Supported by Office of Science

Divertor heat flux reduction and detachment in the National Spherical Torus eXperiment

College W&M
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

V. A. Soukhanovskii

Lawrence Livermore National Laboratory, Livermore, CA

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

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

APS-DPP Meeting
Nov. 11-15, 2007
Orlando, FL

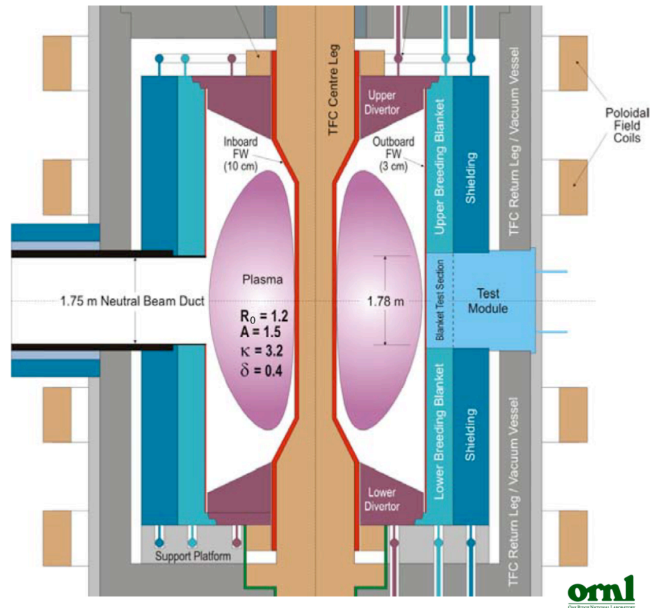
Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAERI
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

Acknowledgments

This work was performed under the auspices of the U.S. Department of Energy under Contracts W-7405-Eng-48, DE-AC52-07NA27344, DE-AC05-00OR22725, DE-AC02-76CH03073, and W-7405-ENG-36.

Divertor heat flux mitigation is key for present and future fusion plasma devices

- **Radiative divertor** is envisioned for present and future devices (e.g. ITER) as the **steady-state** heat flux mitigation solution
  - Divertor q_{peak} < 10 MW/m^2
  - Large radiated power fractions (f_{rad} = 0.50 - 0.80)
  - Integration with pedestal and core

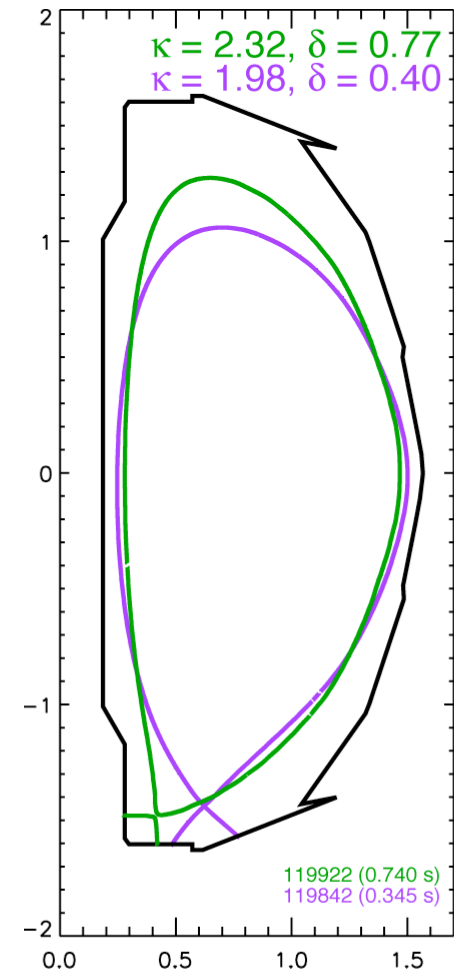


Peng et al, PPCF 47, B263 (2005)

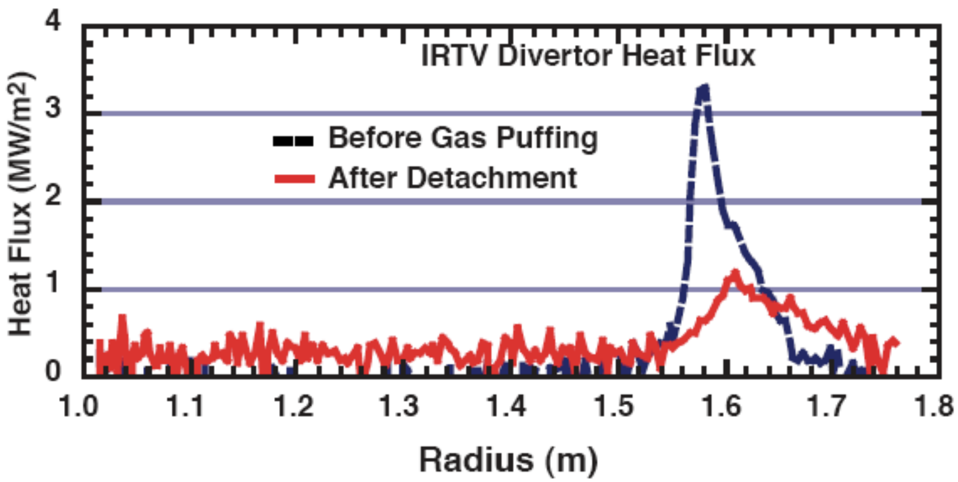
- Radiative divertor in NSTX
  - Does radiative divertor work in a spherical torus (ST) with a compact high $q_{||}$ divertor? What are the limitations?
  - Experimental basis for radiative divertor optimization and projections to ST-CTF

Talk Outline

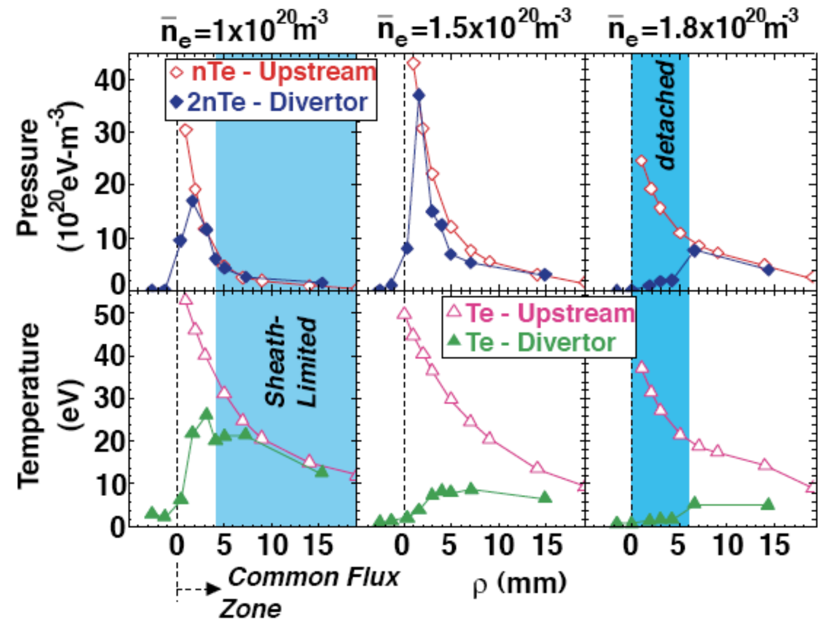
- Introduction - radiative divertors might be challenging for STs
- Radiative divertor experiments in NSTX
  - Low κ, δ H-mode plasmas
  - High κ, δ H-modes (high flux expansion divertor)
  - Partially detached divertor (PDD) in high κ, δ H-mode plasmas
- Six-zone model predictions
- Conclusions and future work



Radiative divertor concept developed in divertor tokamaks in the 1990s



Petrie et al., NF 37, 321 (1997)



LaBombard PoP 2, 2242 (1995)

