

Status of “The Development of Long-Pulse Heating and Current-Drive Actuators and Operational Techniques Compatible with a High-Z Divertor and First Wall”

Presented by Stephen J Wukitch MIT

On behalf: Edward Doyle (UCLA), Joel Hosea (PPPL), Saskia Mordjick (WM), George Tynan (USCD), Xueqiao Xu (LLNL)

1. Collaboration has made substantive contributions in engineering, technical and diagnostic areas which have strongly benefited the EAST program.
2. Physics collaborations have been more challenging, we began with overly optimistic goals and underappreciated the challenges.

Presentation Organization:

Accomplishments

Challenges

Lessons Learned

Collaborative Team: An Introduction

Integrated US team leveraging collective expertise and experience to develop and collaboratively implement high Z divertor capable of steady state heat flux exhaust, RF actuators and operational scenarios compatible with high Z PFC for EAST and future FNSF device.

- MIT and PPPL provide leadership in divertor and RF engineering along with physics support.
- UCLA and UCSD provide invaluable diagnostic and physics analysis critical to understanding divertor and RF interaction with scrape-off layer plasma physics.
- WM and LLNL provide simulation capability to understand the effects of divertor design and scenario optimization in long-pulse tokamaks with high Z wall materials.

Began a new collaboration in August 2013.

- Decided to focus on EAST due to limited collaboration funds and tight resources at KSTAR.

Assist EAST in Implementing Tungsten Divertor with > 20 MW of Coupled RF Power

Power exhaust: assist in implementation of ITER-like tungsten monoblock divertor with up to 10 MW/m² thermal capacity.

- Water-cooled tungsten divertor design analysis (MIT, PPPL)
- Physics of divertor plasma and impurity sources (MIT, USCD, WM)
- Disruption analysis and experiments (MIT)

Power injection: assist EAST in optimizing their ICRF system to deliver power to the plasma and heat effectively.

- EAST ICRF transmission, antenna, and antenna coupling optimization (MIT, PPPL)
- Assess ICRF interaction and modification of the SOL (MIT, PPPL, UCSD, UCLA, LLNL, WM)
- Implement critical edge/SOL diagnostics (USCD, UCLA)

Identify and implement operation scenarios with of low impurity confinement compatible with high energy confinement.

- Identify discharge conditions where I-mode, H-mode like energy confinement with L-mode like particle confinement, may be accessible. (MIT, LLNL)

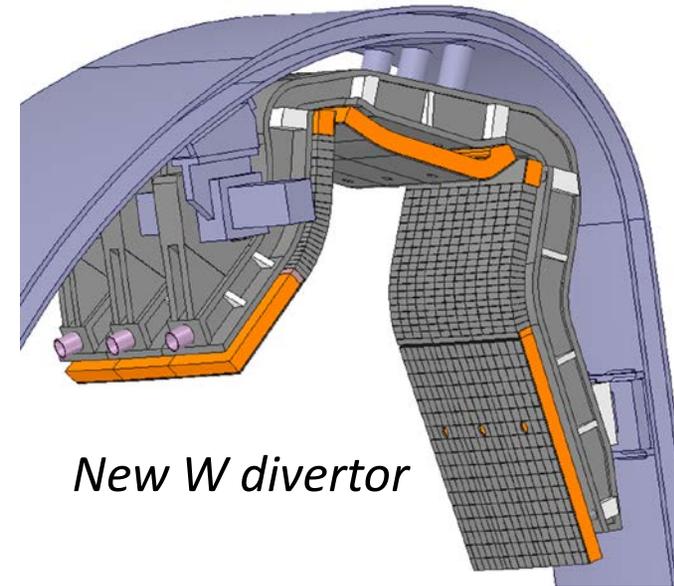
ITER-like Tungsten Divertor Successfully Implemented

First Tungsten divertor operation was achieved in August 2015.

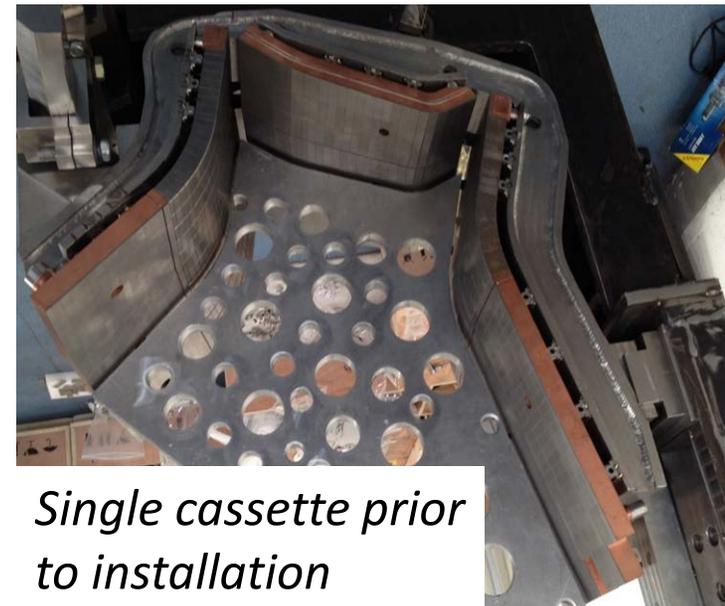
- Designed for 10 MW/m² thermal heat loads.
- Very challenging – first actively cooled divertor structure in operation.
- Geometry and design is very similar to ITER.

Installation was completed in May 2014.

- During initial operations, nitrogen leaks developed after operation.
- Thermal stress from machine bake was identified as source of majority of weld failures.
- Problem was resolved with installation of bellows section in cooling loop.



New W divertor



Single cassette prior to installation

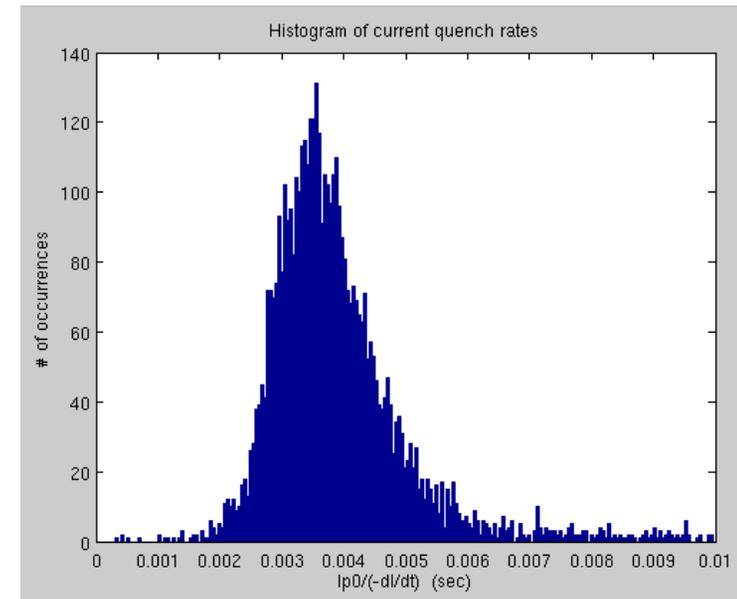
Critical Contributions to W-Divertor Implementation

Implementation of a disruption database – first database to be implemented at EAST – encouraged data centralization.

