Real-time Electron Temperature and Density Profile Measurements for NSTX-U

Egemen Kolemen

Ahmed Diallo, Greg Tchilinguirian

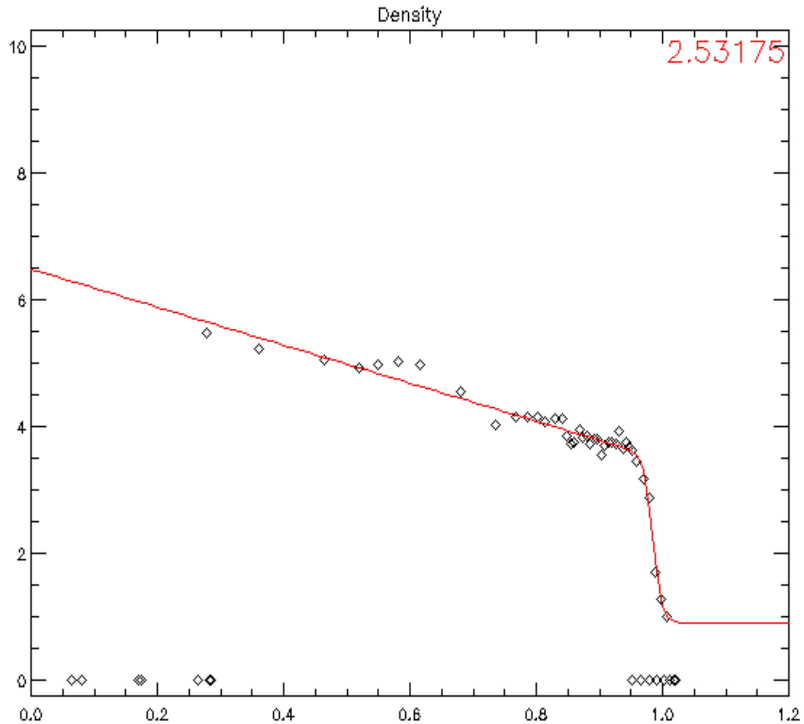
Mechanical & Aerospace Engineering
Jointly appointed with the Andlinger Center for Energy and the Environment
and the Plasma Physics Laboratory (PPPL)

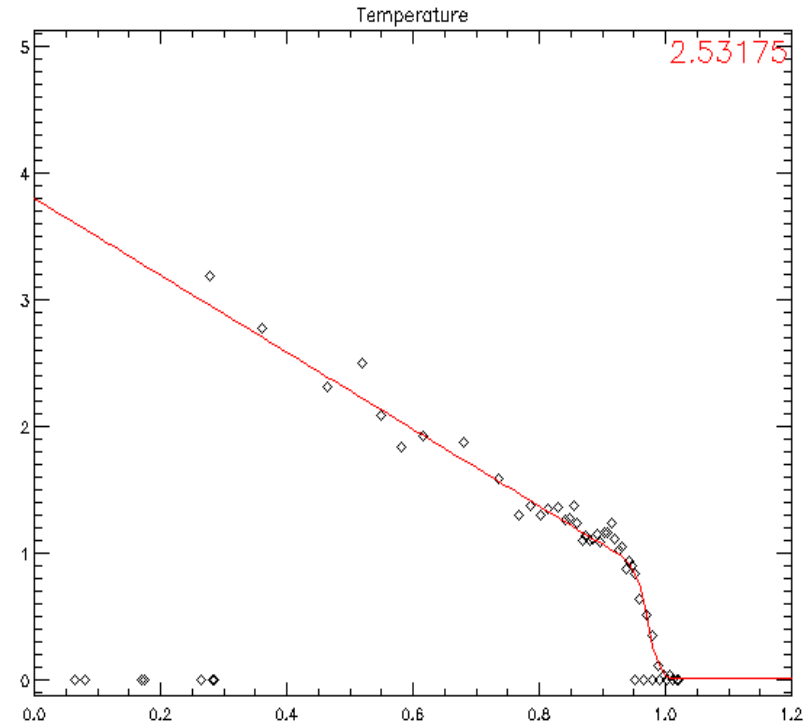
PRINCETON UNIVERSITY

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

andlinger center
for energy+the environment

Technical Aim: Real-time Thomson Diagnostics





- We want to acquire the Thomson (MPTS) data in real-time.
- Share with PCS. Calibrate and fit it.

