United States Burning Plasma Organization

# US Contributions to ITER Physics

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*Director, US Burning Plasma Organization*

presented at the

Fusion Power Associates

38th Annual Meeting and Symposium

December 7, 2017

Washington, DC

http://burningplasma.org

This work is supported by the US DOE under DE-FC02-04ER54698.

# The US Fusion Energy Sciences Community is actively working to ensure a successful ITER research program

USBPO
U.S. BURNING PLASMA ORGANIZATION

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  - ELM suppression or mitigation
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  - Measurement in a burning plasma environment

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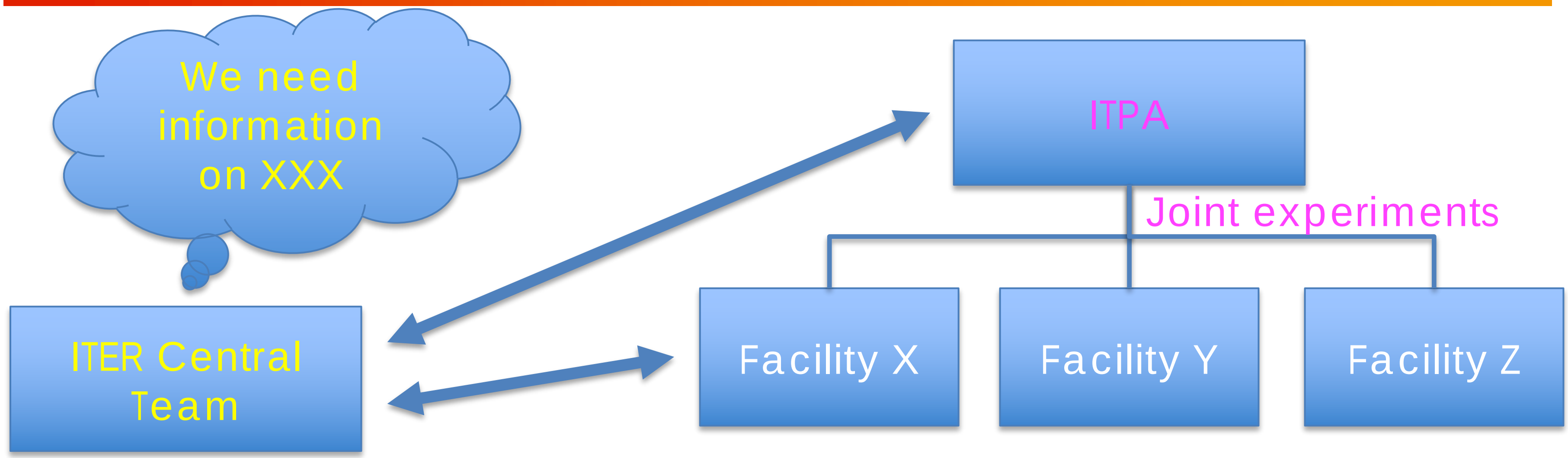
# ITER physics tasks are a communal responsibility (all seven parties)




- Usually identified by ITER Organization
  - Could be addressed through ITPA
  - Could be organized directly with individual facilities
- Communication with ITER Science and Operations Division has been excellent
  - We expect this to continue under new leader Tim Luce (formerly of GA)
- In many areas, different facilities/parties work together
  - ITER personnel frequently participate

ITER physics tasks are often carried out in a collaborative manner, crossing borders between partners. This talk focuses on work done by and in the US FES community

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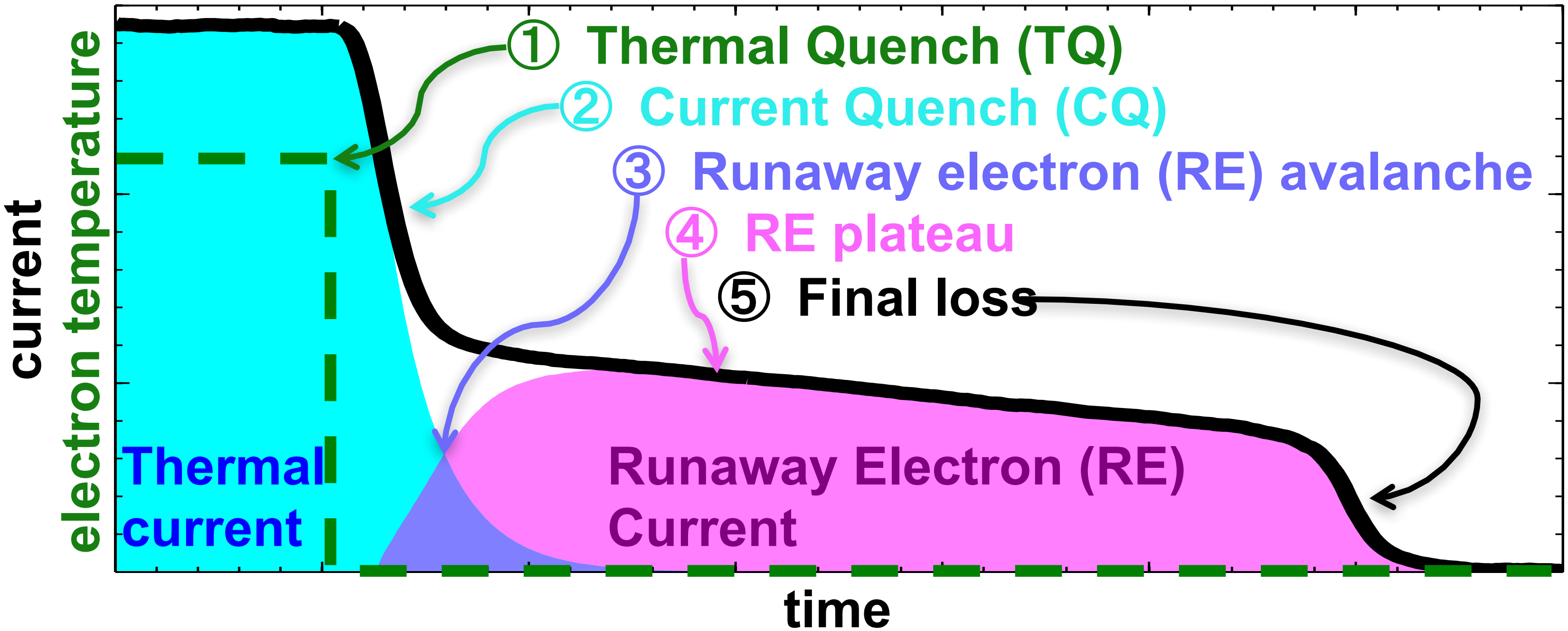
# 2016 FES Joint Research Target: Explore disruption avoidance and mitigation

Mitigation techniques inject particles into plasma to radiate away energy content

- MGI: Massive Gas Injection
- SPI: Shattered Pellet Injection



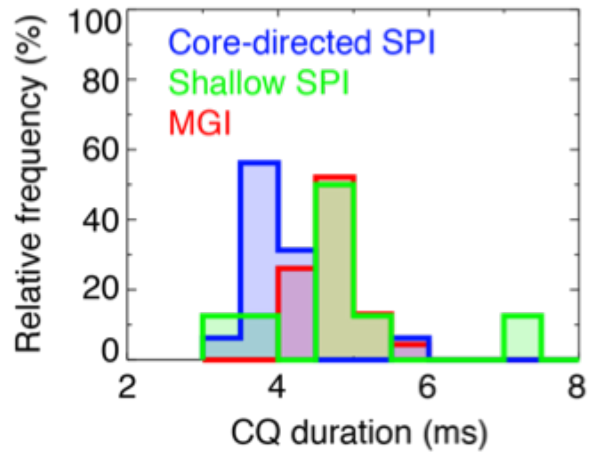

- Compared MGI mitigation of “sick” and “healthy” plasmas (C-Mod, DIII-D)
- Tested and installed 3 ITER-like MGI valves (NSTX-U)
- Runaway physics studied (C-Mod and DIII-D)
- Develop and install multi-machine disruption warning algorithm (NSTX/NSTX-U)
- Explored advanced MHD control techniques (DIII-D)

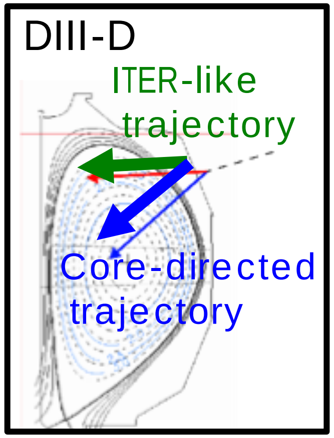
# Shattered Pellet Injection (SPI) selected as ITER's day 1 DMS

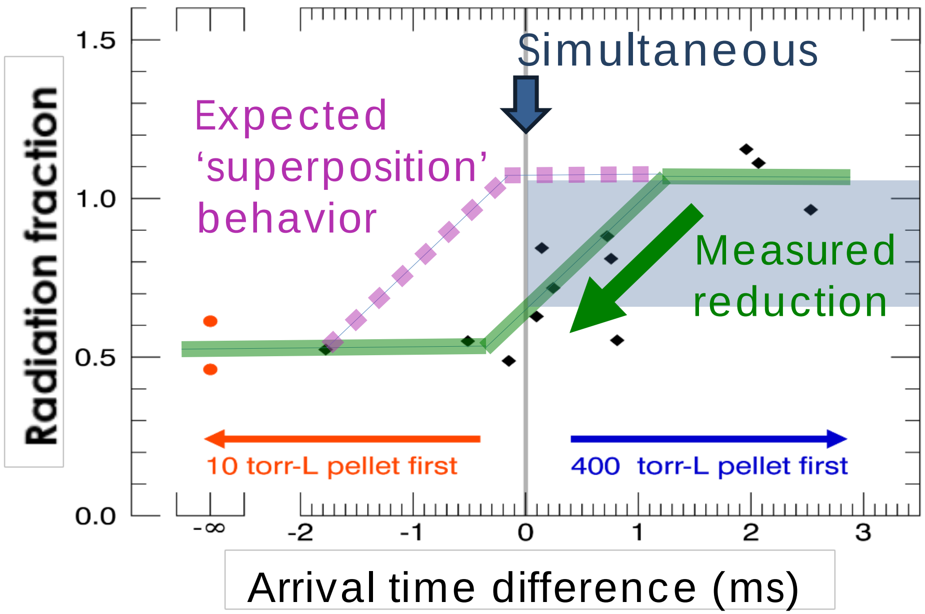
- Wine-bottle-cork-scale pellet fired into the tokamak, shattering on the way in
  - Tested with $D_2$ and Ne (high-Z better)

