Final Report for the Early Career Award Titled:
Physics-Based Real-time Analysis and Control to Achieve Transient-Free Operations for the ITER Era

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Sponsor Award Number: DE-SC0015878

Report Number: DOE-PRINCETON-0015878

DOE/Office of Science Program Office (ASCR, BER, BES, FES, HEP, or NP): FES

Topic Area: Magnetic Fusion Energy Science Experimental Research

Topic Area Program Manager: Mark Foster

Years of the Award: 2016 - 2021

Is the PI in a Tenure-Track Appointment? Yes

Final Report for the Early Career Award Titled: Physics-Based Real-time Analysis and Control to Achieve Transient-Free Operations for the ITER Era

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This is the final report for the early career award for Prof. Egemen Kolemen that aimed to develop the physics and technical basis of real-time transient – i.e. disruptions and Edge Localized Modes (ELMs) – avoidance and feedback control at the DIII-D nuclear fusion facility for the ITER era. During this project, we reconstructed high quality real-time DIII-D equilibria using kinetic information from the motional Stark effect (MSE), Thomson Scattering (TS), and Charge Exchange Recombination (CER) spectroscopy. These equilibria were analyzed in real-time to determine the low-n ideal MHD stability and the pedestal stability thresholds, and to obtain plasma response models. These calculations were used to understand which physical process evolves to lead to the onset of disruption in ITER-relevant scenarios at DIII-D, and how disruption can be predicted using stability analysis as opposed to the current methods of correlation of various signals, which are descriptive but lack predictive power. In the disruption studies, we focused on tearing modes, since these constitute the vast majority of disruptions in this regime. With this knowledge, real-time disruption avoidance algorithms were developed and tested. The enhanced situation awareness and physics insight were used in advanced real-time feedback control of pedestal and core profiles, which allowed the pursuit and sustainment of transient-free high-confinement regimes that cannot be achieved via feed-forward design based on in-between shot analysis.

I. Research Accomplishments:

For ease of understanding, can categorize the develop the physics and technical basis of real-time disruption avoidance and feedback control at the DIII-D nuclear fusion facility for the ITER era into parts below. In the following we explain the accomplishments in each of these five fields during the award period. We include the publications for the award.

1. Diagnostics and Hardware

With the Department of Energy Early Career Award, a 5-year award for "Physics-Based Real-Time Analysis and Control to Achieve Transients-Free Operations for the ITER Era," I have developed a real-time stability analysis system to avoid disruptions for DIII-D, with applicability for ITER. A main component of stability analysis is to obtain accurate kinetic equilibrium reconstruction. Standardly, the DIII-D real-time equilibrium reconstruction code, rt-EFIT, in which the Grad-Shafranov equations are solved, uses magnetic loops and MSE data. These reconstructions are good enough for boundary shape control, but in order to be able to make intelligible stability calculations, improved internal kinetic profiles are necessary. Consistent Automated Kinetic Equilibrium (CAKE) reconstruction, the platform we implemented that produces automated kinetic equilibria, is running on a dedicated server for all DIII-D plasma discharges in the 2020 campaign, and it has already started being used for physics analysis [**A.O. Nelson (grad student), F.M. Laggner (postdoc)**, R.J. Groebner, B.A. Grierson, **O. Izacard (postdoc), D. Eldon (postdoc)**, M. Shafer, A.W. Leonard, D. Shiraki, A.C. Sontag, and **E. Kolemen**, "Setting the H-mode pedestal structure: variations of particle source location using gas puff and pellet fueling", Nuclear Fusion 60 046003 (2020); **A. Xing (postdoc), D. Eldon (postdoc), M.A. Roelofs (visiting grad student), W.J. Eggert (grad student), A.S. Glasser (grad student),** N.C. Logan, Q. Hu, D.A. Humphreys, O. Meneghini, S.P. Smith, and **E. Kolemen**, "Development of an automatic kinetic equilibrium reconstruction work flow for tokamak plasma stability analysis", Fusion Engineering and Design 163, 112163 (2021)]. While the process of achieving accurate "kinetic EFITs" is historically done offline with human interface, taking days of work, CAKE achieves the same automatically.

