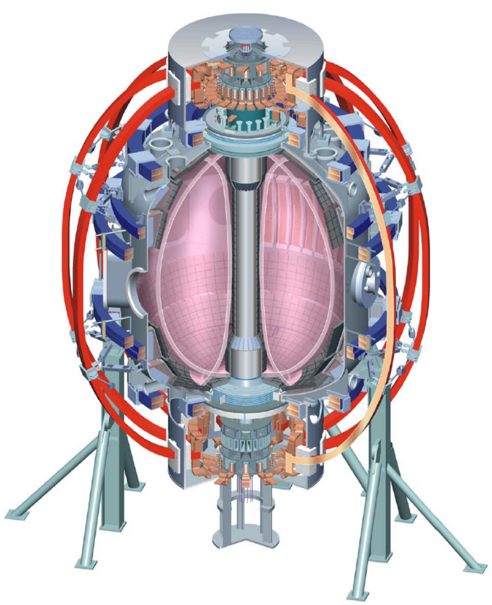
Supported by Office of Science

Dissipative divertor experiments in NSTX

V. A. Soukhanovskii, R. Maingi, C. J. Lasnier,
R. E. Bell, C. Bush, R. Kaita, H. W. Kugel,
B. P. LeBlanc, J. Menard, D. Mueller, S. F. Paul,
R. Raman, A. L. Roquemore, S. Sabbagh,
NSTX Team

47th APS – DPP Meeting
Oct 24-28, 2005
Denver, Co.

College W&M
Colorado Sch Mines
Columbia U
Comp-X
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
PSI
Princeton U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Maryland
U Rochester
U Washington
U Wisconsin



Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAERI
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

SOL and divertor physics in ST geometry are studied in NSTX

• Divertor heat load mitigation - one of key Boundary Physics issues in large aspect ratio tokamaks, more so in Spherical Tori (ST)

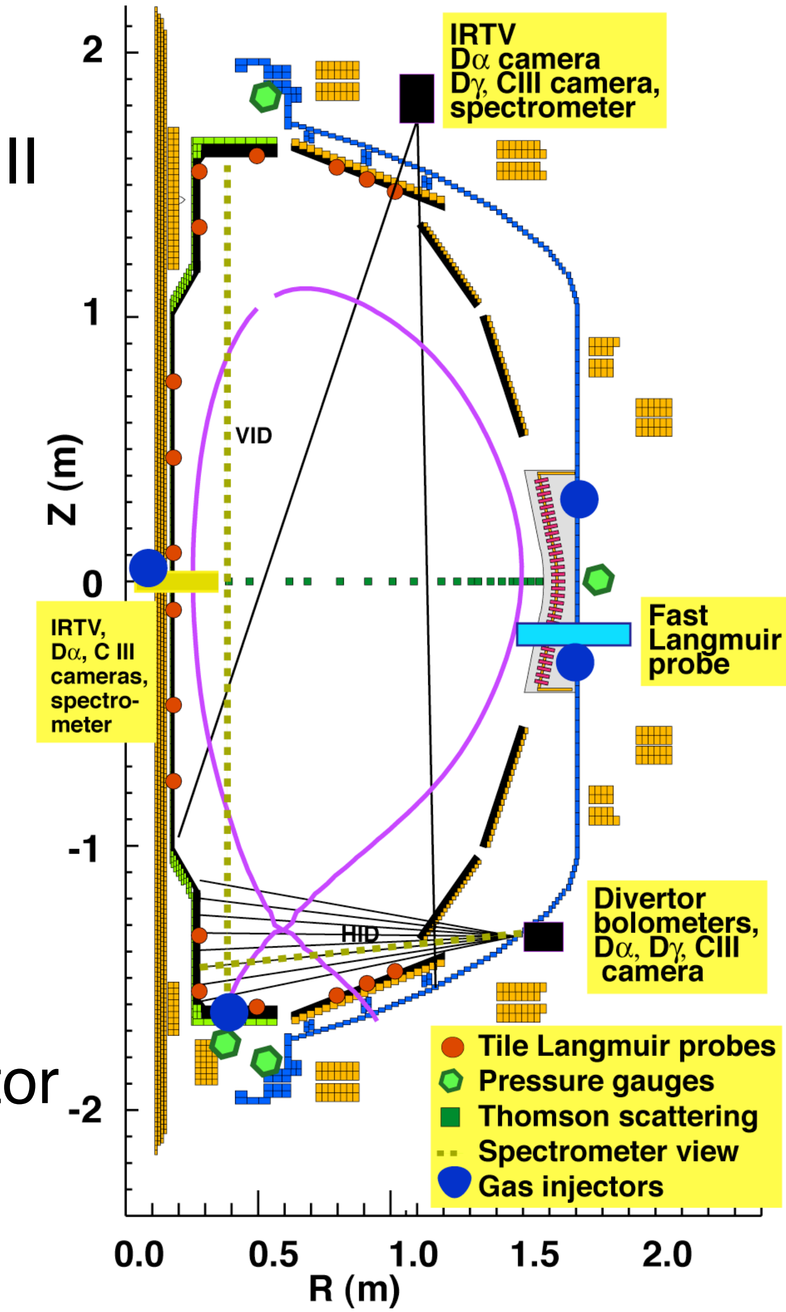
- Compact divertor - small divertor volume
- High edge q (8-20) - smaller PFC plasma-wetted area
- Typical divertor tile temperature in ~ 1 s NSTX pulses $T < 300$ C. Engineering limit is $T = 1200$ C. Long pulses will require steady-state heat flux mitigation solution

• Present focus is on divertor regime characterization and development of heat flux mitigation scenarios for plasmas with κ=1.8 - 2.5, δ=0.4 - 0.9, at low aspect ratio A = 1.35, $q_{out} < 6$ MW/m^2, $P_{in}/R < 9$

Development of NSTX diagnostic set enabled detailed lower single null divertor studies in FY05

- Divertor IRTV
- Divertor/SOL cameras with D_α, D_γ, C III filters
- Neutral pressure gauges
- Divertor UV-VIS spectrometer
- Midplane and divertor bolometry
- Divertor and Center Stack Langmuir probes
- Midplane Multi-point Thomson scattering

