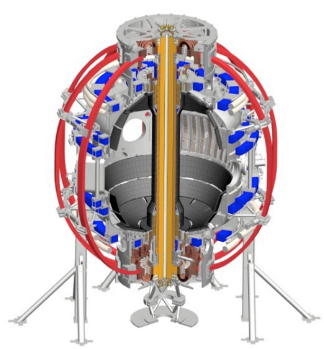
NSTX-U Supported by U.S. DEPARTMENT OF ENERGY Office of Science

Divertor Scenario Development for NSTX Upgrade

V. A. Soukhanovskii,
A. G. McLean, E. T. Meier, T. D. Rognlien, D. D. Ryutov, LLNL, R. E. Bell, A. Diallo, S. P. Gerhardt, R. Kaita, E. Kolemen, B. P. LeBlanc,
J. E. Menard, M. Podesta, F. Scotti, PPPL



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Abstract

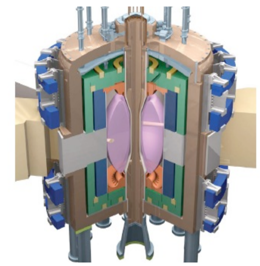
In the NSTX-U tokamak, initial plans for divertor plasma-facing components (PFCs) include lithium and boron coated graphite, with a staged transition to molybdenum. Steady-state peak divertor heat fluxes are projected to reach 20-30 MW/m2 in 2 MA, 12 MW NBI-heated discharges of up to 5 s duration, thus challenging PFC thermal limits. Based on the recent NSTX divertor experiments and modeling with edge transport code UEDGE, a favorable basis for divertor power handling in NSTX-U is developed. The snowflake divertor geometry and feedback-controlled divertor impurity seeding applied to the lower and upper divertors are presently envisioned. In the NSTX snowflake experiments with lithium-coated graphite PFCs, the peak divertor heat fluxes from Type I ELMs and between ELMs were significantly reduced due to geometry effects, increased volumetric losses and null-point convective redistribution between strike points. H-mode core confinement was maintained at H98(y,2) 1 albeit the radiative detachment. Additional CD4 seeding demonstrated potential for a further increase of divertor radiation.

Plasma-material interface development is key for present and future fusion plasma devices

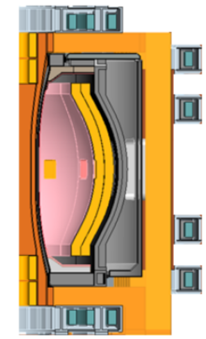
- **Divertor solution** is envisioned for present and future devices (e.g. ITER, ST-FNSF) for **steady-state** power and particle exhaust control
  - Divertor q_{peak} < 5-10 MW/m^2
    - Large divertor radiated power fractions ($f_{rad} \leq 0.80$)

$$q_{peak} \simeq \frac{P_{SOL}(1-f_{rad})f_{geo}\sin\alpha}{2\pi R_{SP} f_{exp} \lambda_{q_{||}}}$$

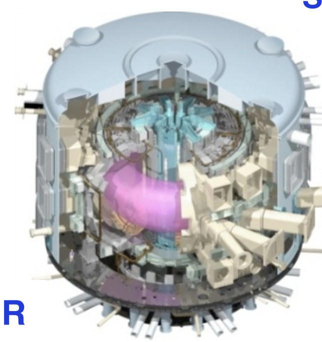
  - Keep divertor T_e low to reduce PFC sputtering rate
    - $E_i = 2kT_i + 3\, Z_i\, kT_e$
    - $E_i \sim 50 – 300$ eV -> $Y_C \sim 0.01$
    - Need to obtain $E_i \leq 20\text{-}40$ eV ($T_e \leq 5$ eV)
  - Integration with high-pressure pedestal and core
  - Partial divertor strike point detachment is the most promising regime



Fusion Nuclear Science Facility (FNSF)



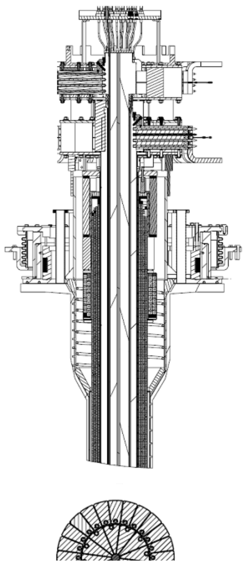
ST Pilot Plant



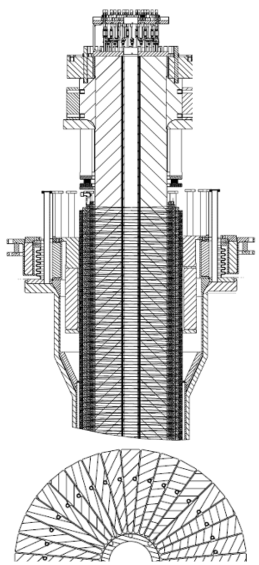
ITER

$$A_{wet} = 2\pi R\, f_{exp}\, \lambda_{q_{||}}$$

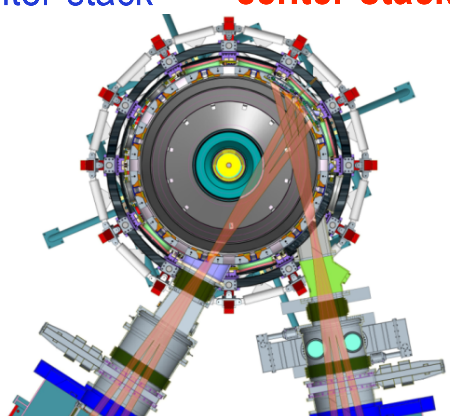
NSTX Upgrade will address critical plasma confinement and sustainment questions by exploiting 2 new capabilities



TF OD = 20cm
Previous center-stack



TF OD = 40cm
New center-stack



Present NBI   New 2nd NBI

New center-stack

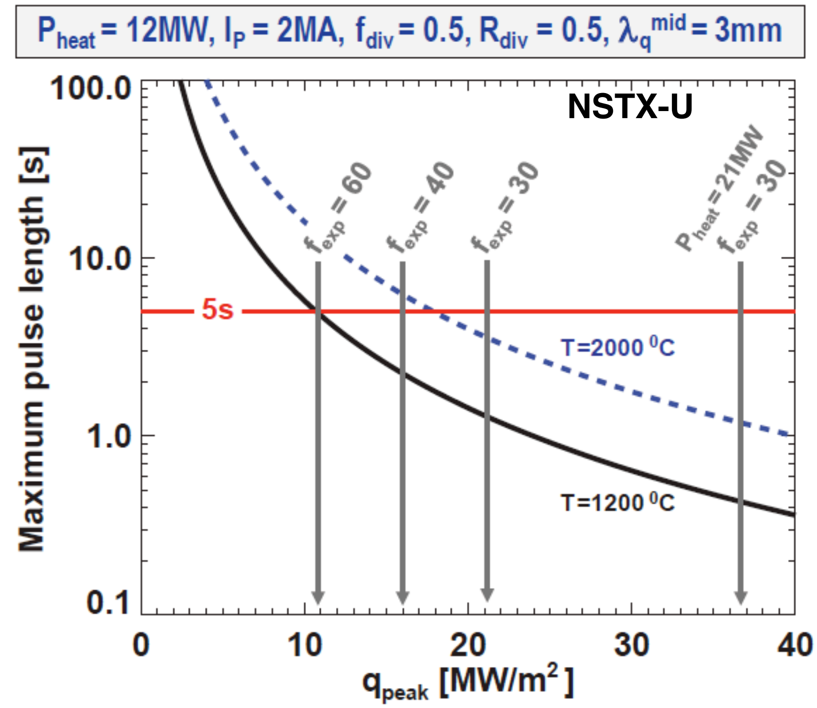
- **Reduces ν^* → ST-FNSF values to understand ST confinement**
  - Expect 2x higher T by doubling B_T, I_P, and NBI heating power
- **Provides 5x longer pulse-length**
  - q(r,t) profile equilibration
  - Tests of NBI + BS non-inductive ramp-up and sustainment

New 2nd NBI

- **2x higher CD efficiency from larger tangency radius R_{TAN}**
- **100% non-inductive CD with q(r) profile controllable by:**
  - NBI tangency radius
  - Plasma density
  - Plasma position

Impurity-seeded radiative divertor with feedback and snowflake geometry are the leading NSTX-U heat flux mitigation candidates

- NSTX-U mission elements:
  - Advance ST as candidate for Fusion Nuclear Science Facility
  - Develop solutions for PMI
  - Advance toroidal confinement physics for ITER and beyond
  - Develop ST as fusion energy system
- Challenge for NSTX-U divertor
  - 2-3 X higher input power
    - P_{NBI} < 12 MW, I_p < 2 MA
    - λ_q^{mid} ~ 3 mm
  - 30-50 % reduction in n/n_G
  - 3-5 X longer pulse duration



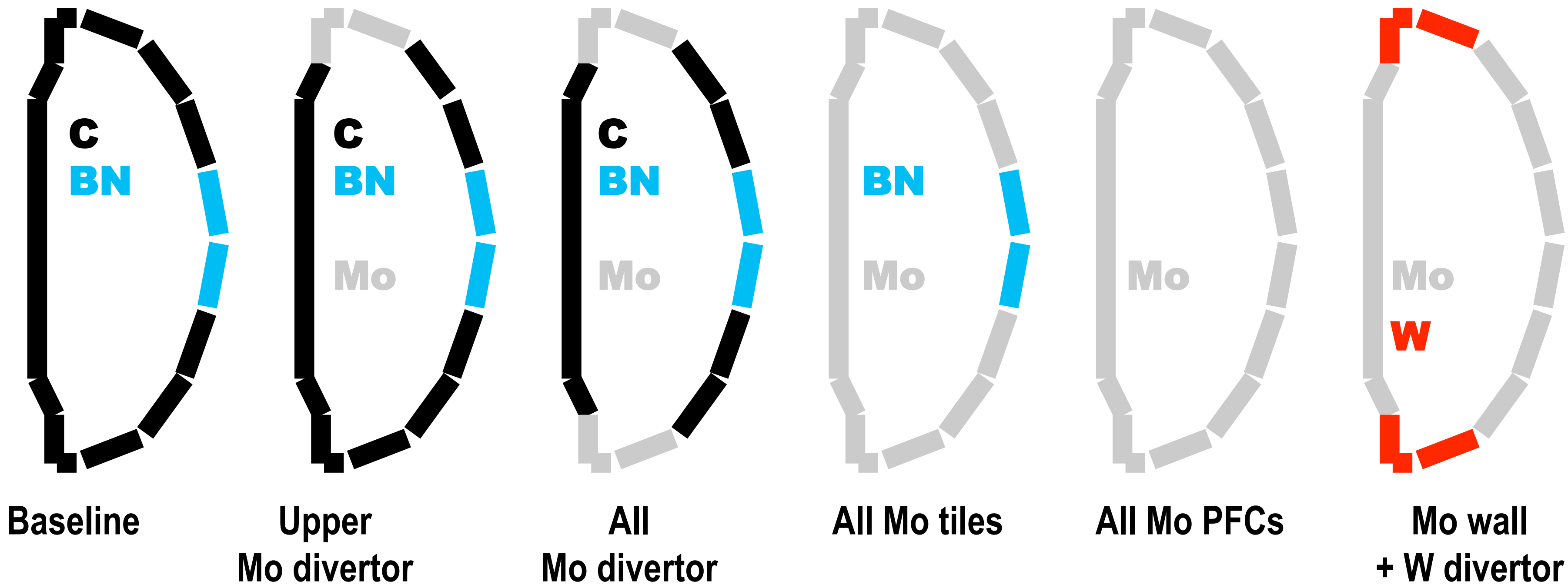
R. Maingi (ORNL)

- Scenarios with high I_p and P_{NBI} are projected to challenge passive cooling limits of graphite divertor PFCs
- Projected NSTX-U peak divertor heat fluxes up to 25-40 MW/m^2

Plans for divertor power and particle control are developed for NSTX-U

- Particle control objective is
  - Access to reduced core collisionality
    - $n_e \sim 0.6\text{-}0.9\ n_G$ for transport, stability, start-up, high non-inductive current fraction scenario studies for future STs (e.g., NSTX-Upgrade)
    - $n_e \sim 0.3\text{-}0.7\ n_G$ for adequate NBI current drive efficiency in scenarios relevant to fusion and nuclear science ST-based devices
  - Long-pulse ion / electron density control
  - Impurity control
- Particle control plans
  - Cryo-pump – see PP8.00030: J. Canik, Physics design of a cryo-pumping system for NSTX-U
  - Lithium coatings – see PP8.00032: M. Jaworski, Collaborative Research and Development on Liquid Metal Plasma Facing Components
- Power control plans – THIS POSTER
  - Snowflake divertor configuration
  - Radiative divertor with impurity seeding and feedback control

Divertor heat flux mitigation options are affected by NSTX-U plasma-facing component development plan

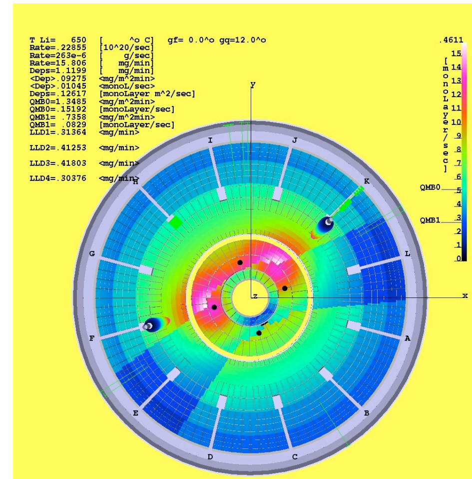


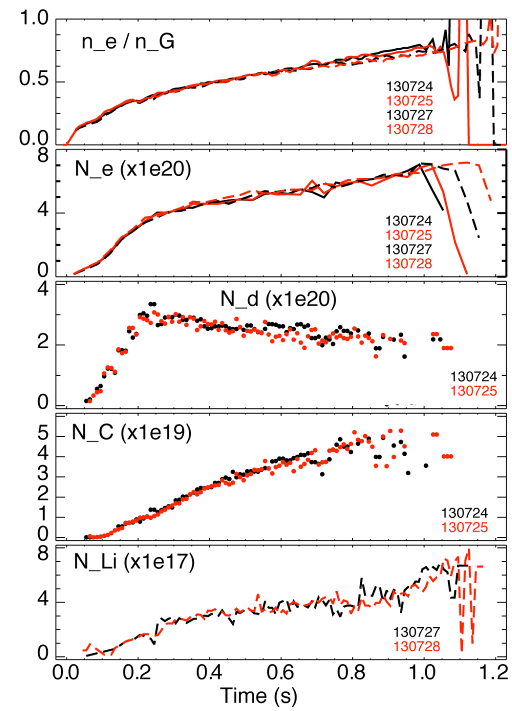
- Developing PFC plan to transition to full metal coverage for FNSF-relevant PMI development
- Wall conditioning: GDC, lithium and / or boron
- PFC bake-out at 300-350^{o}C
- Divertor impurity seeding:
  - Graphite PFCs compatible with D_2, CD_4, Ne, Ar
  - Molybdenum PFCs compatible with D_2, CD_4, N_2, Ne, Ar

Evaporated lithium coatings on graphite plasma-facing components are envisioned for density control in NSTX-U

- Surface pumping reduced ion inventory (density) by up to 50 %
- Recycling reduced by up to 50 % in both divertors and wall
- Local recycling coefficients reduced on inner wall and far SOL, remained similar in the outer strike point region
- Parallel heat transport regime in the SOL changes from conduction-limited to sheath-limited (low-recycling)
- Core lithium density low, uncorrelated with divertor source

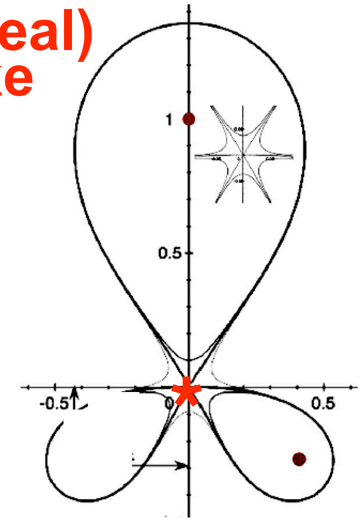
- Lithium can potentially be used for highly radiative divertor power exhaust solutions – see
  - PP8.00031: T. Rognlien, A mechanism for large divertor plasma energy loss via lithium radiation in tokamaks
  - PP8.00032: M. Jaworski, Collaborative Research and Development on Liquid Metal Plasma Facing Components

