NSTX-U

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

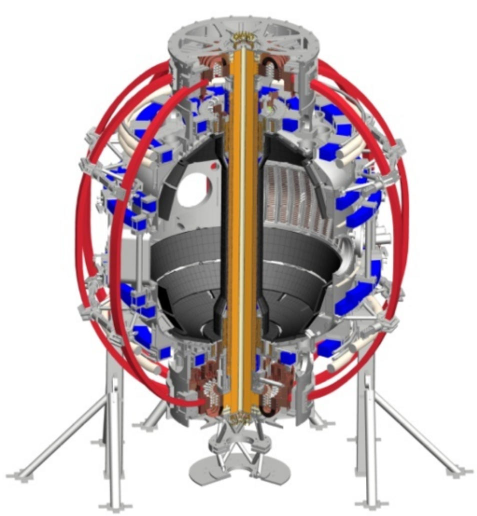
Plans for Scrape-off Layer and Divertor Research on NSTX-U

V. A. Soukhanovskii (LLNL)

for the NSTX-U Research Team

Coll of Wm & Mary
Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Lehigh U
Nova Photonics
Old Dominion
ORNL
PPPL
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Tennessee
U Tulsa
U Washington
U Wisconsin
X Science LLC

NSTX-U PAC-35 Meeting
PPPL – B318
June 11-13, 2013



Culham Sci Ctr
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Inst for Nucl Res, Kiev
Ioffe Inst
TRINITI
Chonbuk Natl U
NFRI
KAIST
POSTECH
Seoul Natl U
ASIPP
CIEMAT
FOM Inst DIFFER
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

Outline

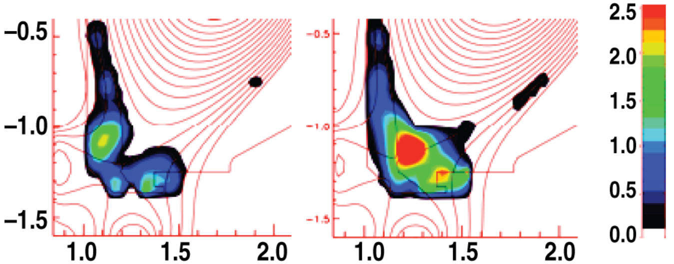
- Research Thrusts from Boundary TSG 5 Year Plan
  - BP-1: Assess and control pedestal structure, edge transport and stability
    - A. Diallo's talk, next
  - BP-2: Assess and control divertor heat and particle fluxes
    - Divertor heat flux mitigation with impurity seeding and divertor geometry
    - SOL transport and turbulence, impurity transport
  - BP-3: Establish and compare long-pulse particle control methods
    - Validate cryo-pump physics design, assess density control and recycling
    - Compare cryo to lithium coatings for particle (collisionality) control
- Research highlights – collaborations, NSTX
- Research plans for FY2015-2016
- Summary

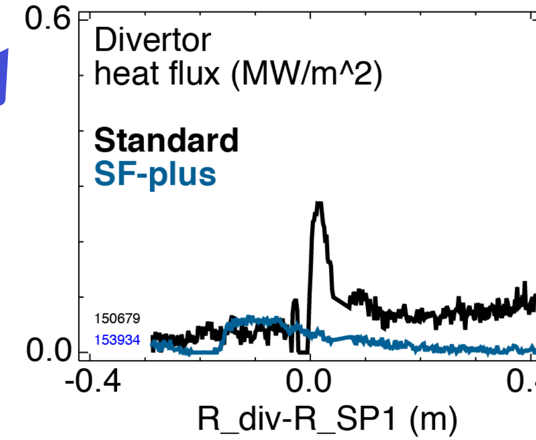
Boundary Physics TSG is involved in several research milestones

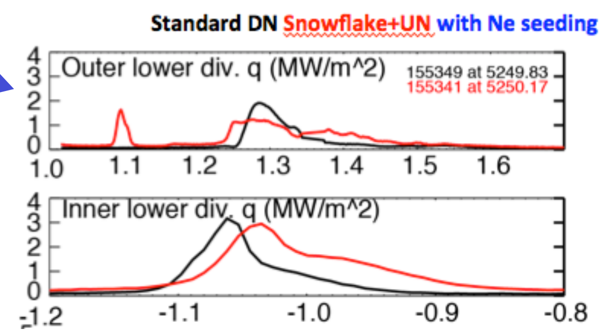
- **FY2014**
  - JRT on plasma response to 3D magnetic fields
  - R(14-1): Assess access to reduced density and collisionality in high-performance scenarios
  - R(14-3): Develop advanced axisymmetric control in sustained high performance plasmas
- **FY2015**
  - R(15-1): Assess H-mode energy confinement, pedestal, and scrape off layer characteristics with higher B_T, I_P and NBI heating power
  - R(15-3): Develop the physics and operational tools for obtaining high-performance discharges
  - IR(15-1): Develop and assess the snowflake divertor configuration and edge properties
- **FY2016**
  - R(16-1): Assess scaling and mitigation of steady-state and transient heat-fluxes with advanced divertor operation at high power density
  - R(16-2): Assess high-Z divertor PFC performance and impact on operating scenarios

Studying critical radiative and snowflake divertor physics in DIII-D National Campaign in preparation for NSTX-U

- Impact of 3D fields (n=3) on detachment
  - In NSTX, re-attachment of outer strike point
  - In DIII-D, no effect on divertor heat flux profiles
- Inter-ELM and ELM heat transport in radiative snowflake divertor
  - Magnetic feedback control development
    - Enabled exact and snowflake-plus configurations
  - Radiation distributed more uniformly in radiative SF
  - ELM energy and peak heat flux reduced in radiative snowflake divertor (cf. NSTX)
  - Combined with AT scenario (H98(y,2)~1.4, β_N~3)
    - P_{in}=11 MW exhausted into upper and lower divertors
    - Neon-seeded snowflake effective
  - Used DTS to measure high β_p in the null region
- Radiative divertor control
  - Closed loop D_2 seeding with constant core density
  - DTS T_e, P_{rad} as control signals

