Slowly Rotating 3D Field For Locked Mode Avoidance and H-mode Recovery in DIII-D

-and Simultaneous Control of Quasi-interchange (QI) mode core Te collapse-

[1]M. Okabayashi, [2]L. Sugiyama, [1]D.P. Brennan, [3]S. Inoue, [4]E.J. Strait, [5]M. Austin, [4]C. Chrystal, [4]R.J. La Haye, [6]N.C. Logan, [6]C. Holcomb, and [6]B. Victor

[1]PPPL, [2]MIT [3]QST.[4]GA, [5]Univ. Of Texas, [6]LLNL

28th IAEA FUSION ENERGY CONFERENCE, May 10-15, 2021

Acknowledgement: This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, using the DIII-D National Fusion Facility, a DOE Office of Science user facility, under Award(s) DE-FC02-04ER54698, DE-FG02-86ER53218, DE-AC05-00OR22725, DE-AC02-09CH11466 and DE-SC0018313.

Motivation

- **Slowly Rotating 3D field** has been pursued as a promising path for **Locking avoidance and H-mode recovery after large Neoclassical Tearing Mode is excited.** Yet, better understanding of the core and edge effects is required for full application to reactors[1,2].
- Recently, **numerical simulation** of a DIII-D ITER baseline shaping target with q_{95}~4.0 by **M3D** [3,4] discovered **unique features** around q(0)~1 core of the **Quasi-Interchange-driven crash** [5]. The process is **highly nonlinear**, but characterized:
  - Dominantly composed of **lowest toroidal numbers n=1 and n=2**
  - Perpendicular plasma flow crosses q=1 region **without reconnection, little magnetic island** -> favorable for **interfacing the applied 3D field with the QI-Te(0) crash**

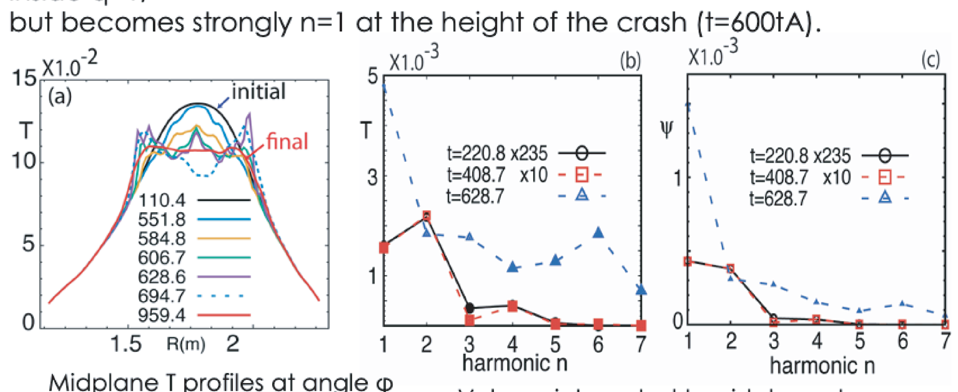
Outline

- **Numerical Simulation: M3D code simulation [3,4] predictions** (POP submitted, 2020 [5])
  - Quasi-interchange (QI) mode–driven sawtooth crash in an H-mode recovery of ITER baseline scenario development shot
- **Experimental consistency:**
  - QI-driven crash in the H-mode recovery shots
    - Analysis using Reconstructed **toroidal mode structure** with magnetic sensor signals
      - confirming n=1 and n=2 components
  - **Possibility of two helicity-q =unity rational surfaces** at r ~0.2 and ~0.4.
- **QI-driven crash in Feedback locking avoidance shot**
  - Phasing control in applied 3D field changes QI character

  A second helicity-q=unity rational surface region separates the core from other MHD events at off-axis domain
- **Summary**

M3D code simulation with ITER baseline plasma-shaping condition predicts new physics issues in QI sawtooth crash [3]

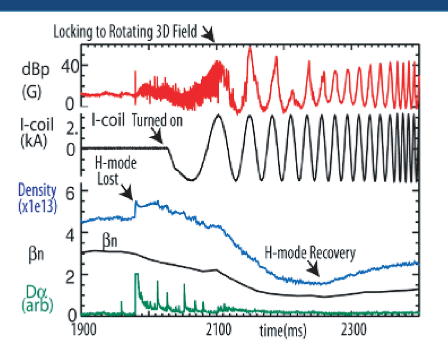
Due to the **low magnetic shear**, the QI modes in the initial stages of the crash are **fundamentally nonlinear**, characterized by **lowest two toroidal numbers n=1 and 2 of comparable magnitude** that grow at the same rate, at small amplitude (t=200-400tA), these are the 1/1 and 2/2 inside q=1, but becomes strongly n=1 at the height of the crash (t=600tA).



