Transport & Turbulence and Boundary Physics Five Year Plan (FY '04-'08)

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NSTX parameters challenge existing theory framework

- Local $\square_t$ $\square$ 100%
- Trapped particle fraction $\square$ 1
- $\square_i$/L~0.2 (near edge); $\square_i$~1 - 3 cm
- High $\square$B, ExB flow (>200 km/sec) $\square$ flow shear (10^5 to 10^6/sec)
- V_{fast}/v_{Alfven} ~3 to 4
- $\square_{fast}$/a~1/5-1/3

Validity of present gyrokinetic treatment

NSTX transport goals aim to determine attractiveness of the ST and contribute to toroidal transport physics

- Establish key global ($□_E$) and local (□) transport scalings
  - e^- vs i^+ transport, dependence on $□^{□}$, $□_T$, $□_{ExB}$
- Assess roles of low- and high-k turbulence in heating and transport
- Assess fast ion confinement
  - Influence on neoclassical, turbulent heating and transport
- Determine influence of E_r ($□_{ExB}$) on turbulence, L-H

Use knowledge gained to control plasma transport

Produce p(r), j(r), for high $□_T$, non-inductive current

Transport & Turbulence contributes to integration goals through H-factor and bootstrap current control

NSTX

IPPA attractiveness; stability and high beta, $\tau_{pulse} >> \tau_E$

IPPA: extrapolable, $\tau_{pulse} >> \tau_{skin}$, high performance

FY02 | 03 | 04 | 05 | 06 | 07 | 08 | 09

Understanding

P(r),J_{BS} optimize

Feedback with heating, CD, V_ϕ, fueling

Transport & turbulence relation
Low/high k spectra theory/experiment

Momentum & power balance, local transport studies, H-mode physics

Global confinement scalings

Integration

Highest performance

- **β_T = 30%, Δt > τ_E**
- **β_N = 5: > no wall limit**
- **HH = 1**

- **β_T = 40%,**
- **β_N = 8**
- **Δt >> τ_E , *HH = 1.4***

Solenoid-free

- **J_{NI} > 60%, Δt ~ τ_{skin}**
- **Non-solenoid startup demo**

- **J_{NI} ~ 100%, Δt > τ_{skin}**
- **Solenoid-free up to hi I_p**

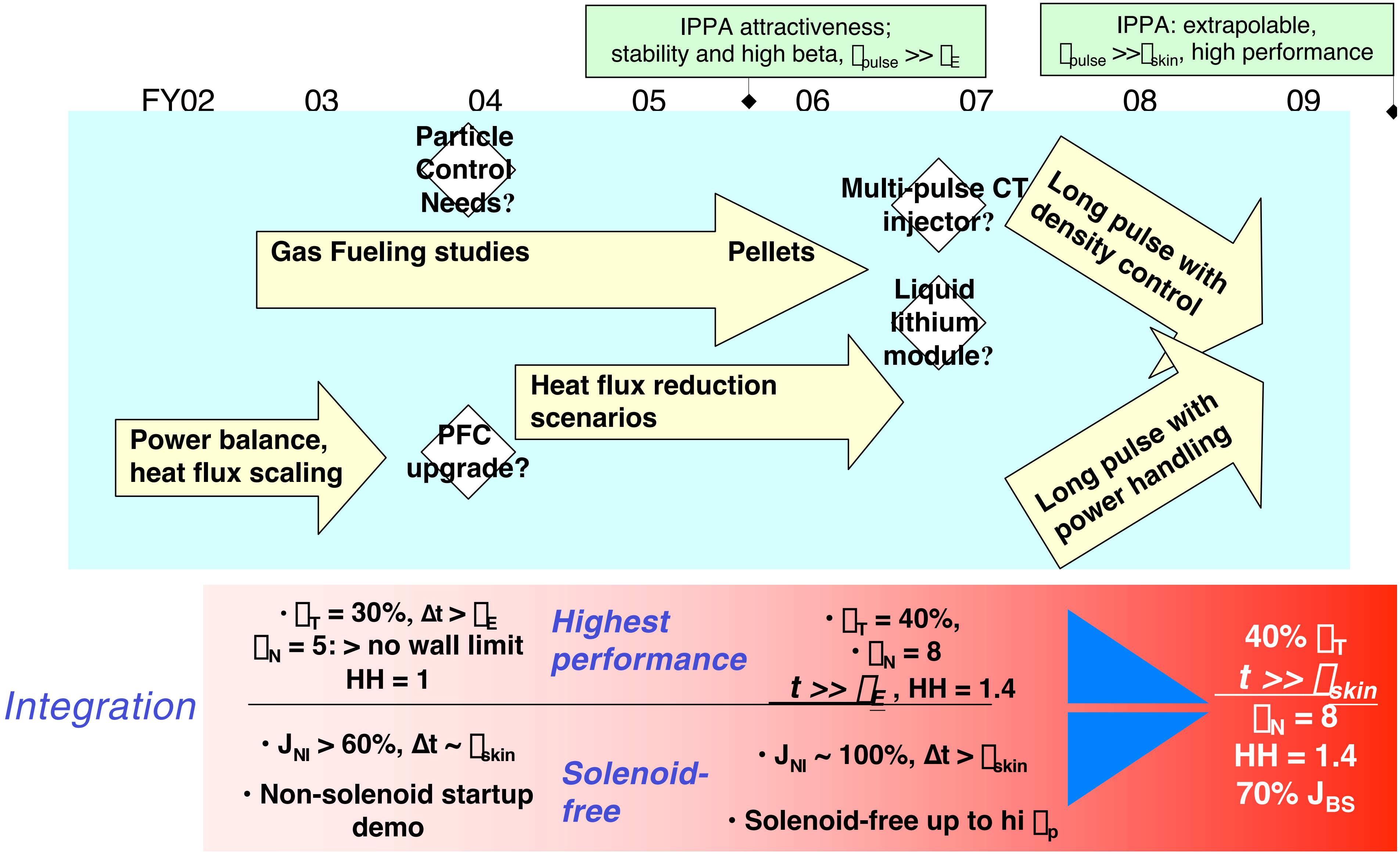
40% β_T
Δt >> τ_{skin}
β_N = 8
HH = 1.4
70% J_{BS}

Boundary physics activities have both science goals and enabling technology responsibility

- Science goals
  - characterize edge power and particle transport regimes
    - *parallel vs. cross-field*
    - *do conventional aspect ratio models fit?*
  - understand effect of ST features on boundary physics, e.g.
    - *large in/out B_t ratio*
    - *large SOL mirror ratio and short connection length*

- Enabling technology - tailor edge plasma to optimize discharges
  - evaluate power handling needs and solutions
  - assess fueling and particle pumping needs
  - develop and evaluate wall conditioning techniques

Boundary physics must provide particle and power handling to achieve long pulse integration goals



Outline

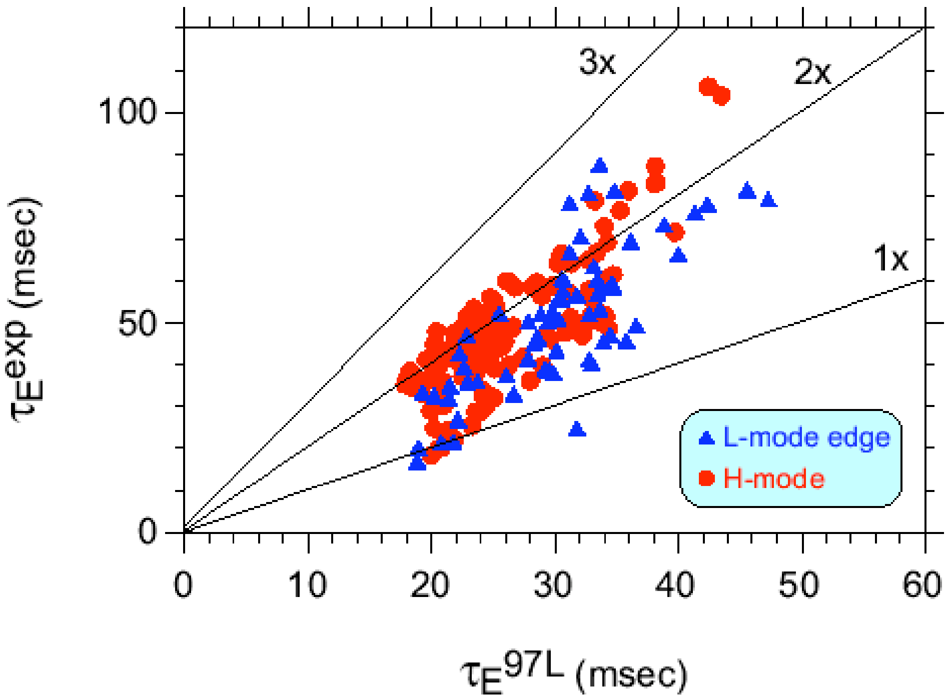
- Core Transport
  - Global energy confinement and scalings
  - Local transport studies
    - Ion and electron transport
    - Momentum and particle/impurity transport
  - Fast Ion Transport

- Boundary transport and characterization
  - Edge and SOL turbulence and transport studies
  - H-mode power threshold, pedestal and ELM studies
  - Particle and power control
    - Fueling, sources and sinks
    - Power handling and mitigation

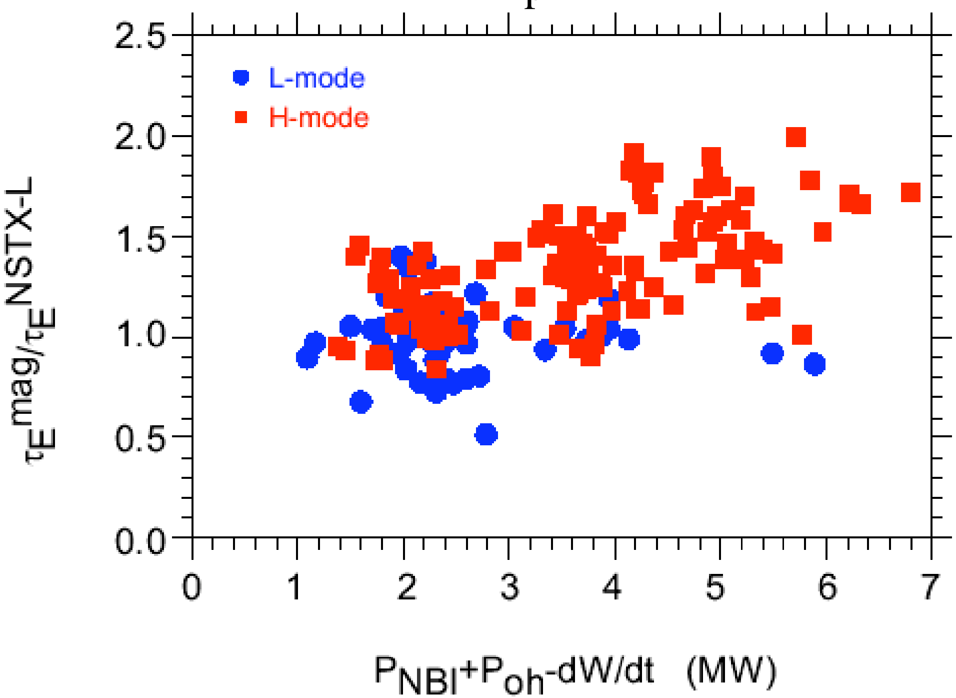
Global confinement scalings of NSTX data commencing

NSTX

$\tau_E^{97L} \sim I_p^{0.74} B_T^{0.20} P_L^{-0.57}$



$\tau_E^{NSTX\text{-}L} \sim I_p^{0.76} B_T^{0.27} P_L^{-0.76}$

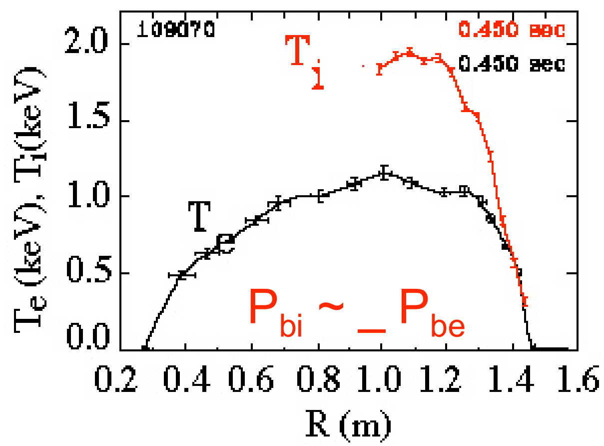


- τ_E^{exp} from EFIT reconstruction
  - Includes fast ion component
- Quasi-steady conditions

- Less severe power degradation in H-mode $\tau_E \sim P^{-0.50}$
  - MHD vs confinement limit?
- Different parametric dependencies for more transient L-mode plasmas
  - Role of rotation?