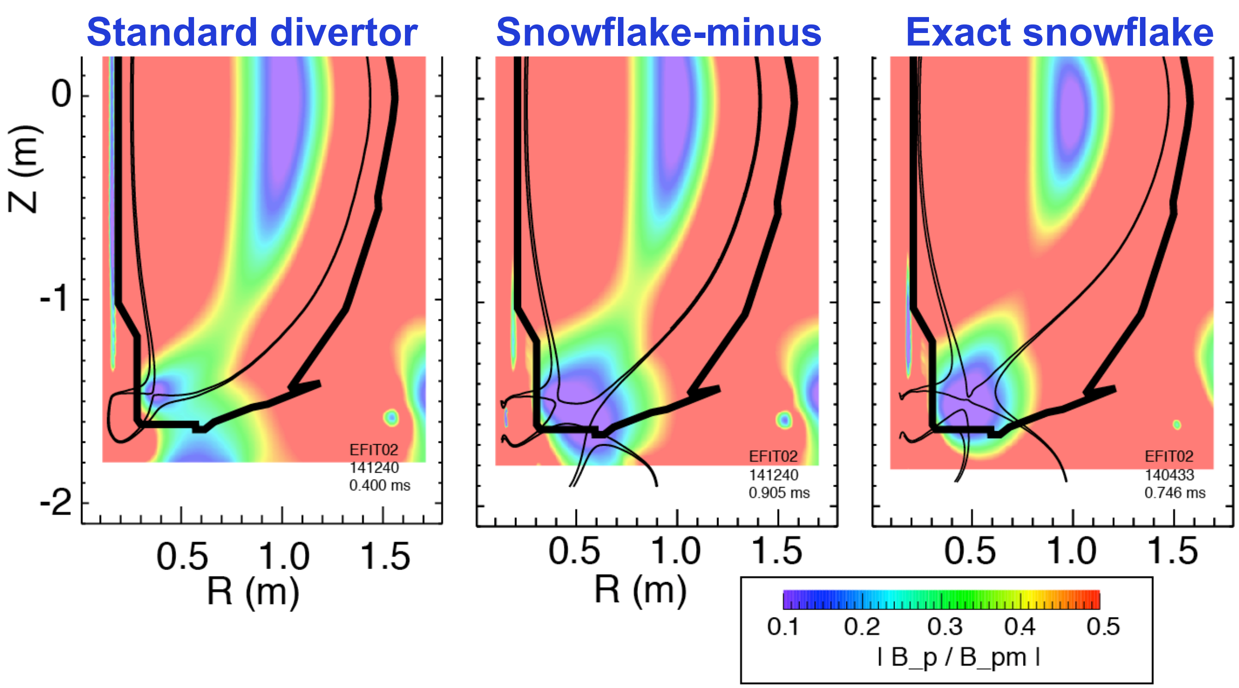


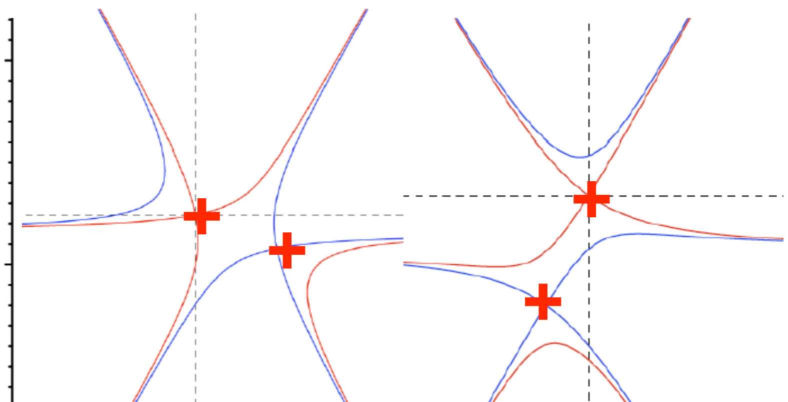


Snowflake divertor geometry takes advantage of second-order poloidal field null properties

- Snowflake divertor configuration
  - Second-order null
    - $B_p \sim 0$ and *grad* $B_p \sim 0$ (Cf. first-order null: $B_p \sim 0$)
  - Obtained with existing divertor coils (min. 2)
  - Exact snowflake topologically unstable
  - Deviation from ideal snowflake: $\sigma = d / a$
    - *d* – distance between nulls, *a* – plasma minor radius







D. D. Ryutov, PoP 14, 064502 2007
EPS 2012 Invited, subm. to PPCF

Snowflake divertor geometry has benefits over standard X-point divertor geometry

- Predicted geometry properties in snowflake divertor (cf. standard divertor)
  - Increased edge shear :ped. stability
  - Add'l null: H-mode power threshold, ion loss
  - Larger plasma wetted-area A_{wet} : reduce q_{div}
  - Four strike points : share q_{II}
  - Larger X-point connection length L_x : reduce q_{II}
  - Larger effective divertor volume V_{div} : incr. P_{rad} , P_{CX}

$$q_{pk} \simeq \frac{P_{heat}\,(1 - f_{rad}) f_{out/tot} f_{down/tot} (1 - f_{pfr}) \sin\alpha}{2\pi R_{SP} f_{exp} \lambda_{q_{||}}}$$

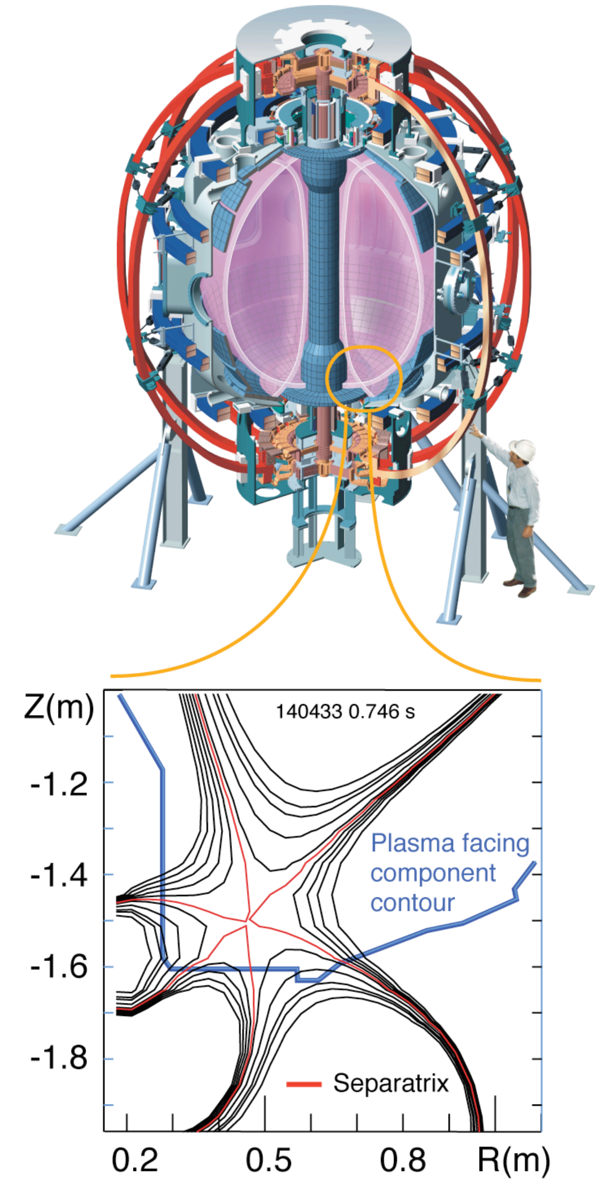
$$f_{exp} = \frac{(B_p/B_{tot})_{MP}}{(B_p/B_{tot})_{OSP}}$$

D. D. Ryutov, PoP 14, 064502 2007

$$A_{wet} = 2\pi R\, f_{exp}\, \lambda_{q_{||}}$$

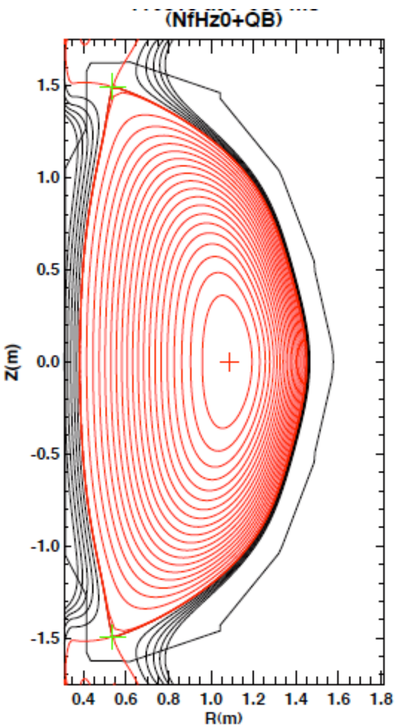
Snowflake divertor is a promising solution for mitigating divertor heat loads, and projects favorably to future fusion devices

- Snowflake divertor configuration in NSTX
  - Core H-mode confinement unaffected, core carbon concentration reduced
  - Pedestal stability modified: suppressed Type I ELMs re-appeared
  - Divertor heat flux significantly reduced
    - Between-ELM reduction due to geometry and radiative detachment
    - ELM heat flux reduction due to power sharing between strike points, radiation and geometry
- Snowflake divertor is a leading candidate for NSTX-U
  - Divertor coils enable a variety of snowflakes
  - In 2 MA, 12 MW NBI-heated discharges
    - SOL power width λ_{SOL} = 3 mm projected
    - $q_{div} \leq$ 15 - 25 MW/m^2 projected in standard divertor
    - $q_{div} \leq$ 3 MW/m^2 projected in snowflake divertor

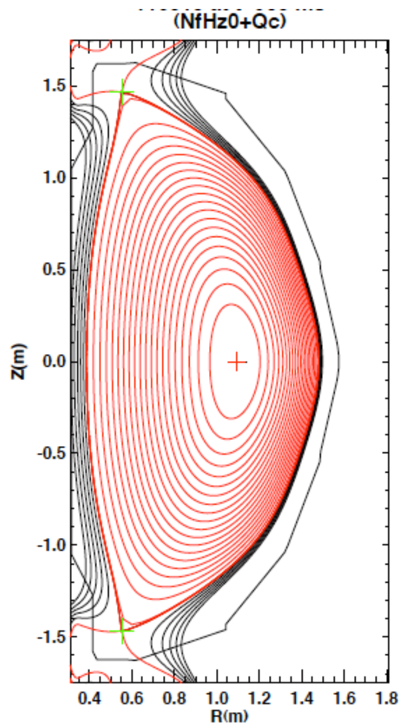


Snowflake divertor is a leading heat flux mitigation candidate for NSTX-U

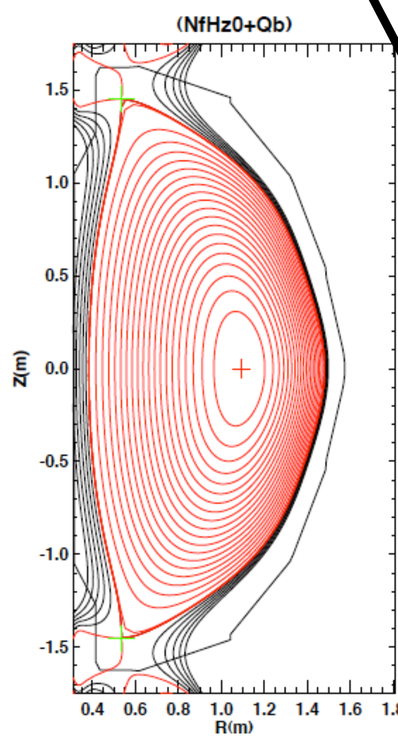
- Single and double-null radiative divertors and upper-lower snowflake configurations considered
  - Supported by NSTX-U divertor coils and compatible with coil current limits
  - ISOLVER modeling shows many possible equilibria
    - Impact of changing I_{OH} on snowflake minimal
    - Reduced divertor coil set can be used for snowflakes



NSTX-U double-null

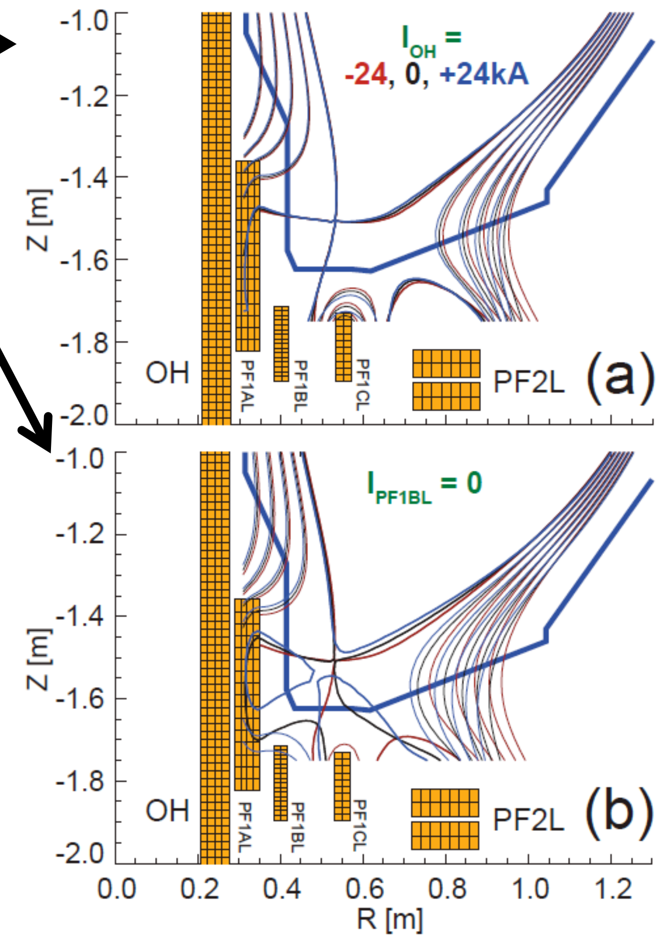


NSTX-U double-snowflake-plus



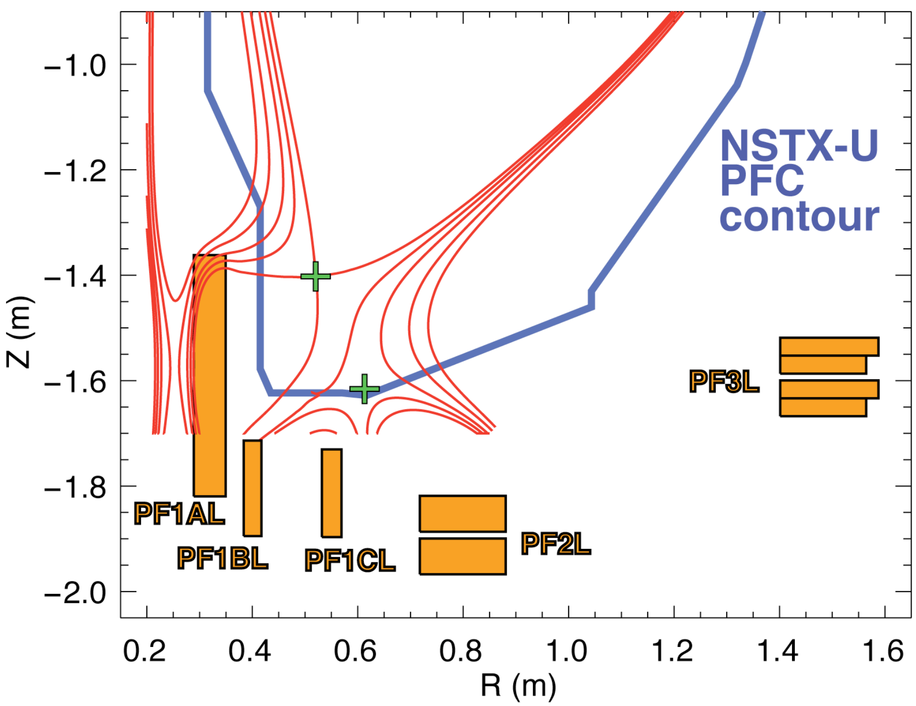
NSTX-U double-snowflake-minus

NSTX-U simulation



Four divertor coils should enable flexibility in boundary shaping and control in NSTX-U

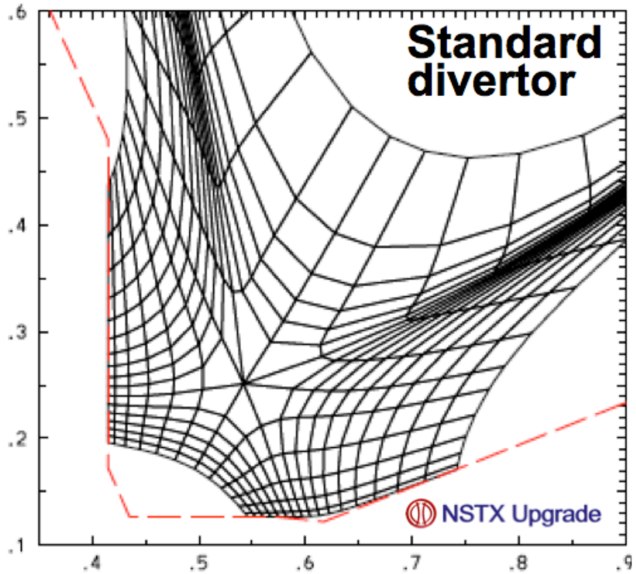
- A variety of lower and both lower and upper divertor snowflake configurations are possible in NSTX-U with four coils per divertor
  - ISOLVER free-boundary Grad-Shafranov solver used
  - Four coils can be used to control up to four parameters (X-pts, OSP, etc)

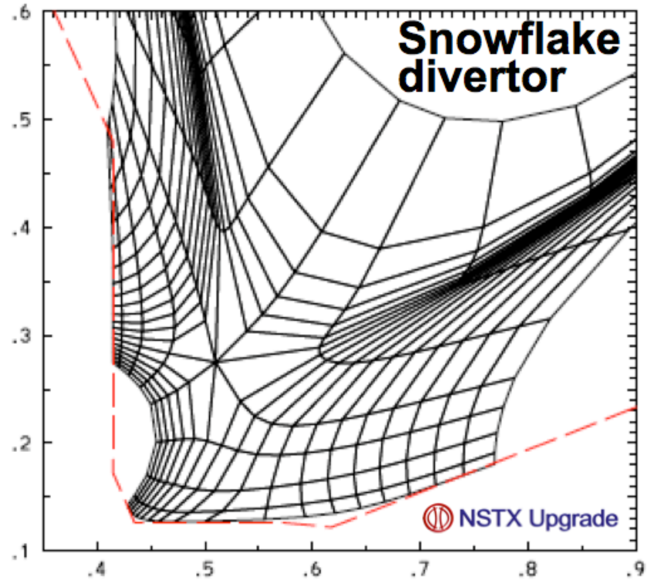


Midplane flux surface	0.0	1.5 mm	3.0 mm	6.0 mm	9.0 mm
L_{tot} (m)	38.3	20.4	13.9	9.9	8.3
L_X (m)	16.5	4.0	2.2	1.6	1.5
Angle (deg.)	1.6	0.8	0.99	3.0	3.9

- X 2-3 in plasma wetted surface area and connection length vs standard divertor

Multi-fluid two-dimensional model using UEDGE code is developed for snowflake and radiative divertors