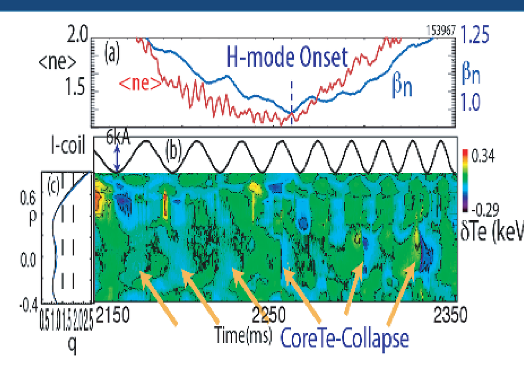
Midplane T profiles at angle φ where the QI mode moves Vertically off the midplane.

Volume integrated toroidal spectra for T and poloidal magnetic flux ψ

Macro-formation of QI-Te(0) crash pattern evolves in time gradually with the plasma conditions



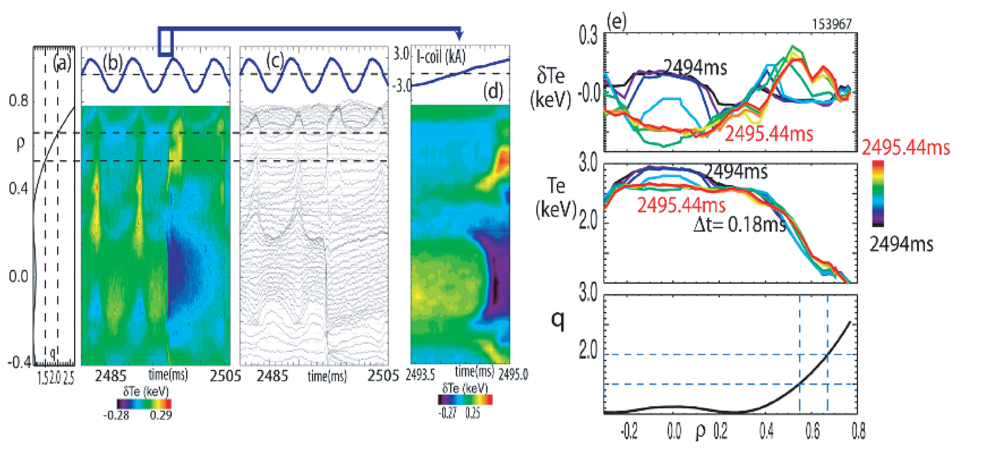
- Onset of a 2/1 NTM **unexpectedly caused a massive gas inflow** (a burst in Da at t≃1980), inducing **a fast Te pedestal decay** and loss of the H-mode.
-Just after the L-mode began, the AC frequency **began at 20 Hz** and quickly increased in time [6].
- At the **H-mode recovery** time, the frequency was around 50Hz.



- **Partial QI-driven core collapses** began when the 3D AC field was applied, and then H-mode recovered.
- **Geometrical pattern of crash changed in time** such as two off-centered cool regions (t=2300ms)
-Te crash(blue) became sharper around t=2335ms while the quality of the H-mode improved (a factor of four increase of Pe edge gradient) (not shown).

The fast time scale of QI-driven core crash structure is in good agreement with the simulation results

- First large central crash after H-mode fully regained t≃2495 ms
- ~130 Hz rotating 3D field: δTe-core collapse midplane profile similar to "simulation without 3D field."