This is attained by first applying full pressure constraints that are calculated from electron, ion, and fast ion pressures using Thomson and Charge Exchange Recombination (CER) diagnostics. MSE measurements and numerical bootstrap calculations are used to constrain the current profile. All the constraints are then used in a consistent way to solve for the equilibrium.

In order to obtain kinetic equilibria in real-time, we built a real-time system to acquire and analyze CER for the pedestal of DIII-D. This is now allowing us to control edge rotation and ELM behavior. In collaboration with the DIII-D Thomson group, I commissioned real-time electron density and temperature profile fitting. This system enabled control of pedestal density, ELMs, and WMHD. It also allowed us to implement and test the real-time automated kinetic EFIT on the Plasma Control System (PCS). Ricardo Shousha, graduate student, led the optimization of the system in the 2020/2021 DIII-D campaign. These systems pave the path for better stability predictions and control.

2. Analysis/Simulations

2.1. Real-Time Analysis: Tearing island instabilities are the most common instabilities in DIII-D and many tokamaks. My group developed real-time analysis methods to suppress them as they appear and to avoid their occurrence by keeping plasma away from the instability boundary.

Physics-Based: Alex Glasser, graduate student, and I formulated a δW stability analysis method with a Hamilton-Jacobi theory that converts the stability calculation to a Riccati differential equation. This reformulation enabled us to develop significantly faster and more robust algorithms (without any of the singular behavior of previous approaches) for the computation of ideal and resistive MHD stability. δW stability, calculated in ~200 ms, is now implemented and experimentally tested on DIII-D [**A.S. Glasser (grad student), E. Kolemen**, and A.H. Glasser, "A Riccati solution for the ideal MHD plasma response with applications to real-time stability control", Physics of Plasmas 25, 032507 (2018)]. We developed a new resistive stability code, called STRIDE, that builds upon the ideal case, and that can calculate resistive MHD Δ' matrices for DIII-D discharges in ~300 ms [**A.S. Glasser (grad student) and E. Kolemen,** "A robust solution for the resistive MHD toroidal Δ' matrix in near real-time", Physics of Plasmas, 25, 082502 (2018)]. Alex and Rory Conlin, graduate student, expanded upon this work and are continuing experiments on DIII-D [**A.S. Glasser (grad student)**, A.H. Glasser, **R. Conlin (grad student),** and **E.**

Kolemen, "An ideal MHD δW stability analysis that bypasses the Newcomb equation", Physics of Plasmas, 27, 022114 (2020)]. Rory further showed that combining better parallel computation methods and better physics insights reduces the calculation to ~20 ms, which we are actively working on implementing on DIII-D.

Matthijs Roelofs wrote his master's thesis under my supervision at Eindhoven University of Technology while he was visiting Princeton in AY 2016-2017. He obtained the stability error bar using an Unscented Transform method, which is thousands of times faster than a Monte-Carlo approach. Analyzing the DIII-D database with this approach shows that, in most cases, the stability error bar increases by an order of magnitude before a tearing mode onset. Thus, the plasma equilibrium becomes "touchy" before tearing; i.e., minor variations in profiles can lead to instability [**M.A. Roelofs (supervised grad student)**, "Ideal magnetohydrodynamics based filter for tearing mode prediction on the DIII-D", Masters' Thesis, Science and Technology of Nuclear Fusion Mechanical Engineering, Eindhoven University of Technology, (2018)].

This project led to an invited talk at the APS meeting in 2018 and two invited talks at the 2018 MHD workshop, for Alex Glasser and me.