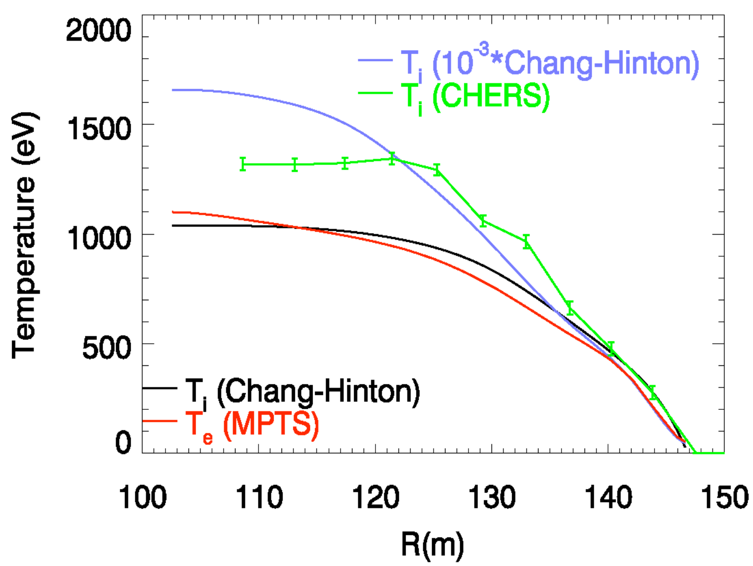
Kaye, PPPL

T_i>T_e during NBI indicates relatively good ion confinement



ITG suppressed (GK calculations)

Ion confinement sometimes "too good"

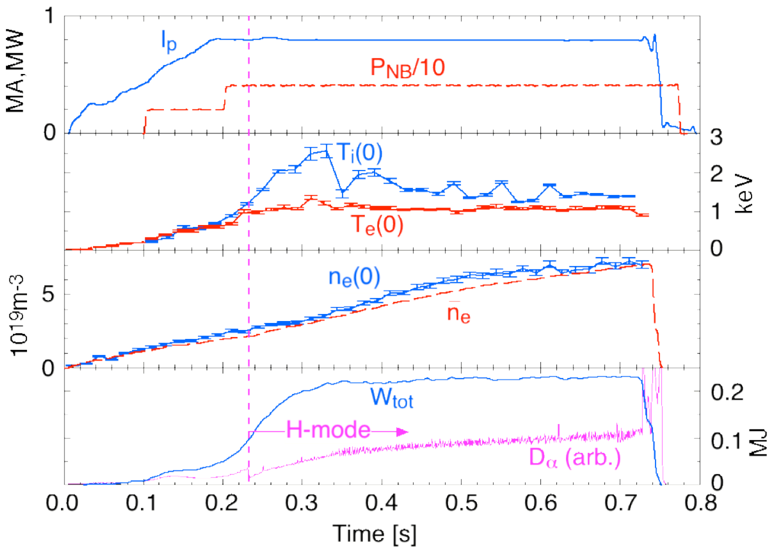


Independent validation of T_i profile needed (2-D X-ray crystal diagnostic)

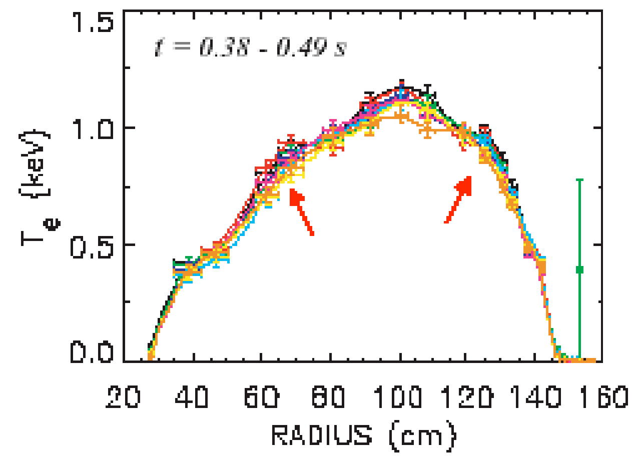
Gates, Kaye, LeBlanc, Bell, PPPL

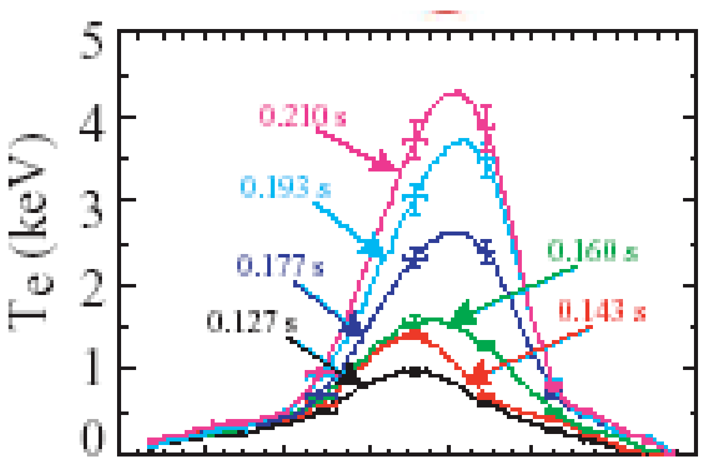
"Stiff" T_e Profiles during flattop period with NBI but sometimes peaked with RF heating

NSTX

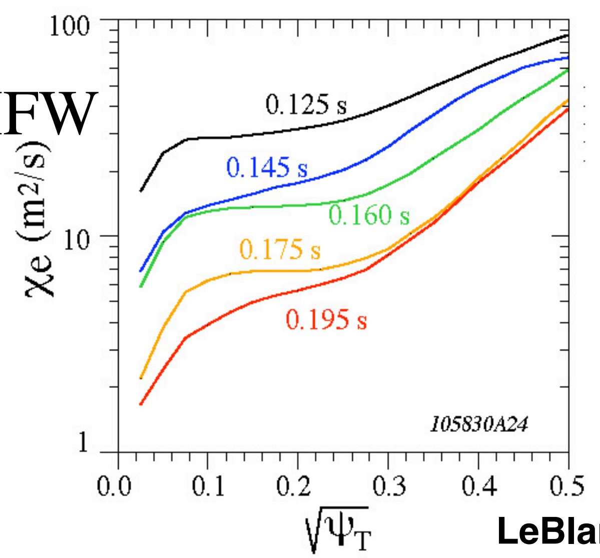


Profile Resilience?





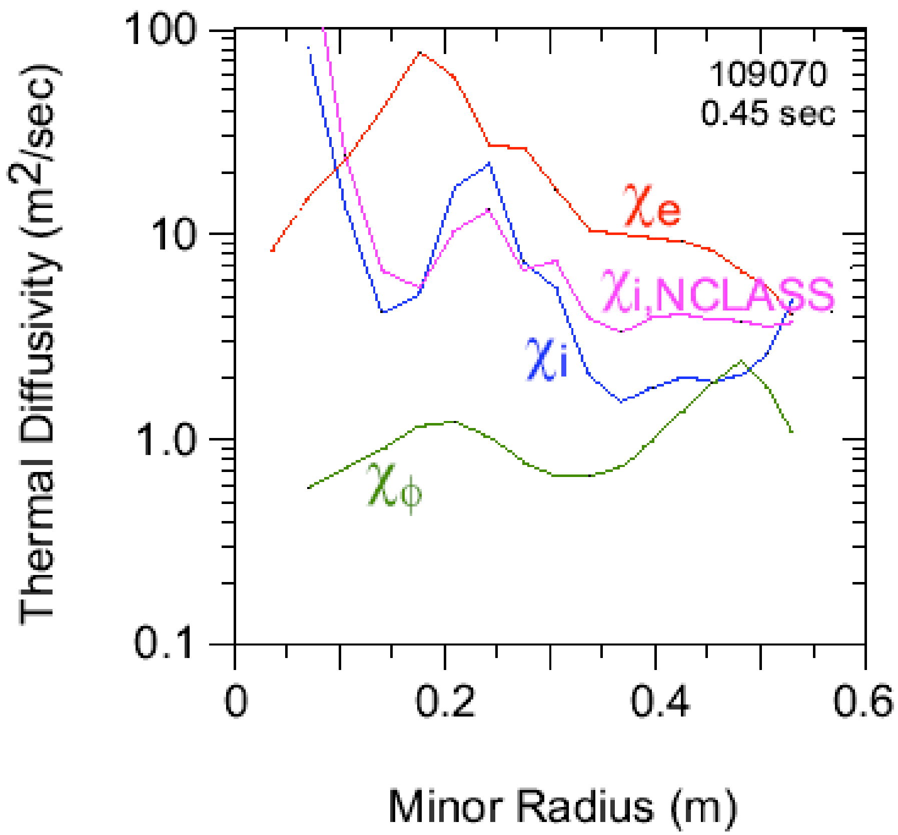
ITB w/ HHFW



LeBlanc, PPPL

Momentum transport slower than thermal transport

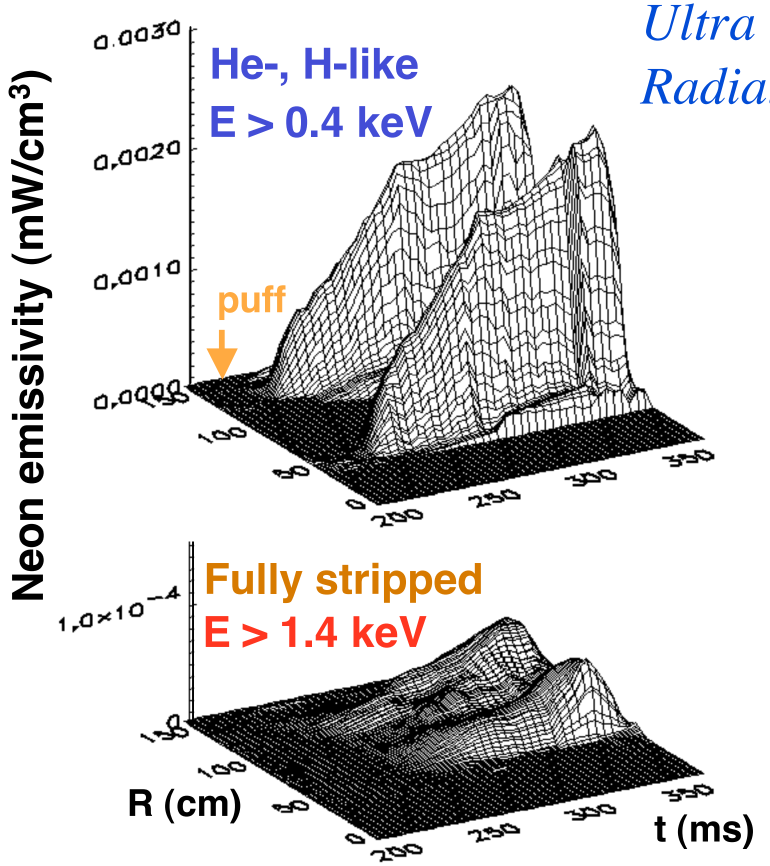
- Inferred transport coefficient ordering: $\chi_\phi < \chi_i \approx \chi_{neo} \approx \chi_e$