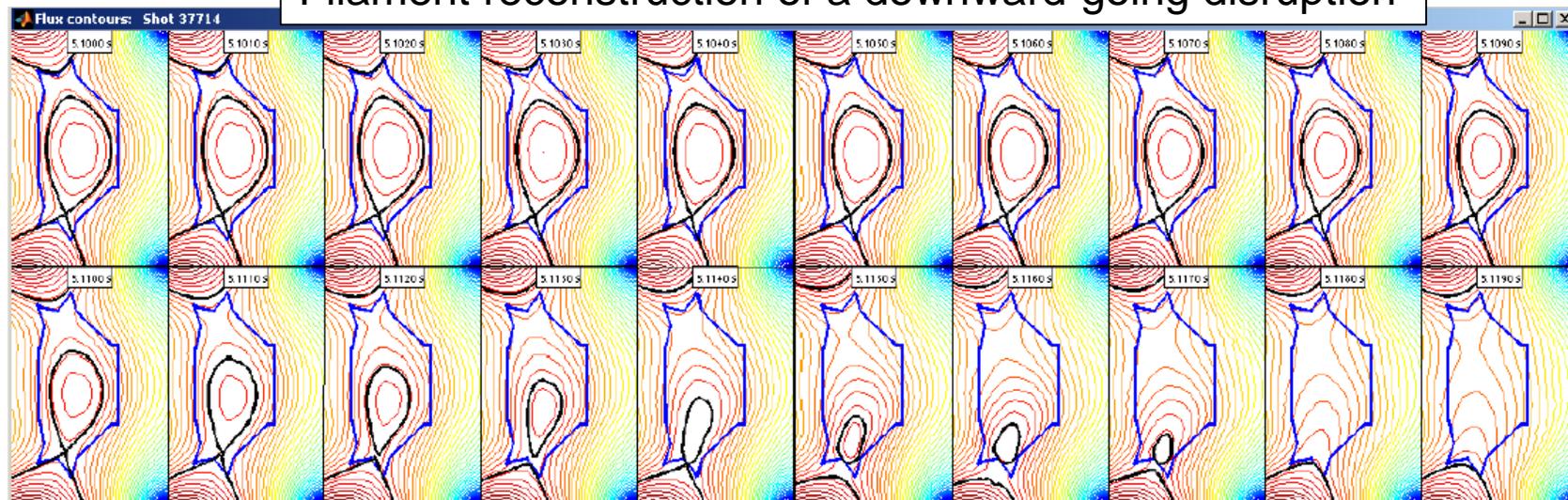
- C. Dalong, R. Granetz, S. Biao, Y. Fei, Q. Jinping, and X. Bingjia, Chin. Phys. B 24, 025205 (2015).

Filament reconstruction to follow and identify plasma contact with in-vessel components.

- Allows determination of where halo current enters and exits in-vessel components.



Filament reconstruction of a downward going disruption



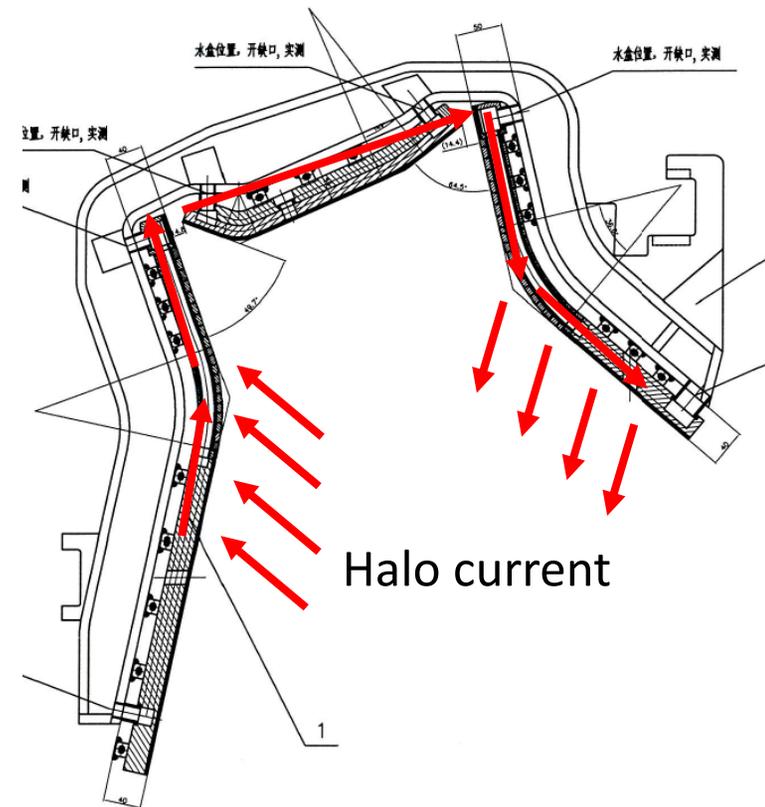
Critical Contributions to W-Divertor Implementation

Identified halo current path in tungsten divertor was through the cooling tubes rather than through stainless steel divertor support structure.

- Used field lined reconstruction to show that the halo current would be enter via the target plates.
- Showed that the cooling tubes would carry majority of the current – lowest resistive path.
- As in lower divertor, rogowski coil measurements to monitor halo current would miss majority of halo current.

Analysis showed that the divertor attachment to the stainless steel structure would likely fail.

- Attachment was modified to prevent exceeding stress design limit.



J. Doody et al., "Analysis of EAST's New Tungsten Divertor and Cooling System during a Disruption with Halo Currents," Fusion Science and Technology (TOFE Anaheim) (2014).