➔ Use during the shot for better control to achieve physics goals

1. **RT-Kinetic EFIT**
2. **ITER RT-Control Development:**
    1. Pedestal Control
    2. ELM Stability/Control
3. **Achieve Advanced Regimes**
    1. Lithium ELM Free Scenario
    2. Enhanced Pedestal H mode

Real Time Kinetic Equilibrium Reconstruction Can be Implemented by Adding P and J Constraints to EFIT

- **EFIT solves the Grad-Shafranov Equation**

$$\Delta^* \psi = -\mu_0 R^2 p' - \mu_0^2 f f'$$

$$J_R = -\frac{1}{R}\frac{\partial f}{\partial Z}$$

$$J_Z = \frac{1}{R}\frac{\partial f}{\partial R}$$

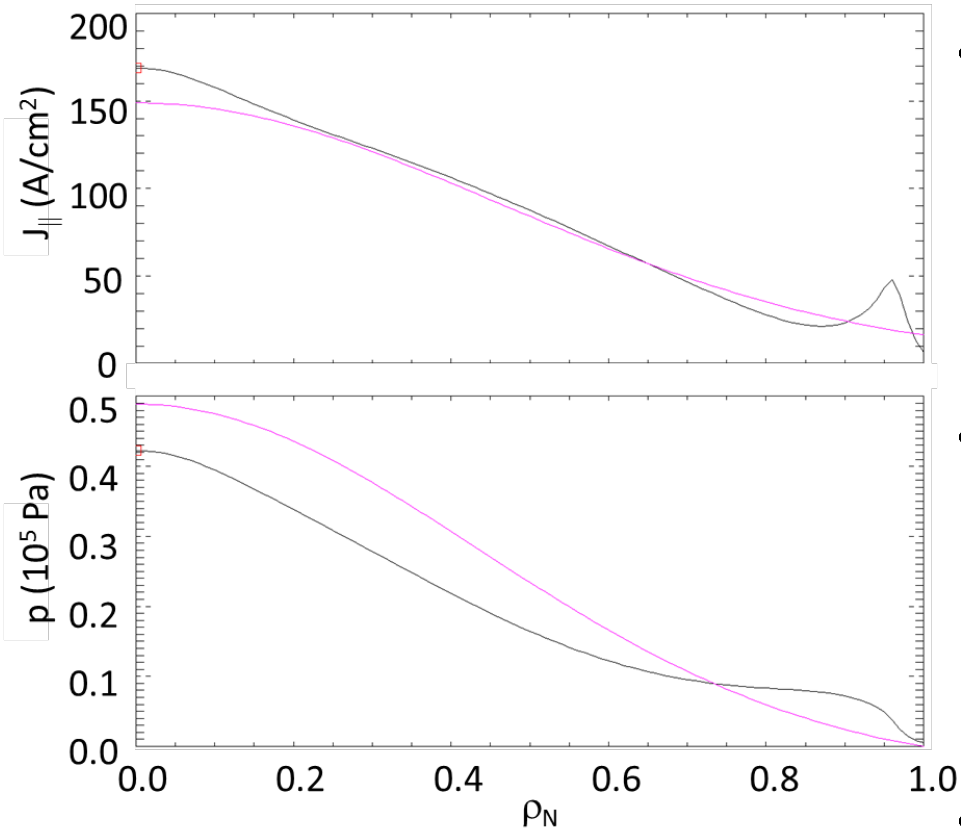
- **ψ constrained by magnetics**
- **J constrained by magnetics and MSE**

- **Additional constraints in a kinetic EFIT:**
  - p is constrained by TS calculations
  - J is further constrained by $J_{BS} + J_{OHM}$ calculations

