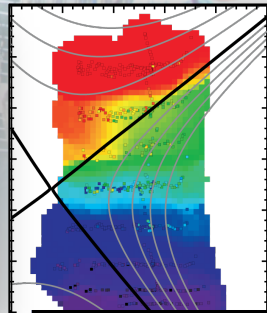
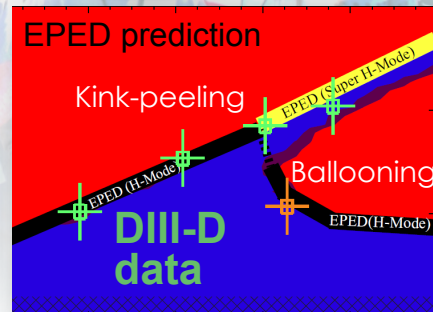
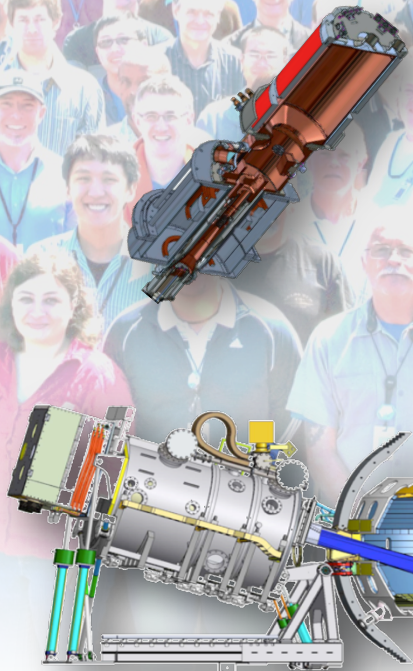
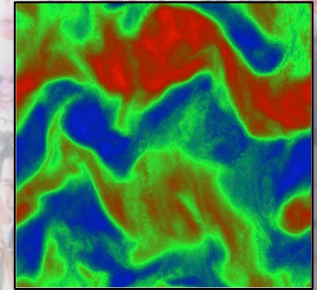
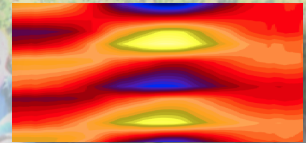
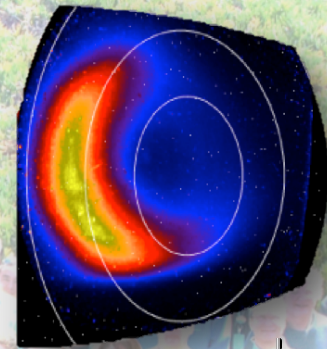


DIII-D Research to Address Key Challenges for ITER and Fusion Energy

by
R.J. Buttery

Presented at the
**25th IAEA Fusion
Energy Conference**
St Petersburg, Russia

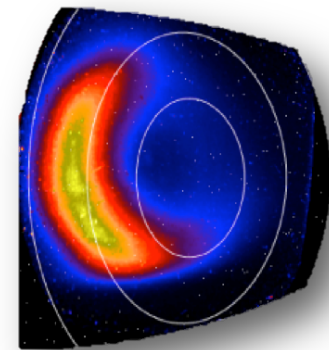
October 2014



DIII-D Focus is on Developing the Required Solutions for Fusion Energy Through Improved Scientific Understanding

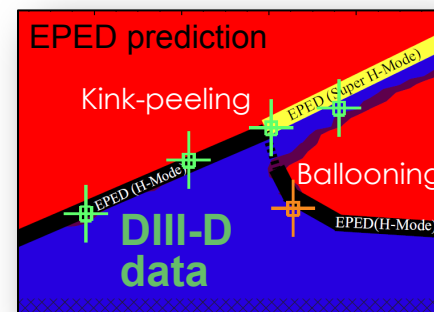
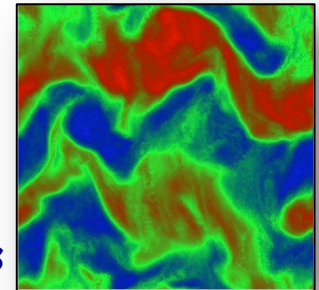
- Addressing Critical Design and Research Issues for ITER
- Achieving High Performance in Future Burning Plasmas
- Expanding the Frontier toward Fusion Energy

**Science → Better Solutions
and Confident Projection**



*Pitch angle
runaway
dissipation*

*Turbulent
Transport
in burn
relevant
conditions*



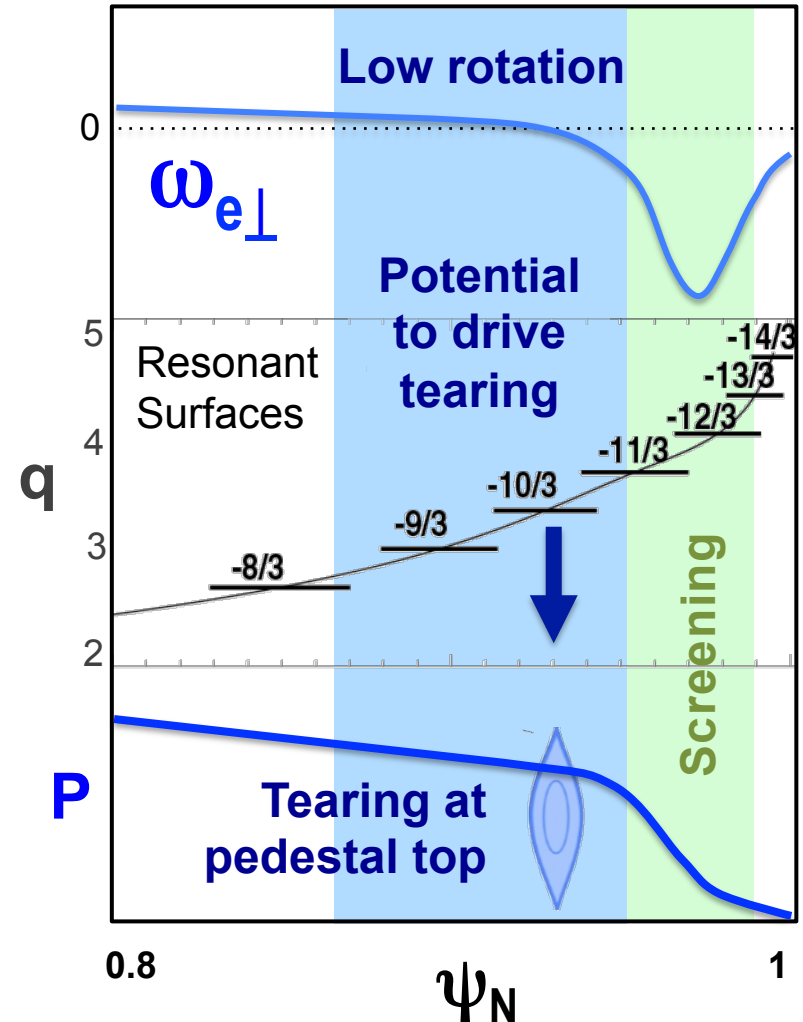
*Super
H-Mode*

Addressing Critical Design and Research Issues for ITER

- ELMs, Disruptions, Test Blanket, Non-nuclear operation

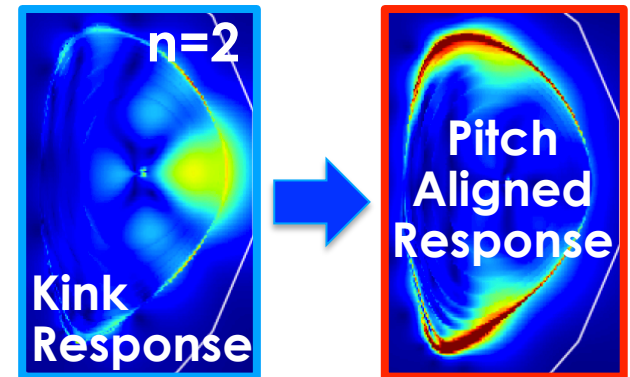
RMP-ELM Suppression Requires a Validated Physics Theory To Provide Confidence for ITER

- Hypothesis: 3D fields drive tearing at pedestal top to restrict its width
→ Prevents ELM instability
- *Requires co-alignment of*
 - Low $\omega_{e\perp}$ rotation region
 - Tearing-resonant surfaces
 - ...at the pedestal top



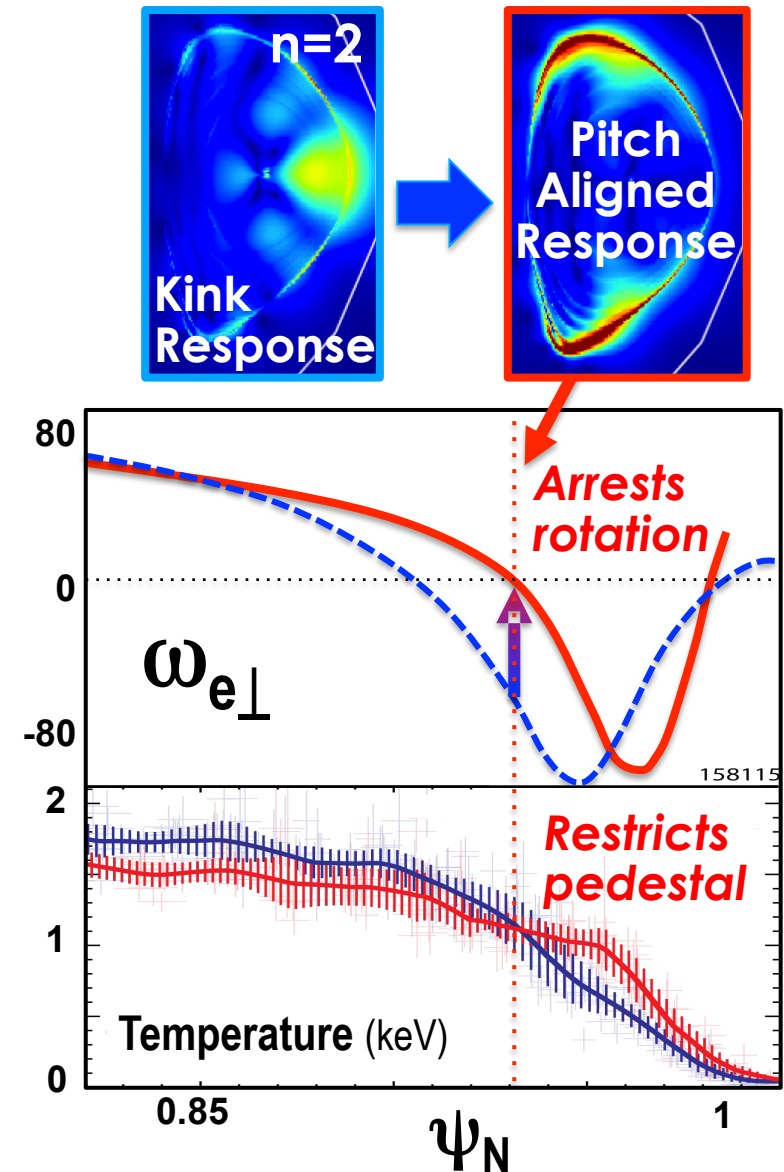
New Evidence for Resonant Field Penetration as Explanation of RMP-ELM Suppression

- Vary $n=2$ field structure from **kink** to **pitch-aligned** resonance
 - Two distinct ideal MHD plasma modes
 - Ramp from exciting one to the other



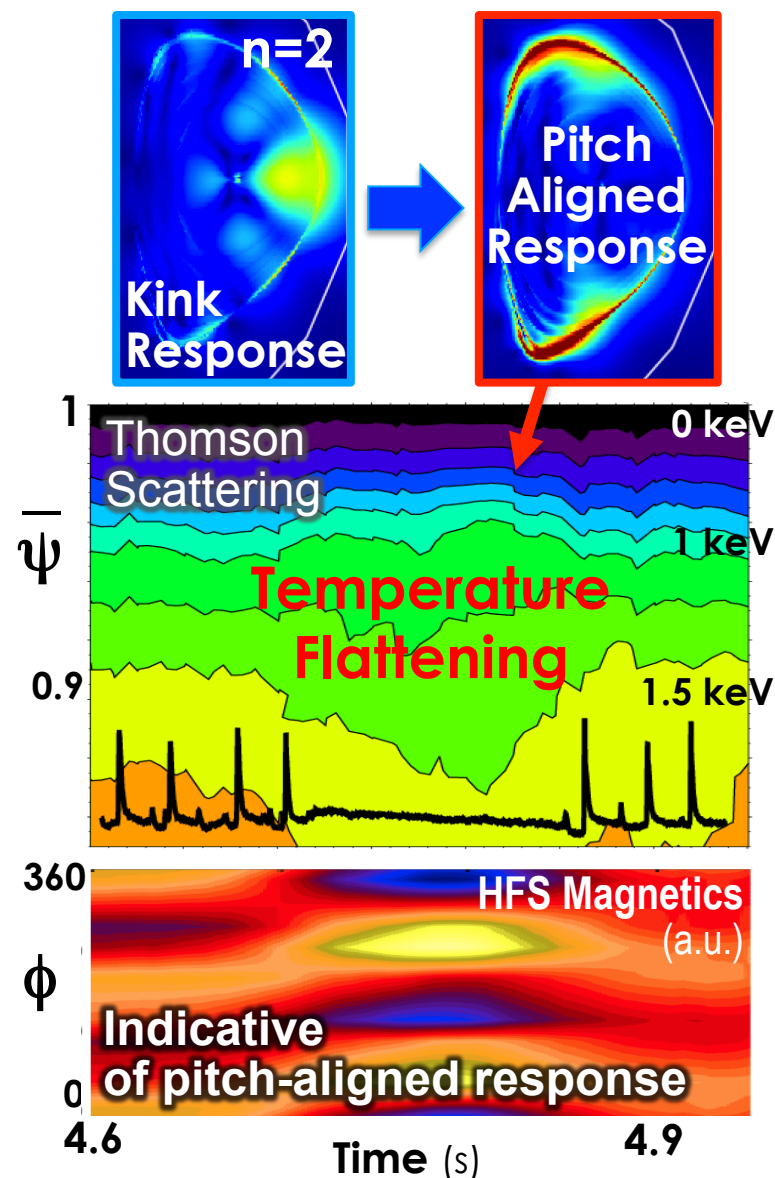
New Evidence for Resonant Field Penetration as Explanation of RMP-ELM Suppression

- Vary $n=2$ field structure from **kink** to **pitch-aligned** resonance
- Penetration of pitch-aligned field
 - $\omega_{e\perp} \rightarrow 0$ at pedestal top
 - Pedestal width narrows
 - Transition to ELM suppression



New Evidence for Resonant Field Penetration as Explanation of RMP-ELM Suppression

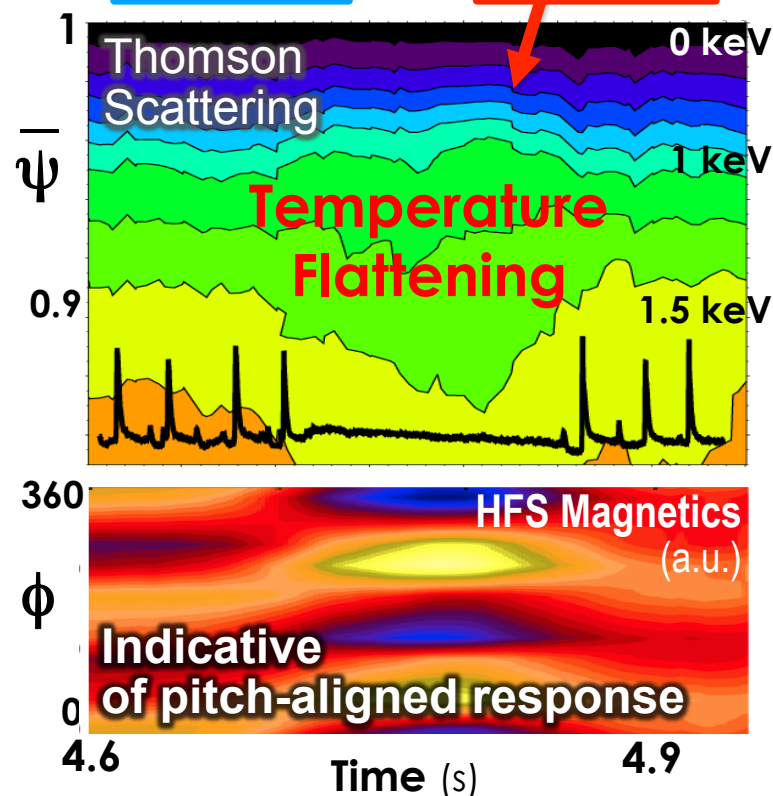
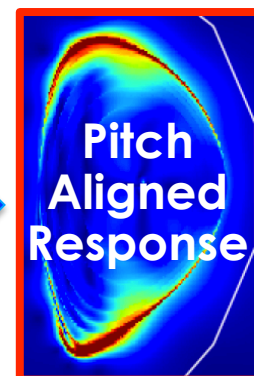
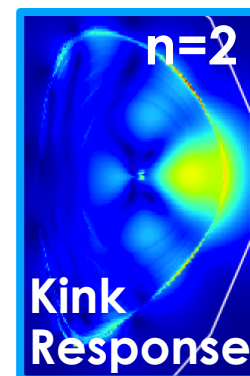
- Vary $n=2$ field structure from **kink** to **pitch-aligned** resonance
- Penetration of pitch-aligned field
 - $\omega_{e\perp} \rightarrow 0$ at pedestal top
 - Pedestal width narrows
 - Transition to ELM suppression
 - Flattens pedestal temperature
 - Non-linear growth of pitch aligned response



New Evidence for Resonant Field Penetration as Explanation of RMP-ELM Suppression

- Vary $n=2$ field structure from **kink** to **pitch-aligned** resonance
- Penetration of pitch-aligned field
 - $\omega_{e\perp} \rightarrow 0$ at pedestal top
 - Pedestal width narrows
 - Transition to ELM suppression
 - Flattens pedestal temperature
 - Non-linear growth of pitch aligned response
- Validates 2-fluid MHD predictions of island formation & overlap (M3D-C1)

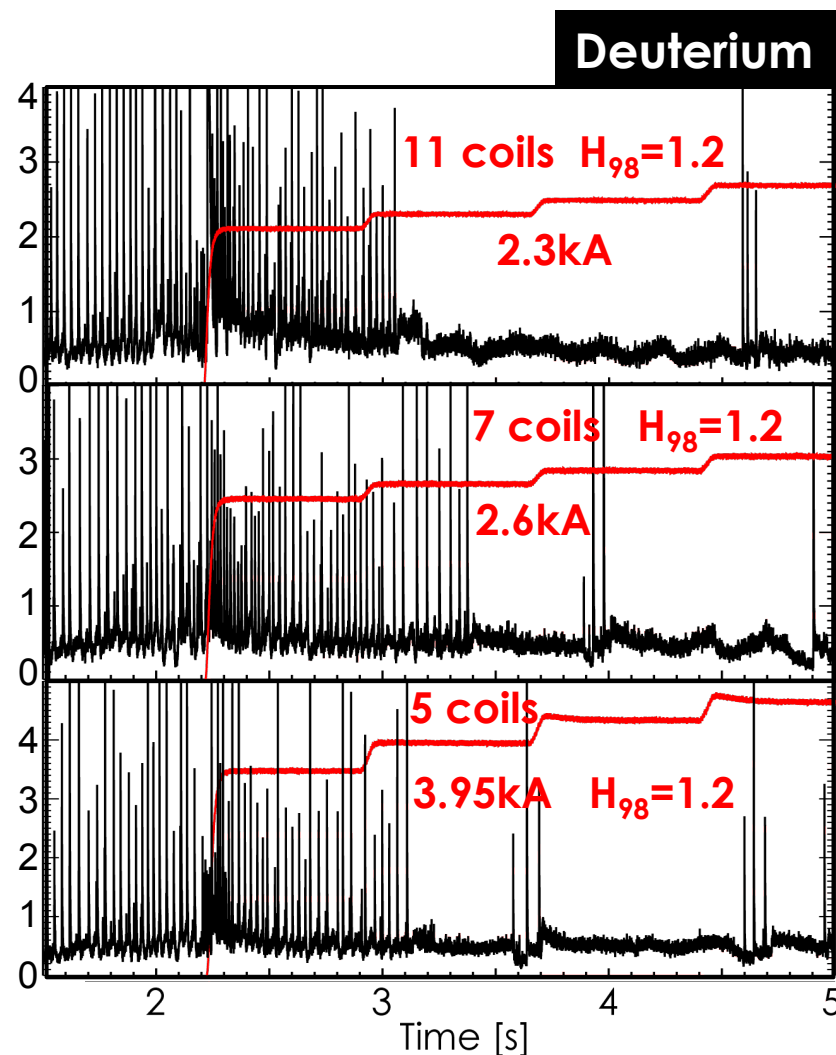
✓ Increased confidence in predictions for ITER



