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High flux expansion divertor studies in NSTX

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Summary

- High flux expansion divertor studies have been carried out in NSTX using steady-state X-point height variations from 22 to 5-6 cm

- Small-ELM H-mode confinement was maintained at all X-point heights

- Flux expansions from 6 to 26-28 were obtained, with associated reduction in X-point connection length from 5-6 m to 2 m. Peak heat flux was reduced from 7-8 MW/m^2 to 1-2 MW/m^2. In low X-point configuration, outer strike point became nearly detached

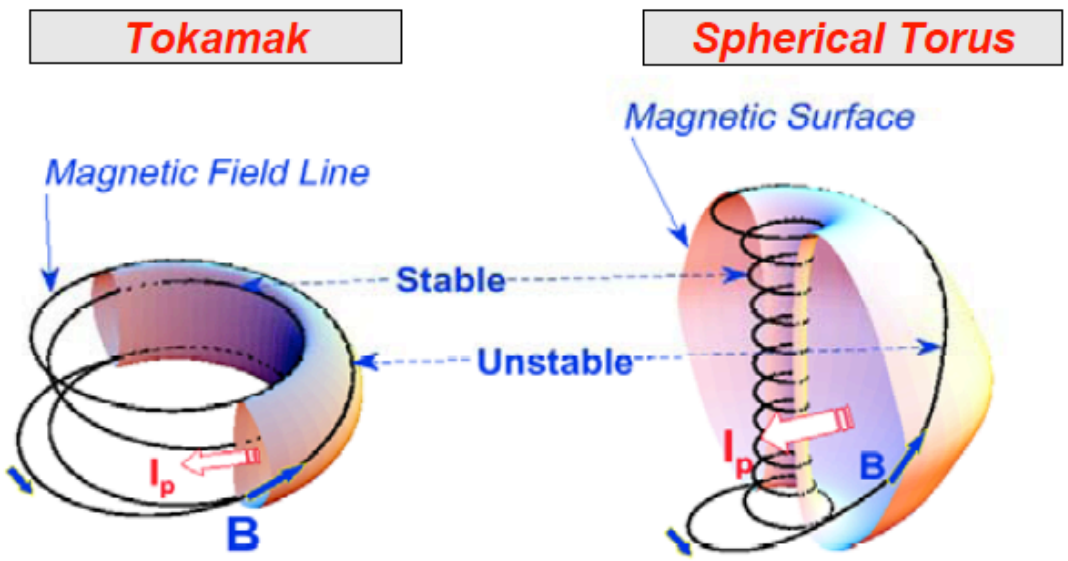
- Among factors affecting deposition of parallel heat flux in the divertor, the flux expansion factor appeared to be dominant

Experiments in NSTX demonstrated several ways of divertor peak heat flux reduction in ST

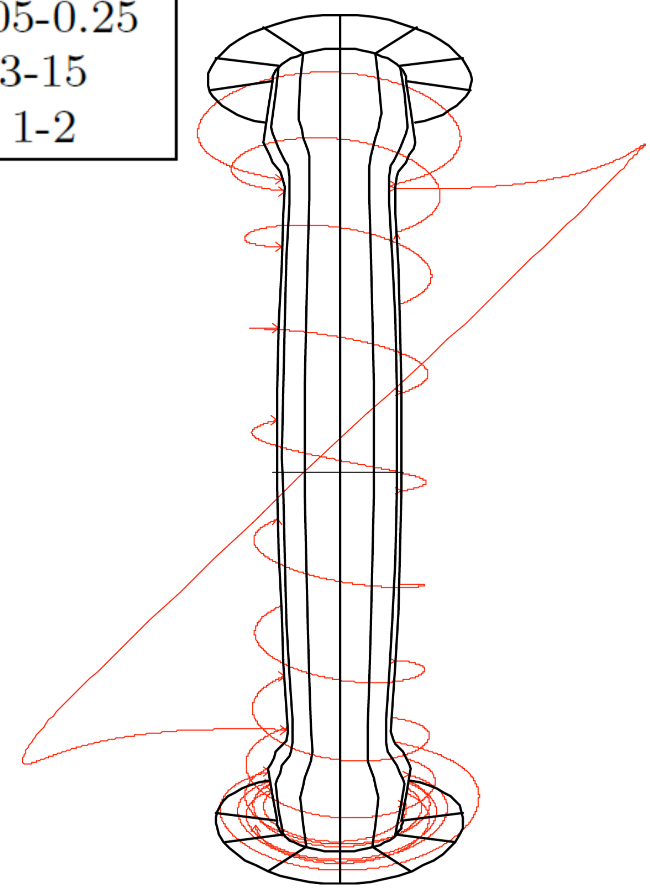
- **Divertor heat flux mitigation solutions:**
  - ✓ Poloidal flux expansion at outer strike point (OSP)
    - Particularly well suited for STs, reduced q_{peak} by up to 50 % in NSTX
  - ✓ Strike point sweeping (Plasma stability and control issues?)
  - ✓ Radiative divertor
    - reduced q_{peak} by up to 60 % in NSTX with D_2 injection while maintaining good confinement
  - ✓ Radiative mantle
    - reduced q_{peak} by up to 50 % in NSTX (w/ neon) albeit confinement degradation
  - ✓ Divertor materials and geometry (plate tilt, closure, number of divertors…)
- **These solutions must be compatible with good core plasma performance (H-mode confinement, MHD, ELM regime, density)**
- **Solutions must scale to very high q_{peak} (15 - 60 MW/m^2) for future devices (e.g., NHTX, ST-CTF)**
  - Combinations of solutions may work

SOL / divertor geometric properties are different in spherical tori and large aspect ratio tokamaks

Quantity	NSTX	Tokamak
Aspect ratio	1.4-1.5	2.7
In-out plasma boundary area ratio	1:3	2:3
Midplane to target connection length L_c (m)	8-10	30-80
X-point to target parallel length L_x (m)	5-7	10-20
X-point to target poloidal length L_p (m)	0.05-0.15	0.05-0.25
Poloidal magnetic flux expansion f_m at OSP	16-24	3-15
Magnetic field angle at target (degree)	2-5	1-2