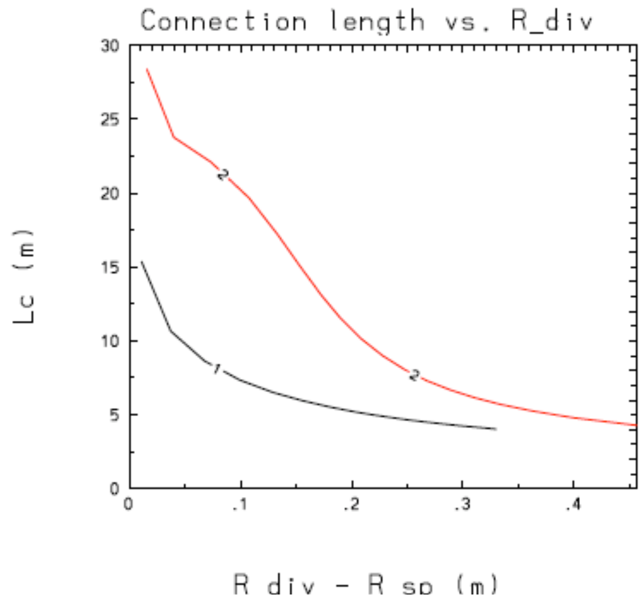


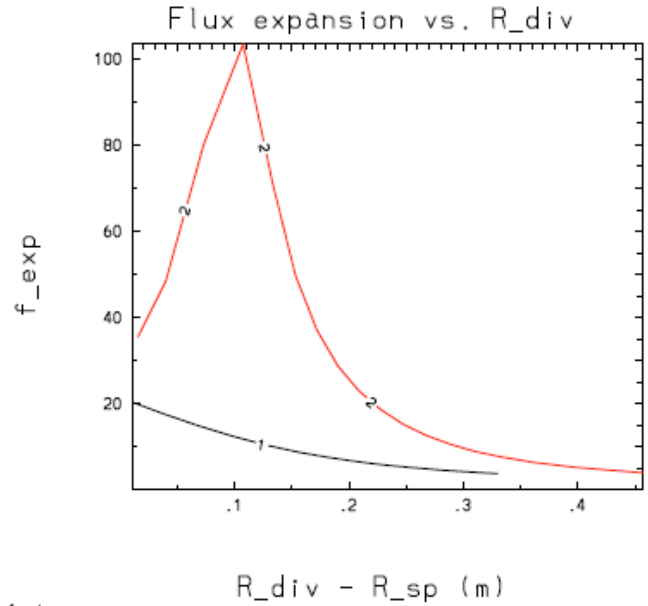
- **See PP8.00028: E. T. Meier, UEDGE modeling of NSTX and NSTX-U snowflake divertor configurations**

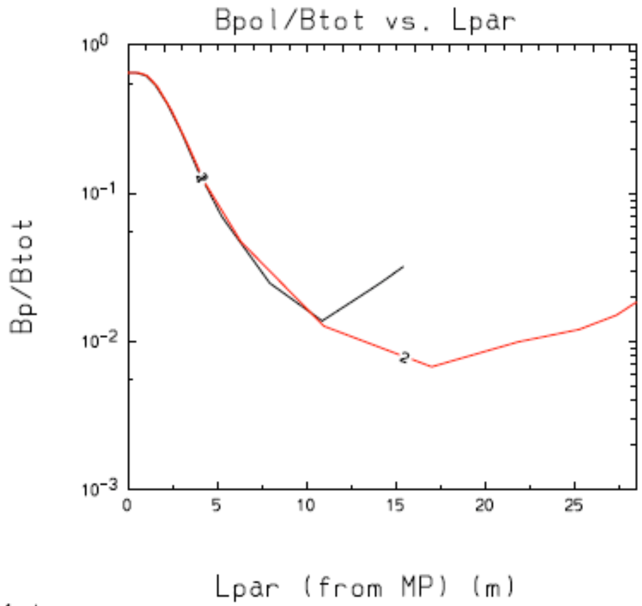
- Fluid (Braginskii) model for ions and electrons
- Fluid for neutrals
- Classical parallel transport, anomalous radial transport
- Core interface:
  - P_{SOL90} = 5; 7; 9 MW
- D = 0.1-0.5 m^2/s
- $\chi_{e,i}$ = 1-2 m^2/s
- R_{recy} = 0.99
- Carbon 5 %

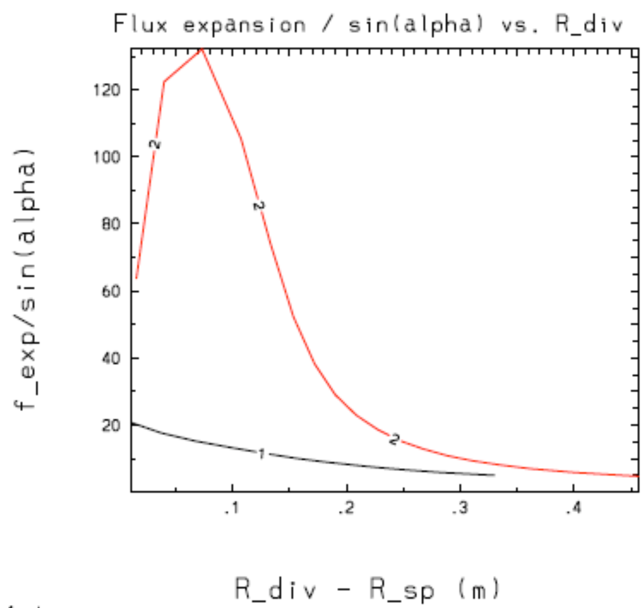
- Grids extend from psi=0.9 to psi=1.2
- STD grid covers 3.1 cm outside the separatrix at the outer MP
- SNF grid covers 3.4 cm outside the separatrix at the outer MP.

In modeled NSTX-U snowflake configuration magnetic geometry shows clear benefits (cf. standard divertor)

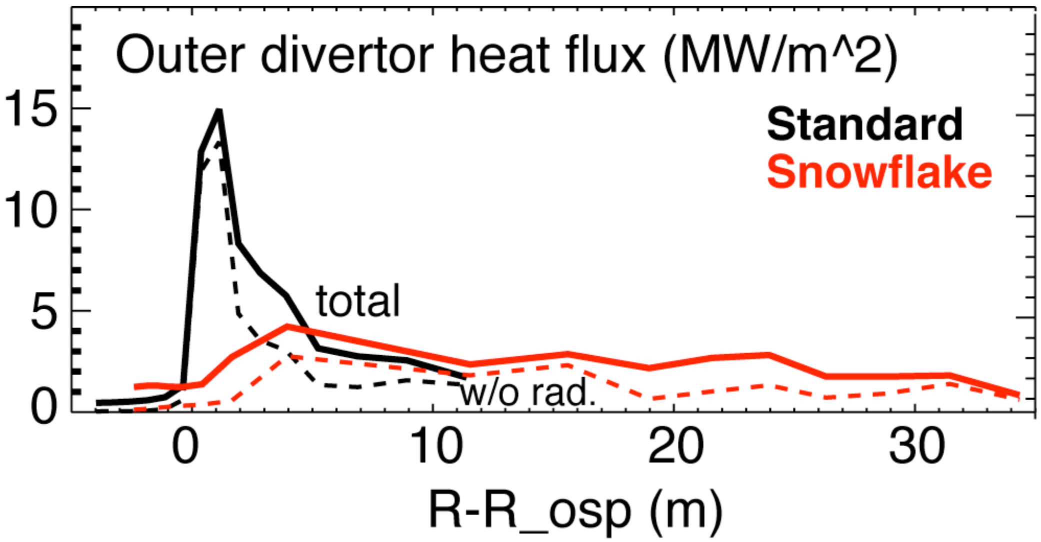


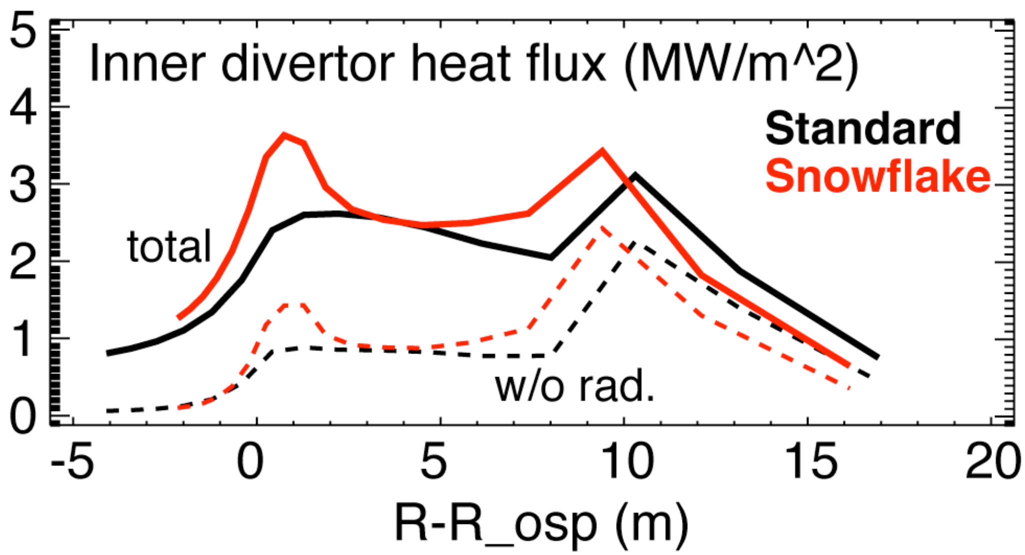






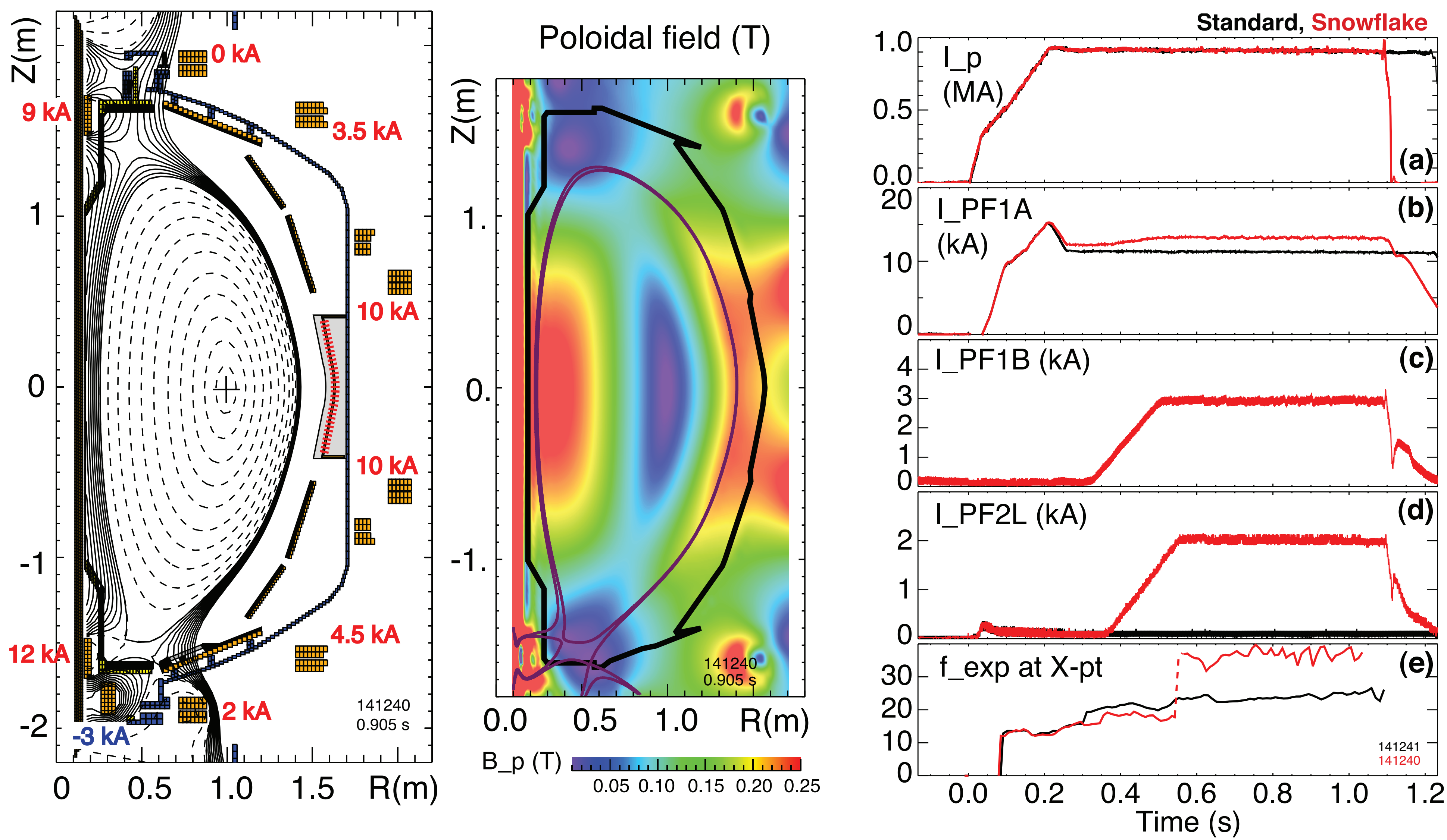
UEDGE predicts significant divertor heat flux reduction and attached conditions in NSTX-U at 12 MW NBI heating



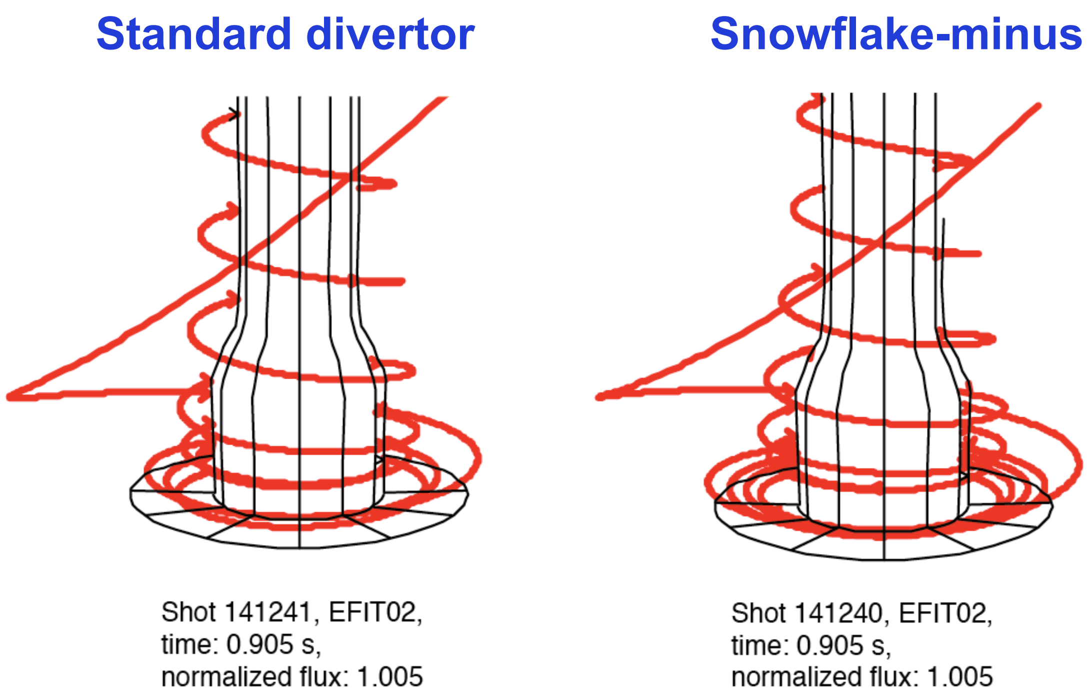


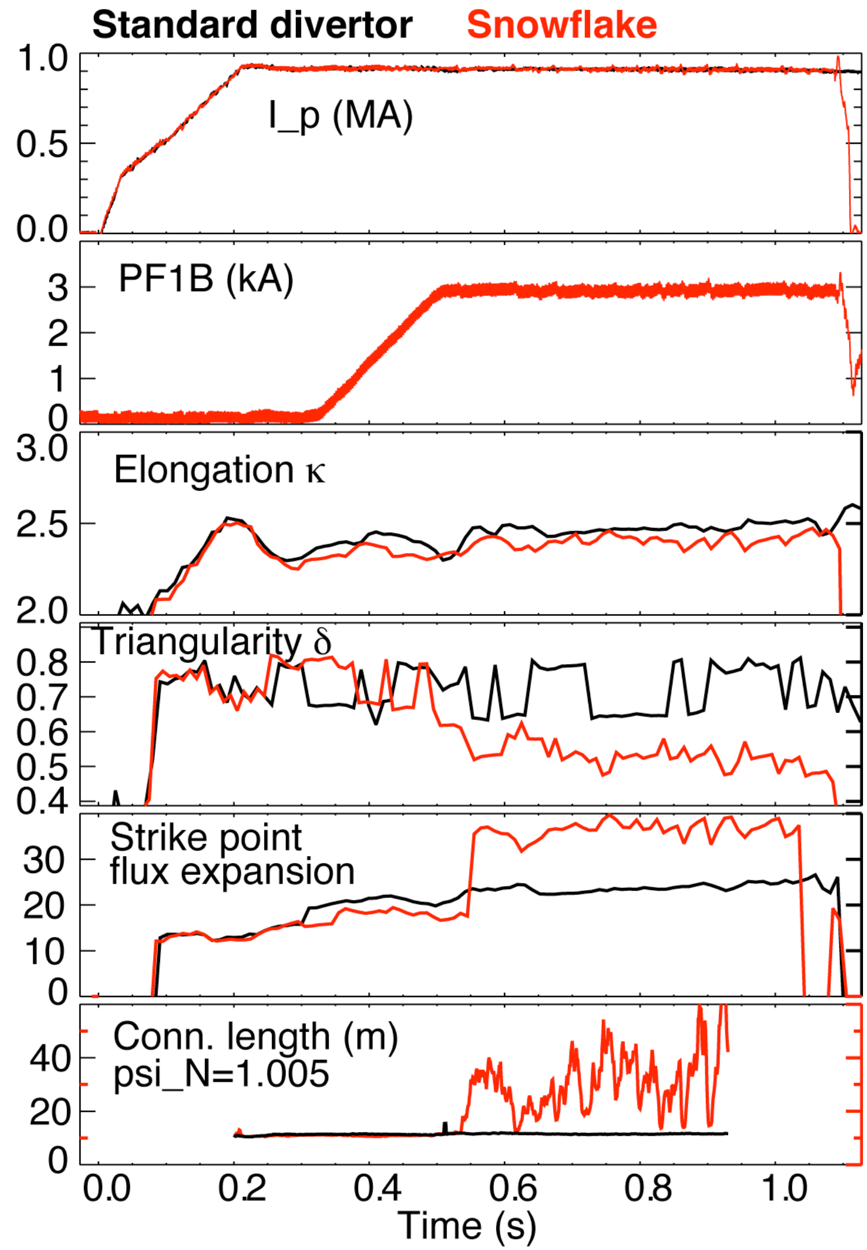
- Predictions for 12 MW NBI case
  - P_{SOL}=9 MW
  - Outer divertor attached
    - T_e, $T_i \leq$ 80 eV
  - Inner divertor detached

