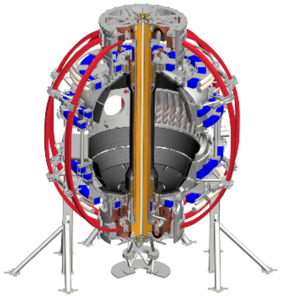
NSTX-U is sponsored by the
U.S. Department of Energy Office of Science
Fusion Energy Sciences

NSTX-U Researcher Collaboration Activities

S.M. Kaye

NSTX-U PAC-39
PPPL, Princeton Univ.
9-10 January 2018



Researchers remain active during Recovery period

- Participation in and development of collaborations for FY17-19
  - Experiments on other facilities/theory that address NSTX-U **Research Goals** for guiding future operations, and which are of benefit to STs and non-STs
  - **DIII-D** major collaboration through integration of PPPL researchers and dedicated run campaign
  - **MAST-U** collaboration has started
  - **Other** collaborations on both domestic and international devices
  - Collaboration activities contribute to answering **key science questions**
- Analysis of NSTX-U results ongoing: EP/AE physics, divertor turbulence, transport and confinement, EF/stability to address milestones

NSTX-U Research Goals will be accomplished by several means

- Research Milestones (R-): formal list of NSTX-U deliverables
  - Primarily carried out by PPPL researchers directly funded by NSTX-U, ITER & Tokamak and/or Theory Divisions
- Research Activities (RA-): research that can benefit both ST- and non-ST devices
  - Work carried out by both PPPL and non-PPPL researchers
  - Non-PPPL researcher work supported by transferred and/or separate funding on other devices
  - Means by which collaborators who worked on NSTX-U can keep in touch and communicate ongoing work

NSTX-U Research Milestones and Activities cover the full range of science topics

- JRT18: Test predictive models of fast ion transport by multiple AEs

- R18-1: Develop/benchmark reduced heat flux and thermo-mechanical models for PFCs/ monitoring
- R18-2: Develop simulation framework for ST breakdown and current ramp-up
- R18-3: Validate/further develop reduced models for thermal e^- transport in STs
- R18-4: Optimize energetic particle distribution function for improved plasma performance
- RA18-1: Validation of non-axisymmetric plasma response modeling
- RA18-2: Develop self consistent calculation of fast wave and energetic ion interactions
- RA18-3: Assess transient CHI startup potential for ST current initiation

- R19-1: Assess H-mode energy confinement and pedestal with higher B_T, I_p and NB heating power
- R19-2: Demonstrate optimized ramp-up scenarios in STs
- R19-3: Validate tearing mode physics for tearing avoidance in high performance scenarios
- R19-4: Assess effects of NB injection parameters on fast ion distribution and NB-driven current profile
- RA19-1: Expand disruption prediction and avoidance capability for tokamaks
- RA19-2: Assess importance of H-species in HHFW-heated NSTX-U full-field plasmas

DIII-D collaboration: two types of opportunities

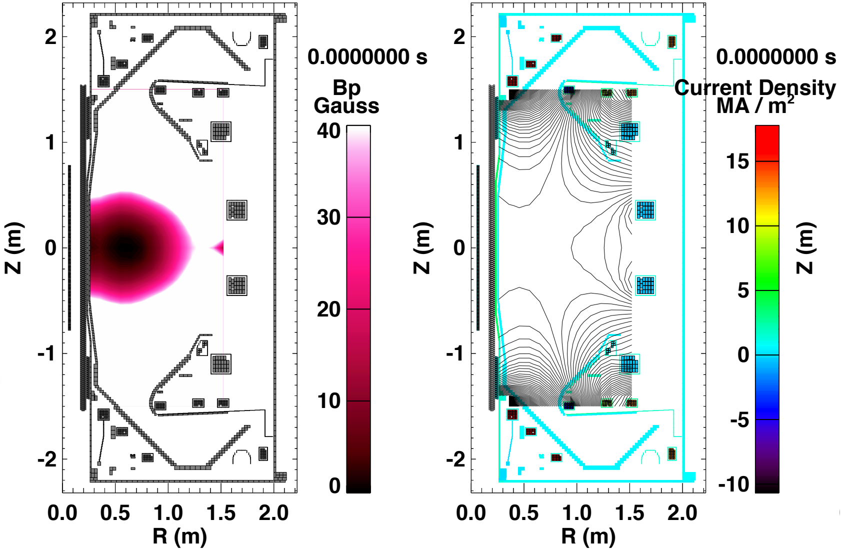
- >Σ3 PPPL FTE researchers funded directly through ITER and Tokamak (I&T) Division to work with PPPL Team on DIII-D
  - NSTX-U researchers contributed to 2017 I&T Notable Outcome on modeling EP losses due to AEs
- Two week (8 days) dedicated campaign in 2017
  - Proposals submitted and prioritized based on near-term NSTX-U goals (including JRT), well-defined ideas that require minimal development time, early career considerations
  - Selections finalized after discussions with GA, FFCC in December 2016
  - Approximately 50% of run time allocated to non-PPPL researchers

MAST-U collaboration has started

- Plasma startup scenario development in anticipation of MAST-U ops in Spring '18 (plasma/config commissioning), Fall '18 (physics experiments)
  - D. Battaglia spent 2 ½ months at MAST-U Summer 2017; plans additional visits

- ST devices have common goals
  - Robust, flexible startup with active feedback assist
  - Broad j(r)/low ℓ_i to increase κ, avoid low-q_0 MHD activity
  - Minimize flux consumption

- Ported LRDFIT for startup modeling **(R18-2, 19-2)**
  - Validated on MAST data
  - Developed high order null scenario



- Additional collaborations being developed in areas of transport, EP and core MHD
  - **R18-3,4, R19-1,3,4**

Researchers are actively engaging in other domestic and international collaborations during Recovery

- EAST (China): edge physics, plasma materials interactions, effect of lithium
- ASDEX-U, W7-X (Germany): wall conditioning using boron powder
- QUEST (Japan): Full non-inductive operation (CHI, ECCD)
- HL-2A (China): LH stabilization of ELMs, effects of NTMs on fast ions
- KSTAR (S. Korea): Core MHD, rotation physics, plasma control
- LAPD: RF coupling and heating physics

How do collaborations address key questions?