Data-Based: In large-scale tokamaks such as ITER, most potential disruption must be accurately predicted and avoided. Because not all instabilities can be quantified with first-principle approaches, it is important to develop and test data-based Machine Learning Algorithms (MLA). Using the DIII-D database, Yichen Fu, graduate student, Kornee Kleijwegt, visiting graduate student from Eindhoven University of Technology, and I developed several MLAs based on decision tree and ensemble methods, the best of which predicted DIII-D disruptions correctly >95% of the time with 10% false positives [**Y. Fu (grad student), D. Eldon (postdoc)**, K. Erickson, **K. Kleijwegt, L. Lupin-Jimenez,** M. D. Boyer, N. Eidietis, **N. Barbour (undergrad), O. Izacard (postdoc),** and **E. Kolemen**, "Machine learning control for disruption and tearing mode avoidance", Physics of Plasmas 27, 022501 (2020), **"Featured Article" by the PoP Editors** (2020)]. MLA trained with the tearing modes database that we developed at DIII-D provided 'tearability' to quantify the likelihood that a tearing would occur with high probability and evaluate the stability of the plasma.

Joe Abbate, graduate student, Rory, Leonard Lupin, undergraduate student, and Jalal-ud-din Butt, undergraduate student, developed cutting-edge machine learning models that combined Long Short-Term Memory (LSTM), neural networks, and recurrent neural networks to predict the temporal evolution of the kinetic plasma profiles. Past plasma states along with past and future control actuators requests were used as the input of the neural network and results show that a direct data-based approach might be a useful tool for plasma prediction and control. In 2019, I gave an invited talk on the application of machine learning to profile evolution prediction and tokamak control at the IAEA Technical Meeting on Fusion Data Processing, Validation and Analysis in Vienna, Austria. In 2020, I gave an invited talk on machine-learning algorithms such as our plasma evolution predictor adapt themselves during the plasma discharge as new data is streamed results and the application of real-time physics-based and data-based systems for fusion reactors at the IAEA Technical Meeting on Plasma Disruptions and Their Mitigation at ITER Headquarters, France.

2.2. Numerical Physics Simulation: Understanding the Scrape-Off-Layer (SOL) is crucial to pedestal stability (Edge Localized Modes, ELMs) and heat flux control to the divertor. Olivier Izacard, former postdoctoral fellow, and Anthony Xing, postdoctoral fellow, developed the autoUEDGE (automated UEDGE) fluid SOL simulations of experiments at DIII-D, KSTAR and NSTX-U, allowing the investigation of the time evolution of the modeled transport model and detachment. (Previously, achieving a single time slice was a substantial project for a researcher.) Oak and Anthony showed that, directly after an ELM crash, the outer divertor enters a regime of high-recycling characterized by enhanced divertor density, D_α emission, and incident current. The ELM cycle model, based only on upstream profiles and the 100s of autoUEDGE runs, reproduces this divertor behavior, suggesting a strong link between the pedestal profiles and the divertor conditions directly after an ELM crash [**A.O. Nelson (grad student), Z.A. Xing (postdoc), O. Izacard (postdoc), F.M. Laggner (postdoc), E. Kolemen**, "Interpretative SOL modeling throughout multiple ELM cycles in DIII-D" Nuclear Materials and Energy, 26 100883 (2021)].

3. Plasma Control Experiments

3.1. Pedestal Control: In high confinement mode (H-mode), an edge transport barrier forms, increasing the plasma confinement. This is advantageous for fusion reactors and ITER is designed to operate in this regime. However, the 'pedestal' that forms at the edge in this mode is not stable and leads to ELMs, which introduce periodic high heat fluxes at the divertor that need to be mitigated or avoided at ITER.

I developed a comprehensive adaptive real-time ELM control system and showed that improved performance could be achieved by exploiting the key properties of ELM, MP ELM suppression physics, and an extensive set of diagnostic inputs to make real-time decisions about the control of multiple actuators to sustain ELM suppression/mitigation. The control system adjusts the 3D magnetic perturbation (MP) coil phasing for ELM suppression in real time based on calculations of the vacuum edge pitch-resonant and kink-resonant harmonics of the applied 3D MP and data from offline analysis of full 3D plasma response. The amplitude of the 3D coil is regulated to achieve a given ELM frequency (or none) using ELM detection based on the D_α measurements from the divertor region.

