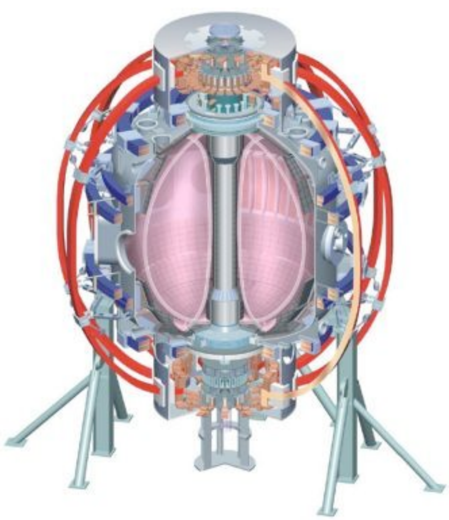
Boundary Physics Progress and Plans

College W&M
Colorado Sch Mines
Columbia U
CompX
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 Illinois
U Maryland
U Rochester
U Washington
U Wisconsin

Vlad Soukhanovskii, LLNL
Rajesh Maingi, ORNL
Daren Stotler, PPPL

27th NSTX PAC Meeting
Princeton Plasma Physics Laboratory
4 February 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

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

- **2 upcoming DOE Joint Research Targets in boundary physics:**
  - FY 2010 - Thermal transport in the SOL
  - FY 2011 - Pedestal structure (joint experiment and theory)
- NSTX research milestones
  - FY 2010 - R(10-3) H-mode pedestal and ELM stability
  - FY 2011 - IR(11-2) Pedestal and SOL response to 3D fields
  - FY 2012 - R(12-2) Very high flux expansion divertor operation
- NSTX-U divertor design
  - Divertor configurations
  - PFC material and design
  - Pumping tools
- ITPA participation and high-priority ITER research needs
- In longer-term - ReNeW Themes 3, 5 and Thrusts 9-12, 16

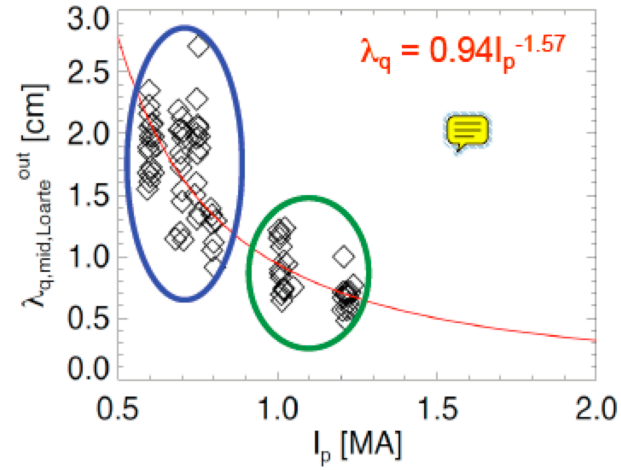
NSTX Boundary Physics Program Outline

- SOL and divertor transport, turbulence, and PSI
  - Thermal heat transport in the SOL
  - Blob physics
  - Divertor heat flux mitigation
  - Particle retention and control
  - Dust studies

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

NSTX contributing unique data to understanding SOL width scaling, divertor heat flux characteristics

- FY 2009 highlights
  - Obtained data at δ~ 0.5 and δ~ 0.7 in a range of I_p and P_{NBI}
    - **SOL width contracts with I_p**
    - **Divertor peak heat flux varies directly with I_p and P_{NBI} and inversely with flux expansion**



