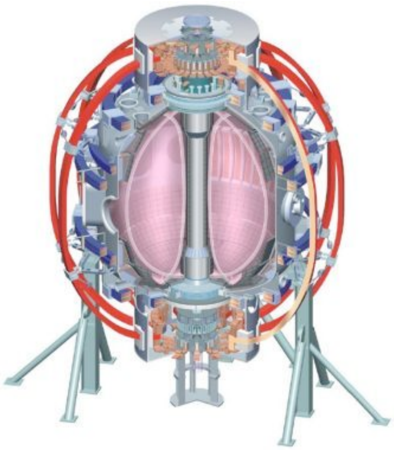
Divertor options for NSTX and NSTX-Upgrade

College W&M
Colorado Sch Mines
Columbia U
Comp-X
General Atomics
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
PSI
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Maryland
U Rochester
U Washington
U Wisconsin

Rajesh Maingi, Oak Ridge National Laboratory

On behalf of the NSTX Research Team

NSTX Program Advisory Committee Meeting
Princeton, NJ
Feb. 3-5, 2010



Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

This talk responds to a PAC-25 request

- The PAC recommends that the NSTX Team consider ways to devote additional resources to the investigation and development of a high heat flux divertor for NSTX. A high heat flux divertor with sufficient particle control is critical to the NSTX Program. Therefore, the PAC recommends even greater emphasis be placed in the research program, run plan, and diagnostic implementation plan for addressing Li divertor issues. For next year's PAC meeting, we request that the NSTX National Team make an explicit presentation detailing what will be the heat flux targets required in post-upgrade discharges and identification of high-heat flux divertor options compatible with reasonable density control targets.

- ➢ *Lithium coatings provide transient pumping, and the power handling schemes in this talk are all thought to be compatible*
    - *LLD experiments this year will determine if pumping can be extended*
- ➢ *Other techniques, such as cryopumps, are more sensitive to strike point locations, and are presently being considered as backup options*

Divertor options for NSTX-U

- Base plan: use high flux expansion divertor for heat flux handling, and liquid lithium for pumping
  - Up/down power sharing (double-null), plus small inner gap for inner wall power exhaust sharing may be required
  - Gas puffing for radiative/detached divertor would be used for safety margin, but should not be required a priori
- Backup option: use Super-X divertor for heat flux handling, and a cryopump for density control
- PFC material choice undecided: carbon (baseline) or high-Z?
  - High-Z more reactor relevant
  - ➢ *Considering changing inner divertor graphite tiles in NSTX with Mo tiles for improved compatibility with lithium in high δ discharges*

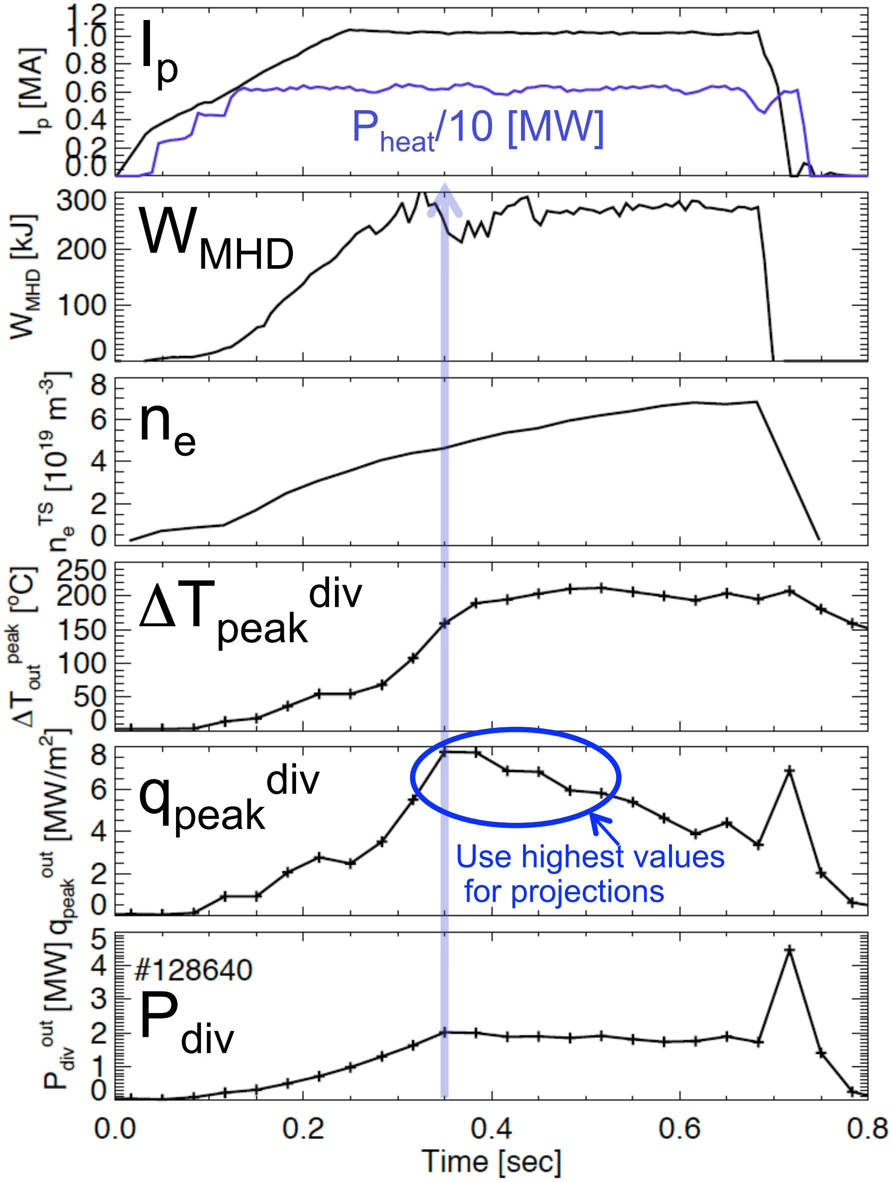
➢ <u>Research goal</u>: project NSTX-U heat flux from NSTX data

  ➢ *Assess NSTX-U operational window (I_p, P_{heat}, n_e, pulse length)*

Outline

- Heat flux projection methods
  - 0-D: Heat flux peak (q_{peak}) and width (λ_q) scalings
  - 2-D modeling: extrapolate based on NSTX data
- Heat flux mitigation techniques
  - High flux expansion divertors
  - Gas puffing for extra radiation and partial detachment
    - ✓Successful in NSTX, shown at previous PACs
- Experiment and analysis plan

Divertor peak heat flux evolves during discharge



- I_p flat-top at 0.25 sec (L-H transition at 0.13 sec)
- Stored energy usually flat -tops after I_p flat-top
- Density ramps throughout the discharge (large δ_r^{sep}, small ELMs)
- Peak divertor temperature rise flattens as density rises
- Outer divertor heat flux peaks when W_{MHD} flat-tops; rolls over as density rises
- Total outer divertor power relatively constant (i.e. profile broadens)

Simplest 0-D heat flux projection based on power balance extrapolates from measured NSTX heat flux profiles

- IR thermography measures heat flux profile $q_{div}^{out}(r)$ for calculation of divertor power loading: $P_{div}^{out} = \int_{R_{\min}}^{R_{\max}} 2\pi R_{div}^{out} q_{div}^{out} dr$
- Define characteristic divertor heat flux scale length, $\lambda_{q,div}^{out}$:

$$\lambda_{q,div}^{out} = P_{div}^{out} \Big/ \left(2\pi R_{div,peak}^{out} q_{div,peak}^{out}\right)$$

- Assume $\lambda_{q,div}^{out}$ related* to characteristic midplane scale length through flux expansion f_{exp}: $\lambda_q^{mid} = \lambda_{q,div}^{out} / f_{\exp}$ with $f_{\exp} = \dfrac{R_{mid} B_\theta^{mid}}{R_{div} B_\theta^{div}}$

– Project NSTX-U q_{peak}^{div}: I_p=2 MA, P_{loss}=10 MW, B_t=1 T, f_{exp}=30

  – For P_{loss} extrapolation, use $P_{div}^{out} = f_{div} P_{loss}$ with $f_{div} = 0.5$

$$\boxed{q_{div,peak}^{out} = f_{div} P_{loss} \Big/ \left(2\pi R_{div,peak}^{out} f_{\exp} \lambda_q^{mid}\right) \quad \text{with } \lambda_q^{mid} = f\left(I_p, P_{loss}, B_t, f_{\exp}\right)}$$