Science Group and presenter	Key research questions: First 1-3 years, 3-5 years, 5-10 years
Scenarios D. Battaglia	• Can a high-performance ST have 100% non-inductive current, equilibrated?
Core W. Guttenfelder, M. Podesta, S. Sabbagh	• Does "ST" confinement scaling persist to (3× to 6×) lower collisionality ν^*? • Can Alfvénic instabilities be modelled/understood, manipulated to control core? • Can passive & active RWM stabilization be achieved at low ν^* and sustained?
Boundary A. Diallo, M. Reinke, M. Jaworski	• How will pedestal transport & turbulence vary vs lower ν^*, higher I_P, Li coatings • How does heat-flux width scale? Can n_e control be sustained? (see backup) • Can heat fluxes be mitigated consistent with high core performance? • Can liquid metals provide a solution for higher confinement, power exhaust?
Scenarios R. Perkins, R. Raman	• Can high-harmonic fast-waves provide reliable heating and CD in H-mode? • Can NSTX-U demonstrate solenoidal-free initiation, ramp-up, and flat-top?

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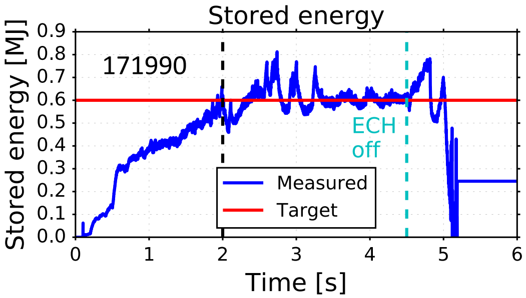
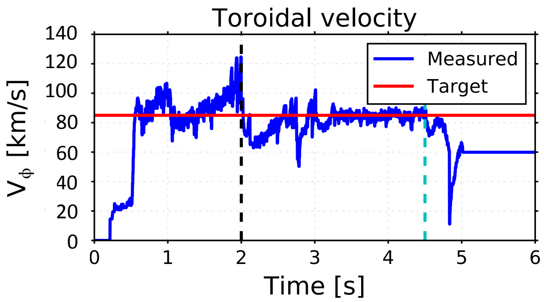
- Can high-harmonic fast-waves provide reliable heating and CD in H-mode?
- Can NSTX-U demonstrate solenoidal-free initiation, ramp-up, and flat-top?

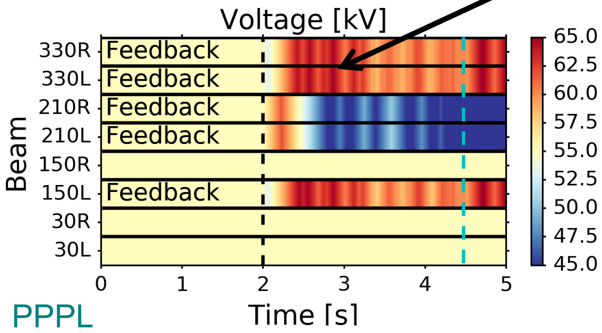
Rotation and stored energy control necessary to achieve target **high performance** plasmas

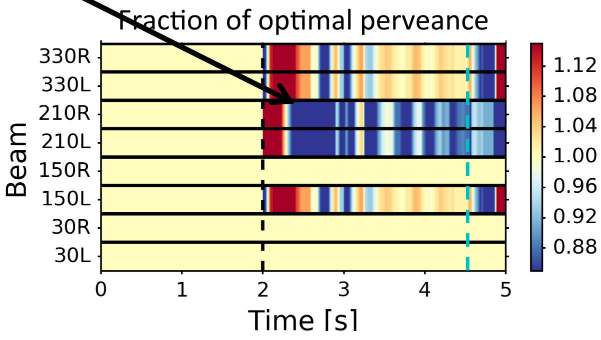
- Control algorithms developed for NSTX-U, adapted and implemented on DIII-D
- Constrained optimization finds beam voltage & perveance variation to produce required torque & power to achieve target rotation & energy
- Planning to expand to shear/profile control





Perveance changes faster to compensate slower voltages, but saturates trying to compensate sudden confinement changes

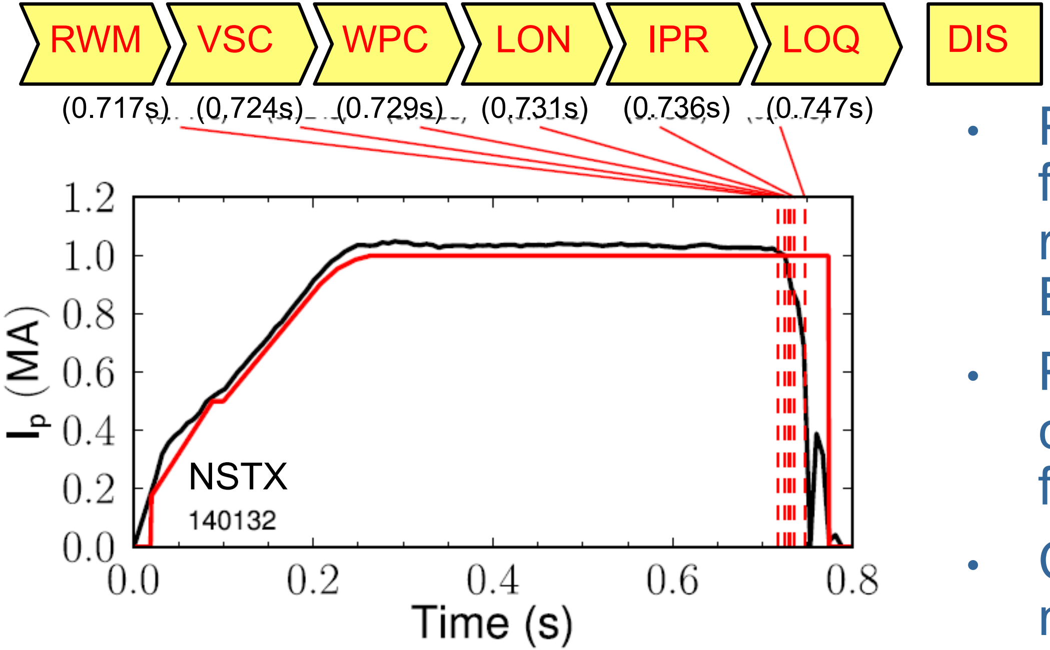




D. Boyer, PPPL

Disruption Event Characterization and Forecasting (DECAF) development for maintenance of **high-performance** plasmas