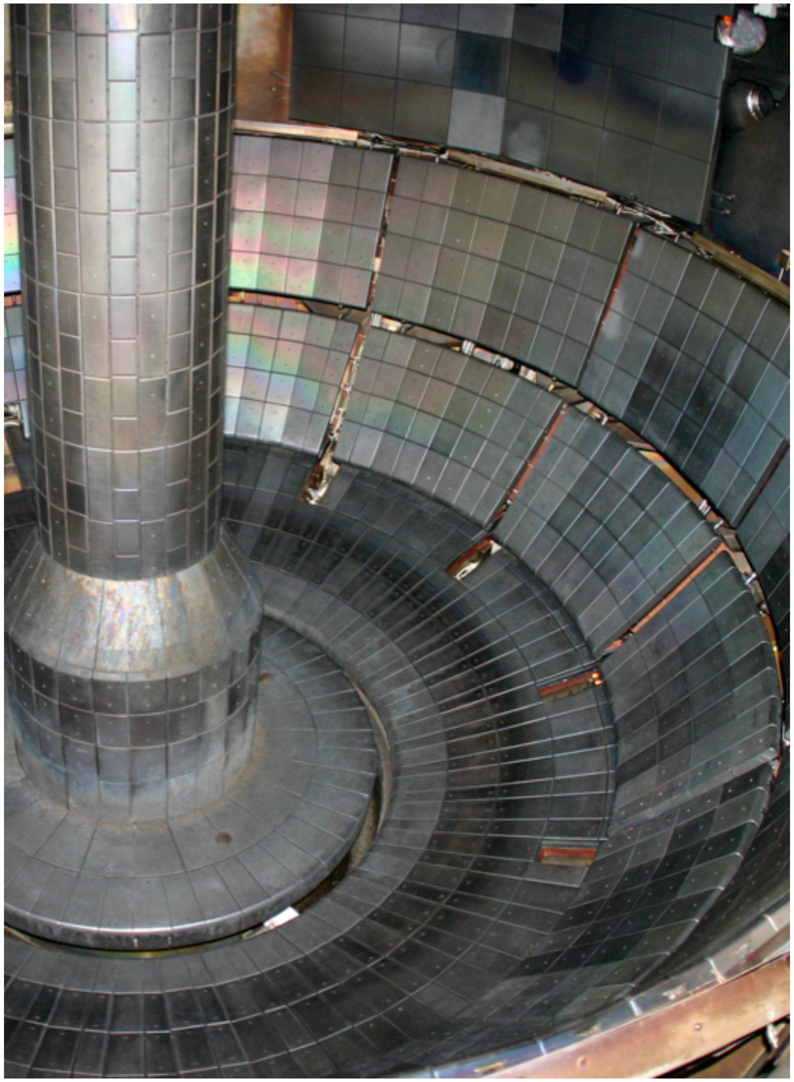
R/a=2.5-4, κ=1.5-2, q_e=3-5   R/a=1.1-1.6, κ=2-3, q_e=6-15



Open geometry NSTX divertor enables flexibility in plasma shaping

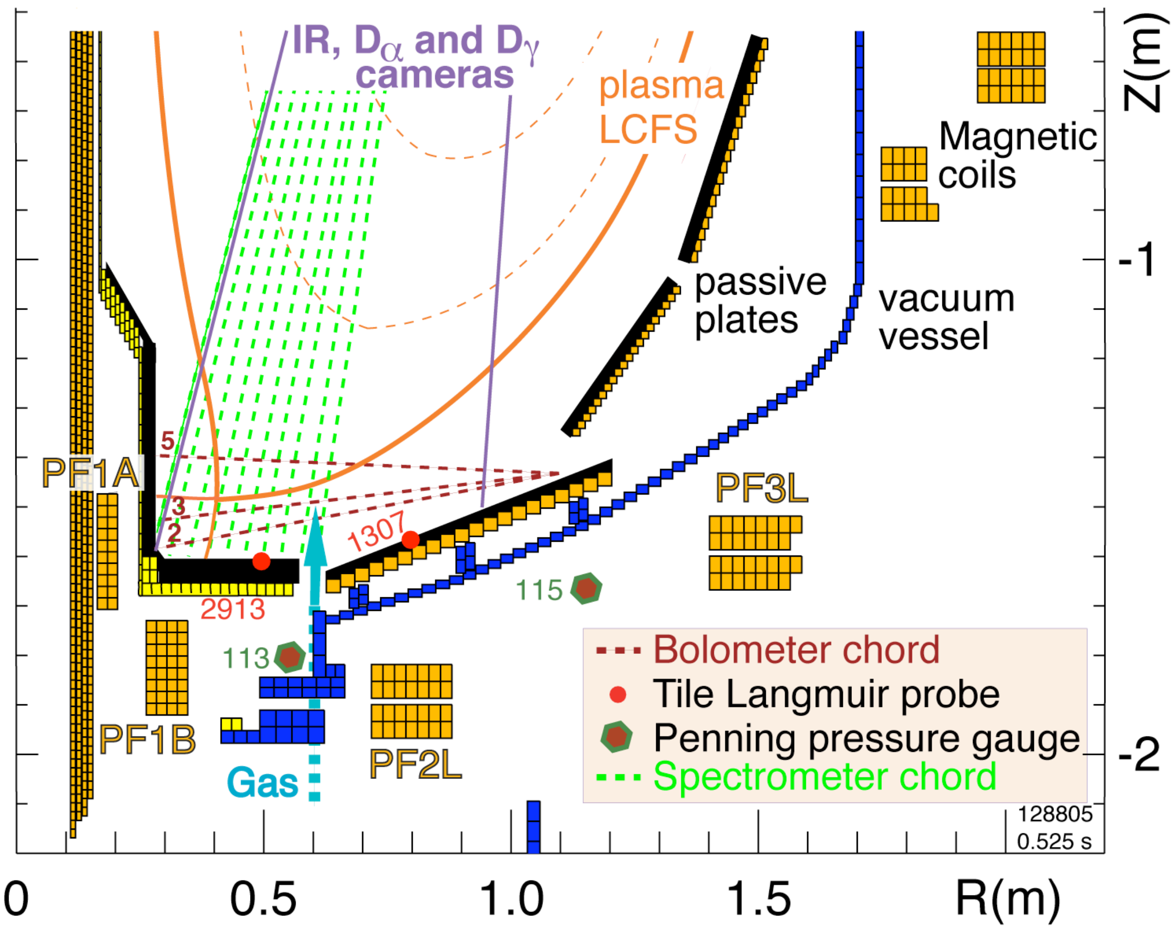
- Plasma facing components
  - ATJ and CFC tiles
  - Carbon - erosion, sputtering
  - Max P_{rad} fraction limited by carbon radiation efficiency
  - Typical divertor tile temperature in 1 s pulses T < 500 C ($q_{peak} \leq 10$ MW/m^2)

- No active divertor pumping
  - Experiments with lithium coatings for reduced recycling