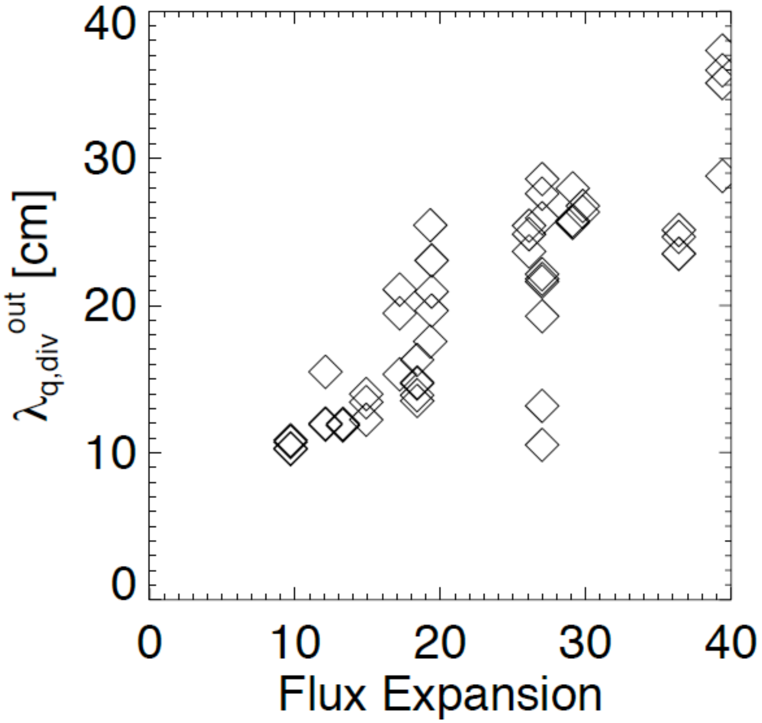
➢ Determine dependence of λ_q^{mid} on external parameters (I_p, P_{loss}, B_t, flux expansion) from NSTX data (FY10 Joint Research Target)

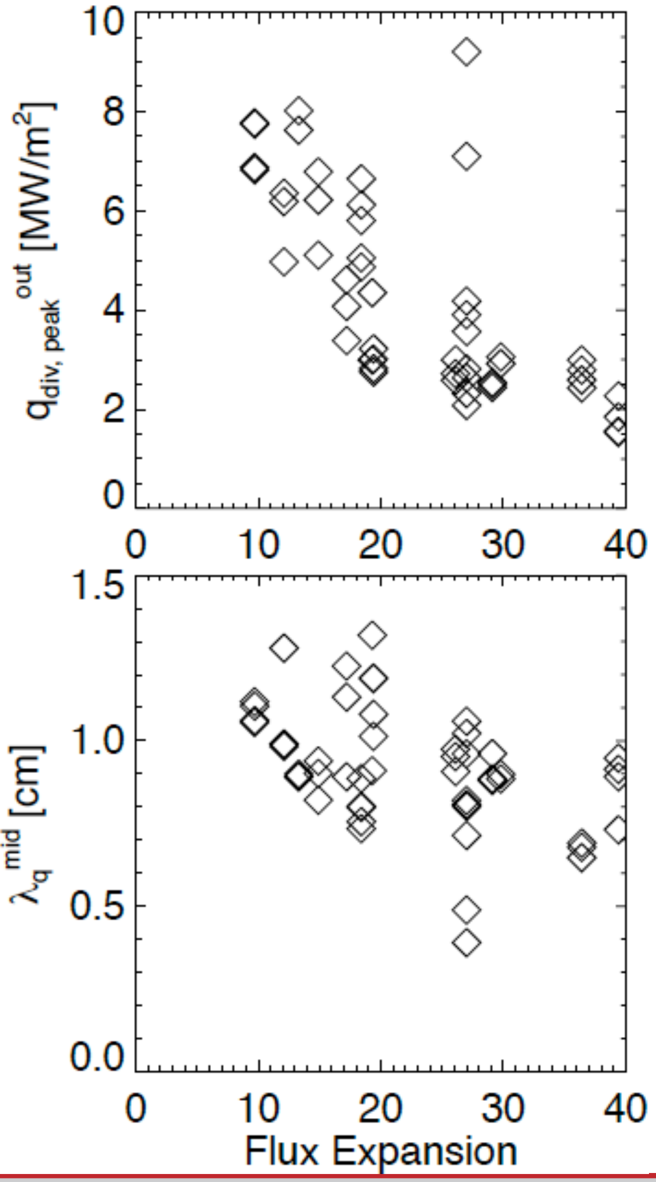
*Loarte, JNM 1999

Peak heat flux decreases inversely with flux expansion with roughly constant λ_q^{mid}

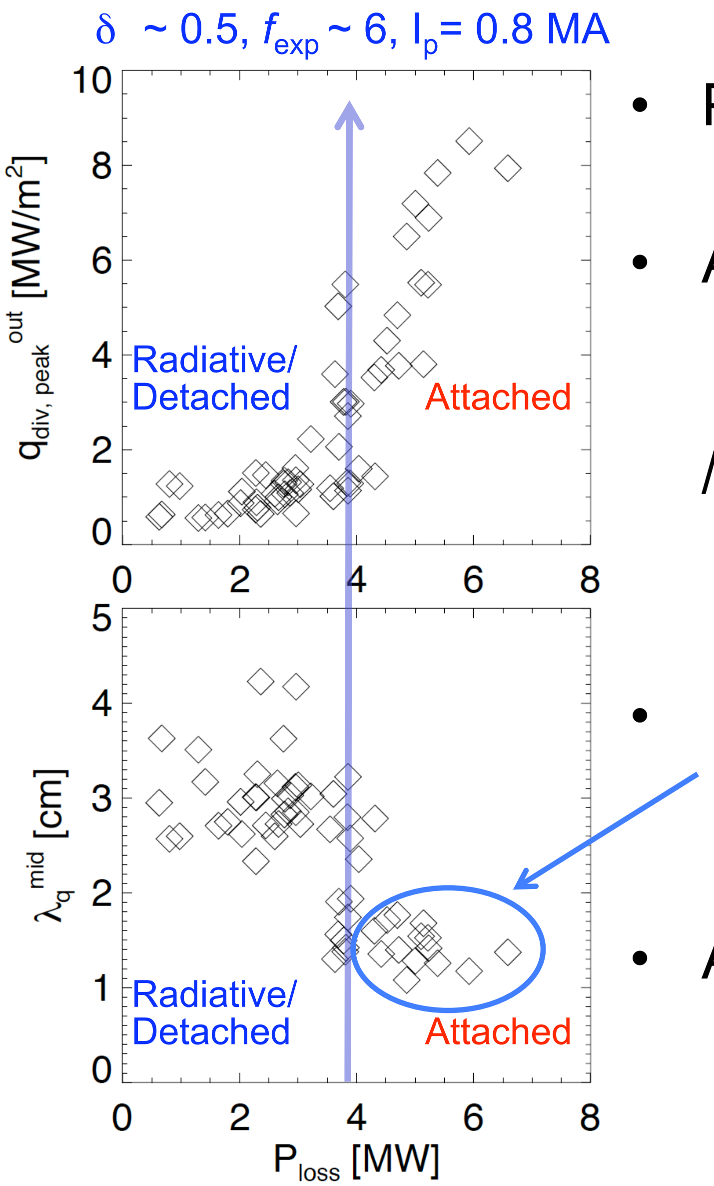
- λ_q^{div} increases with flux expansion

- λ_q^{mid} stays approximately constant during the scan





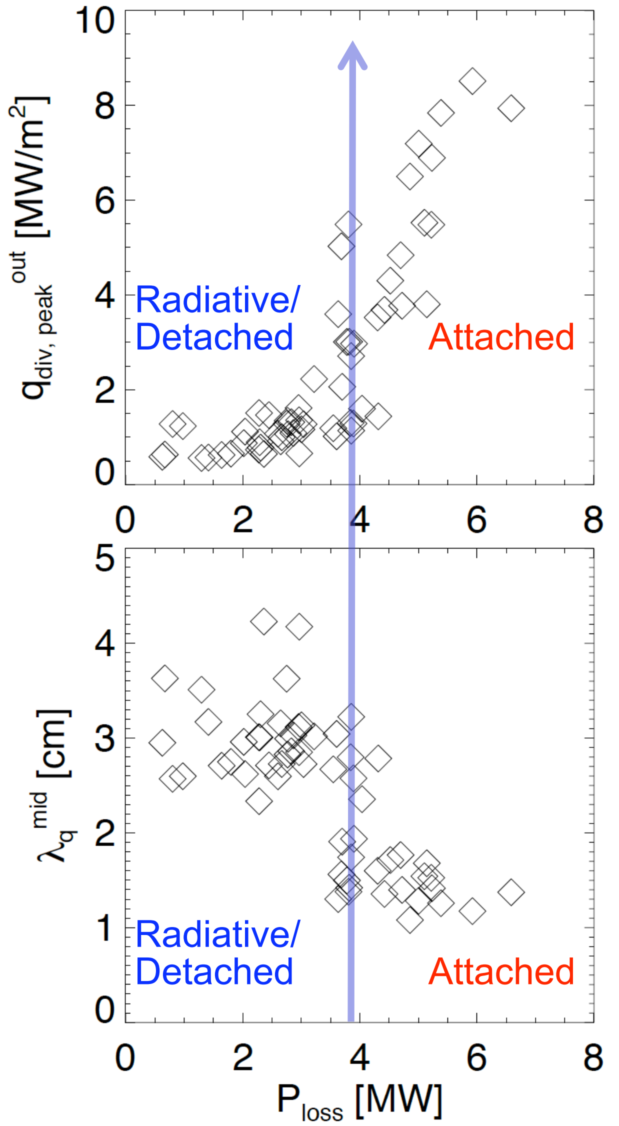
Heat flux width λ_q^{mid} largely independent of P_{loss} in attached plasmas