Automated disruption event chain analysis to cue avoidance systems **(RA19-1)**

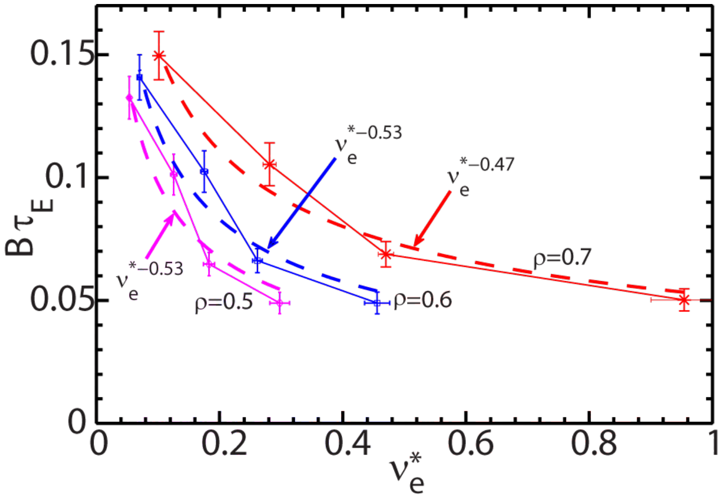


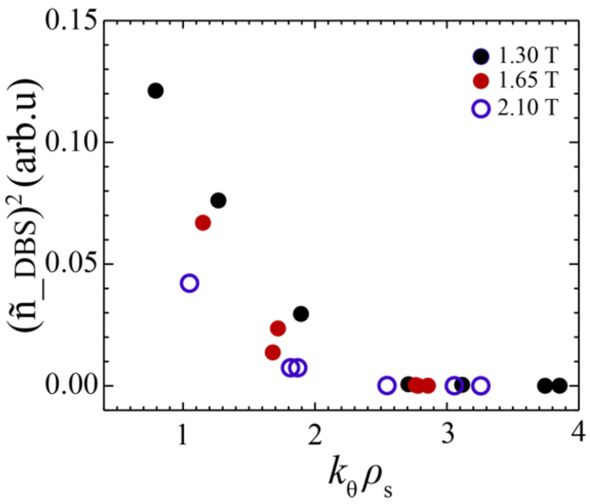
S. Sabbagh, J. Berkery, Columbia U.

- Physics-based disruption forecasting models (e.g., reduced kinetic RWM model: Berkery, 2017)
- Prediction quantitatively compared to experiment (7% false positive)
- Collaborative (inter)national multi-device studies starting (incl. NSTX/-U, KSTAR, DIII-D, TCV)

Core low-k turbulence reduced as **collisionality** decreases in Advanced Inductive Hybrid Scenario at **ST-relevant q_{95}**

- Experiment on DIII-D designed to understand improvement of confinement with decreasing collisionality in STs **as well as** at higher aspect ratio **(R18-3, 19-1)**
- DBS measurement indicates reduction of turbulence with increasing B_T (decreasing collisionality), consistent with energy confinement improvement
- E-S/E-M gyrokinetic simulations (flux tube & global) to understand cause of trend





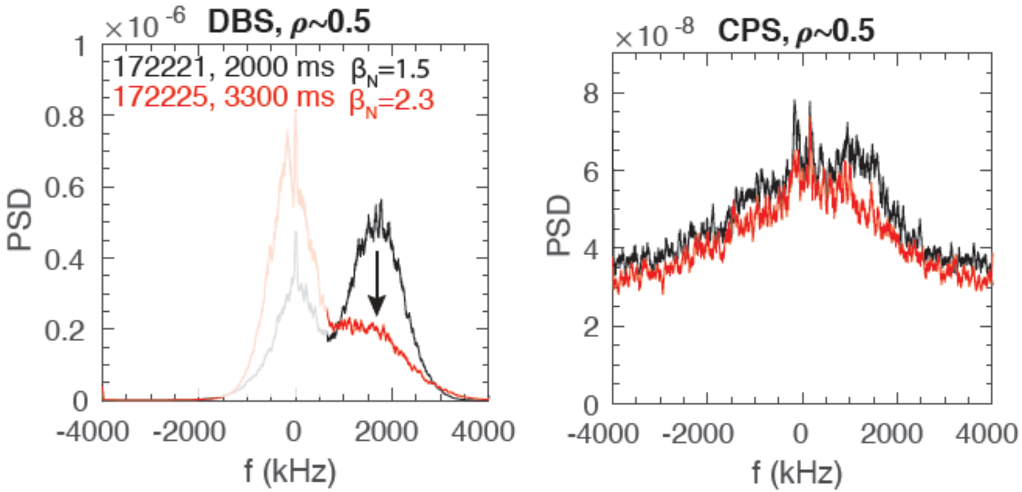
DBS measurement at ρ~ 0.55-0.65, averaged for t=3.75-4 s

Y. Ren, PPPL

What is the influence of electromagnetic microturbulence at **high β**?

- Enhanced coupling to δB at increasing β is stabilizing to ITG/TEM **(R19-3, 19-1)**
- Measured simultaneous δn (DBS) & δB (CPS) as far in as r~0.4 in QH-modes on DIII-D
- Use results to validate electromagnetic gyrokinetic simulations

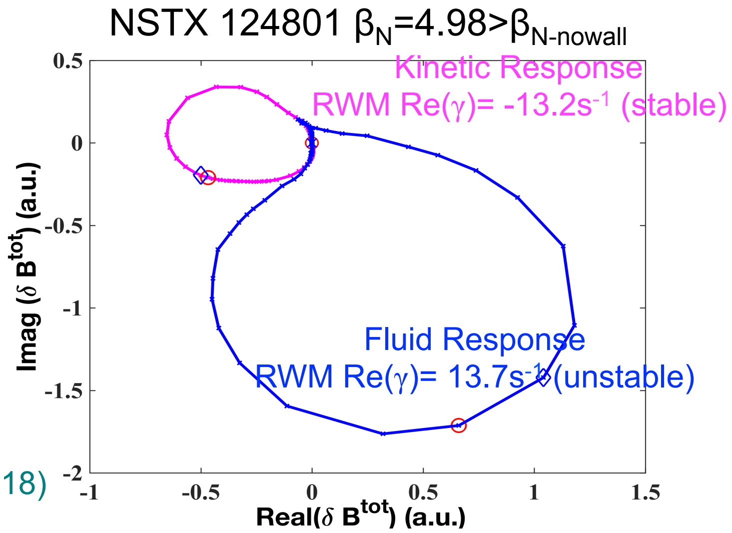
  - Ratio of CPS/DBS amplitudes ~δB/δn increases with β, expected from theory
  - Requires ray tracing, gyrokinetic simulations + synthetic diagnostics for validation (ongoing for IAEA FEC 2018)



