# ELMs and the Performance of Burning Plasma Experiments

**Arnold H. Kritz**[1]

**G. Bateman**[1]**, T. Onjun**[2] **and A.Y. Pankin**[3]

[1]Lehigh University Physics Department, Bethlehem, PA 18015, USA
[2]Sirindhorn International Institute of Tech., Pathumthani 12121, Thailand
[3]SAIC, San Diego, CA 92121, USA

**IEA Workshop on Burning Plasma Physics and Simulation**
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# *Predictive Modeling of Burning Plasmas*

- **In late 1980's and early 1990's theory based transport models evolved**
  - **Singer, Comments on Plasma Phys. and Contr. Fusion 2 (1988) 165**
- **Predictive integrated modeling of burning plasmas dates back to BPX modeling studies and before**
  - **Fusion Technology 21 (1992) 1039 - 1306**
- **In the mid-1990's the BALDUR code, with core transport modeled with MMM, was used to carry out simulations of ITER – EDA**
  - **Bateman *et al*., Phys. Plasmas 5 (1998) 2355**
- **IFS/PPPL model was used to model ITER - EDA**
  - **Kotchenreuther *et al*., 1996 IAEA Paper F1-CN-64/D1-5**
- **Transport models used in predictive integrated model codes have continued to evolve with particular emphasis on validation against experimental data**
  - **GLF23, MMM95, Mixed-Bohm/gyro-Bohm**

# *Recent Advances in Predictive Modeling*

- **During the last few years, calibrated predictive models have been developed for H-mode pedestal and ELMs**
  - **These models provide predictive boundary conditions for integrated modeling simulations using calibrated core transport models**
- **Initially, static pedestal models were developed to predict pedestal height, without considering ELM dynamics**
  - **These semi-empirical models for the temperature and density at the top of the pedestal were calibrated against experimental data**
- **More recently, dynamic models have been developed to simulate pedestal formation and ELM cycles**
  - **An edge transport barrier produces the pedestal on the code grid**
  - **Ideal MHD instabilities trigger ELM crashes**
- **Results are shown for simulations of burning plasma experiments using static and dynamic pedestal models**

# Core and Static Pedestal Models Used in BALDUR

- Predictive model for pedestal at edge of H-mode plasmas
  - L-H Transition: An empirical model based on power threshold results in pedestal
  - Pedestal temperature: A theory based model using $\Delta \propto \rho s^2$ and pressure gradient limited by 1st stability of ideal ballooning mode
    - *Models for Pedestal Temperature at the Edge of High Mode Plasmas in Tokamaks*, Phys. of Plasmas, 9, (2002) 5018, by T. Onjun, G. Bateman, A. H. Kritz, and G. Hammett.
    - Pedestal density: An empirical model based on average density
  - Pedestal model provides boundary condition for simulations
  - All these models are in the NTCC PEDESTAL module
    - A. Kritz *et al.* Comp. Phys. Comm. 9 (2002) 5018
    - PEDESTAL module will be installed in the predictive version of TRANSP as part of the NTCC project
- Multi-Mode core transport model
  - Thoroughly tested against experimental data

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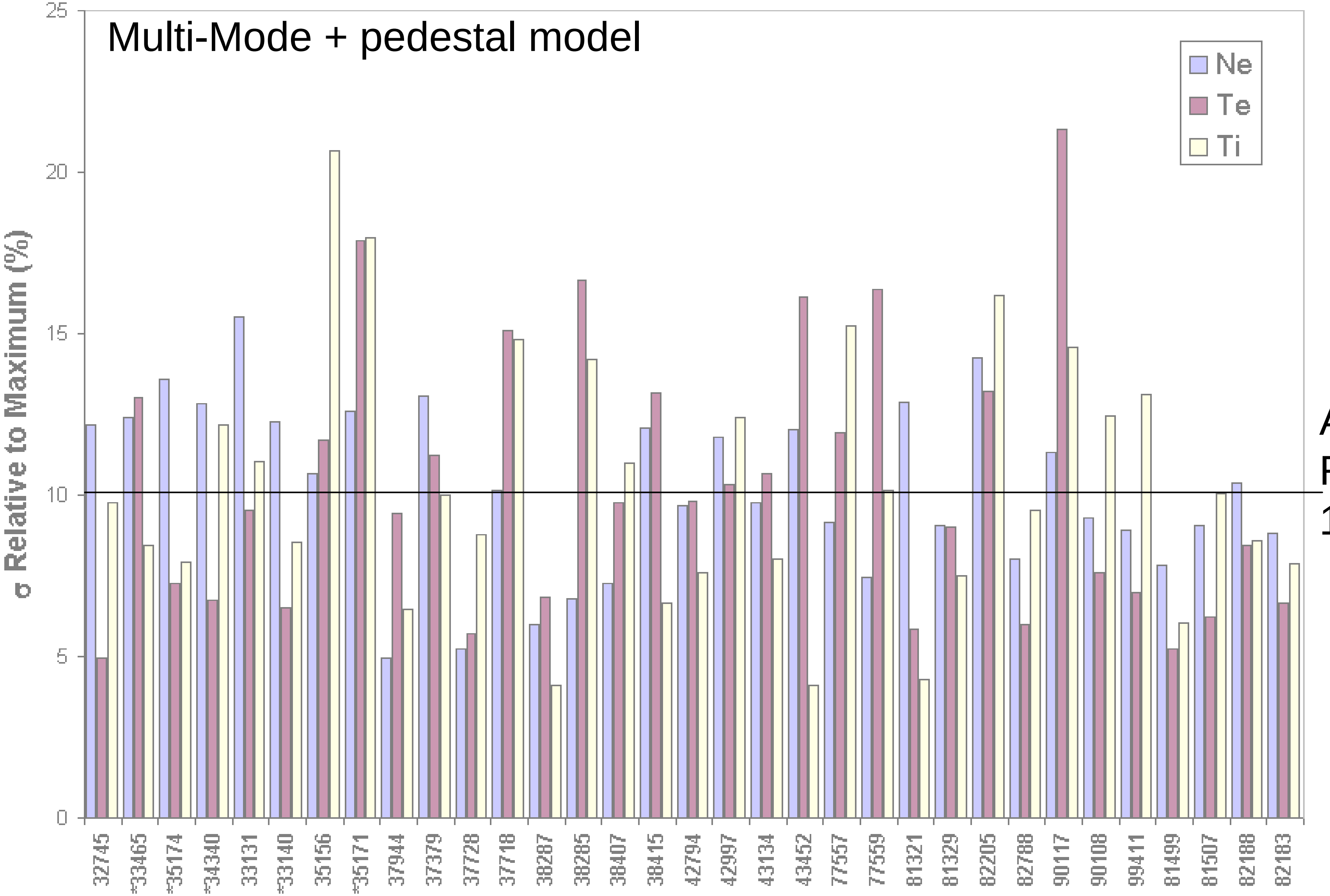
# *Combination of Core and Static Pedestal Models in Simulations of JET and DIII-D Discharges*