Our control experiments at DIII-D showed a path dependence, therefore, hysteresis of plasma confinement when transitioning to/from ELM suppression [**F.M. Laggner (postdoc), D. Eldon (postdoc), A.O. Nelson (grad student)**, C. Paz-Soldan, A. Bortolon, T.E. Evans, M.E. Fenstermacher, B.A. Grierson, **Q. Hu (partial postdoc)**, D.A. Humphreys, A. Hyatt, R. Nazikian, O. Meneghini, P.B. Snyder, E.A. Unterberg, and **E. Kolemen,** "Pedestal optimization with real-time control of 3D fields on DIII-D", Nuclear Fusion 60 076004 (2020)]: First, transitioning to ELM suppression with higher initial MP coil currents leads to lower confinement, even if the same final MP coil currents are applied, and second, entry into ELM suppression requires higher MP coil current than sustainment. Exploiting these hystereses, adaptive ELM control was shown to be effective for ELM-free operations with minimum 3D perturbations and thus highest possible confinement. This demonstrates the need for a control system to keep the ITER MP close to the ELM suppression/sustainment threshold at all times to enable high confinement and, respectively, a high fusion energy gain factor (Q).

In H-mode, performance of the fusion plasma is highly dependent on pedestal parameters. Thus, my group developed a pedestal control system that acquires real-time Thomson scattering diagnostic data and fits the pedestal width/height for temperature and density profiles. Based on the Thomson fits, the PCS regulates the pedestal density by adjusting the gas-puffing rate to increase particle source and RMP density "pump-out" to reduce it. This system has been in extensive use at DIII-D. Florian and I performed a DIII-D control experiment in which we demonstrated the capability to control the plasma edge density in the high performance 'Super H-mode,' a scenario that requires excellent tuning of the edge density [P.B. Snyder, J.W. Hughes, T.H. Osborne, C. Paz-Soldan, W.M. Solomon, M. Knolker, D. Eldon, T. Evans, T. Golfinopoulos, B.A. Grierson, R.J. Groebner, A.E. Hubbard, **E. Kolemen**, B. LaBombard, **F.M. Laggner**, O. Meneghini, S. Mordijck, T. Petrie, S. Scott, H.Q. Wang, H.R. Wilson and Y.B. Zhu, "High fusion performance in Super H-mode experiments on Alcator C-Mod and DIII-D", Nuclear Fusion 59 086017 (2019)]. Since the edge density is crucial to access and sustainment of this regime, our advanced control scheme greatly enabled reliable achievement of Super H-mode, which allowed us to conduct physics studies of the edge transport barrier structure in this regime.

We designed and conducted an experiment at DIII-D that compared the density profile structure between gas-fueled and pellet-fueled discharges. This is of special interest because, in contrast to current, gas-fueled experiments, future reactors will need to be fueled by pellets. Oak showed that the use of deuterium pellets to ionize fuel closer to the tokamak core contributes to a wider pedestal by flattening the edge temperature gradient, leading to sustainment of a higher pedestal and core pressure. This work implies an optimistic global effect of pellet fueling [**A.O. Nelson (grad student), F.M. Laggner (postdoc)**, R.J. Groebner, B.A. Grierson, **O. Izacard (postdoc), D. Eldon (postdoc)**, M. Shafer, A.W. Leonard, D. Shiraki, A.C. Sontag, and **E. Kolemen**, "Setting the H-mode pedestal structure: variations of particle source location using gas puff and pellet fueling", Nuclear Fusion 60 046003 (2020)].

Furthermore, we ran another experiment at DIII-D, which investigated the plasma edge stability by modifying the edge current. Current was induced in the plasma by vertically oscillating the plasma column. We successfully demonstrated that this current can control the pedestal instabilities, which can be observed in fluctuations. In addition, our analysis showed that the three phases of ELM are interlinked with the onsets of different kinds of pedestal fluctuations [**F.M. Laggner (postdoc),** A. Diallo, M. Cavedon, and **E. Kolemen**, "Inter-ELM pedestal localized fluctuations in tokamaks: Summary of multi-machine observations", Nuclear Materials and Energy, Vol. 19, pp. 479-486 (2019)].

