Simulating the Pedestal Height and ELM Frequency in Tokamaks

Glenn Bateman and Arnold H. Kritz

Lehigh University Physics Department
Bethlehem, PA, USA

US-Japan Workshop, September 2004

Collaborations

Lehigh University: Thawatchai Onjun, Jon Kinsey, Alexei Pankin[1], Irina Voitsekhovitch[2], Stacy Snyder, John McElhenny, Chris MacDonald

JET: Vassili Parail, J. Lönnroth, H. Wilson

Canada: G.W. Pacher and H.D. Pacher

Germany: G. Janeschitz, G. Pereverzev

France: G. Huysmans

Russia: A. Dnestrovski

General Atomics: T. Osborne

ORNL: M. Murakami

PPPL: G. Hammett

[1]Current address: SAIC, 10260 Campus Point Dr., San Diego, CA 92069, USA

[2]Current address: Euratom/UKAEA Fusion Assoc., Culham Science Center, Abingdon, Oxon, OX14 3DB, UK

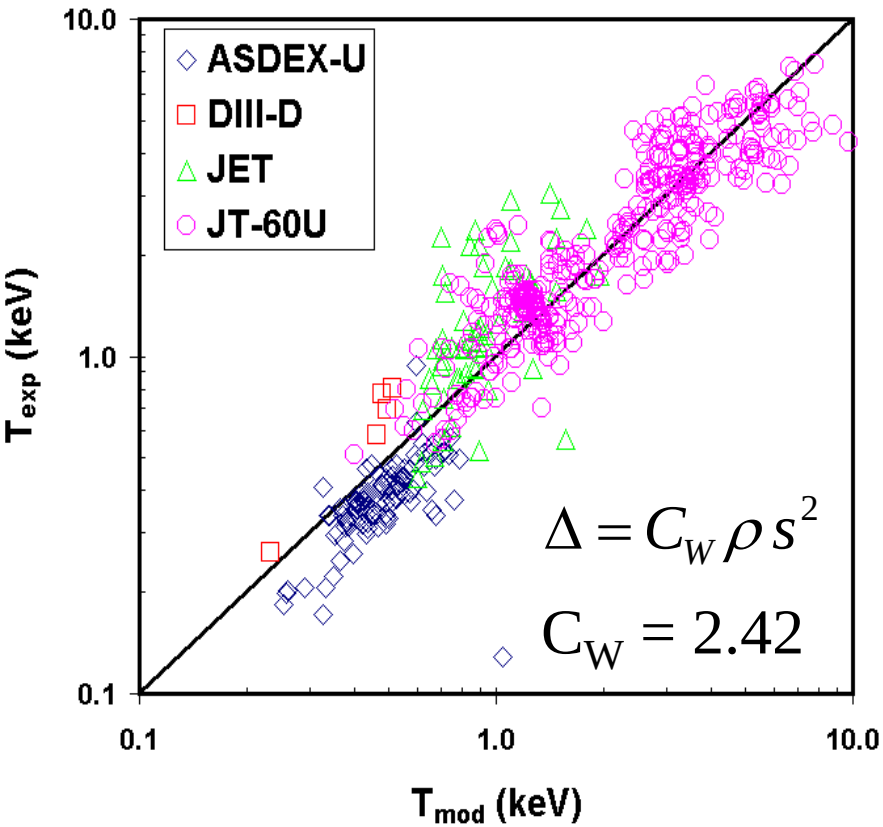
Summary

- **Objectives:**
  - Develop models for integrated simulations of tokamak H-modes to predict:
    - Height, width and shape of the pedestal
    - Frequency and effect of ELMs
    - Effect of pedestal and ELMs on the core plasma profiles
- **Integrated simulation models used by the Lehigh group:**
  - Pedestal height model used as a boundary condition in the BALDUR and XPTOR codes
    - Calibrated against experimental data
    - Used to simulate burning plasma experiments
  - Pedestal and ELM model used in the JETTO code
    - Investigating the physics of the ELM cycle
  - Pedestal and ELM model developed in the ASTRA code
    - Investigating pedestal formation and ELM cycle
- **Issues that need to be resolved**

Pedestal Model used as Boundary Condition

- Combine separate models for the core and H-mode pedestal
  - Models for height of pedestal taken from:
    - T. Onjun *et al.* Phys. Plasmas 9 (2002) 5018
    - G. Cordey *et al.*, 2002 IAEA, Nucl. Fusion 43 (2003) 670
  - Multi-Mode or GLF23 model used for core transport
  - Complete protocol developed for BALDUR and XPTOR predictive modeling simulations of H-mode discharges
    - Simulations use top of the pedestal as outer boundary condition
    - These simulations do not have time-dependent model for ELM crashes
- Simulations of experimental discharges have been carried out using this protocol in BALDUR and compared with data
  - Profiles agree with data as well as before
    - G. Bateman *et al.*, Phys. Plasmas 10 (2003) 4358
- Simulations of burning plasma experiments using this protocol
  - Predicted performance of burning plasma experiment depends on the choice of core and pedestal models
    - G. Bateman, *et al.*, Plasma Phys. Control. Fusion 45 (2003) 1939.
    - J. Kinsey, *et al.*, Nucl. Fusion 43 (2003) 1845.

H-mode Pedestal Temperature

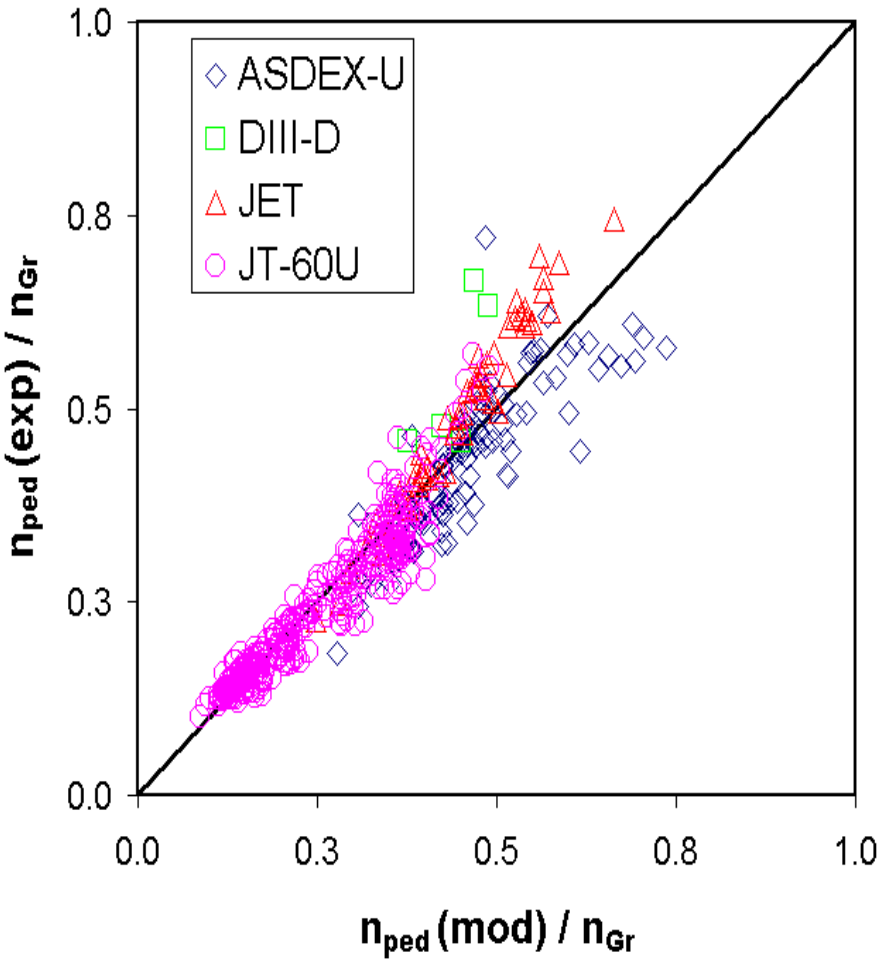


Onjun, Bateman, Kritz, Hammett
Phys. Plasma, 9 (2002) 5019

- Model based on Sugihara scaling for pedestal width $\Delta = C_w \rho s^2$
  - M. Sugihara, *et al.*, Nuclear Fusion, 40 (2000) 1743
- Pedestal pressure gradient limited by 1st ballooning stability limit
- Calibrated against 533 data points from the Pedestal Database v3.1
  - Logarithmic RMSE = 32.0%
  - Non-linear equation solved since *s* and *q* are functions of Δ
- PEDESTAL available in the NTCC Library (http://w3.pppl.gov/NTCC)

