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

by

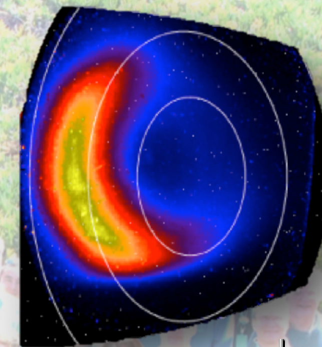
R.J. Buttery

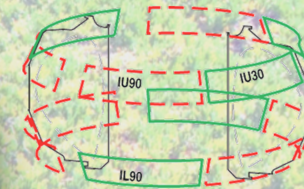
Presented at the

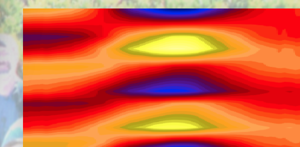
25th IAEA Fusion Energy Conference

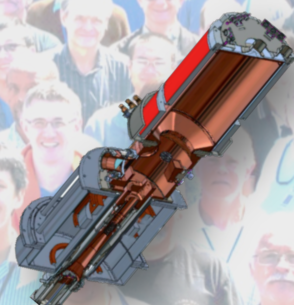
St Petersburg, Russia

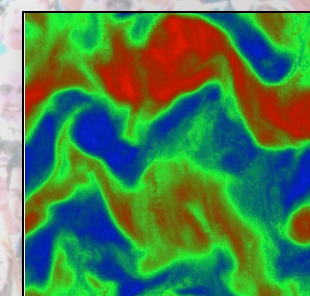
October 2014

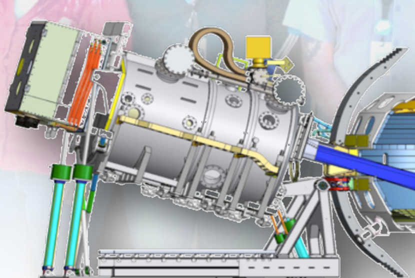


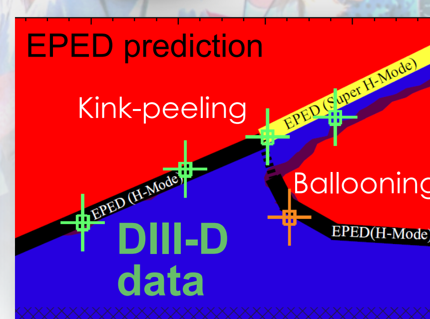


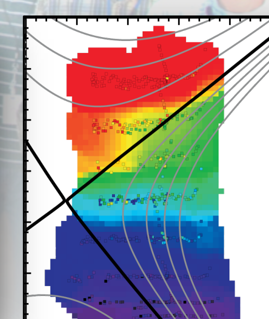












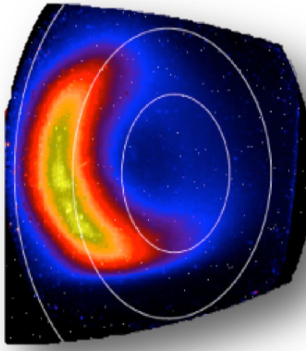
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

GENERAL ATOMICS

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

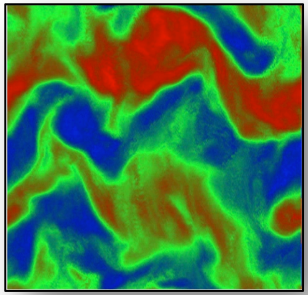
- **Addressing Critical Design and Research Issues for ITER**
- **Achieving High Performance in Future Burning Plasmas**
- **Expanding the Frontier toward Fusion Energy**

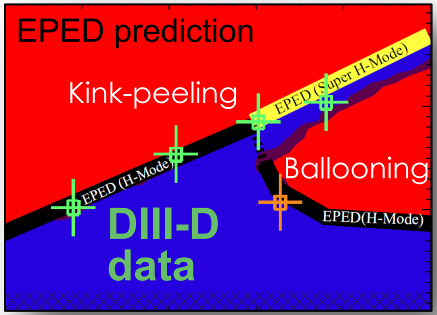
Science → Better Solutions and Confident Projection



Pitch angle runaway dissipation

Turbulent Transport in burn relevant conditions





Super H-Mode

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

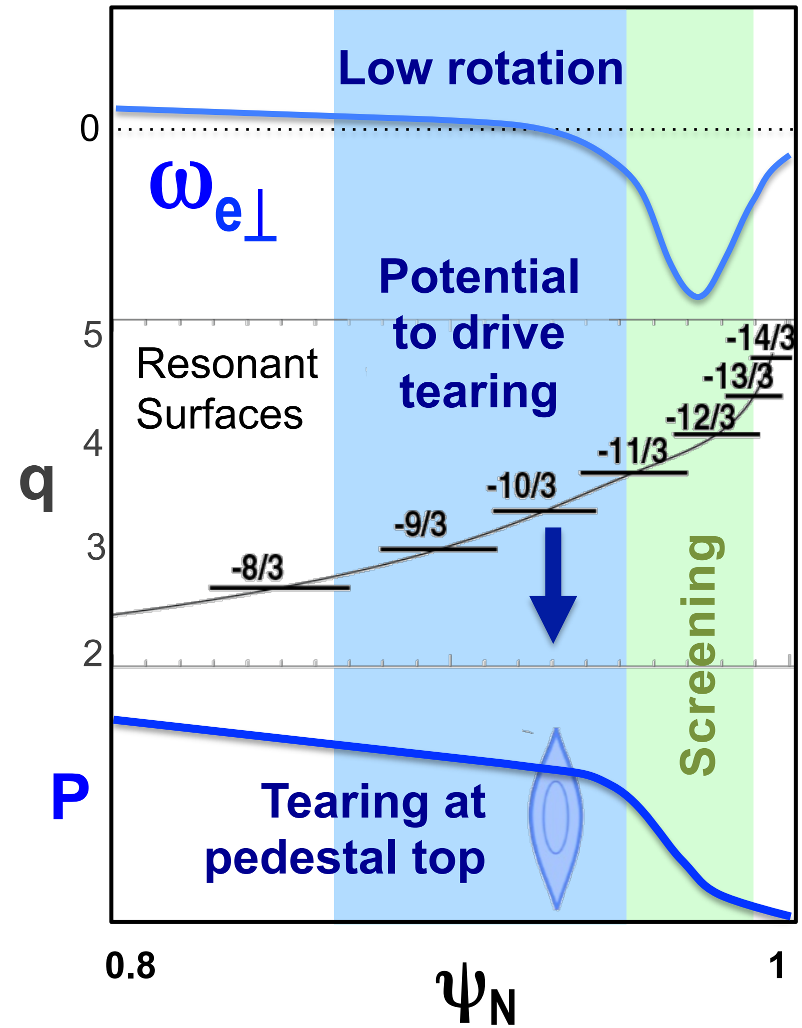
Addressing Critical Design and Research Issues for ITER

– 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

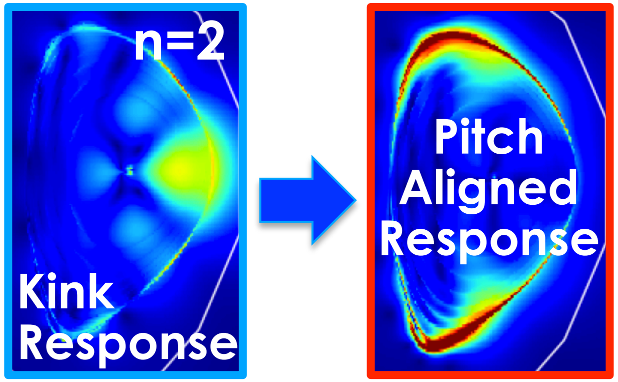
- ***Requires co-alignment of***
  - Low $\omega_{e\perp}$ rotation region
  - Tearing-resonant surfaces
  - …at the pedestal top



Nazikian/Wade

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

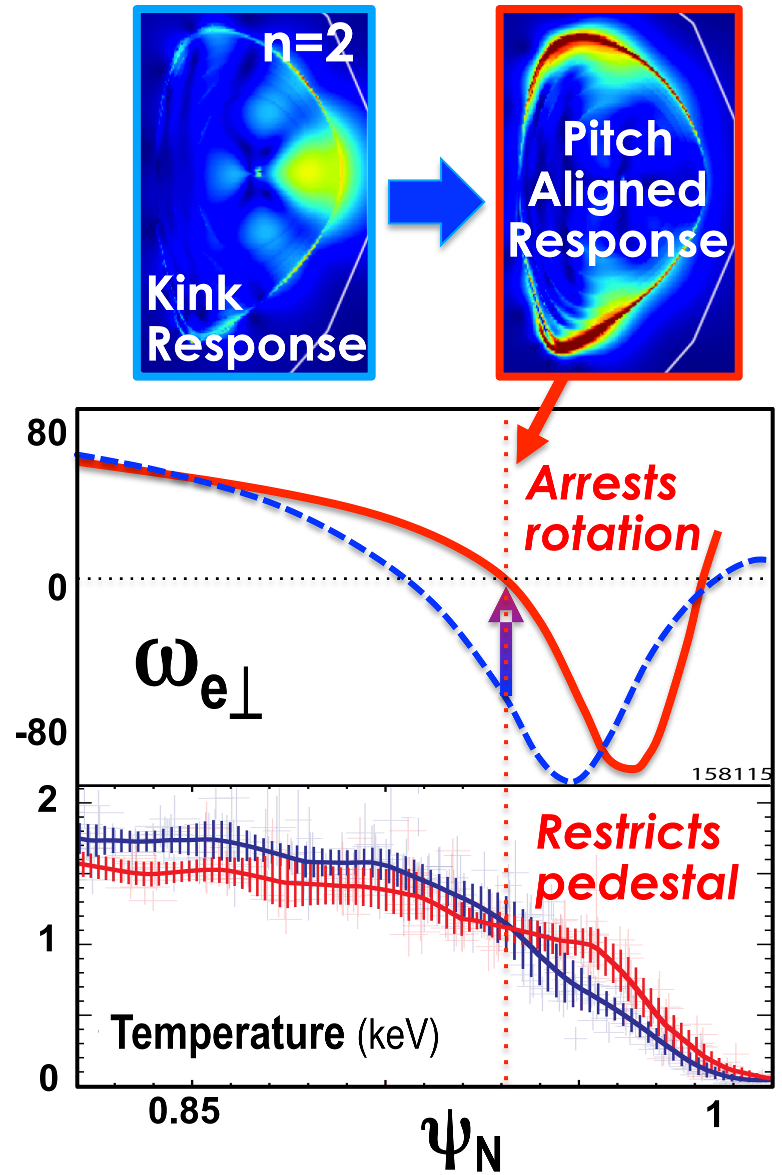
- **Vary n=2 field structure from kink to pitch-aligned resonance**
  - Two distinct ideal MHD plasma modes
  - Ramp from exciting one to the other



Nazikian/Wade

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

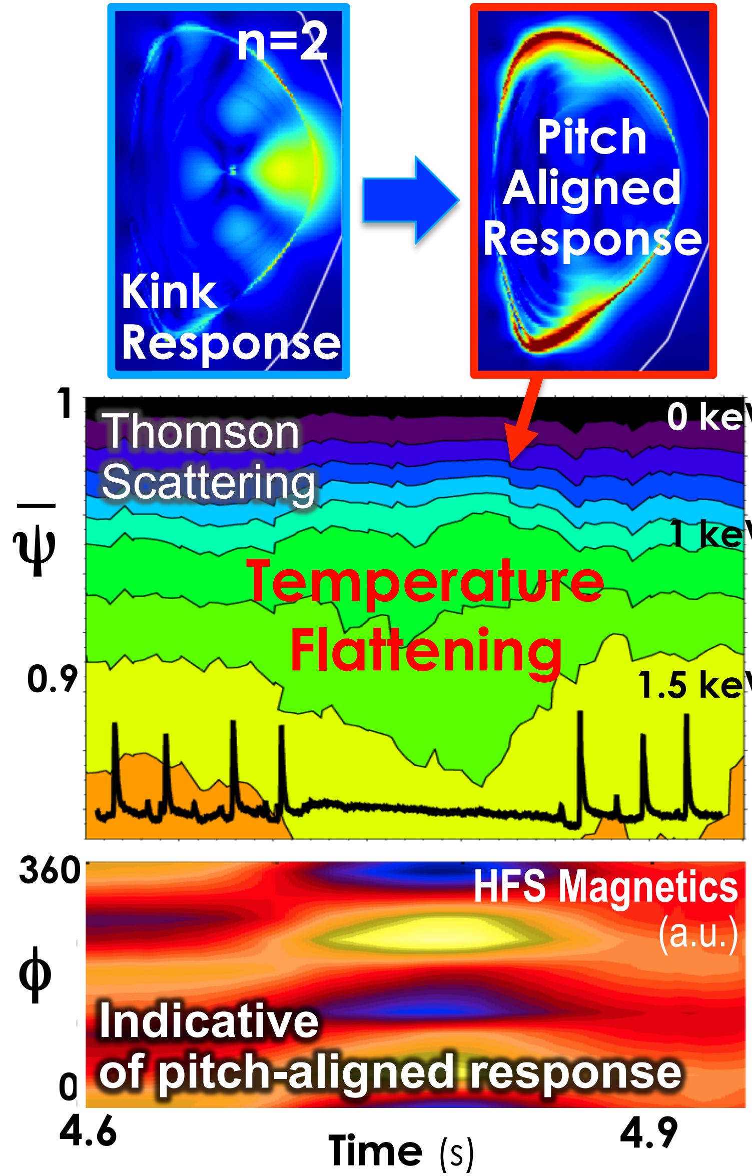
- **Vary n=2 field structure from kink to pitch-aligned resonance**
- **Penetration of pitch-aligned field**
  - $\omega_{e\perp} \rightarrow 0$ at pedestal top
  - Pedestal width narrows
  - Transition to ELM suppression



Nazikian/Wade

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

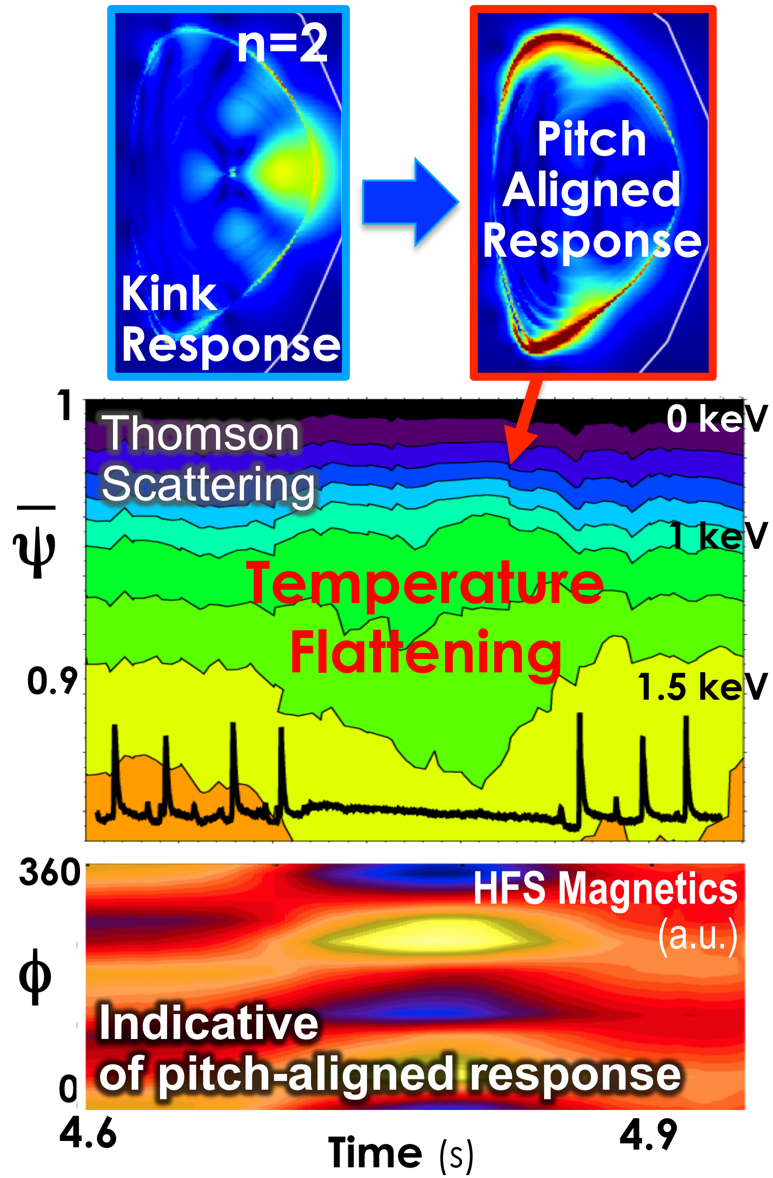


Nazikian/Wade

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)**

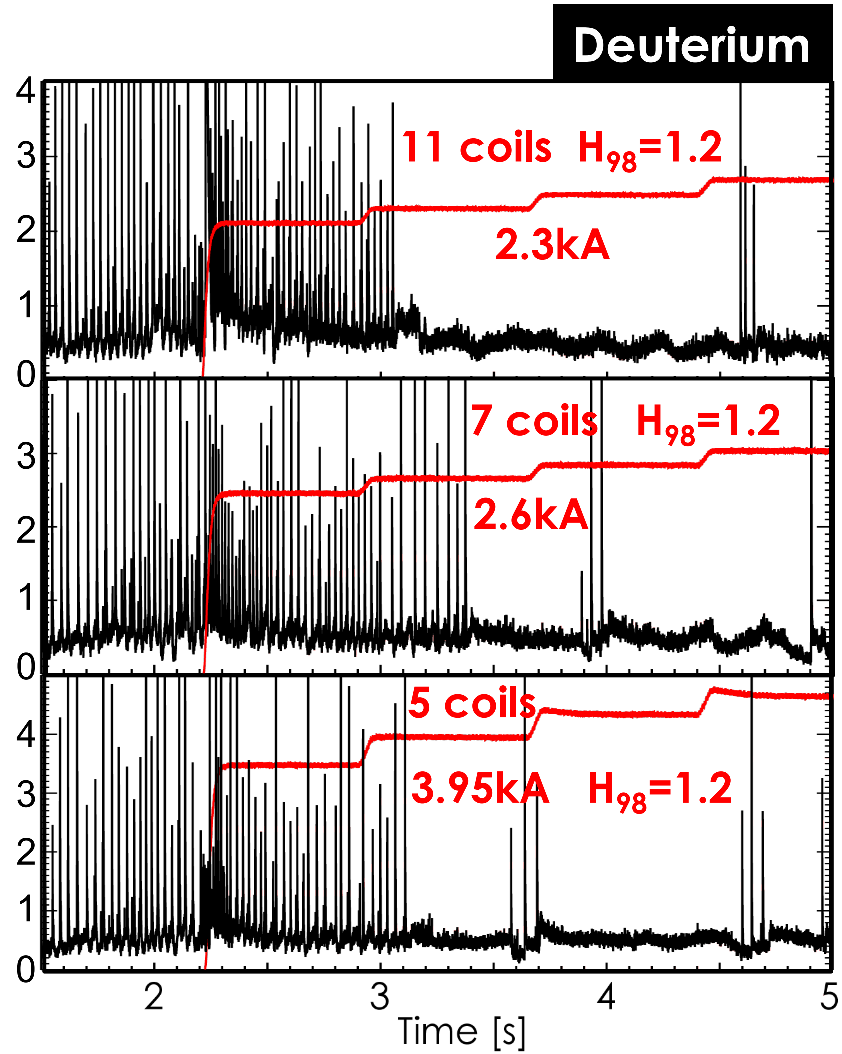
✓ **Increased confidence in predictions for ITER**