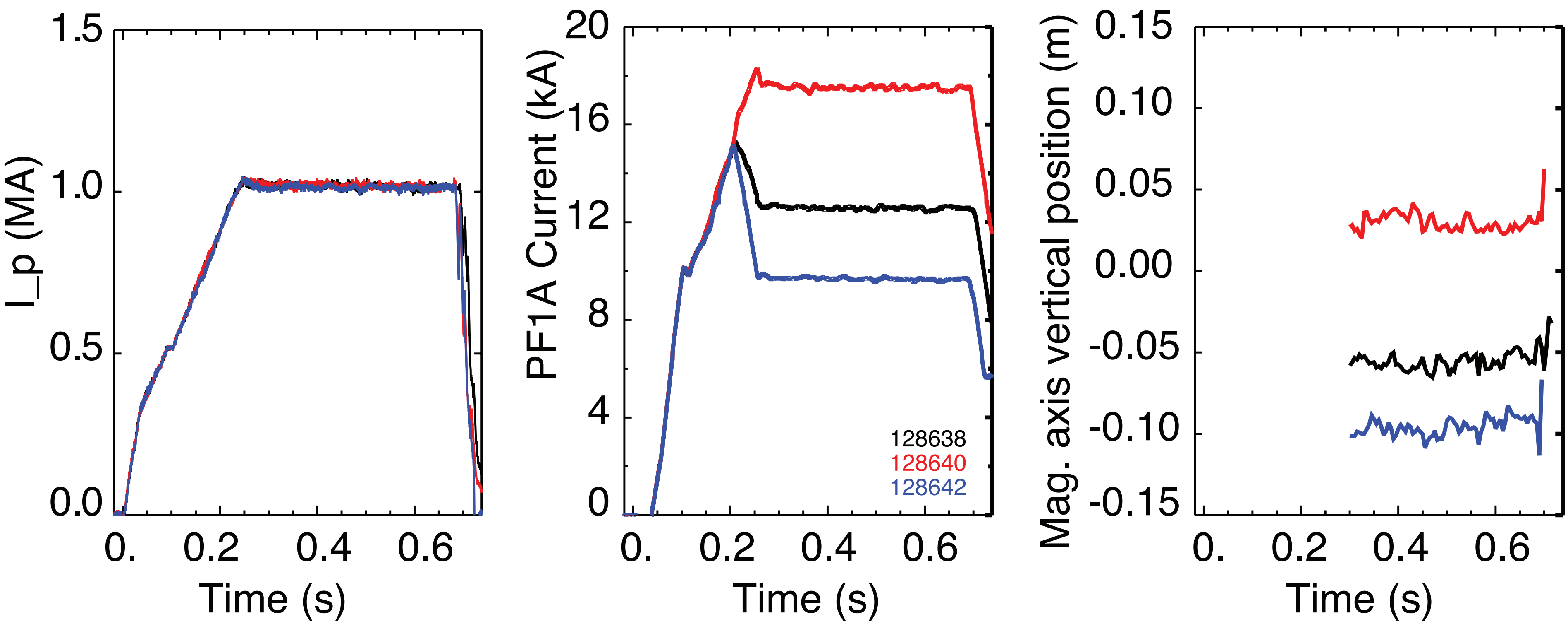


Multiple diagnostic measurements are analyzed to elucidate on divertor physics in NSTX

- Diagnostic set for divertor studies:
  - IR cameras
  - Bolometers
  - Neutral pressure gauges
  - Tile Langmuir probes
  - Dα, Dγ filtered CCD arrays
  - UV-VIS spectrometer (10 divertor chords)
- Midplane Thomson scattering and CHERS systems
- Divertor gas injector Γ_{gas} = 20-200 Torr l / s



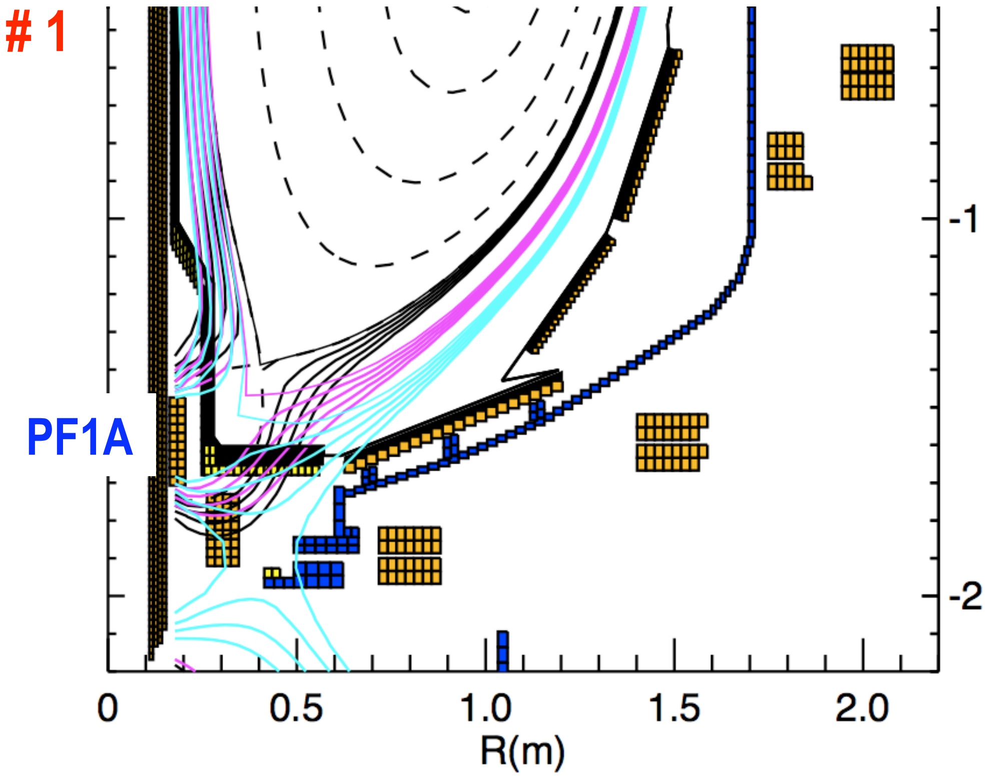
Steady-state H-mode discharges with various X-point heights were obtained

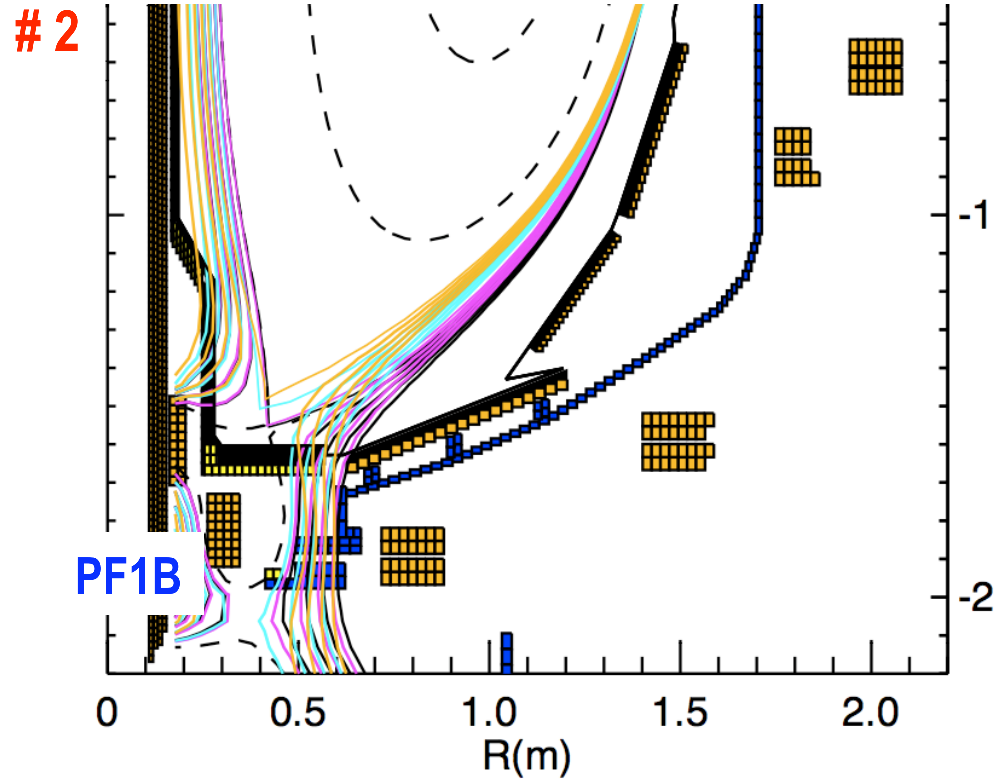


- X-point height was changed by shifting the plasma up and down by several cm using PF1A divertor coil
- Plasma shape parameters were maintained
  - elongation 2.20-2.40, triangularity 0.7-0.85, drsep ~ 5 – 10 mm

Color coded X-point heigh:
Low (6-7 cm)
Medium (9-12 cm)
High (20-22 cm)

