NSTX-U

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Boundary Physics Progress and Plans

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NSTX PAC-31
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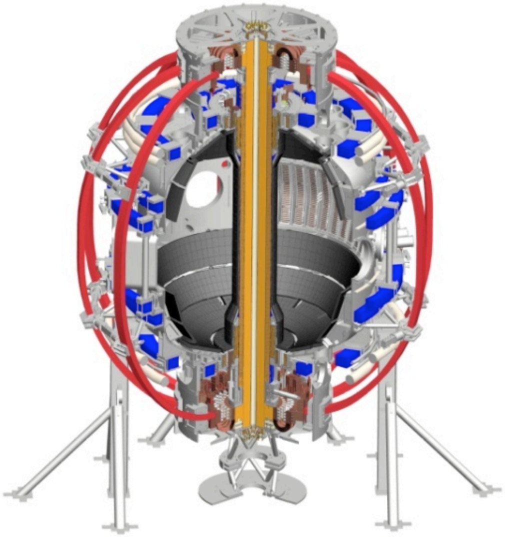

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NSTX Boundary Physics program contributes to a critical research area for ITER/tokamaks and STs

- DOE Joint Research Targets
  - FY 2013: Enhanced confinement regimes without ELMs

- NSTX research milestones
  - R(12-2): Project deuterium **pumping** capabilities for NSTX-U using lithium coatings and cryo-pumping (with LR and ASC TSGs)
  - R(13-2): Investigate the relationship between **lithium-conditioned surface** composition and plasma behavior (with LR TSGs)
  - R(14-2): Develop **advanced axisymmetric control** in sustained high performance plasmas (with ASC and MS TSGs)

- Divertor solution for NSTX-U
  - Integrated power, impurity and density control aimed at future STs

- ITPA participation and high-priority ITER research tasks

Outline

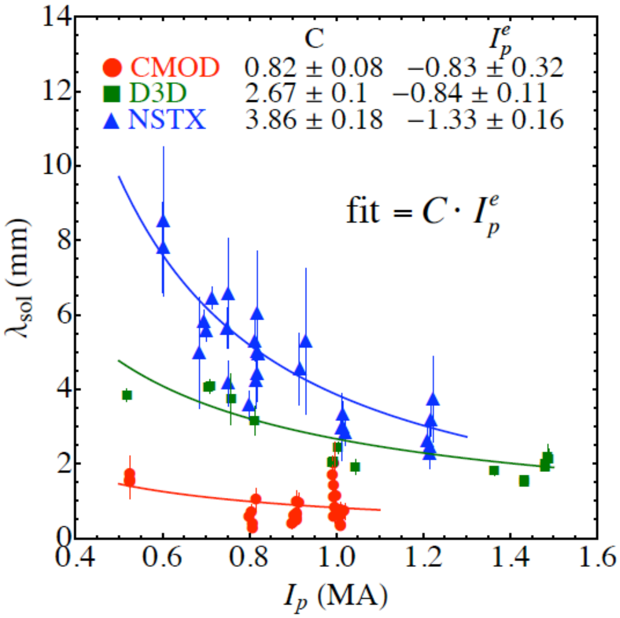
- Boundary physics progress and near-term plans
  - Edge transport and plasma-surface interactions
    - Thermal heat transport in the SOL and divertor, heat flux mitigation
    - SOL transport and turbulence studies
    - Impurity source control
  - H-mode physics
    - Pedestal physics studies
    - ELM characterization and control
- Planning Boundary research for NSTX-U
  - Initial years (1-2) of NSTX-U operation
  - Later years (3-5) of NSTX-U operation
  - Facility and diagnostic improvements, divertor power control plans
- Summary

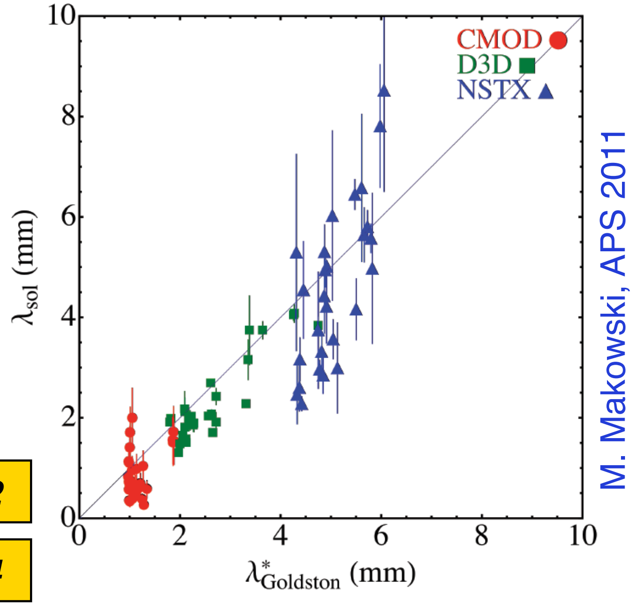
SOL width studies in NSTX elucidate on divertor projections for NSTX-U, ST-FNSF and ITER

- JRT 2010 on heat transport
  - λ_q^{mid} contracts with increasing I_p: $\lambda_q^{mid} \sim I_p^{-1.6}$
- Comparison with SOL models
  - Parallel transport: conductive/convective, cross-field : collisional / turbulent / drift
  - XGC0 reproduced I_p dependence $\lambda_q^{mid} \sim I_p^{-1.0}$
  - SOLT: I_p scaling is weaker than observed
    - P_{SOL}, collisionality, $L_{||}/R$ set cross-field transport and turbulence structure that affect λ_q
  - Goldston drift-based model of SOL flows
    - Attached H-mode regimes
    - ∇B and curvature drift motion sets SOL width $\lambda_{SOL} \sim (2a/R)\, \rho_i$, Spitzer thermal conduction sets T_{sep}
  - Exploring mechanisms setting steep pressure gradient region and connection to SOL width
- Projections to NSTX-U
  - $\lambda_q^{mid} = 3 \pm 0.5$ mm
  - As $q_{peak} \sim I_p$ and $q_{peak} \sim P_{SOL}$, $q_{peak} \sim$ 20-30 MW/m^2

PAC29-12

PAC29-14

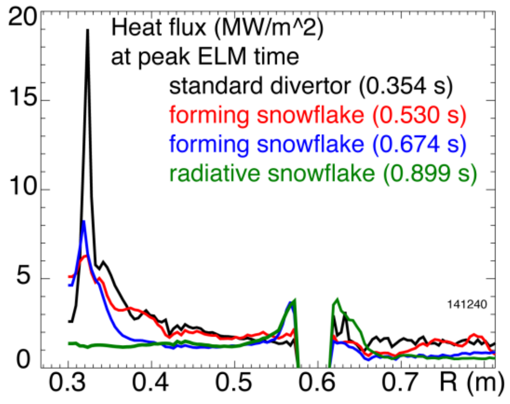


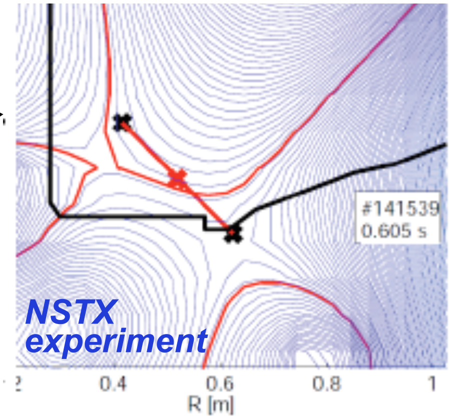


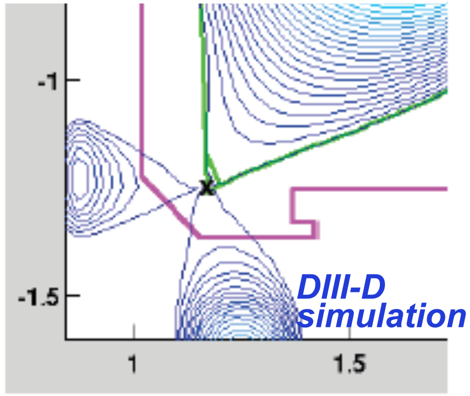
M. Makowski, APS 2011

Further studies of snowflake divertor configuration contribute to NSTX-U divertor heat flux control options

- NSTX snowflake divertor
  - Second divertor null maintained with existing coils for ≤10 τ_E
  - H-mode confinement, reduced core carbon
  - Effective in heat flux dissipation
    - Reduction from 3-7 MW/m^2 to 0.5-1 MW/m^2 between ELMs
    - Reduction from ~ 20 MW/m^2 to 2-8 MW/m^2 at ELM peak
- New collaboration with DIII-D
  - Configuration control algorithm implemented in PCS
  - Experiment proposed at ROF 2012
    - If control demonstrated, positive outlook for run time in FY2012
    - Excellent pedestal and divertor diagnostic capabilities to clarify outstanding questions (e.g. power balance, pedestal stability, particle control with cryo-pumping and argon seeding)
- Modeling of NSTX snowflake experiment data
  - Analysis of pedestal stability with BOUT++
  - UEDGE modeling of heat transport and radiation

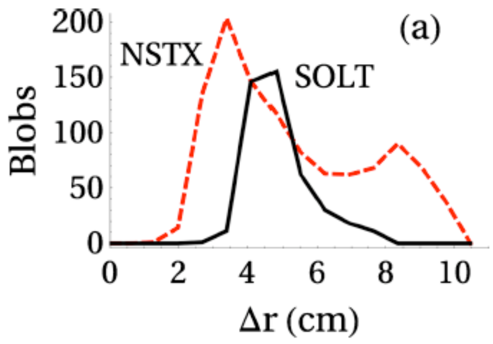




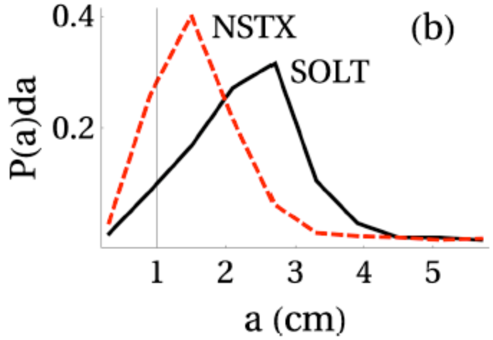


R(14-2)

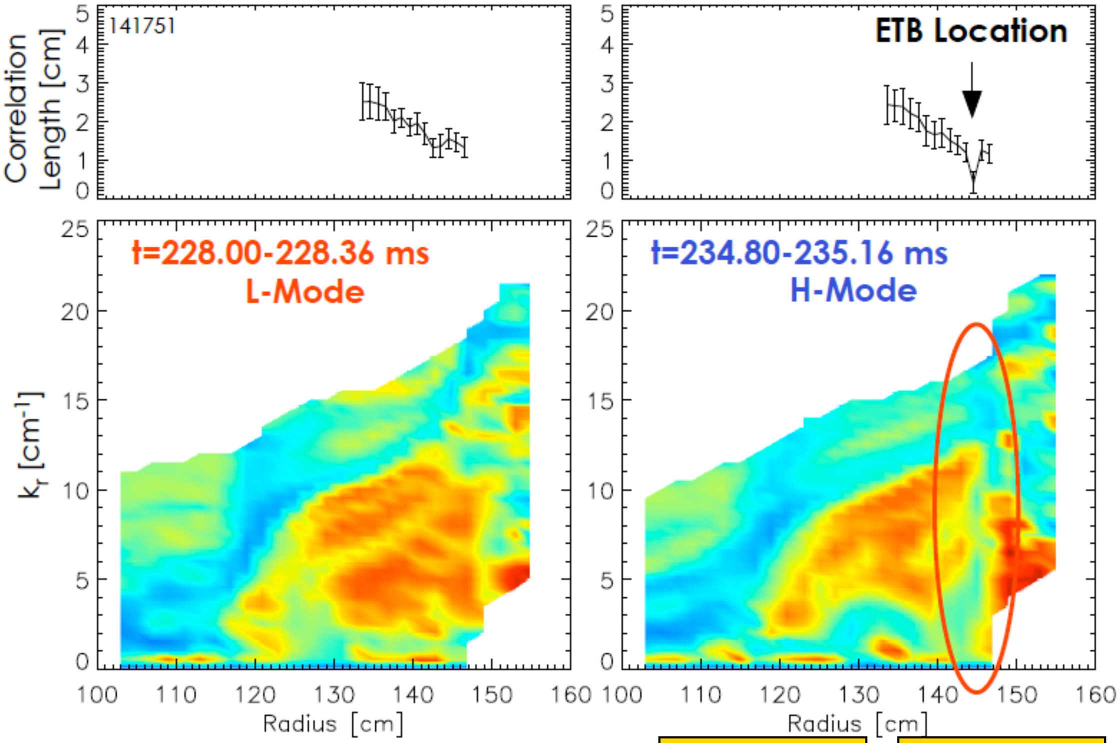
Pedestal / SOL turbulence measurements with reflectometry, BES and GPI contribute to model validation and L-H transition studies



- Comparison of NSTX L-mode GPI turbulence data with SOLT simulation in agreement
  - Number of blobs vs radius and probability distribution of blob poloidal half-width
- Collaborating with EAST in GPI turbulence measurements



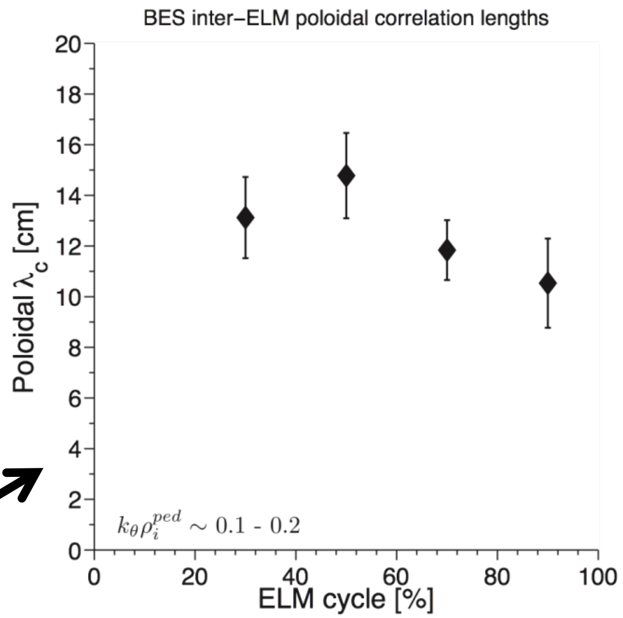
- Reflectometry data at ohmic L-H transition shows:
  - Edge k_r spectra: turbulence suppression
  - Correlation lengths decreases
- Further studies – comparison with GPI and BES

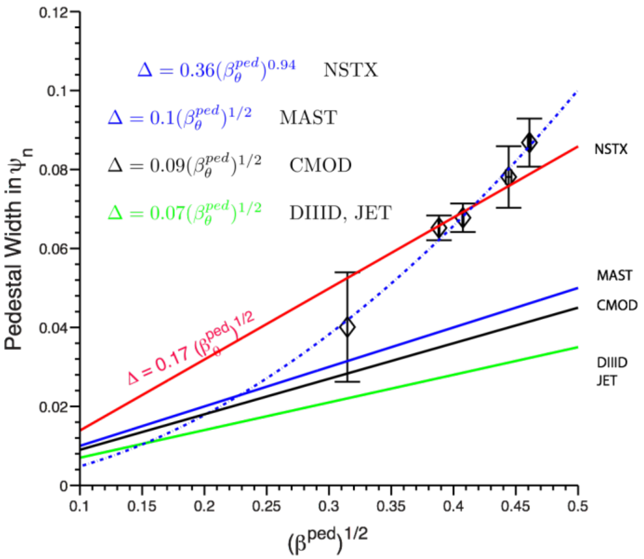


PAC29-13 **PAC29-16**

NSTX data from JRT 2011 on pedestal structure, stability and fluctuations to aid model development and projections to NSTX-U