- Protocol for core and edge modeling in H-mode simulations developed using the BALDUR code
- Same models used and identical procedure employed for running all the simulations
  - Used MMM and PEDESTAL module
    - Simulations do not have time-dependent model for ELM crashes
  - Evolution of density, temperature and current profiles
  - Self consistent heating including fast ion effects
  - Time dependent sawtooth oscillations
- This protocol has been tested using data from existing experiments
  - Simulations of 33 JET and DIII-D H-mode discharges
  - Average normalized RMS deviation between each predicted profile and data is approximately the same as when the protocol uses boundary conditions taken from the data for each discharge
    - *Integrated Predictive Modeling of High-mode Tokamak Plasmas Using a Combination of Core and Pedestal*, Phys. of Plasmas 10 (2003) 4358, by G. Bateman, M. Bandres, T. Onjun, A. H. Kritz, A. Pankin.

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



Multi-Mode + pedestal model

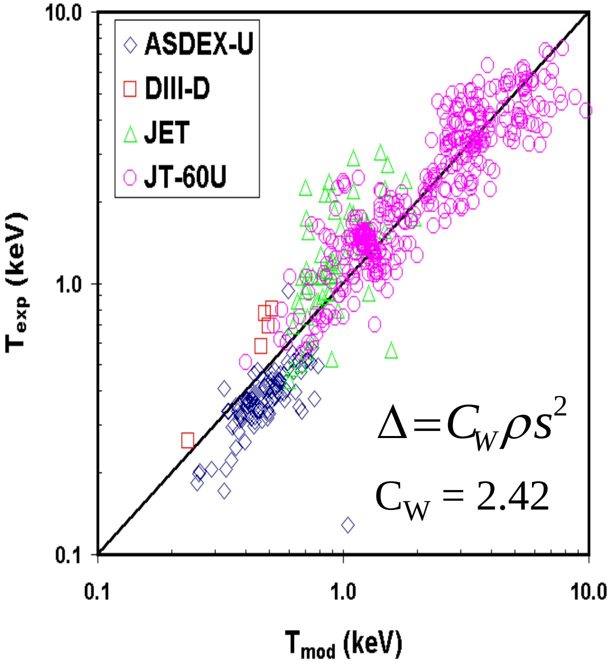
Avg
RMS
10%

JET

DIII-D

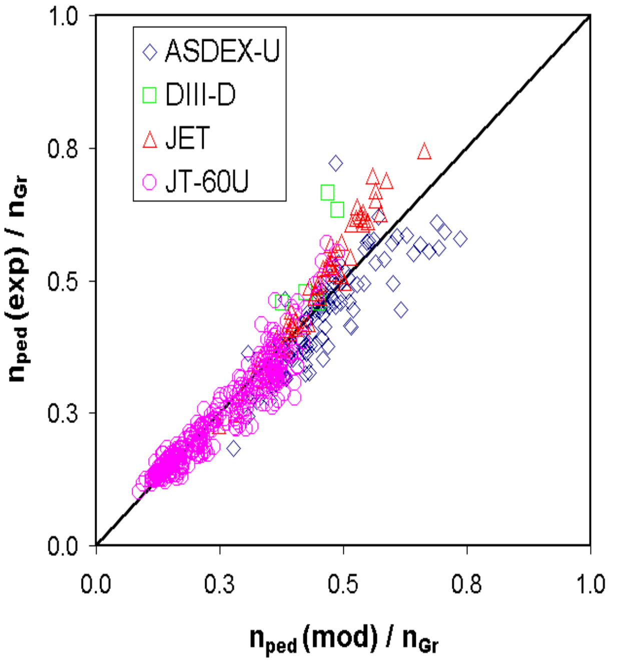
# *Protocal Applied to ITER Simulations*

- **Simulations of burning plasma experiments**
  - **Carried out using combination of core and static pedestal models and protocol tested in simulations of existing experiments**
  - **Scans carried out over auxiliary heating power, plasma density, and impurity concentration**
  - **Sensitivity of results was determined by varying the coefficient in the pedestal temperature model over one standard deviation**