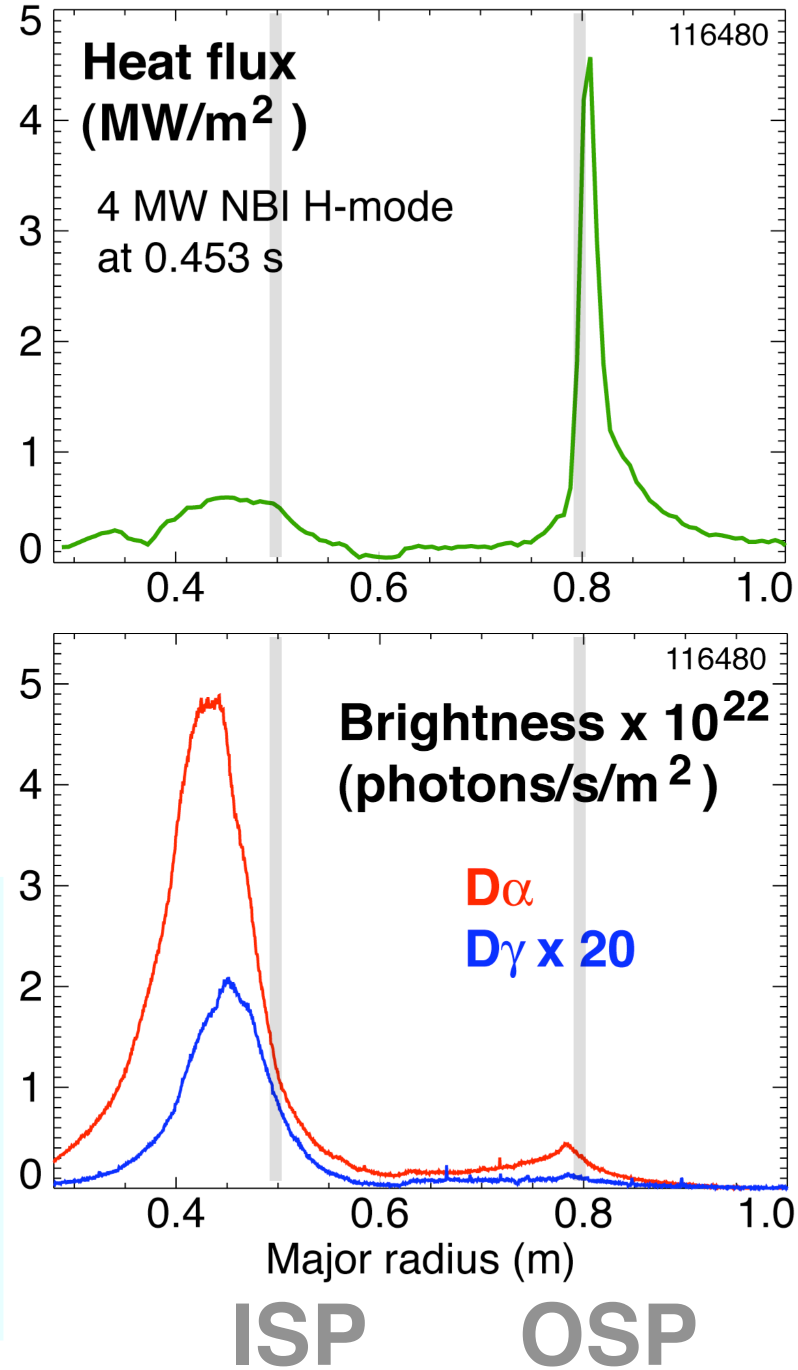
- Gas Injectors at various poloidal locations - midplane high field side (HFS), low field side (LFS), lower divertor with inj. rates $\Gamma < 10^{22}$ s^{-1}