<u>Recent results (PRELIMINARY)</u>

- Shallow (ITER upper port) trajectory reduces SPI effectiveness vs. core directed injection
- Effectiveness of multiple SPI depends on injection timing
  - 2nd smaller pellet leads to less radiation than single large pellet
  - New experiment with two identical 400 torr-L pellets performed, results pending interpretation
- Work is continuing…



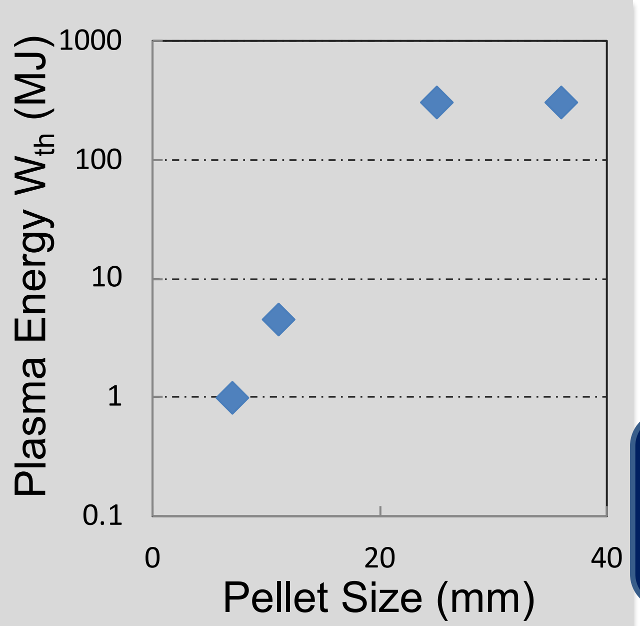



# Collaboration on JET Shattered Pellet Injector will inform ITER disruption mitigation requirements

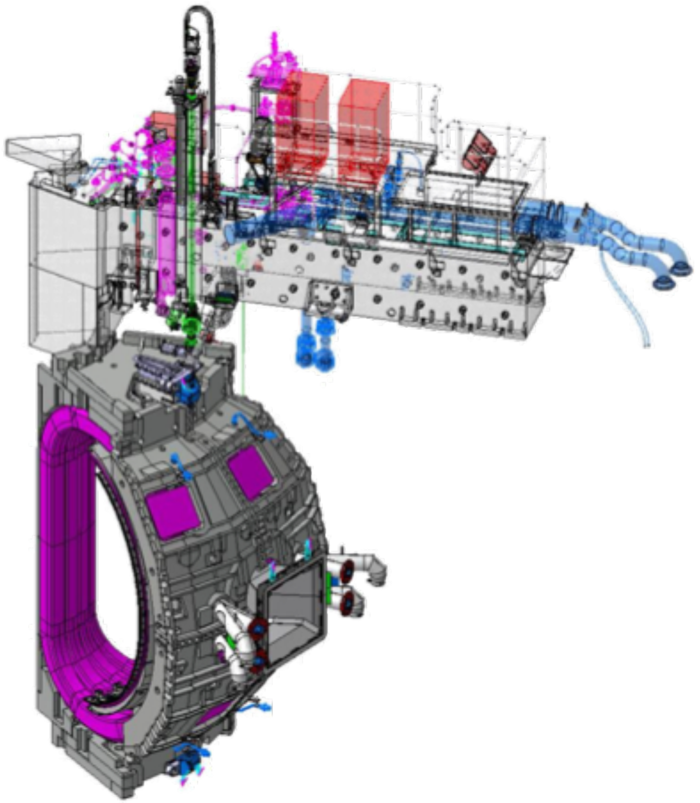
## Status of U.S. Contributions

- D pellet injector from ORNL tested successfully
- Mechanical punch designed to dislodge high-Z pellets in the largest barrel requires further development, works in the two smaller barrels
- Cold zone for large barrel may be reduced to achieve desired performance
- Shipment to JET is imminent

*Also being deployed in J-TEXT, HL-2A, MST*




**JET SPI has ITER-like 3-barrel injector and injection trajectory**



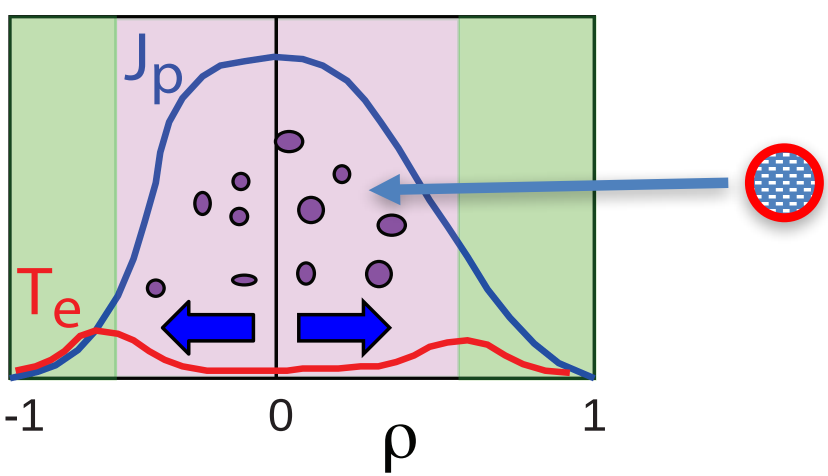
***Large Collaborative effort involves JET/EUROfusion, ORNL, USIPO, ITER Org, EC, and US DOE***

# Alternative DMS approaches under study

- ITER DMS can be upgraded if better alternatives are available and developed to maturity by ~2029
- Two options currently under study in the US

## Low-Z dust-filled shell
(N. Eidietis, GA)

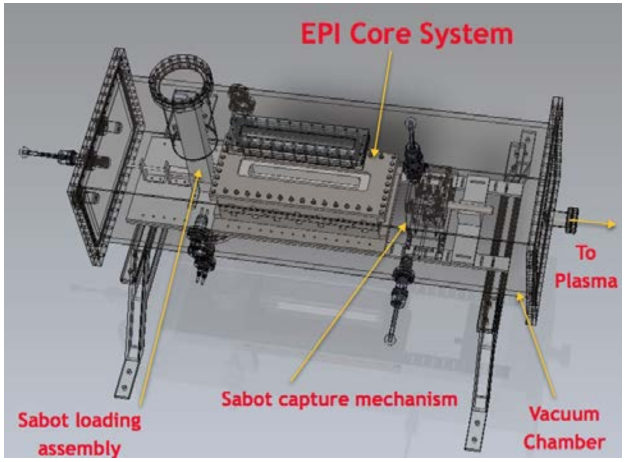
"Inside-out" thermal quench mitigation + stochastic runaway electron deconfinement & high $n_e$ suppression + maintains moderate current quench rate




## Electromagnetic Particle Injector
(R. Raman, U Washington)

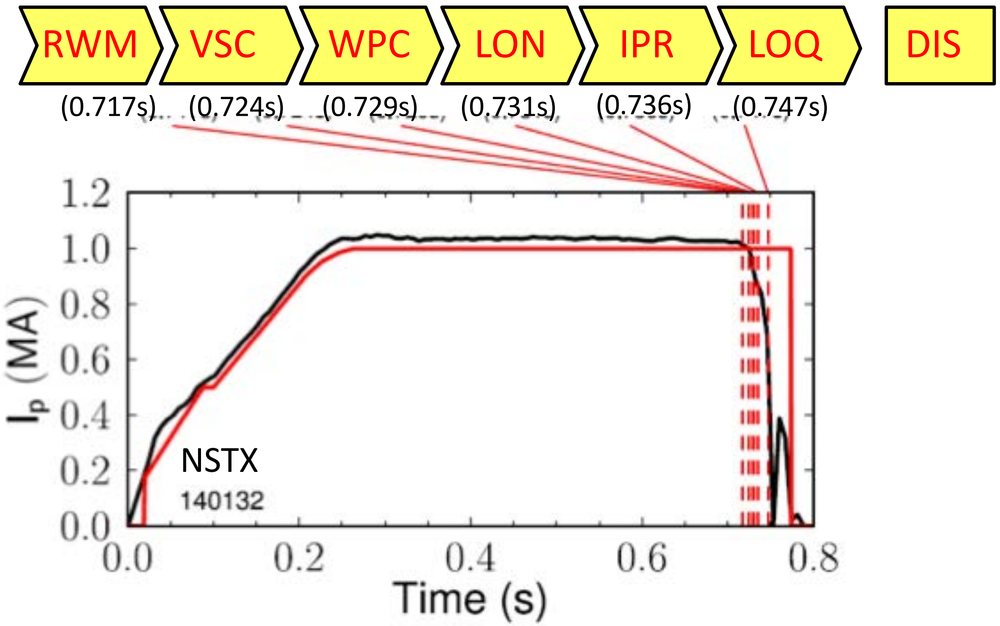
Rapid delivery of impurities deeper into the plasma with fast time response