Snowflake divertor configurations obtained with existing divertor coils, maintained for up to 10 τ_E



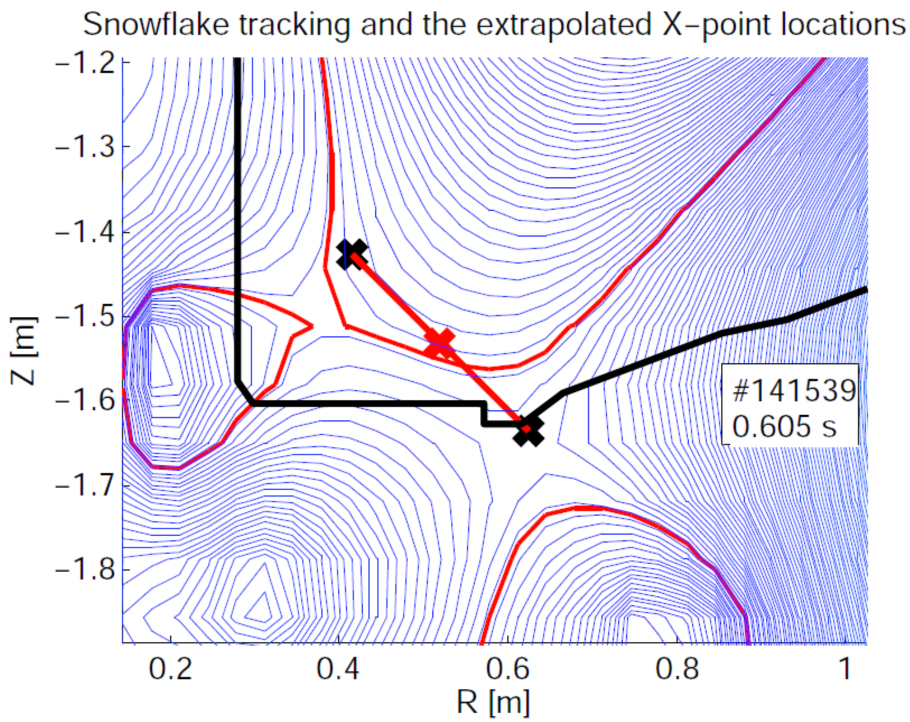
Plasma-wetted area and connection length are increased by 50-90 % in snowflake divertor





- These properties observed in first 30-50 % of SOL width
- B_{tot} angles in the strike point region: 1-2°, sometimes < 1°

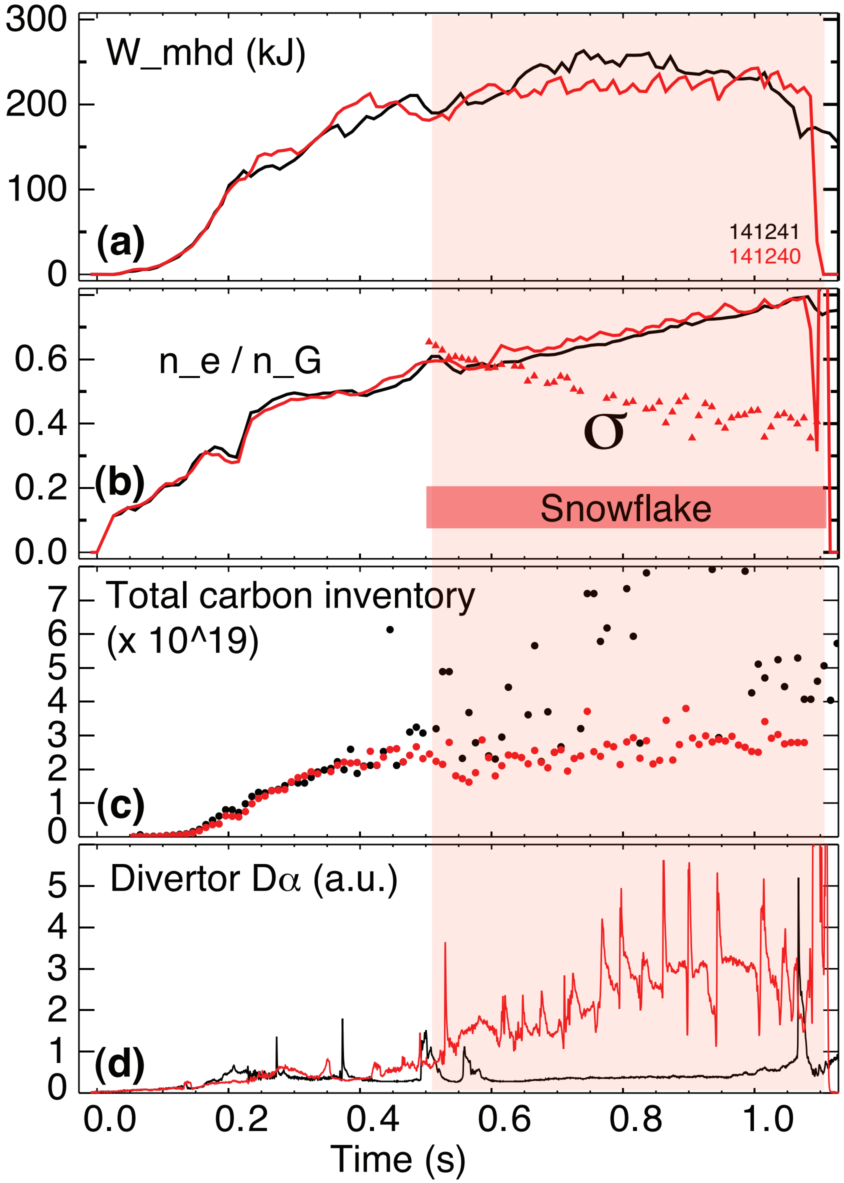
Close-loop feedback control of divertor coil currents is desirable for steady-state snowflake



M.A. Makowski & D. Ryutov, "X-Point Tracking Algorithm for the Snowflake Divertor"

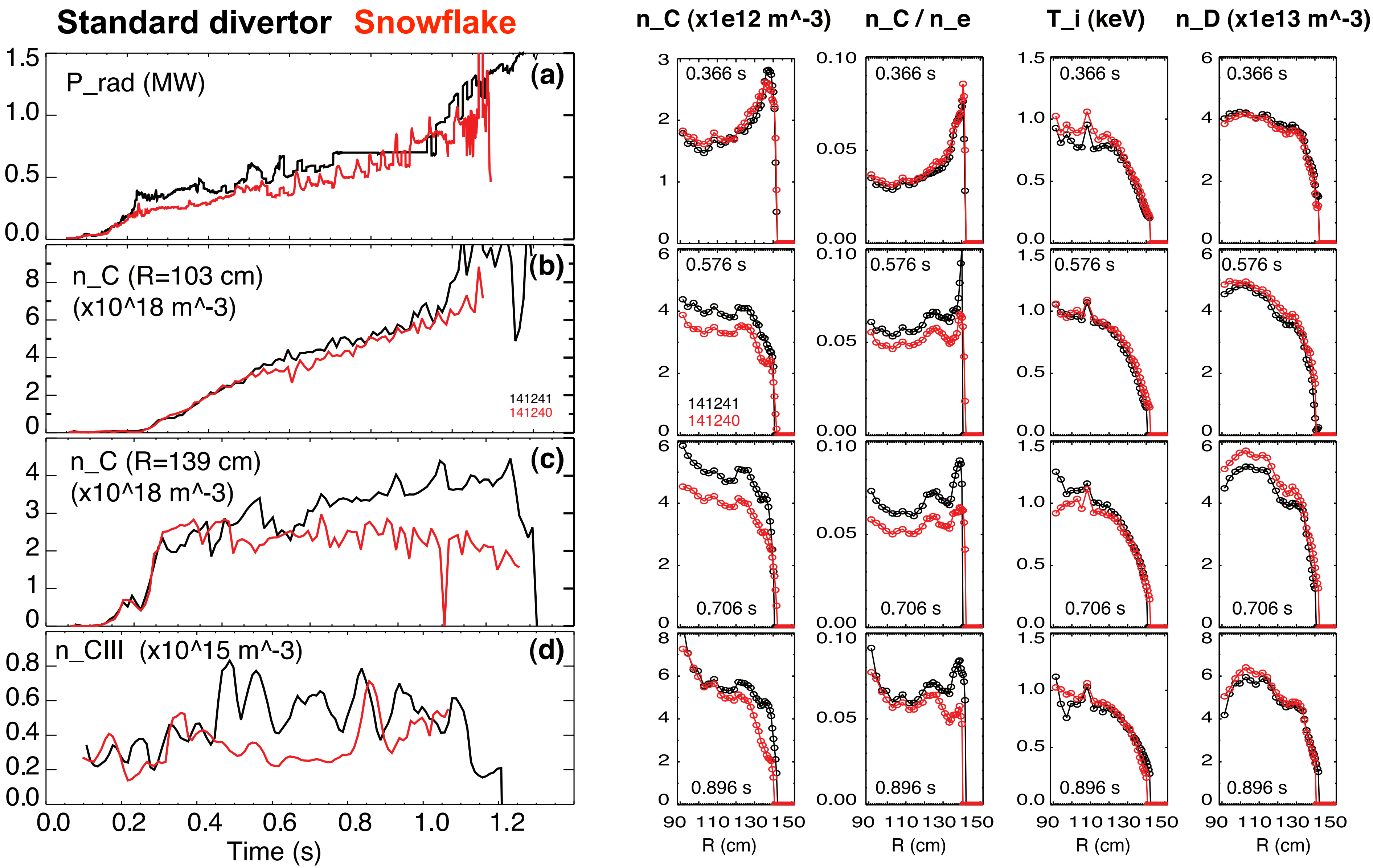
- All configurations are obtained reproducibly under feed-forward control in NSTX
- In NSTX
  - Developed X-point tracking algorithm that locates nulls and centroid
  - Algorithm tested on NSTX snowflakes successfully
  - Implementing snowflake control in digital plasma control system

Good H-mode confinement properties and core impurity reduction obtained with snowflake divertor



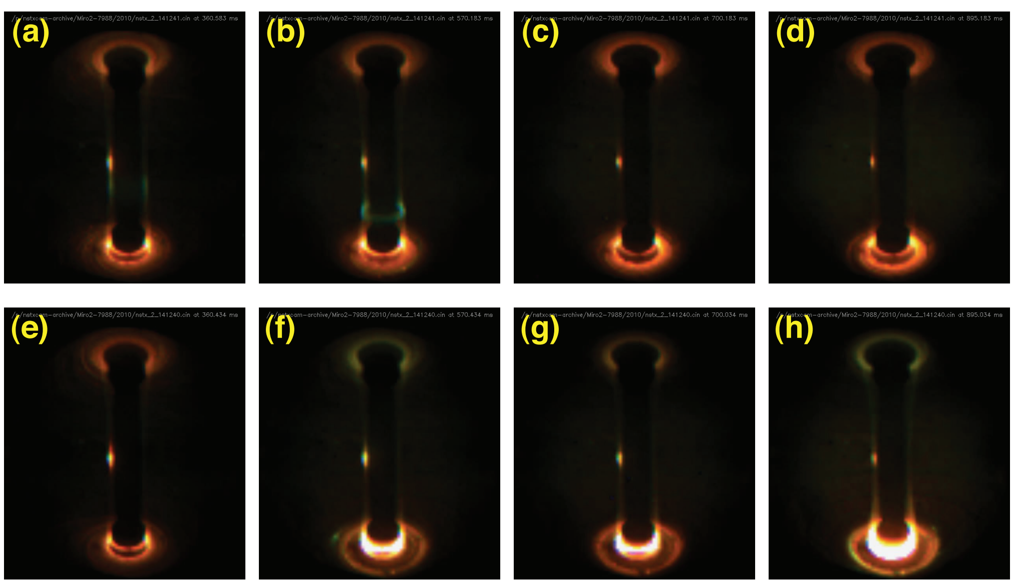
- 0.8 MA, 4 MW H-mode
- κ=2.1, δ=0.8
- Core T_e ~ 0.8-1 keV, T_i ~ 1 keV
- β_N ~ 4-5
- Plasma stored energy ~ 250 kJ
- H98(y,2) ~ 1 (from TRANSP)
- ELMs
  - Suppressed in standard divertor H-mode via lithium conditioning
  - Re-appeared in snowflake H-mode
- Core carbon reduction due to
  - Type I ELMs
  - Edge source reduction
    - Divertor sputtering rates reduced due to partial detachment

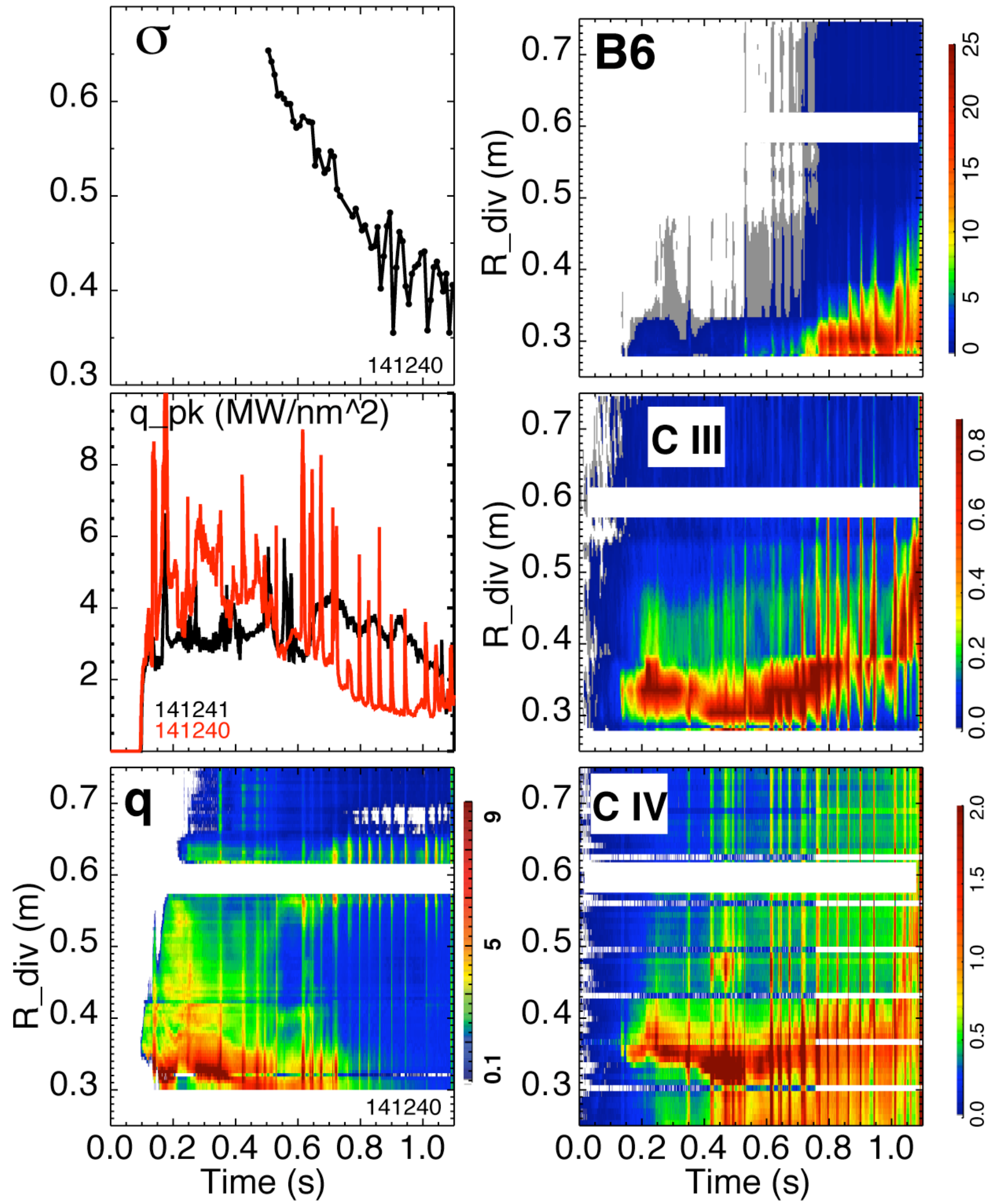
Core carbon density significantly reduced with snowflake divertor



