NSTX

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

Boundary Physics Progress and Plans

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NSTX PAC-29

PPPL B318

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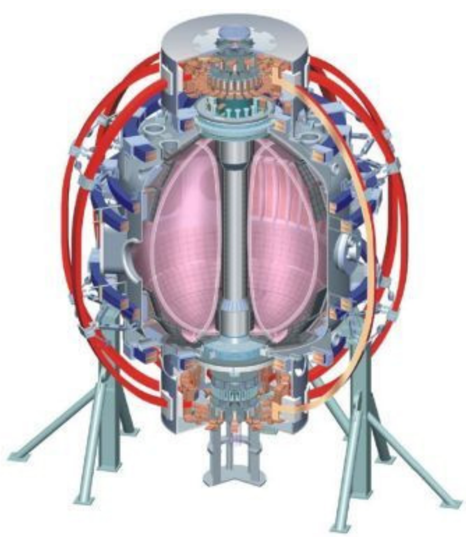

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NSTX Boundary Physics program contributes to a critical research area for ITER/tokamaks and STs

- DOE Joint Research Targets
  - FY 2010: thermal SOL transport
  - FY 2011: pedestal structure (joint experiment and theory)
- NSTX research milestones
  - R(10-3): H-mode pedestal and ELM stability
  - R(11-3): Assess very high flux expansion divertor operation (w/ ASC)
  - R(11-4): H-mode pedestal transport, turbulence, and stability response to 3D fields (w/ ITER-CC, T&T ,MS)
  - R(12-1): Investigate the relationship between lithium-conditioned surface composition and plasma behavior (w/ LR)
  - R(12-3): Assess access to reduced density and collisionality in high-performance scenarios (w /ASC + MS)
- Integrated divertor solutions for NSTX-U
- ITPA participation and high-priority ITER research needs

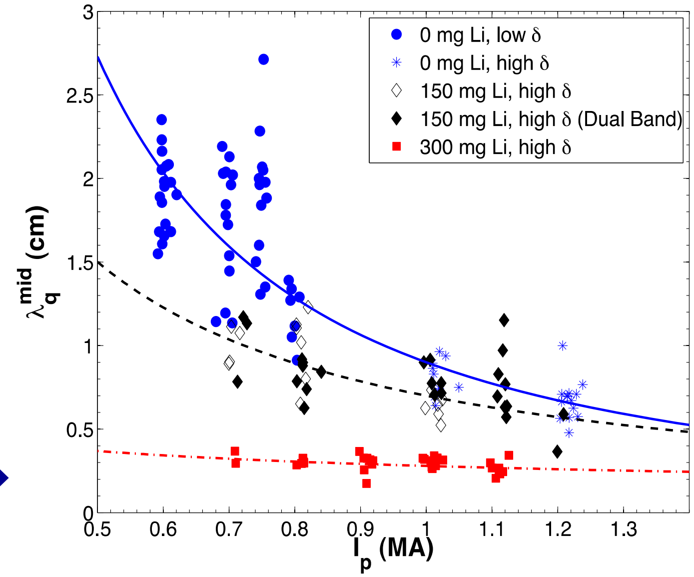
Outline

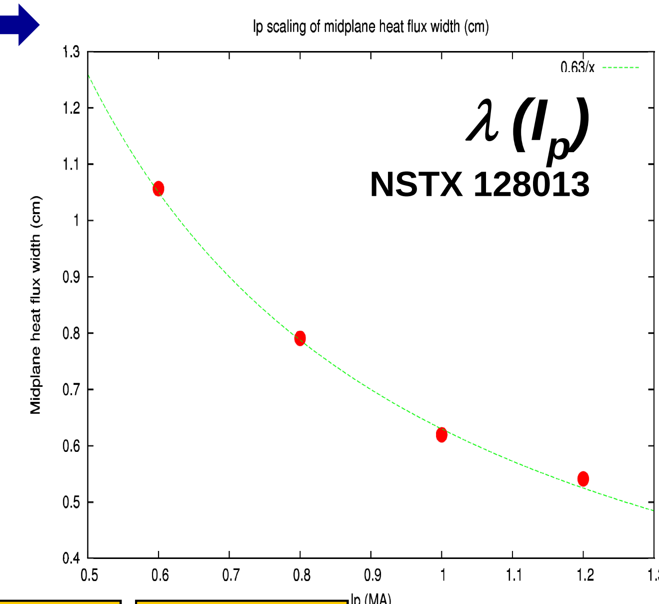
- Edge transport and plasma-surface interactions
  - Thermal heat transport in the SOL
  - SOL turbulence studies
  - Divertor transport and heat flux mitigation
  - Impurity sources, fueling optimization

- H-mode physics
  - Pedestal physics studies
  - ELM characterization and control

SOL width and divertor heat flux studies in NSTX inform NSTX-U and ITER divertor projections

- Completed FY 2010 DOE JRT
  - λ_q^{mid} characterized in experiment
    - independent of P_{SOL} and B_t
    - constant with increasing f_{exp}
    - contracts with increasing *drsep*; and I_p: $\lambda_q^{mid} \sim I_p^{-1.6}$ (DIII-D: $\lambda_q^{mid} \sim I_p^{-1.2}$; Alcator C-Mod: $\lambda_q^{mid} \sim I_p^{-1.0}$)
    - λ_q contracts with increasing lithium deposition
  - and modeled
    - XGC0 modeling reproduced I_p dependence (NSTX: $\lambda_q^{mid} \sim I_p^{-1.0}$; DIII-D: $\sim I_p^{-0.8}$; C-Mod: $\sim I_p^{-0.3}$)
    - SOLT modeling: weak λ_q scaling with P_{in}; I_p scaling is weaker than observed
- Further studies
  - Connect λ_q^{mid} to pedestal width and edge turbulence
  - λ_q^{mid} data analysis for ITER / future STs
    - For NSTX-U parameters, λ_q^{mid} = 3±0.5 mm

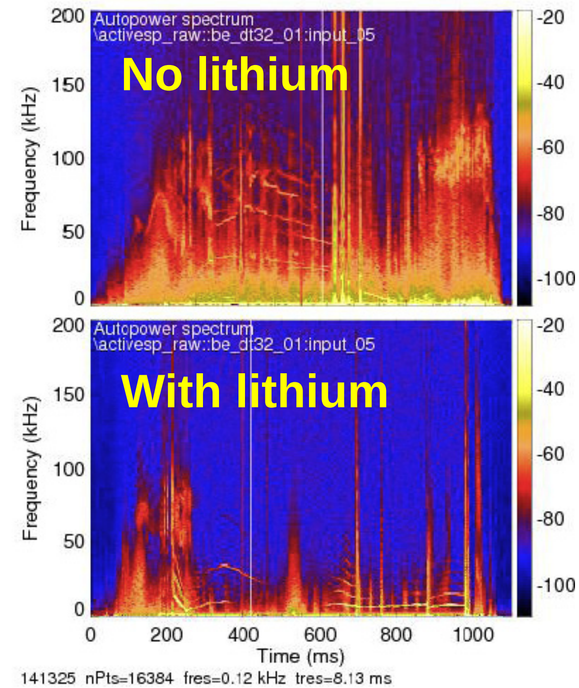


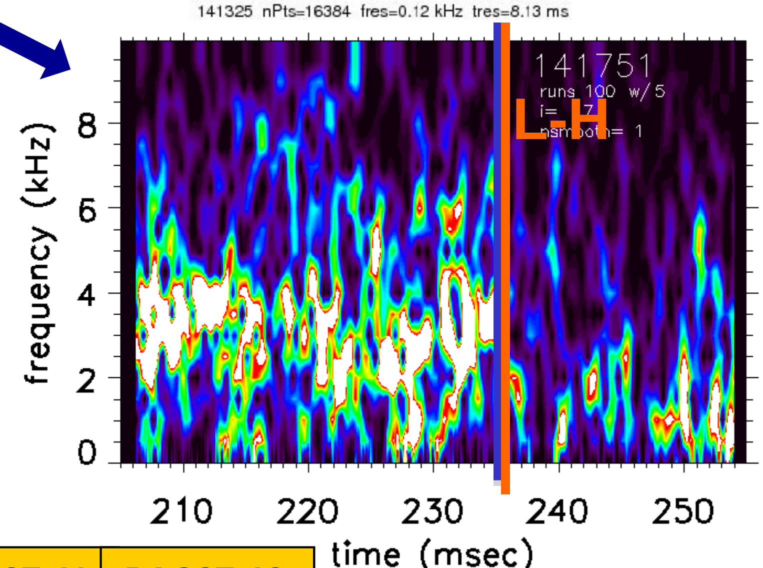


PAC27-10 **PAC27-11**

Pedestal / SOL turbulence measurements and modeling contribute to edge transport and L-H transition studies

- Transport and turbulence with lithium
  - Turbulence reduction with lithium
    - Low-k δn/n in pedestal measured by BES
    - δn/n from ~10 % to 1 % from edge reflectometer
    - δn/n in pedestal measured by high-k scattering
  - UEDGE and SOLPS transport modeling
- L-H transition physics
  - edge zonal flow/GAM and turbulence modulation at ~3 kHz preceding L-H transition (from velocimetry of edge turbulence flow speed)
  - No systematic changes in poloidal flow shear during ~1 msec just before L-H transition at ±3 cm around separatrix – no clear L-H trigger
- Planned research (R11-3)
  - Spatial localization of L-H transition
  - Validation of SOLT, GAMs, XGC-1, BOUT simulations using NSTX data
  - Effect of 3D fields, SOL currents, X-points on edge transport and ELMs

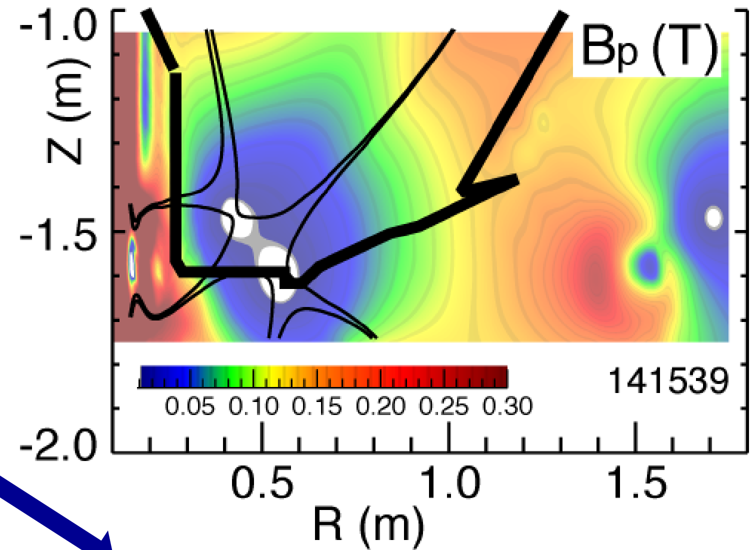


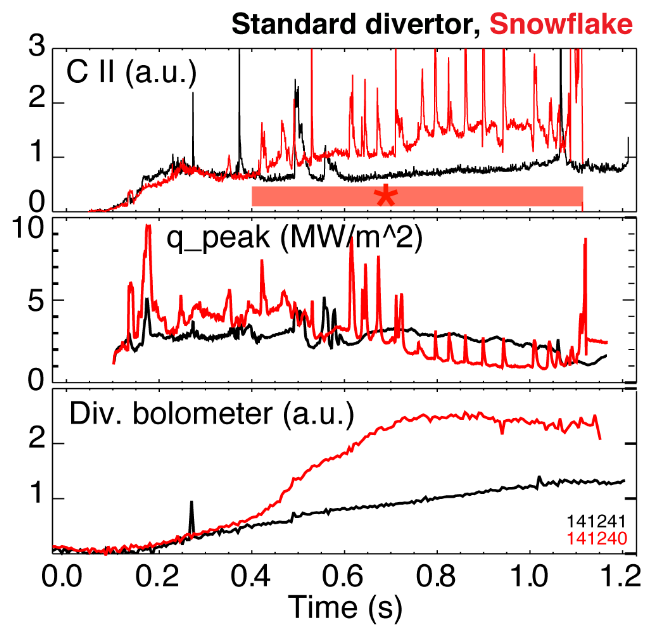


PAC27-11 | **PAC27-12**

Snowflake divertor studies inform divertor solutions for NSTX-U, future high power density tokamaks