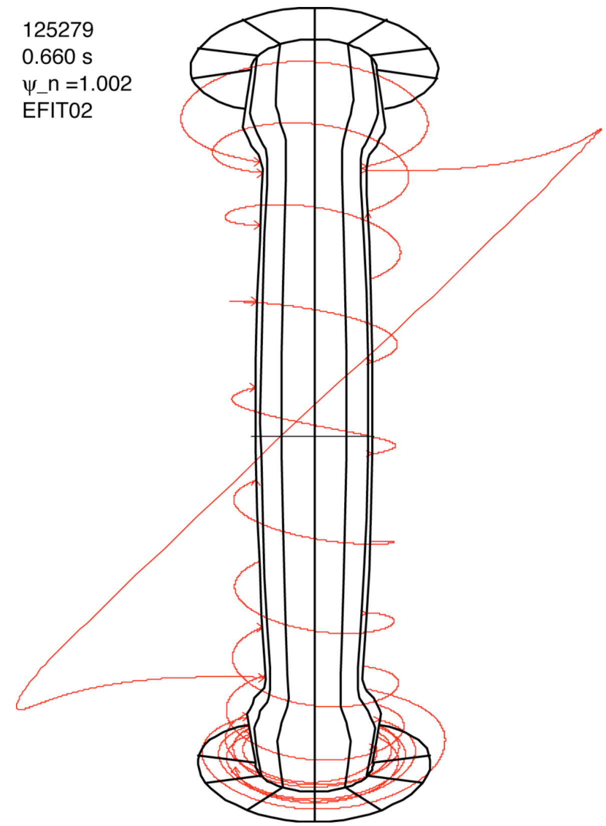
- Parallel momentum and power balance:

$$\frac{d}{ds}(m_i n v^2 + p_i + p_e) = \underbrace{-m_i(v_i - v_n)S_{i-n}}_{\text{CX \& elastic}} + \underbrace{m_i v S_R}_{\text{recombination}}$$

$$\frac{d}{ds}((-\kappa T_e^{5/2}\frac{dT_e}{ds}) + nv_{||}(\frac{5}{2}(T_i + T_e) + \frac{1}{2}m_i v_{||}^2 + I_0)) = \underbrace{S_E}_{\text{Rad. power}}$$

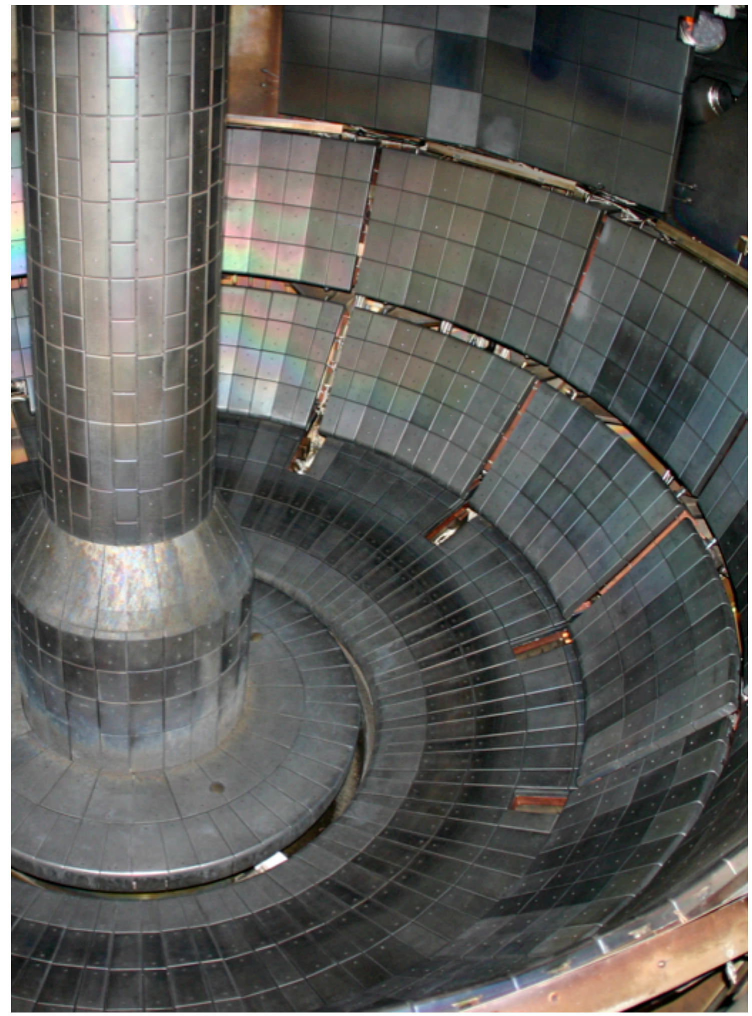
Divertor geometry in NSTX is different from high aspect ratio tokamak divertors

	NSTX high κ,δ	Tokamak
Aspect ratio	1.3	2.7
In-out SOL area ratio	1:3	~ 2:3
Parallel connection length $L_{\|\|}$, midplane to target (m)	8-12	30-80
$L_{\|\|}$, X-point to target (m)	5-8	10-20
Angle at target (deg)	5-15	1-2



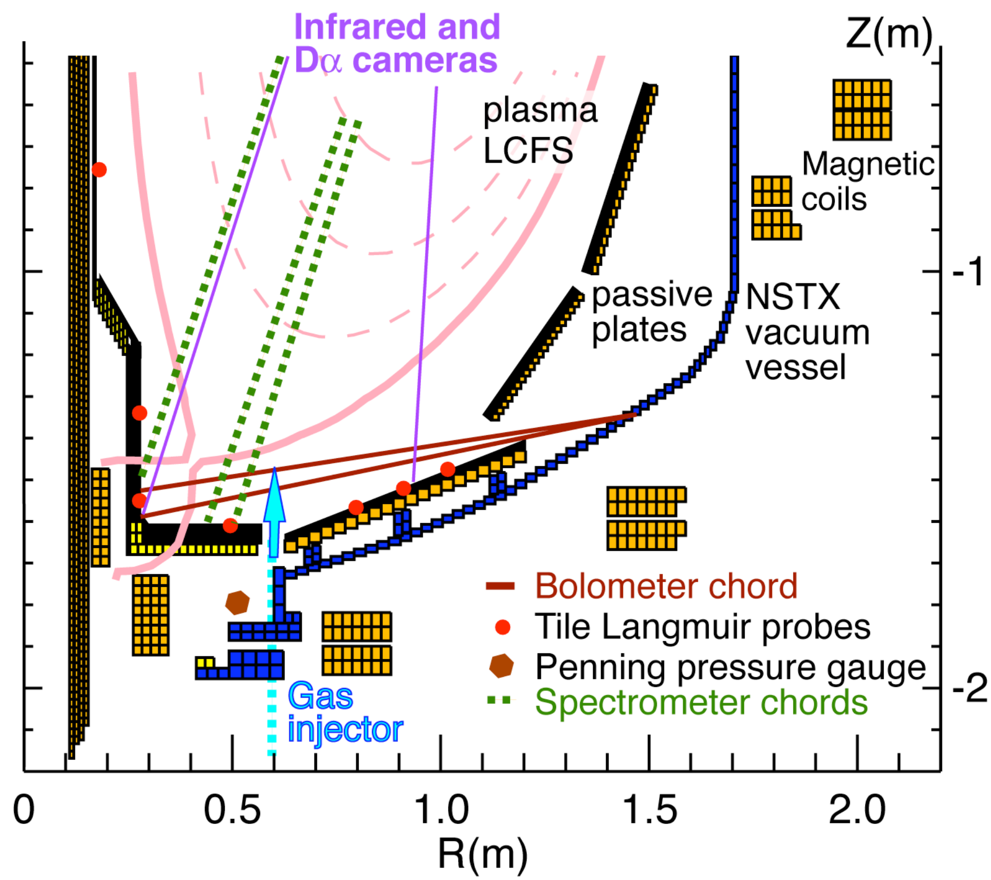
Open geometry NSTX divertor enables flexibility in plasma shaping

- Plasma facing components
  - ATJ and CFC tiles
  - Carbon - erosion, sputtering
  - Max P_{rad} fraction limited by carbon radiation efficiency
  - Typical divertor tile temperature in 1 s pulses $T < 500$ C ($q_{peak} \leq 10$ MW/m^2)
- No active divertor pumping
  - Experiments with lithium coatings for reduced recycling