First the Thomson Scattering only addition for kinetic EFITs

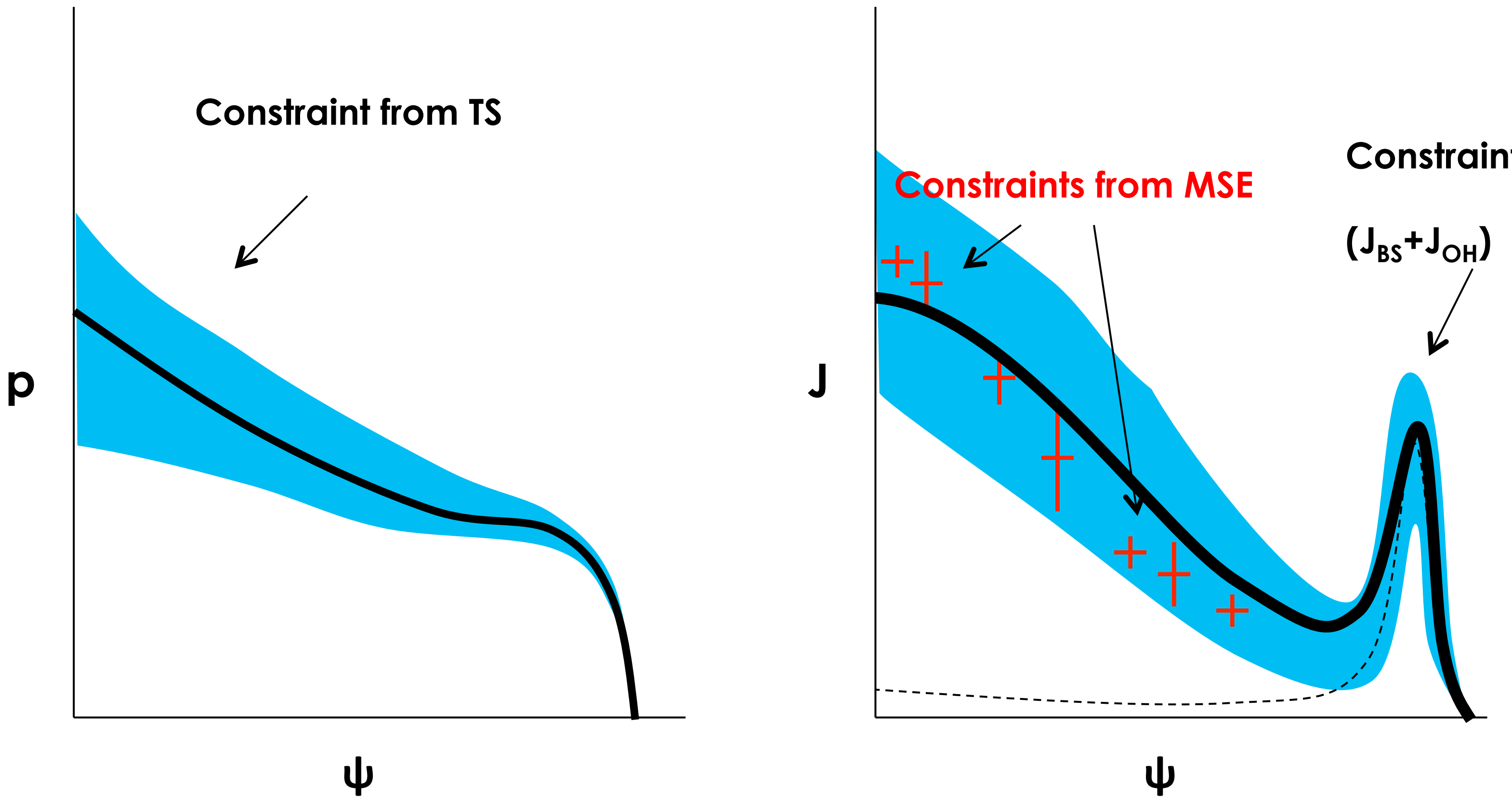
With Steve Sabbagh, Keith Ericsson, Dan Boyer

Real Time Kinetic Equilibrium Reconstruction Difference between regular versus kinetic-EFIT



- **Example profiles of parallel current density and total pressure for a kinetic EFIT (black) and a basic, magnetics-only EFIT (magenta).**
- **Failure to properly account for the pedestal pressure gradient and the resulting bootstrap current introduces errors throughout the profiles.**
- **Thus, it is critical that pressure constraints be used when constructing equilibria for stability analysis.**

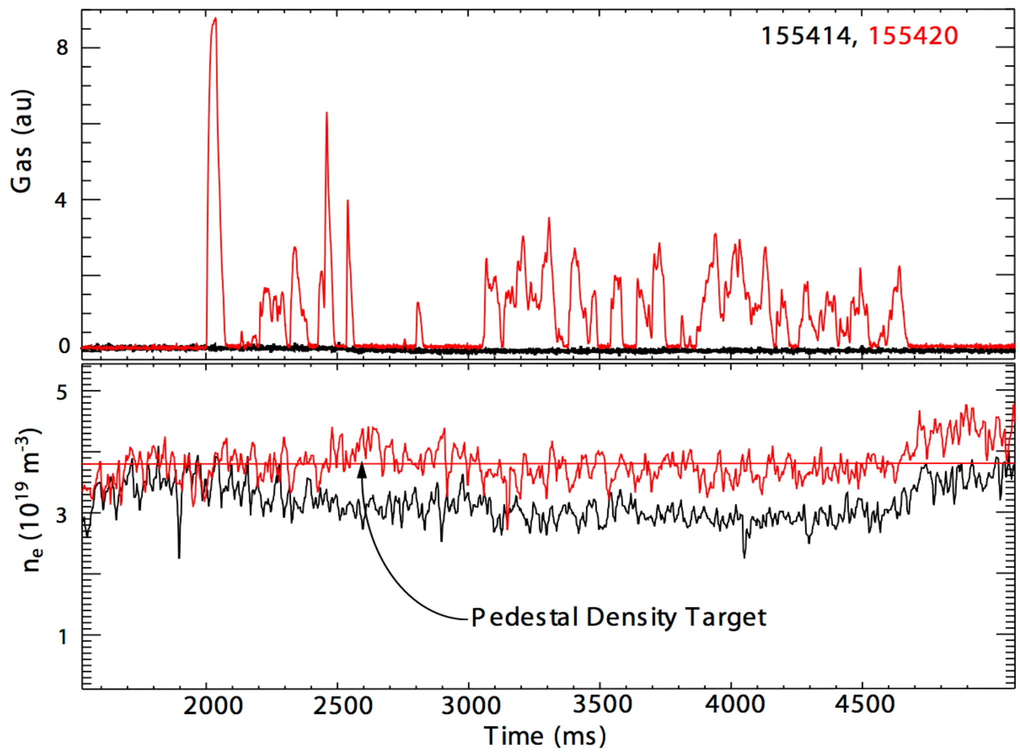
Add constraints on the Current and Pressure to EFIT