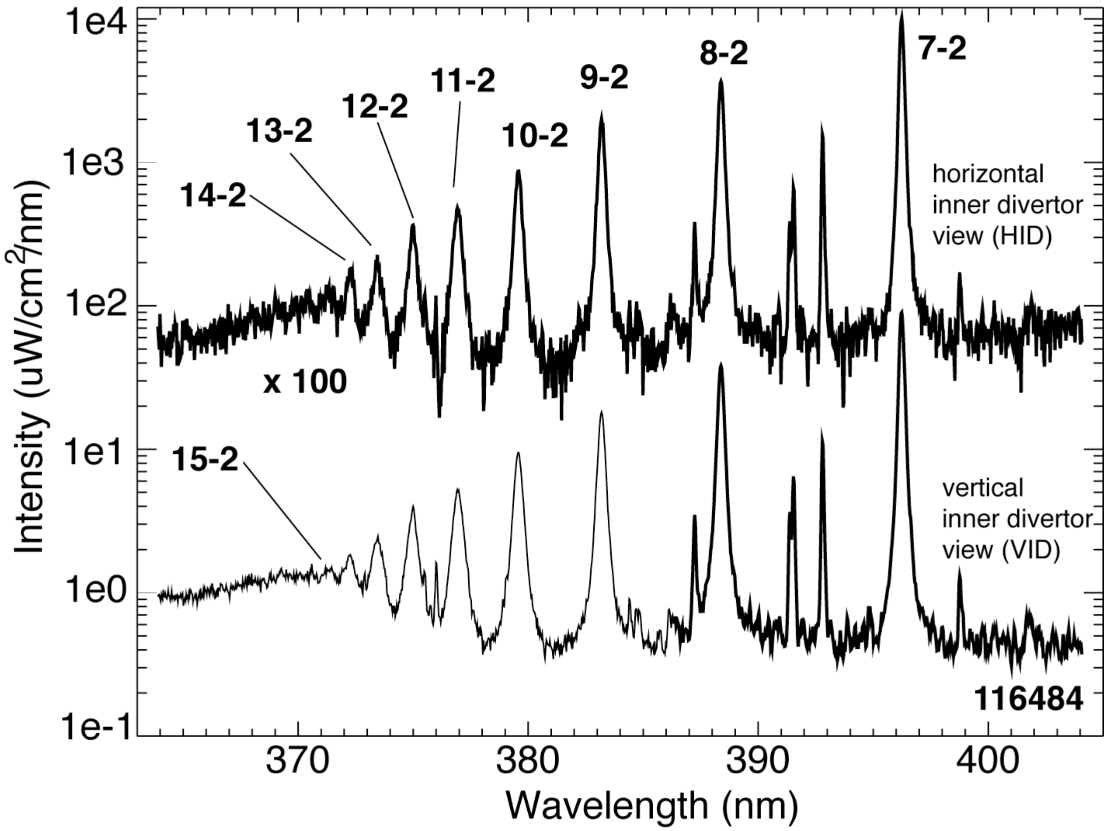
NSTX divertor regimes

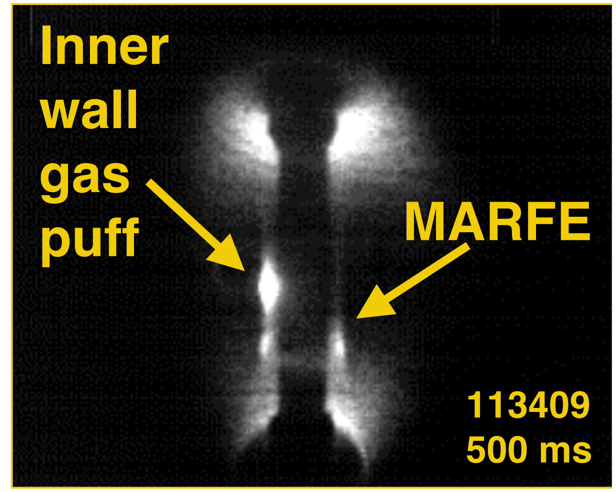
- Observations and measurements:
  - Heat flux asymmetry always $q_{out}/q_{in} > 1$, typically q_{out}/q_{in}= 2-4. Typical peak heat flux $q_{in} <$ 0.5-1.0 MW/m^2, $q_{out} <$ 2-6 MW/m^2 in 2-6 MW NBI-heated plasmas
  - Recycling in-out asymmetry up to 15 from divertor D_α profiles
  - Divertor D_γ observed in inner divertor only, typical ratio D_γ/ D_α about 0.020 - 0.030 - 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 $n_e \sim n_G$

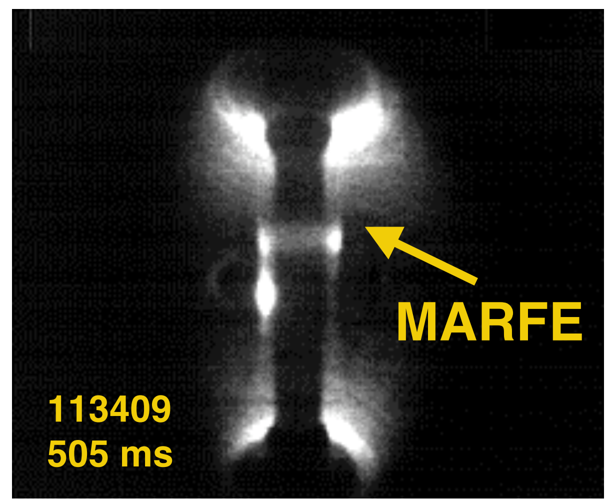


High n_e, low T_e inferred from Balmer series line emission measured in detached inner divertor