LEHIGH UNIVERSITY

H-mode Pedestal Density Model



A.H. Kritz *et al.*, EPS meeting 2002

- **An empirical approach is used to develop a pedestal density model**
  - **Pedestal density is directly proportional to line averaged density**

$$n_{\mathrm{ped}} = 0.71 < n >$$

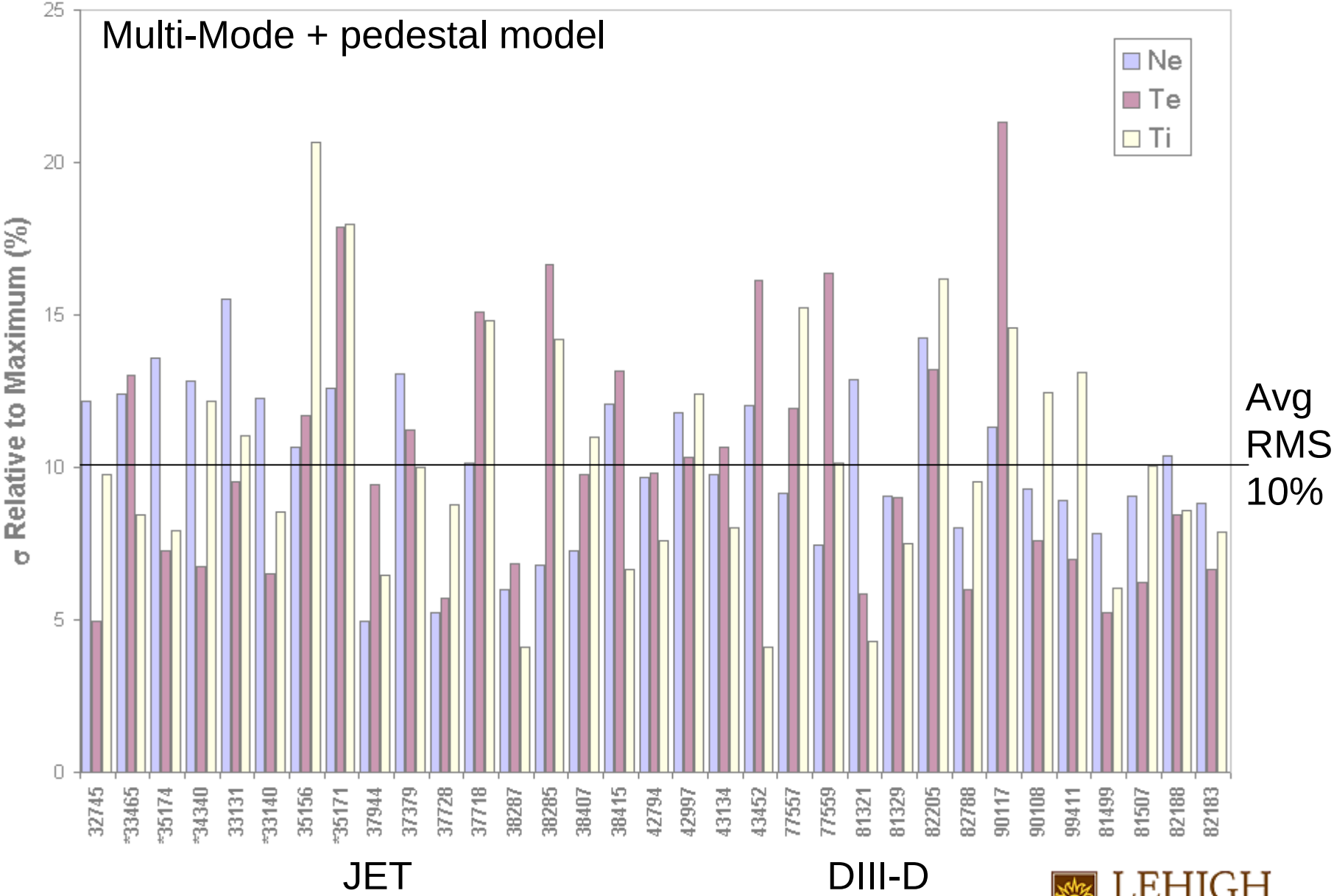
  - **RMSE of 12.1% with 533 data points from the ITPA Pedestal Database 3.1**
  - **Agreement begins to break down at high density**

Combined Model in BALDUR Simulations

- **H-mode pedestal models are combined with Multi-Mode core transport model in BALDUR simulations**
  - **Almost all of the BALDUR input values are taken from the controls that the experimentalists use**
    - ***B***, I_p, $\langle n_e \rangle$, P_{NBI}, **and plasma shape, as a function of time**
  - **Only exception is boundary impurity concentration n_Z/n_e which is taken from experimental measurements**
  - **During the Ohmic and L-mode stages of the simulation, boundary conditions are taken from experimental data**
  - **During the H-mode stage of the simulation, the pedestal model predicts the boundary temperatures and densities**
- **Simulations were carried out for 33 H-mode discharges**
  - **20 JET and 13 DIII-D discharges**
  - **All but 5 JET discharges (indicated with * in plot) are from the International Profile Database**

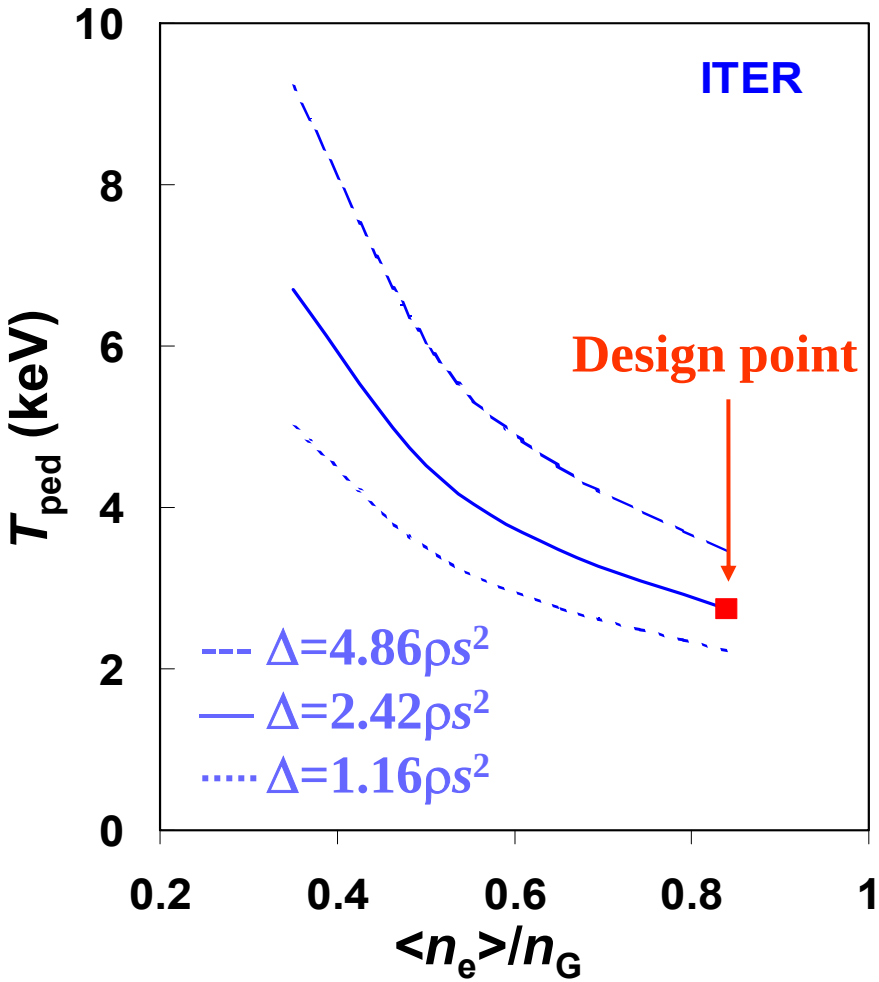
***Integrated Predictive Modeling of High-mode Tokamak Plasmas Using a Combination of Core and Pedestal*, Phys. of Plasmas 10, 4358 (2003), by G. Bateman, M. Bandres, T. Onjun, A. Kritz, A. Pankin**

RMS Deviations for 33 H-mode Discharges (JET and DIII-D)