ELM Suppression is Robust to Loss of Coils and Helium Operation

- ELM suppression maintained as coils reduced from 12 to 5 →
 - Good H factor maintained
- Current required for suppression is similar in most cases
 - 30% less n=3 power
 - n=2 and n=4 fields increase as n=3 field reduced
- ELM suppression also effective in Helium plasmas
 - Relevant torque & e⁻ heating

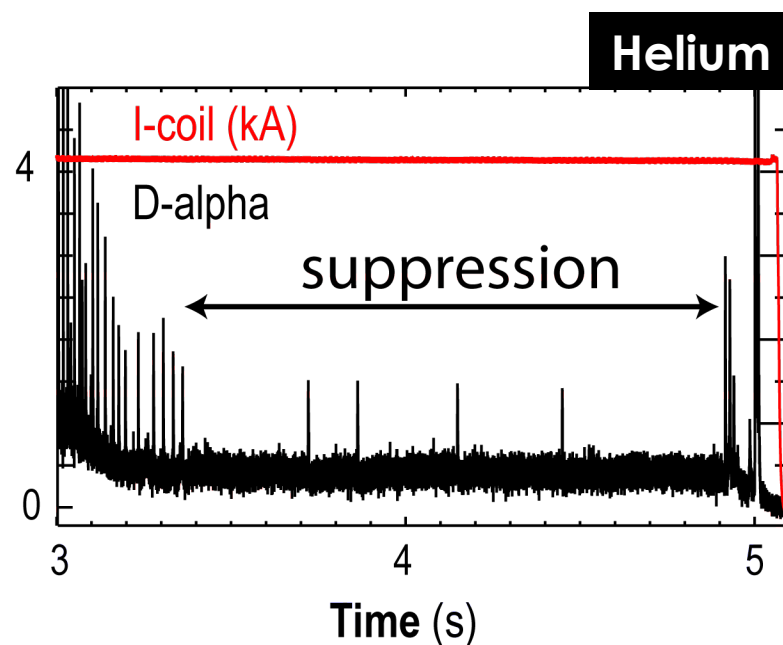
✓ Affirms ITER's Research Plan



ELM Suppression is Robust to Loss of Coils and Helium Operation

- ELM suppression maintained as coils reduced from 12 to 5
 - Good H factor maintained
- Current required for suppression is similar in most cases
 - 30% less n=3 power
 - n=2 and n=4 fields increase as n=3 field reduced
- **ELM suppression also effective → in Helium plasmas**
 - Relevant torque & e⁻ heating

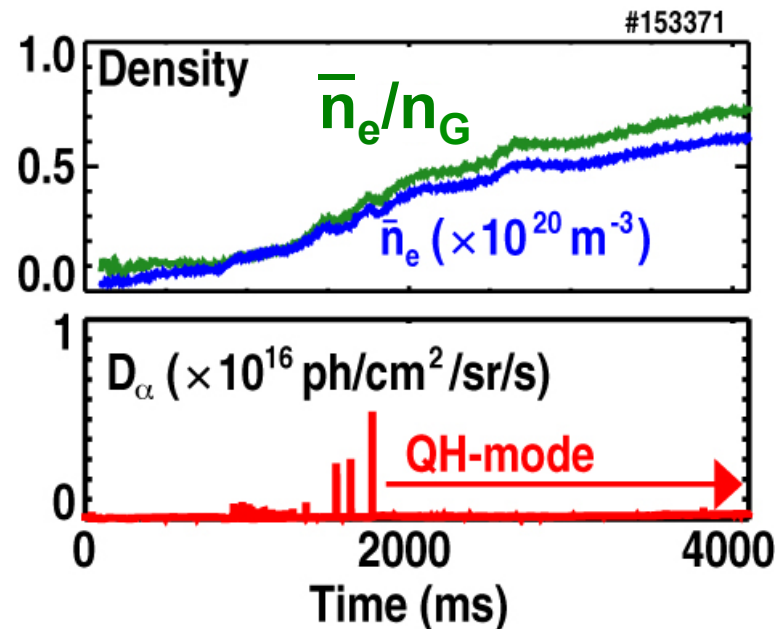
✓ **Affirms ITER's Research Plan**



ELM-stable QH Mode Shown Compatible with ITER Greenwald Density and Good Impurity Flushing

QH mode relies on an Edge Harmonic Oscillation to regulate the edge

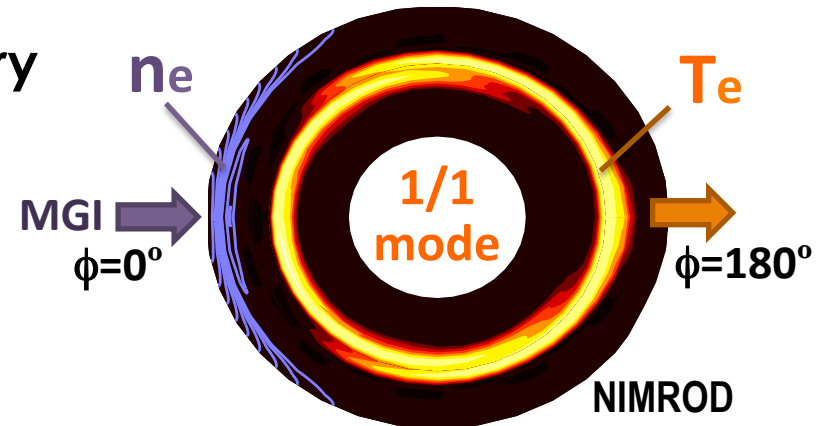
- **Compatible with high gas injection →**
 - Greenwald density fractions over 70% achieved
 - Accessed by raising triangularity as predicted by EPED model
- **Edge Harmonic Oscillation found to provide good impurity control**



✓ Improved confidence of QH mode access in ITER

Massive Gas Injection Experiments Consistent with NIMROD Predictions of Modest Disruption Radiation Asymmetry

- **NIMROD predicts radiation asymmetry governed by $n=1$ mode**
 - Mode redistributes radiation away from MGI port
- **Confirmed by DIII-D data**
 - Initial mode 180° away from MGI



Massive Gas Injection Experiments Consistent with NIMROD Predictions of Modest Disruption Radiation Asymmetry

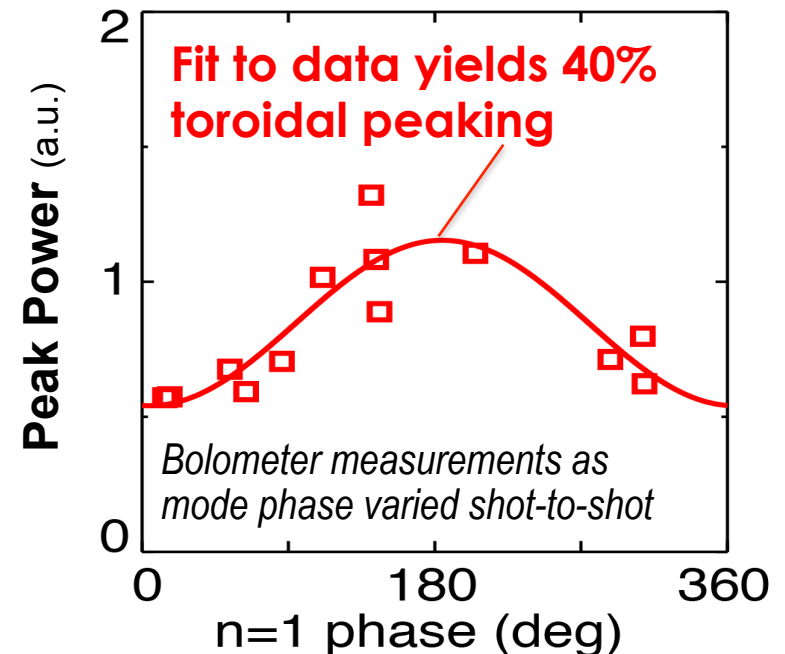
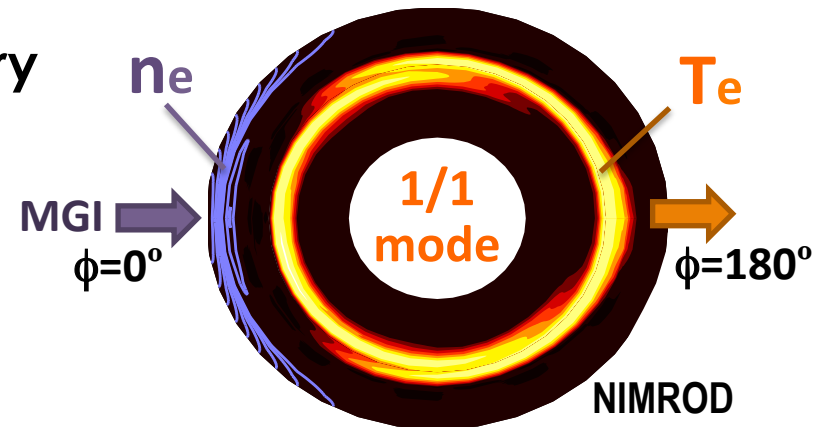
- **NIMROD predicts radiation asymmetry governed by $n=1$ mode**

- Mode redistributes radiation away from MGI port

- **Confirmed by DIII-D data**

- Initial mode 180° away from MGI
- **Can control mode with 3D field to rotate past bolometer in steps**
 - Yields modest 40% peaking
- ✓ Matches NIMROD prediction of 40% peaking

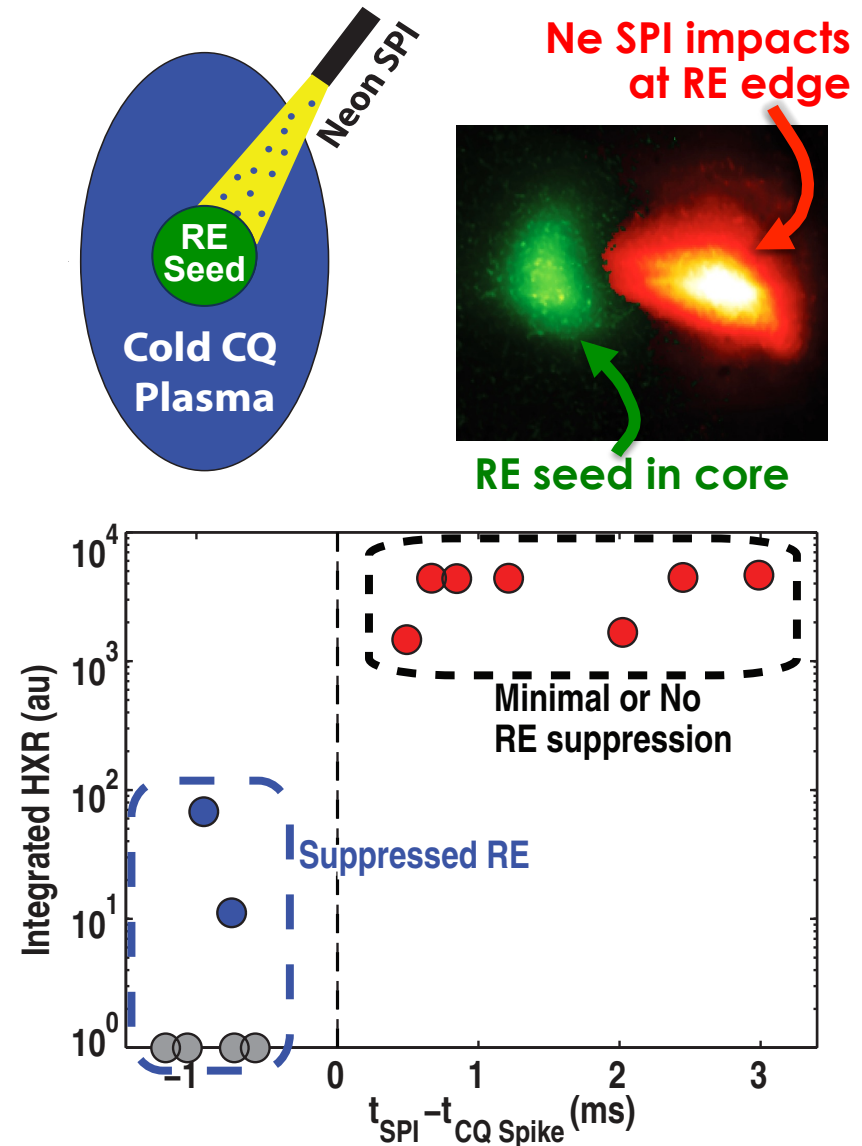
✓ **Modest toroidal radiation asymmetries predicted in ITER**



DIII-D Developed Promising Runaway Electron Mitigation Solution for ITER

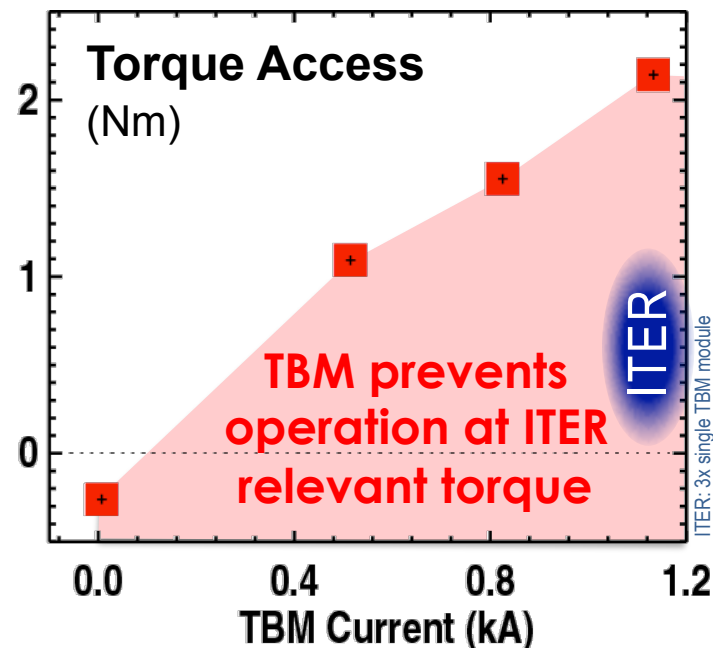
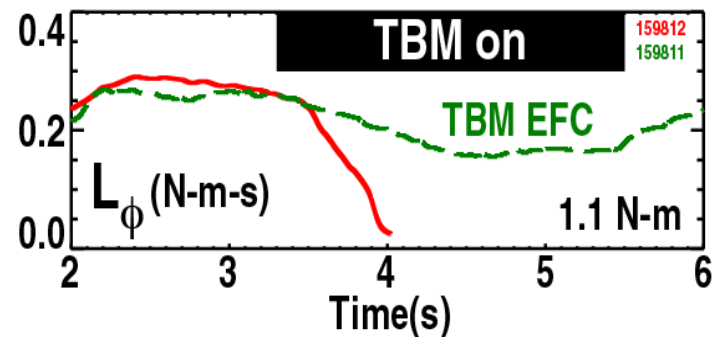
- Injection of Ne Shattered Pellets into early CQ may provide viable path to suppress runaway growth
- RE current dissipation explained by RE-ion pitch angle scattering
 - Higher Z more effective at RE dissipation

✓ First demonstration of potential solution for ITER



Correction of ITER Test Blanket Module Fields Enables Low Torque and High β Operation

- Test Blanket Module simulation coil lead to disruptions in low torque baseline

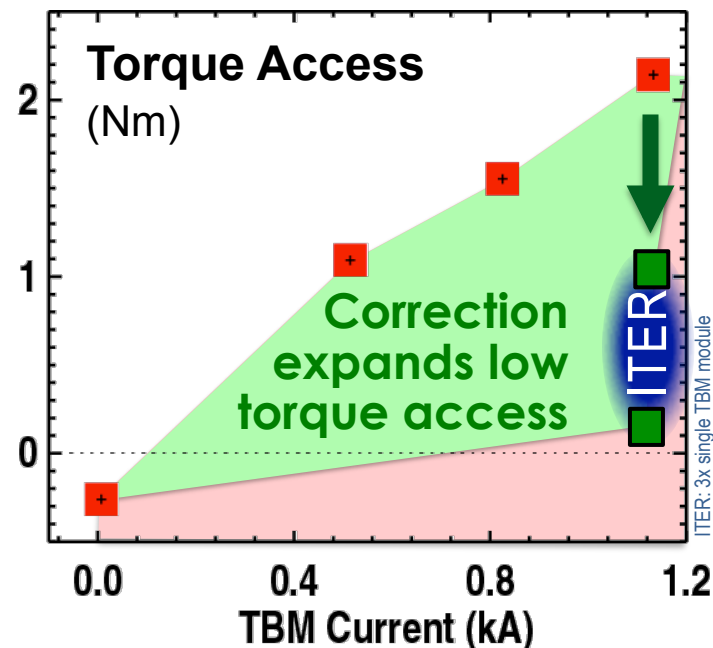
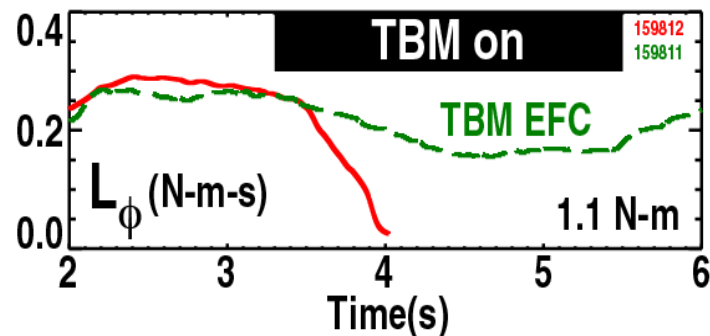


Correction of ITER Test Blanket Module Fields Enables Low Torque and High β Operation

- Test Blanket Module simulation coil lead to disruptions in low torque baseline
- **Correction fields** prevent disruption
 - *Restores low torque window of operation for ITER*
 - Also recovers performance at high β , reducing local heat loads by 80%



✓ ITER Test Blanket Module tolerable with good error field correction

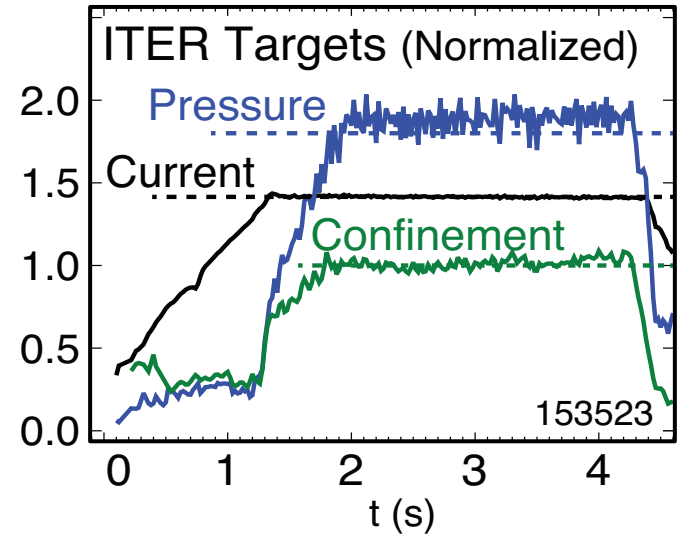


Achieving High Performance in Future Burning Plasmas

- Predictive understanding of optimization and control in relevant conditions

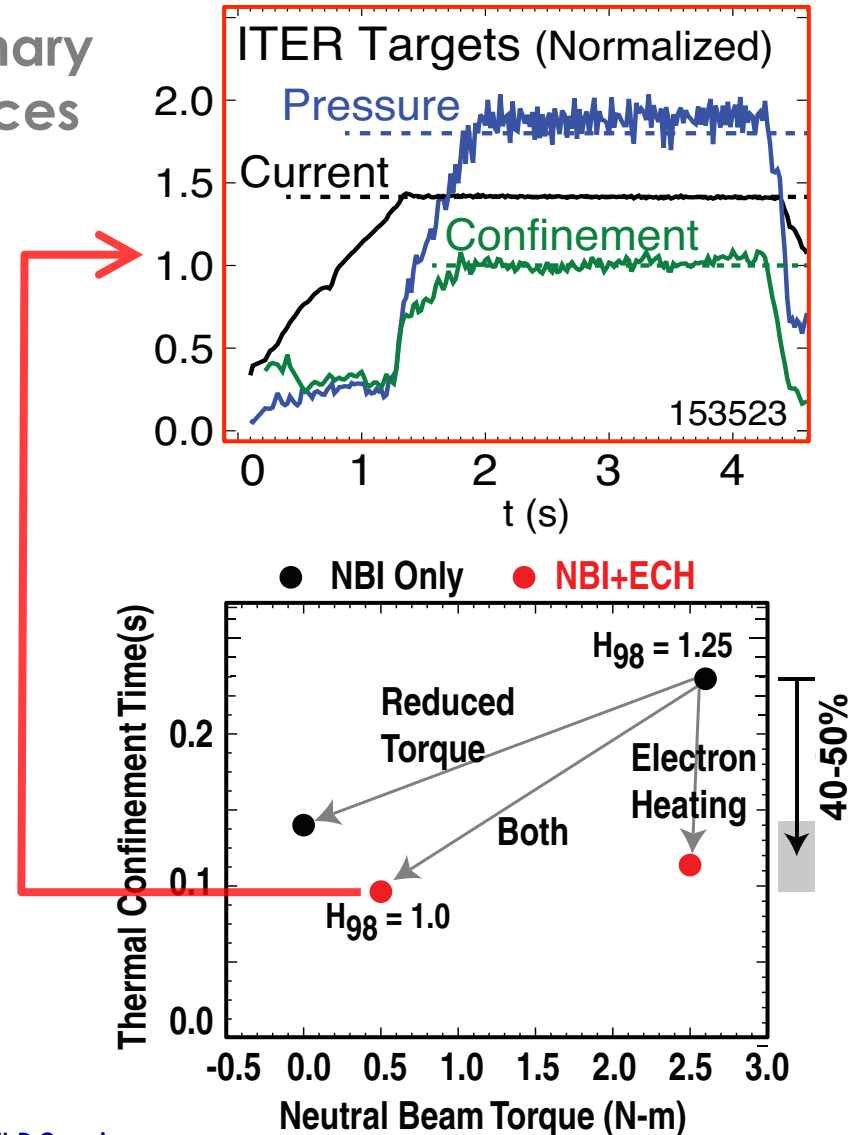
Unique DIII-D Capabilities Advance Baseline Scenario Toward ITER-Relevant Conditions