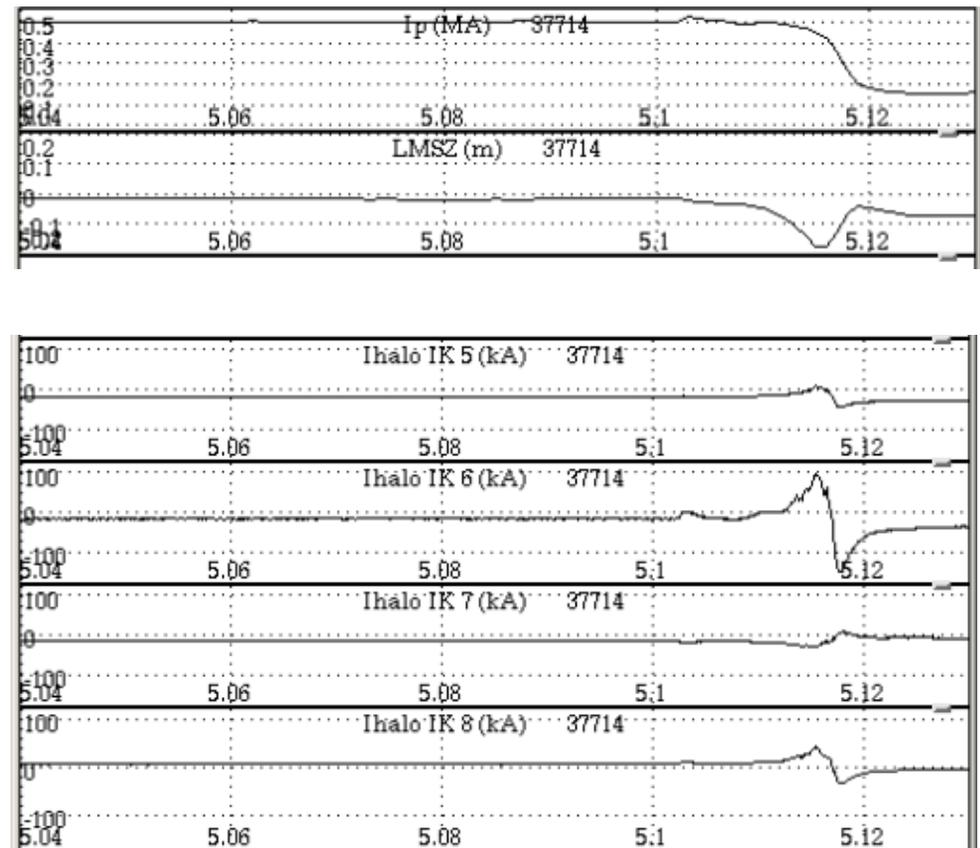
Critical Contributions to Disruption Diagnostics

Rogowski signals have large uncompensated loop area which corrupts halo current measurements.

- Signal changed polarity during largest di/dt

Identified design to eliminate uncompensated area.

- Worked with D.L. Chen (ASIPP graduate student) to build compact, compensated Rogowski coils.
- Instrumented lower dome and upper divertor plates.



D.L. Chen, B. Shen, R.S. Granetz, Y. Sun, J.P. Qian, Y. Wang, B.J. Xiao, "Halo current diagnostic system of EAST", Rev. Sci. Instrum. 86, 103506 (2015).

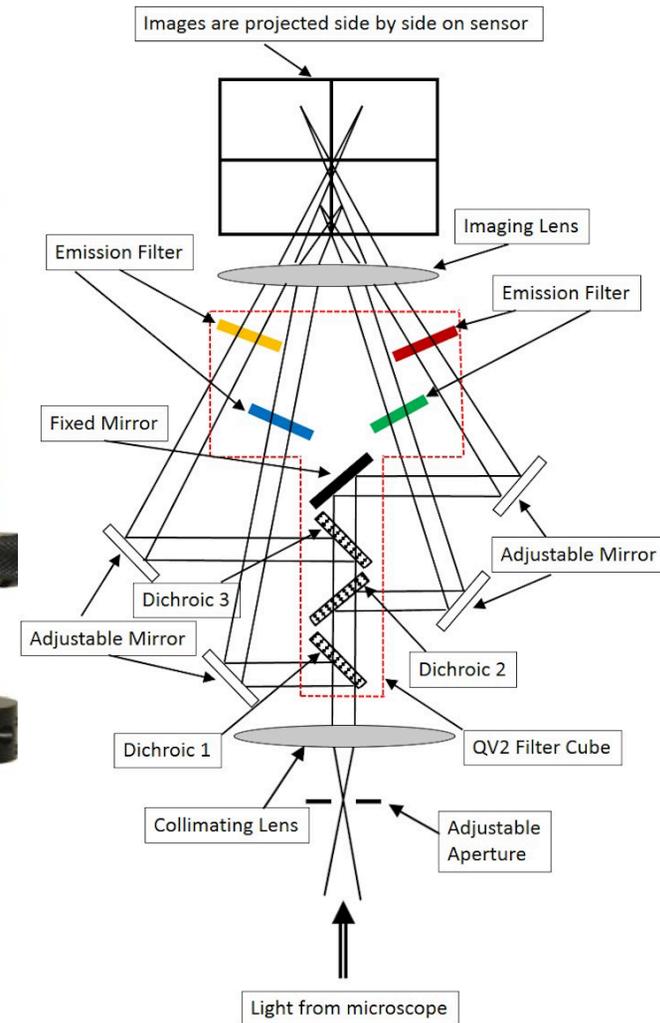
Physics of Divertor Plasma and Impurity Sources

Goal is to provide assistance in edge plasma diagnostics, data analysis and physics interpretation.

- Identified opportunity to provide radial profiles of plasma density and electron temperature profiles and turbulent particle fluxes.

Developed a 4-channel imaging system for fast camera to permit simultaneous measurement of both density and electron temperature over a 2D image.

- With sufficient light intensities, possible to image turbulent fluctuations.
- Data will be used by the collaboration modeling efforts to constraint SOLPS5 time-averaged fluid code modeling of these discharges.



SOLPS5: Assess Neutral fueling and Heat Flux

Goal is to model the plasma edge for plasma-wall interactions as well as input for RF heating simulations (WM).