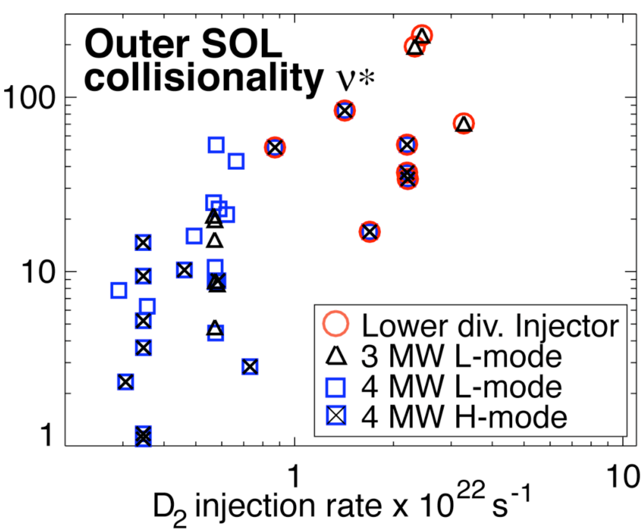


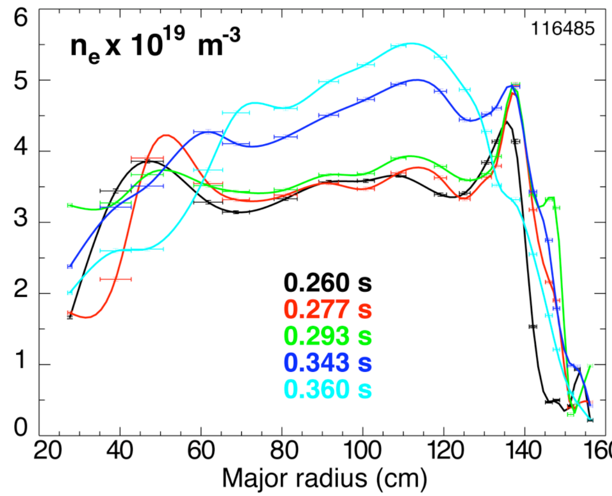
Fish-eye view of NSTX plasma

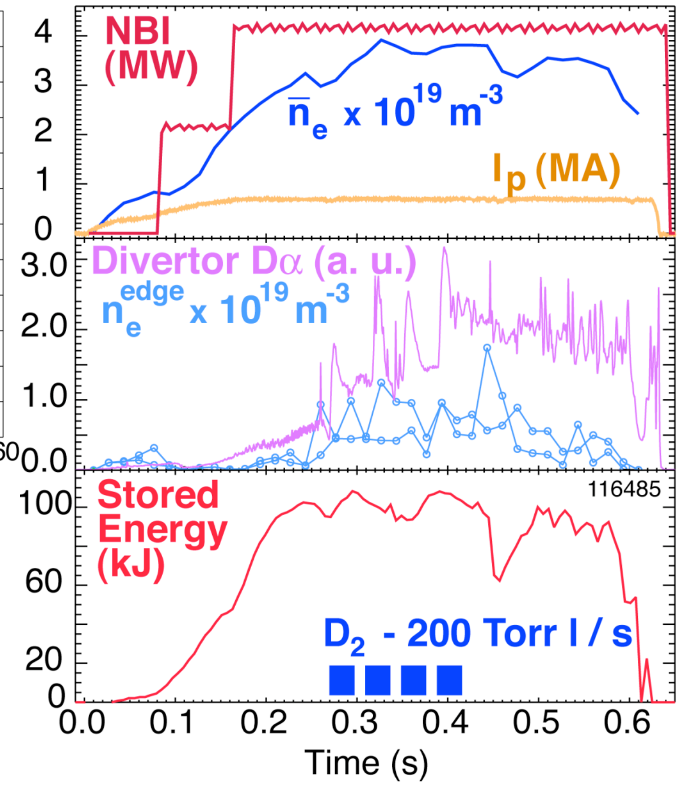


- Stark broadening of 8-2 line yields $n_e = 1\text{-}5 \times 10^{20}$ m^{-3}
- Line intensity ratios (Saha-Boltzman population distribution): $T_e = 0.3\text{-}1.0$ eV
- Inner SOL MARFE oscillating between midplane and divertor often observed by visible cameras
- Inner divertor region is a cold dense opaque plasma
  - challenge for modeling!

Inject D_2 to detach outer divertor leg







• Target plasma: ELM-free H-mode, LSN, 0.7 MA, B_t = 0.45 T , 4 MW NBI, ∇B down, q_{edge} = 12 - 20, central Z_{eff} = 1.2-1.3, fueled by HFS Inj. at 40-65 Torr l /s

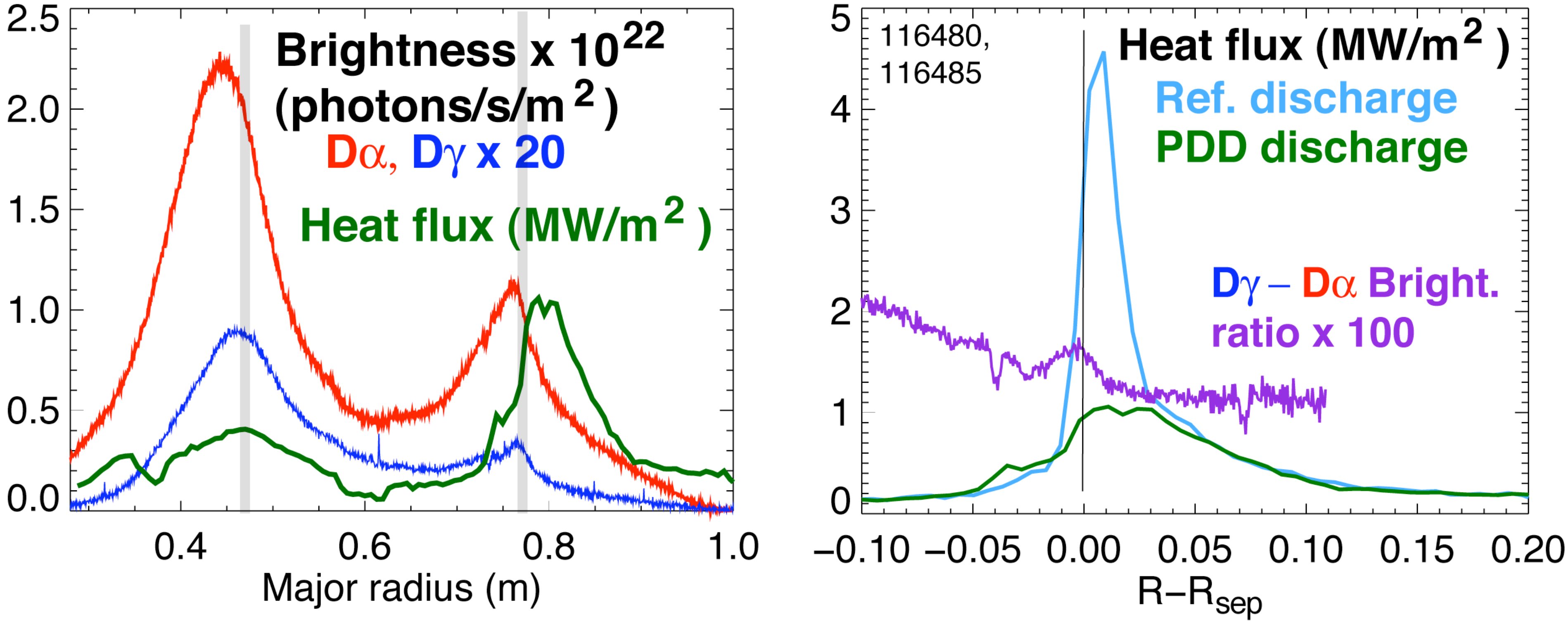
• Injected D_2 at LFS midplane at 20 - 120 Torr l / s and / or lower divertor (LD) at 0 - 200 Torr l / s - found that **D_2 poloidal injection location matters**!

• Retained H-mode for 5 x τ_E and detached outer leg with LD injection only

• Midplane injections quickly bring plasma to operational limits (confinement degradation, locked modes, large low *m,n* MHD modes)

• Concluded outer leg *partial* detachment from peak heat flux reduction, radial peak shift, and volume recombination onset (D_γ/D_α ratio)

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



- D_2 puffing from lower divertor
  - Decreases peak q_{out} by 4-5, with peak shift outward by up to 3 cm
  - Broadens D_α and D_γ brightness profiles and increases outer leg D_γ / D_α ratio from typical 0.010-0.015 to 0.015-0.020
  - No change in detached inner divertor - $q_{in} < 0.5$ MW/m^2, $D_\gamma/D_\alpha = 2\text{-}3 \times 10^{-2}$
- Apparently partial detachment
- Separatrix location from LRDFIT