LEHIGH UNIVERSITY

Range of Predicted ITER Pedestal Temperature as a Function of Density

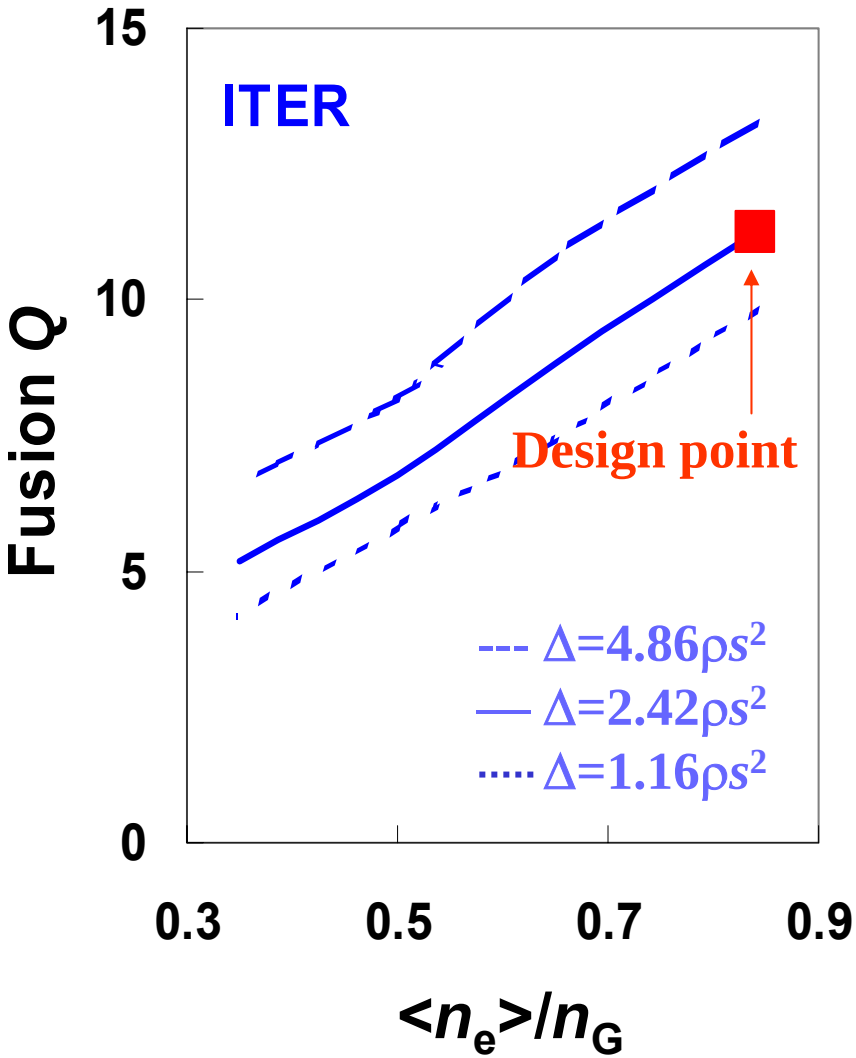


Design Parameters for ITER

R	6.2 m
a	2.0 m
I_p	15.0 MA
B	5.3 tesla
κ_{95}	1.7
δ_{95}	0.33
$\langle n_e \rangle / n_G$	0.84
Impurity	2% Be, 0.12% Ar
P_{aux}	40 MW

LEHIGH UNIVERSITY

Fusion Q vs $\langle n_e \rangle / n_G$ for ITER



- **Fusion Q increases as density increases**
  - **T_{i0} varies from 28 to 19 keV as density is increases from $\langle n_e \rangle / n_G$ = 0.35 to 0.85**
  - **Since the central temperatures are high in ITER, fusion power production is less efficient at low density**
    - **The best range for fusion power production is 10 keV< T_0 < 20 keV**
    - **Fusion $Q \propto (n_0 T_0)^2$**
- **Plasma density can be controlled in tokamaks**

LEHIGH UNIVERSITY

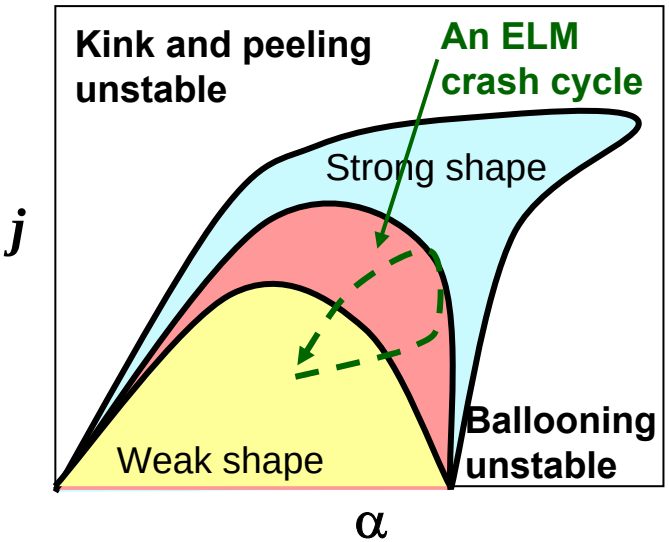
Comments on BALDUR Simulations

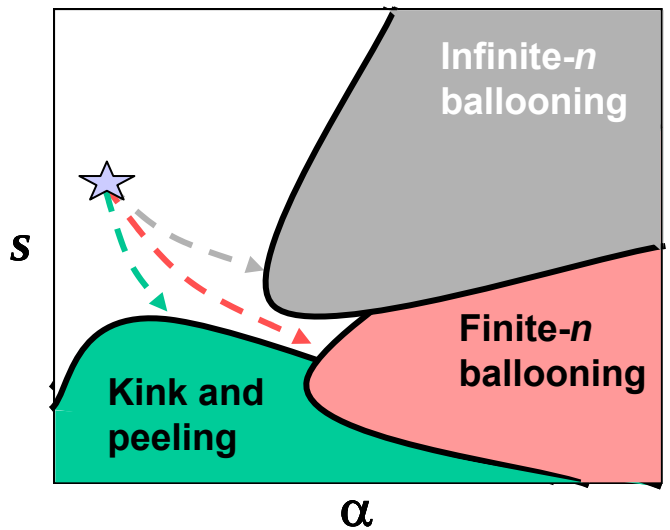
- Pedestal and transport models are available in the NTCC Module Library http://w3.pppl.gov/NTCC
  - These models could be used in other transport codes
- BALDUR simulations do not include ELM cycles
  - Pedestal gradient is implicitly limited by ELM stability limit
- Pedestal model is not logically connected to the plasma core models
  - Pedestal is not included on the BALDUR grid
  - Logically different models are pieced together
- RMS error in core profiles (10%) is smaller than RMS error in pedestal height (32%)
  - The data used for the pedestal might be at random phases during the ELM cycles

Pedestal and ELMs in the JETTO code

- **Implemented by V. Parail *et al.* in the JETTO code and used by T. Onjun and S. Snyder at Lehigh**
  - **V. Parail *et al.*, Plasma Physics Reports 29 (2003) 539**
  - **T. Onjun *et al.*, Phys. Plasmas 11 (2004) 1469**
  - **T. Onjun *et al.*, Phys. Plasmas 11 (2004) 3006**
- **Neoclassical transport used in the pedestal**
  - **Determines height of temperature and density pedestal**
- **Two criteria to trigger ELMs: Pressure-driven ballooning mode and current-driven peeling mode**
  - **Determines frequency of ELMs**
- **Criteria used in JETTO code calibrated using HELENA and MISHKA MHD stability codes**
  - **Transition from 1st to 2nd stability region is observed**

Edge Localized Modes (ELMs)





- **An ELM crash is an abrupt phenomenon (order of msec)**
  - **Triggered by ballooning mode, or kink and peeling mode**
  - **ELM trigger mode depends on evolution of edge current**
    - **Slow edge current evolution ⇒ pressure-driven ballooning mode**
    - **Fast edge current evolution ⇒ current-driven ballooning mode**
  - **Access to second stability normally obtained in strongly shaped plasma (high triangularity)**

ELM Model in JETTO Code

- **An ELM crash occurs when an instability condition is satisfied anywhere within the pedestal**
  - **ELM crash triggered by either of two instabilities: pressure-driven ballooning mode or a current-driven peeling mode**
- **When ELM crash condition is achieved, crash is produced by transiently increasing transport within pedestal**
  - **This is not intended to be a model for the details of an ELM crash**
    - **Would need 3-D non-linear extended MHD computation or a fully gyro-kinetic simulation to model each ELM crash accurately**
  - **The model in the JETTO code is only intended to produce the observed changes in the plasma temperature and density profiles**

ELMs Triggered by Pressure-driven Ballooning Mode

- **If normalized pressure gradient α exceeds the ballooning limit α_c in JETTO code, an ELM crash occurs**

$$\alpha \equiv -\frac{2\mu_0 q^2}{\varepsilon B_T^2}\left(\frac{dp}{d\rho}\right) > \alpha_c$$

where *q* is a safety factor and B_T is the toroidal field

- **The critical pressure gradient, α_c, is a number that is calibrated using the HELENA and MISHKA MHD codes**

ELMs Triggered by Current-driven Peeling Mode

- **If the edge current density satisfies the peeling condition, an ELM crash occurs**
  - **The peeling mode criterion can be written in the form**

$$\sqrt{1-4D_m}+C<1+\frac{1}{2\pi q'}\oint\frac{J_{||}B}{R^2B_p^3}dl$$

D_m = Mercier coefficient, proportional to pressure gradient

C = 0.2 due to effect of vacuum region

$J_{||}$ = parallel current density

***dl* = poloidal arc length element; *R* = major radius**

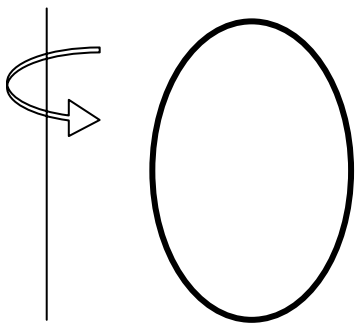
***B* = toroidal magnetic field; B_p = poloidal magnetic field**

***q'* = differentiation of safety factor respect to poloidal flux**

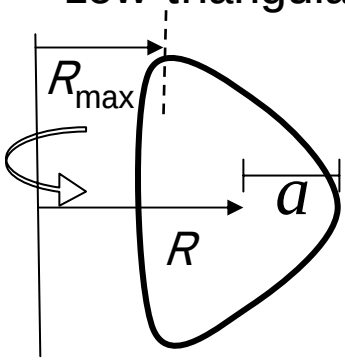
  - **Details in article by H. R. Wilson *et al*., Nucl. Fusion, 40 (2000) 713**

