NSTX

U.S. DEPARTMENT OF ENERGY | Office of Science

Boundary Physics Progress and Plans

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Columbia U
CompX
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
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MIT
Nova Photonics
New York U
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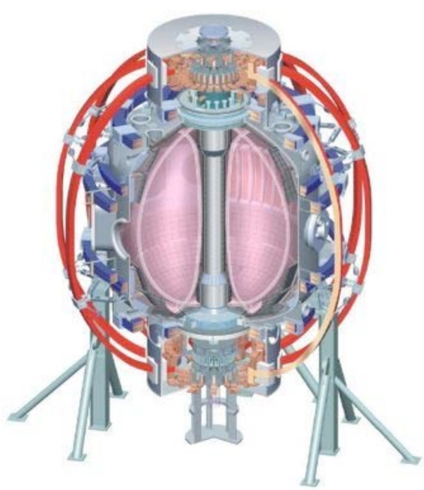
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Washington
U Wisconsin

R. Maingi, Oak Ridge National Laboratory

For the NSTX Research Team

NSTX PAC meeting
Conference Room LSB-B318, PPPL
Feb. 18-20, 2009



Culham Sci Ctr
U St. Andrews
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U Quebec

Boundary physics program in NSTX mainly focused on NSTX-U and next step ST design needs

Program also contributes to toroidal confinement and ITER physics

- SOL and divertor physics
  - Particle control: Lithium for pumping and a concomitant fueling program for density control } **1**
  - SOL turbulence and transport & SOL width studies
  - Divertor physics, emphasis on heat flux management } **2**
- H-mode Physics
  - Pedestal and ELM studies
  - Participation in L-H power threshold studies (transport & turbulence group) } **3**

Lithium
Thrust
Skinner

Increasing importance of boundary physics program in NSTX highlighted by upcoming Joint Research Targets (JRT)

- SOL and divertor physics
  - Particle control: Lithium for pumping and a concomitant fueling program for density control
  - SOL turbulence and transport & SOL width studies
  - Divertor physics, emphasis on heat flux management
- H-mode Physics
  - Pedestal and ELM studies
  - Participation in L-H power threshold studies (transport & turbulence group)

2009 JRT:
hydrogen
retention in Li

2010 JRT:
heat transport
peak heat flux
SOL width

2011 JRT:
(proposed)
pedestal
physics

Major facility upgrades (yellow boxes) represent both opportunities to and responsibilities for the boundary physics program

- SOL and divertor physics
  - Particle control: Lithium for pumping and a concomitant fueling program for density control
  - SOL turbulence and transport & SOL width studies
  - Divertor physics, emphasis on heat flux management
- H-mode Physics
  - Pedestal and ELM studies
  - Participation in L-H power threshold studies (transport & turbulence group)

LLD program
Skinner's talk

CS upgrade
Long pulse div.
2^{nd} NBI

CS upgrade
2^{nd} NBI
NCC upgrade

Outline

- **SOL and divertor physics for prediction of plasma-wall interaction footprint using theory-based cross-field transport models**
  - **Divertor heat and particle flux optimization**
    - **Interpretive analytic and 2-D modeling**
  - **Edge transport and turbulence ⇔ SOL width**
    - **World-class SOL turbulence measurements**

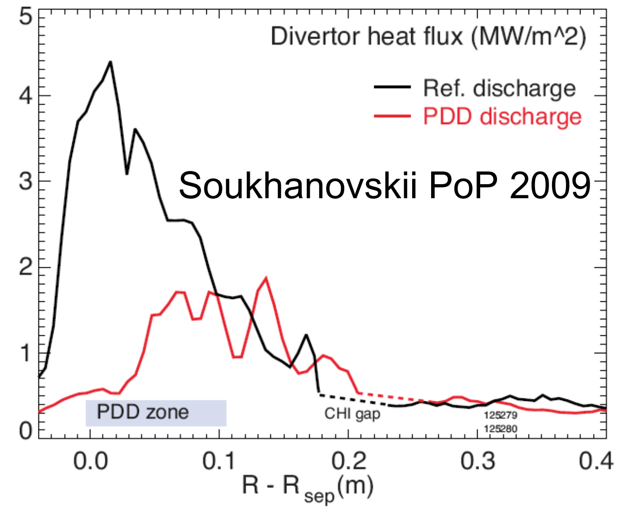
2010 JRT:
heat transport
peak heat flux
SOL width

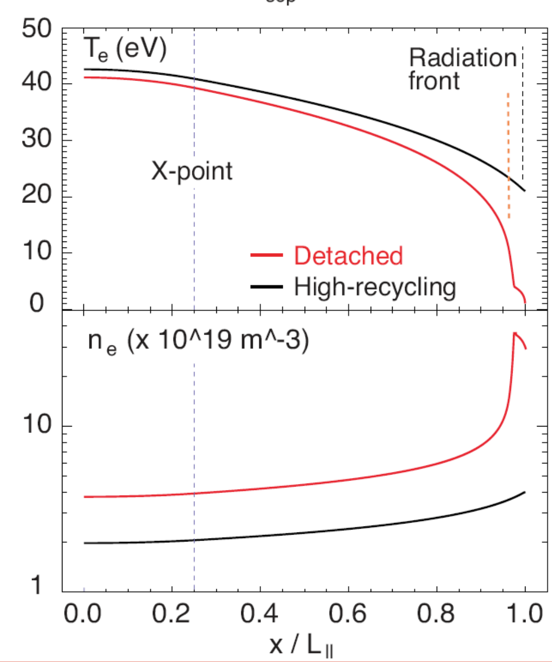
- Pedestal and ELM Physics

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
  - Considering He, CD_4 puffing

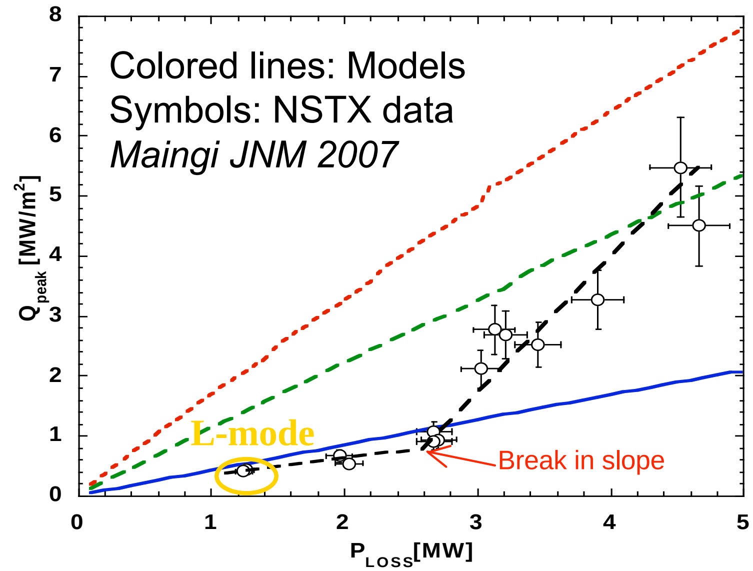
PAC23-09

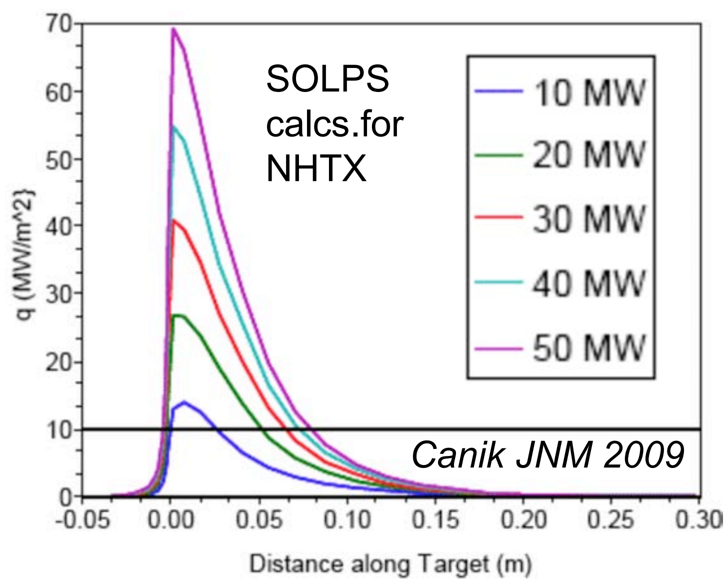




Long pulse center stack upgrade and 2nd NBI will challenge existing carbon PFCs while presenting prospect of very high heat flux studies

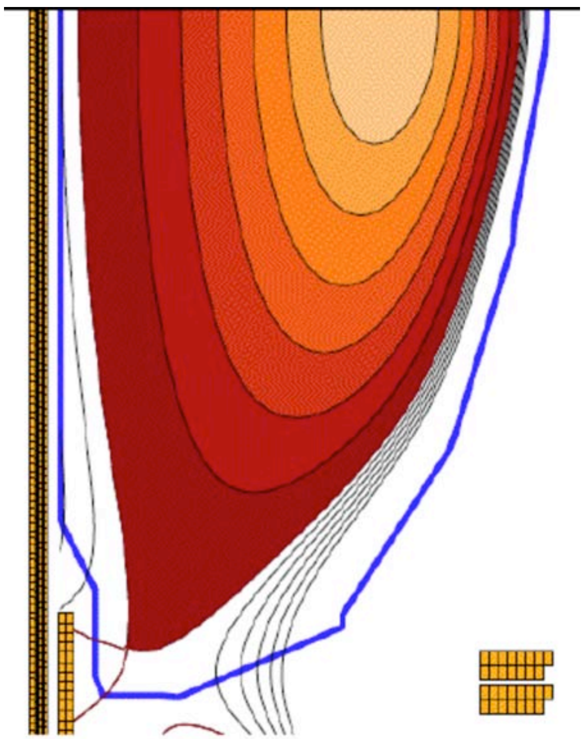
- Maximum pulse length of 2-3 sec for existing graphite ATJ PFCs
  - NSTX data (upper panel): P_{NBI}=6 MW, LSND, I_p=0.8 MA, B_t=0.45 T
  - q_{peak} of 20-30 MW/m^2 may be possible with 2nd NBI, if scaling holds
- q_{peak} might be even higher at I_p=2 MA
  - q_{peak} increases non-linearly with I_p, because λ_q falls quickly
  - q_{peak} also drops when ELM-free (w/Li)
  - Might require double-null geometry, or novel divertors (X-D, super X-D, or snowflake)
- High heat flux allows broader parameter range for experiments and improved predictive capability for next step STs,
  - NHTX low flux expansion (lower panel)



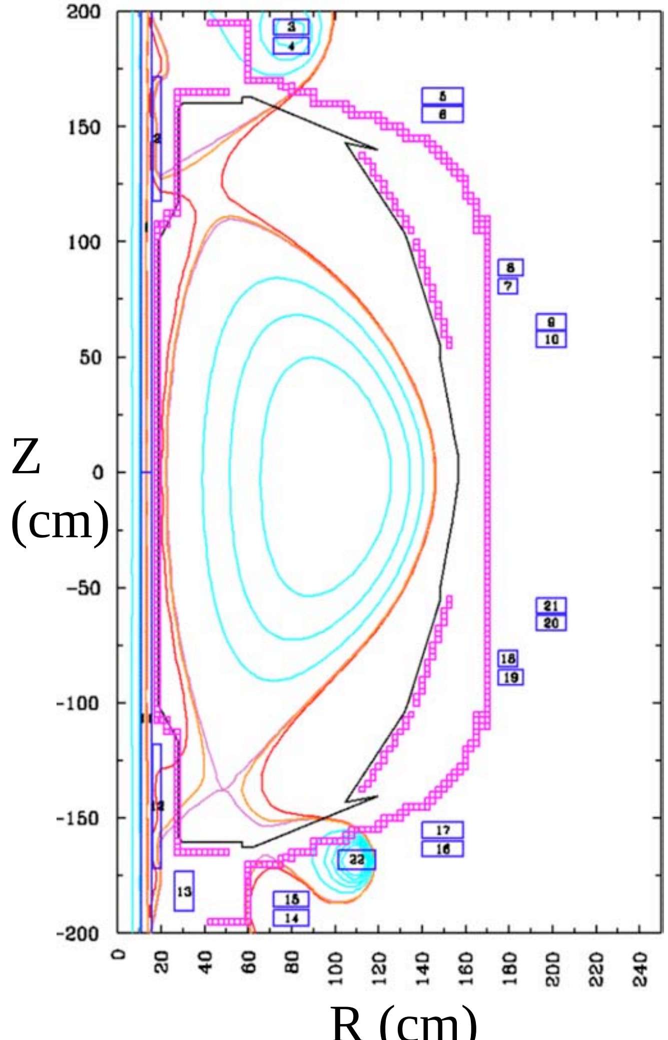


Novel divertors (X, Super-X, snowflakes) being considered for heat flux management with center stack and 2nd NBI upgrades