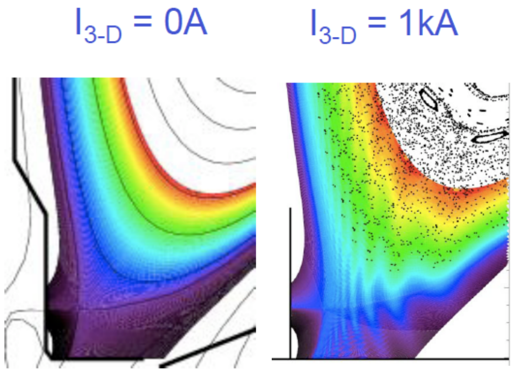
- Pedestal structure and stability with Type I ELMs
  - $P_{tot\ ped} \sim I_p^2$, increases with δ_{bot}, independent of B_t
    - Saturates only in the last 30% of the ELM cycle at low and intermediate I_p, and not at the high I_p > 1 MA
  - ΔP_{tot} increases during the ELM cycle, independent of I_p
  - Pressure gradient is clamped during most of the ELM cycle
  - Characterization of fluctuations during the inter-ELM phase
    - Reflectometry: a coherent density fluctuation, λ_r
    - BES: modest change in pol. correlation length, propagation in ion diamagnetic direction
    - Ion scale turbulence $0.2 \leq k_\perp \rho_i \leq 0.7$ with $\lambda_\theta > \lambda_r$
    - ITG, ITG/TEM, KBM stability modeling underway
- Transition from ELMy to ELM-suppressed H-modes with lithium coatings
- Comparison with models: ELITE, Paleoclassical, XGC1
- Further work
  - Collaboration with Alcator C-Mod on O-mode correlation reflectometry and M3D modeling
  - Microturbulence (GS2) and microturbulence-neoclassical (XGC1) modeling

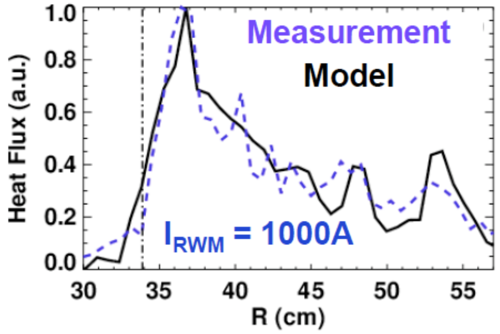




NSTX studies of ELM regimes and ELM control contribute to mitigation strategies for ITER and future STs

- ELM triggering with n=3 RMP
  - Weak RMP impact on pedestal transport
  - Strong impact on stability
    - T_e, pressure gradient increase
    - PEST shows edge unstable with n=3
  - Triggered ELMs are phase locked to the imposed 3D fields for n=1 and n=3
- Divertor heat and particle structures during ELMs, intrinsic and 3D fields
  - Applied 3D fields reattach detached divertor plasma
  - Developing model of toroidally non-uniform heat and particle flux structures using EMC3-EIRENE
- Small transport ELM-like events from 3D field application below ELM triggering threshold (w.r.t. duration or amplitude)
- Collaboration with MAST in perturbed equilibria modeling
- Discussing collaboration with ASDEX in small ELM analysis, effects of 3D fields on detachment

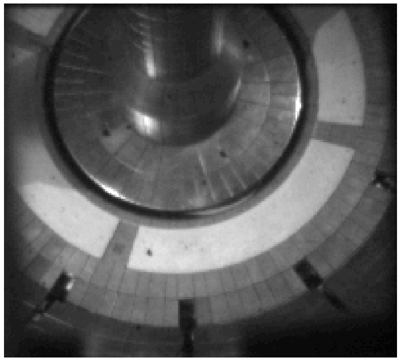




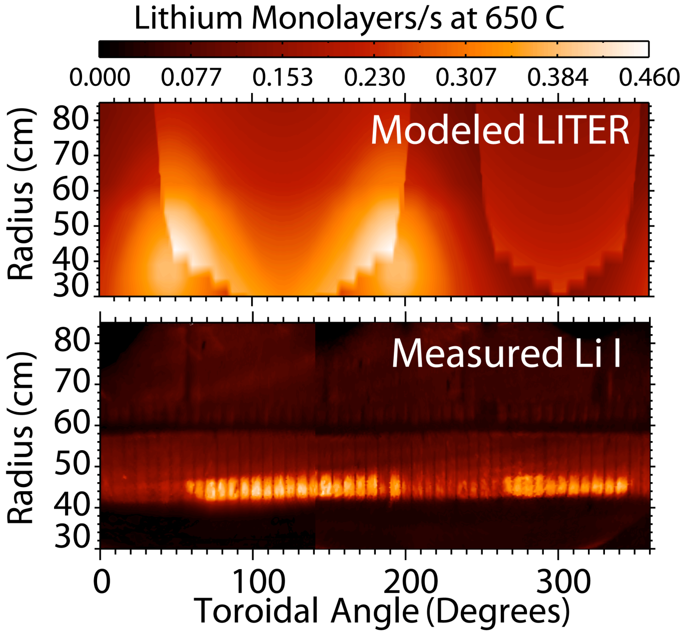
PAC29-48

JRT 2013

Diagnosis and analysis of impurity sources and transport aimed at understanding means to reduce impurity accumulation in NSTX-U



- Carbon accumulation in ELM-free H-mode discharges w/ lithium
  - Increased inward core carbon transport from NCLASS multi-species analysis
  - Divertor carbon influx slightly decreased (from SXB analysis)
  - SOL parallel transport being analyzed with UEDGE
- Toroidally non-uniform erosion fluxes due to LITER deposition patterns
  - Result in mixed impurity fluxes (Li, C)
- Assessment of high Z PFC materials for NSTX-U
  - Collaboration with Alcator C-Mod on molybdenum gross and net erosion diagnosis using intensified filtered camera
    - Collaboration with ADAS consortium on Mo I and Mo II SXB and PEC



PAC29-17
PAC29-18
PAC29-47

R(12-2)
R(13-2)

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    - Impurity source control
  - H-mode physics
    - Pedestal physics studies
    - ELM characterization and control
- Planning Boundary research for NSTX-U
  - Initial years (1-2) of NSTX-U operation
  - Later years (3-5) of NSTX-U operation
  - Facility and diagnostic improvements, divertor particle and power control plans
- Summary

Boundary Research in years 1-2 of NSTX-U operation aims at comparing results to NSTX trends, extending to longer pulse

- Re-establish reliable H-mode operation
- Complete assessment of trends w.r.t. NSTX
  - Pedestal structure
    - Dependence on B_t, I_p, shaping
  - Response to 3D magnetic field perturbations
    - ELM studies, ELM control development, pedestal transport
  - H-mode research
    - EPH-mode, I-mode development
  - Edge and SOL physics
    - Midplane and divertor turbulence, zonal flows, L-H transition
  - Divertor research
    - Heat flux width scaling, connection to SOL models
    - Snowflake divertor studies and control development
    - Radiative divertor with D_2, Ne, Ar seeding
    - Impurity erosion and SOL transport studies
    - Experiments to support validation of cryo-pump designs

Advanced diagnostic and facility capabilities of NSTX-U aim to establish Boundary Physics basis for ST-FNSF in Years 3-5

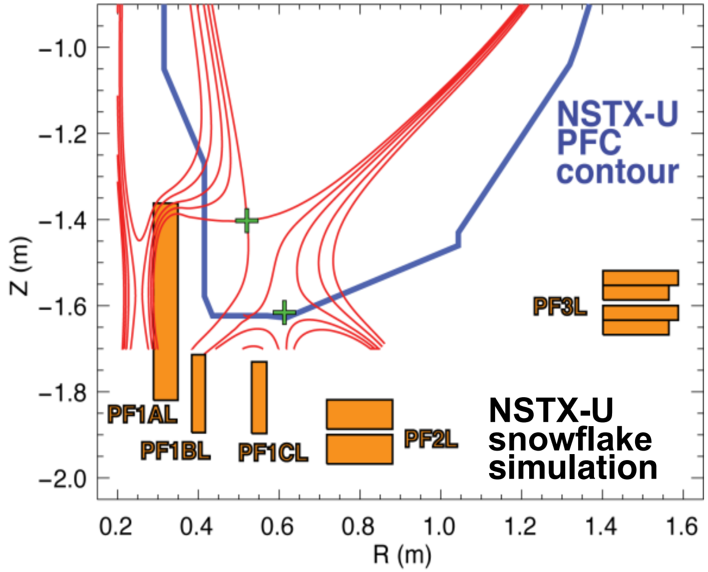
- Assess Mo divertor PFCs and their impact on H-mode confinement
  - Core moly density and transport in baseline scenarios
  - Effect of lithium coatings on molybdenum PFCs (synergistic study with EAST)
  - Divertor Mo influx in baseline and impurity-seeded radiative divertor scenarios

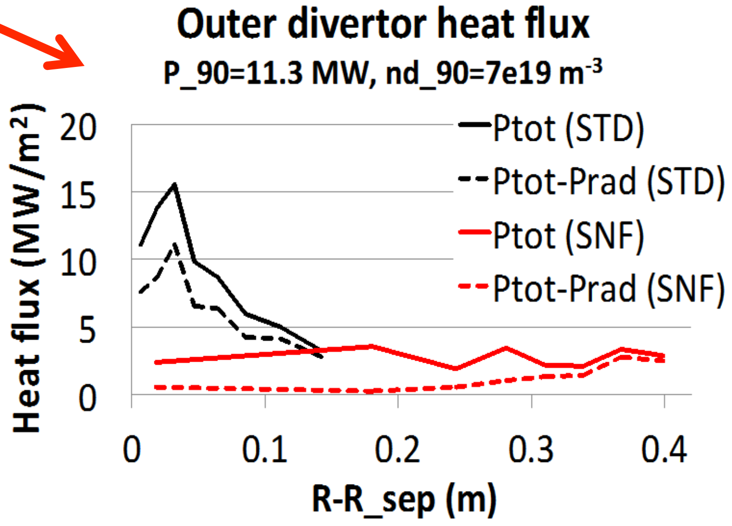
- Develop and validate divertor heat and particle control
  - Support projections of heat flux width and divertor scenarios to ST-FNSF
  - Utilize magnetic control for long-pulse snowflakes with reduced heat flux
  - Implement radiative divertor control

- Assess and optimize pedestal structure and SOL parameters for advanced ST operation
  - Utilize 3D fields to optimize pedestal transport and stability
  - Perform experiments and develop models enabling projections to FNSF

Snowflake geometry and impurity-seeded radiative divertor with feedback control are the leading heat flux control candidates

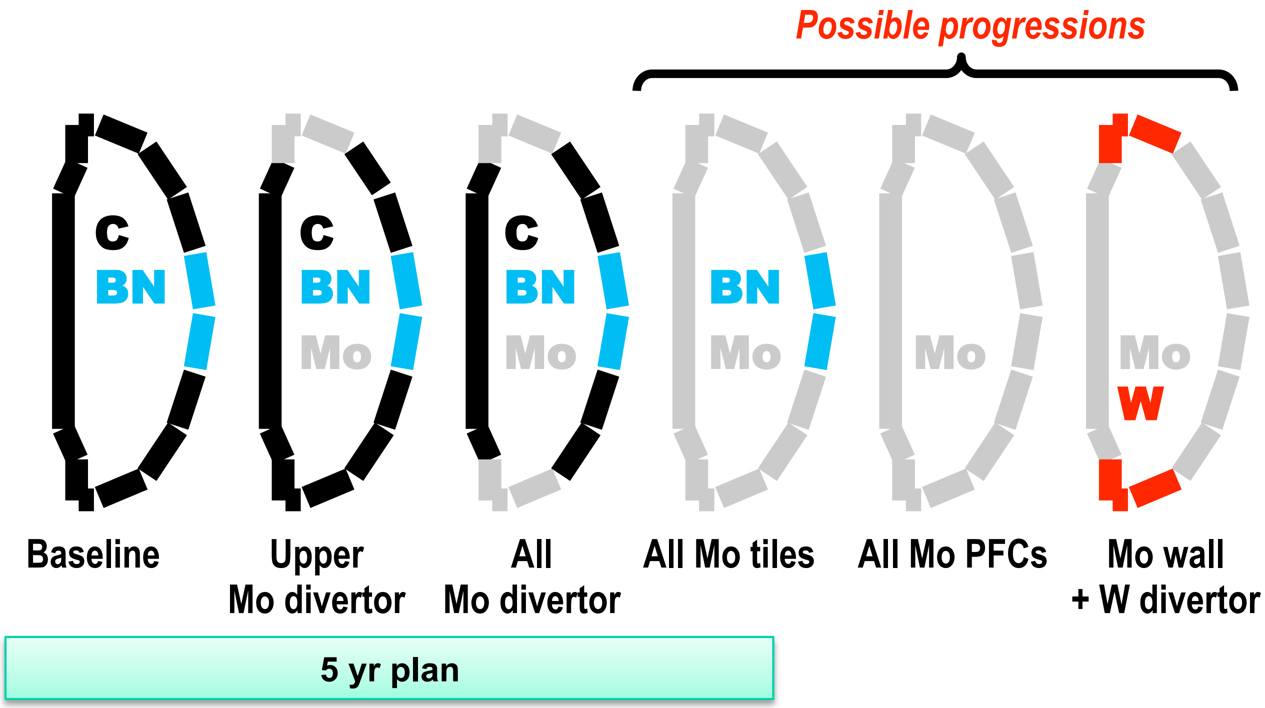
- NSTX-U scenarios with high I_p and P_{in} projected to challenge thermal limits of graphite divertor PFCs
- Single and double-null radiative divertors and upper-lower snowflake configurations considered
  - Supported by NSTX-U divertor coils and compatible with coil current limits
- Snowflake divertor projections to NSTX-U optimistic
  - UEDGE modeling shows radiative detachment of all snowflake cases with 3% carbon and up to P_{SOL}~11 MW
    - q_{peak} reduced from ~15 MW/m^2 (standard) to 0.5-3 MW/m^2 (snowflake)
- Radiative divertor feedback control development
  - Divertor monitor development and prototyping
    - Heat flux, surface temperature, radiation, neutral pressure, recombination
  - Considering improvements to divertor gas system & controls, PCS capability w/ ASC TSG
  - Discussing collaboration with DIII-D





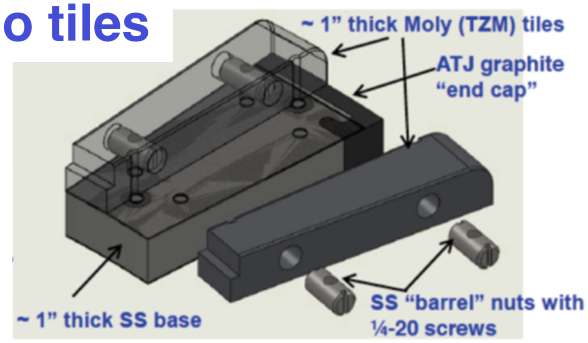
NSTX-U facility improvements and capabilities should provide excellent support of Boundary Research

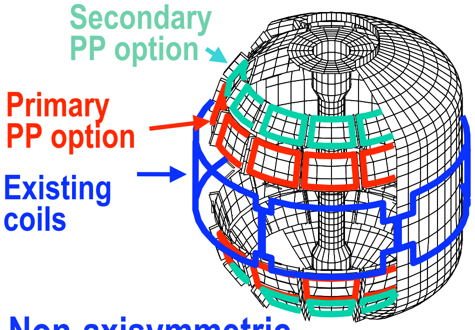
- Developing PFC plan to transition to full metal coverage for FNSF-relevant PMI development
- Wall conditioning: GDC, Li and / or boron coatings
- PFC bake-out at 300-350^{o}C
- PCS control of divertor coils
- Non-axisymmetric control coils



- Fueling tools:
  - Near-term: NBI, edge gas injection (including HFS and SGI) with PCS feedback control
  - Divertor impurity gas seeding
  - Longer term: pellet, molecular cluster, compact toroid injectors

Mo tiles

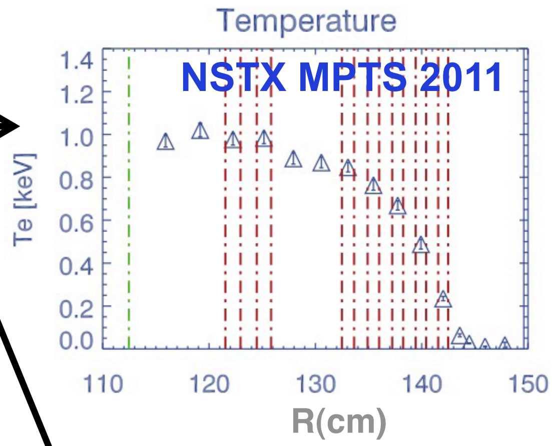


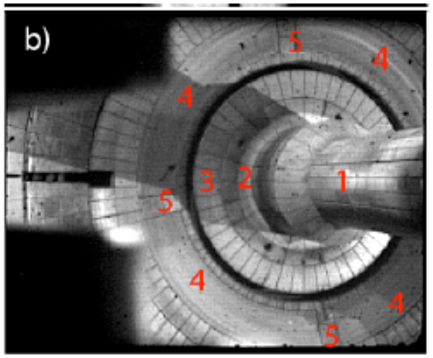


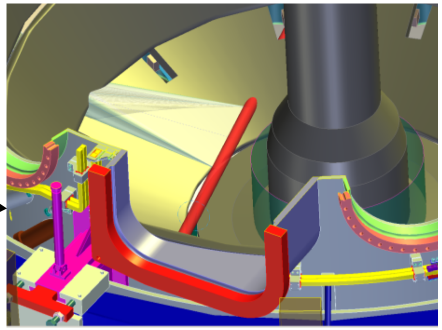
Non-axisymmetric Control Coils (NCC)