- RT-Thomson (two-three years of the proposal), MSE (in development – Howard)

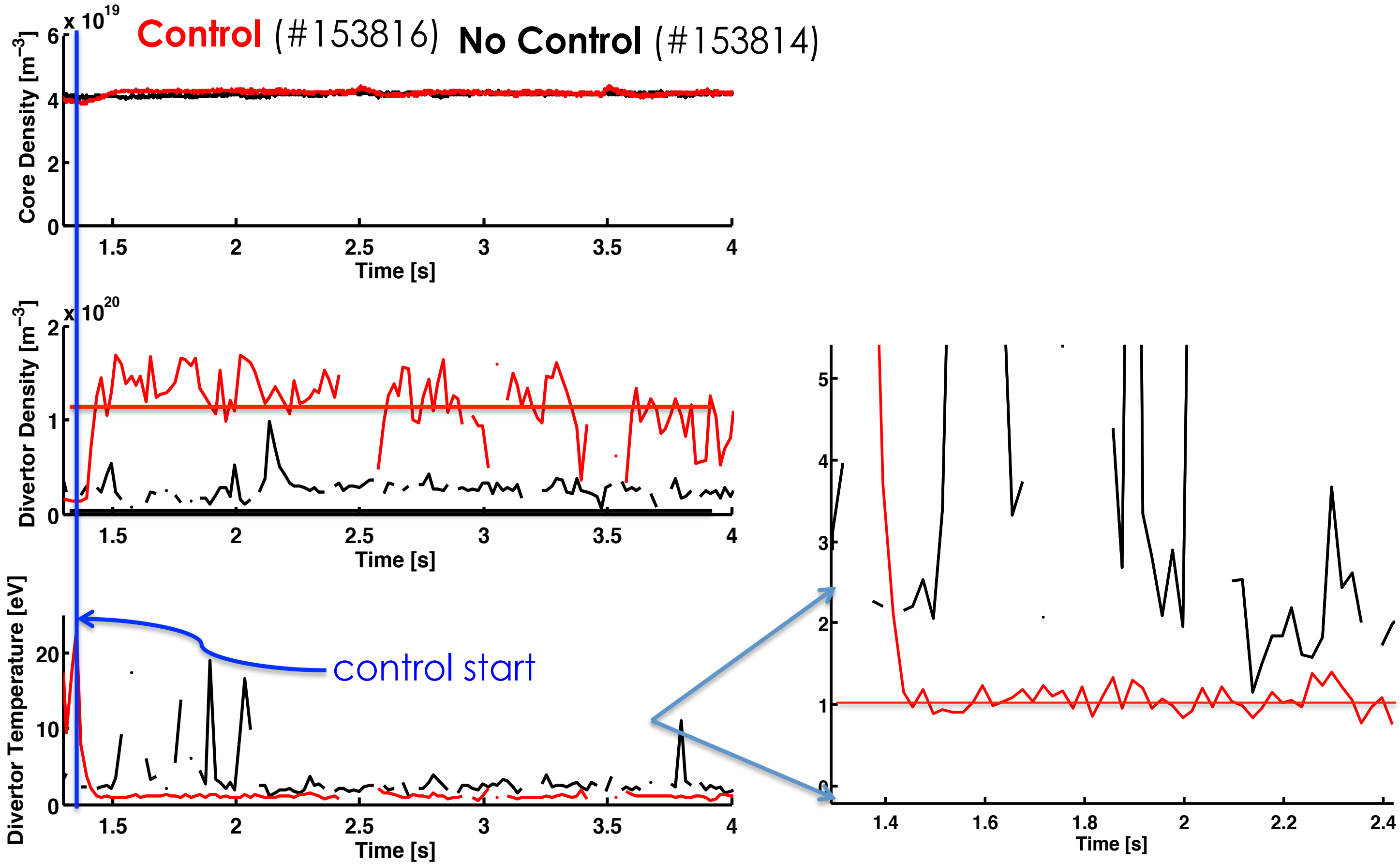
1. **RT-Kinetic EFIT**
2. **ITER RT-Control Development:**
    1. Pedestal Control
    2. ELM Control
    3. RWM Control
3. **Achieve Advanced Regimes**
    1. Lithium ELM Free Scenario
    2. Enhanced Pedestal H mode

