Integrated Scenario Modeling for Advanced Tokamak Scenario Development in DIII-D

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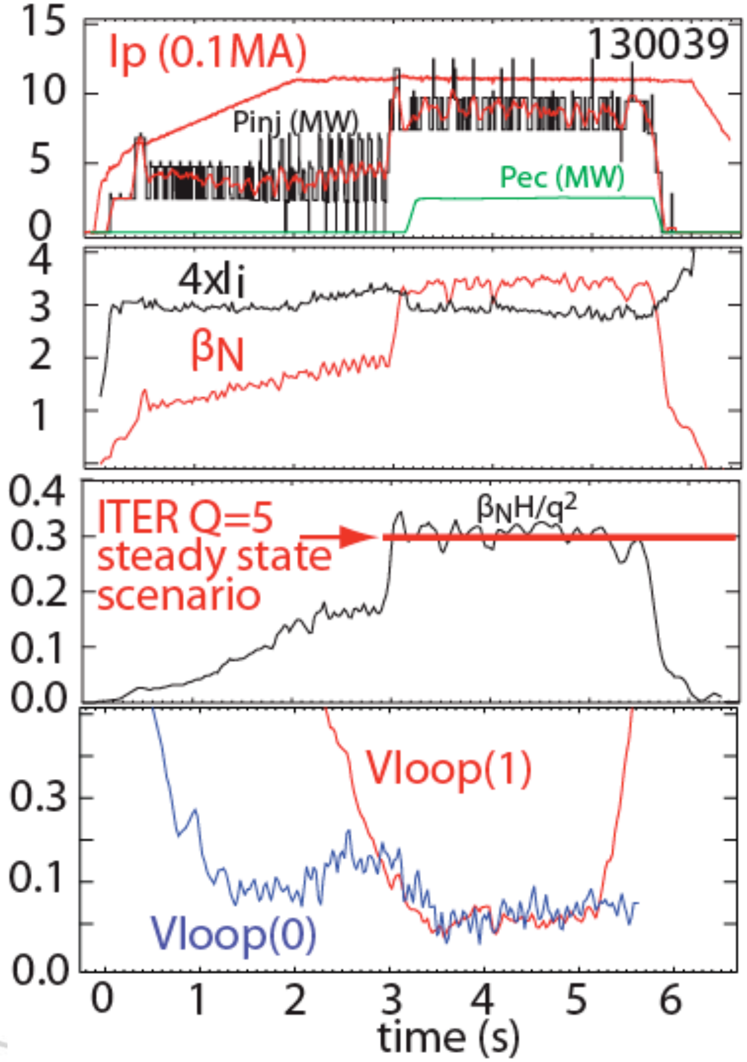
OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

UT-BATTELLE

Recent Focus of DIII-D Advanced Tokamak (AT) Research is Optimization for Fully Noninductive High β Operation

- **Experiments with weakly negative central magnetic shear achieve performance necessary for ITER Q=5 steady-state scenario: $\beta_N \leq 3.5$, $G \leq 0.3$ and $f_{NI} \approx 100$ %**
- **Nearly fully noninductive, stationary discharge was obtained with extended duration, limited Only by Hardware: $\beta_N \approx 3.5$, $G \approx 0.3$ with $\tau > \tau_R$**
- **Shape optimization allows access to higher performance, extending stationary operational space to $\beta_N \leq 4$ and $G \leq 0.4$**
- **Integrated modeling has been carried out to guide *AT* experiments with upgraded DIII-D hardware**
  - Validated against DIII-D AT discharges
  - Extrapolate to **100 % fully noninductive operation with $\beta \approx 4$ and $G \approx 0.4$** using higher power ECCD and FW

Nearly Fully Noninductive, Stationary Discharge Obtained with Extended Duration, Limited Only by Hardware



- **β_N = 3.4, G=0.3, H_{89} = 2.4**
  $\tau_{dur} \approx 1.3\ \tau_R$
- **Very stationary but not fully noninductive**
- **Limited by NBI, not by EC**