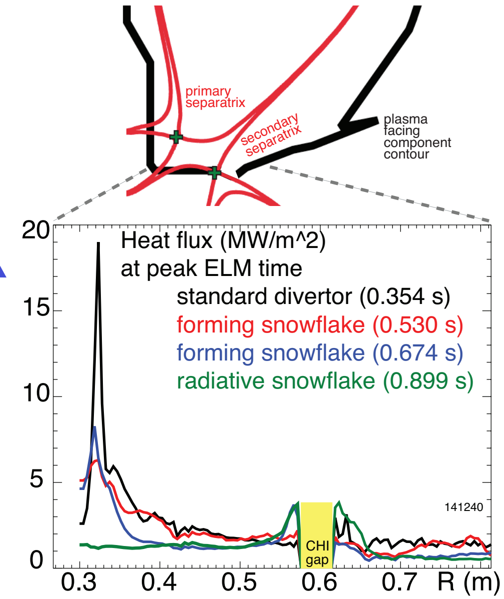


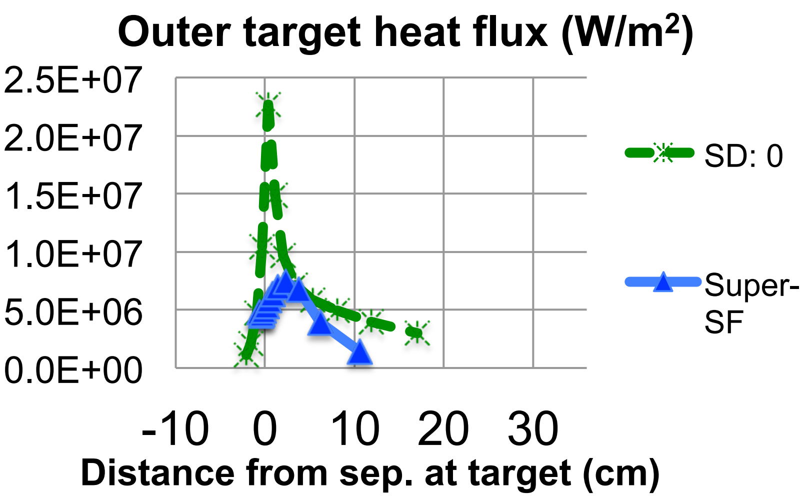


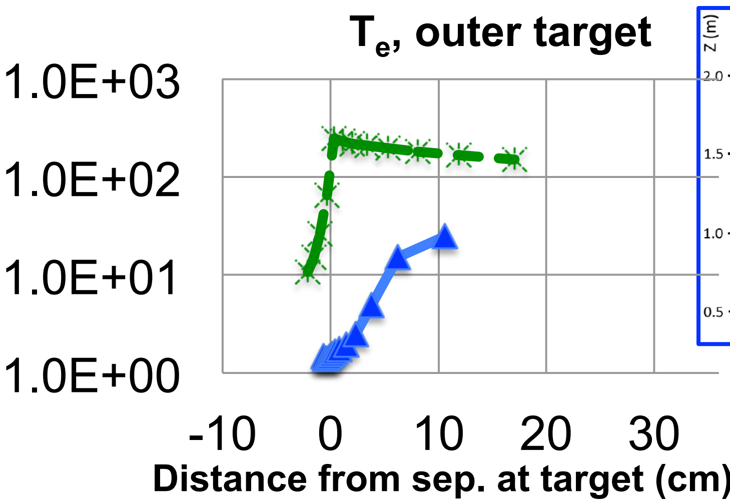


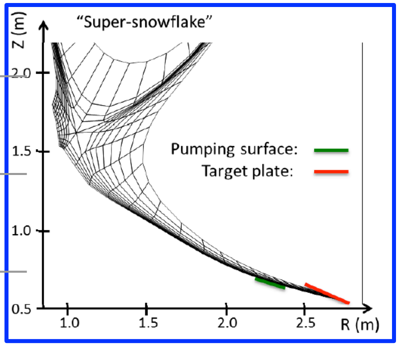
Modeling of radiative snowflake being performed in preparation for NSTX-U operation and for design of ST-FNSF

- ELM heat deposition from fast thermography
  - A_{wet} decreases during Type-I and III ELMs
  - A_{wet} decrease leads to q_{peak} increase with increase of ELM energy loss – mitigation needed (e.g., with rad. snowflake)
- UEDGE modeling of ST-FNSF divertor
  - Nitrogen-seeded tilted-plate and long-legged snowflake divertor provided x4 reduction in heat flux from ≤ 25 MW/m^2
    - NSTX-like transport $\chi_{i,e}$= 2-4 m^2/s
    - P_{SOL}=30 MW, 4% nitrogen, R=1 (saturated metal plate)
    - Both compatible with particle control via cryopumping



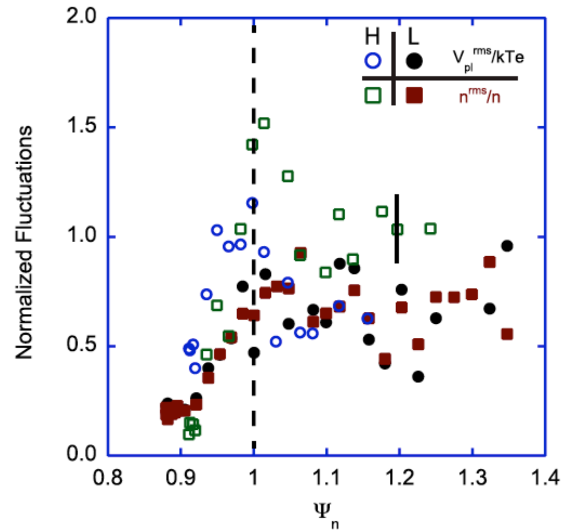


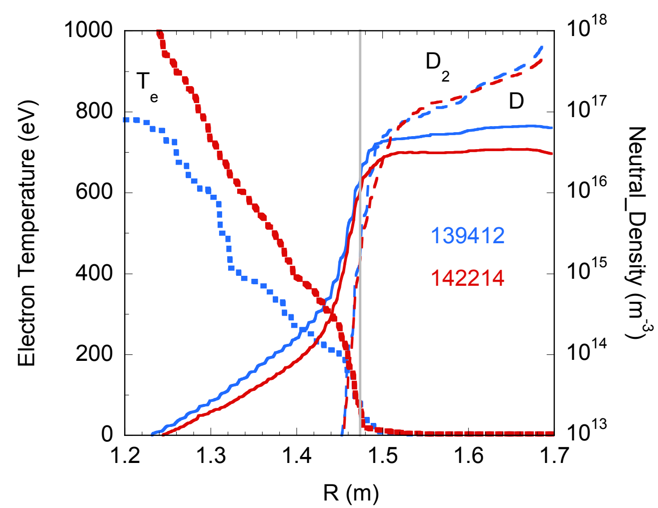




Analysis of NSTX edge data supports planning of SOL research and diagnostics for NSTX-U

- Normalized potential and density fluctuation levels high in L- and H-mode SOL (reciprocating probe)
  - 10 % inside SOL and up to 150 % in outer SOL
  - Strong SOL intermittency
- Comparison of GPI and BES measurements of edge fluctuations commenced
  - Measured poloidal corr. lengths and decorrelation time show reasonable agreement, fluctuation statistics differ
  - Dominant fluctuation band of 4-30 kHz
    - exhibits short-lived, intermittent time-frequency behavior
- Edge neutral density from DEGAS 2 based inversion of edge D_β camera light
  - Useful for TRANSP, edge passive CHERS
  - Assume uniform D_2 flux at wall, MPTS profiles





Near-future (FY2015) SOL and divertor studies will focus on heat flux mitigation and model validation

- Establish SOL width and divertor database vs. engineering and physics parameters
  - IRTV, bolometers, Langmuir probes, filtered cameras, spectrometers
- Re-establish edge turbulence measurements
  - GPI, BES, fast cameras, probes
- Initial radiative divertor experiments with seeding and lithium
  - Re-establish operating space of radiative divertor with D_2, CD_4, Ne seeding
- Develop snowflake divertor magnetic control and initiate experiments
  - Assess pedestal stability, divertor power balance, turbulence, impact of 3D fields as functions of engineering parameters
- Validate cryopump physics design
  - Verify divertor neutral pressure, T_e, n_e as functions of engineering parameters and compare with SOLPS model
- Comparison with multi-fluid and gyro-kinetic models
  - UEDGE and SOLPS models awaiting benchmarking with NSTX-U edge data
  - XGC SOL width modeling, application to snowflake geometry
- Finalize conceptual design of divertor Thomson scattering diagnostic
  - Present design based on the polychromator-based upgraded DIII-D DTS

Research in FY2016 to focus on divertor heat flux scaling and mitigation using radiative divertor and geometry

- R(16-1): Assess scaling and mitigation of steady-state and transient heat-fluxes with advanced divertor operation at high power density
  - SOL cross-field transport scalings at twice the I_P, B_t, and heating power
  - Divertor inter-ELM and ELM heat flux mitigation, impurity production, impact on pedestal using various techniques
    - magnetic balance (i.e. double-null operation)
    - radiative divertor operation, feedback control testing
    - snowflake divertors with feedback control
    - ELM pacing with 3D fields and granules
  - Compare with gyro-kinetic and fluid transport and turbulence codes UEDGE, SOLPS, SOLT, XGC
  - Aid in the validation of divertor power and particle exhaust models for ITER and FNSF

Research in FY2016 also to focus on PFC performance and edge impurity transport

- R(16-2): Assess high-Z divertor PFC performance and impact on operating scenarios
  - Erosion and SOL transport of low-Z coatings and high-Z PFCs
    - Initiate modeling with multi-fluid codes (UEDGE, SOLPS) and erosion codes (e.g., ERO)
    - Use laser-blow-off system to study edge transport of low-Z and high-Z impurities and benchmark fluid turbulence codes
  - Core and pedestal evolution
    - Connect edge source (divertor sources and SOL transport) with pedestal and core transport models (TRANSP, MIST/STRAHL, UEDGE)
    - Assess penetration factors of high-Z impurities
  - Compatibility with heat-flux mitigation schemes
    - Assess impact of CD_4, N_2, Ne seeding on high-Z target erosion and edge transport