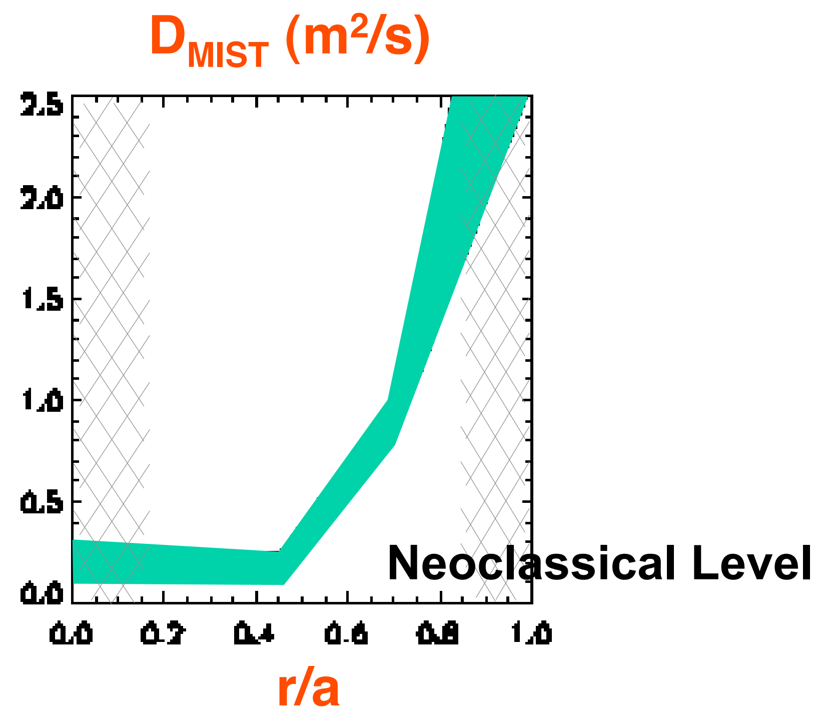
Menard, Kaye, LeBlanc, Bell, PPPL

Core neon transport near neoclassical

Neon injection: Line radiation in He, H-like and continuum in fully stripped



Ultra Soft X-ray Radiation



Stutman, JHU

Local transport and global scaling studies
FY 03-04 Plans

-------------------------------------- FY 03 -----------------------------------

- Establish χ_e , χ_i , χ_ϕ baseline with NBI and/or RF
- Determine if and when χ_i anomalous
- Start to test role of ITG
- Measure D_ϕ at higher β_T with impurity gas injection
- Similarity experiments with MAST/DIII-D
- R/a dependence in ohmic **(rtEFIT control)**

-------------------------------------- FY 04 -----------------------------------

- Ion transport relation to rotation
- Assess modes for possible stochastic heating **(calibrated reflectometry)**
- Test T_e resiliency and assess role of ETG
- Relate transport and ITB formation to q(r) **(MSE)**
- Transient vs steady-state confinement dependencies/role of rotation

*** New capabilities**

Local transport and global scaling studies
FY 05-08 Plans

NSTX

-- FY 05 --

- Co vs counter NBI to study effect of flow shear **(poloidal CHERs)**
- Role of $n_e(r)$ for ITG, ETG study **(pellets)**
- Assess low-k and high-k fluctuations **(advanced turbulence diagnostics)**
- Deuterium pellet injection for perturbative particle transport

------------------------------------ FY 06-08 --

- Detailed study of ion and electron transport to full-k turbulence
- Relate transport fluxes to changes in q(r), $E_r(r)$ **(LIF MSE)**
- Relate E_r **(LIF MSE)** to flows (CHERS)
- Relate E_r, $v_{\square}$ and q(r) with ITB generation
- Determine rotation/confinement dynamics causality **(1 ms CHERS)**
- Impurity pellet injection for perturbative particle transport

*** New capabilities**

Fast ion confinement studies just starting

NSTX

Results

- Decay of neutrons consistent with classical slowing down
- Loss rate measurements lower than modeling
- Variations in neutron rate for nominally similar discharges

Plans

- FY03: Overall confinement trends with parameter, L vs H **(sFLIP)**
- FY04: Control loss fraction (vary gap)
- FY05: Non-ambipolar losses (co vs ctr); power deposition profile **(neutron collimators)**
- FY06-08: Extend studies **(array of solid state detectors)**

*** New capabilities**

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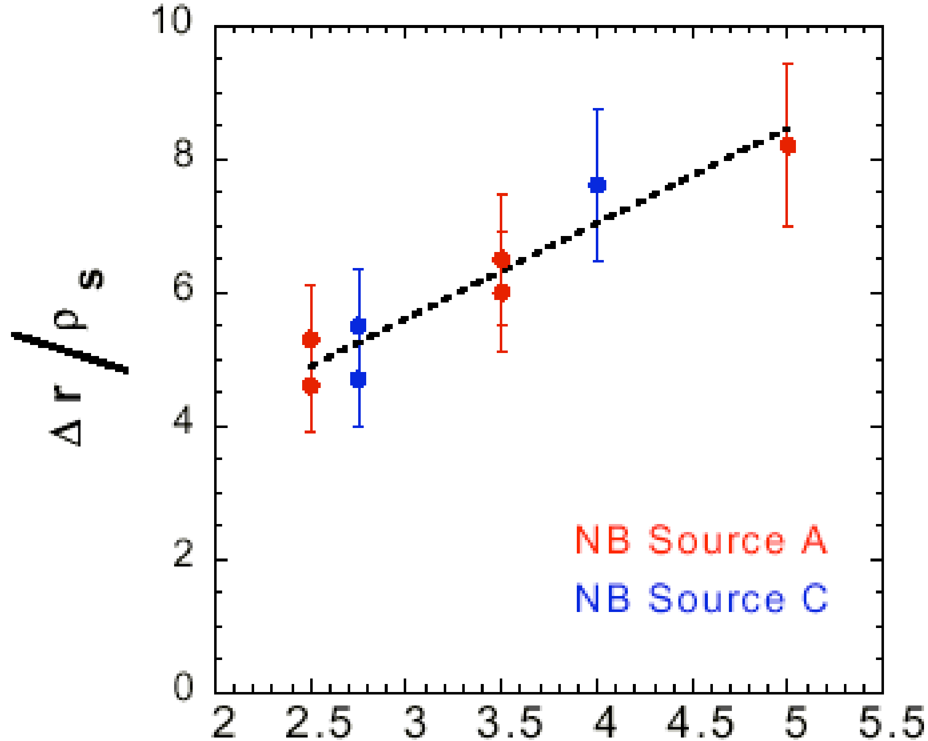
Fluctuation characteristics measured vs. plasma parameters and confinement modes

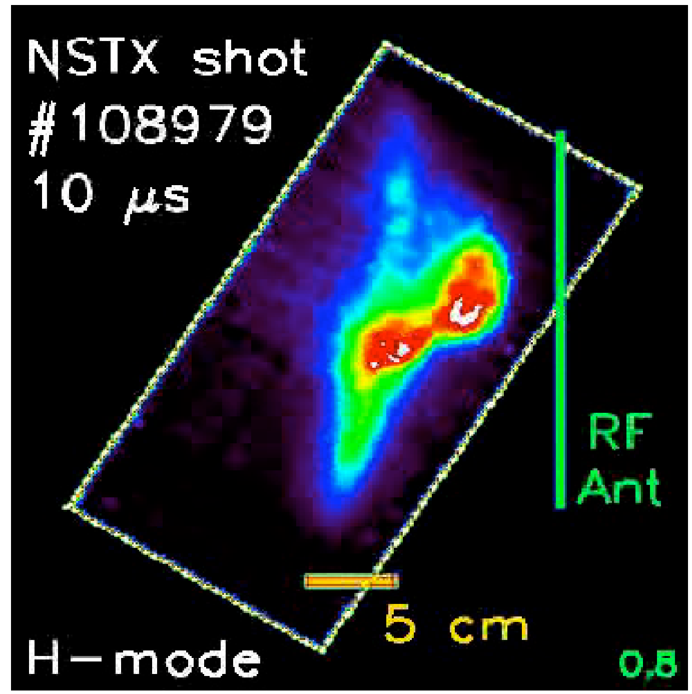
NSTX

Δr normalized to ρ_s vs. $\overline{nL}$



Line Avg Density (x 10^{15} cm^{-2})

ñ/n goes down from L to H



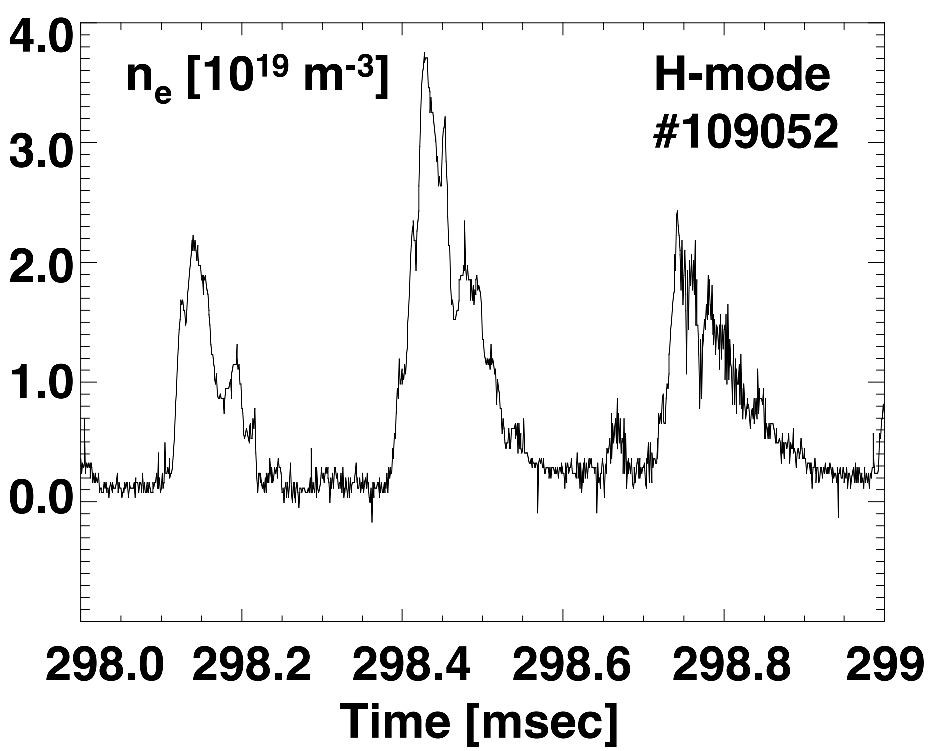
Convective-cell ("blob") transport potentially significant

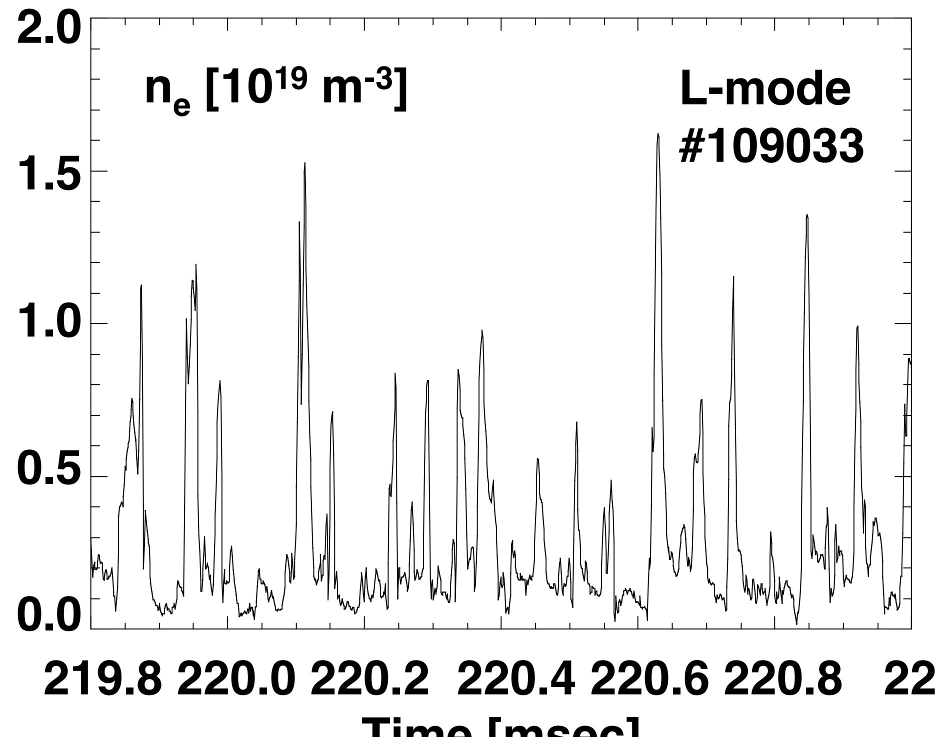
Gilmore (UCLA)