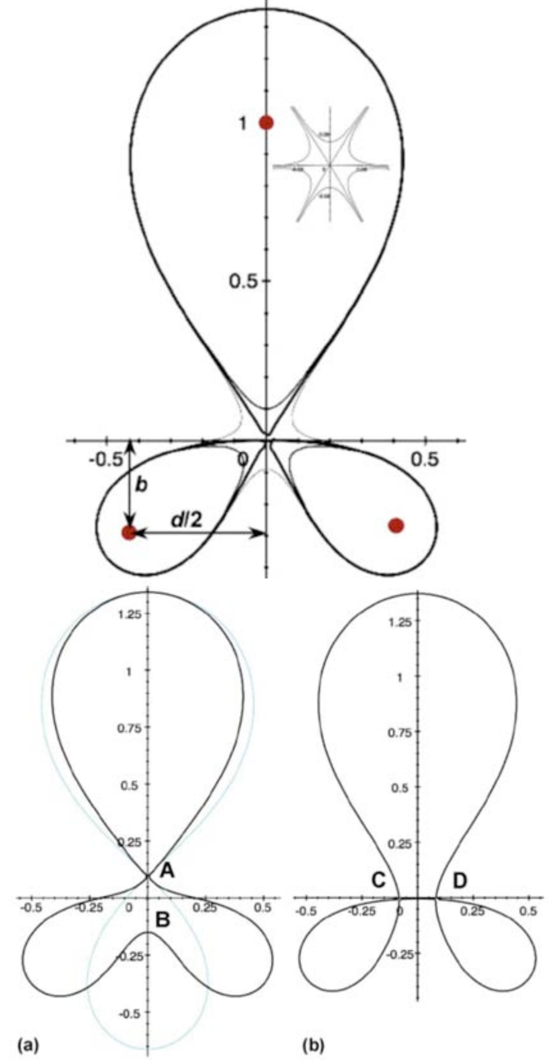
X-divertor



Super X-divertor



Snowflake divertors



Divertor and detachment Physics Plan

2009-2011

- Lower divertor power accountability and transient loading studies
- Improved detachment control for long pulse discharges
- Divertor performance dependence on geometry
- MARFE characterization studies
- Effect of 3-d fields on heat flux spreading

New tools: Fast IR camera (09), divertor bolometer (09), divertor imaging spectrometer (10)

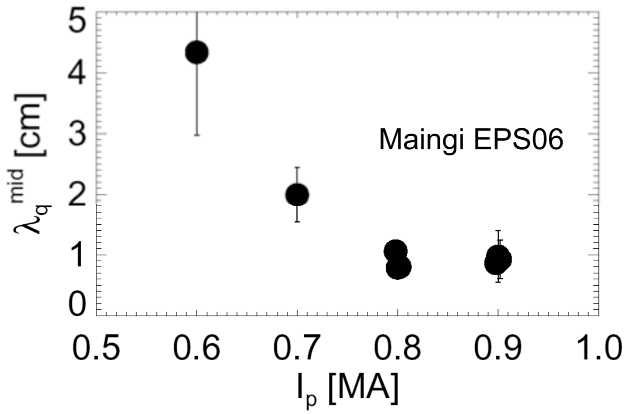
Once CS and NBI upgrades become available

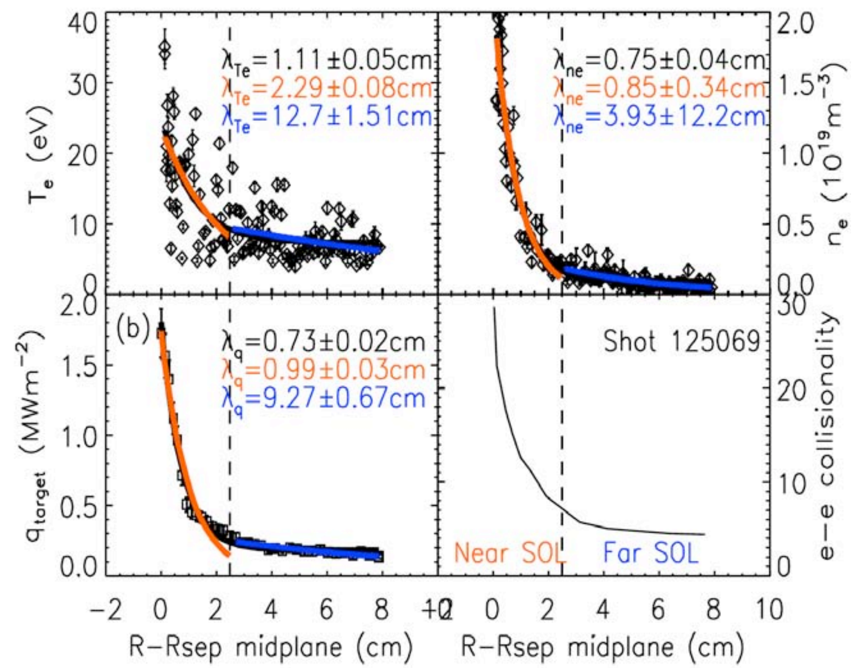
- Long pulse heat management at high I_p, B_t, P_{NBI}
- Private flux region physics studies

New tools: Long-pulse divertor, divertor Thomson, 2nd NBI, X-point/divertor VUV spectroscopy

Edge T & T studies will focus on connection between measured turbulence characteristics and SOL widths

- Dependence of heat flux width (λ_q^{mid}) not well understood in tokamaks
  - λ_q^{mid} larger in NSTX than high aspect ratio tokamak analytic scalings
  - Strong I_P dependence of NSTX λ_q^{mid}, but magnitude at high I_p overlaps with tokamak database
    - λ_q^{mid} further reduced by ~ 50% in lithium induced ELM-free H-modes
  - Ratio of λ_{Te}/λ_q consistent with electron conduction dominance in near SOL (Ahn, PoP 2008)
- Modeling of effect of turbulent transport on SOL widths commencing
  - Turbulence modeling already connecting to analytic theory of blob propagation
  - New BES system will augment gas-puff imaging for SOL turbulence measurement





Ahn PoP 08

Edge T & T Physics Plan

<u>2009-2010</u>

- Comparison of midplane and div. turbulence characteristics with models, e.g. blob behavior in highly radiative plasmas: SOLT(Lodestar), BOUT(LLNL)
- Scaling of midplane λ_n, λ_T, λ_Γ, λ_q with major parameters
  - Comparison with SOL width models: semi-analytic (ORNL/UCSD), 2-D SOLPS (ORNL) and UEDGE (LLNL), kinetic XGC-0 (CPES)
  - Comparison with turbulence characteristics
- Edge biasing with local electrodes and probes for SOL width control - convective cell generation test

New tools: fast IR camera (09), BES (10), divertor biasing capability (10), LLD(10)

<u>2011-2013</u>

- More detailed comparisons with above codes and new diagnostics; XGC-1 (CPES) turbulence code will also be used for detailed comparisons
- Upgraded biasing capability, if warranted

New tools: new divertor diagnostics

Outline

- SOL and divertor physics

- **Pedestal and ELM physics toward pedestal width prediction and improved understanding of ELM suppression**

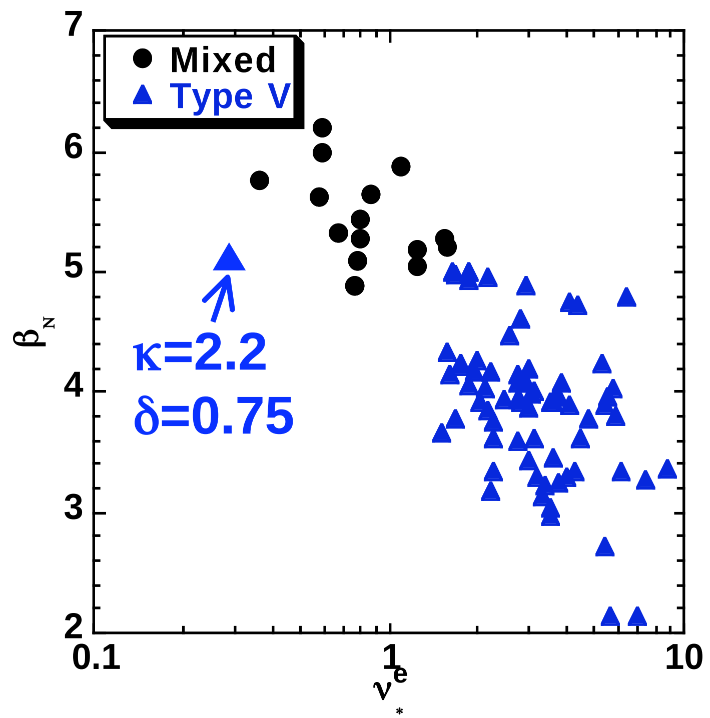
  ***** Critical for ITER: *limit on ELM $\Delta W/W_{tot}$ < 0.3%***

  - **Characterization and theory comparison at low R/a**
  - **Active control with 3-D fields**

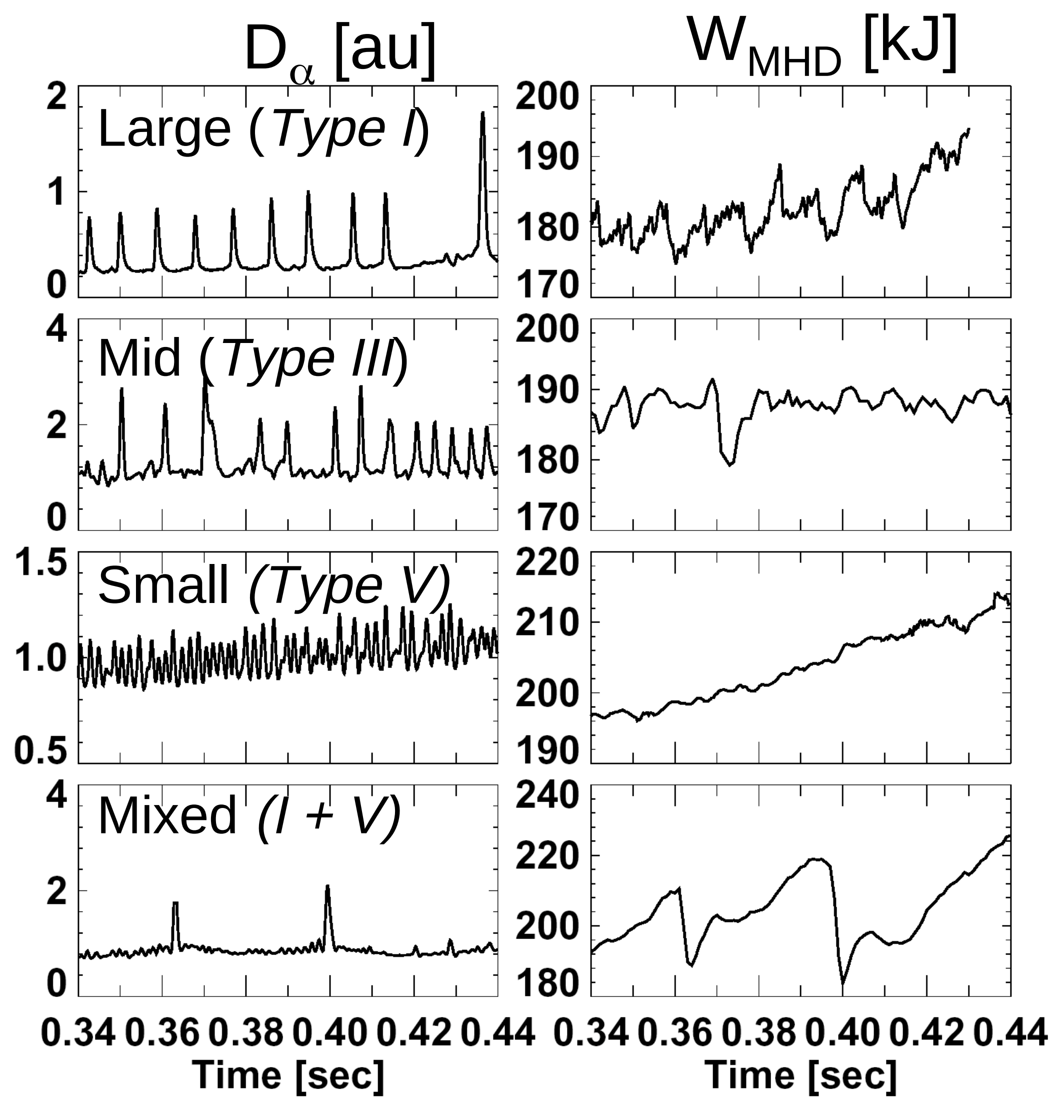
2011 JRT: (proposed) pedestal physics

Variety of ELM regimes observed in NSTX, with ELM size generally decreasing with collisionality

