Supported by

Office of Fusion Energy Sciences

Excellent Science Attractive Energy

Office of Science

Heat flux amelioration in highly shaped plasmas in NSTX

V. A. Soukhanovskii[1], R. Maingi[2], D. A. Gates[3], J. Menard[3], R. Raman[4], R. E. Bell[3], C. E. Bush[2], R. Kaita[3], H. W. Kugel[3], B. P. LeBlanc[3], S. F. Paul[3], A. L. Roquemore[3], and the NSTX Team

[1] Lawrence Livermore National Laboratory, Livermore, CA
[2] Oak Ridge National Laboratory, Oak Ridge, TN
[3] Princeton Plasma Physics Laboratory, Princeton, NJ
[4] University of Washington, Seattle, WA

Poster P2.023

34th EUROPEAN PHYSICAL SOCIETY

Conference on Plasma Physics

Warsaw, Poland

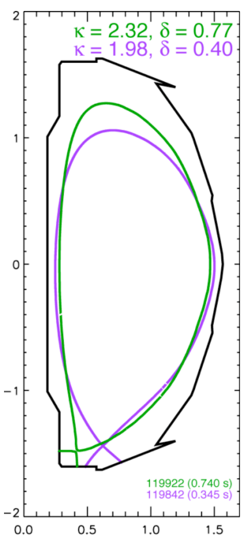
July 2-6, 2007

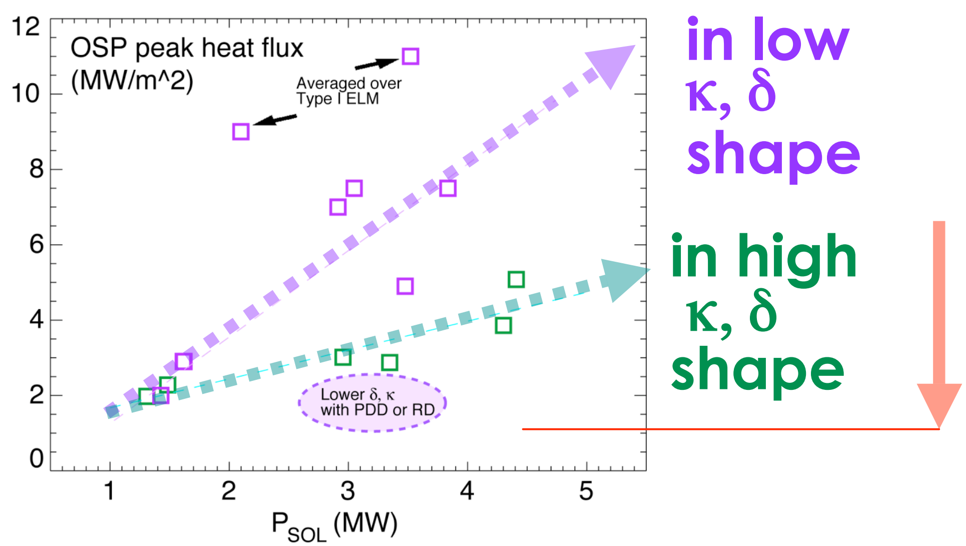
Summary

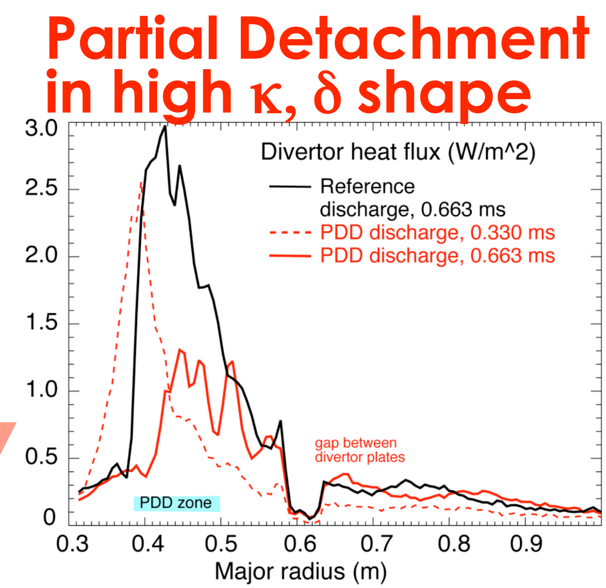
- Steady-state divertor heat flux amelioration in low aspect ratio geometry is studied in 0.8-1.2 MA 4-6 MW NBI **highly shaped** H-mode plasmas in NSTX

- Significant (x 2-3) reduction in divertor peak heat flux is achieved by using **high flux expansion divertor** (in comparison with low κ, δ lower single null configuration)

- Divertor peak heat flux is reduced further by x 2-3 using **partially detached divertor regime** with divertor D_2 injection



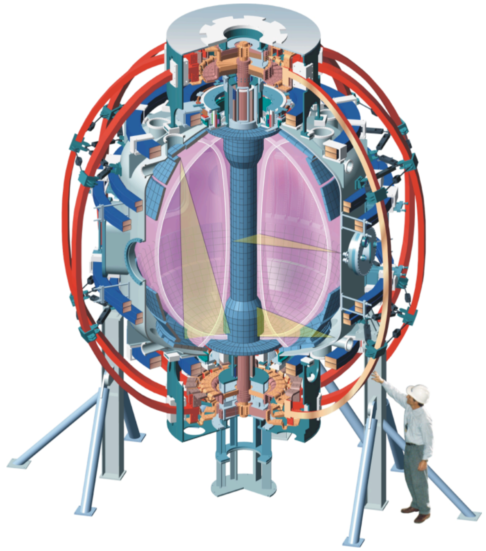




Goal: develop steady-state divertor heat load mitigation scenarios in a large Spherical Torus

- **Divertor heat flux mitigation solutions:**
  - Poloidal flux expansion at outer strike point
  - Strike point sweeping
  - Radiative divertor: outer SOL in high-recycling regime with enhanced radiation at divertor plate
  - Dissipative divertor (detachment)

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

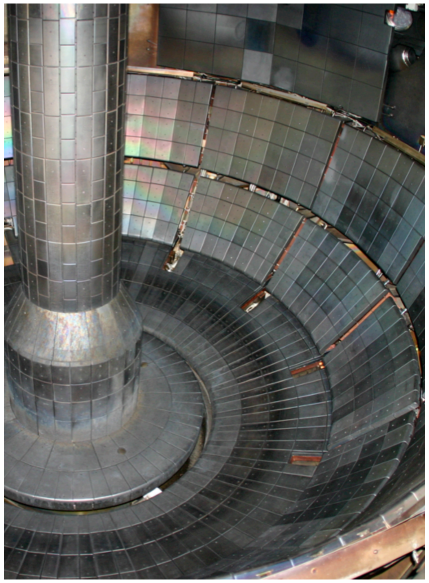


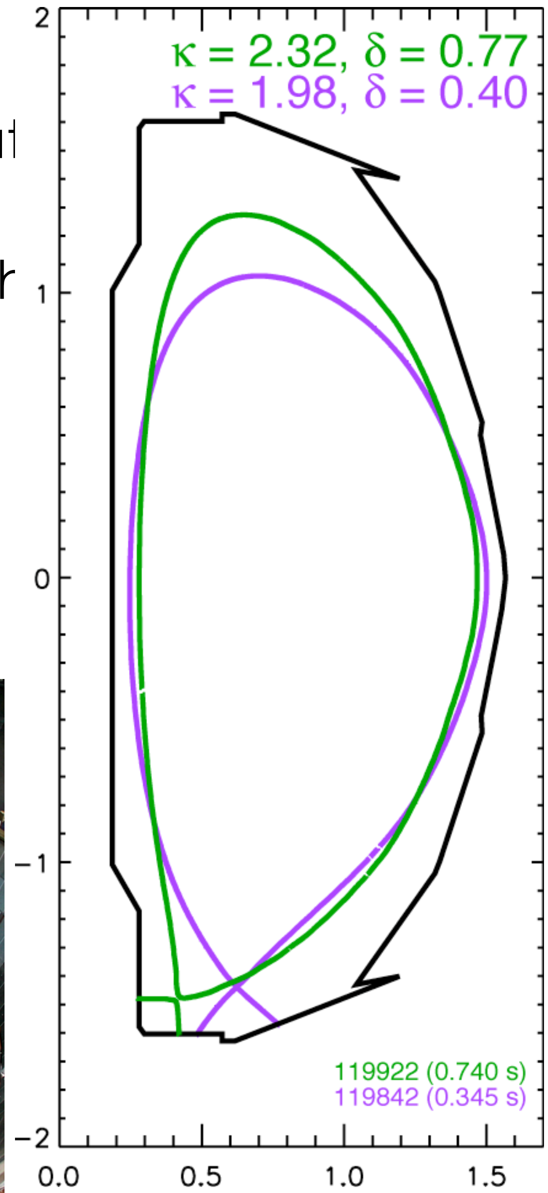
  - **Study λ_q scaling with I_p and P_{NBI} - R. Maingi, Poster P2.020**

Is divertor physics different at low aspect ratio?