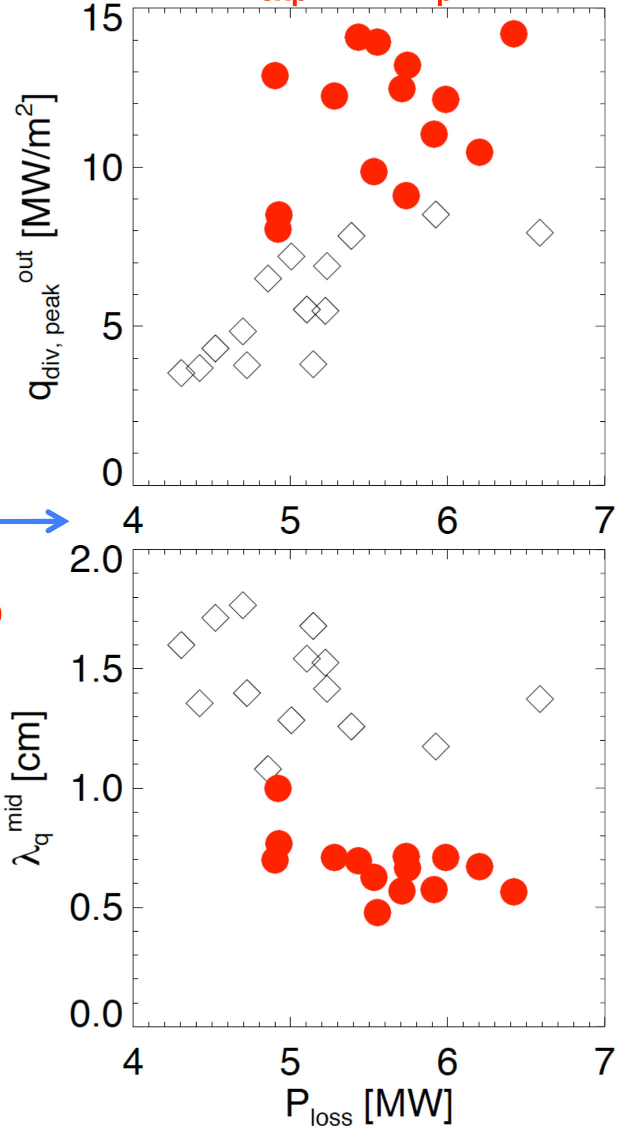
- Peak divertor heat flux increases with P_{loss}
- Apparent change in slope near P_{loss}=4 MW in these conditions, as divertor transitions from a radiative /detached divertor to an attached divertor
- λ_q^{mid} relatively independent of P_{loss} in high heat flux regime
- All data in this talk averaged over ELMs and before lithium coatings

Heat flux width λ_q^{mid} largely independent of P_{loss} in attached plasmas

δ ~ 0.5, f_{exp} ~ 6, I_p= 0.8 MA

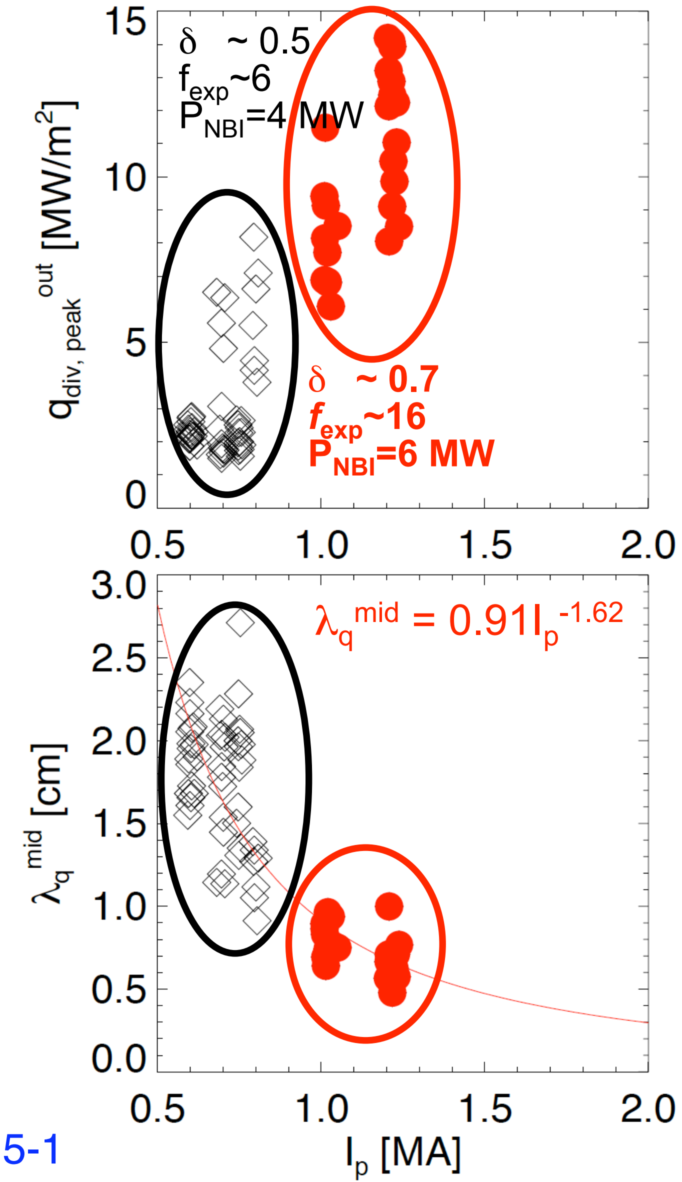


+ δ ~ 0.7, f_{exp} ~ 16, I_p= 1.2 MA



- Narrow P_{loss} plot range
- Add in high δ data
- Apparent I_p or q_{95} effect