- Progress in snowflake divertor studies
  - Magnetic control: snowflake-minus w/ three divertor coils up to 600 ms
  - Partial detachment of outer strike point
    - q_{pk} reduced from 3-7 to 0.5-1 MW/m^2 at P_{SOL}~ 3 MW due to increased divertor P_{rad} (up to 50 %) and high flux expansion (increased up to 90 %)
    - Core and pedestal carbon concentration reduced by up to x 50 %
  - ELM regime modification (no ELMs -> Type I)
  - UEDGE modeling commencing
- Planned research (R11-3, R12-3)
  - Divertor power balance, radiation and turbulence characteristics, pumping with lithium, impurity seeding
  - Pedestal structure, P.-B. stability, ELM control
  - NSTX-U divertor scenarios
    - NSTX-U shaping, upper+lower snowflake

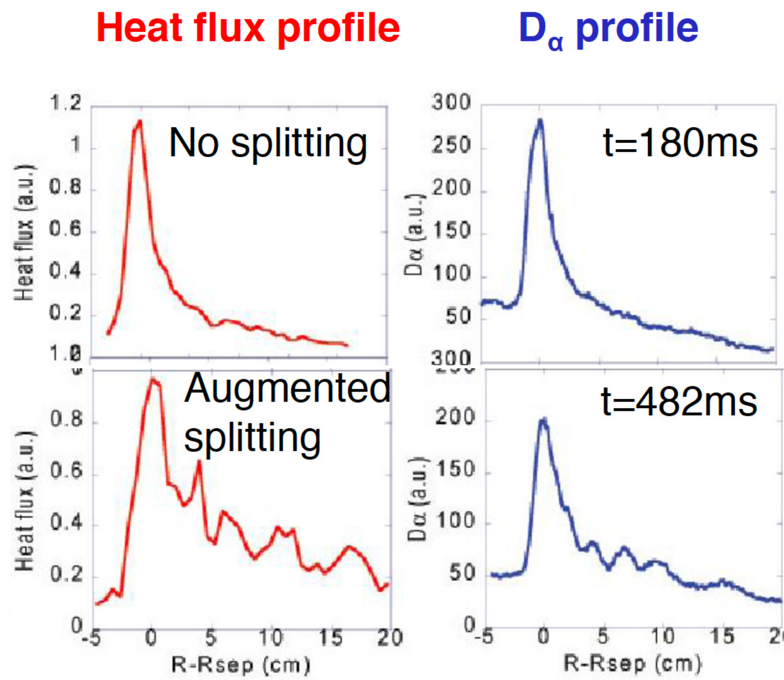


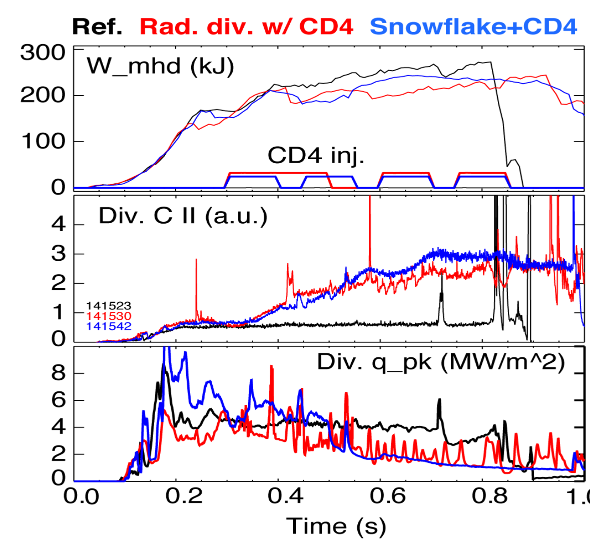


PAC27-2 **PAC27-16**

Understanding impact of 3D fields and impurity gas seeding on divertor heat flux footprint critical for ITER, NSTX-U

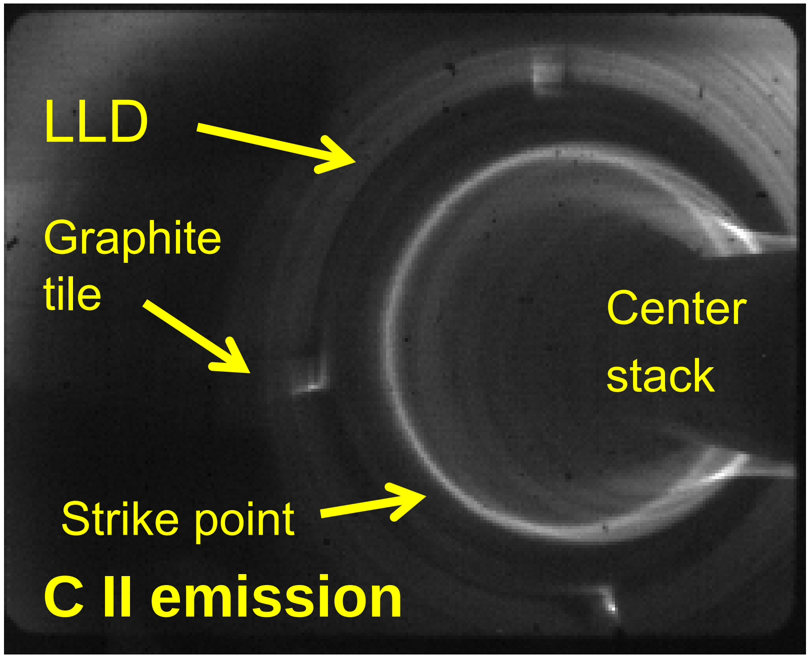
- Effect of non-axisymmetric magnetic perturbations on divertor profiles
  - Intrinsic and 3D field induced splitting
    - In agreement with vacuum field line tracing
  - Applied 3D fields can reattach detached outer strike point (done at ITER request)
- Radiative divertor with CD_4 seeding
  - Enhanced divertor carbon radiation reduced peak heat flux by up to 70 %
  - Combined with snowflake configuration and increased div. carbon radiation
- Planned research (R11-3, R11-4)
  - SOL transport and turbulence w/ 3D fields and impact on divertor
  - Optimize impurity-seeded radiative divertor scenario, develop divertor monitors for radiative divertor w/ feedback control





Recent diagnostic and facility upgrades enable improved understanding of impurity production and fueling control

- Extra resources for impurity studies
  - New hardware
    - Two Phantom cameras with narrow-badpass interference filters (H, Li, C, Ne, Mo)
    - Multichannel divertor spectrometer
    - Multiple fast gas injectors, incl. SGI
  - Princeton Univ. PhD thesis in progress
  - New postdoctoral researchers



Top view of lower divertor

- Planned research (R11-3, R11-4, R12-1, R12-3)
  - Assessment of PFC candidate materials for NSTX-U
    - Impurity flux from moly tiles
    - Impurity yield and sputtering studies
  - Impurity transport in SOL and pedestal
  - Development of H-mode scenarios with reduced controlled density

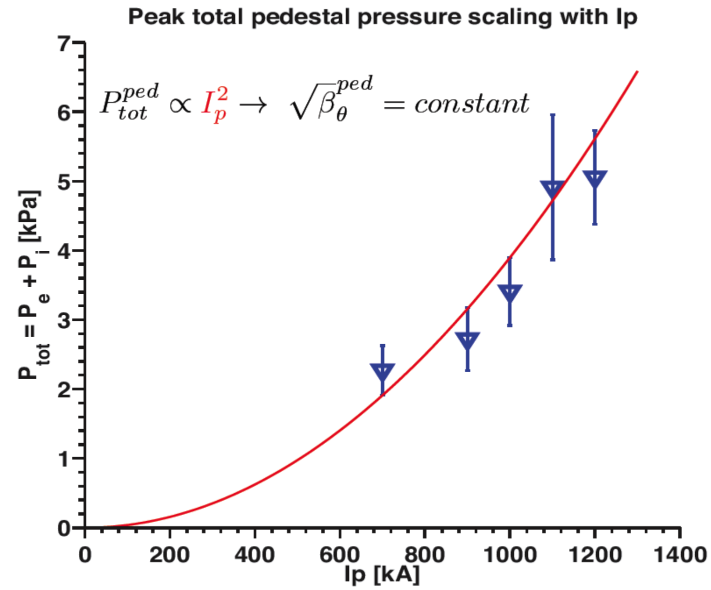
PAC27-2

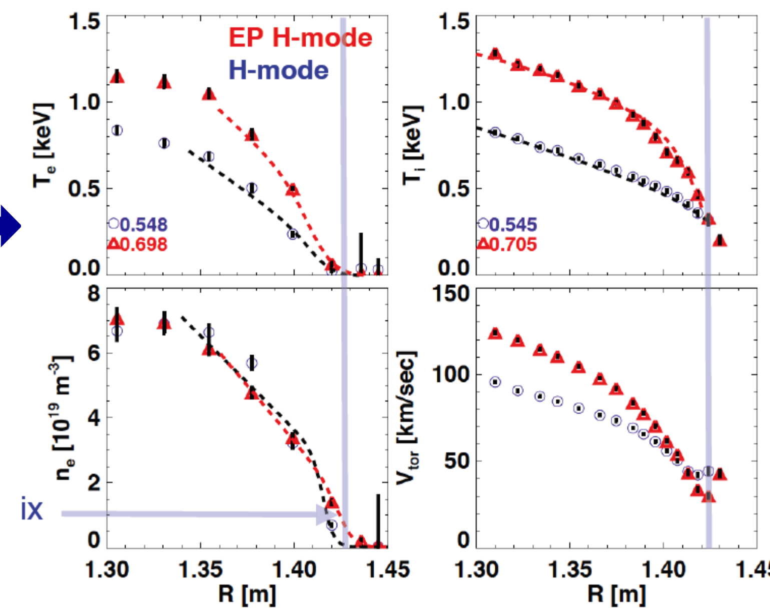
PAC27-3

PAC27-16

Pedestal structure and underlying MHD/transport mechanisms will be elucidated by FY 2011 JRT effort

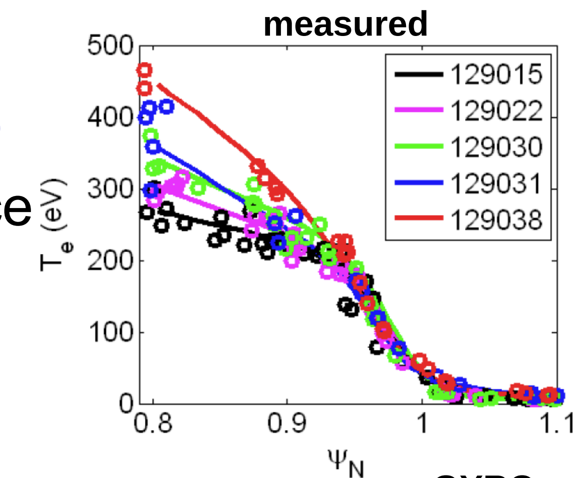
- Continuing progress in pedestal studies
  - Pedestal workshop w/ Alcator C-mod (09/2010)
  - Application of pedestal analysis tools and interface with modeling
  - FY 2010 – FY 2011 experiments
    - Pedestal pressure
      - $P_{ped} \propto I_p^2$ and increases with triangularity
      - Builds up during ELM cycle, saturates at lower I_p late in ELM cycle
      - Analysis of pedestal data with PB theory
    - Physics of EP H-mode with H98~1.7
- Planned research (R11-4)
  - Pedestal transport, turbulence, stability with 3D fields
    - Roles of particle and thermal heat transport