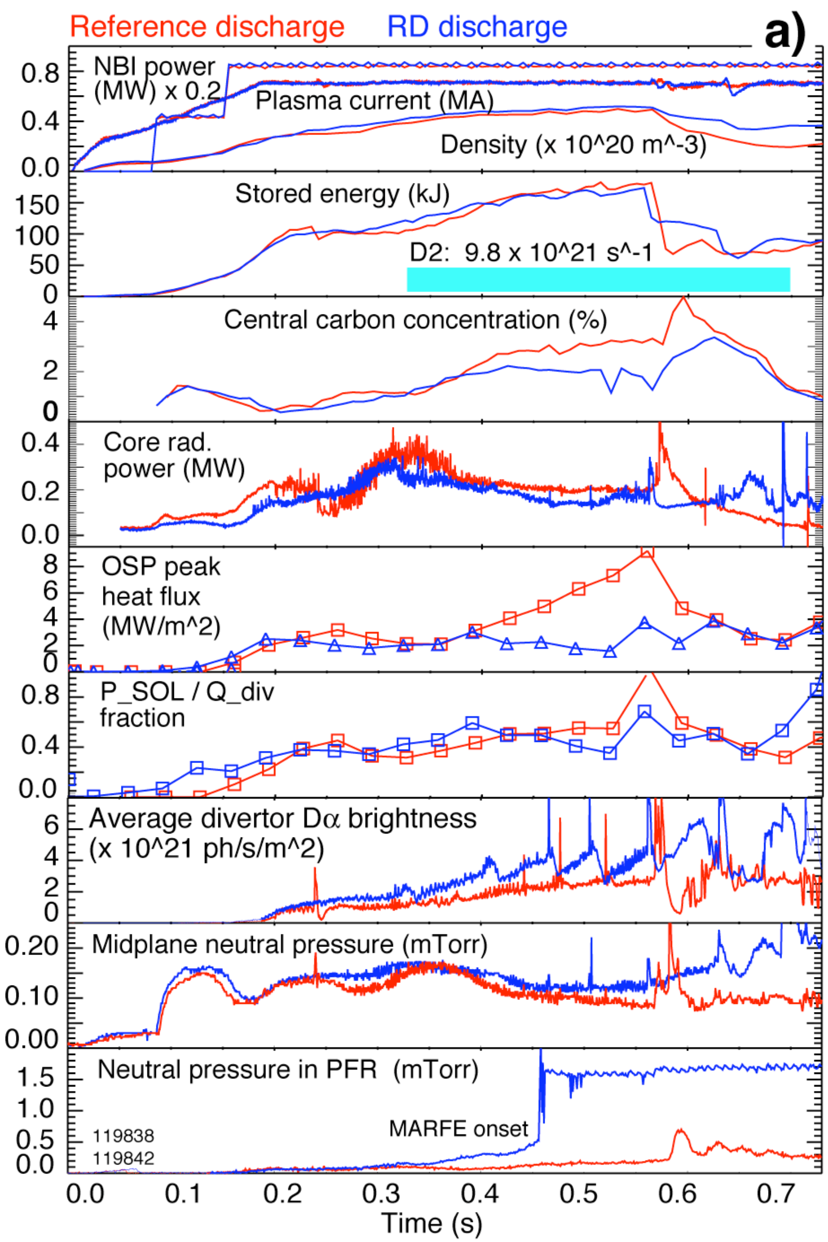
- **NSTX divertor**
  - Open geometry enables much flexibility
  - One horizontal target & one 24° tilted target plat
  - Graphite 2.5-5.0 cm thick tiles
  - No active pumping (recently experimenting with lithium coatings)
  - Typical divertor tile temperature in ~ 1 s NSTX pulses $T < 300$ C. Engineering limit is $T = 1200$ C. Long pulses will require steady-state heat flux mitigation solutions
  - $q_{out} < 10$ MW/m^2, P/R < 9

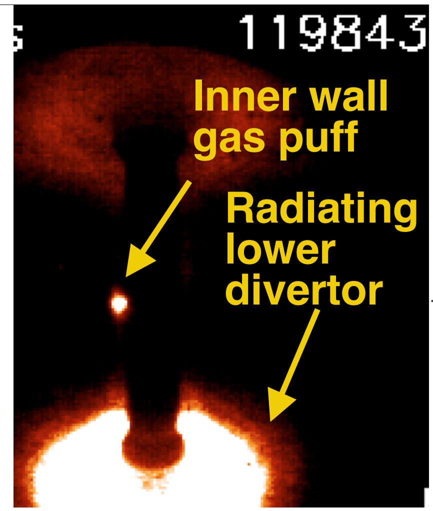
- **Low aspect ratio configuration**
  - small divertor volume
  - small plasma wetted area
  - high $q_{||}$
  - short connection length $L_{||}$
  - High SOL mirror ratio $M=|B_{min}| / |B_{max}|$
  - SOL area factor: $A_{out} > A_{in}$

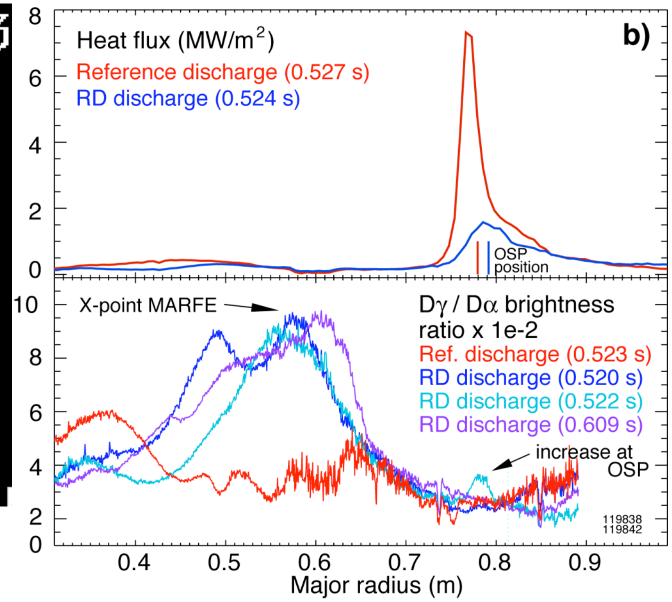




Radiative divertor in low κ, δ LSN configuration reduced peak heat flux by up to 70 %

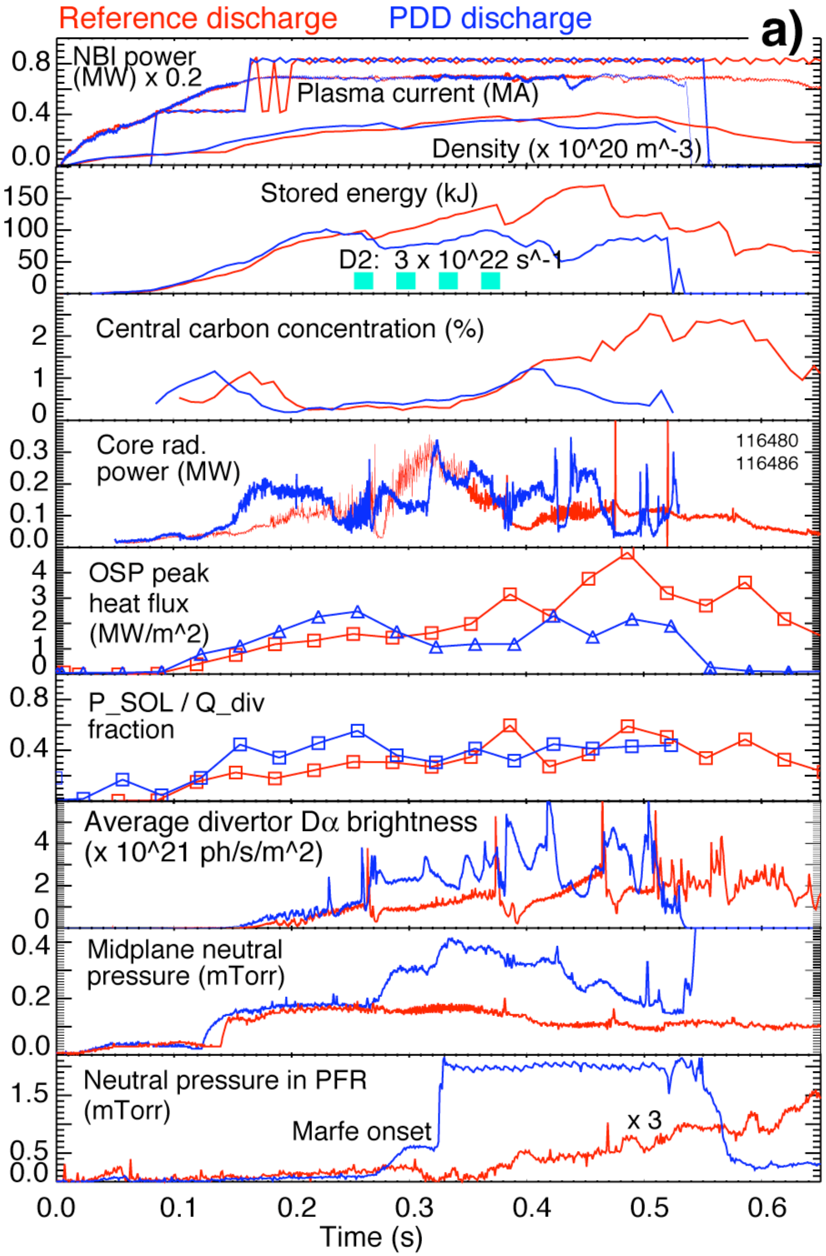


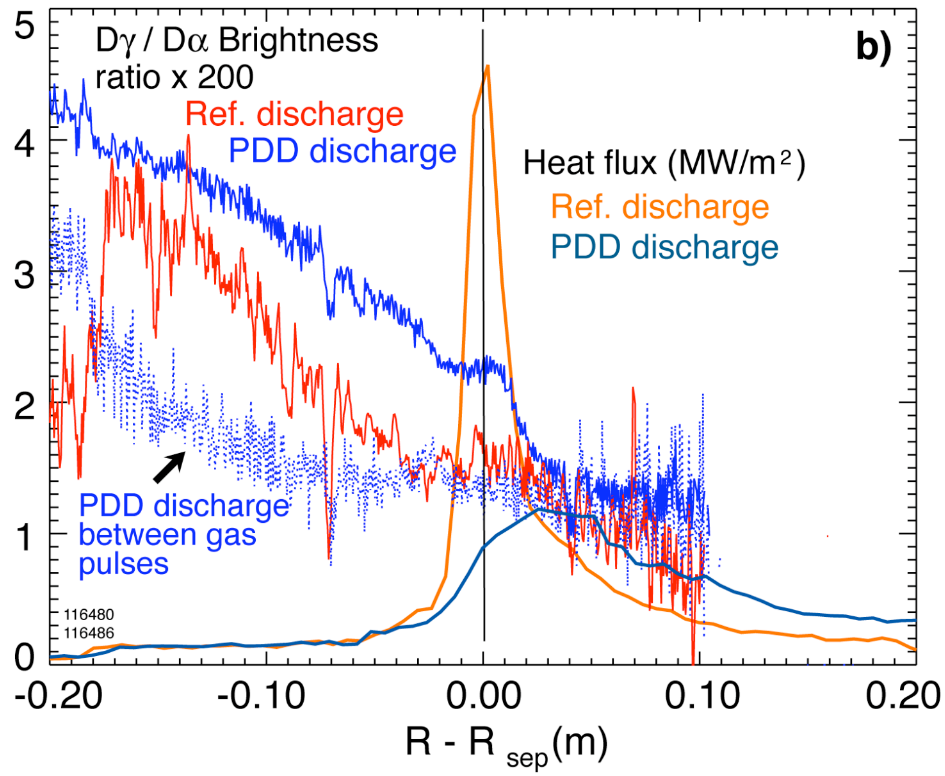




- Outer peak heat flux reduced by x 2-5, but no sign of recombination
- X-point MARFE develops during gas injection
- At highest D_2 puffing rate Dγ/Dα ratio at strike point transiently increases
- **Generally compatible with high performance and H-mode confinement**