Divertor poloidal magnetic flux and area expansion scans were carried out in experiment





Experiment	Coils	X-pt height	OSP major radius	Flux expansion
# 1	PF1AL	6-23 cm	0.30-0.39 m	6-26
# 2	PF1AL & PF1B	4-11 cm	0.42-0.45 m	14-35

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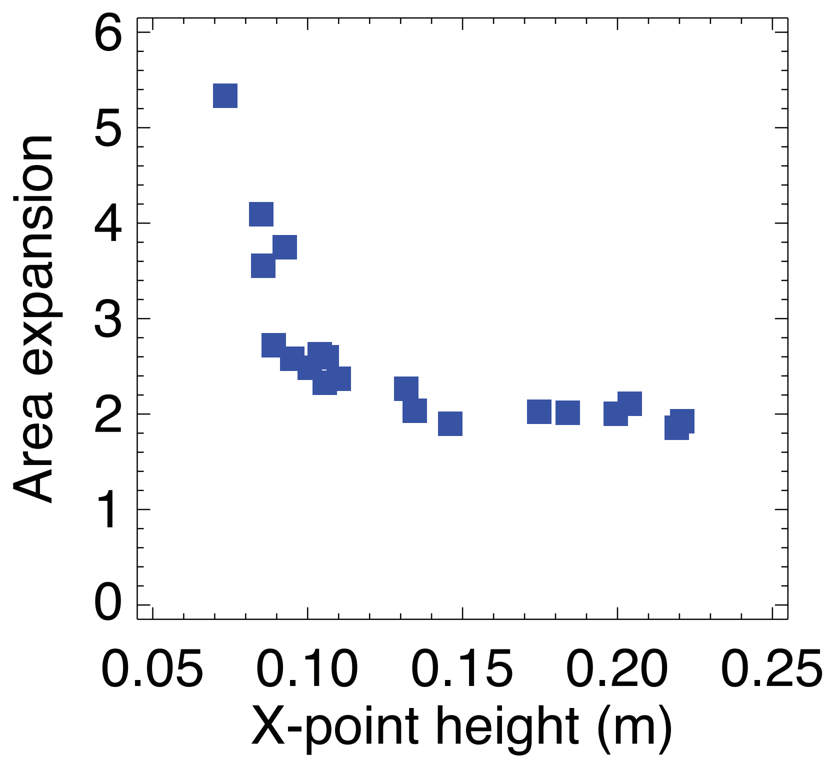
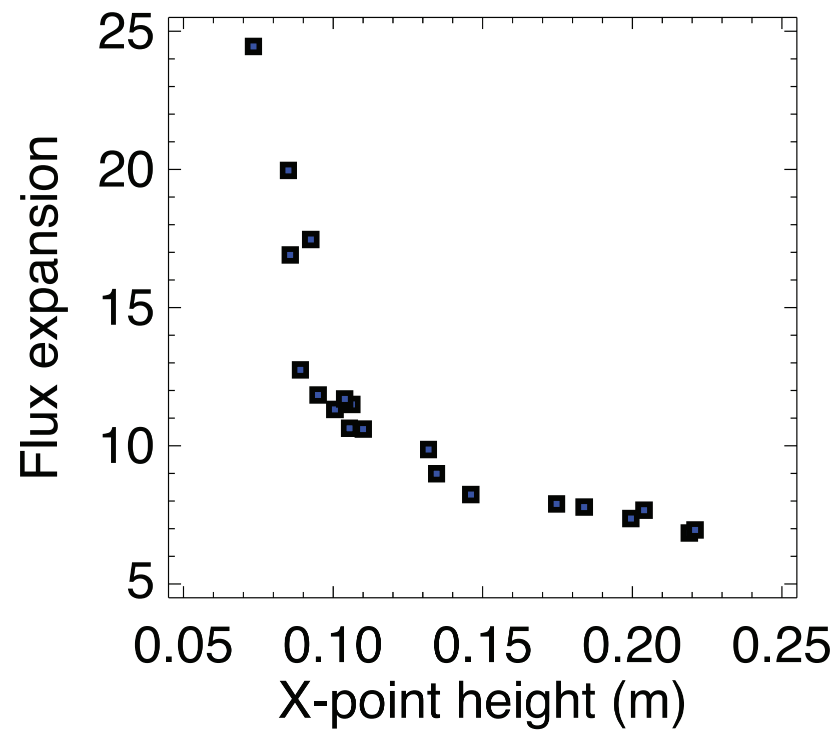
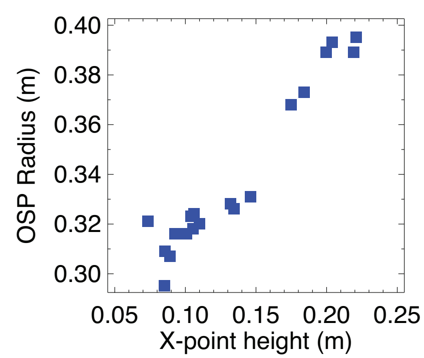
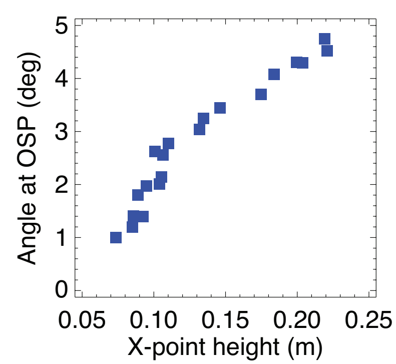
(future analysis)

X-point height variation between 6 and 22 cm resulted in large variations of divertor geometry