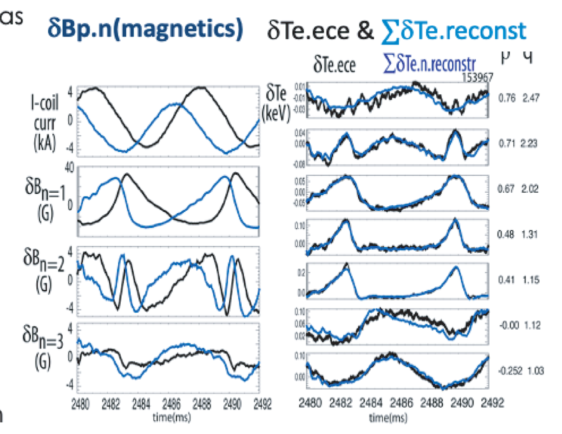


-Observed ECE $\delta T_{e.j}$ matches well with the sum of magnetic toroidal harmonics of n=1, =2 and =3

- $\delta Te.$ **from the ECE** decomposed as a sum over the lowest **toroidal geometrical harmonics of 10 magnetic sensor Signals toroidally,** as

$$\delta T_{e.j.reconstructed} = \sum_{n=1,2,3} C_{n.j}(r,j) * \delta B_n(t)$$

- **Assumption:** the internal magnetic events involved in the crash are directly connected to sensor signals, without dissipation

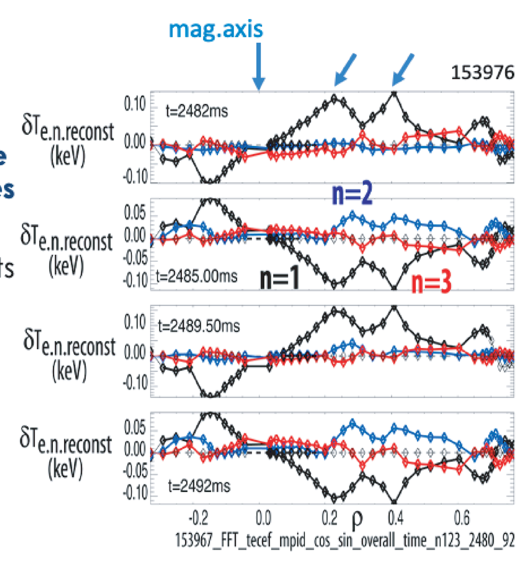


- $\delta Bn(t)$ **:** complex decomposed toroidal mode number of magnetic signals.
- **Complex coefficient** $C_{n.j}$: determined over one cycle of 3D field average.
- **Local toroidal phase shift** : included through the complex coefficient $C_{n.j}(r,j)$.
- This approach is applicable in slowly evolving domain in time (assessed later)

The reconstructed $\delta T_{n=1.j.reconst}$ indicates two helicity-q=unity rational surface appearance at ρ=0.2 and 0.4

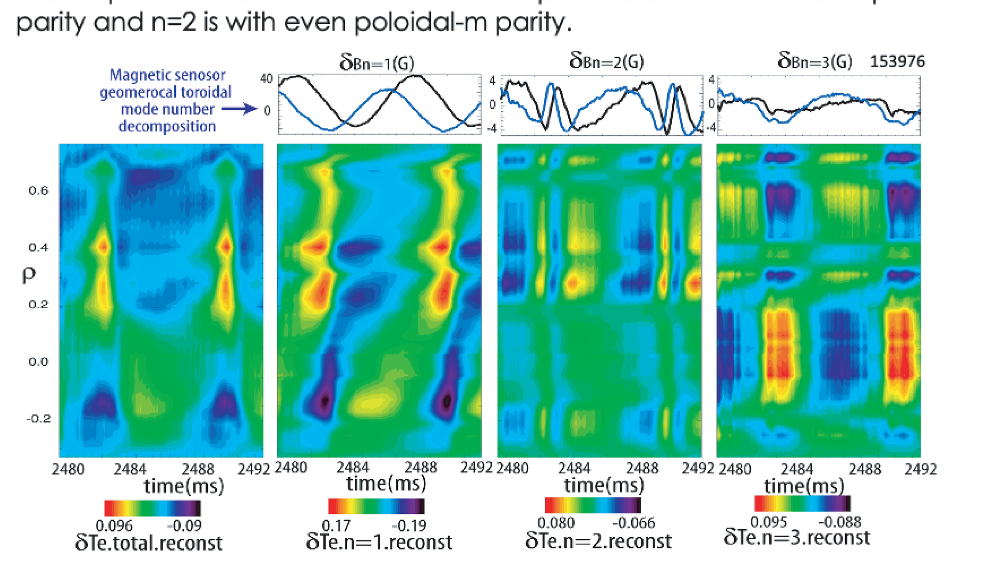
The reconstructed radial $\delta T_{n=1.j.reconst}$ profile at time slices between two QI-driven-crash crashes shows **the helical structure response** with **two rational surfaces at ρ ~ 0.2 and ~0.4.**

- The odd-parity behavior suggests m=1 over -0.2 < ρ < 0.2
- ρ =0.65 peak corresponds to a 2/1 mode (island) at q=2.
- The n=2 reconstructed $\delta T_{n=2.j.reconst}$ may indicate a resonance at ρ =0.4.