JET Triangularity Scan

- **All plasma parameters are similar, except triangularity**



Low triangulairity



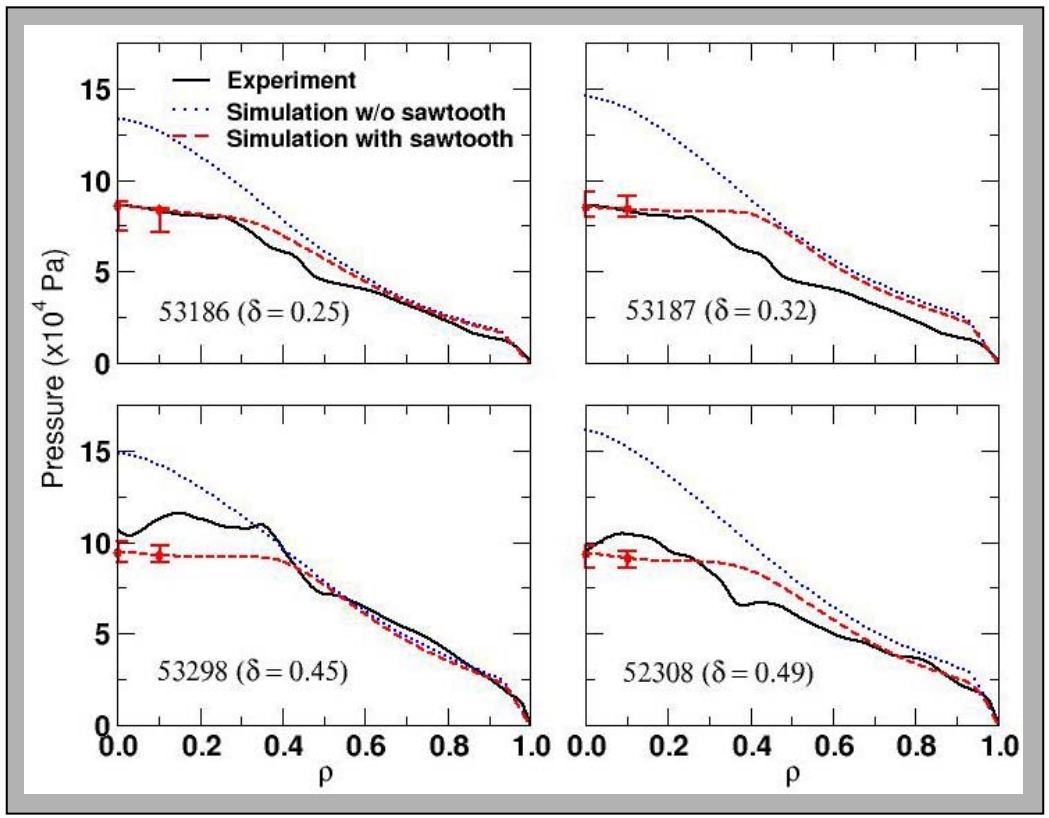
High triangulairity

$$\delta \equiv \frac{R - R_{max}}{a}$$

Parameter	53186	53187	53298	52308
R [m]	2.91	2.92	3.01	2.99
a [m]	0.94	0.92	0.89	0.90
I_p [MA]	2.50	2.50	2.49	2.50
B_T [T]	2.61	2.61	2.68	2.69
κ	1.69	1.74	1.72	1.74
δ	0.25	0.32	0.45	0.49
A_H [AMU]	2.00	2.00	2.00	2.00

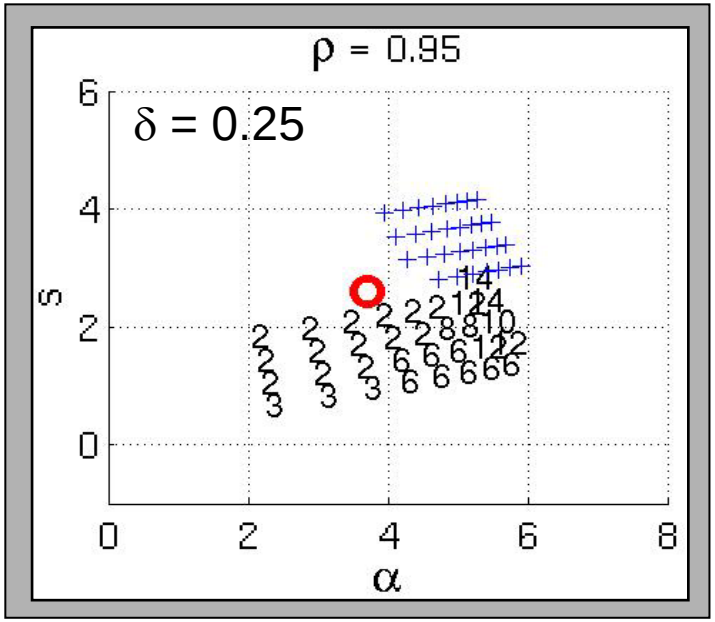
Comparison of Pressure Profiles in Triangularity Scan

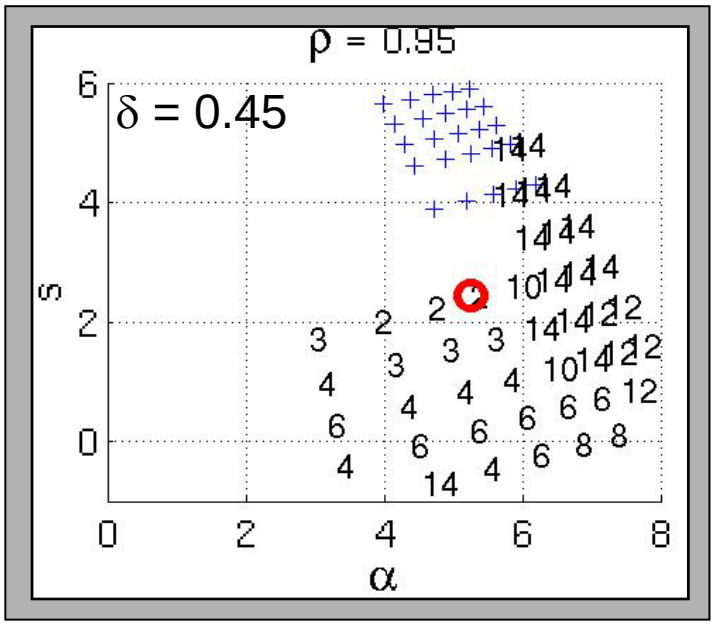
- **Simulations using $\Delta = 2.42\rho s^2$ and ELMs triggered by ballooning mode only**



- **Simulation profiles can reproduce the experimental profiles**
- **Including sawtooth oscillations improves the core agreement**
- **Pedestal width in the simulations is in the range of experiment (about 5% of minor radius)**

Stability Analysis for JET Triangularity Scan Discharges



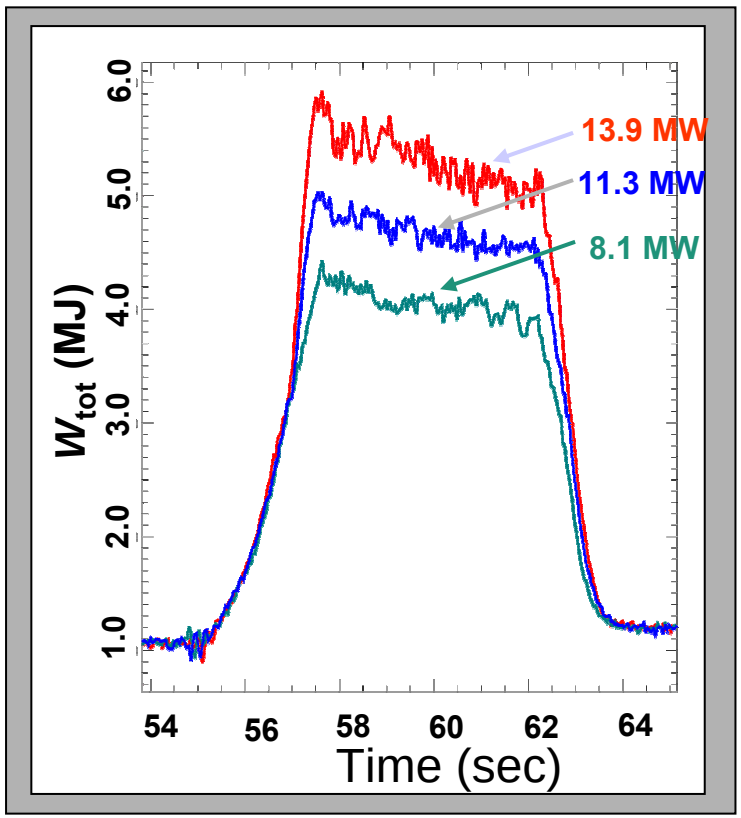


- **Stability analysis carried out for low triangularity (δ = 0.25) and high triangularity (δ = 0.45)**
  - **Results shows in a s-α diagram**
    - **s-α diagrams are shown for 95% flux surfaces**
  - **No access to 2nd stability in low triangularity discharge**
    - **Access to 2nd stability closed by *n*=2 current-driven mode**
  - **Access to 2nd stability seen in high triangularity discharge**