Diagnostic improvement strategy focuses on baseline support in Years 1-2, advanced capabilities in Years 3-5

- NSTX existing pedestal and SOL/divertor diagnostics would provide sufficient capabilities for initial experiments
- High priority improvements for initial NSTX-U operation:
  - Pedestal and SOL fluctuation diagnostics (2D BES, 3D GPI)
  - Divertor Langmuir probes
  - Divertor bolometry
  - Upper divertor IR and visible cameras and spectroscopy
  - Inner divertor (lower and upper) IR and visible cameras and spectroscopy
- Longer term NSTX-U Boundary diagnostic goals:
  - Molybdenum core, edge, divertor spectroscopy (VUV, visible)
  - Edge profile reflectometry
  - Full plasma radiation tomography
  - Edge neutral density measurements (LIF or LII)
  - Divertor Thomson Scattering system
  - SOL flow measurements
  - SOL and divertor ion energy or temperature
  - SOL current sensors







NSTX Boundary Physics Program Summary

- ✓ Improving understanding of SOL heat and particle transport to enable their control in NSTX-U and projections to ITER and ST-FNSF

- ✓ Improving understanding of H-mode pedestal structure, ELM stability and 3D physics

- ✓ Preparing for NSTX-U research
  - Collaborating on experiments and modeling
  - Developing prioritized research plans
  - Improving diagnostic and facility capabilities in support of research plans

Backup

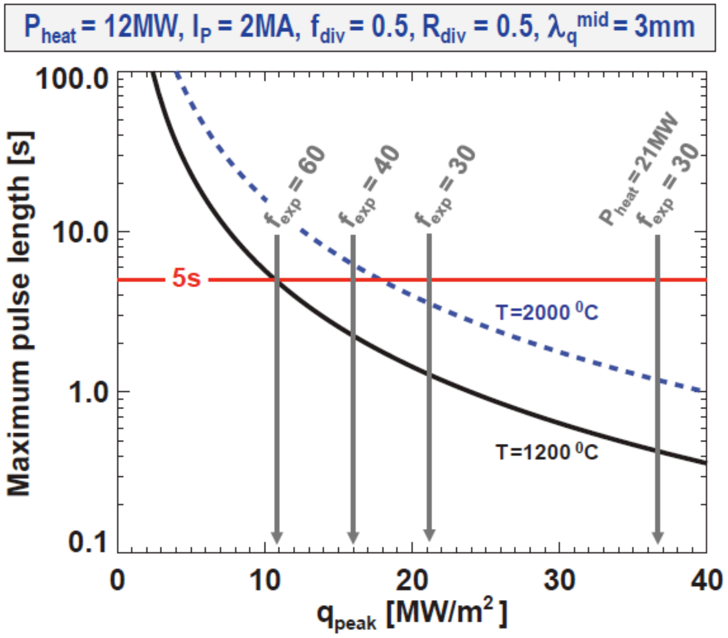
Overview of NSTX Contributions to JRT 2013 on Enhanced Confinement Regimes without ELMs

- Original intention was that NSTX would collect targeted data during the operation period July 2011-February 2012.
  - TF magnet failure during machine commissioning →NSTX last collected data in Oct. 2010 → will contribute analysis of existing data

- NSTX contributions under consideration:
  - Heat flux measurements during type-V ELMs.
  - Further study of type-V ELM regime access conditions.
  - Occurrence of EHOs and the potential to actively drive them.
  - Modifications to particle and heat transport with 3D fields.
    - Not RMP ELM suppression.
  - Search for I-mode in the database.
  - Other…EPH, Lithium application, IPEC+NTV

Courtesy of
S. Gerhardt,
R. Maingi

NSTX-U scenarios with high current and power are projected to challenge passive cooling limits of graphite divertor PFCs

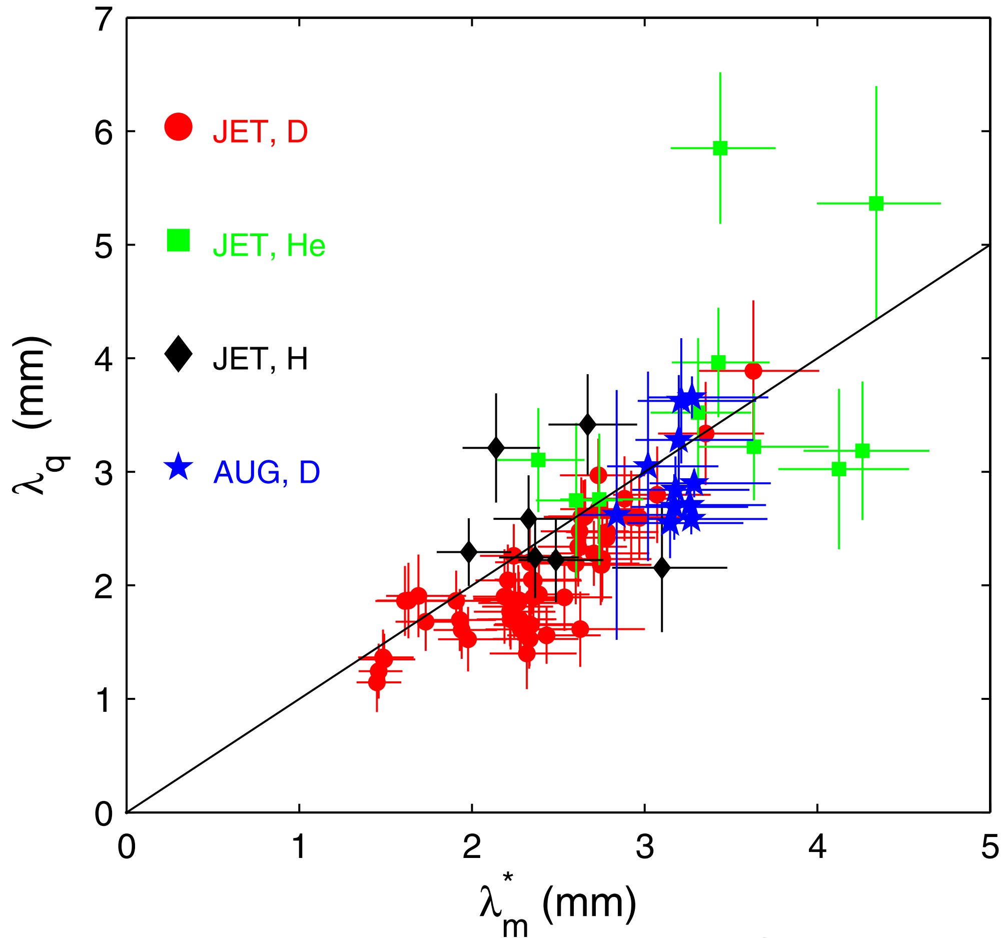

P_{heat} = 12MW, I_P = 2MA, f_{div} = 0.5, R_{div} = 0.5, λ_q^{mid} = 3mm

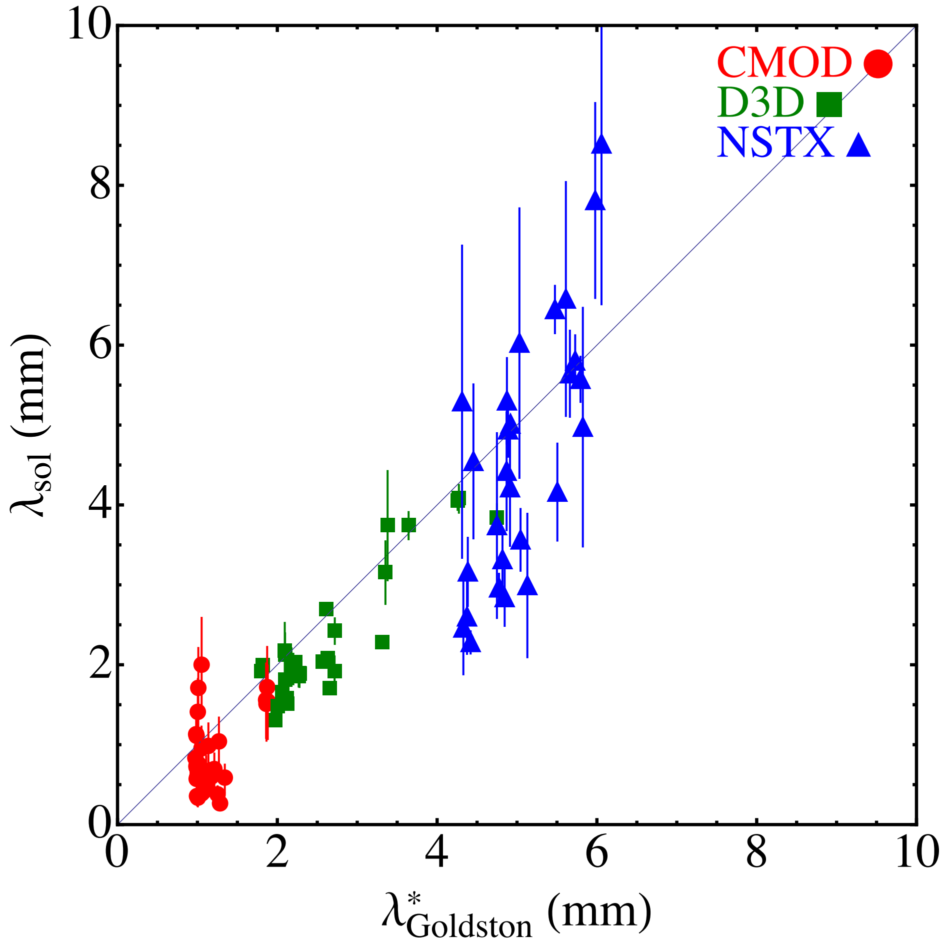
NSTX Upgrade Scenarios

Device and scenario	NSTX-U 100% NICD		NSTX-U Long-pulse		NSTX-U Max I_P		NSTX-U Max I_P, P_{heat}		NSTX-U 100% NICD		NSTX-U Max I_P		NSTX-U High f_{BS}	
Confinement scaling	H98y2	H98y2	H98y2	H98y2	H98y2	H98y2	H98y2	H98y2	ST	ST	ST	ST	ST	ST
I_P [MA]	1.10	1.02	0.90	0.90	2.00	2.00	2.00	2.00	1.50	1.46	2.00	2.00	1.11	1.16
B_T [Tesla]	1.00	1.00	0.75	0.75	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Aspect ratio A	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
R_0 [m]	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93
Elongation κ	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75
P_{NBI} [MW]	10.0	10.0	5.0	5.0	10.0	10.0	15.0	15.0	6.0	6.0	6.0	6.0	2.0	2.0
P_{RF} [MW]	0.0	0.0	0.0	0.0	0.0	0.0	4.0	4.0	0.0	0.0	0.0	0.0	2.0	2.0
P_{ind} [MW]	0.00	0.00	0.05	0.08	0.23	0.37	0.10	0.18	0.00	0.00	0.10	0.21	0.00	0.00
P_{heat} [MW]	10.0	10.0	5.05	5.08	10.2	10.4	19.1	19.2	6.00	6.00	6.10	6.21	4.00	4.00
Greenwald fraction	0.50	1.00	0.50	1.00	0.50	1.00	0.50	1.00	0.50	1.00	0.50	1.00	0.50	1.00
n_e-bar [10^{20}m^{-3}]	0.54	1.00	0.44	0.88	0.98	1.96	0.98	1.96	0.73	1.43	0.98	1.96	0.59	1.23
I_P flat-top time [s]	5.0	5.0	10.0	10.0	5.0	5.0	0.3	0.3	5.0	5.0	5.0	5.0	5.0	5.0
$\tau_{current\text{-}redistribution}$ [s]	1.04	0.57	0.65	0.37	1.37	0.79	1.83	1.05	2.41	1.13	2.23	1.05	1.76	0.81
# redistribution times	**4.8**	**8.7**	**15**	**27**	**3.6**	**6.3**	**0.2**	**0.3**	**2.1**	**4.4**	**2.2**	**4.8**	**2.8**	**6.2**
Stored energy [MJ]	0.68	0.54	0.36	0.33	0.96	1.08	1.35	1.37	1.04	1.00	1.20	1.26	0.65	0.70
β_N [%mT/MA]	5.4	4.6	4.7	4.2	4.2	4.7	5.9	5.9	6.0	6.0	5.2	5.5	4.9	5.0
β_T [%]	10.3	8.2	9.8	8.8	14.7	16.4	20.5	20.8	15.8	15.3	18.3	19.1	9.9	10.7
q*	6.8	7.3	6.2	6.2	3.7	3.7	3.7	3.7	5.0	5.1	3.7	3.7	6.2	5.9
Power fraction to divertor	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
$R_{strike\text{-}point}$ [m]	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
SOL heat-flux width [mm]	7.9	8.9	10.9	10.9	3.0	3.0	3.0	3.0	4.8	5.0	3.0	3.0	7.8	7.3
Poloidal flux expansion	22	22	22	22	62	62	62	62	22	22	38	38	22	22
Peak heat flux [MW/m^2]	9.1	8.1	3.4	3.4	8.7	8.8	16.2	16.2	9.0	8.6	8.4	8.6	3.7	4.0
Time to T_{PFC} = 1200°C [s]	6.1	7.6	44	44	6.7	6.5	1.9	1.9	6.1	6.7	7.1	6.8	36	31
Fraction of T_{PFC} limit	**0.96**	**0.76**	**0.24**	**0.24**	**0.97**	**1.00**	**0.94**	**0.95**	**1.00**	**0.91**	**0.92**	**0.96**	**0.16**	**0.19**

- High I_P scenarios projected to have narrow λ_q^{mid} → ~3mm
  - At high power, peak heat flux ≥ 9MW/m^2 even with high flux expansion ~60 with U/L snowflake
  - Numbers shown ignore radiation, plate tilt, strike-point sweeping
- **Passive cooling ok for low-I_P scenarios**
- **Long-pulse + high I_P and power may ultimately require active divertor cooling**

Heuristic Drift Scaling Fits Recent Data from JET, AUG, C-MOD, DIII-D and NSTX in Attached H-Mode Regimes





$$\Delta = 5671 \cdot P_{SOL}^{1/8} \frac{\left(1+\kappa^2\right)^{5/8} a^{17/8} B^{1/4}}{I_p^{9/8} R} \left(\frac{2A}{(1+Z)}\right)^{7/16} \left(\frac{Z_{eff}+4}{5}\right)^{1/8}$$

Courtesy of R. J. Goldston

GradB and curvB drift motion sets SOL width, Spitzer thermal conduction sets edge T
NSTX data constrain aspect ratio scaling roughly in agreement with theory

Various techniques developed for reduction of heat fluxes $q_{||}$ (divertor SOL) and q_{peak} (divertor target)