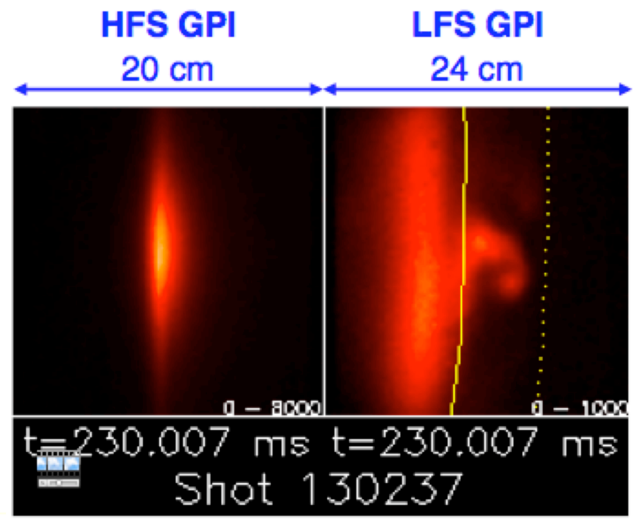
- Plan for 2010 (JRT FY 2010)
  - Measure divertor heat flux profiles and plasma characteristics in the tokamak SOL to investigate the underlying thermal transport processes…Develop common analysis methods, compare to theory and simulation
  - **Unique NSTX contributions**: $q_{||}$ up to 300 MW/m^2, q_{peak} up to 15 MW/m^2, low $l_{||}$~5-12 *m*, low in/out power split ~1:3, low A, strong shaping κ, δ
  - **Coordinated experiments** – match edge ν*, β, ρ* between DIII-D and NSTX at the same minor radius, κ and δ
- Longer-term plans (2011-2012)
  - Support innovative divertor geometry studies
  - Develop heat flux scalings for NSTX-U and tokamaks

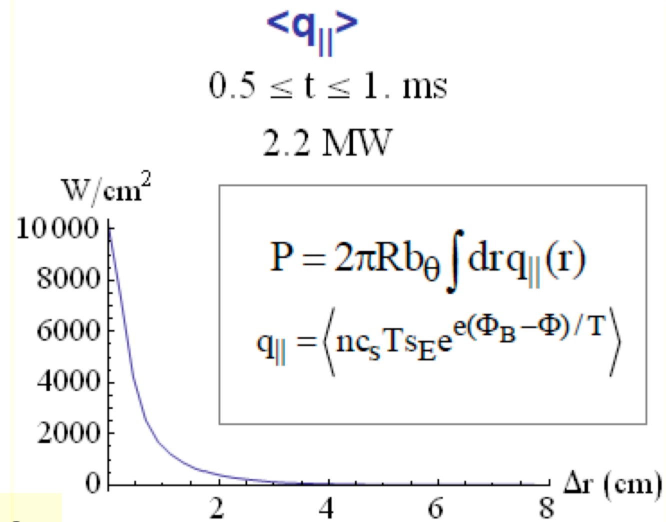
TOOLS: ***IR cameras, divertor bolometry, fast visible cameras, divertor spectroscopy***
Two-dimensional edge codes UEDGE, SOLPS, DEGAS 2

Investigating SOL turbulence and blob properties, relation to divertor heat flux scalings and SOL width

- FY 2009 highlights
  - Statistical comparison between intermittency and edge turbulence characteristics
  - SOL transport control with biased electrodes
  - Measured SOL profiles and turbulence characteristics modeling with SOLT code
- Plan for FY 2010 and beyond
  - Scaling of midplane SOL width with major parameters (JRT FY2010)
  - Comparison of edge turbulence properties to theory
    - Poloidal and 2-point correlation in L-mode & H-mode
    - SOL filament length wrt to magnetic balance
  - Convective cell generation with divertor biasing

In-out turbulence asymmetry measured with gas puff imaging





$$P = 2\pi R b_\theta \int dr\, q_{||}(r)$$

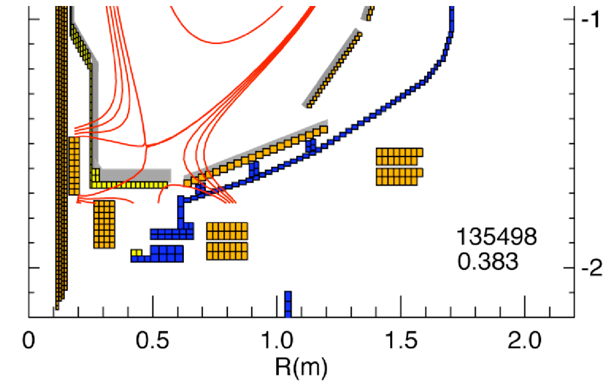
$$q_{||} = \left\langle n c_s T s_E e^{e(\Phi_B - \Phi)/T} \right\rangle$$