- Many ELM types observed in NSTX, including promising small ELM regime
- Occurrence of large ELMs at low ν^* motivates research



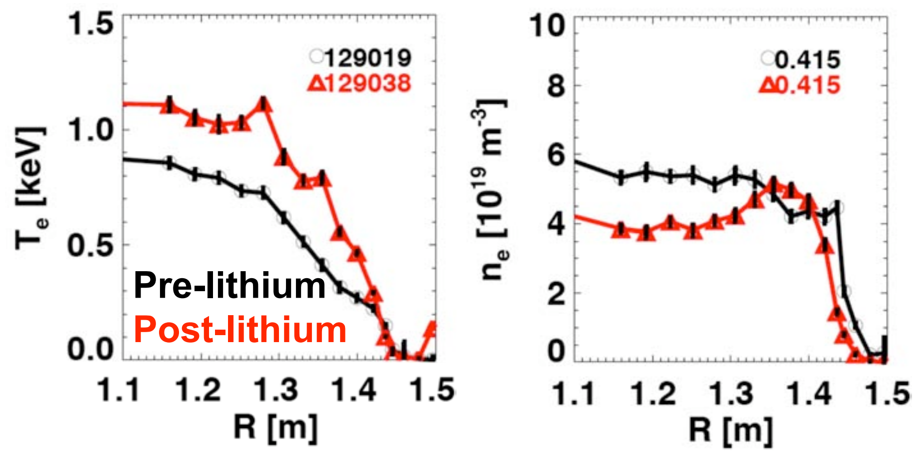
Maingi PoP06

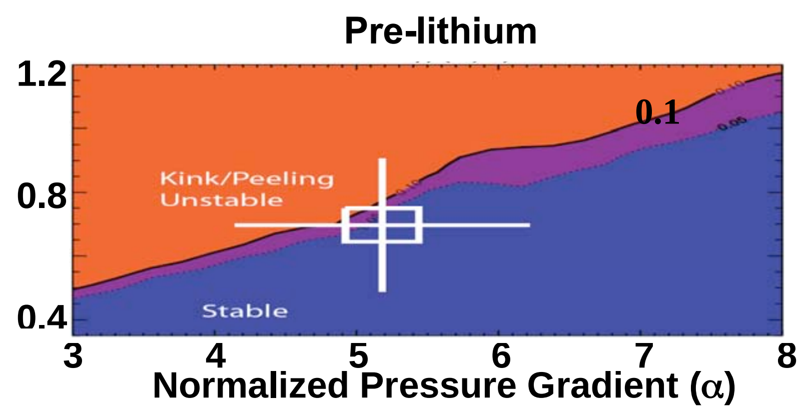


Studies of R/a pedestal dependencies aim to determine the range of applicability of edge stability models

- ELITE calculations suggest existence of high P_{ped} at low R/a and constant pedestal width
  - ➢ Requires low ν* -> high T_{ped}
- Pedestal dependence on R/a investigated in NSTX, DIII-D, and MAST through ITPA
  - – No clear evidence of larger pressure gradients at low R/a
- *Lithium conditioning eliminated ELMs*
  - – Density profile shift -> pressure profile broadening -> ELM stabilization (PEST)
  - – Mystery: diamagnetic stabilization predicted to stabilize peeling modes in pre-Lithium discharge also (ELITE)

• **Pedestal defined by 3 Thomson channels**
--> *More Thomson channels needed!*

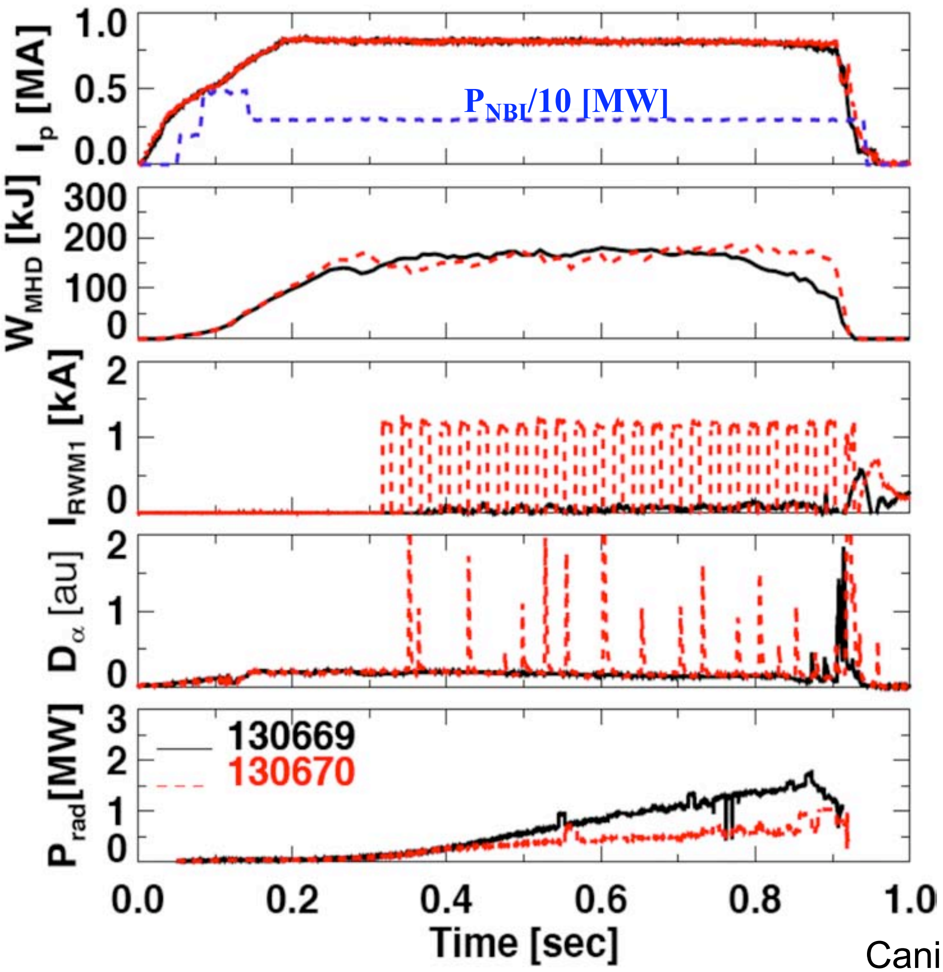




Maingi, PRL submitted

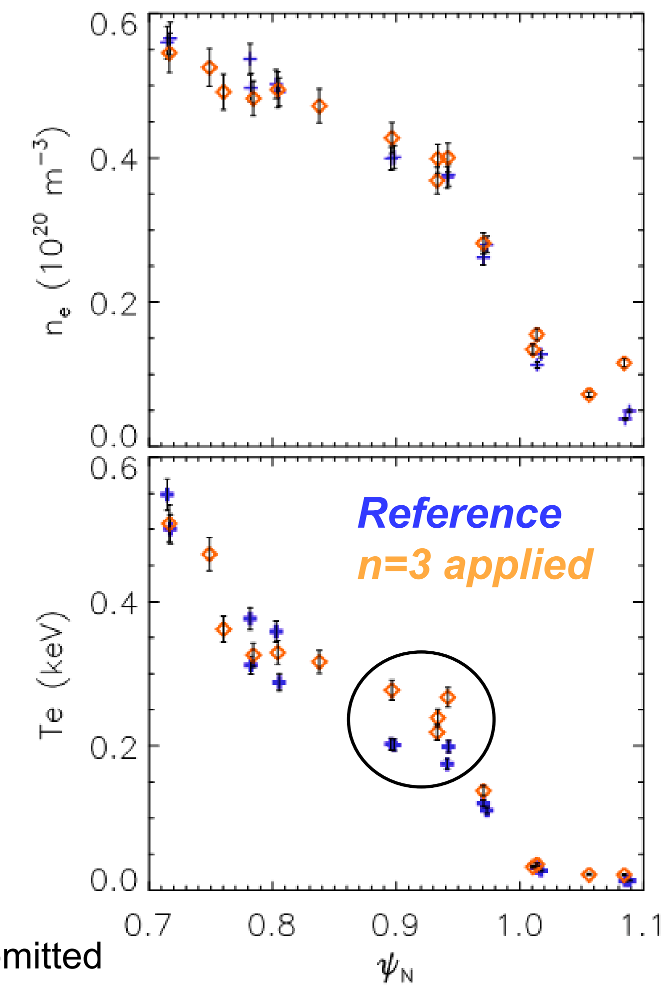
3-D fields used to alter ELM behavior - provides a possible scenario for impurity and radiation control of ELM-free Lithium discharges

Type I ELMs triggered for impurity control (post-lithium, n=3)



Canik, PRL submitted

Edge T_e and dT_e/dr increased --> n=3 more unstable (PEST)



ELM and Pedestal Physics plan

2009-2010

- Assess edge stability of different ELM types, including impact of aspect ratio on pedestal gradients and widths
- Identify dependence of ELMs on δ, κ, SN vs. DN
- Assess effect of lithium on ELM regimes
- Assess effects of 3d fields on edge stability
- Compare pedestal parameters with XGC-0

New tools: LLD (10), edge SXR for fast T_e reconstruction (10)

2011-13

- n=1 feedback with arbitrary n=2,3 for ELM stability (2nd SPA)
- High m,n RMP impact on ELMs and heat flux (internal coils)

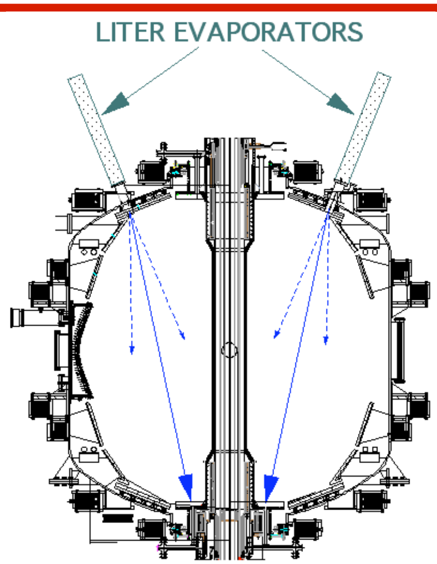
New tools: extra edge Thomson channels, NCC upgrade for higher m/n, new divertor diagnostics

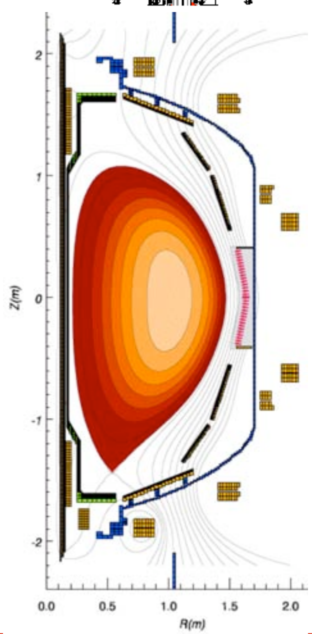
NSTX boundary physics program effectively utilizes facility and diagnostic enhancements in 2009-2011