W. Guttenfelder, PPPL

Collaborations on 3D MHD show importance of rotational and kinetic effects in identification and detection of MHD modes

- MARS-K shows rotational and drift kinetic effects fundamentally change 3D plasma response and RWM stability in high performance plasmas
  - Predicted frequency response to 3D fields can be largely different between fluid and kinetic simulations
  - RWM stability inferred from kinetic Nyquist contour explains 3D response in **high β and low ν*** NSTX plasmas
  - Consistent with Berkery/Sabbagh results
  - **RA18-1**

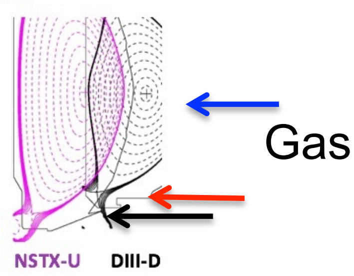


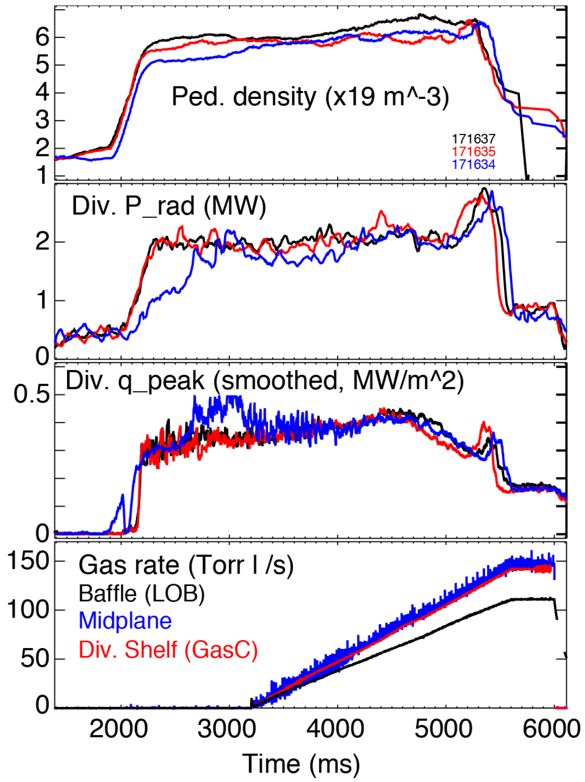
Z. Wang et al, NF 58 016015 (2018)

- Advanced 3D MHD spectroscopy, based on Nyquist method, has been used to identify and detect MHD stability and multi-mode response on EAST and DIII-D
  - **Tested in 2017 and 2018 EAST and DIII-D experimental campaign**
  - First time successfully extracted experimental transfer function between applied field and plasma response
  - This is one method that can be used to develop real-time global MHD stability monitor and improve RWM feedback controller in NSTX-U and other devices

Divertor detachment is one method for **heat flux mitigation**

- Divertor detachment studied in highly-shaped NSTX/NSTX-U similar plasmas on DIII-D **(JRT17)**
- NSTX demonstrated partial detachment sensitivity on
  - Gas injection location
  - Divertor flux expansion
  - Divertor separatrix angle with PFCs
- FY2017 result in DIII-D: little change in divertor detachment characteristics with gas injection location (midplane, divertor shelf, divertor baffle)
- Analysis to understand differences ongoing





V. Soukhanovskii, LLNL

UCLA's LArge Plasma Device (LAPD) serves as a "test stand" to understand **HHFW** losses and to improve NSTX-U **heating** performance

On NSTX, there is a significant loss of HHFW power to the SOL. What is the reason for this?

- Can far-field rectification dissipate substantial HHFW power?
- Is this related to the misalignment of the current straps with $\mathbf{B}_{\mathbf{TOT}}$ in NSTX(-U)?

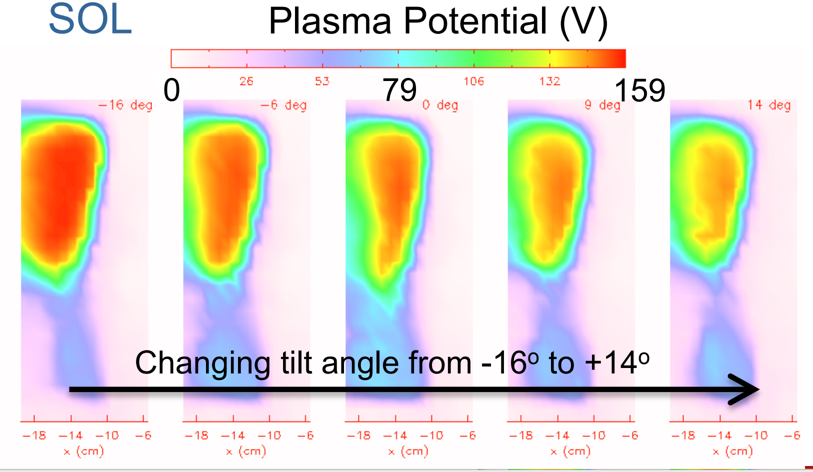
Preliminary result:

- The amplitude of potential changes significantly as antenna is tilted relative to field
- LAPD has identified regions of enhanced potential on side of single-strap antenna
- Studying reason for change in potential & impact of tilt effect in the far-field [analog to divertor in NSTX(-U)]

R. Perkins, PPPL

LAPD offers opportunity to study these topics in detail

- Flexible setup & diagnostic accessibility
- Detailed 2D and 3D data sets, which are not obtainable on major tokamaks due to time and access constraints
- Plasma parameters are similar to NSTX SOL



Summary

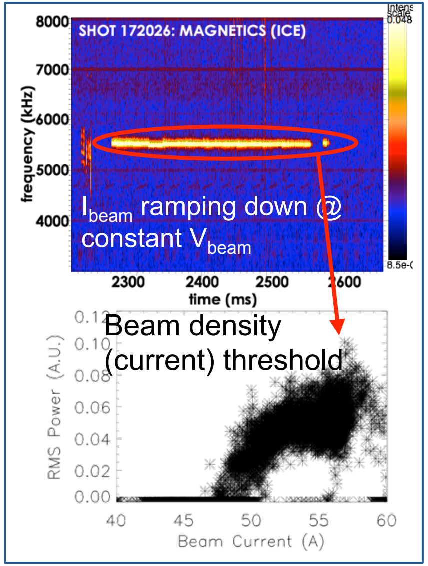
- Results from collaborations (active and planned) address NSTX-U research elements and will provide guidance for future operational scenarios
- Opportunities for non-PPPL researchers to collaborate exist (or have been proposed) to provide a means to maintain research activities, and to communicate results with the NSTX-U Team