Heat flux width decreases with I_p

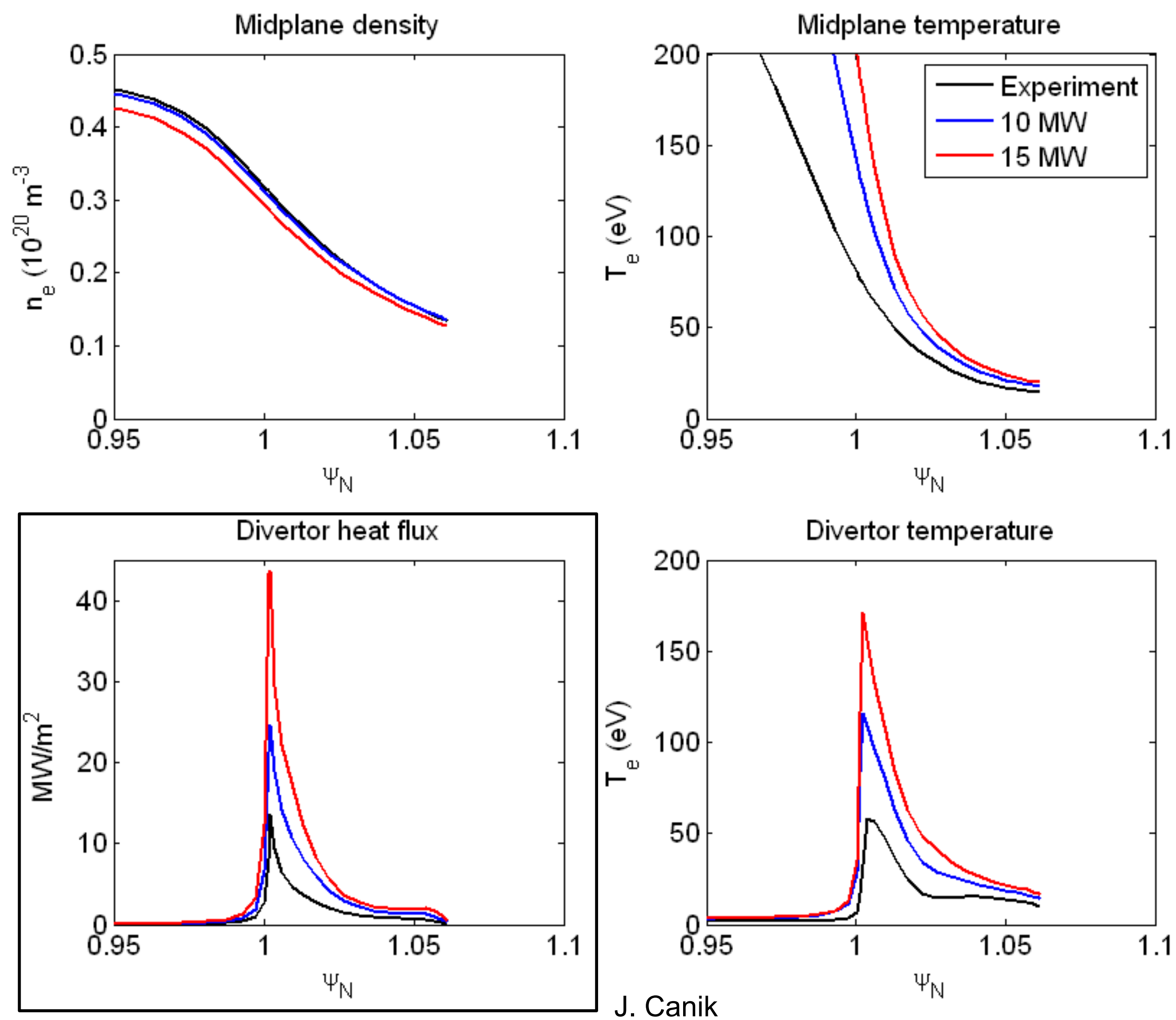


- Combined data from dedicated I_p scans in low δ and high δ discharges
  - I_p dependence also in DIII-D, JET
  - Different P_{NBI} and f_{exp}, but previous slides shows no P_{loss} or f_{exp} effect on λ_q^{mid}
  - q_{95}, $\ell_{||}$ different
- Power law fit: λ_q^{mid} ~ 3 +/- 0.5 mm @ 2 MA
- Project q_{peak} = 24 +/- 4 MW/m^2
  - Flux expansion = 30
  - P_{loss} = 10 MW, f_{div} = 0.5
- Note: n/n_{GW} ~ 0.5 in projection
  - Anticipate NSTX-U operation with n/n_{GW} from 0.5-1

2D modeling used to extrapolate from NSTX discharges to NSTX-U

- Generate grid based on discharge equilibrium
- Prescribe power and particle fluxes through inner boundary from data
- Vary free parameters ($\chi(\psi)$, $D(\psi)$, target recycling coefficients) to match measured midplane and divertor profiles
- Use above values to extrapolate to higher heating power
  - Extrapolate based on NSTX data from 1.2 MA, 6 MW discharge, which have highest measured heat flux

Interpretive 2D modeling also projects to very high peak heat flux with increased heating power



J. Canik

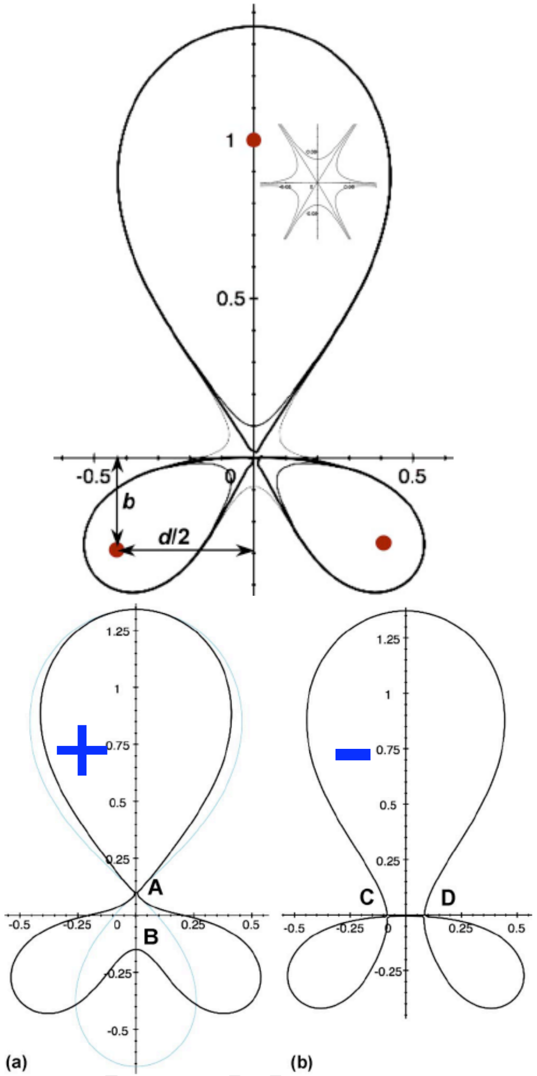
- Peak divertor heat flux to 25 MW/m^2 at 10 MW power
- Differences here and through 0-D projection:
  - Cross-field transport χ, D independent of I_p
  - f_{exp}=16
- Near term work will incorporate scalings, detachment, NSTX-U geometry

Outline

- Heat flux projection methods
  - 0-D: Heat flux peak (q_{peak}) and width (λ_q) scalings
  - 2-D modeling: extrapolate based on NSTX data
- Heat flux mitigation techniques
  - High flux expansion divertors
  - Gas puffing for extra radiation and partial detachment, *i.e. operate with* $0.5 < n/n_{GW} < 1$
    - ✓Successful in NSTX, shown at previous PACs
- Experiment and analysis plan

Heat flux solution: Snowflake divertor configurations predicted to facilitate power handling

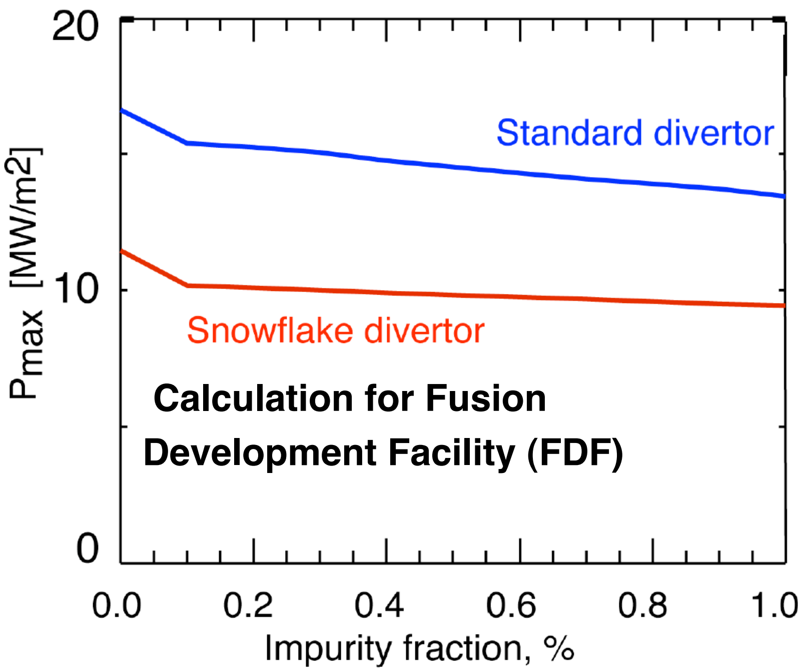
Snowflake divertors



Ryutov, PoP 2007

Snowflake topological features

- Higher magnetic flux expansion
- Longer $\ell_{||}$ near separatrix

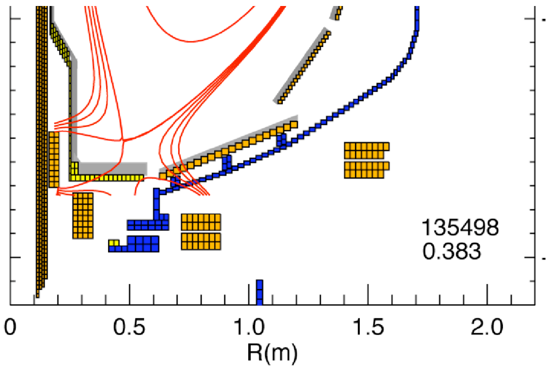


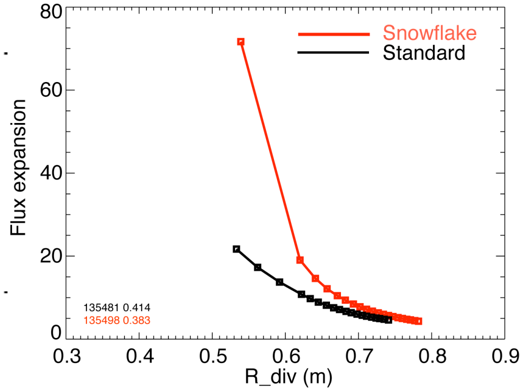
Calculation for Fusion Development Facility (FDF)