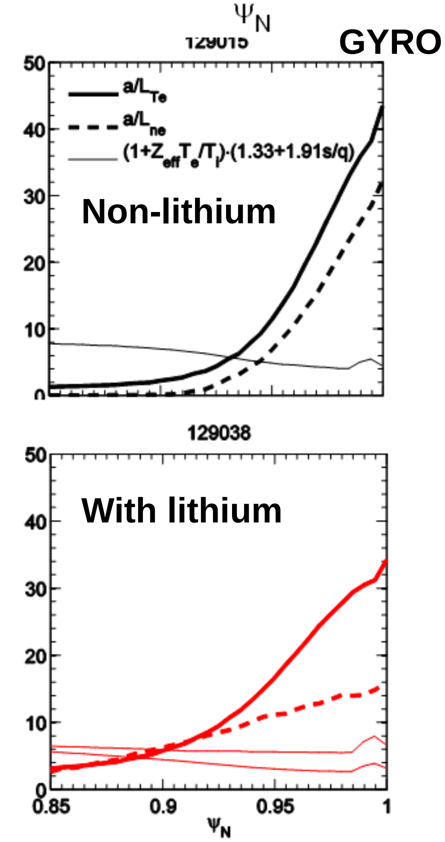




Pedestal structure and underlying MHD/transport mechanisms will be elucidated by FY 2011 JRT effort

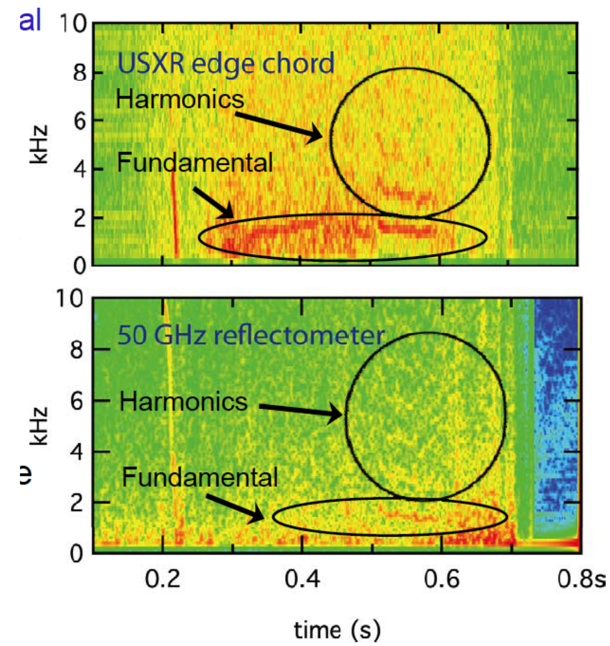
- Document dependence of pedestal structure in on I_p, B_t, δ
  - Stability analysis with ELITE, PEST; height analysis with EPED
- Evaluate edge transport rates and correlate with turbulence
  - With lithium: role of recycling and fueling (SOLPS, UEDGE)
  - In regimes with separate particle and thermal transport channels, e.g. EP H-mode and I-mode
  - Compare with paleoclassical and neoclassical (XGC) transport models
  - Evaluate role of ETG in limiting edge T_e gradient (GYRO)
    - ETG unstable in steep gradient region ($\psi_N > 0.92$)
      - threshold likely set by density gradient
    - ETG stable at top of pedestal ($\psi_N = 0.88$)
      - threshold likely sensitive to $Z_{eff} T_e / T_i$ and s/q
- Continue ELM stability studies
  - Role of n_e and T_e gradients, and lithium
  - Role of diamagnetic stabilization (BOUT)

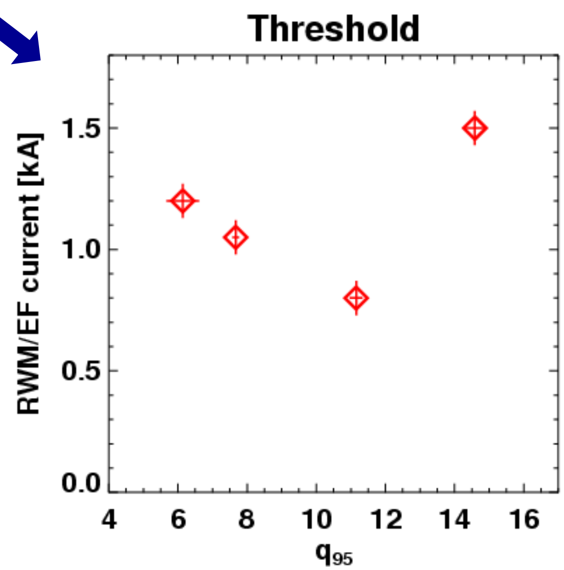




NSTX studies of ELM regimes and ELM control contribute to mitigation strategies for ITER and future STs

- ELM response to lithium, 3D fields, X-points
- Small ELM (Type V) regime
  - Type I ELMs stabilized
  - Observed EHO-like edge instability (f <10 kHz)
- Initiated ELM suppression experiment using n=3 off-midplane coils
  - Developed stable plasma shifted down by 20 cm
- With midplane n=3 coils, found threshold current and optimal q_{95} window for ELM triggering
  - ELM triggering on NSTX: weak pedestal modification, vacuum Chirikov width > 0.3, no pitch-aligned with wide q_{95} range (~9~11), ν^*_e>0.5
- Planned research in FY2011-2012
  - Development of small ELM regimes at low ν^*, high P_{in}
  - ELM dependence on shape and magnetic balance
  - 2nd SPA for flexible spectrum (n=1,2,3) for ELM stability studies





Research planned for FY 2013 will summarize NSTX boundary studies and prepare plans for NSTX-U

- Data analysis, modeling of NSTX experiments
- Collaboration with MAST, DIII-D, Alcator C-mod
- Examples of design activities and initial plans for NSTX-U research
  - Diagnostic upgrades
    - E.g., divertor Thomson scattering system, materials probe
  - Divertor heat flux mitigation scenario development
    - Equilibria and edge transport modeling of snowflake and X-divertor w/ NSTX-U divertor coils
  - Divertor particle control development
    - Cryopump, upgraded lithium deposition systems
  - PFC program development
    - Graphite, molybdenum tiles
  - Fueling program
    - Divertor SGI, cryo-SGI
    - Compact toroid injector, massive gas injection system
    - Pellet injector

NSTX Boundary Physics Program Summary

- Improving understanding of SOL heat and particle transport for STs and tokamaks

- Developing innovative methods for mitigating divertor heat flux

- Improving understanding of H-mode pedestal structure and ELM stability

Research is vital to NSTX-U, ITER, next-steps

Backup slides

NSTX is actively contributing to Edge and Pedestal, as well as divertor and SOL ITPA groups

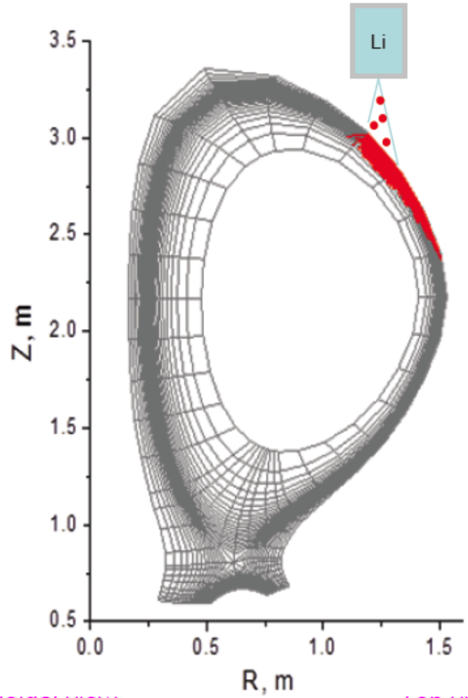
- PEP-6 Pedestal structure and ELM stability in DN
- PEP-19 Basic mechanisms of edge transport with resonant magnetic perturbations in toroidal plasma confinement devices
- PEP-23 Quantification of the requirements for ELM suppression by magnetic perturbations from off-midplane coils
- PEP-24 Minimum pellet size for ELM pacing
- PEP-25 Inter-machine comparison of ELM control by magnetic field perturbations from midplane RMP coils
- PEP-26 Critical parameters for achieving L-H transitions
- PEP-27 Pedestal profile evolution following L-H/H-L transition
- PEP-28 Physics of H-mode access with different X-point height
- PEP-29 Vertical jolts/kicks for ELM triggering and control
- 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
- PEP-33 Effects of current ramps on the L-H transition and on the stability and confinement of H-modes at low power above the threshold
- PEP-34 Non-resonant magnetic field driven QH-mode

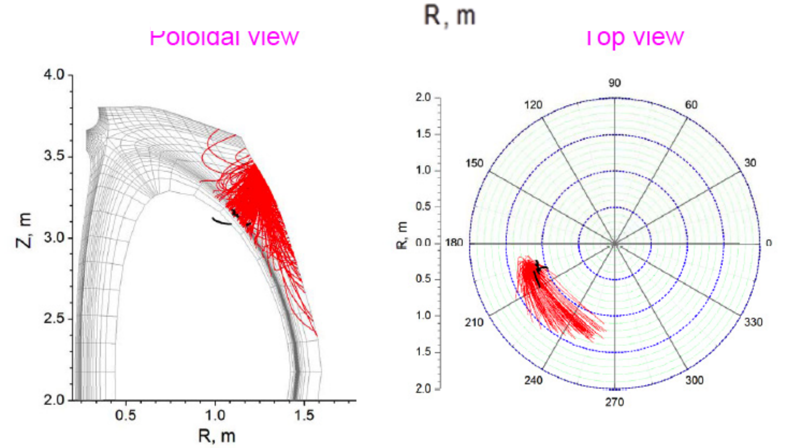
- DSOL-20 Transient divertor reattachment
- DSOL-21 Introduction of pre-characterized dust for dust transport studies in divertor and SOL
- DSOL-24 Disruption heat loads
-
- MDC-1 Disruption mitigation by massive gas jets

NSTX makes leading contributions in tokamak dust research

- First demonstration of remote detection of surface dust on NSTX
- Calibration of dust detector with carbon and lithium (as e.g., Be proxy)
  - In-situ detector cleaning technique developed
  - Electrostatic dust conveyor demonstrated with tungsten and carbon particles
- Modeling of lithium and tungsten dust injection in NSTX
  - Important for model benchmarking and application to ITER
- Modeling of different dust injection scenarios for evaluation of possibility of divertor heat load mitigation in NSTX-U

Configuration of modeled Li dust injection





FY 2011JRT on Pedestal Structure

- **Conduct experiments on major fusion facilities to improve the understanding of the physics mechanisms responsible for the structure of the pedestal and compare with the predictive models described in the companion theory milestone. Proposed description: The goal of the joint theory-experiment milestones (or replace with research campaigns depending on what OFES prefers) is to understand the physics mechanisms responsible for the structure of the pedestal and develop a predictive capability. The edge of high performance tokamaks is characterized by very steep pressure gradients forming a pedestal in the pressure profile. Core confinement is strongly correlated with the value of the pressure at the top of the pedestal, which is predicted to significantly impact the fusion power in ITER.**

- ***Experiment:*** *Improve the understanding of the physics mechanisms responsible for the structure of the pedestal and compare with the predictive models described in the companion theory milestone. Perform experiments to test theoretical physics models in the pedestal region on multiple devices over a broad range of plasma parameters (e.g., collisionality, beta, and aspect ratio). Detailed measurements of the height and width of the pedestal will be performed augmented by measurements of the radial electric field. The evolution of these parameters during the discharge will be studied. Initial measurements of the turbulence in the pedestal region will also be performed to improve understanding of the relationship between edge turbulent transport and pedestal structure.*
- ***Theory:*** *A focused analytic theory and computational effort, including large-scale simulations, will be used to identify and quantify relevant physics mechanisms controlling the structure of the pedestal. The performance of future burning plasmas is strongly correlated with the pressure at the top of the edge transport barrier (or pedestal height). Predicting the pedestal height has proved challenging due to a wide and overlapping range of relevant spatiotemporal scales, geometrical complexity, and a variety of potentially important physics mechanisms. Predictive models will be developed and key features of each model will be tested against observations, to clarify the relative importance of various physics mechanisms, and to make progress in developing a validated physics model for the pedestal height.*