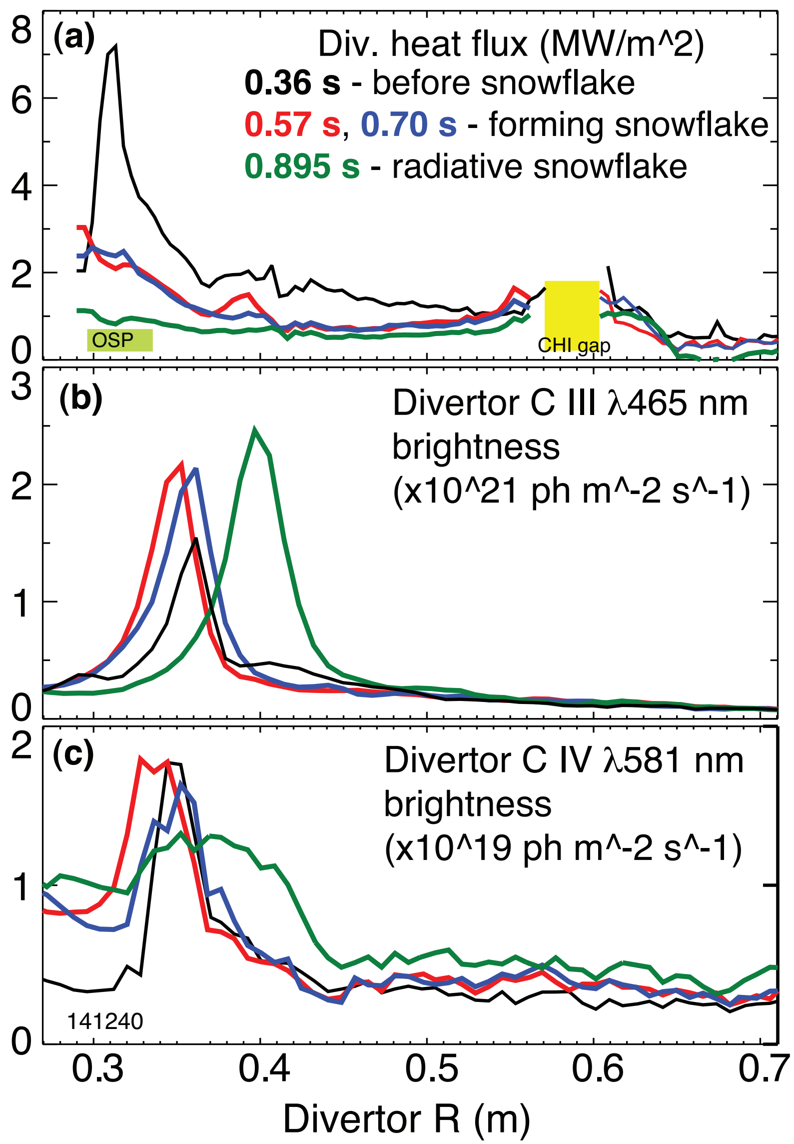
Radiative detachment with strong recombination and high radiated power observed in snowflake divertor

- Attached standard divertor - snowflake transition - snowflake + detachment
- P_{SOL} ~ 3 MW (P_{NBI} = 4 MW)
- Q_{div} ~ 2 MW -> Q_{div} ~ 1.2 MW
  -> Q_{div} ~ 0.5-0.7 MW

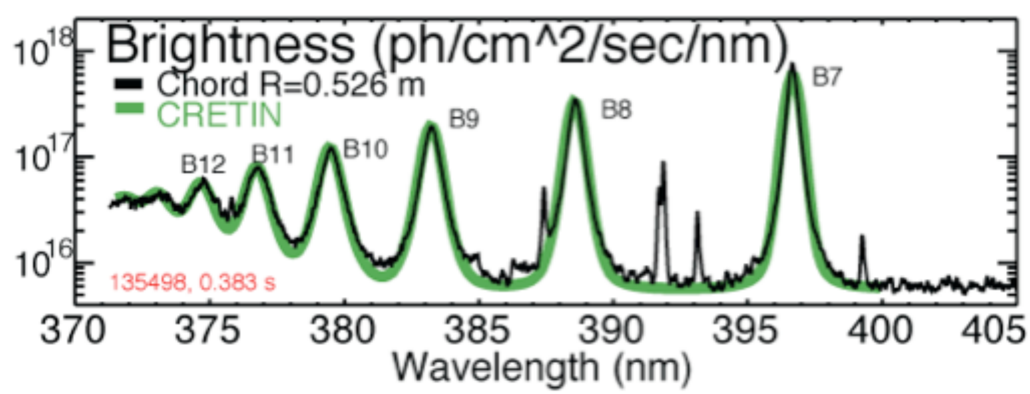




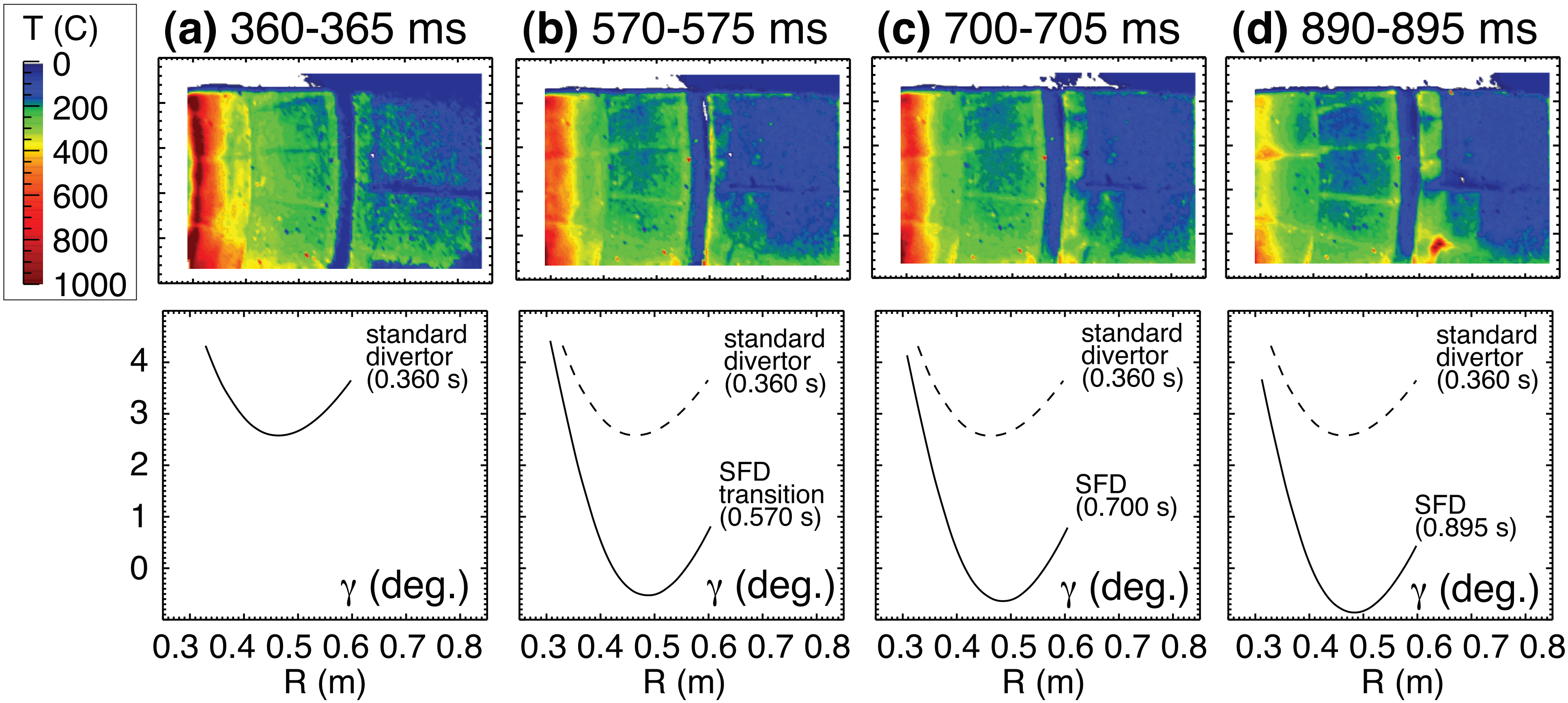
Divertor profiles show low heat flux, broadened C III and C IV radiation zones in the snowflake divertor phase



- Heat flux profiles reduced to nearly flat low levels, characteristic of radiative heating
- Divertor C III and C IV brightness profiles broaden
- High-*n* Balmer line spectroscopy and CRETIN code modeling confirm outer SP detachment with $T_e \leq 1.5$ eV, $n_e \leq 5 \times 10^{20}$ m^{-3}
  - Also suggests a reduction of carbon physical and chemical sputtering rates



No leading edge PFC tile heating observed at shallow magnetic field incidence angles

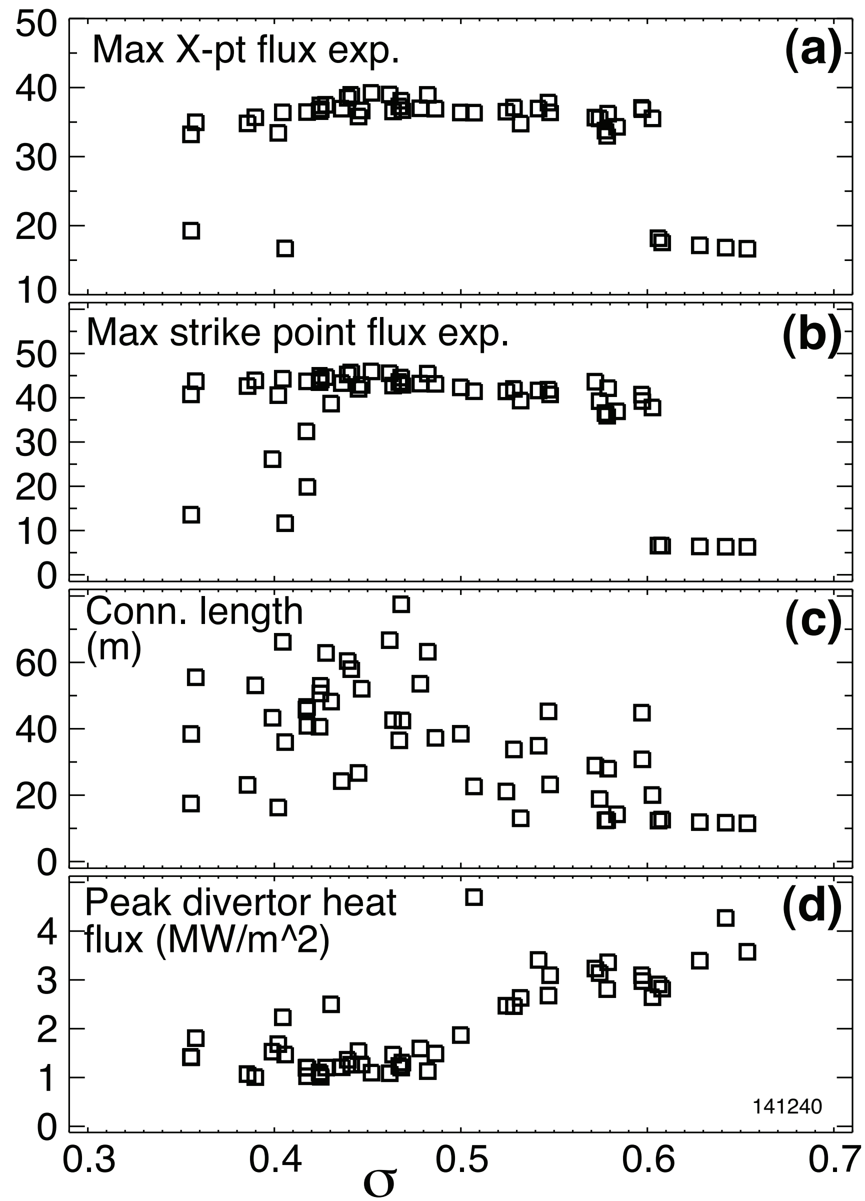


- Reduction of $q_{||}$ due to radiative detachment is considered

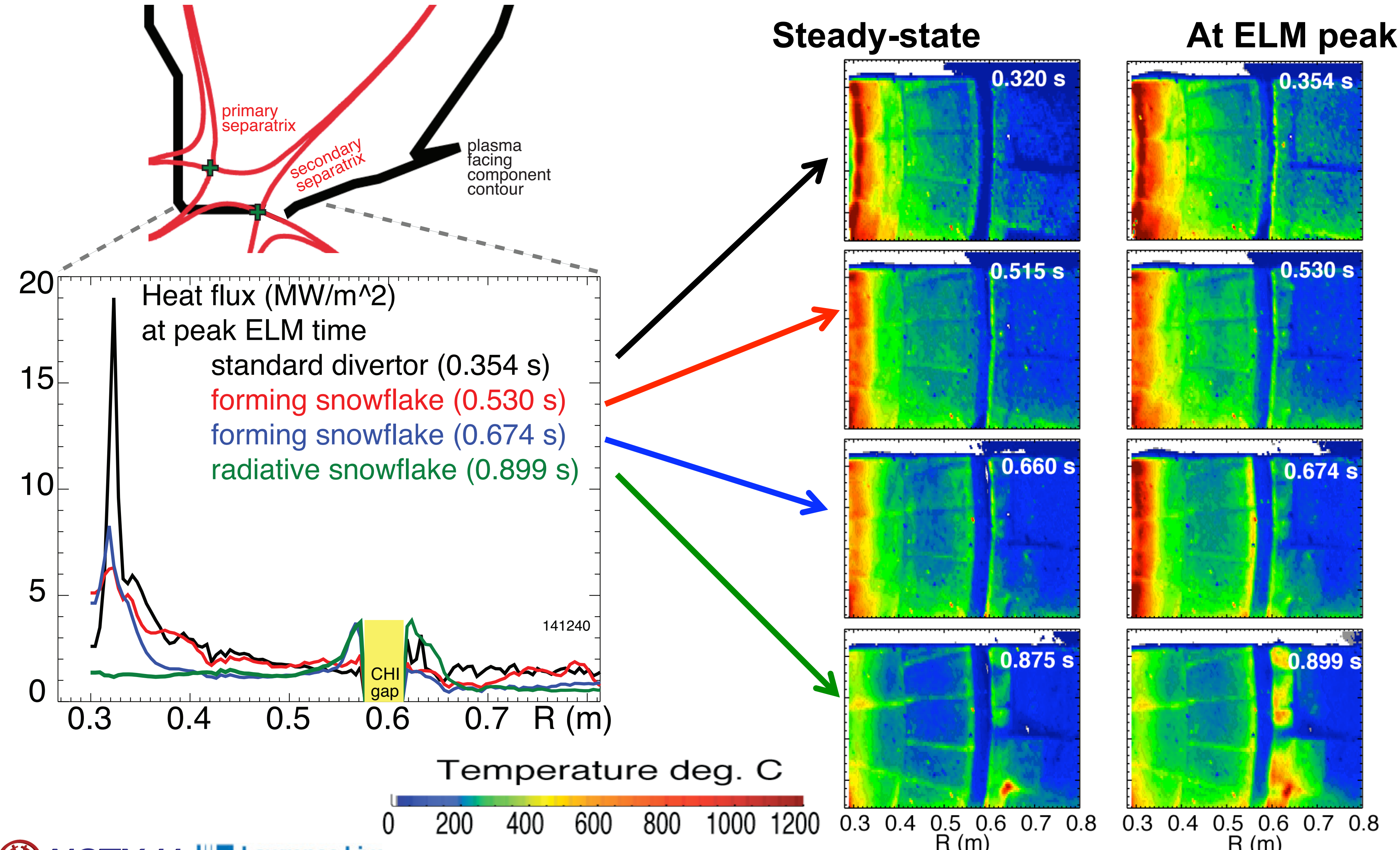
Peak divertor heat flux decreases with stronger snowflake effects (lower σ)

- Deviation from ideal snowflake: $\sigma = d / a$
  - *d* – distance between nulls, *a* – plasma minor radius

- Clear trends of flux expansion, connection length, and peak heat flux with σ observed

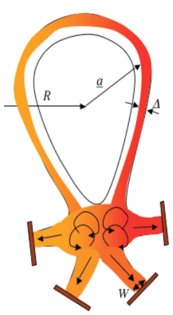


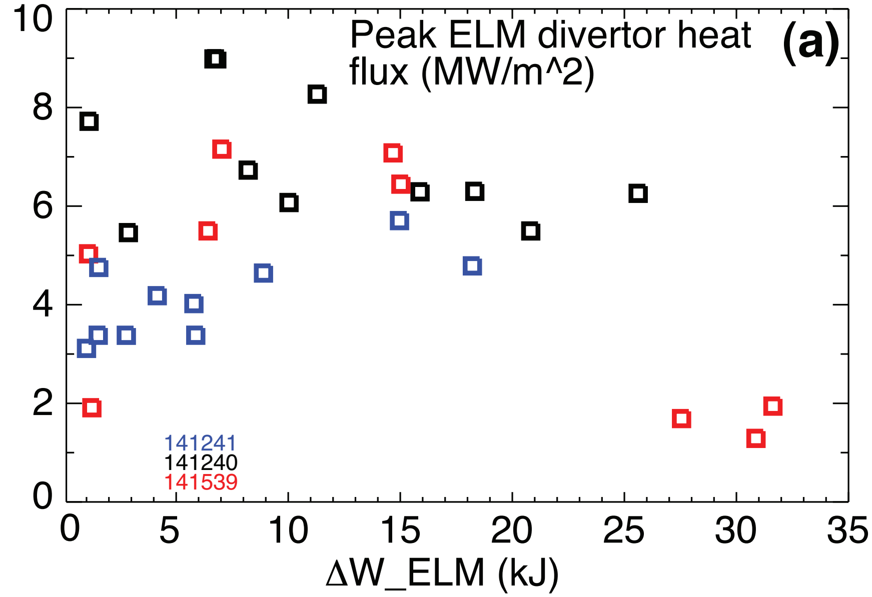
Impulsive heat loads due to Type I ELMs are mitigated in snowflake divertor