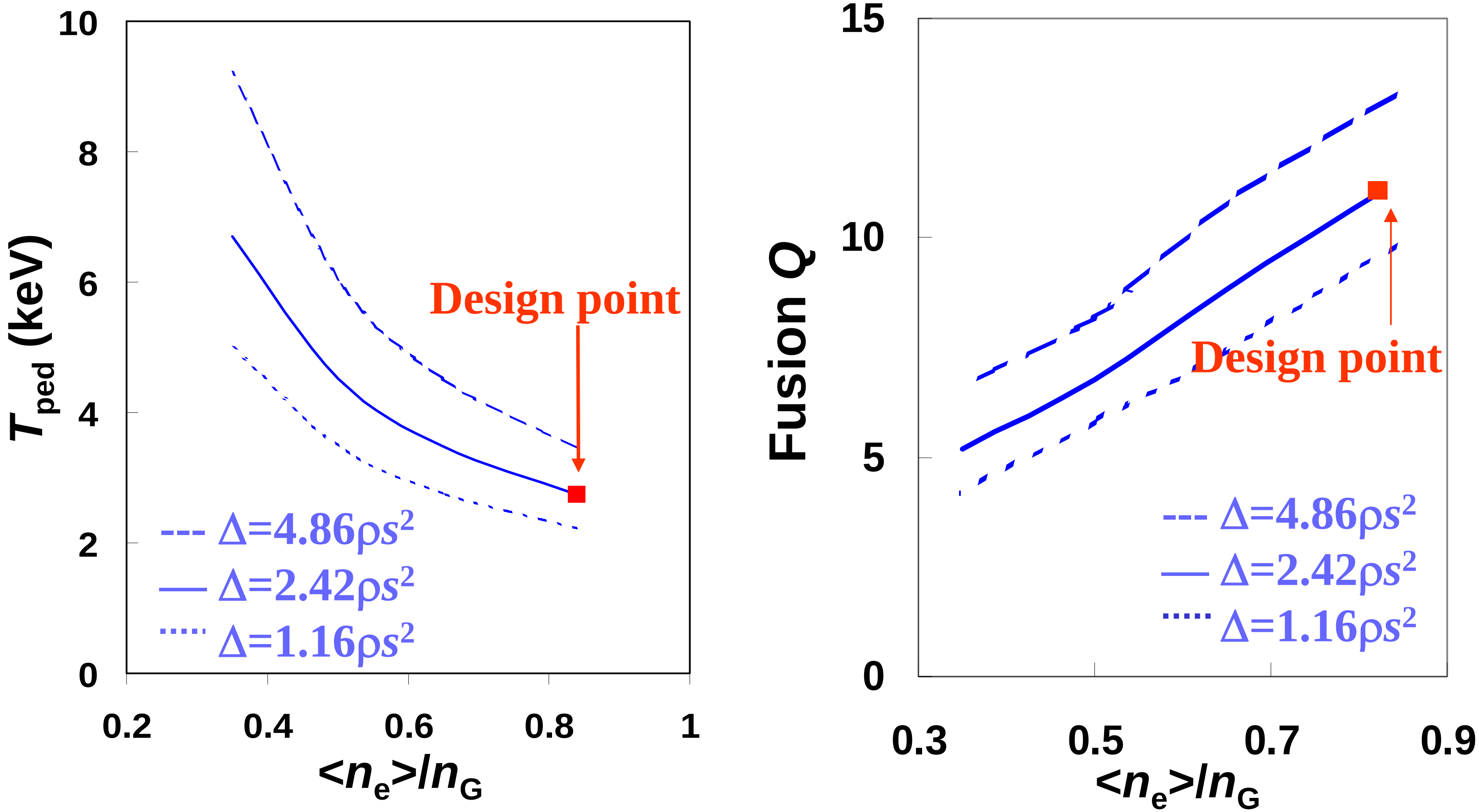


$$\Delta = C_W \rho s^2$$

$C_W = 2.42$

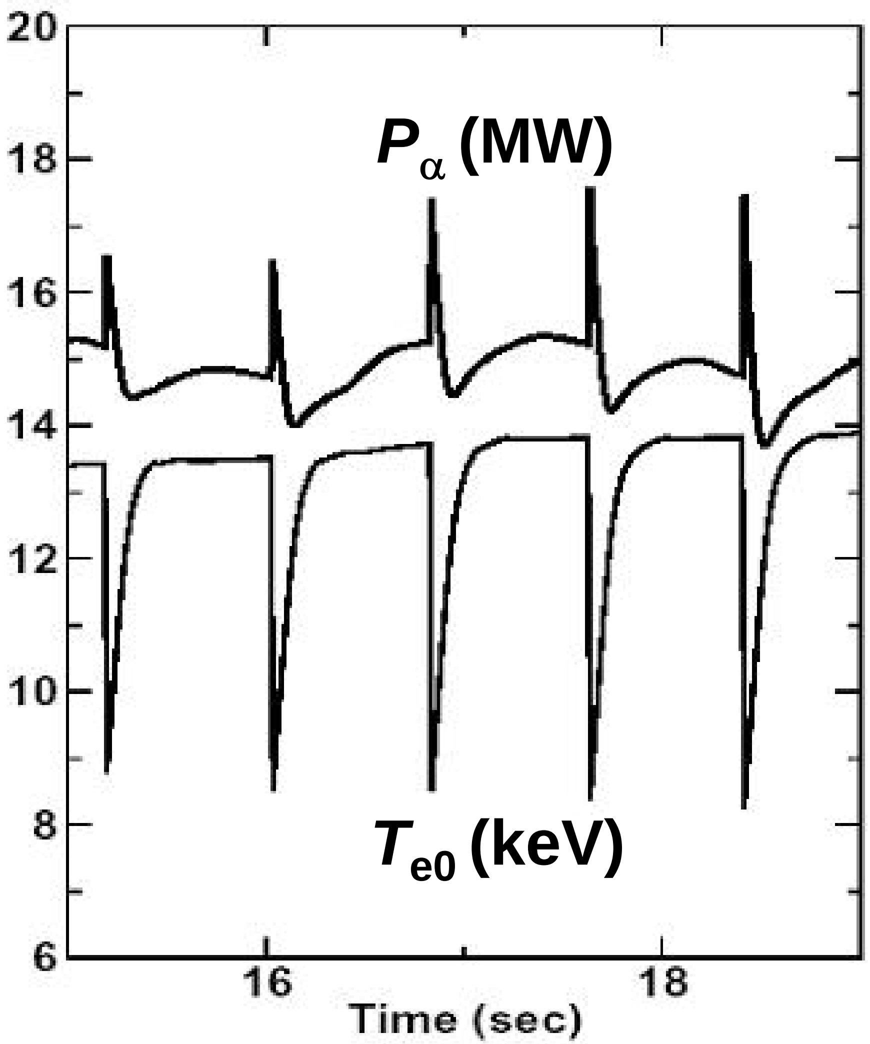


# Predictions for ITER Performance



***Integrated Predictive Modeling Simulations of Burning Plasma Experiment Designs***, **Plasma Phys. Control. Fusion, 45 (2003) 1939, by G. Bateman, T. Onjun, and A. H. Kritz.**

# Effect of Sawtooth Oscillations in FIRE Simulation



- Self-consistent effect in the BALDUR simulations
  - – Demonstrated in time evolution of alpha heating power $P_\alpha$ and central electron temperature $T_{e0}$
- Sawtooth oscillations have the following effect:
  - Central temperature decreases due to sawtooth oscillation
  - Slowing down time for fast alpha particles is reduced
  - Plasma reheated more rapidly by fast alpha particles
  - As a result rapid rise in central temperature after sawtooth
  - Fast alpha distribution is depleted and slowly restored