Prototype tested, time response and velocity consistent with predictions

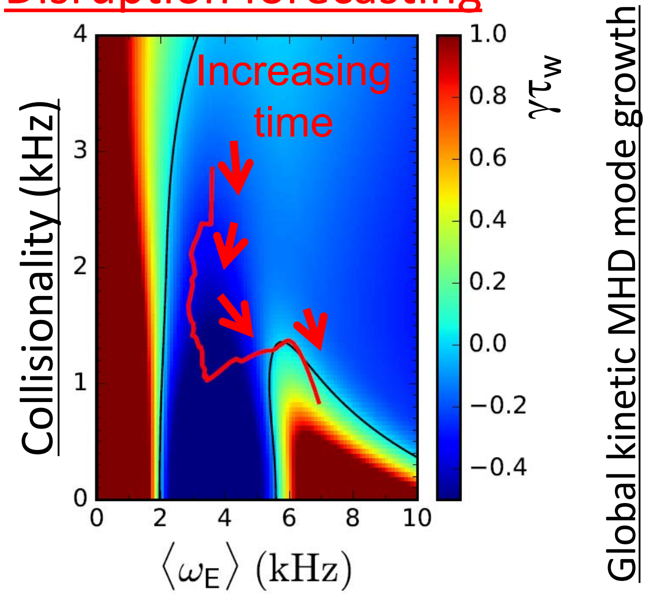



# Disruption Event Characterization and Forecasting innovation to enable disruption avoidance

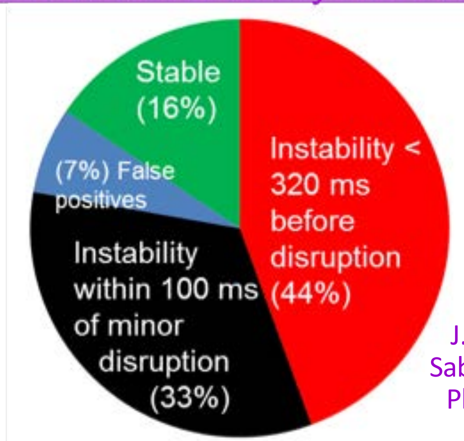
## Automated disruption event chain analysis




## Disruption forecasting




## Predicted instability statistics




J.W. Berkery, S.A. Sabbagh, et al., Phys. Plasmas **24** (2017) 056103

## Analysis aimed to cue disruption avoidance systems

- Physics-based disruption forecasting models begun
- Prediction quantitatively compared to experiment
- Collaborative (inter)national multi-device studies starting (incl. NSTX/-U, KSTAR, DIII-D, TCV)

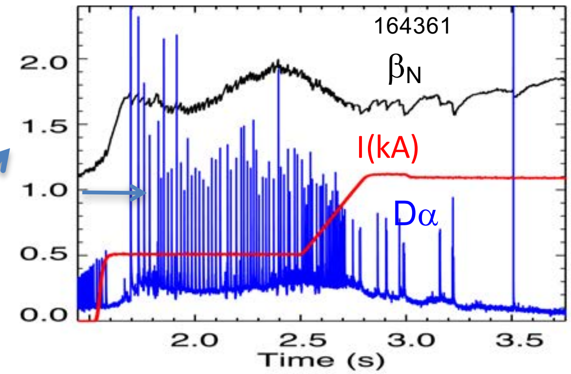
DECAF code

# ELM control with magnetic perturbations produced by internal coils is planned for ITER

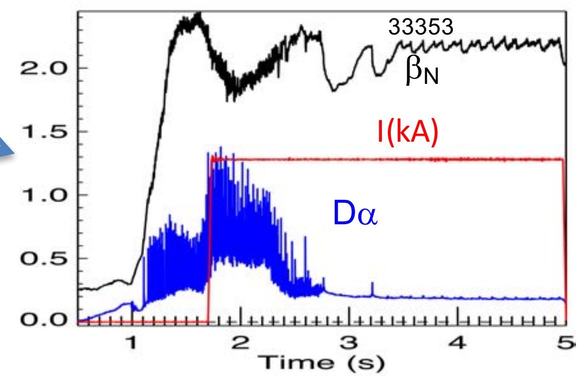
## Resonant Magnetic Perturbations (RMP)

- Full suppression demonstrated on ASDEX-U through collaboration with DIII-D
- Result on DIII-D suggested lower collisionality on AUG is key
- Follow on experiment on AUG achieved ELM suppression
- Encouraging result for ITER

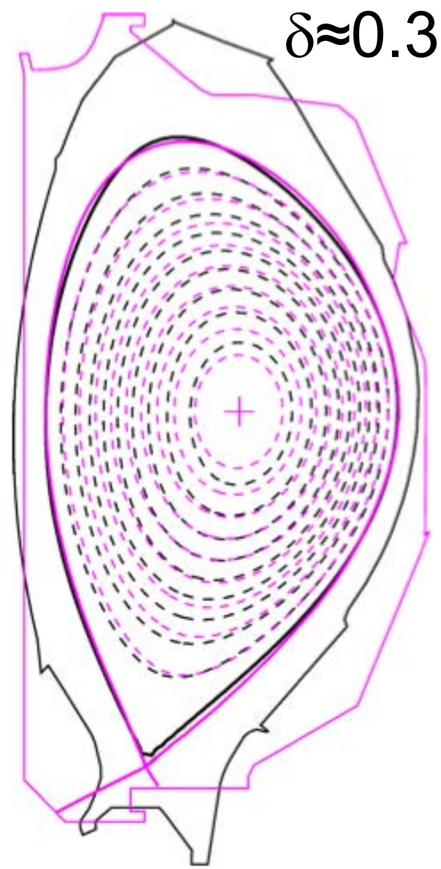
**DIII-D n=3 RMP**



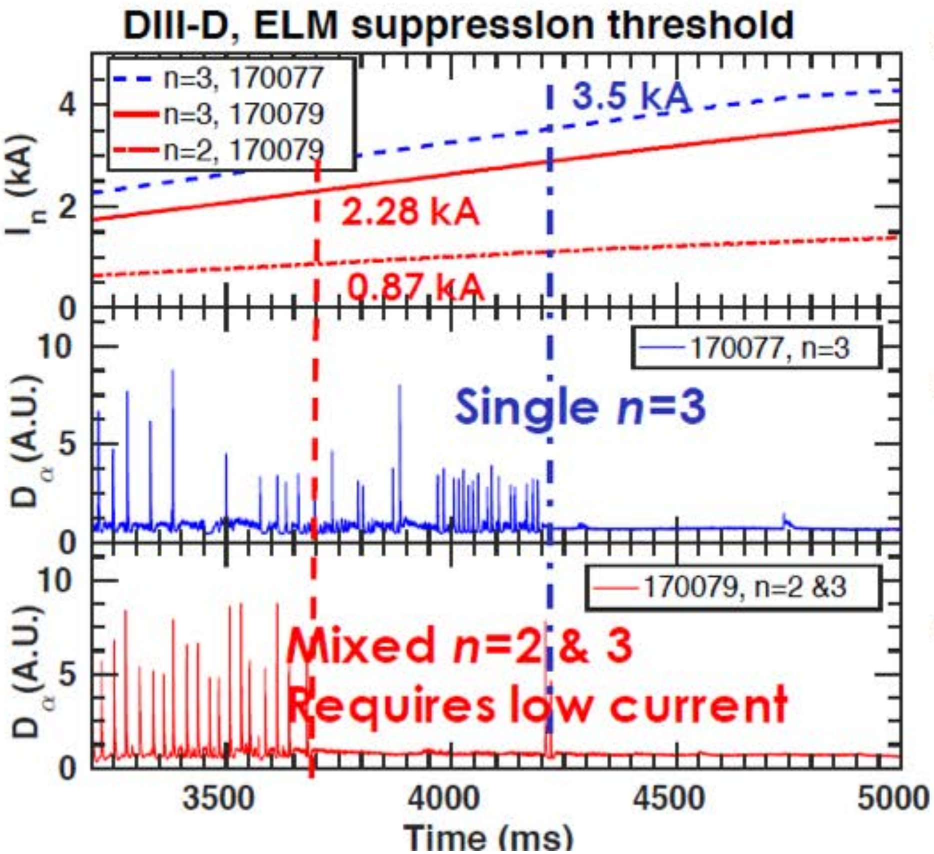

**AUG n=2 RMP**




**Shape overlay DIII_D/AUG**



# Multi-mode RMP lowers threshold current for ELM suppression in DIII-D



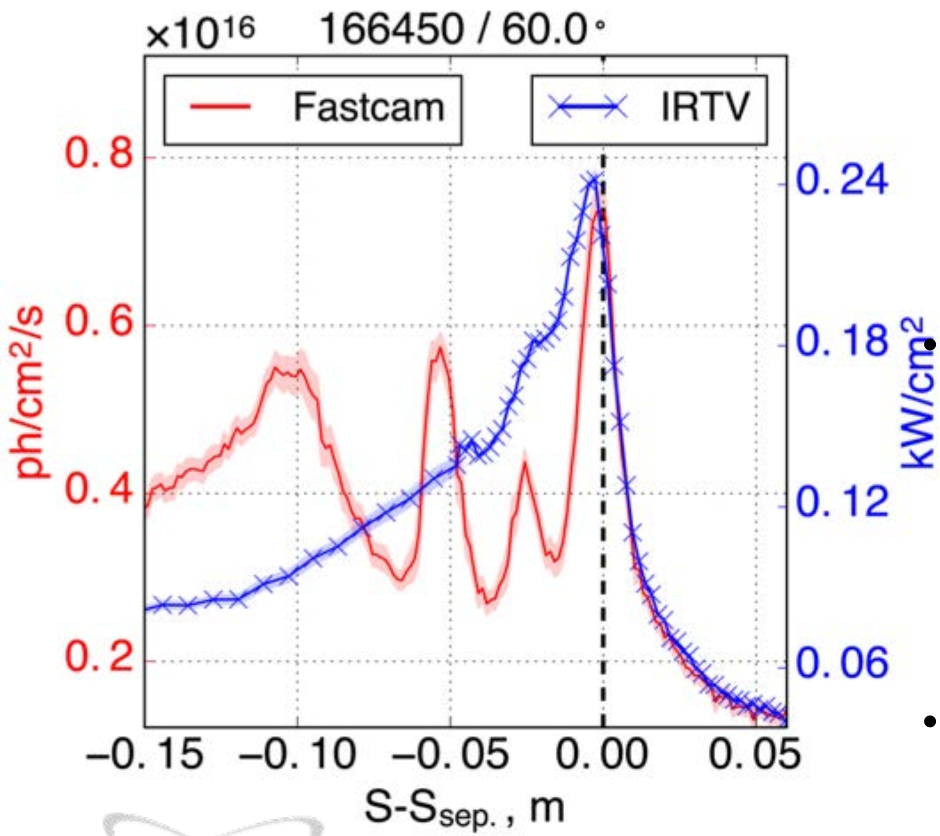

- Multi-mode RMP with **mixed *n*=2 and 3** lowers total coil current to access ELM suppression compared with pure *n*=3 case
- **Maximal current**
  **2.28 + 0.87 = 3.15kA < 3.50kA**
- $\propto$ **Energy$^{1/2}$**
  **$(2.28^2 + 0.87^2)^{1/2}$ = 2.44 kA < 3.50kA**