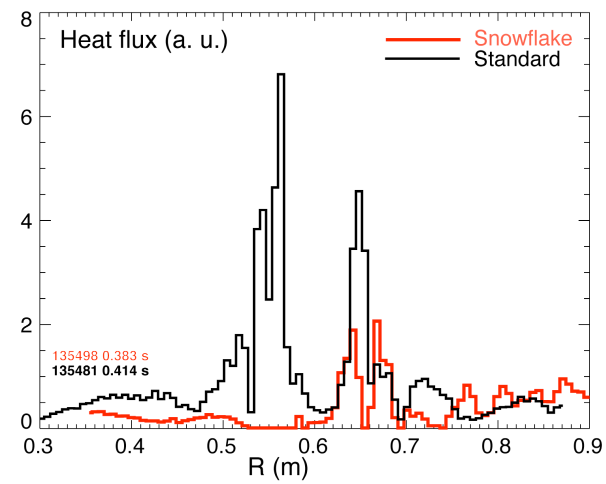
PAC25-16

TOOLS: ***Gas Puff Imaging (GPI), fast cameras, new Langmuir probes, biasing electrodes, edge turbulence codes SOLT, BOUT, XGC0***

NSTX is developing high flux expansion divertors and radiative techniques for heat flux management

- FY 2009 highlights
  - "Snowflake" divertor obtained using PCS
    - **Heat flux reduction** via partial strike point detachment even with lithium conditioning
    - **Impurity control** (core carbon and P_{rad} reduction)
  - Shape modeling identified possibilities for X-divertor
- Plan for 2010
  - "Snowflake" divertor transport and turbulence, long pulse magnetic control development
  - Radiative divertor with impurities (CD_4, neon)
  - Synergy with LLD pumping
- Longer-term plans (2011-2012)
  - Prototyping advanced configurations for NSTX-U
    - "Snowflake", X-divertor, double null, radiative divertor
  - Implementation of configuration and feedback control

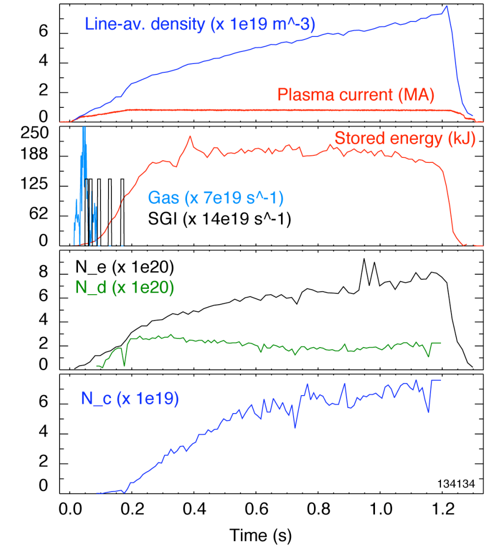




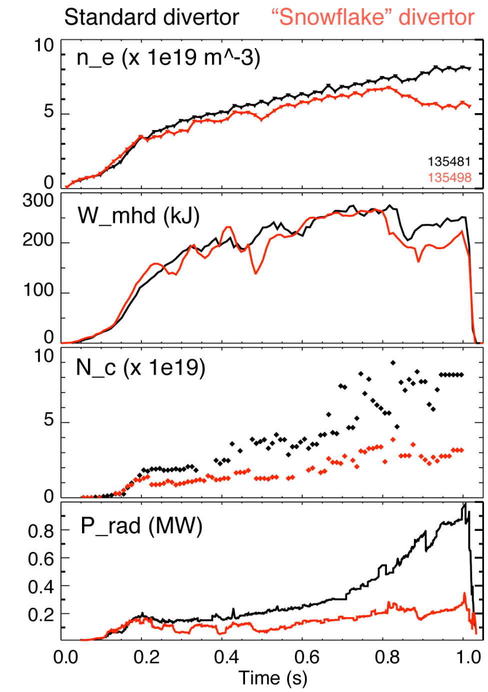
***TOOLS*: IR cameras, vis. cameras, divertor bolometry, divertor spectroscopy**
Edge transport codes UEDGE, SOLPS, DEGAS 2, BOUT; equilibrium codes ISOLVER and CORSICA

Understanding and controlling fueling, retention, recycling, impurities critical for advanced scenarios

- FY 2009 highlights
  - JRT FY 2009: high prompt carbon PFC retention (~ 90 %)
  - Long-pulse SGI-fueled H-mode discharge
    - Reduced nearly constant N_i and n_i with lithium pumping
    - SGI fueling efficiency x 2 higher than LFS gas
  - Core impurity control with radiative / “snowflake” divertor