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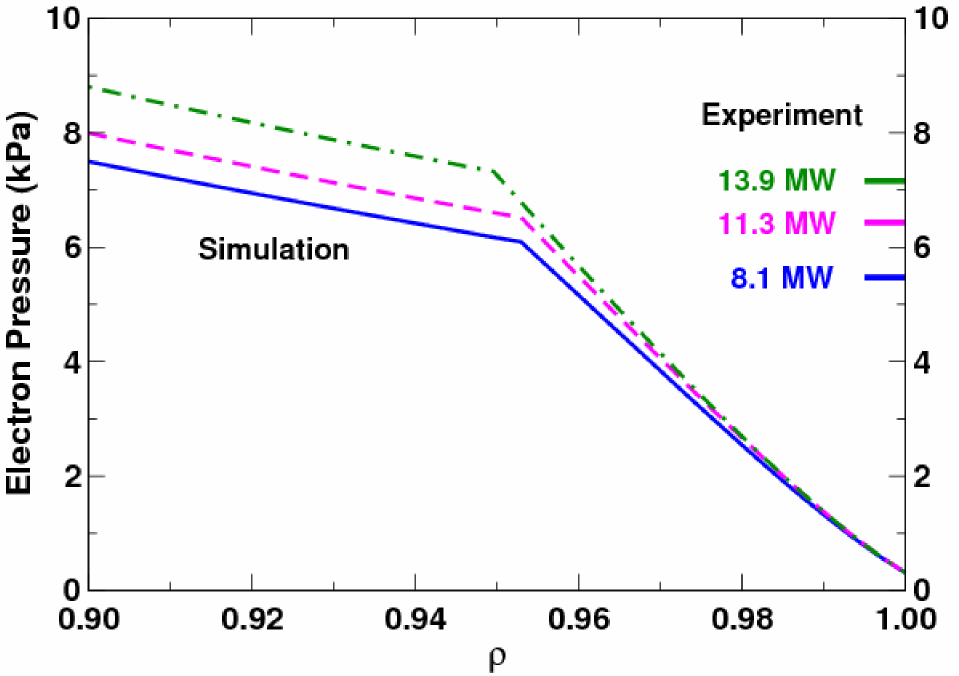
# Dynamic Model for Pedestal and ELMs Used in the JETTO code

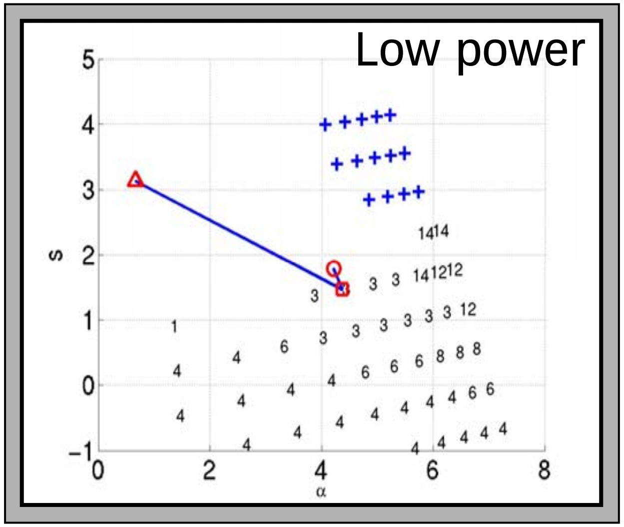
- Pedestal and ELM cycles simulated on JETTO grid
  - Mixed-Bohm/gyro-Bohm transport model used in core plasma
  - Ion neoclassical transport computed at top of pedestal used for all channels of transport through the pedestal
  - Pedestal width is prescribed separately
  - Two ideal MHD stability criteria used to trigger ELM crashes
    - Pressure-driven ballooning mode
    - Current-driven peeling mode
    - Stability criteria used in JETTO calibrated using HELENA and MISHKA
  - Transport transiently enhanced in pedestal to simulate ELM crash
    - Thermal transport enhanced by factor of 300
    - Particle transport enhanced by factor of 100
    - Typically 0.5 msec ELM crash duration