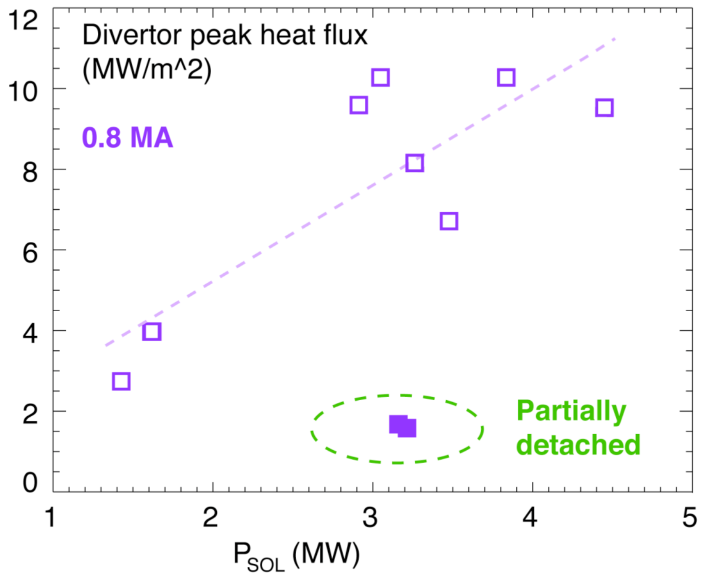


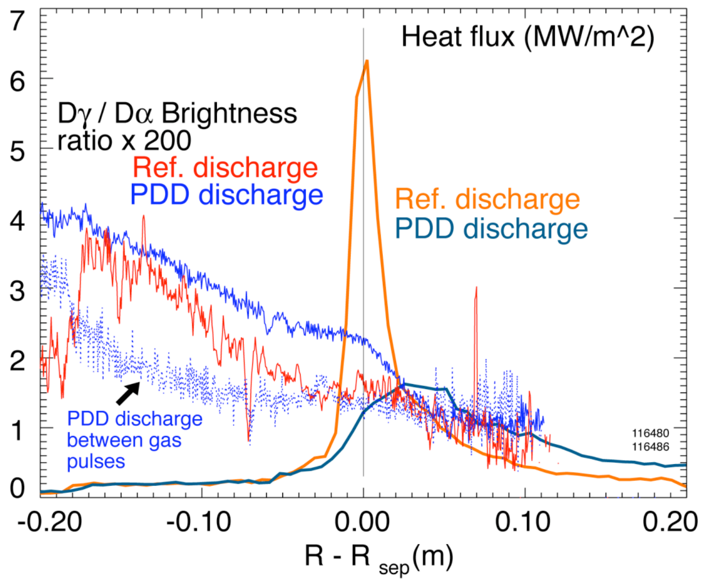
NSTX diagnostics set enables divertor characterization

- Diagnostic set for divertor studies:
  - IR cameras
  - Bolometers
  - Neutral pressure gauges
  - Tile Langmuir probes
  - 1D CCD arrays for Dα, Dγ
  - UV-VIS spectrometer (3 divertor chords)
- Midplane Thomson scattering and CHERS systems
- Divertor gas injector Γ_{gas} = 60-160 Torr l / s



q_{peak} reduction by PDD at low κ, δ achieved albeit with confinement degradation



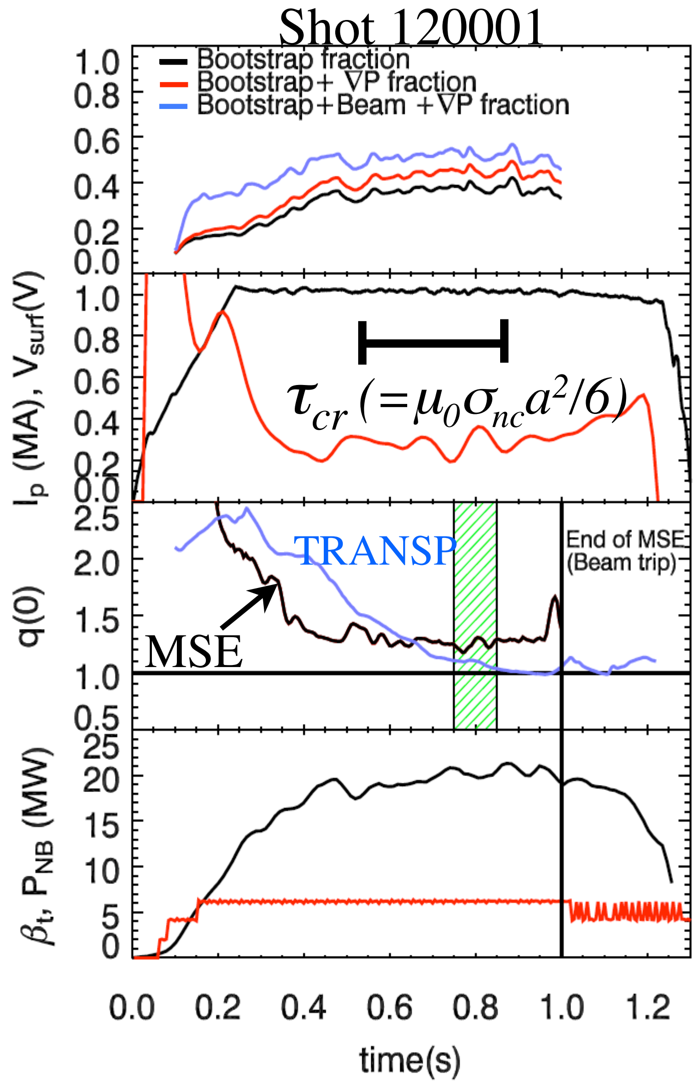


- Peak heat flux in outer divertor (**Maingi JNM 363-365, 196 (2007)**):
  - ITER-level q_{out}< 10 MW/m^2
  - Scaling of q_{peak}: linear with P_{sol} (P_{NBI}), linear-monotonic with I_p
  - Large q_{peak} asymmetry - 2-10; inner divertor always detached
- Experiments using D_2 injection (**Soukhanovskii IAEA 2006**):
  - q_{peak} reduced by up to 60 % in transient PDD regime
  - X-point MARFE degraded confinement within 2-3 x τ_E

High plasma performance and reduced q_{pk} are attained in highly shaped plasmas

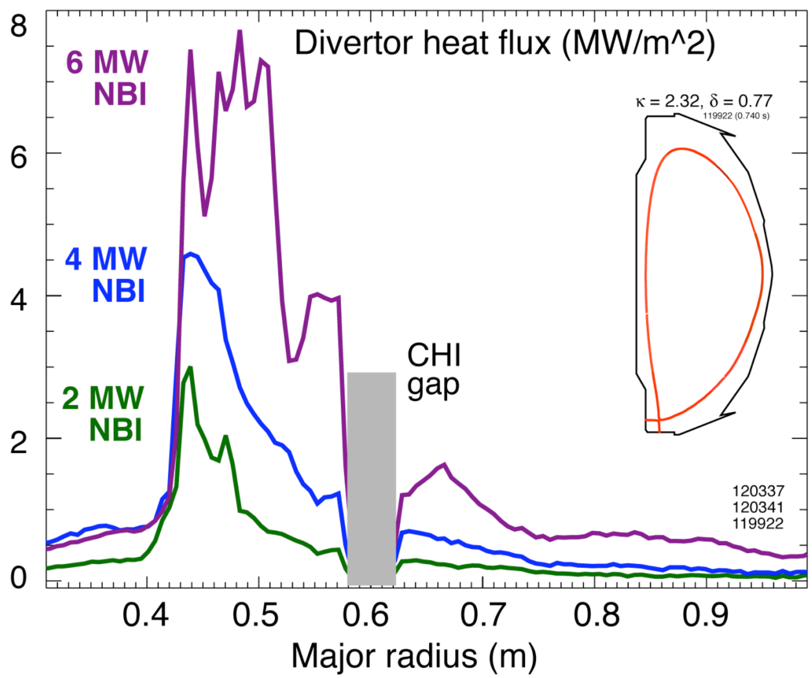
- High performance H-mode
  (**Gates APS 2005, Maingi APS 2005, Menard IAEA 2006**)
  - κ = 2.2-2.3, δ = 0.65-0.75, *drsep* ~ 5-10 mm
  - H89P ~ 2.0
  - β_t = 15 - 25 %
  - f_{bs} = 45 - 50 %
  - longer pulses ~50 x τ_E
  - smaller ELMs