**Multi-spectral tailoring of applied field made possible by new power supplies from ASIPP/EAST**

ASIPP

# Weak heat flux splitting in DIII-D RMP ELM suppression → dynamic RMP control may not be required in ITER

## Does ITER need to rotate the RMP perturbation?

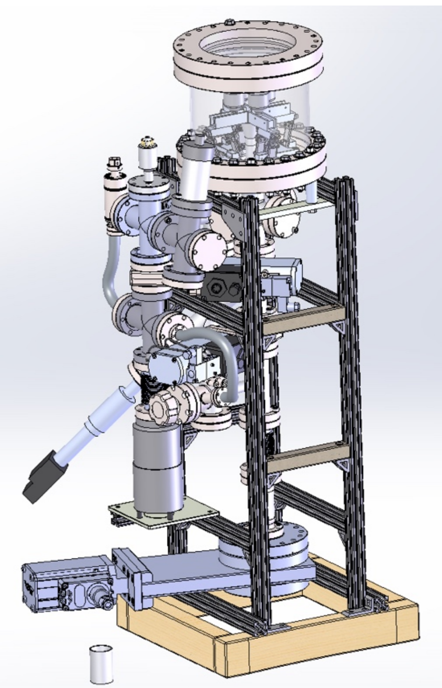



R. Moyer, D. Orlov (UCSD)

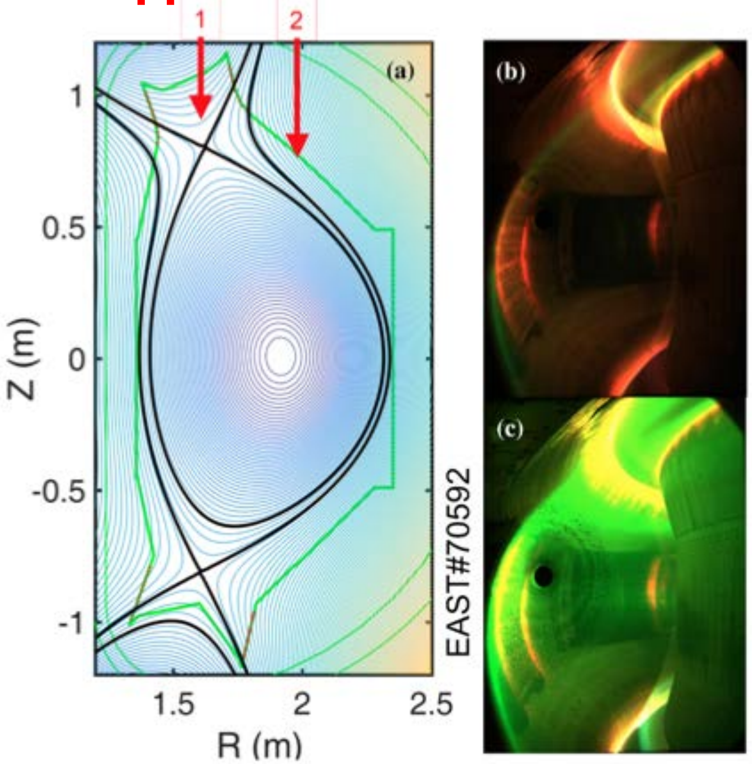
- Heat (IRTV) and particle flux (Fastcam visible imaging) splitting measured in DIII-D RMP ELM suppressed discharges with ITER similar shape and operating conditions shows
  - clear splitting in particle flux
  - no clear splitting seen in heat flux
- Divertor strike point particle flux splitting exceeds vacuum predictions by 3x-5x
  - challenges linear plasma response models which result in predominantly screening
- Partial HFS strike point heat flux detachment achieved with mid-Z puffing.
  - RMP ELM suppression maintained over wide range of collisionalities

# ELMs Eliminated in EAST Using PPPL Impurity Dropper in Scenarios with Tungsten Divertor

## PPPL Impurity Dropper on EAST



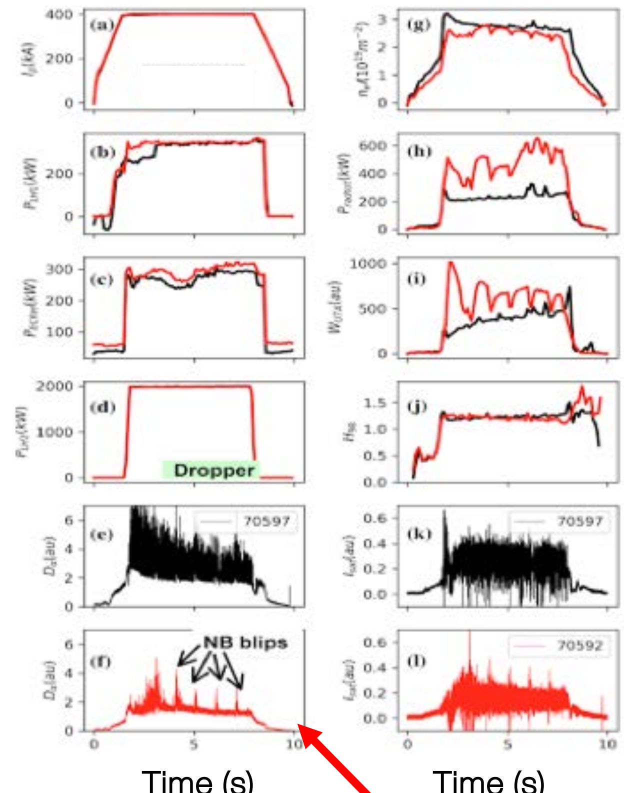
## Dropper Locations




R. Maingi, Nucl. Fusion (2017) submitted

## Dropper OFF

## Dropper ON




**ELMs suppressed**

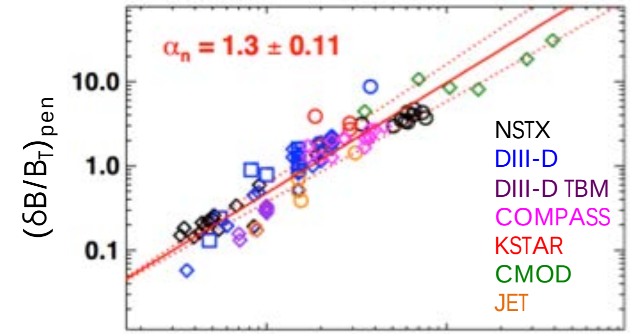
ASIPP

PPPL

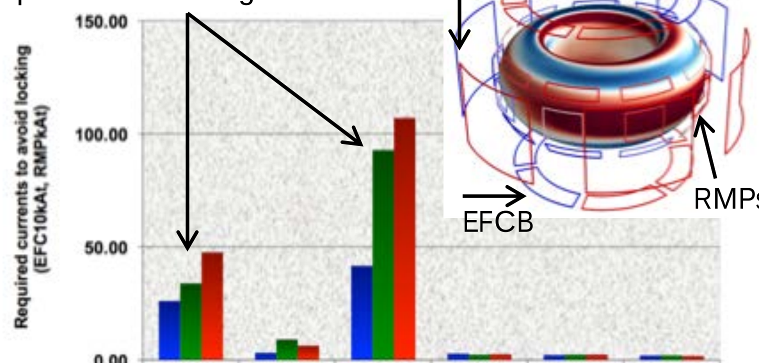
# US leading international efforts to develop ITER error field correction strategy (ITPA MDC-19)

- On-going effort to predict error field (EF) tolerance of ITER operation (MDC-19)
  - Using 3D MHD response metrics
  - Resonant n=1 EF criterion (2017): $(\delta B/B_T)_{pen}=0.0006(n_e)^{1.3}B_T^{-1.7}R^{0.7}\beta_N^{-0.78}$
  - New resonant n=2 EF criterion is due on 2018 March ITPA MHD meeting
  - Two more EF criteria on NTV and heat flux splitting are under investigation
- MDC-19 will provide final report and recommendation for 3D coils by 2019, based on each EF correction capability
  - In particular, on top and bottom ex-vessel coils (EFCT, EFCB), which are found 10 times less efficient to control n=1,2 resonant fields

Error field penetration thresholds vs. density




10 times higher currents are required to avoid EF-resonant disruption when using EFCT/B




| | EFCT (10kAt) | EFCM (10kAt) | EFCB (10kAt) | RMPU (10kAt) | RMPM (10kAt) | RMPL (10kAt) |
|---|---|---|---|---|---|---|
| Scen2_Flat | 26.00 | 3.13 | 41.60 | 2.77 | 2.19 | 1.98 |
| Scen2_Burn | 33.77 | 9.06 | 92.88 | 2.32 | 2.32 | 2.01 |
| Scen4_Burn | 47.56 | 6.29 | 107.00 | 2.52 | 2.38 | 1.78 |

J.-K. Park, et al.