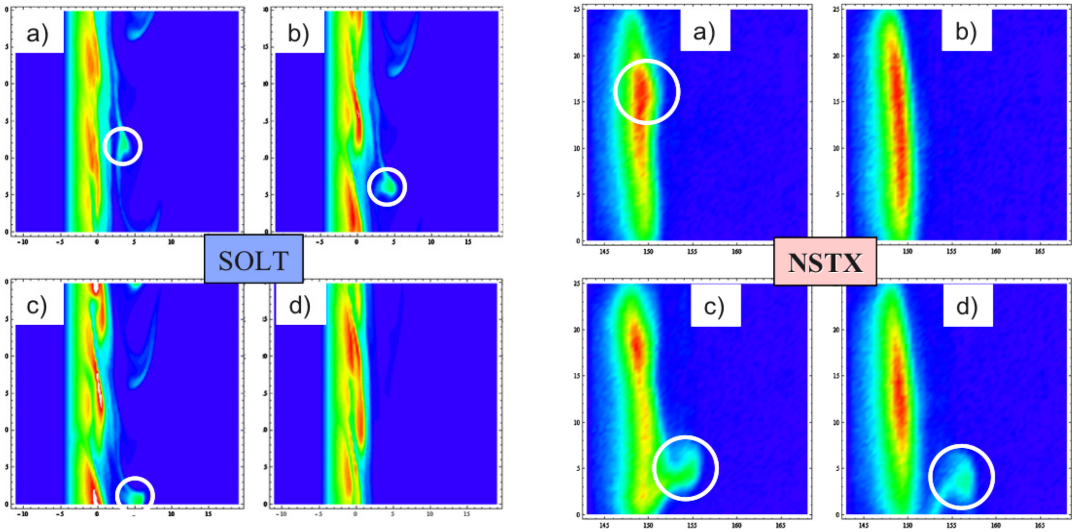
Numerical modeling of NSTX measurements for DOE FY2010 JRT performed with two codes

- SOLT code (Lodestar)
  - classical parallel + turbulent cross-field transport
  - evolves n_e, T_e, Φ with parallel closure relations
  - sheath connected, with flux limits, collisional
  - strongly nonlinear: $\delta n/n \sim 1 \Rightarrow$ blobs
  - model supports drift waves, curvature-driven modes, sheath instabilities
  - synthetic GPI diagnostic
  - flexible sources for n_e, T_e, v_y
- XGC0 code (CPES)
  - 5D Lagrangian guiding center dynamics
  - Axisymmetric solution for radial electric field *Er*
  - Ion/electron/neutral, full-f
  - Momentum-energy-particle conserving Monte-Carlo collisions
  - $\Phi(\psi)$ electric potential solver
  - XGC0 evaluates kinetic bootstrap current, and reconstruct the Grad-Shafranov equilibrium

Validation of edge turbulence simulations in NSTX

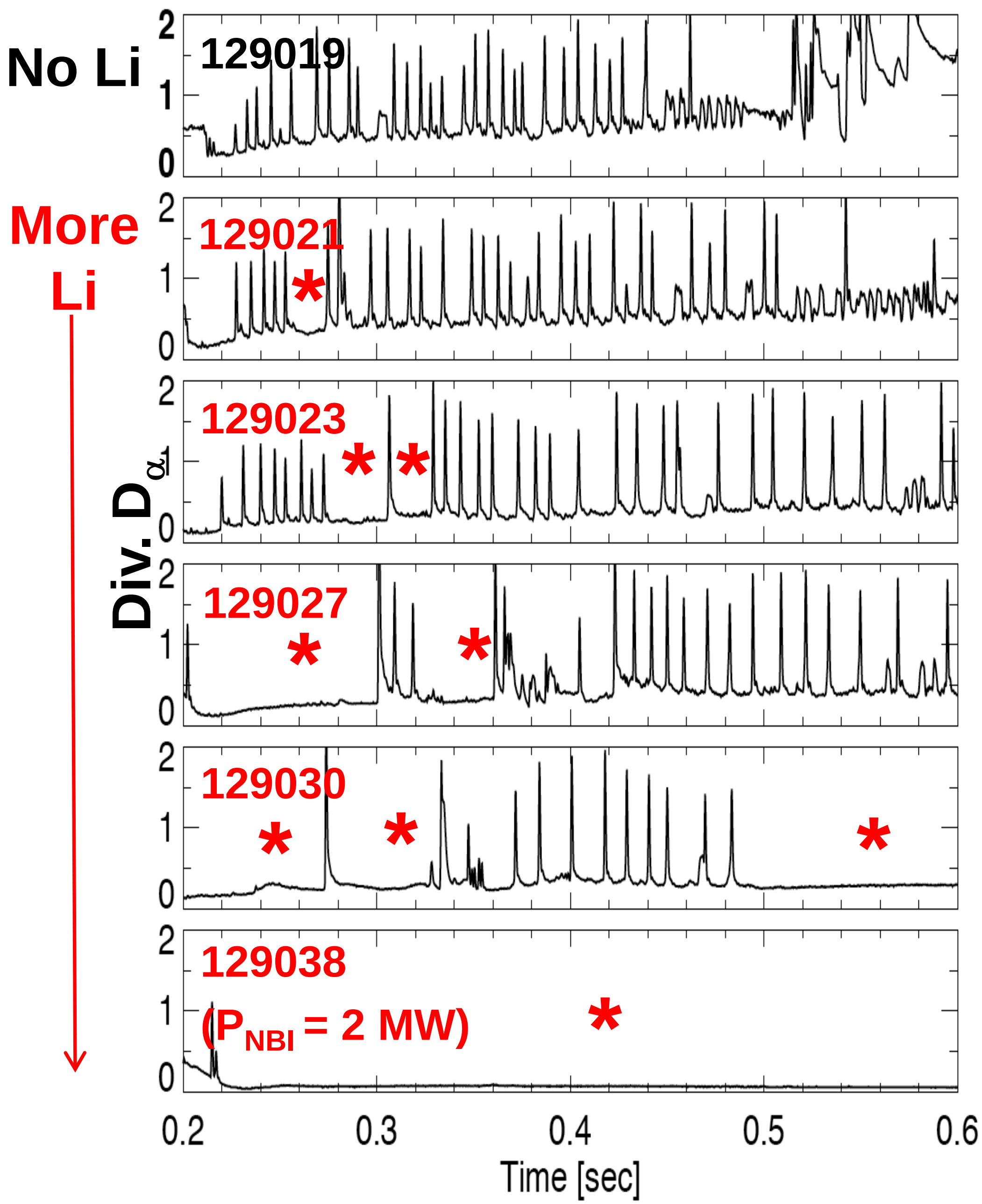
- Boundary transport most likely due to edge turbulence, but simulations are only partially validated by experiment
  - NSTX can test existing simulations codes such as SOLT using GPI, BES, reflectometry, and other diagnostics
  - Midplane turbulence in SOLT explains some, but not all, of observed λ_q^{mid} scalings

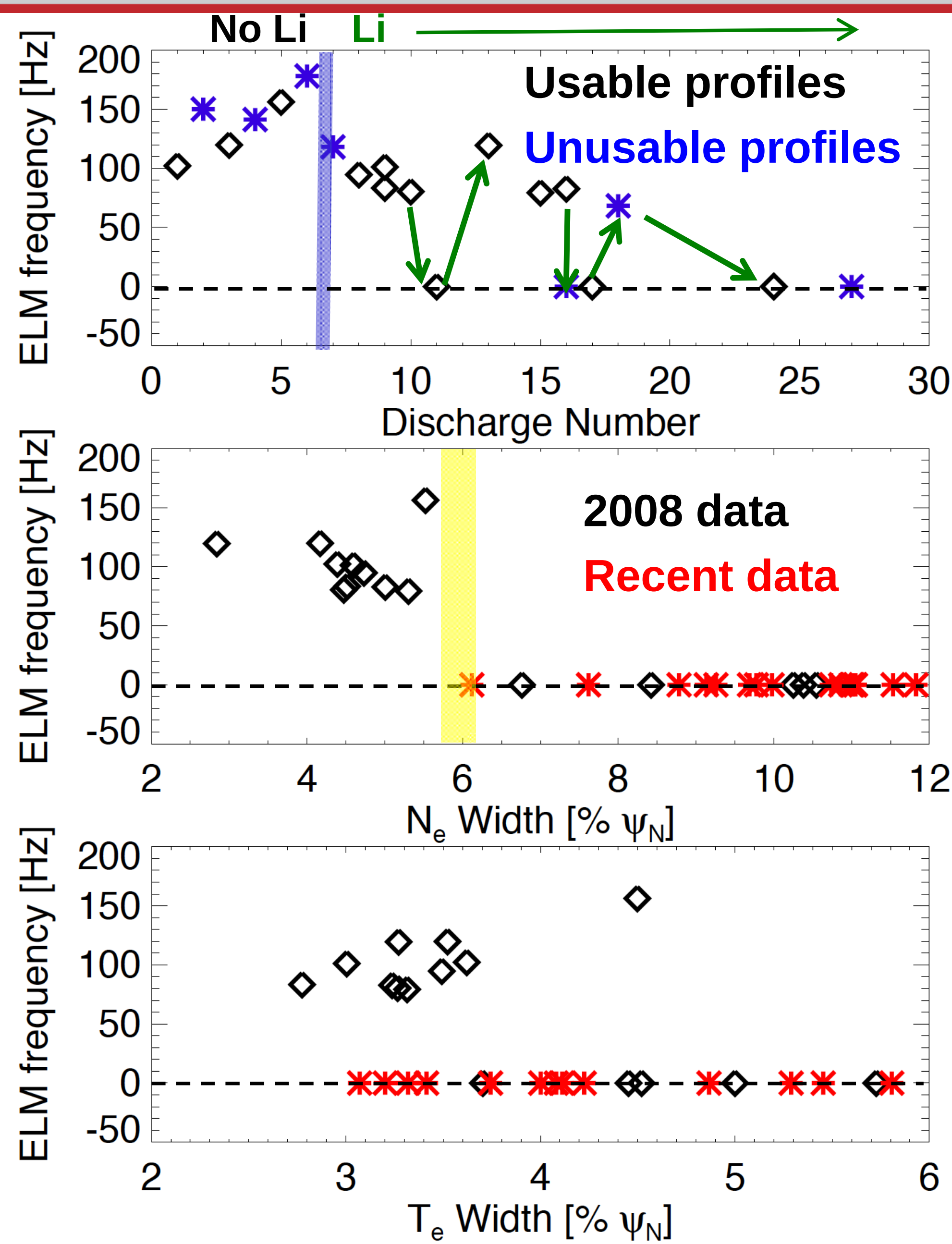
Blob formation in SOLT is similar to Gas Puff Imaging diagnostic data



shot	I_p(MA)	P(MW)	λ_q NSTX (cm) midplane	λ_q SOLT (cm) midplane
135009	0.8	0.8	0.36	0.30
135038	0.8	1.3	0.50	0.41
128013	0.8	5.8	1.73	0.76
128797	1.2	6.1	0.56	0.58