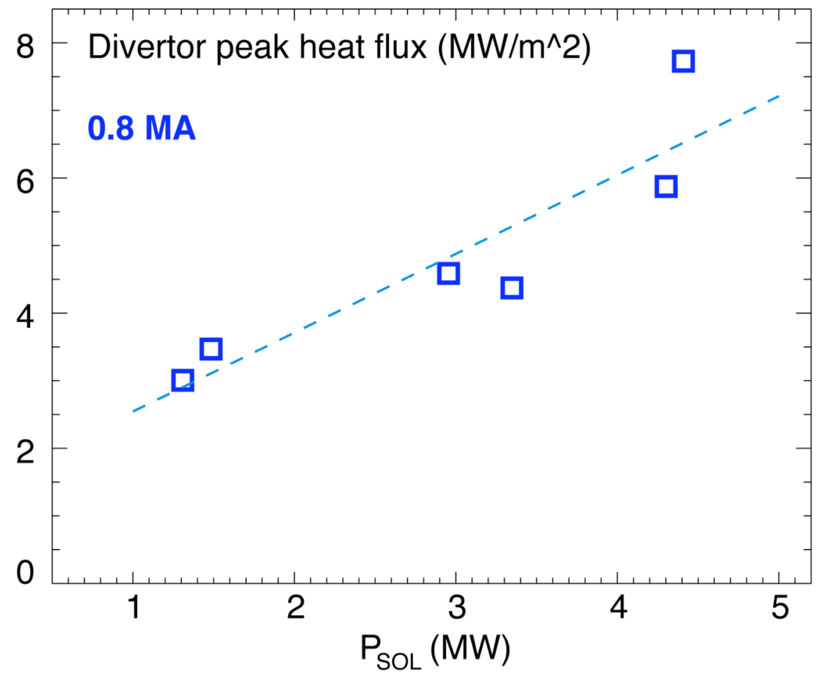
- Divertor in highly shaped plasmas
  - Flux expansion, area expansion (q_{peak} ↓)
  - Higher isothermal SOL volume (P_{rad} ↑)
  - Lower L_p (neutral penetration ↑)
  - Neutrals recycle toward separatrix



Reduced q_{peak} is a natural benefit of highly shaped configuration

- q_{peak} scales linearly with P_{SOL} with lower slope than at low κ, δ
- Flux expansion 16-24, area expansion 5-8
- While q_{peak} is reduced, total Q_{div} is not

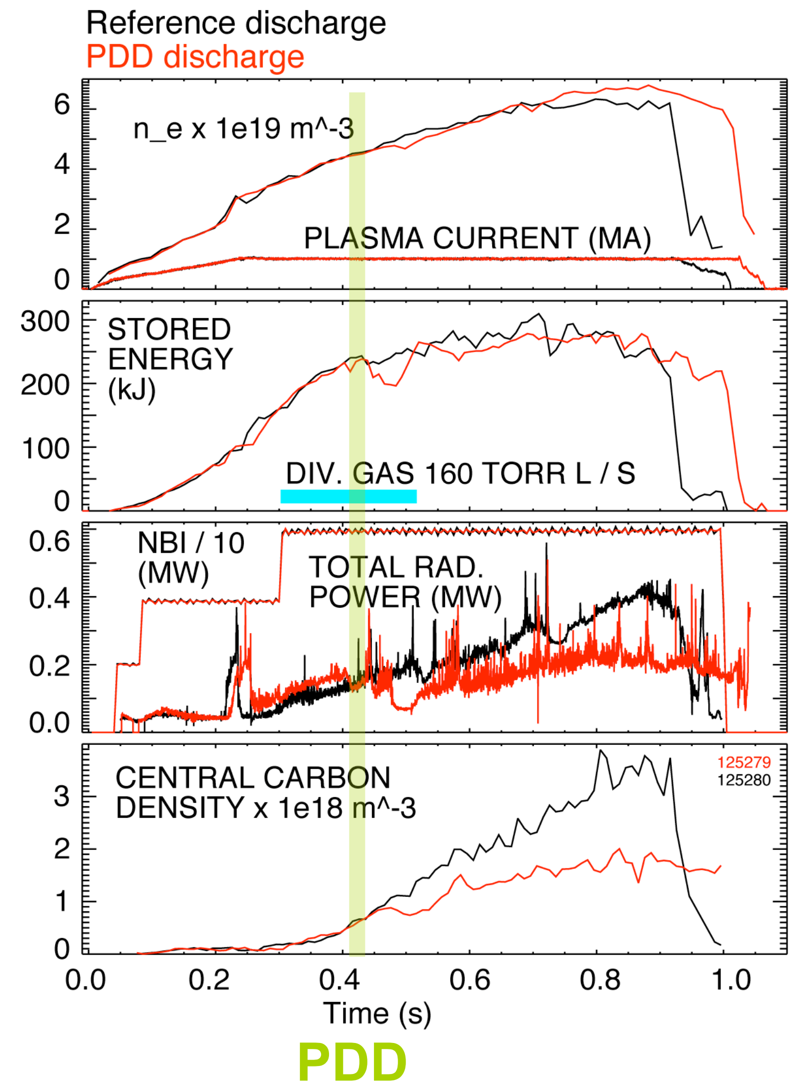




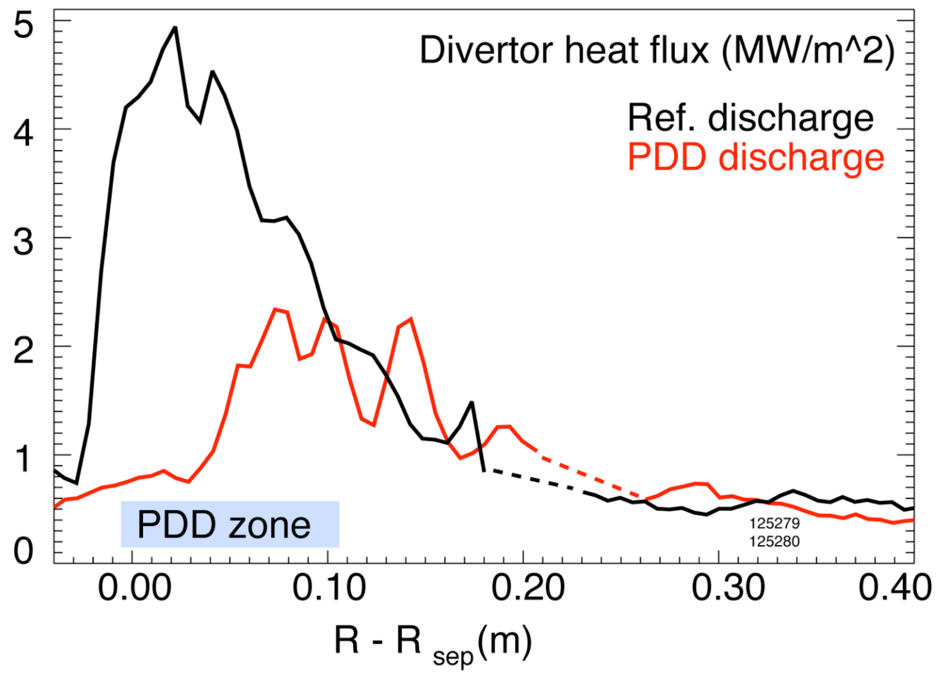
High core and pedestal plasma performance during PDD is achieved in high κ, δ configuation