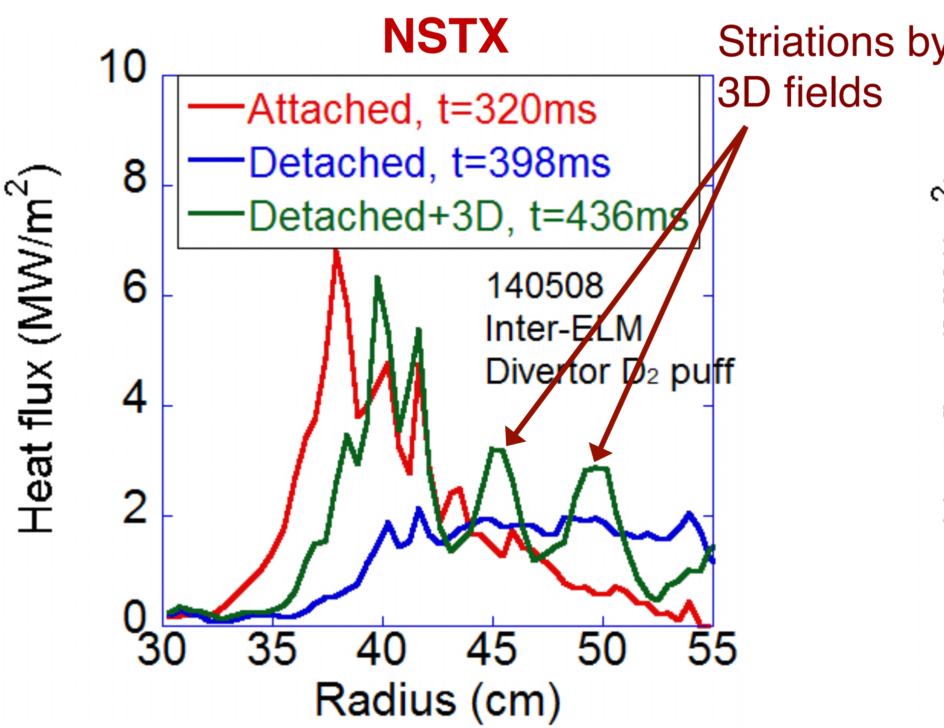
Summary: Research in FY2015-2016 focuses on power and particle mitigation studies with new NSTX-U capabilities

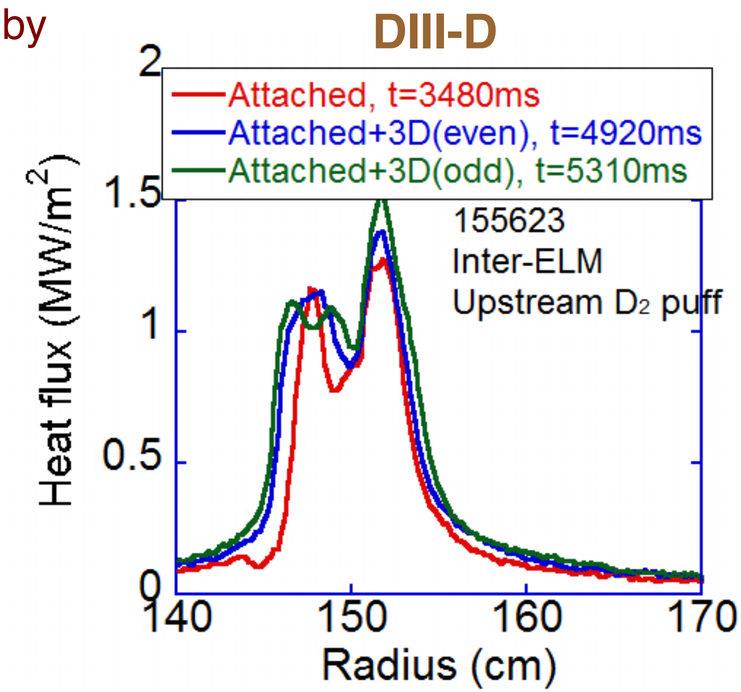
- Power and particle handling: obtain standard divertor baseline, further develop snowflake and radiative divertors
  - Assess heat flux and SOL width scalings
  - Test key predictions of snowflake configuration, and evaluate synergy with radiative divertors, graphite and high-Z plasma facing components
  - Prepare for particle control studies with cryopumping

- Planned research aims at providing SOL and divertor physics basis for ST-FNSF

Backup

Applied 3D fields yielded different effects on divertor detachment at NSTX and DIII-D

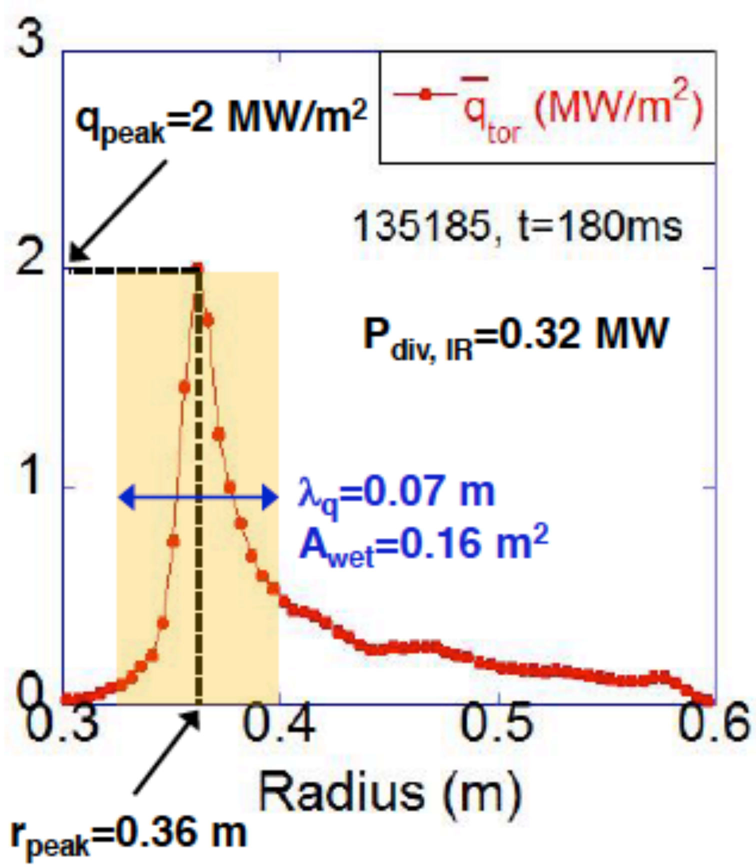




- NSTX showed re-attachment of detached plasma due to applied 3D fields
- 3D fields did not produce striations, leading to no effect on divertor plasma at DIII-D
  - Work in progress for the role of plasma response fields (amplitude and phase) in the generation of strike point splitting

Peak heat flux and heat flux width are determined by total power and wetted area

Average radial heat flux profile



- Total deposited power to divertor:

$$P_{div,IR} = \int 2\pi r \bar{q}_{tor}(r)dr$$

- Wetted area

$$A_{wet} = P_{div,IR} / \bar{q}_{peak,tor}$$

- Integral heat flux width

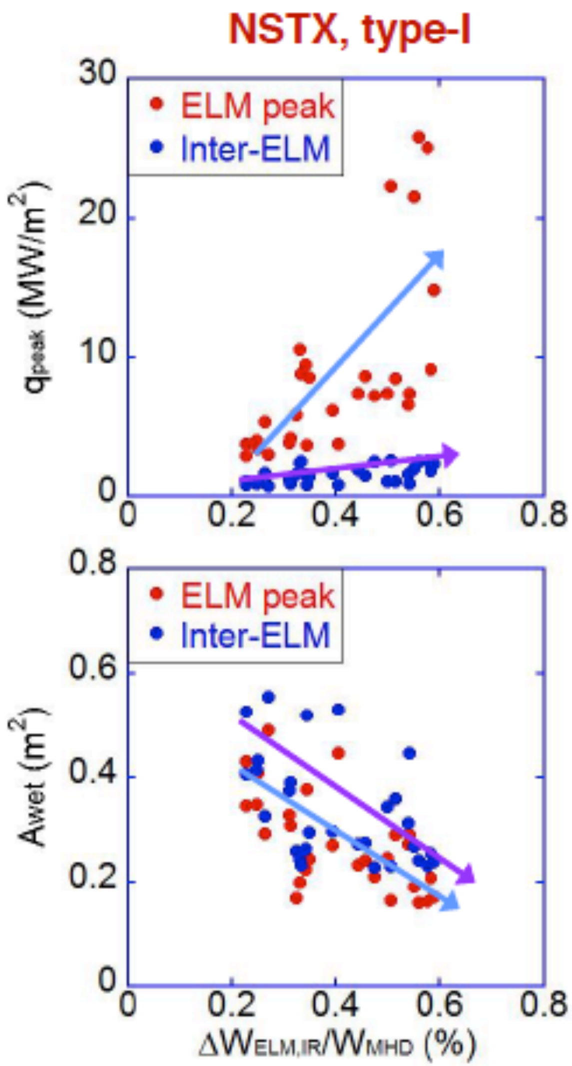
$$\bar{\lambda}^{int}_{q,tor} = P_{div,IR} / 2\pi r_{peak} \bar{q}_{peak,tor}$$
$$= A_{wet} / 2\pi r_{peak}$$