LEHIGH UNIVERSITY

JET power scan

- **Stored energy and pedestal pressure increases with heating power**

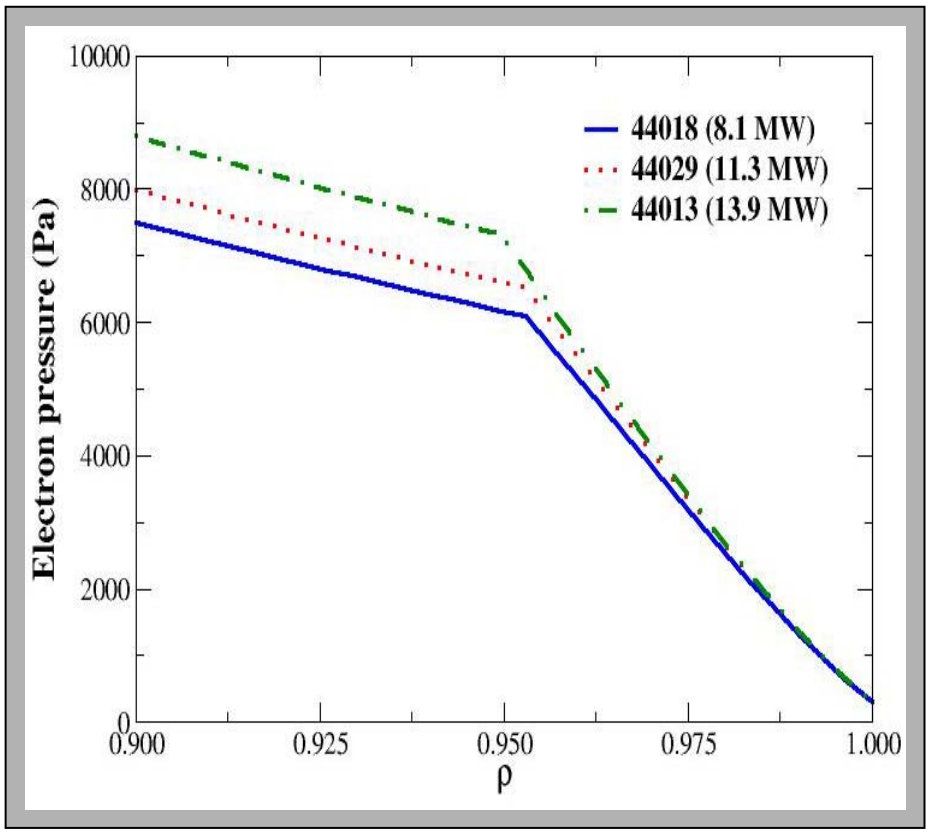


  - **Based on ballooning mode limit, pedestal pressure is independent of heating power**

Shot	Heating power (MW)	$W_{tot,\ exp}$ (MJ)	$p_{e,ped}$ (x10^4 Pa)
44018	8.1	4.00	5.47
44029	11.3	4.59	6.43
44013	13.9	5.18	7.16

ELMs Triggered by Current-driven peeling modes

- **When ELMs triggered by peeling modes included, pressure at the top of the pedestal before ELMs increases with heating power**

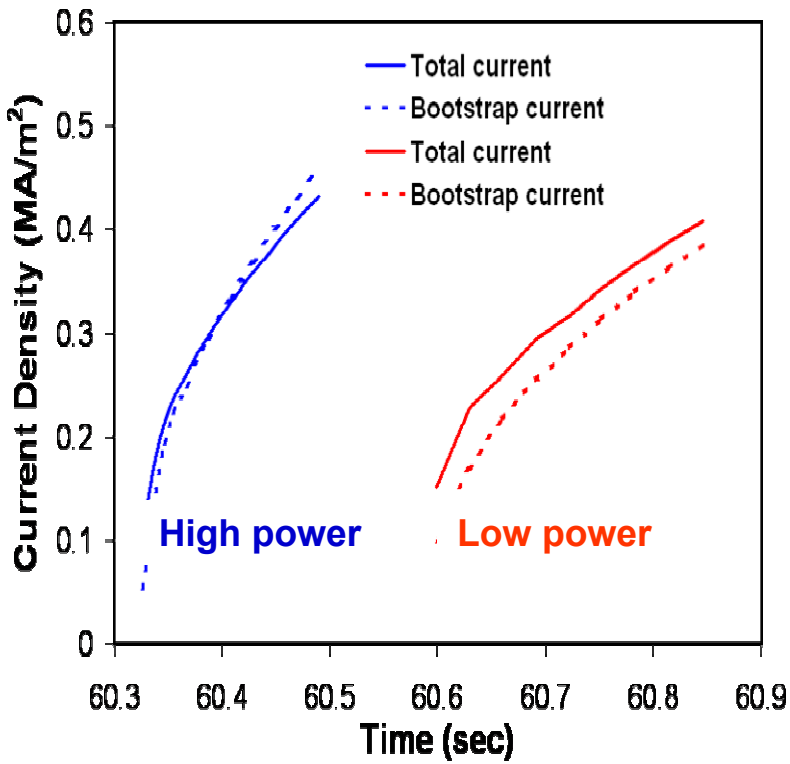


  - **Agrees with the trend observed in experiment**
  - **If ELMs were triggered by pressure-driven ballooning modes alone, simulations fail to agree with experimental trend**

LEHIGH UNIVERSITY

Evolution of Current Density between ELMs at r/a = 0.97

- **Prior to ELM crash, the bootstrap current (j_b) is higher than the total current (j_{tot}) in high power discharge, but lower in low power discharge**



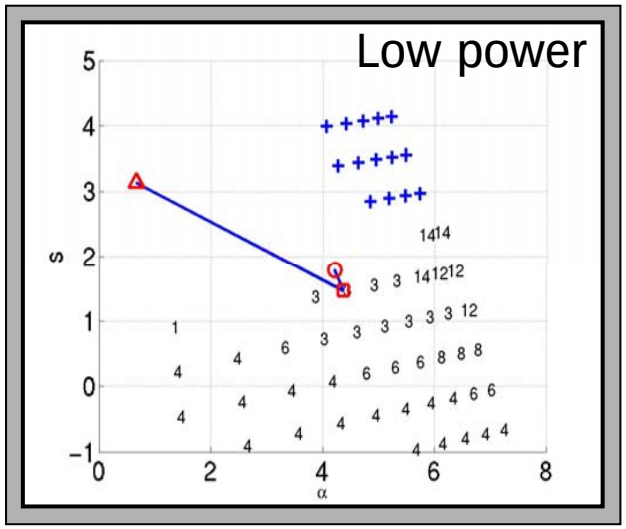
  - **In high power, rapid rising j_b results in large back EMF to reduce j_{tot}, so j_{tot} is less than j_b in the pedestal region**
  - **In low power, more slowly rising j_b results in small back EMF to reduce j_{tot} so j_{tot} is higher than j_b**

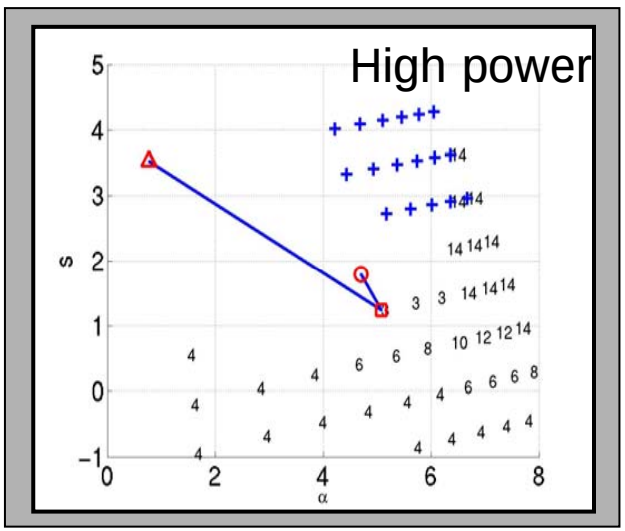
LEHIGH UNIVERSITY

Explanation of Power Dependence

- **The following physical processes can be used to explain how the pedestal pressure increases with plasma heating power**
  - **ELM crashes are triggered by current-driven mode**
  - **Pedestal pressure gradient and resulting bootstrap current rise more rapidly with increased heating power**
  - **Back EMF prevents the current density in the pedestal from rising as rapidly as the bootstrap current density**
  - **Hence, pedestal pressure increases to higher levels at higher heating power between ELM crashes**

Stability Analysis For Power Scan Discharges

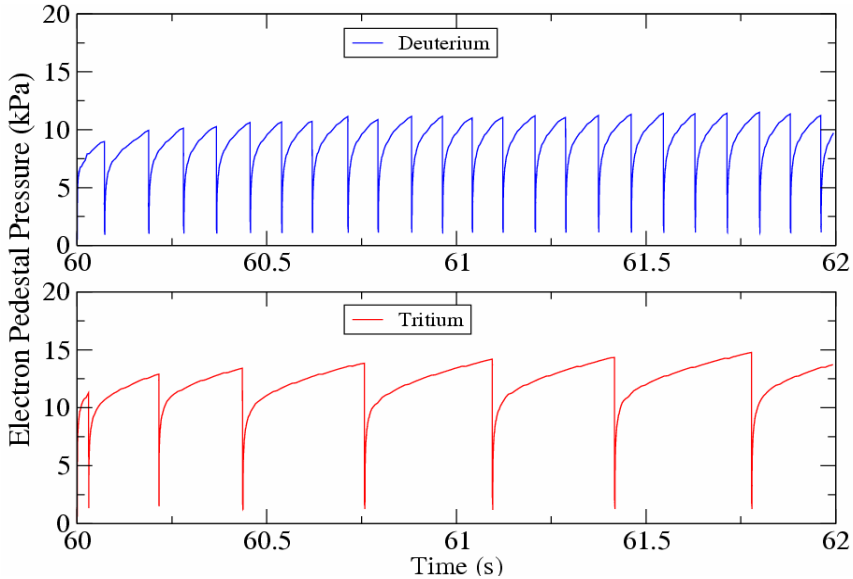




- **Stability analysis for 95% flux surface shown on s-α diagram**
  - **Operational points are indicated for 3 flux surfaces (92%, 95%, 98%)**
- **Top of barrier is located close to the 95% flux surface**
  - **Operating point is close to being unstable to kink/peeling modes**
  - **Maximum normalized pressure gradient, α, increases as P_{heat} increase**