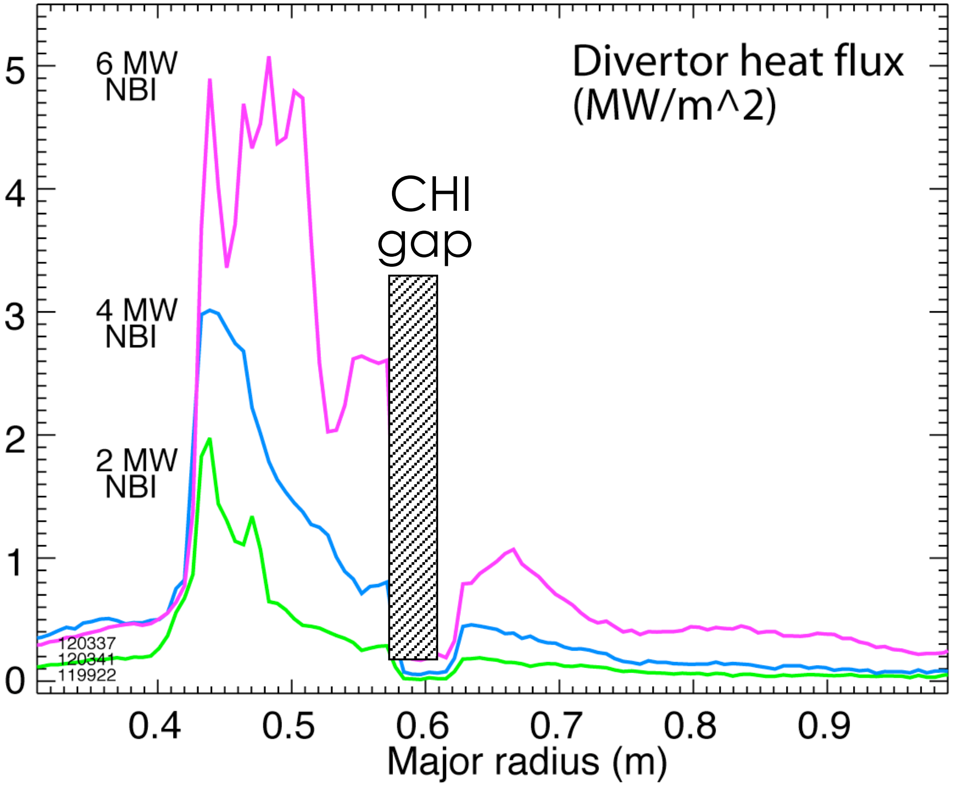
Partially detached divertor in low κ, δ LSN configuration incompatible with long H-modes

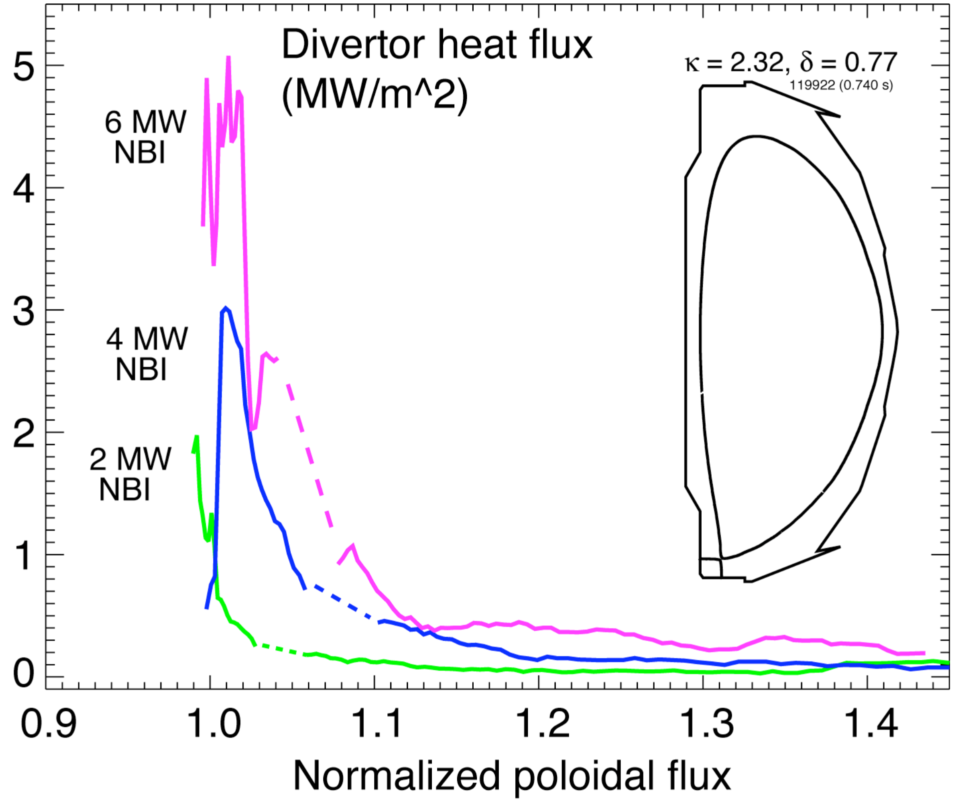




- High D_2 injection rate (< 400 Torr l / s)
- Core plasma parameters degrade quickly, X-point MARFE develops
- **Peak heat flux reduced by x 4-5**
- Volume recombination in outer divertor

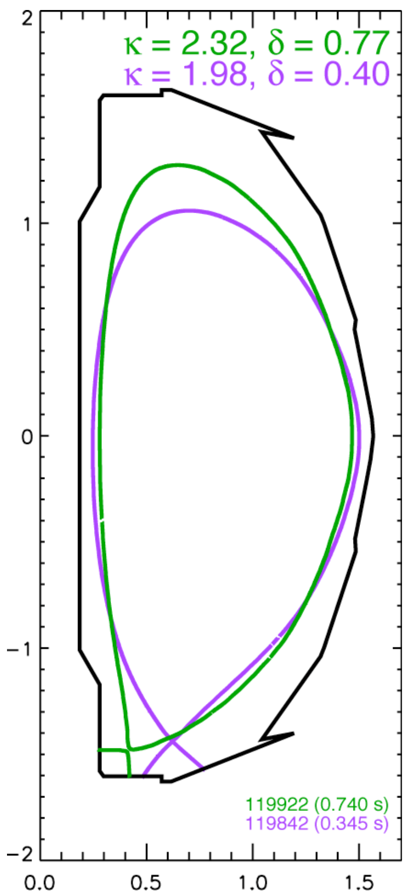
Significant peak heat flux reduction can be achieved by poloidal flux expansion

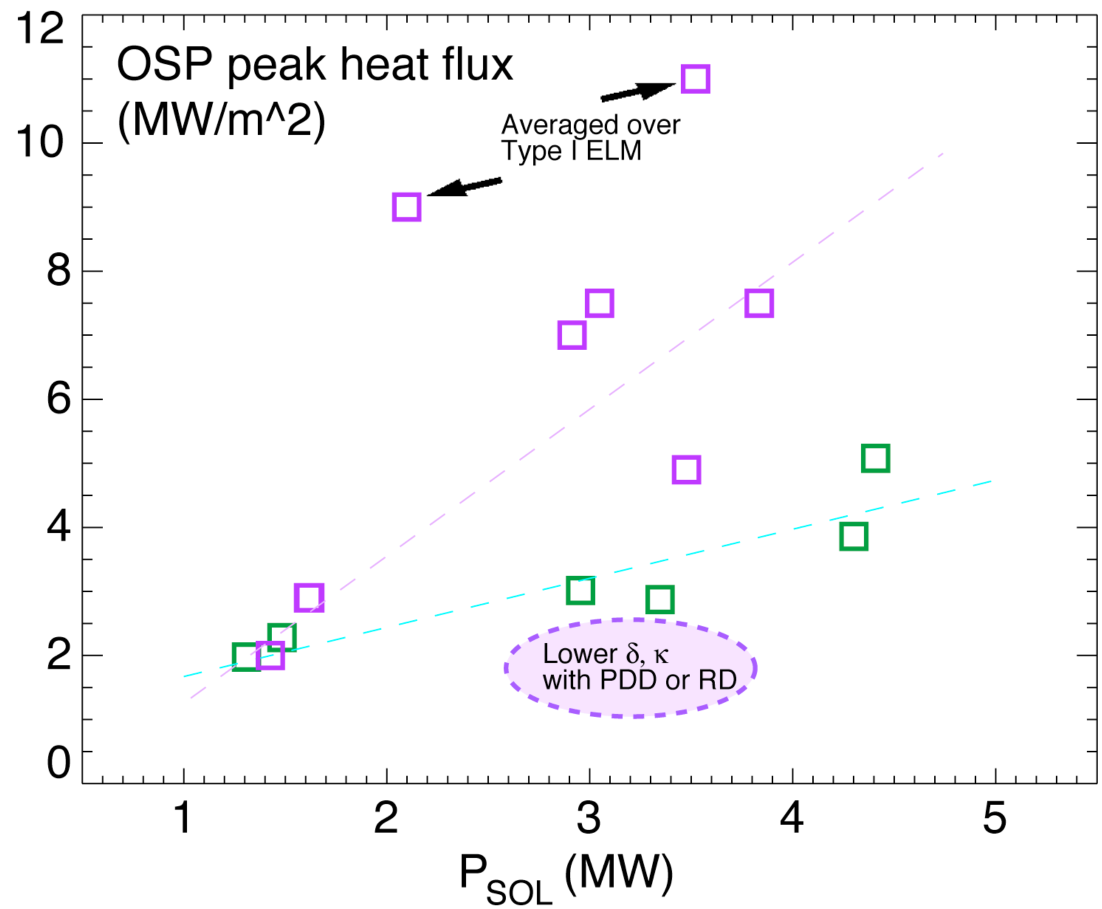




- High-performance long-pulse H-mode plasmas (Menard OV-2-4, IAEA FEC 2006)
- Poloidal flux expansion at OSP 16-24
- Inner strike point detached, outer strike point on horizontal target - attached