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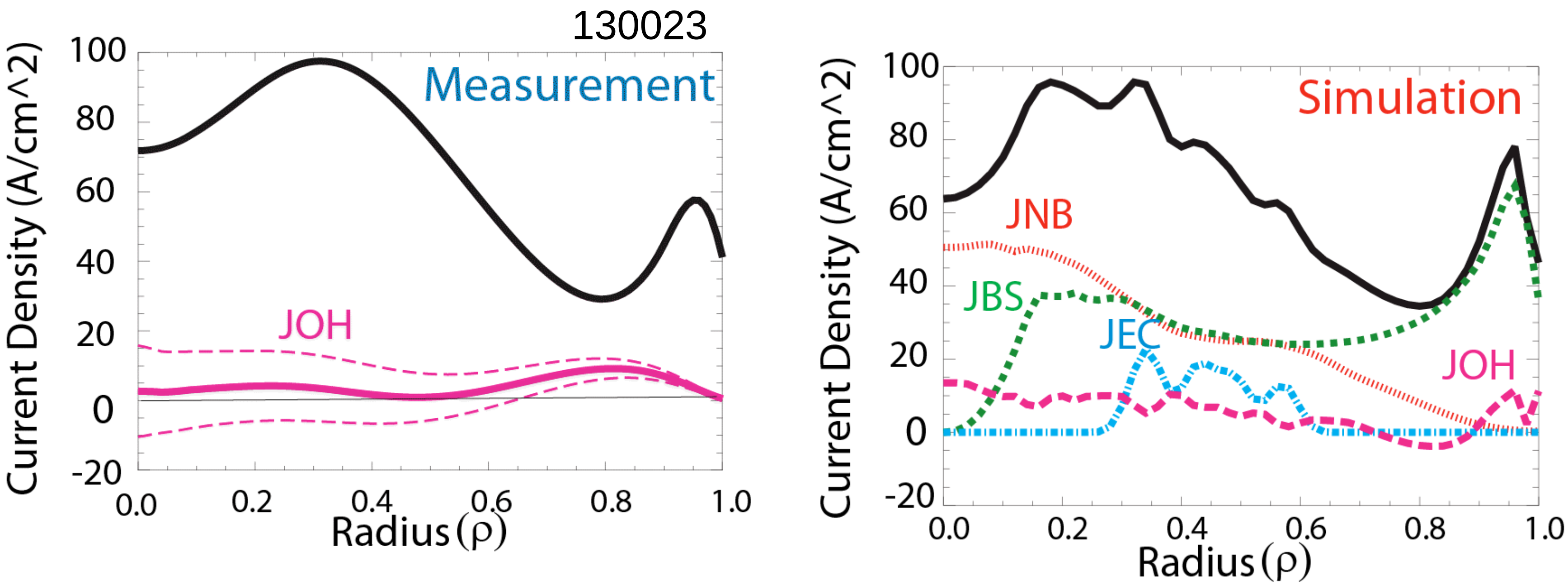
Both Measurement and Simulation Indicate Stationary Current Profile with f_{NI} > 90%



- **Measurement (Loop voltage analysis):**
  - f_{ind} ~ 10 %, f_{NI} ~ 90 %
- **Simulation (Current profile evolution):**
  - f_{ind} = 8 %, f_{NI} = 92 %
  - f_{BS} = 60 %, f_{NB} = 28 %, f_{EC} = 5 %