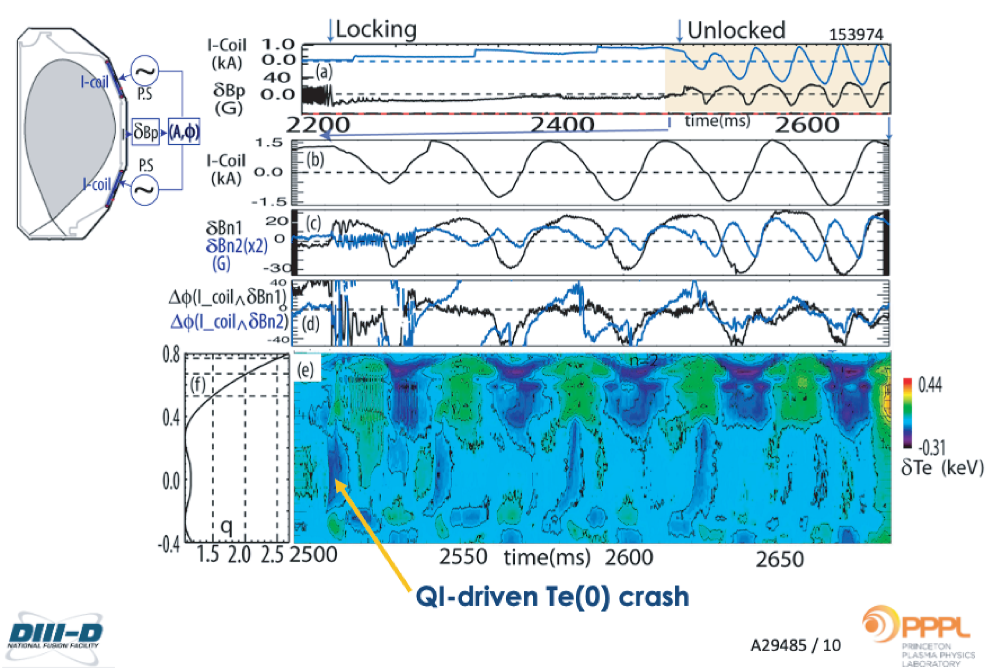


The applied 3D field serves as "active MHD spectroscopy" between the QI-driven crashes period

- The response indicates that the QI-driven crash condition is marginally stable. The amplification of n=1 and n=2 are comparable and n=1 with odd poloidal-m parity and n=2 is with even poloidal-m parity.

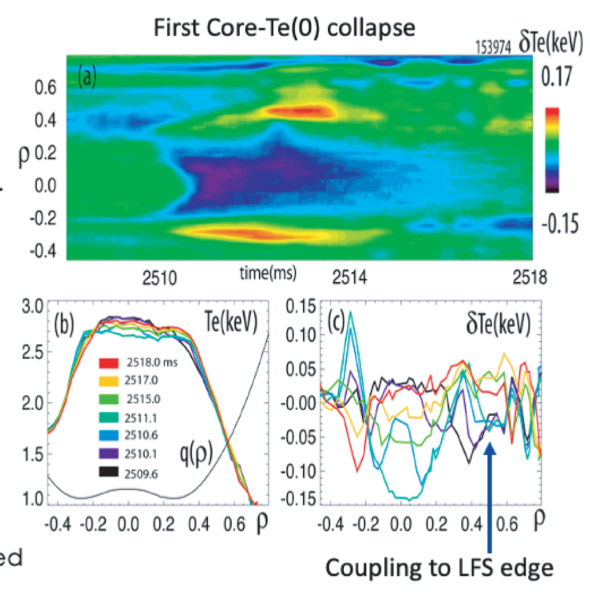


Feedback sustains the QI mode in phase with the applied 3D field and impacts the Te(0) crash (compare no FB)