LEHIGH UNIVERSITY

Effect of Isotope Mass on H-Mode Pedestal and ELMs



JET Simulation results for pedestal width proportional to thermal Larmor radius

- If pedestal width is proportional to thermal Larmor radius in the simulations, then
  - Pedestal pressure *increases* with isotope mass, as in experiment
  - ELM frequency *decreases* with isotope mass, as in experiment
  - Quantitative agreement with experimental data is obtained, as shown below
- If the pedestal width were fixed
  - Pedestal pressure *decreases* with isotope mass, unlike experiment
  - ELM frequency *decreases* with isotope mass, as in experiment

		Deuterium	Tritium
	JET Discharge	43154	43003
Pedestal Pressure (kPa)	Simulation	11.4	14.5
	Experiment	10.1	13.6
ELM Frequency (Hz)	Simulation	8.5	3.5
	Experiment	6 - 18	3 - 5

Comments on the JETTO Simulations

- Simulations show how ELMs affect pedestal height
  - Complex physics of ELM trigger strongly affects pedestal height
- Transition to 2nd stability indicated by HELENA and MISHKA
  - Particularly clear in triangularity scan
- Pedestal width is prescribed separately in the JETTO model
  - Not self-consistently predicted
  - Isotope scan showed that pedestal width increases with mass
- All transport through the pedestal is given by the ion thermal neoclassical transport computed at top of pedestal
  - More physically motivated model needed for electron thermal and particle transport
- Transient increase in transport is used to simulate the effects of each ELM crash

Pedestal and ELMs in the ASTRA Code

ASTRA simulations are used to predict:

Pedestal Profiles

- Pedestal Width
- Pedestal Height
- Pedestal Shape

Dynamics of ELMs

- ELM Frequency
- Width of the region affected by ELMs
- Transport between ELMs
- Effects of pedestal profiles

Overall objective is to follow plasma evolution

Ohmic → L-mode → H-mode → ELMs

in integrated predictive time-dependent modeling of tokamak plasmas

Theory-based model used for pedestal and ELMs at the edge of H-mode plasmas

– **Flow shear stabilization of anomalous transport**

- **Edge transport consistent with core transport**
- **Local self-consistent calculation of plasma profiles from core through pedestal**

Pedestal Model in ASTRA Code

- **Anomalous transport within the pedestal is suppressed by *ExB* shear, except for short wavelength ETG mode**
  - **Different modes of turbulence are suppressed at different rates**

$$\chi = \frac{\chi_{\text{L-mode}}}{1 + C\,(\omega_{E\times B}\tau_{j,MMM})^2} + \chi_{\text{neoclassical}}$$

where $\chi_{\text{L-mode}}$ is Multi-Mode transport model without flow shear

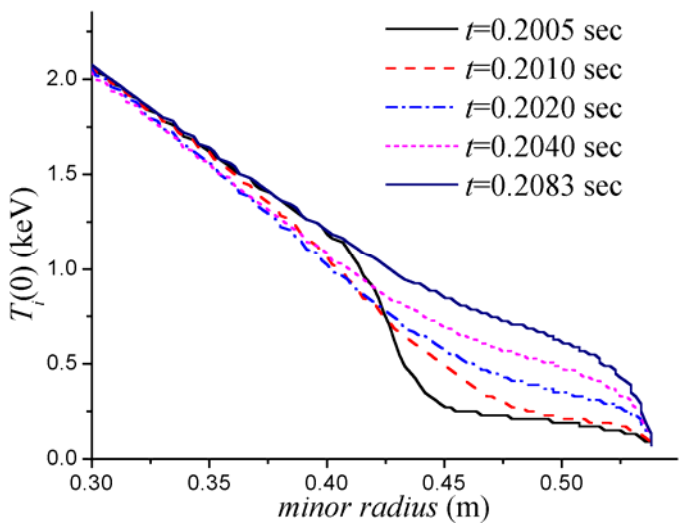
$\omega_{E\times B}$ is the flow shear rate

$\tau_{j,MMM}$ is the turbulence correlation time for each mode

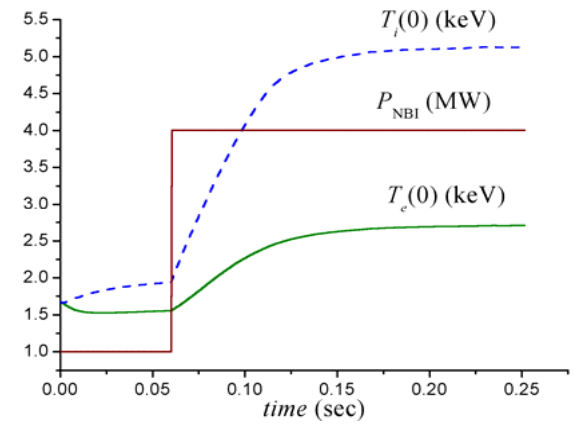
H-mode Simulations Using ASTRA Code With ETG Electron Thermal Transport

- **Simulations include both core and pedestal region**
- **Effects of ELM crash included**
- **Self determined L-H transition**

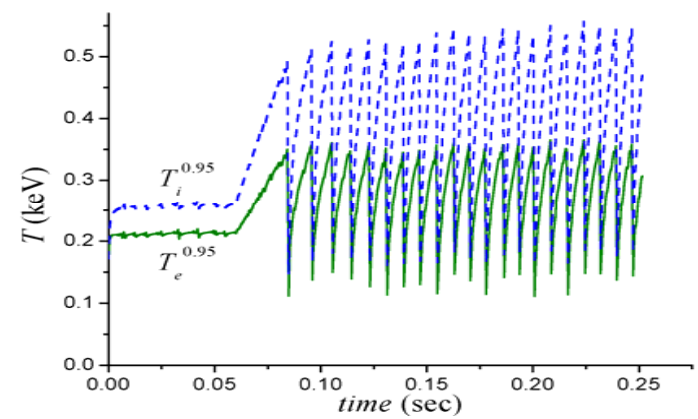
Reconstruction of profile after ELM crash



Evolution of central temperature

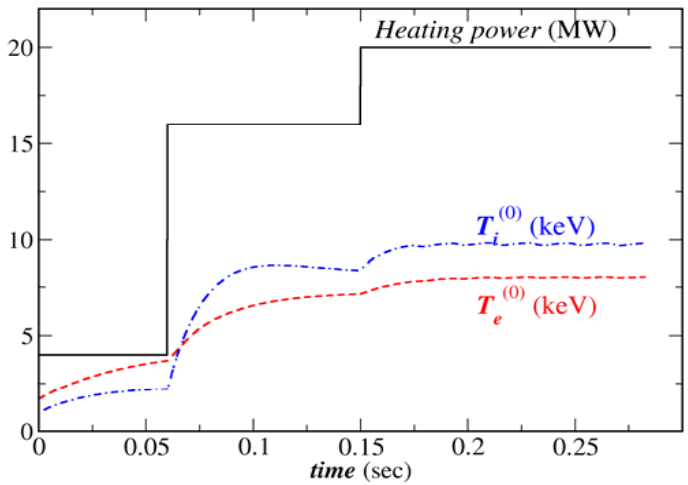


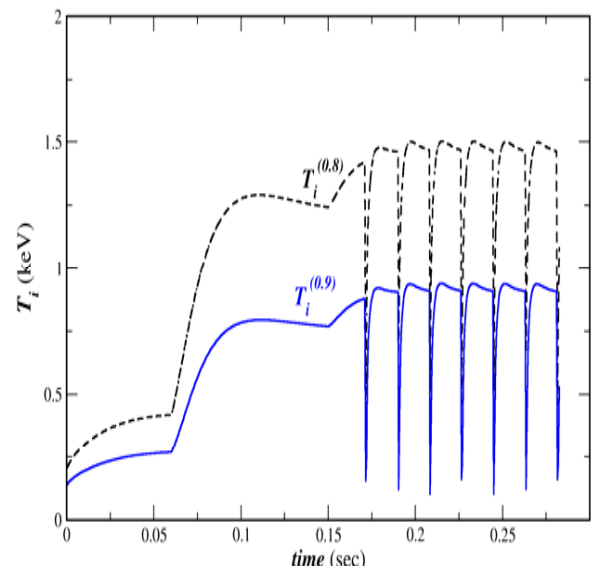
Evolution of edge temperature

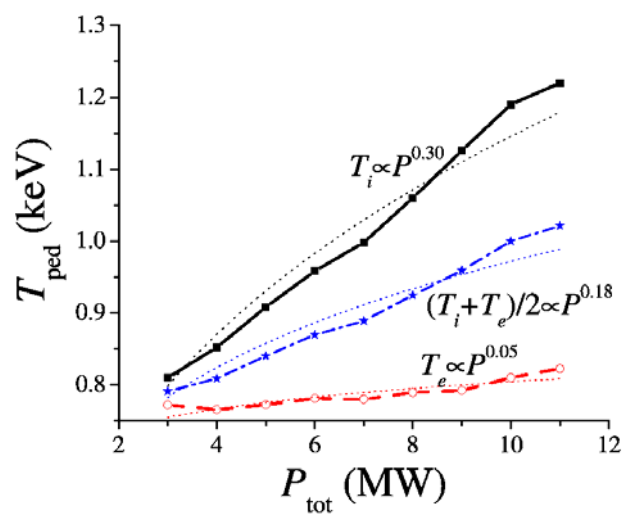


Testing Combined Model with ASTRA Code

- A DIII-D-like geometry is used as an example
- Prescribed density profile and heat sources