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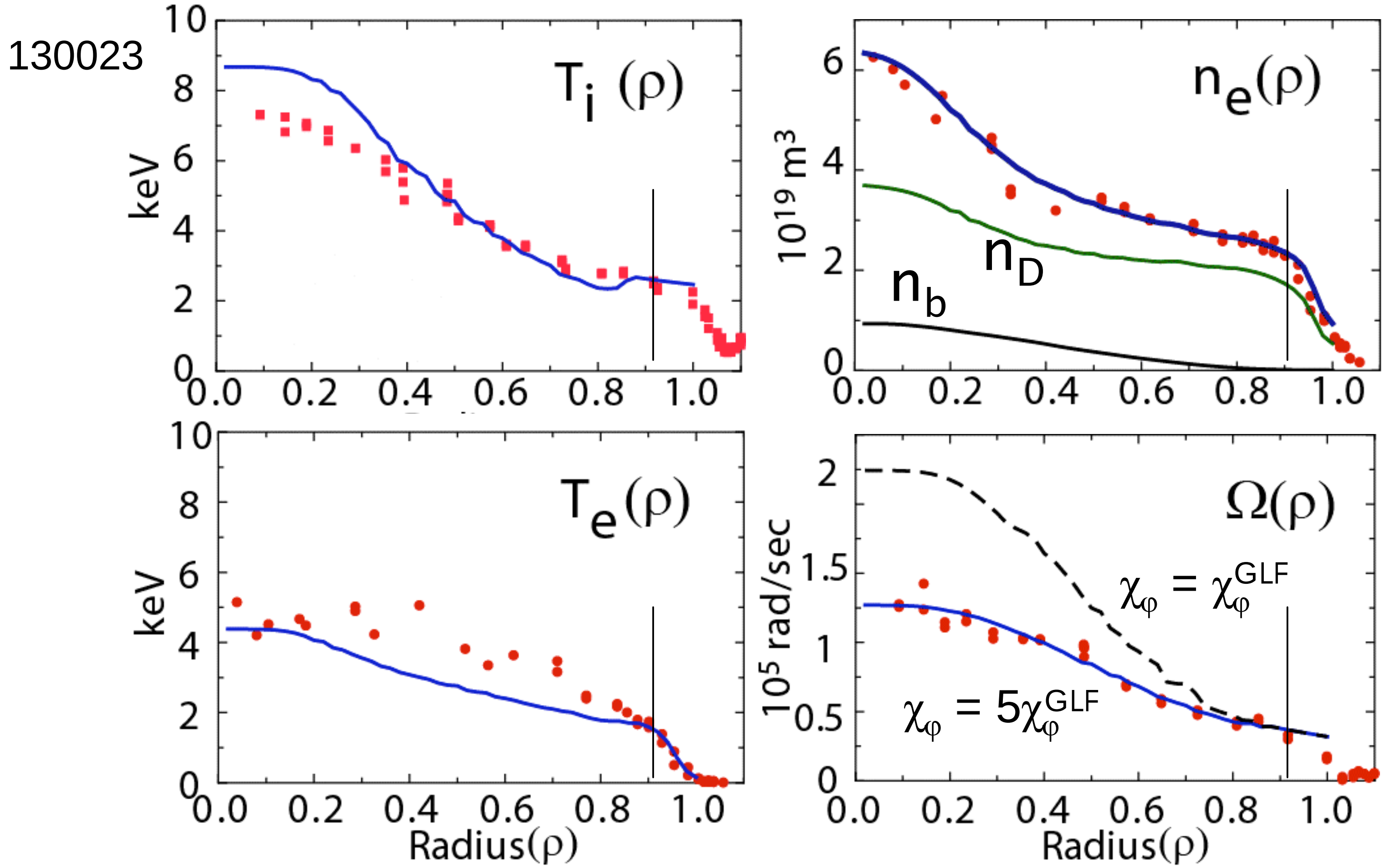
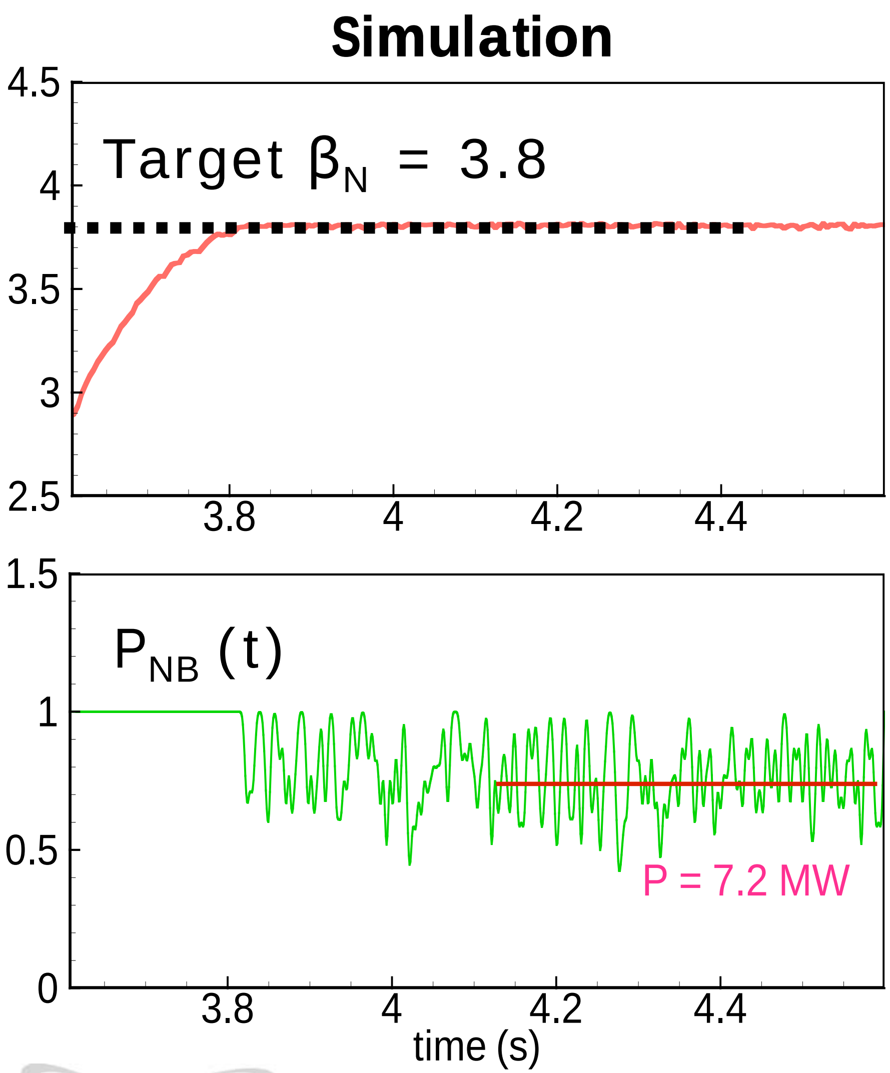
Theory-Based GLF23 Model with Self-consistent Source & Sink Calculation Validated Against DIII-D AT Discharges