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

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

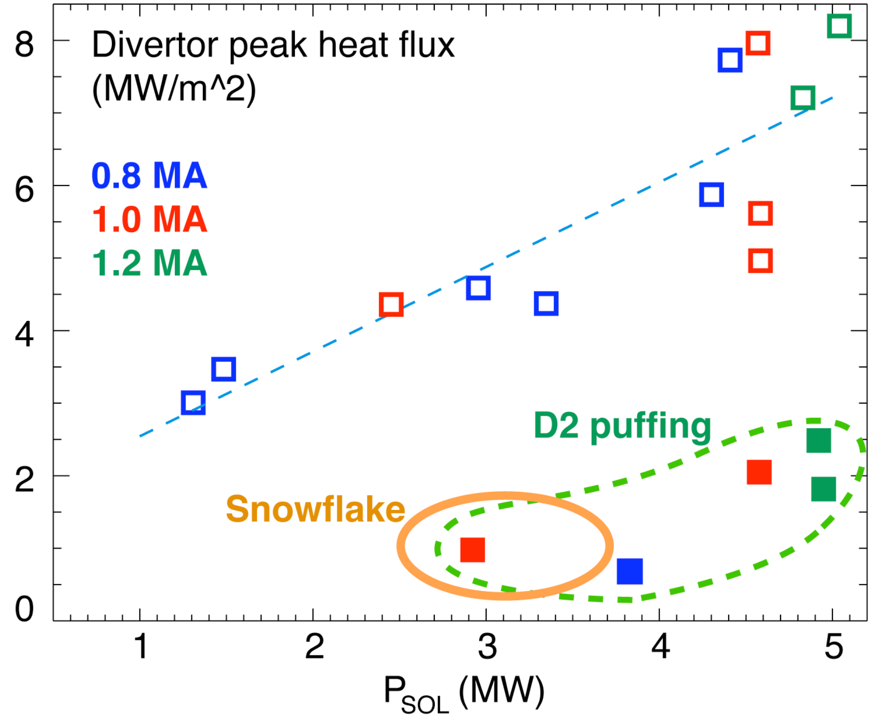
$$f_{exp} = \frac{(B_p/B_{tot})_{MP}}{(B_p/B_{tot})_{OSP}}$$

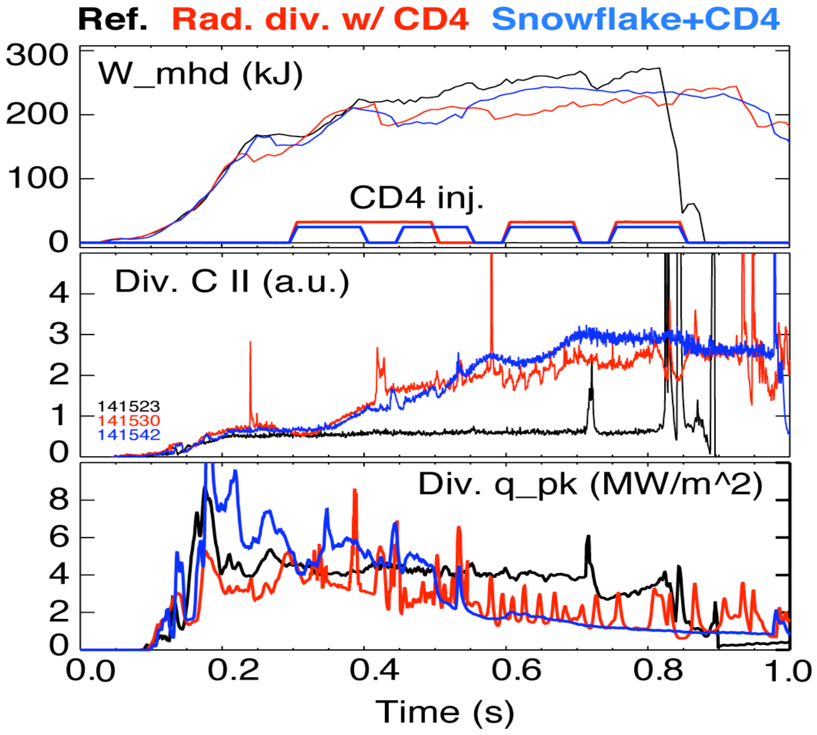
- Promising divertor peak heat flux mitigation solutions:
  - Divertor geometry
    - ➢ poloidal flux expansion
    - ➢ divertor plate tilt
    - ➢ magnetic balance
  - Radiative divertor
- Recent ideas to improve standard divertor geometry
  - X-divertor (M. Kotschenreuther *et. al*, IC/P6-43, IAEA FEC 2004)
  - Snowflake divertor (D. D. Ryutov, PoP 14, 064502 2007)
  - Super-X divertor (M. Kotschenreuther *et. al*, IC/P4-7, IAEA FEC 2008)

Snowflake geometry and impurity-seeded radiative divertor are the leading heat flux mitigation candidates for NSTX-U

- Conventional and snowflake radiative divertors demonstrated divertor heat flux reduction simultaneously with H-mode confinement in NSTX
  - Standard radiative divertor with D_2 or CD_4 seeding
  - Snowflake divertor with D_2 or CD_4 seeding
    - Increased divertor radiation beyond standard radiative divertor

NSTX data





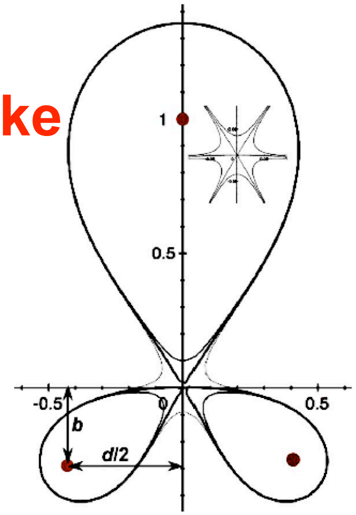
Snowflake divertor geometry attractive for heat flux mitigation

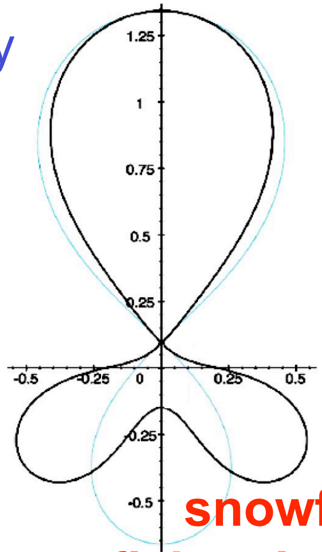
- Snowflake divertor
  - Second-order null
    - $B_p \sim 0$ and *grad* $B_p \sim 0$ (Cf. first-order null: $B_p \sim 0$)
  - Obtained with existing divertor coils (min. 2)
  - Exact snowflake topologically unstable

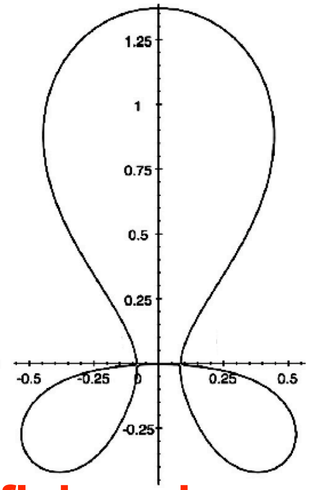
- Predicted geometry properties (cf. standard divertor)
  - Larger region with low B_p around X-point: ped. stability
  - Larger plasma wetted-area A_{wet} : reduce q_{div}
  - Larger X-point connection length L_x : reduce $q_{//}$
  - Larger effective divertor volume V_{div} : incr. P_{rad} , P_{CX}

- Experiments
  - TCV (F. Piras *et. al*, PRL 105, 155003 (2010))
  - NSTX

Exact snowflake divertor







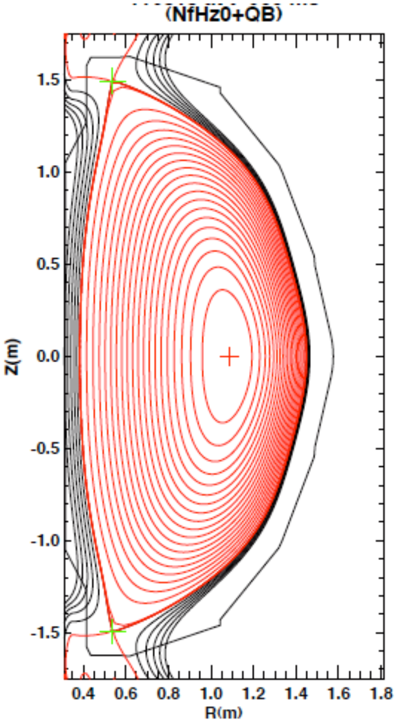
snowflake-minus

snowflake-plus

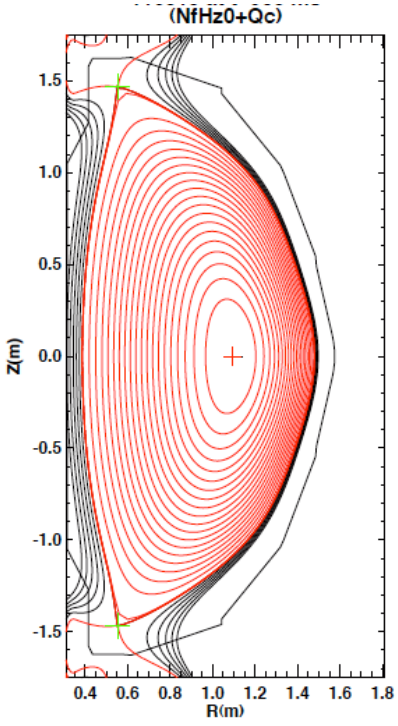
D. D. Ryutov, PoP 14, 064502 2007

Boundary magnetic configuration modeling for NSTX-U

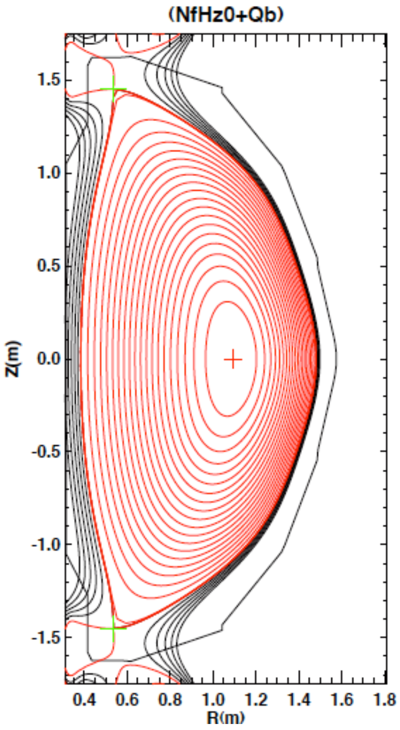
- Single and double-null radiative divertors and upper-lower snowflake configurations considered
  - Supported by NSTX-U divertor coils and compatible with coil current limits
  - ISOLVER modeling shows many possible equilibria
    - Impact of changing I_{OH} on snowflake minimal
    - Reduced divertor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



NSTX-U double-null

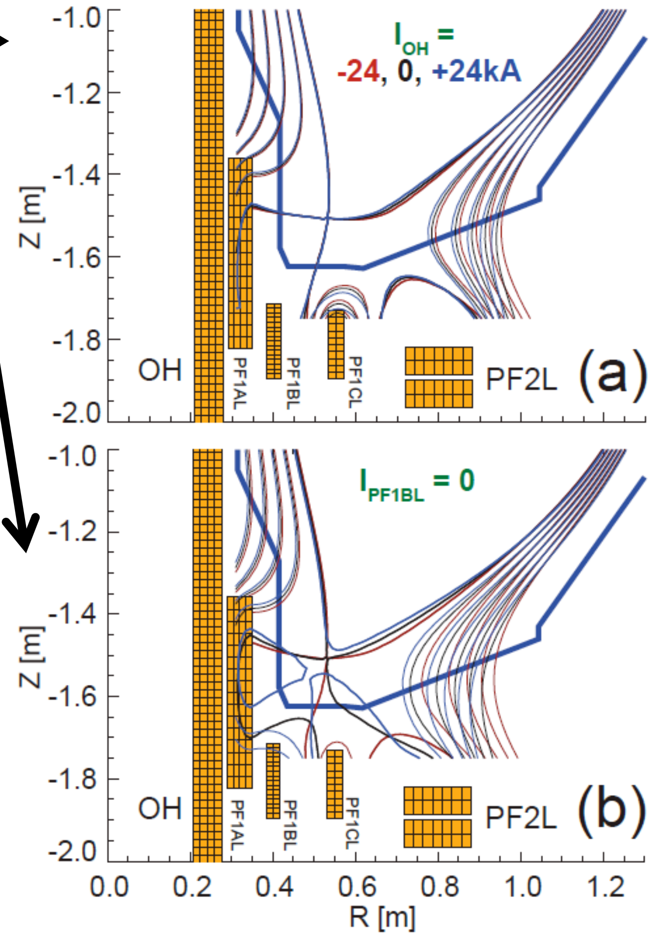


NSTX-U double-snowflake-plus



NSTX-U double-snowflake-minus

NSTX-U simulation

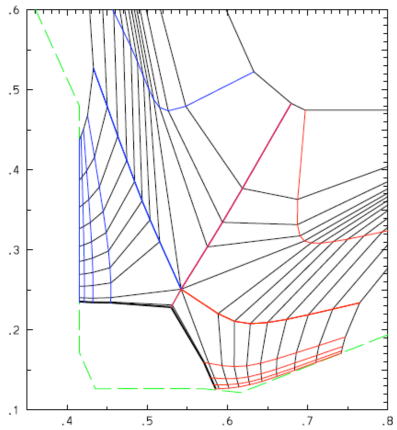


Snowflake divertor transport modeling with UEDGE for NSTX-U

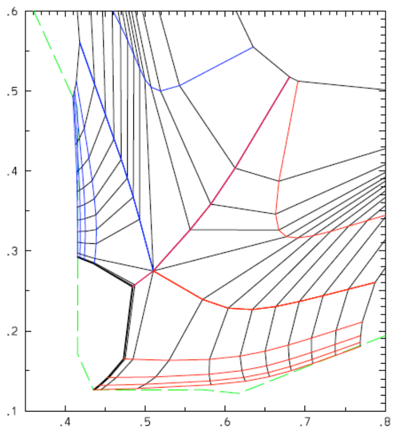
- 2D multi-fluid code UEDGE
  - Mesh setup based on modeled equilibria:
    - psi=0.9 to psi=1.055
    - STD grid covers 9.1 mm at midplane
    - SNF grid covers 10.5 mm at midplane
  - Fluid (Braginskii) model for ions and electrons
  - Fluid for neutrals (diffusive model used)
  - Classical parallel transport, anomalous radial transport
    - $D = 0.25\ \mathrm{m}^2/\mathrm{s}$; $\chi_{e,i} = 0.5\ \mathrm{m}^2/\mathrm{s}$
  - recycp=.98; recycw=1; fixed fraction C – 3%
  - Core boundary conditions based on TRANSP
    - Year 3-5: B_t=1.0 T, I_p=1700 kA, P_{inj}=12.6 MW
    - Scan in UEDGE power and density around TRANSP values +/- 20%:
      - P_90 = 7.6, 9.5, and 11.3 MW
      - nd_90 = 7e19, 8.5e19, and 1e20 m^{-3}

Courtesy of E. Meier

Standard divertor



Snowflake divertor



nd_90 (m^{-3})

D *	D *	A
D	A	A
A	A	A

P_90 (MW)

nd_90 (m^{-3})

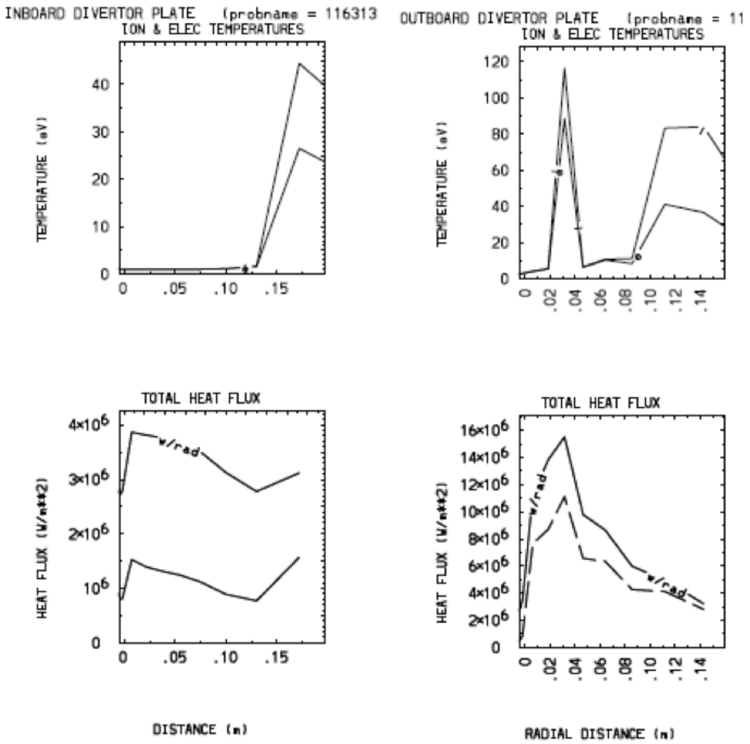
D	D	D
D	D	D
D	D	D

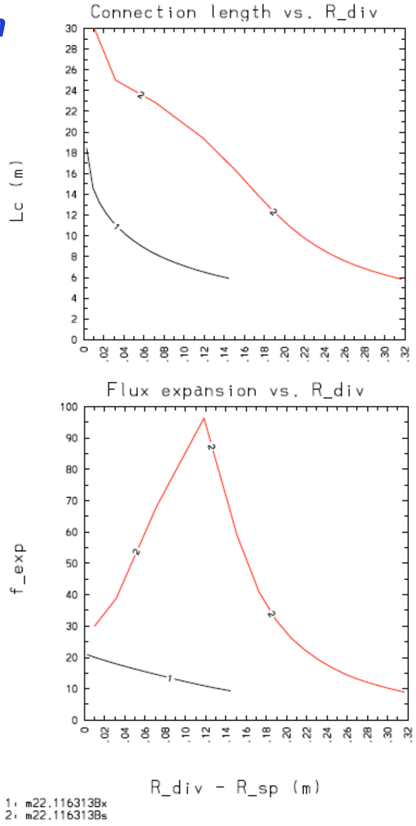
P_90 (MW)