ELM suppression correlates with broadening of n_e profile, but not T_e profile

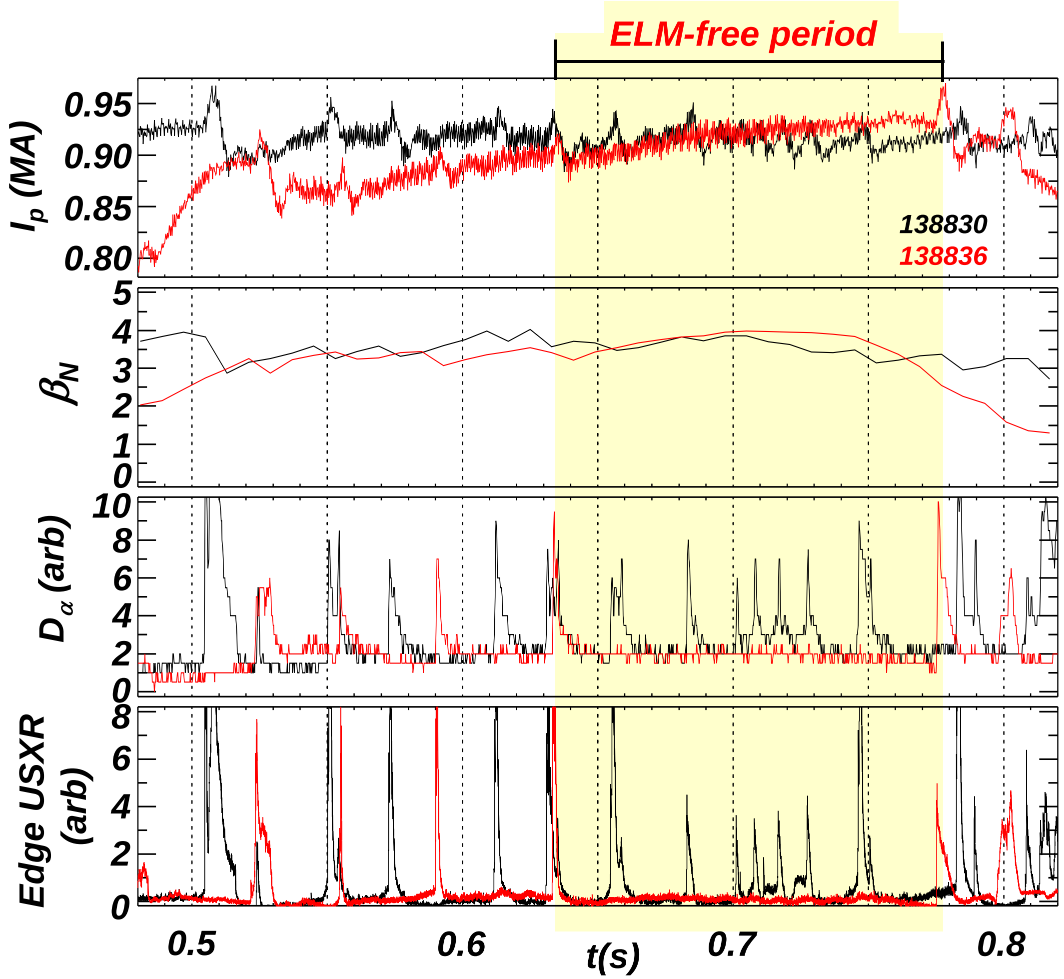




Macrostability TSG to support ITER milestone R11-4 by examining/modeling plasma response to 3D fields

R(11-4)

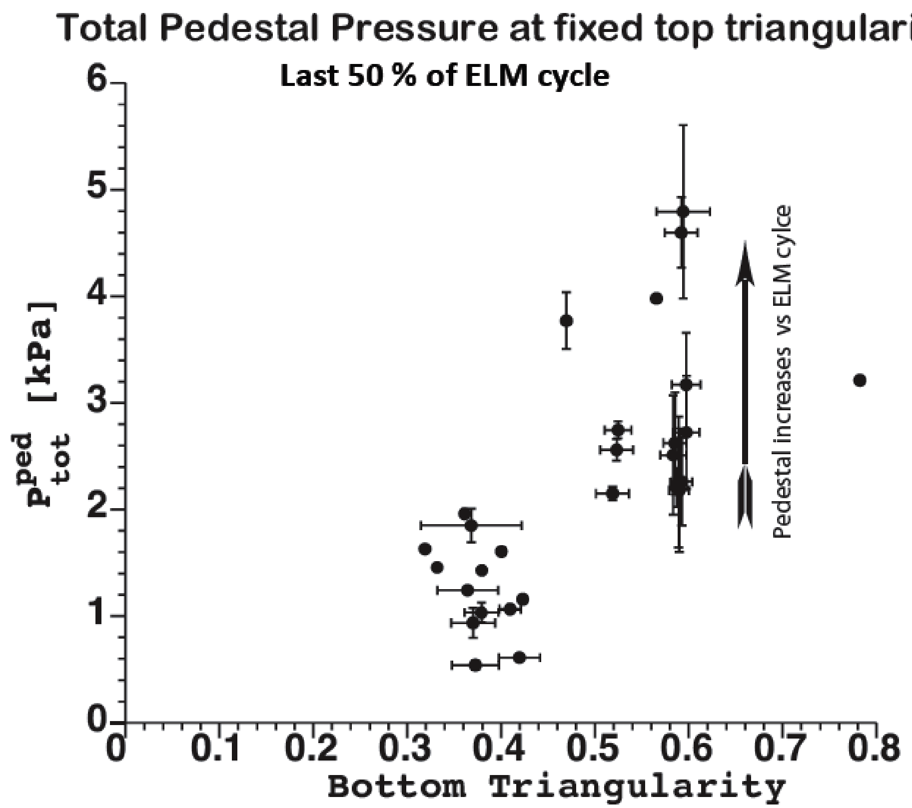
- **Plans 2011**: Milestone R(11-4)
  - Use IPEC to determine equilibrium variations due to 3D fields, variation of Chirikov criterion with plasma response, validate rotation damping / correlate to particle transport
  - Explore higher-n ideal stability calculations with improved 2D tools; utilize new tools (M3D-C^1) for stability, determine key physics differences of stable/unstable plasmas

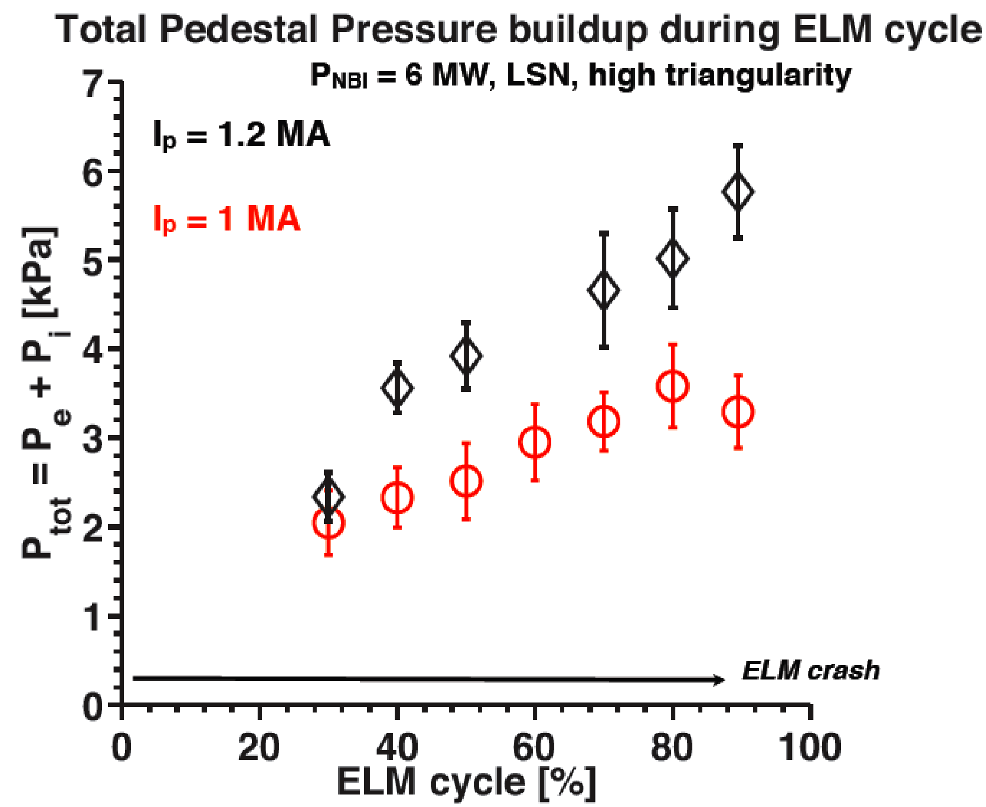


- ELM stabilization: 3D field + positive current ramp
  - Did not stabilize with negative current ramp
  - Plasma without 3D fields did not stabilize with I_p ramps
    - Modification to equilibrium, change in q profile, resonance effect ?

ITPA PEP-25

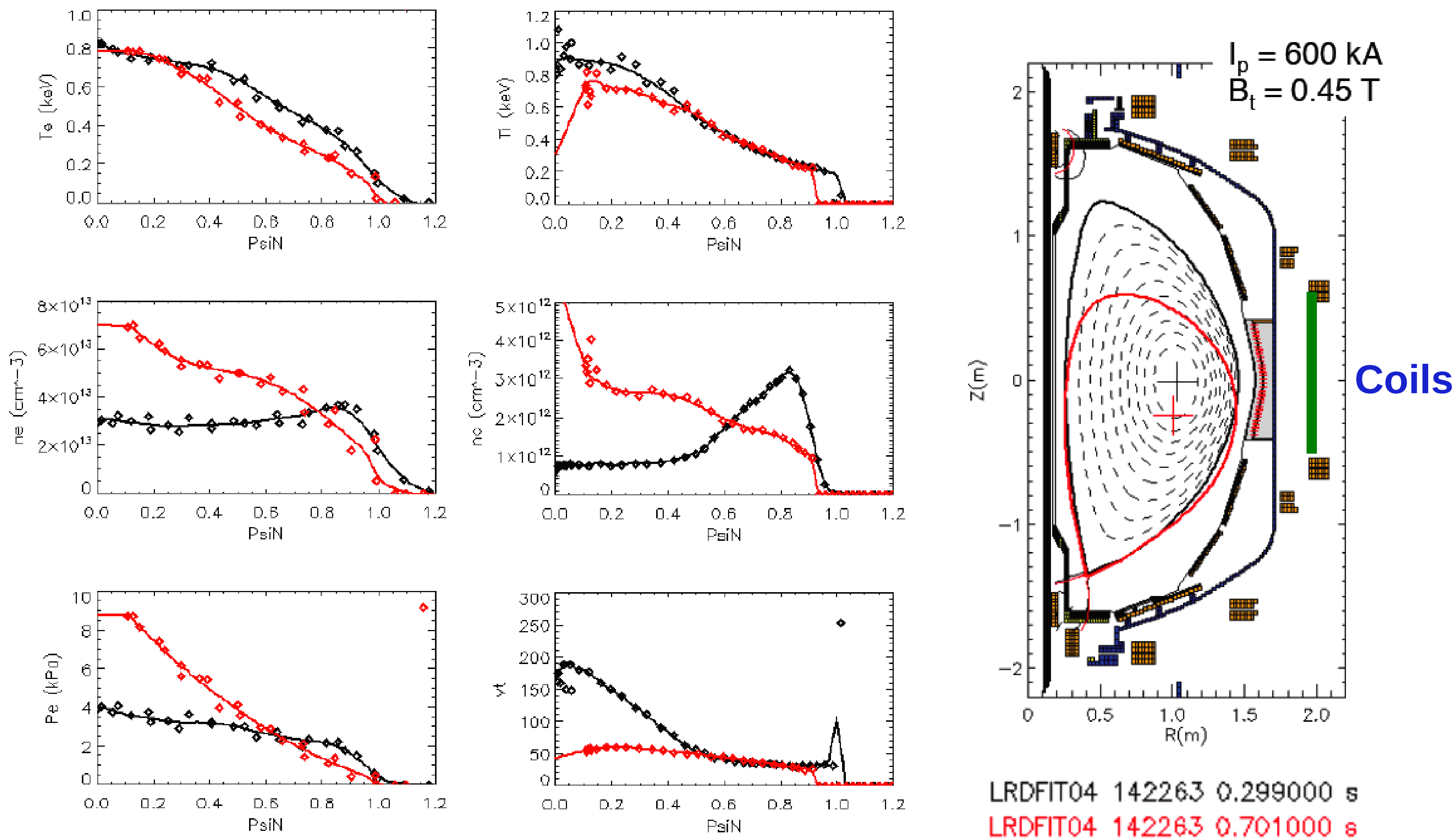
Pedestal structure and underlying MHD/transport mechanisms will be elucidated by FY 2011 JRT effort





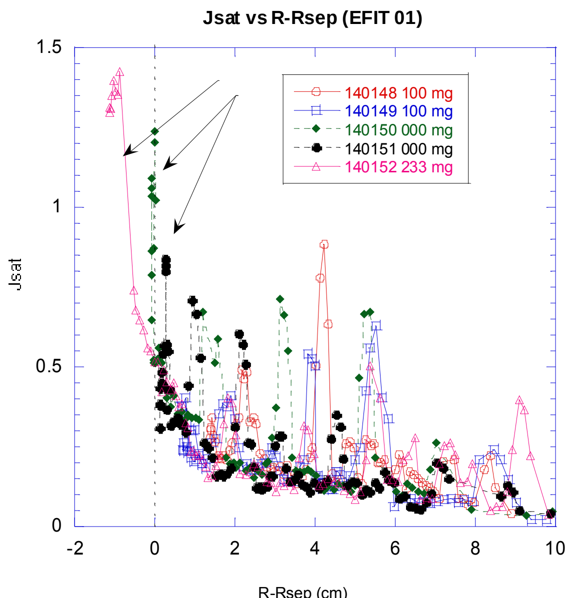
- Continuing progress in pedestal studies
  - FY 2010 – FY 2011 experiments
    - $P_{ped} \propto I_p^2$ and increases with triangularity
    - Builds up during ELM cycle, saturates at lower I_p late in ELM cycle, no clear saturation at high I_p