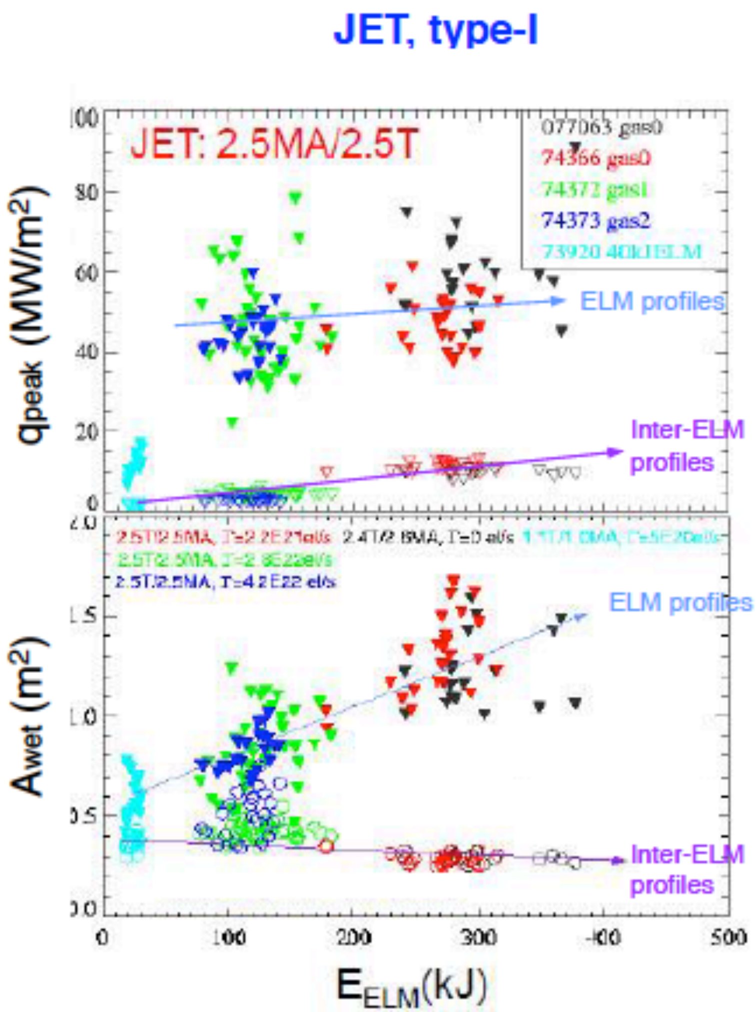
- Total deposited energy to divertor

$$W_{div,IR} = \int P_{div,IR} dt$$

Temporal evolution and dependence on the ELM size of $P_{div,IR}$ and A_{wet}

A_{wet} decrease leads to q_{peak} increase with increasing ELM energy loss for type-I ELMs in NSTX



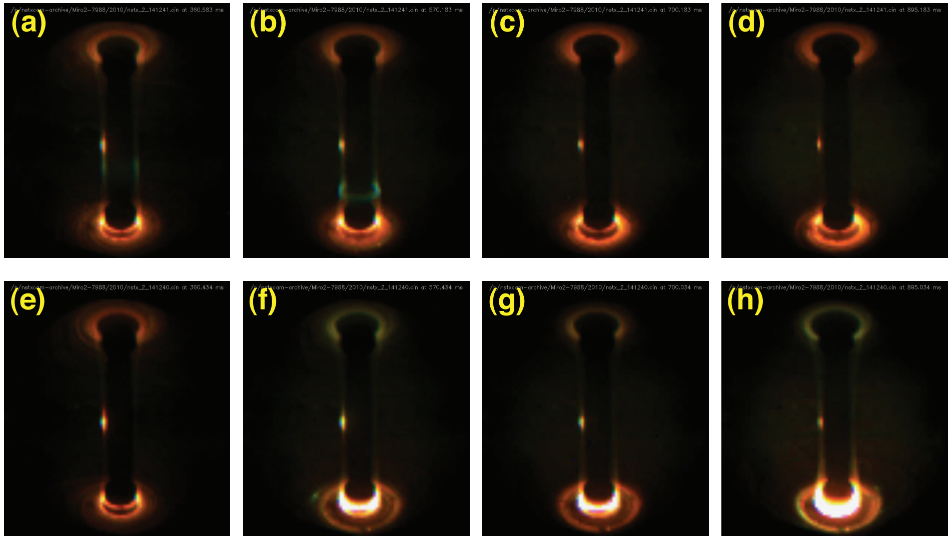


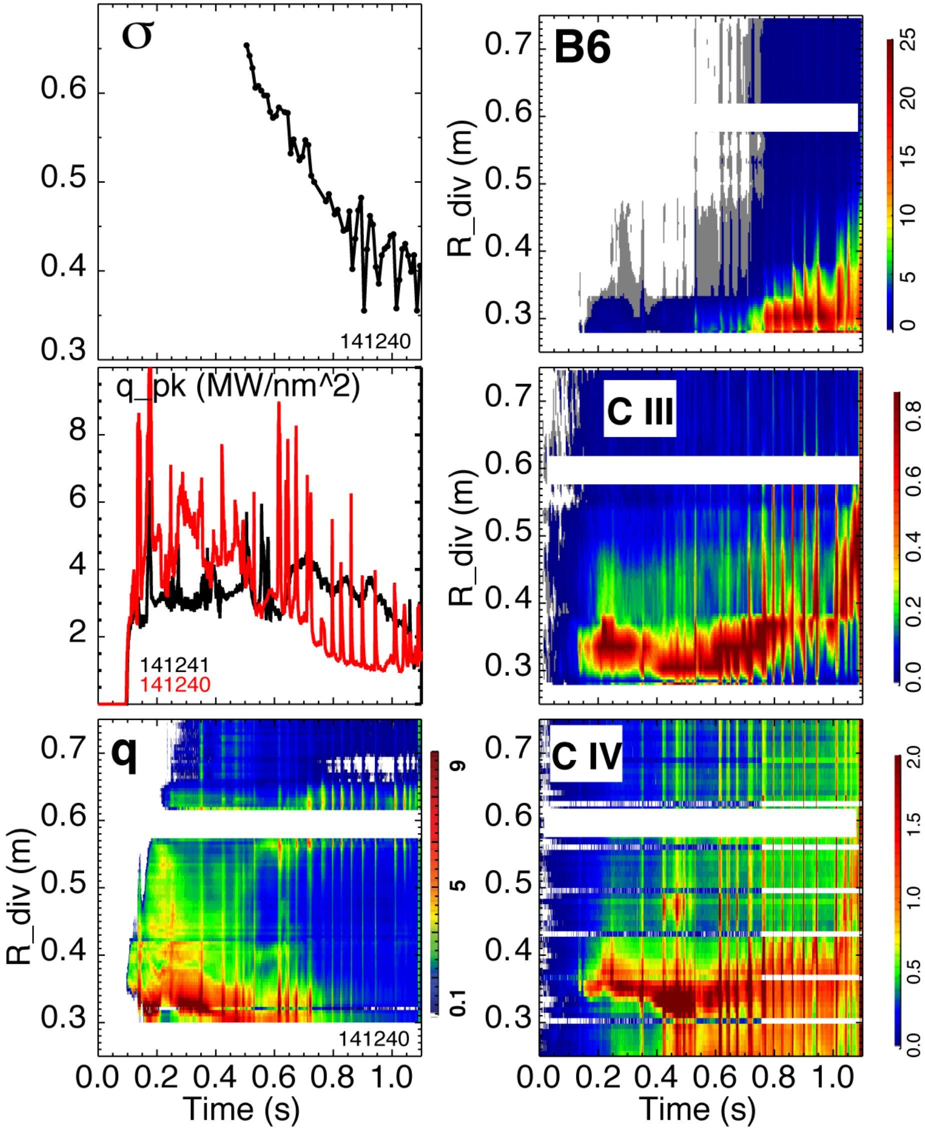
- NSTX: A_{wet} decreases with ELM energy loss → q_{peak} increases
- JET [1]: A_{wet} increases with ELM energy loss → q_{peak} constant
- Both machines show A_{wet} ↓ and q_{peak} ↑ for inter-ELM profiles