Nazikian/Wade

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



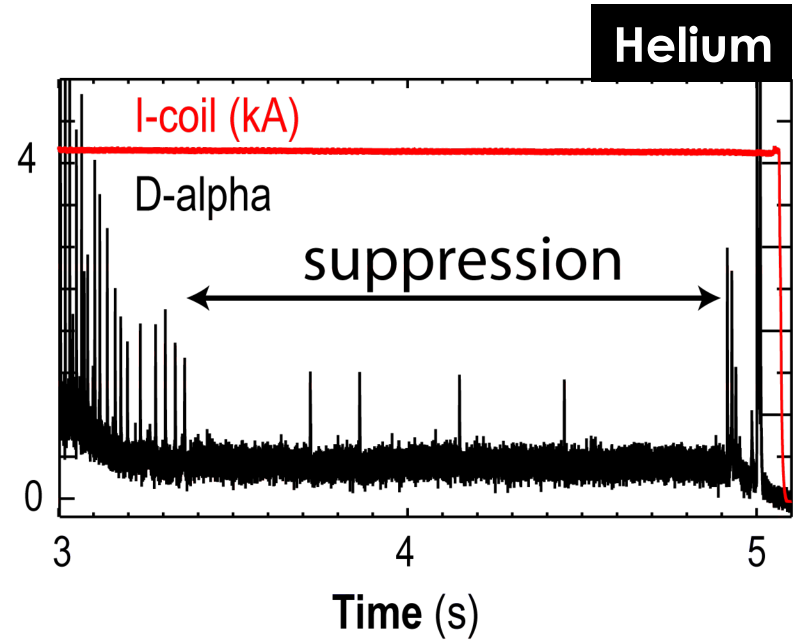
✓ **Affirms ITER's Research Plan**

Orlov

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

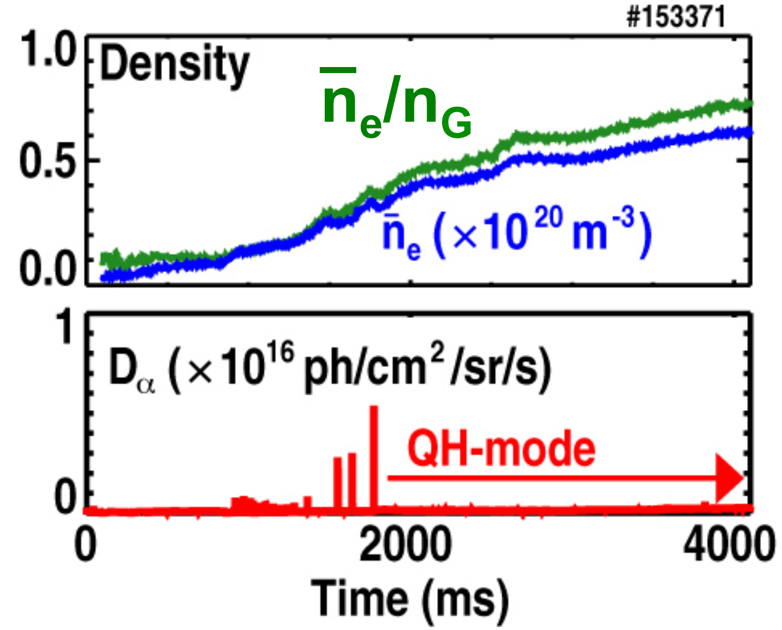


Orlov

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**

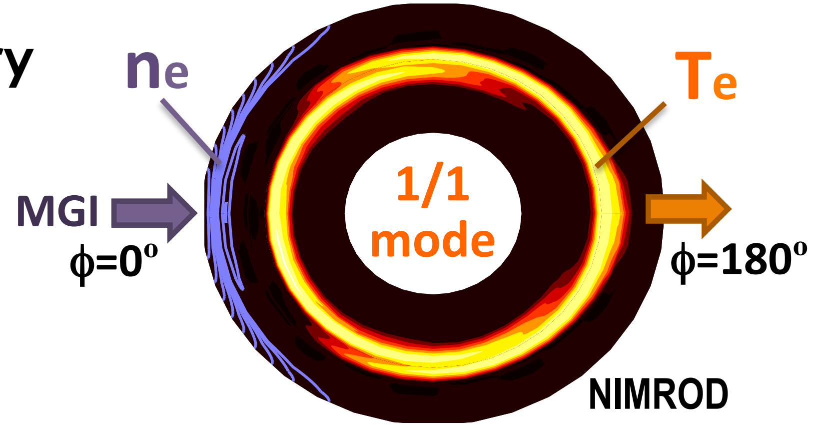


✓ Improved confidence of QH mode access in ITER

Solomon

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 180º away from MGI



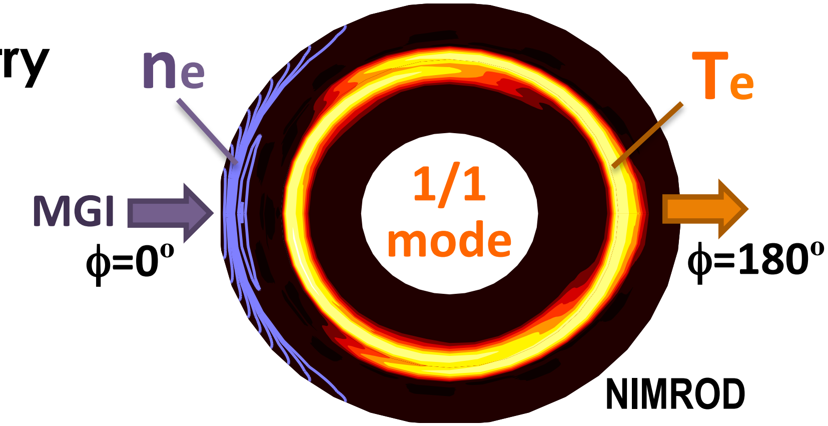
Izzo

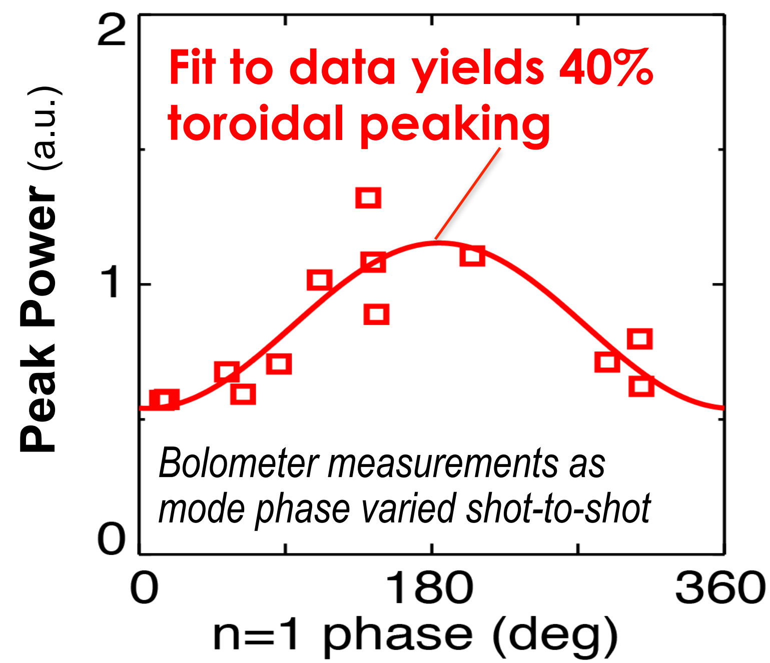
Massive Gas Injection Experiments Consistent with NIMROD Predictions of Modest Disruption Radiation Asymmetry

- **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

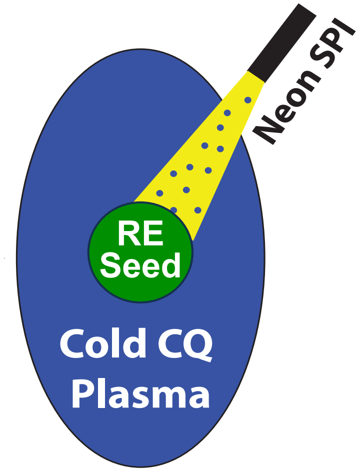
Izzo

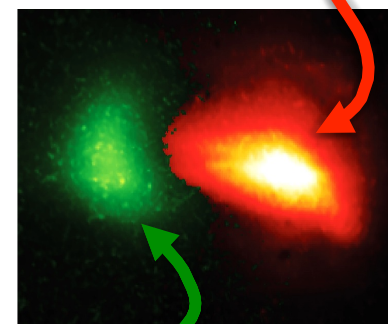
DIII-D Developed Promising Runaway Electron Mitigation Solution for ITER

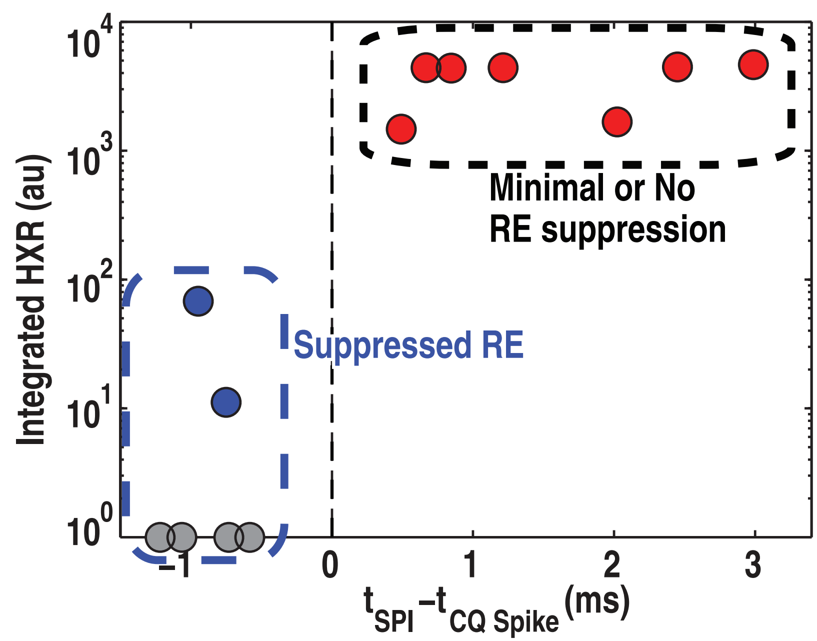
- **Injection of Ne Shattered Pellets into early CQ may provide viable path to suppress runaway growth**

- **RE current dissipation explained by RE-ion pitch angle scattering**
  – Higher Z more effective at RE dissipation

✓ **First demonstration of potential solution for ITER**

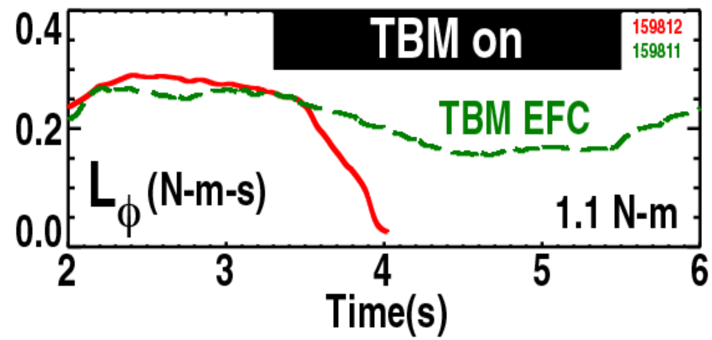


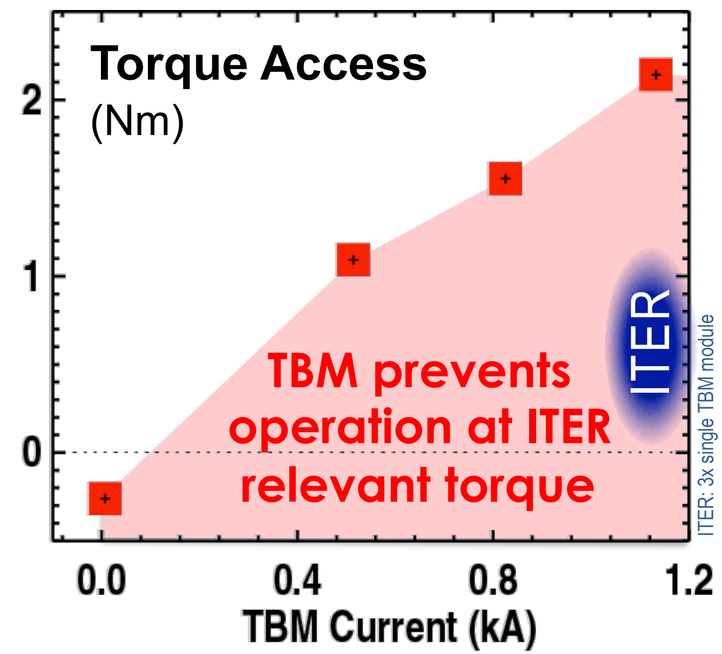




Correction of ITER Test Blanket Module Fields Enables Low Torque and High β Operation

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

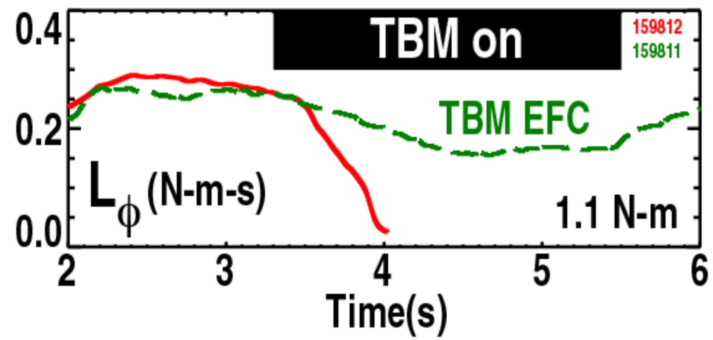




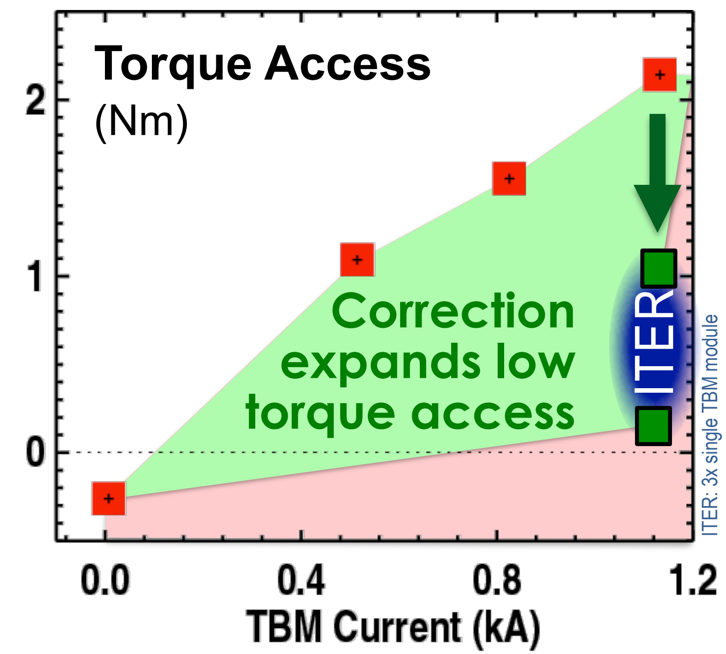
…in collaboration with ITER

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 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**

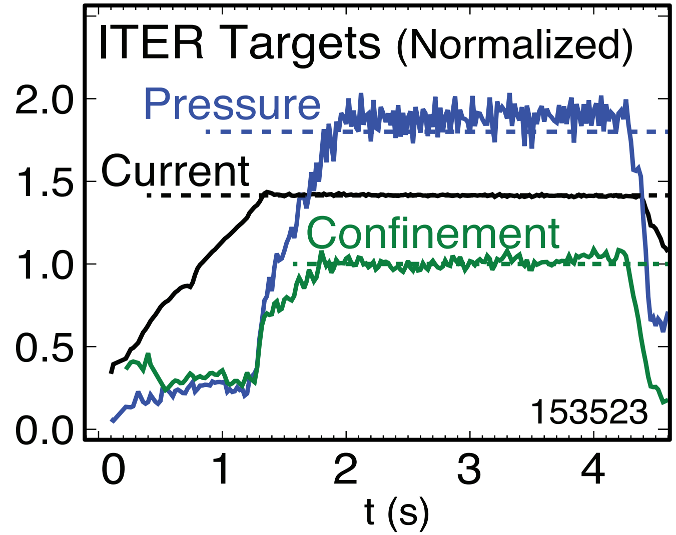
…in collaboration with ITER

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 (>2τ_R) with relevant sources**
  - Dominant electron heating
  - Low torque
  - Reduced core fueling

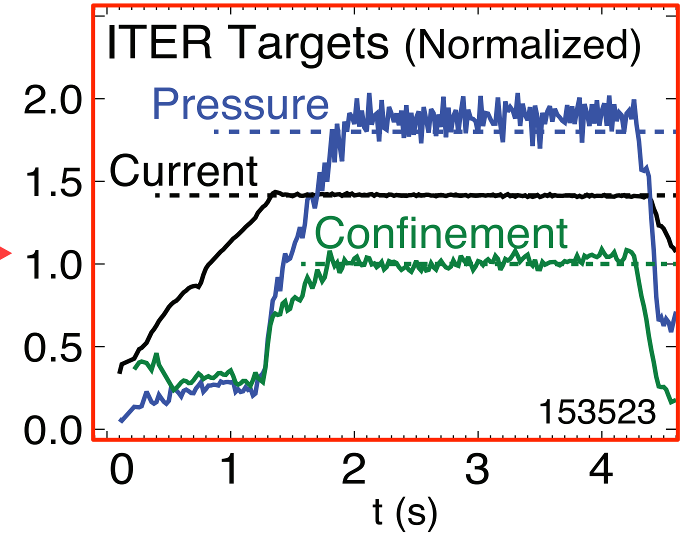


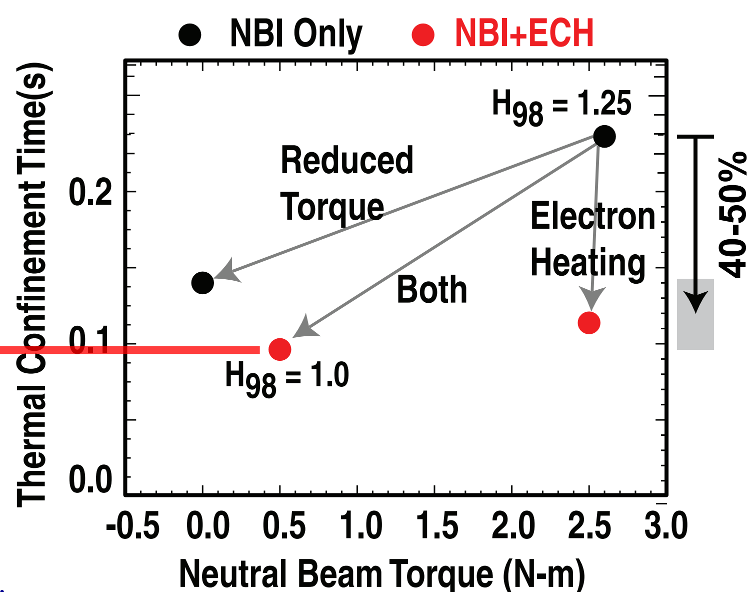
- **Avoid tearing instability:**
  - Error field correction
  - Pedestal/ELM regulation
  - Maintain differential rotation