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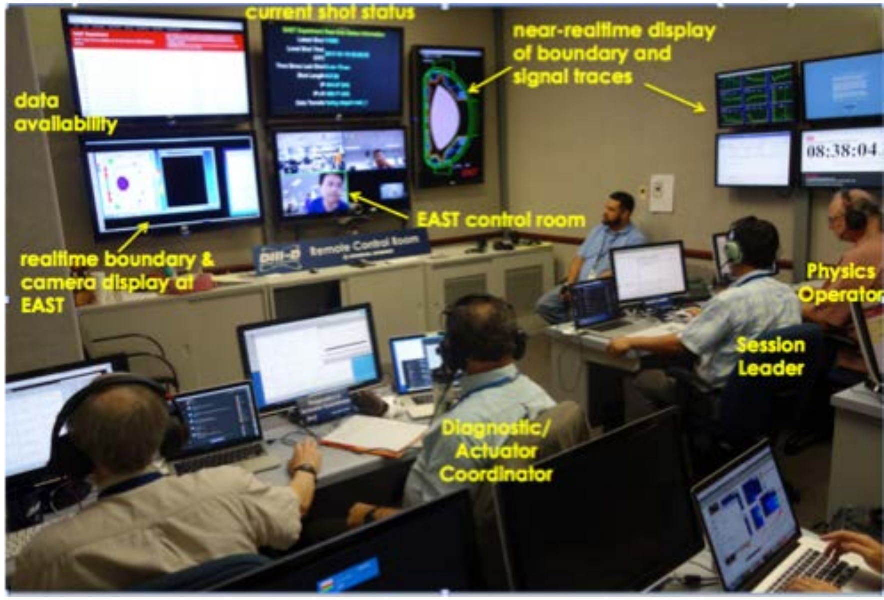
# US contributions to ITER control

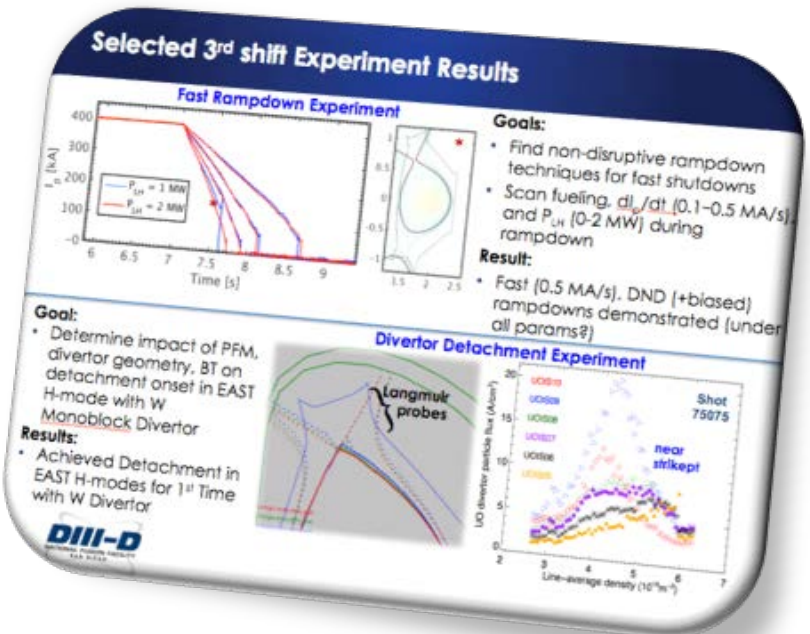
- Development of ITER-relevant controls on US tokamaks
  - Plasma shape, current, & vertical position control
  - Non-axiysymmetric (e.g., RWM, NTM) stability control
  - Current profile control
  - ELM control
  - Off-normal event detection and handling
  - Divertor control
  - Alfvén Eigenmode control
- Participation in design of ITER real-time framework and PCS
- Support for development of ITER Plasma Control System Simulation Platform (PCSSP)
  - PCSSP is a software platform for development and validation of ITER PCS

# Effective remote experiments demonstrated during EAST 3rd shift operations

Scientific Achievements in 2017:

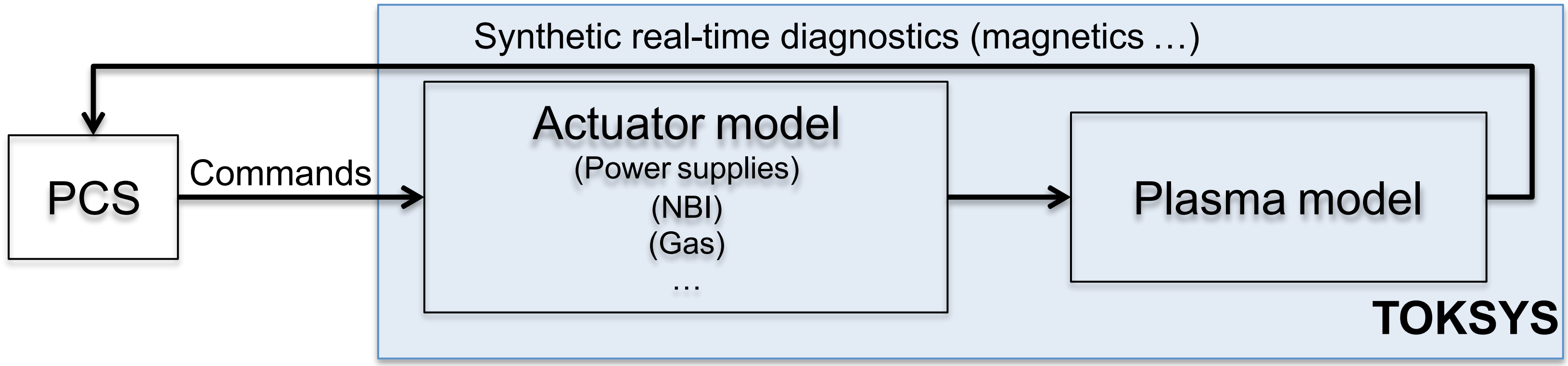
- Remote technology challenges addressed (audio, data transfer)
- Four expt's carried out over 5 shifts (1 wk)
- New EAST capabilities demonstrated
  - Divertor detachment
  - Fast rampdown without disruption




- Prototype for remote participation in ITER
- Remote control rooms now available at
  - GA (EAST, KSTAR)
  - PPPL (KSTAR, W7-X)
  - MIT (in preparation)

# Modeling framework aims to accelerate ramp-up scenario and control development

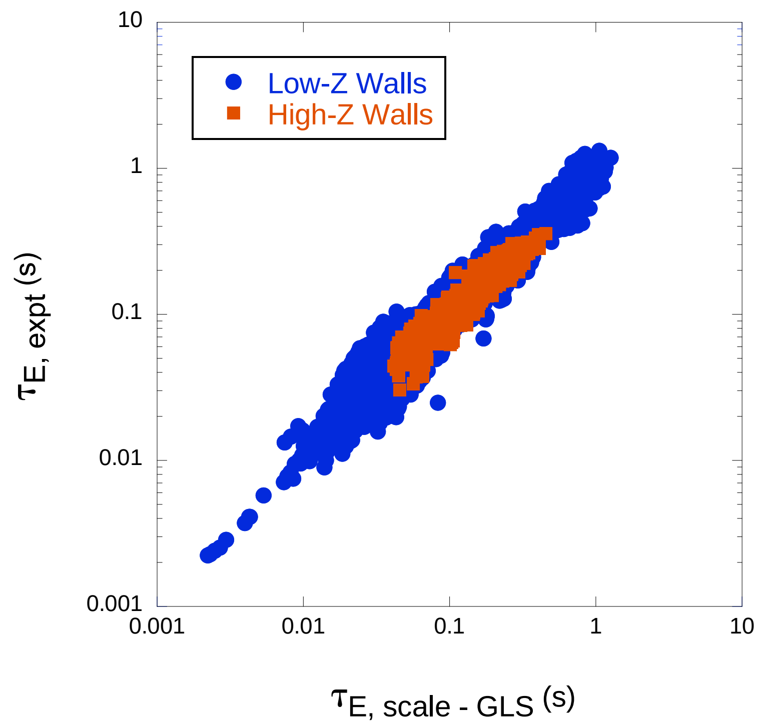



- **TOKSYS: Matlab code used to develop actuator and plasma models for testing PCS algorithms (supported by GA)**
- **Two major development efforts**
  - Design and validate plasma model using experimental data and simulations (i.e. TRANSP, DCON)
  - Develop non-linear models and/or switching between linear models
    - Flattop modeling typically uses linearized model around a reference case
- **Ultimate goal: develop, test and optimize scenarios and control in the ramp-up phase in offline simulations**