- **Baseline targets achieved in stationary conditions ($>2\tau_R$) with relevant sources**
 - Dominant electron heating
 - Low torque
 - Reduced core fueling
- **Avoid tearing instability:**
 - Error field correction
 - Pedestal/ELM regulation
 - Maintain differential rotation



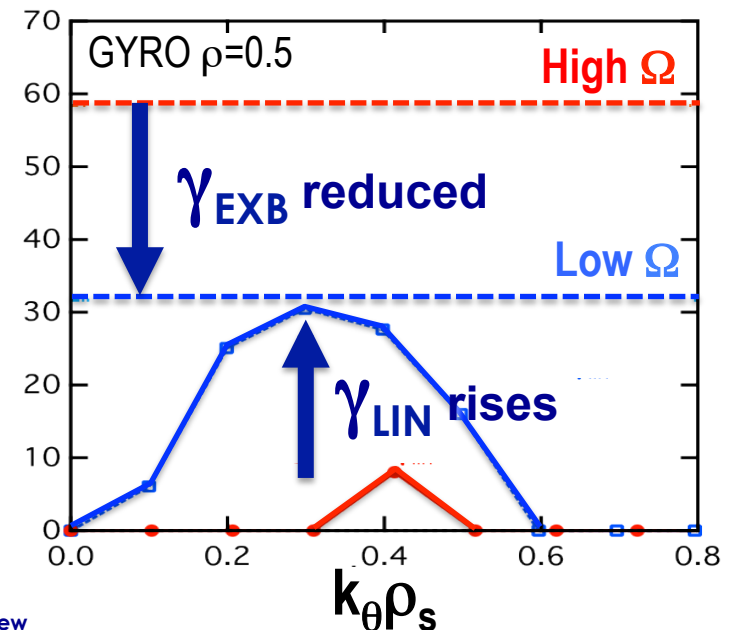
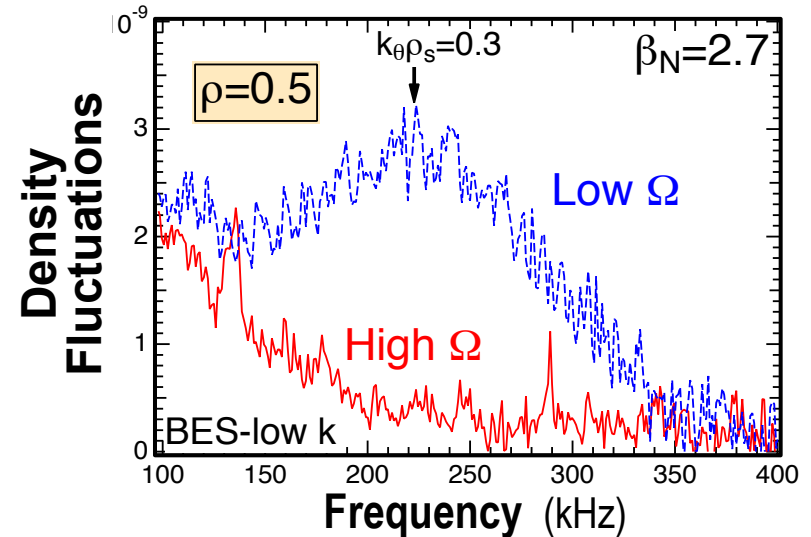
Unique DIII-D Capabilities Advance Baseline Scenario Toward ITER-Relevant Conditions

- **Baseline targets achieved in stationary conditions ($>2\tau_R$) with relevant sources**
 - Dominant electron heating
 - Low torque
 - Reduced core fueling
- **Avoid tearing instability:**
 - Error field correction
 - Pedestal/ELM regulation
 - Maintain differential rotation
- **Integration of ITER requirements leads to reduced confinement**



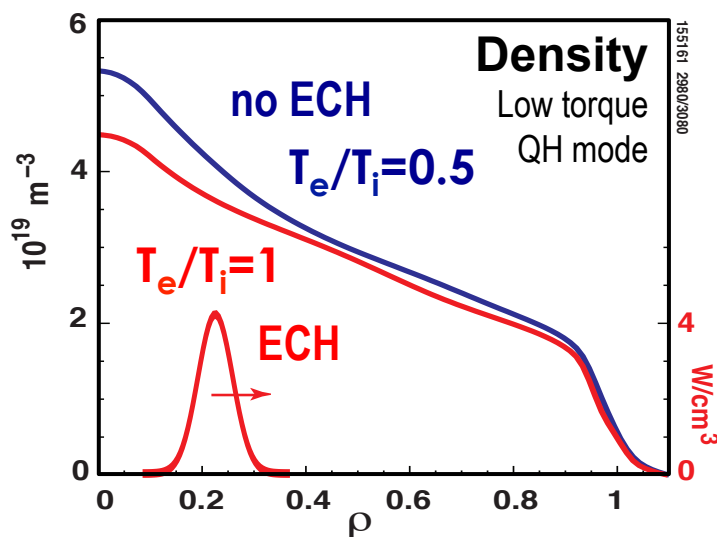
Confinement Reduction at Low Torque Consistent with Turbulence Rise and Transport Models

- Large rise in turbulence with lower rotation
- Interpreted by GYRO simulation
 - Reduction in ExB flow shear stabilization
 - Increase in linear growth rates



At Low Torque Electron Heating Induces Density Flattening Consistent with Increased Trapped Electron Modes

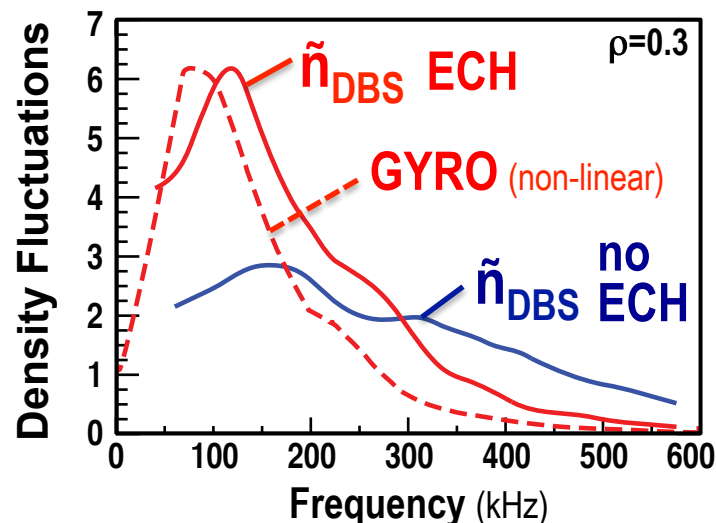
- Density flattening observed when ECH raises T_e/T_i



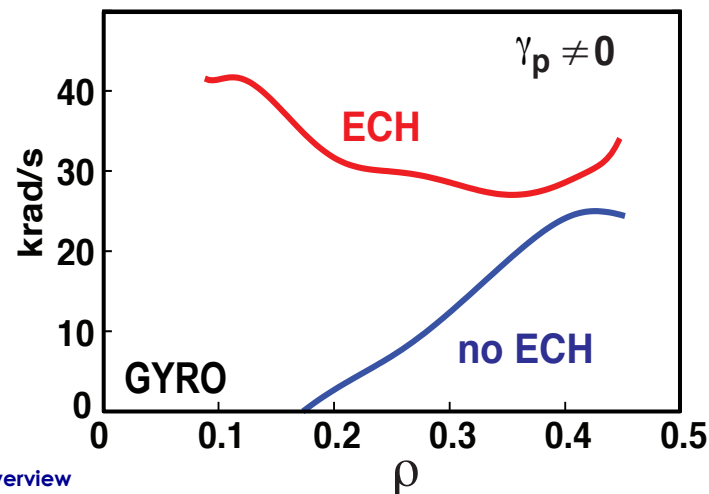
GYRO: Raising T_e/T_i lowers critical density gradient for TEM leading to increased turbulence

US National Campaign with CMOD NSTXU participation

- Explained by rise in turbulence



- Increased TEM growth in core

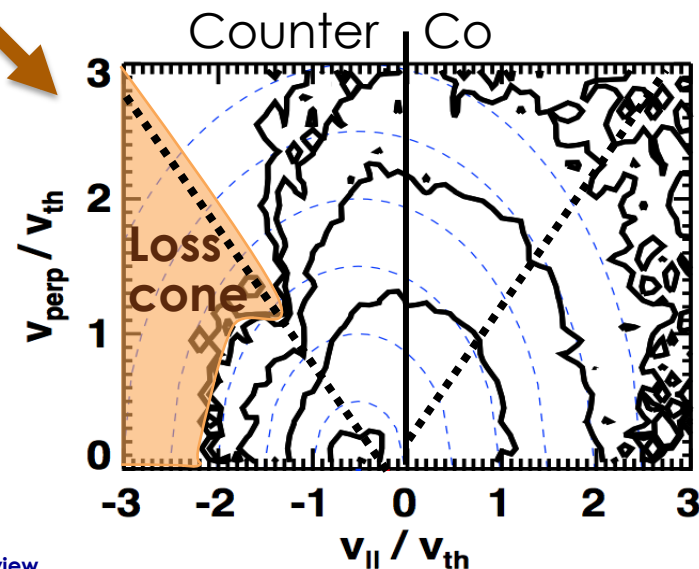
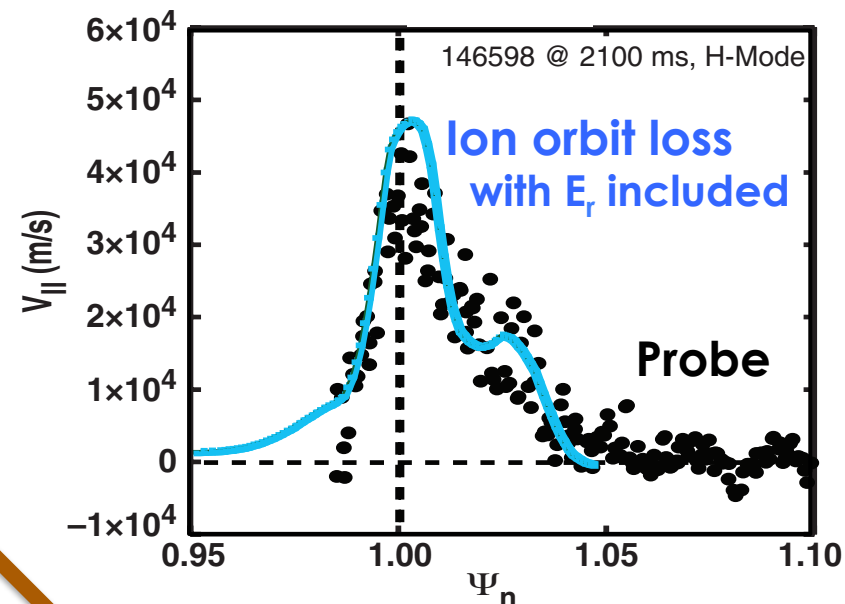


Ion Orbit Loss Models Capture Intrinsic Plasma Rotation Behavior

Rotation critical to transport and stability projection

- Simple model matches → probe measurements
 - Also replicated by XGC0 code
 - **Empty loss cone shifts velocity in co- I_p direction**
 - Probe measurements confirmed by main ion CER
- Core rotation found to correlate with edge rotation

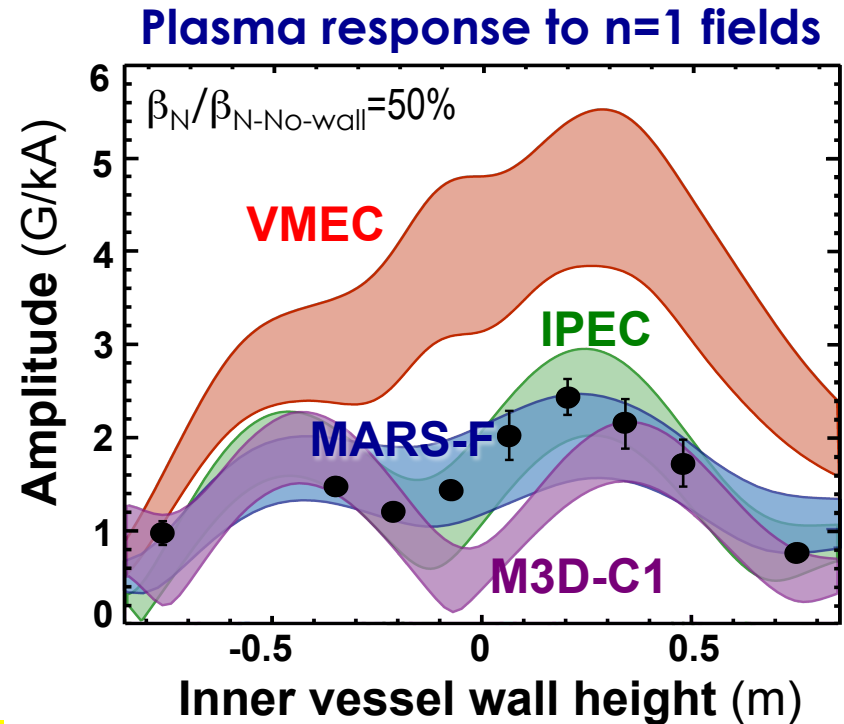
✓ Expected to generate similar local edge flow velocity in ITER



Upgraded 3D Magnetics Reveal Sensitivities and Differences in MHD Models of 3D Plasmas

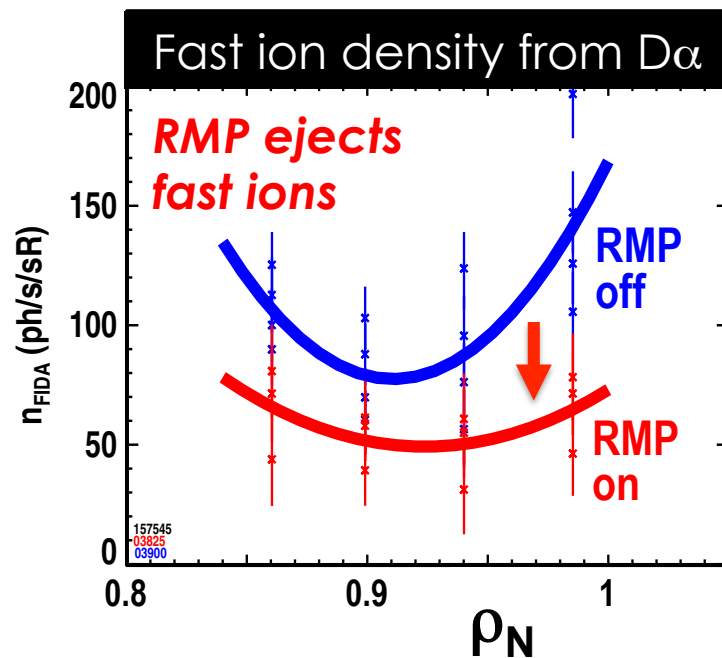
- **Linear ideal MHD broadly captures 3D response**
 - M3D-C1 reveals sensitivities to edge conductivity
- **Non-linear VMEC over-predicts response**
 - Discrepancies being investigated

New magnetics helping refine and develop physics models of plasma response to 3D fields



3D Fields for RMP-ELM Suppression Lead to Significant Energetic Particle Losses

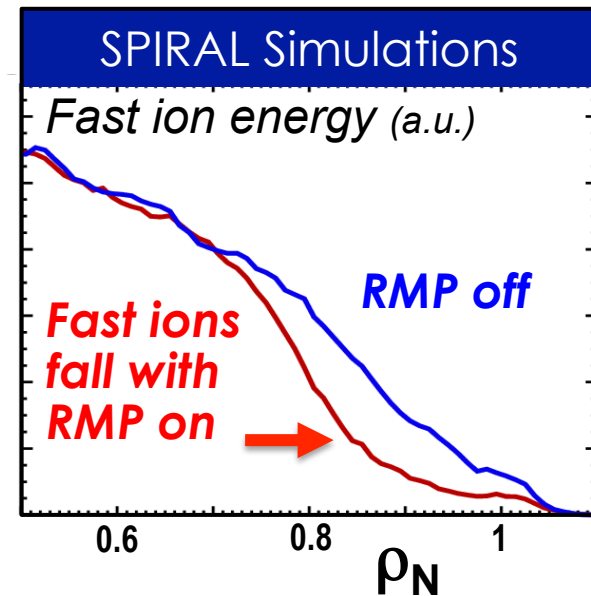
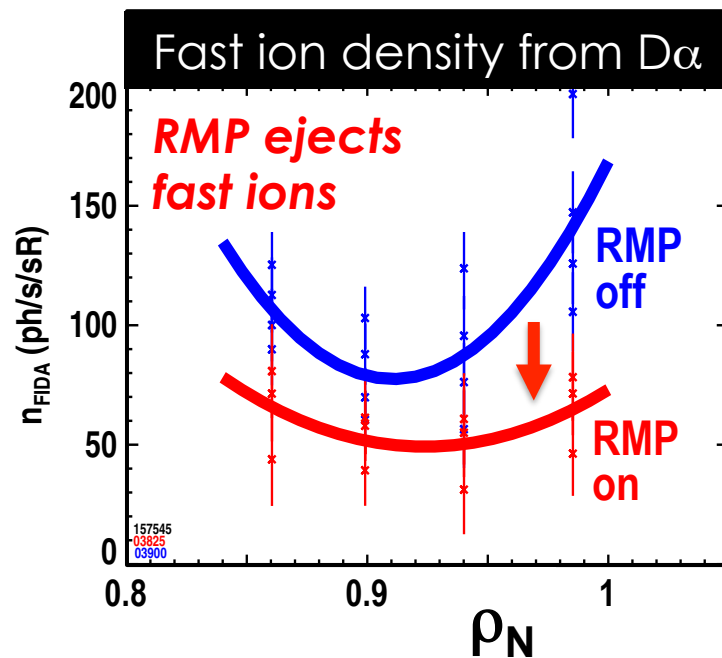
- Notches in n=3 field show RMP ejects edge fast ions
 - ELM suppression maintained



Leads to increased divertor heat load in model and experiment

3D Fields for RMP-ELM Suppression Lead to Significant Energetic Particle Losses

- Notches in $n=3$ field show RMP ejects edge fast ions
 - ELM suppression maintained
 - Consistent with SPIRAL+M3D-C1 full orbit predictions