Simulations used to predict:

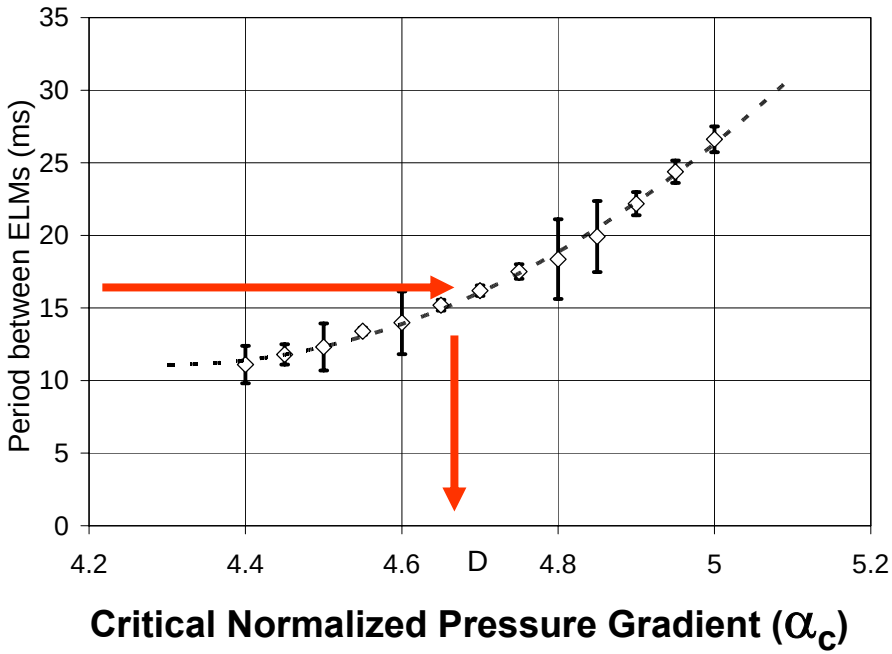
- time evolution of temperature profiles
- current profile diffusion with neoclassical current conductivity

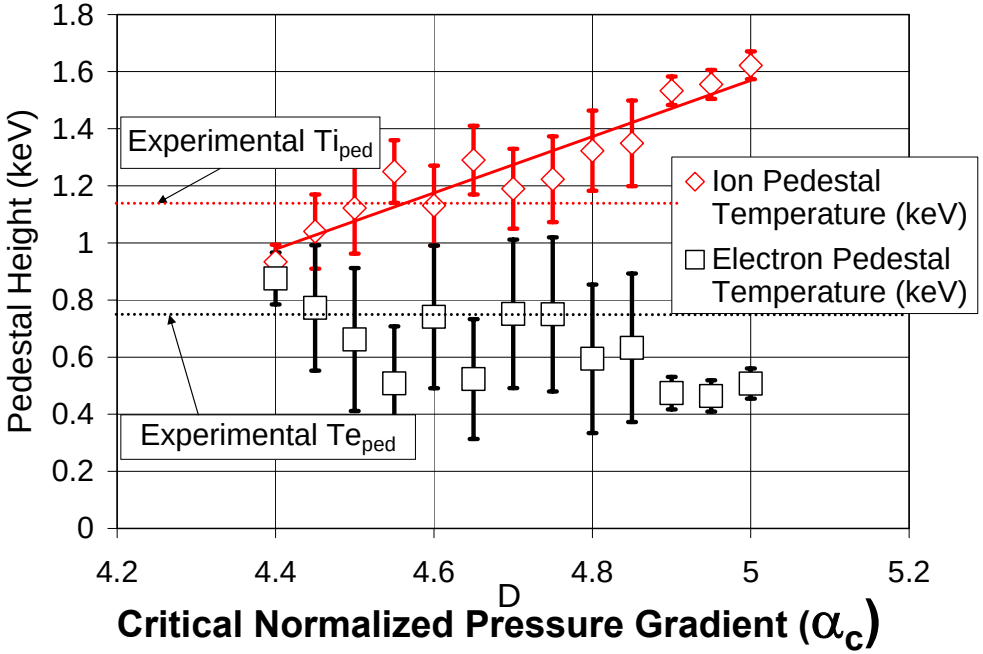
LEHIGH UNIVERSITY

Scaling of Pedestal Temperature and ELM Frequency

- **Pedestal and ELM model in ASTRA has been used to study scaling of pedestal temperature and ELM frequency**
  - **Pedestal temperature decreases with pedestal density:** $T_{ped} \sim 1/n^{\alpha}_{ped}$; $\alpha > 1$
  - **Pedestal temperature and ELM frequency increase with plasma heating power**
    - **This effect is caused by changes in pedestal current density and the resulting magnetic shear**
  - **Pedestal temperature increases slowly with increasing toroidal magnetic field (with fixed plasma current)**
    - **ELM frequency decreases with magnetic field**
- **Many of the trends are consistent with experimental data**

Calibration of ASTRA Pedestal and ELM Model





- **Experimental data for DIII-D 98889 obtained from Tom Osborne at GA**
  - **Noise reduced by overlaying data from consecutive ELM cycles**
- **Once flow shear large enough, the critical normalized pressure gradient for triggering ELM crashes (α_c) is most important calibration constant**
  - **$\alpha_c \approx 4.7$ yields observed ELM period (left) and approximate pedestal height**

LEHIGH UNIVERSITY

Comments on the ASTRA Simulations

- **The model is evolving**
  - **Detailed calibration of the model is in progress**
  - **Need time-dependent density equation in our version of model**
    - **Pachers and Janeschitz include density equation in their version G.W. Pacher *et al.*, Nucl. Fusion 43 (2003) 188**
- **Simulations reproduce many, but not all trends**
  - **Pedestal height and ELM frequency are consistent with experimental trends as a function of heating power and B field**
    - **A.Y. Pankin, I. Voitsekhovitch, *et al.*, submitted for publication**
  - **Pedestal height inversely related to plasma density as in the experimental results**
    - **ELM frequency decreases with increasing plasma density which is not consistent with experimental observations**

Issues to be Resolved

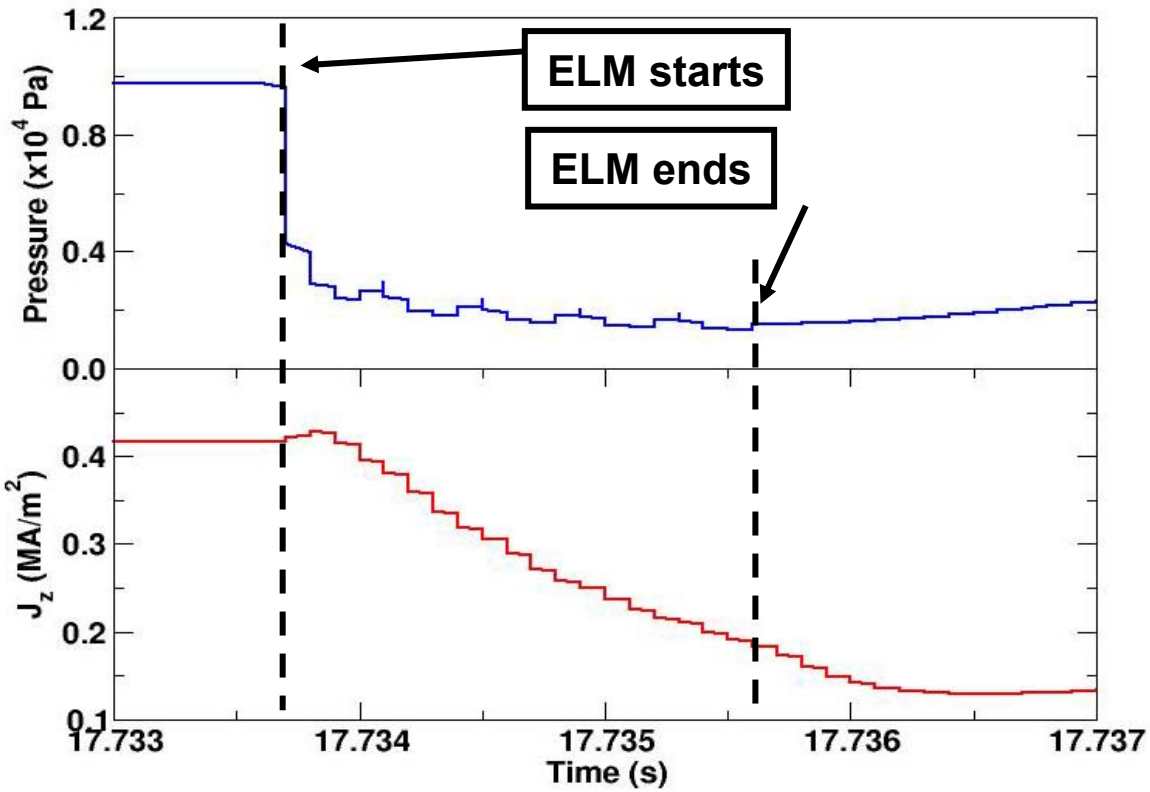
- **Effect of ELM crashes on current density in the pedestal**
  - **What fraction of the current density is removed during each ELM crash?**
  - **Where does the current go (to the wall or into the plasma)?**
- **To what extent are different channels of anomalous transport suppressed by flow shear in the pedestal?**
  - **Does electron thermal transport persist?**
- **Model needed for particle source in response to ELM crashes**
  - **How do the density and temperature profiles evolve between ELMs?**
- **Vertical asymmetry of the L→H-mode transition**