Umansky, NF 2009

Snowflake-like topology showed broad region of low heat flux

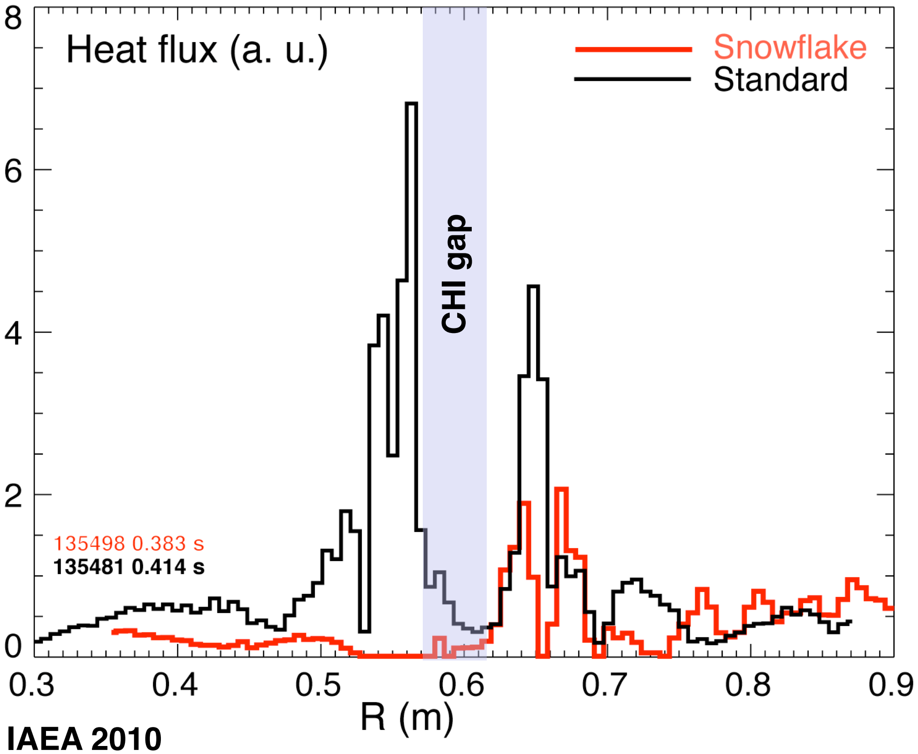
- Approximate snowflake divertor configuration achieved, with higher f_{exp} (3 mm flux surfaces shown)





- Heat flux profile made broader with reduced peak value

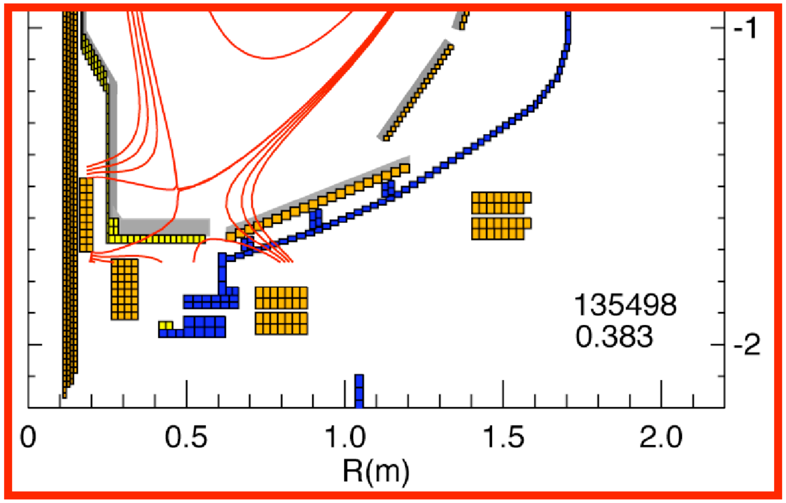
- Substantial high-n Balmer emission, indicative of volume recombination



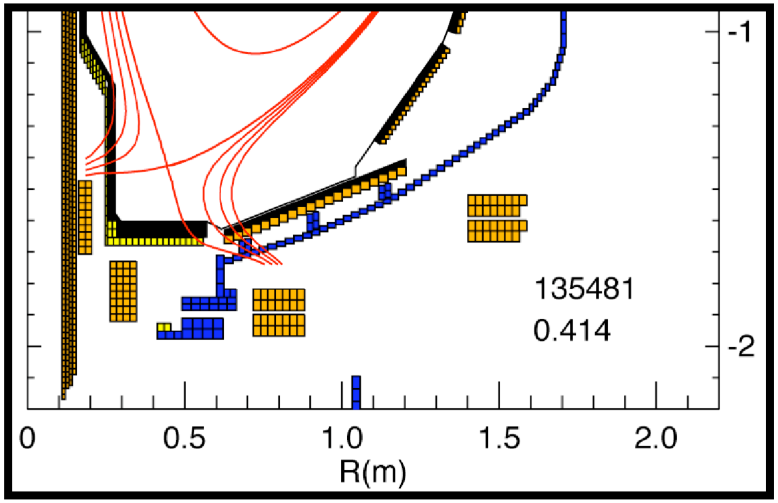
Soukhanovskii, IAEA 2010

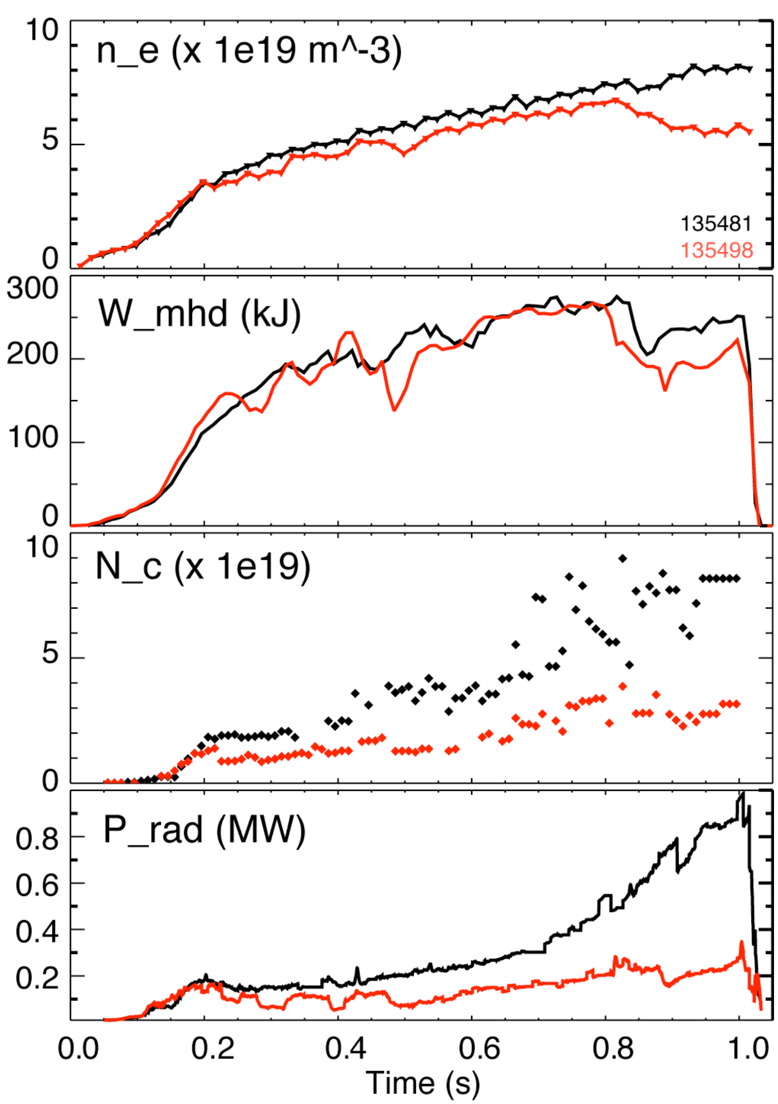
Discharges with snowflake configuration appear promising for impurity control