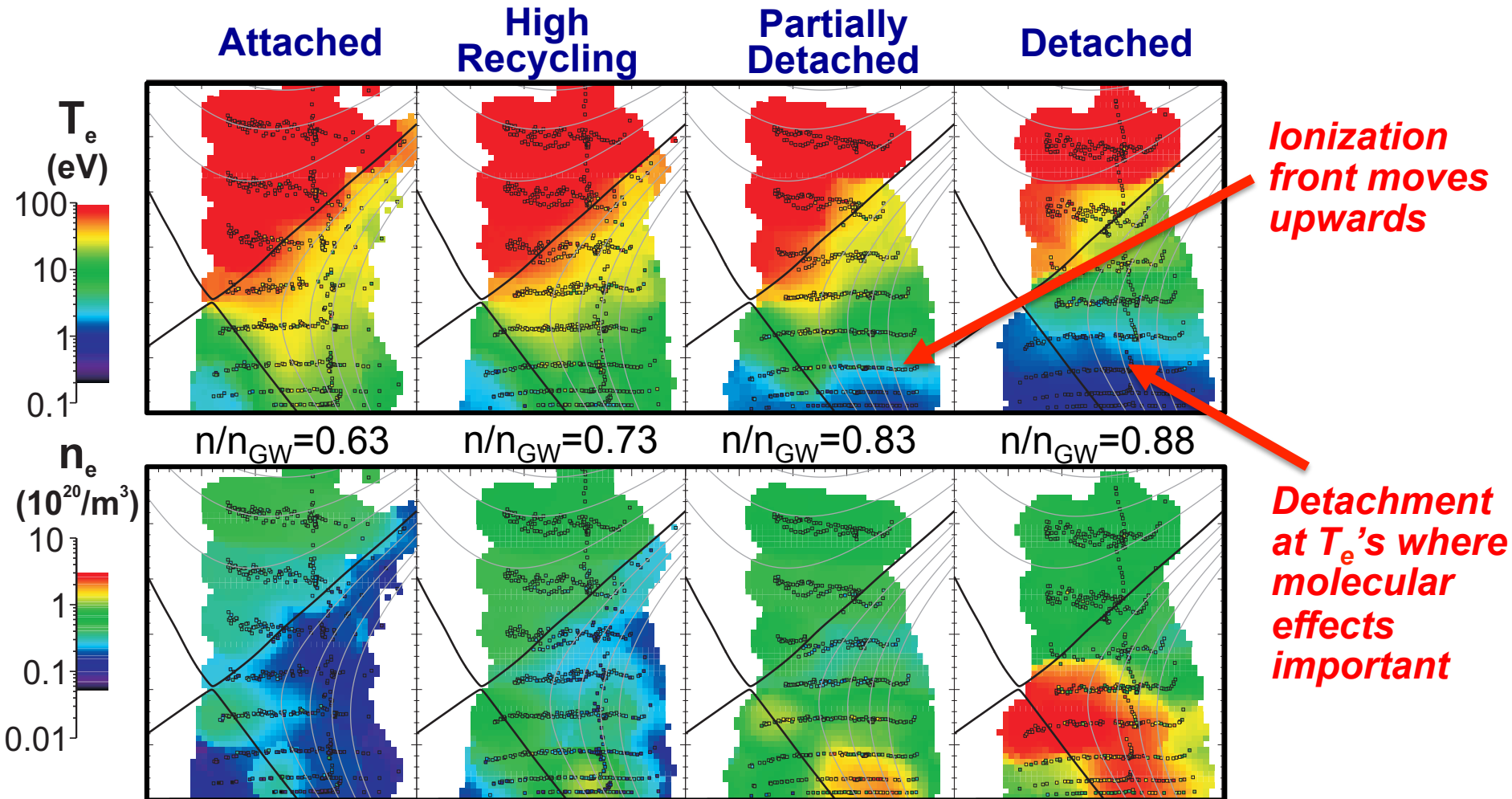
Leads to increased divertor heat load in model and experiment

Expanding the Frontier to Fusion Energy

*Future fusion devices require better
solutions for core and boundary*

Sub-eV 2D Divertor Thomson Scattering Measurements Reveal Dynamics of Divertor Detachment

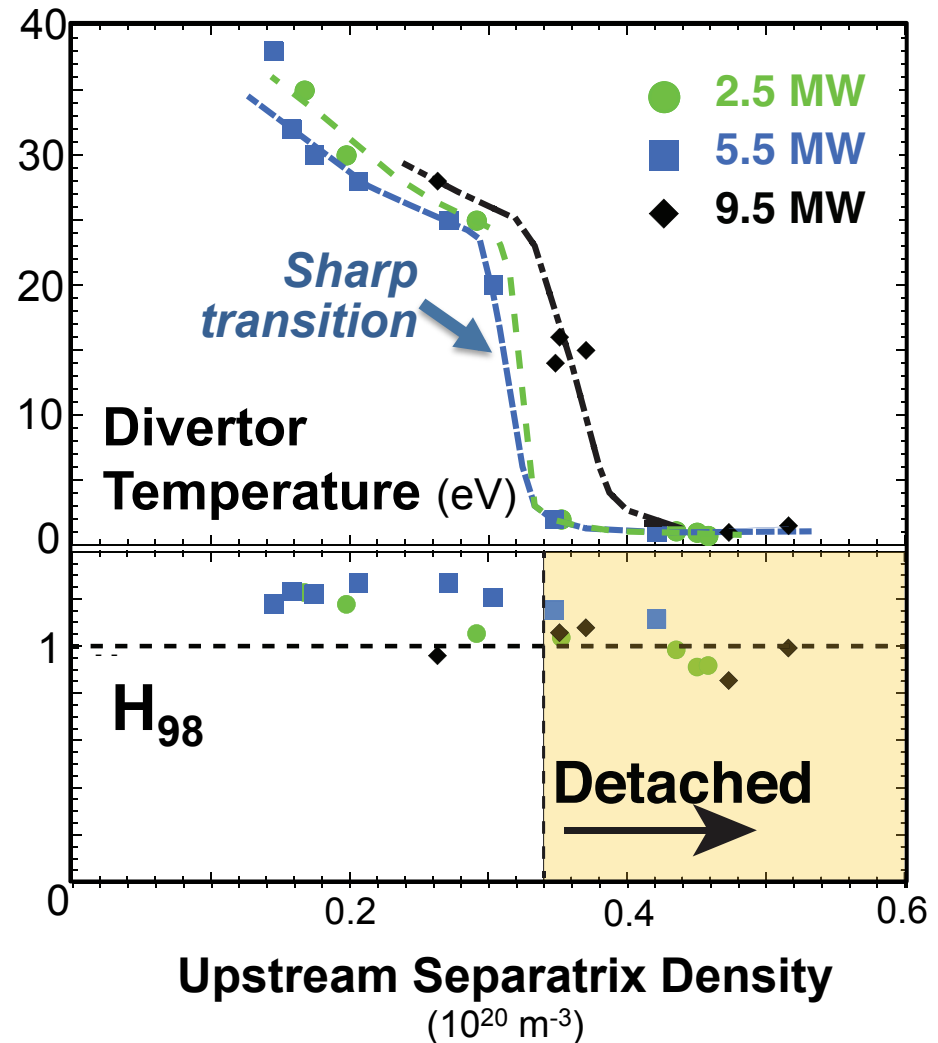
DIII-D focusing on the physics of an improved detached divertor



Sub-eV 2D Divertor Thomson Scattering Measurements Reveal Dynamics of Divertor Detachment

- Transition to detachment in a narrow density range
 - Nearly independent of heating power
- Detachment onset has a weak effect on H_{98}

Good performance can be maintained while detached



Detachment Studies Reveal Radiation Shortfall in Simulation Models

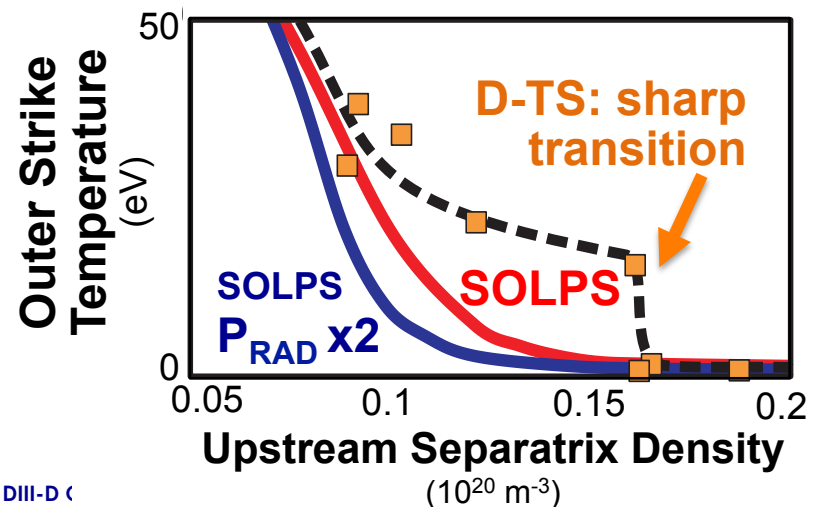
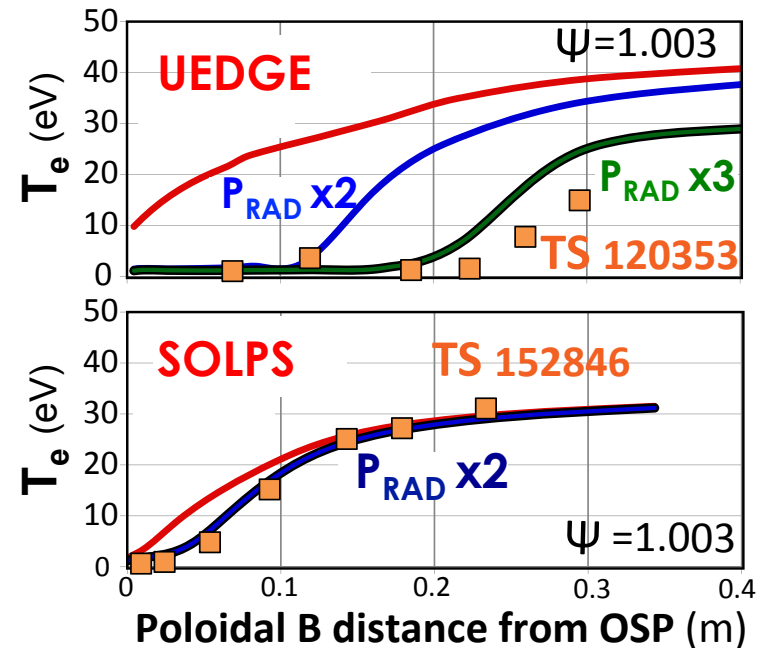
Previous modeling captured attached plasma conditions well

Detachment:

- **Both models** over-predict T_e and under-predict P_{RAD}
- Increasing P_{RAD} to measured levels enables T_e match
 - Over-predicts line radiation

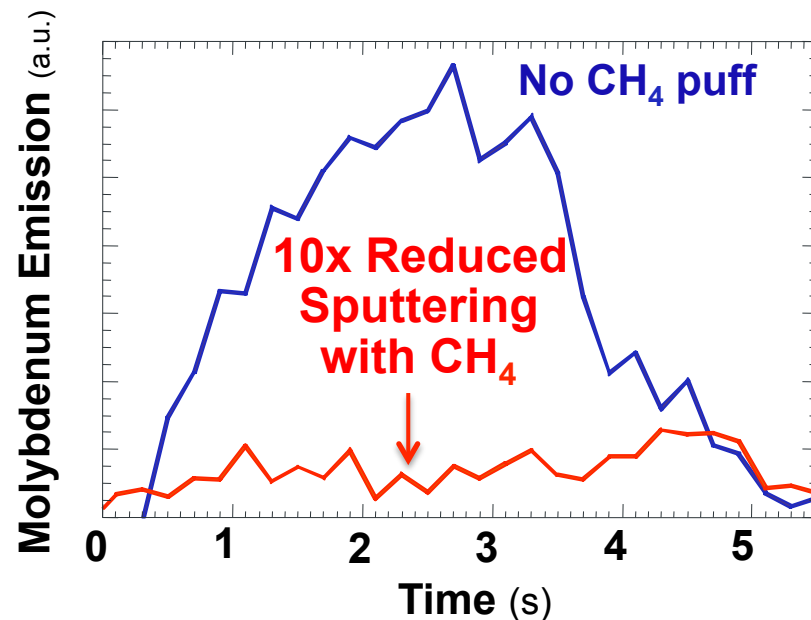
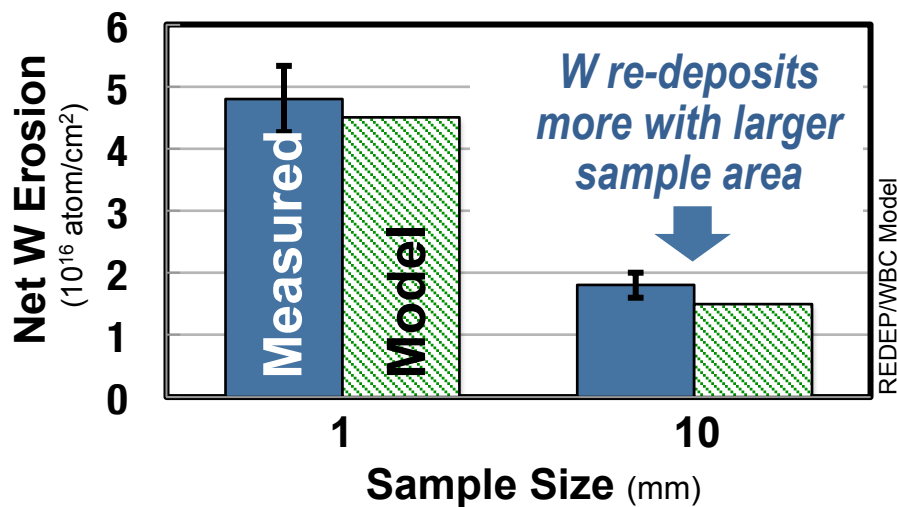
Hard to capture sharp transition to detachment

Better cold, molecular and atomic species models required



High-Z *in-situ* Materials Studies Show Promising Results for Future Devices

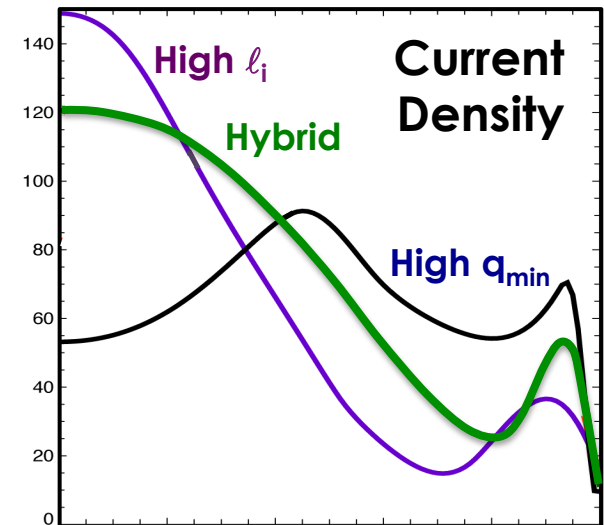
- **Net Tungsten erosion is weak**
 - Gross erosion compensated by re-deposition
- ✓ *Validates model that indicates low net erosion in ITER*
- **Erosion of high-Z sample mitigated by low Z renewable coatings**
 - CH₄ used as proxy for Be, Li, B, other low-Z possibilities
- ✓ *Potential for real time protective coating of key areas*



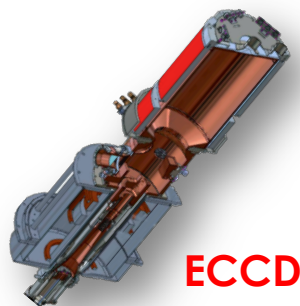
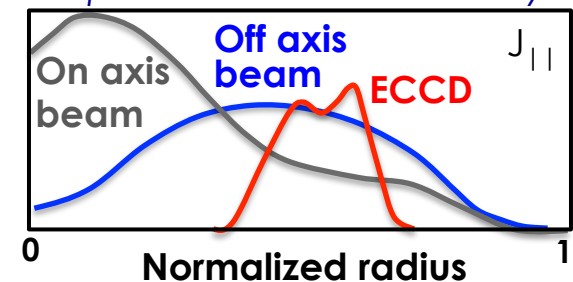
DIII-D Utilizing Flexible Heating and Current Drive Systems to Develop Path to High β Steady State

- Potential solutions from **peaked** to **broad** current profiles
 - From **efficient on-axis current drive** to **high bootstrap current**

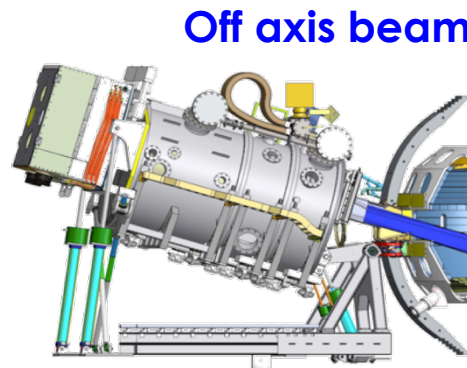
Regime	Strength	Challenge
High I_i	$\beta_N=5$ without RWM	Sustainment; Tearing
Hybrid	High confinement	Current evolution
High q_{min}	$\beta_N=5$ potential; Low disruptivity	Fast ion transport



Required tools for stationarity:



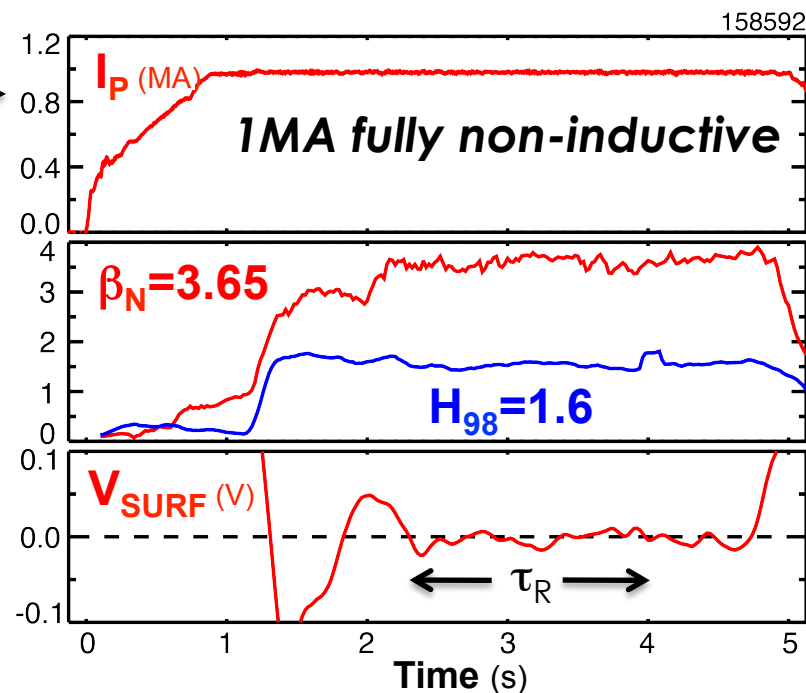
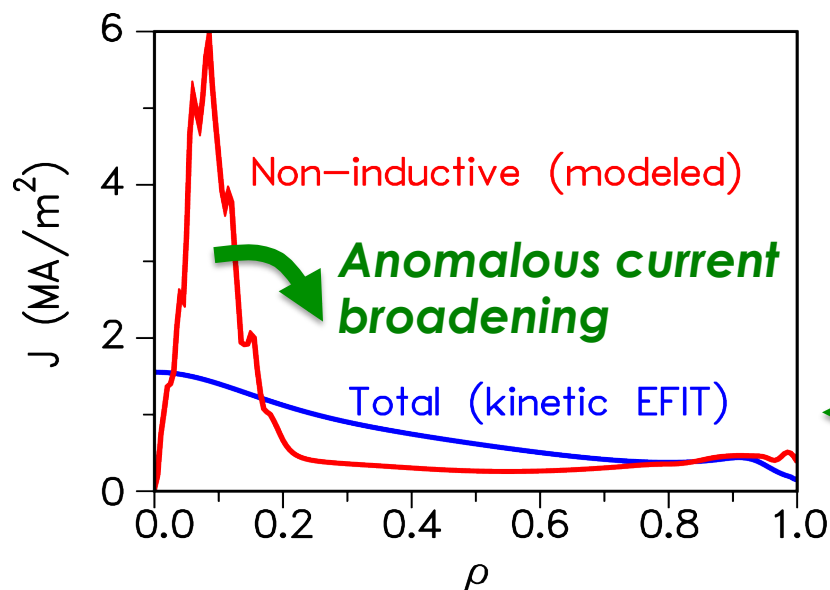
ECCD



Off axis beam

Steady-State “Hybrid” Scenario Established with 1 Mega-Amp Fully Non-inductive Current

- Stationary $\beta_N=3.65$ sustained using NB & EC current drive
 - High confinement $H_{98}=1.6$
 - 50% bootstrap, 40% Greenwald