Insufficient experimental EAST data available to begin SOLPS5 modeling for EAST

- Trained Dr. Hang Si (EAST) to use SOLPS5

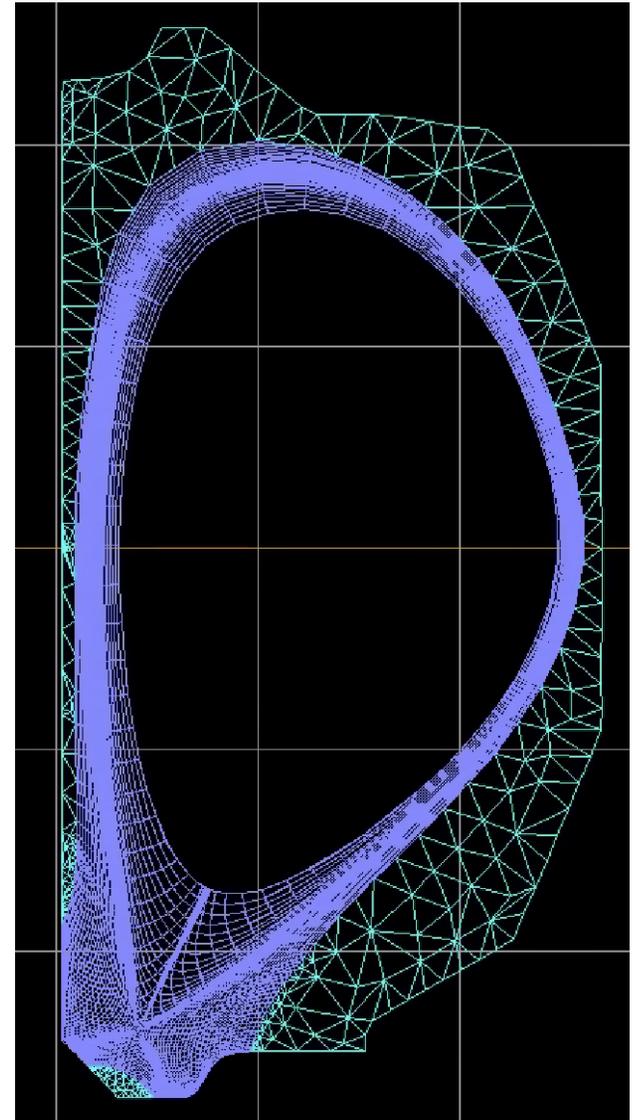
Utilized test cases to gain SOLPS5 modeling experience

- Investigated effects of neutral fueling vs. inward pinch in JET and DIII-D.

New grids have been generated with DivGeo software.

- Grids have triangulated regions suitable for modeling with EIRENE Monte Carlo code.

Developed familiarity with developer tools to enables close collaboration with primary SOLPS-ITER developers.

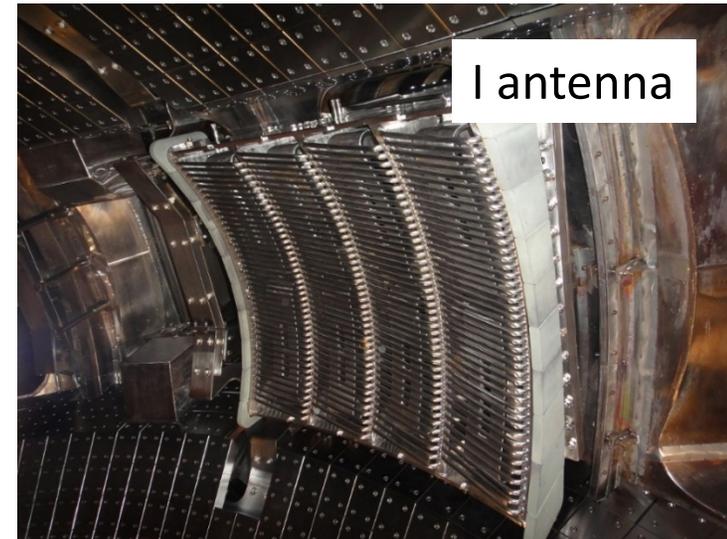


Assist EAST to Optimize their ICRF to Effectively Heat

EAST has a goal to reliably couple 70% of 12 MW source power into plasma for >100 s.

- Increasing coupling efficiency is critical.
- Maximum coupled power from two antennas is 2.8 MW into L-mode plasma.

Pursued parallel paths: assess paths to increasing coupled power and study impact on plasma edge.



Breakthrough: Higher heating effectiveness was observed utilizing low $k_{\parallel} \sim 2.4 \text{ m}^{-1}$ and standard $k_{\parallel} \sim 14.4 \text{ m}^{-1}$.

- ~3 time higher heating effectiveness is than standard antenna phase.
- Implies potential to increase coupled power by 55%.

Indicates that the antenna needs to be modified as well to improve coupling and achieve 70% coupled power.

- Unlike divertor task, there is no convincing model for predicting antenna performance; thus, evaluation of ideas is more difficult and subjective.

Measurements indicate Significant RF power Remains in Plasma Edge

From visible camera images, identify possible RF power deposition locations. (PPPL)

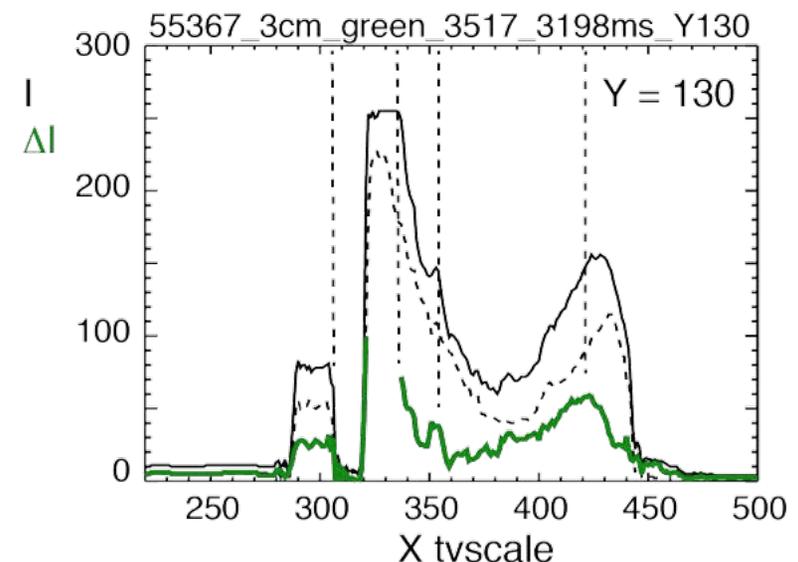
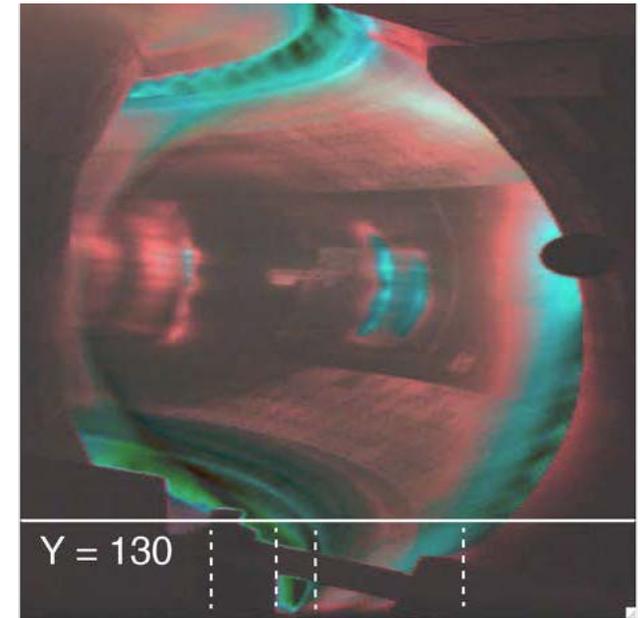
Subtract a camera frame without RF from a frame with RF, emission profile is increased in amplitude and broader.