Pedestal Control with Gas: Real-time Thomson



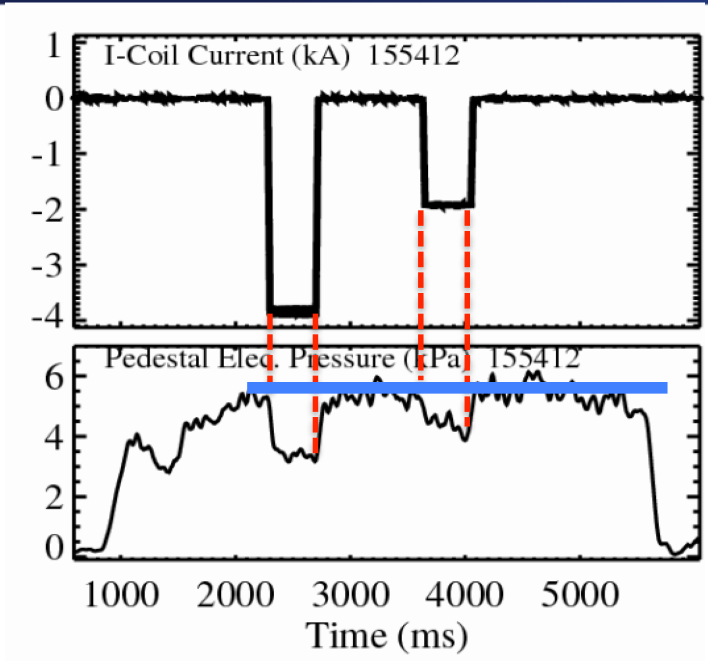
- **Example pedestal density height feedback at DIII-D using Deuterium fueling: uncontrolled discharge shown in black and controlled shot shown in red**

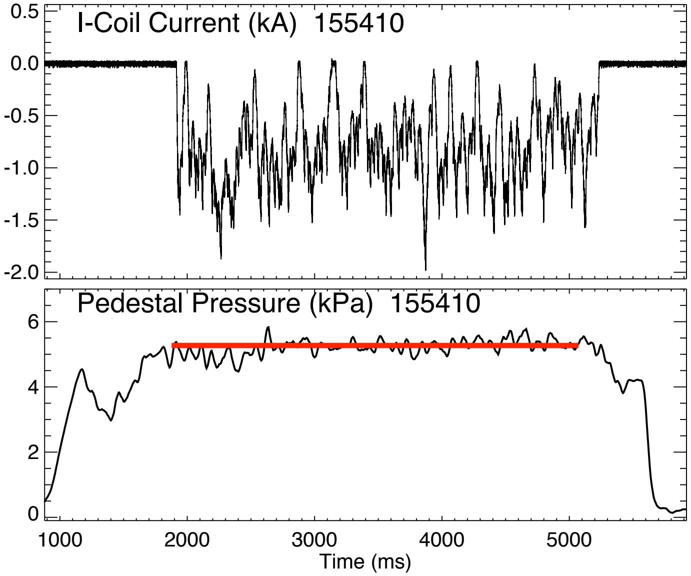
Detachment Control with Gas: Real-time Thomson (Divertor)



Data showing feedback control of divertor detachment. Red—detachment feedback control on. Black—detachment control off (no divertor fueling). Top: line average core density. Middle: divertor density. Bottom: electron temperature above divertor plate.

Pedestal Control with 3D Coils: Real-time Thomson





- **3D coils for pedestal control:**
- **Left) Effect of the n=3 RMP at DIII-D on the pedestal electron pressure (the blue line shows the undisturbed flattop pedestal electron pressure).**
- **Right) Pedestal electron pressure in RMP regulation**

1. **RT-Kinetic EFIT**
2. **ITER RT-Control Development:**
    1. Pedestal Control
    2. ELM Stability/Control
3. **Achieve Advanced Regimes**
    1. Lithium ELM Free Scenario
    2. Enhanced Pedestal H mode

Adaptive ELM Control Implemented and Tested on DIII-D

Vacuum Calculation Online ➔ **Plasma Response Calculations Offline (Jong-Kyu, Paz-Sol)** ➔ **RT-ELM Control Algorithm**

3D coil currents

Rt-EFIT $(q_{R,Z}, \Psi_{R,Z})$

↓

Biot-Savart ➔ $\delta B_{Ped\text{-}Top}$

↓

Straight-line field coords SURFMN (Schaffer). Find response for all modes ➔ $B_{r(m,n)}$

W_p matrix: Vacuum to Full Plasma Response Conversion Matrix

Find Island sizes (w_p) and Chirikov island over lap parameter (σ_{chir}) in pedestal For Vacuum+Plasma