D. Boyer, PPPL

# Update and reanalysis of international H-mode database for ITPA Transport and Confinement TG

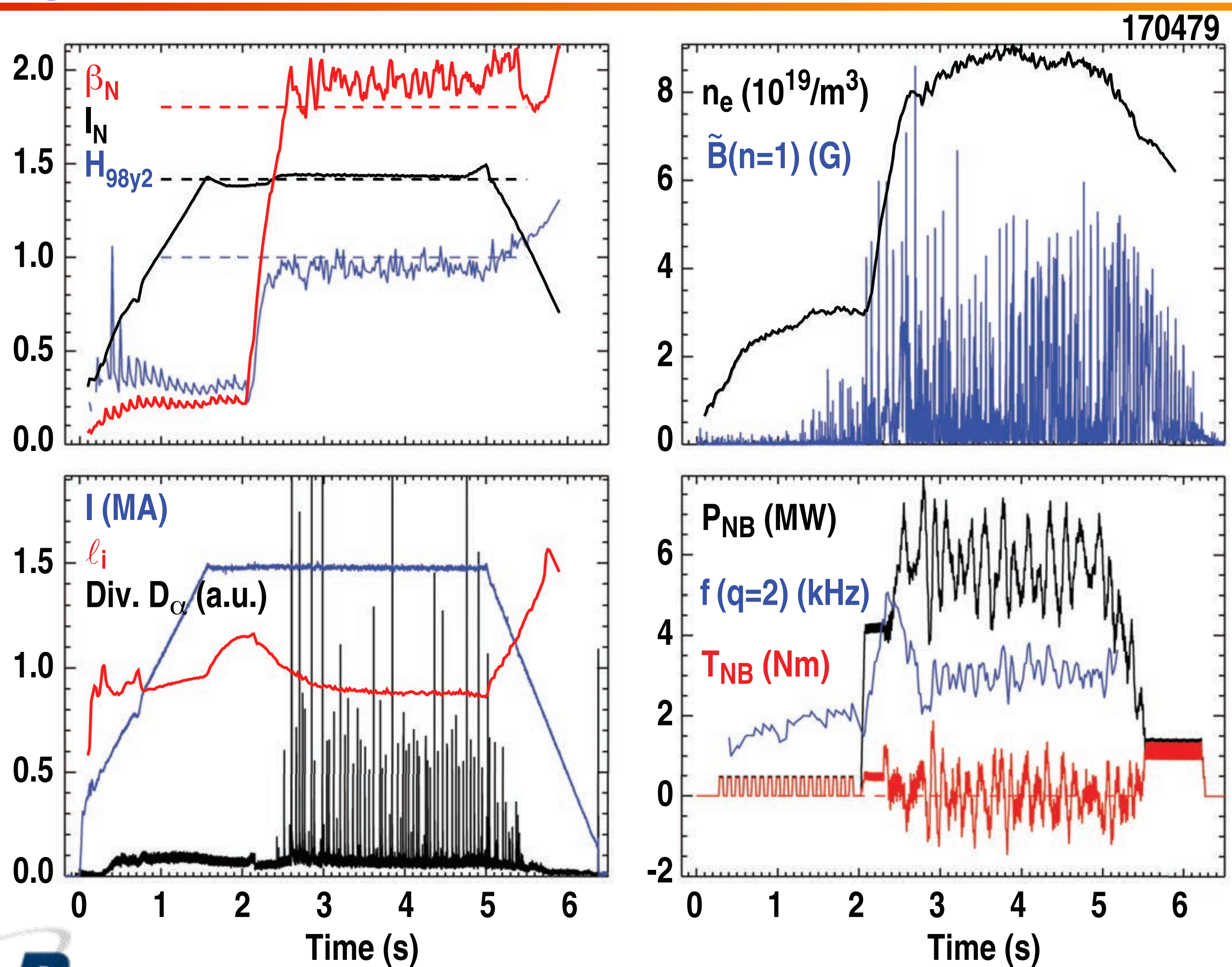
- Add data closer to ITER baseline conditions + hybrids, including data from high-Z wall devices
- Expand parameter range and explore new variables (torque, $n_{e,SOL}$ and $n_{e,sep}$, improved fast ion content)
- Separate core and pedestal scalings, provide a more realistic density dependence
- 2 devices included so far: JET and ASDEX-Upgrade
  - AUG: 613 W-wall ITER baseline discharges
  - JET: 630 data points with ILW




**New C-Mod dataset under preparation**

S. Kaye, PPPL

# Stable zero-torque ITER Baseline Scenario discharges achieved

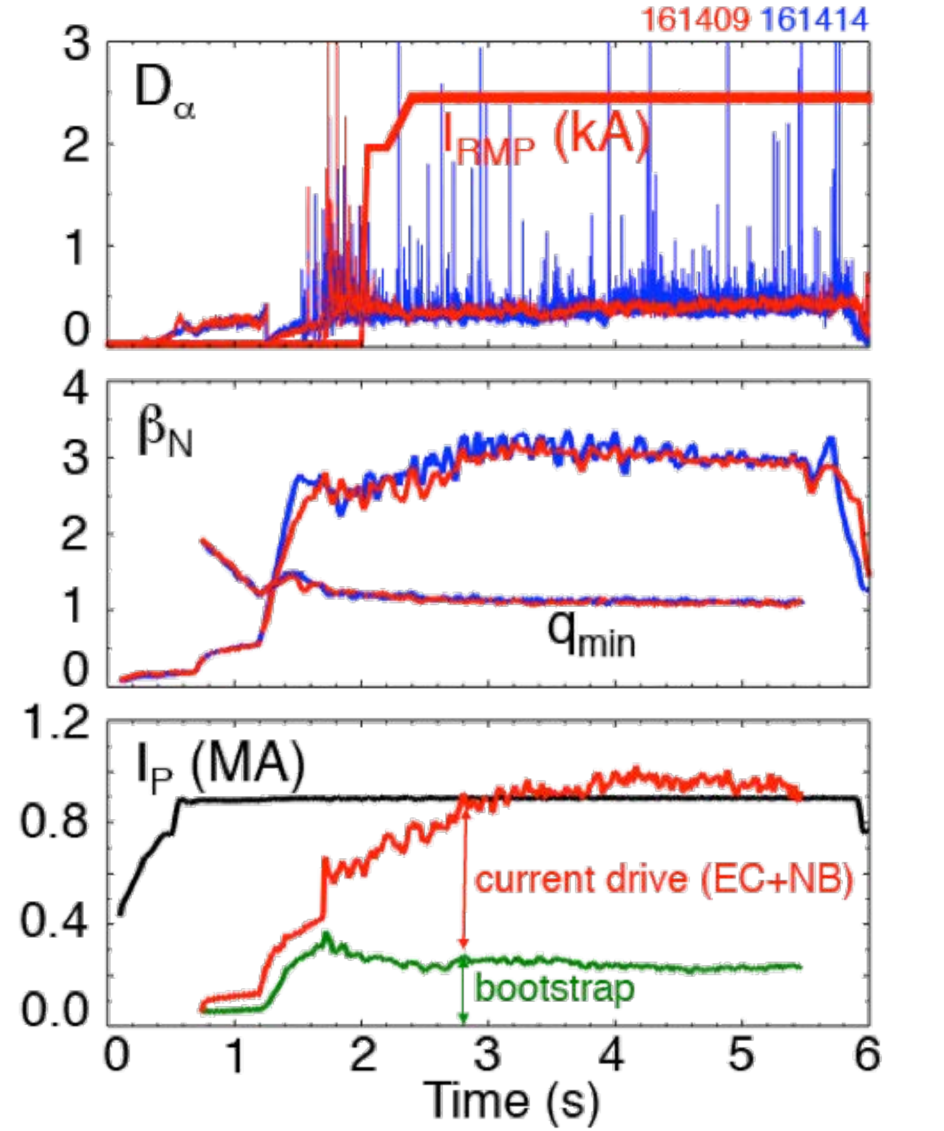



F. Turco, APS17

# Experiments in DIII-D have applied ELM suppression to a high-β, fully noninductive scenario

<u>High power, high-**β** hybrid scenario</u>

- n = 3 odd parity RMP excites edge kink modes that are marginally stable and amplifying
  - Benefits: modest RMP amplitude, wide $q_{95}$ window, small effect on pedestal, ELM suppression at low rotation
- Integrated with Argon-based radiating divertor, reducing heat flux by 50%
- Scenario scales to steady-state in ITER with $P_{fus} \approx 460$ MW @$Q_{fus} \approx 5$ and $H_{98y2} = 1.2$ (further optimization possible)




C. Petty, IAEA16

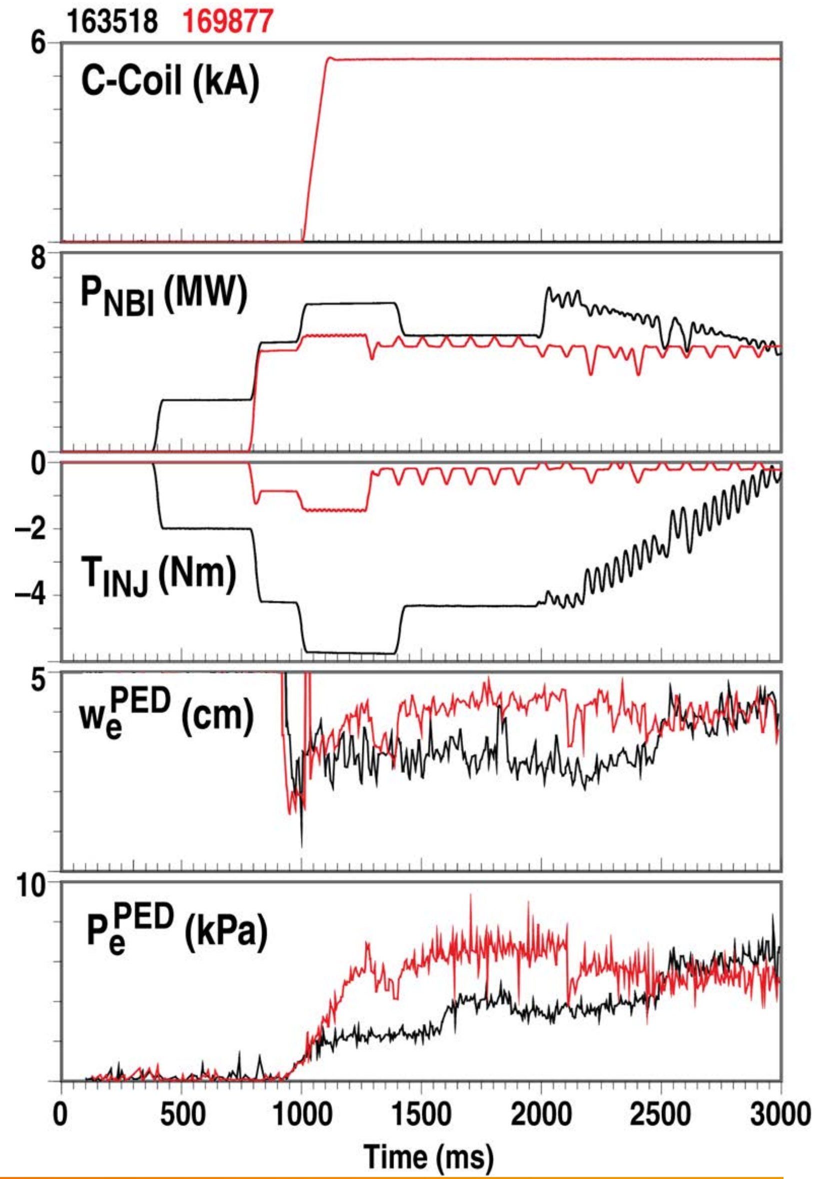
# Significant progress towards QH-mode startup with zero net NBI torque