- Significant peaking in the divertor regions
- possible RF power deposition inboard and outboard of the divertor regions

Significant RF power transfer through the plasma to the divertor.

- Deposition in plasma needs to be studied
- Dependence on antenna phase needs to be investigated.

J. Hosea et al., "RF power deposition explorations in tokamaks using cameras and Langmuir probes," 57th APS-DPP, GP12.00072 (2015).



UCLA Collaboration with USTC Developed Advanced Density Profile Measurements on EAST

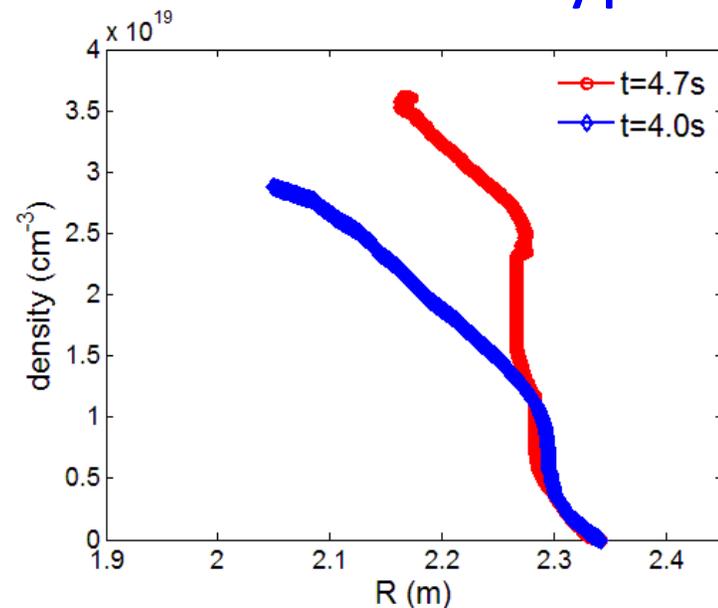
Goal is to provide key support for measurements of the electron density profile and density fluctuations on EAST.

- Accurate measurement of the density profile with high temporal and spatial resolution is critical for antenna loading and simulation effort.
- In conjunction with University of Science and Technology of China collaborators (USTC) at the (USTC), UCLA successfully designed, built and installed new microwave reflectometer systems for EAST.
- Recent discussions with EAST ICRF group indicate that they gaining confidence in the diagnostic.

Microwave front-end installed on EAST



Measured EAST density profiles



ICRF Influence on the SOL and Plasma Wall Interaction

Goal is to develop physics understanding of RF interaction in the plasma edge.

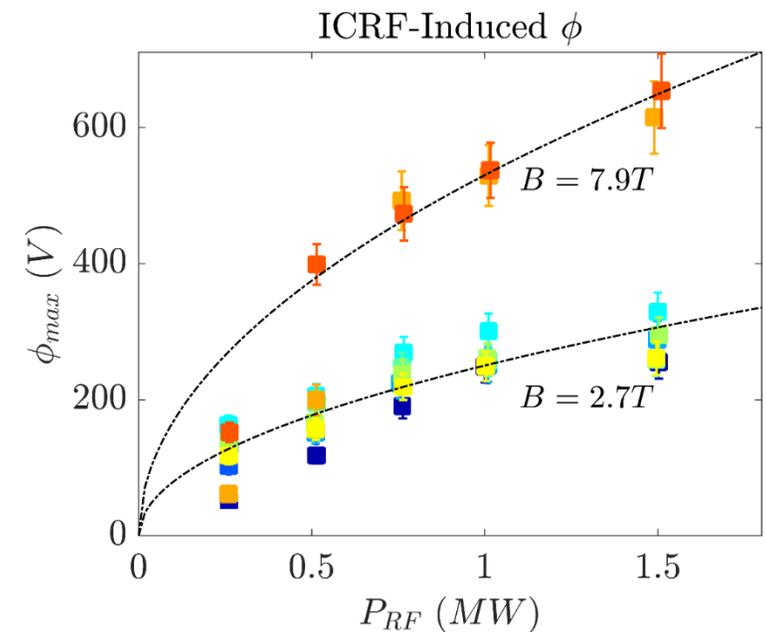
Coordinated effort between MIT, PPPL, LLNL, UCSD, UCLA, and WM.

Experienced difficulty and delays with diagnostic implementation at EAST.

- R. Hong (UCSD PhD graduate student) spent the 2014 campaign period at ASIPP.
- Re-focused his effort to analyze C-Mod data deducing in preparation for EAST experiments.

Plasma edge conditions have strong influence on RF enhanced plasma potential.

- Induced peak potential is significantly larger for 7.9 T discharge.
- Poloidal velocities driven by RF scale more weakly with B-field than expected.
- Width of induced sheath is larger at B=7.9 T.



Develop Simulation Capability to Evaluate RF Impact on Plasma Performance and Low Impurity Confinement Regimes

Motivation was to use BOUT++ to better understand the effects of divertor design and scenario optimization in long-pulse tokamaks with high Z wall materials.

Three primary tasks:

- Improved BOUT++ simulations by adding kinetic impurity module to investigate impurity transport in turbulent plasmas and under ELM events.
- Developed an electric field solver across the separatrix with RF limiter and divertor plate sheath boundary condition, which is used for Impurity ExB drift BOUT++ turbulence and ELM simulations.
- Implement PIC-Fluid hybrid code to simulate interplay between plasmas and kinetic impurity dynamics.

Effort greatly amplified by ASIPP visitors to LLNL to work on extending BOUT++ capability.

Work evolved to utilize BOUT++ to investigate physics of I-mode using C-Mod data.