“Snowflake” divertor



Standard divertor

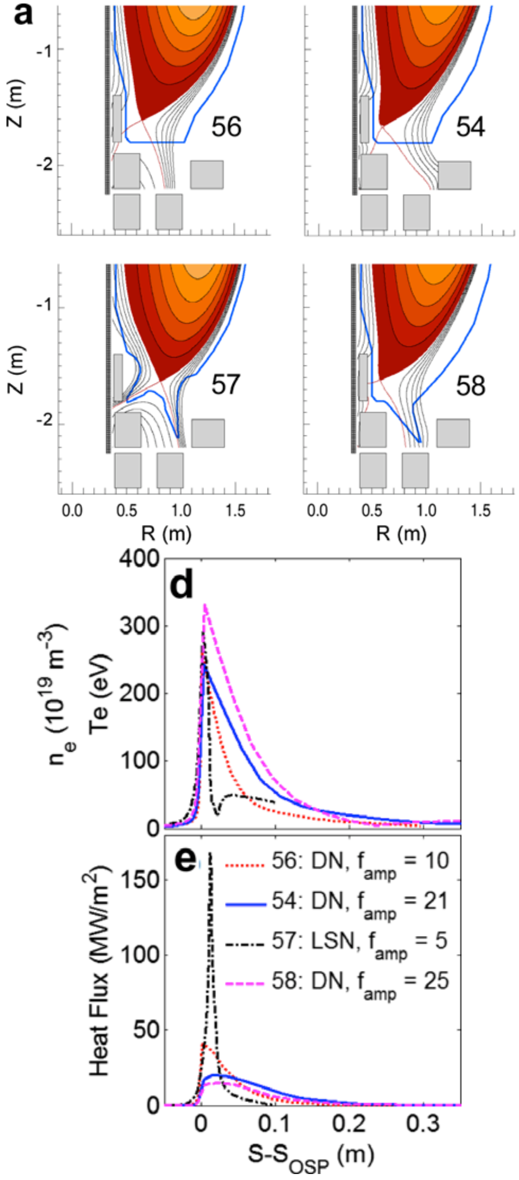




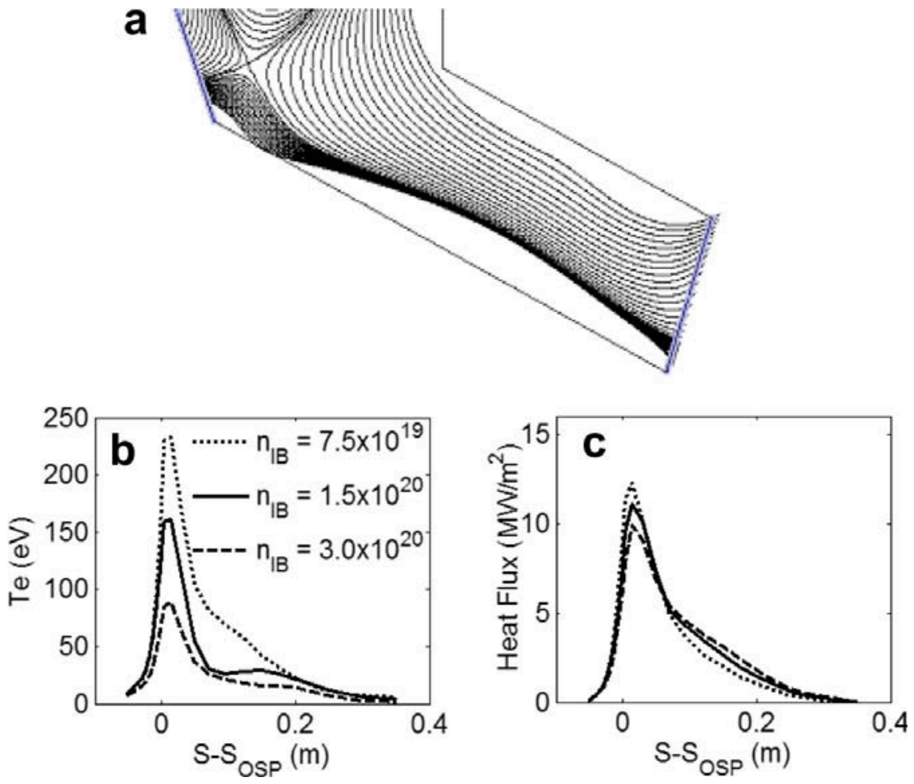
Soukhanovskii, IAEA 2010

Heat flux solution: Super-X divertor (SXD) predicted to reduce peak heat flux in low R/a NHTX

Baseline



Super-X

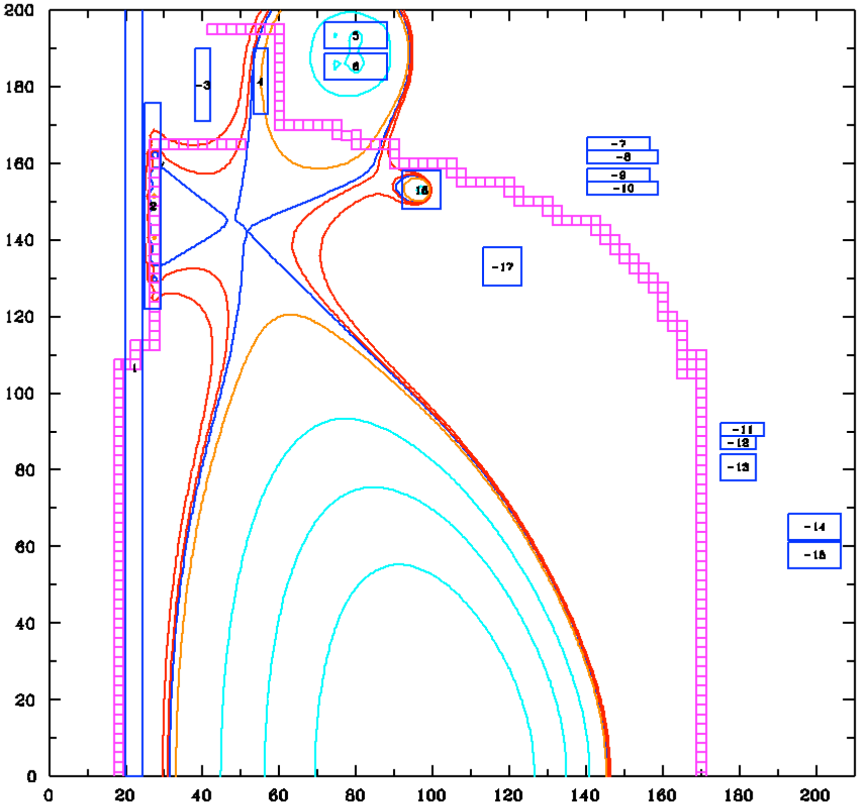


Canik, JNM 2009

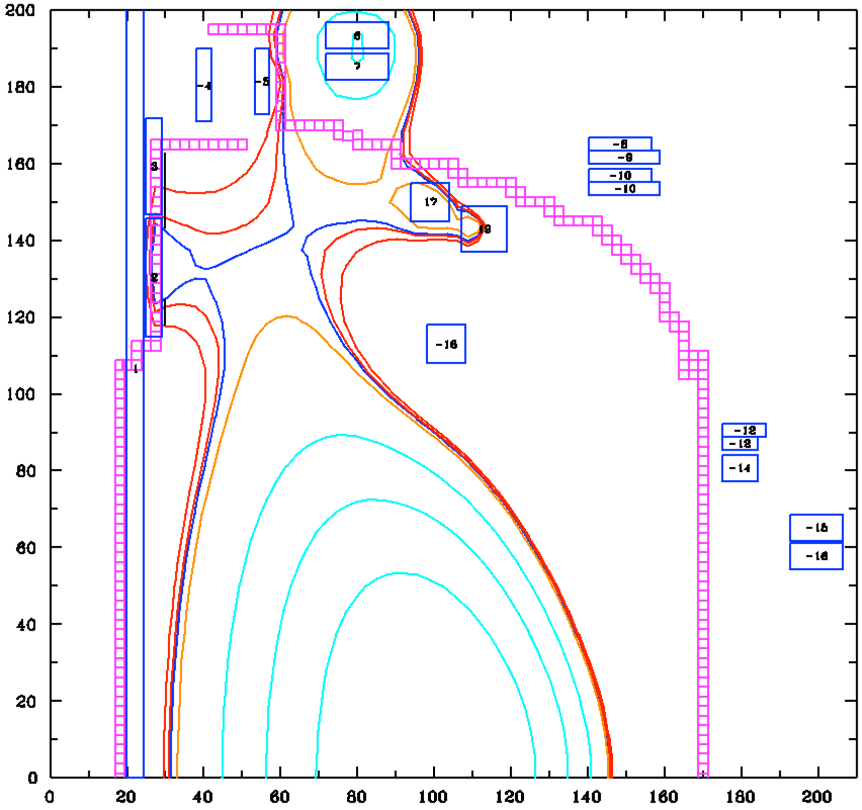
Multiple SXD options available with in-vessel coils

- NSTX-U options being explored by Univ. Texas (with NSTX team)
  - –Could be used in conjunction with large-R cryopump, if desirable
  - –Coils shown are consistent with present Center Stack design
  - –Cost of in-vessel coils not included in NSTX-U, i.e. future possibility

NSTX-U sxdhh



NSTX-U SXD short



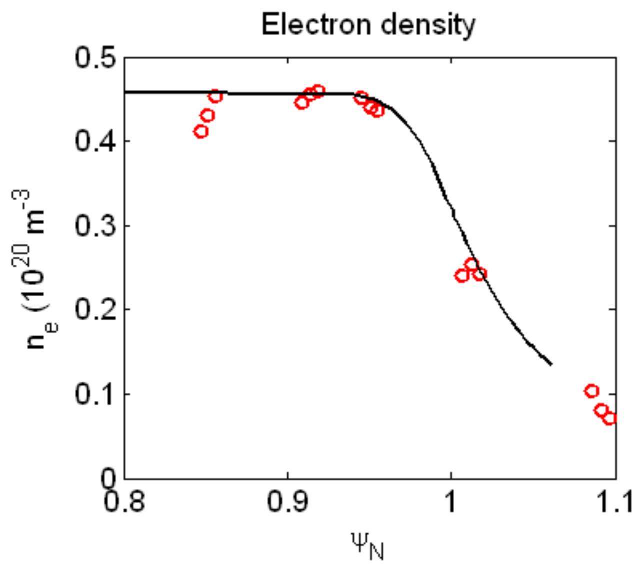
Valanju

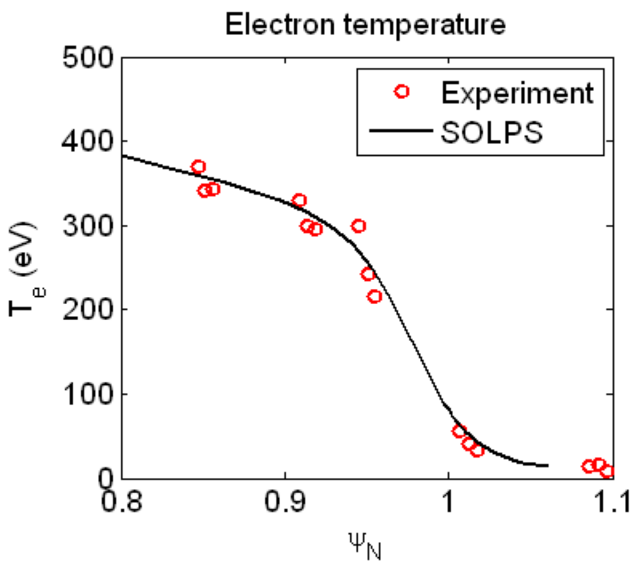
FY 2010 experiment and analysis plan forNSTX-U divertor design