Luce, Paz-Soldan

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

- **Baseline targets achieved in stationary conditions (>2τ_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**

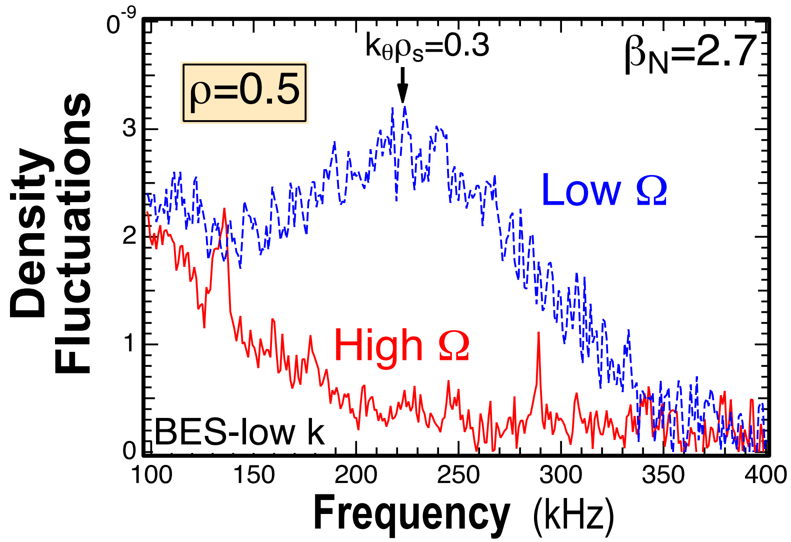




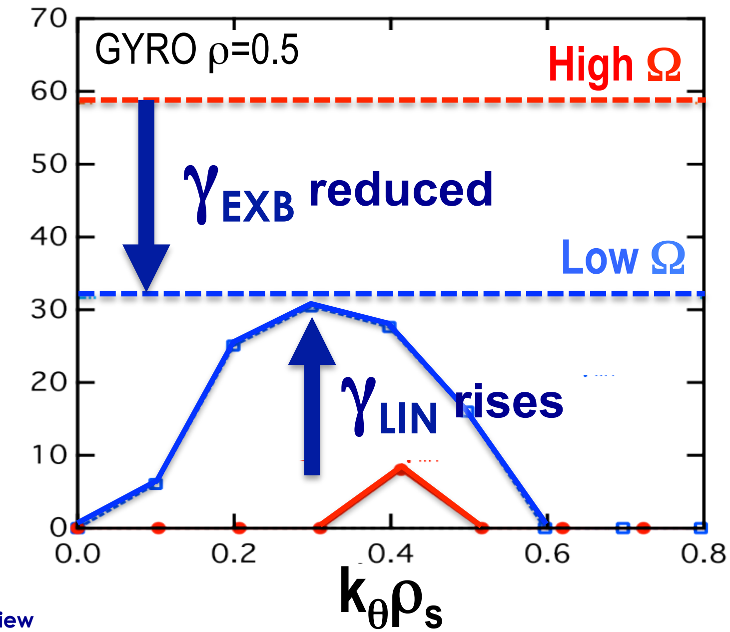
Luce, Paz-Soldan

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

- **Large rise in turbulence with lower rotation**



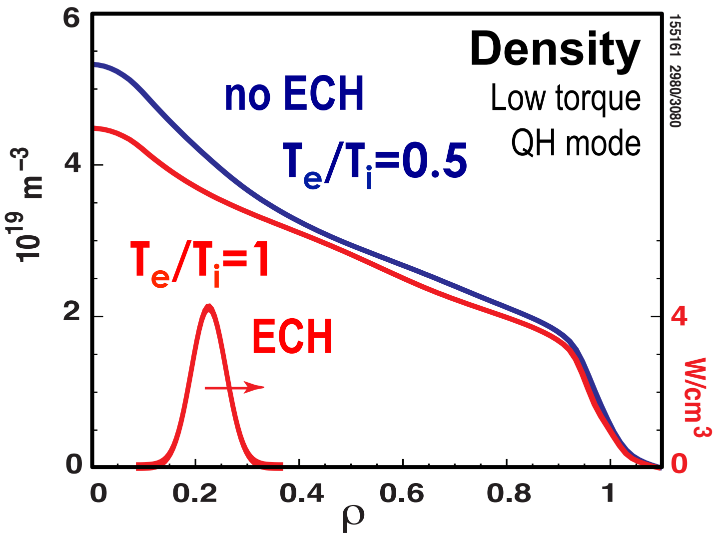
- **Interpreted by GYRO simulation**
  - Reduction in ExB flow shear stabilization
  - Increase in linear growth rates



DIII-D NATIONAL FUSION FACILITY SAN DIEGO
McKee

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

- **Density flattening observed when ECH raises T_e/T_i**

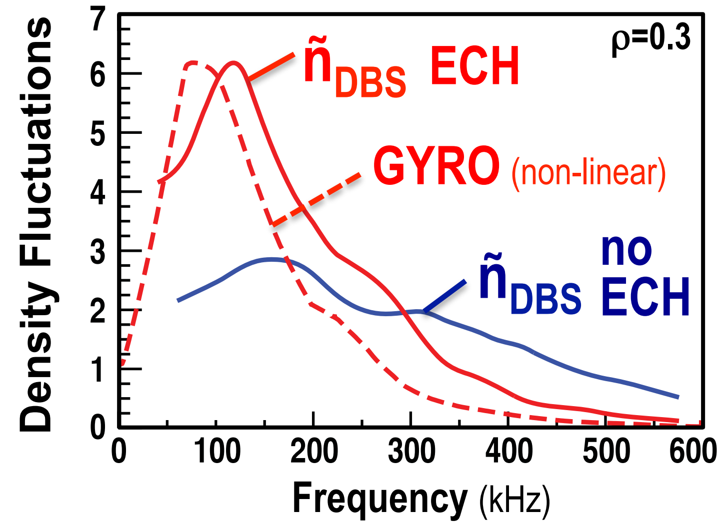


GYRO: **Raising T_e/T_i lowers critical density gradient for TEM leading to increased turbulence**

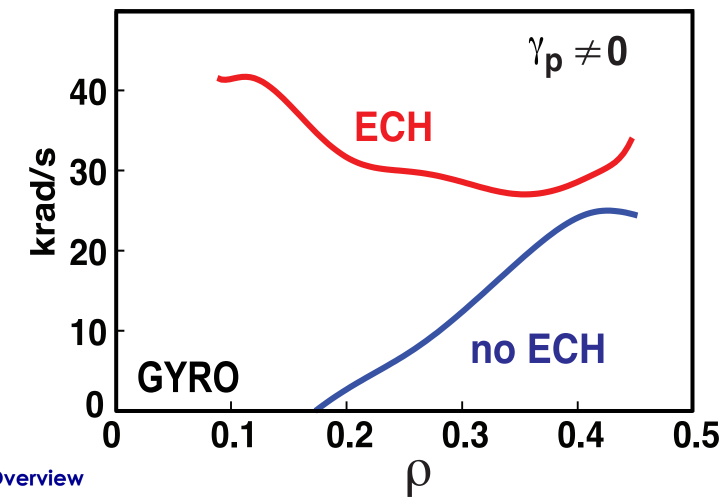
US National Campaign with CMOD NSTXU participation

Ernst

- **Explained by rise in turbulence**



- **Increased TEM growth in core**



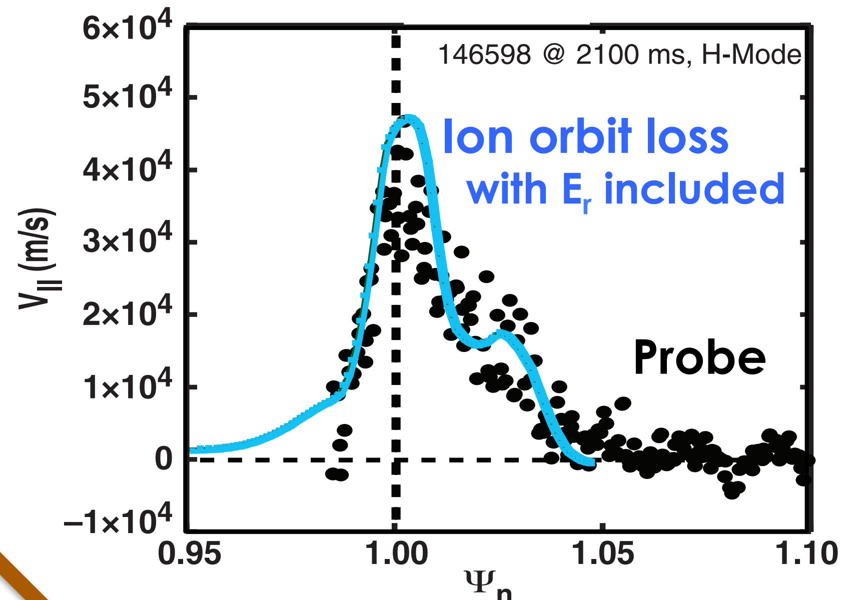
Ion Orbit Loss Models Capture Intrinsic Plasma Rotation Behavior

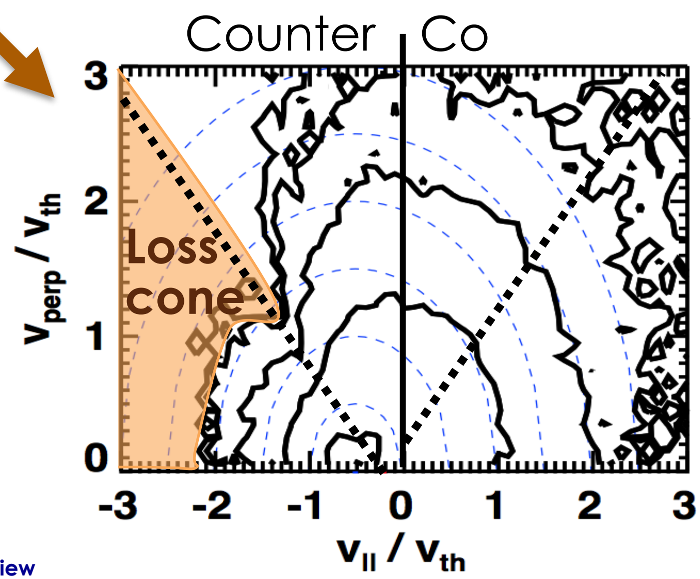
Rotation critical to transport and stability projection

- **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**



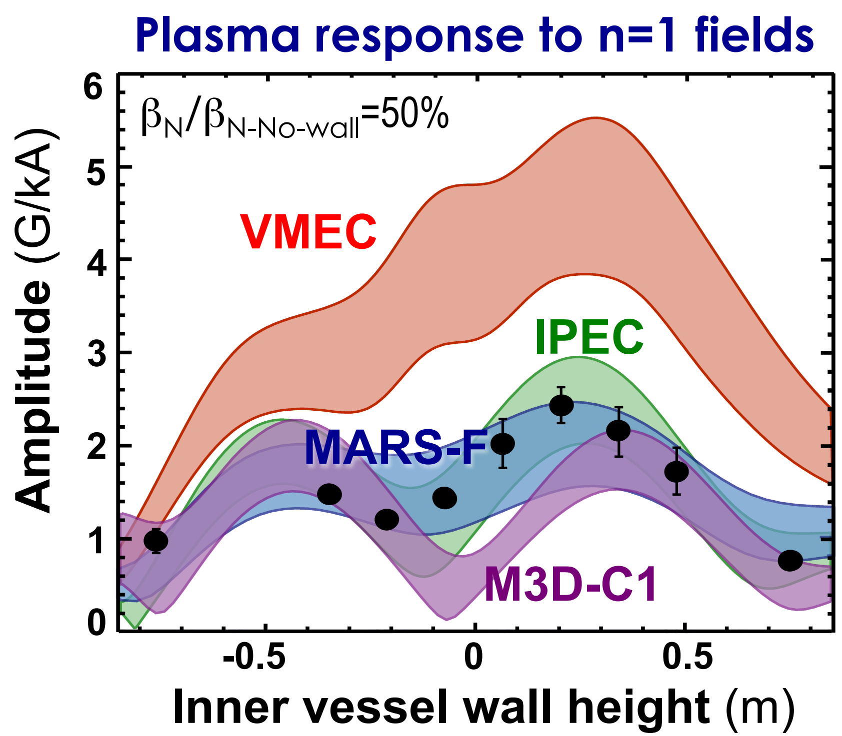


Battaglia

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

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



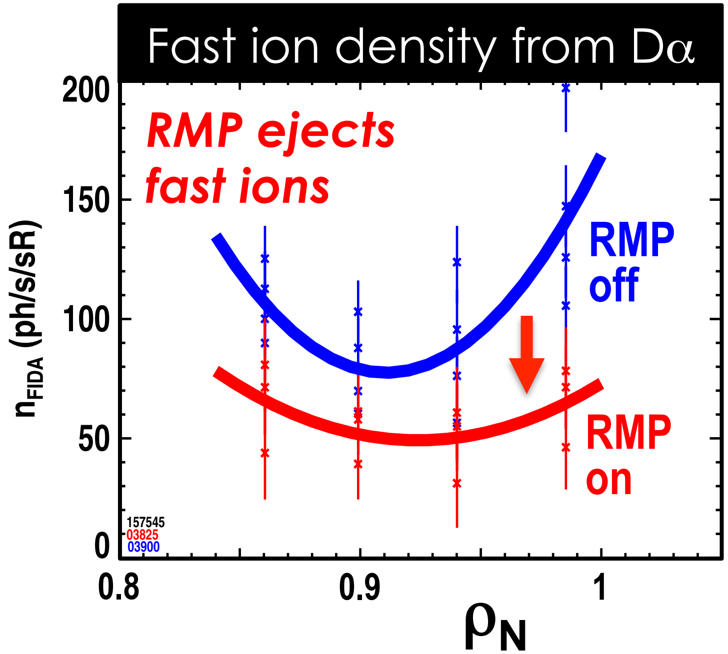
New magnetics helping refine and develop physics models of plasma response to 3D fields

Paz-Soldan

US joint theory and experiment initiative

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

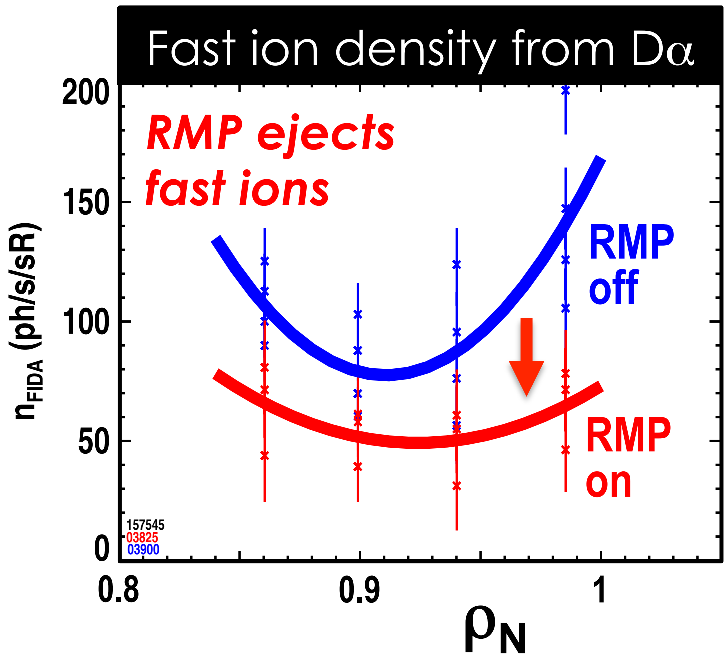


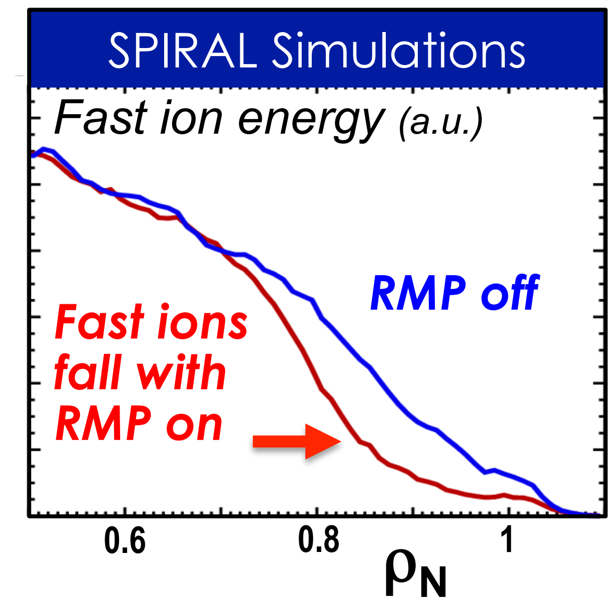
Leads to increased divertor heat load in model and experiment