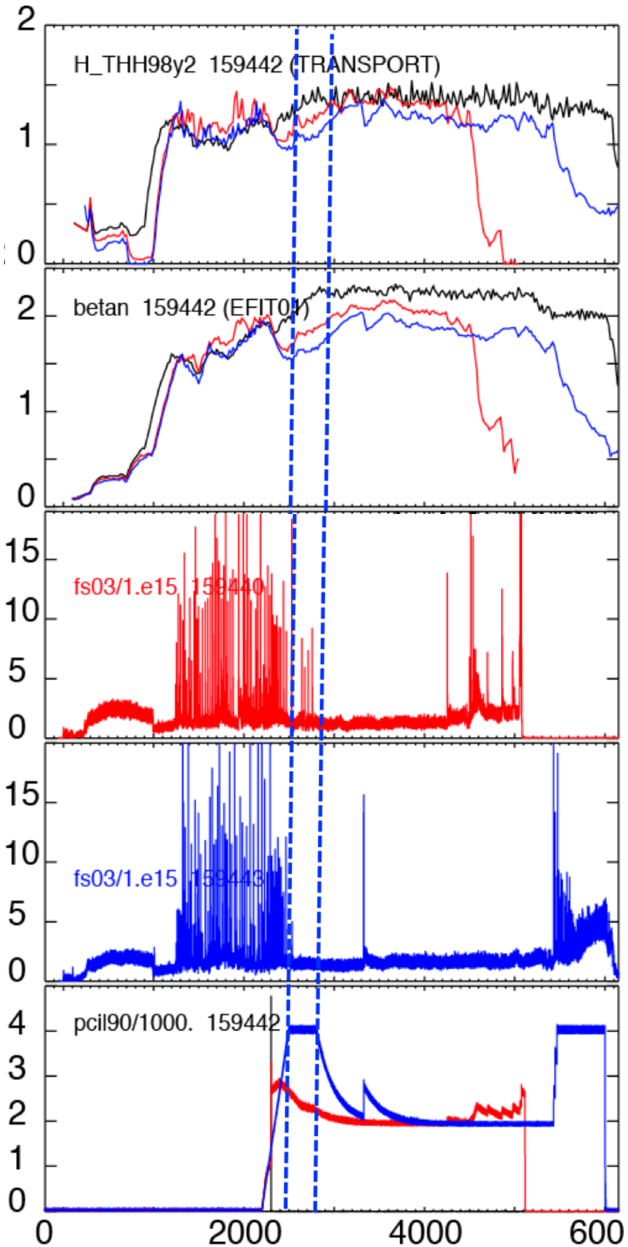
$$w_p = \sqrt{\frac{16}{m}\frac{q}{q'}\frac{S}{(2\pi)^2}B_{r(m,n)}}$$

↓

I_coil = Find I Coil Direction Current to Max(σ_{chir}) or Max(kink-resonant)

- Tested the control at DIII-D (kink-resonance, n=2, I coil) ➔ 20-100 ms
- Results ~ good correspondence with offline prediction with q variation

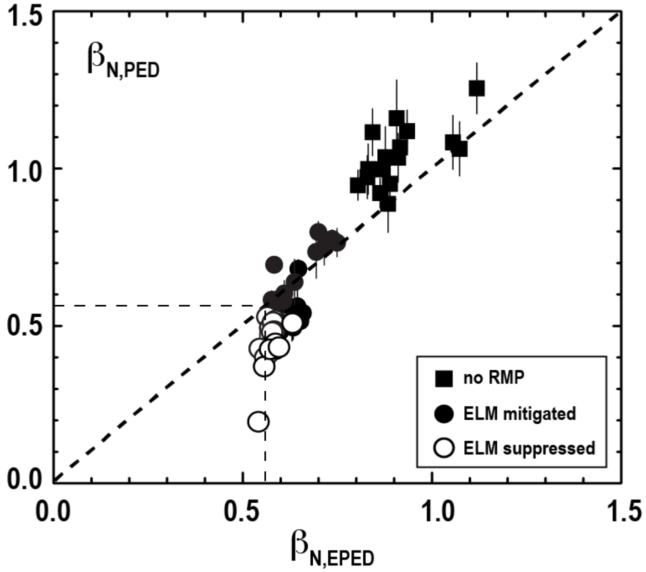
Adaptive ELM Control Implemented and Tested on DIII-D

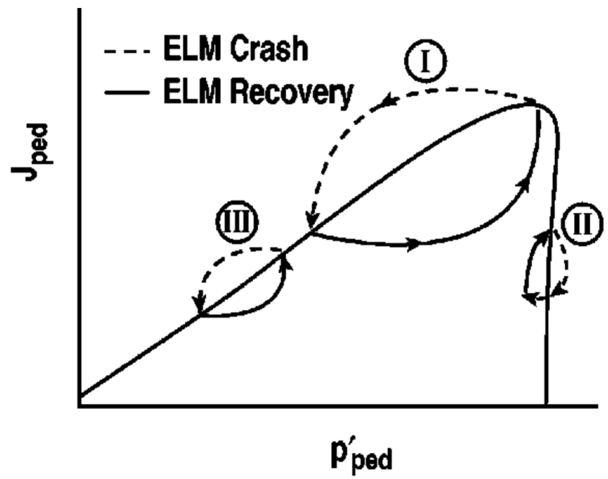


- **Adaptive ELM Control Algorithm reduces the coil current down while maintaining ELM Suppression**
- **Suppression with 1.9 kA I coil current**
- **~ H98 recovered**
- **BetaN increased (not fully recovered)**
- **H98 and BetaN recovery dependent on the *initial coil currents***