Zweben (PPPL), Maqueda (LANL)

Intermittent behavior observed in L and H-mode density

- Rate of bursts is ~ 2 kHz in H-mode and ~ 20 kHz in L-mode
- Poloidal field is much less intermittent
- Instantaneous particle flux ~10^{19} $m^{-2}s^{-1}$

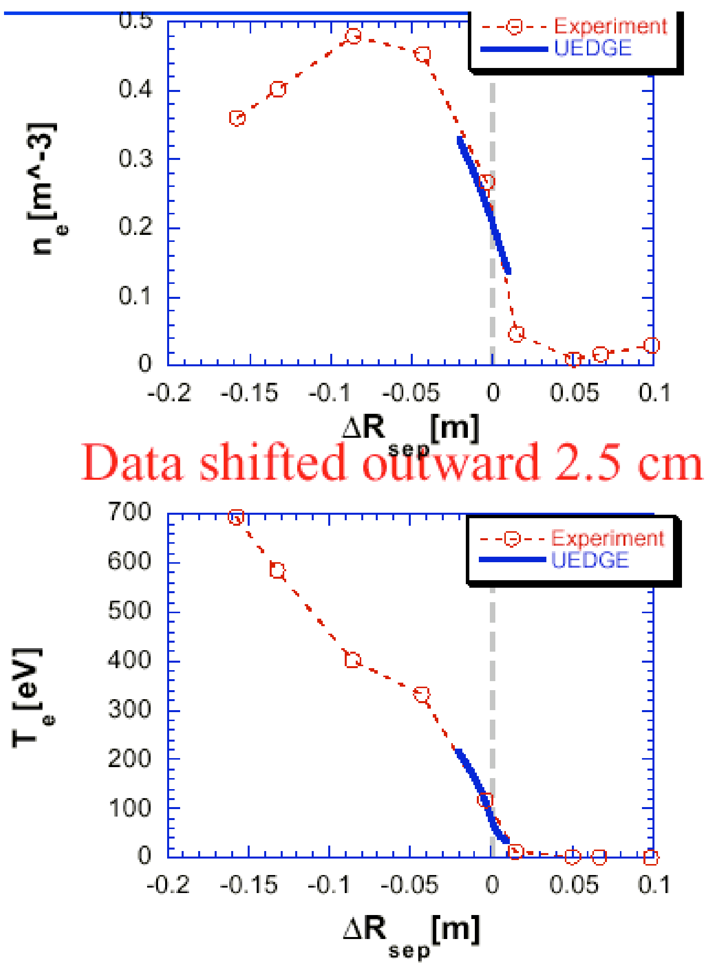




Boedo (UCSD)

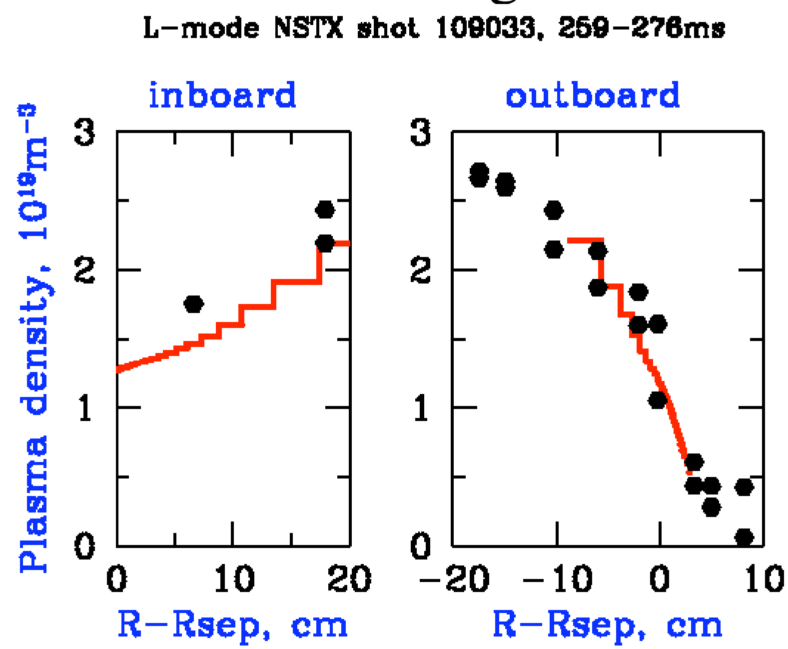
UEDGE modeling needed to estimate transport rates

$D_{\perp} = 1\ m^2/sec$, $\chi_{\perp} = 3\ m^2/s$



Porter (LLNL)

- LLNL using diffusive cross-field transport model for H-mode discharges
- UCSD examining convective cross-field transport model for L-mode discharges



Pigarov (UCSD)

L-H power threshold and ELM studies reveal differences with conventional aspect ratio tokamaks

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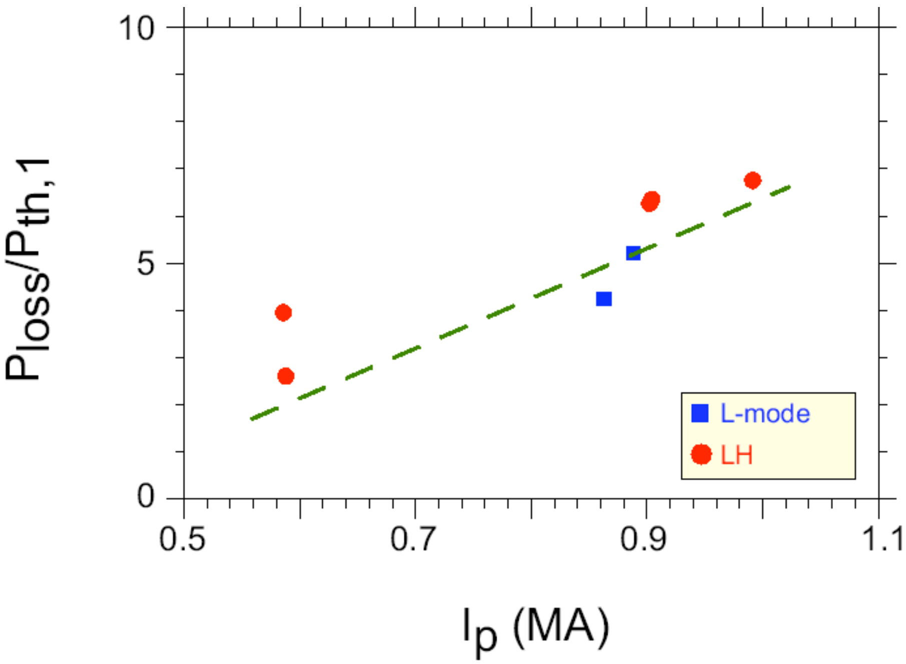
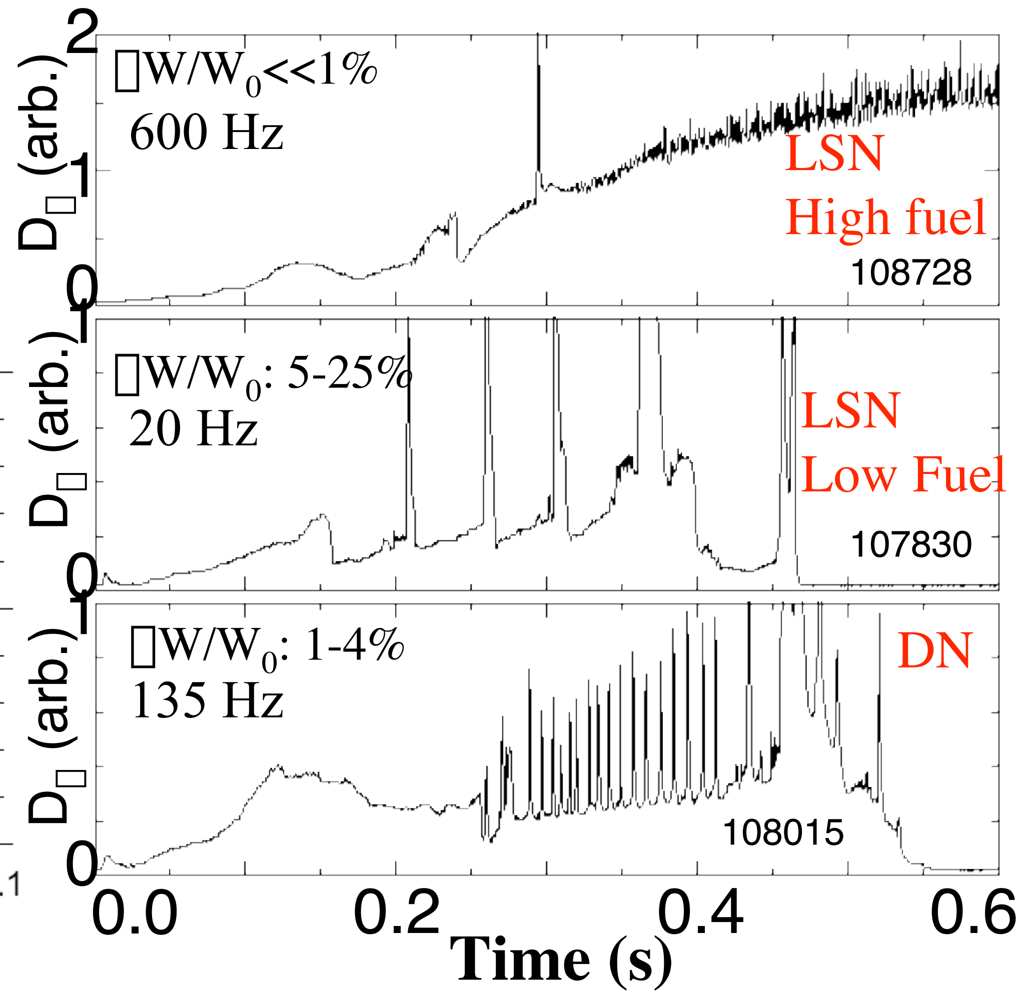
- L-H transition: $P_{L\text{-}H}^{NSTX} > P_{th,1}$
- I_p dependence
  - related to E_r through fast ion loss?