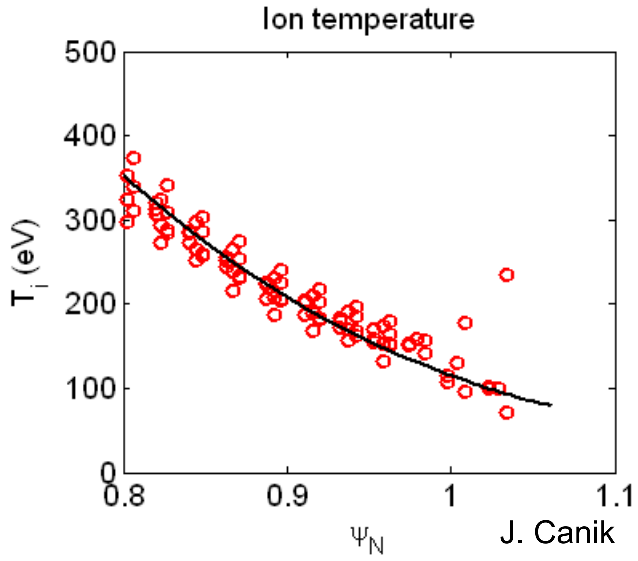
- Measure I_p, P_{heat}, n_e, B_t dependences on heat flux profile with lithium at high I_p for improved scaling
- Continue snowflake divertor development
- Continue 2D modeling of scenarios
  - Unmitigated heat flux: decrease χ, D with I_p, increase flux expansion, and use computed NSTX-U equilibria
  - Detached case: add impurities, increase P_{heat}, and use χ=f(I_p)
  - Begin to model snowflake results, including lithium/LLD effects
  - Begin to model super-X with LLD and/or cryo
- Quantify density dependence of heat flux profiles, and examine high core radiated power scenarios
- New data with LLD, including evaporative cooling
- Assess replacing lower inboard div. C tiles with Mo

BACKUP

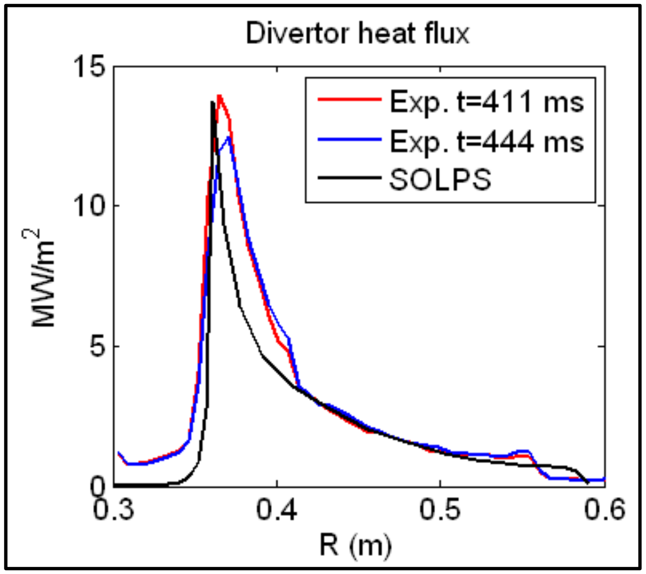
Interpretive 2D modeling sets cross-field transport and recycling coefficients to match plasma profiles





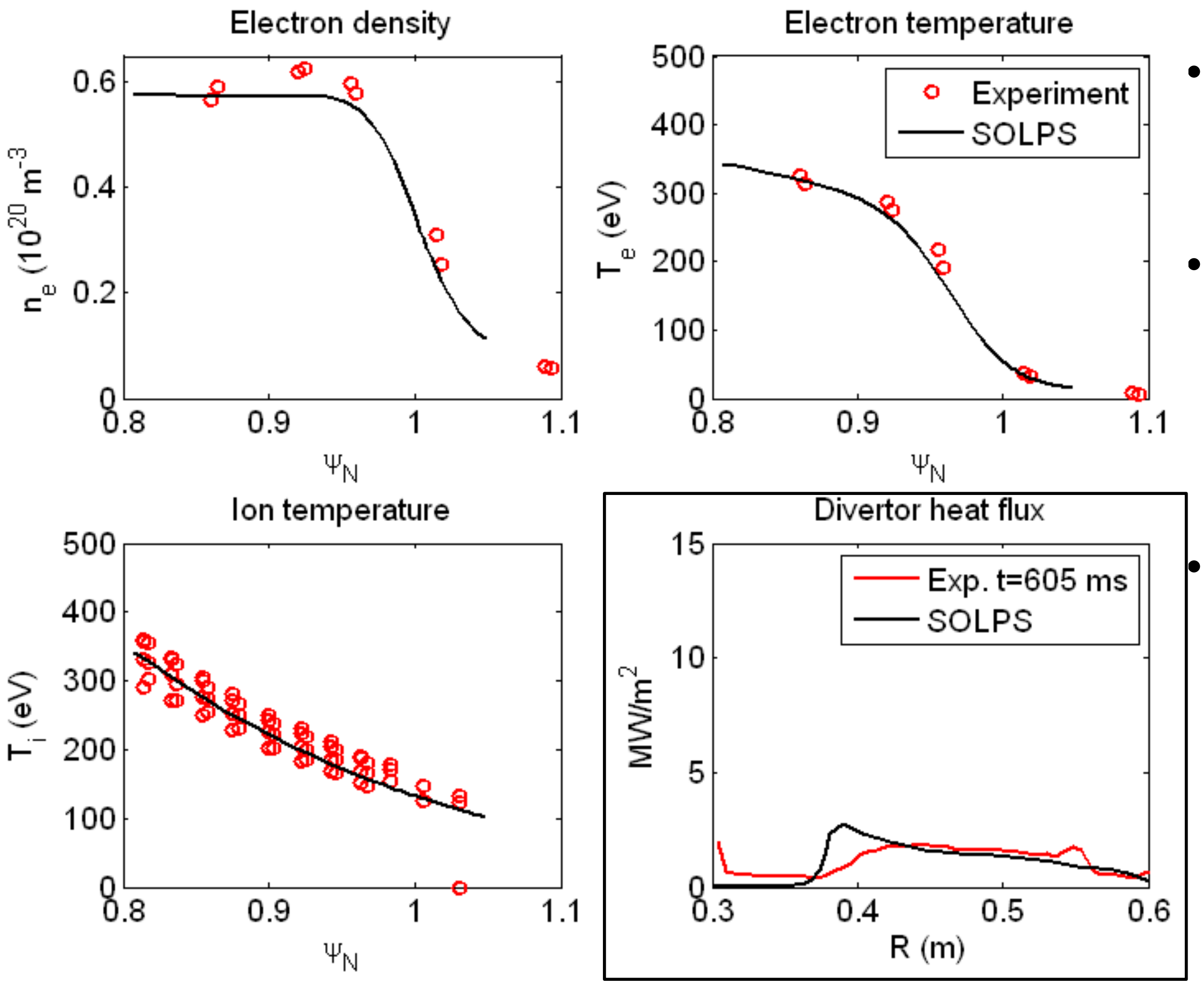


J. Canik



- 1.2 MA, 6 MW NBI with high peak heat flux data
- Code calculations reasonably match measured profiles
- Deuterium only in simulations (impurity radiation small in sheath limited regime)