Van Zeeland

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

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

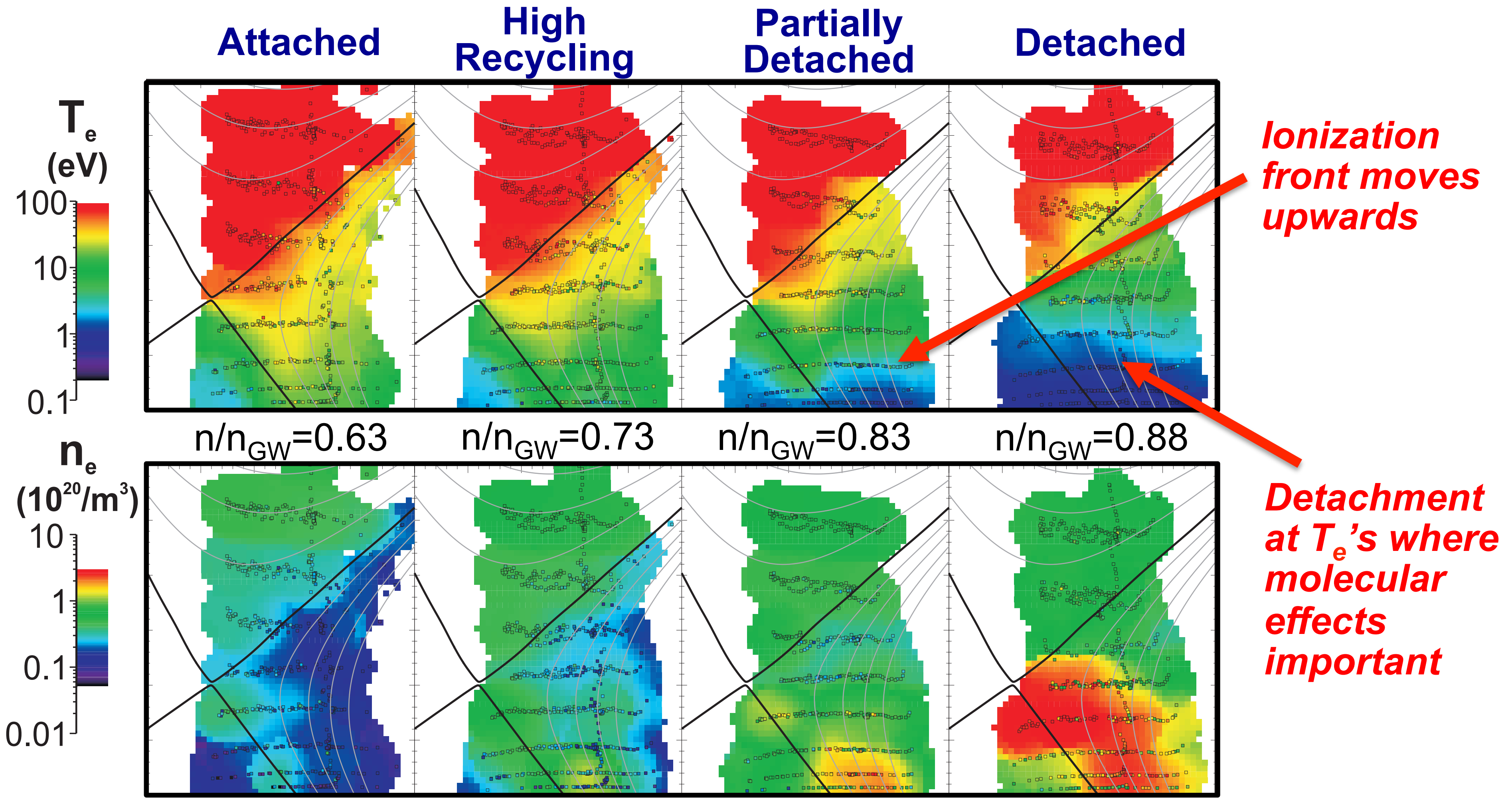
Van Zeeland

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

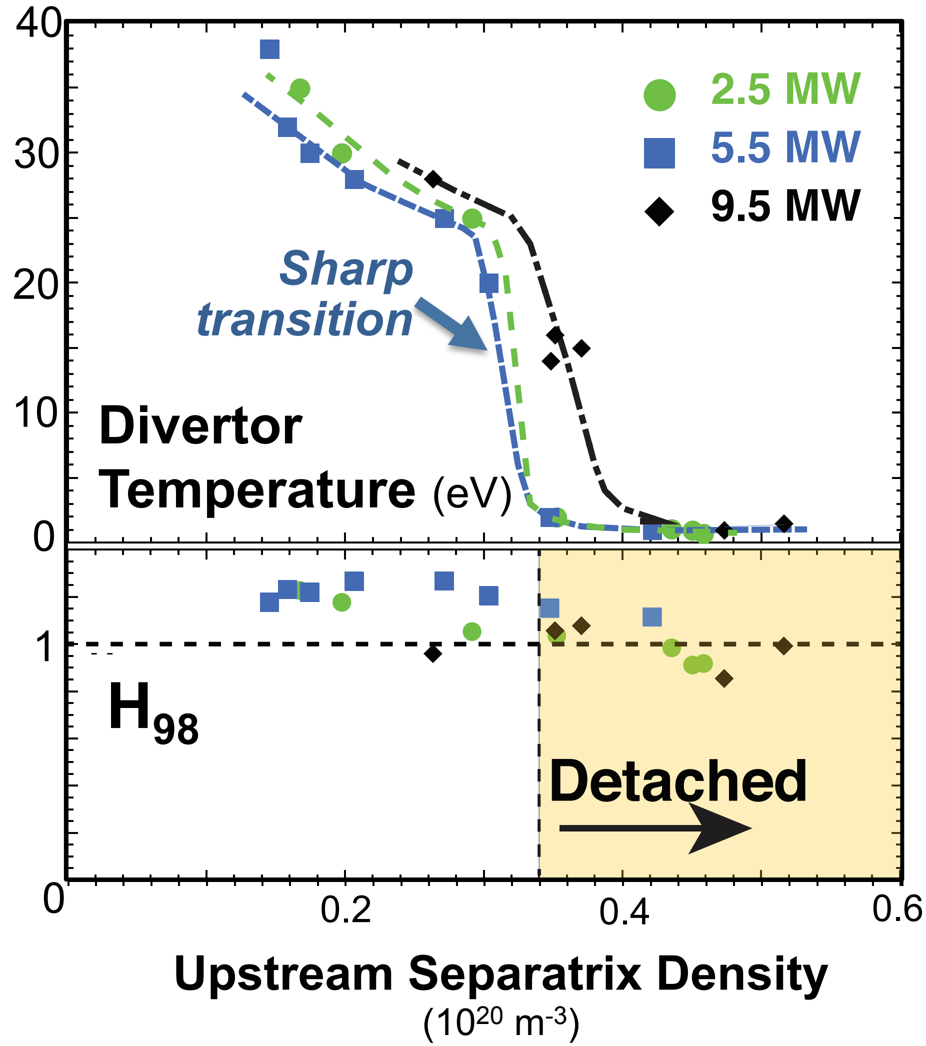


McLean

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



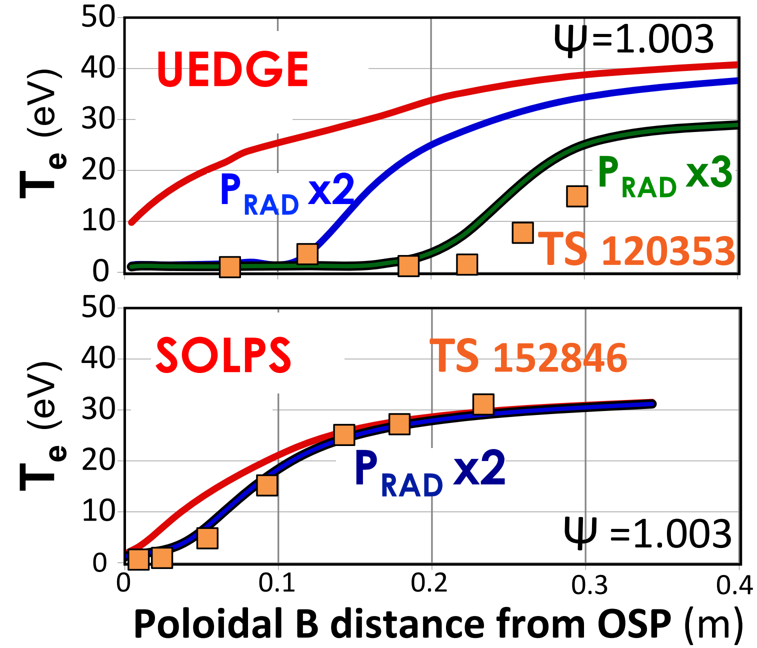
DIII-D NATIONAL FUSION FACILITY SAN DIEGO
McLean

Detachment Studies Reveal Radiation Shortfall in Simulation Models

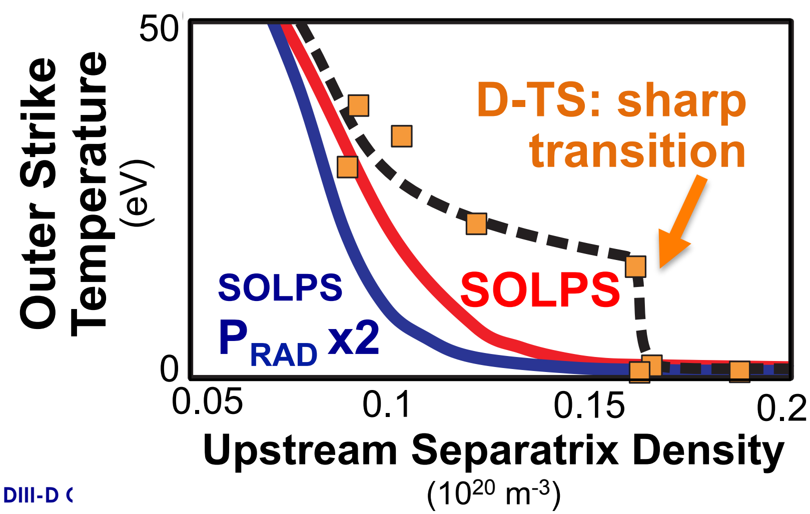
Previous modeling captured attached plasma conditions well

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



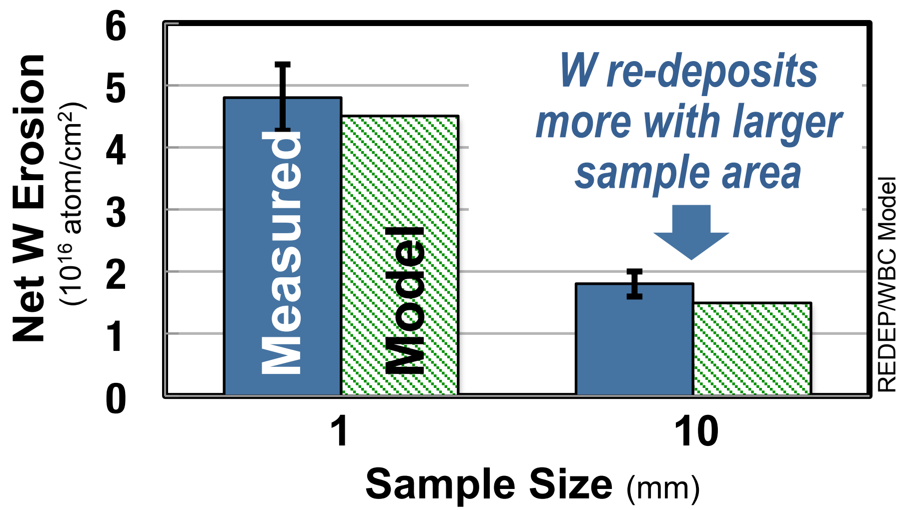
Better cold, molecular and atomic species models required

McLean

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

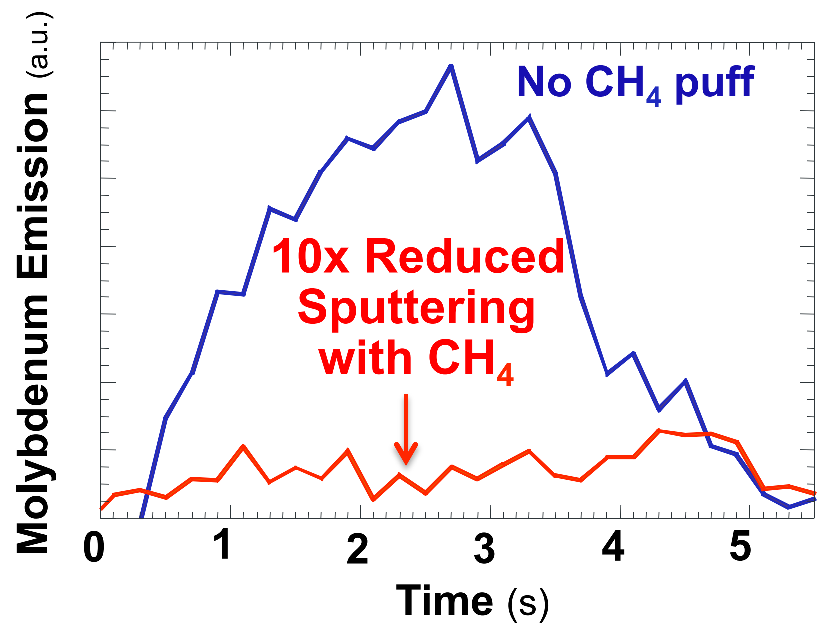
- **Net Tungsten erosion is weak**
  - Gross erosion compensated by re-deposition

✓ ***Validates model that indicates low net erosion in ITER***



- **Erosion of high-Z sample mitigated by low Z renewable coatings**
  - CH_4 used as proxy for Be, Li, B, other low-Z possibilities

✓ ***Potential for real time protective coating of key areas***



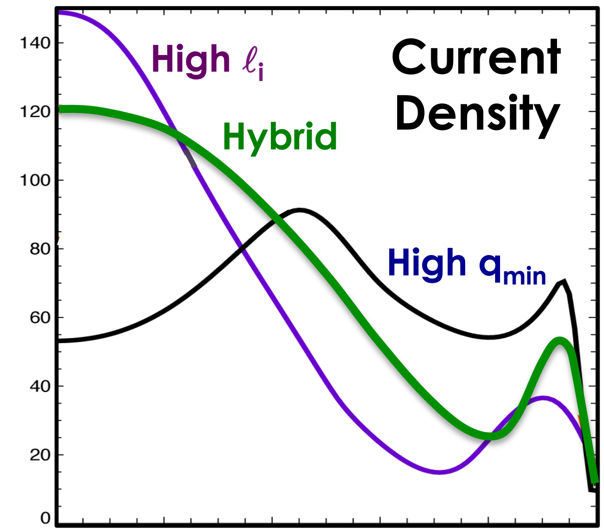
Rudakov

In collaboration with materials facilities

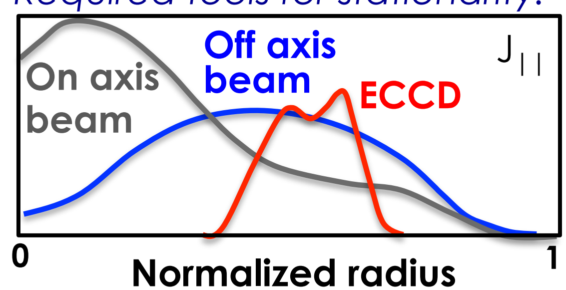
DIII-D Utilizing Flexible Heating and Current Drive Systems to Develop Path to High β Steady State

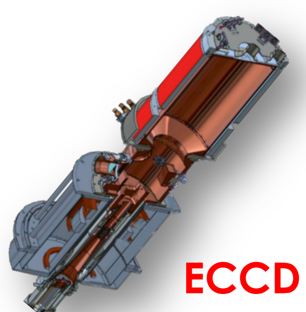
- **Potential solutions from peaked to broad current profiles**
  - From **efficient on-axis current drive** to **high bootstrap current**

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



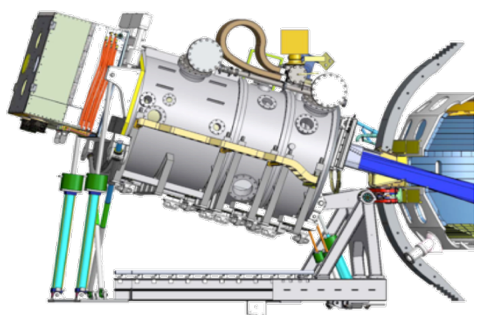
Required tools for stationarity:





ECCD

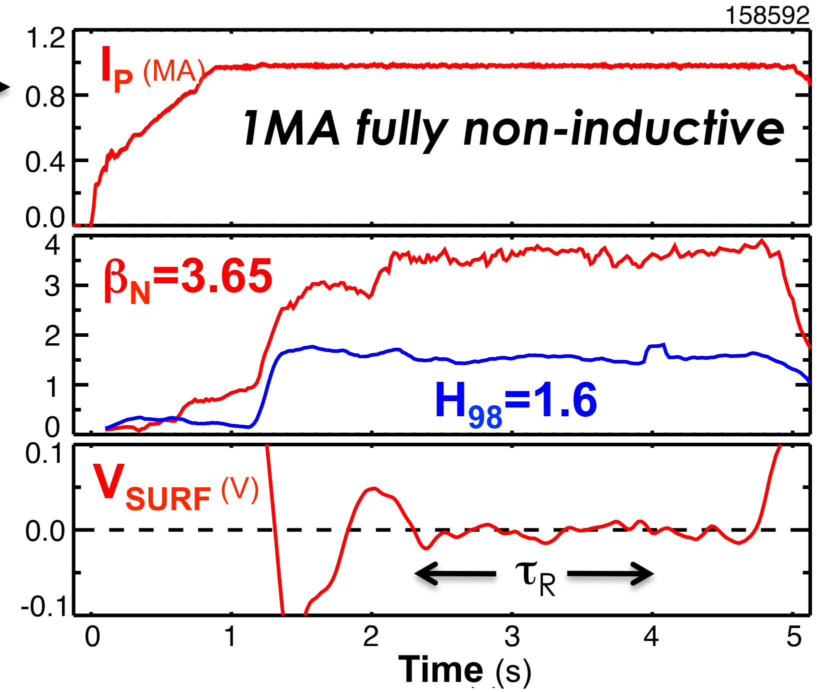
Off axis beam

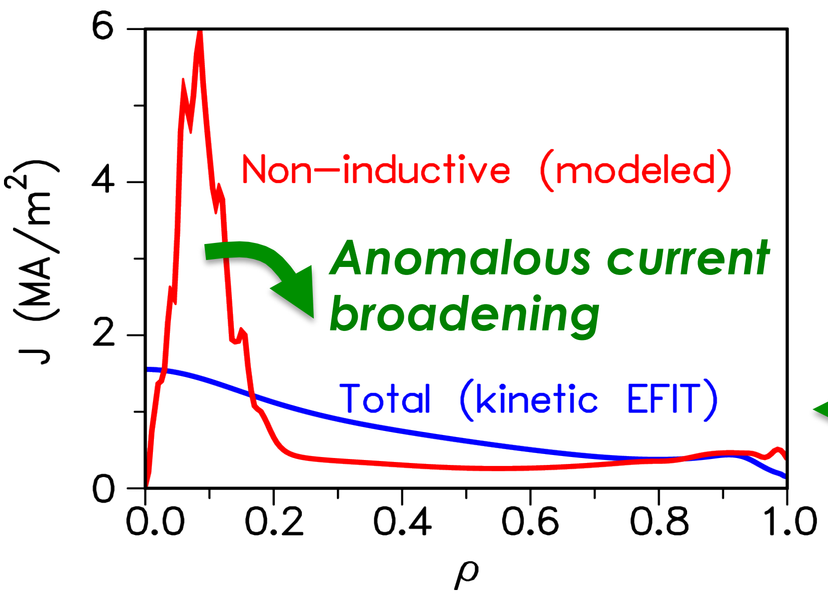


DIII-D NATIONAL FUSION FACILITY SAN DIEGO

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

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





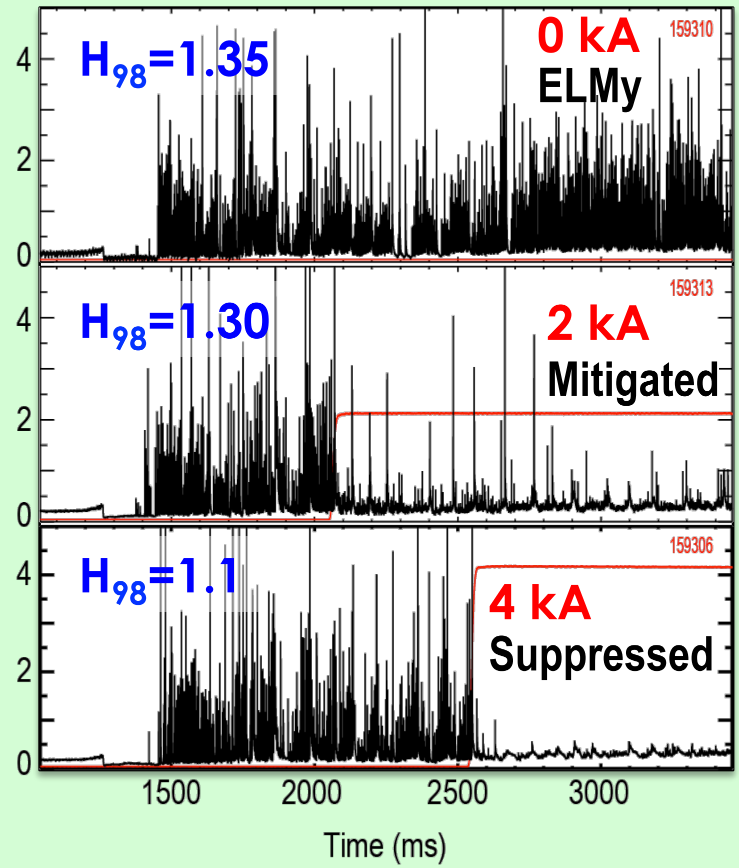
- **Can overdrive current on axis**
  - Anomalous broadening maintains q_{min}~1.1