[1] T. Eich, PFMC 2013

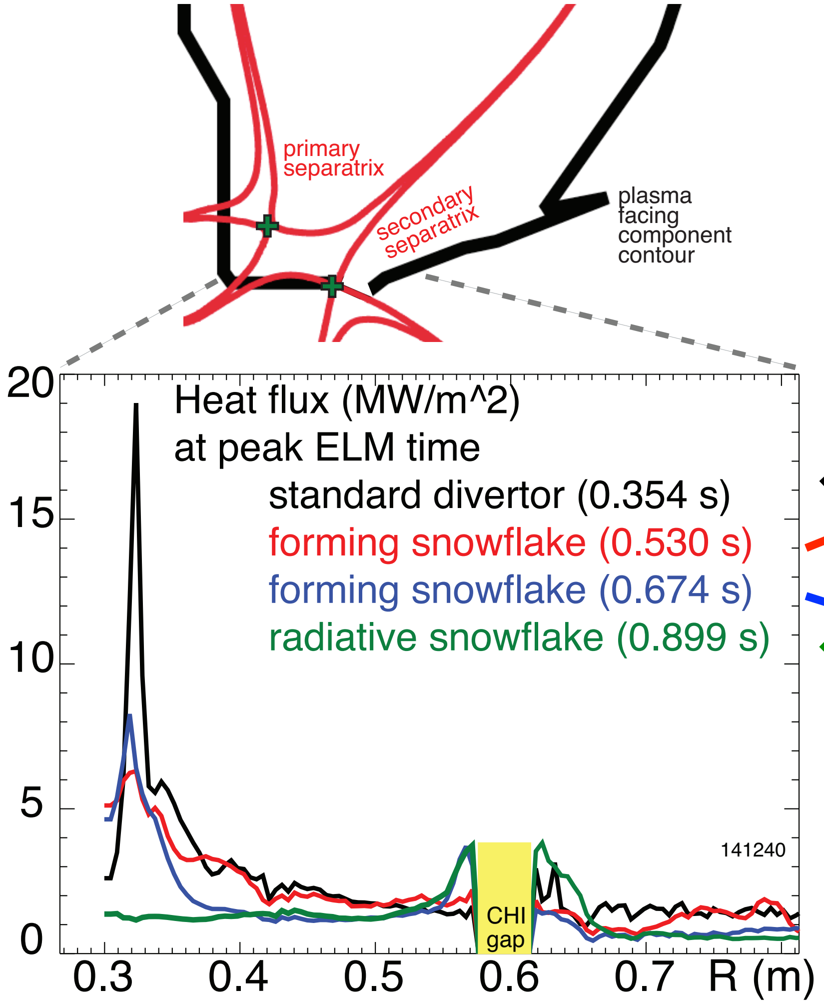
Radiative detachment with strong recombination and high radiated power observed in snowflake divertor

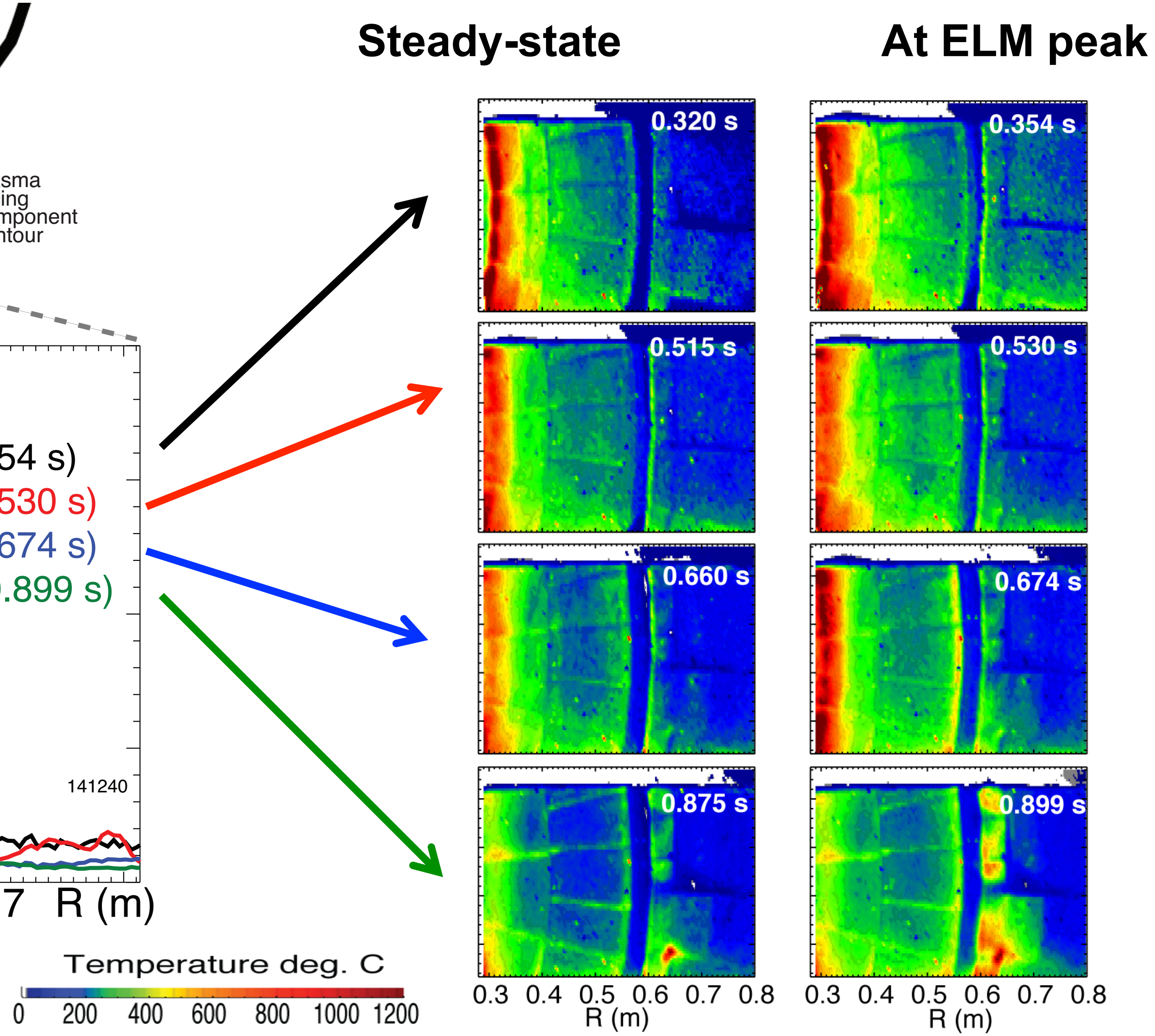
- Attached standard divertor - snowflake transition - snowflake + detachment
- P_{SOL} ~ 3 MW (P_{NBI} = 4 MW)
- Q_{div} ~ 2 MW -> Q_{div} ~ 1.2 MW -> Q_{div} ~ 0.5-0.7 MW