NSTX developed stable plasma with Δz < -20 cm to study response to 3D fields from off-midplane coil



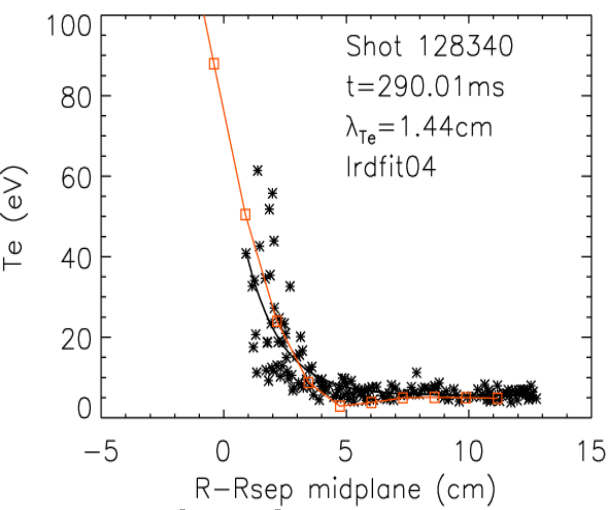
- Shifted shape expected to lead to reduced non-resonant fields compared to standard NSTX shape

Multiple diagnostic data contribute to understanding of SOL thermal transport and power width



Midplane particle flux as function of lithium quantity

- Available profile diagnostics
  - Divertor IR cameras
  - Divertor Langmuir probes
  - Midplane fast reciprocating probe
  - Midplane MPTS with additional SOL channels
  - Midplane SOL reflectometry (n_e only)



Comparison between MPTS and fast probe T_e profiles

- Future diagnostics under consideration
  - Additional divertor Langmuir probes
  - Divertor Thomson scattering system

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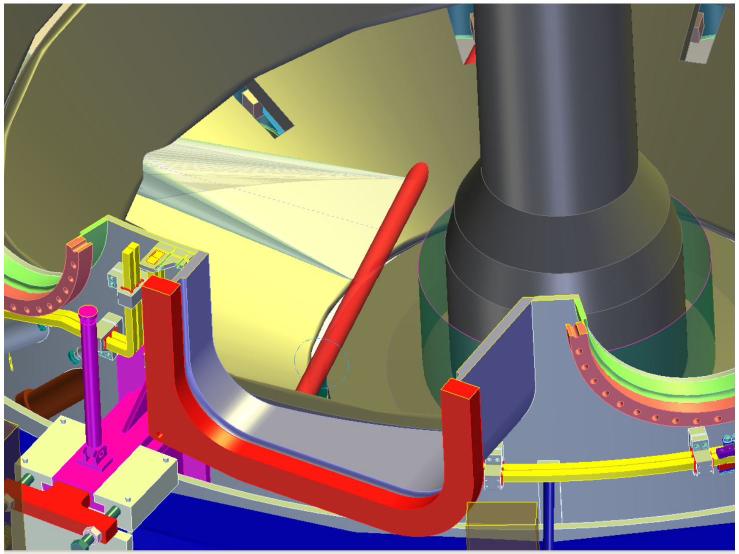
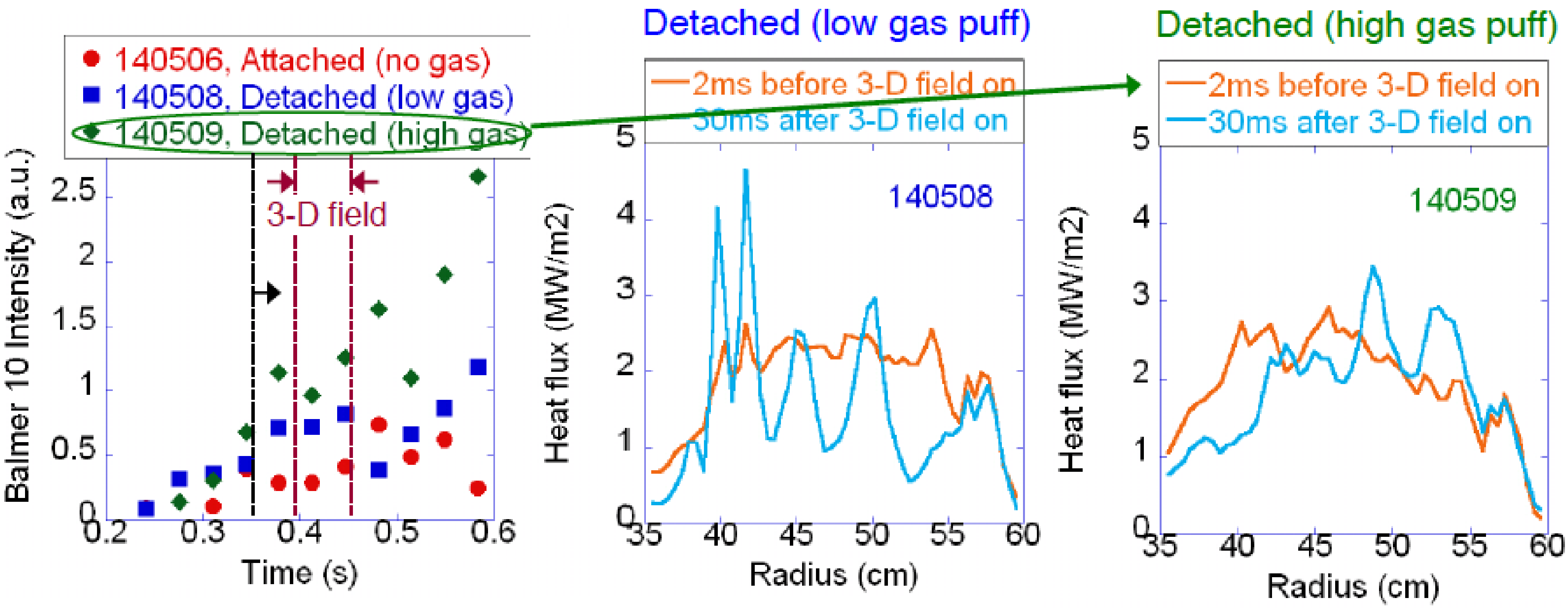
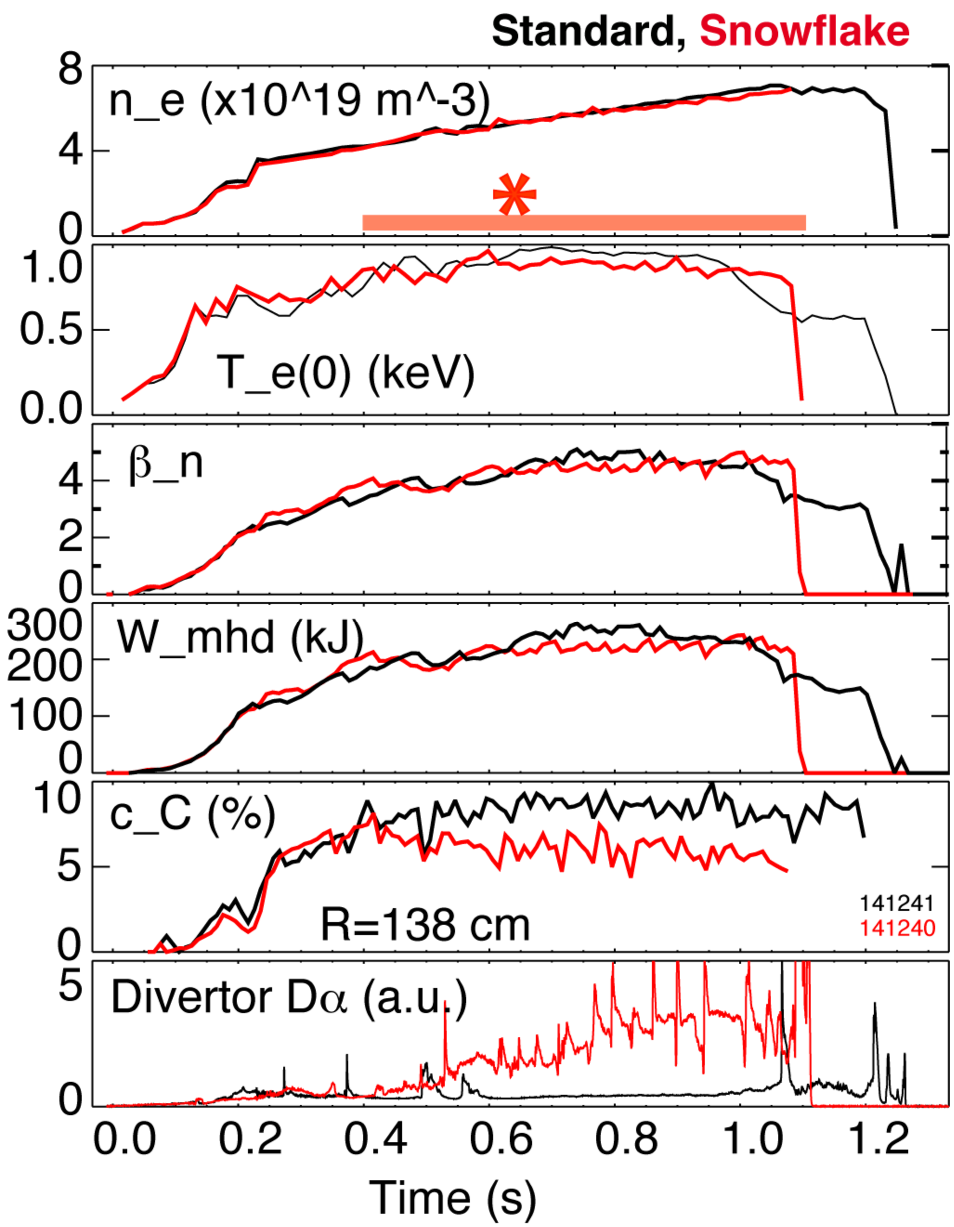


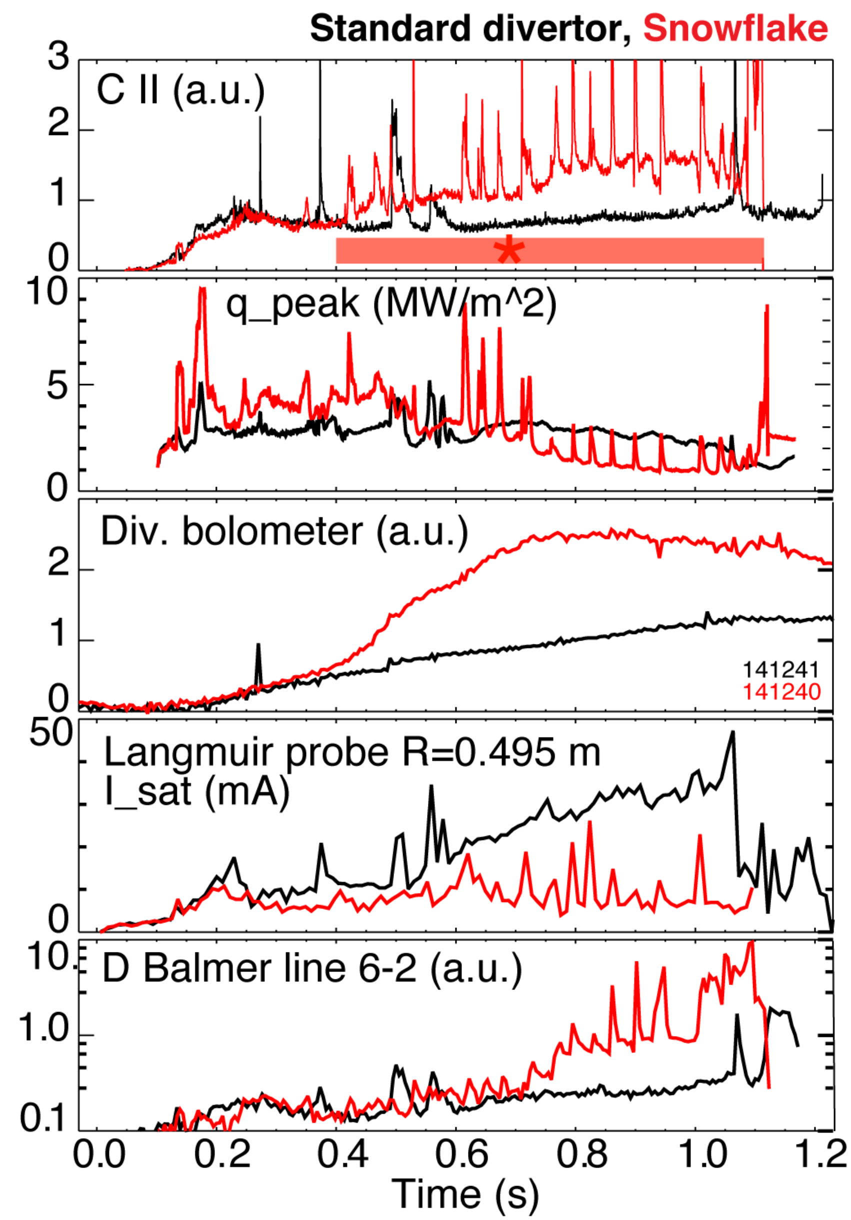
Applied 3-D fields can reattach detached plasma but it can be avoided by high gas puffing