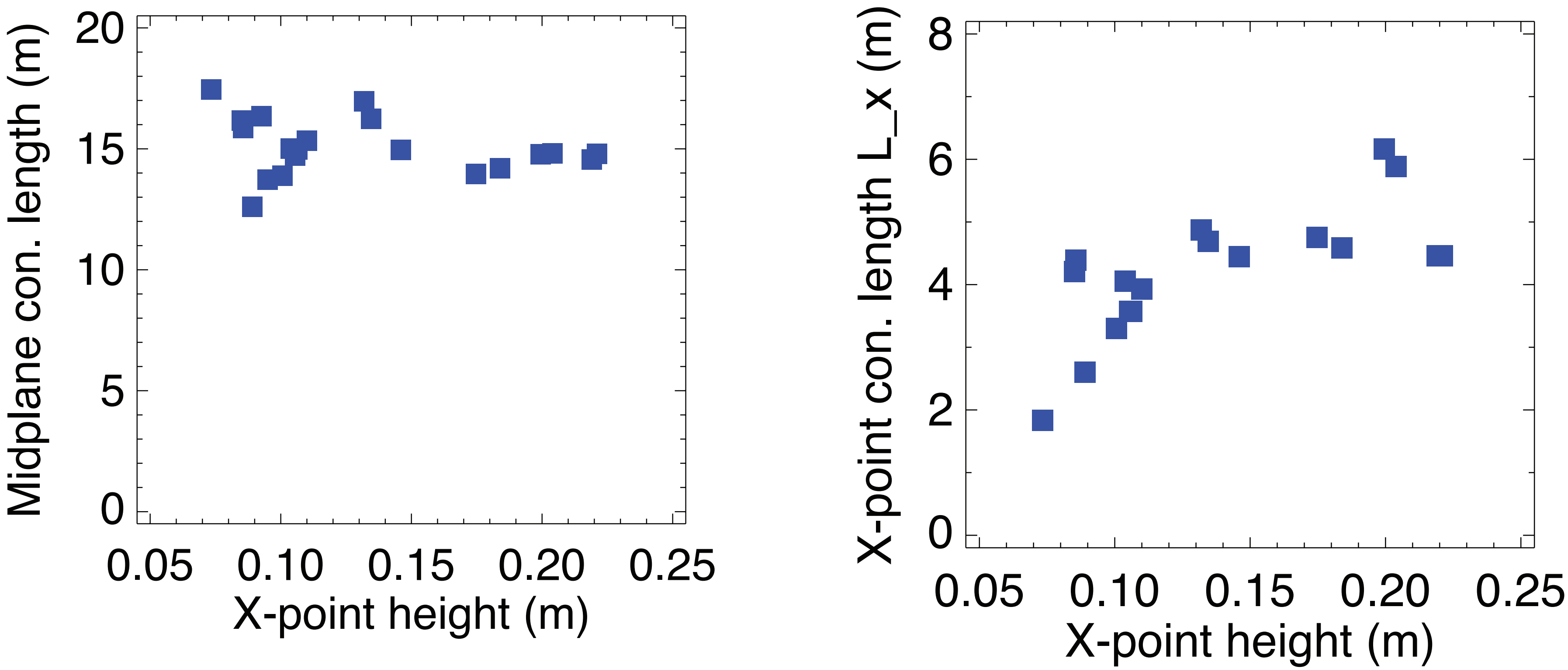






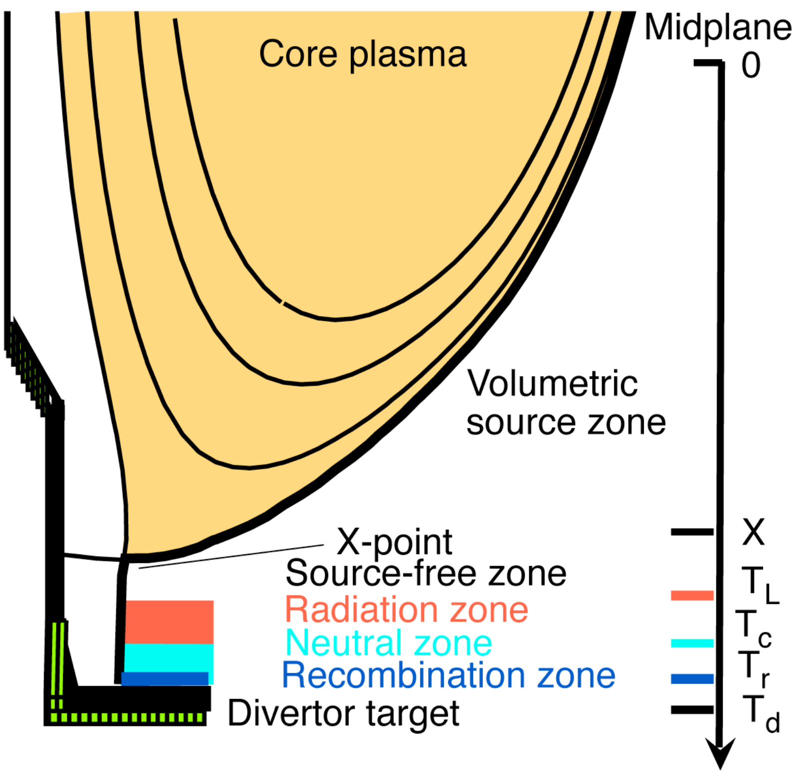


X-point connection length was reduced by x 3 in the X-point scan



- Midplane to divertor ("total") connection length remained nearly constant 15+/- 3 m

NSTX divertor geometry studies



Relation between $q_{||}$ and q_{peak}

- Flux expansion
- Private flux region transport
- Heat conduction losses
- Dissipative losses

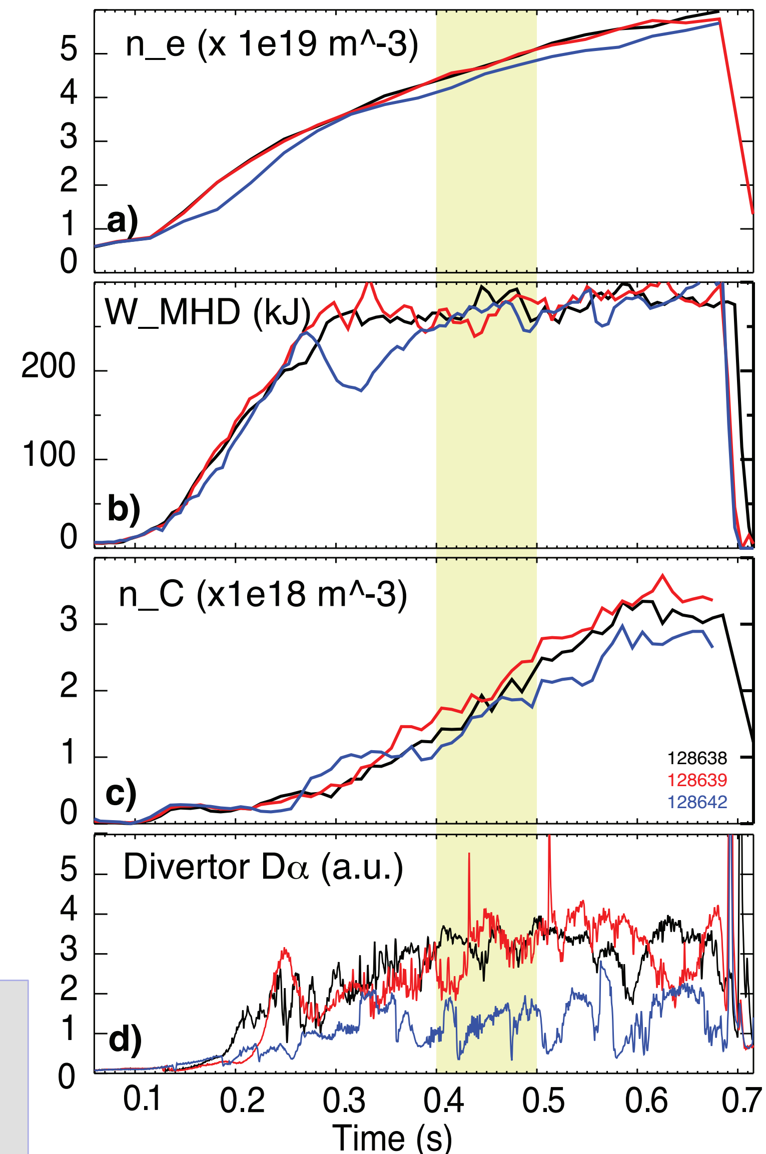
- Divertor poloidal flux expansion: $f_{exp}=(B_\theta/B_{tot})^{MP\text{-}SEP} / (B_\theta/B_{tot})^{OSP}$
- Study as a function of f_m and L_X
  - Power balance, divertor heat flux
  - Ion momentum balance
  - Recycling, carbon sputtering and recombination rates
  - Neutrals behavior, plasma "plugging effect"
  - Role of gyro-radius and mean free path effects
- **Goal – understand and predict divertor heat flux transport for heat handling and particle pumping**
  - **Performance and limitations of X- , super-X and "snowflake" divertors with very high flux expansion**