- **Solve all transport (n_e, T_e, T_i, Ω_{tor}, J) equations**
- **ELM average profiles as boundary condition at $\rho = 0.9$**
- **Simulation tends to overestimate Ω in the core ➔ $\chi_\varphi = 5\chi_\varphi^{GLF} + 2\chi_i^{Neo}$**

Feedback Control Included in Integrated Modeling for Predictive Simulations of DIII-D AT Discharges



- β Feedback control in ONETWO/GLF23 transport simulation
- NB Power is modulated In the same way as DIII-D experiment to keep β_N constant
- Various model feedback control methods implemented into ONETWO/GLF23

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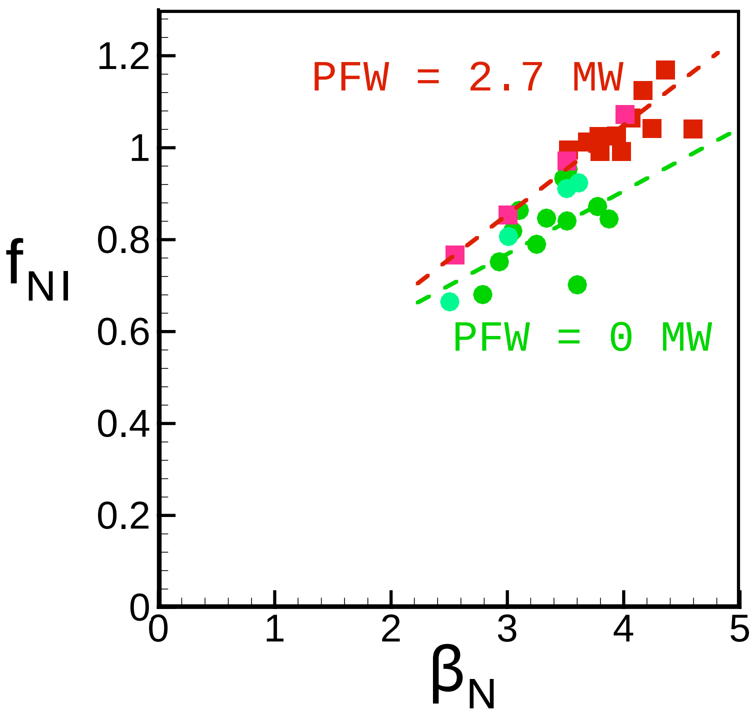
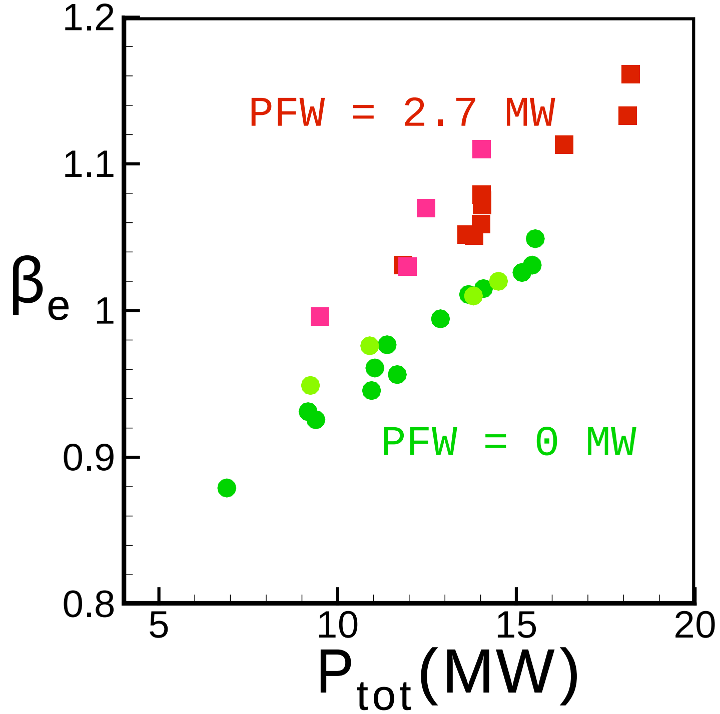
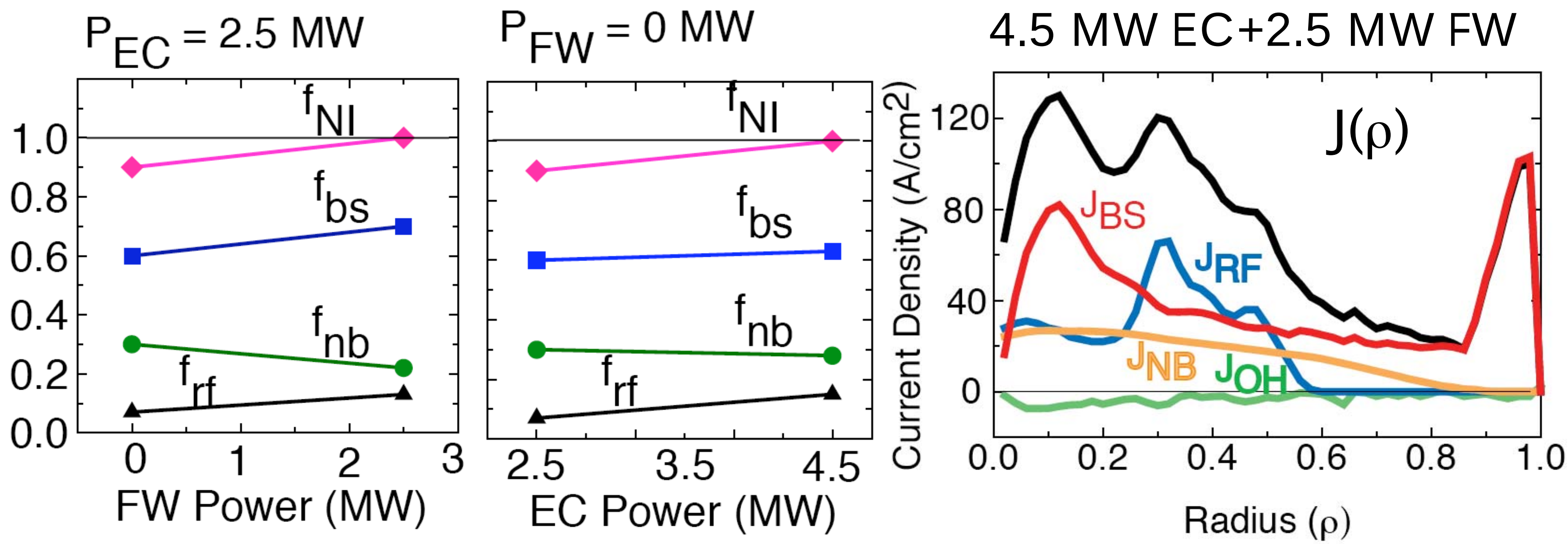
ONETWO/GLF23 Predicts FW H&CD Allows Operation at Higher f_{NI} at Given β_N





- **FW heating is more efficient in region where χ_e and χ_i are lowest**
- **FW Heating increases β_e, resulting in higher f_{bs} and improved off-Axis ECCD efficiency**

4.5-MW EC and 2.5-MW FW Can Achieve f_{NI} = 100 % at β_N = 3. 5 for $\tau_{dur} \geq 2\ \tau_R$