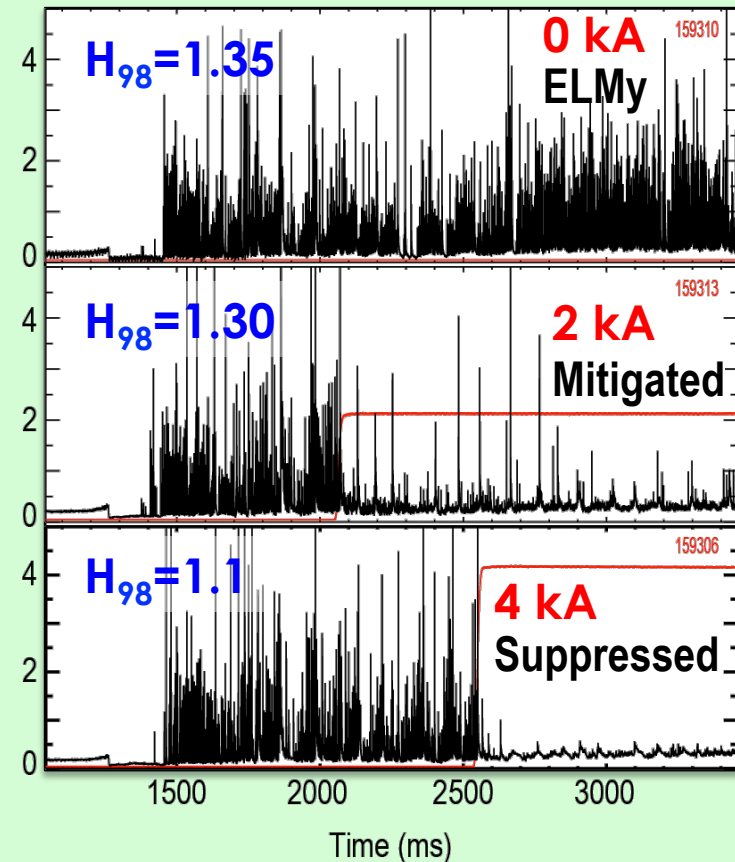
- Can overdrive current on axis
 - Anomalous broadening maintains $q_{min} \sim 1.1$

Good ITER and FNSF candidate regime with efficient on-axis CD

Steady-State “Hybrid” Scenario Established at High β_N with 1 Mega-Amp Fully Non-inductive Current

Breaking news

- **$n=3$ RMP ELM suppression established in SS hybrid**
 - But reduced confinement in full suppression case
- Trade-off to be optimized between 2 and 4 kA

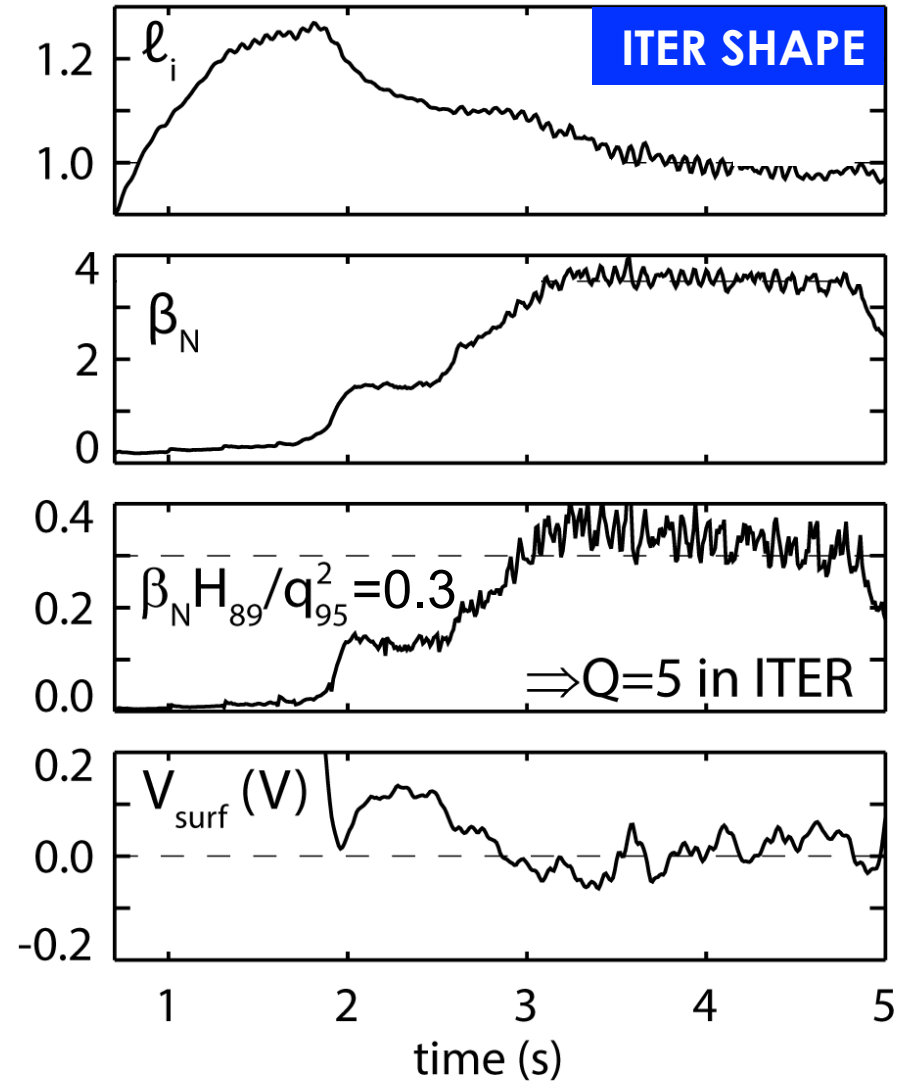


**Good ITER and FNSF candidate regime
with efficient on-axis CD**

High I_i Plasmas Demonstrate Excellent Performance

- More peaked current raises performance further
 - H&CD tools 'freeze in' stable profiles
- ITER $Q_{\text{equiv}}=5$ performance → demonstrated in SN plasmas

✓ Promising for ITER steady state with day 1 H&CD systems



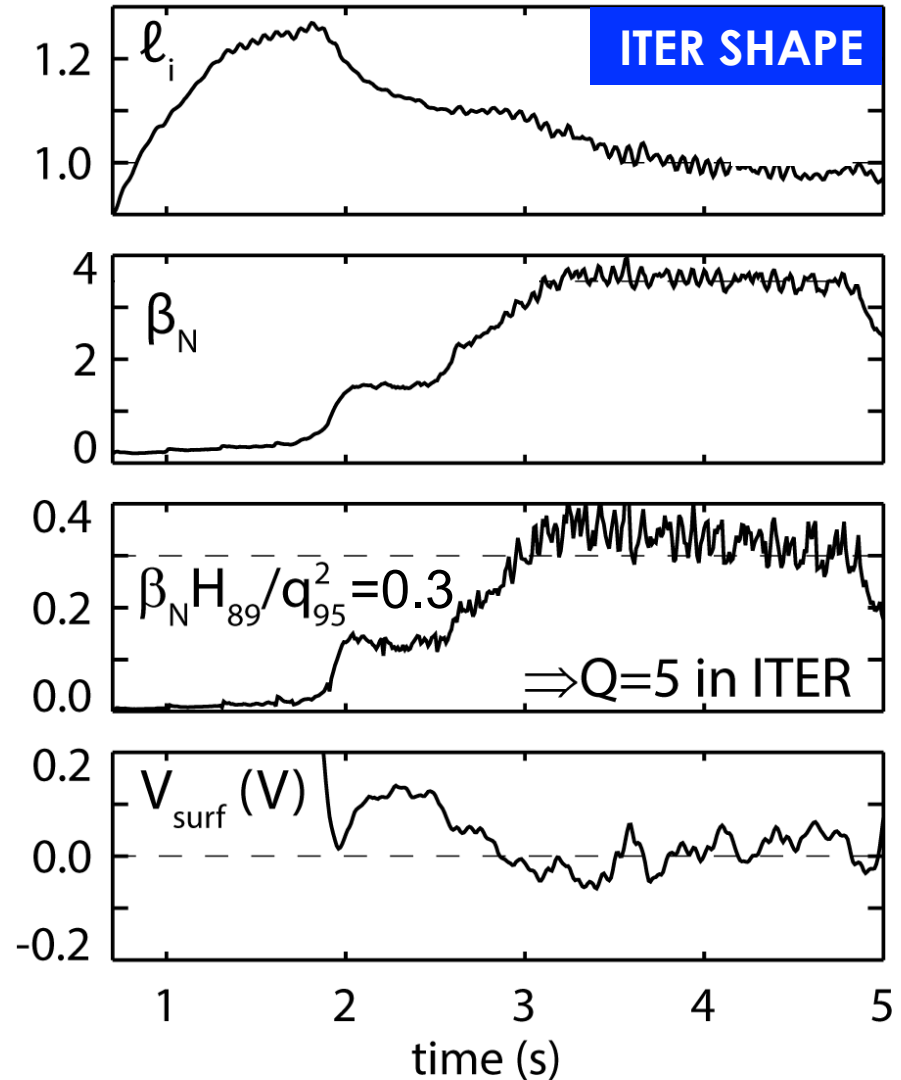
High I_i Plasmas Demonstrate Excellent Performance

- More peaked current raises performance further
 - H&CD tools 'freeze in' stable profiles
- ITER $Q_{\text{equiv}}=5$ performance → demonstrated in SN plasmas

✓ Promising for ITER steady state with day 1 H&CD systems

- Extended to $\beta_N=5.3$ in double null configuration
 - $H_{98}=1.8$ and 80% bootstrap

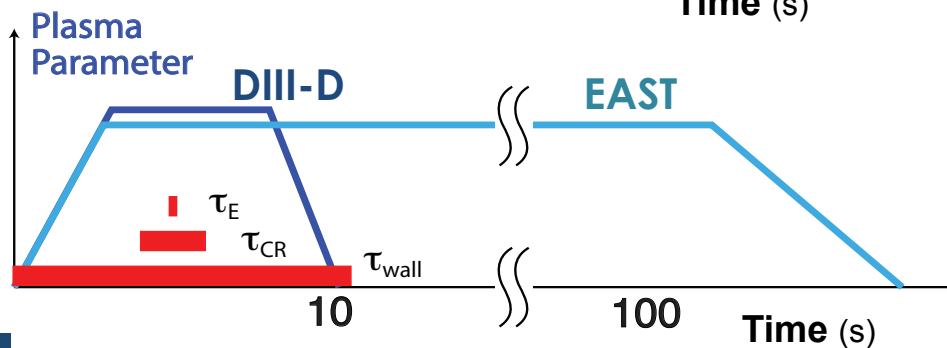
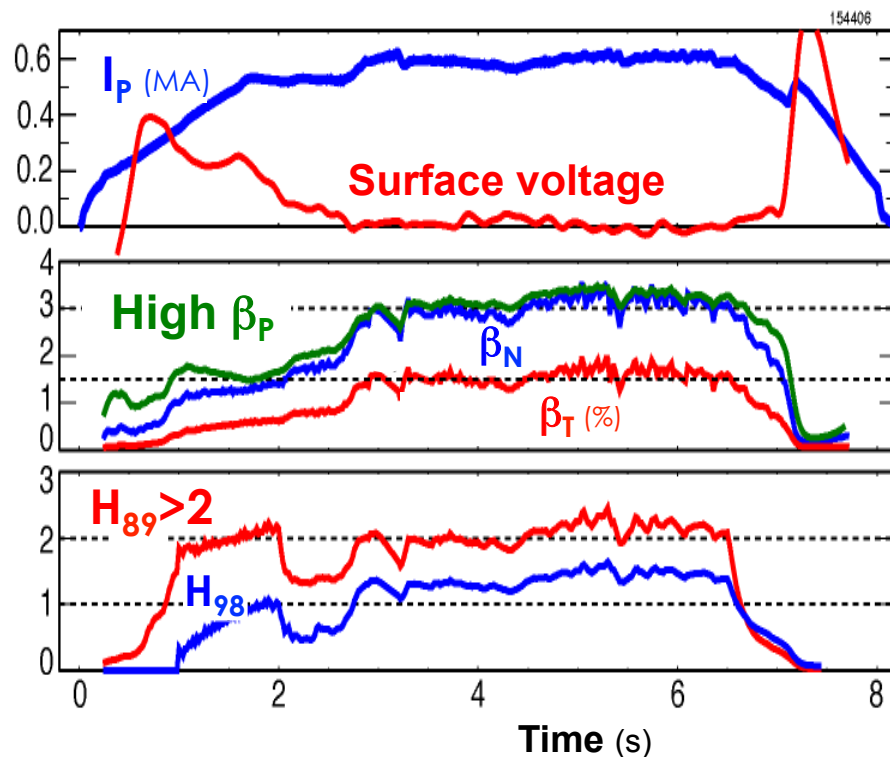
Future fusion reactor option



High q_{\min} Path: High Bootstrap Fully Non-inductive Scenario Developed for Long Pulse Operation

- Reduced torque and current ramp rate to match EAST
 - 80% bootstrap sustained for two current redistribution times
- $\rho=0.7$ transport barrier gives good fast ion confinement

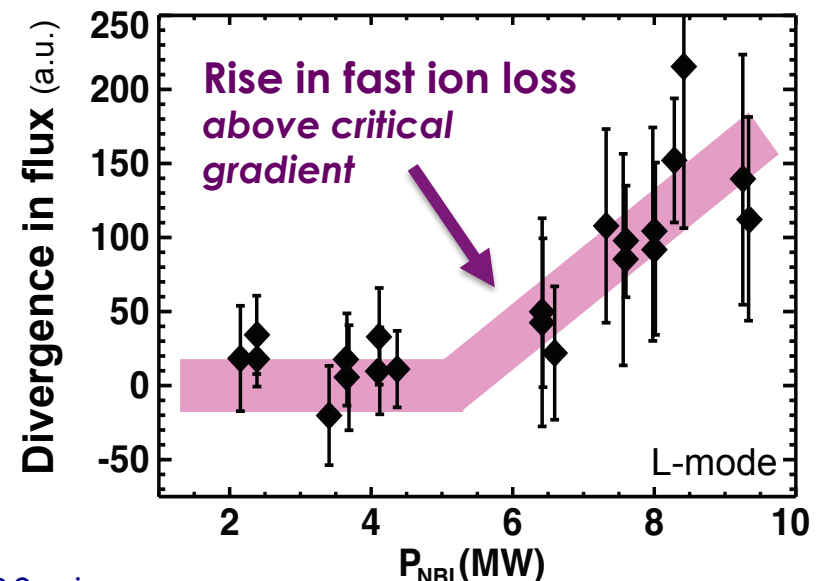
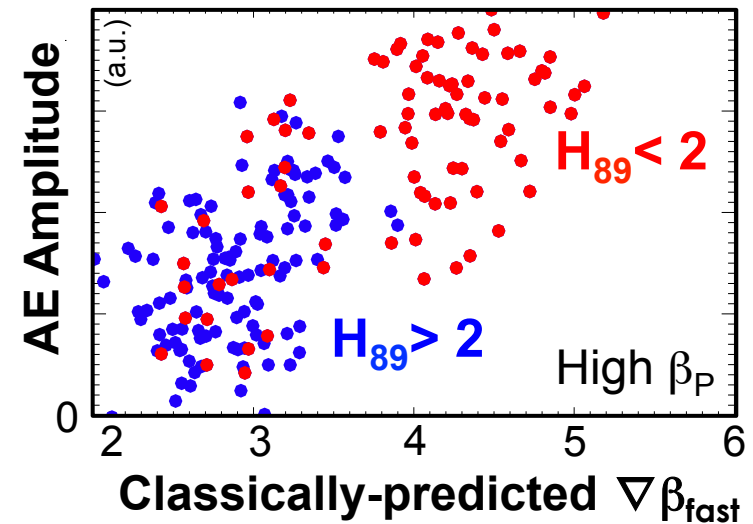
Fully non-inductive target for EAST



Higher Performance in High q_{\min} Encounters Enhanced Fast Ion Transport due to Alfvén Eigenmodes

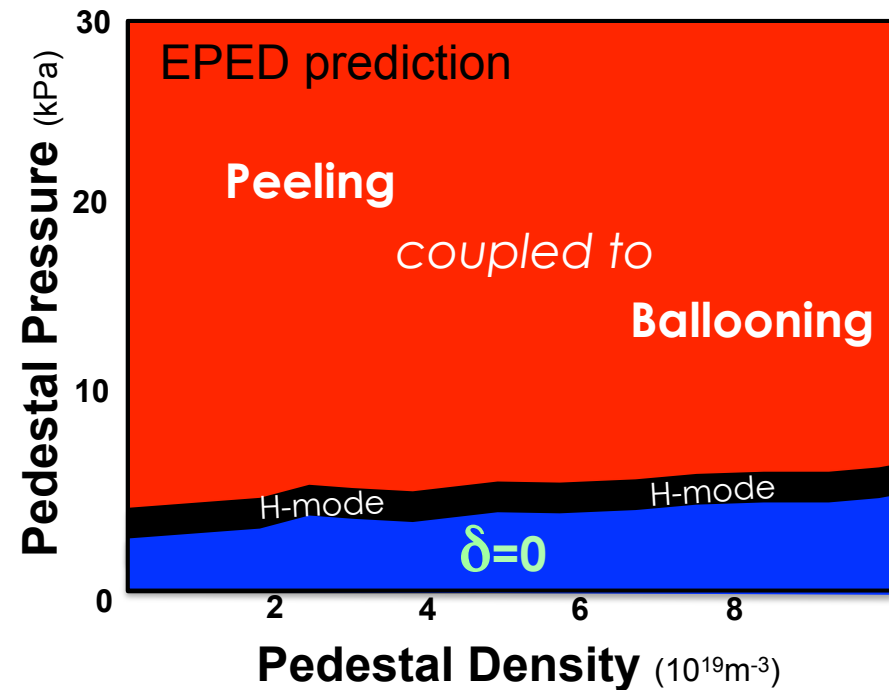
- Confinement decrease at high q_{\min} with rising Alfvén activity
- Rises in fast ion loss consistent with critical gradient model
 - Hypothesis: due to overlapping wave-particle resonances

→ Reduce central $\nabla\beta_{\text{fast}}$ through increased off-axis NBI & ECH



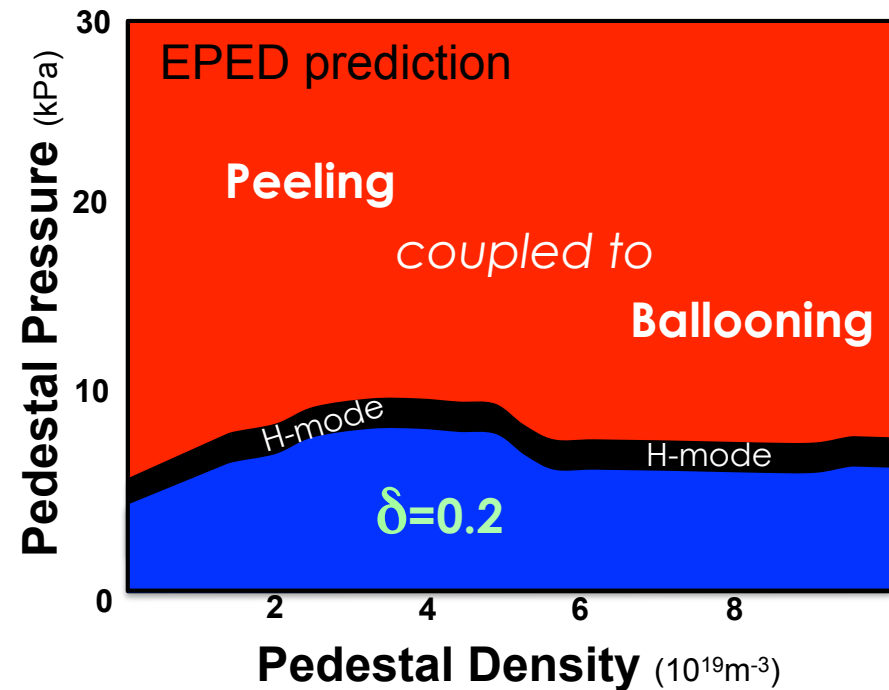
EPED Physics Model Predicts Path to “Super H-Mode” with Doubled Pedestal Pressure

- Strong shaping decouples peeling from ballooning mode
 - Opens valley in pedestal stability



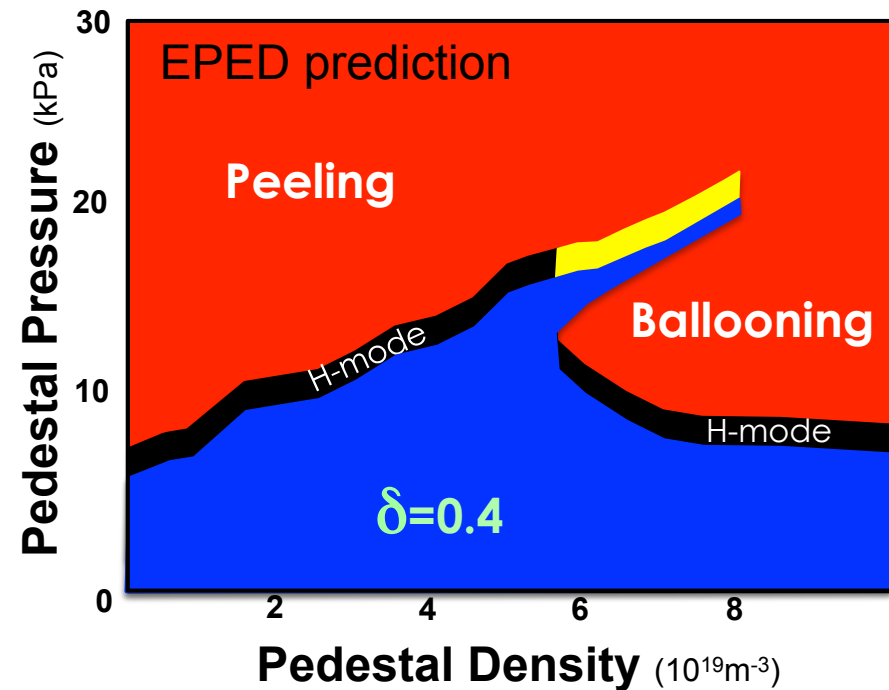
EPED Physics Model Predicts Path to “Super H-Mode” with Doubled Pedestal Pressure