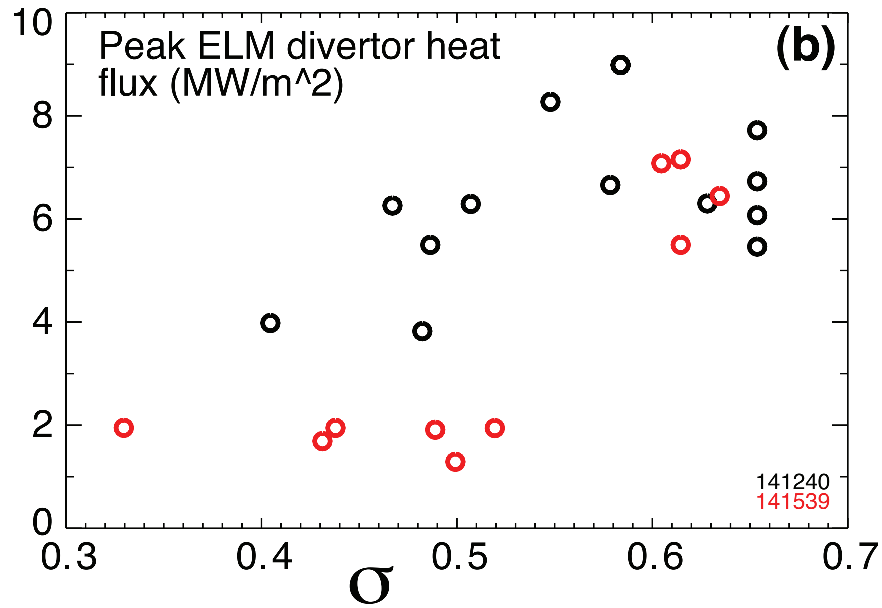


ELM peak heat flux strongly decreases with stronger snowflake effects (lower σ)

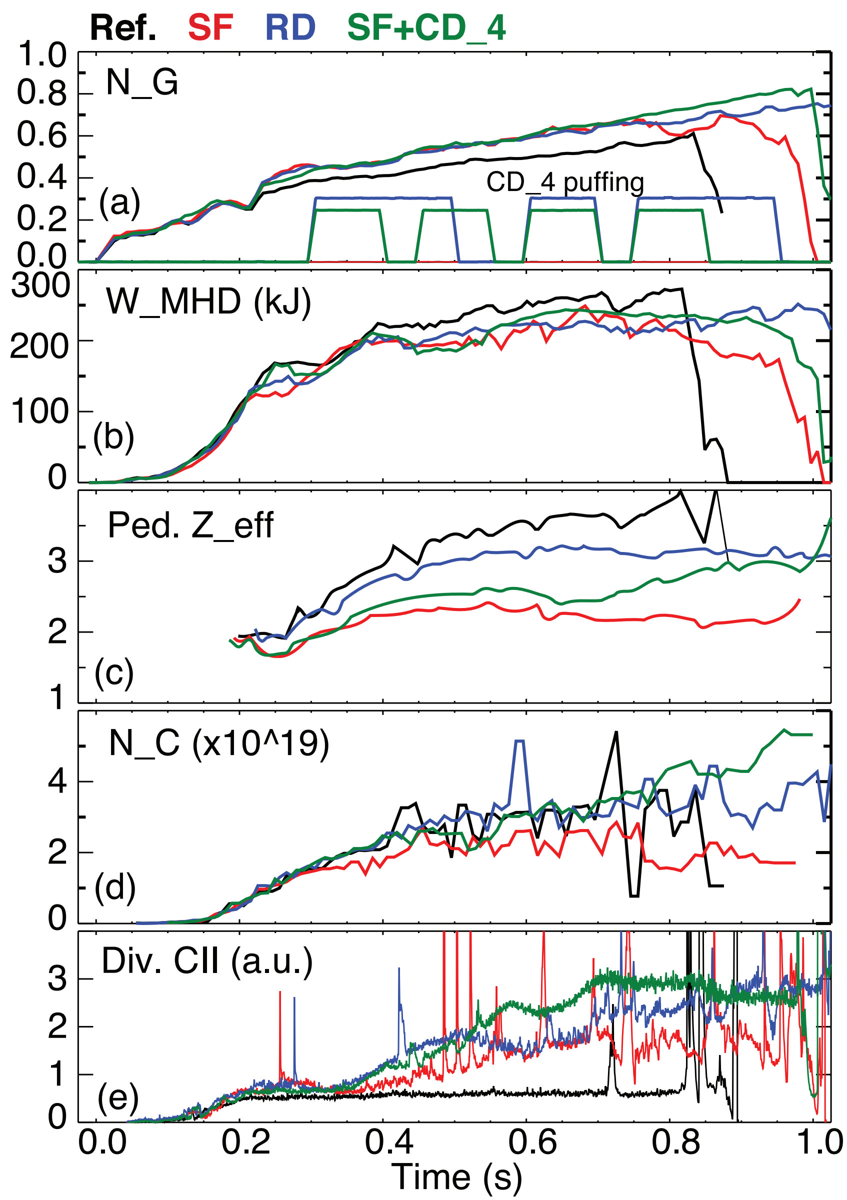
- H-mode standard divertor discharge
  - W_{MHD} ~ 220-250 kJ
  - Type I ELMs suppressed by lithium conditioning
  - Occasional ELMs occur
- In the snowflake phase
  - Type I ELM (*ΔW/W* ~ 5-15 %) re-appeared
  - ELM peak heat flux lower
- Theory (D. Ryutov, TH/ P4-18)
  - Reduced surface heating due to increased ELM energy deposition time
  - Convective mixing of ELM heat flux in null-point region -> heat flux partitioning between separatrix branches



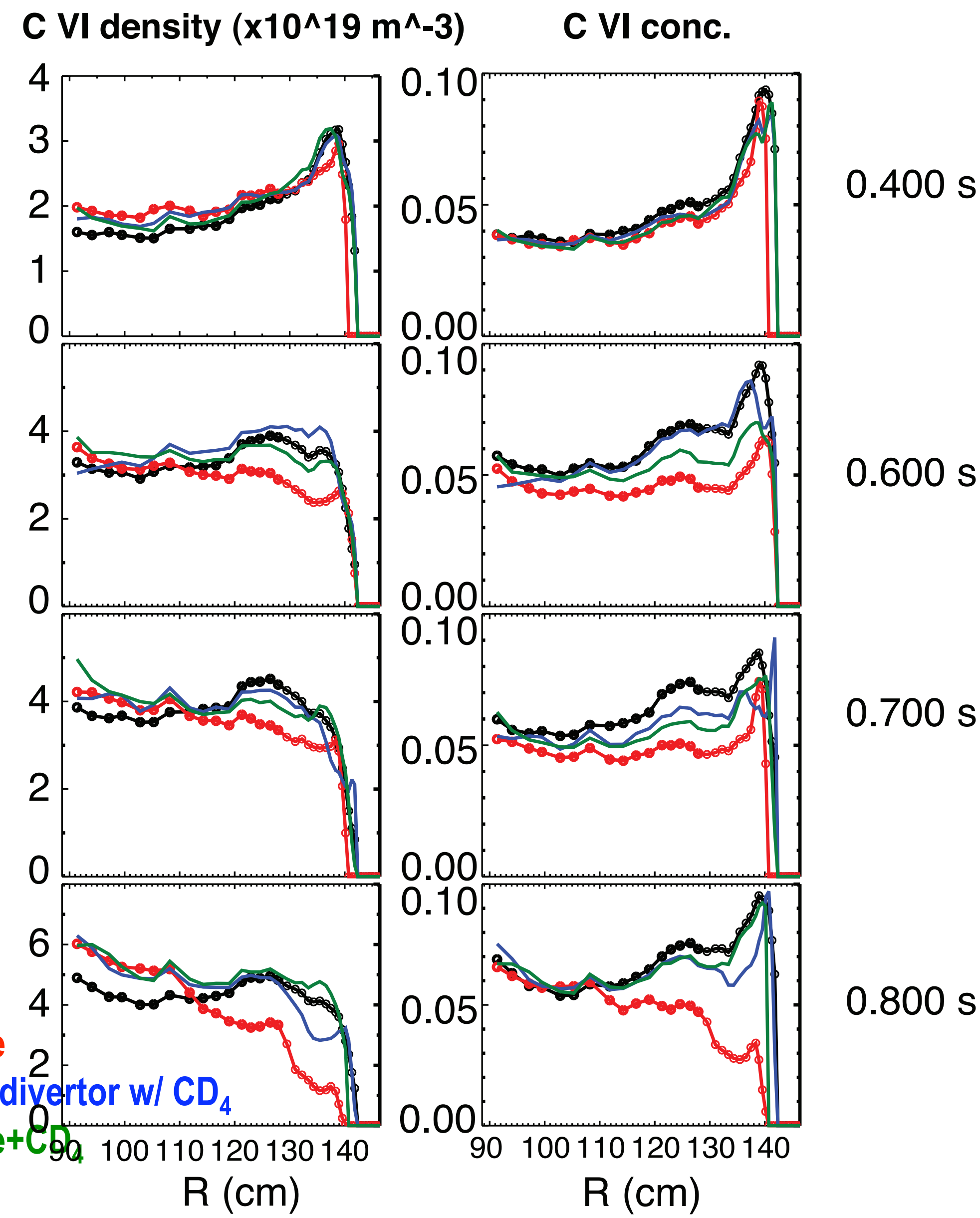




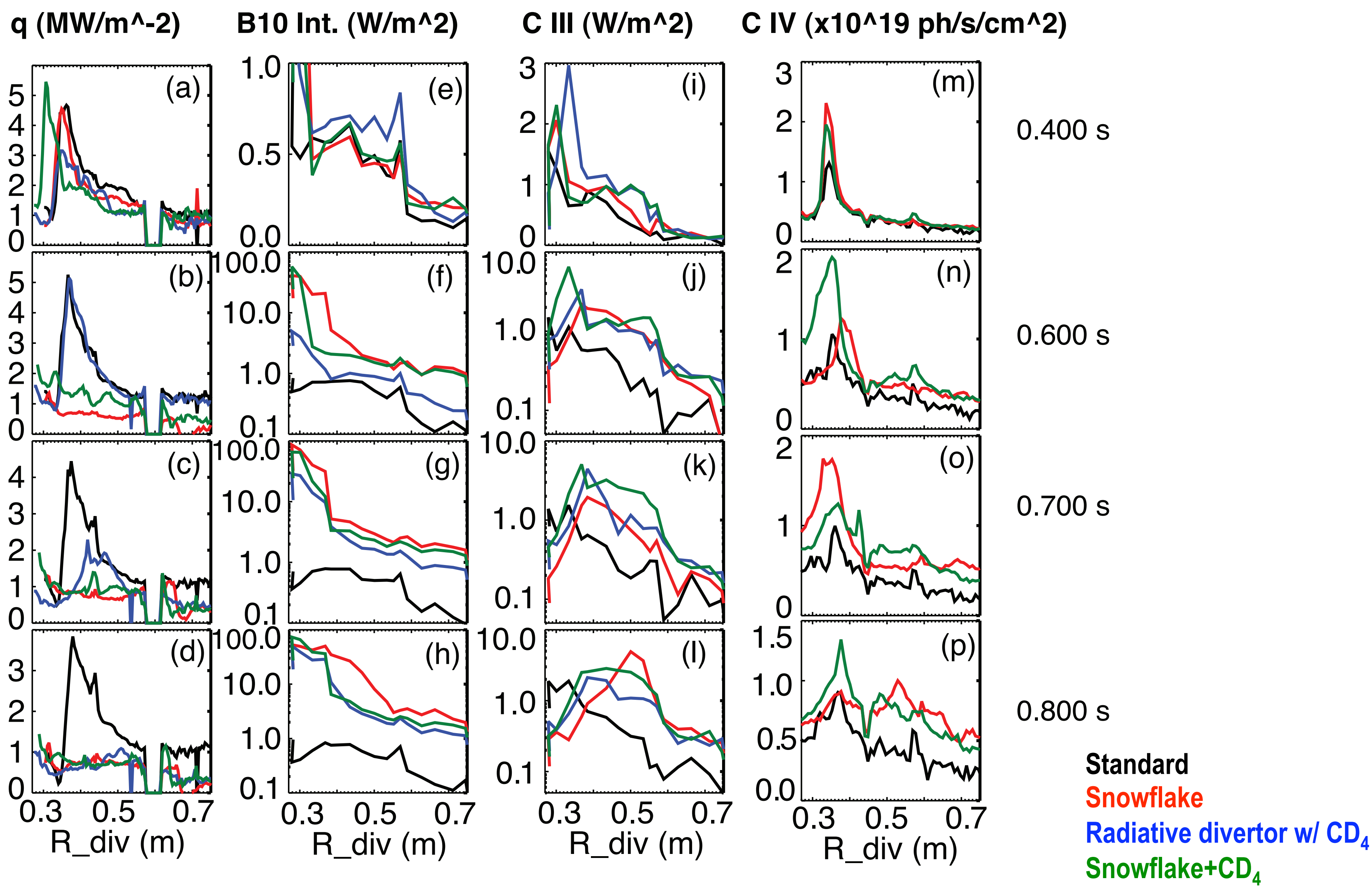
Good H-mode confinement properties retained or slightly reduced with CD_4-seeded snowflake divertor



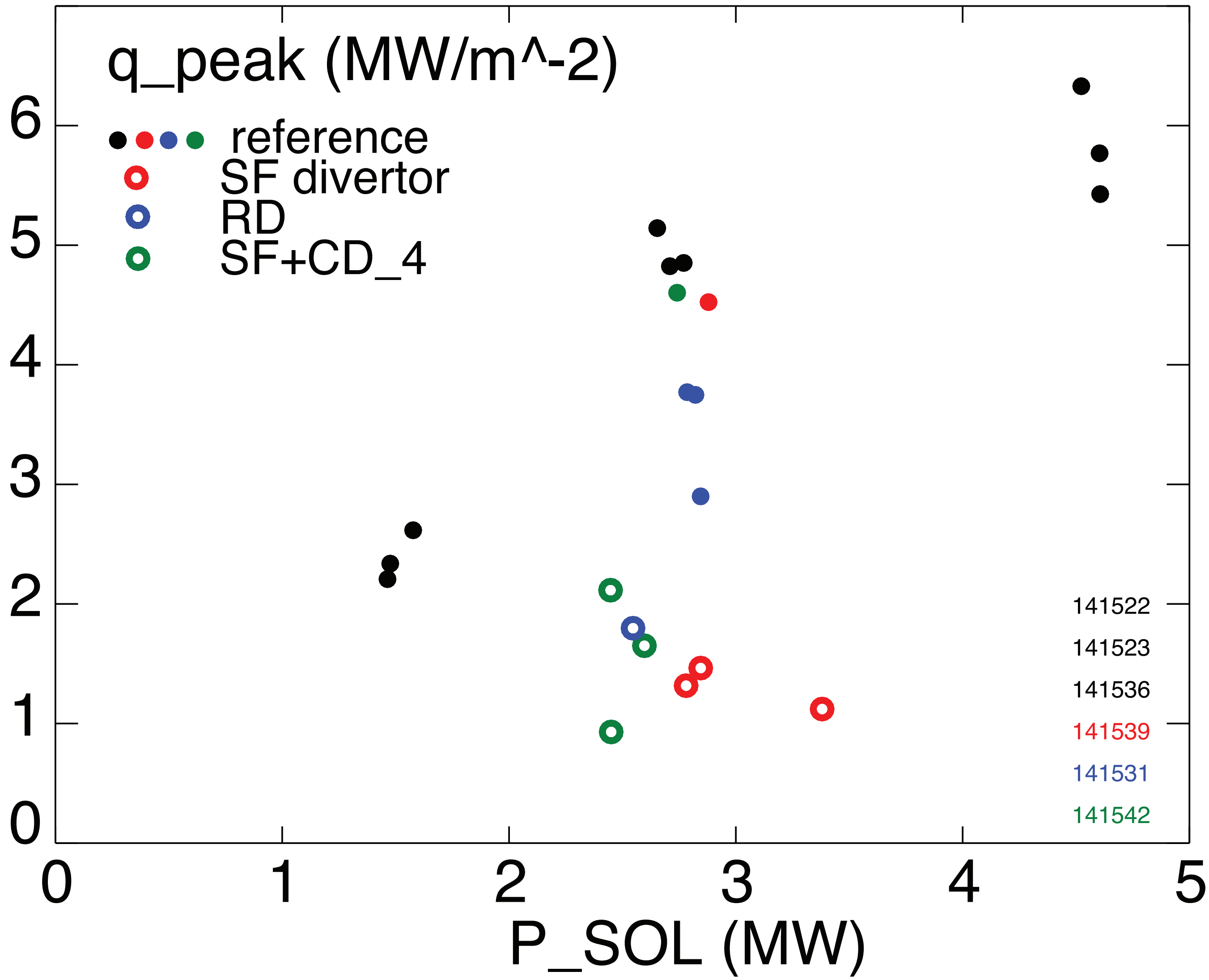
Standard
Snowflake
Radiative divertor w/ CD_4
Snowflake+CD_4



Divertor profiles show enhanced radiation and recombination zone in snowflake divertor w/ and w/o CD_4



Divertor heat flux reduced by radiation and/or geometry in radiative and snowflake divertors