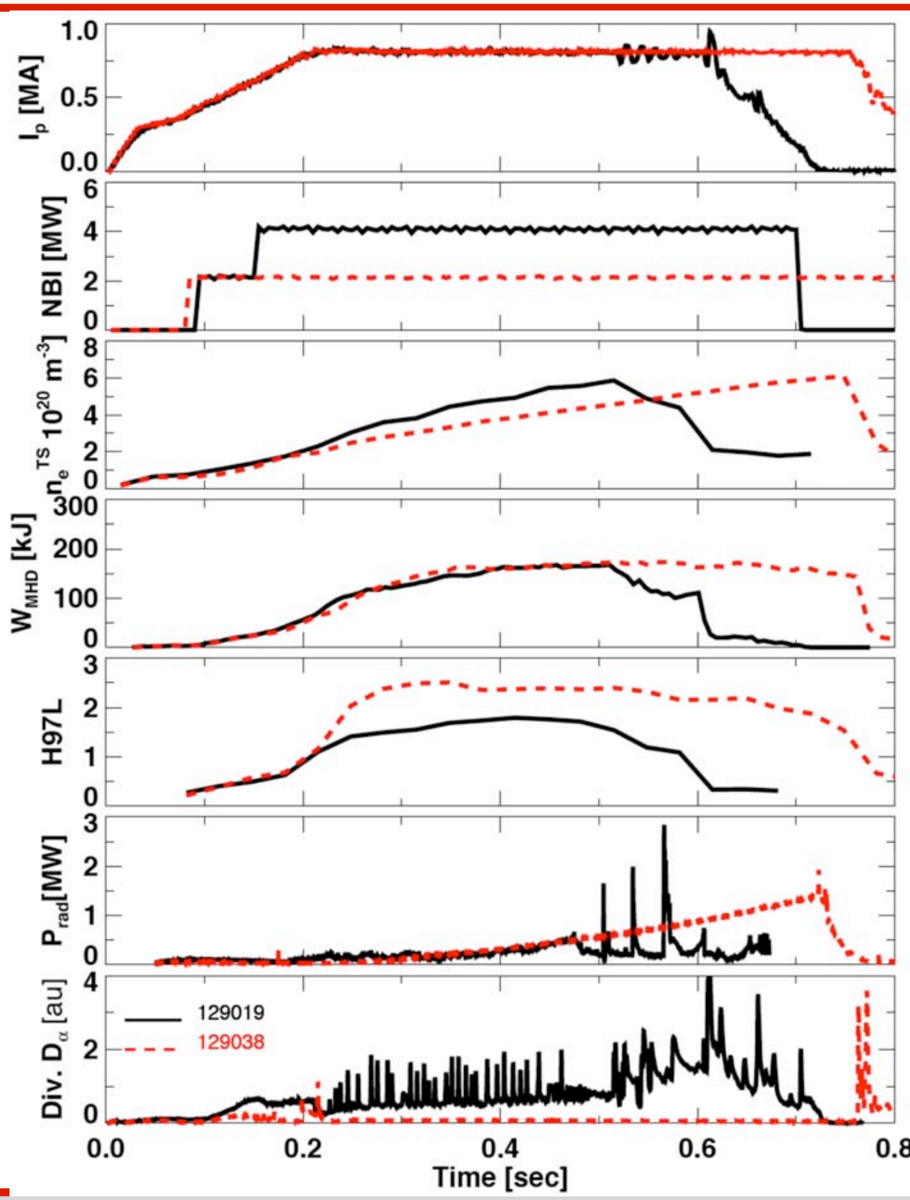
- Particle control and fueling program
  - Uses LLD and associated new diagnostics
- SOL and divertor physics for prediction of plasma-wall interaction footprint using theory-based cross-field transport models
  - Uses new diagnostics (e.g. BES, div. bolometry, fast IR camera, Ly-α)
  - *Additional edge Thomson channels (incremental) very important*
- Pedestal and ELM physics toward pedestal width prediction and improved understanding of ELM suppression
  - Uses new diagnostics
  - *Additional edge Thomson channels (incremental) critical*

Backup

ELM-free H-mode induced by lithium wall coatings

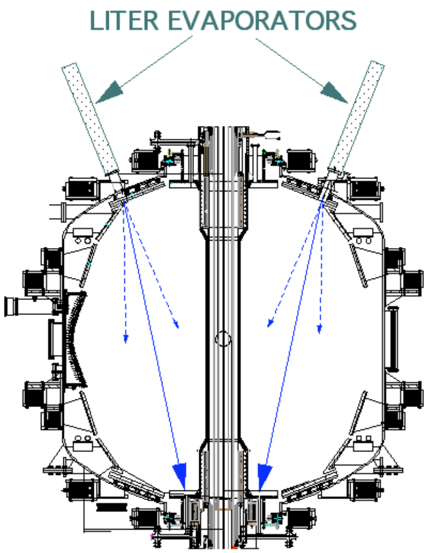


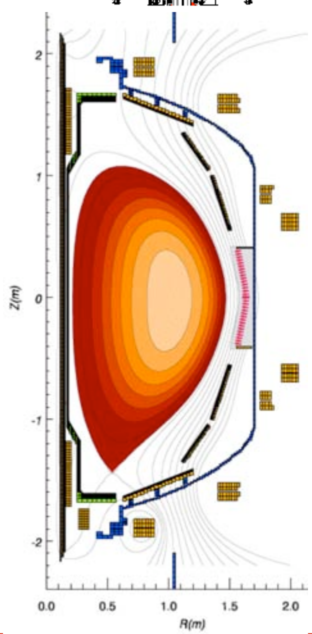


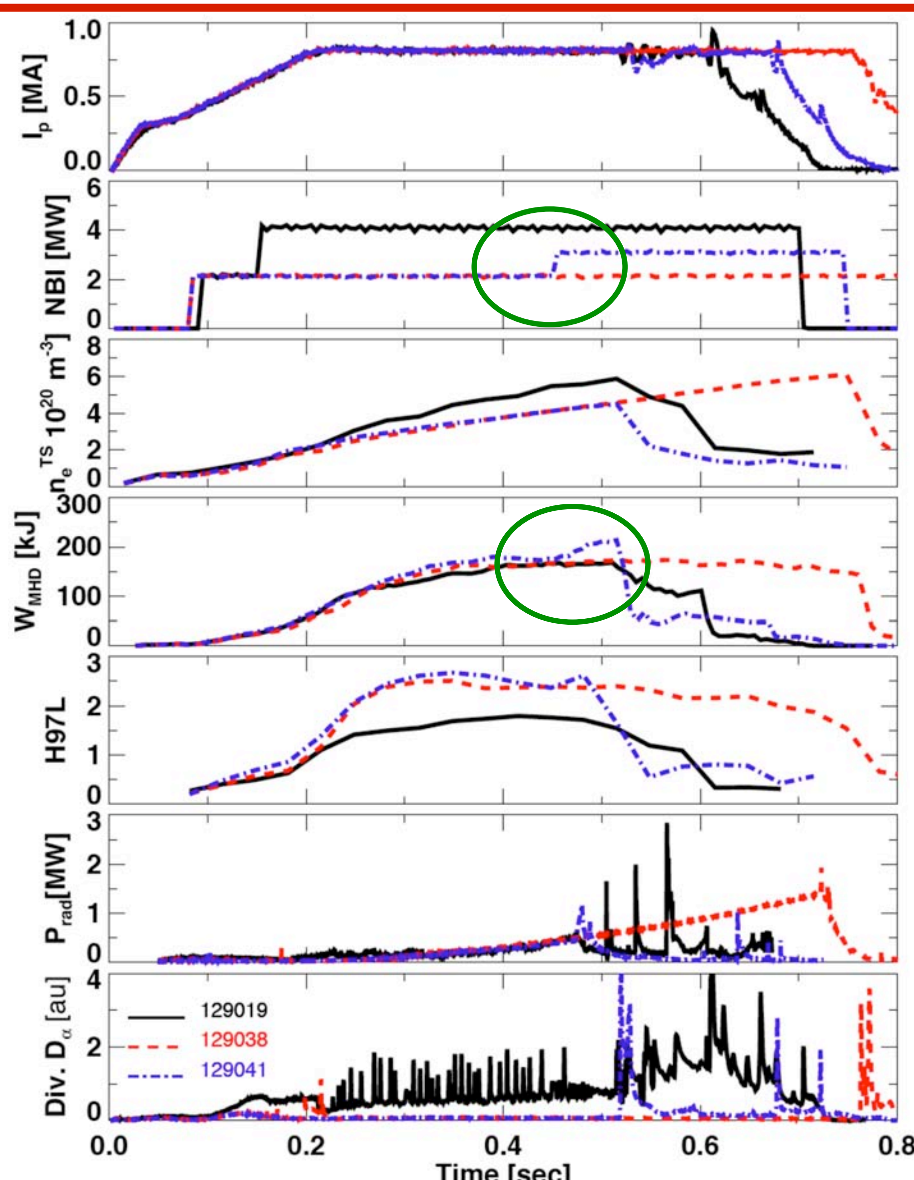


- Pre-Li, Post-Li
- Lower NBI to avoid β limit
- Lower n_e
- Similar stored energy
- H-factor 40%↑ (more than hi δ,κ)
- Higher P_{rad} /P_{heat}
- ELM-free, reduced divertor recycling

Global β_N limit encountered before edge stability limit with lithium coatings

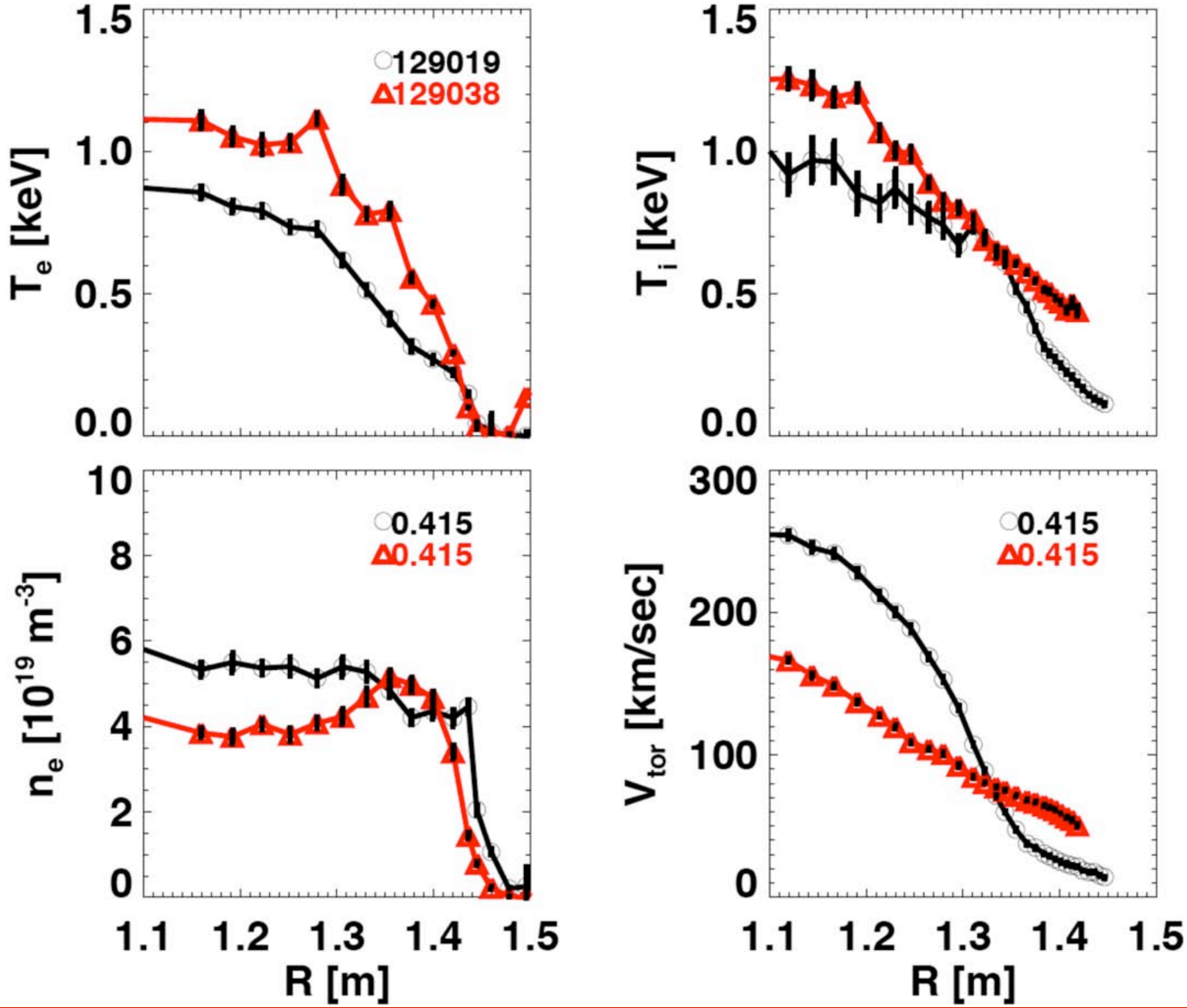






- Pre-Li, Post-li, Post-li at β limit
- Intermediate NBI to probe β limit
- β limit at P_{NBI}=3 MW (β_N =5.5)