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**

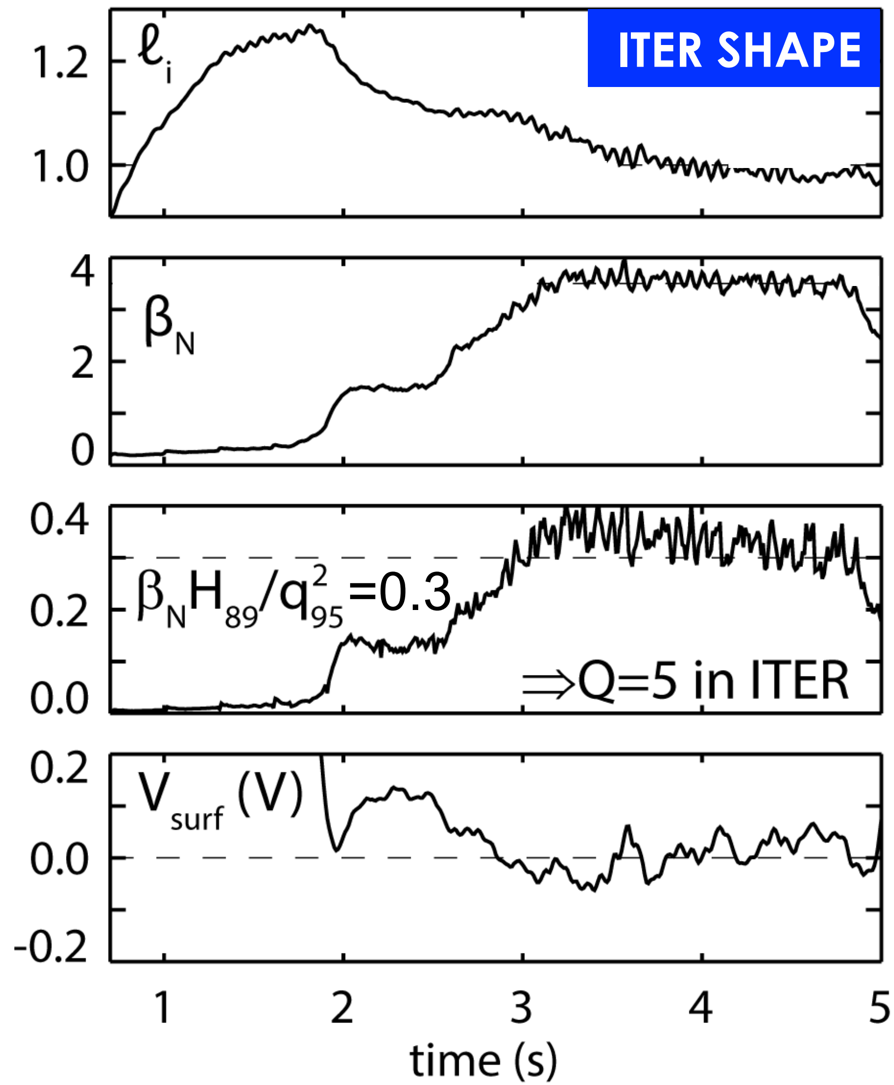


Good ITER and FNSF candidate regime with efficient on-axis CD

High l_i Plasmas Demonstrate Excellent Performance

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

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



Ferron

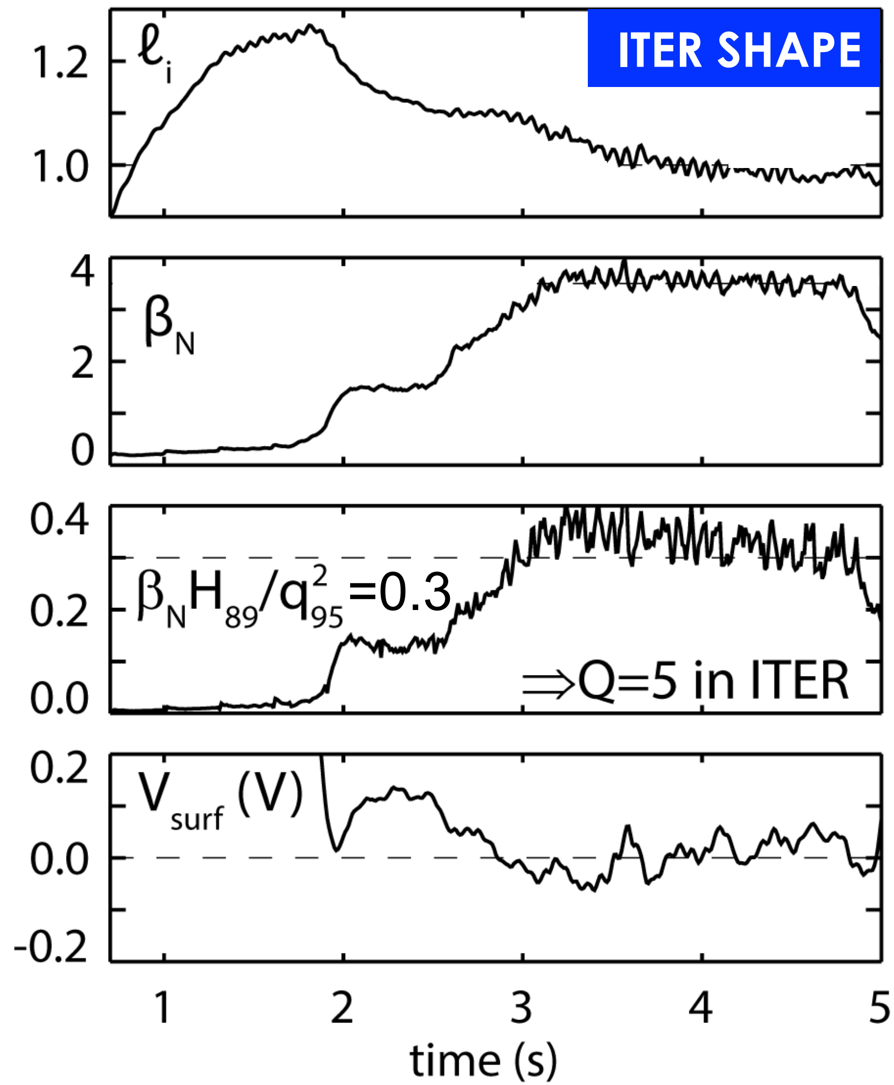
High l_i Plasmas Demonstrate Excellent Performance

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

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

- **Extended to β_N=5.3 in double null configuration**
  - H_{98}= 1.8 and 80% bootstrap

Future fusion reactor option



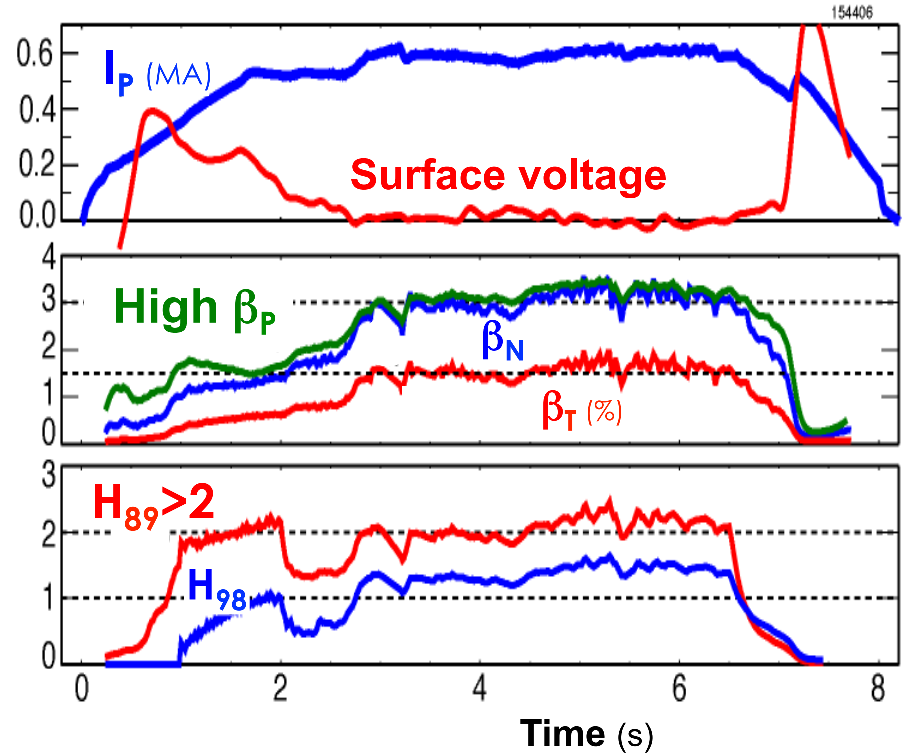
Ferron

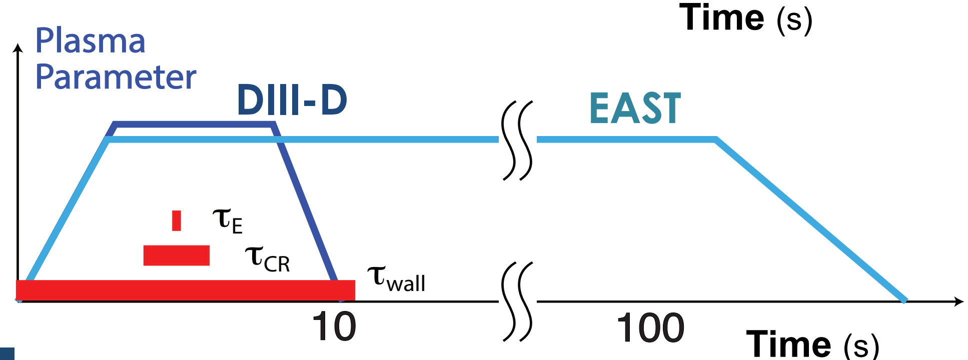
High q_{min} Path: High Bootstrap Fully Non-inductive Scenario Developed for Long Pulse Operation

- **Reduced torque and current ramp rate to match EAST**
  - 80% bootstrap sustained for two current redistribution times

- **ρ=0.7 transport barrier gives good fast ion confinement**

Fully non-inductive target for EAST





Garofalo, Gong

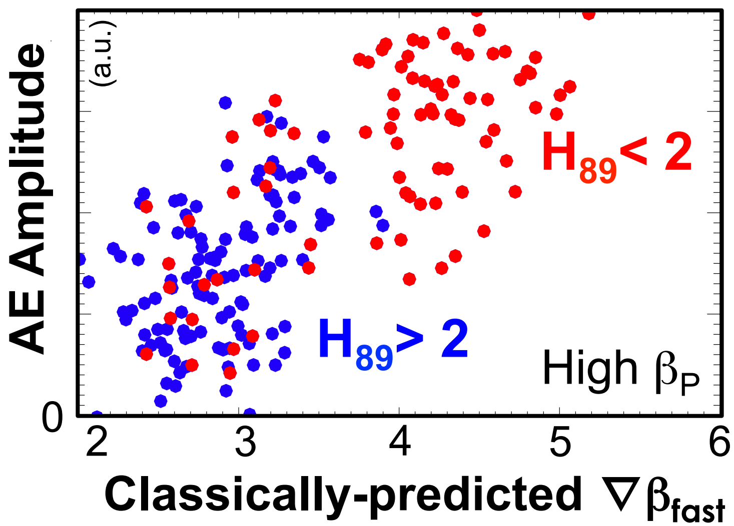
Joint initiative with EAST

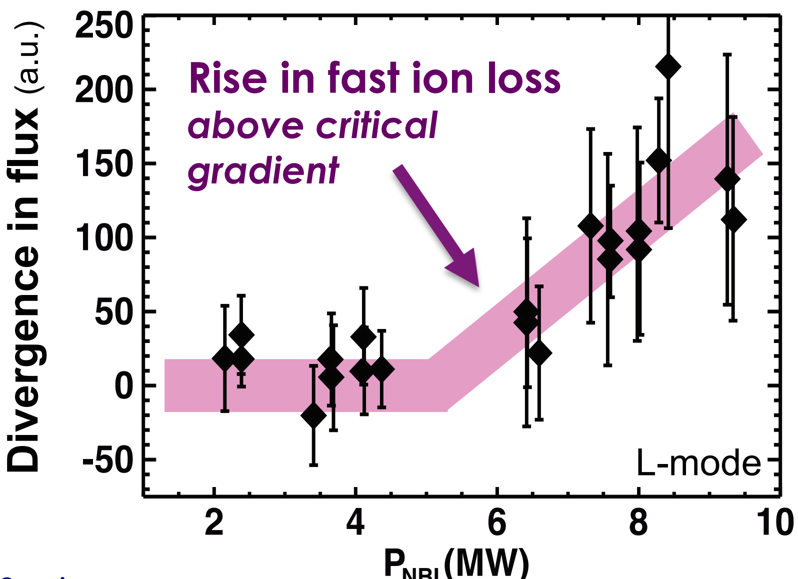
Higher Performance in High q_{min} Encounters Enhanced Fast Ion Transport due to Alfvén Eigenmodes

- **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 $\nabla\beta_{fast}$ through increased off-axis NBI & ECH

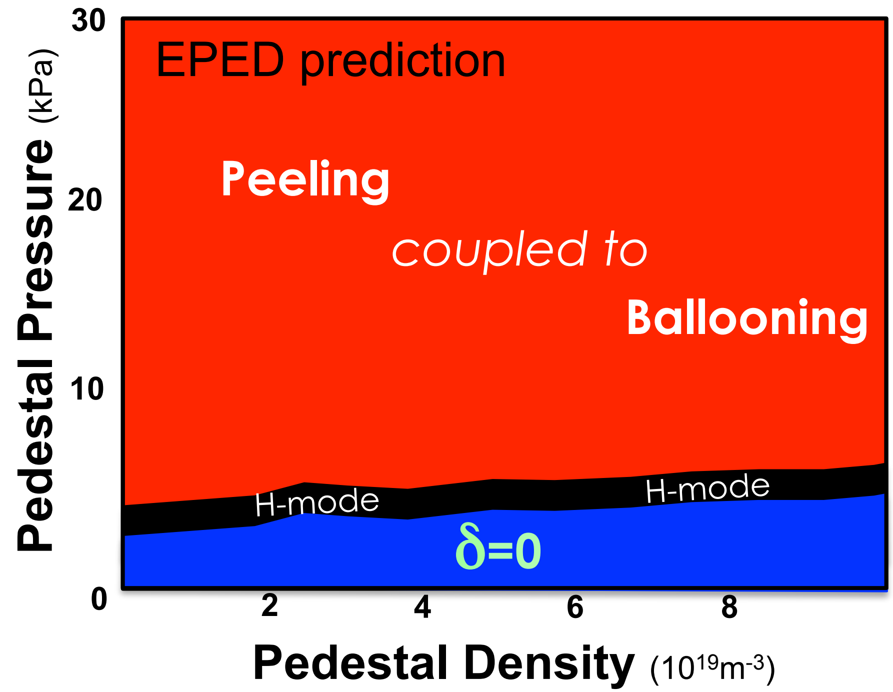




Heidbrink, Bass, Todo

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

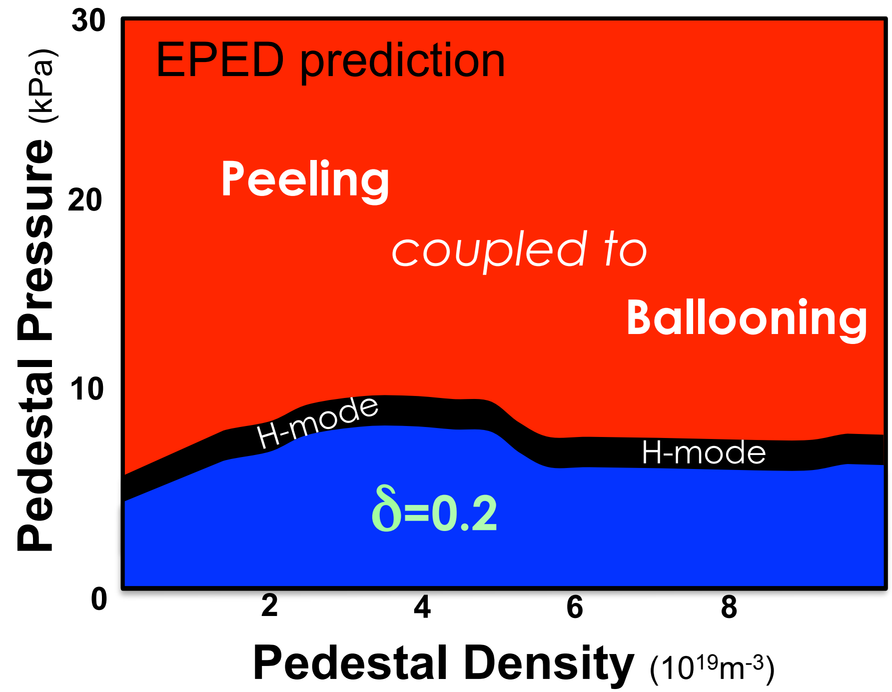
- **Strong shaping decouples peeling from ballooning mode**
  - Opens valley in pedestal stability