A → attached
D → detached (at outer target, T_e < 5 eV within 8 cm of SP)
**** → not converged (solution is oscillating in detached state)***

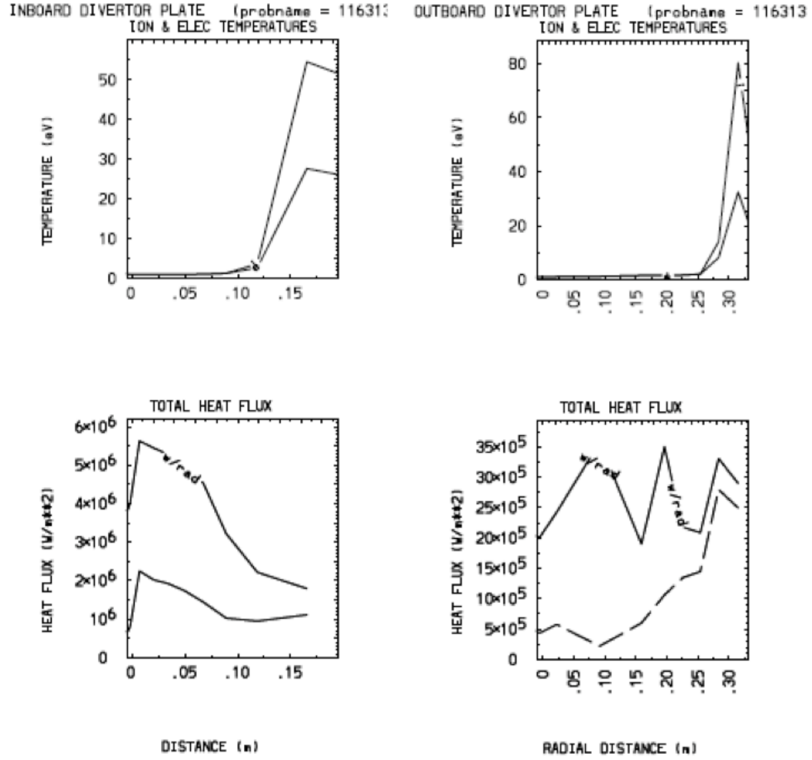
UEDGE modeling shows radiative snowflake divertor detachment for all NSTX-U cases up to P_{90}=11.3 MW, $n_{d,90}$=7e19 m^{-3}

Standard divertor *λ_q^{mid} = 3-5 mm*





Snowflake divertor

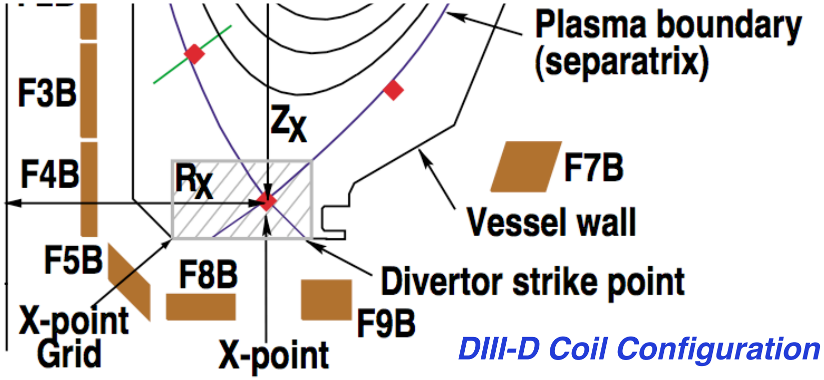


	P_90	**Pdiv,out**	**Pdiv,in**	**Pwall**	**Prad**
A: STD	9.5	3.95 (2.54)	1.73 (0.62)	0.83	5.48
A: SNF	9.5	3.07 (0.61)	1.66 (0.71)	0.69	6.95
B: STD	11.3	5.08 (3.66)	1.75 (0.64)	0.78	6.49
B: SNF	11.3	3.56 (1.50)	1.65 (0.70)	0.65	8.28

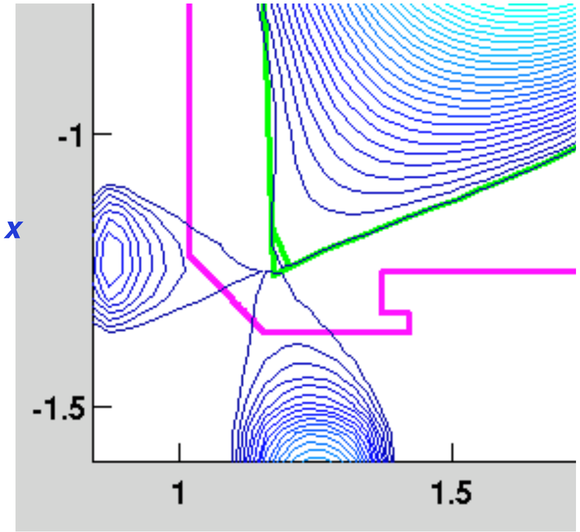
Courtesy of E. Meier

Modeled DIII-D Snowflake configurations are compatible with coil limits and operation requirements

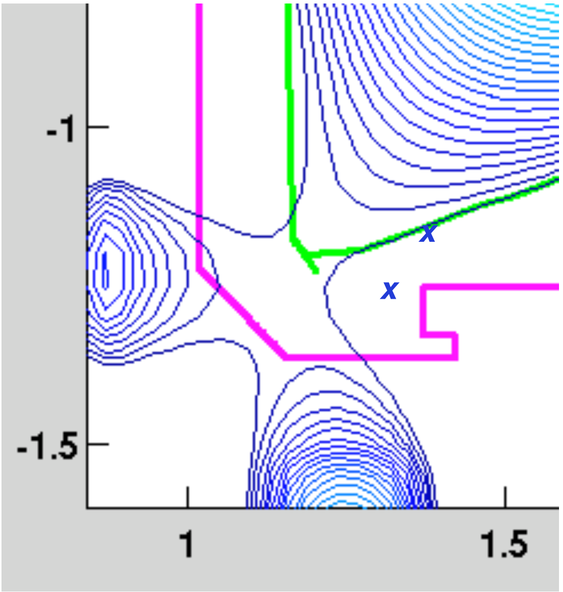
- Perfect snowflake and snowflake -/+ are possible at DIII-D with F4B, F5B, F8B.

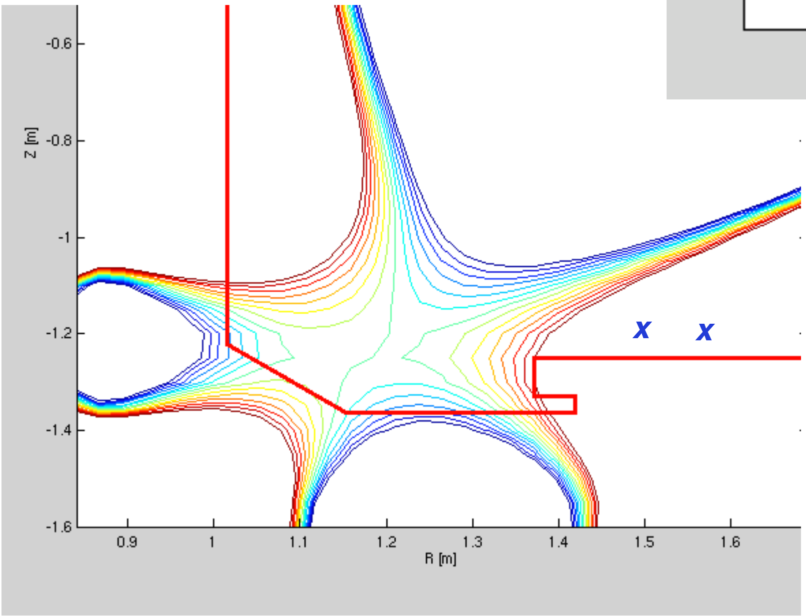


DIII-D Coil Configuration



DIII-D Perfect Snowflake



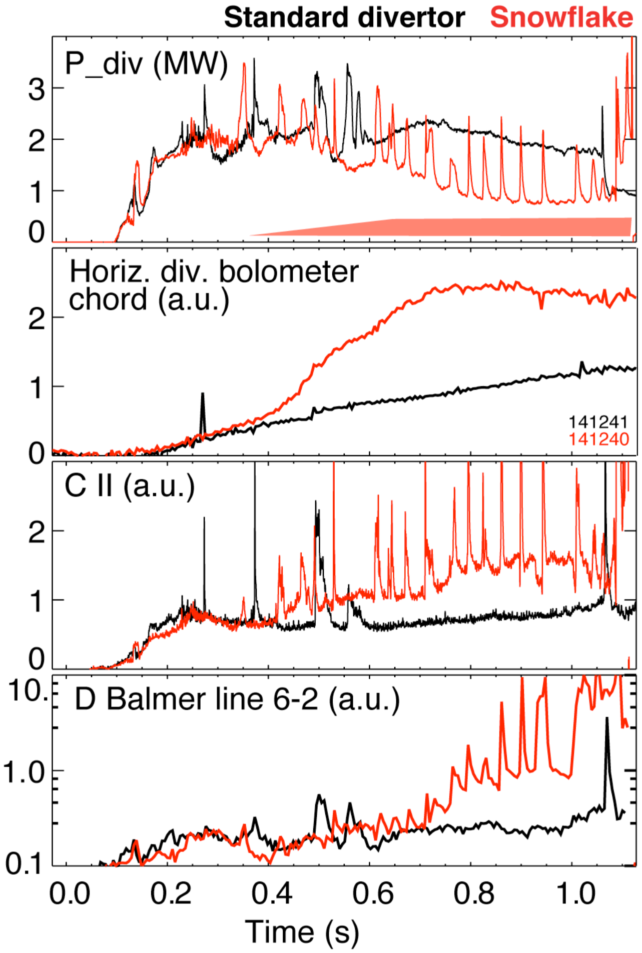


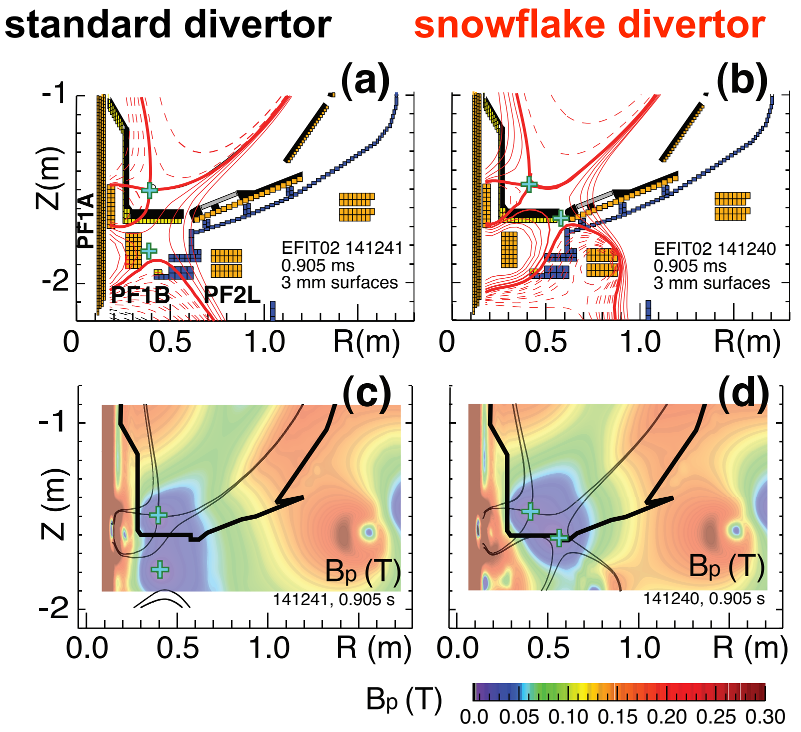
Courtesy of E. Kolemen

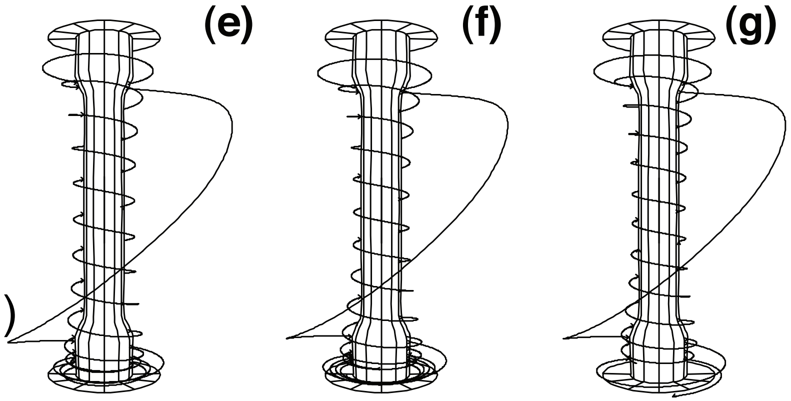
DIII-D Snowflake +

DIII-D Snowflake -

Snowflake configuration formation was followed by radiative detachment in NSTX







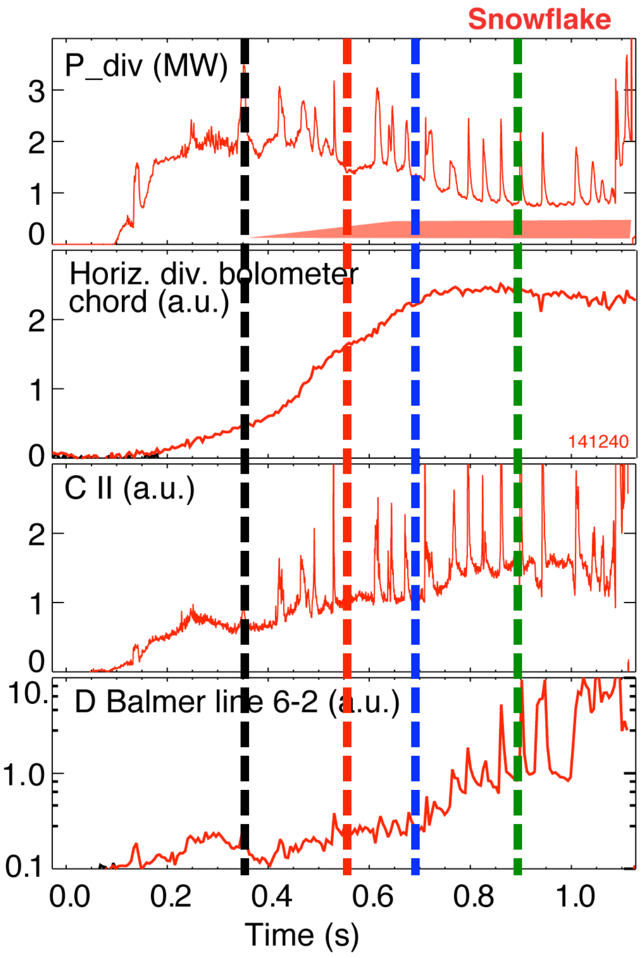
Shot 141241, EFIT02,
time: 0.905 s,
normalized flux: 1.005