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



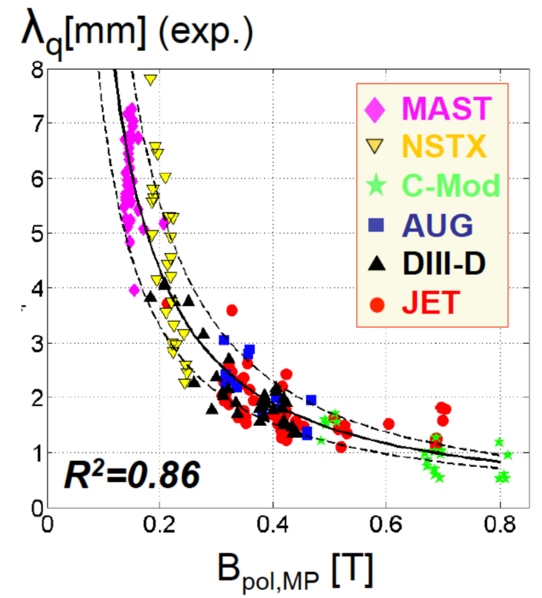


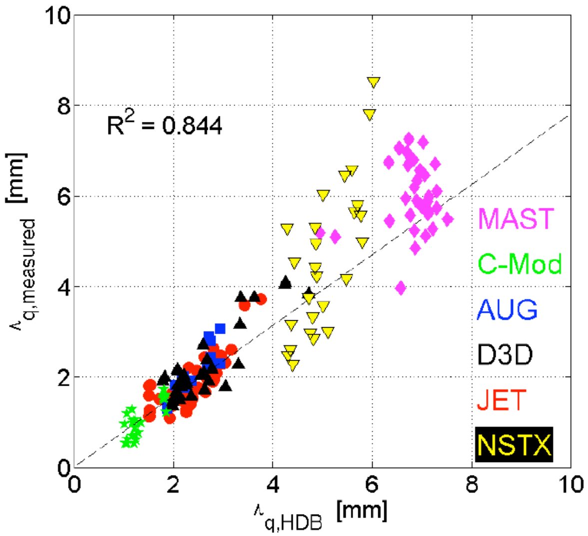
NSTX-U data will help reduce SOL width scaling uncertainties and assess relative importance of turbulent and drift-based transport

- SOL width scaling
  - In NSTX: $\lambda_q^{mid} \sim I_p^{-1.6}$, independent of P_{SOL} and B_t
    - For NSTX-U (2 MA): $\lambda_q^{mid} = 3\pm0.5$ mm
  - Multi-machine database (Eich IAEA FEC 2012): →

    λ_q^{mid} (mm) = $(0.63+/-0.08) \times B_{pol,MP}^{-1.19}$
    - For NSTX-U (B_p~0.55 T): $\lambda_q^{mid} \sim 1.3$ mm
- Comparison of λ_{SOL} with SOL models
  - Parallel transport: conductive/convective, cross-field : collisional / turbulent / drift
  - Goldston drift-based model
    - $\lambda_{SOL} \sim (2a/R)\ \rho_{\theta}$, for NSTX-U: $\lambda_q^{mid} \sim 6$ mm
  - Exploring mechanisms setting steep pressure gradient region and connection to SOL width
  - XGC0 (drift-kinetic): $\lambda_q^{mid} \sim I_p^{-1.0}$
  - XGC1 (collisionless, no neutrals): $\lambda_q^{mid} \sim I_p^{-0.8}$ (neoclas.)
  - SOLT (fluid turbulence): I_p scaling is weaker than observed

Diagnostics: MPTS, GPI – multiple views, BES, reflectometry, Langmuir probes





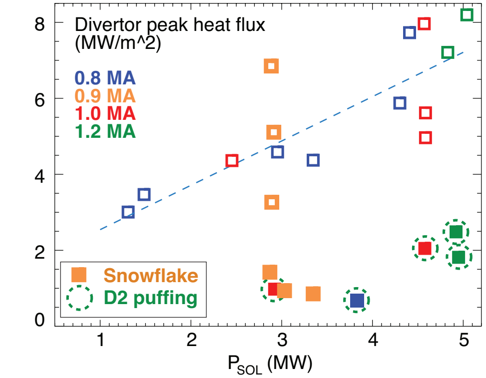
Snowflake and impurity-seeded radiative divertor with feedback control are planned for NSTX-U

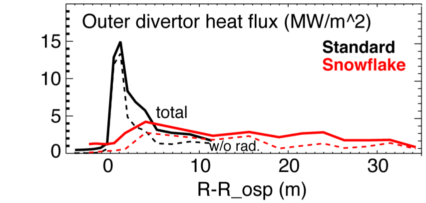
- Divertor peak heat flux scaling
  - $q_{peak} \sim P_{SOL}$ and $q_{peak} \sim I_p$
  - For NSTX-U q_{peak} ~ 20-30 MW/m^2

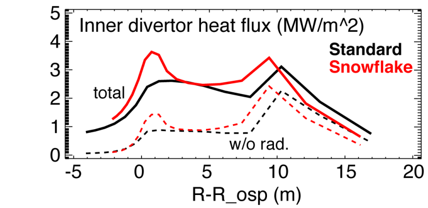
$$q_{pk} \simeq \frac{P_{heat}\,(1-f_{rad})f_{out/tot}f_{down/tot}(1-f_{pfr})\sin\alpha}{2\pi R_{SP} f_{exp} \lambda_{q_{||}}}$$

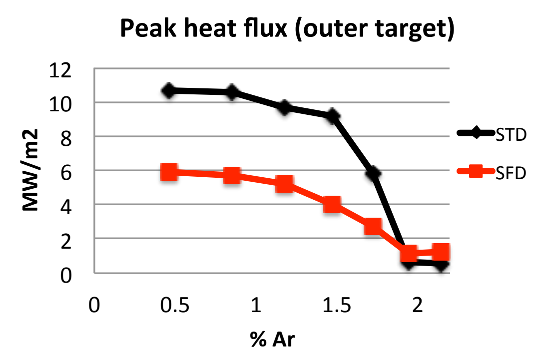
- Snowflake divertor development
  - Implementation of control algorithms
  - Initial assessment and model validation
- Radiative divertor development
  - In NSTX, heat flux reduction in radiative divertor compatible with H-mode confinement
  - Seeded impurity choice dictated by Z_{imp} and PFC
  - Li/C PFCs compatible with D_2, CD_4, Ne, Ar seeding
  - UEDGE simulations show Ar most effective
  - Feedback control of divertor radiation via impurity particle balance control