- Strong shaping decouples peeling from ballooning mode
 - Opens valley in pedestal stability



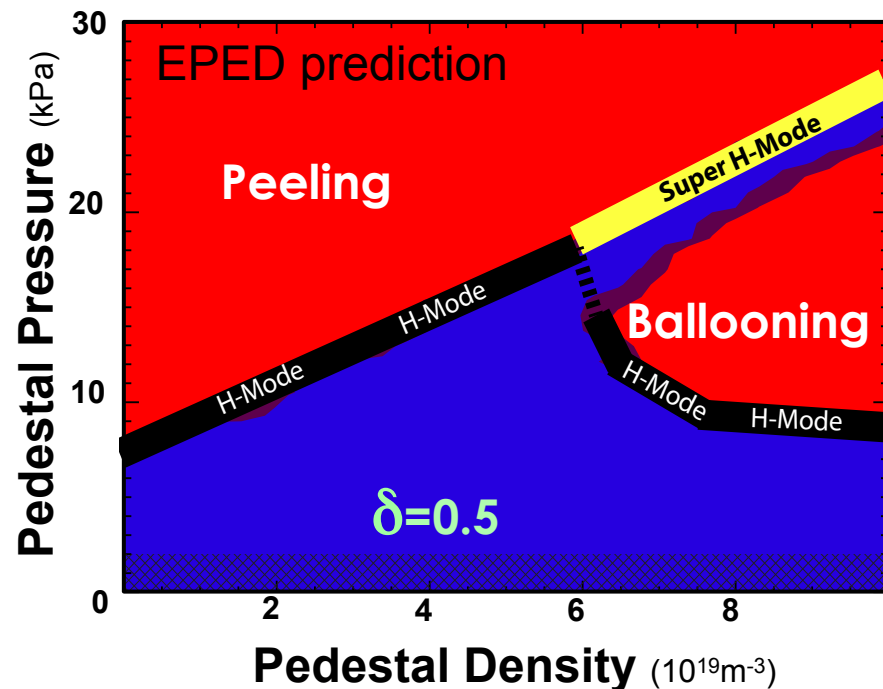
EPED Physics Model Predicts Path to “Super H-Mode” with Doubled Pedestal Pressure

- Strong shaping decouples peeling from ballooning mode
 - Opens valley in pedestal stability



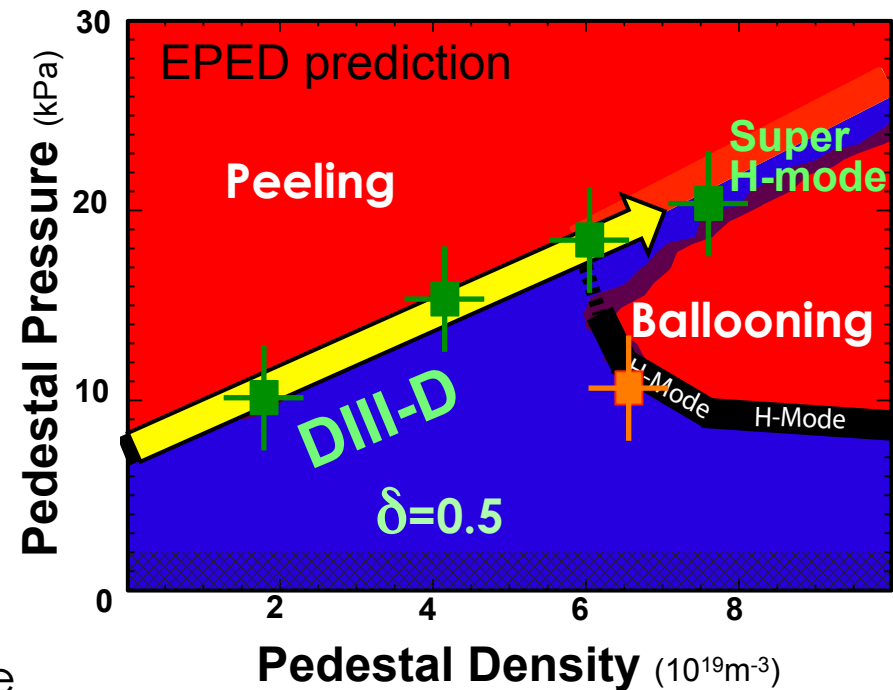
EPED Physics Model Predicts Path to “Super H-Mode” with Doubled Pedestal Pressure

- Strong shaping decouples peeling from ballooning mode
 - Opens valley in pedestal stability



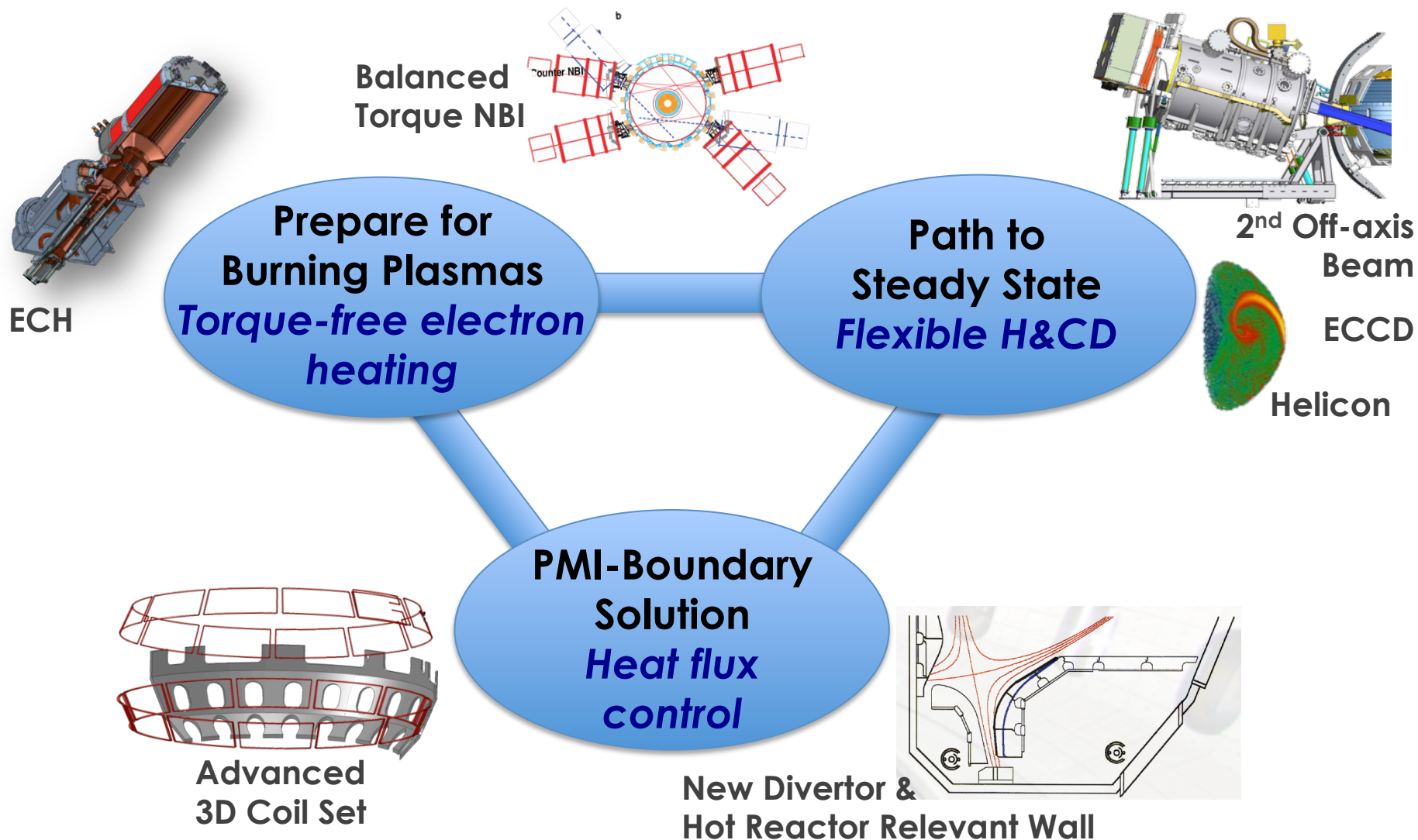
EPED Physics Model Predicts Path to “Super H-Mode” with Doubled Pedestal Pressure

- Strong shaping decouples peeling from ballooning mode
 - Opens valley in pedestal stability
- Super H-Mode discovered
 - EHO provided benign saturation mechanism to navigate valley
 - Record $\beta_N=3.1$ with quiescent edge



EPED predicts Super H-mode possible in ITER

DIII-D Future Exploitation Focuses on Three Key Challenges for Fusion Energy

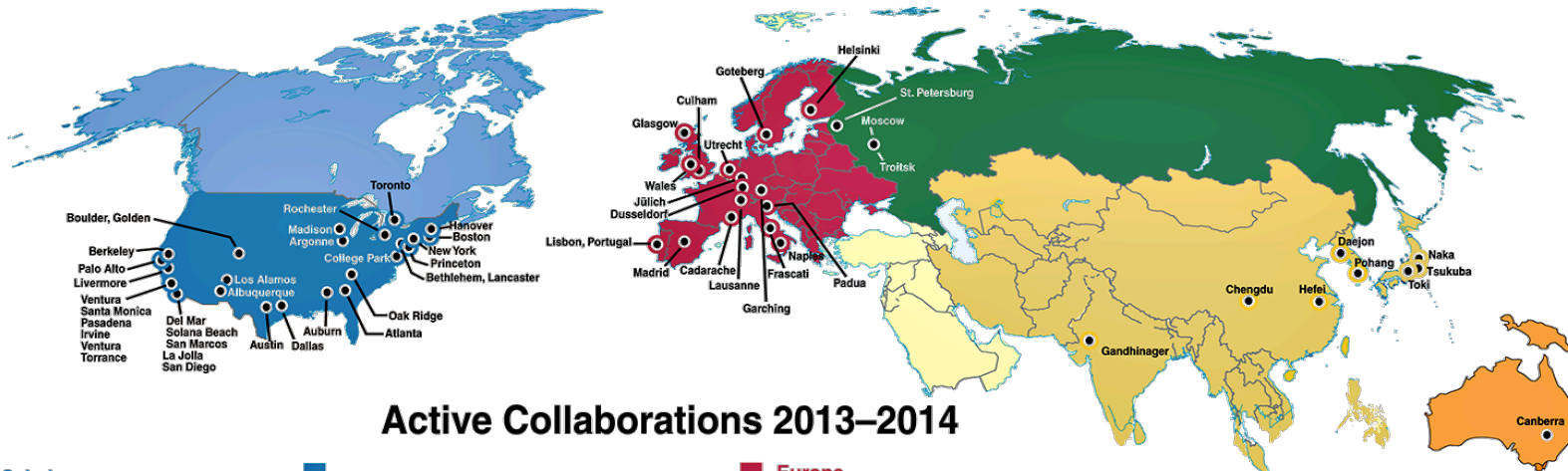


DIII-D is Addressing Key Challenges for ITER and Fusion Energy

- **Improved physics basis for critical ITER needs**
 - ELM control, disruption mitigation, validated test blanket and non-nuclear plans
- **Enhanced predictive understanding of performance defining physics and control for burning plasmas**
 - Turbulence, rotation, energetic particles, 3D response and viable operating scenarios
- **Characterized high performance core and edge solutions for steady state operation**
 - Divertor detachment and high β core

Increased confidence in high performance in ITER and informs decisions on future fusion devices

DIII-D Collaborators Around the World



Active Collaborations 2013–2014

U.S. Labs

LBLN (Berkeley, CA)
LLNL (Livermore, CA)
NASA Ames (Mtn View, CA)
NREL (Golden, CO)
ORNL (Oak Ridge, TN)
PPPL (Princeton, NJ)
SNL (Sandia, CA, NM)

U.S. Industries

ALITRON (Solana Beach, CA)
Calabazas Creek (San Mateo, CA)
CompX (Del Mar, CA)
CPI (Palo Alto, CA)
FAR-TECH, Inc. (San Diego)
General Atomics (San Diego)
Lightcraft Technologies
 (Bennington, VT)
Lodestar (Boulder, CO)
National Instruments
 (Austin, TX)
Tech-X (Boulder, CO)

North American Universities

Auburn U. (Auburn, AL)
Columbia U. (New York, NY)
College of William & Mary (Williamsburg, VA)
Courant Institute (NY)
Georgia Tech (Atlanta, GA)
Lehigh (Bethlehem, PA)
MIT (Cambridge, MA)
ORAU (Oak Ridge, TN)
ORISE (Oak Ridge, TN)
Palomar College (San Marcos, CA)
Purdue U. (W. Lafayette, IN)
U. Arizona (Tucson, AZ)
UCB (Berkeley, CA)
UC Davis (Davis, CA)
UCI (Irvine, CA)
UCLA (Los Angeles, CA)
UCSD (San Diego, CA)
CIPS, U. Colorado (Boulder)
U. Maryland (College Park, MD)
U. Rochester (NY)
U. Texas (Austin, TX)
U. Toronto (Toronto, Canada)
U. Tulsa (Tulsa, OK)
U. Wisconsin (Madison, WI)
West Virginia U. (Morgantown, WV)
Yeshiva U. (New York, NY)

Europe

CCFE (Culham, United Kingdom)
CEA (Cadarache, France)
CFN-IST (Lisbon, Portugal)
CIEMAT (Madrid, Spain)
CRPP-EPFL (Lausanne, Switzerland)
D-TacQ Solutions (Scotland)
DIFFER (Nieuwegein, Netherlands)
ENEA (Frascati, Italy)
ENEA Consorzio RFX (Padua, Italy)
ENEA Consorzio CREATE (Naples, Italy)
EURATOM-FOM (Utrecht, Netherlands)
EURATOM-Tekes, Aalto U. (Helsinki, Finland)
Fusion for Energy (Barcelona, Spain)
FZ-Julich (Germany)
HH U. of Dusseldorf (Germany)
IFP-CNDR (Italy)
IPP, AS CR, EURATOM/IPP, Prague
ITER (Cadarache, France)
JET EFDA (Culham, United Kingdom)
Max Planck-IPP (Garching, Greifswald)
U. of Helsinki (Finland)
U. Padova (Padua, Italy)
U. Strathclyde (Glasgow, Scotland)
U. of York (York, United Kingdom)
VTT (Finland)

Russia

D.V. Efremov Institute
 (St. Petersburg, Russia)
RCC Kurchatov Institute (Moscow)

Asia

ASIPP (Hefei, China)
IPR (Gandhinagar, India)
JAEA (Naka, Japan)
KAIST (Daejeon, S. Korea)
Kyoto University (Japan)
KBSI-NFRI (Daejeon, S. Korea)
NIFS (Toki, Gifu-ken, Japan)
Pohang U. (S. Korea)
Seoul Nat. U. (S. Korea)
SWIP (Chengdu, China)
Tohoku University (Sendai, Japan)

Australia

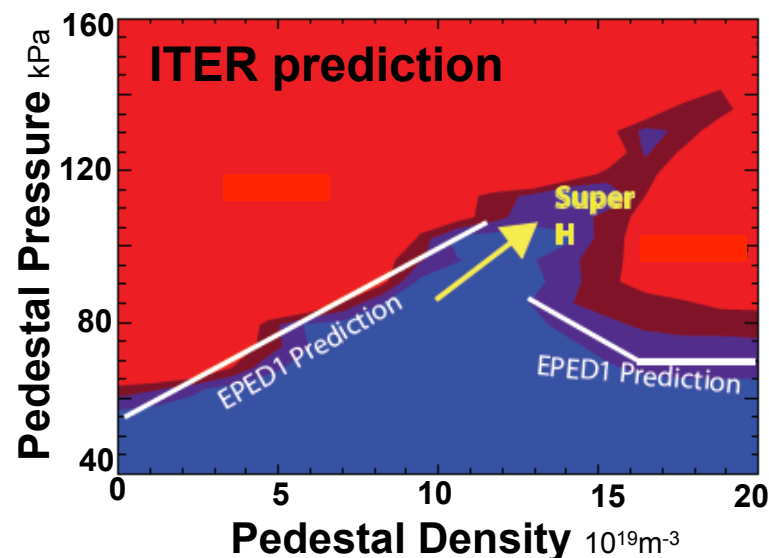
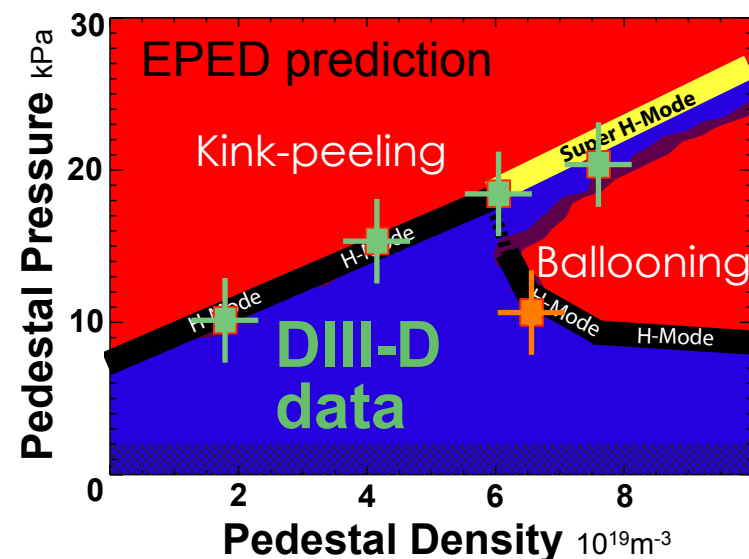
Australia National U. (Canberra)

Reserve Slides

First Principles EPED Physics Model Predicted Path to Access “Super H-Mode” with Doubled Pedestal Pressure

- Strong shaping decouples kink-peeling from ballooning mode
 - Opens valley in pedestal stability
- Super H-Mode discovered in DIII-D
 - Raise density to navigate valley
 - EHO provides benign saturation of pedestal pressure
 - $H_{98}=1.4$ $\beta_N=3.1$

✓ Validates model predicting ITER → able to access Super-H mode

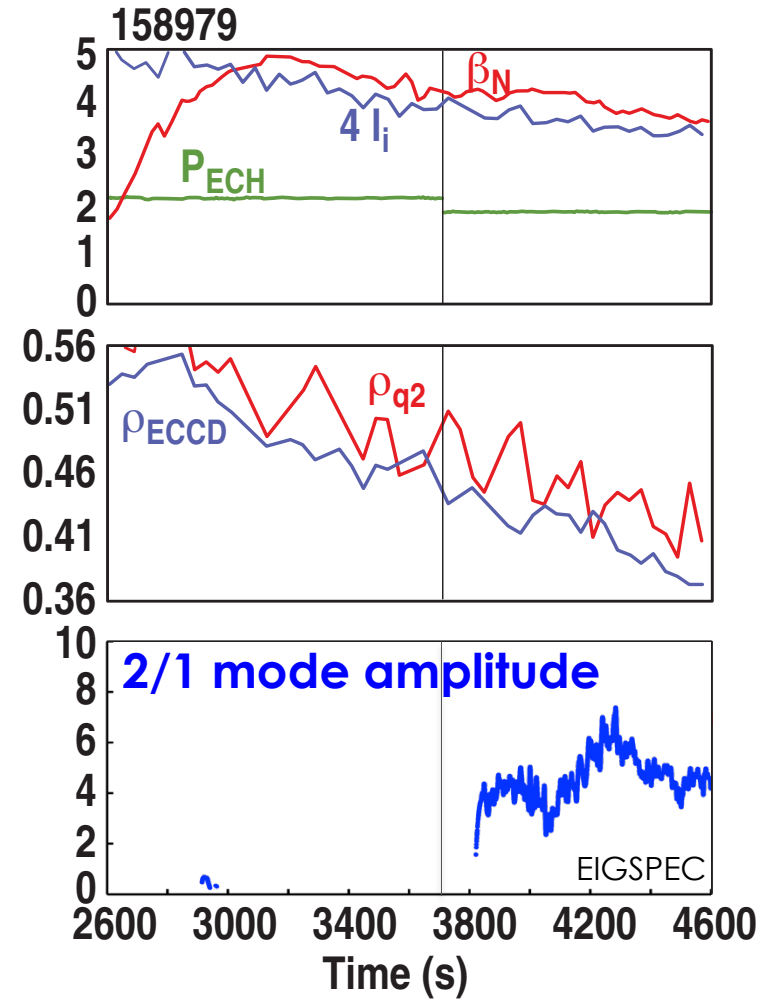


Real Time ECCD NTM Control Enables Access to $\beta_N=5$ Double Null High I_i Scenario