Radiation Control: Even with increased flux expansion and divertor detachment, studies show that, in order to stay below the maximum allowable heat flux, future devices will need to operate at >75% core radiated power fractions and substantial divertor dissipation. Although high radiation fraction is necessary to protect PFCs, radiating too much power can trigger a radiative collapse leading to disruption or interfere with H-mode operation: there is an optimal level of radiated power. David Eldon, former postdoctoral fellow, and I developed and tested a new radiation control system to show that desired radiation level control is feasible. We have continued to expand upon this capability to control the radiation levels from the core, edge, and divertor. The system controls the flow of deuterium and impurities such as nitrogen to achieve the radiation distribution in the plasma [**D. Eldon (postdoc), E. Kolemen**, D.A. Humphreys, A.W. Hyatt, A.E. Jarvinen, A.W. Leonard, A.G. McLean, A.L. Moser, T.W. Petrie, and M.L. Walker, "Advances in radiated power control at DIII-D", Nuclear Materials and Energy, Vol. 18, pp. 285-290 (2019)]. In order to measure the radiation levels in DIII-D, my group has worked to establish real-time data acquisition from bolometry diagnostics. The radiation level at the divertor, edge, and core are then calculated with a real-time inversion algorithm that closely agrees with post-shot analysis. David gave an invited talk in 2017 on "Divertor control development at DIII-D and implications for ITER" at the IAEA Technical Meeting on Control, Data Acquisition, and Remote Participation for Fusion Research in Greifswald, Germany, that covered our new insights.

Detachment Control: The real-time pedestal reconstruction and gas feedback capabilities we developed were used extensively to stabilize regimes which were not feasible before. By increasing the density close to the divertor, we achieve divertor "detachment," where the particle flux at the target plates drops by more than an order of magnitude. However, it is difficult to stabilize this effect when plasmas become fully detached. While some degree of detachment is essential for the health of ITER's divertor, more deeply detached plasmas have greater radiative losses and, at the extreme, confinement degradation, making it desirable to limit detachment to the minimum level needed to protect the target plate.

To this aim, our real-time and control algorithms were used (mainly the Thomson measurements and gas feedback). I previously showed that we can keep the detachment front fixed anywhere between the strike point and the X-point throughout the discharge in L-mode operation. David expanded this work to H-mode by adding D_α based ELM filtering of divertor Thomson. We showed that the inter-ELM detached divertor plasma state can be stabilized in close proximity to the threshold for reattachment. However, in H-mode, we demonstrated that it is not physically possible to hold the plasma at the threshold; the resulting T_e profiles separated into two groups, with one group consistent with marginal detachment and the other with marginal attachment. Fortunately, the cold edge of the threshold offers an attractive partially detached solution and can be stabilized with detachment control [8]. As a keynote speaker, I presented these results at the Taming the Flame; Divertor Detachment Control in Tokamaks Workshop.

3.3. Core Control:

Tearing mode suppression: At DIII-D, I previously to this grant developed a real-time system that detects the island formation onset automatically, turns on the gyrotrons, and promptly moves the steerable Electron Cyclotron Current Drive (ECCD) launcher mirrors to drive current at the location of the islands. This was achieved by combining my prior work – (1) fusing measurements from multiple diagnostics to find the instability locations; (2) software for decision-making; (3) in-house-built control boards; and (4) fast mirror motor and encoder hardware – and new research – (5) parallel real-time ray tracing to locate the power deposition location; and (6) many hardware upgrade. This was a world-first demonstration of the techniques required in ITER. Furthermore, I demonstrated that tearing mode instabilities can be detected and suppressed with active control even in the absence of continuous ECH power if island formation is detected sufficiently rapidly, thus allowing operation at higher fusion gain, *Q*.

As an alternative, Oak and I developed a method for the simultaneous determination of both the radial position of a magnetic island and the deposition location of ECCD, using a single radial array ECE radiometer diagnostic. This approach eliminates the cross-calibration issues that are encountered when multiple diagnostics are combined [**A.O. Nelson (grad student),** A.S. Welander, M.E. Austin, R.J. La Haye, **E. Kolemen,** "Simultaneous detection of neoclassical tearing mode and electron cyclotron current drive locations using electron cyclotron emission in DIII-D", Nuclear Engineering and Design, Vol. 141, pp. 25-29 (2019)] and may be a better solution for fusion power plants.