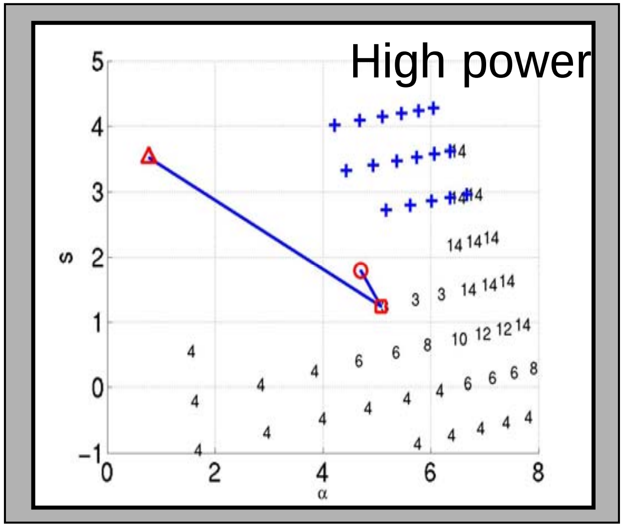
# Effect of Heating Power on Pedestal Height

- Pedestal pressure height increases with heating power
  - Reasonable agreement between simulation and experiment
- Physical processes in simulations are understood
  - Pedestal height limited by ELMs
  - ELM crashes are triggered by current-driven peeling mode
  - Frequency of ELM crashes increases with heating power
    - Pedestal rebuilds more rapidly with higher heating power
  - Bootstrap current drives pedestal current density
  - Inductive effects slow the rebuilding of pedestal current density
    - T. Onjun *et al.* Phys. Plasmas 11 (2004) 1469