Diagnostics: IR thermography, MPTS, Spectroscopy, Langmuir probes



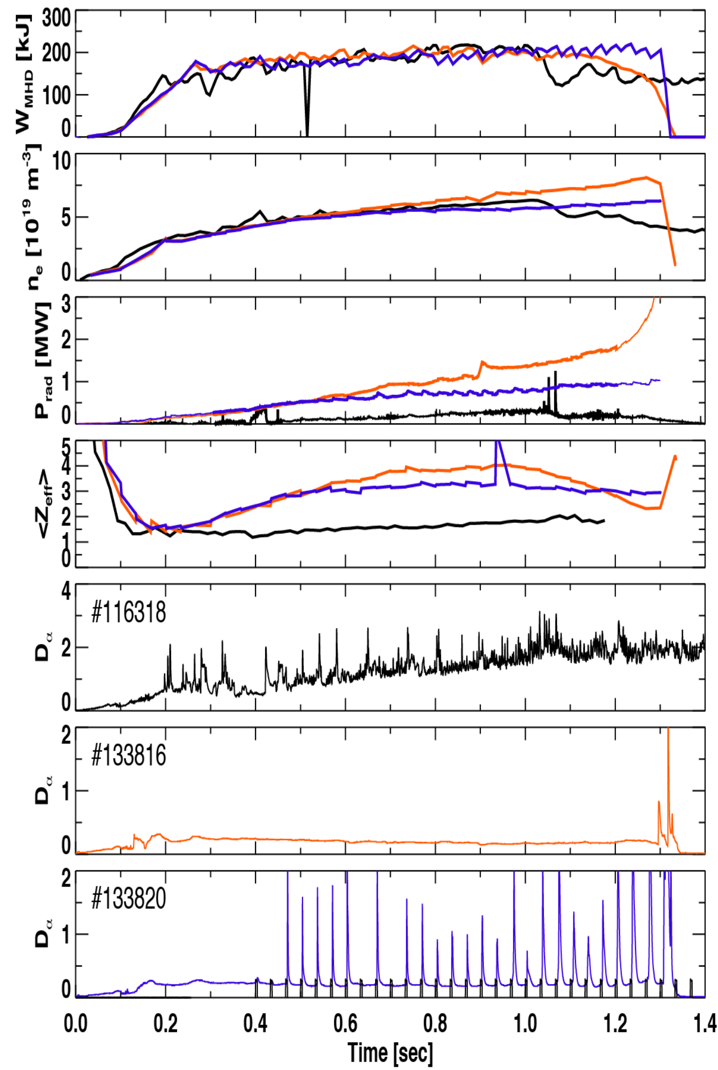




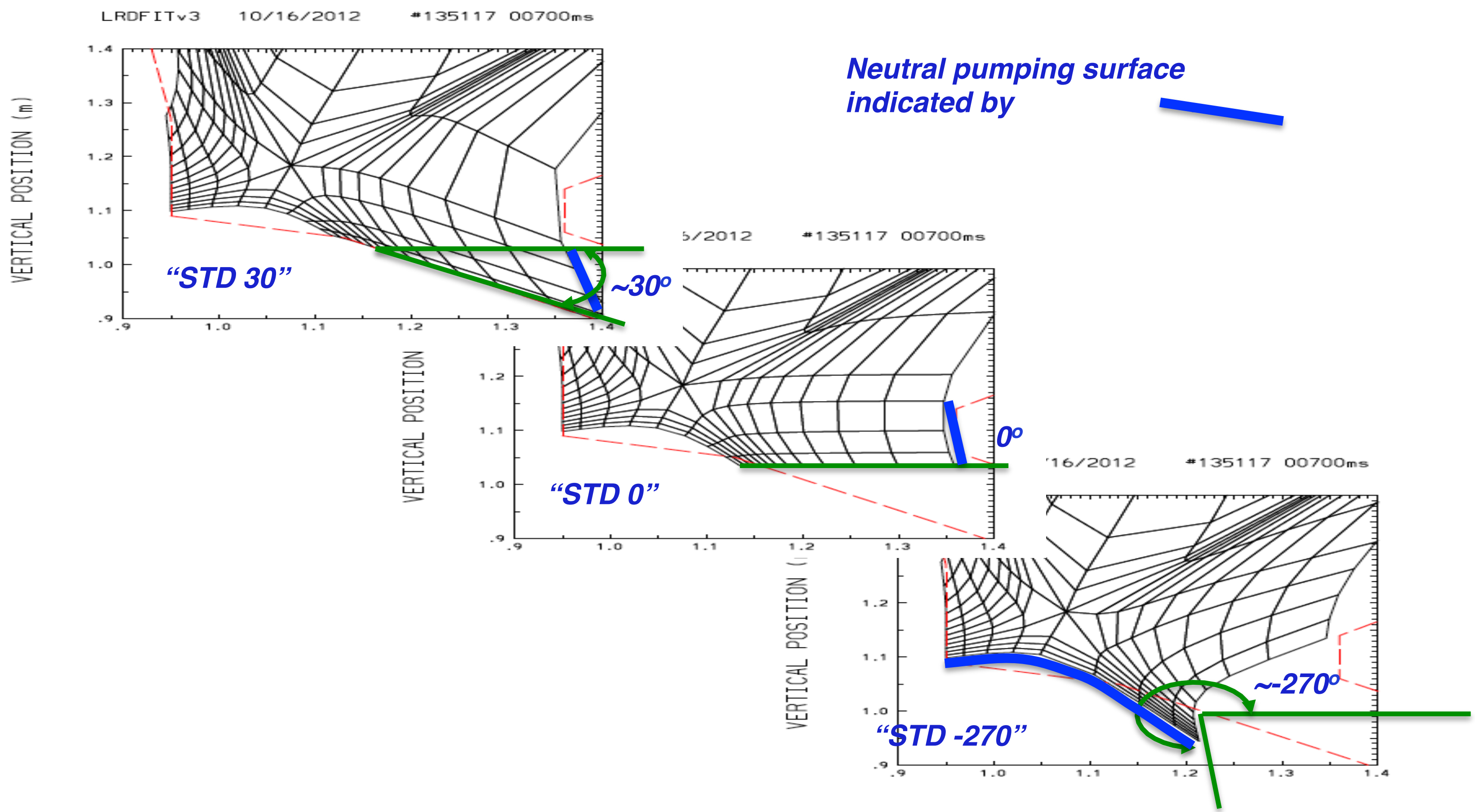


Particle control in NSTX-U will be accomplished with variety of fueling and exhaust techniques

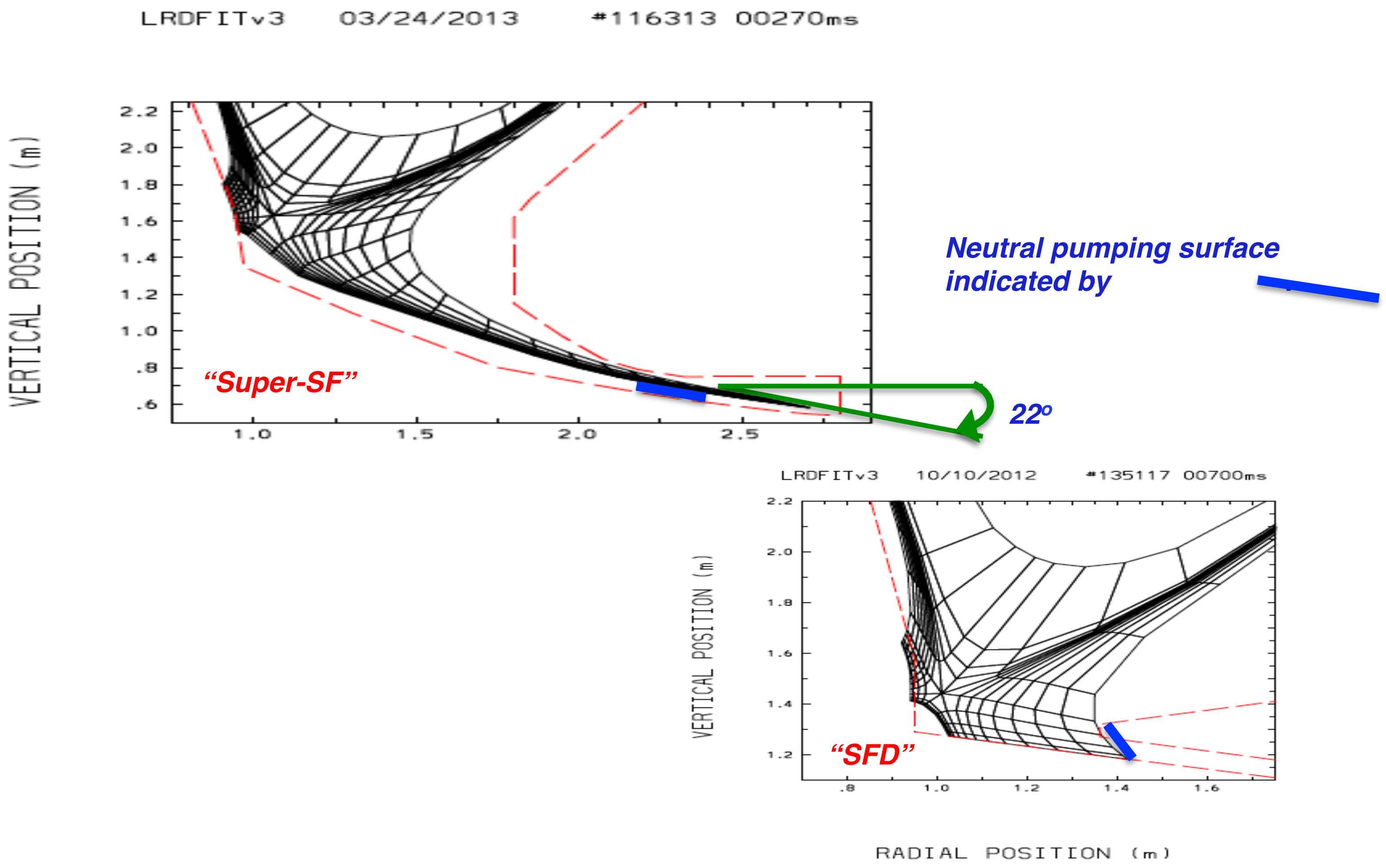
- Density control goals for NSTX-U:
  - Lower density to access reduced collisionality
    - As low as f_G~0.3-0.5 desired
  - Need to avoid density limit in long-pulse shots
    - Greenwald fraction f_G~0.7-1.0 sufficient for non-inductive studies
  - Develop FNSF-relevant pumping scenarios
- Novel and conventional pumping and fueling techniques for density control
  - Lithium coatings for deuterium pumping
  - Cryopumping
  - Conventional and supersonic gas injectors
- Impurity control goal Z_{eff} ~ 2-2.5
  - ELMy H-modes with boronized carbon PFCs
  - ELM-triggering with 3D fields and lithium granules to expel impurities in H-modes with lithium