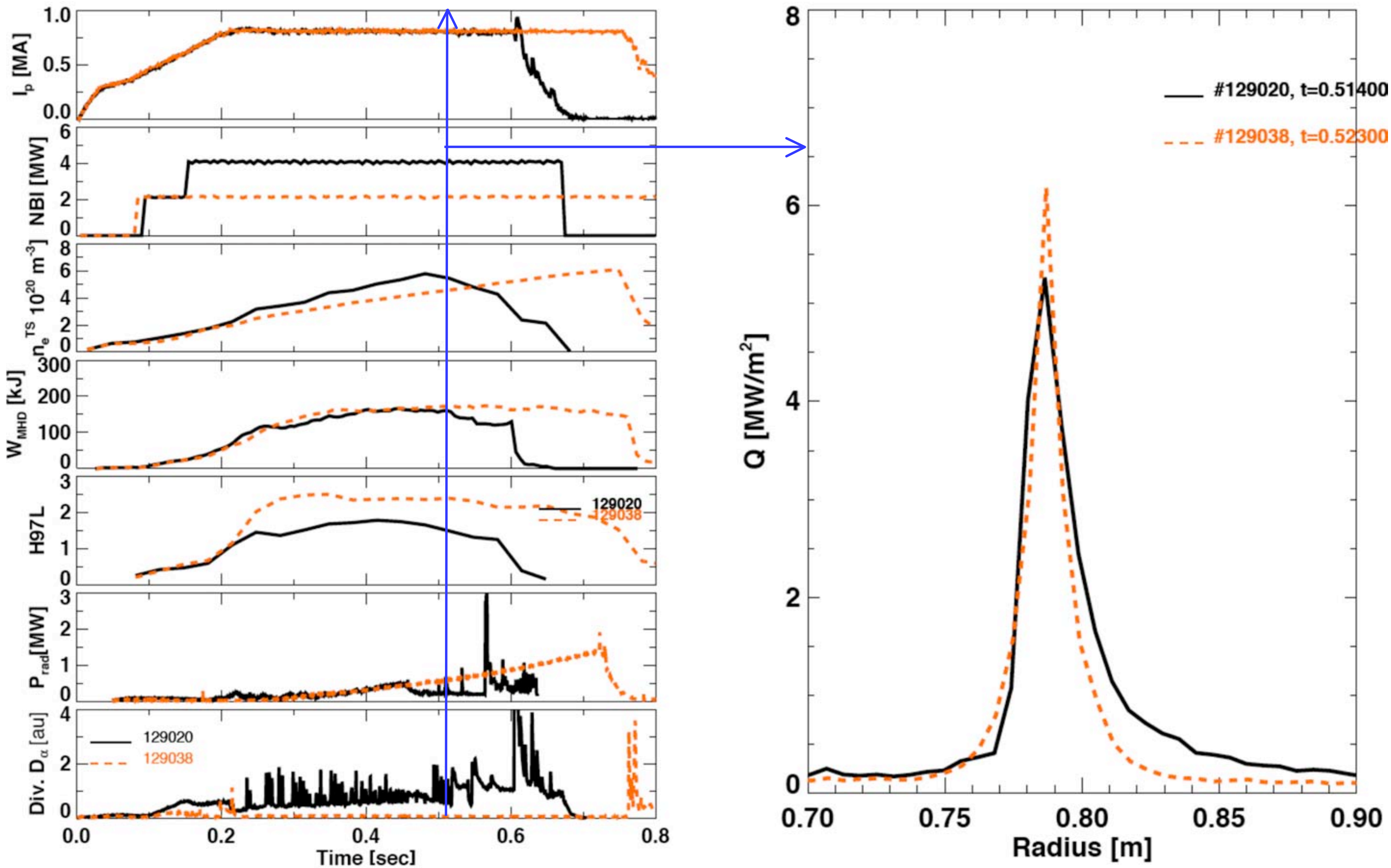
T_e, T_i increased and edge n_e decreased with lithium coatings



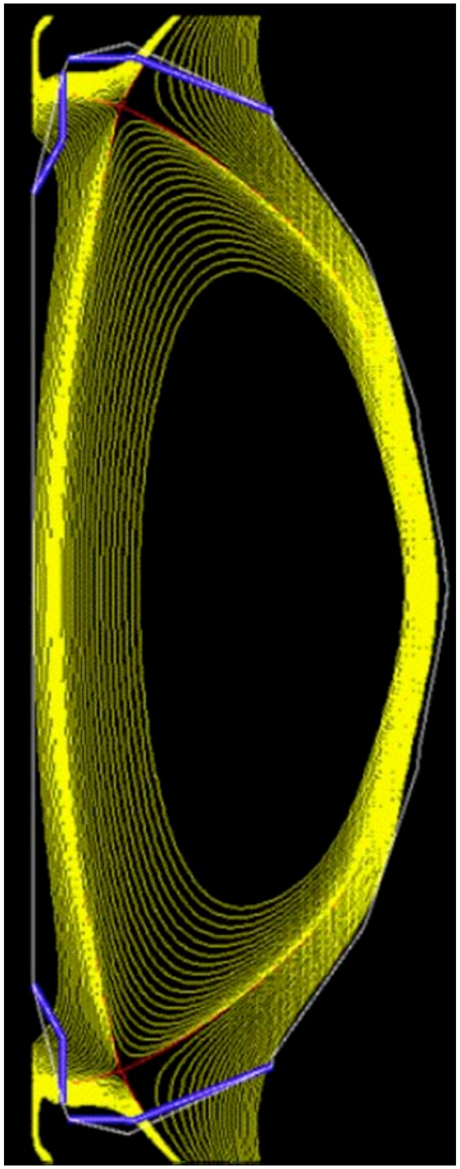
No lithium

With lithium

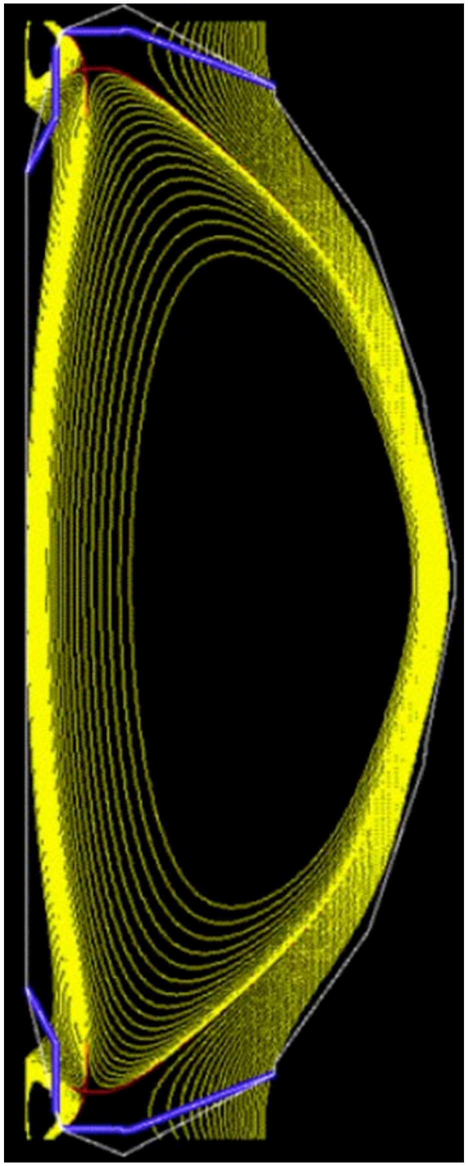
Heat flux profile becomes more peaked and triangular with Li-enhanced ELM-free operation



2-D edge transport calculations with SOLPS begun for two equilibria with new center stack

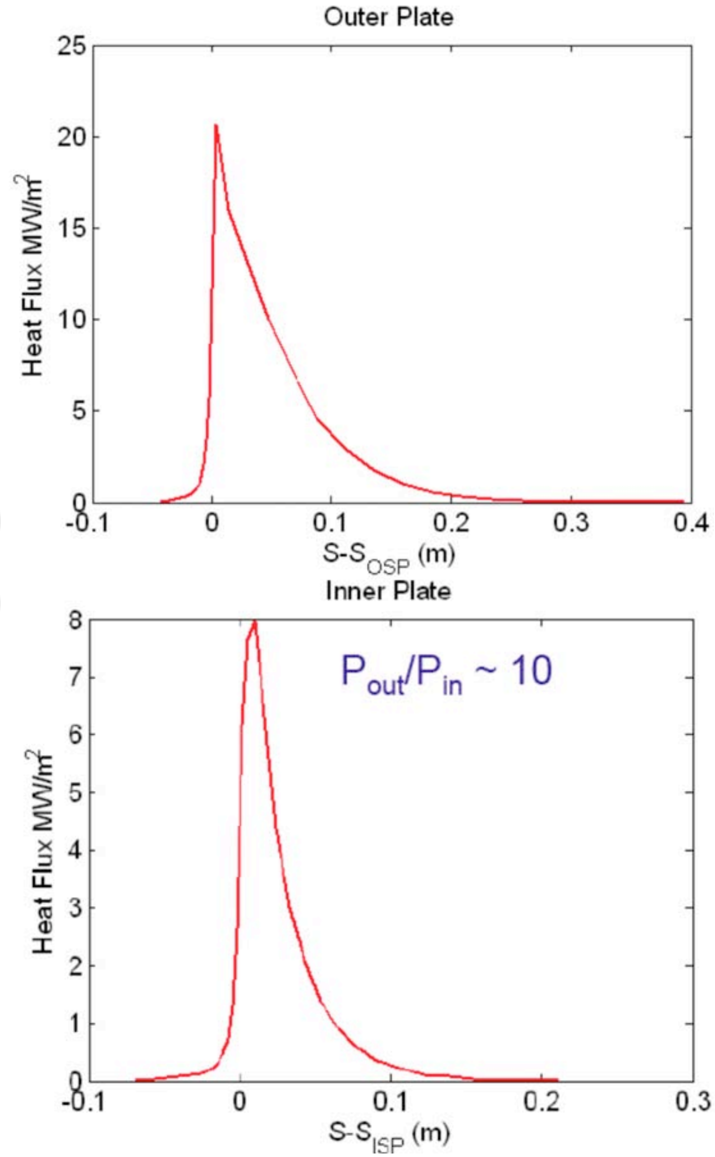


- Usual X-point (DN) with flux expansion ~ 20
- X-divertor like geometry with flux expansion ~ 60
  - Violates 1° min. angle criterion $B_\theta/|B|$



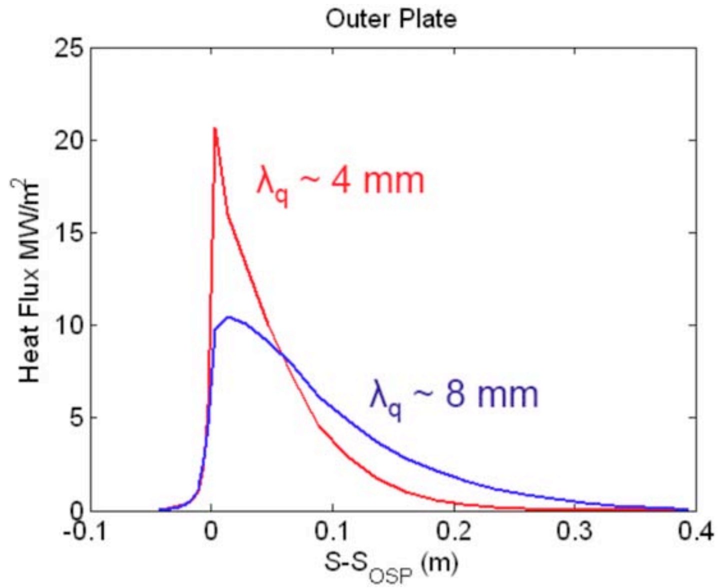
First calculations: heat flux predicted to peak at outer divertor (normal flux expansion case)

Input power: 16 MW
Ped. Density = 10^{20}
-> sep density ~ 2-3x10^{19}
"Low" recycling: outer plates R=0.95
inner plates R=0.98
ITER transport coeffs:
D=0.3, χ=1.0 m^2/s

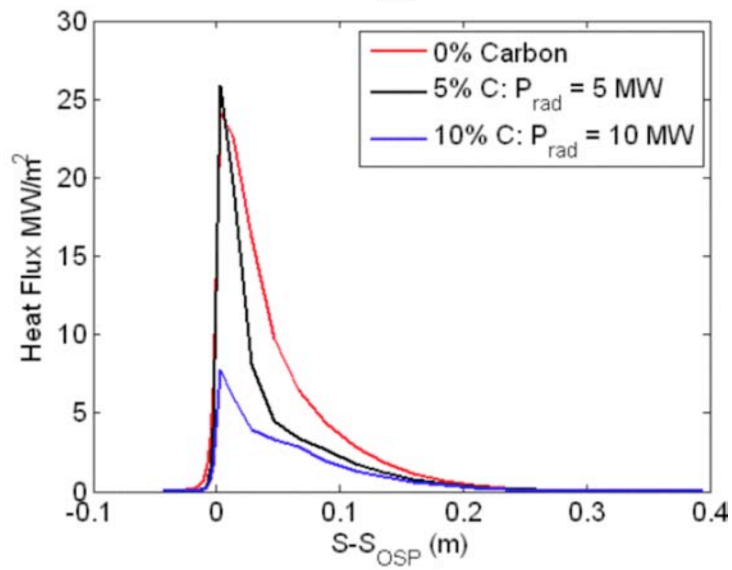


Heat flux can be reduced by either higher cross-field transport or higher recycling/radiation (normal flux expansion)

- D, χ increased by factor of 4
  - SOL widths double
  - Peak heat flux decreased



- Target recycling coefficient increased R=0.99 and carbon concentration varied
  - Need lots of carbon to bring down q_{peak}