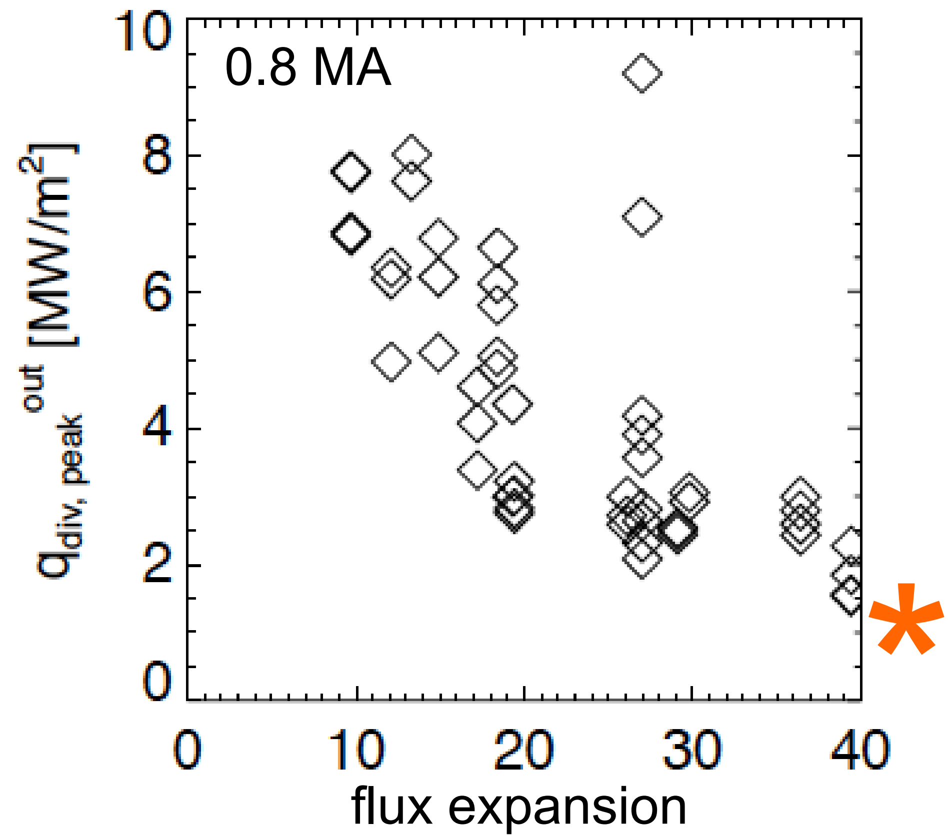
- Applied 3-D fields make the detached divertor plasma re-attach in medium divertor gas level, leading to a peaked heat flux profile again
- If the divertor gas puffing is high enough, plasma stays in the detached regime even with 3-D field applied

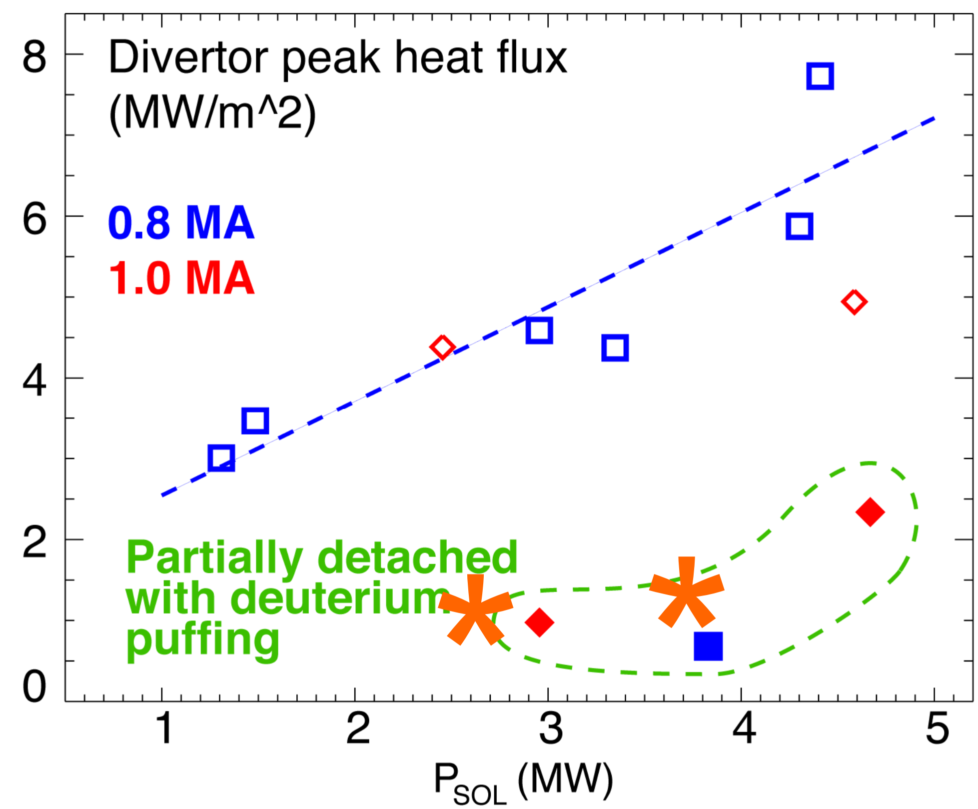
Good H-mode confinement with reduced impurities and outer strike point detachment using snowflake divertor





Snowflake divertor heat flux consistent with NSTX divertor heat flux scalings





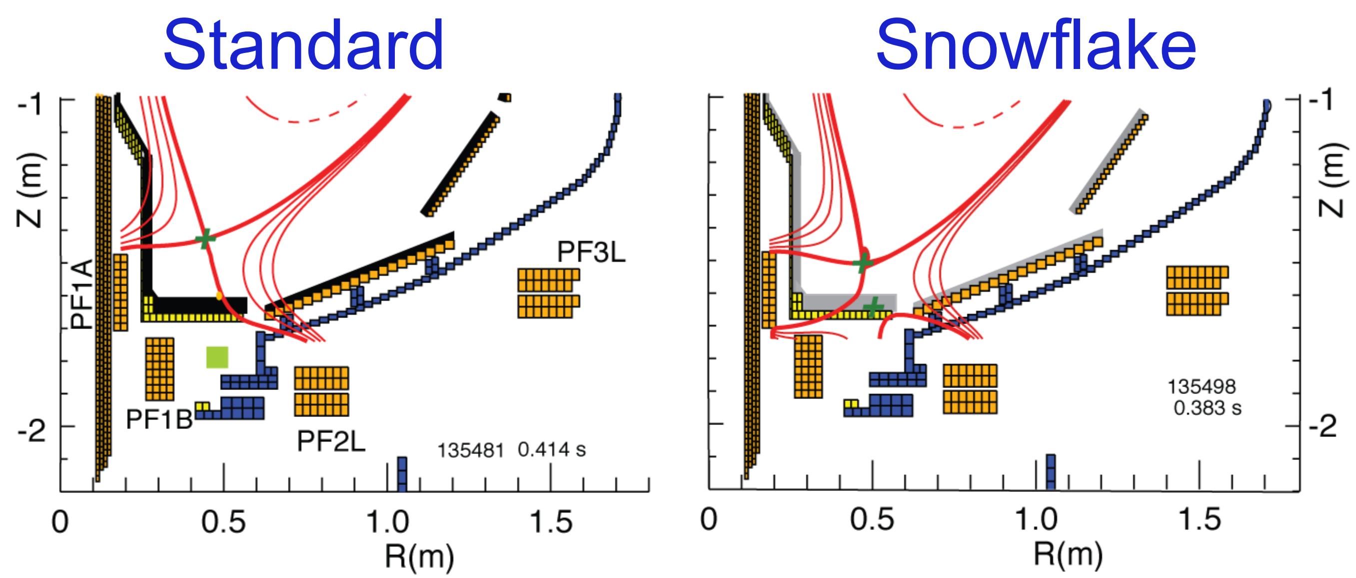
- Snowflake divertor (*): P_{SOL}~3-4 MW, f_{exp}~40-80, q_{peak}~0.5-1.5 MW/m^2

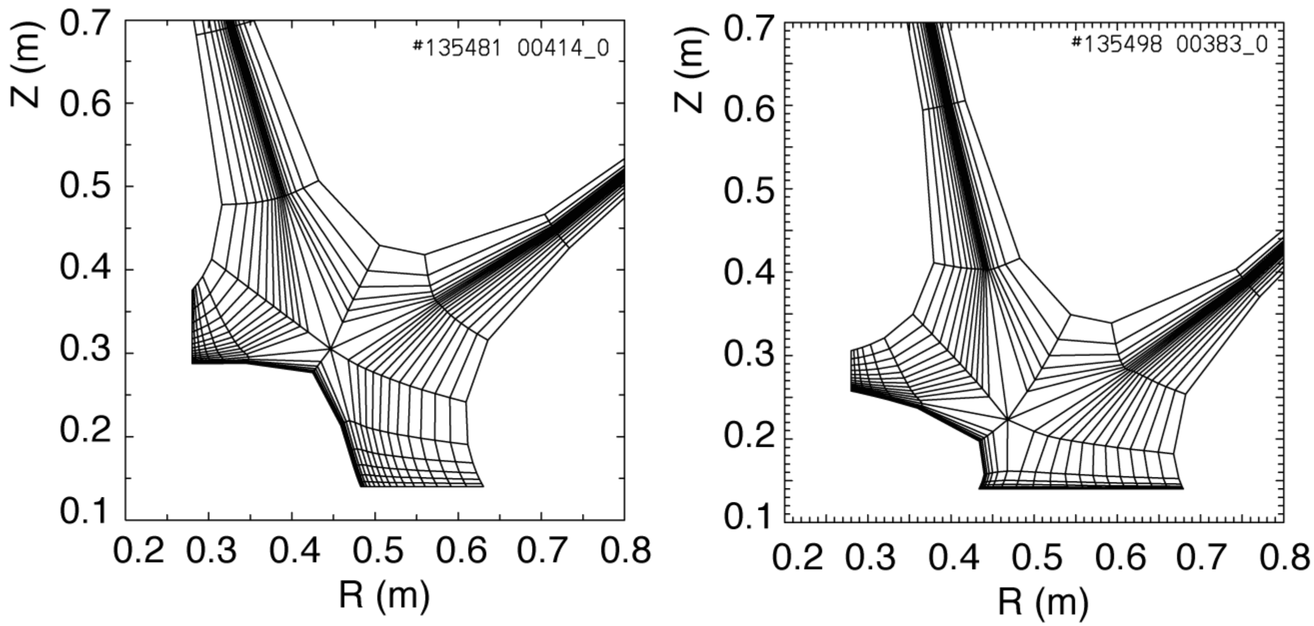
T. K. Gray et. al, EX/D P3-13, IAEA FEC 2010