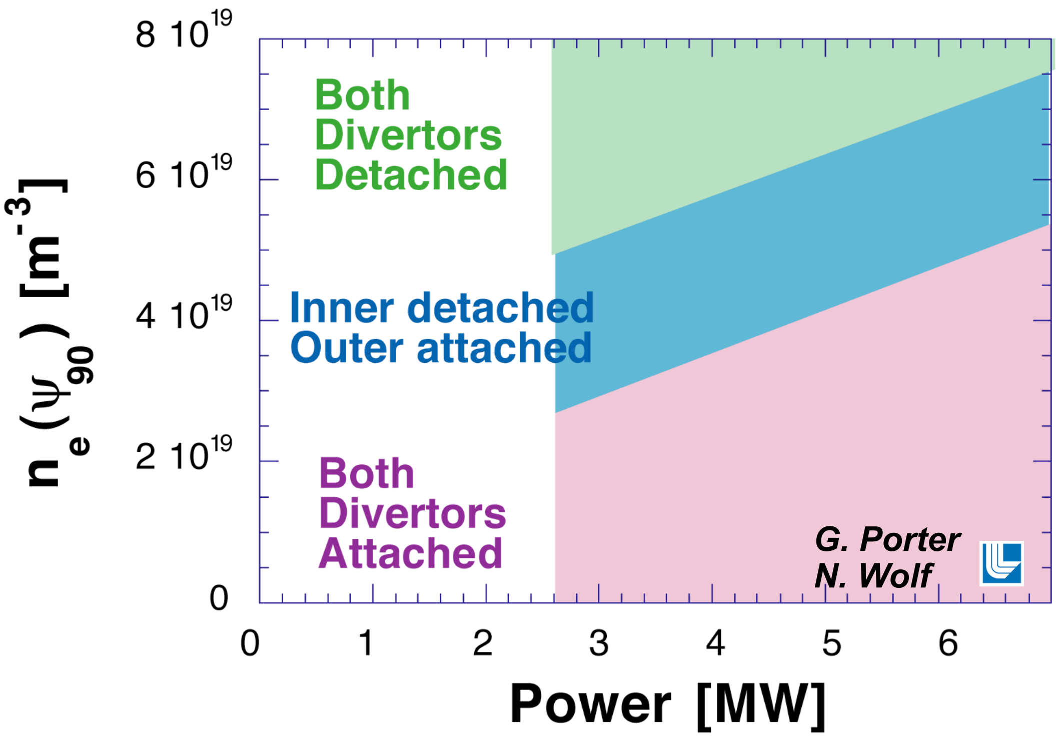


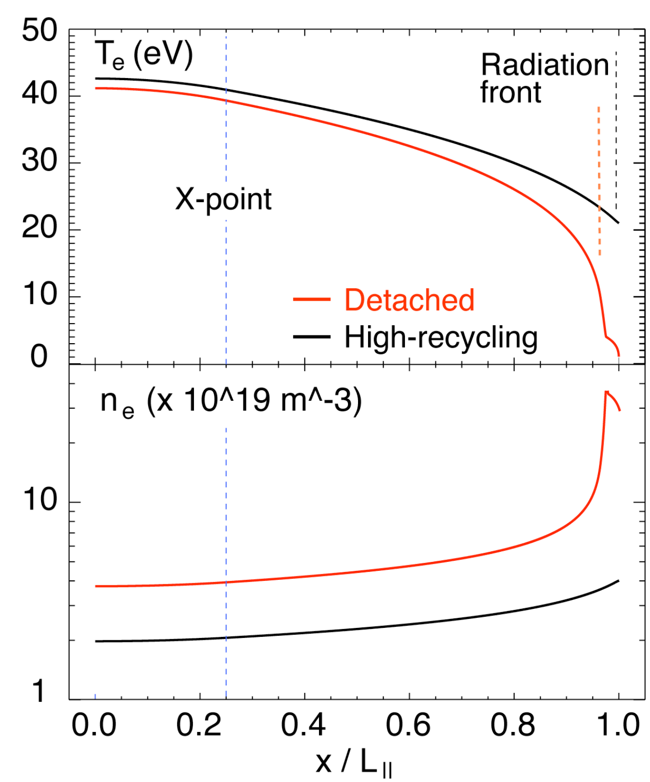
Stnadard
Snowflake
Radiative divertor w/ CD_4
Snowflake+CD_4

Summary: Developing real-time radiative divertor feedback control for NSTX-U

- Impurity-seeded radiative divertor technique is one of the leading candidates to mitigate divertor heat flux in NSTX-U discharges
  - Unmitigated 20-30 MW/m^2 peak heat fluxes predicted
- Radiative divertor feedback control being developed for NSTX-U
  - Proportional, integral, derivative process controller to be used in digital plasma control system
  - Fast piezoelectric valve is the actuator
    - Gas flow rate is proportional to control voltage
  - Control signal diagnostics for divertor detachment identification and control (System ID) are discussed in this poster
    - Divertor ID diagnostics
      - IR thermography
      - Thermoelectric current
      - Impurity VUV spectroscopy and bolometry
      - Neutral gas pressure
      - Electron-ion recombination rate via UV/NIR spectroscopy
    - Pedestal ID diagnostics

Models used to simulate detachment operation space and divertor plasma parameters during detachment





- Operating space P_{in}, n_e
- UEDGE calculations predicted limited "window" of outer divertor strike point detachment
- Radiation from intrinsic carbon at 3-5 %

- 5-zone 1D SOL model predicts typical T_e and n_e in NSTX during detachment
- High f_{rad} ~0.8-0.9 used for detachment simulation

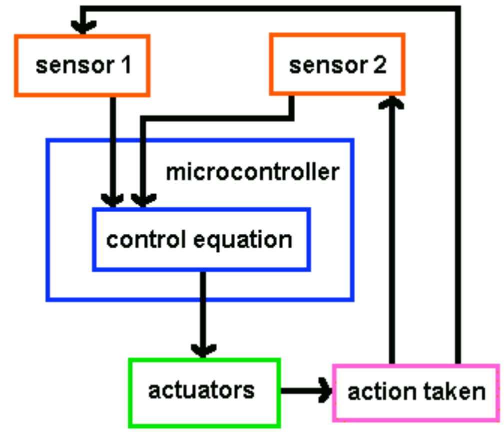
SOUKHANOVSKII, V. et al., Phys. Plasmas 16 (2009) 022501,
SOUKHANOVSKII, V. et al., J. Nucl. Mater. 363-365 (2007) 432.

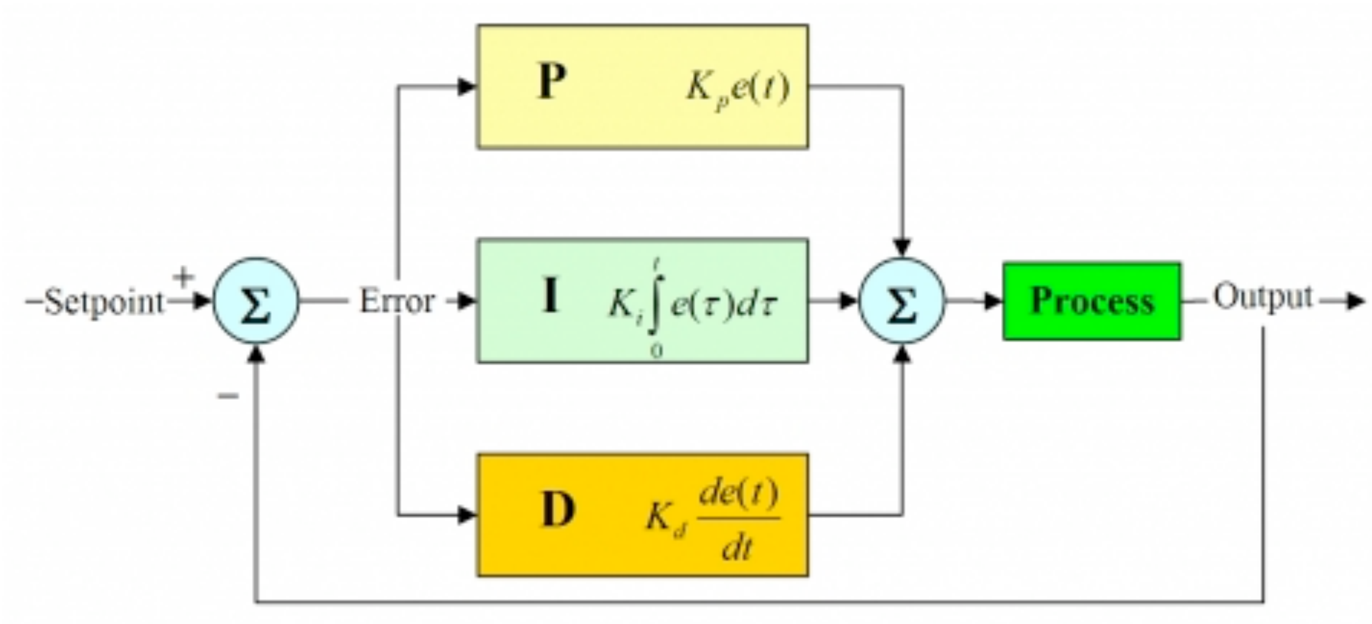
Conceptual design of radiative divertor feedback control system is based on PID control

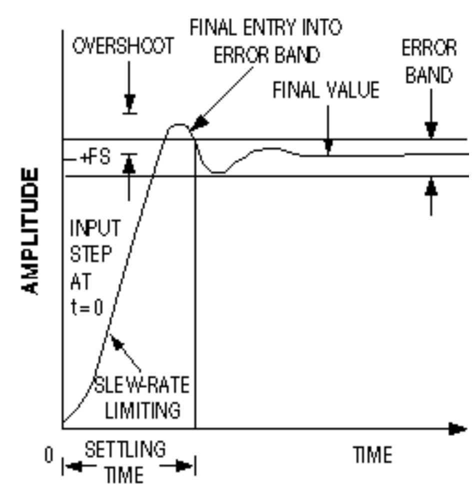
- Proportional, integral, derivative controller

$$\Delta S = S_c - S_{ref}$$

$$V = K_0 + K_p \Delta S + K_i \int_{t_1}^{t_2} \Delta S dt + K_d \frac{d\Delta S}{dt}$$

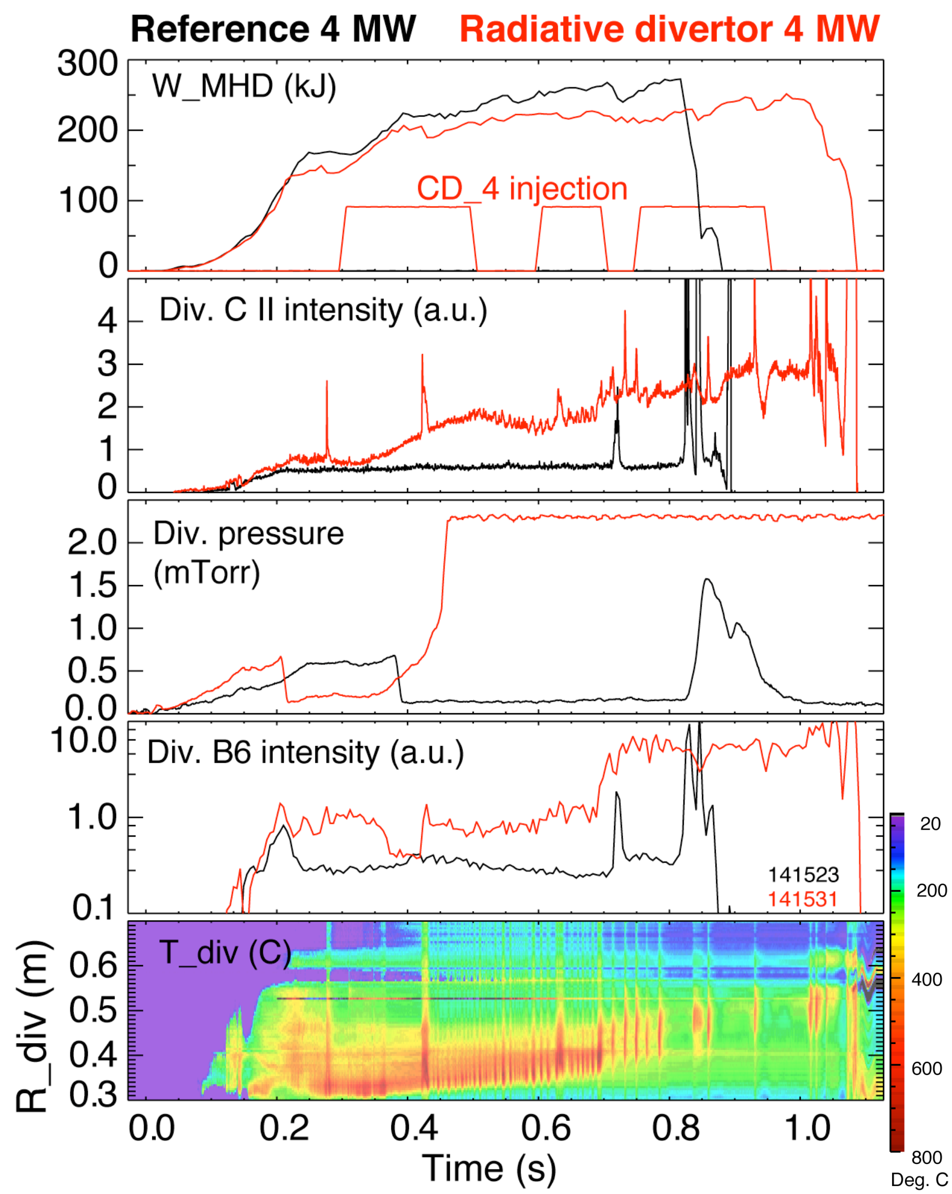






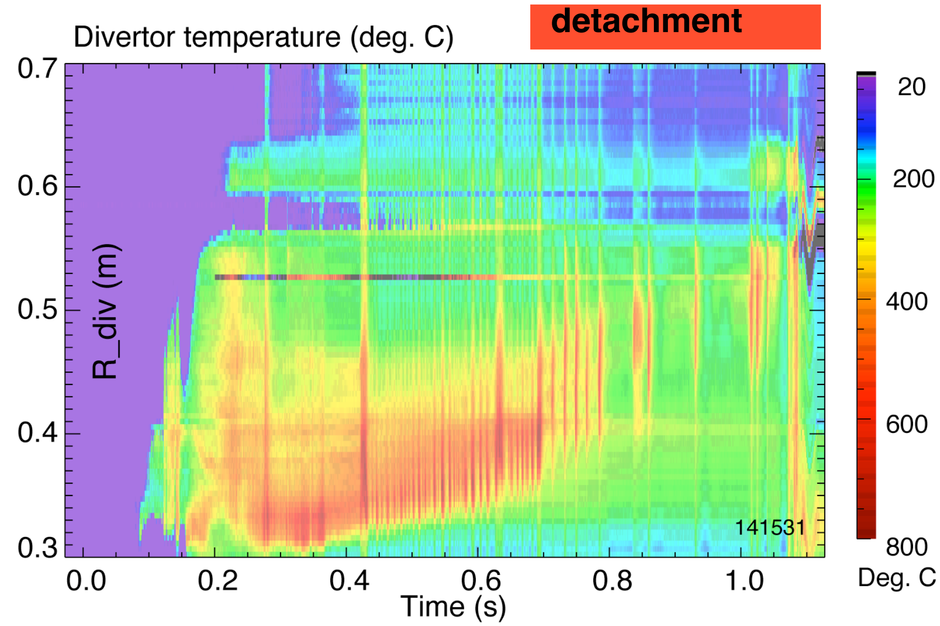
Control signal options demonstrated using divertor outer strike point partial detachment with D_2 or CD_4 puffing

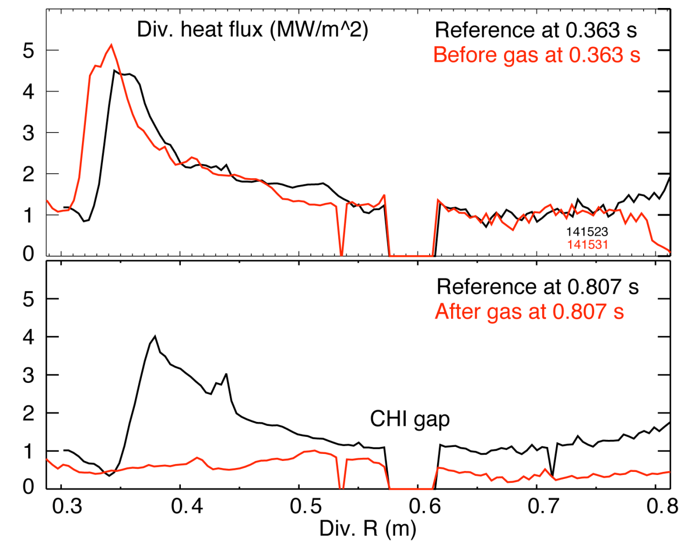
- 4MW NBI-heated H-mode
  - CD_4 injection preprogrammed wave form
- Outer strike point detachment occurred at about 0.7 s (red traces)
  - Characteristic onset time 50 ms
- Divertor detachment affected divertor power balance
  - Carbon radiation and P_{rad} increased
  - Divertor heat flux decreased
- Divertor detachment affected SOL momentum balance
  - Neutral pressure increased (also due to gas puffing)
  - Divertor volumetric recombination rate increased (Balmer line intensities increased)



Option 1: IR thermography for divertor surface temperature monitoring

- Diagnostic principle and description
  - Measure PFC surface IR emission, calibrate for temperature
  - IR arrays (1D or 2D) or single-channel IR diode with strike-point region view
- Signal details from NSTX experiments
  - Detached region localization: 5-12 cm
  - Characteristic time: 1 ms
  - X 4 reduction during detachment
- Advantages:
  - Direct PFC temperature monitoring
- Issues:
  - Toroidal and poloidal localization
  - Interpretation and calibration issues due to PFC coatings (e.g., lithium)
- Implementation
  - Needs special IR and relay optics
  - IR optics

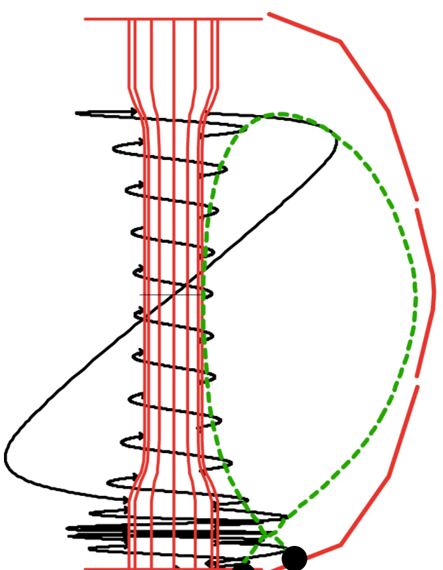




AHN, J.-W. et al., Rev. Sci. Instrum. 81 (2010) 023501.