# HELENA and MISHKA Ideal MHD Stability Analyses For Power Scan Discharges

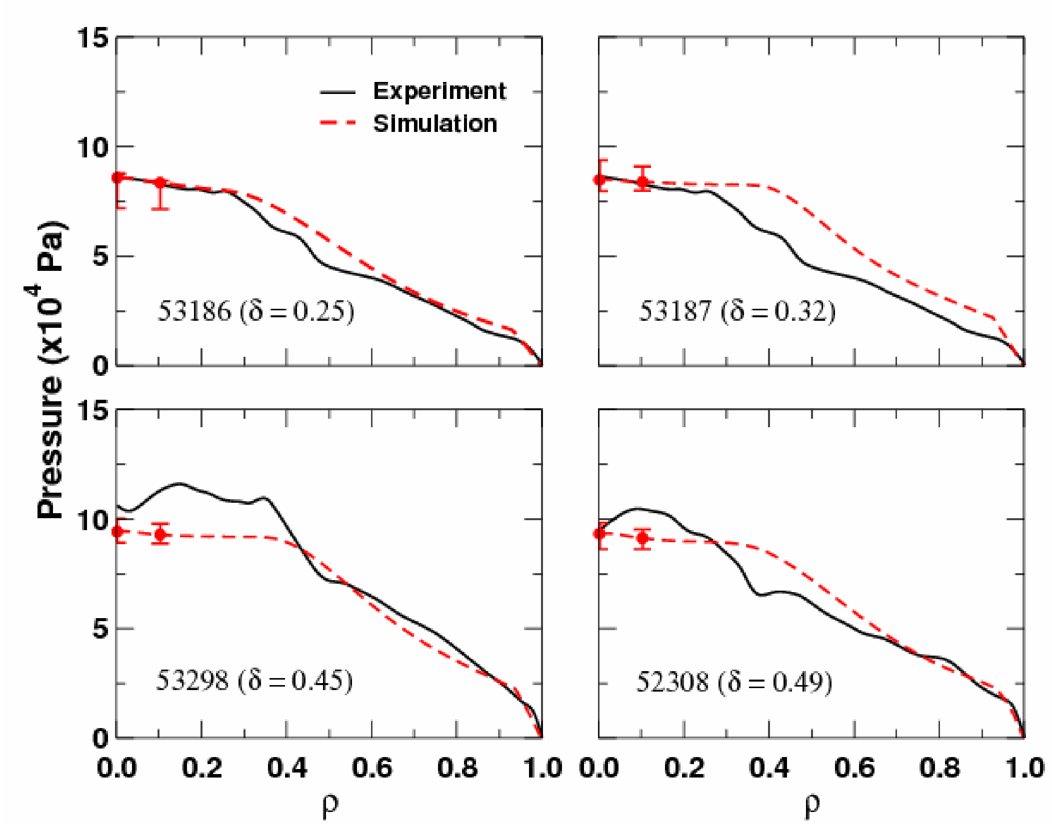




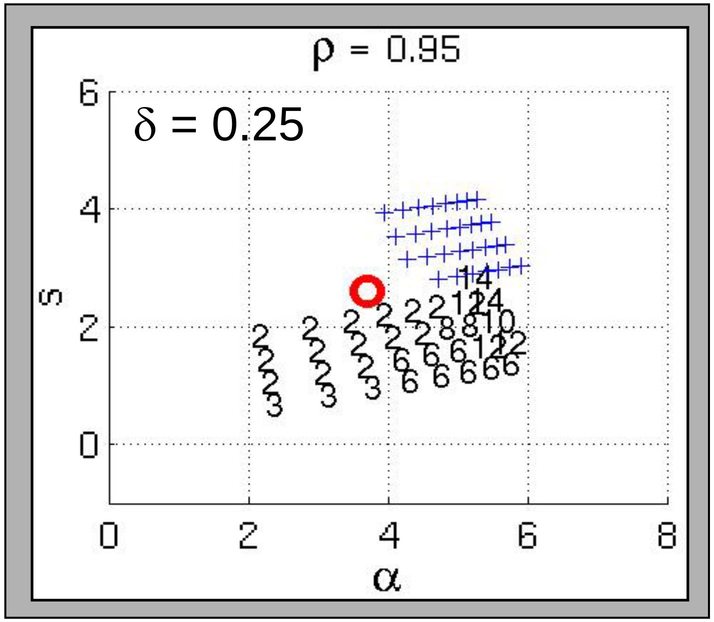
- **HELENA and MISHKA stability analyses confirm that ELMs are triggered by current-driven modes**
- **Stability analysis for 95% flux surface shown on s-$\alpha$ diagram**
  - **Operational points are indicated for 3 flux surfaces (92%, 95%, 98%)**
- **Top of barrier is located close to the 95% flux surface**
  - **Operational point is close to being unstable to kink/peeling modes**
  - **Maximum normalized pressure gradient, $\alpha$, increases as $P_{heat}$ increases**

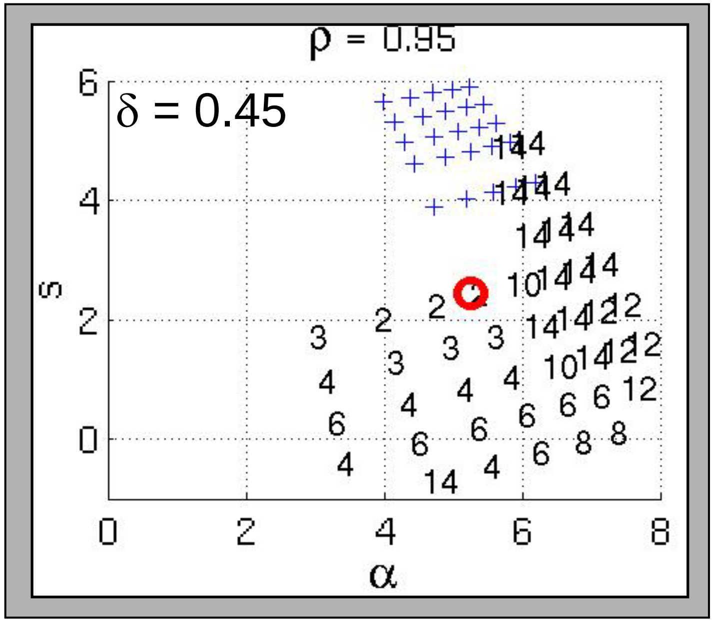
# *Effect of Triangularity on Pressure Profiles*

- **Pedestal height increases with increasing plasma triangularity, in agreement with experimental data**
- **Simulations using $\Delta = 2.42\rho s^2$ and ELMs triggered only by ballooning modes**



- **Simulation profiles reproduce JET experimental profiles**
- **Including sawtooth oscillations improves the core agreement**
- **Pedestal width in the simulations is in the experimental range (about 5% of minor radius)**
  - **T. Onjun *et al.* Phys. Plasmas 11 (2004) 3006**

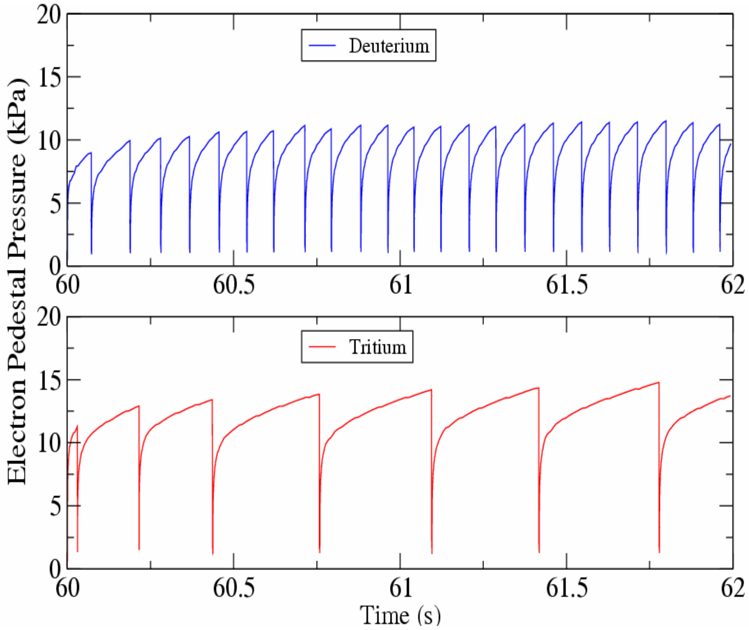




# Stability Analysis for JET Triangularity Scan Discharges

- **HELENA and MISHKA stability analyses carried out for low triangularity (δ = 0.25) and high triangularity (δ = 0.45)**
- **s-α diagrams for 95% flux surface show:**
  - **–No access to 2nd stability in low triangularity discharge**
    - **Access to 2nd stability closed by *n*=2 current-driven mode**
  - **–Transition from 1st to 2nd stability occurs as triangularity is increased**