Snyder

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

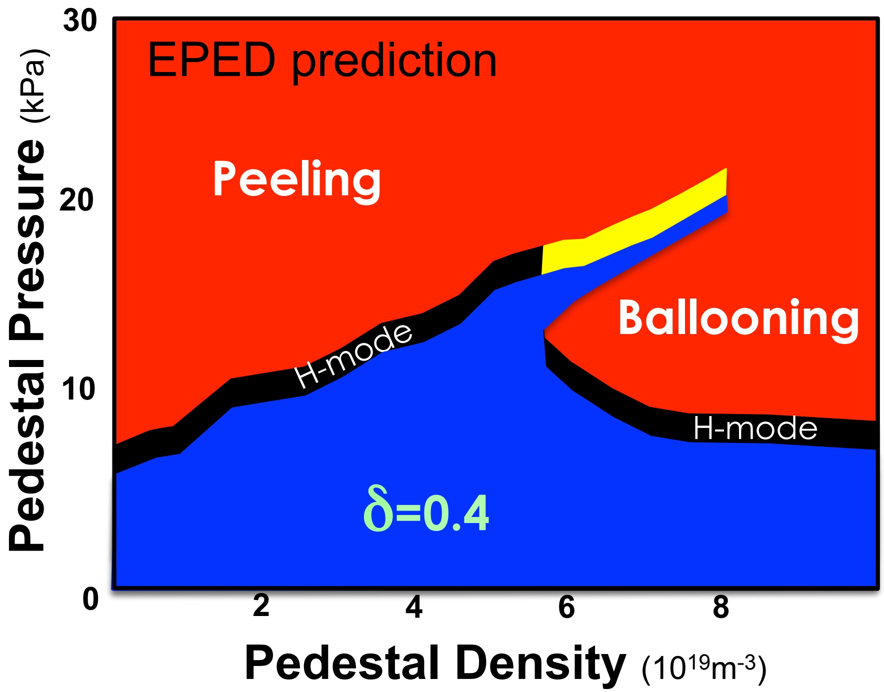
- **Strong shaping decouples peeling from ballooning mode**
  - Opens valley in pedestal stability



Snyder

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

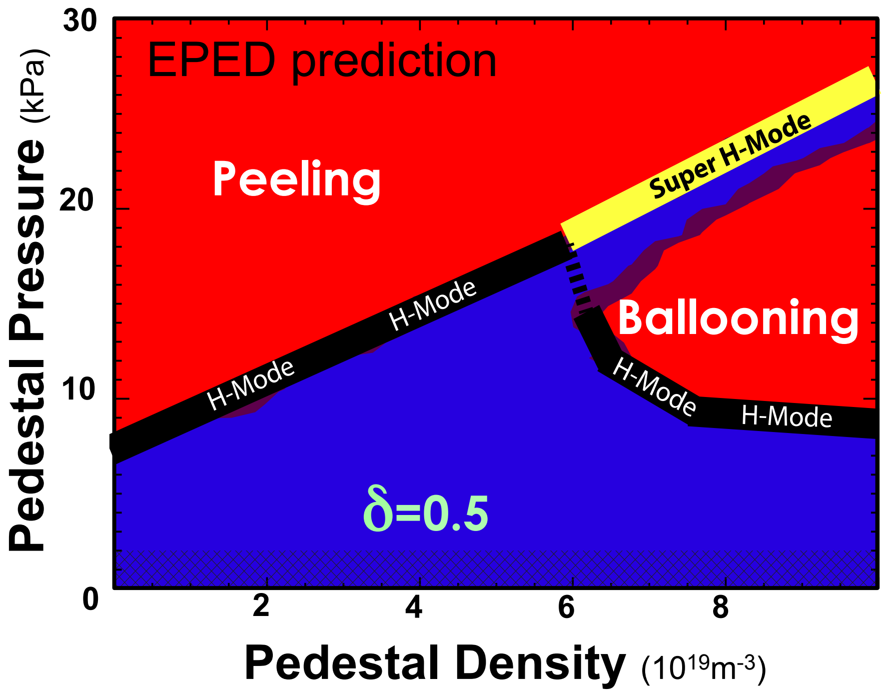
- **Strong shaping decouples peeling from ballooning mode**
  - Opens valley in pedestal stability



Snyder

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

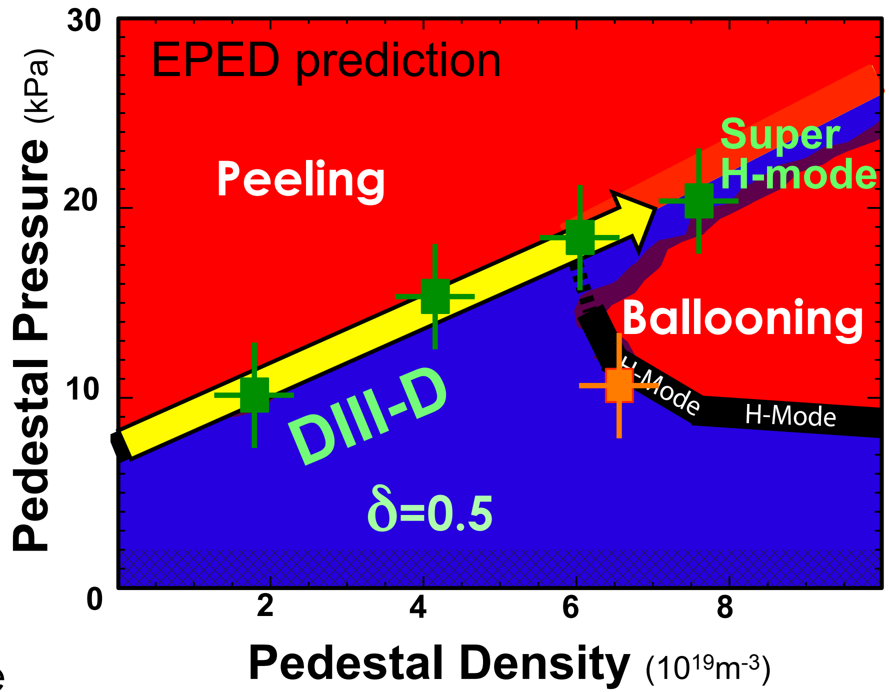


DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Snyder

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

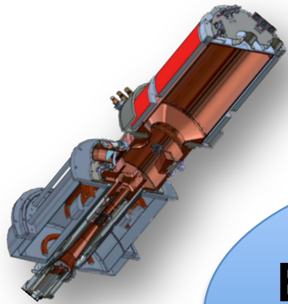
- **Strong shaping decouples peeling from ballooning mode**
  – Opens valley in pedestal stability
- **Super H-Mode discovered**
  – EHO provided benign saturation mechanism to navigate valley
  – Record β_N=3.1 with quiescent edge



EPED predicts Super H-mode possible in ITER

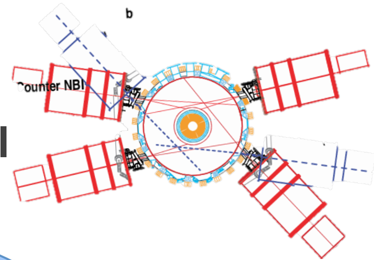
Snyder

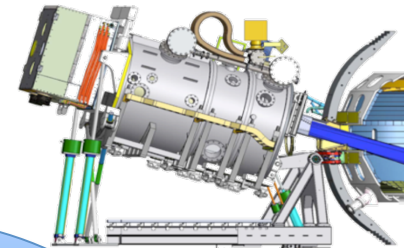
DIII-D Future Exploitation Focuses on Three Key Challenges for Fusion Energy



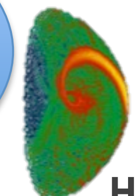
ECH

Balanced Torque NBI





2nd Off-axis Beam



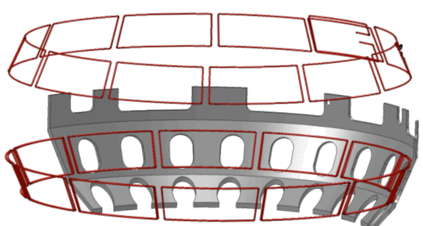
ECCD

Helicon

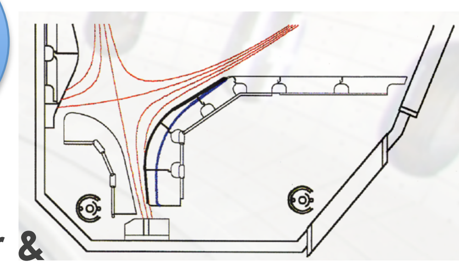
Prepare for Burning Plasmas
Torque-free electron heating

Path to Steady State
Flexible H&CD

PMI-Boundary Solution
Heat flux control



Advanced 3D Coil Set



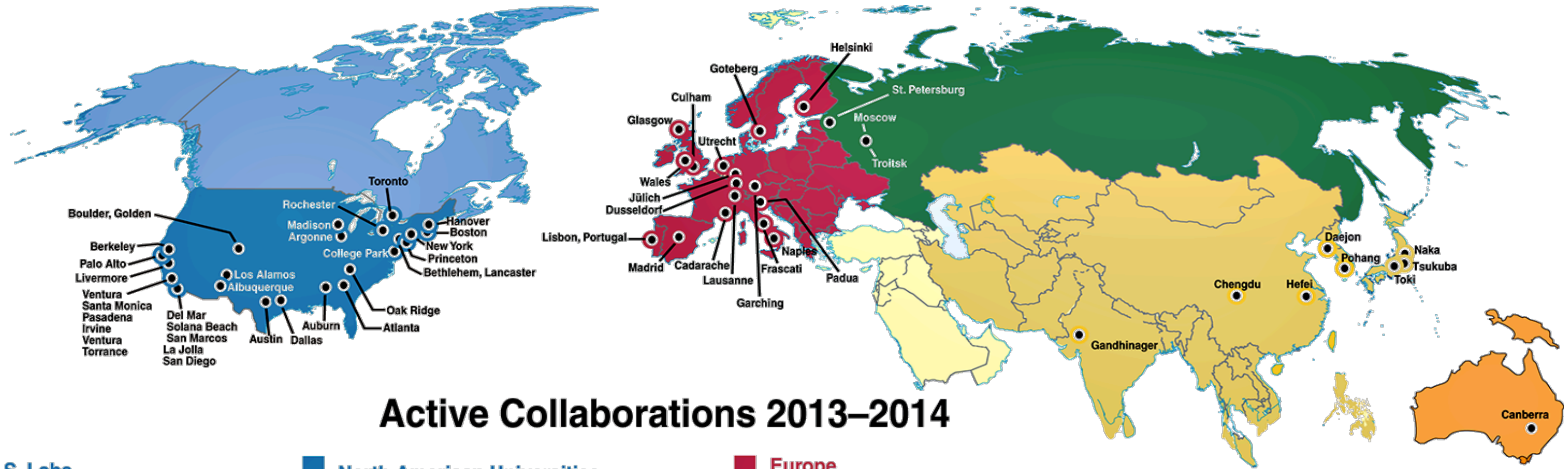
New Divertor & Hot Reactor Relevant Wall

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

LBNL (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 (Tuscon, 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

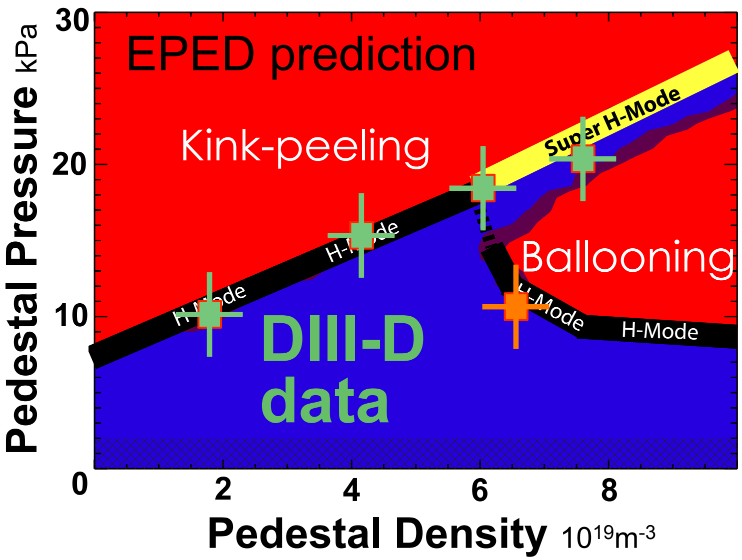
Australia National U. (Canberra)

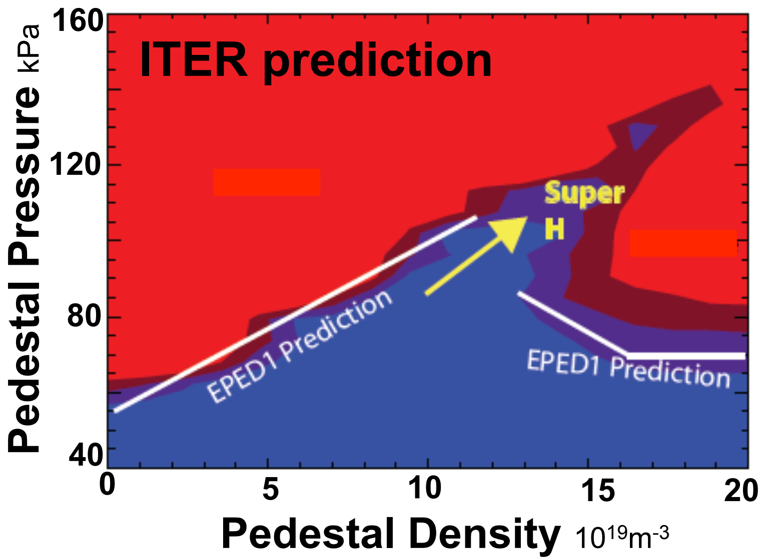
Reserve Slides

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 β_N=3.1

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



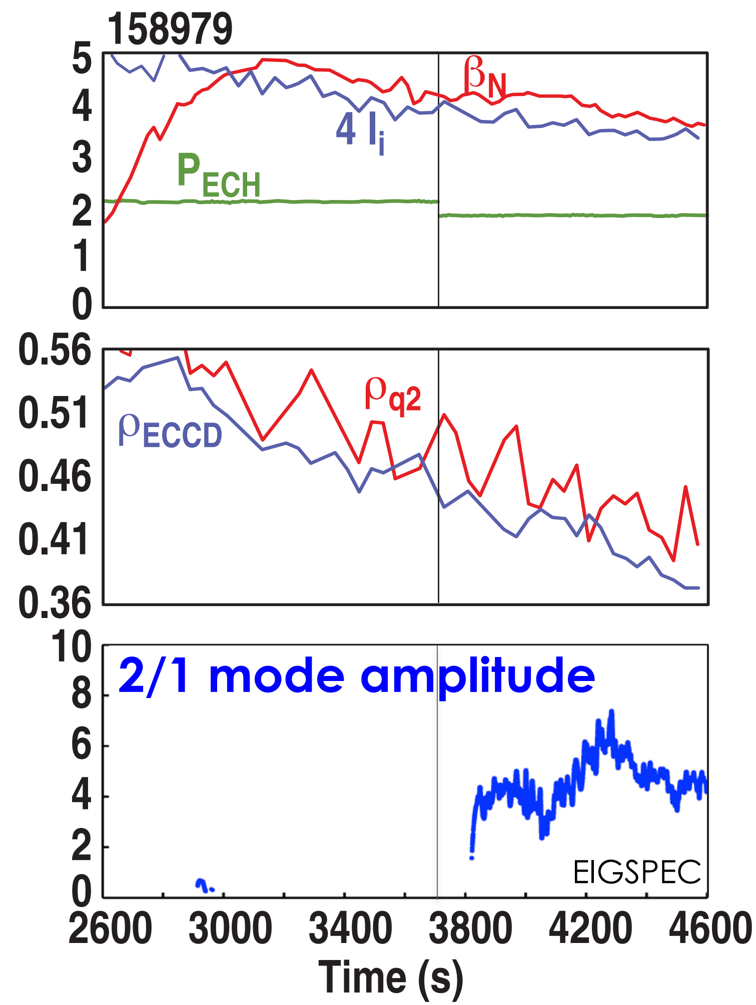


DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Snyder

Real Time ECCD NTM Control Enables Access to β_N=5 Double Null High l_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 li an exciting alternative for a fusion reactor**

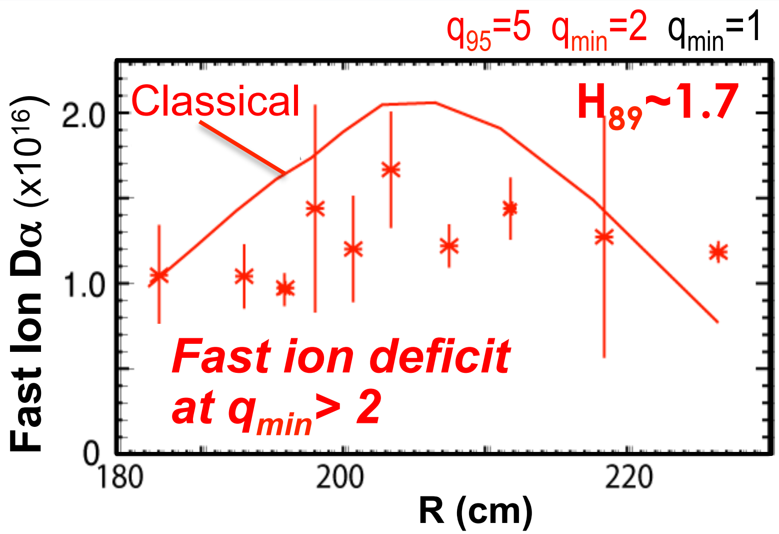
Snyder

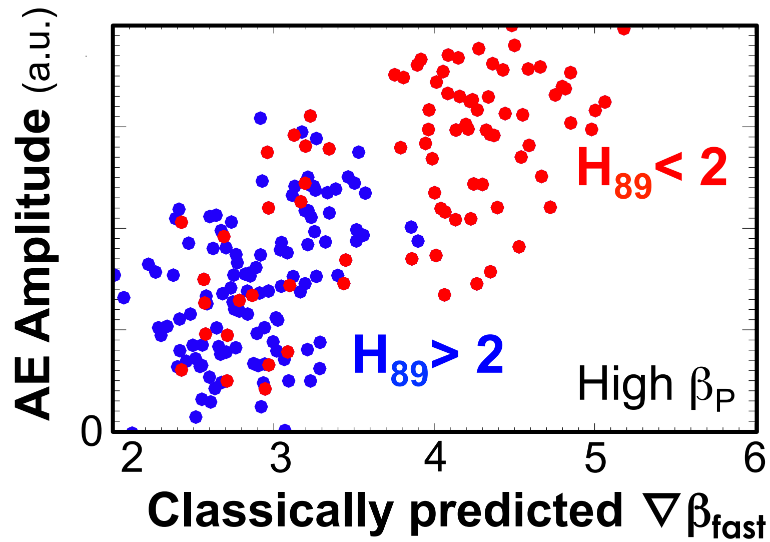
Ferron

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:

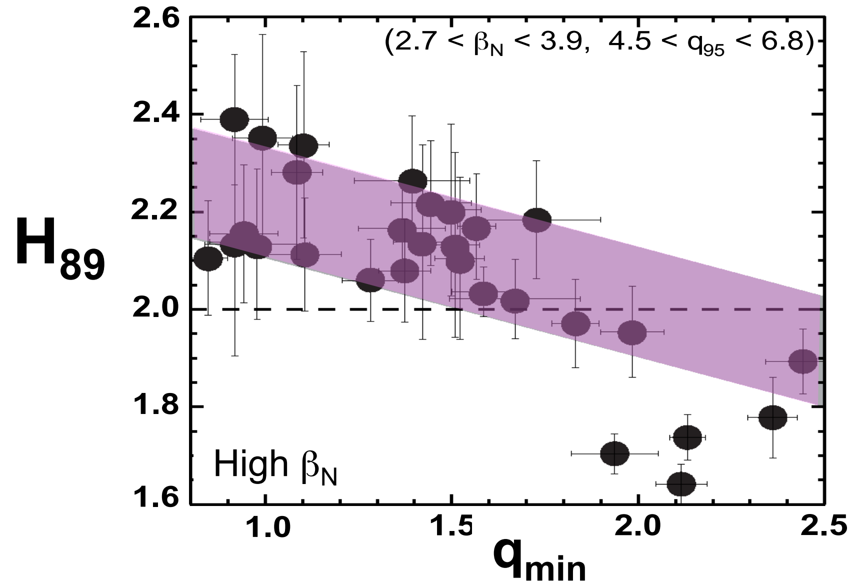
- *Off-axis NBI & ECH to reduce reduce central $\nabla\beta_{fast}$ and optimize thermal transport*
- *Improve pedestal*

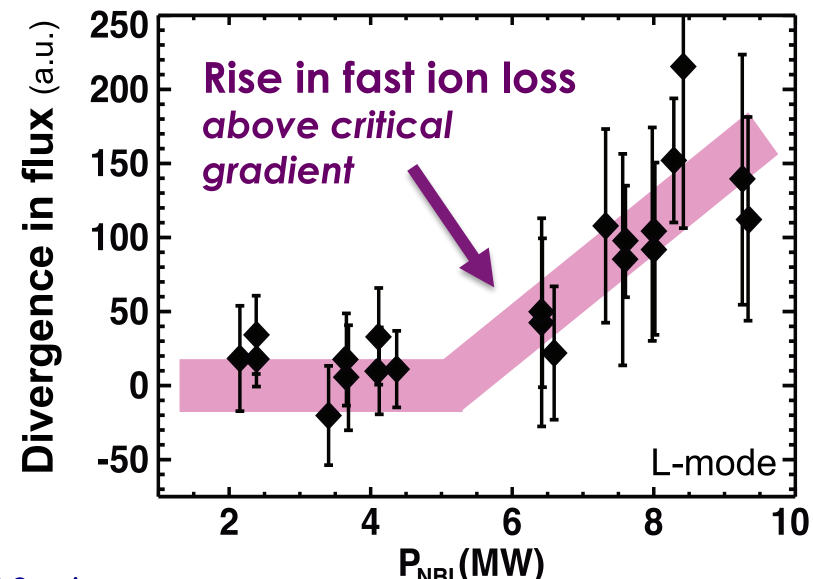
Heidbrink

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



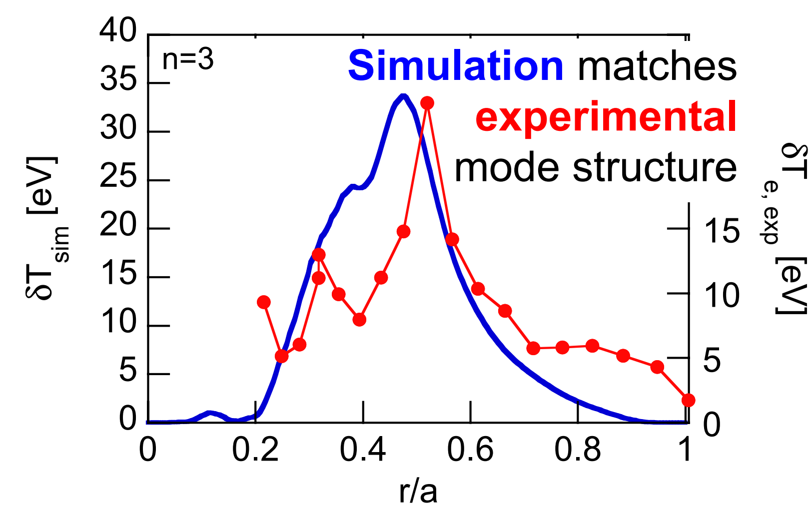


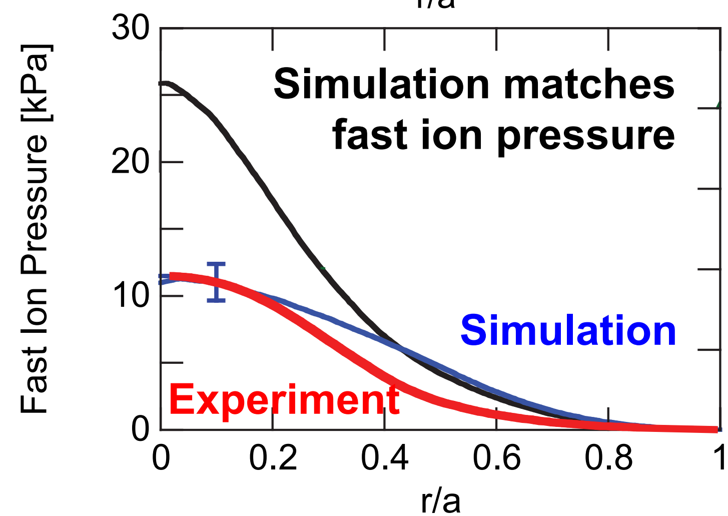
Heidbrink, Bass, Todo

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**





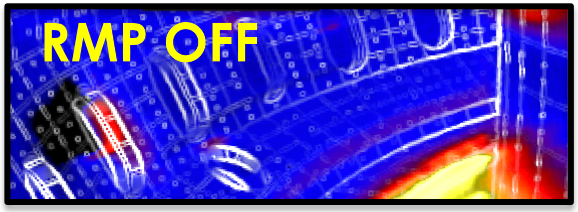
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

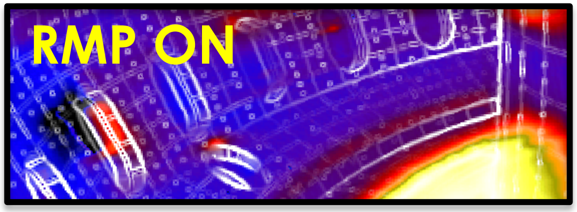
Todo

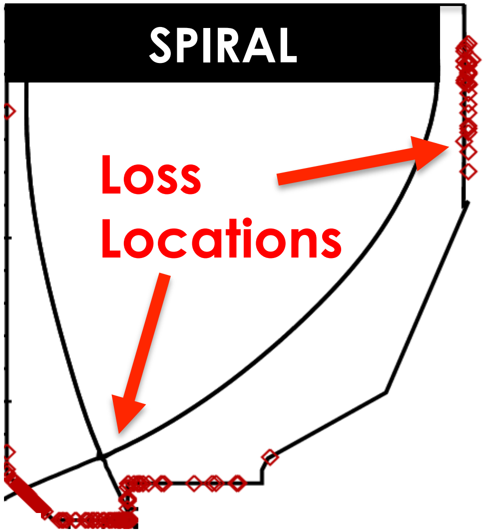
3D Fields for RMP-ELM Suppression Lead to Significant Energetic Particle Losses

- **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**



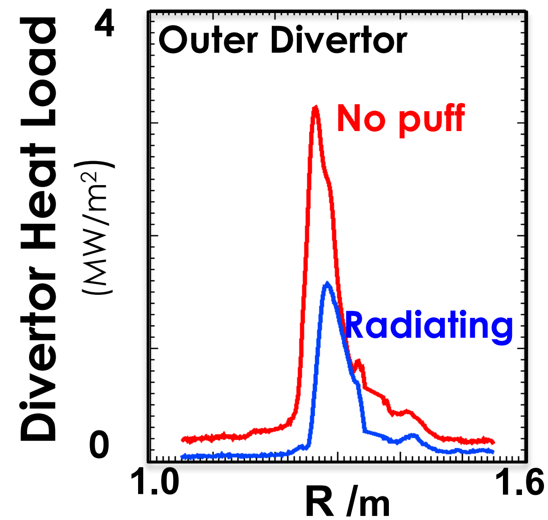


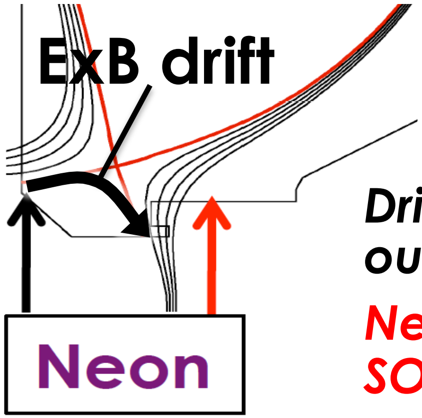


Van Zeeland

Techniques for Integrated Core-Edge Solutions Developed

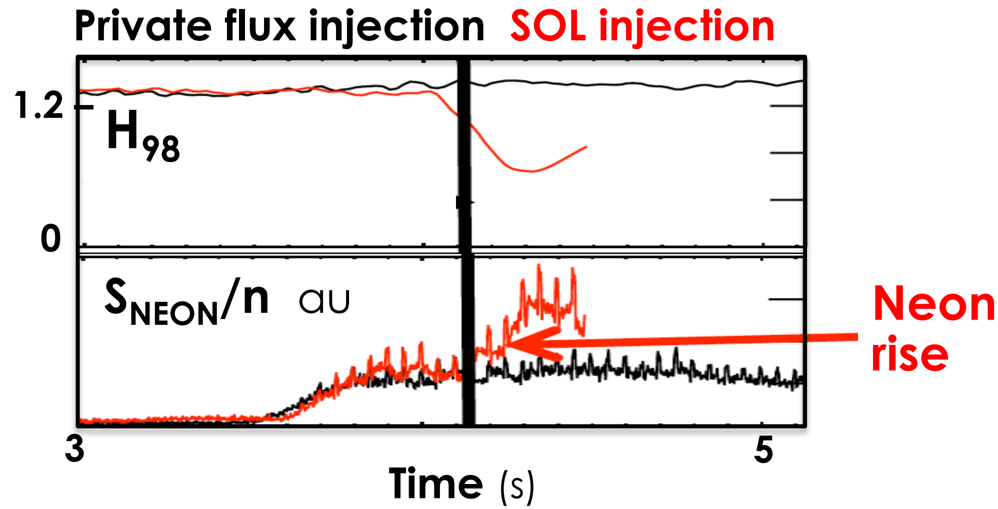
- **Combine radiative divertor with high performance steady state core**
  - Good performance maintained with β_N = 3.0, H_{98} = 1.3 throughout
  - Divertor heat flux reduced by x2
- **ExB drift important in optimizing divertor radiation and core dilution**
  - Neon injection required in private flux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





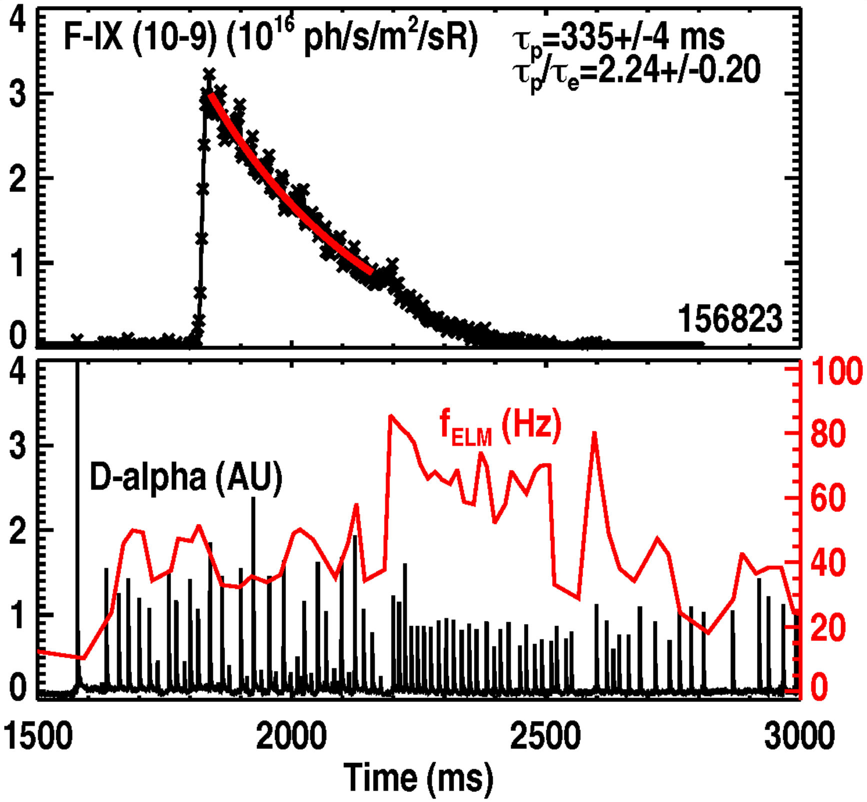
Drifts carry neon to outer strike point

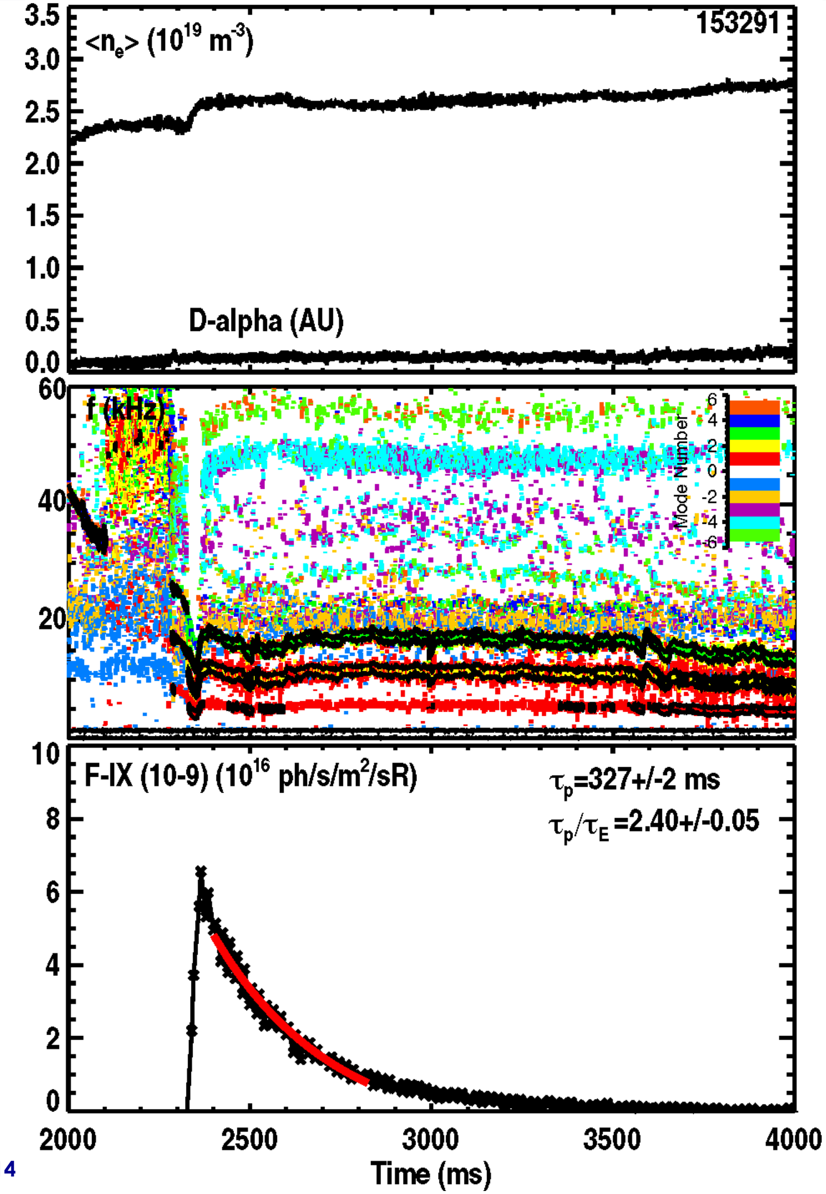
Neon escapes with SOL puffing



Petrie

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

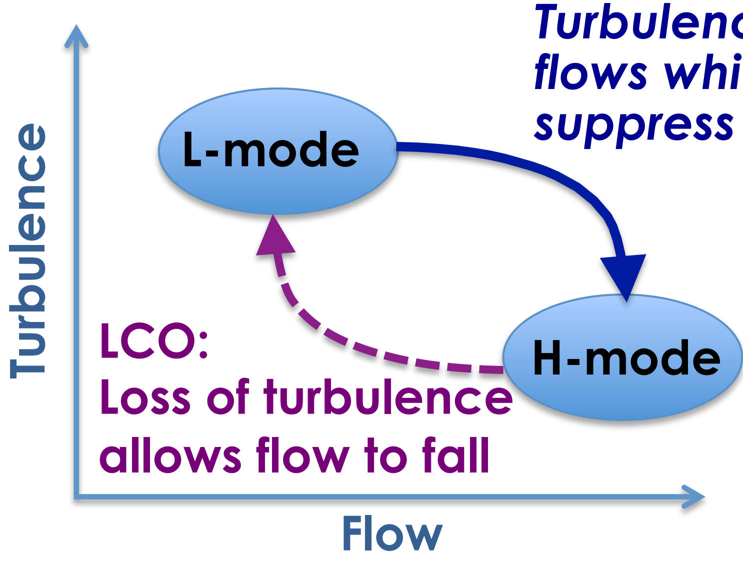




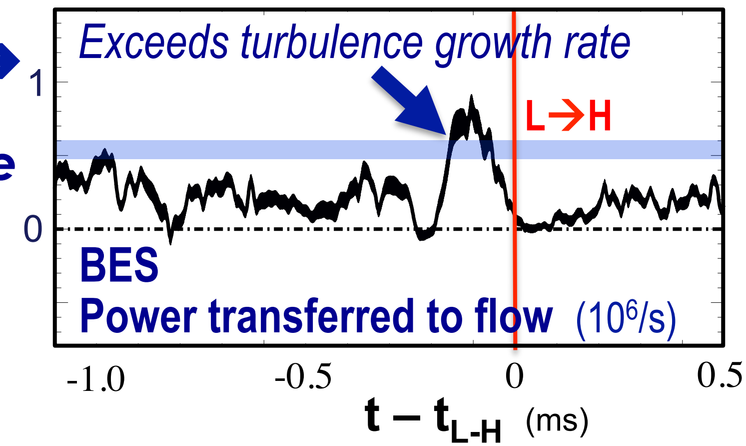
- **Measured by CER with non-recycling fluorine injection**