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





- Scaling sensitive to fueling location and gas injection rate
- P_{SOL} is determined from measured and TRANSP-calculated quantities as

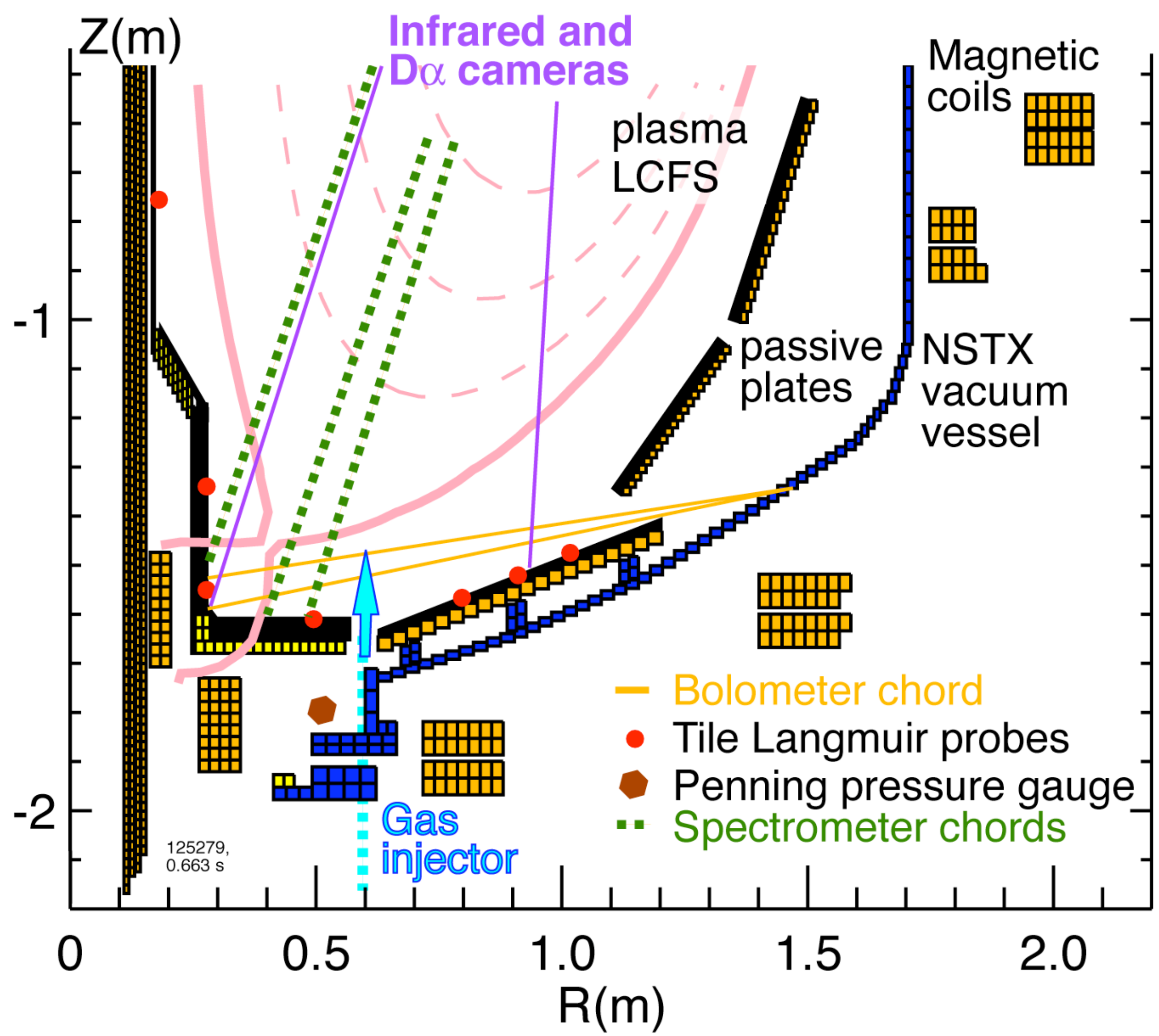
$$P_{SOL} = P_{NBI} + P_{OH} - dW_{MHD}/dt - P_{rad}^{core} - P_{fast\ ion}^{loss}$$

Study radiative divertor and detachment in highly shaped plasmas

- Highly shaped plasmas mean high performance
  - » higher bootstrap current fraction at higher κ
  - » thermal confinement scales as κ^{α}
  - » higher edge pressure gradient with higher δ
  - » small ELM regimes at higher δ

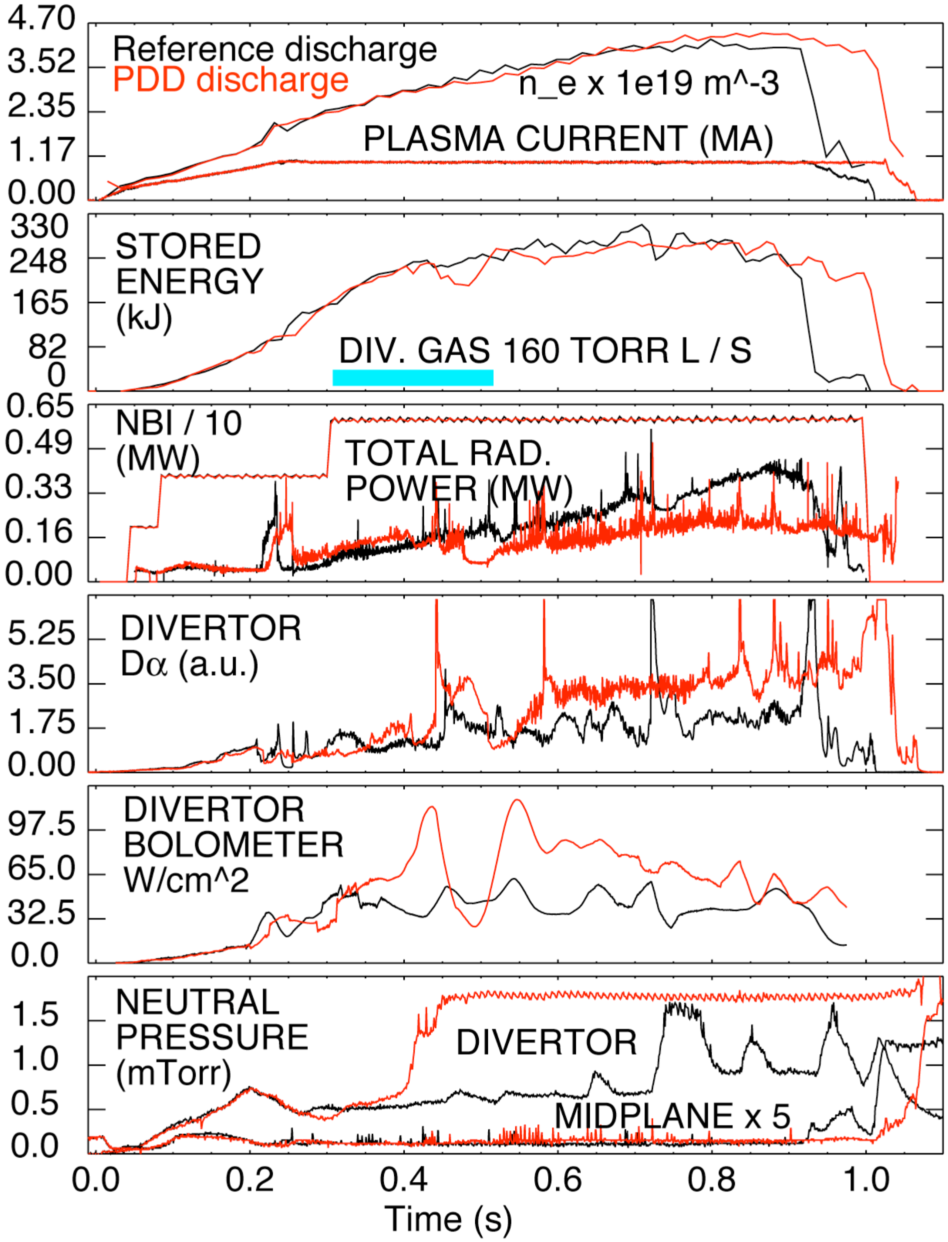
- Highly shaped plasmas have high flux expansion divertor
  - » Reduced peak heat flux - favorable for detachment threshold
  - » Higher neutral penetration (?)
  - » Higher "plasma plugging" (?) - Important in open divertor
  - » Higher isothermal radiating volume (?)
  - » Sputtering yield (?)
  - » Parallel and poloidal connection lengths are shortest

Proper diagnostic configuration and rtEFIT shape control were essential for success of experiment