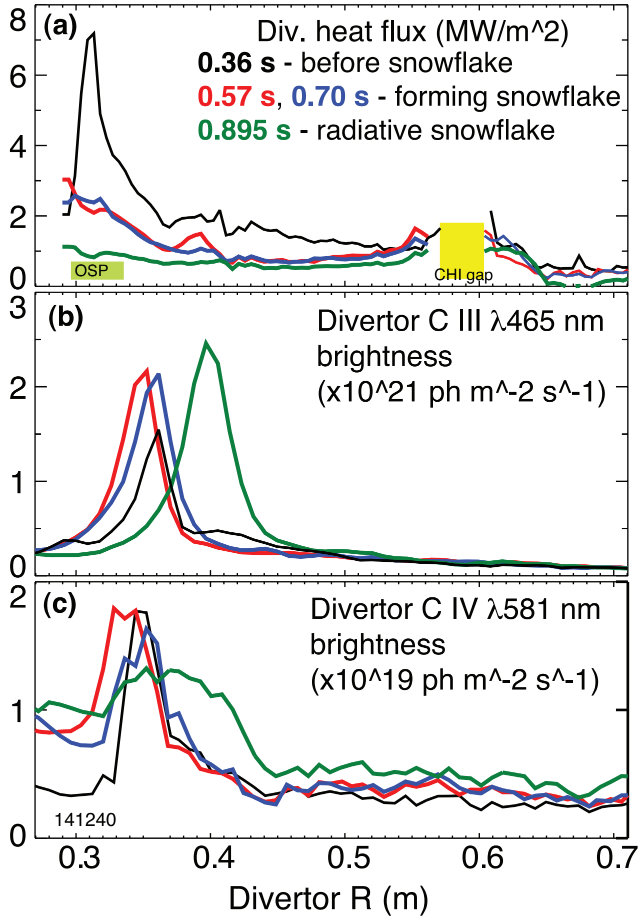
Shot 141240, EFIT02,
time: 0.905 s,
normalized flux: 1.005

Shot 141240, EFIT02,
time: 0.905s,
normalized flux: 1.015

- P_{SOL} ~ 3 MW (P_{NBI} = 4 MW)
- Attached divertor -> snowflake transition (still attached) -> snowflake + detachment
- Q_{div} ~ 2 MW -> Q_{div} ~ 1-1.2 MW -> Q_{div} ~ 0.5-0.7 MW

Significant reduction of steady-state divertor heat flux observed in NSTX snowflake divertor

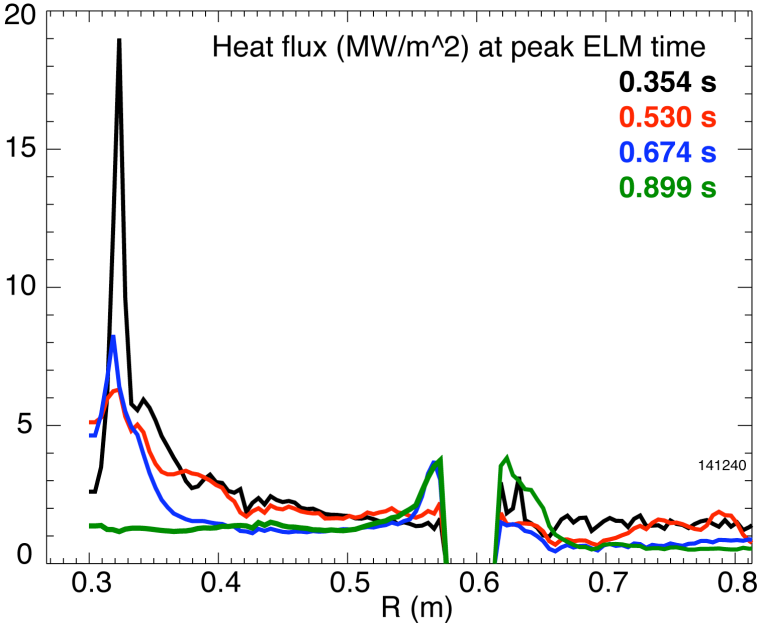


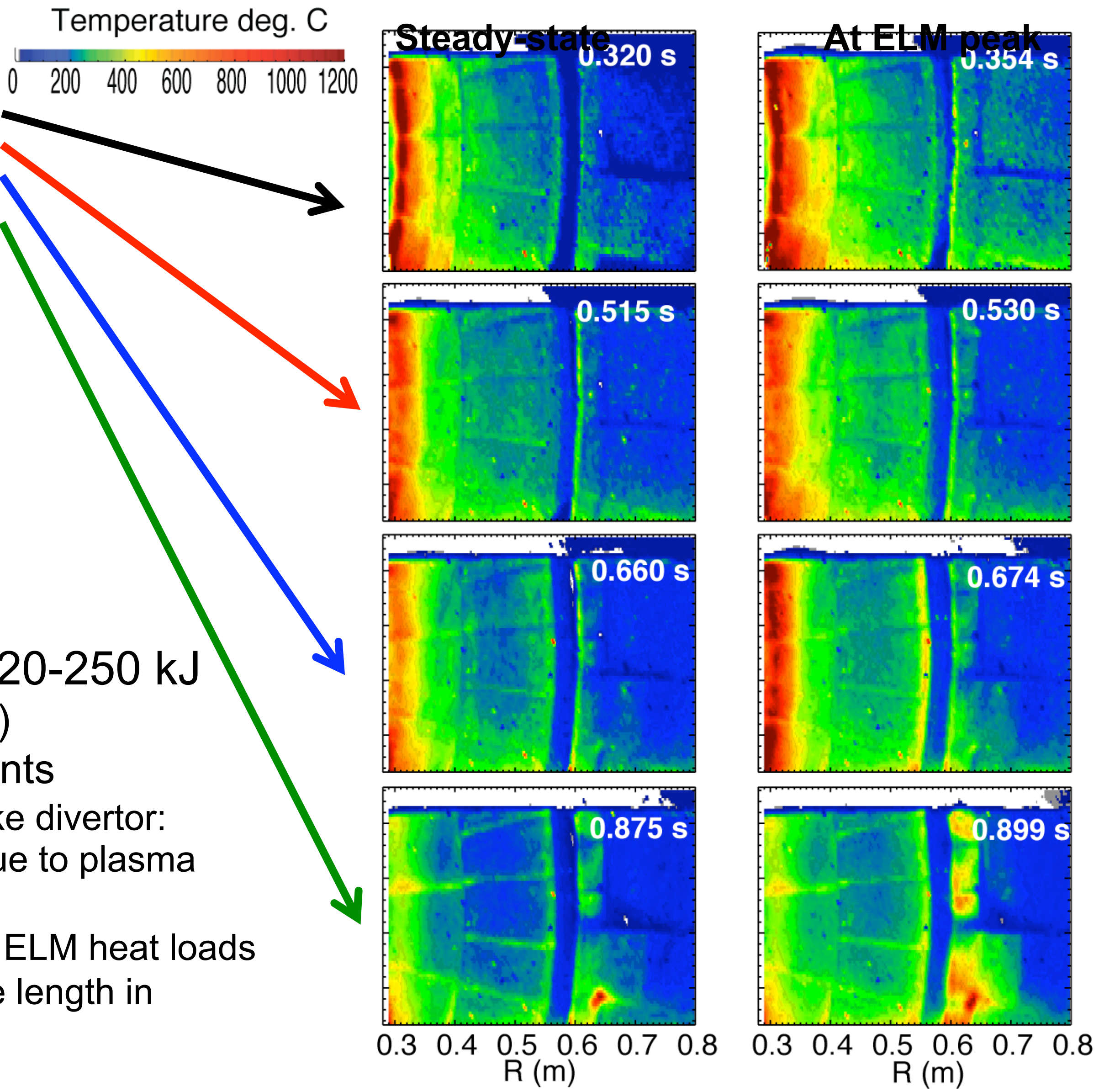


C III, CIV profiles courtesy of F. Scotti

- **Attached standard divertor** -> snowflake transition -> snowflake + detachment
- More experiments and modeling needed to understand geometry vs radiative effects

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

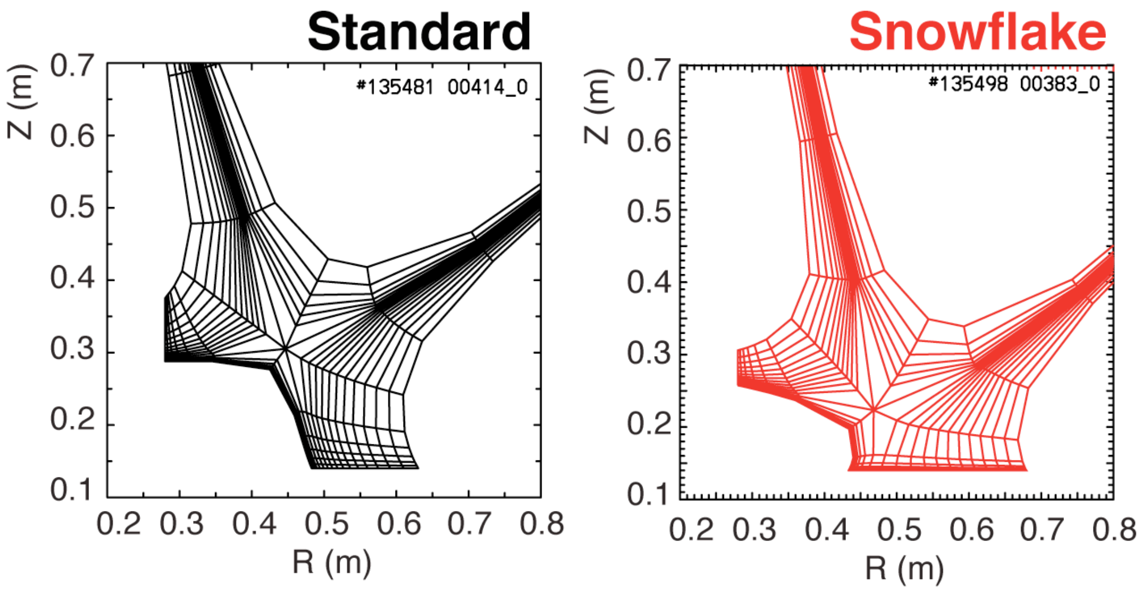




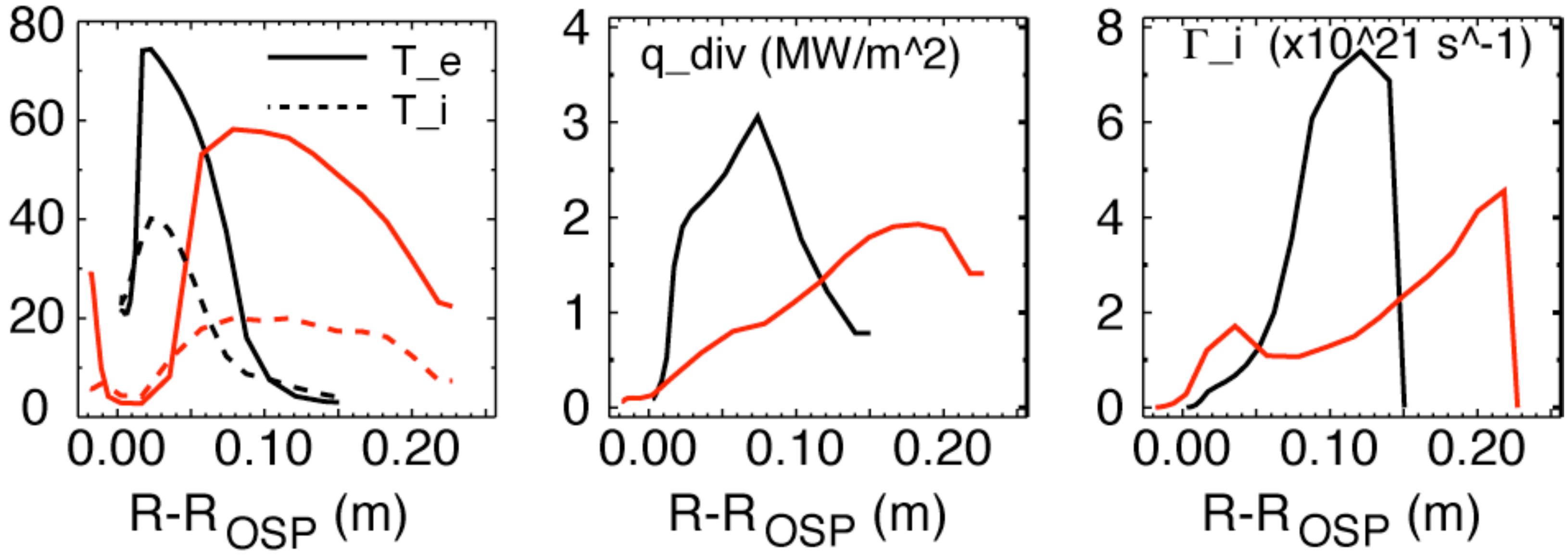
- H-mode discharge, W_{MHD} ~ 220-250 kJ
  Type I ELM ($\Delta W_{tot}/W_{tot}$ ~ 5-10 %)
- Theory and modeling developments
  D.D. Ryutov, JP9.00104 : A snowflake divertor: reduction of the ELM heat load due to plasma convection
  T.D. Rognlien, JP9.00105 : Reduced ELM heat loads from increased magnetic field-line length in snowflake configurations

2D modeling shows a trend toward reduced temperature, heat and particle fluxes in NSTX snowflake divertor

- 2D multi-fluid code UEDGE
  - Fluid (Braginskii) model for ions and electrons
  - Fluid for neutrals
  - Classical parallel transport, anomalous radial transport
    - *D* = 0.25 m^2/s
    - $\chi_{e,i}$ = 0.5 m^2/s

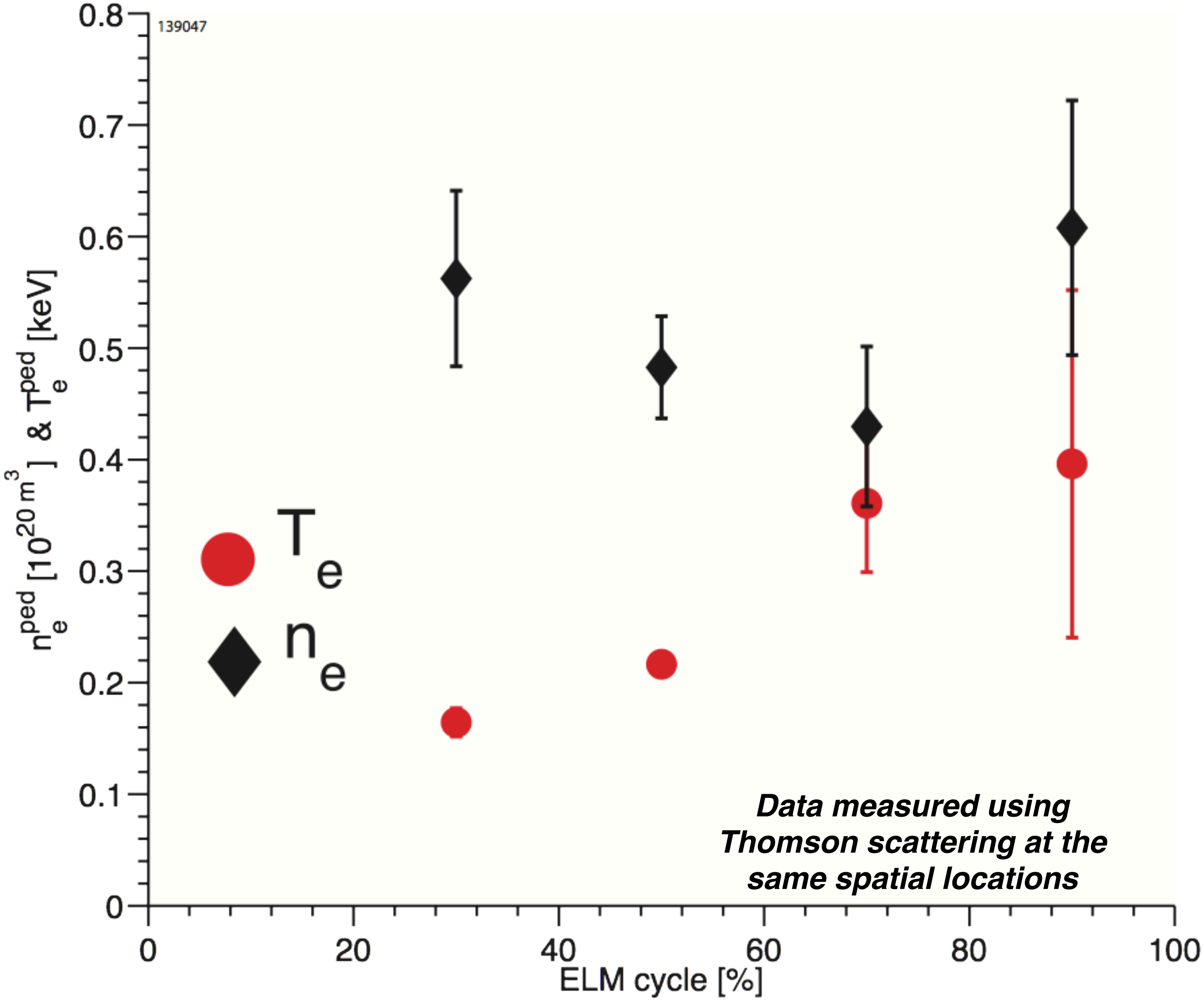


Core interface:
$T_{e,i}$ = 120 eV
n_e = 4.5 x 10^{19}
R_{recy} = 0.95
Carbon 3 %