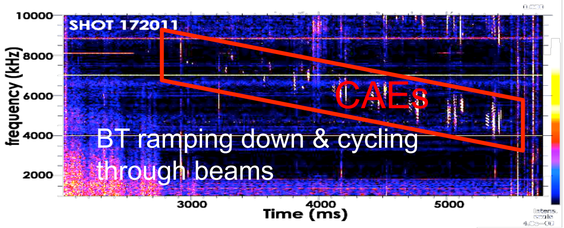
- **Non-PPPL researchers remain interested in NSTX-U, and we look forward to them bringing their full research expertise back to NSTX-U when operations resume**

Back-up

Dedicated campaign experiment on DIII-D investigates stability and *f* & *n* scaling of compressional Alfvén eigenmodes on DIII-D

- Observed CAEs consistent with many aspects of theory:
  - Frequency dependent on beam injection geometry
  - Beam density threshold observed
    - Beam current ramped at constant voltage (variable perveance beams)
  - Observed B_T & n_e thresholds consistent with resonance condition — *f* increases with v_A as expected
- Preliminary 2-point *n* results
  - n < 0 consistent with Doppler shifted cyclotron resonance
  - *f* increases as |*n*| decreases
- Addresses NSTX-U **JRT18, R18-4, 19-4**
  - Results will be used to validate HYM linear and non-linear simulations

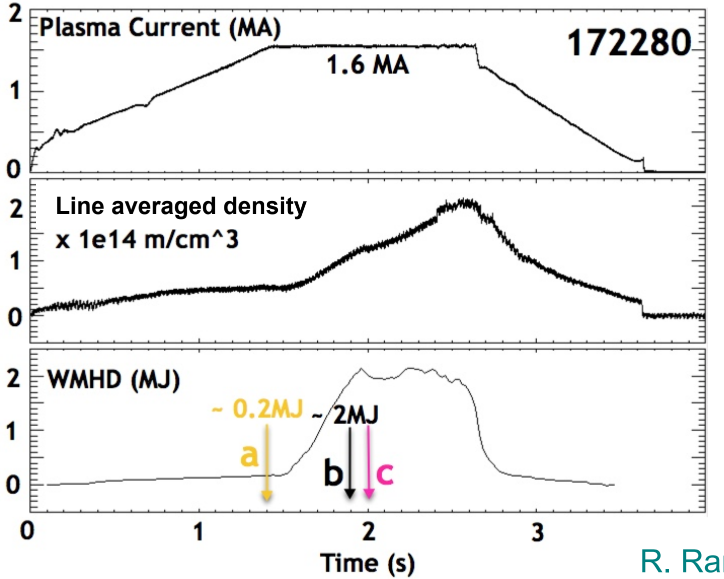




S. Tang, UCLA

SPI experiments carried out to determine whether pellets can penetrate high temperature edge

- Disruption mitigation experiment carried out in DIII-D with low & high-power (L- & H-mode)
- Relevance for ITER, Electromagnetic Particle Injector concept for NSTX-U
- Results support continued EPI development for higher velocity pellet

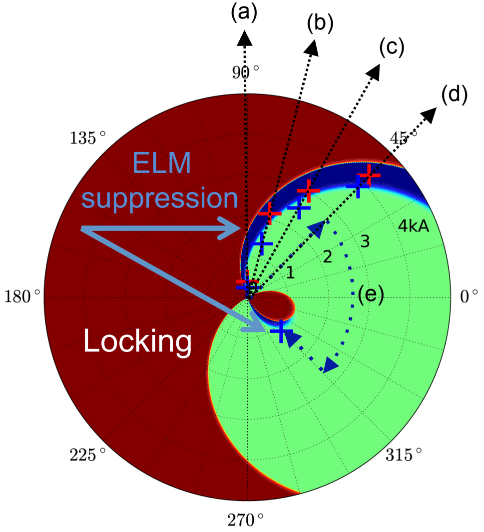


R. Raman, U. Washington

KSTAR 3D physics collaboration demonstrated remarkable predictability of ELM suppression window in n=1 RMP coil space

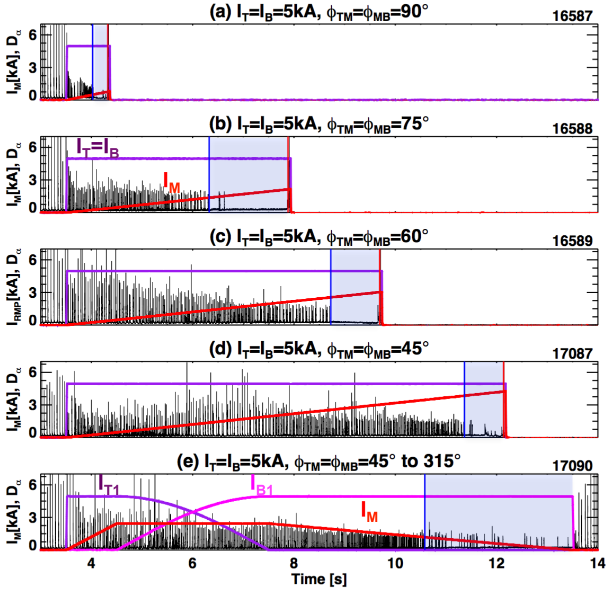
- Used resonant metrics in linear 3D MHD with edge vs. core decoupling
- Fully identified 3-rows KSTAR RMP coil operating windows for ELM suppression
- Validated its predictability with new RMPs, including dynamically deployed RMP (e)