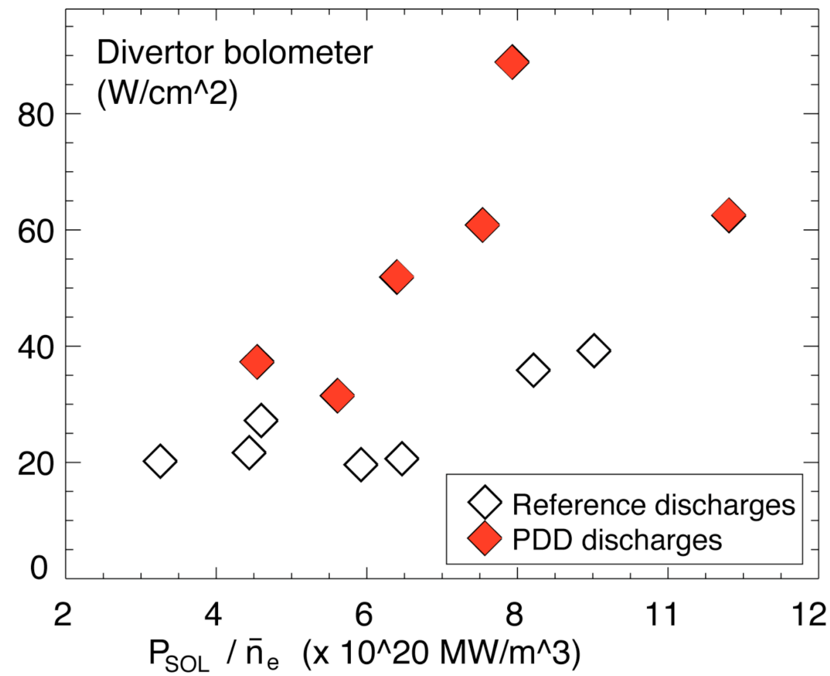
- Detachment experiments
  - I_p = 0.8 - 1.0 MA
  - P_{NBI} = 4 -6 MW
  - n_e=0.85 x n_G
  - D_2 injection in divertor

- High core plasma performance during PDD phase
  - No effect on W_{MHD} or pedestal
  - Core P_{rad} and n_c decreased
  - Small ELMs ($\Delta W_{MHD} / W_{MHD} \leq$ 1%) and mixed ELMs



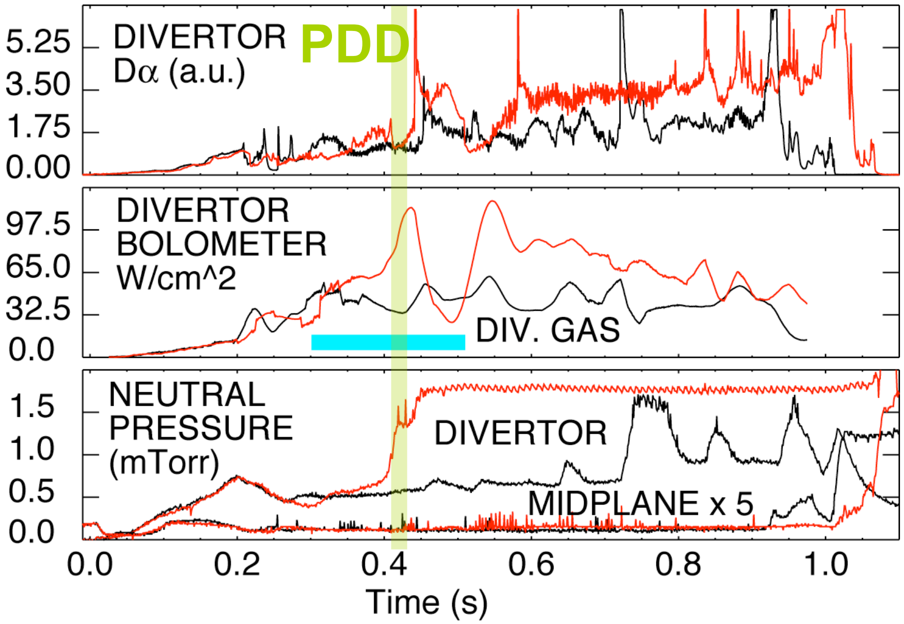
Peak heat flux reduced by 60 % in PDD phase

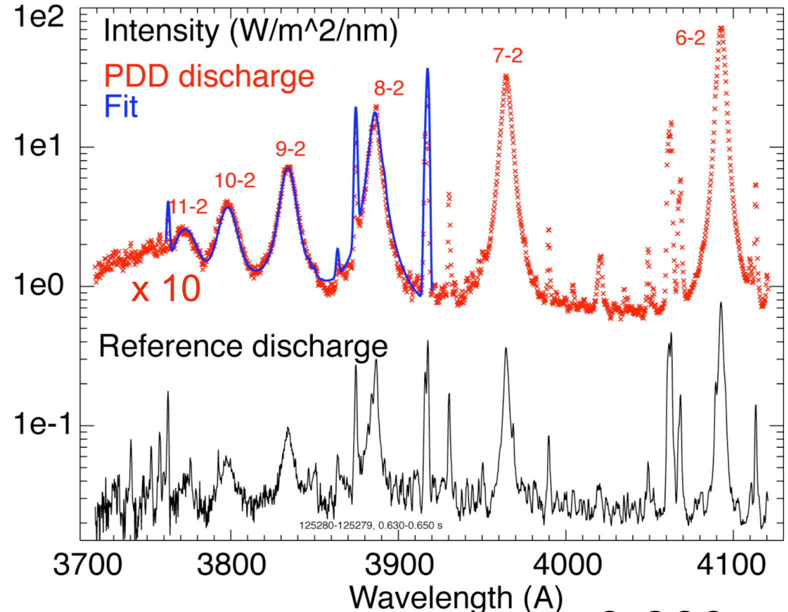




- λ_q changed from 5-10 cm to 10-15 cm
- PDD zone 10-15 cm
- Bolometer signal (P_{rad}) increased by 30-60 % in PDD phase

Neutral pressure, radiated power, and recombination rate increase in PDD phase



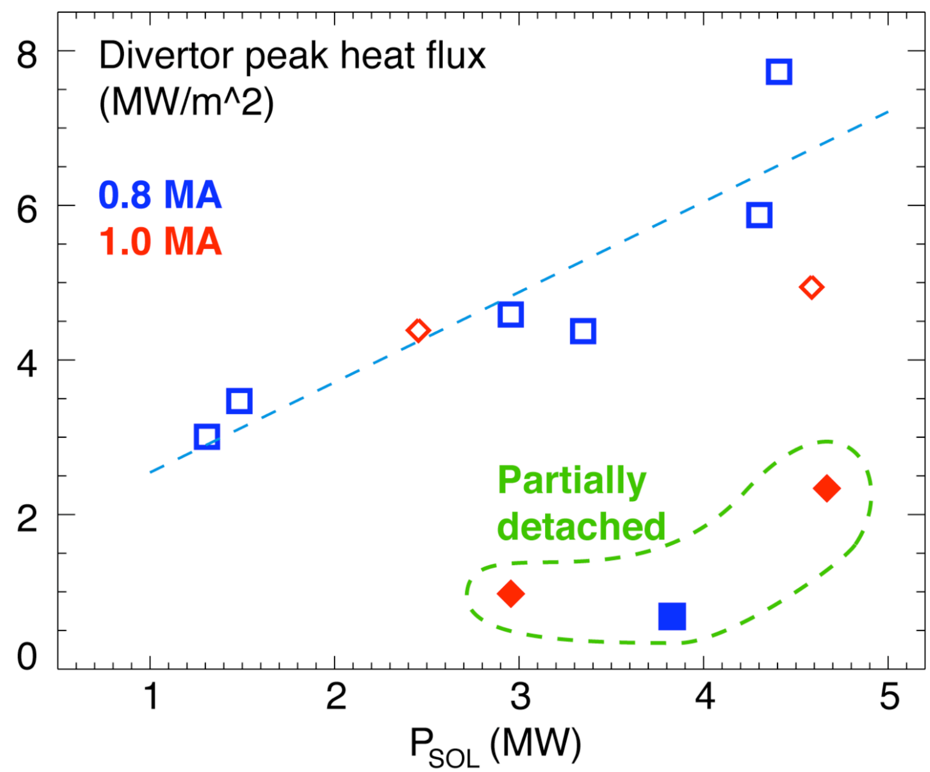


0.660 ms

- Onset of PDD phase within 50-100 ms from start of gas:
  - P_{rad} increased 50 %
  - Divertor neutral pressure increased x 3, midplane pressure did not increase
  - Increase in recombination rate, D I Balmer spectra (8…11 - 2) indicate
    - T_e < 0.7-1.2 eV (from line intensity ratio according to Saha-Boltzman formula)
    - $n_e \sim$ 2-6 x 10^{20} m^{-3} (from Stark broadening and MMM calculations)
- More measurements needed to characterize power and momentum loss in outer leg