First Issue: Effect of ELM Crashes on Pedestal Current Density

- Relatively high current density driven in the pedestal by bootstrap current resulting from steep pressure gradient
  - That current density can drive a peeling or kink mode
  - Pedestal current can also affect pressure-driven ballooning mode
  - An ELM crash can be triggered either a pressure-driven ballooning mode or by current-driven peeling instability
- Experimental data indicates that each ELM crash results in loss of energy and particles from the plasma edge
  - It is not clear what fraction of the current density is reduced
- If pedestal current is not reduced rapidly during ELM crash, peeling modes unrealistically extend ELM crash duration
  - Resistive current diffusion during ELM crash is too slow
  - Magnetic reconnection probably removes edge current faster
  - Model is needed to determine the fraction of the pedestal current that is removed during ELM crash

Edge Pressure Reduces Quickly But not Edge Current

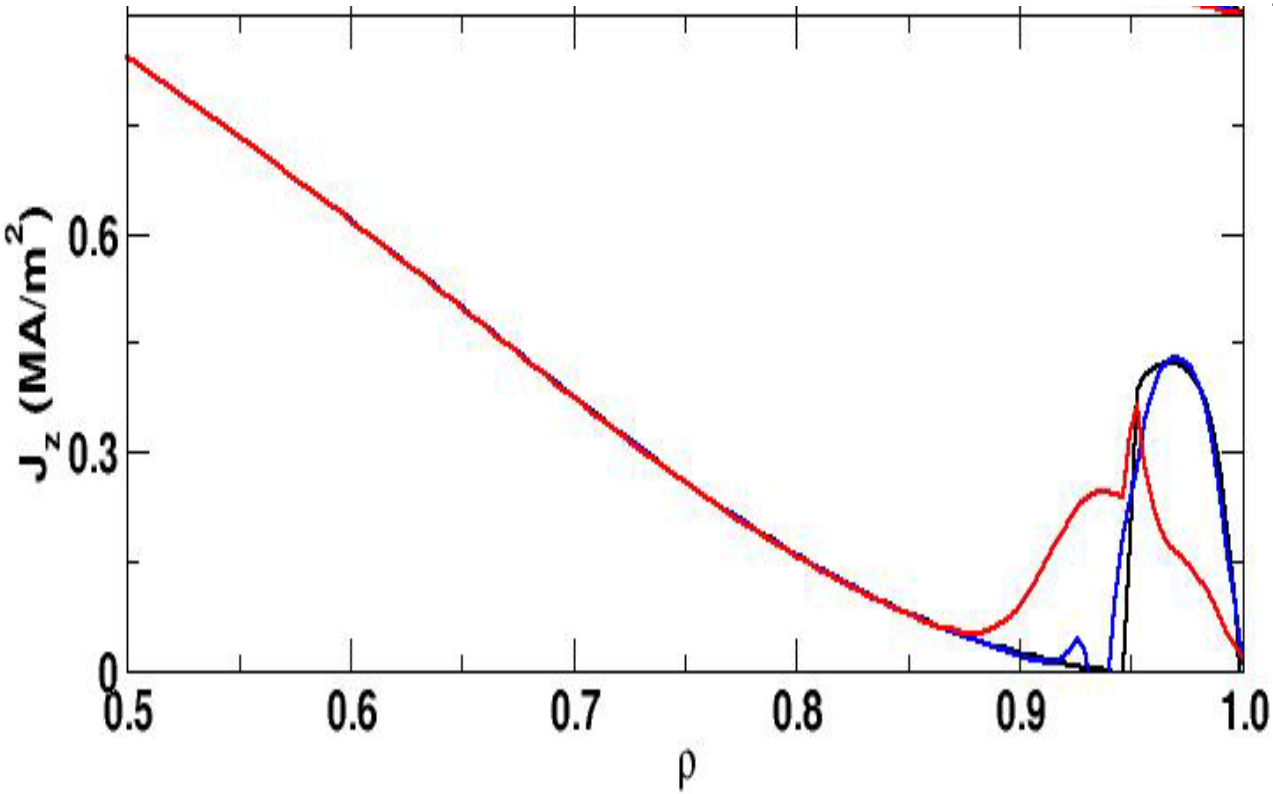
- **Plot of pressure and current density at ρ = 0.97 during an ELM crash**



- **Edge pressure drops quickly during first part of ELM crash**
- **While edge current decreases gradually**
- **Better model for removing the edge current during an ELM crash is needed**

LEHIGH UNIVERSITY

Change in Current Density Profile during ELM Crash



Just before ELM crash starts

Just after the first small part of ELM

Just after end of ELM crash sequence

- **In JETTO simulations, pedestal current is driven into the plasma during an ELM crash**

Interaction of Pedestal Current and Wall During ELM Crashes

- **When an ELM crash occurs, does the pedestal current go into the plasma or out to the scrape-off-layer and wall?**
  - **In the JETTO and ASTRA simulations, the pedestal current is assumed to be driven into the core plasma**
  - **The simulation codes probably need to be changed to allow the pedestal current to go to the wall as an eddy current**
- **If the pedestal current goes to the wall during each ELM crash, then the wall might affect the period of ELMs**
  - **Inductive/resistive time scale for decay of eddy currents in the wall would affect the return of the current to the plasma**
  - **Total plasma current is being held fixed while current is driven in the pedestal by bootstrap current and removed by ELM crashes**
  - **Simulate dynamics of current in core plasma, pedestal, and wall**

Second Issue: Transport within the Pedestal

- Ion pedestal temperature tends to be higher than electron pedestal temperature
  - ASDEX-U experiments indicate that $T_{i,ped} \approx 1\text{-}2T_{e,ped}$
    - W. Suttrop et al., Plasma Phys. Control. Fusion 42 (2000) A97
- If one assumes that all anomalous transport within the pedestal is completely suppressed
  - Neoclassical transport then becomes the only transport in the pedestal region
  - Electron neoclassical transport is significantly smaller than ion neoclassical transport
    - Results in electron pedestal temperature higher than ion pedestal temperature, which disagrees with experimental observation
- Anomalous electron transport might not be fully suppressed
    - ETG mode can provide electron thermal transport within the pedestal

Third Issue: Edge Particle Source

- **An accurate model is needed for the edge particle source to model reconstruction of density profile between ELMs**
  - **Experimental evidence indicates that the density profile is more perturbed by ELM crashes than the temperature profiles**
  - **Neutrals from the wall and gas puffing are mostly ionized in the pedestal region**
    - **Hence the source of ions is strongly localized near the pedestal**
  - **Simulations indicate that there is a lot of recycling of edge neutrals just after each ELM crash**
- **The time-dependent shape of the pedestal density profile probably has a strong effect on the behavior of the ELMs**
  - **Affects shape of pedestal pressure profile and collisionality**
    - **J-S. Lönnroth, et al., Plasma Phys. Cont. Fusion 45 (2003) 1689**

Fourth Issue: Vertical Asymmetry Effect in L-H Transition

- **Experimental observation indicates that the power required for the L-H transition is lower when the direction of ∇B drift is away from the X-point than in the direction toward the X-point**
  - **By a factor of 2 – 3 difference**
- **Possible explanation is based on the neoclassical cross-field fluxes of both heat and particles driven by poloidal temperature gradients on the open field lines in the SOL**
  - **F. L. Hinton Nucl. Fusion 25 (1985) 1457**

Summary

- **Models for pedestal and ELMs have been developed for use in predictive integrated modeling codes**
  - **Static models implemented in BALDUR and XPTOR codes**
    - **Calibrated against experimental data and used to predict ITER**
  - **Dynamic models implemented in the JETTO and ASTRA codes**
    - **Predict many observed scalings for ELM frequency and pedestal height**
    - **Detailed calibrations in progress and models being improved**
- **Several important issues still remain**
  - **Fraction of pedestal current removed during each ELM crash**
    - **Fraction of pedestal current that goes to the wall or into plasma**
  - **Electron transport within the pedestal**
  - **Accurate model for edge particle source needed to follow time-dependent plasma density profile between ELM crashes**
  - **Vertical asymmetry effect in L→H-mode transition**