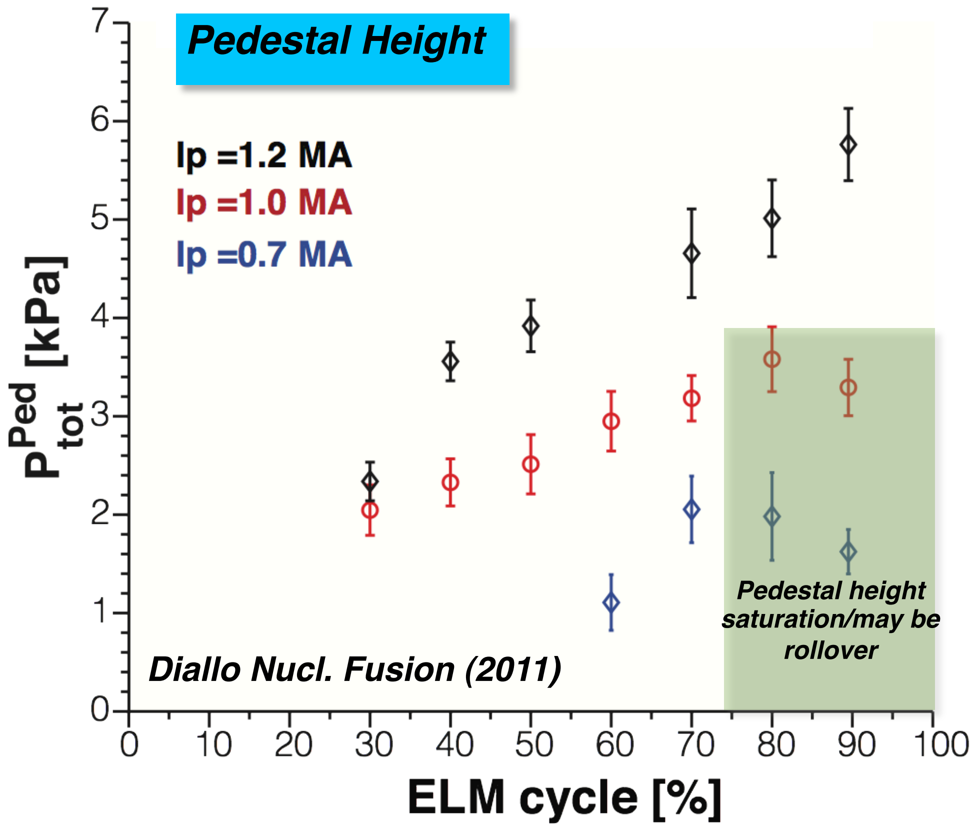
Temperature pedestal height increases during the ELM cycle while the density pedestal show no convincing trend

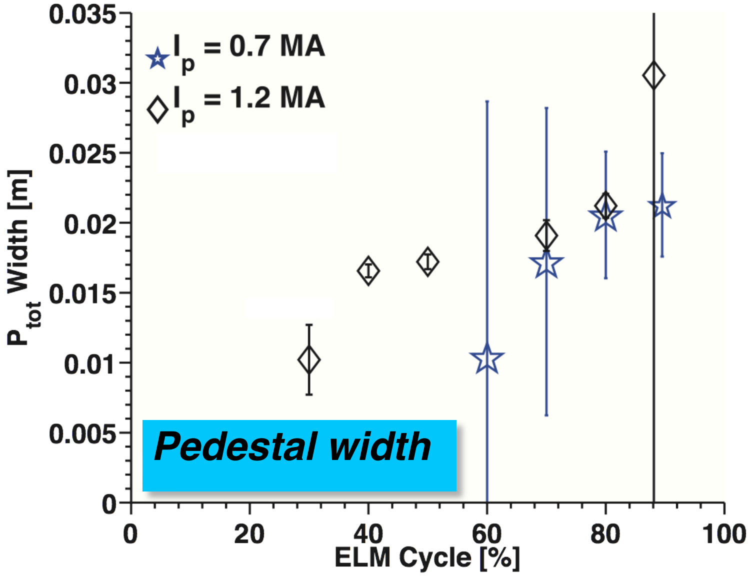
- More than a factor of two increase in pedestal temperature
- Density pedestal is much less sensitive to the ELM cycle
- Heat and particle evolutions appear to be decoupled

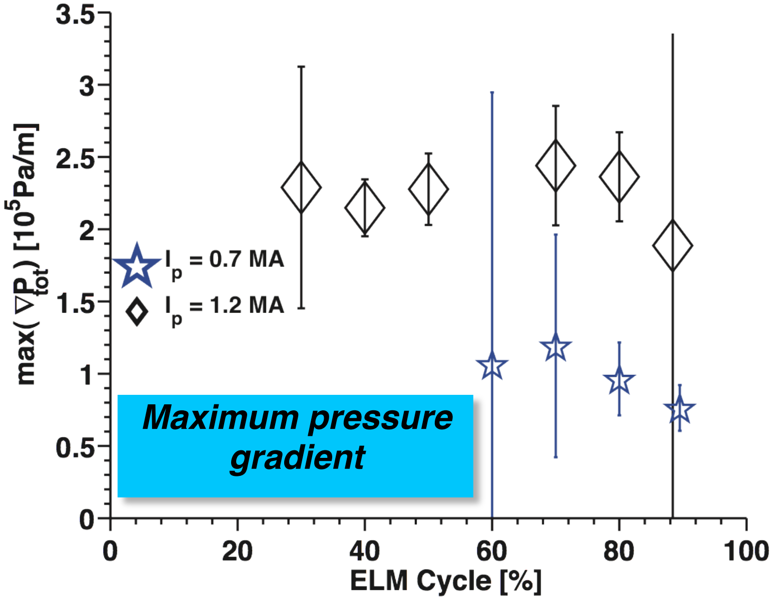


Data measured using Thomson scattering at the same spatial locations

Pedestal width and height progressively increase during ELM cycle but the peak pressure gradient remains clamped

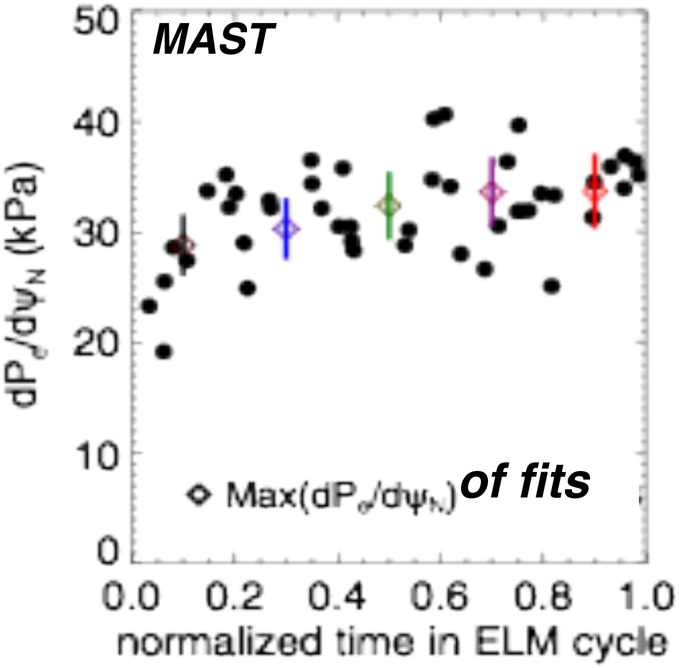


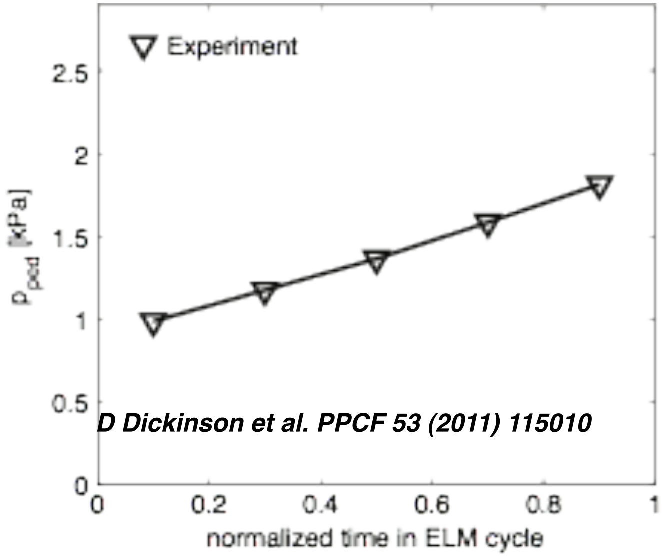




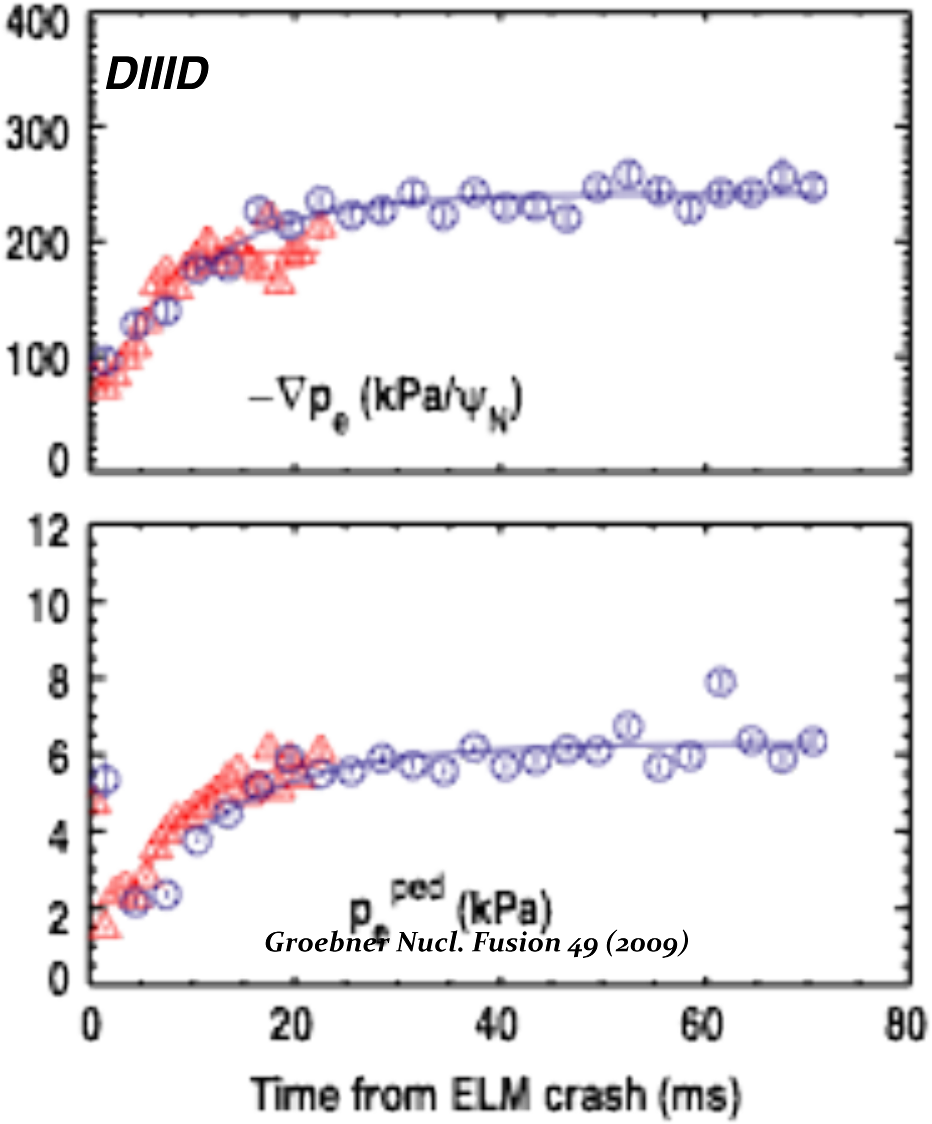
- Pedestal height increases by a factor ≤ 3
  - Height scales with I_p
- Pedestal width increases independently of I_p
- Gradient is clamped early in ELM cycle

Saturation of the gradient is ubiquitous across devices, but different trends in pedestal height evolution are observed





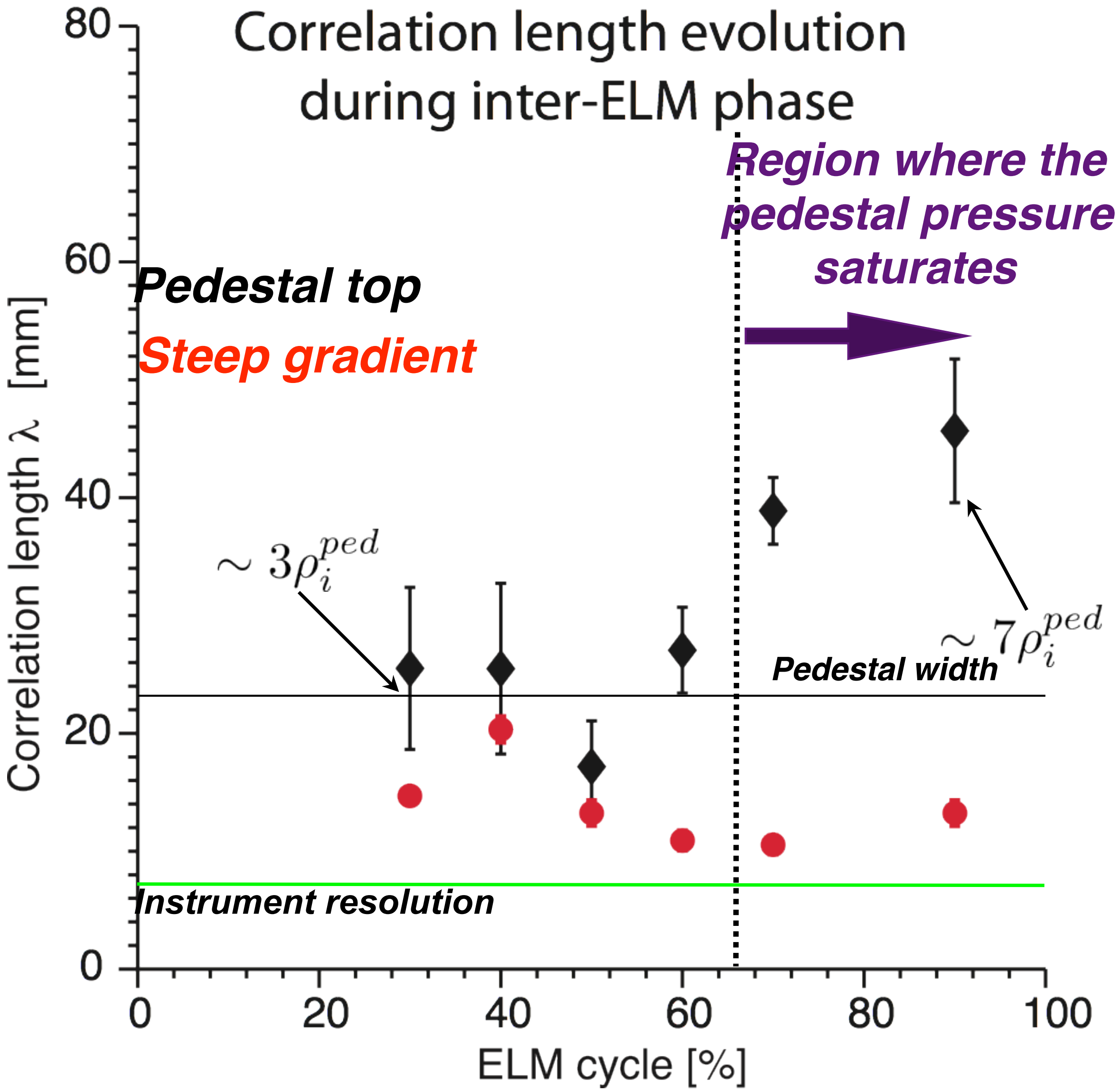
D Dickinson et al. PPCF 53 (2011) 115010