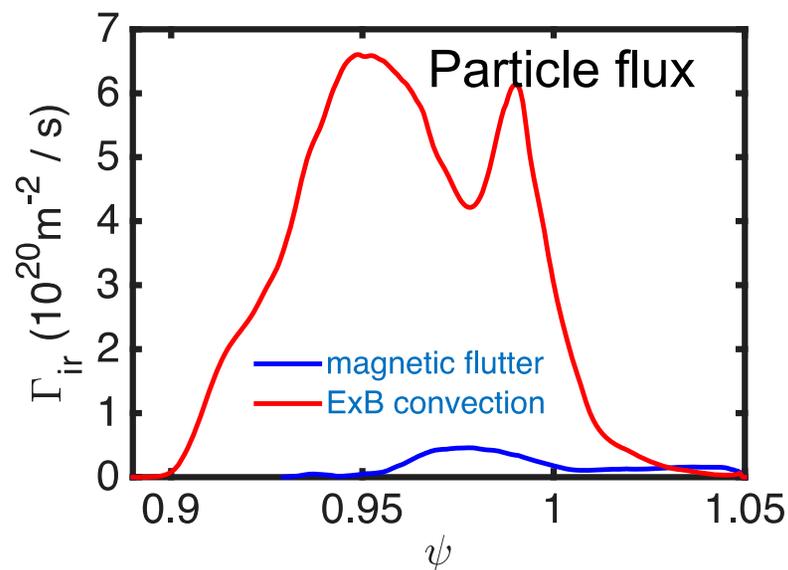
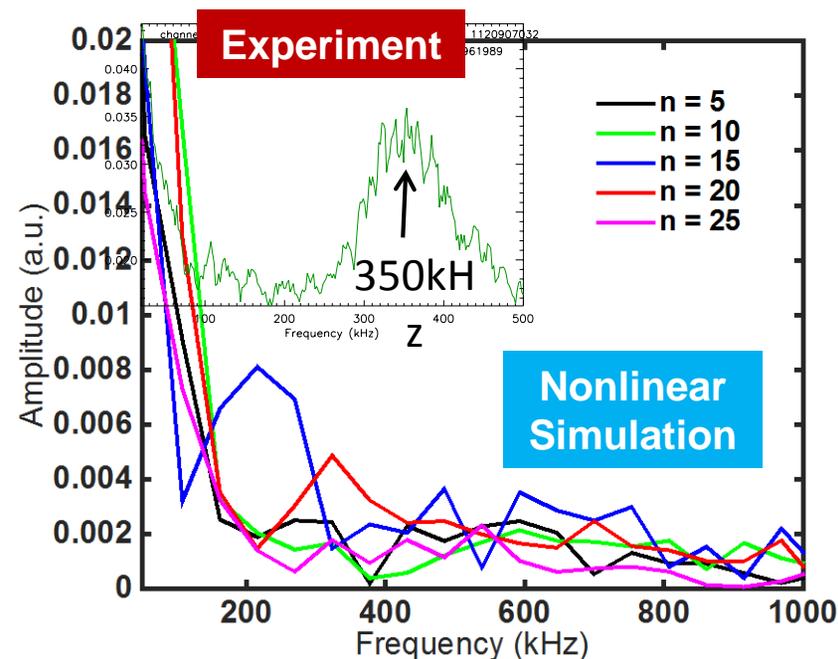
Developing Discharges and Simulation Capability for Advanced Low Impurity Confinement Regimes

A. Hubbard (MIT), X. Gao and Z. Lui (ASIPP) have identified potential I-mode discharges on EAST.

Current effort has been to utilize BOUT++ to investigate I-mode physics using C-Mod data. (Z. Lui ASIPP and X. Xu LLNL).

Simulations show promising agreement with weakly-coherent-modes (WCMs) on C-Mod.

- Find a broad feature which is consistent with Drift Alfvén Wave.
- Frequency spectrum of the mode at $n=20$ is similar to reflectometry measurements.
- Particle diffusivity is larger than the thermal diffusivity - consistent with the key feature of I-mode.



Challenges: EAST Management and Experimental Capabilities are Evolving

Major tokamak upgrade completed in May 2014 – New ITER like tungsten divertor, expanded diagnostics, additional auxiliary heating, etc.

- New control room resulted in relocation of nearly all diagnostics.
- Schedule has been difficult to monitor.

Transition to new leadership occurred in August 2015.

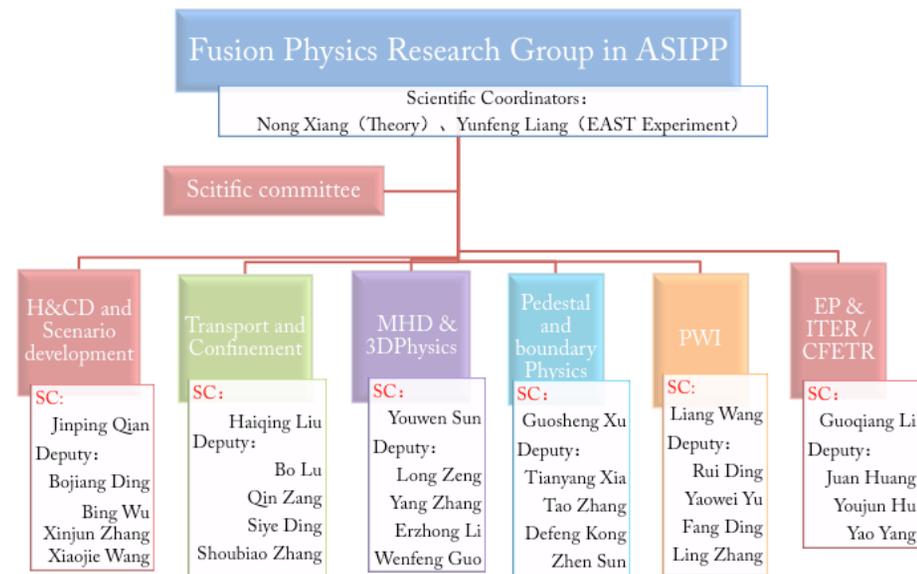
- Prof. Baonian Wan now leads the project.
- Re-organization of Fusion Physics Research group.
- New task forces and working groups have been delineated.

Process to propose physics experiments has been opaque.

- First research opportunities forum open to direct participation in January 2016.
- EAST Proposal Management system (website) has recently been launched.

EAST proposal execution has been complicated by operations: machine operator may limit session leader's plan despite prior approval.

- Particularly vexing if one travels for specific experiment.



Challenges continued

First author publications in prestigious journals using EAST data and experiments are difficult to obtain.

- Review process needs to be clarified.
- R. Granetz is submitting an abstract to IAEA meeting on joint disruption database work on C-Mod and EAST, with strong support from Prof. Li Jiangang.

Data availability is hindered due to lack of central repository.

- Gradual migration towards central repository has begun.

EAST experiment has had limited operation since grant began.

- Limited number of long pulse (~100 s) discharges.
- Plasma parameters remain significantly less than planned.

Little official publication of schedules and what schedule information provided has been incomplete.

- Access to schedule information has been improving.

EAST plasma operation has become reliant on heavy Li conditioning to obtain good plasma performance.

- Plasma material interaction studies have become complicated by mixed materials – C, Li, W.

Lessons Learned

Scientific productivity is closely linked to tokamak operation, diagnostic, and scenario capabilities/availability.

For productive collaboration, EAST and our mutual interest must align.

- Each researcher or group is attempting to work out a relationship between EAST and themselves.
 - Provide scientific expertise in return for physics research.
 - If not perceived as valuable, very difficult to have productive physics research.
- Other international collaborators at EAST can impact progress/compete directly with your task.

EAST is a difficult environment for students and young scientists.

- Work place safety is very different from expected conditions in the US.
- Competition for resources at EAST is fierce.
- Research on EAST is moving towards compelling opportunities at the leading edge of fusion research but presently are more limited than elsewhere.

Living conditions are environmentally unhealthy.