RT-ELM Stability Using NEUPED for NSTX-U

Normalized pedestal beta (vertical axis) vs the EPED prediction for the DIII-D ELM experiments. (Nazikian 2014)

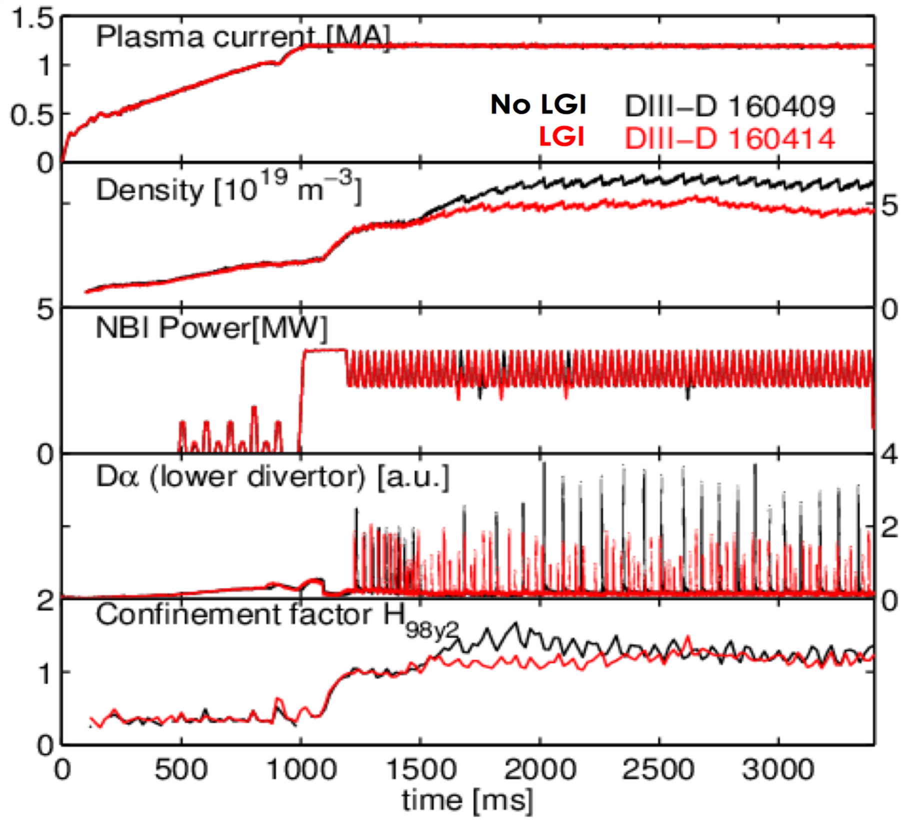




Simplified model of small and large ELM cycles

- **Train neural network based fit to EPED1 simulations – nueped (with O. Meneghini)**
- **RT capable simplified model with regression fit to EPED1 simulations**
- **10 input parameters: $n_{e,ped}$, $Z_{eff,ped}$, β_N, I_p, B_T, a, R, κ, δ, m_i**
- **4 input parameters: p_{ped}, p_{top}, w_{ped}, w_{top}**

RT-ELM Control Using rt-LGI for NSTX-U



- **LGI is ready for experiments!**
- **Turn on/off and change the frequency of LGI based on the rt-ELM-stability calculations**

1. **RT-Kinetic EFIT**
2. **ITER RT-Control Development:**
   1. Pedestal Control
   2. ELM Stability/Control
3. **Achieve Advanced Regimes**
   1. Lithium ELM Free Scenario
   2. Enhanced Pedestal H mode