Good core plasma performance and significant q_{peak} reduction obtained in PDD regime

- q_{peak} reduced by 60 - 80 % in PDD phase
- q_{peak} in PDD appears to scale with P_{SOL} - *radiative heating?*
- Observed PDD properties similar to tokamaks (e.g. DIII-D *)



* Petrie et al., NF 37, 321 (1997)

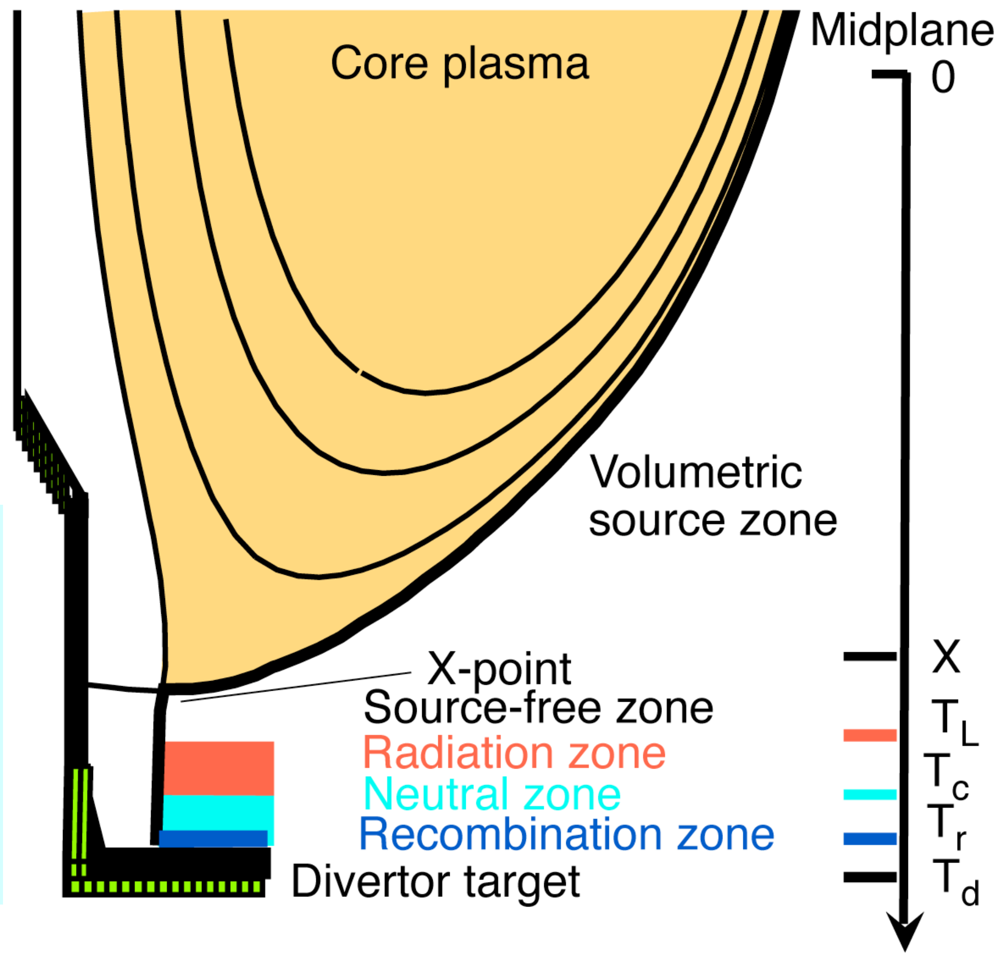
Six-zone 1D analytic SOL / divertor model captures essential features of detachment

- **Goswami PoP 8, 857 (2001)**
- Zone locations defined by temperature of process
- Sources and sinks $Q_{\perp}$, $S_{\perp}$, $\Gamma_{i\text{-}div}$, f_{rad}, R_{rec}, $\nu_{i\text{-}n}$ as input

$$\text{Continuity: } \frac{d}{dx}(nv) = S_n$$

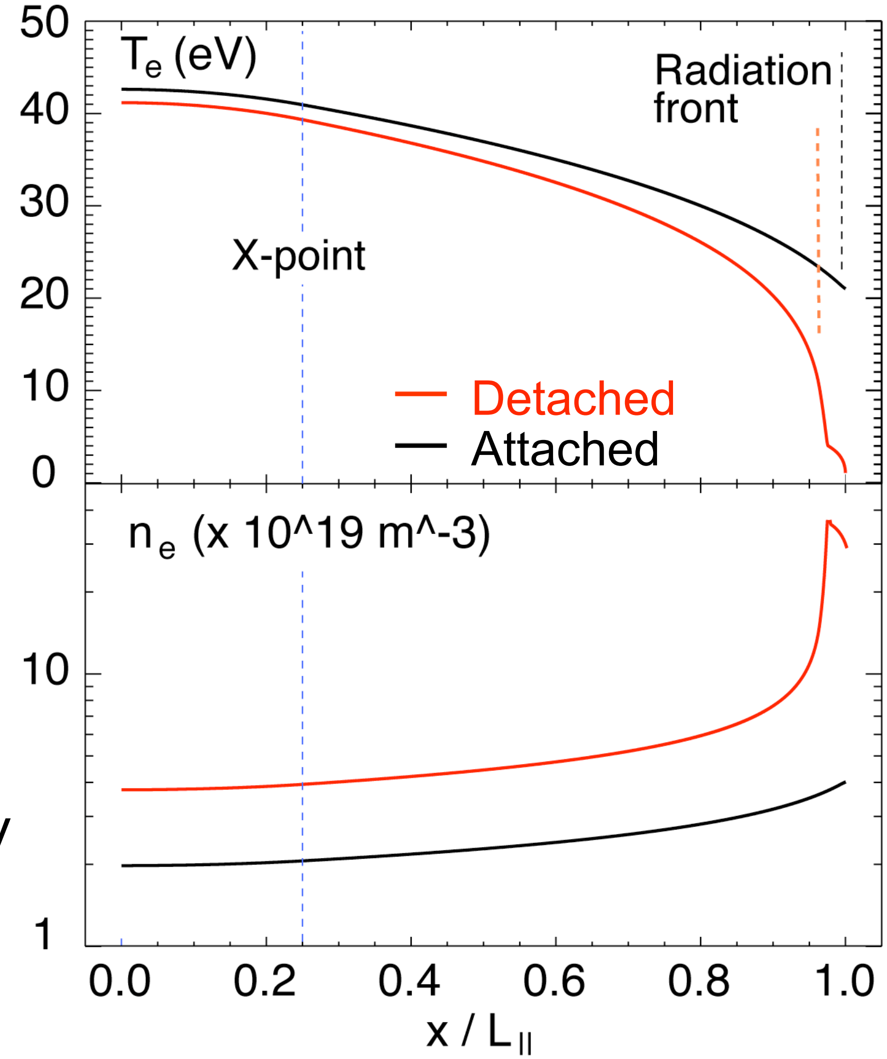
$$\text{Momentum: } \frac{dp}{dx} = S_p$$

$$\text{Energy: } \frac{d}{dx}\left(\kappa_0 T_e^{5/2} \frac{dT_e}{dx}\right) = S_q$$