- Difficult to convince people to re-locate or visit for extended periods.
- Hinders developing strong collaboration due to lack of permanent staff.

Summary

Collaboration has made substantive contributions in engineering, technical and diagnostic areas which have strongly benefited the EAST program.

- Tungsten divertor has been successfully installed.
- ICRF coupled power has remained below desired level – require closer collaboration and commitment from ASIPP to improve.
- Understanding high performance, low impurity confinement regimes has progressed through simulation and utilizing data from C-Mod.

Physics collaborations have been more challenging, we began with overly optimistic goals and underappreciated the difficulties.

- Achieve greater success when mutual interest of EAST and collaborators align.
- First author publications in prestigious journals using EAST data and experiments are difficult to obtain.

Presentations/Publications

- N. Bertelli et al, "Full wave simulations of fast wave efficiency and power losses in the SOL of tokamak plasmas in mid/high harmonic and minority heating regimes". Nucl. Fusion 56 (2016) 016019
- B. Gui, X. Q. Xu, T. Y. Xia, "Edge electric field structure with RF sheath", to be submitted to Nuclear Fusion, 2016
- X. T. Xiao and X.Q. Xu, "PIC simulations for impurity distribution in divertor geometry", to be submitted to Computer Physics Communication, 2016
- T. F. Tang, X. T. Xiao and X. Q. Xu, "PIC simulations for impurity distribution in turbulent plasmas", to be submitted to Physics of Plasmas , 2016
- N. Bertelli, "Fast wave SOL losses of tokamak plasmas in minority, mid/high harmonic, and helicon heating regimes" Oral contribution at 10th Asia Plasma and Fusion Association conference (December 2015, India)
- X.Q.Xu, et al., "Toward integrated multi-scale pedestal simulations", submitted to Phys. Plasmas (2015)
- J. Hosea et al., "RF power deposition explorations in tokamaks using cameras and Langmuir probes," 57th APS-DPP, GP12.00072 (2015).
- Xu, Xueqiao, et al., "Toward integrated multi-scale simulations for a full ELM cycle with ELM dynamics," 57th APS-DPP, BI2.00002 (2015).
- Z.X. Liu et al., "Analysis of Weakly Coherent mode on C-Mod with the BOUT++ code," 57th APS-DPP, GO4.00005 (2015).
- X. Xiao et al., "Development of test particle module for impurity transport in BOUT++ framework," 57th APS-DPP, TP12.00127 (2015)
- B. Gui et al., "Self-consistently simulation of RF sheath boundary condition in BOUT++ framework," 57th APS-DPP, TP12.00128 (2015).
- T. Tang et al., "Development of test particle module for impurity transport in BOUT++ framework," 57th APS-DPP, TP12.00127 (2015).
- D.L. Chen, B. Shen, R.S. Granetz, Y. Sun, J.P. Qian, Y. Wang, B.J. Xiao, "Halo current diagnostic system of EAST", Rev. Sci. Instrum. 86, 103506 (2015).
- A. Salmi, T. Tala, A. Jarvinen, P. Mantica, L. Meneses, S. Mordijck, V. Naulin, J. Juul Rasmussen, J. Svensson, L. Giacomelli, R. Gomes, M. Groth, T. Koskela, C. Maggi, M. Maslov, G. Sips, H. Weisen and JET contributors, "Particle source and edge transport studies in JET H-mode gas puff modulation experiments" Proceedings of 42nd EPS Conference on Plasma Physics (2015).
- T. Tala, A. Salmi, C. Bourdelle, C. Giroud, J. Hillesheim, C. Maggi, P. Mantica, L. Meneses, M. Maslov, S. Menmuir, S. Mordijck, V. Naulin, J. Juul Rasmussen, G. Sips, A. Sirinelli, M. Tsalas, H. Weisen and JET contributors, "Dimensionless collisionality scans for core particle transport in JET," Proceedings of 42nd EPS Conference on Plasma Physics (2015).
- L. Zhou, W.K. Beck, P. Koert, Q.X. Yang, C.M. Qin, X.J. Zhang, J. Doody, R.F. Vieira, S.J. Wukitch, R.S. Granetz, J.H. Irby and Y.P. Zhao, "RF, disruption and thermal analyses of EAST antennas," 26th Symposium on Fusion Engineering --SOFE 2015, Austin, Texas, USA.
- G. Wang, E.J. Doyle, W.A. Peebles, X. Nguyen, and C. Wannberg, A.D. Liu, H. Li, C. Zhou, J.Q. Hu, M.Y. Wang, X.H. Zhang, W.D. Liu, and C.X. Yu, "Laboratory Testing and First Plasma Measurements with a New, Integrated Profile Reflectometer and Doppler Backscattering System for the EAST tokamak." Presented at the 12th International Reflectometry Workshop, Juelich, Germany, May 18-20, 2015.