- **P_{NB} = Feedback controlled to maintain β_N = 3.5**
- **f_{bs} increases with P_{FW} at given β_N**
  - FW power results in higher f_{NI} with reduced average NB power
- **P_{EC} = 4.5 MW and P_{FW} = 2.5 MW leads to 100 % noninductive operation with $P_{NB} \approx$ 4.5 MW**

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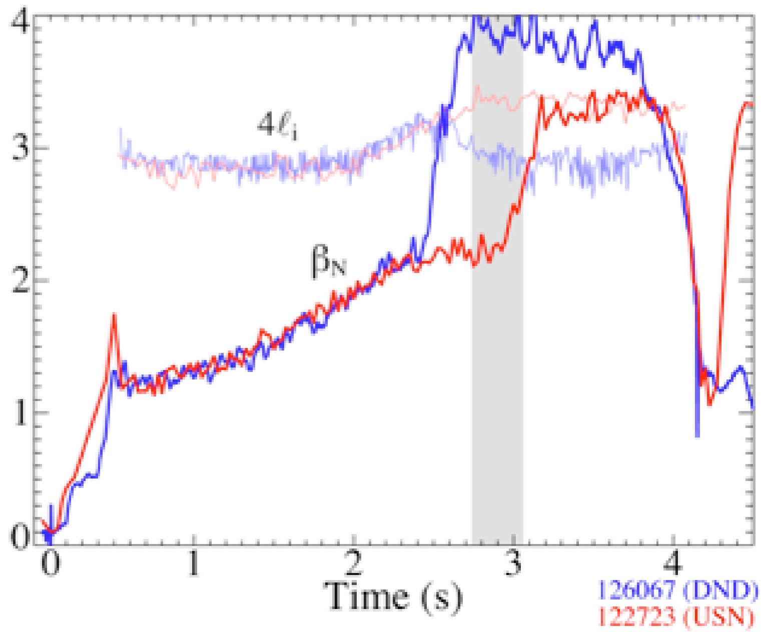
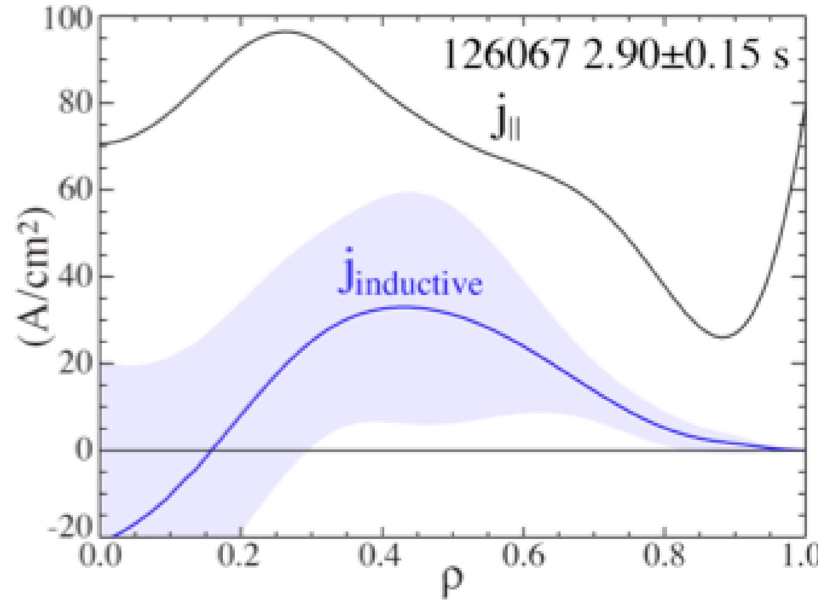
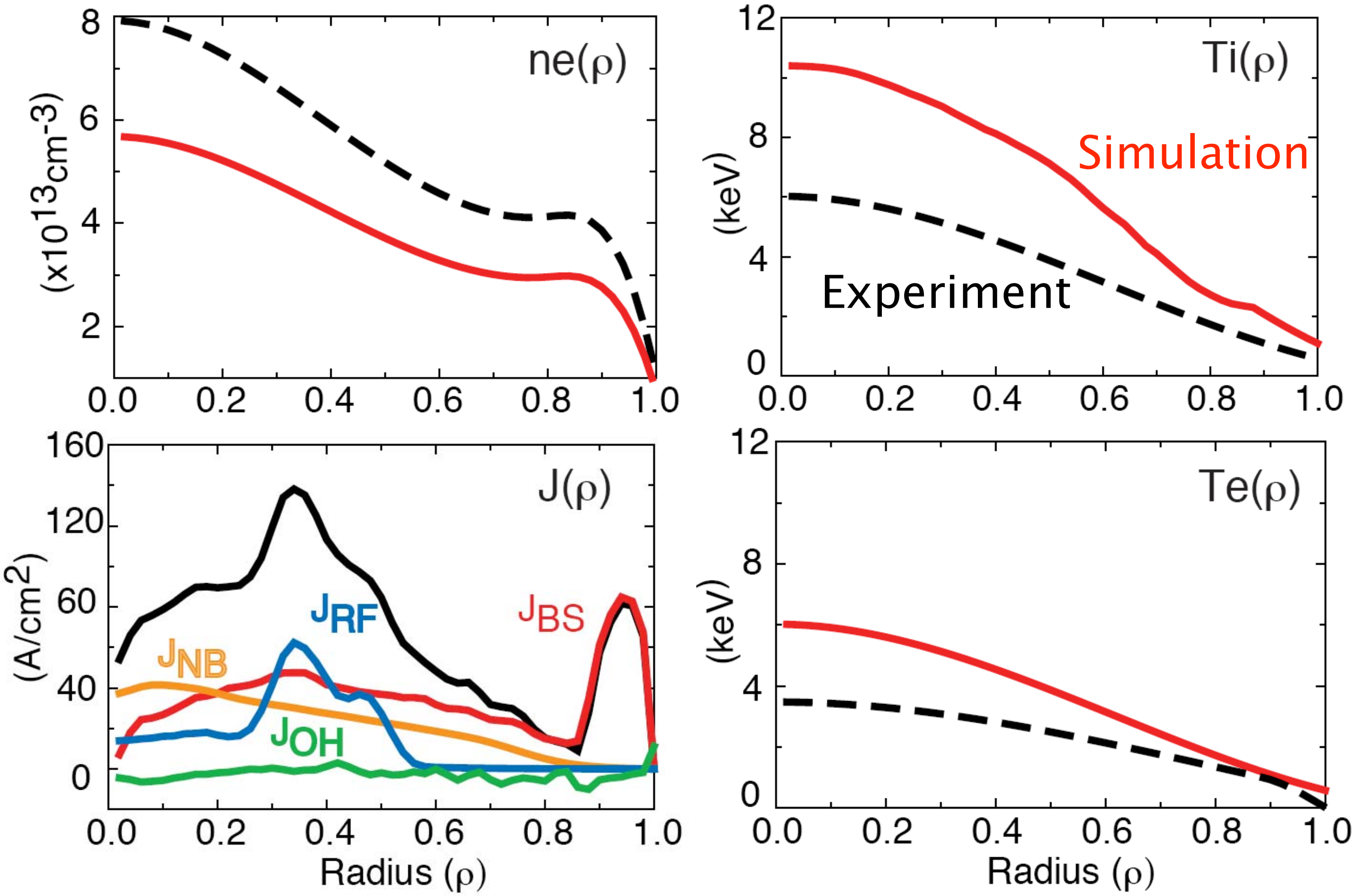
Shape Optimization Allows Access to Higher Performance





- **Double-null divertor experiments have achieved:**
  - $\beta_N \approx 4$, $G \approx 0.4$
- **Current profile analysis indicates additional off-axis current drive required to reach fully noninductive condtions**
  - feasibility study of off-axis NB [**JP8 Murakami**]

ONETWO/GLF23 Predicts Density Pumping Leads to Fully Noninductive Operation at $\beta_N = 4.0$



- **P_{EC} = 4.5 MW and P_{FW} = 2.5 MW leads to 100 % noninductive operation at <n> = 4.0 x10^{13}/cm^3**

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Conclusion

- **Integrated scenario modeling based on ONETWO/GLF23 has been successfully validated against recent DIII-D AT experiments with new modeling capabilities**

- **Integrated modeling predicts continued progress in future DIII-D AT experiments with improved heating and current drive capabilities:**
  - Combined 4.5 MW EC and 2.5 MW FW will allow f_{NI} = 100 % at β_N = 3.5 for $\tau > 2\tau_R$
  - Double-null operation with density pumping will achieve f_{NI} = 100 % at β_N = 4.0