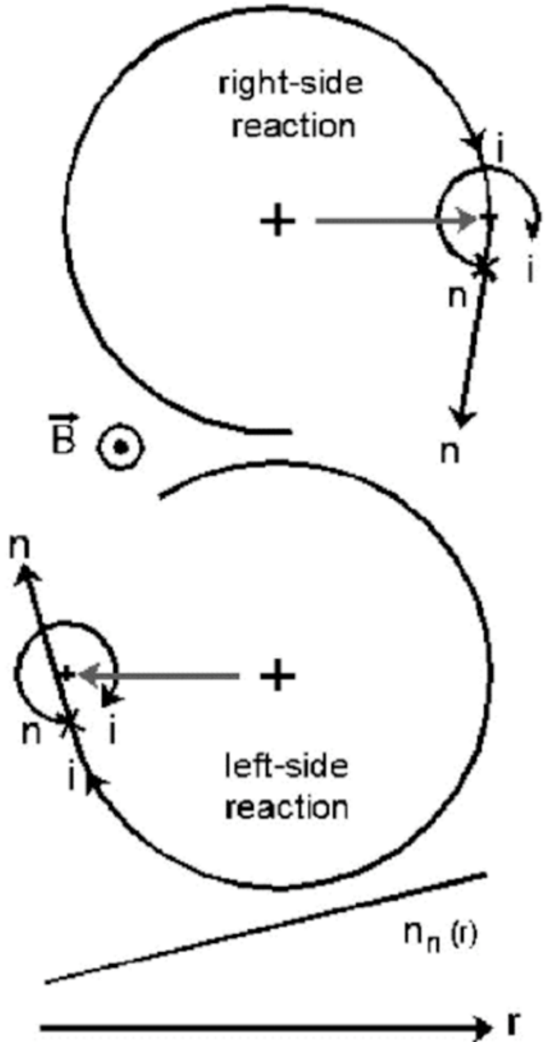


L-H studies focus on main parametric dependencies

- Measure empirical dependencies of L-H transition power on shape, rotation, and major external parameters (I_p, B_t, n_e)
- Test recent L-H theories, e.g. Gyro-center shift theory for origin of E_r

New tools: new divertor and X-point diagnostics, center stack upgrade for wider I_p, B_t *range*

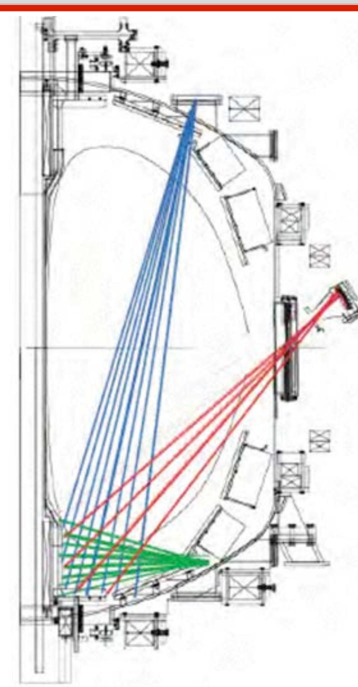
Gyro-center shift theory



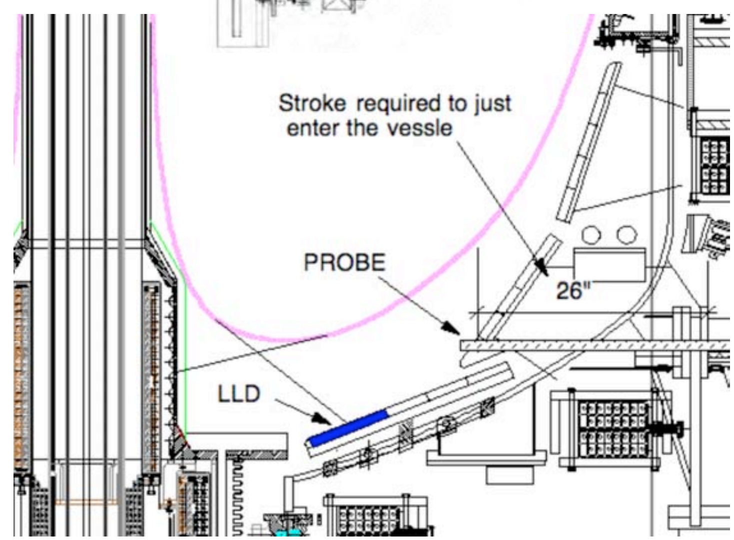
KC Lee, PoP06

Divertor bolometer and surface probe diagnostics

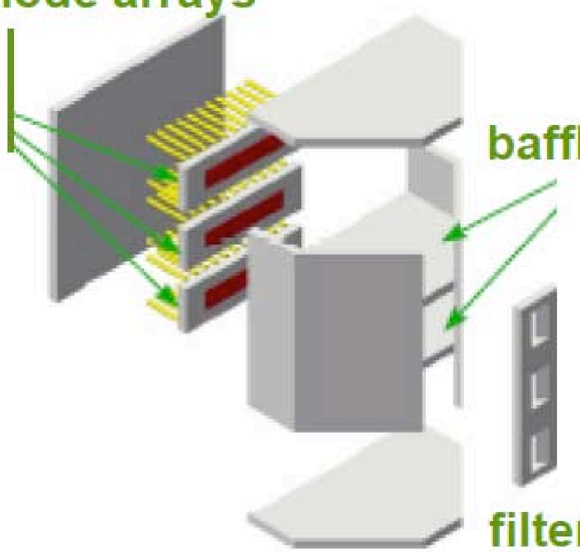
- Divertor bolometer upgrade for improved power balance analysis
  - 3 crossing views for 2-D profiles

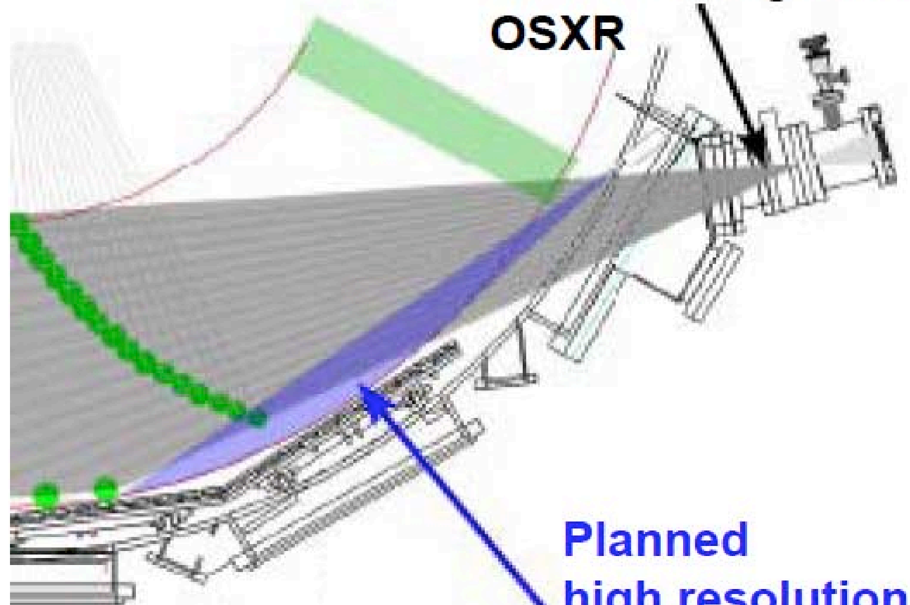


- Surface analysis probe for erosion redeposition modeling
  - Collaboration with Purdue U.



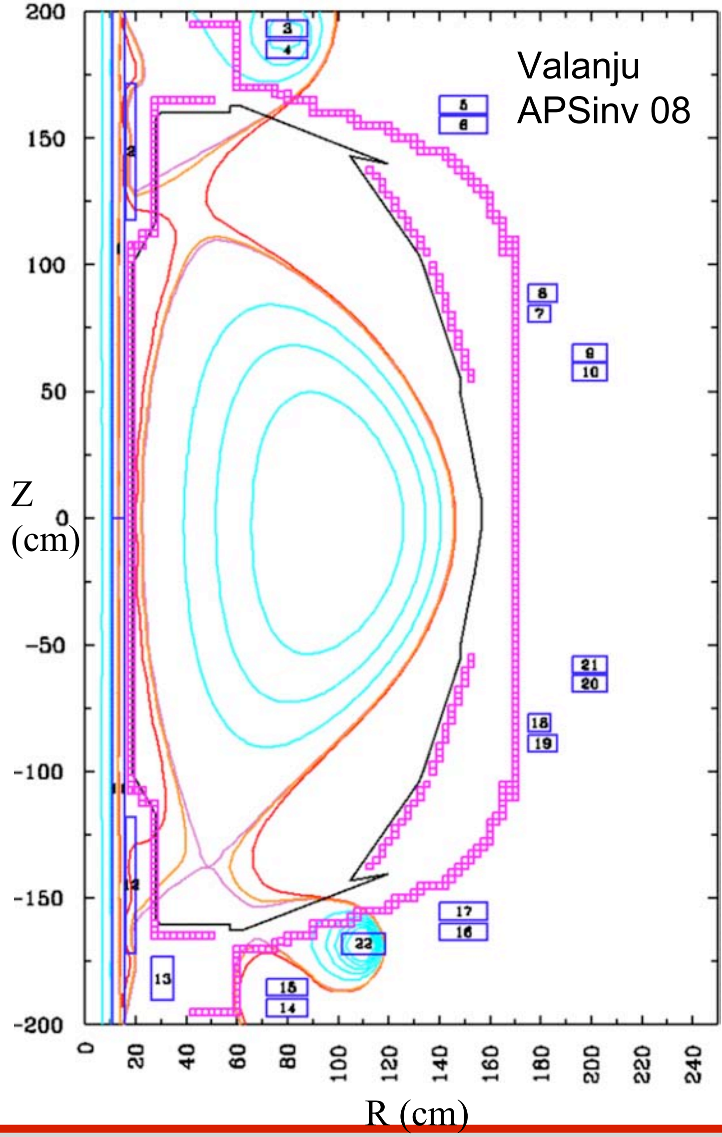
High resolution tangential SXR system (Johns Hopkins) will provide fast Te with good spatial resolution for pedestal studies



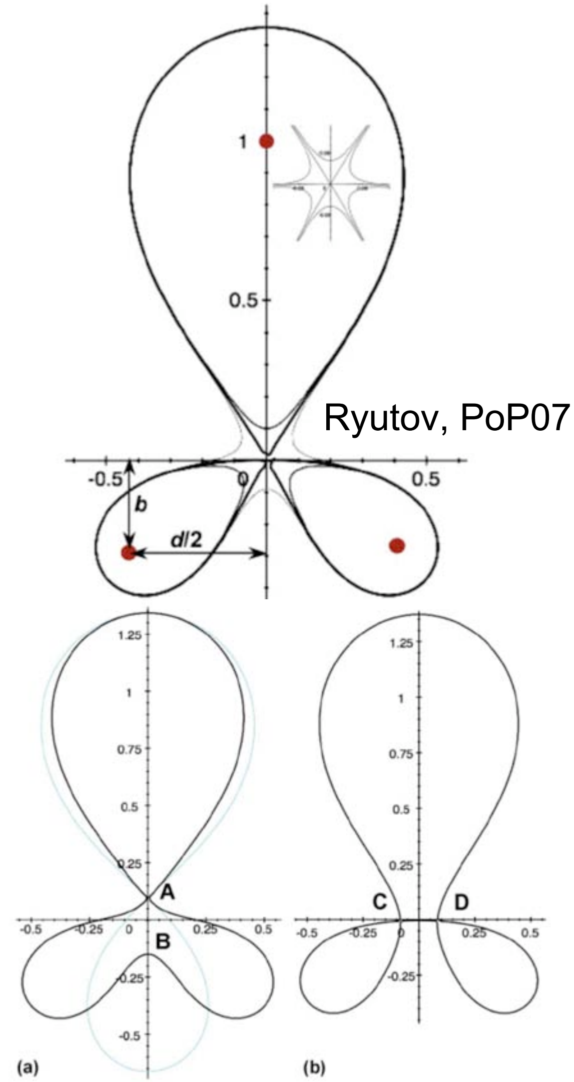


- $T_e(r,t)$ with ≤ 1 cm, few μs resolution (n_e, n_z with $\int ne\, dl$ constraint)
- Extend core electron/particle transport studies to pedestal (ELM, pellet)
- ELM structure, precursors, non-thermal electron distribution
- Develop ME-SXR for feedback and control (ELM, position, RWM)

Novel divertors may be required for heat flux management in NSTX-U



- X-divertor possible with center stack upgrade
- Super-X divertor with incremental budget (left)
- Snowflake divertor being assessed (right)