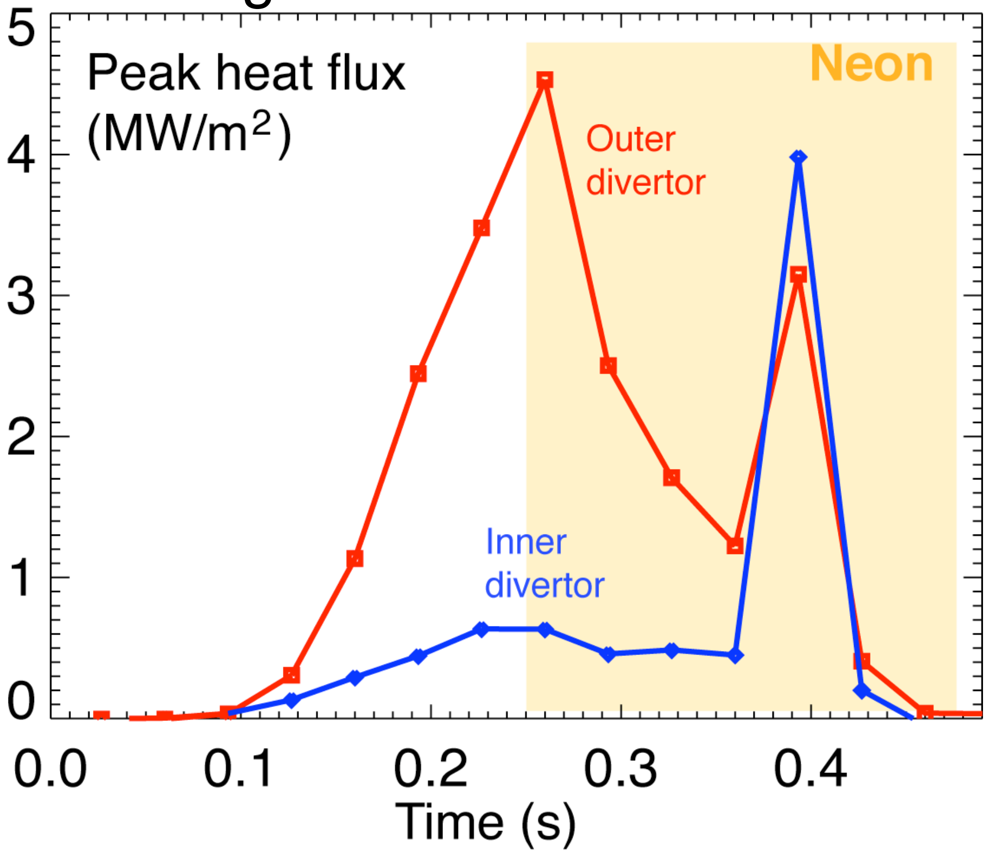
Summary and Future work

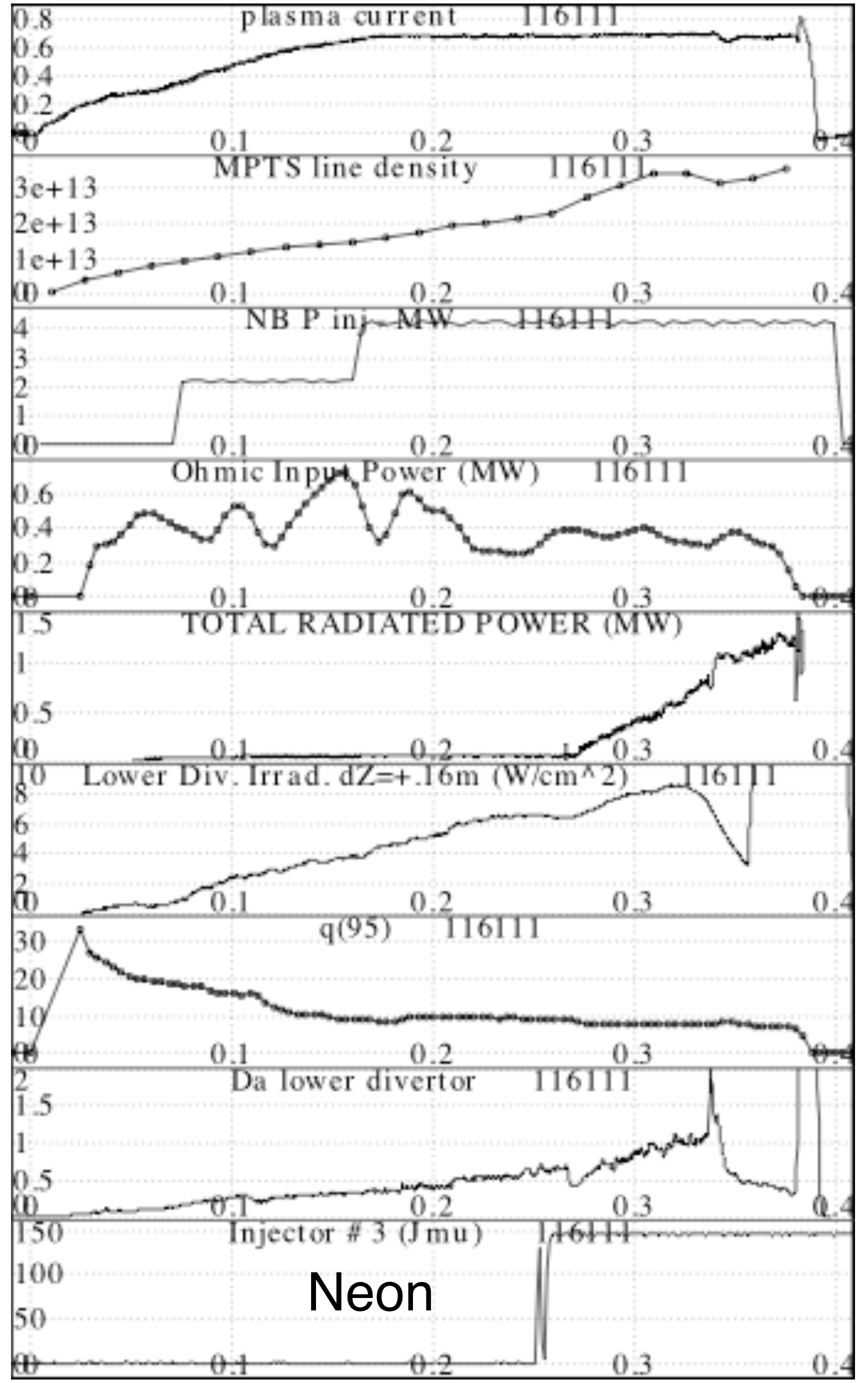
- SOL and divertor physics at low aspect ratio are studied in NSTX
- Longer pulses may cause difficulties in divertor heat flux handling given the naturally occurring NSTX divertor regimes
- D_2 injections were used to detach outer divertor leg in 3-4 MW NBI-heated L- and H-mode plasmas
- Signs of outer leg partial detachment were obtained in 4 MW H-mode plasmas with D_2 injections from lower divertor region: reduction of peak heat flux, shift of heat flux peak, and spectroscopic signatures of volume recombination
- Future work will focus on
  - further characterization of outer leg detachment
  - dissipative divertor scenario development for high δ, κ H-mode plasmas