- rtEFIT control was used for *drsep*, R_{OSP}, and gap control

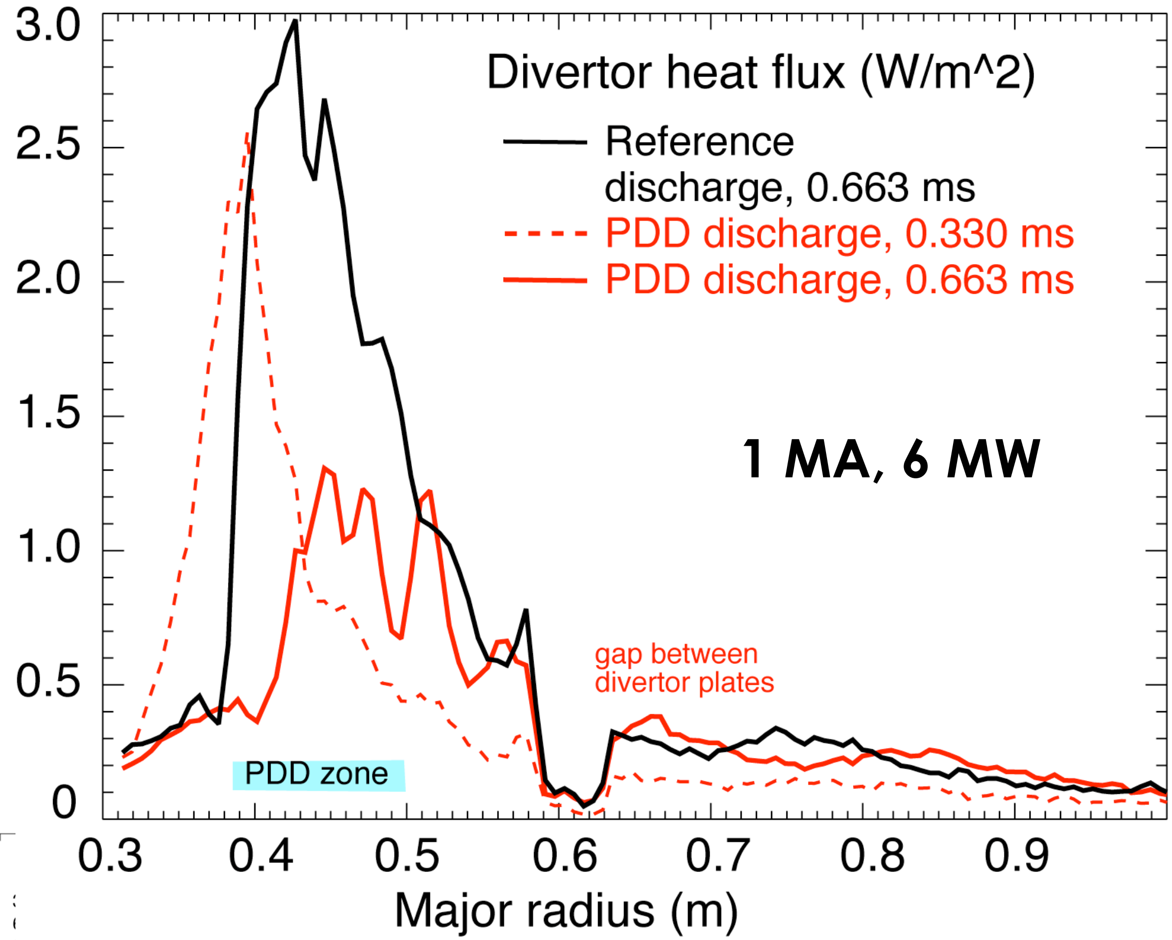
Partial strike point detachment is obtained using D_2 divertor injection

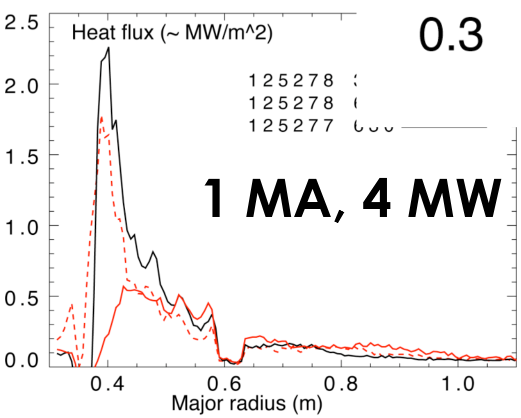


- D_2 injected for 200 ms
- Peak heat flux reduced x 2-3
- Core confinement and performance were not affected
- Core carbon concentration reduced x 1.5
- Clear signs of divertor radiated power increase and neutral pressure increase
- No signs of X-point MARFE (?)
- Volume recombination in outer divertor

- Same PDD picture in 1 MA, 4 MW; **1 MA, 6 MW;** 1.2 MA, 6 MW cases

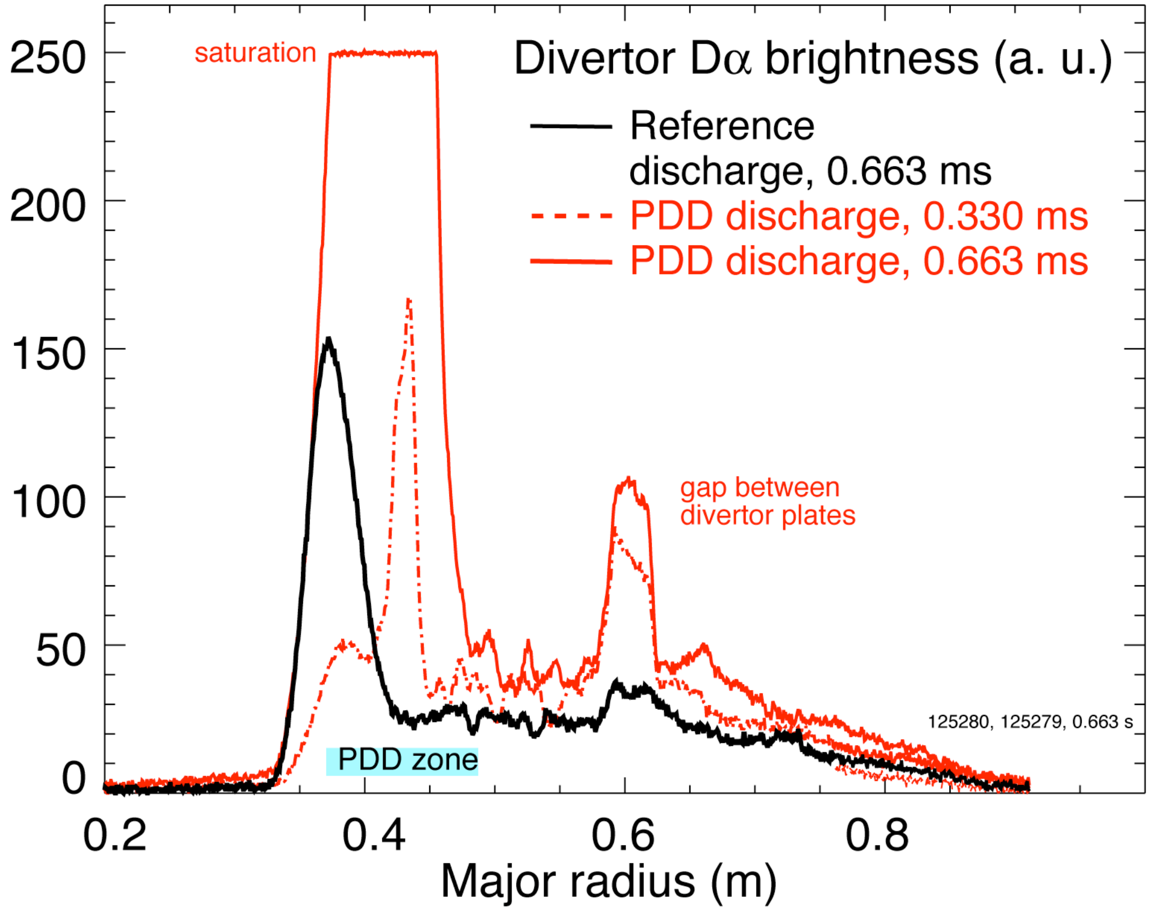
Divertor peak heat flux significantly reduced during partial detachment phase





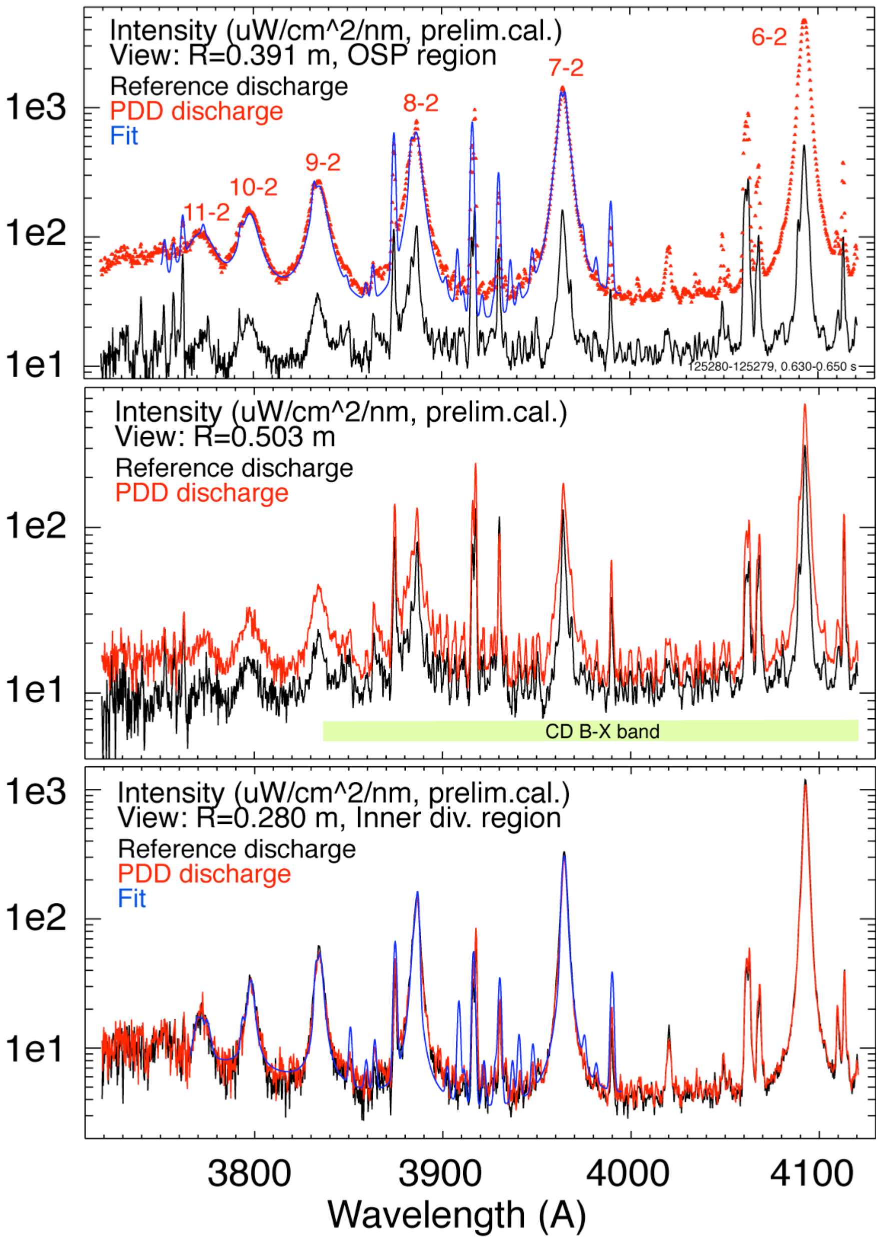
- Peak heat flux reduced by 2-3
- Profile λ_q changes from 5-10 to 20-20 cm
- PDD zone is 10-15 cm (0.01-0.02 in ψ_N)