- Pre-emptive ECCD mode tracking prevents appearance of NTM
 - Real time MSE, T-S and deposition calculation
- $H_{98} = 1.8$ and 80% bootstrap
- Also applied in high q_{\min} and ITER baseline scenarios

✓ Real time localized ECCD an effective NTM control tool

✓ High I_i an exciting alternative for a fusion reactor



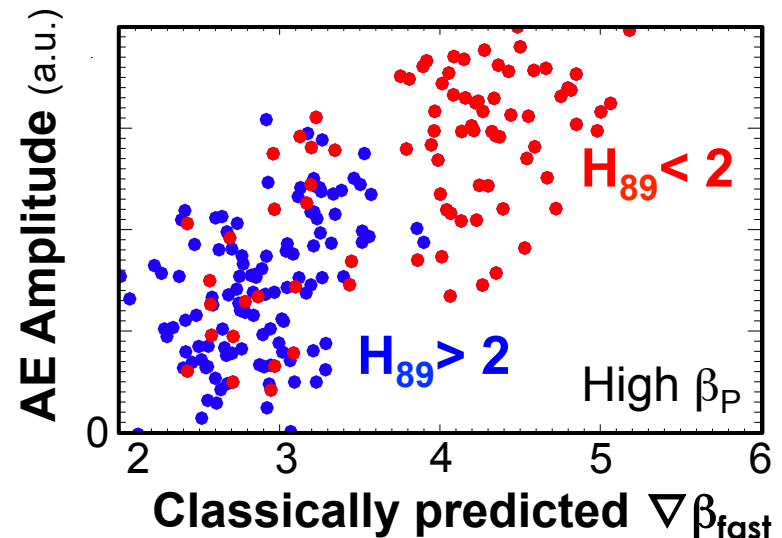
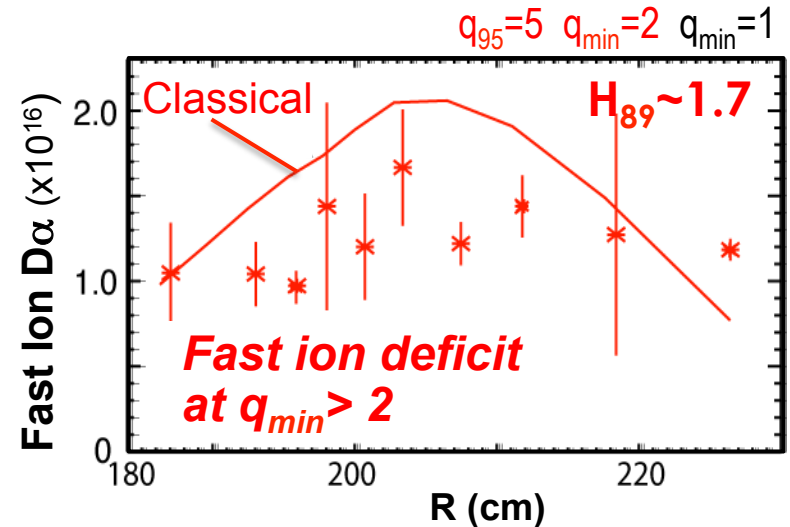
Higher β_T in High q_{min} Encounters Enhanced Fast Ion Transport due to Alfvén Eigenmodes

Experiments at higher β_T and high q_{min} show reduced confinement

- **Observe deficit in fast ions over classical predictions**
 - Correlated with increase in Alfvén activity
- **High β_p plasmas reveal AE amplitude rises with $\nabla\beta_{fast}$**

Path to improved performance:

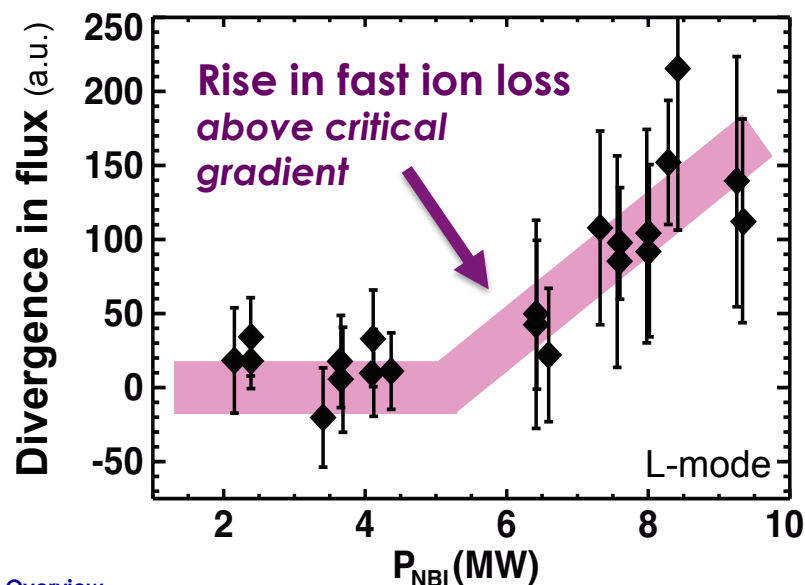
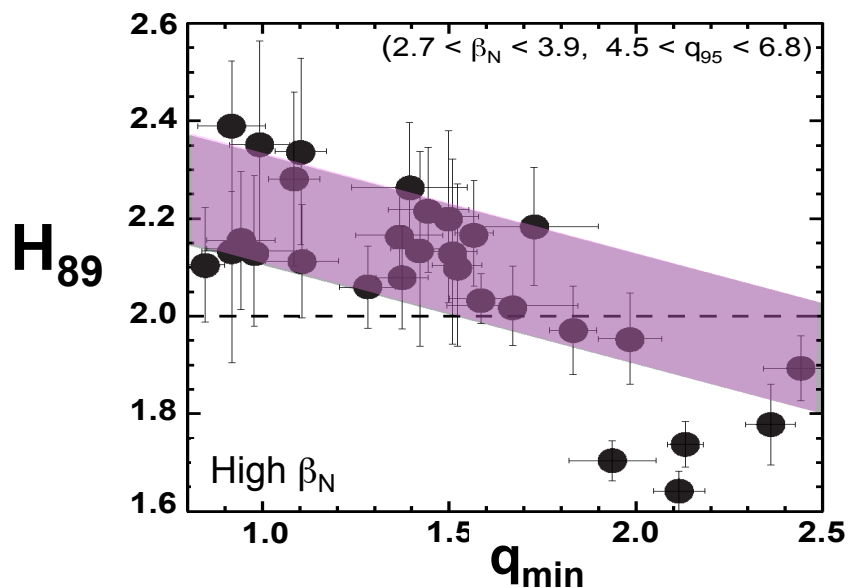
- Off-axis NBI & ECH to reduce central $\nabla\beta_{fast}$ and optimize thermal transport
- Improve pedestal



Higher β_T in High q_{\min} Encounters Enhanced Fast Ion Transport due to Alfvén Eigenmodes

- Confinement decrease at high q_{\min} with rising Alfvén activity
- Rises in fast ion loss consistent with critical gradient model
 - Hypothesis: due to overlapping wave-particle resonances

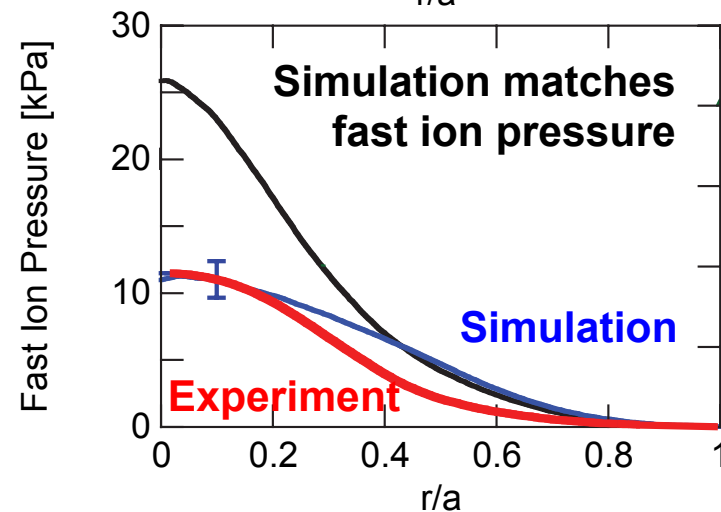
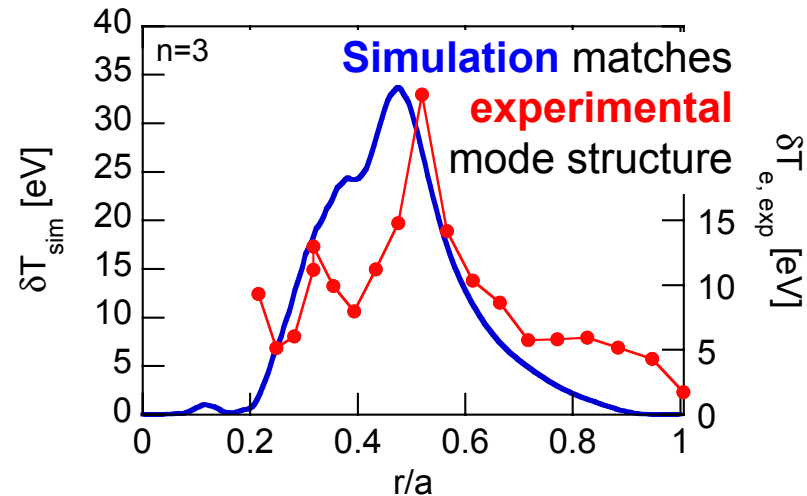
→ Reduce central $\nabla\beta_{fast}$ through increased off-axis NBI & ECH



Recent Data Identifies Critical Gradient Model of Alfven Eigenmode (AE) Induced Fast Ion Transport

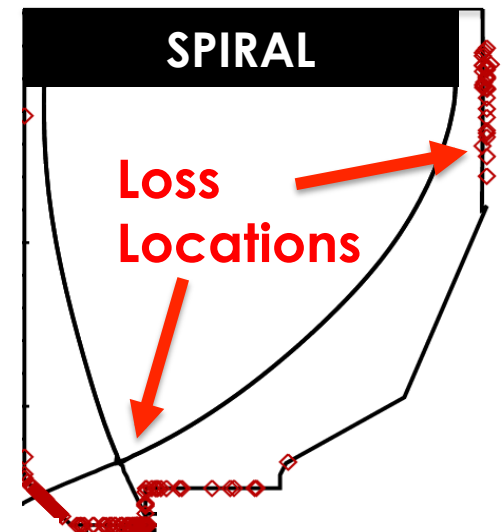
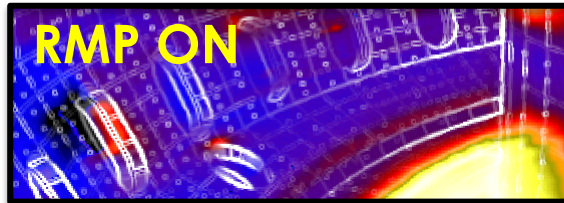
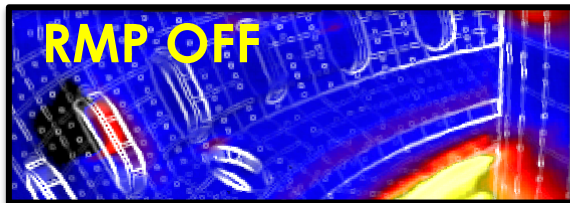
- Power scan reveals saturation in EP density above threshold
 - Due to overlapping wave-particle resonances in AT plasmas
- Divergence of flux rises above a critical gradient
 - Simplifies EP prediction
- Data also validates fully non-linear AE-EP simulations

✓ Basis for fully predictive EP simulation



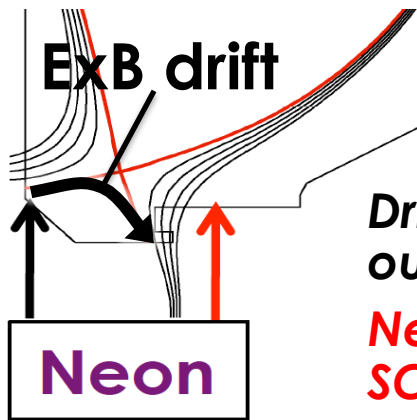
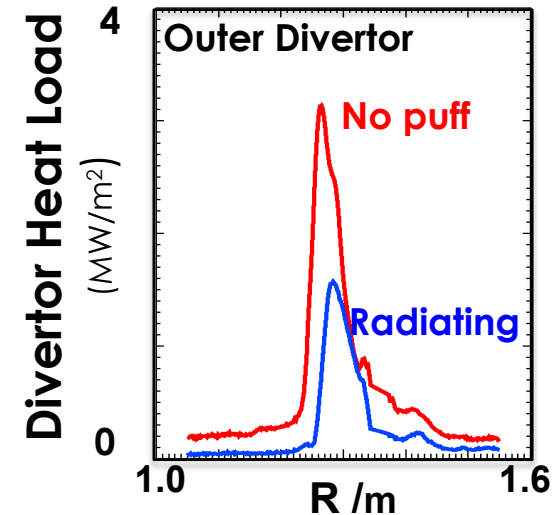
3D Fields for RMP-ELM Suppression Lead to Significant Energetic Particle Losses

- **Notches in $n=3$ field show RMP ejects edge fast ions**
 - ELM suppression maintained
 - Consistent with SPIRAL+M3D-C1 full orbit predictions
- **Leads to increased divertor heat loads in simulation and experiment**

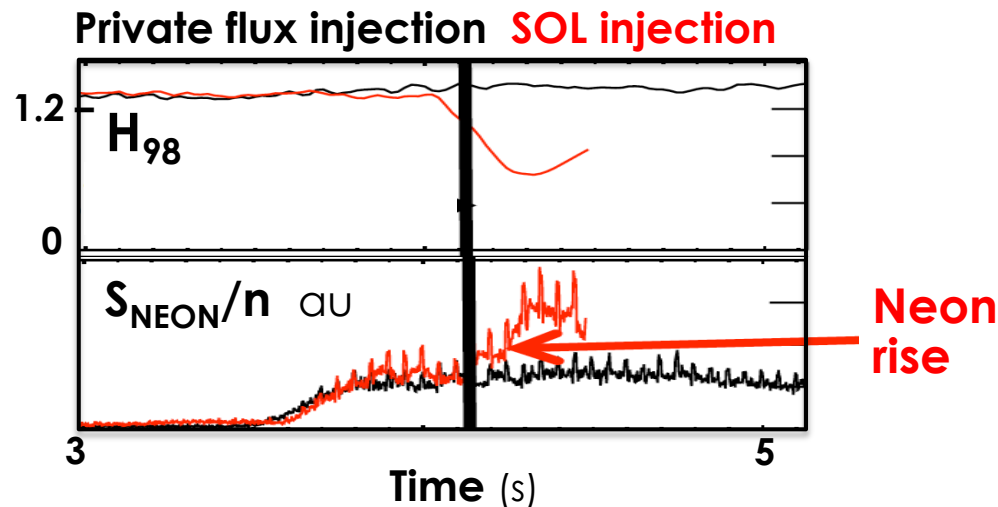


Techniques for Integrated Core-Edge Solutions Developed

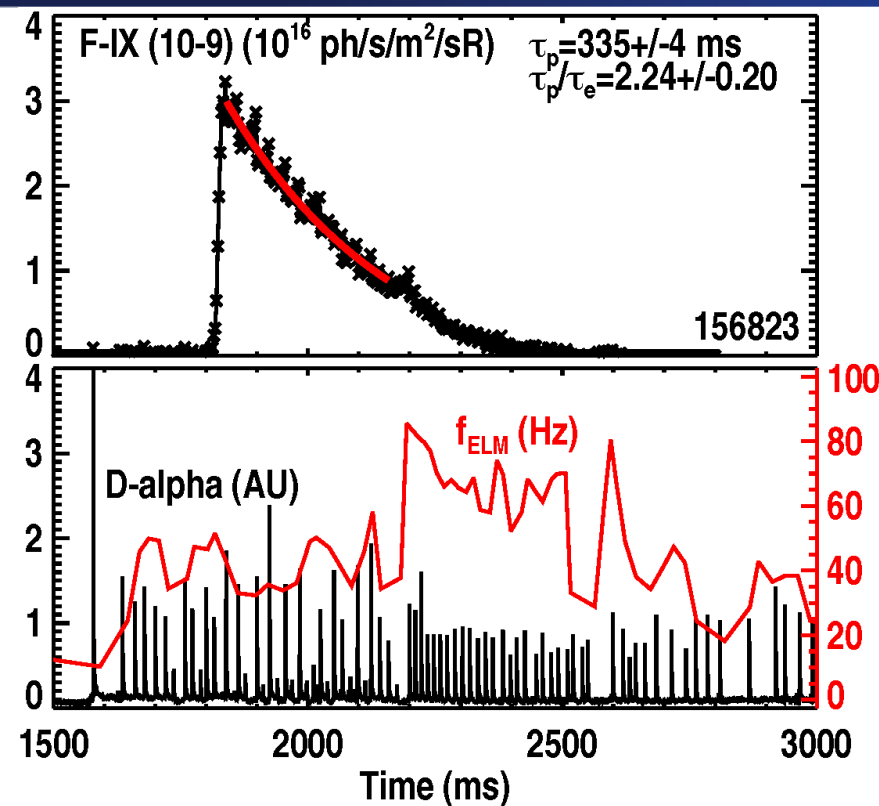
- **Combine radiative divertor with high performance steady state core**
 - Good performance maintained with $\beta_N = 3.0$, $H_{98} = 1.3$ throughout
 - Divertor heat flux reduced by x2
- **ExB drift important in optimizing divertor radiation and core dilution**
 - Neon injection required in private flux region away from ion $B \times \nabla B$



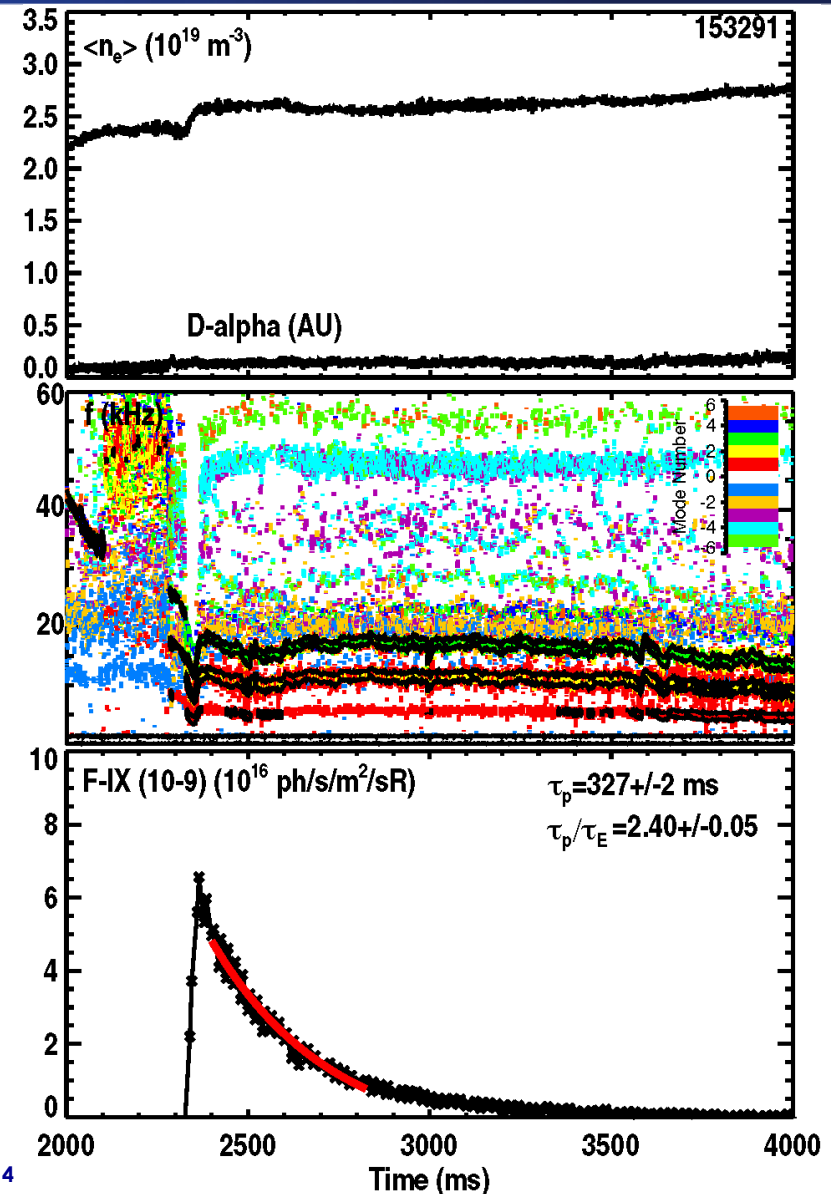
Drifts carry neon to outer strike point
Neon escapes with SOL puffing



