 μs
- Analysis in progress - look at many ELM arrival times at several locations (⬣), develop self-consistent picture (n_e, n_i, ν^*, $L_{||}$)
- ELM Type I propagates from outboard at $c_s=(T_{e,ped} + T_{i,ped})^{1/2}/m_i$

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

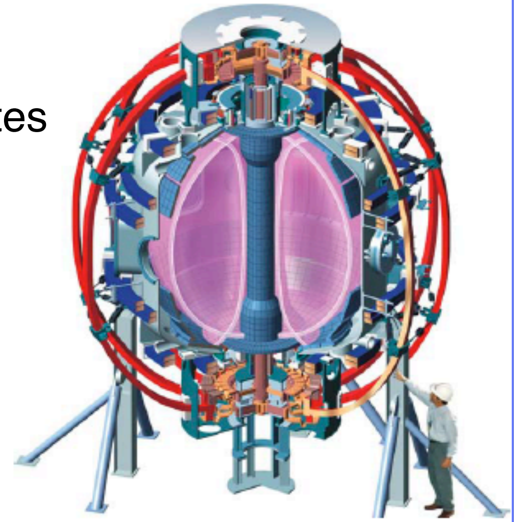
- Between shots He GDC, He conditioning plasmas
- TMB and Plasma TMB

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