Control of ELM Free Regimes in Lithium Conditions

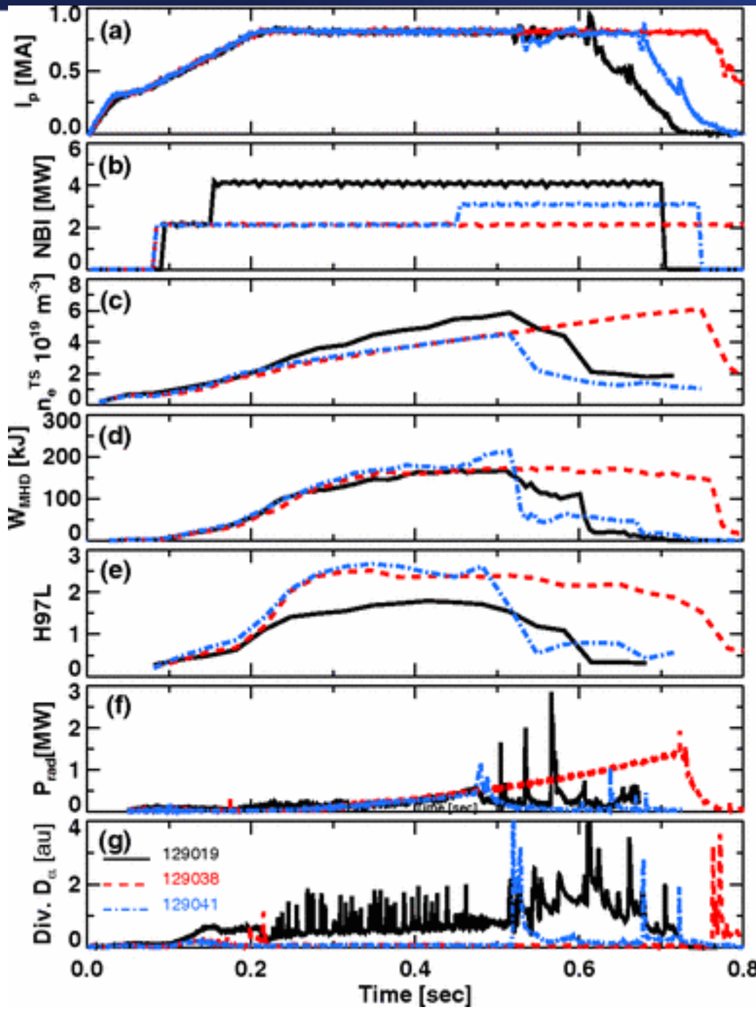
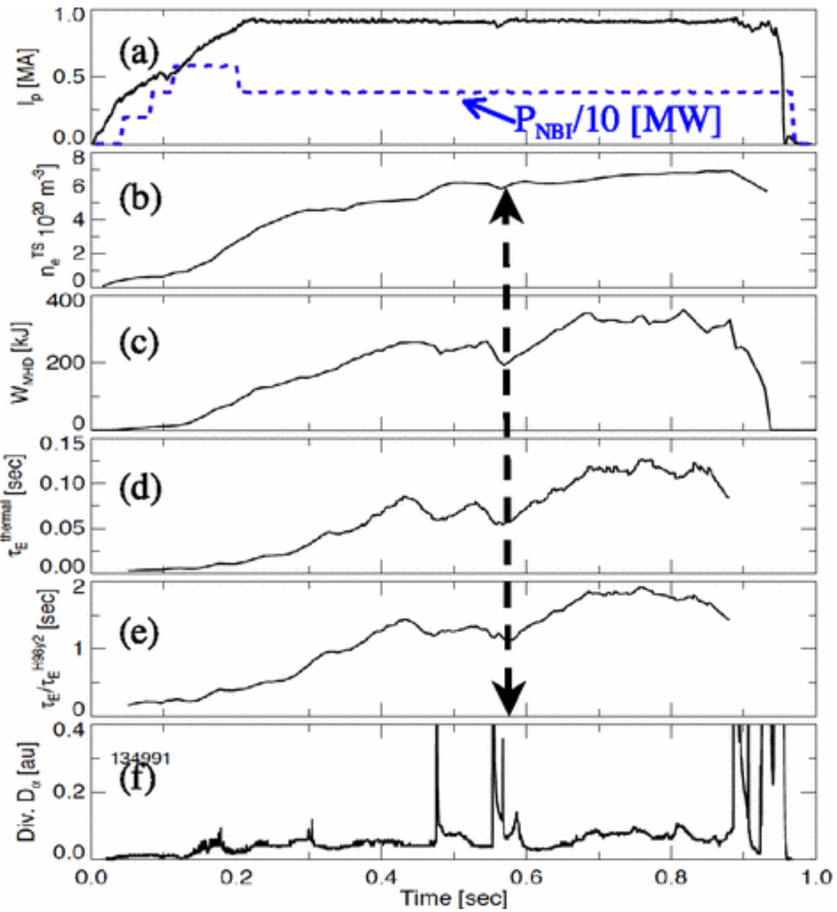


Figure 4. Comparison of pre-lithium ELMy discharge (black), and two post-lithium discharges with different NBI power (blue, red)

- Core density accumulation in Lithiated conditions will be a challenge for NSTX-U
- Calculation of the ELM stability and control using the rt-LGI to trigger ELMs
- Gas, HHFW and shape change etc. can be incorporated when the stability is knows

1. **RT-Kinetic EFIT**
2. **ITER RT-Control Development:**
    1. Pedestal Control
    2. ELM Stability/Control
3. **Achieve Advanced Regimes**
    1. Lithium ELM Free Scenario
    2. Enhanced Pedestal H mode

Control of Enhanced Pedestal H-mode



Time evolution of discharge with transition to the enhanced pedestal H-mode. The H-mode to EP H-mode transition is indicated by an arrow.

- EP H-mode is a new high performance regime has been observed in NSTX
- EP H-mode can be generated reliably
- But it can not be maintained
- We will test the monitoring of the pedestal parameters in real-time and take action when the plasma comes close to EP H-mode drop threshold with the pedestal and ELM control techniques mentioned.