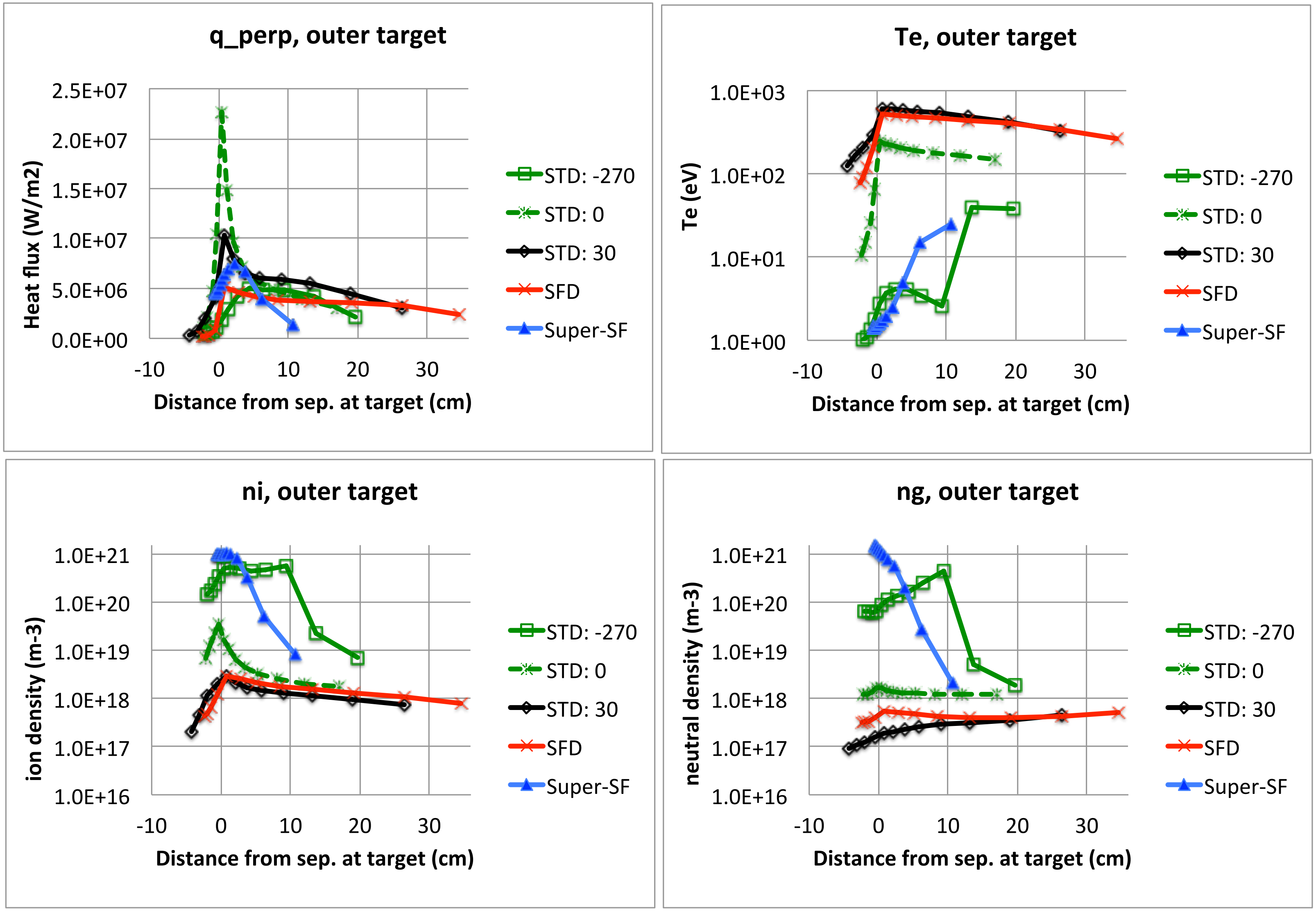
Standard (STD) grids used in ST-FNSF divertor study with UEDGE code



Snowflake (SFD) grids used in ST-FNSF divertor study with UEDGE code

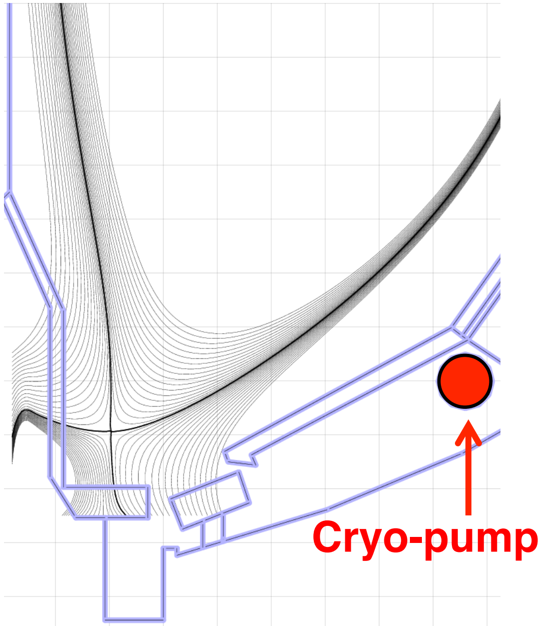


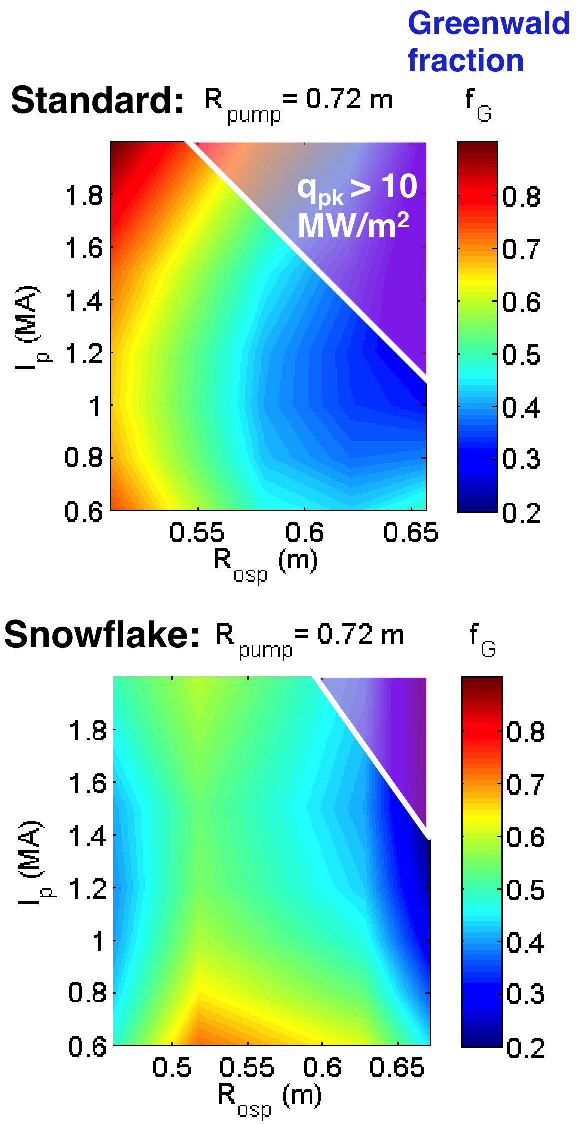
Outer divertor profiles



Cryo-pump will be key for density and collisionality control in Years 4-5

- Cryo-pump is proven technology for plasma density control
  - NSTX-U design is similar to DIII-D
  - Need plenum pressure of 0.6 mTorr to pump NBI input





- Pressures >1 mTorr can be reached over wide range of plasma shapes and SOL widths
  - Semi-analytic pumping model used to optimize plenum geometry
- Optimized plenum geometry can pump conventional and snowflake divertors over a range of R_{OSP}, I_p
  - Cannot sustain f_G < 1 at 2 MA with standard divertor
  - High snowflake flux expansion results in better pumping