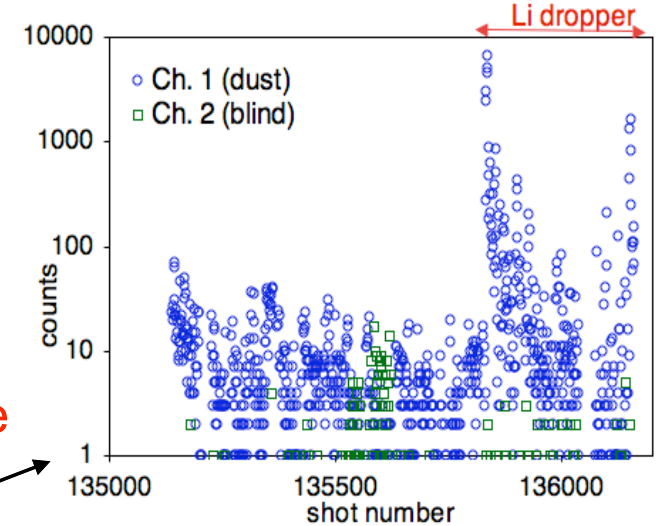


- Plans for 2010-2012
  - Density control
    - Improved HFS gas injection control
    - Density feedback control
    - Development of density control with LLD
  - Assessment of PFC candidate materials for NSTX-U (Li, C, Mo, W)



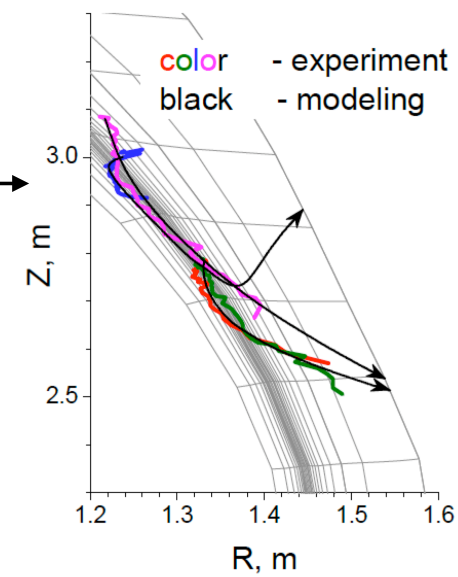
<u>TOOLS</u>: ***SGI, gas injectors, Langmuir probe array***
Edge codes UEDGE, SOLPS, DEGAS 2, BOUT, WallPSI, WGB

Dust issues for ITER and future tokamaks motivate research on NSTX



- FY 2009 highlights
  - Carbon dust mobilization from ITER-scale castellations in NSTX
    - Dust near top of castellation gaps is mobilizable
  - Dust detector development
    - First real-time detection of carbon dust *in any tokamak* with electrostatic detector
    - NSTX is leading ITPA Diag-4 dust measurement
  - Dust trajectory modeling with DUSTT code
- Plan for FY 2010 – FY2012
  - Develop in-situ cleaning techniques for dust detector
  - Dust transport code benchmarking