Divertor D_α profiles are indicative of partial detachment

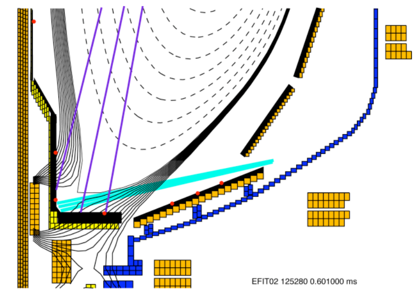


- Camera signal saturated during PDD (indication of X-point MARFE ?)
- Increase consistent with low T_e, high n_e plasmas
- Outside of PDD zone - high-recycling SOL
- PDD zone is 10-15 cm (0.01-0.02 in ψ_N)

Significant volume recombination is observed at outer strike point during detachment



- Balmer series lines 2-6…11
- Sign of strong volume recombination
- Stark broadening yields n_e
- Intensities determined by Saha-Boltzman level population distribution



- $n_e \sim$ 2-3 x 10^{20} m^{-3} in inner divertor (bottom panel)
- $n_e \sim$ 4-6 x 10^{20} m^{-3} at outer strike point (top panel)
- $T_e < 1.5$ eV
- Interim calibration used
- **Soukhanovskii et. al., Rev. Sci. Instrum. 77, 10F127 (2006)**

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

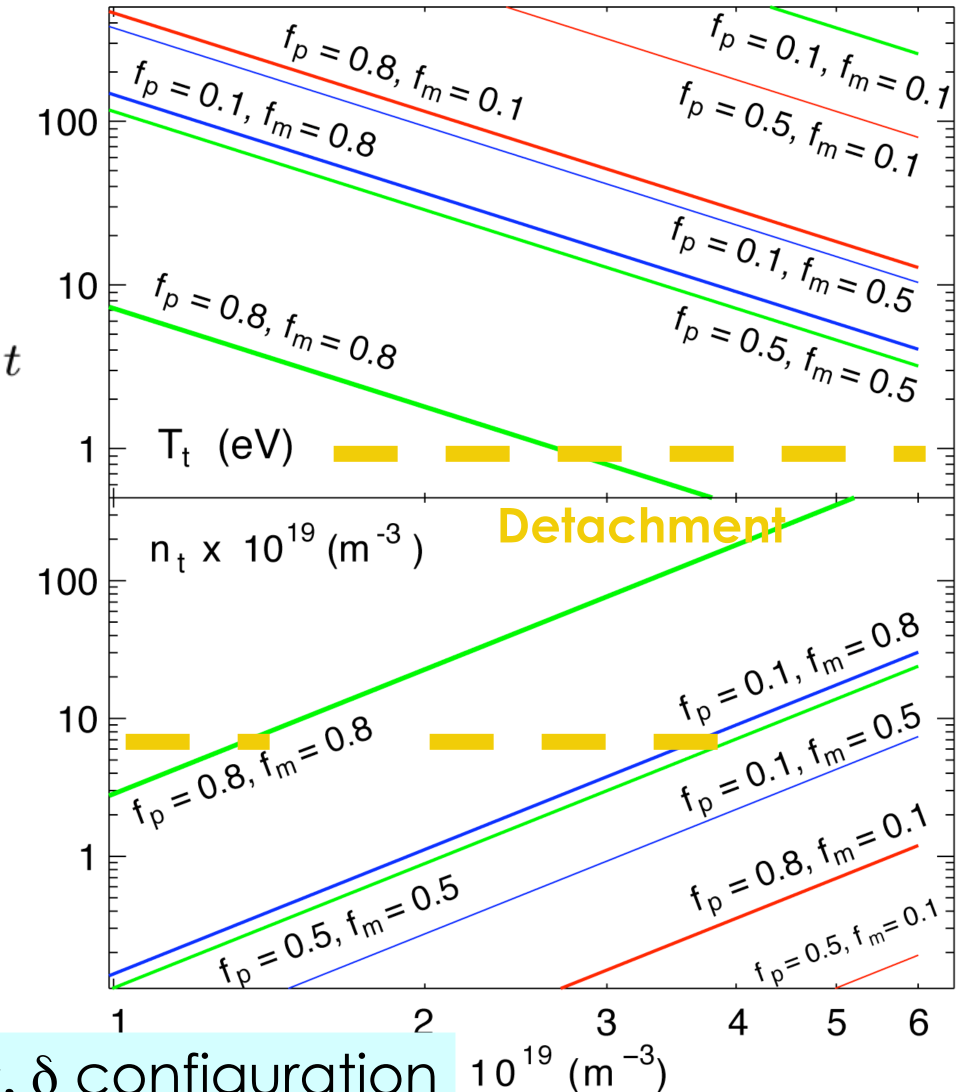
- Two point model with losses
- f_p, f_m scanned, f_{cond}=0.9
- n_u, $q_{||}$, L_c from experiment

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

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

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

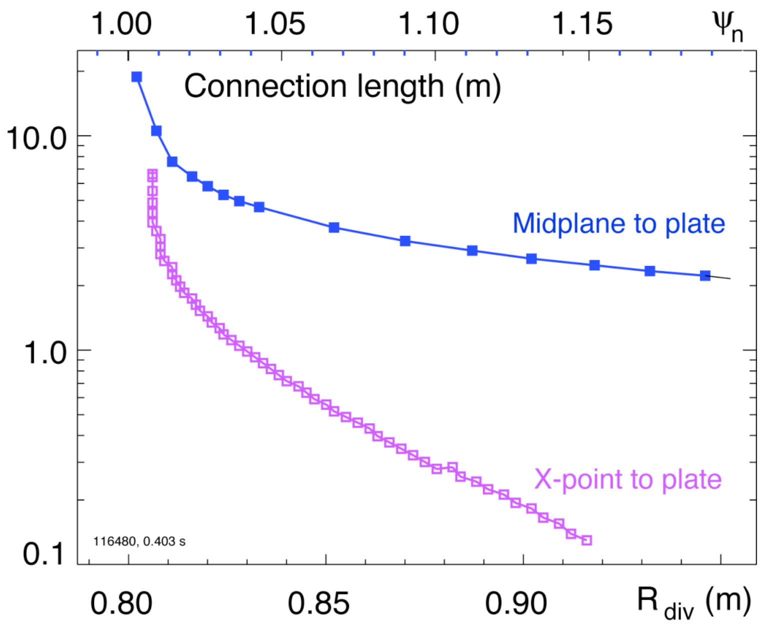
$$\Gamma_t \sim \frac{f_{mom}^2\, f_{cond}^{4/7}}{1 - f_{power}}$$



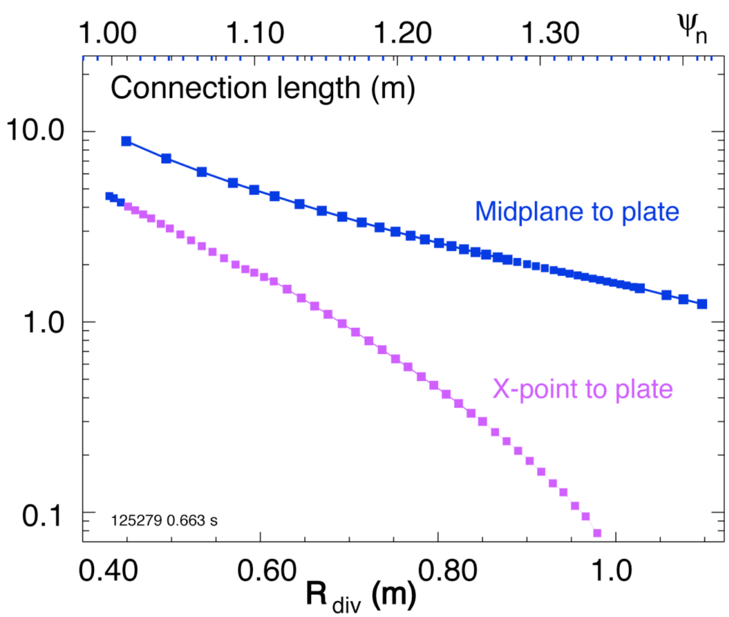
L_X =6-8 m, $q_{||}$ = 25-30 MW/m^2 - low κ, δ configuration
L_X =2-3 m - high κ, δ configuration