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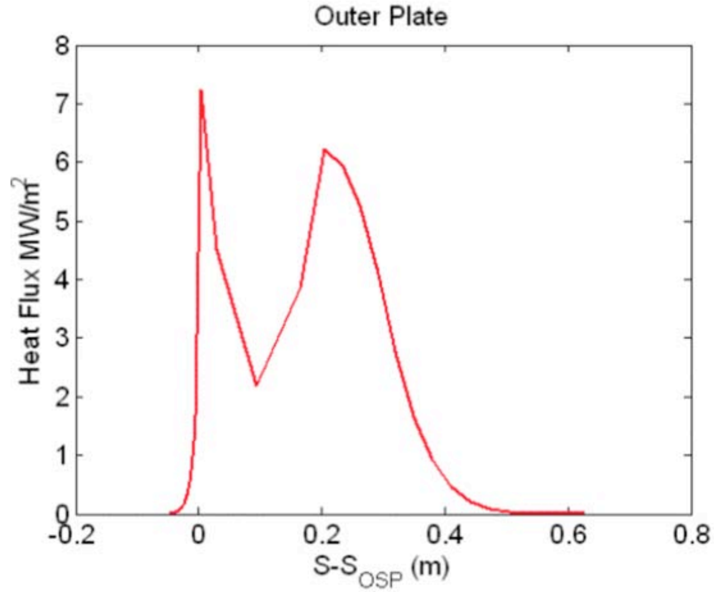
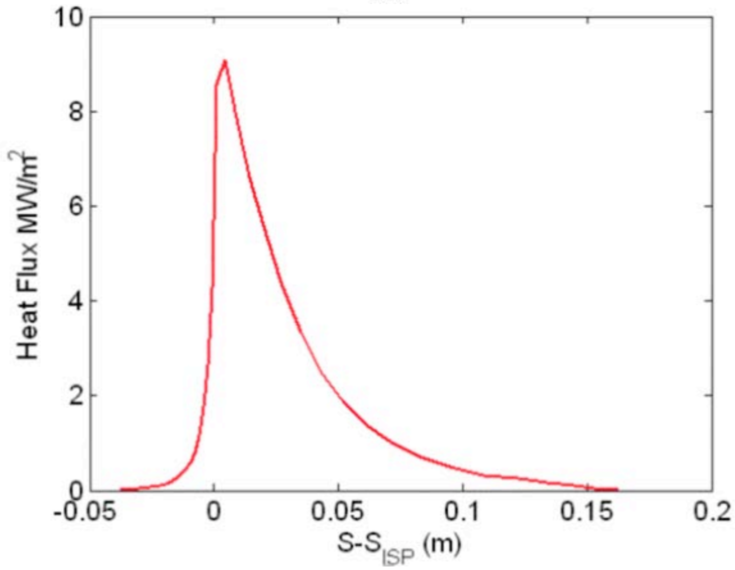
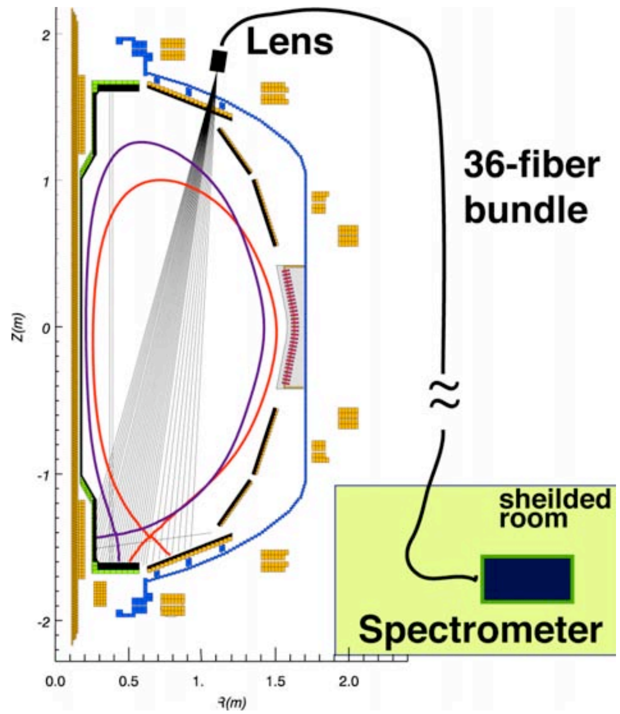


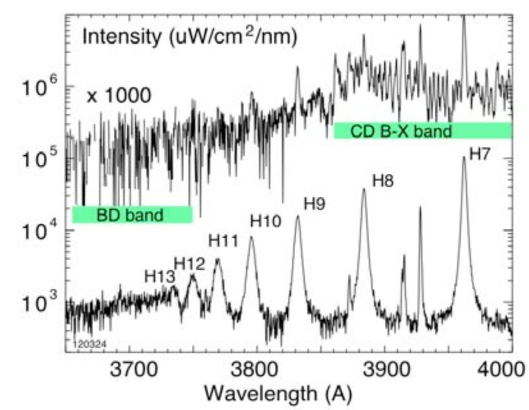


- Outer divertor and inner divertor peak heat flux comparable
- Caveat: configuration violates 1^o engineering min. angle criterion $B_\theta/|B|$
  - Angle highly dependent on $S\text{-}S_{OSP}$ for outer divertor, from 0.1-0.5^o
  - Profiles at midplane are exponential and monotonic

Divertor spectrometer will provide new divertor measurement capabilities needed for detailed divertor studies

- Divertor plasma profiles - T_i, n_e, T_e, v, Γ_i
  - —Line and continuum profiles
  - —Spectral line Doppler broadening for T_i profiles
  - —Spectral line Doppler shift measurements for flow velocities
  - —Balmer or Paschen series line broadening for n_e profiles, line intensities for T_e profiles in recombining divertor
  - —Particle influx profiles - molecular, neutral, impurity ions
- Fiber-optic array is already installed on NSTX
- Prototype of ITER divertor monitor

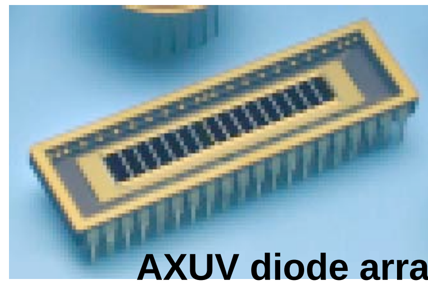




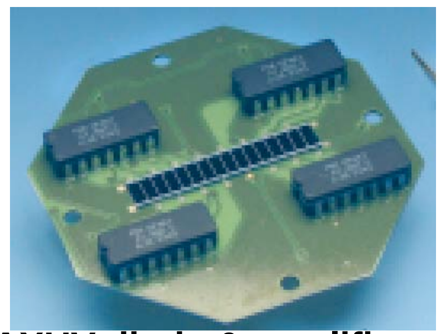
Ly-α array will be used for recycling measurements from highly reflective LLD

- Mirror-like LLD surface will complicate interpretation of visible (400-750 nm) spectroscopic diagnostics

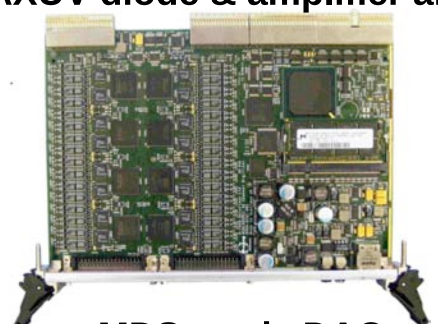
- AXUV diode arrays with bandpass filters measure Ly-α *n*=1-2 H/D transition at 121.6 nm, where reflections are negligible



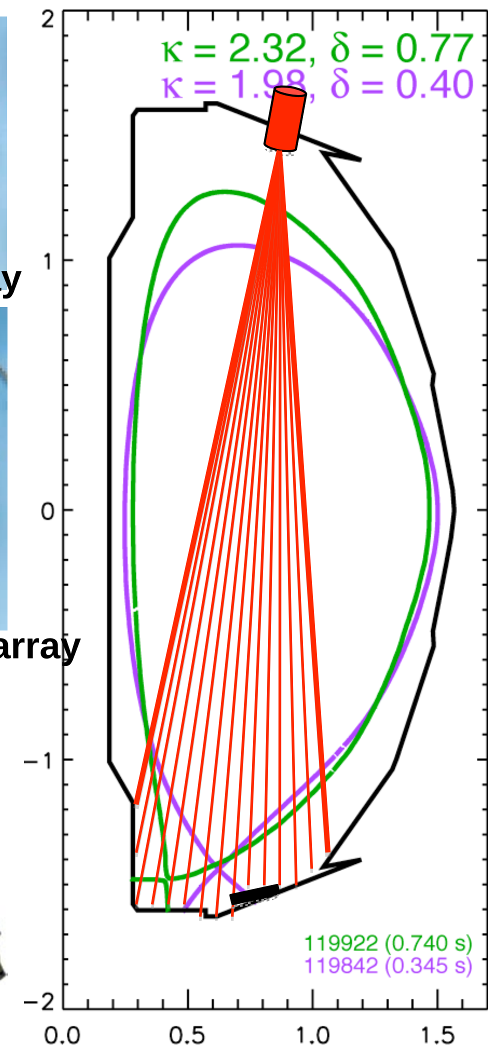
AXUV diode array



AXUV diode & amplifier array

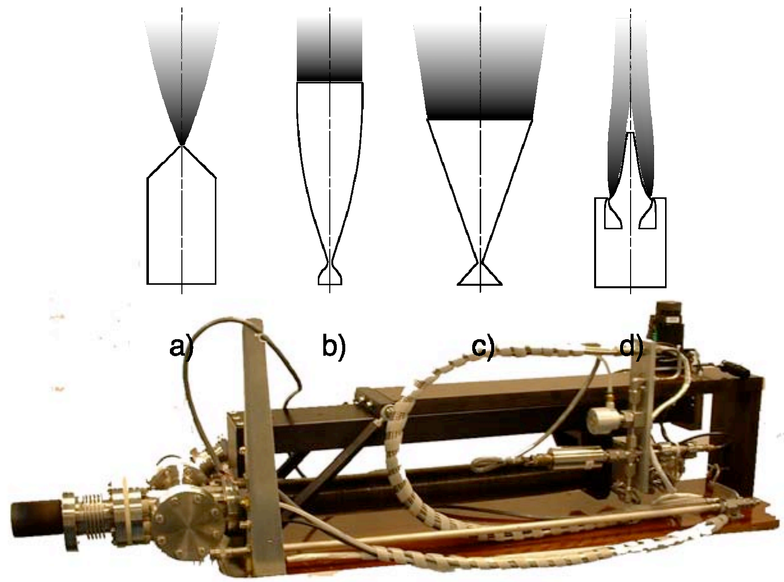


MDS-ready DAQ



Supersonic Gas Injector will be upgraded to improve fueling efficiency

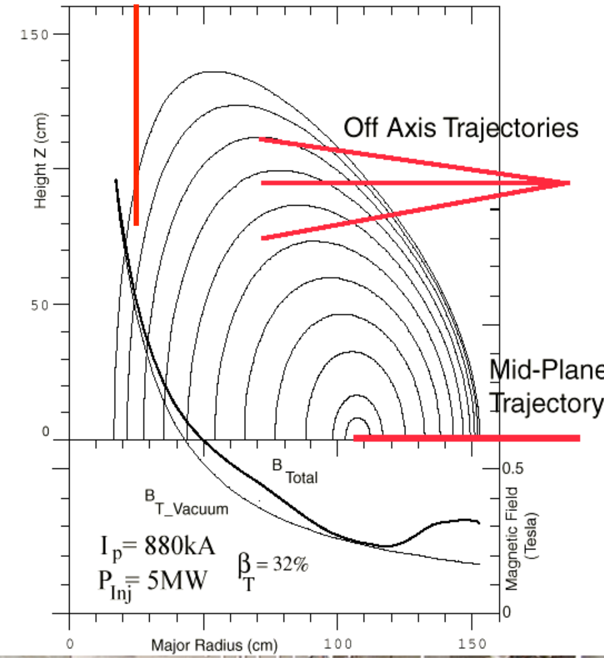
- Present capabilities
  - Controllable calibrated flow rate
    Γ = 10 - 200 Torr l / s
  - Multi-pulse control
  - Controllable radial position
  - High H-mode fueling efficiency 0.1-0.4

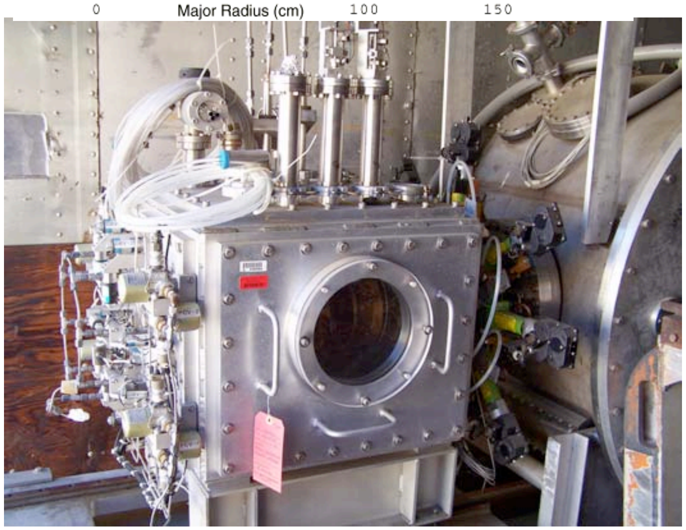


Upgrade	Benefit
PCS feedback & control	Fueling control
New nozzle design for increased gas jet density	Higher fueling efficiency
Cryogenic nozzle for deuterium molecular cluster formation	Higher fueling efficiency
Compactness for possible placement in new CS	H-mode access and fueling