Predicted stability diagram (I_M,φ) with a special choice of I_T=I_B=5kA



+: Experimental locking threshold
+: Experimental ELM suppression threshold

(a-e) Experimental RMP traces

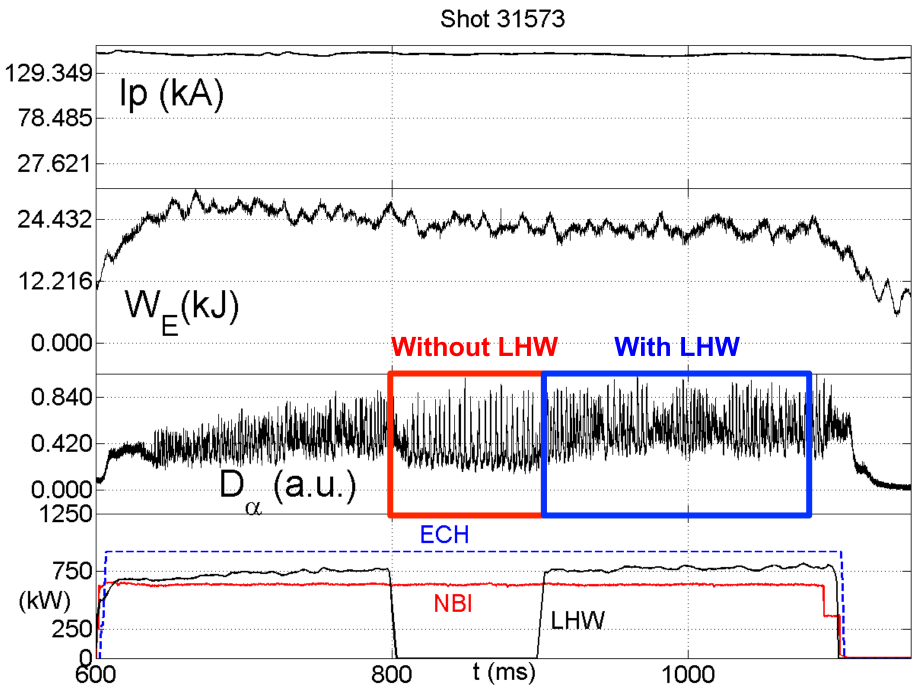


(J.-K. Park et al., under review in Nature Physics (2017, EPS Invited 2018))

Effect of LHCD on **edge plasma stability** studied in HL-2A L-mode plasmas

- ELM control important for operation of future fusion devices (e.g., ITER)
  - Widely believed ELMs due to peeling-ballooning modes
  - EAST reported mitigation of ELMs by LH (Chen, NF 2015)

- Clear modification of ELM behavior by LH observed in HL-2A
  - Analysis ongoing to understand whether modification due to heating or current drive
  - Understanding of factors influencing pedestal structure **(JRT19, R19-1)**

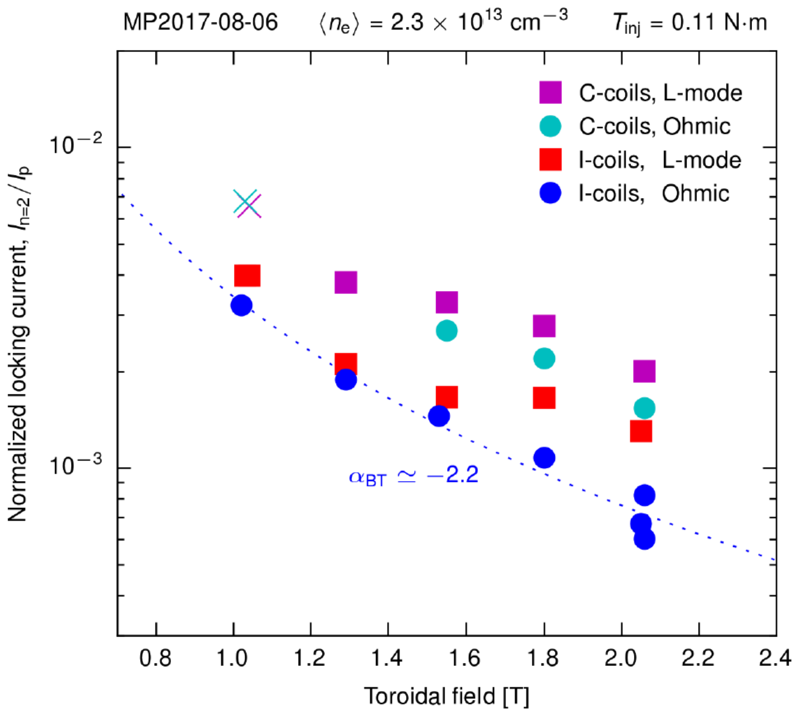


P_{LHW}~760kW

Y. Ren, PPPL

DIII-D collaboration through national campaign shows first systematic negative B_T scaling for n=2 error field thresholds

- n=2 locking threshold decreases strongly with increasing B_T in 22 DIII-D shots
  - Similar decrease well-known for n=1 EF
- Suggests common mechanisms for resonant locking of n=1 and n=2
- Future ST and ITER will be more sensitive to field errors due to higher B_T **(R19-3)**
- Experiment also showed a small torque (as in L-mode) can increase EF threshold substantially

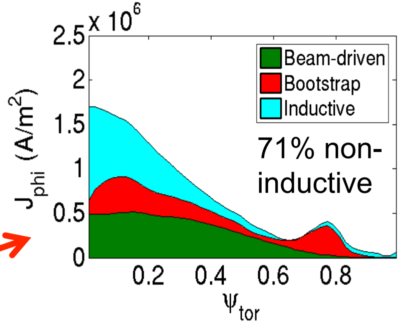


C. Myers (PPPL) and DIII-D research team
PRL (2017 submitted)

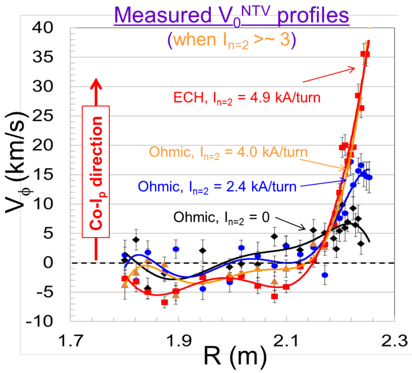
Expanded KSTAR collaborative stability/transport research complements NSTX/-U research and available database

- Significant motivation: Understand influence of aspect ratio (*A*)
  - Equilibrium, stability, transport physics all influenced by *A*
  - Leverage large aspect ratio difference: KSTAR = 3.5, NSTX(-U) > 1.3

Sabbagh et al., Columbia U.