P. C. Stangeby. The plasma boundary of Magnetic Fusion Devices. IoP, Bristol, 2000.

Magnetic field line path is different in highly and low shaped plasmas

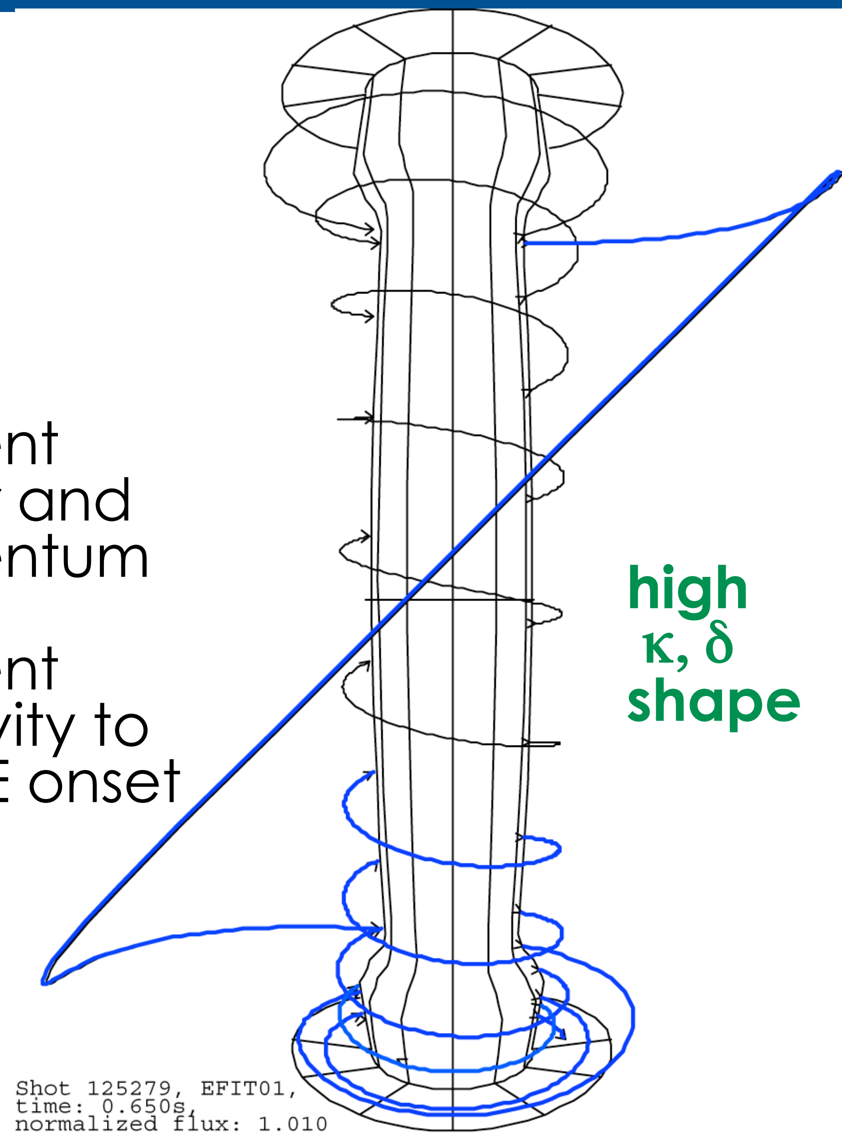


low κ, δ shape



high κ, δ shape

- Different power and momentum losses
- Different sensitivity to MARFE onset

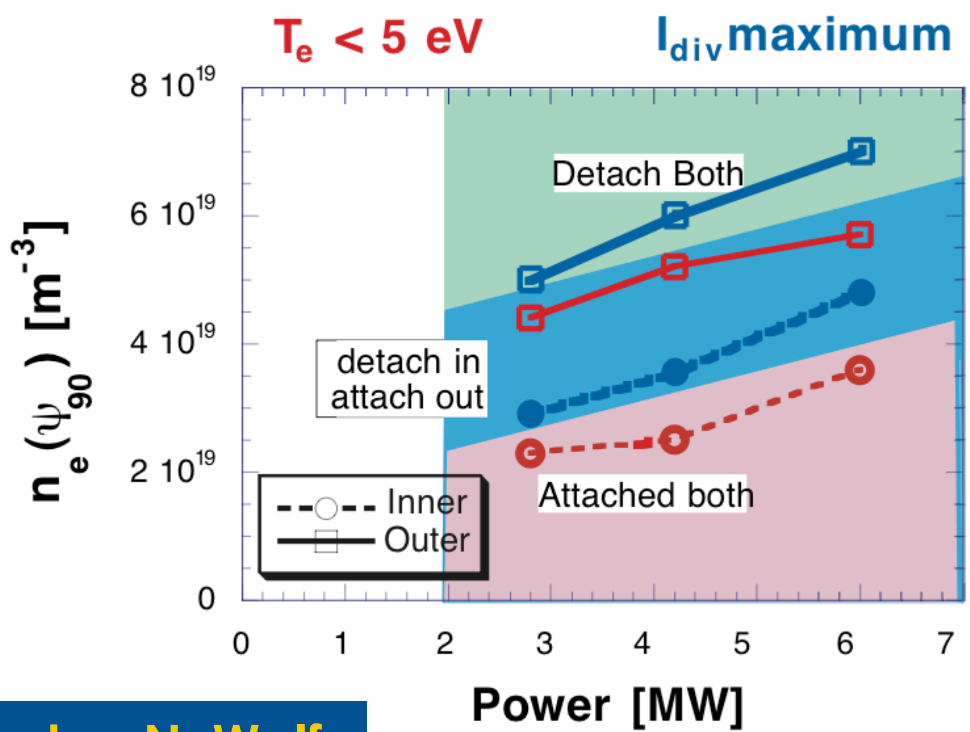


high κ, δ shape

Figure courtesy of Dr M. Bell (PPPL)

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



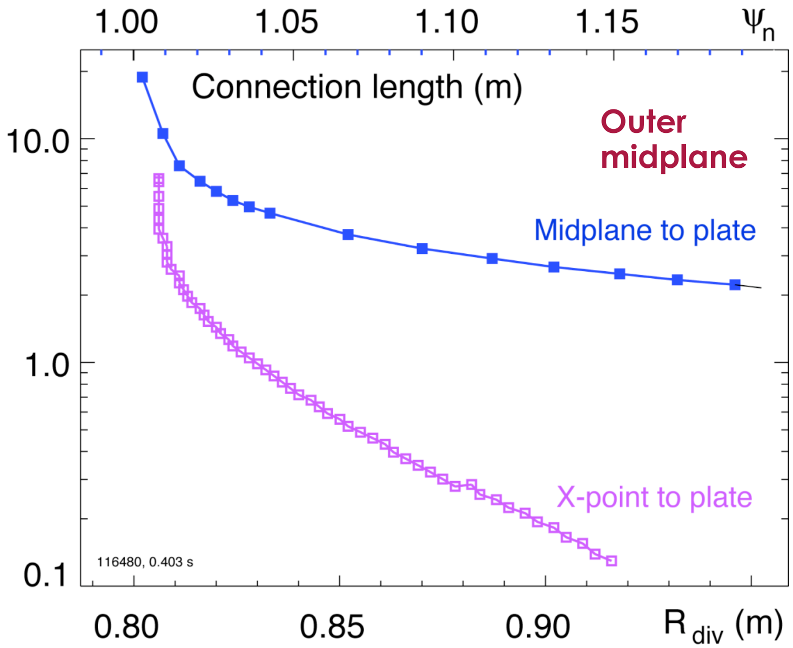
G. Porter, N. Wolf

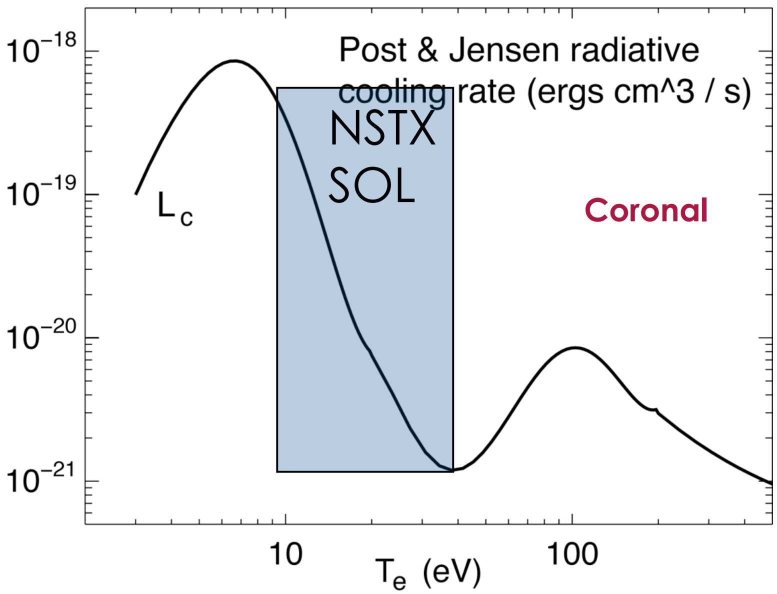
Parallel momentum and power balance:

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

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

Why is it difficult to obtain detachment in low κ, δ configuration?





- 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)

Sign-up sheet

Abstract

High divertor heat loads and material erosion are of particular concern for the high power density spherical torus (ST) because of its compact divertor design. Steady-state divertor heat flux mitigation techniques are investigated in NSTX in a lower single null (LSN) open divertor geometry. Deuterium injection in the divertor region was used to obtain a radiative and a partially detached divertor regimes in 2-4 MW NBI-heated H-mode plasmas in a low elongation $\kappa \sim 1.8-2.0$ and triangularity $\delta \sim 0.5$ shape. The outer strike point (OSP) peak heat flux was reduced from 4-6 MW/m^2 to a manageable level of 1-2 MW/m^2 [1]. However, because of an inherently small divertor volume and a short connection length, future ST-based devices may not be able to fully utilize radiative and dissipative divertor techniques. Another approach to reduce peak heat flux is by poloidal magnetic flux expansion in the divertor region. It comes as a natural benefit of the ST relation between strong shaping and high performance as was demonstrated recently in high performance long pulse highly shaped ($\kappa \sim 2.2-2.5$, $\delta \sim 0.6-0.8$) LSN H-mode plasmas with small ELMs, high β_N, high non-inductive (bootstrap) current fraction [2]. Peak heat flux at the divertor OSP in these plasmas was up to 60 % lower than that measured in the lower κ,δ plasmas at similar scrape-off power levels P_{SOL}. In addition, we conjecture that a number of divertor geometry effects may lead to higher divertor momentum and radiated power loss in highly shaped plasmas, and as a result, to a lower detachment threshold. Divertor conditions in the highly shaped 2-6 MW NBI-heated H-mode plasmas are analyzed in preparation for experiments that would use radiative and dissipative divertor techniques for further heat flux reduction. **This work is supported by U.S. DOE under Contracts No. W-7405-Eng-48, DE-AC05-00OR22725, DE-AC02-76CH03073, and DE-AC02-76CH03073.**

References

[1] V. A. Soukhanovskii et al., Divertor Heat Flux Reduction and Detachment in NSTX, Paper EX/P4-28, IAEA FEC 2006, Chengdu, China, 2006

[2] J. E. Menard et al., Recent Physics Results from NSTX, Paper OV/2-4, IAEA FEC 2006, Chengdu, China, 2006

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 350° C
- Li coatings deposited by Li evaporator
- Li pellet injector