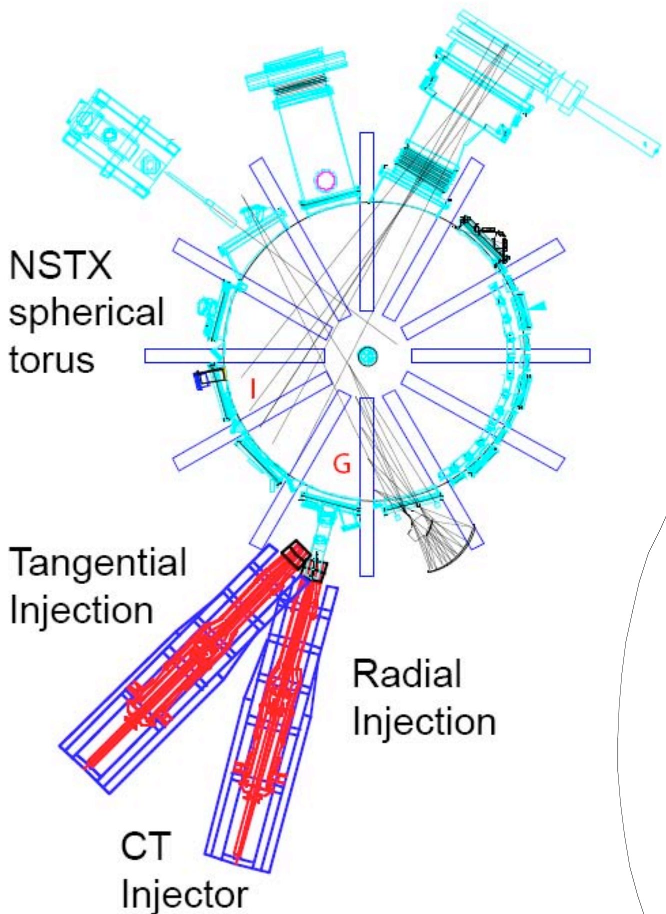
Compact Pellet Injection System planned for NSTX

- **NSTX machine size and target plasmas well matched to simplified pellet injection system**
  - **8 - barrels , 1.0 - 2.7 mm diameter ($5x10^{19}$ – $9x10^{20}$ atoms), 200-1500 m/sec pellet speed**
  - **High β discharges can have a |B| well, such that pellet drift could be inward, even from outer midplane**
- **Simplified advanced design utilizes self contained LHe refrigerator – external LHe supply not required**
- **Several trajectories possible - innermost one part of center stack upgrade**



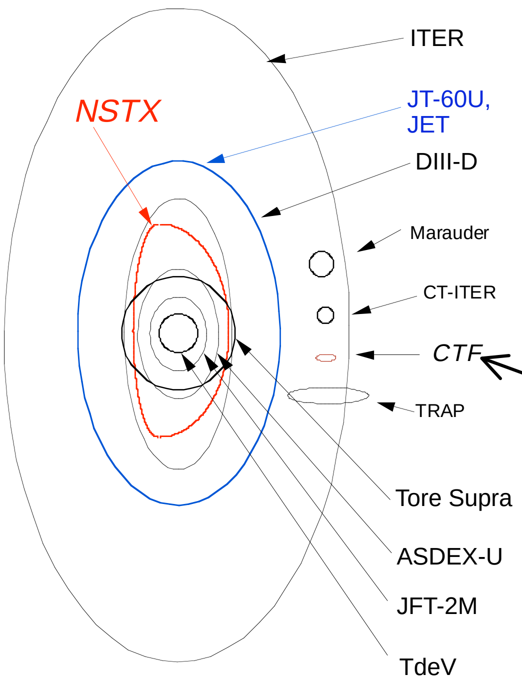


A Compact Toroid injection system could provide real-time density profile control with momentum injection



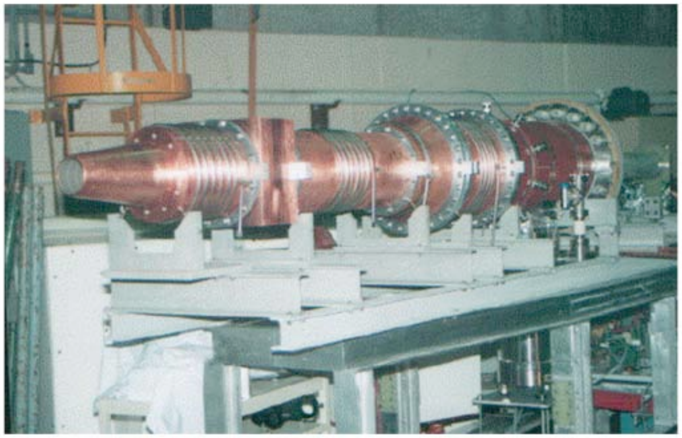
R. Raman, Advanced Fuelling System for use as a Burn Control Tool in a Burning Plasma Device, Fusion Science and Technology, 50 (2006) pg. 84

- Research Plan:
  - Establish localized fueling and conduct transport studies
  - Establish momentum injection
  - Establish multi-pulse fueling



* Previous facilities too small to study localized core fuelling

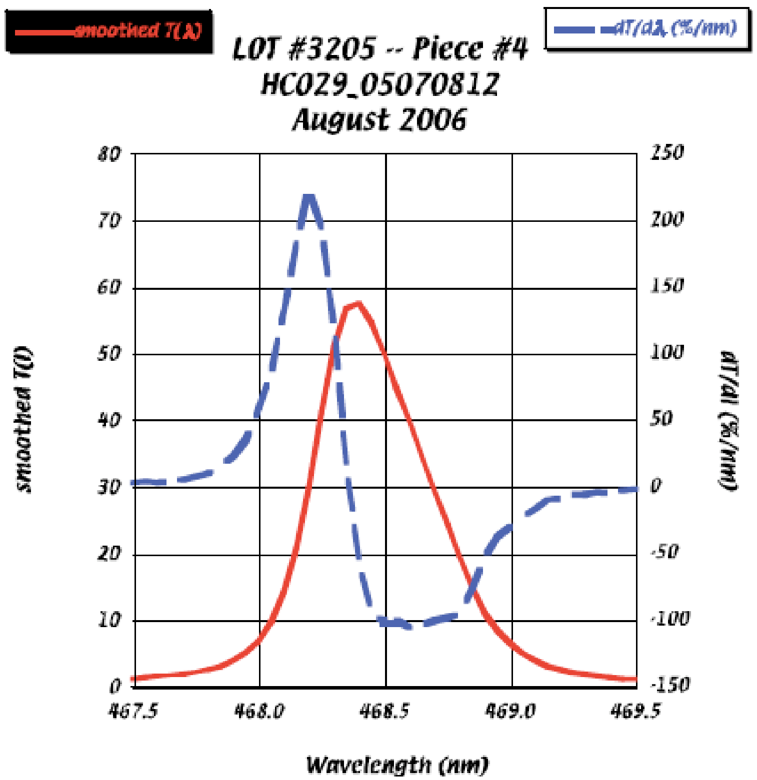
The CTF-II injector (in storage at PPPL)

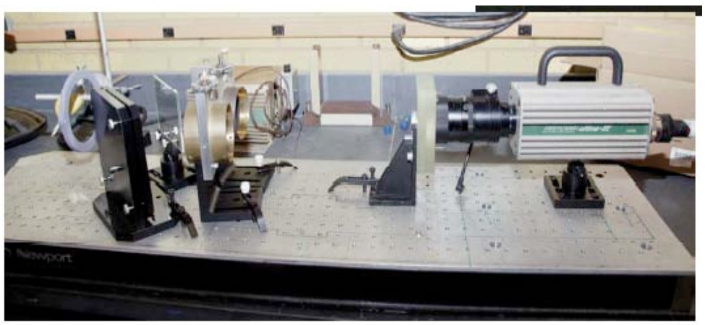


Novel SWIFT diagnostic enables measurements of 2-D flow patterns in edge

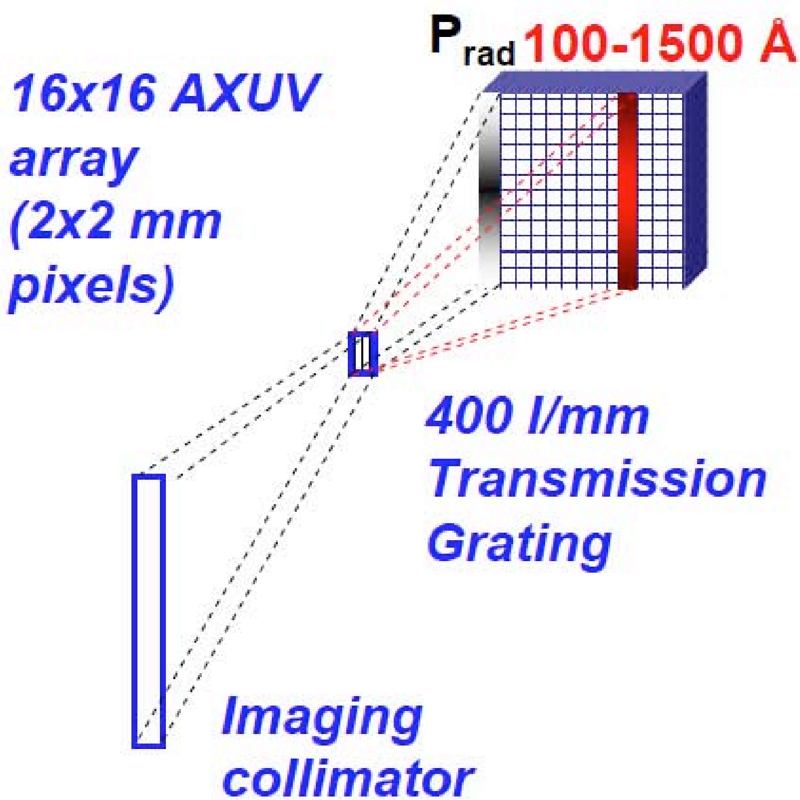
- Diagnostic images flowing plasma

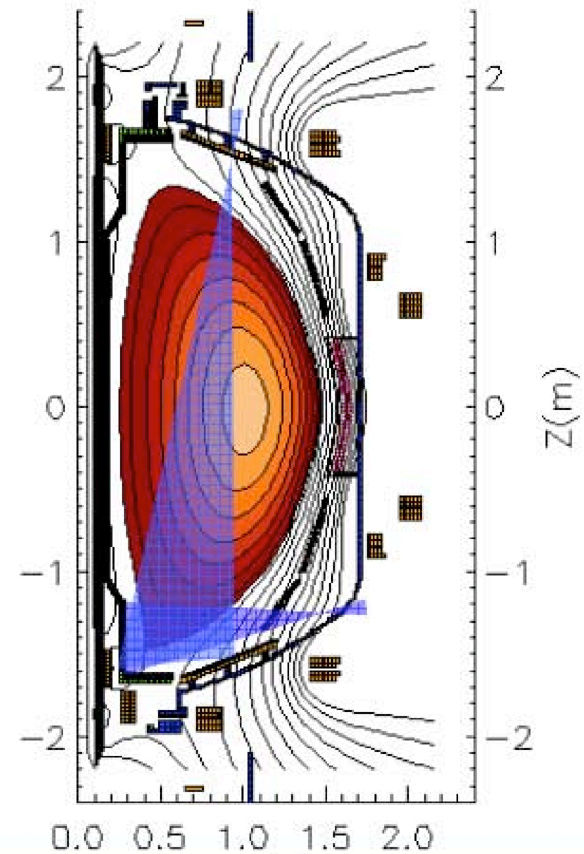
- Based on Doppler shift of He II line measurements with crossed interference filters





Divertor SXR system (Johns Hopkins - incremental budget) will provide divertor n_e, Te





- Narrow-band (80-100 Å) 'radiometers' based on VUV TG + AXUV diodes
- 2-D T_e, n_z, n_e (in conjunction with TS, $\int n_e dl$, or spectroscopy constraint)

Combination of center stack upgrade (2 MA, 1 T), 2nd NBI , and successful density control program allows access to wide collisionality range

- Low ν^* affects:
  - Pedestal bootstrap current, which in turn determines peeling/ballooning stability for Type I ELM onset
  - Pedestal transport
  - Scrape-off layer transport, both parallel and cross-field
  - Ability to mitigate divertor heat flux through radiation and detachment