V. A. Soukhanovskii et. al, PoP 16, 022501 (2009)

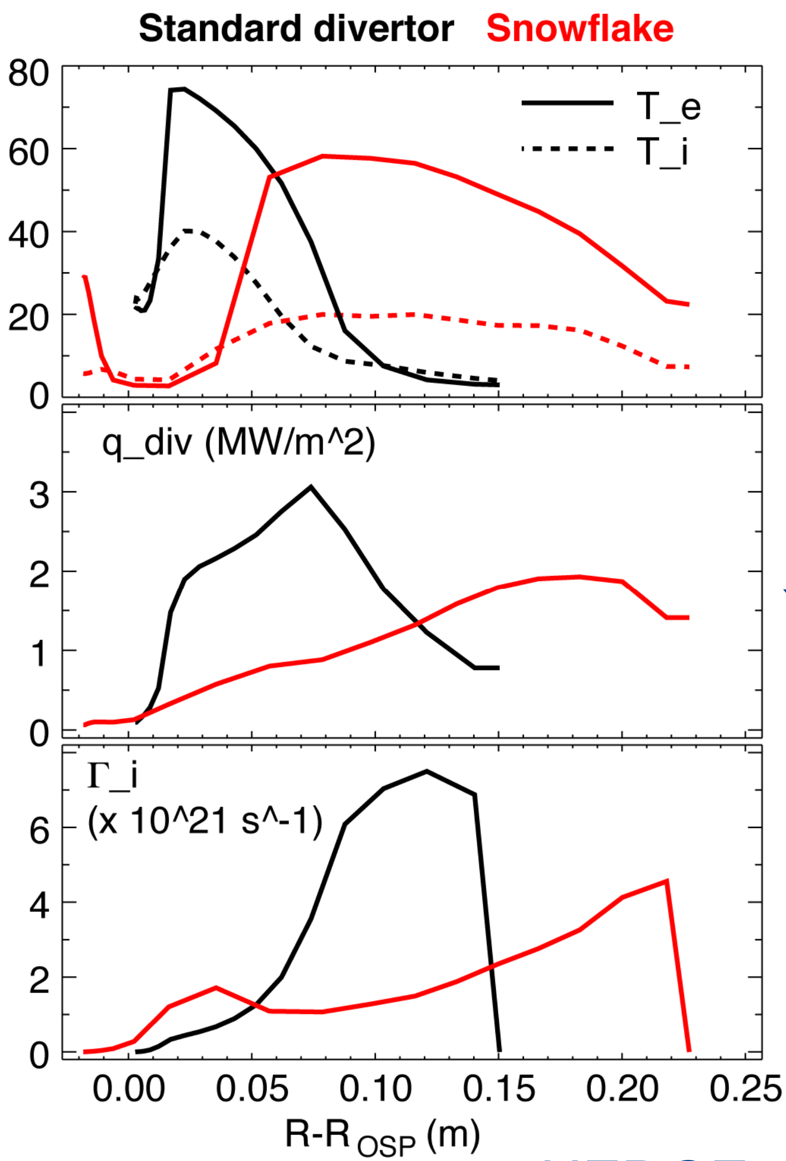
2D multi-fluid edge transport code UEDGE is used to study snowflake divertor properties

- Fluid (Braginskii) model for ions and electrons
- Fluid for neutrals
- Classical parallel transport, anomalous radial transport
- Core interface:
  - T_e = 120 eV
  - T_i = 120 eV
  - $n_e = 4.5 \times 10^{19}$
- $D = 0.25\ m^2/s$
- $\chi_{e,i} = 0.5\ m^2/s$
- $R_{recy} = 0.95$
- Carbon 3 %





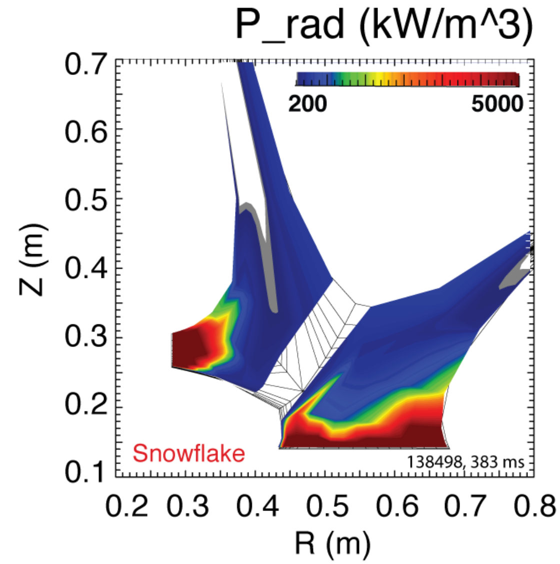
UEDGE model shows a trend toward detachment in snowflake divertor outer leg (cf. standard divertor)

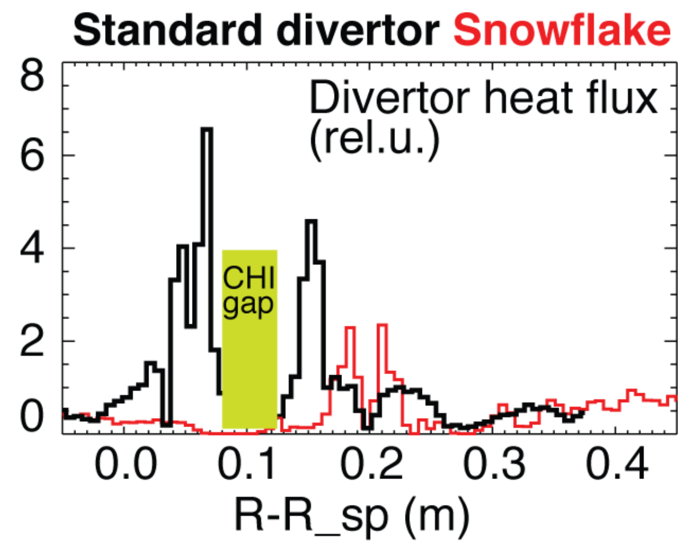


UEDGE model

In the snowflake divertor outer strike point region:

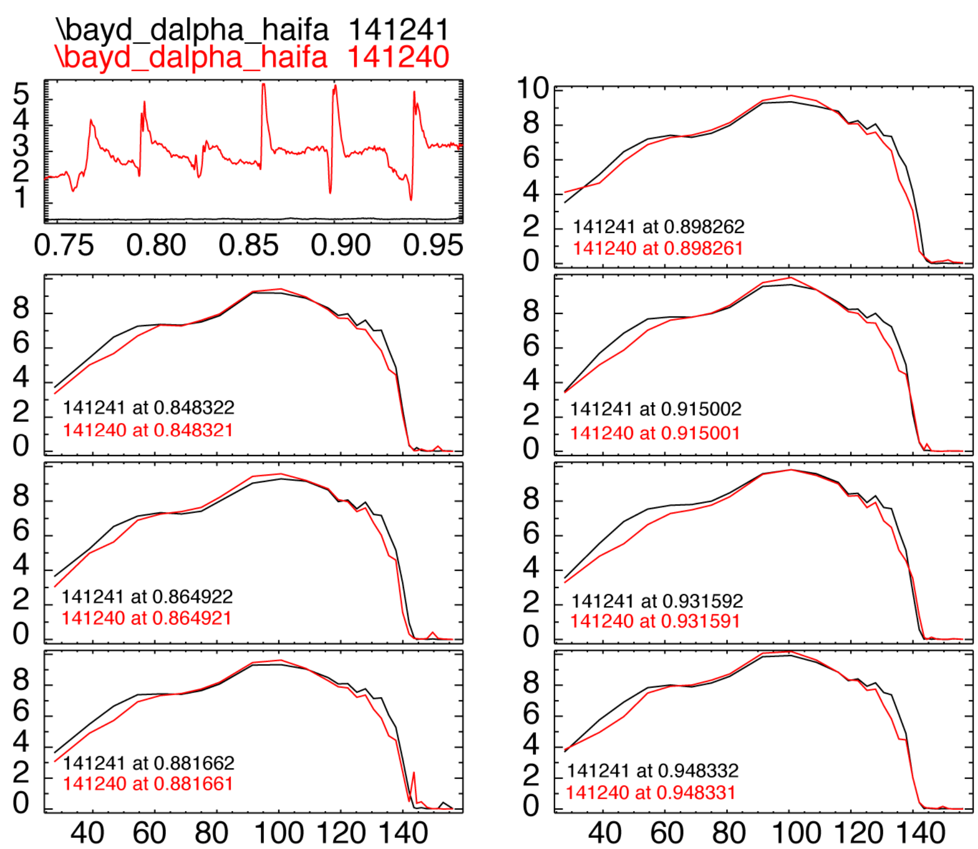
- T_e and T_i reduced
- Divertor peak heat flux reduced
- Particle flux low
- Radiation broadly distributed

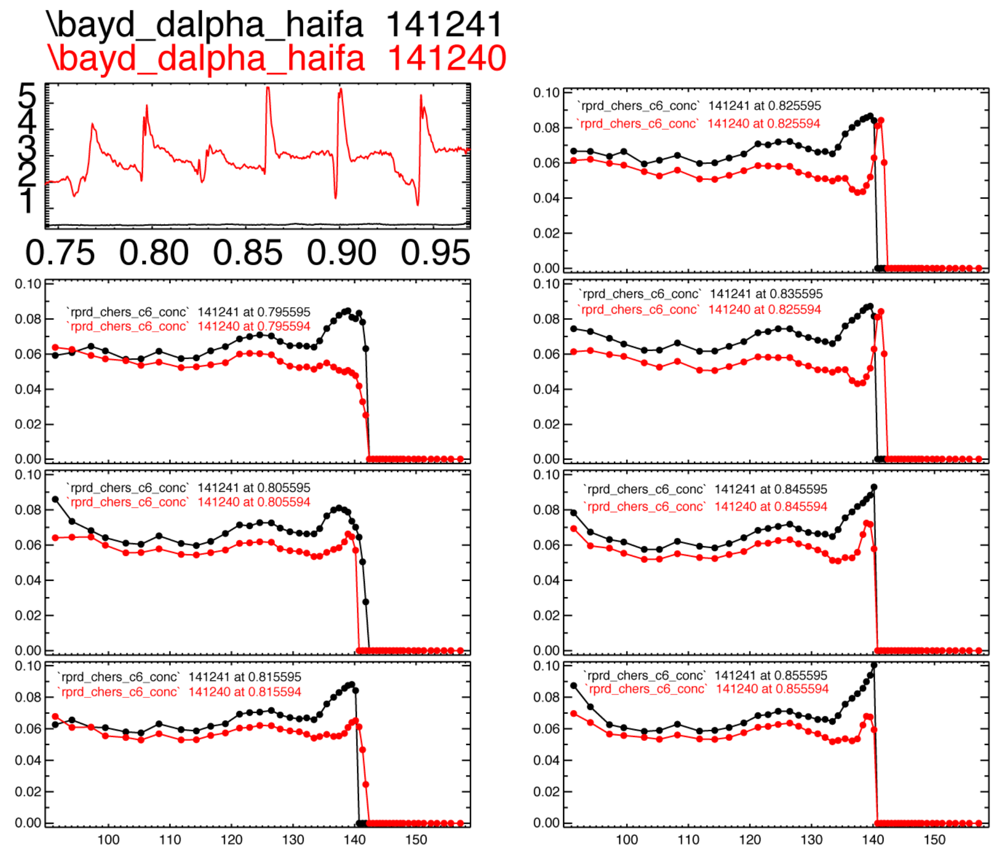




Experiment

Edge profiles during ELMy snowflake phase are different than those in ELM-free standard divertor discharge





- n_e reduced in top pedestal region (due to carbon reduction?)
- Carbon concentration reduced by 10-20 % in the pedestal region

Snowflake divertor alters divertor heat load deposition profile due to ELMs