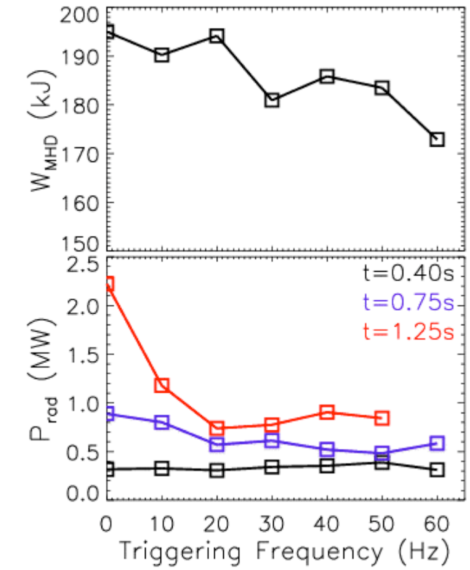
Sample dust trajectories

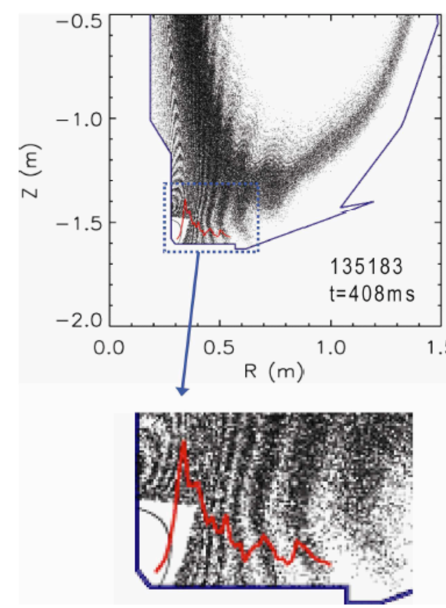


<u>TOOLS</u>: Upgraded dropper for Li, C, W dust, PMI probe, high-sensitivity electrostatic dust detector; Fast cameras, DUSTT code

NSTX is developing and utilizing 3D fields for ELM triggering and impurity control

- FY 2009 highlights
  - ELM triggering optimization with n=3 perturbations
    - Higher frequency reduces ELM size
  - Impact of n=3 perturbation on divertor profiles
- FY 2010 plan (R10-3)
  - Study 3D field effects on edge transport and fluxes
  - Studies of n=3 RMP ELM triggering threshold vs q_{95} window
  - ELM suppression using n=3 off-midplane fields
  - Access to ELM-free H-mode with LLD
  - Study 3D field and thermoelectric current effects
- Longer-term plans (2011-2012)
  - Development of small ELM regimes at low ν^* and high P_{in}
  - ELM dependence on shape and magnetic balance
  - 2nd SPA for ELM pacing optimization w/ mix of n=1,2,3 fields

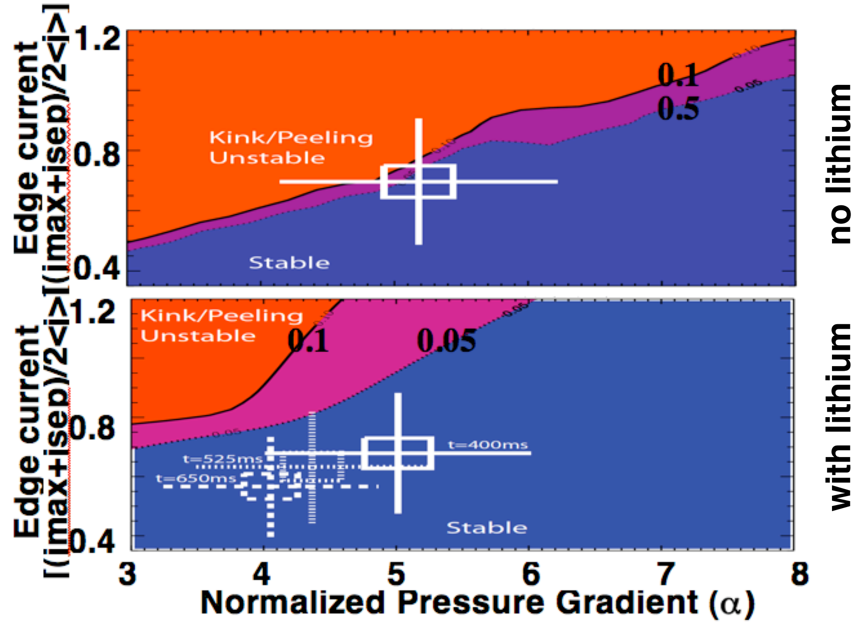




<u>TOOLS</u>: Fast IR and visible cameras, high spatial resolution edge MPTS, Linear and non-linear ELM-stability codes (ELITE, PEST, M3D)

Characterizing ST H-mode pedestal structure and transport, comparing to conventional aspect ratio

- FY 2009 highlight
  - Modification of density gradient with lithium led to stabilization of ELMs (ELM-free H-modes)
- FY 2010 plan
  - I_p, B_t scan to maximize range in pedestal height
  - Access to ELM-free H-mode with LLD



- Longer-term plans (2011-2012)
  - Assess pedestal response to externally applied 3D fields
  - Develop predictive capability for pedestal parameters (JRT 2011)
    - NSTX unique contribution - aspect ratio, collisionality, beta
    - Measure height and width of pedestal, edge electric field, long-wavelength turbulence
    - Test predictive models (EPED)

<u>TOOLS</u>: ***high spatial resolution edge MPTS, BES***

Linear and non-linear ELM-stability codes (ELITE, PEST, M3D), EPED 1/1.5/2, XGC0

PAC25-05

NSTX Boundary Physics Program Summary

- Measuring SOL widths and improving understanding of SOL transport for STs and tokamaks