H-mode core plasma parameters varied modestly with X-point height variations

- Visible differences in n_e , n_C due to midplane (Z=0) Thomson scattering and Charge exchange recombination spectroscopy measurement position

- Small ELM regime was maintained as pedestal parameters varied little

- Presented profiles and data between 0.4 s and 0.5 s (yellow region) between ELMs



Color coded X-point heigh:

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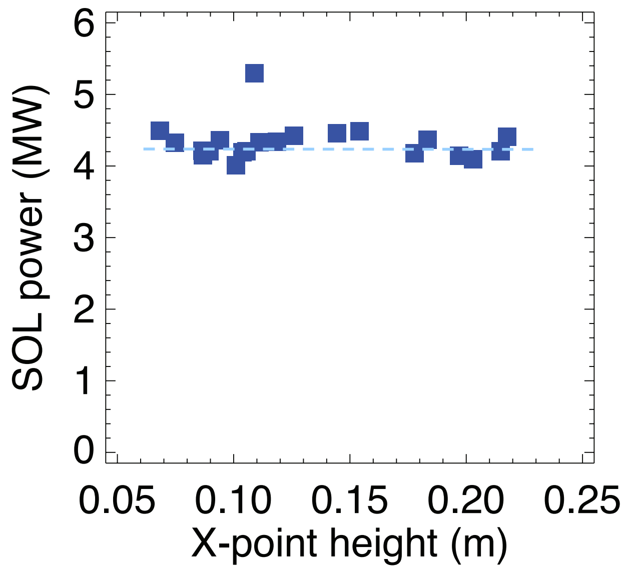
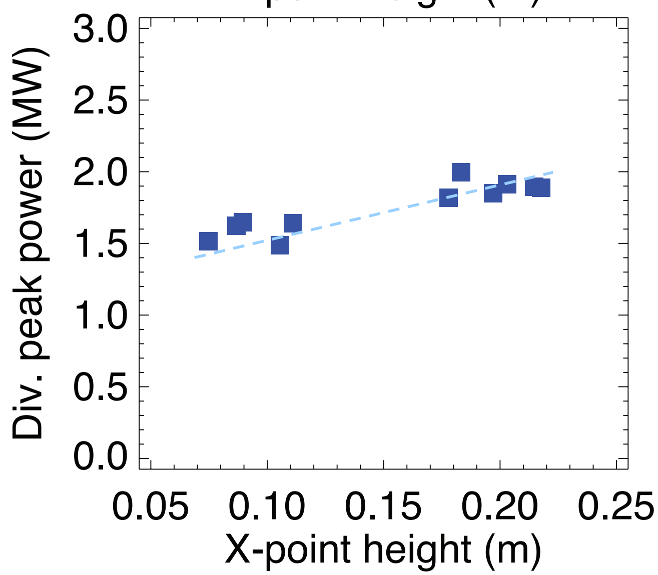
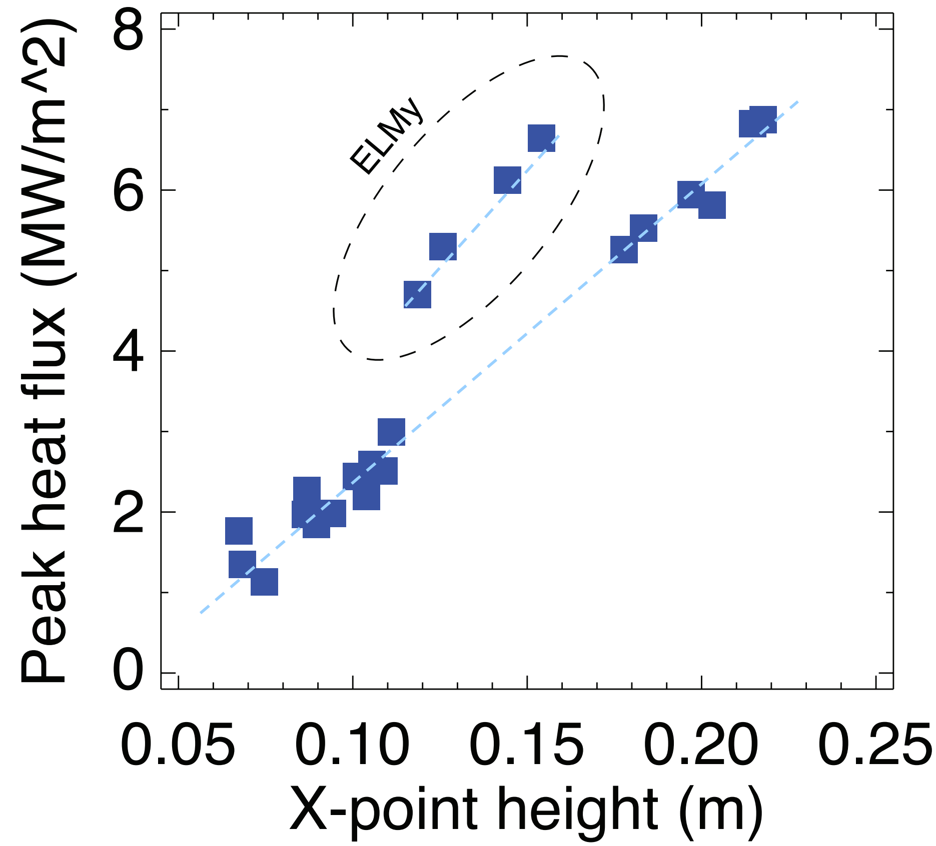
Medium (9-12 cm)

High (20-22 cm)

Peak divertor heat flux scaled linearly with X-point height

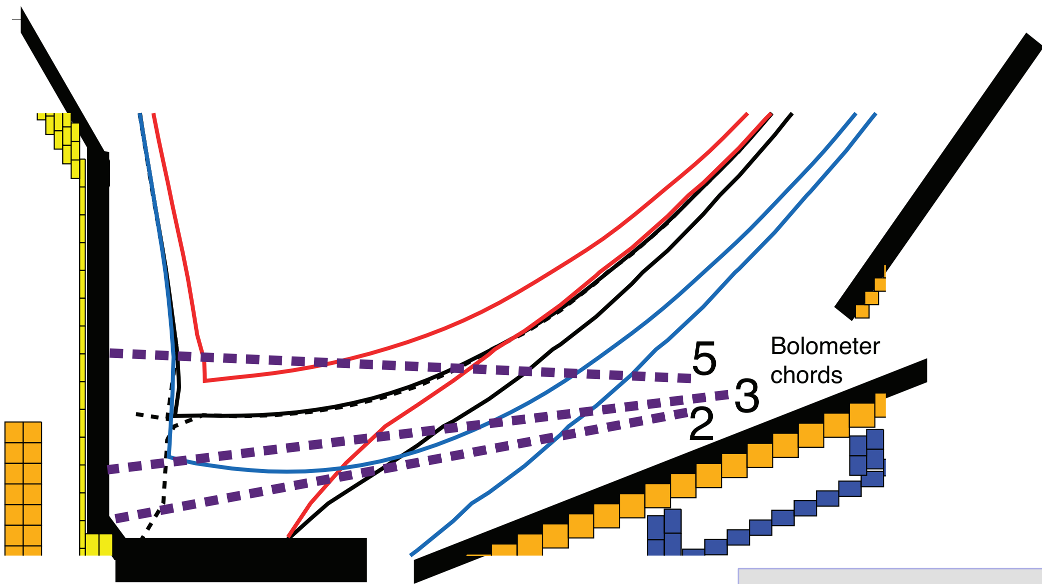






- P_{SOL} ~ 4.5 MW and constant
- P_{DIV} lower at low X-point height due to increased radiation losses
- q_{pk} maps to $q_{||}$ = 50-100 MW/m^2