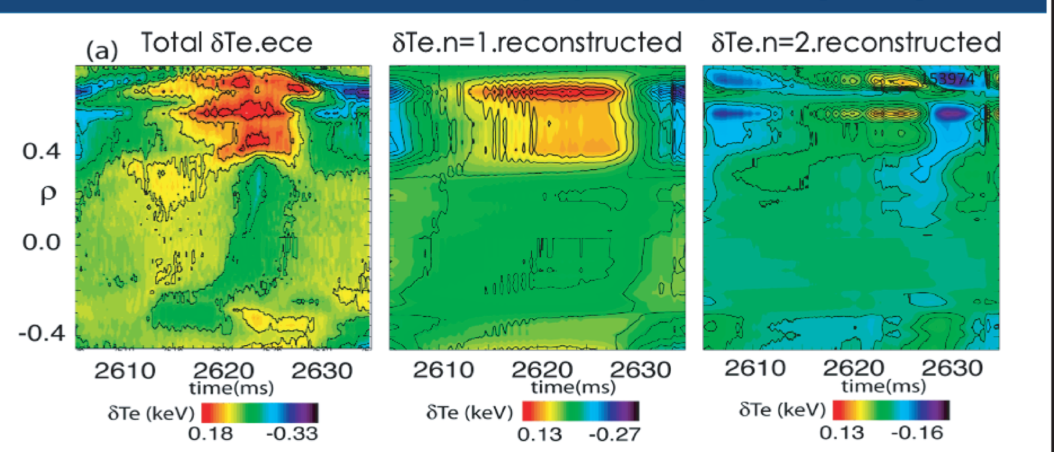


QI-driven Te crash begins with LFS/HFS symmetric similar to with DC 3D Field, but the off-axis LFS/HFS asymmetry indicates the coupling to LFS 3D Field

- The first Te crash at t=2510ms is **similar to the case of DC field** But, off-axis area couples with the applied 3D field
- (in previous page) second crash began to drift into the LFS. This situation became more clear with the crash of the third cycle at t=2582ms and fourth cycle at t=2622ms. The QI crash **shifts later in toroidal phase** relative to the n=1 3D field (3D field phase is shown by islands at r>0.4)
- (in next page) The crashes end by expelling Te to well outside q=1,where **the same positive response** was seen to the applied field.

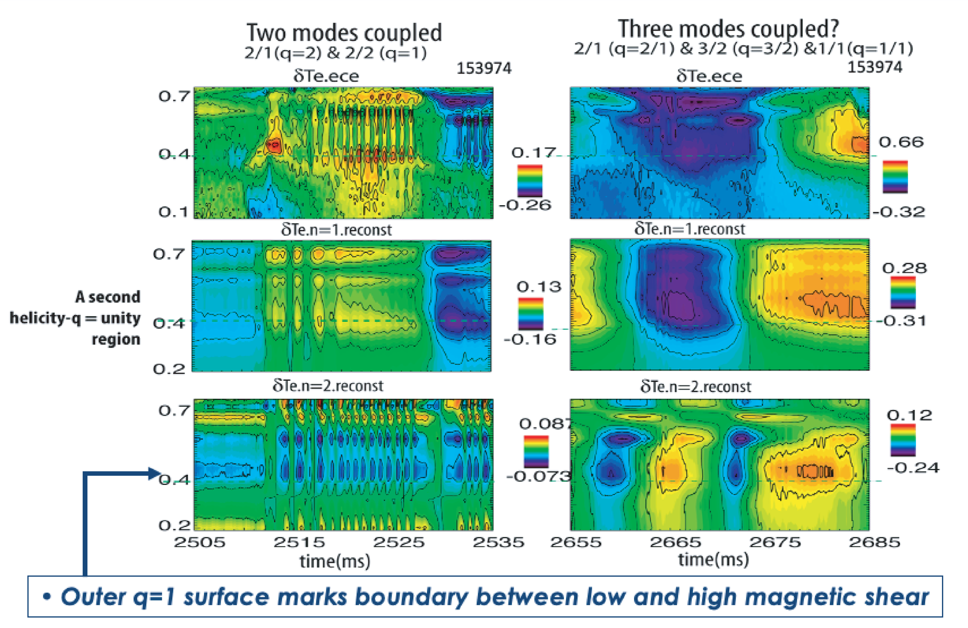


Toroidal harmonics n=1 and n=2 respond to QI-driven core crash at helicity-q ~ unity area(r~0.4)