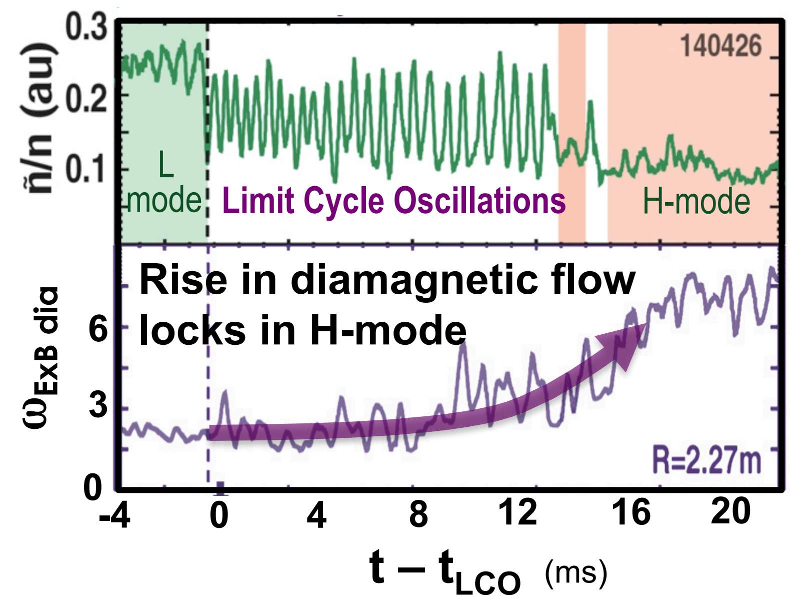
Solomon

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



Turbulence drives ➔ flows which suppress turbulence



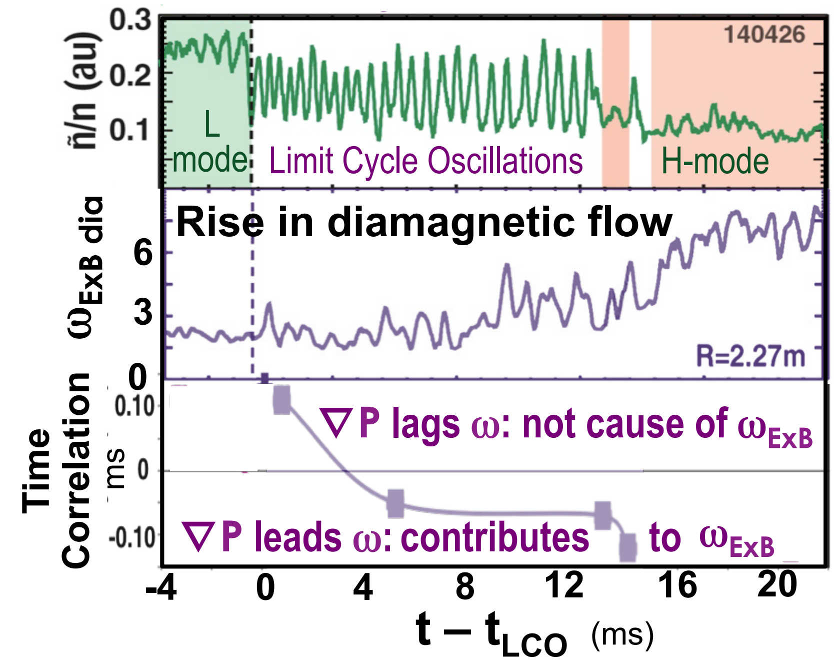


- **Limit cycle discharges** show ➔ ion diamagnetic flows required to lock in H-mode transition

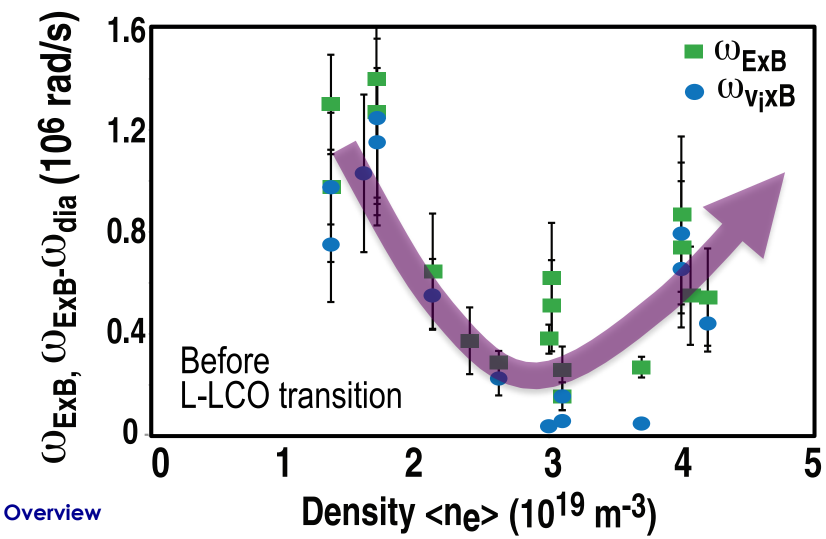
Schmitz

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**

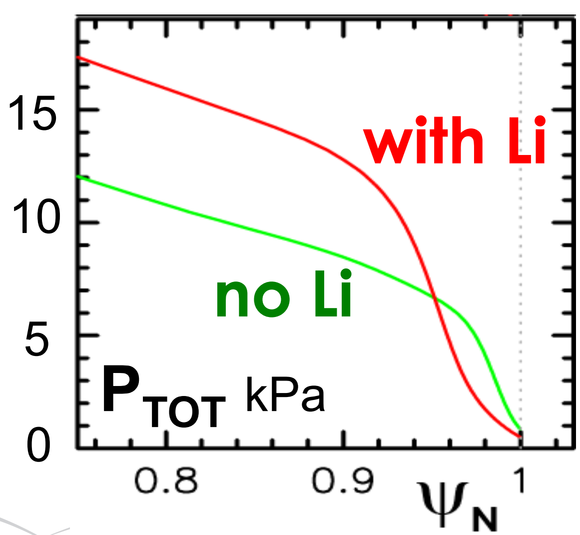


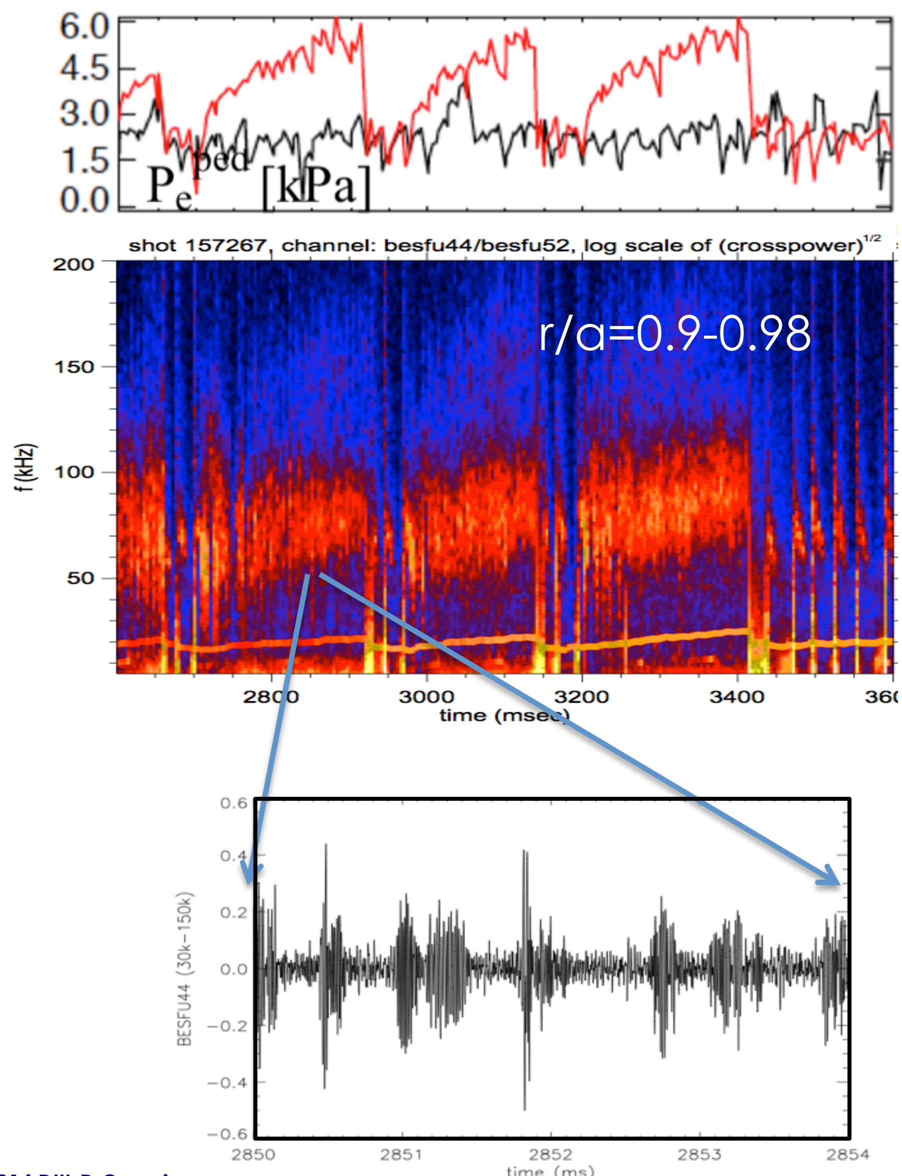
✓ **Promising foundation for physics based L-H prediction**

Schmitz

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

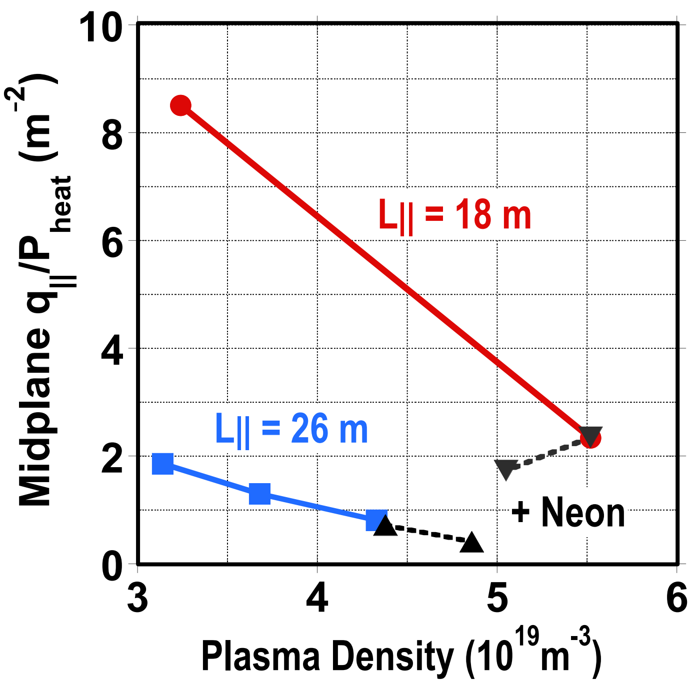


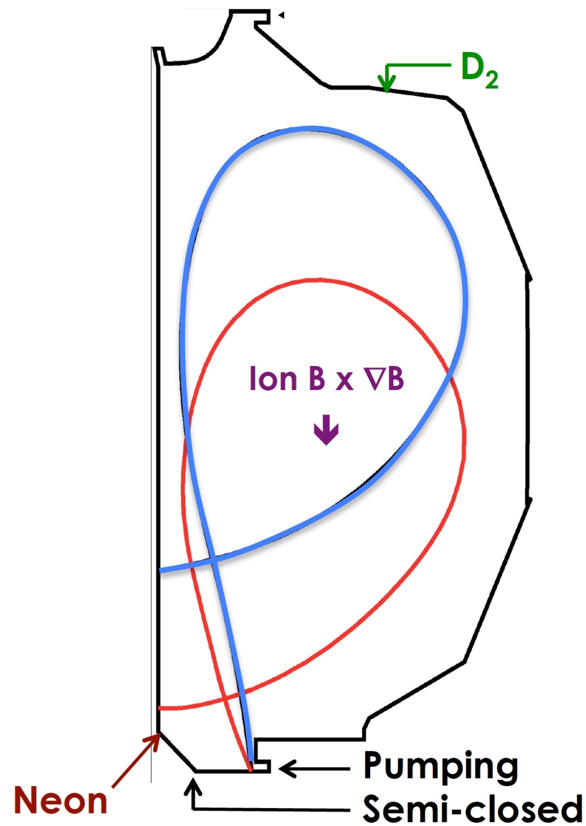


Jackson

Experiments Confirm Reduced Heat Flux with Increased Connection Length

- **Increased divertor volumetric losses**
  - Despite decreased flux expansion
  - Consistent with modeling



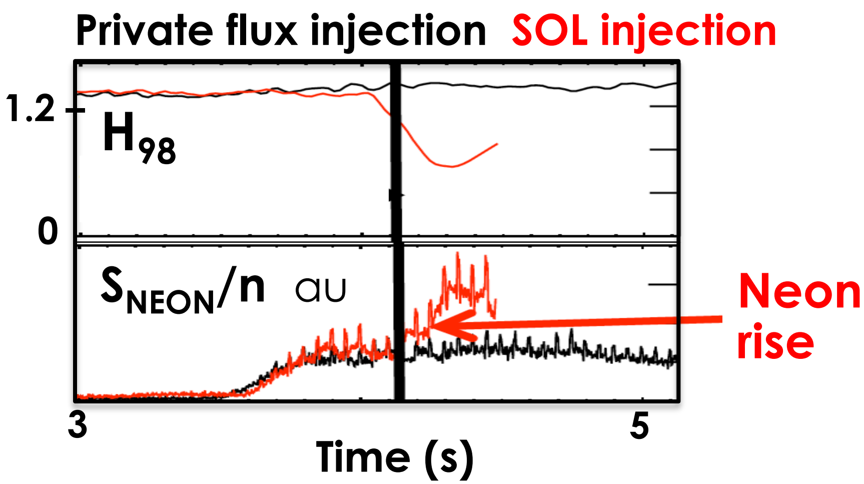


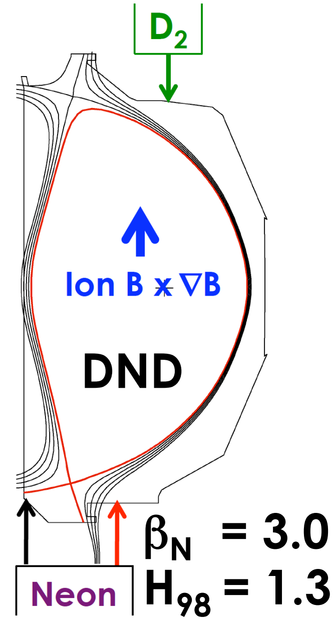
Divertor leg geometry an important aspect of divertor optimization

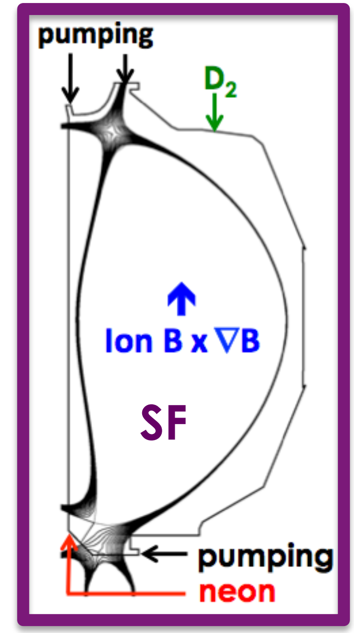
Petrie

Techniques for Integrated Core-Edge Solutions Developed

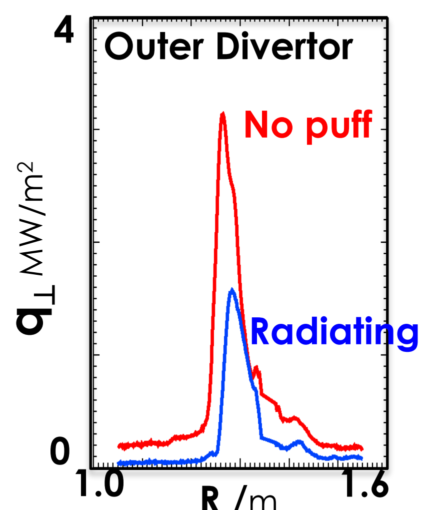
- **Injection in private flux region away from ion B×∇B reduces core impurity rise**
  - Radiative divertor halves heat flux

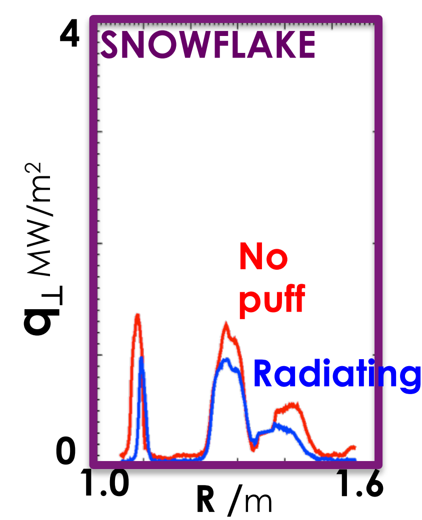






- **Snowflake divertor further reduces heat loads in AT plasmas**
  - Modest benefit with Ne radiation
  - But 30% increased Ne in core

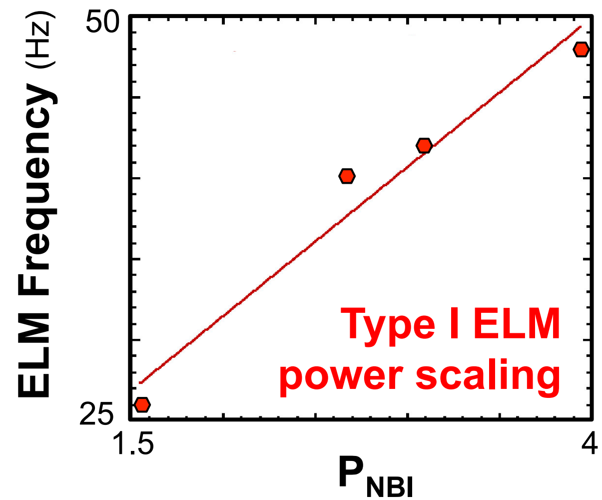


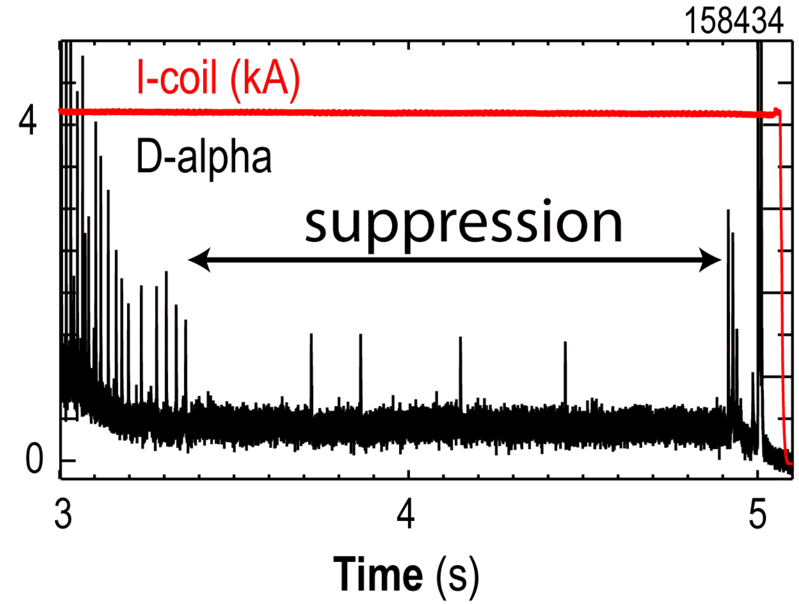


Petrie, Soukhanovski

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**

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Nazikian/Wade

...in collaboration with ITER