Interpretive 2D modeling of detached discharge shows much lower peak heat flux

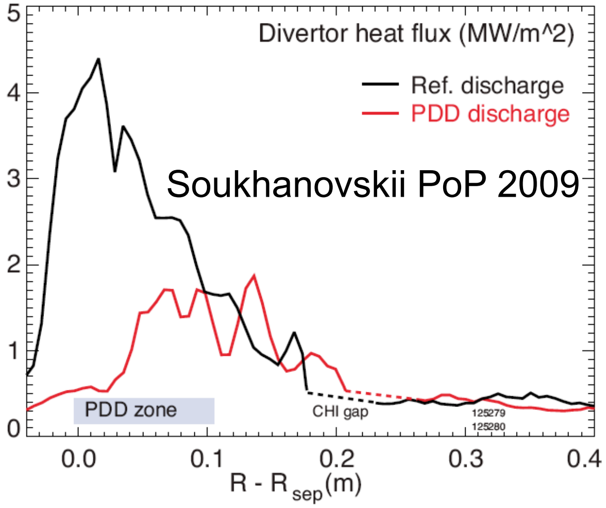


J. Canik

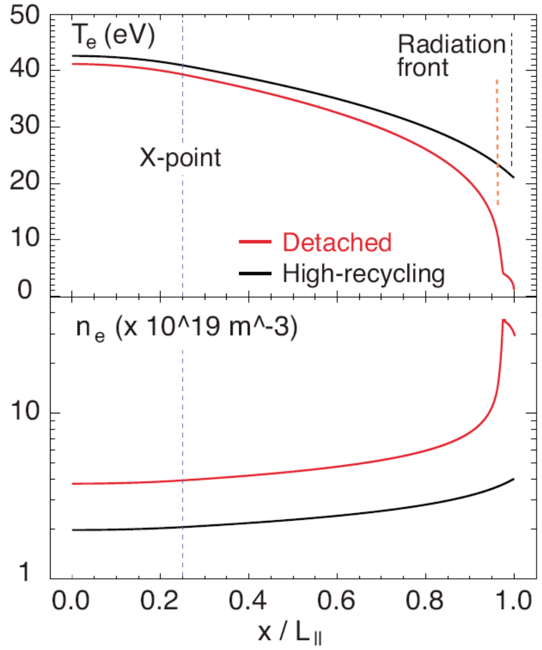
- Projection of this scenario in progress
- Deuterium only in simulations so far– inclusion of impurities needed
- Differences between this and baseline case (higher n_e, lower T_e) folded in through transport coefficients, i.e. no divertor puff here

Divertor physics and detachment physics program focuses on needs for NSTX-Upgrade and next step ST design

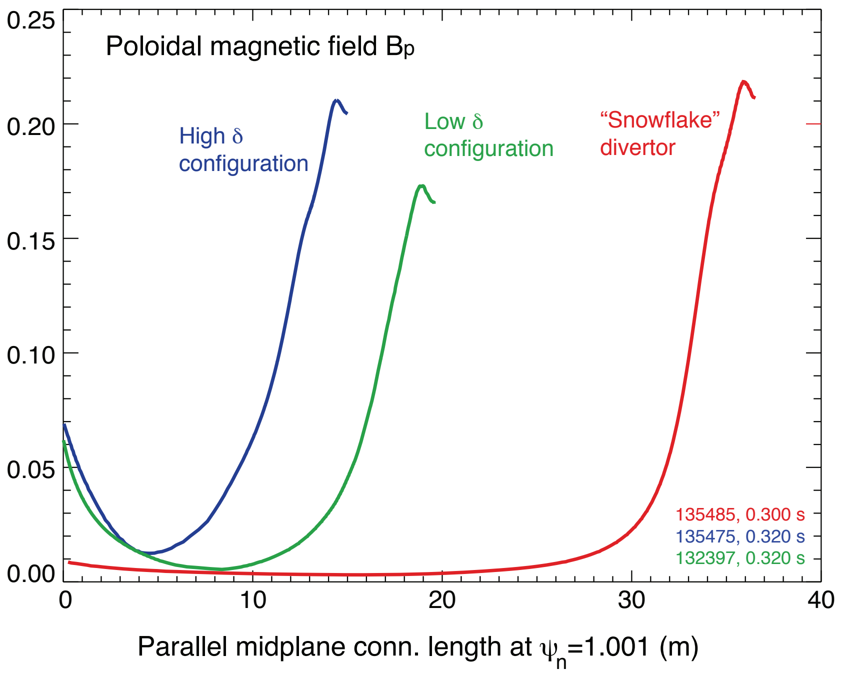
- ST effects: low $\ell_{||}$, small R, low in /out power split make outer leg detachment difficult
  - — *Power management through flux expansion and partial detachment (PDD) will be required for heat dissipation in high power ST's*
  - — *ST effects above allow broader test of detachment physics in 2-D codes*
- Heat flux management through plasma shaping and detachment with good confinement shows promise in NSTX
  - – Need to to extend to highest I_p

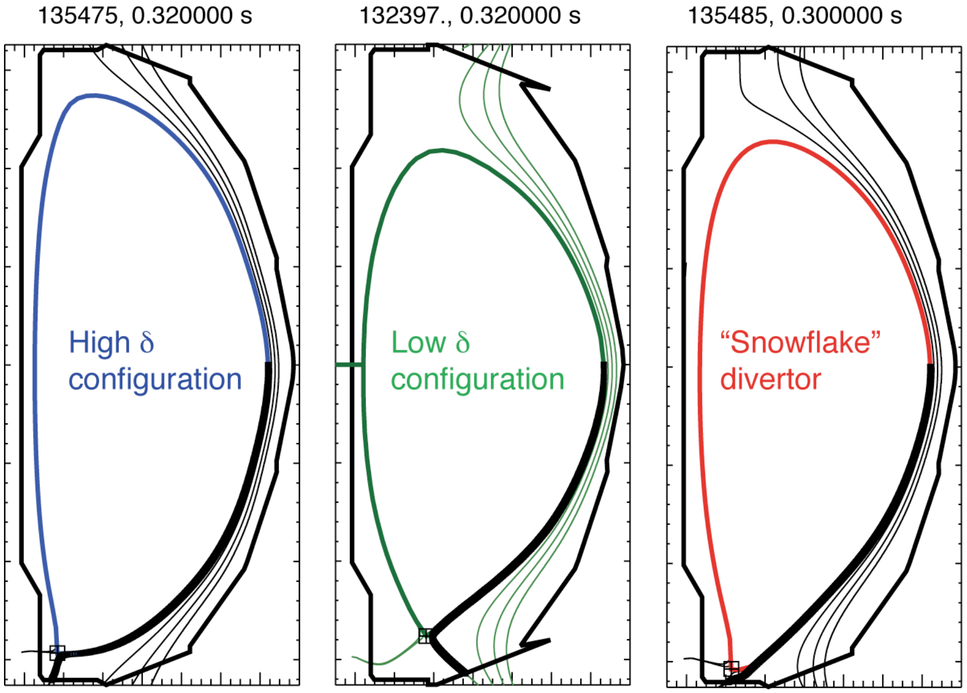


Soukhanovskii PoP 2009



Snowflake-like magnetic topology achieved in NSTX



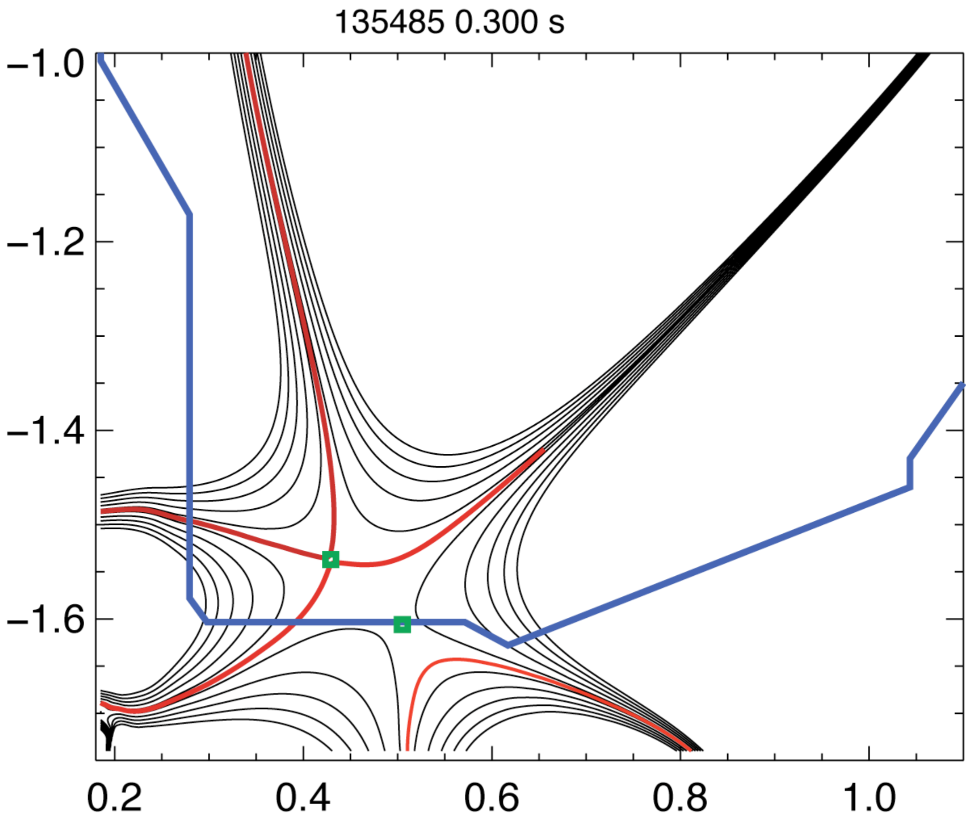


Configuration	Flux expansion	L_x (m)	L_{tot} (m)
SFD	68.1	16.3	36.5
Low δ	4.3	8.4	19.6
High δ	10.0	4.5	15.0

Soukhanovskii, IAEA 2010

Snowflake equilibria generated for NSTX-Upgrade

NSTX – actual



NSTX-U – model