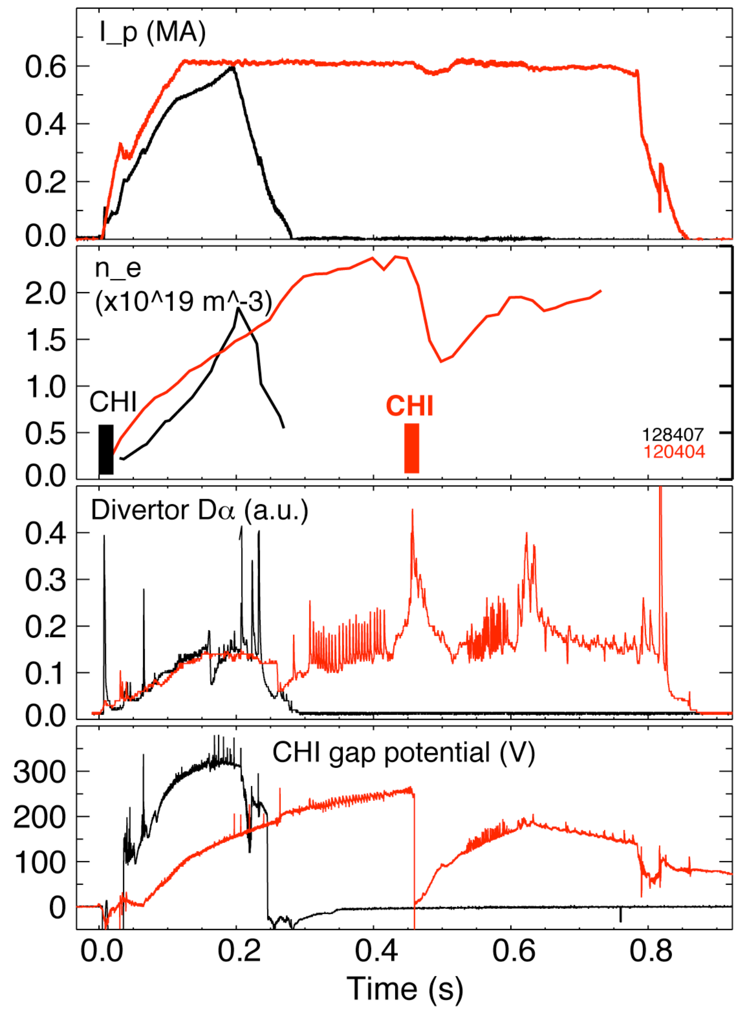
Option 2: monitor SOL thermo-electric current representative of divertor electron temperature

- Diagnostic principle and description
  - SOL thermoelectric current due to divertor T_e difference
  - Electric current and potential
- Signal details from NSTX experiments
  - In NSTX inner and outer vessels electrically isolated
  - Potential V measured in CHI exp's



- Advantage:
  - Toroidally-averaged current and potential, linked to divertor T_e
- Issues:
  - More experiments needed to improve interpretation

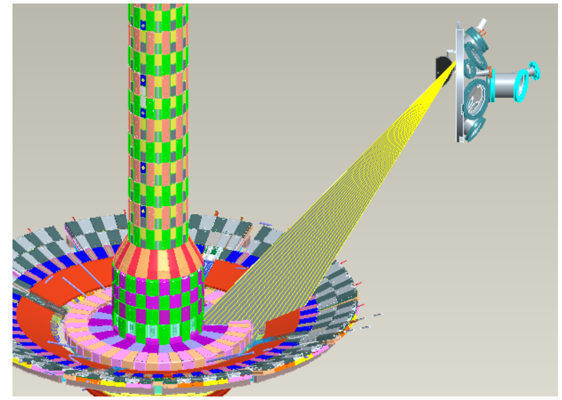
Measure V, I



RAMAN, R. et al., Nucl. Fusion 49 (2009) 065006
STAEBLER, G. et al., Nucl. Fusion 29 (1989) 1820
KALLENBACH, A. et al., J. Nucl. Mater. 290-293 (2001) 639

Option 3: Monitor divertor radiated power or spectroscopic representation of radiated power

- Diagnostic principle and description
  - Fast bolometer or AXUV diode (or array) to monitor divertor rad. power
  - VUV spectroscopy
- Advantage:
  - Toroidally-averaged quantity linked to seeded impurity radiation
- Issues:
  - Need to know radiation distribution and spectral composition
- Implementation
  - Existing AXUV diode array (s)
  - Divertor SPRED
  - Dedicated divertor VUV monitor



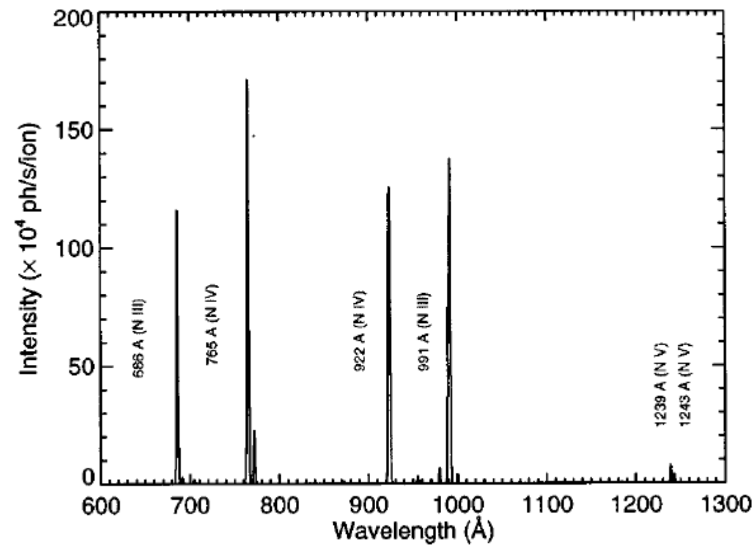
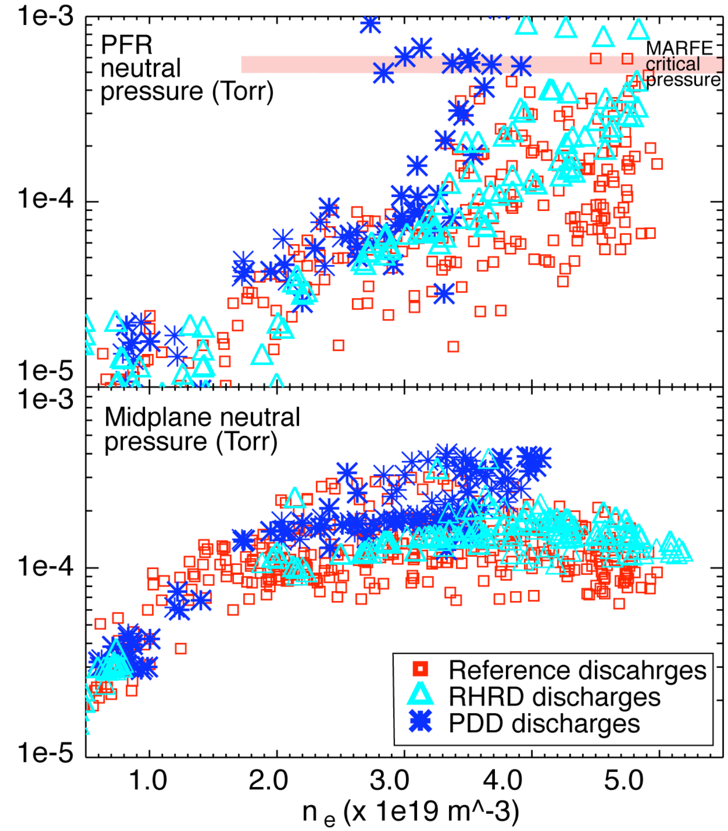


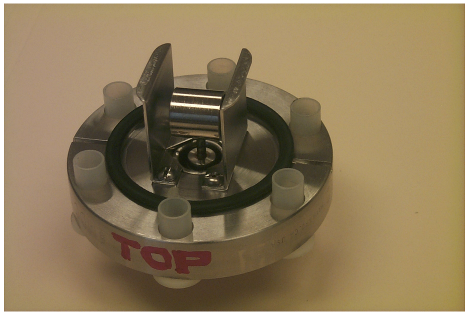
FIG. 2. Modeled N III, N IV, and N V spectrum at $T_e=9.7$ eV and $n_e=5\times10^{14}$ cm^{-3}. Calculated intensities were given a Gaussian profile with $\Delta\lambda_{FWHM}=1$ Å.

SOUKHANOVSKII, V. et al., Rev. Sci. Instrum. 70 (1999) 340
SOUKHANOVSKII, V. et al., Rev. Sci. Instrum. 72 (2001) 3270

Option 4: Monitor neutral pressure

- Diagnostic description
  - Penning gauge for gas pressure monitoring in range 0.1-5 mTorr
- Signal details from NSTX experiments
  - Divertor pressure measured in private flux region, outer strike point region
- Advantages:
  - Direct seeding gas pressure measurement
- Issues:
  - Need to understand links to detachment characteristics
- Implementation
  - Straightforward, existing gauges can be used
  - Developing calibrated spectroscopic monitoring of Penning gauge

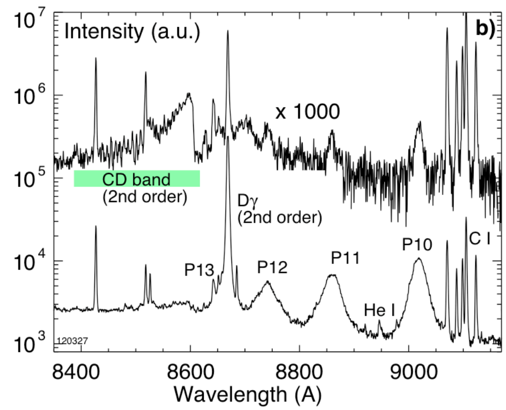


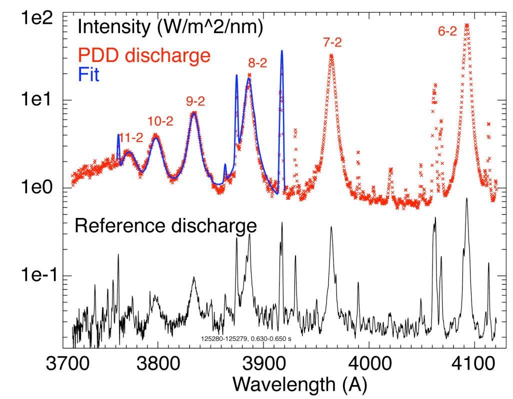


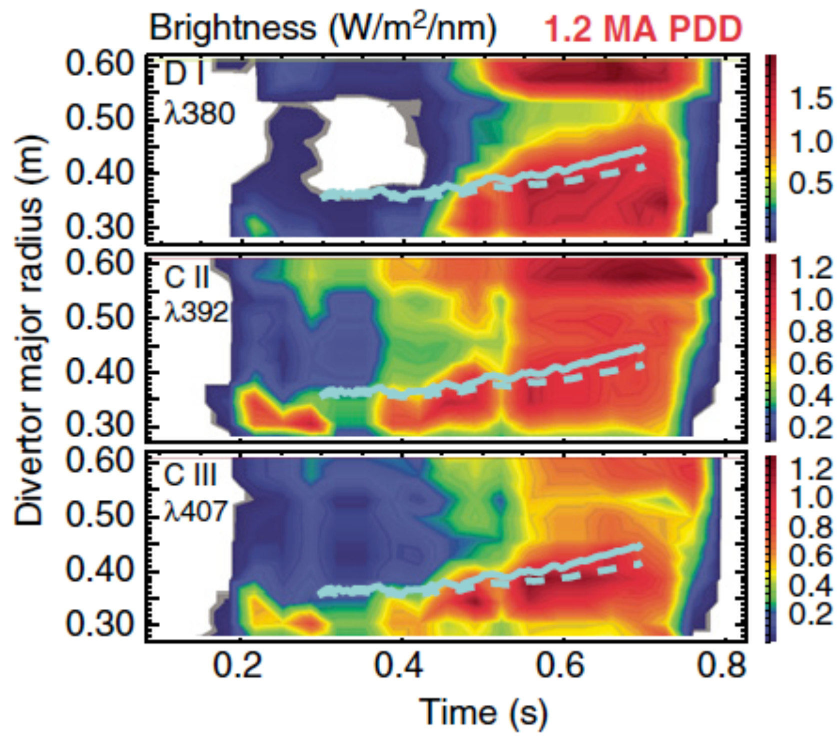
FINKEN, K. et al., Rev. Sci. Instrum. 63 (1992)

Option 5: Monitor recombination rate via Balmer or Paschen line spectroscopy

- Diagnostic description
  - UV or NIR spectroscopy to monitor emission line intensity from high-n Balmer or Paschen series lines
- Signal details from NSTX expt's
  - Strong indication of detachment, signal increases by up to 10^2
  - Observed *n*=2-*m*, m=3-12 (Balmer)
  - Observed *n*=3-*m*, m=5-10 (Paschen)
- Advantages:
  - Toroidally-averaged quantity
  - Direct measure of recombination rate
- Implementation
  - Can use existing UV and NIR fibers and instruments



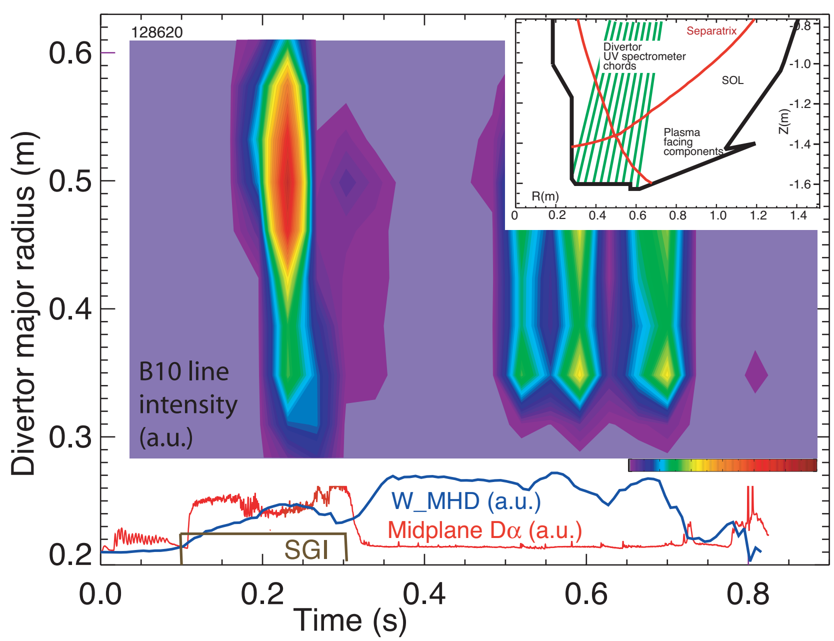




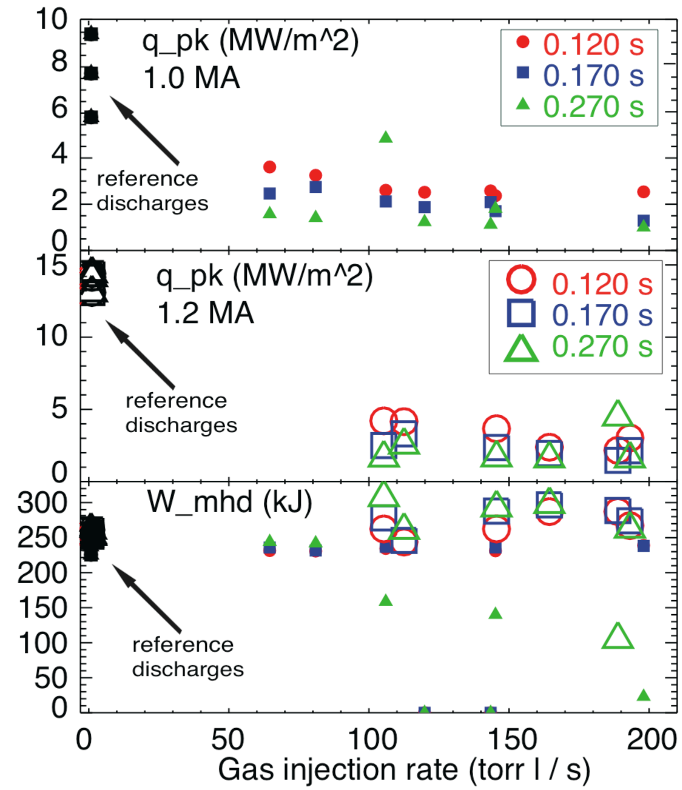
SOUKHANOVSKII, V. et al., Rev. Sci. Instrum. 77 (2006) 10127
SOUKHANOVSKII, V., Rev. Sci. Instrum. 79 (2008) 10539
SOUKHANOVSKII, V. et al., Rev. Sci. Instrum. 81 (2010) 10723.

Option 6: need “security” monitoring for signs of confinement degradation (pedestal temperature or MARFEs)

- Diagnostic principle and description
  - Monitor pedestal T_e (100-600 eV)
    - Soft X-ray arrays, real-time Thomson
  - Monitor MARFE formation
    - Edge neutral pressure
    - Divertor recombination rate



X-point MARFE formation during high-rate supersonic gas injection. Balmer B10 line intensity is plotted.



Optimal D_2 injection rate found (used 300 ms pulses)

- 50-100 Torr l /s for 1.0 MA discharges
- 110-160 Torr l /s for 1.2 MA discharges

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