It is possible that some of the gyrotrons at ITER might fail, reducing ECCD, or that the tearing mode control might be late. Under these circumstances, the tearing mode is expected to grow and stop rotating ("lock to the wall"), which sets the stage for a disruption. Our tearing mode control experiments at DIII-D showed that, in these "locked" modes, bootstrap current reduces, allowing much lower power to restore fast plasma rotation and H-mode. Disruptions can thus be avoided at DIII-D [**A.O. Nelson (grad student),** N. Logan, W. Choi, E. Strait, and **E. Kolemen,** "Experimental evidence of ECCD-based NTM suppression threshold reduction during mode locking on DIII-D" Plasma Physics and Controlled Fusion 62 9 (2020)], suggesting a similar disruption avoidance path for ITER.

Tearing mode preemption: Yichen and I implemented the MLAs developed by our group on DIII-D's PCS. This allowed regulating neutral beams injection (NBI) to keep the plasma at the highest possible performance while keeping it stable. If the control fails due to disturbances and the predicted disruptivity becomes too high, the system ramps down the plasma to avoid a full-fledged disruption. The algorithm was used to control the NBI power to prevent the 'tearability' metric from exceeding a user-defined threshold: when the 'tearability' was low, NB power was increased, and vice versa. If the 'tearability' increased further and exceeded the maximum allowed stability threshold, the system ramped down the plasma to avoid disruptions [**Y. Fu (grad student), D. Eldon (postdoc)**, K. Erickson, **K. Kleijwegt, L. Lupin-Jimenez,** M. D. Boyer, N. Eidietis, **N. Barbour (undergrad), O. Izacard (postdoc),** and **E. Kolemen**, "Machine learning control for disruption and tearing mode avoidance", Physics of Plasmas 27, 022501 (2020), **"Featured Article" by the PoP Editors** (2020)]. This paper showed the first use of a real-time feedback machine learning control system in fusion and was chosen as a featured article by the Physics of Plasmas Editors and highlighted as a *Scilight* [A. Liebendorfer, "Machine learning mitigates tearing modes in plasmas tori using real-time feedback", AIP Scilight, https://doi.org/10.1063/10.0000729, 7 February 2020], while an article on this work appeared on *The Register* [K. Quach, "Yes, true, fusion reactors don't work quite yet, but, er, maybe AI can help us stop our experiments from imploding", The Register, 18 March 2020]. In 2019, I gave an invited talk on this first demonstration of machine learning control in tokamaks at the International Conference on Data Driven Plasma Science in Marseille, France.

II. Educational Accomplishments:

As Princeton University professor my main duty is to educate the leaders of the future. The Early Career Award funding have been used very effectively for the education and development of many students and junior researchers. Many PhD graduate students in my research group have been involved with the research project at various levels. These are Joe Abbate (Princeton Program in Plasma Physics, PPPP), William 'Rory' Conlin (Mechanical and Aerospace Department, MAE), Daniel Dudt (MAE), Oak Nelson (PPPP), Ricardo Shousha (MAE), Yichen Fu (PPPP) and Alexander Glasser (PPPP). Also, a masters student Mr. Ebbert was trained at Princeton MAE on this project. Among the PhD students, Oak graduated and started working as a postdoctoral fellow at Columbia University leading the negative triangularity at DIII-D fusion reactor. They have given many talks and presentation which are listed in the research section.

Three international graduate students have visited my group for long-term research stays in relatation to this research: Kornee Kleijwegt, Joost Lammers, and Matthijs Roelofs. Matthijs Roelofs wrote a master's thesis entitled "Ideal magnetohydrodynamics based filter for tearing mode prediction on the DIII-D" based on this work.

I trained many postdoctoral fellows in the fusion plasma control and analysis area. My previous postdoctoral fellows have all been competitive in the job market and made an impact in the fusion research. Dr. David Eldon was hired at General Atomics to work on DIII-D and he is now leading their plasma control group now. Dr. Anthony Xing was hired at General Atomics working on control development for ITER and many other fusion reactors. Dr. Olivier Izacard started working in the private sector in data science area. Prof. Florian Laggner was hired at PPPL fater finishing his postdoctoral research with me and then he became a professor at University of North Carolina.