Neon injections did not detach outer divertor

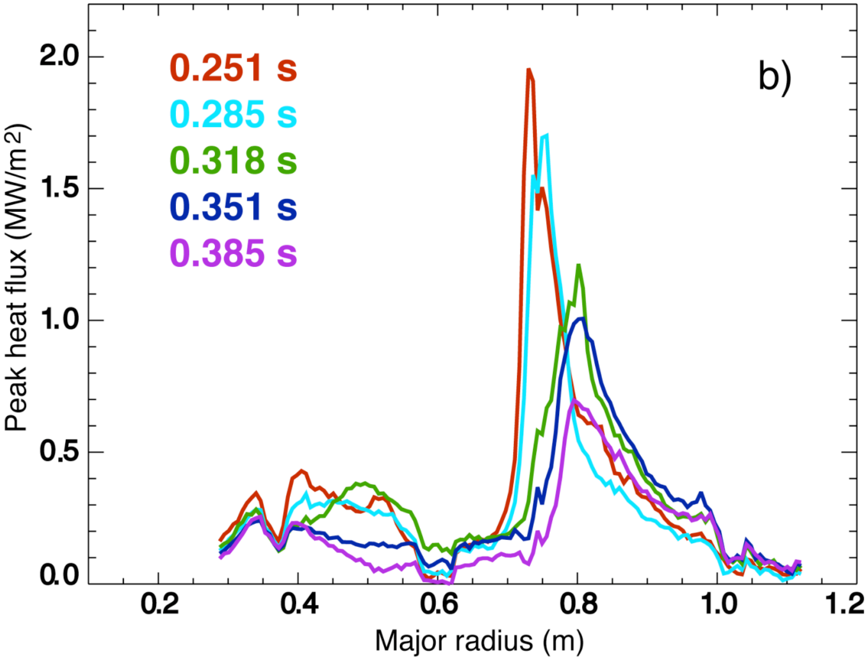
- Neon puffed into 4 MW H-mode
- Did not cause H-L transition
- Puffing rate 1.5 x 10^{20} s^{-1}
- P_{rad} = 0.3 x P_{in}
- Outer peak heat flux reduced x4,

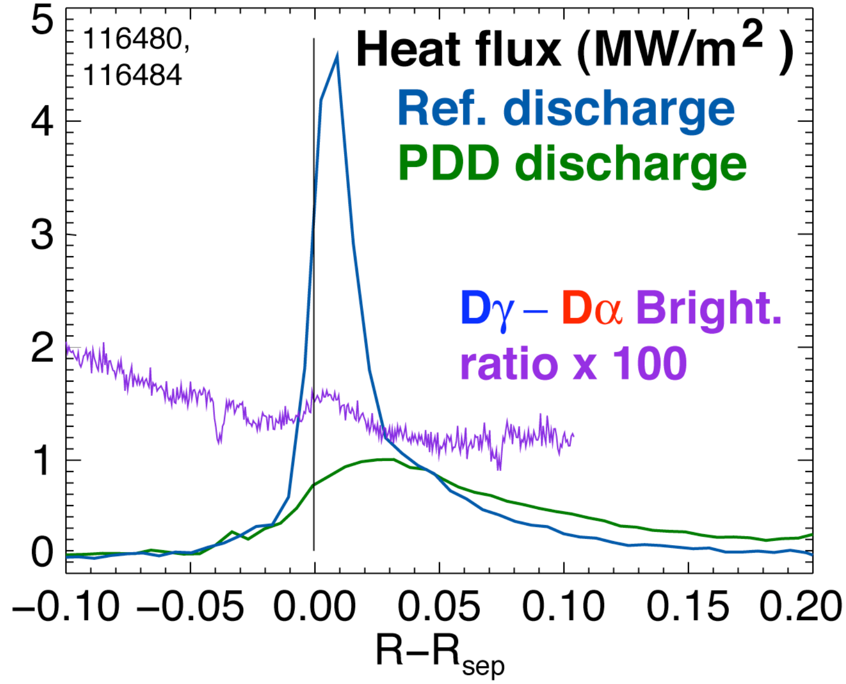
but no sign of volume recombination!