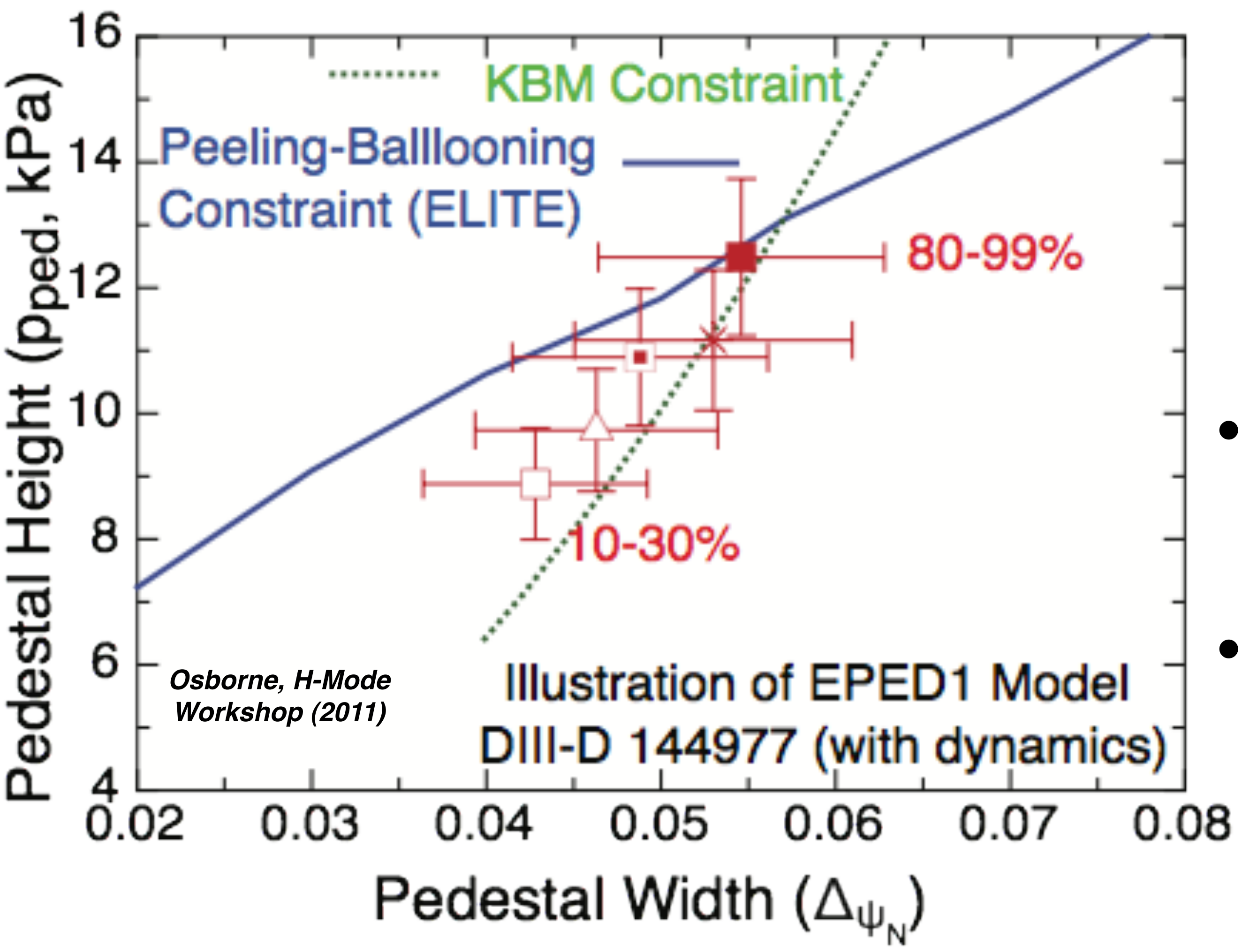
Groebner Nucl. Fusion 49 (2009)

Radial correlation length evolution depends on location inside pedestal region

- Radial correlation length increases at the pedestal top
  - A factor of 2 increase during the last 50% of ELM cycle
  - Increase size of eddies
    - ➡suggesting enhanced radial transport during the ELM cycle
- Steep gradient correlation length is unchanged
- Quantify the geometric effects on the measured correlation?



In the EPED model, peeling ballooning provides a sufficient constraint for the pedestal height and KBM limits the width



Osborne, H-Mode Workshop (2011)

- Kinetic ballooning mode (KBM) has been proposed to limit the pedestal gradient in standard aspect ratio tokamaks

Snyder et al. PoP 9 (2002)

- KBM-like modes are observed in DIIID

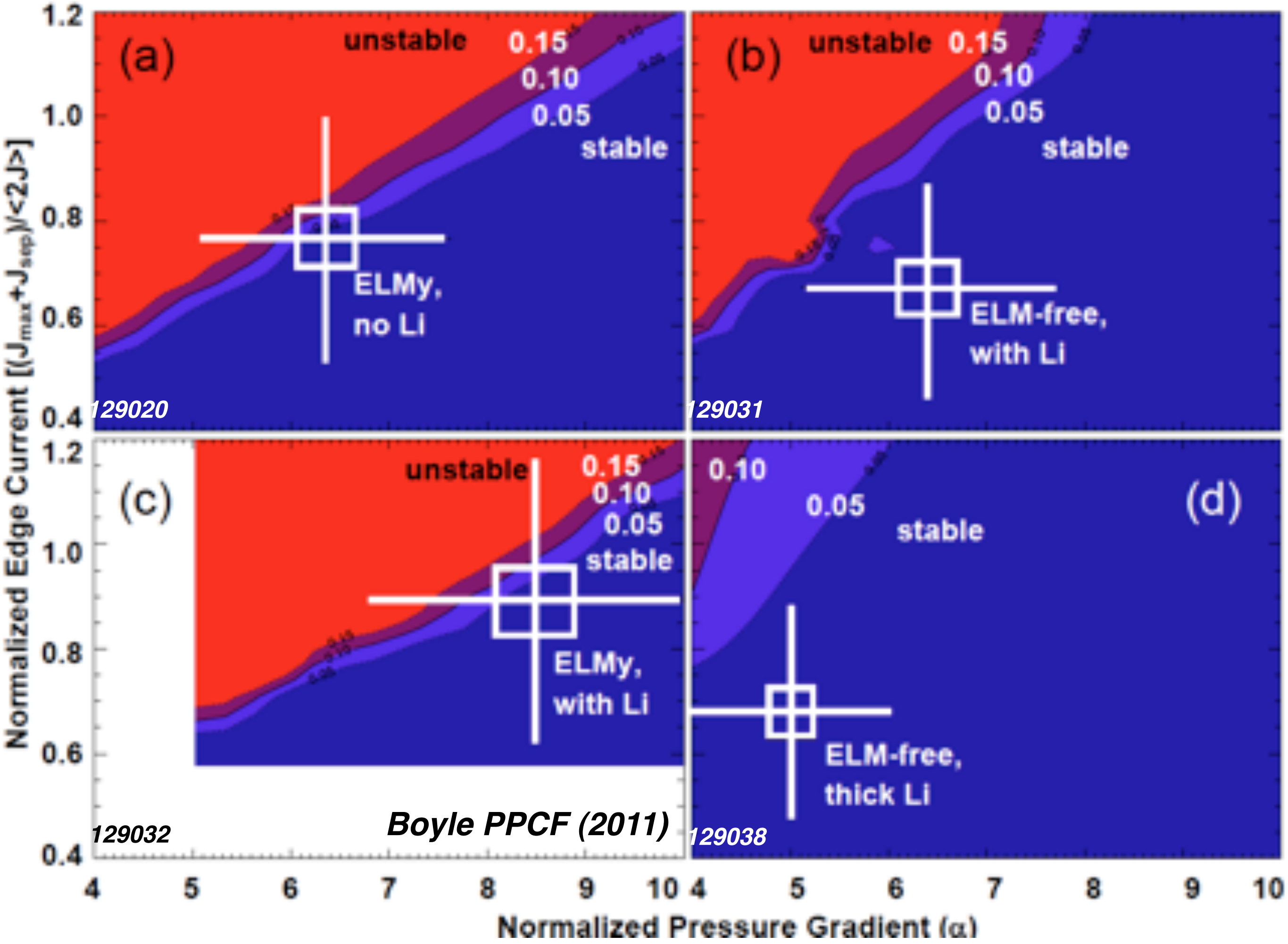
Yan, PRL, (2011)

- MAST and NSTX have shown using GS2 and GYRO the existence of both microtearing and KBM near the pedestal top

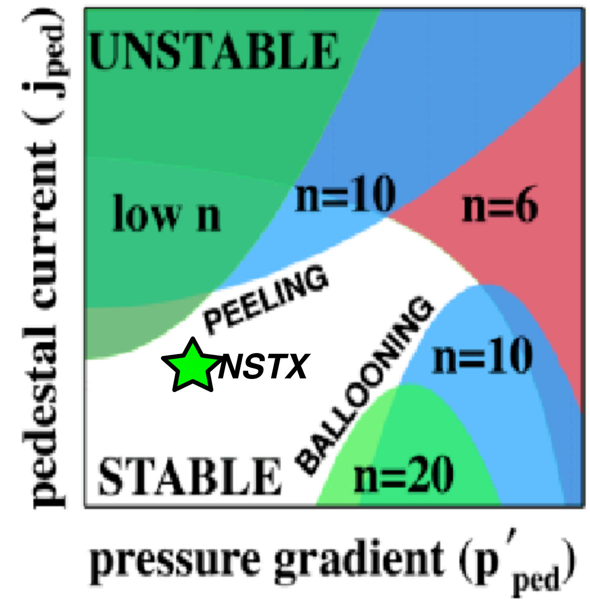
Dickinson, PPCF, (2011)

Guttenfelder, submitted PoP, (2011)

Stability diagram with and without lithium: Lithium cases are farther away from the kink/peeling boundary



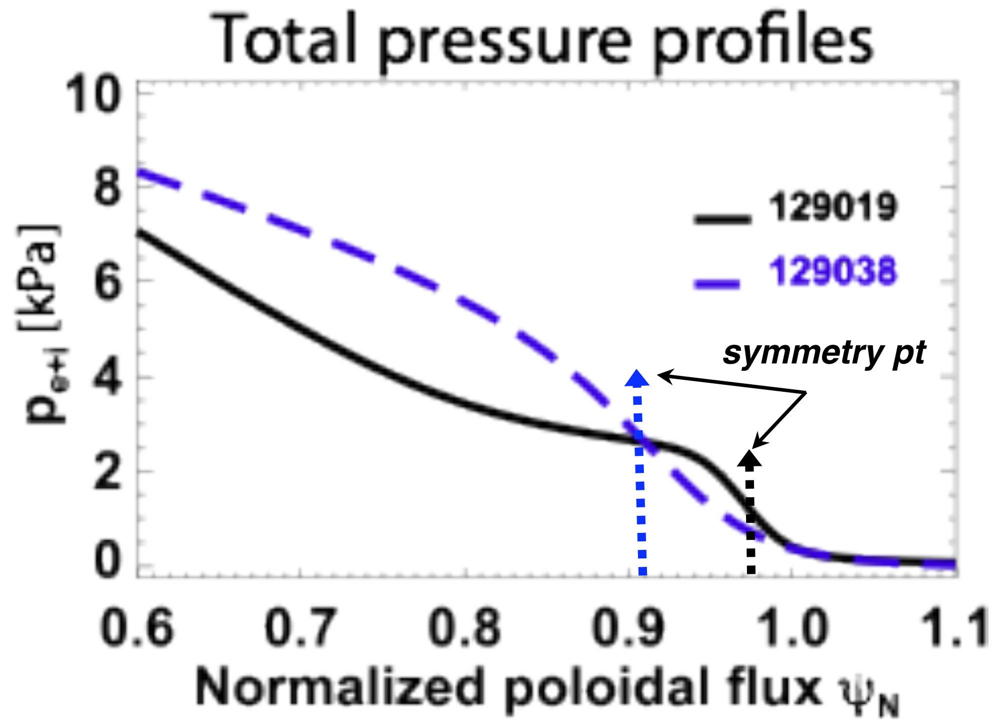
Boyle PPCF (2011)



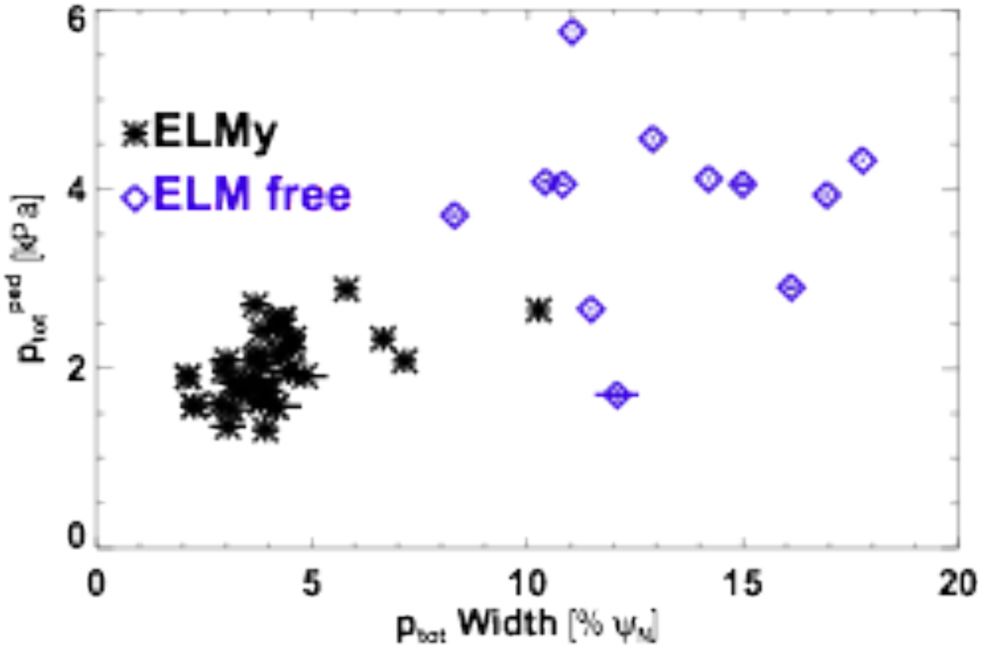
Consistent with NSTX close to the kink/peeling stability boundary

Lithium coatings are a useful tool for shifting peak pressure gradient inward and stabilizing kink/peeling modes.

ELMy regimes transition to ELM-free regimes with the application of lithium on the divertor to access larger pedestal pressure and width



Pedestal height vs width



- ELM-free regimes exhibit a pedestal height and width larger than in ELMy cases
  - Application of lithium clearly modifies the edge pressure
- Inward shift of the peak pressure gradient

NSTX Participation in ITPA Joint Experiments and Activities

Boundary Physics

– PEP-6	Pedestal structure and ELM stability in DN
– PEP-19	Edge transport under the influence of resonant magnetic perturbations
– PEP-23	Quantification of the requirements of ELM suppression by magnetic perturbations from internal off mid-plane coils
– PEP-25	Inter-machine comparison of ELM control by magnetic field perturbations from midplane RMP coils
– PEP-26	Critical edge parameters for achieving L-H transitions
– PEP-27	Critical edge parameters for achieving L-H transitions
– PEP-28	Physics of H-mode access with different X-point height
– PEP-31	Pedestal structure and edge relaxation mechanisms in I-mode
– PEP-32	Access to and exit from H-mode with ELM mitigation at low input power above PLH
– DSOL-24	Disruption heat loads