# Effect of Isotope Mass on H-Mode Pedestal and ELMs



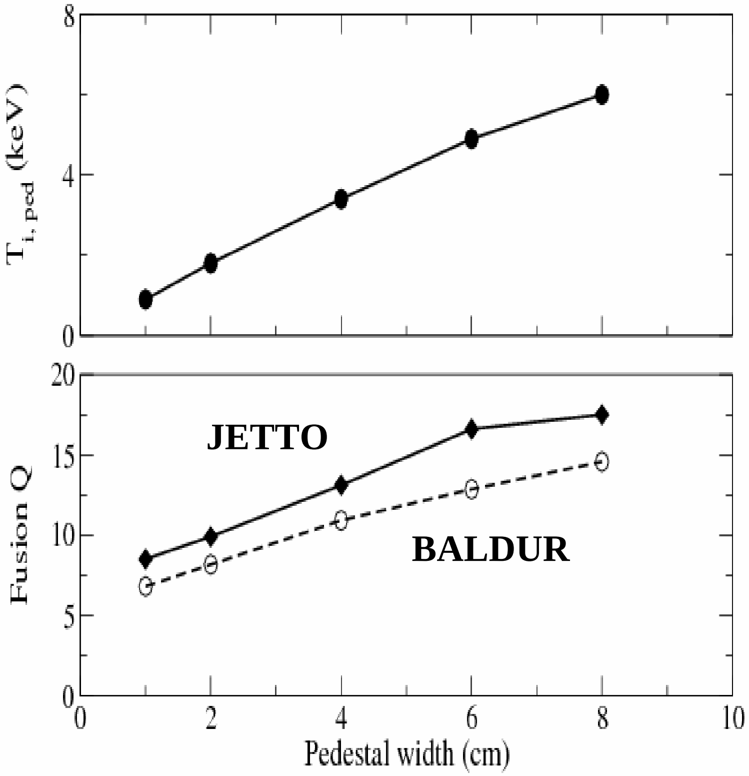
JET Simulation results for pedestal width proportional to ion thermal Larmor radius

- **With pedestal width proportional to thermal ion Larmor radius**
  - **Pedestal pressure *increases* and ELM frequency *decreases* with isotope mass, as in experiment**
  - **Quantitative agreement with experimental Hdata is obtained, as shown below**
- **However, if the pedestal width is fixed**
  - **Simulation pedestal pressure *decreases* with increasing isotope mass in contrast to the experimental result**

| | | 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 |

# Predicted Fusion Q for ITER

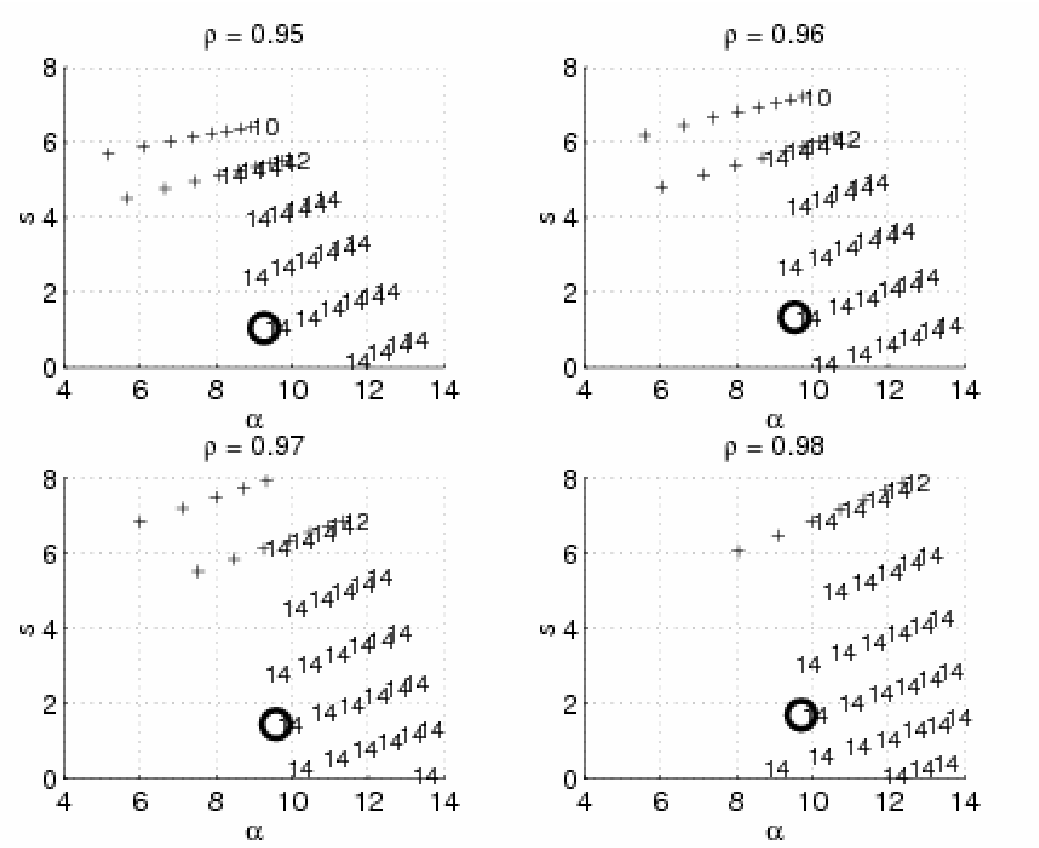
- Models used in JETTO simulations:
  - Mixed-Bohm/gyro-Bohm core transport model
  - Dynamic model for pedestal and ELMs
- Models used in BALDUR simulatio
  - Multi-Mode (MMM95) transport model
  - Pedestal temperature from JETTO simulations provide boundary condition in the BALDUR code
- Predicted values of fusion $Q \equiv 5\, P_\alpha / (P_{aux} + P_\Omega)$
  - JETTO and BALDUR simulations agree within error bounds



*MHD-calibrated edge localized mode model in simulations of ITER*, to appear in Phys. Plasmas (2005), by T. Onjun, G. Bateman, A. H. Kritz, and V. Parail.