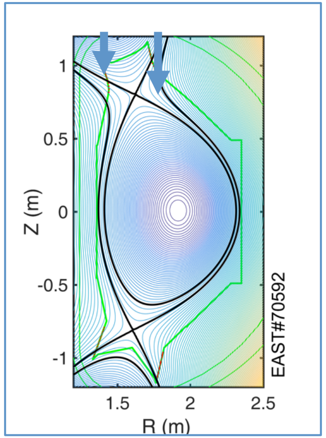
- Significant progress (all shown at APS DPP '17)
  - Improvements and new capabilities enabling disruption characterization / forecasting research plan in long pulse, high b_N
    - More detailed equilibrium reconstruction: kinetic reconstructions with MSE
    - TRANSP analysis of KSTAR high beta and high non-inductive plasmas
    - Stability codes (kinetic MHD, NTM, kink/ballooning/RWM) initially tested on KSTAR kinetic equilibria; compare dominant stabilization physics to NSTX
    - Significant co-I_p plasma rotation+ shear generated for the first time by NTV
  - Improvements/support to key diagnostics
    - C-Mod MSE background polychrometer sent to KSTAR (10 channels), building 15 more channels to support 25 total channels (2018)
  - Active control of dynamic error fields and global MHD instability
    - Created/implemented critical sensor DC and AC compensation for KSTAR RWM PID control (initial control testing 2018 – compare to NSTX results)

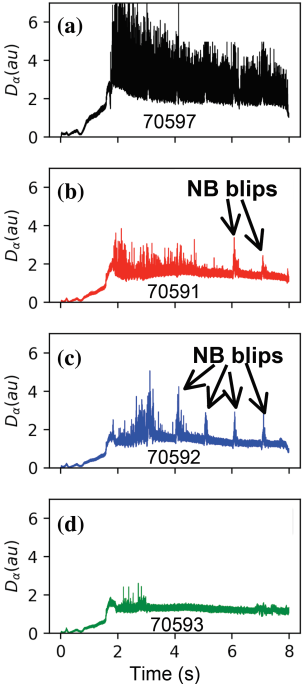


Lithium shown to control ELMs on EAST

Recycling and ELMs progressively reduced with constant Li injection rate

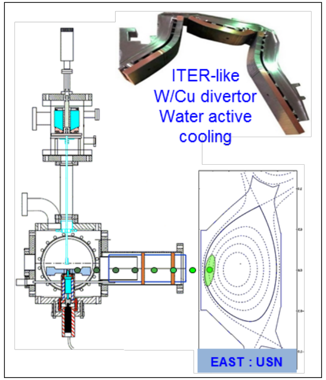
Two droppers installed

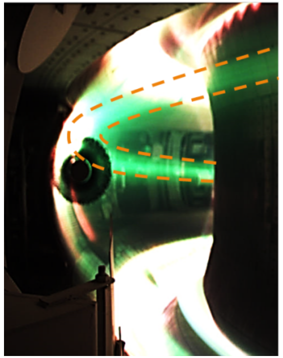


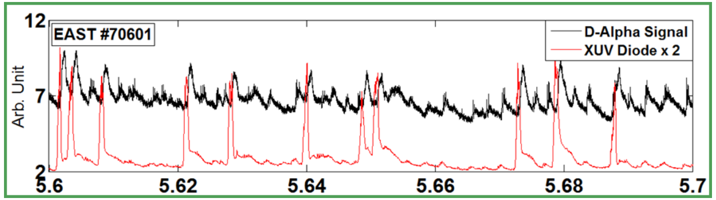


R. Maingi, Nucl. Fusion (2017) submitted
J. Canik, IEEE Trans. Plasma Sci. (2017) submitted

Granule injector triggers and paces ELMs



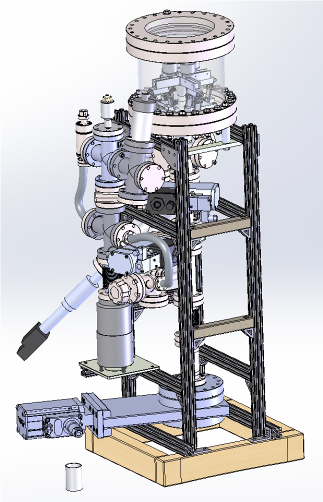




R. Maingi, PPPL

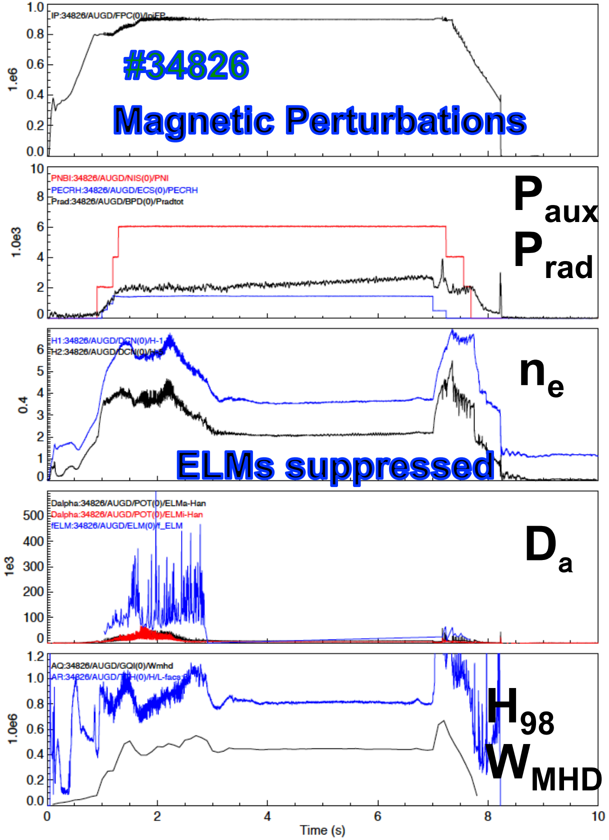
Powder droppers installed on ASDEX-U and W7-X

- ASDEX-U
  - Impurity Powder dropper installed with BN and B powder. Initial experiments on real time wall conditioning promising
- W7X
  - Compact Injector being designed to go on Multi-purpose probe for in-vessel B_4C powder injection



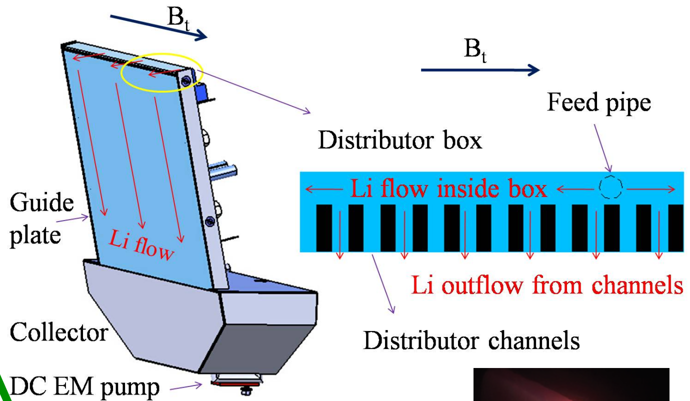
ELM suppression with MP achieved after B injection in AUG