NSTX pumping

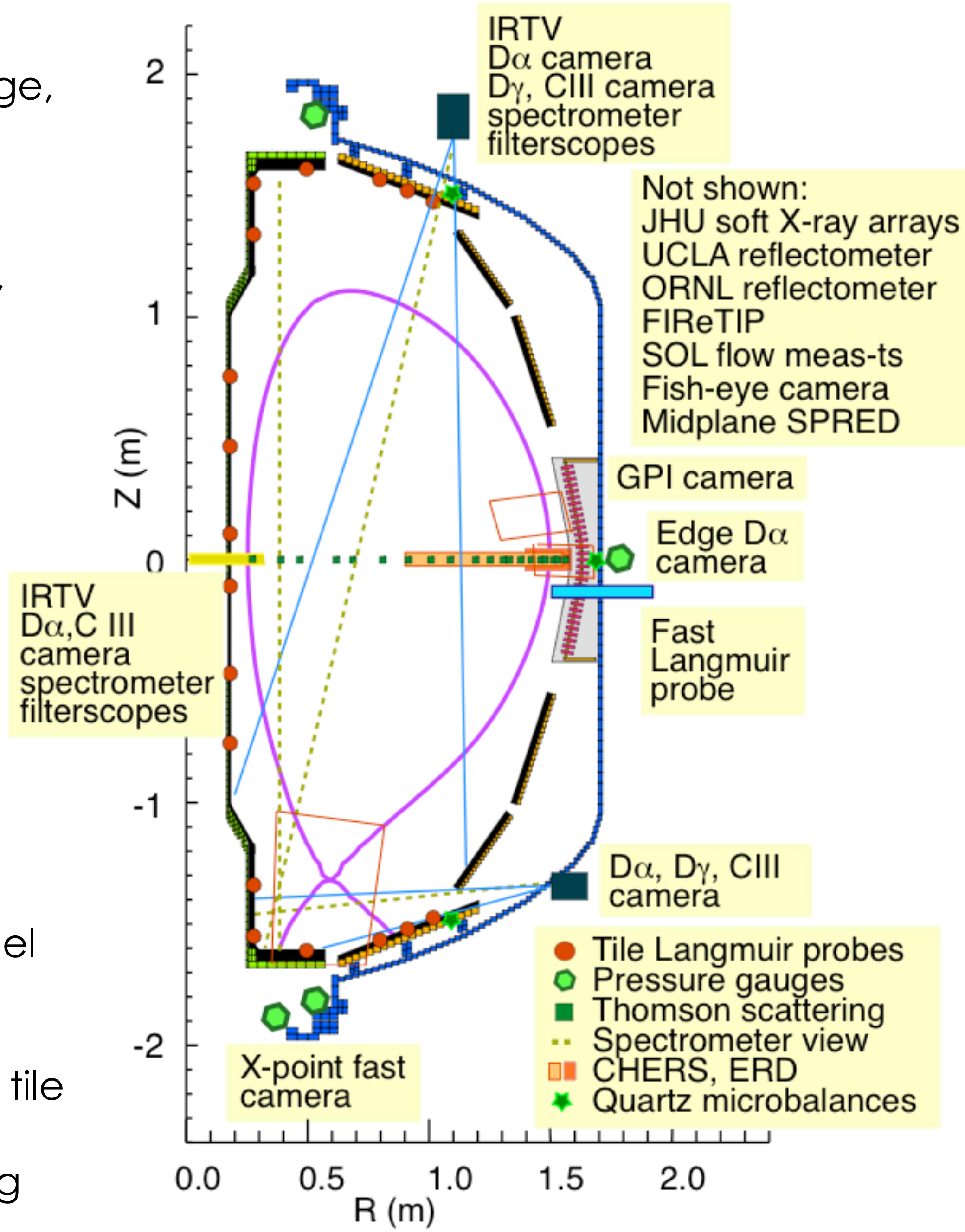
- Turbomolecular pump (3400 l / s)
- NBI cryopump (50000 l / s, in NBI plasmas only)
- Conditioned walls, Li coatings

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

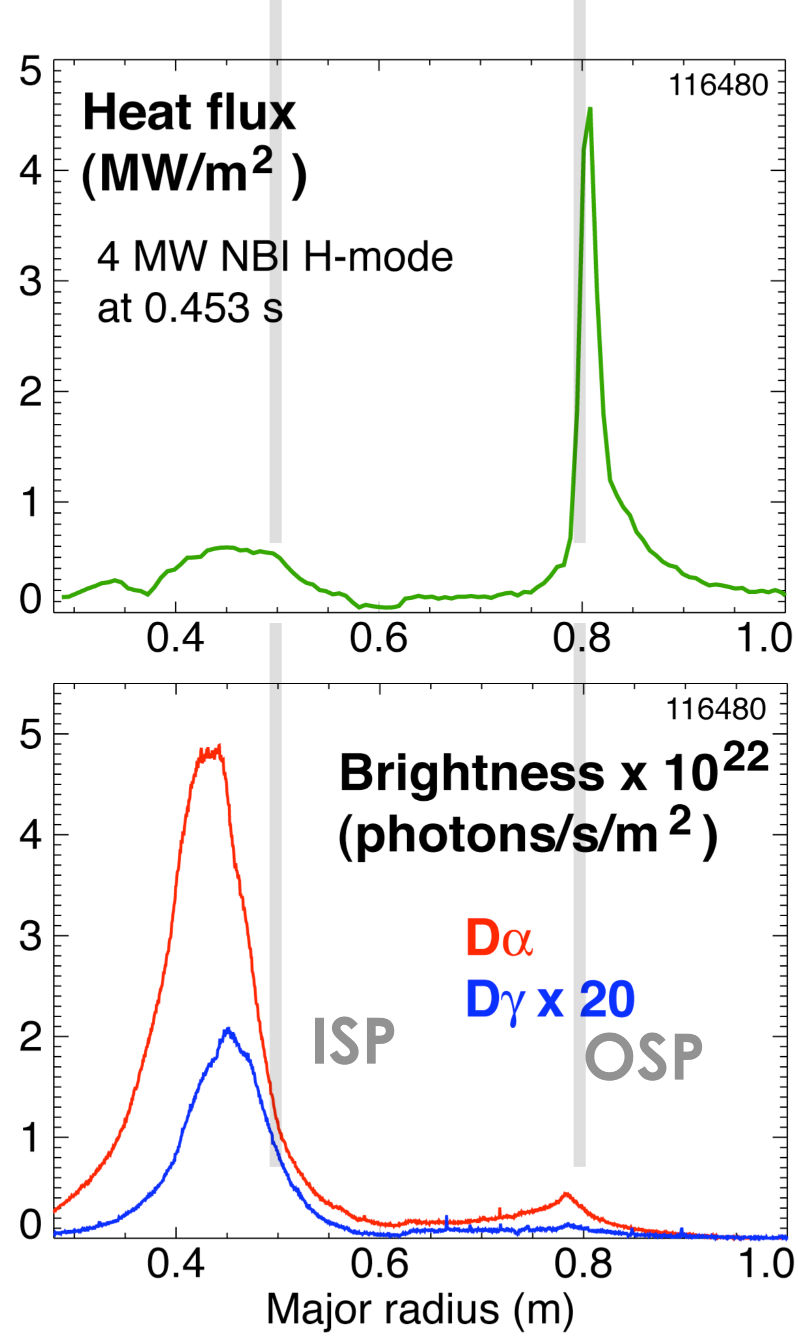
- **IRTV**: two Indigo Alpha 160 x 128 pixel microbolometer cameras, 7-13 mm range, 30 ms frame rate
- **Dα, Dγ, C III filtered cameras**: four Dalsa 1 x 2048 pixel CCDs, filter FWHM 10-15 A, frame rate 0.2 - 1 ms
- **Neutral pressure gauges**: four micro-ion gauges on top and at midplane, two Penning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



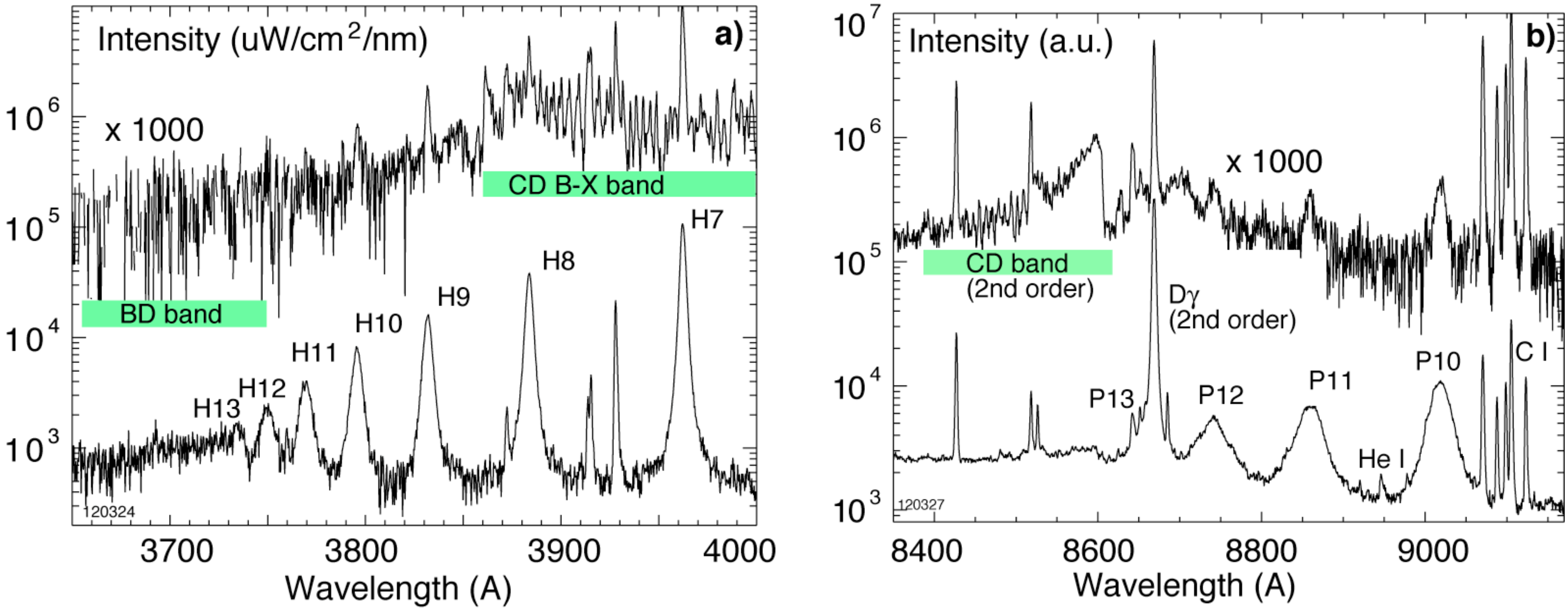
NSTX divertor regimes

- 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)

Open divertor geometry determines observed midplane and PFR pressure trends at low κ, δ

- 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)