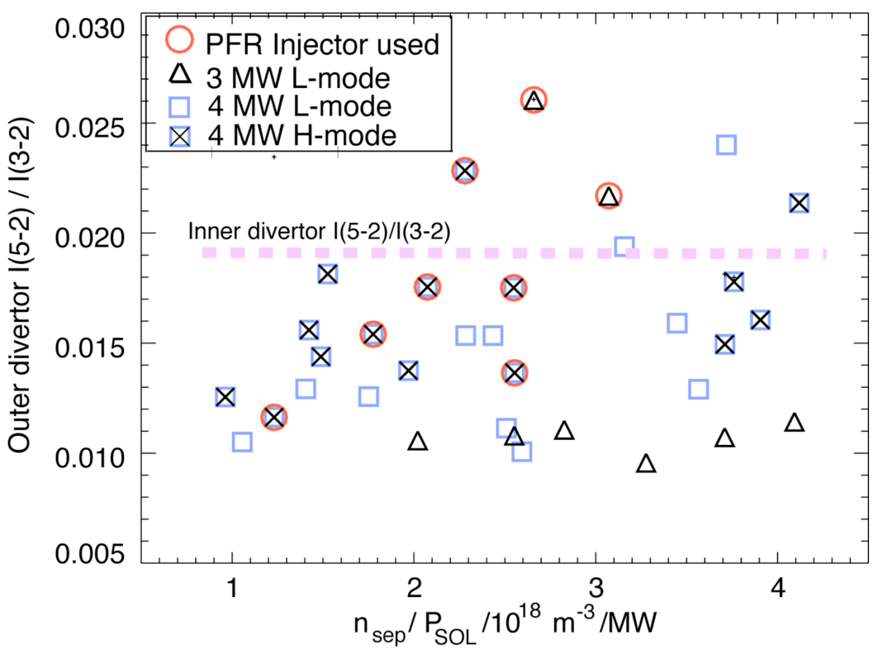


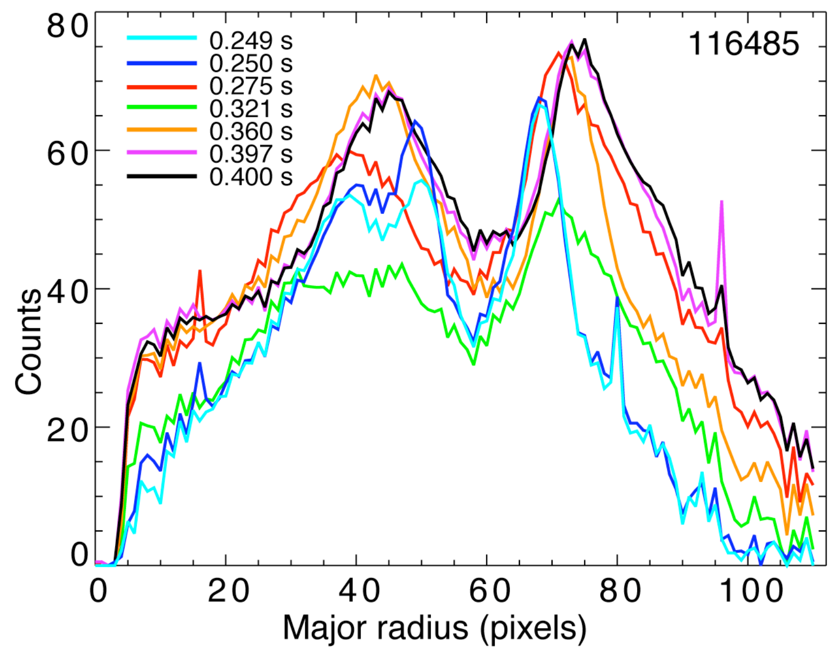


Stronger gas puff leads to stronger detachment









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)

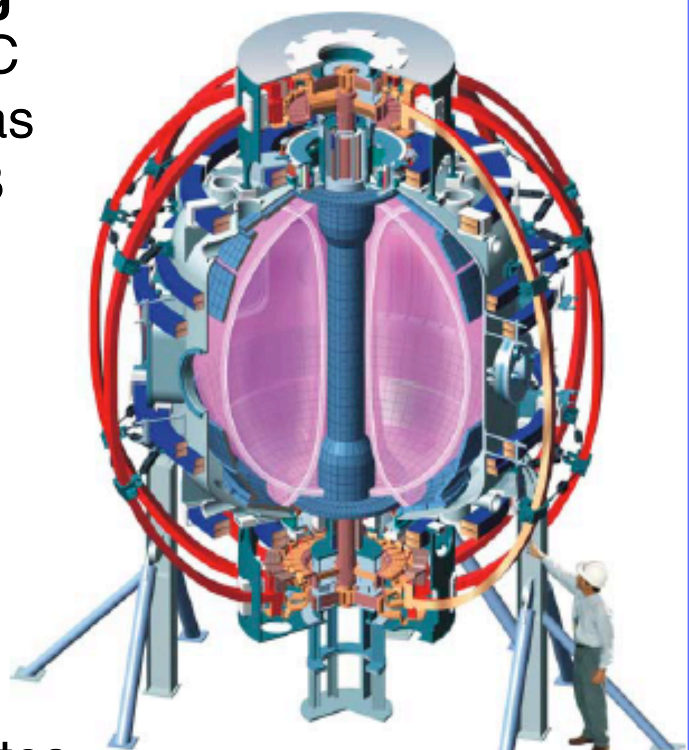
• Conditioned walls

PFC

• ATJ graphite tiles on divertor and passive plates

• ATJ and CFC tiles on center stack

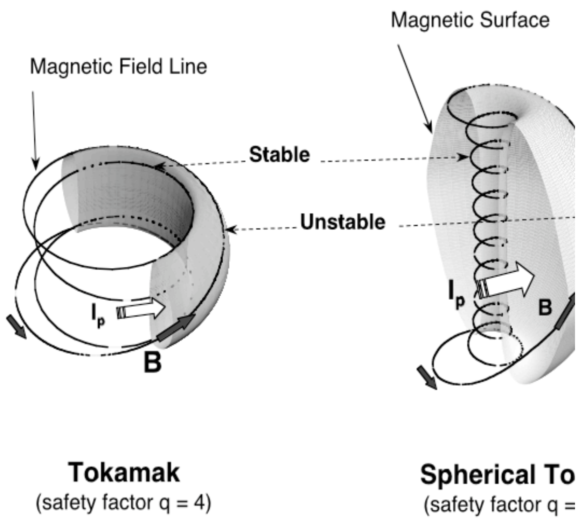
• Thickness 1” and 2”