- If QH-mode is to be used in future devices such as ITER, we need to demonstrate creation and sustainment with essentially zero NBI torque

- Experiment in 2017 focused on reducing the input NBI torque needed for wide pedestal QH-mode
  - Counter-$I_p$ torque from NTV from nonaxisymmetric n=3 fields was used to supplement NBI

- Time integrated torque needed for wide pedestal was reduced by 90%

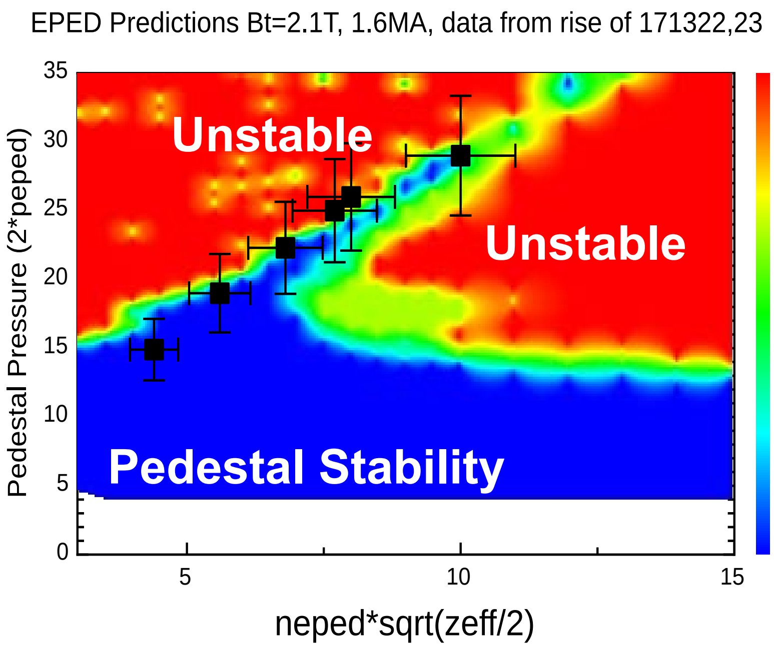
- Next issue to confront is locking of core tearing modes

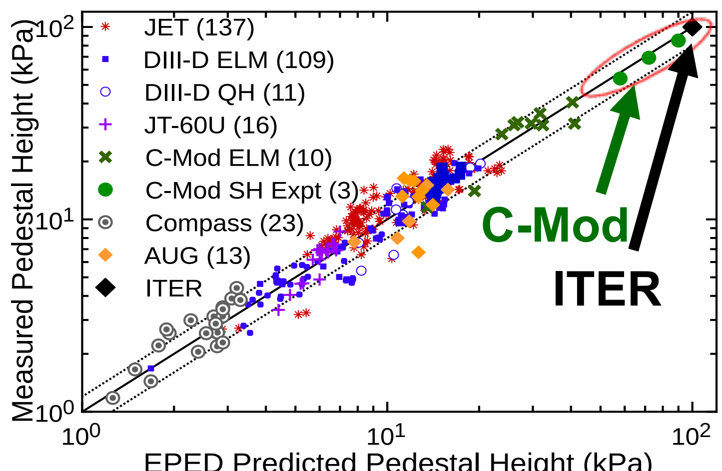



K. Burrell APS17

# Super H-mode Scenario Sustained in DIII-D & Applied in C-Mod to Achieve ITER-level Pedestal

- Sustained in DIII-D for 2.5s with $H_{98}$~1.6
  - RMP-ELM mitigation
  - $\beta_N$~2.9, 1.9MJ, $\tau_E$=200-600ms
- Possible record DIII-D $P_{ped}$=30kPa
  - $H_{98}$ reaches 2.5, $Q_{DT, EQUIV}$ reaches 0.35
  - On-axis n, $T_i$ similar to ITER mid radii
- Understanding applied to achieve ITER-level pressure pedestal in C-Mod
  - Demonstration of Super H-mode benefits at higher field
    - World record pressure achieved in three scenarios: Super H, EDA H-mode, I-mode
- May be applicable to other devices

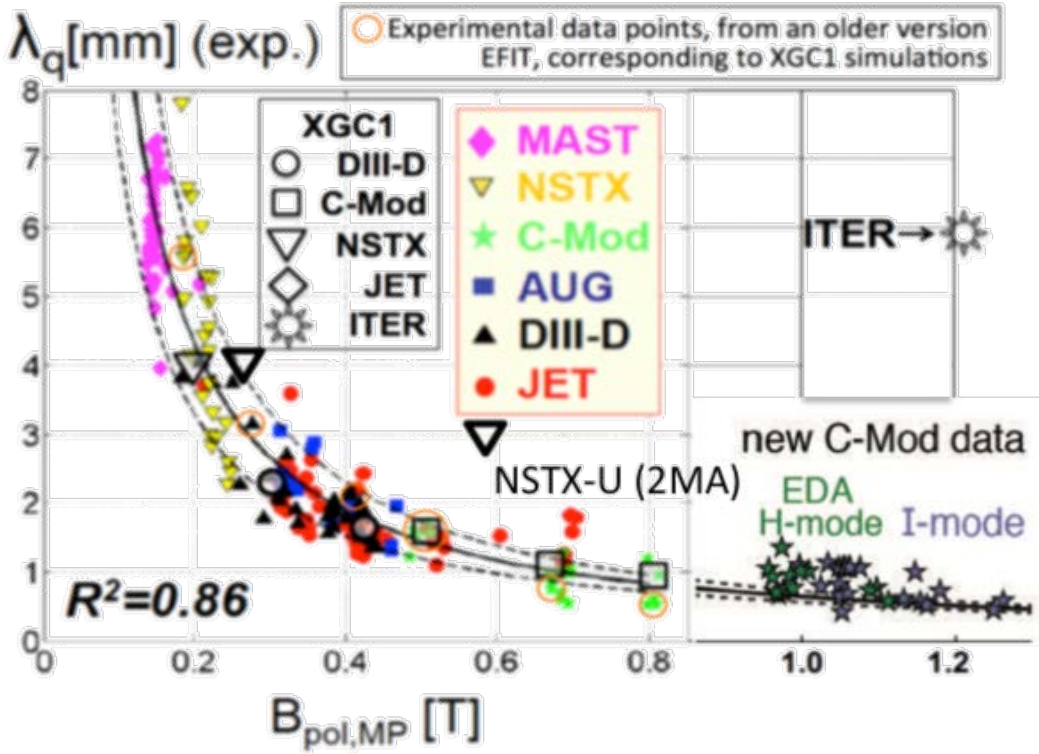



Snyder APS17, Hughes APS17

# First and only $\lambda_q$ measurements taken at ITER-level $B_p$ in Alcator C-Mod

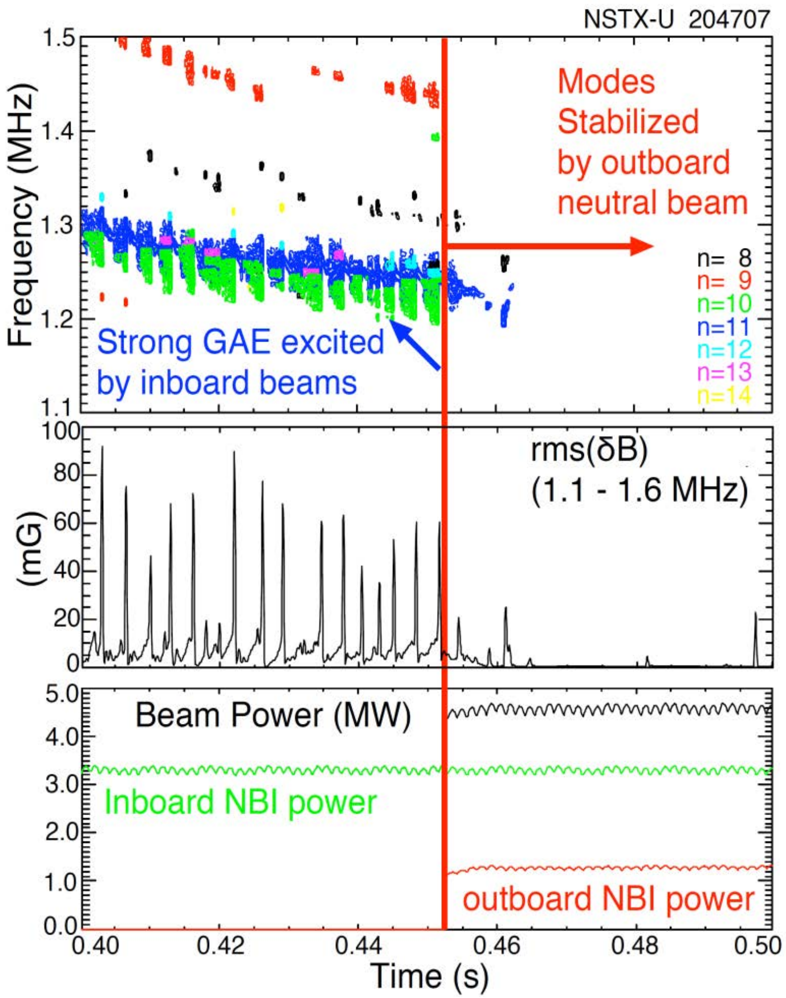
- No major departure from inverse poloidal field scaling
- H- and I-modes at similar poloidal field have similar heat flux widths: similar physics controlling for both?
- Heuristic Drift model agrees with C-mod $\lambda_q$, although C-Mod has largest deviation in multi-machine database