$P_{th,1} \sim n_e^{0.61} B_T^{0.78} a^{0.89} R^{0.94}$

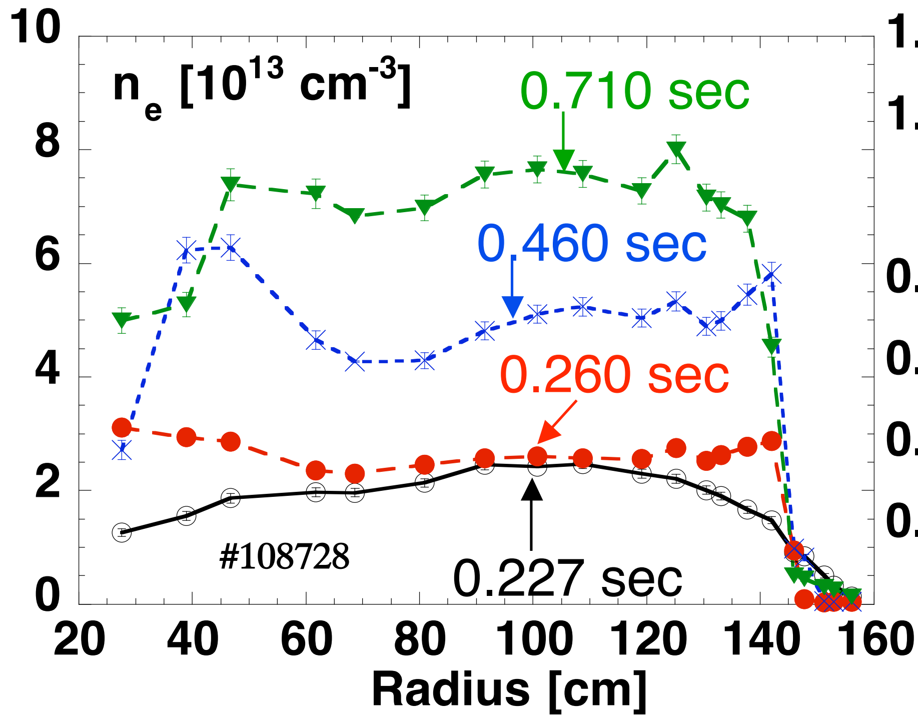


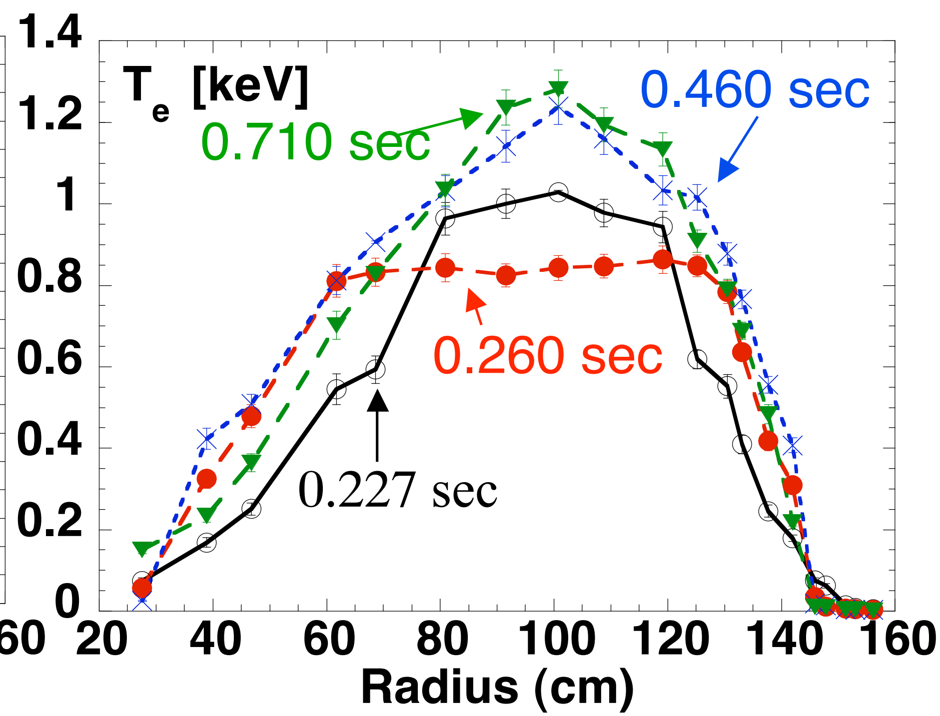


Bush, ORNL

High n_e and relatively low T_e pedestal observed

NSTX





- n_e profile hollow after transition and fills in 300-500 ms
- Moderate in/out n_e asymmetry usually observed
- T_e profile flattens initially and peaks later in time

Boundary transport and H-mode characterization
FY 03-04 Plans

- Boundary Turbulence and transport:
  - Extend intermittent transport studies (L/H, density limit)
  - Extend radial correlation length studies
  - Determine if classic divertor heat flow models apply
  - Measure SOL midplane width scaling
- L-H transition, ELMS and pedestal physics:
  - Continue power threshold scaling; submit to ITER database
  - Identify dimensionless variables controlling L-H; test theories
  - Study role of E_r on transitions with gap, I_p variations, NBI vs RF
  - Continue studies on role of fueling in H-mode access **(supersonic and new gas injectors)**
  - Characterize edge pedestal; compare w/MAST, DIII-D
  - Characterize ELM sizes and dependencies

*** New capabilities**

Boundary transport and H-mode characterization FY 05-08 Plans

NSTX

- Boundary Turbulence and transport:
  - extend studies of low- and high-k turbulence, comparison with non-linear gyrokinetic results
  - extend intermittent transport studies
  - measure density dependence of boundary transport **(pellets, pump)**
  - Measure SOL kinetic effects on SOL transport
- L-H transition, ELMS and pedestal physics:
  - Co vs ctr NBI for assessment of E_r on L-H **(poloidal CHERS)**
  - height, width, and maximum gradient scalings of pedestal **(more edge TS channels)**
  - role of fueling profile in setting pedestal density width **(pellets, pump)**
  - role of shape and fueling in ELMs; conductive vs. convective loss
  - optimization of ELMs for density and impurity control
  - edge transport barriers with **CT injection**

*** New capabilities**

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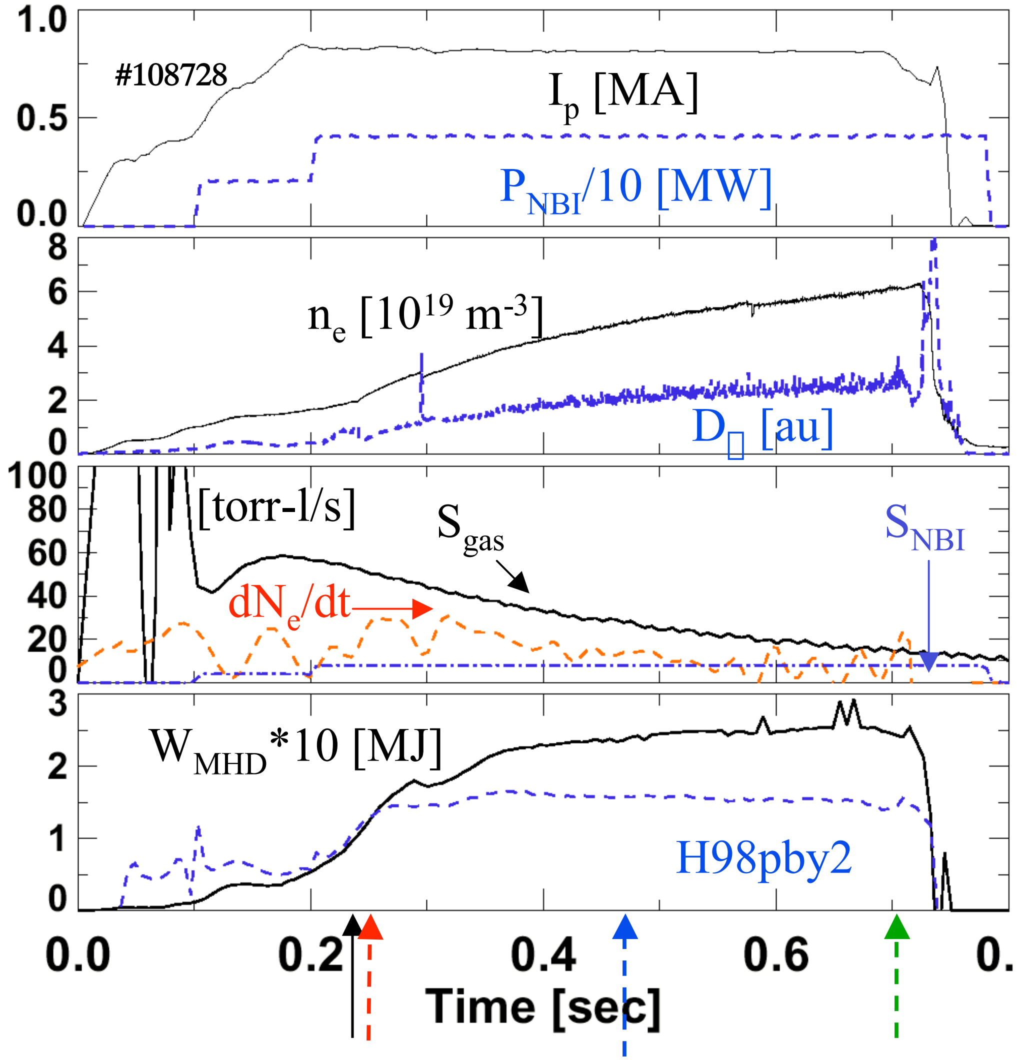
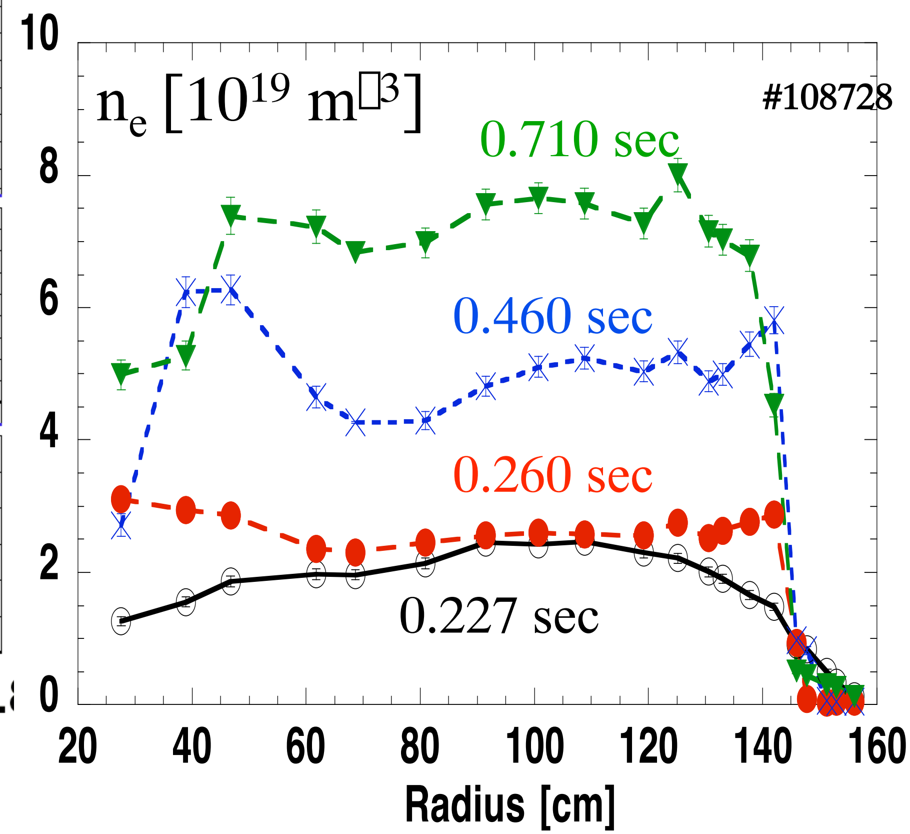
  - H-mode power threshold, pedestal and ELM studies
  - Particle and power control
    - Fueling, sources and sinks
    - Power handling and mitigation

