Award No. DE-SC0008520

"Physics and Control of Locked Modes in the DIII-D Tokamak"

Final Technical Report

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Note: the Award was made in 2011 in connection with the DOE Early Career Award, when the PI was an Assistant Professor at the University of Wisconsin, Madison. The PI then moved to Columbia University, in New York, in 2012, and the award was transferred to the said institution.

1. Introduction

The research project was dedicated to the study and control of non-rotating magnetic islands ("locked modes") in tokamak plasmas. Locked modes are one of the main causes of disruptions in present tokamaks, and could be an even bigger concern in ITER, due to its relatively high beta (favoring the formation of Neoclassical Tearing Mode islands) and low rotation (favoring locking). For these reasons, this research had the goal of studying and learning how to control locked modes in the DIII-D National Fusion Facility under ITER-relevant conditions of high pressure and low rotation.

The goal was articulated in two main objectives:

1. To analyze the island dynamics in terms of balance between electromagnetic and non-electromagnetic torques acting on it.
2. To analyze the growth, saturation and stabilization of locked islands and of their rotating precursors, if any. *Note that the modified Rutherford equation for a locked island in presence of continuous Electron Cyclotron Current Drive (ECCD) is similar to the case of an island rotating in the presence of modulated ECCD.*

Attention was also devoted to the cross-fertilization of these two points, namely to understand the effect of rotation and flow-shear on island stability, and of island size on rotation, locking, and unlocking.

A third objective was to prove that locked islands, forced to rotate by applied rotating fields, can be used to diagnose error-fields.

Major results relevant to all objectives were accomplished and published. The main section of this report, Sec.2, is a description of the main physics results obtained under this Award. The results are grouped according to the first-authored journal papers where they were published, in chronological order. Sec.3 is dedicated to coauthored papers, and Sec.4 contains a list of international invited talks. Finally, Sec.5 describes the impact of our locked mode research on national and international experiments, and Sec.6 reports about the training of two students and two post-docs in nuclear fusion research.

2. Journal Papers first-authored by the PI or by his students and post-docs (underlined)

1) **F.A. Volpe**, M.E. Austin, G. Campbell, and T. Deterly

"Oblique electron-cyclotron-emission radial and phase detector of rotating magnetic islands applied to alignment and modulation of electron-cyclotron-current-drive for neoclassical tearing mode stabilization"

Rev. Sci. Instrum., **83**, 103507 (2012)

> Preventing locked modes with rotating precursors requires rapid stabilization of the magnetic island while this is still rotating, before it locks. To that end, it is important to rapidly align the ECCD with the radial location of the island, and to modulate the ECCD in synch with the island rotation and in phase with the transit of its O-point. This paper presents a system achieving these two goals at DIII-D. The system is based on oblique Electron Cyclotron Emission (ECE) radiometry through a line-of-sight nearly identical to the one used for ECCD injection (only toroidally displaced, to avoid the complication of sharing the same line for high-power heating and a low-power diagnostic). This special line-of-sight maximizes the symmetry between ECE and ECCD and streamlines the interpretation and real-time deployment of the former for the optimization of the latter. A simple toroidal extrapolation was sufficient to lock the modulation to the O-point phase. This was accomplished by a specially designed phase shifter of nearly flat response over the 1–7 kHz range. Moreover, correlation analysis of two oblique ECE channels slightly above and below the ECCD frequency allowed checking the radial alignment to the island, based on the fact that for satisfactory alignment the two signals are out of phase.

2) **F.A. Volpe**, L. Frassinetti, P.R. Brunsell, J.R. Drake, K.E.J. Olofsson

"Error Field Assessment from Driven Rotation of Stable External Kinks at Extrap-T2R Reverse Field Pinch"

Nucl. Fusion, **53**, 043018 (2013)

It was proposed in this grant (and eventually demonstrated –see publications 3 and 5) that magnetic steering of locked modes might be used to detect and characterize error fields. The idea is based on the effect that error fields have on mode rotation (which becomes non-uniform) and mode amplitude (which becomes modulated). This paper describes an initial proof of that idea, realized at the EXTRAP-T2R Reverse Field Pinch at KTH Stockholm, with which we have a collaboration. One difference is that that plasma does not exhibit locked tearing modes, except under special circumstances. We therefore tested the idea on different modes, namely on Resistive Wall Modes (RWMs). This was actually a bonus, in the sense that it generalized the original idea and proved its applicability to other modes. The RWMs were stable, externally driven by magnetic perturbations. They rotated non-uniformly and were modulated in amplitude as expected, and permitted to rapidly, non-destructively quantify error fields. The efficacy of the error compensation was indicated by the increased discharge duration.

3) D. Shiraki, R.J. La Haye, N. Logan, E.J. Strait and **F.A. Volpe**

"Error Field Detection in DIII-D by Magnetic Steering of Locked Modes"

Nucl. Fusion, **54**, 033006 (2014)

The paper demonstrates that error fields can be inferred from the non-uniform rotation and amplitude-evolution of a locked mode in response to applied, uniformly rotating magnetic fields. The new technique exhibited reasonable agreement with the pre-existing low-density locked mode onset "compass scan" technique. Note that the new technique is non-destructive and only requires a fraction of a plasma discharge. The old one, by contrast, needs at least four discharges, often ending in disruptions. The slight discrepancy can be attributed to the different regimes: by definition, the old technique only works at record-low densities, whereas the new one is not limited to low density, neither, as a result, to low β. The paper also contains at least two examples of excellent agreement between modeling and experiments. The first one is the agreement between calculated and measured torques exerted by error fields on the locked mode. The second one is the agreement between "synthetic diagnostics" (that is, simulated magnetic signals, based on our knowledge of the mode shape and dynamics) and actual magnetic diagnostics. This gives confidence in our "current filament" model, treating the island as a family of current-filaments winding on the rational surface with the same helicity, each one carrying a different current: despite its simplicity, the model appears to be more than satisfactory for predictive, interpretive and control purposes.