I have advised senior thesis students, Bora Kiyan (MAE) and Jinjin Zhao (COS) on DIII-D control realted thesis projects.

I advised many summer interns on DIII-D real-time data and control: Alex Liu (COS), Yashodhar Govil (COS), Jalal-ud-din Butt (SULI program), Jinjin Zhao (COS), Nathaniel Barbour (SULI), Robert Gates (summer intern) and Leonard Lupin (SULI), Aaron Wu (COS) and Milan Wolff (College of William & Mary). Among these students, Jalal and Nathaniel has pursued PhD in plasma physics and control.

Even after students leave my group, I continue to take a strong interest in their careers. Former undergraduate students whose research I advised related to this project and for whom I wrote recommendation letters were accepted into doctoral programs in various R1 universities.

III. Impact and Recognition from the Community

My early career award research work has been recognized by the research community with a keynote at the Taming the Flame: Divertor Detachment Control in Tokamaks Workshop, and invited talks at the IAEA Fusion Energy Conference, American Physics Society (APS) Meeting, International Conference on Data Driven Plasma Science, IEA Workshop on Theory and Simulation of Disruptions, MHD workshop, and IAEA Technical Meeting on Plasma Disruptions and Their Mitigation. I have also received the Torkil Jensen Award (with Luis F. Delgado-Aparicio) at DIII-D. In 2020, I received the David J. Rose Excellence in Fusion Engineering Award for the work I conducted for my early career award.

I was selected as an ITER Scientist Fellow among a group of 6 control scientists from across the world to solve challenging research issues and ensure the success of ITER's mission. Our paper on the first use of a real-time feedback machine learning control system in fusion was chosen as a featured article by the Physics of Plasmas Editors and highlighted as a *Scilight* [A. Liebendorfer, "Machine learning mitigates tearing modes in plasmas tori using real-time feedback", AIP Scilight, https://doi.org/10.1063/10.0000729, 7 February 2020], while an article on this work appeared on *The Register* [K. Quach, "Yes, true, fusion reactors don't work quite yet, but, er, maybe AI can help us stop our experiments from imploding", The Register, 18 March 2020].

The work for this grant has been recognized by invited talks. I listed the important ones presented by me below and by students in the research narrative. Our group also gave dozens of talks at APS and other national international conferences. My research has attracted significant attention in the form of requests by colleagues to collaborate and applications by students to join my group.

Selected Invited talk on this research:

1. E. Kolemen, "Real-time Prediction and Avoidance of Fusion Plasmas Instabilities using Feedback Control," *Invited Presentation* IAEA Technical Meeting on Plasma Disruptions and Their Mitigation, ITER Headquarters, France, remote, Jul. 2020

2. E. Kolemen, "Machine Learning Control for fusion devices," *Invited Speaker* at the International Conference on Data Driven Plasma Science, Marseille, France, May 2019

3. E. Kolemen, "Application of machine learning to profile evolution prediction and tokamak control," *Invited Speaker* at the IAEA Technical Meeting on Fusion Data Processing, Validation and Analysis, Vienna, Austria, May 2019

4. E. Kolemen, "Data-based plasma stability analysis and control," *Invited Speaker* at the MHD Workshop, Los Angeles, CA, Nov. 2018

5. E. Kolemen, “Path to Stable Tokamak Operation: Plasma stability analysis using physics-based and data-based approaches for real-time control,” *Invited Speaker* at the APS-DPP, Portland, OR, Nov. 2018

6. E. Kolemen, “Plasma Control for Energy,” *Invited Speaker* at PPPL’s Science on Saturday Public Speaker Series, Jan. 2017

7. E. Kolemen, “Detachment and Radiation Control at DIII-D,” *Keynote Speaker* at the Taming the Flame; Divertor Detachment Control in Tokamaks Workshop, Lorentz Center, Netherlands, Sep. 2016