Uncontrolled (non-disruptive) density rise in long pulse H-modes

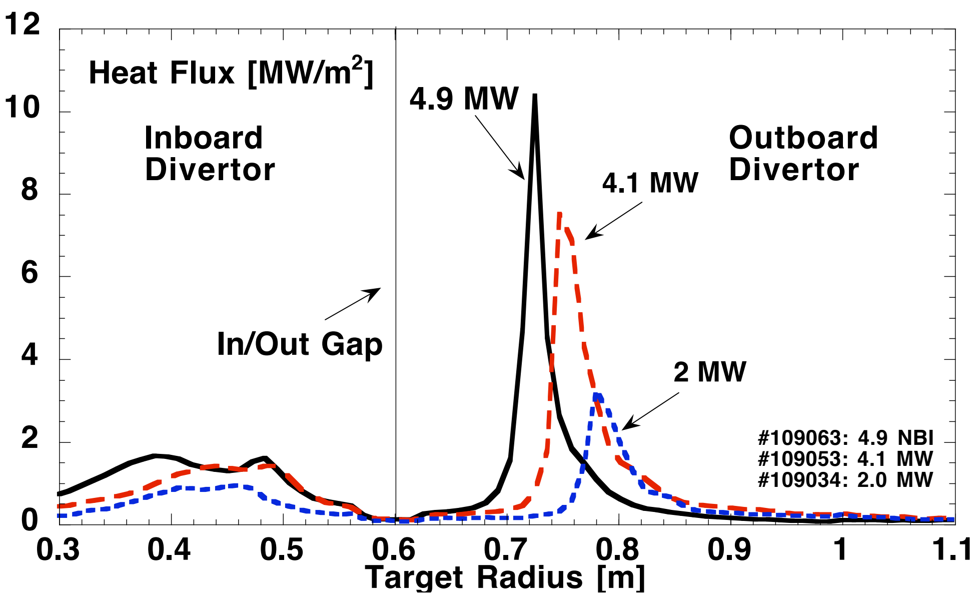


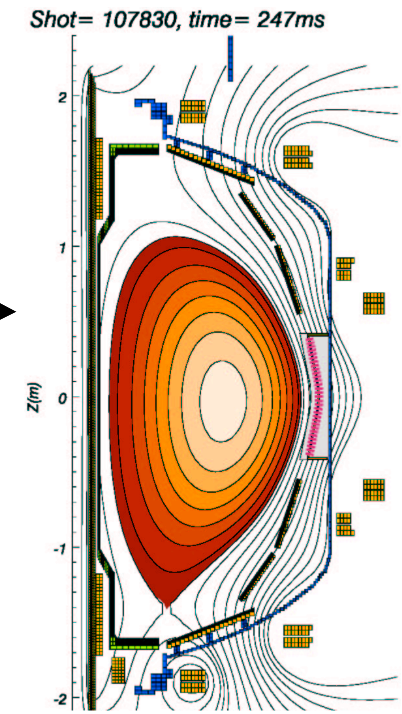
- Density control needed for improved current drive efficiency, transport studies, and power and particle handling research

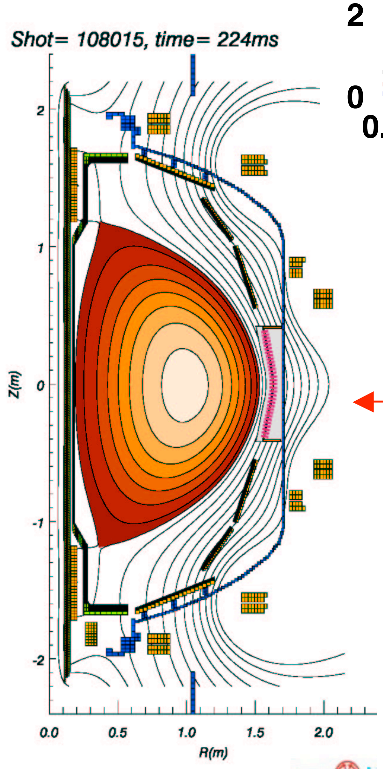


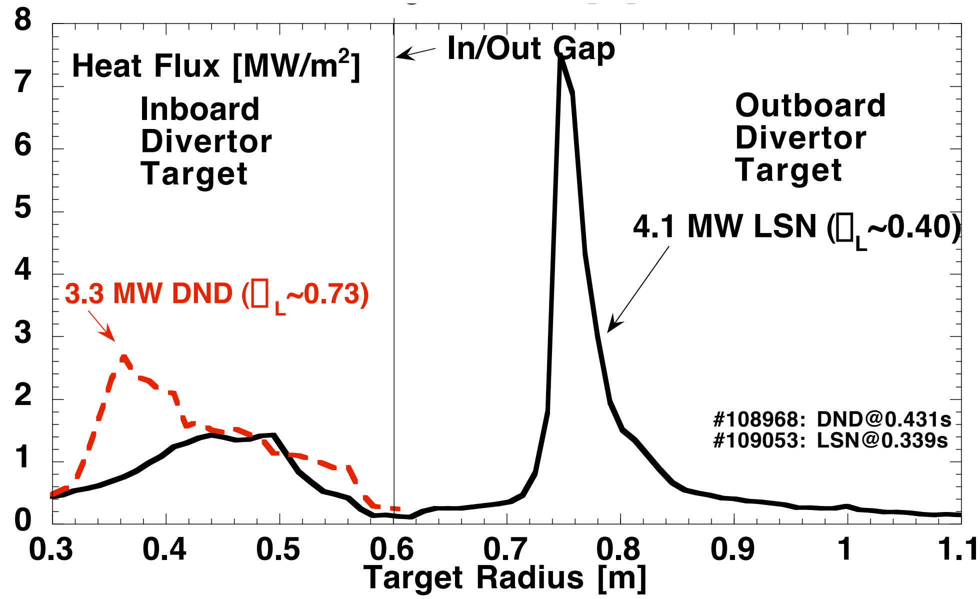
Maingi, ORNL

Peak heat flux increased with NBI power in lower-single null, but lower in double-null









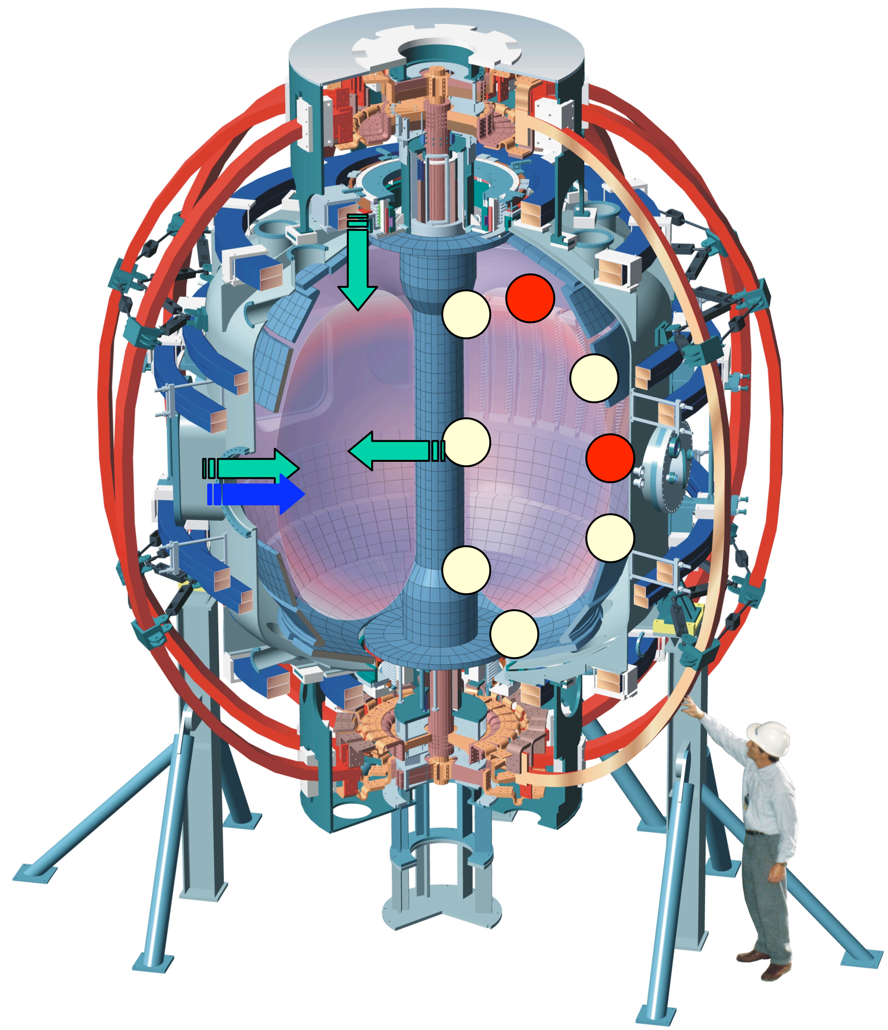
Maingi, ORNL

Fuel and impurity source control plan

NSTX

- Improved source control
  - more poloidal locations for gas (FY03-04)
  - supersonic gas nozzle (FY03-04)
  - Lithium pellets (FY03)
  - D_2 pellet injection (FY05)
  - CT injection? (FY07 ?)

- New diagnostics
  - D_α cameras for core fueling
  - pellet diagnostics
  - more edge Thomson channels
  - divertor Langmuir probe upgrade

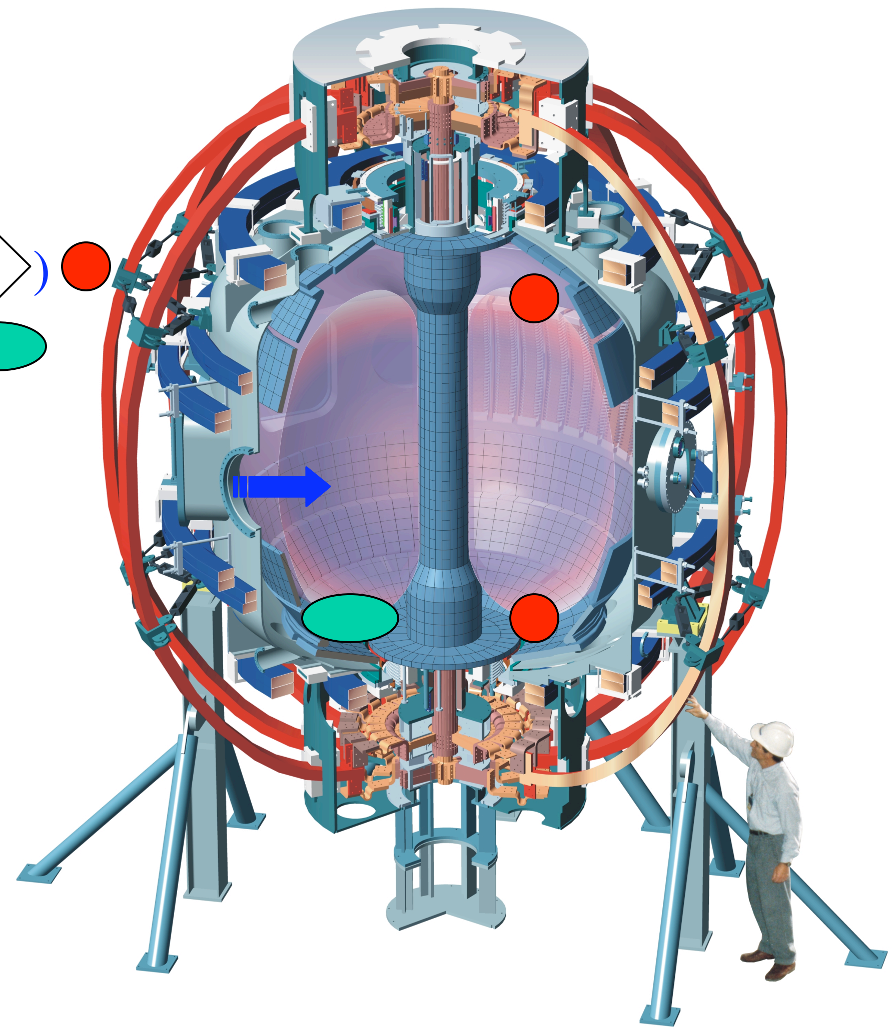


*** New capabilities**

Fuel and impurity sink control plan

- Improved sink (density) control
  - improved boronization (FY03)
  - lithium pellets (FY03)
  - in-vessel cryopumps (FY06,FY04 ?)
  - lithium module(FY08, FY06 ?)