Divertor radiated power increased with lowering X-point



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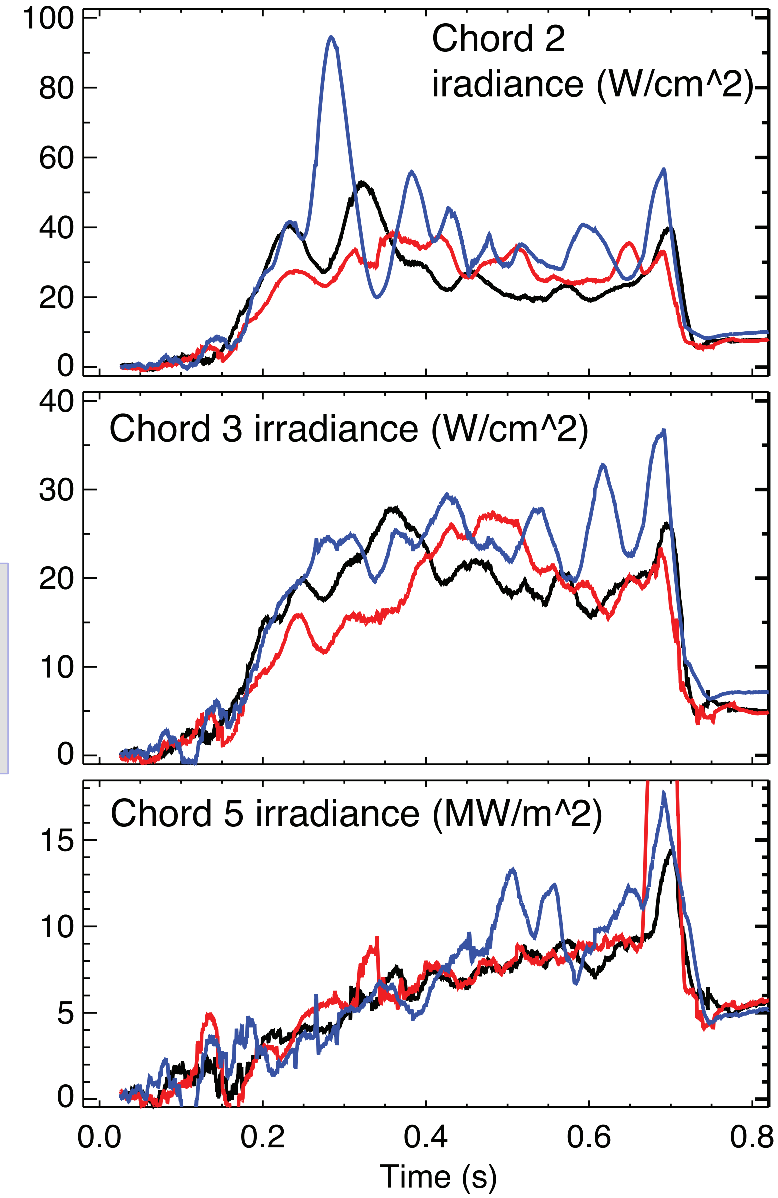

- Divertor bolometer had 3 chords
- Radiated power in low X-point configuration was higher
  - Compare Ch. 2 for blue with Ch. 3 for black and Ch. 5 for red

Divertor approached detachment at lower X-point heights

- Heat flux profiles (a)
  - Peak *q* reduced by x 8
  - Width changed substantially
  - Peak moved away from separatrix
- D-α profiles (b)
  - Higher peak and broader profile at lower X-point due to recombination
- Balmer *n=10-2* line intensity increased in vicinity of outer strike point at lower X-point height (c) – recombination and higher n_e
- Emission from C II and C III increased at outer strike point at lower X-point height (d, e)

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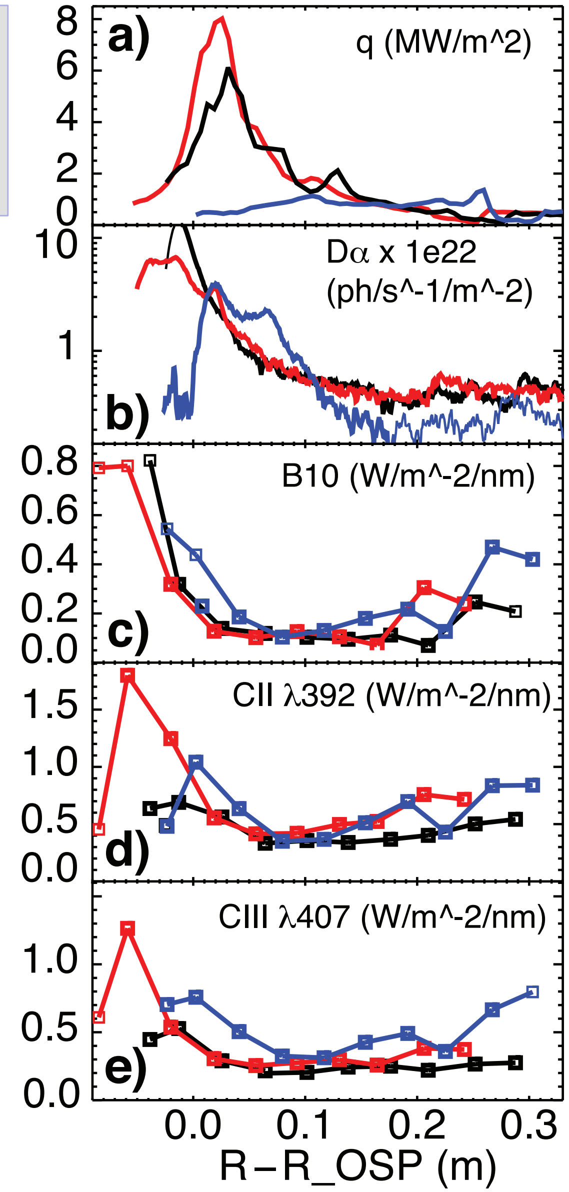
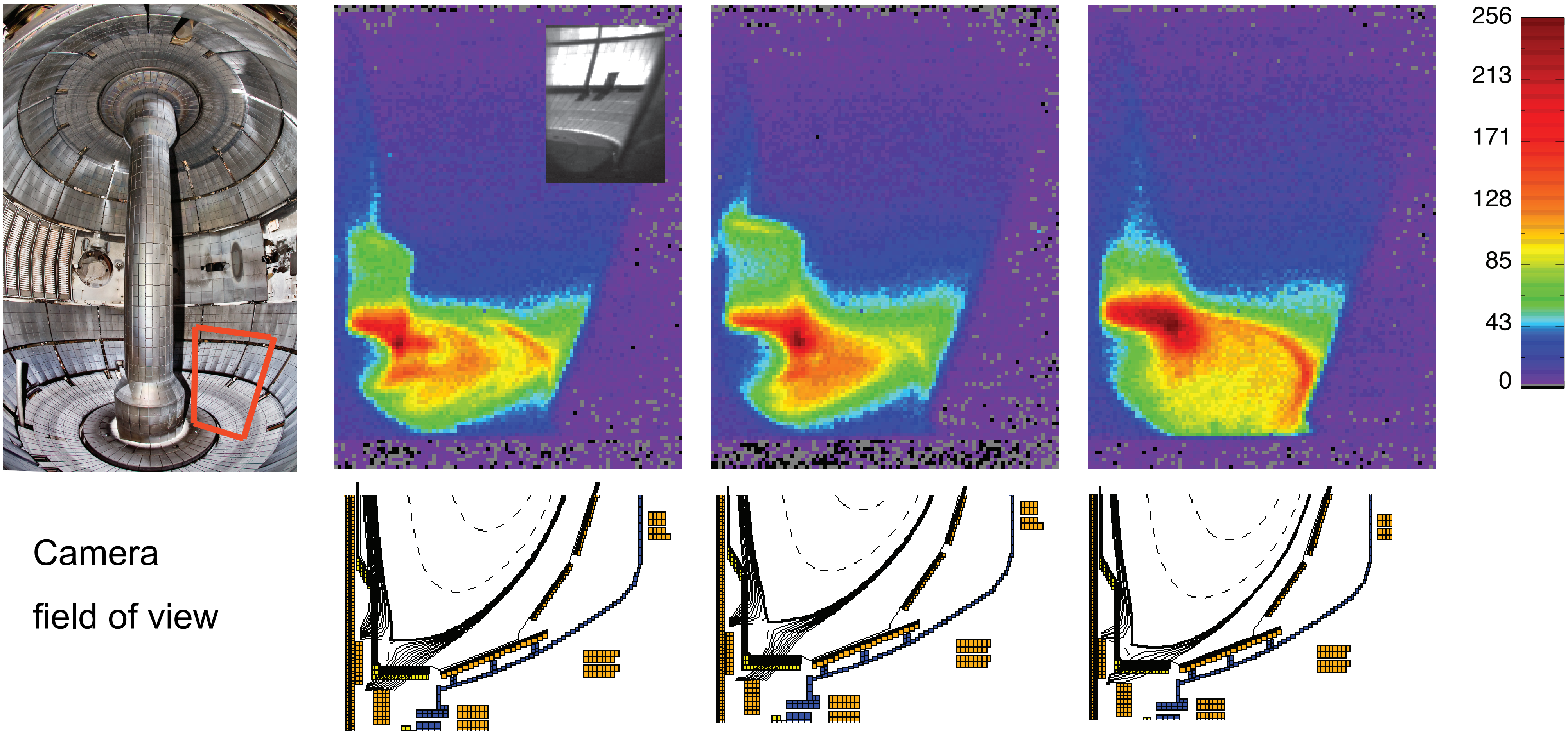
Medium (9-12 cm)
High (20-22 cm)