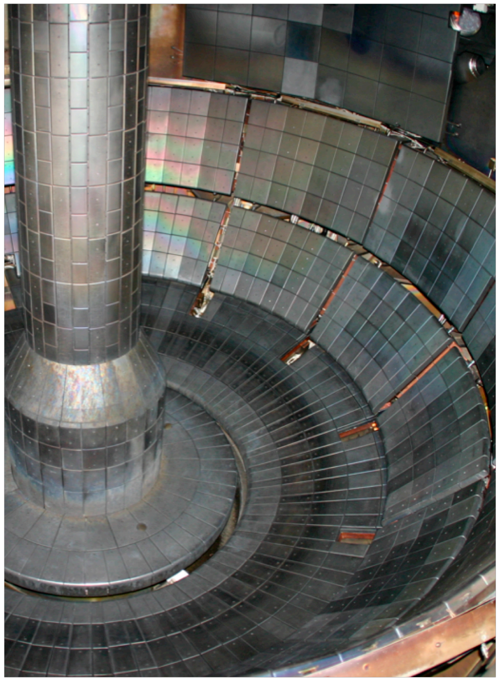
- Developing innovative methods for mitigating divertor heat flux and controlling density and impurities

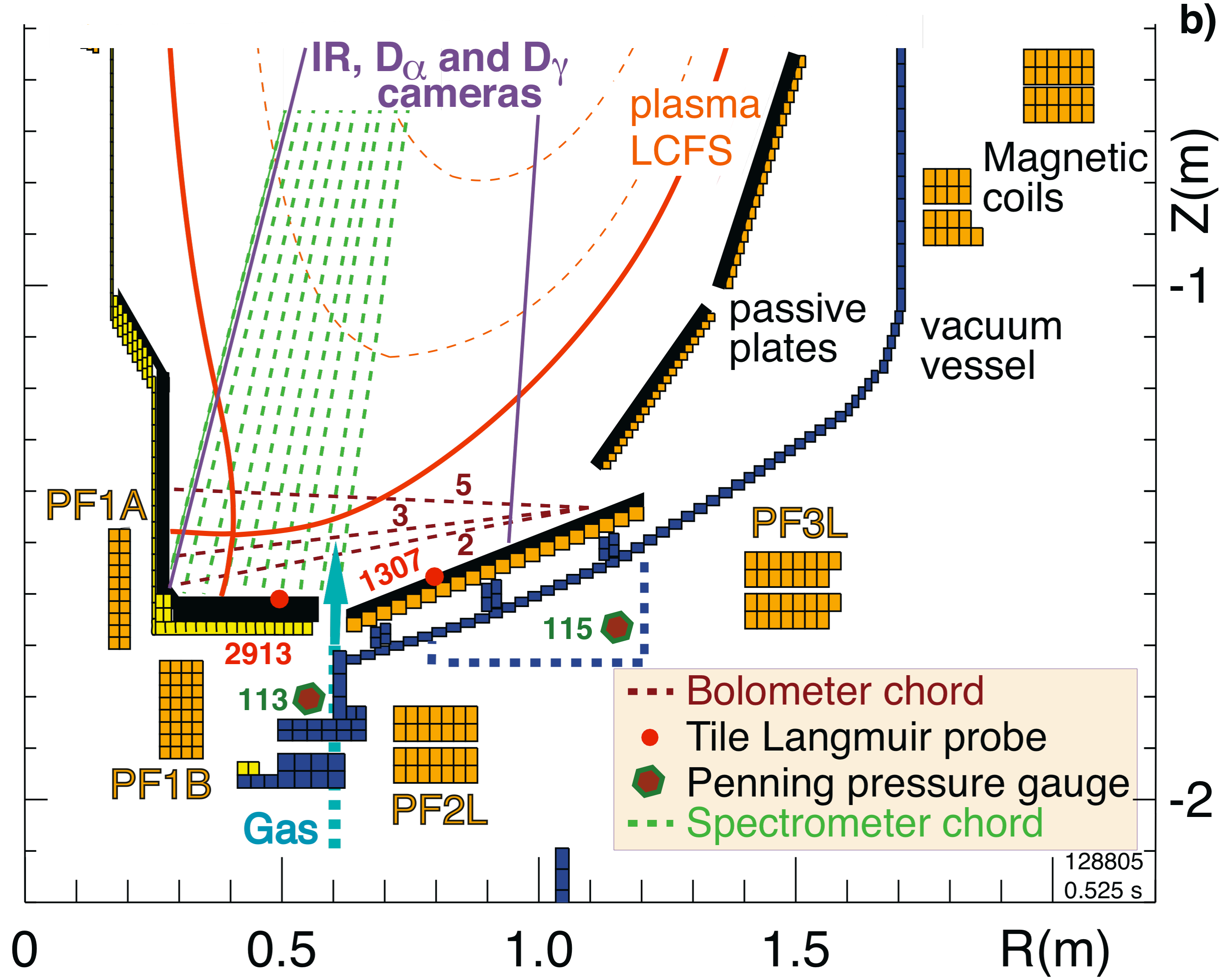
- Utilizing Li and other tools to improve understanding of H-mode pedestal structure and ELM stability