- New diagnostics
  - $n_C(r)$ f/CHERs, Z_{eff} f/MPTS (FY03)
  - D_{α} cameras for core fueling
  - divertor SPRED
  - upgraded Langmuir probe array
  - fast pressure gauges



*** New capabilities**

Power handling and mitigation plan

- Experimental plan
  - Power balance studies (FY02+)
    - divertor heat flux vs core and divertor radiation
    - parallel vs perpendicular transport
  - Detailed comparison between single-nulls and double-nulls (FY03+)
  - Heat flux reduction studies (FY03+)
  - Impact of fast events, e.g. ELMs, IREs, and disruptions (FY05)

- New Diagnostics
  - Cross-calibrate core bolometry with platinum-foils (FY03)
  - Add and optimize divertor bolometer channels (FY03-04)
  - Add two slow and <u>one fast</u> infrared cameras (FY04, <u>FY05</u>, FY07)

*** New capabilities**

FY03 04 05 06 07 08 09

IPPA: 5 *IPPA: 10*

Confinement scalings

Momentum & power balance, strong electon & ion heating, low and high beta

Boundary transport & turbulence

Pedestal characterize

Local transport & turbulence
Low/high k spectra theory/experiment, lo/high beta

Poloidal flows

V_{ϕ} shear & w/error field

□ & pellets

Feedback with heating, CD, V_{ϕ}, fueling

Understanding

P(r),J_{BS} optimize

Transport tools

MSE CIF

CHERS 51 ch

Imaging X-ray crystal

Edge $v_{\square,\square}$

Li pellets

Poloidal CHERS

MPTS upgrades

He beam spectroscopy

Turbulence diagnostics
Initial *Advanced*

Error field coils

Neutron collimator

D pellets

MSE LIF (J, E_r, P); polarimetry

Fast CHERS (edge)

Liquid Li?
CT injection?

Feedback with MSE, heating, CD, rtEFIT

1 – 3 MW EBW

Cryopump

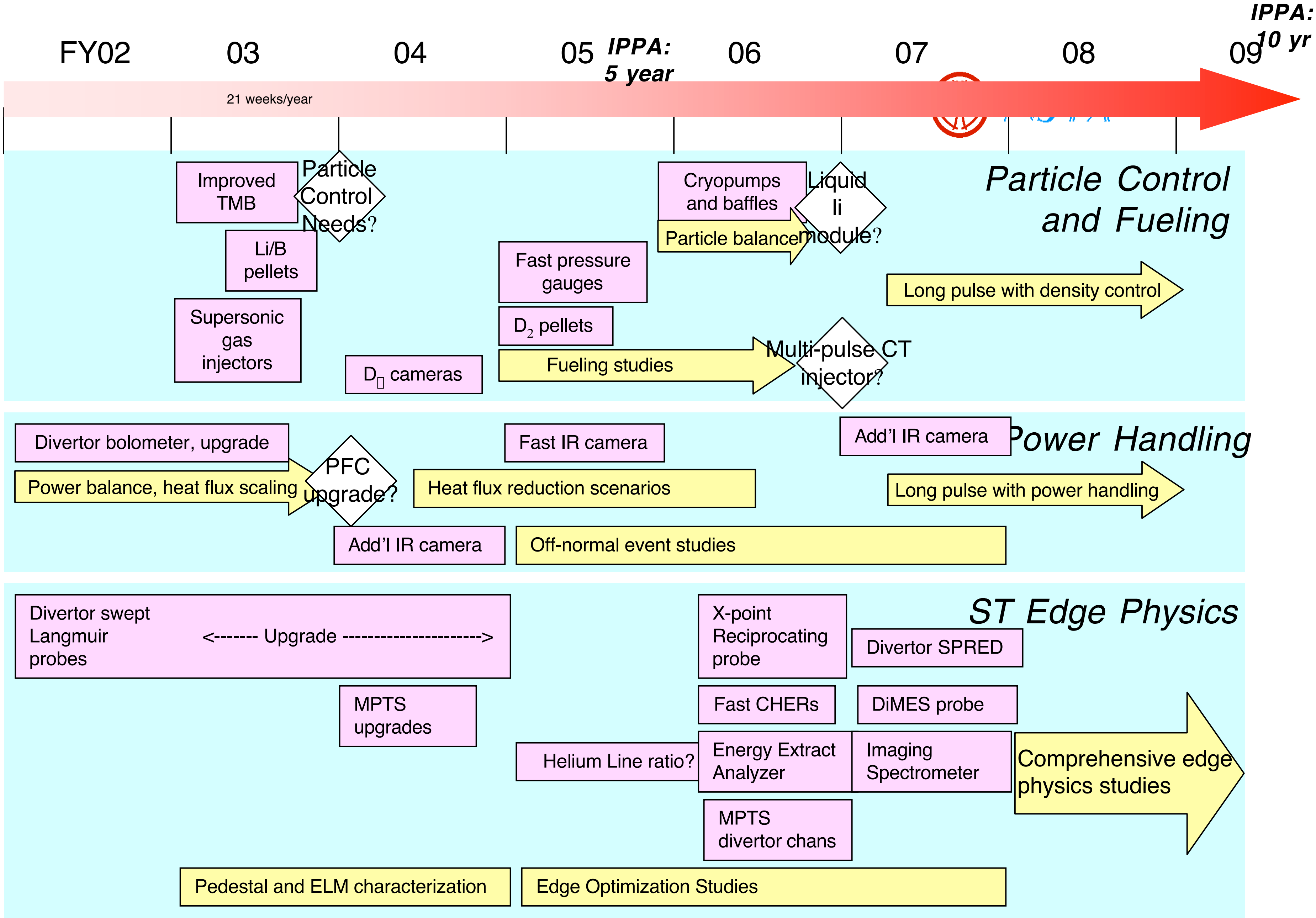
Impurity injector

Solid state neutral particle detectors

Transport theory

Predictive Transp (GLF23, Multi-Mode)
GS2 linear, non-linear
GTC trapped e^- Finite □ High □
Gyro non-adiabatic e^-
Neoclassical: beam-thermal friction, potato orbit, high □/L, B_{pol}/B_{tor}
Non-linear CAE Anomalous heating models

Full predictive transport simulations



FY02
03
04
05
IPPA: 5 year
06
07
08
09
IPPA: 10 yr
21 weeks/year
Particle Control and Fueling
Improved TMB
Particle Control Needs?
Li/B pellets
Supersonic gas injectors
D cameras
Fast pressure gauges
D_2 pellets
Fueling studies
Cryopumps and baffles
Particle balance
Liquid li module?
Multi-pulse CT injector?
Long pulse with density control
Power Handling
Divertor bolometer, upgrade
Power balance, heat flux scaling
PFC upgrade?
Add'l IR camera
Fast IR camera
Heat flux reduction scenarios
Off-normal event studies
Add'l IR camera
Long pulse with power handling
ST Edge Physics
Divertor swept Langmuir probes
<------- Upgrade --------------------->
MPTS upgrades
Helium Line ratio?
X-point Reciprocating probe
Divertor SPRED
Fast CHERs
DiMES probe
Energy Extract Analyzer
Imaging Spectrometer
MPTS divertor chans
Comprehensive edge physics studies
Pedestal and ELM characterization
Edge Optimization Studies

Summary

IPPA attractiveness; stability and high beta, $\tau_{pulse} >> \tau_E$

IPPA: extrapolable, $\tau_{pulse} >> \tau_{skin}$, high performance

FY02 03 04 05 06 07 08 09

NSTX

Transport and Turbulence

Understanding

P(r),J_{BS} optimize

Global confinement scalings

Momentum & power balance, local transport studies, H-mode physics

Transport & turbulence relation
Low/high k spectra
theory/experiment

Feedback with heating, CD, V_ϕ, fueling

Boundary Physics

Particle Control Needs?

Gas Fueling studies

Pellets

Multi-pulse CT injector?

Liquid lithium module?

Long pulse with density control

Power balance, heat flux scaling

PFC upgrade?

Heat flux reduction scenarios

Long pulse with power handling

Backup

Transport Goals are Related to IPPA Goals

- Five year goal (IPPA 3.1.1)
  - Advance the scientific understanding of turbulent transport, forming the basis for a reliable predictive capability in externally controlled systems
- Ten year goal
  - Develop fully integrated capability for predicting the performance of externally controlled systems including turbulent transport, macroscopic stability, wave particle physics and multi-phase interfaces

Boundary goals are linked to IPPA goals

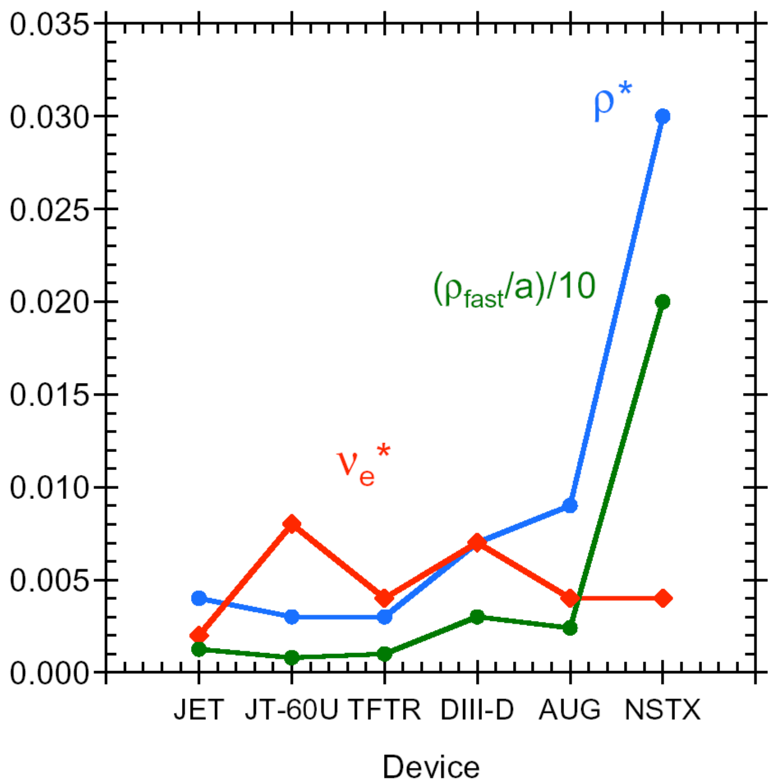
NSTX

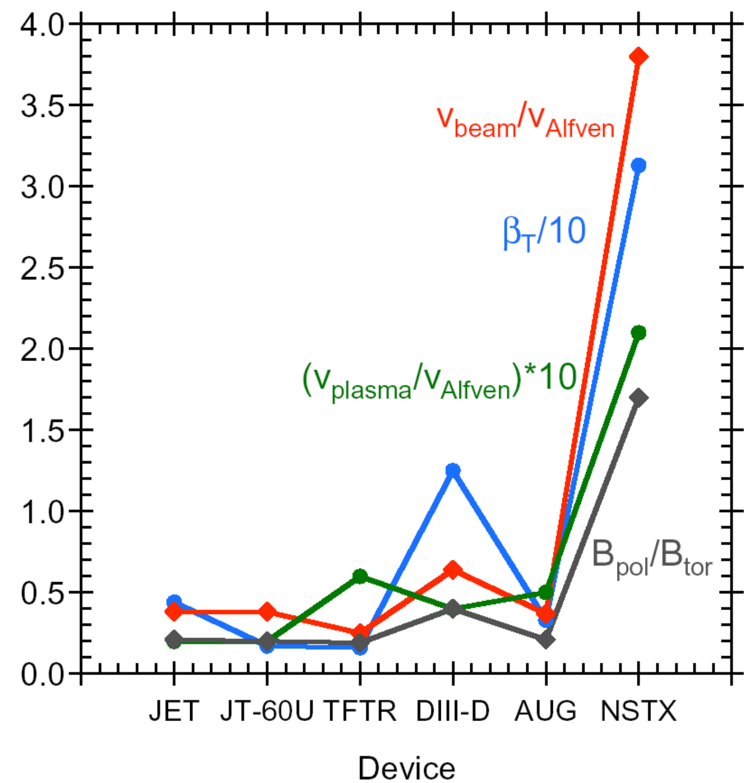
- *5-Year Objective*: Make preliminary determination of the attractiveness of the spherical torus (ST), by assessing high-β_T stability, confinement, self-consistent high bootstrap operation, and acceptable divertor heat flux, for pulse lengths much greater than energy confinement times.