Divertor camera showed plasma interaction regions with divertor plate

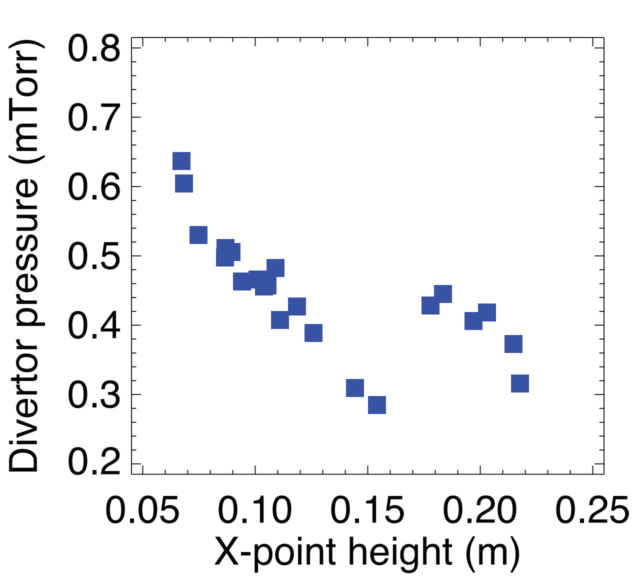


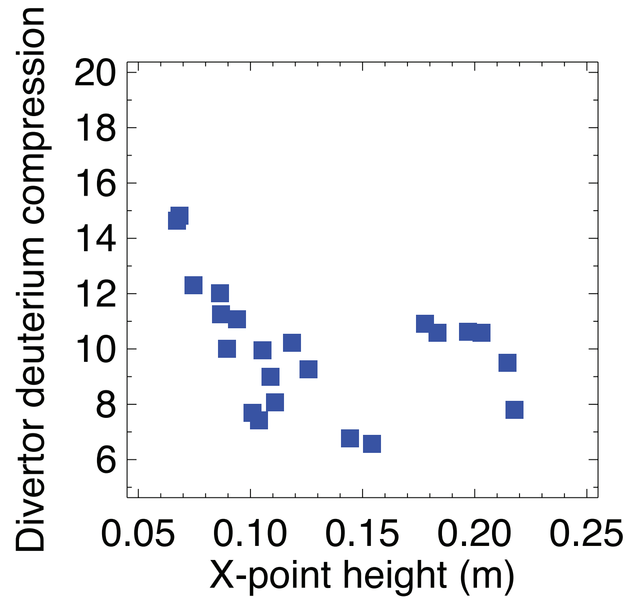
Camera

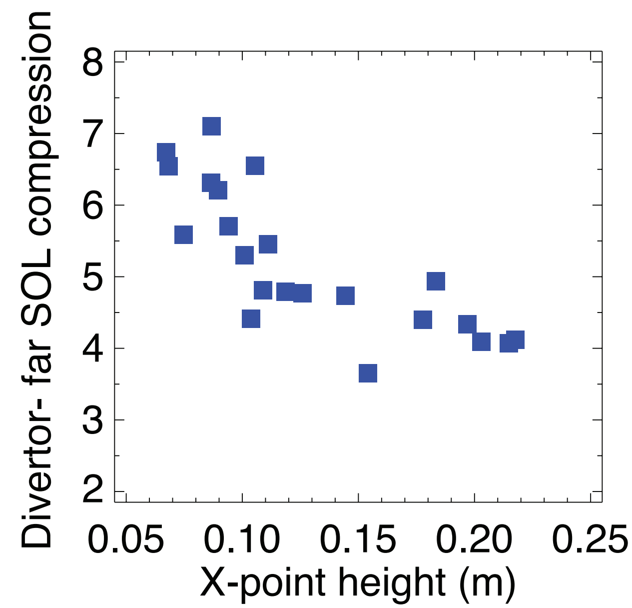
field of view

- Phantom camera averaged over 100 ms
- Filtered for 658 nm C II line emission

Divertor deuterium compression increased at lower X-point height







- Compression P_{div}/P_{mid} increase due to P_{div} increase
- Pressure increase due to colder, denser divertor plasma and volume recombination
  - Divertor in low X-point configuration more opaque to neutrals (?)
  - Ion gyroradius ~ 5-6 mm, comp. to plasma-divertor gap of 30-50 mm.

Flux expansion appears to be dominant factor in reducing $q_{||}$

Relation between $q_{||}$ and q_{peak}

- q_{pk} changed by x 7-8 in X-point scan
- Flux expansion changed by x 4.5
- X-point connection length changed by x 3
- Private flux region heat diffusion proportional to L_X
- Heat conduction losses proportional to $L^{-4/9}{}_X$
- Dissipative losses - e.g. Post radiated power model