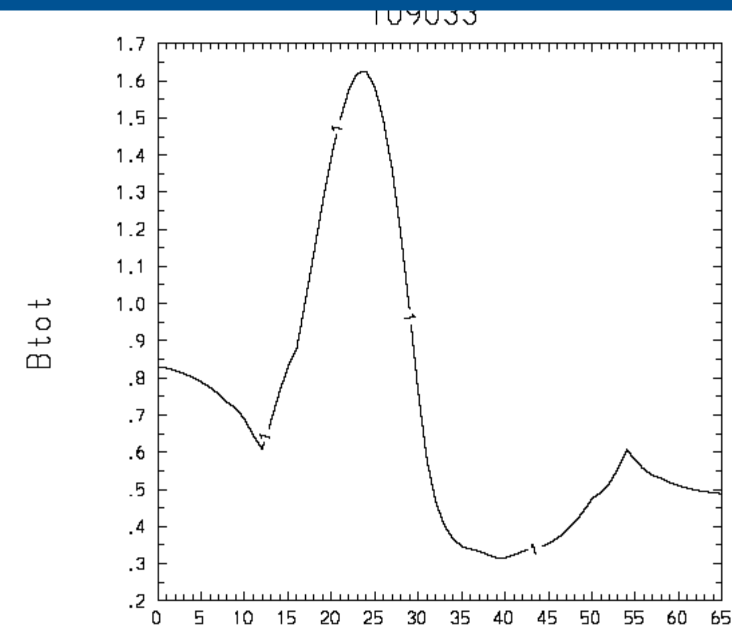


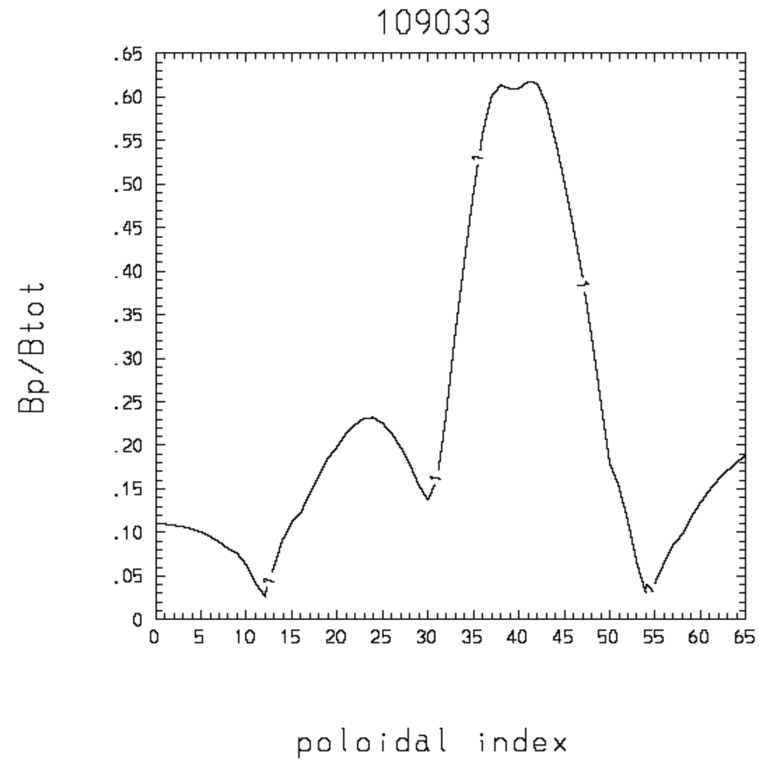
Aspect ratio A	1.27
Elongation κ	2.5
Triangularity δ	0.8
Major radius R_0	0.85m
Plasma Current I_p	1.5MA
Toroidal Field B_{T0}	0.6T
Pulse Length	1s
Auxiliary heating:	
NBI (100kV)	7 MW
RF (30MHz)	6 MW
Central temperature	1 – 3 keV

NSTX reference data

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





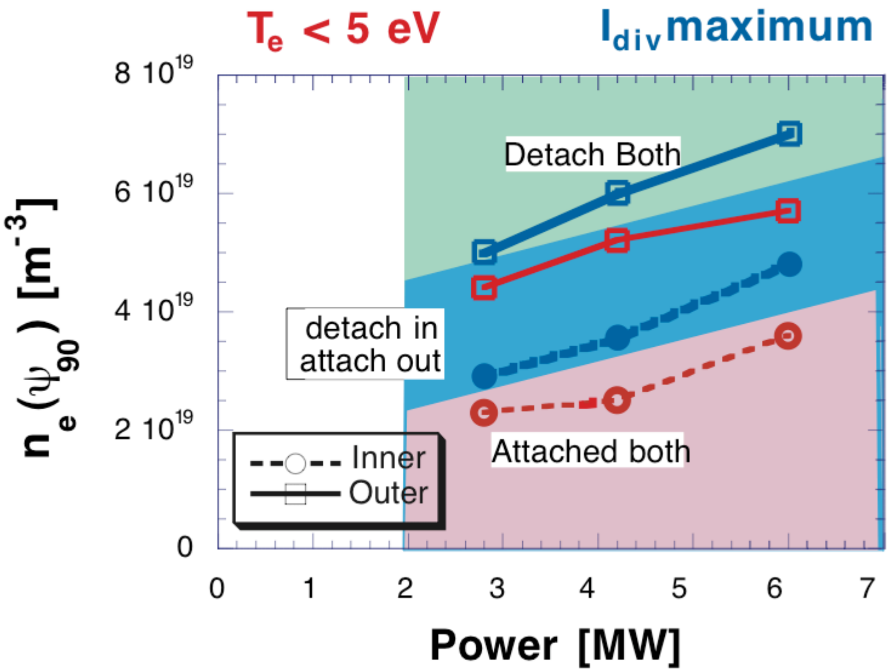


UEDGE modeling guided detachment experiment

• UEDGE - multifluid 2D edge code based on Braginskii equations

• Model divertor conditions *vs* P_{in}, n_{edge} for guiding purposes

• H-mode 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

Attempt to change parallel momentum and power balance:

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

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

Development of NSTX diagnostic set enabled detailed lower single null divertor studies in FY05

- **Divertor IRTV**

two Indigo Alpha 160 x 128 pixel microbolometer cameras, 7-13 μm range, 30 ms frame rate

- **Divertor/SOL cameras with D_α, D_γ, C III filters**

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 divertor UV-VIS spectrometer**

ARC Spectro-Pro 500i, 3 input fibers, time response 15-30 ms, FWHM > 0.6 A

- **Midplane and divertor bolometry**

midplane (AXUV radiometer array), divertor - ASDEX-type four channel bolometer, time response 20 ms

- **Divertor Langmuir probes**

midplane - fast probe, tile LPs - I_{sat}, T_e measurements

- Midplane **Multi-point Thomson** scattering

with 2-4 points in SOL

- **Gas Injectors at various poloidal locations, $R<10^{22}$ s^{-1}**
- **Enhanced shaping capability - Lower Single Null, κ=1.8 - 2.5, δ=0.4 - 0.9**