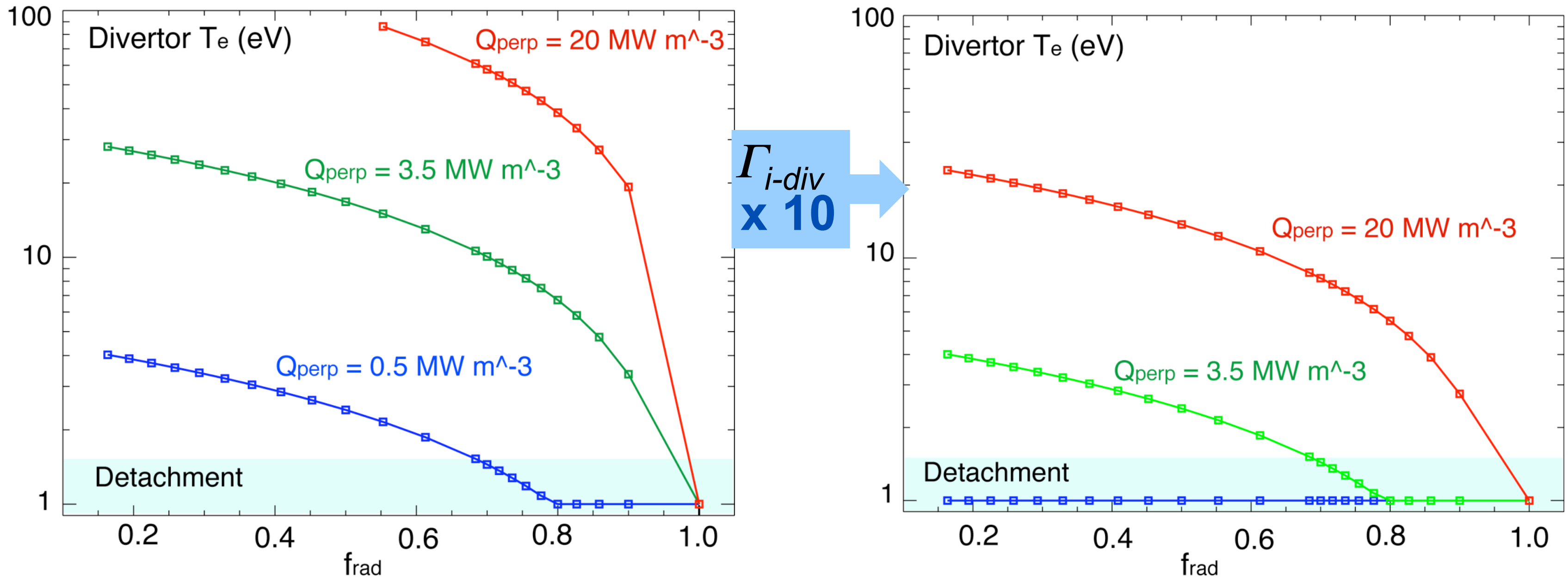
Model predictions consistent with experiment within NSTX range of SOL parameters

- NSTX SOL / divertor parameters
  - $Q_{\perp}$ = 0.5 - 20 MW m^{-3} (high)
  - $S_{\perp}$ = 0.01-3 x10^{23} s^{-1} m^{-3}
  - L_x = 5-10 m (low)
  - R_{rec} = 10^{23} s^{-1} m^{-3}
- Example calculation
  - $Q_{\perp}$ = 10 MW m^{-3}
  - $S_{\perp}$ = 6 x 10^{22} s^{-1} m^{-3}
  - f_{rad} = 0.3 (attached)
  - f_{rad} = 0.9 (detached)
- Recombination onset at T_e < 1.5 eV
- Detachment at T_e < 1.0 eV



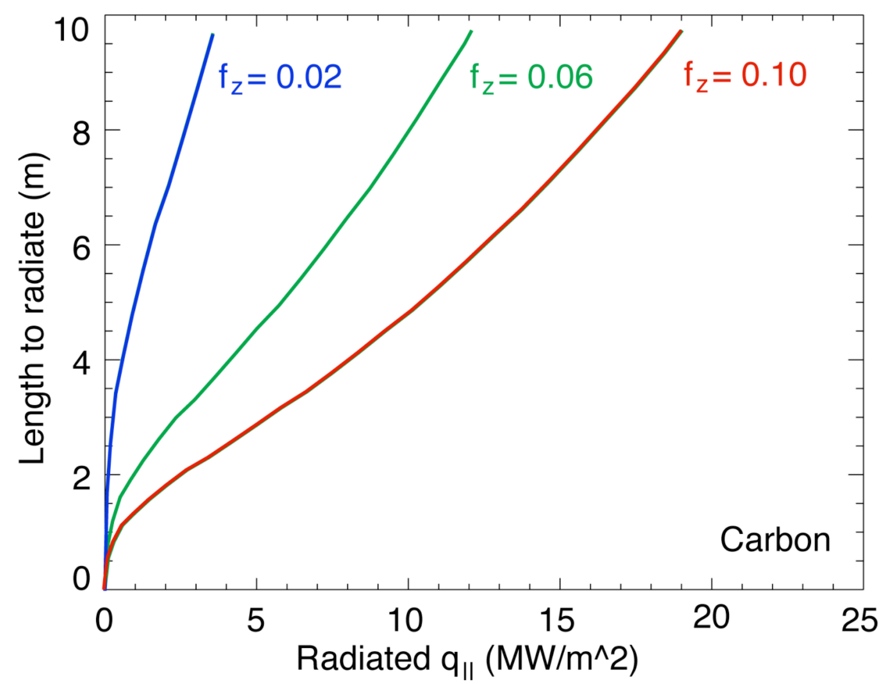
All routes to detachment predicted by model involve high f_{rad}

- Detachment at NSTX-range of $Q_{\perp}$, $S_{\perp}$ can be achieved in model by
  - increasing f_{rad} (shown)
  - increasing $\Gamma_{i\text{-}div}$ (gas puff)
  - increasing $S_{\perp}$ (not shown)



High f_{rad} can be marginally achieved with carbon in NSTX divertor

- Hulse-Post non-coronal radiative cooling curves for low Z impurities for n_0/n_e, n_e-τ_{recy}
- Calculate max $q_{||}$ that can be radiated
- Express max $q_{||}$ as function of distance from heat source for range of f_z (Post JNM 220-222, 1014 (1995))
- Power losses due to deuterium P_{rad} and ionization not considered
- Carbon works marginally in NSTX ($q_{||}$ ~ 25 - 60 MW/m^2)



$$q_{||} = -\kappa_0 T_e^{5/2} \frac{\partial T_e}{\partial x}$$

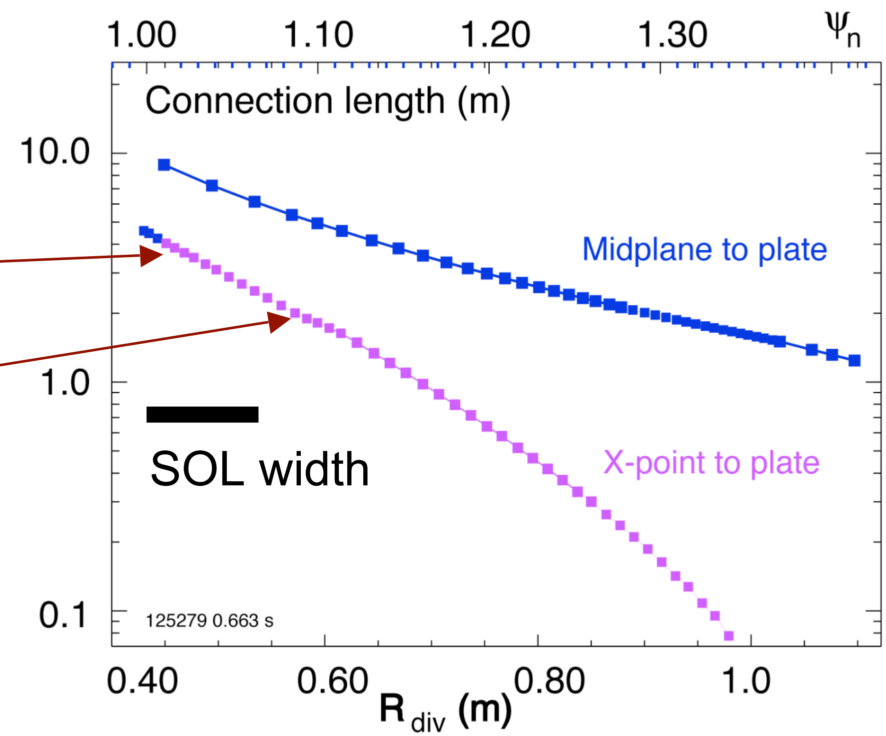
$$\frac{\partial q_{||}}{\partial x} = -n_e n_z L_Z(T_e)$$