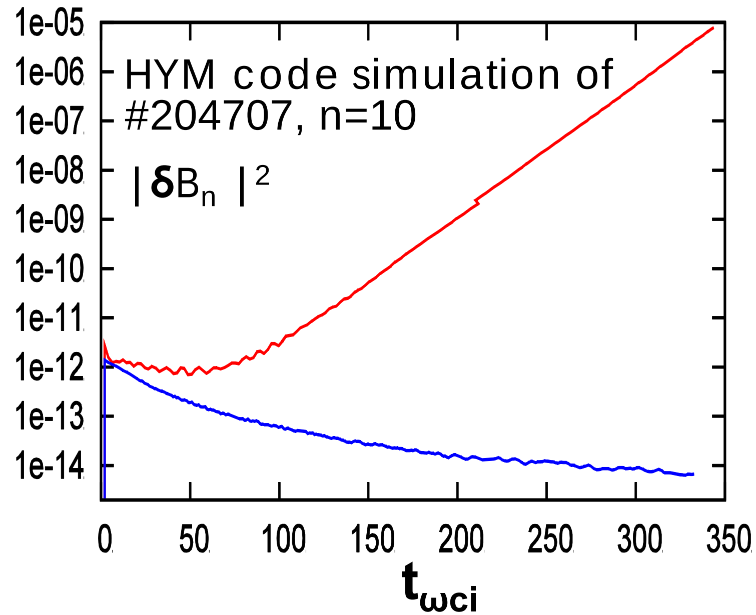

- XGC1 prediction for ITER are 10× wider than empirical trend – due to turbulence broadening
  - Basis for exascale simulations

New C-Mod data: D. Brunner, APS17
XGC1 calculations: S.-H Ku and C.S. Chang

# Energetic particle behavior is becoming increasingly predictable




- **Tangential 2nd neutral beam suppresses Global Alfvén Eigenmode (GAE) in NSTX-U**
- Consistent with HYM simulations




E. Fredrickson, PRL (2017)

NSTX-U

- HYM code: growth of n=10 counter-GAE from 1st NBI
- HYM: suppression of n=10 counter-GAE by 2nd NBI
- Most unstable *n*-number, mode **ω** consistent with HYM

# ITER provides a first opportunity to face the challenges of diagnosing a burning plasma

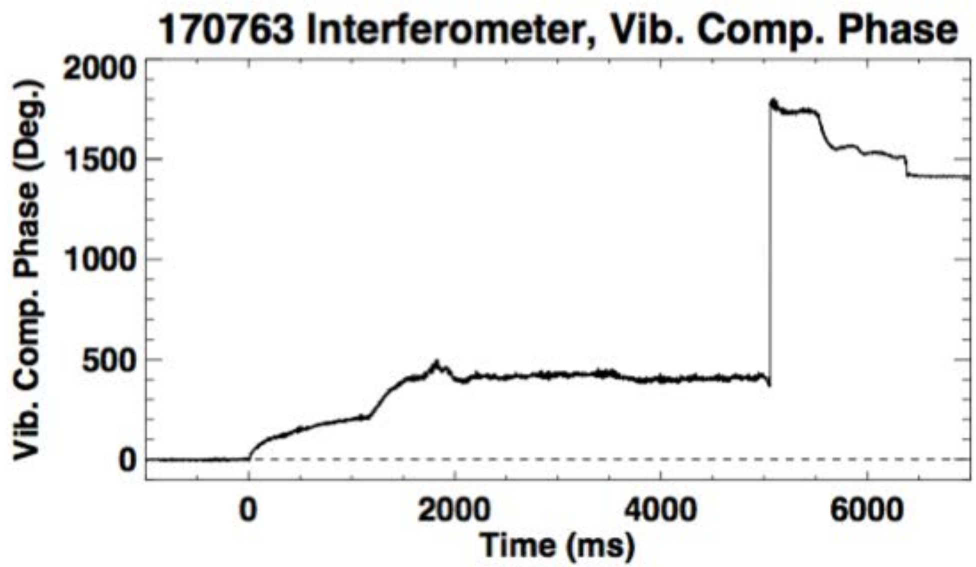
- Diagnostic development and exploitation is a strength of the present-day US Fusion Energy Sciences program
  - Need to maintain leadership
- New challenges for measurement
  - Particle flux and fluence (neutrons, gammas, ions, neutrals)
  - Very limited access (e.g. tritium blanket modules)
  - Very long pulses and high duty factors
  - Reliability, robustness, lack of maintenance
  - Full set of real-time measurements
  - Define minimal set of required diagnostic systems
  - Develop and test new techniques
- Follow-on devices (FNSF, DEMO,...) will be even more demanding
  - All of the above – but more so

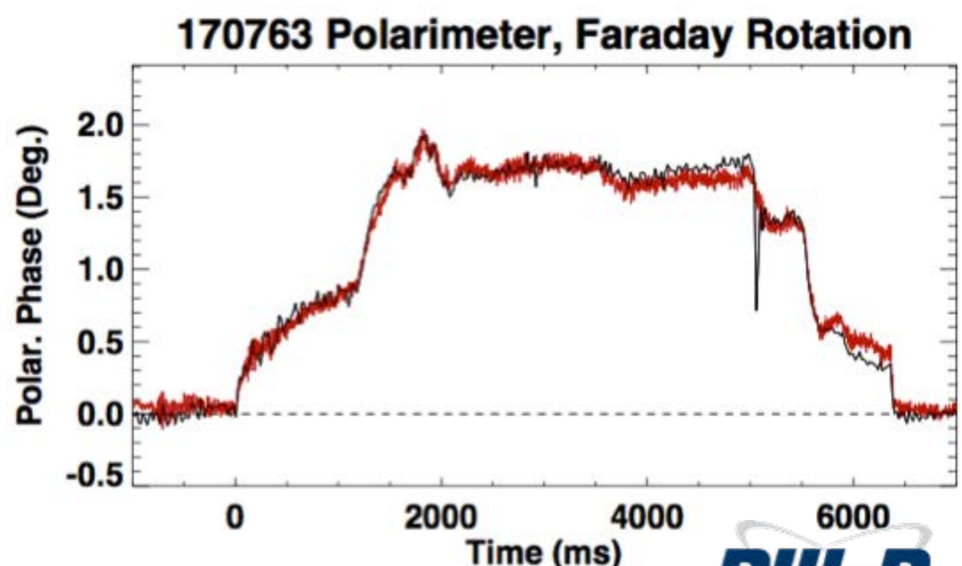
**Diagnostic development for ITER provides opportunities for the US to maintain leadership moving forward to future nuclear facilities**

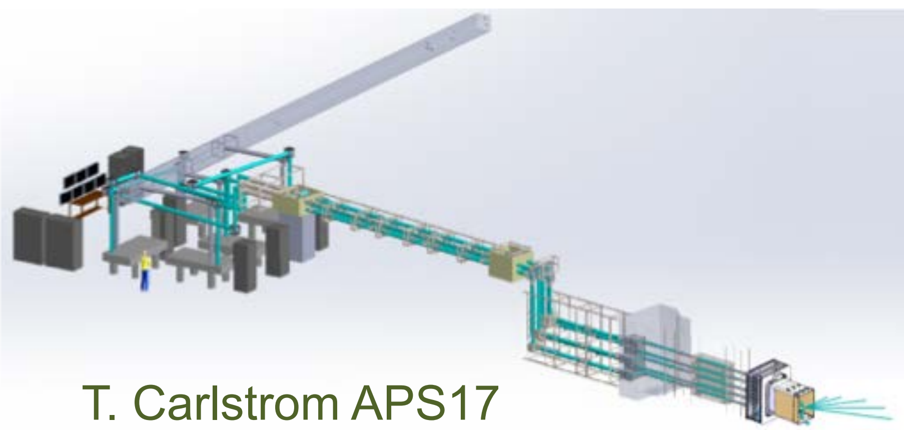
# Prototype of ITER Toroidal Interferometer and Polarimeter (TIP) tested on DIII-D

Just one of many examples…

- Real-Time (1 kHz) control of density
- Crude density profiles
- Global constraints to Thomson scattering density profiles
- Measurement of density fluctuations from turbulence and coherent modes (0-1 MHz)
- Benefit of TIP: Recovery from temporary loss of signal

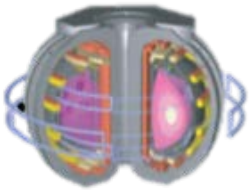


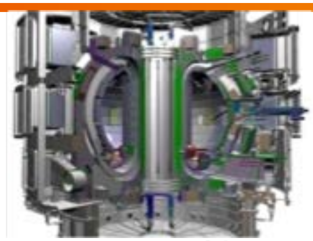
T. Carlstrom APS17

# US Fusion Energy Science community is working with international partners to make ITER succeed


DIII-D


NSTX-U


C-MOD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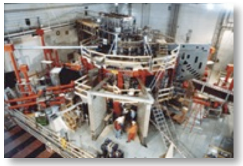
JET


ASDEX-U


JT-60SA

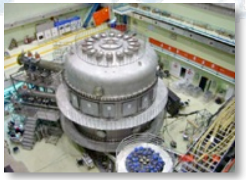
- The US community has been enthusiastic in its support of ITER physics
  - The US is responsible for 9% of ITER construction, but contributions to ITER science have far outpaced that number
  - *The difficulty in preparing this talk was in deciding what to leave out*
- Even eight years before ITER's first plasma, the science is exciting and challenging


MAST-U


TCV


WEST


SST-1


EAST


KSTAR

I would like to acknowledge the many contributions made to this talk by community members, and apologize for all of the material I had to leave out.