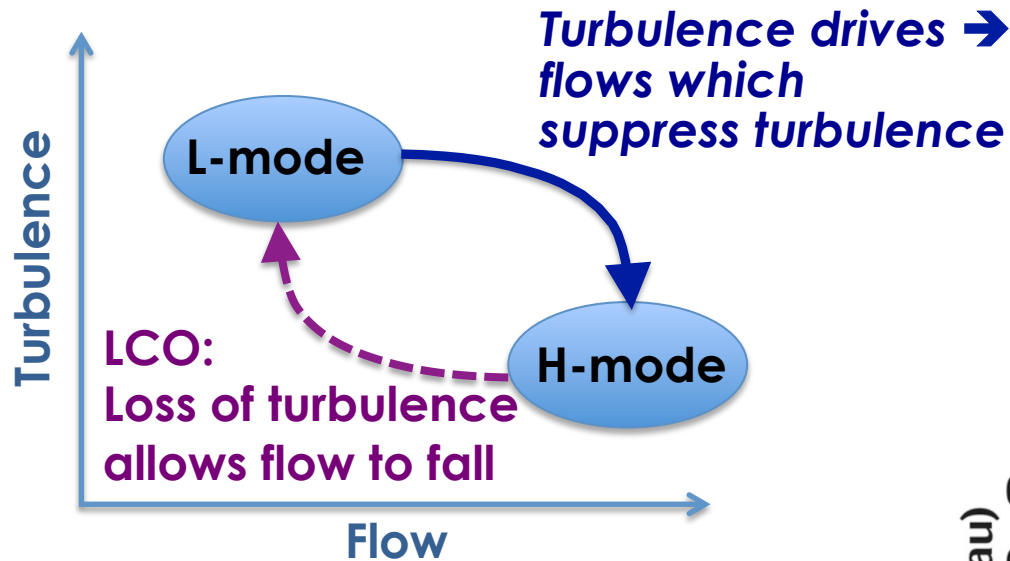
EHO in QH-mode Provides Same Impurity Exhaust as 40Hz ELMs



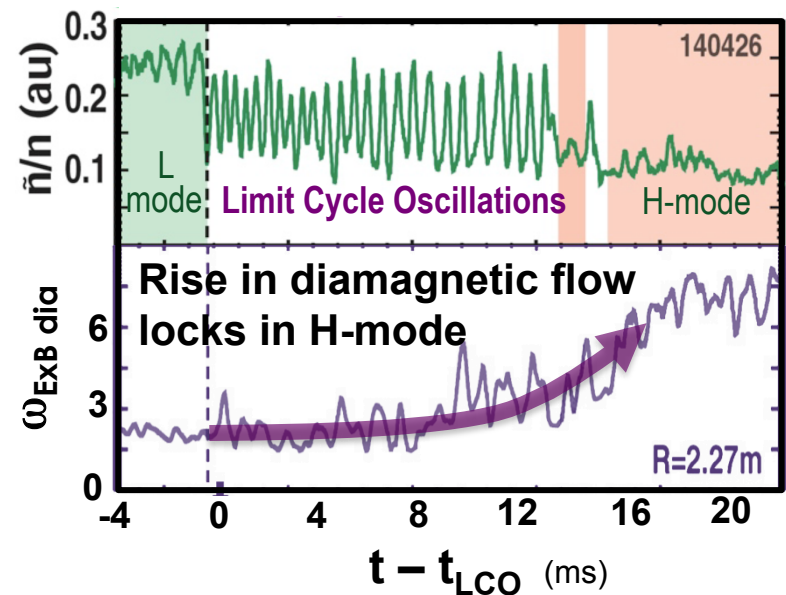
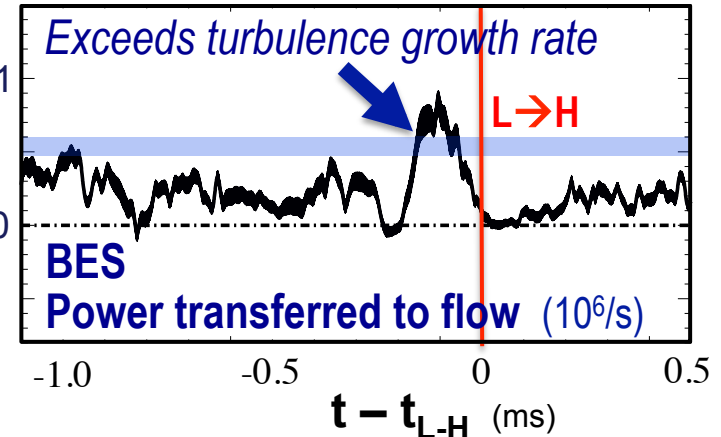
- Measured by CER with non-recycling fluorine injection



H Mode Access: Measurements Confirm Turbulence and Ion Diamagnetic Flows Play Key Role



- Limit cycle discharges show \rightarrow ion diamagnetic flows required to lock in H-mode transition



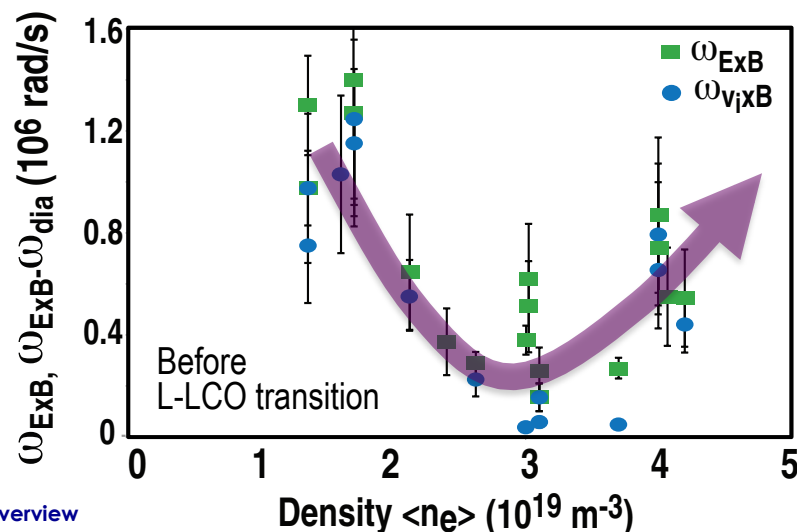
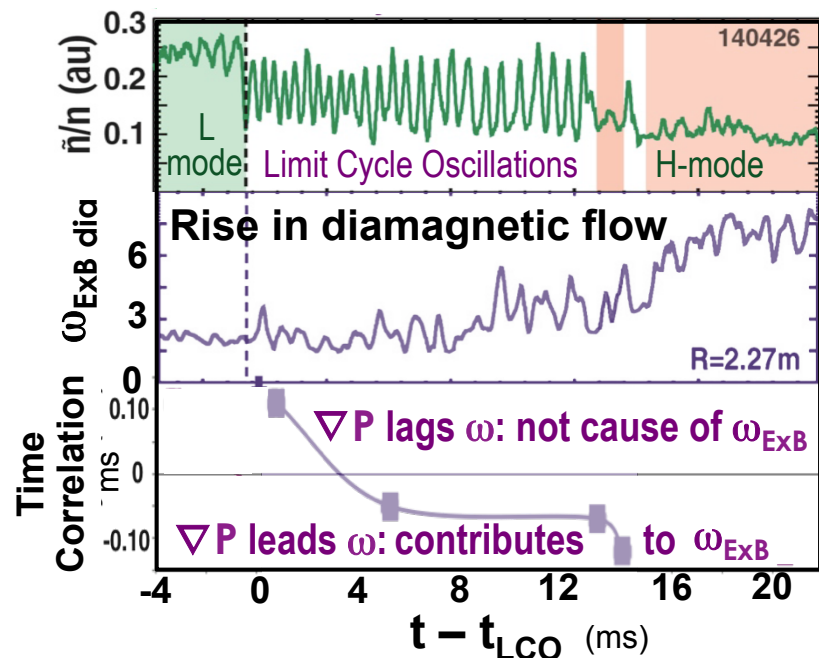
H Mode Access: Measurements Confirm Role of Ion Diamagnetic Flow in L-H Transition

- **Limit Cycle discharge provides laboratory to test L-H physics**

- Turbulence induced flow insufficient to sustain H mode
- H-mode locked in by rise in ion diamagnetic flow
- See ∇P term start to lead drive to ω_{ExB} rotation

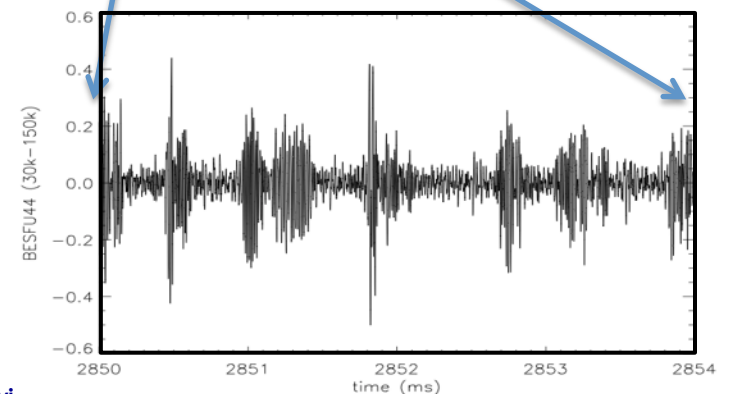
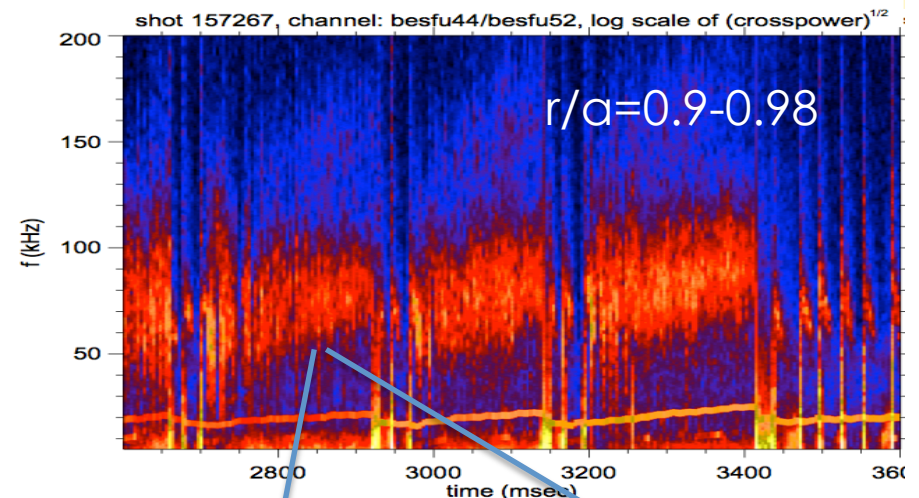
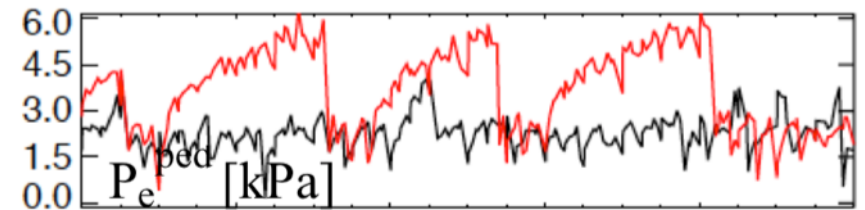
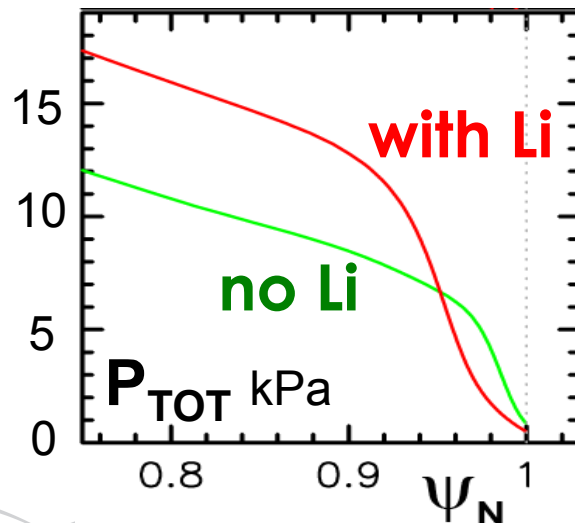
- **Measured L-mode seed flow shear consistent with upturn in L-H threshold**

✓ Promising foundation for physics based L-H prediction



Lithium Injection Causes Bifurcation to Larger Pedestal With Enhanced Edge Fluctuations

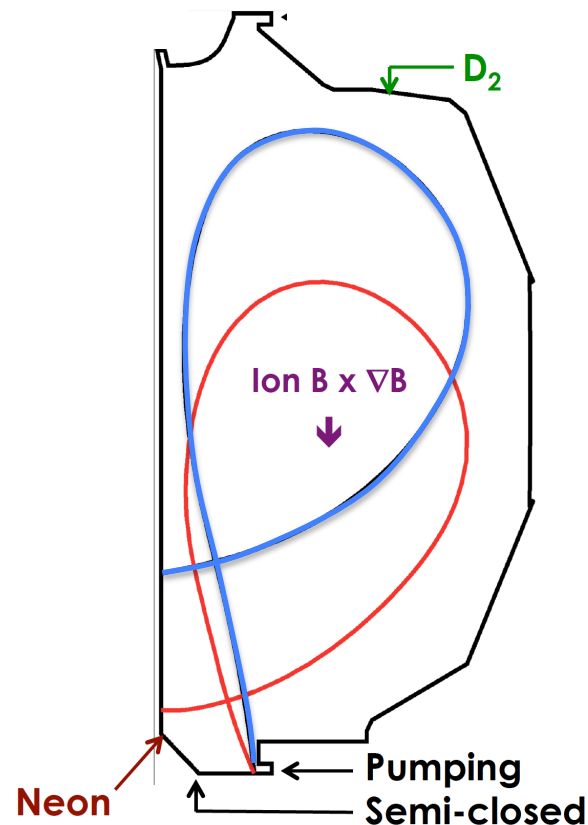
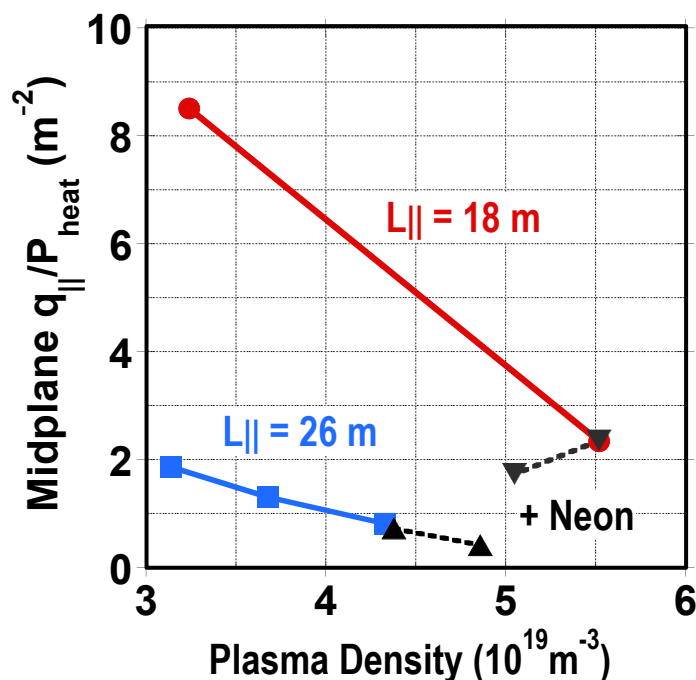
- Lithium leads to sustainment of an edge fluctuation
 - No core C impurity rise
- Doubles pedestal width and height
 - H_{98} increased 60%
 - ELMs delayed



Experiments Confirm Reduced Heat Flux with Increased Connection Length

- **Increased divertor volumetric losses**

- Despite decreased flux expansion
- Consistent with modeling

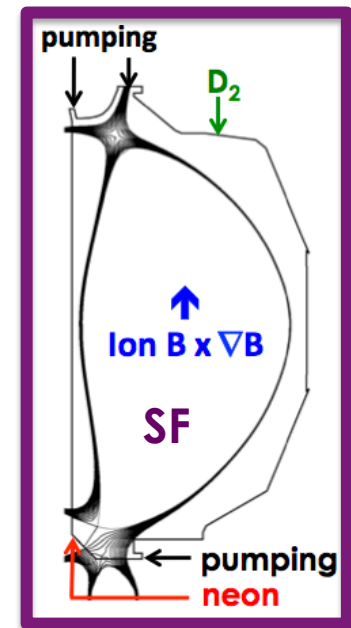
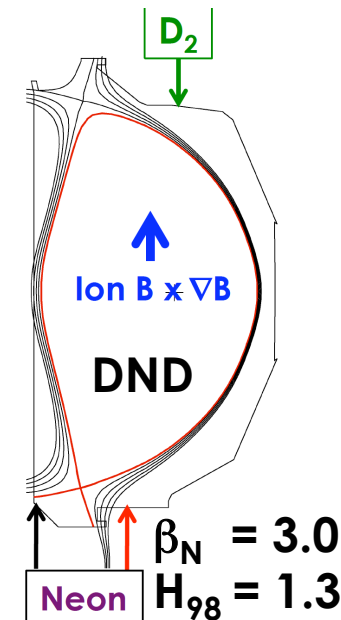
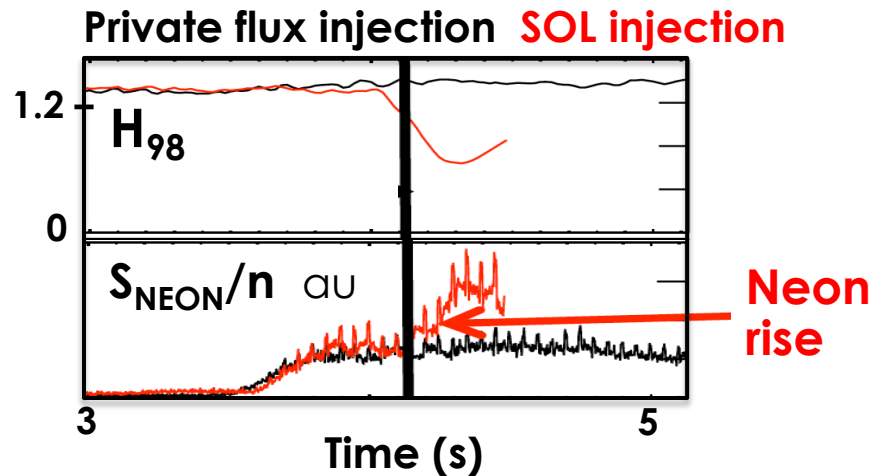


Divertor leg geometry an important aspect of divertor optimization

Techniques for Integrated Core-Edge Solutions Developed

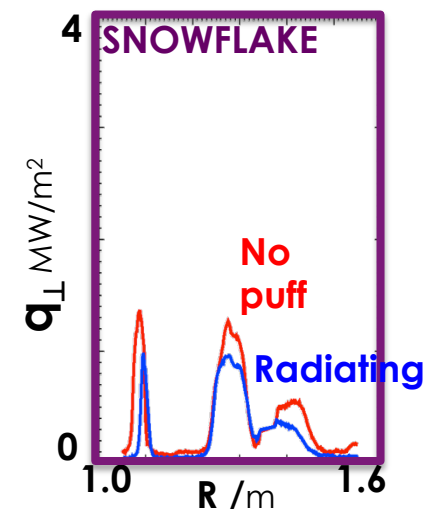
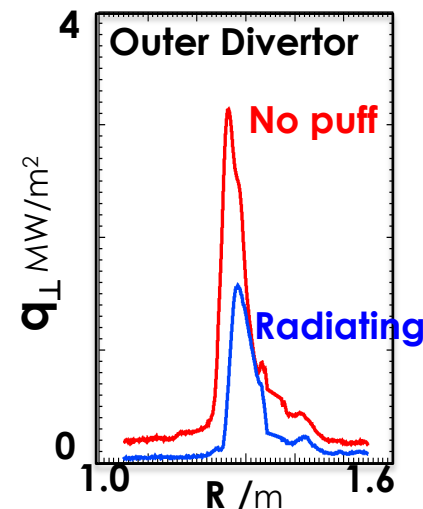
- Injection in private flux region away from ion $B \times \nabla B$ reduces core impurity rise

- Radiative divertor halves heat flux



- Snowflake divertor further reduces heat loads in AT plasmas

- Modest benefit with Ne radiation
 - But 30% increased Ne in core



RMP ELM Suppression in Helium Plasmas Validates ITER Research Plan

- Helium plasmas subject to type I ELMs
- Suppression in Helium in ITER-relevant conditions
 - Relevant torque & rotation
 - Dominant electron heating
 - Close to L-H margin

✓ Commissioning of ELM suppression in Helium on ITER