Volumetric power and momentum losses are limited by L_x (R) at high magnetic field shear

- Fraction of $q_{||}$ to be radiated is a function of L_x for given impurity
  - high f_{rad} only where L_x longest
- Electron-ion recombination rate depends on divertor ion residence time
  - Ion recombination time: τ_{ion}~ 1−10 ms at T_e =1.3 eV
  - Ion residence time: $\tau_{ion} \leq$ 1 ms

possible to detach
L_x ~ 5-6 m

difficult (impossible)
to detach *L_x ~ 5-6 m*



Conclusions and future work

- Significant divertor **peak heat flux reduction** has been demonstrated in highly shaped high-performance H-mode plasmas in NSTX using **divertor magnetic flux expansion and radiative divertor** simultaneously with **high core plasma performance**
  - Good synergy of high performance small ELM H-mode regime with PDD
- Starting to learn detachment characteristics and limitations
  - Detachment achieved only with additional gas injection
  - PDD regime onset is abrupt. High radiated power, neutral pressure, volume recombination rate are measured
  - PDD properties appear to be similar to those observed in tokamaks
- Future work:
  - q_{peak} reduction in PDD regime in double null configuration
  - Liquid lithium divertor - planning for installation in 2008

Related NSTX talks and posters

Session CO3: NSTX and General Spherical Tokamak, **Monday, November 12, 2007 2:00PM**

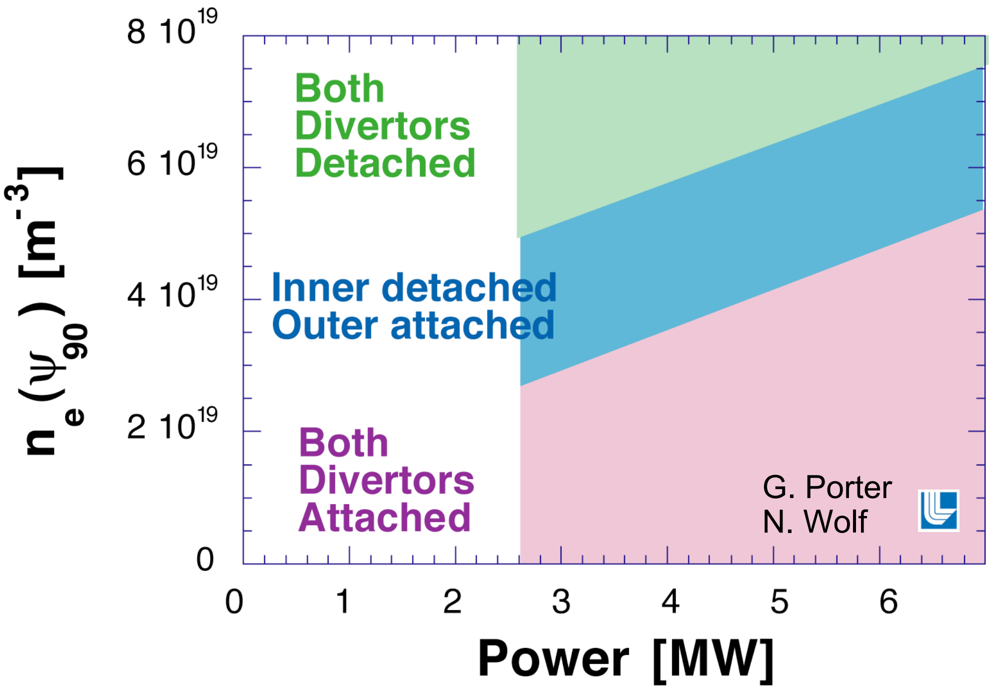
- **CO3.00008**: R. Maingi, T. Biewer, H. Meyer, R. Bell, B. LeBlanc, C.S. Chang, Dependence of the L-H power threshold on magnetic balance and heating method in NSTX
- **CO3.00014**: L.E. Zakharov, R. Majeski, Lithium Loaded Target Plate for driving NSTX toward high performance

Session TP8: Poster Session VII: NSTX Spherical Torus, **9:30 AM, Thursday, November 15, 2007**

- **TP8.068** D.P. Stotler, R. Maingi, A.Yu. Pigarov, M.E. Rensink, T.D. Rognlien, UEDGE Simulations of the NSTX Liquid Lithium Divertor Module
- **TP8.090** J.-W. Ahn, J. Boedo, R. Maingi, V. Soukhanovskii, H. Kugel, L. Roquemore, SOL width scale lengths in NSTX
- **TP8.092** R.J. Maqueda, R. Maingi, C.E. Bush, K. Tritz, J.-W. Ahn, J.A. Boedo, S. Kubota, E. Fredrickson, S.J. Zweben, Structure and evolution of ELMs in the edge and SOL of NSTX
- **TP8.094** D.A. Russell, J.R. Myra, D.A. D'Ippolito, R. Maqueda, V.Soukhanovskii, S.J. Zweben, Reduced simulations of boundary turbulence in NSTX
- **TP8.095** T. Stoltzfus-Dueck, J.A. Krommes, S.J. Zweben, Modeling of Blob Formation in NSTX Edge Turbulence
- **TP8.096** V.A. Soukhanovskii, R.E. Bell, R. Kaita, A.L. Roquemore, R. Maqueda, Spectroscopic T_e and n_e measurements in a recombining divertor region and in MARFEs in NSTX using D I and He II high-*n* series line emission.
- **TP8.100** D.P. Lundberg, V.A. Soukhanovskii, M.G. Bell, R.E. Bell, R. Kaita, H.W. Kugel, B.P. LeBlanc, J.E. Menard, A.L. Roquemore, D.P. Stotler, R. Maingi, R. Raman, Supersonic gas jet fueling efficiency studies

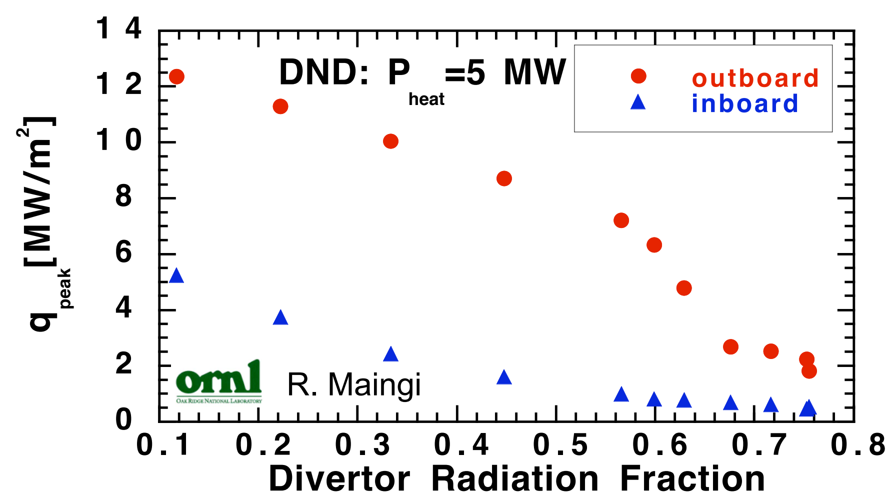
Backup

Divertor detachment is linked to operating space parameters



- Operating space P_{in}, n_e
- Model UEDGE calculations predicted limited "window" of outer divertor detachment

- Simple two-point model predicted high divertor radiation fractions to reduce q_{pk}



NSTX Lawrence Livermore National Laboratory