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

Backup slides and additional material

Boundary Physics diagnostics





Boundary Physics priorities for FY 2010

- Determine the relationship of ELM properties to discharge boundary shape, lithium conditioning, and 3D resonant magnetic perturbations (RMPs), and compare stability of pedestal/ELMs with model calculations (Milestone R10-3)

- Compare divertor heat flux widths to midplane density and temperature widths and edge turbulence characteristics, and determine the scaling of SOL and divertor heat transport (FY10 Joint Research Milestone)

- Understand and develop a predictive capability for the physics mechanisms responsible for the structure of the H-mode pedestal (FY11 Joint Research Milestone)

ITPA Participation

- PEP-6 Pedestal structure and ELM stability in double null
- PEP-16 C-MOD/NSTX/MAST small ELM regime comparison
- PEP-19 Edge transport under the influence of resonant magnetic perturbations
- PEP-25 Inter-machine comparison of ELM control using mid-plane RMP coils

- DSOL-15 Inter-machine comparison of blob characteristics
- DSOL-21 Introduction of pre-characterized dust for dust transport studies in divertor and SOL

- Diag-4 ITER Dust and Tritium Measurement

FY 2010 OFES Joint Research Milestone

Conduct experiments on major fusion facilities to improve understanding of the heat transport in the tokamak scrape-off layer (SOL) plasma, strengthening the basis for projecting divertor conditions in ITER. In FY2010, FES will measure the divertor heat flux profiles and plasma characteristics in the tokamak scrape-off layer in multiple devices to investigate the underlying thermal transport processes. The unique characteristics of C-Mod, DIII-D, and NSTX will enable collection of data over a broad range of SOL and divertor parameters (e.g., collisionality, beta, parallel heat flux, and divertor geometry). Coordinated experiments using common analysis methods will generate a data set that will be compared with theory and simulation.

FY 2010 Research Milestone R(10-3)

Assess H-mode pedestal characteristics and ELM stability as a function of collisionality and lithium conditioning.The high performance scenarios of next-step STs such as NHTX and ST-CTF are based on lower Greenwald density fraction and significantly lower pedestal collisionality than NSTX, which could significantly alter their H-mode pedestal characteristics. Possible differences include deviations from the L-to-H transition threshold power scaling inferred from present ST experiments, different projections for the pedestal height and barrier width, pedestal stability (affecting ELM type and size), and the down-stream divertor plasma and surface conditions, which can also influence the pedestal. Many different ELM regimes have been identified on NSTX, and the dependence of these regimes on collisionality and lithium will be investigated utilizing high-resolution kinetic equilibrium reconstructions coupled to leading linear and non-linear ELM-stability codes to compare to experiments. Pedestal profiles will be compared to kinetic neoclassical predictions to determine if the observed transport is consistent with theory. Particle pumping and density control in these experiments will utilize the liquid lithium divertor (LLD), and a major research focus in this research will be to determine the relative roles of reduced pedestal density and collisionality versus the possible direct effects of lithium. This research will aid development of a predictive capability for pedestal transport and stability limits for the ST, and through comparisons to results from higher aspect ratio tokamaks, will help aid understanding of the role of toroidicity in H-mode confinement.

Proposed text for FY2011 OFES Joint Theory-Experiment Research Milestone

- 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.

- Experimental milestone: 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. 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 milestone: 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. 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. 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.