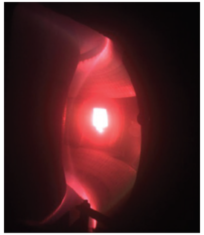
R. Maingi, PPPL

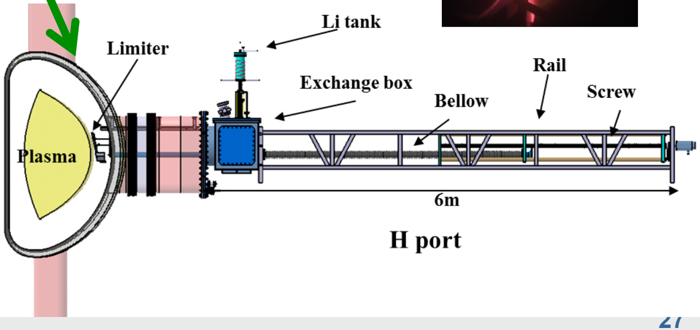


Flowing liquid lithium limiter collaboration: several different limiter designs deployed

- Gen. 1: Made at PPPL
  - Cu heat sink; SS coating
  - Inserted at EAST midplane on MAPES system
  - Compatible with H-mode
- Gen. 2: Improved distributor, thicker SS coating, and 2 ExB pumps
  - Enabled H-mode with transiently high H98 ~ 2
- Gen. 3: solid Mo plate, no SS coating
  - Two version: flat (PPPL) & corrugated for TeMHD flow drive (UIUC)
  - Experiments in 2018



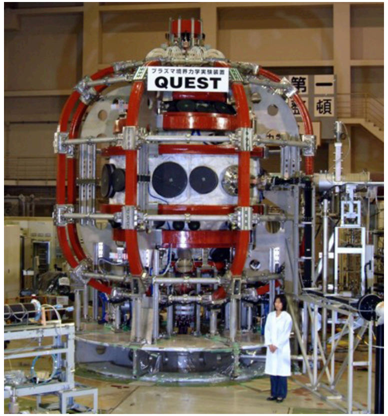




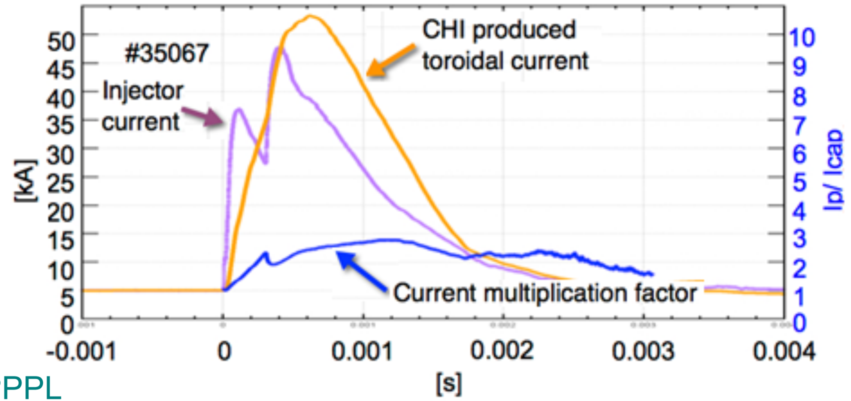
J. Ren et al., *RSI*. **86** (2015) 023504; J.S. Hu et al. NF **56** (2016) 046011
G.Z. Zuo et al. NF **57** (2017) 046017; G.Z. Zuo et al. RSI **88** (2017) 123506

Major goal of the QUEST program is to generate **steady-state fully non-inductive plasmas**

- Coaxial Helicity Injection (CHI) research on QUEST supports NSTX-U longer-term goal of non-inductive startup **(R18-2, RA18-3)**
- The QUEST CHI system has been commissioned by U. Washington
- Steady progress increasing current using CHI
  - Increased peak toroidal current from 29 kA (Dec. 2016) to 48 kA
  - TSC simulations of CHI started



QUEST Spherical Tokamak



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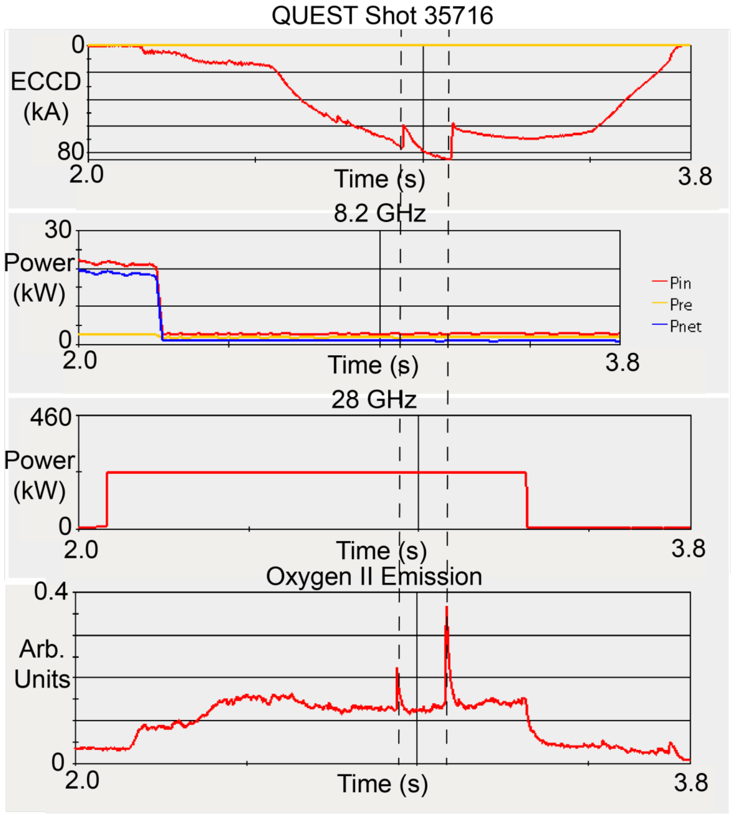
ECCD being used on QUEST to assist **current ramp-up**

- 28 GHz gyrotron being used similar to one proposed for NSTX-U
- Generated up to 85 kA with 230 kW
- Kinetic modeling of energetic electrons and current drive underway



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