- Implementing Approach 3.2.1.5:
  - Disperse Edge Heat Flux at Acceptable Levels
  - Study ST specific effects
    - high mirror ratio
    - high flux expansion

NSTX Offers Unique Opportunities

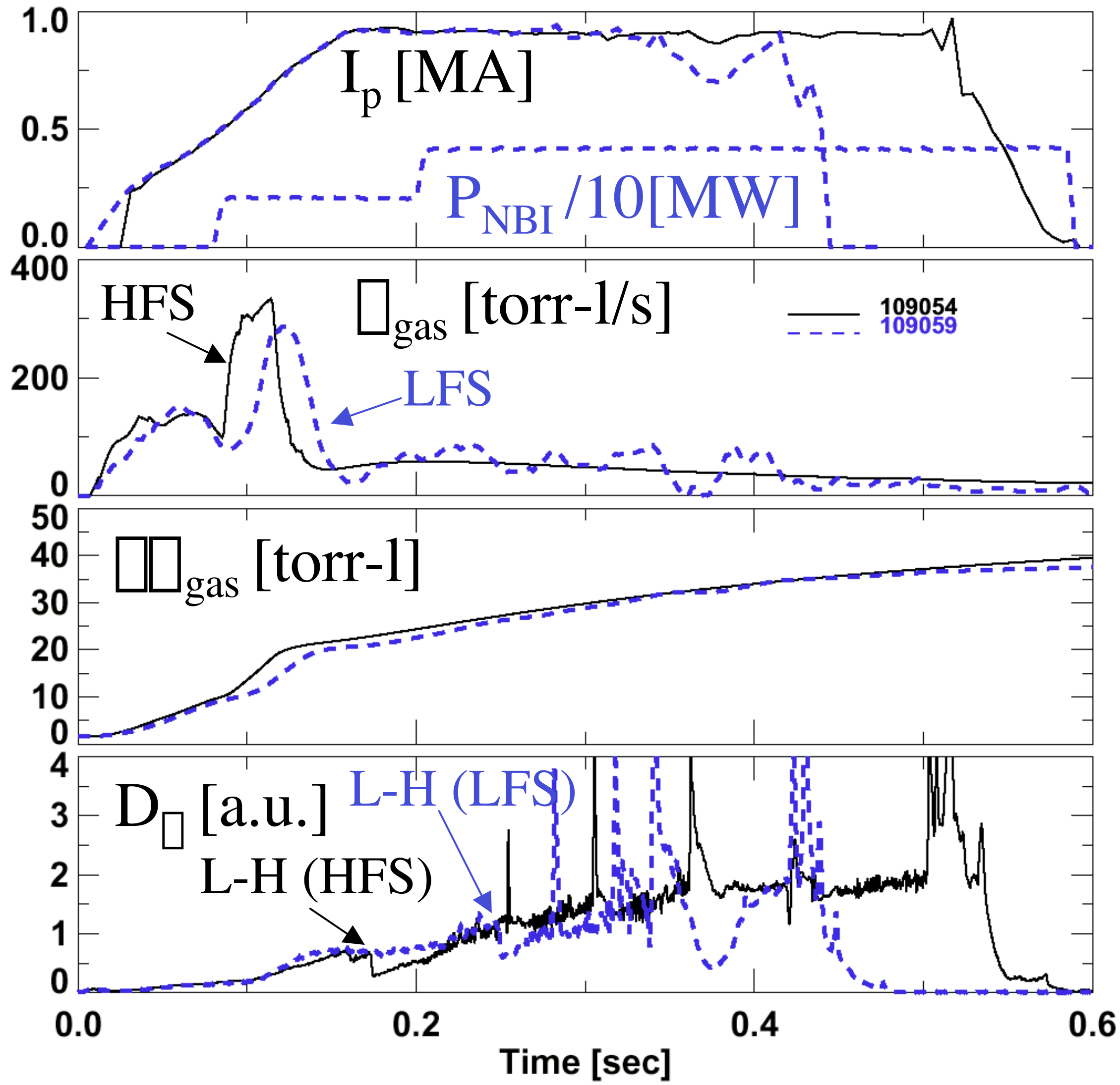
Low B_T □ Large gyro-scale lengths, high □$_T$
Low R/a □ Large field line pitch on LFS
Relatively high beam energy □ High relative velocity





High-Field Side Gas Injector Fueling Allows Early L-H Transition and Longer H-mode Duration

NSTX



Theory and Modeling - Plans

- FY03: Predictive TRANSP using analytic estimates of □'s; validate GK codes in low R/a regime (benchmark); update neoclassical (beam-thermal friction, large □/L); non-adiabatic fast ions; edge transport modeling

- FY04: Predictive TRANSP analysis with □'s from non-linear GK runs; incorporate large $□^*$, $□_T$, f_T, shaping effects into GK codes; non-linear calcs of CAE mode amplitudes; start to compare turbulence measurements to theory

- FY05: Incorporate ExB, non-local effects in GK; extend theory/exp't comparison of turbulence; start developing anomalous heating models

- FY06-08: Start to develop high-confidence predictive capability; combine with MHD stability to form self-consistent package for integrated scenario development

Edge, SOL, divertor and wall conditioning physics background

- Classical divertor heat flow regimes applicable?
  - high divertor T_e, sheath-limited heat flow
  - low divertor T_e, conduction-limited heat flow
  - detachment
- Impact of unique ST features
  - high SOL mirror ratio, short connection length, high flux expansion
  - in/out B_t ratio and target; E X B flows
- Cross-field transport: diffusive vs. intermittent
  - intermittent transport appears strong in both L and H-modes
  - any cross-correlation with ELMs?
- Wall conditioning technique assessment
- Plan: near-term focus on nature of cross-field transport, and longer term on ST kinetic effects

H-mode, pedestal and ELM physics background

- L-H transition physics (common with transport group)
  - P_{LH} higher than scalings - trapped particles, poloidal damping?
  - I_p and maybe B_t dependence of P_{LH} appears different
  - role of E X B shear?
- Pedestal: profile shapes, gradients and widths
  - density pedestal high and in/out asymmetry
  - pedestal $T_e \leq 400$ eV, below predictions
- ELMs
  - Tokamak-like ELMs in double-null
  - Usually ELM-free or very large events in single-null
  - Fueling affects ELM type strongly

- Plan: characterization studies over next few years and optimization studies over longer term

Fuel and impurity particle control background

- Center stack gas injection enabled routine H-mode access
  - higher □ due to lower pressure peaking factor
  - long pulse due to low volt-second consumption rate, owing to high bootstrap fraction from edge pressure gradient

- Limited control leads to uncontrolled density rise

- Location of gas fueling source affects H-mode access

- Goal: make density independent of time

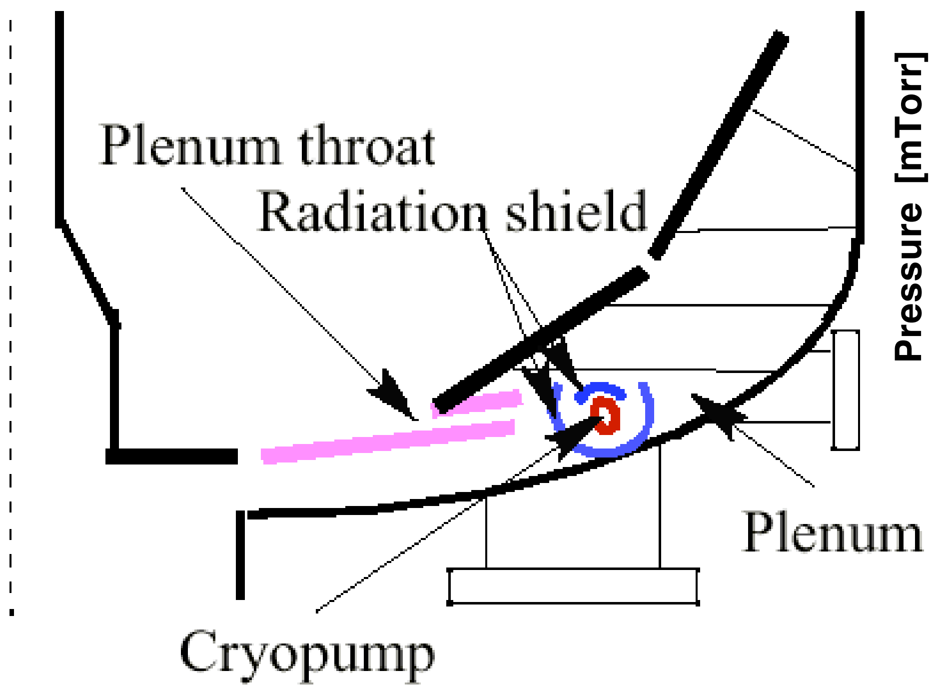
- Staged plan with parallel components
  - improve control of sources, aiming toward higher efficiency
  - improve control of sinks via wall conditioning and active pumping

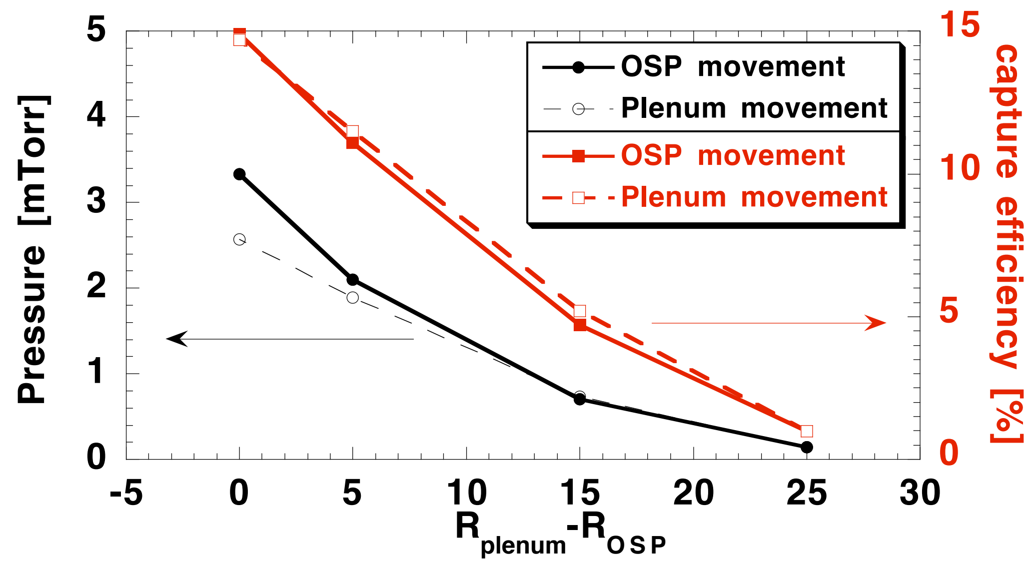
Power handling and mitigation background

- ST's can have high heat flux because of high P_{heat}/R
  - NSTX: $P_{NBI} \sim 7$ MW, $P_{RF} \sim 6$ MW, $P_{heat}/R \sim 15.3$
- Highest q_{peak} in NSTX ~ 10 MW/m^2
  - □$T_{div} \sim 300\ {}^0$C in LSN
  - extrapolates to ~ 3 sec. pulse length limit (□$T_{div} \sim 1200\ {}^0$C)
- For $T_e \leq 2$ keV, current diffusion time << 3 sec.
  - If T_e increases, current diffusion time could approach few seconds
- Goal: assess power balance and survey heat flux in many scenarios (vs. shape, input parameters, etc.)
- Staged plan
  - quasi-steady power balance over next few years
  - transient events in future

Preliminary neutral transport studies show possible plenum pressure sensitivity to strike point

- Same model and n_e, T_e, P_e profiles for DIII-D as in Maingi, et. al., *Nucl. Fusion* **39** (1999) 1190
- Ion current = 5kA, used for normalization
- Leakage conductance = 20 m^3/sec





Menon, ORNL

Wall conditioning physics plan

- Wall conditioning technique assessment (FY03+)
  - how does boronization change wall physics?
  - how do those changes improve the core plasma?

- New Diagnostics
  - quartz crystal deposition monitors for real time flux
  - divertor SPRED for impurities
  - divertor materials probes (like DiMES on DIII-D)
  - plus all other divertor diagnostics...