Presentations/Publications

- N. Bertelli, "Effect of the scrape-off layer in AORSA full wave simulations of fast wave minority, mid/high harmonic, and helicon heating regimes". Invited talk at 21st Topical Conference on RF Power in Plasmas, California, USA (April 2015)
- S.J. Wukitch, Y. Lin, C. Qin, X. Zhang, W. Beck, P. Koert, and L. Zhou, "Field-Aligned ICRF Antenna Design for EAST," 21st Topical Conference on Radiofrequency Power in Plasmas, AIP Conf Proc (2015).
- R. Ellis, "Additive Manufacturing Techniques for ECH Launcher Components". Poster contribution at the KSTAR Conference (February 2015)
- M.H. Woo et al, "Current status of MHD mode feedback control system using ECH in KSTAR". Poster contribution at the KSTAR conference (February 2015)
- Z. X. Liu, X. Q. Xu, X. Gao, A. E. Hubbard, et al., First analysis of I-mode pedestals with the BOUT++ code, U.S. Transport Task Force Workshop, Salem, MA - April 28-May 1, 2015 (submitted to PRL)
- Chen Dalong, Granetz Robert, Shen Biao, Yang Fei, Qian Jinping, and Xiao Bingjia, "Characterization of plasma current quench during disruption in EAST tokamak", Chin. Phys. B **24**, 025205 (2015).
- C. Zhou, A.D. Liu, H. Li, J.Q. Hu, M.Y. Wang, X.H. Zhang, C.X. Yu, W.D. Liu, E.J. Doyle, X. Nguyen, W.A. Peebles, G. Wang, "Preliminary Results from the Eight-channel Doppler Backscattering and Profile Reflectometer Systems on the EAST Tokamak." Presented at the 7th US-PRC Magnetic Fusion Collaboration Workshop, Nanjing, China, November 10-12, 2014.
- A. E. Hubbard, T. Osborne, F. Ryter, X. Gao, J. Ko, L. Barrera Orte, R. M. Churchill, I. Cziegler, M. Fenstermacher, R. Fischer, S. Gerhardt, R. Groebner, P. Gohil, T. Happel, J. W. Hughes, Z.X. Liu, A. Loarte, R. Maingi, A. Marinoni, E. S. Marmor, R.M. McDermott, G. McKee, T. Rhodes, J. J. E. Rice, L. Schmitz, C. Theiler, E. Viezzer, J. R. Walk, A. White, D. Whyte, S. Wolfe, E. Wolfrum, Z. Yan, T. Zhang and the Alcator C-Mod, ASDEX Upgrade and DIII-D Teams, "Multi-device Studies of Pedestal Physics and Confinement in the I-mode Regime," Paper EX/P6-22, Proc. IAEA Fusion Energy Conference, St. Petersburg, (2014).
- Z. X. Liu, X. Q. Xu, X. Gao, A. E. Hubbard, J. Hughes, J. R. Walk, C. Theiler, T. Y. Xia, T. Zhang and J. G. Li, "First analysis of I-mode pedestals with the BOUT++code," 56th APS-DPP Meeting, Bull. APS **59**(15) TP8:9, 303 (2014).
- E.J. Doyle, A.D. Liu, X. Nguyen, W.A. Peebles, G. Wang, C. Wannberg, and C.X. Yu, "Design and Testing of an Integrated Microwave Front-end System for Profile Reflectometer and Doppler Backscattering Measurements on EAST." Presented at the 20th Topical Conference on High Temperature Plasma Diagnostics (HTPD), Atlanta, GA, June 1-5, 2014.
- A. Salmi, T. Tala, C. Bourdelle, H. Buerand, P. Mantica, L. Meneses, S. Mordijck, P. Tamain, M. Groth, J. Hillesheim, C. Maggi, M. Maslov, V. Naulin, J. Juul Rasmussen, G. Sips, A. Sirinelli, M. Tsolas, H. Weisen, M. Wischmeier and JET-EFDA contributors "Gas puff modulation experiments in JET L- and H-mode plasmas" Proceedings of 41st EPS Conference on Plasma Physics (2014).
- Jeffrey Doody, Robert Granetz, Damao Yao, William Beck, Lihua Zhou, Zibo Zhou, Lei Cao, Xuan Xia, Rui Vieira, Stephen Wukitch, James Irby, "Analysis of EAST's New Tungsten Divertor and Cooling System during a Disruption with Halo Currents," Fusion Science and Technology (TOFE Anaheim) (2014).
- Bin Gui, Xueqiao Xu, "Effects of sheath boundary conditions on ELMs", U.S. Transport Task Force Workshop, San Antonio, Texas - April 22-25, 2014

Presentations/Publications

- G. Wang, W.A. Peebles, E.J. Doyle, C. Wannberg, T.L. Rhodes, "Quasi-optical Coupling into Overmoded Corrugated Waveguide for Reflectometry Applications in Existing and Next-step Fusion Plasmas." Presented at the 20th Topical Conference on High Temperature Plasma Diagnostics (HTPD), Atlanta, GA, June 1-5, 2014.
- B. Gui, X. Q. Xu, J. R. Myra and D. A. D'Ippolito, Phys. Plasmas 21, 112302 (2014).
- X.J. Zhang et al., *Lower hybrid current drive and ion cyclotron range of frequencies heating experiments in H-mode plasmas in Experimental Advanced Superconducting Tokamak*, Physics of Plasmas **21** (2014) 061501
- R. Ellis, "Upgrades for the KSTAR ECH Launchers". Oral contribution at the 9th Asia Plasma and Fusion Association conference (November 2013, South Korea)

Original FOA Focused on High Performance Plasmas Suitable for Long Pulse

Call for collaboration proposals referenced 2012 FESAC panel report:
“International Collaboration in Fusion Energy Sciences Research:
Opportunities and Modes during the ITER Era”

Specific area of interest for this FOA: achieving high performance core plasma regimes suitable for long pulse.

1. Exploring and understanding the transport properties of high performance tokamak plasmas, including the dynamics of the current profile evolution consistent with transport behavior;
2. Studying and developing integrated control schemes capable of maintaining high performance plasmas at the desired operating point for long periods of time;
3. Establishing the physics and engineering of auxiliary systems that provide the means of controlling plasmas for long periods of time;
4. Understanding processes that couple the plasma to the material walls and exploring integrated solutions for the plasma material interface compatible with high performance core plasmas; and
5. Investigating and understanding the physics of transient events such as disruptions to ensure that they can be reliably avoided and developing mitigation techniques as a backup.

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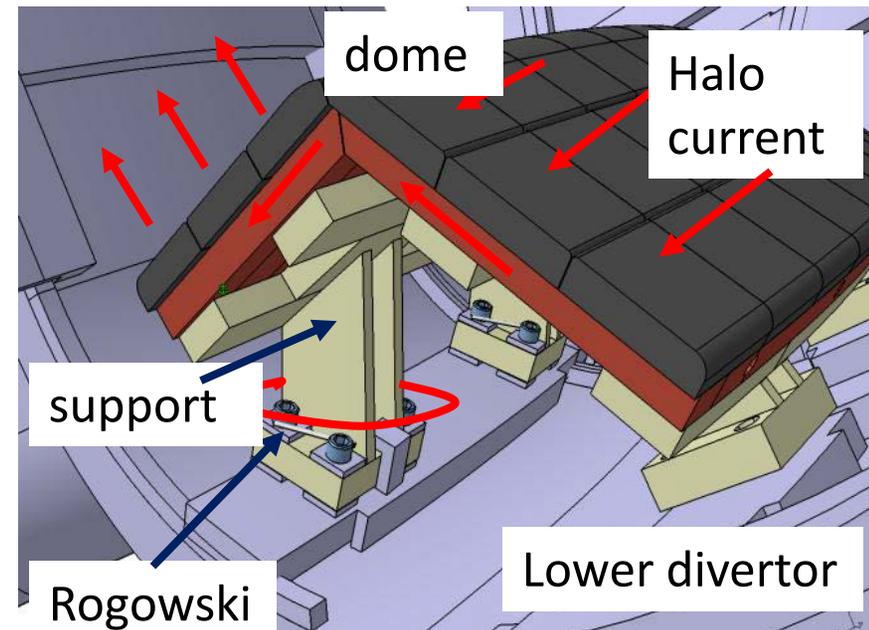
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5. Investigating and understanding the physics of transient events such as disruptions to ensure that they can be reliably avoided and developing mitigation techniques as a backup.

Critical Contributions to W-Divertor Implementation

Provided convincing explanation to lower divertor weld fractures and distorted supports.

Identified that the Halo current measurements miss dominant halo current path through dome.

- $J \times B$ force larger than that expected from measured halo currents.



Filament reconstruction of a downward going disruption