- The QI-driven core crash extends to r ~ 0.4, the outer boundary of a second helical-q= unity region, where the QI mode interacts with the outer domain q>1.
- The outer domain n=1 and n=2 δTe ~ 0.1keV (significant since the overall positive δTe ~0.2 keV) extend inward to r ~ 0.4, where the magnetic shear sharply decay around helical-q unity area.
- The 3/2 resonant-type response is visible in n=2 signal at q=3/2 around ρ =0.5 around 2625-2630ms.

A second Helicity-q = unity region is resilient to other MHD appearance at off-axis area?



- *Outer q=1 surface marks boundary between low and high magnetic shear*

Discussion

- Recently, **M3D numerical simulations**[5] suggest that it may be possible to control the quasi-interchange mode stability together with the NTM-driven disruptive mode using the same slowly-rotating 3D field.
- This is based: **The existence of two lowest toroidal harmonics n=1 and n=2** with similar magnitude **even during non-linear process growth,**
- **Experimentally,** we identified these two toroidal components. In addition, **two helicity-q=unity region existence** was revealed. The **outer helicity-q=unity** plays a dominant role for separating the activity in the QI-crash region from outer MHD activity such as NTM control process takes place.
- The **sustainment of the phase relation** between the applied 3D field and the mode response by feedback made it efficient to control the inner QI crash characteristics such as the QI collapse direction toward outer rational surfaces.
- However, the physical process at **a second outer helicity-q=unity region** is not well understood yet. The effective usage of the two n=1 and n=2 QI components predicted by simulation as well as shown by experiment needs to be quantitatively explored.

Summary

- We have started to extend the application of **an n=1 rotating 3D field of mode-locking avoidance** to **the control of the core QI-driven crash in the q≃1 region** of hybrid configurations.
- The quasi-interchange instability in ITER-baseline shaping plasmas with low magnetic shear central regions **with q≃1 has two dominant toroidal harmonics n=1, 2** that make it well suited to interact with an external 3D field.
- The QI-driven Te(0) crash control will assist the MHD understanding **from the core to the edge integration**, in particular, in higher temperature less-collisional regimes.

References

[1] OKABAYASHI, M., ZANCA. P., STRAIT, E.J., GAROFALO, A.M., HANSON, J.M., IN, Y., LA HAYE, R.J., MARRELLI, L., MARTIN, P., PACCAGNELLA, R., Avoidance of tearing mode locking with electro-magnetic torque introduced by feedback-based mode rotation control in DIII-D and RFX-mod, Nucl. Fusion 57 (2017) 016035

[2] ZANCA, P., MARRELLI, L., MANDUCHI, G., AND MARCHIORI, G., Beyond the intelligent shell concept: the clean-mode-control, Nucl. Fusion 47 (2007) 1425–1436

[3].PARK, W., BELOVA, E.V., FU, G.Y., TANG, X.Z., STRAUSS, H.R., AND SUGIYAMA, L.E., Phys. Plasmas 6, 1796 (1999). Plasma simulation studies using multilevel physics models

[4] SUGIYAMA, L.E AND PARK, W., A nonlinear two-fluid model for toroidal plasmas, Phys. Plasmas 7, 4644 (2000).

[5] SUGIYAMA, L.E., XU, L.Q., AND OKABAYASHI, M [Phys. of Plasmas submitted 2020] Quasi-interchange modes and the sawtooth crash

[6] SHIRAKI, D., OLOFSSON, K.E.J., VOLPE, F.A., LA HAYE, R.J., STRAIT, E.J., PAZ-SOLDAN, C., AND LOGAN, N., Error Field Detection and Mode Locking Avoidance by the Interaction of Applied Rotating 3D Fields with Otherwise Locked Modes, http://meetings.aps.org/Meeting/DPP13/Session/PO4.15

Acknowledgements

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, using the DIII-D National Fusion Facility, a DOE Office of Science user facility, under Award(s) DE-AC02-09CH11466, DE-FC02-04ER54698, DE-AC05-06OR23100, DE-FG02-04ER54761, DE-AC52-07NA27344 and DE-SC-0017992.