# Ideal MHD Stability Analysis

- **HELENA and MISHKA stability analyses are shown for ITER**
  - **Profiles and equilibrium obtained from JETTO just before ELM crash**
- **ITER pedestal in second stability region of parameter space**
  - **Access to second stability in ITER is enhanced by two effects:**
    - **The high triangularity of ITER, δ = 0.48**
    - **High bootstrap current density in the pedestal reduces magnetic shear**
  - **Transition from first to second stability doubles the stable pressure gradient in the pedestal**


ρ = 0.95

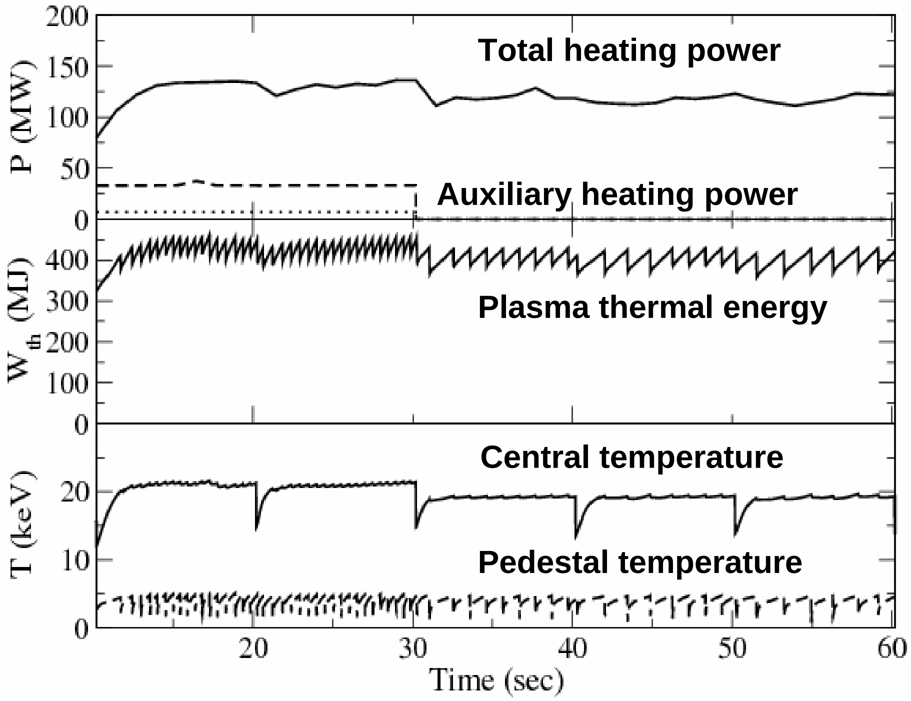
ρ = 0.96

ρ = 0.97

ρ = 0.98

# Ignition is Obtained in JETTO Simulations of ITER

- **Fusion heating persists after auxiliary heating is turned off**
  - **Plasma thermal energy, $W_{th}$, and temperature, $T$, remain nearly the same, after the auxiliary heating is turned off at 30 seconds**
  - **Transients in central temperature are from sawtooth crashes**
  - **Transients in edge temperature are from ELM crashes**



# Simulations Using ASTRA

- A dynamic model for pedestal formation and ELM cycles is evolving in the ASTRA code
  - The pedestal width and shape are predicted by flow shear stabilization of modes of turbulence
  - ELM crashes are triggered by ideal MHD instabilities
  - When the heating power is high enough, simulations exhibit a transition from L to H-mode, pedestal formation, and ELM crashes
- ASTRA simulations have been shown to reproduce the temperature profiles nearly as well as BALDUR simulations
  - Pedestal height and ELM frequency trends similar to experiments
    - *Combined Model for the H-mode Pedestal and ELMs*, Plasma Phys. Control. Fusion, 47 (2005) 483, by A. Y. Pankin, I. Voitsekhovitch, G. Bateman, A. Dnestrovski, G. Janeschitz, M. Murakami, T. Osborne, A. H. Kritz, T. Onjun, G. W. Pacher, and H. D. Pacher.
  - ITER was simulated with an earlier version of this model
    - Time evolution of density profile included in those ITER simulations
    - G.W. Pacher *et al.,* Nucl. Fusion 43 (2003) 188

# Proposed Work on First Principles Simulations

- **Two Edge Fusion Simulation Projects have been proposed**
  - The objective is to carry out first principles simulations of H-mode pedestal formation and a complete ELM cycle
- **The Center for Edge Plasma Simulation led by C.S. Chang**
  - Particle in Cell (PIC) code for pedestal formation and growth
  - M3D code for ELM threshold and nonlinear evolution of ELM crash
- **The Fusion Simulation Prototype Center For Edge Plasmas led by Ron Cohen at LLNL**
  - Continuum kinetic code and fluid code in the same framework to compute turbulence, neoclassical transport and extended MHD
- **The proposed projects are highly collaborative**
  - Researchers from more than 20 institutions involved in the projects
  - Computer scientists, applied mathematicians, and physicists
    - Massively parallel computers will play an important role

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# Summary

- **Predictive models for the H-mode pedestal and ELMs have been developed during the last few years**
  - **As a result, predictive models (with various levels of sophistication) can be used for nearly all parts of integrated H-mode simulations**
  - **The objective is to run simulations in which all of the input variables are parameters that are under the control of experimentalists**
    - **Currently, the exceptions include impurity concentration**
- **BALDUR simulations agree with JETTO simulations of ITER**
  - **JETTO simulations use the Mixed-Bohm/gyro-Bohm transport model together with a calibrated dynamic model for the pedestal and ELMs**
    - **JETTO simulations of ITER ignite**
  - **BALDUR simulations use the MMM95 core transport model and the static PEDESTAL module for the pedestal height**
  - **Fusion *Q* agrees within error bounds as pedestal temperature is varied**
- **Edge Fusion Simulation Projects proposed for first principles studies of pedestal and ELMs**