4) K.E.J. Olofsson, J. Hanson, D. Shiraki, **F.A. Volpe**, D. Humphreys, R.J. La Haye, M. Lanctot, E.J. Strait, A. Welander, E. Kolemen, M. Okabayashi

"Array magnetics modal analysis for the DIII-D tokamak based on localised time-series modelling"

Plasma Phys. Controll. Fusion **56**, 095012 (2014)

Magnetohydrodynamics (MHD) spectrograms in a frequency range f_1-f_2 are typically based on the Fourier analysis of dt long time-series, where $dt > f_1$. This grant proposed to abandon the Fourier Transform paradigm in favor of a wavelet transform, as it can achieve smaller dt and/or resolve lower frequencies f_1 and with higher frequency-resolution. The combination of smaller dt and/or smaller df has numerous advantages, for instance in diagnosing decelerating islands shortly before they lock. In lieu of the wavelet transform, however, the group adopted an estimation technique known as stochastic subspace identification, and adapted it to MHD for the first time. The technique was shown to offer even higher resolution than wavelets and singular value decomposition. In addition, by interrogating several toroidally and poloidally arrayed magnetic probes, the method identifies for each mode not only its toroidal mode number n, as it is customary, but also its dominant poloidal mode number m. From a locked mode control perspective, this is very important, as it allows to distinguish a rotating m/n=2/1 locked mode precursor from a less concerning 1/1 sawtooth precursor. Yet, regularized mode patterns were estimated by maximum likelihood, and shown to differ from simplistic helical patterns of given m and n. Pattern reconstructions of unprecedented accuracy were presented and discussed for neoclassical tearing modes, sawtooth pre- and post-cursors, fishbones and edge harmonic oscillations, revealing asymmetries between the low- and high-field side, changes of helicity previously dubbed 'phase folding', and confirming that a single mode of certain m/n (say, 2/1) can exhibit features of different m/n (say, 3/1).

The EIGSPEC code developed as part of this work, together with a simplified variant for real-time usage, are now routinely used at DIII-D. They were used in several experiments and are having a broader impact on MHD analysis at DIII-D, extending well beyond the scope of the present DOE award (see for example J. Ferron *et al*., *Nucl. Fusion* 2015; B. Tobias *et al*., *Phys*. *Plasmas* 2016; M. Lanctot *et al*., *Nucl. Fusion* 2017).

5) D. Shiraki, C. Paz-Soldan, R.J. La Haye, N.C. Logan, K.E.J. Olofsson, E.J. Strait, R.M. Sweeney, **F.A. Volpe**

"Measurements of the toroidal torque balance of error-field penetration locked modes"

Plasma Phys. Controll. Fusion **57**, 025016 (2015)

This is a refinement of paper 3, but with emphasis on inferring the torques acting on the mode, including the torque due to the error-field, rather than the error-field itself. The study was intentionally restricted to error-field penetration locked modes in low-density Ohmic discharges. The reason for this is that the error field in these discharges is well known based on the mode penetration threshold, allowing resonant and non-resonant torque effects to be distinguished. These m/n = 2/1 locked modes were found to be well described by a toroidal torque-balance between the resonant interaction with n=1 error fields, and a viscous torque in the electron diamagnetic drift direction. This viscous torque was observed to scale as the square of the perturbed field due to the island. Fitting to this empirical torque-balance allows a time-resolved measurement of the intrinsic error field of the device, providing evidence for a time-dependent error field in DIII-D due to ramping of the Ohmic coil current.

6) **F.A. Volpe**, A. Hyatt, R.J. La Haye, M.J. Lanctot, J. Lohr, R. Prater, E.J. Strait, A. Welander

Avoiding Tokamak disruptions by applying static magnetic fields that align locked modes with stabilizing wave-driven currents

Phys. Rev. Lett. **115**, 175002 (2015)

In this work we completely suppressed a locked mode for the first time. Our group and others had succeeded before in unlocking the mode and forcing it to rotate. However, in those cases a large island was still present in the plasma, degrading its confinement, and still at risk of causing a disruption. Instead, in this work we applied static (non-rotating) magnetic perturbations to control the phase of locking in such a way that the island O-point was accessible to gyrotron beams and, thus, to Electron Cyclotron Current Drive (ECCD). In other words, magnetic perturbations and ECCD were simultaneously used to control the mode phase and amplitude, respectively. This resulted in rapid, complete stabilization of the locked island, disruption avoidance, and recovery of high confinement and high pressure. Stabilization improved with the ECCD power as expected, and was complete when the driven current more-than-compensated for the missing bootstrap current. Stabilization also depended on the toroidal alignment with the island O-point as expected. Current drive was confirmed to be more effective at stabilization than EC heating, which is expected to be even more the case in ITER. The recovery of confinement after locked mode suppression was incomplete, which was attributed to ECCD and magnetic perturbations still being on. A future improvement will consist in turning them off when no longer needed for stabilization, as they are both known to affect confinement.

At present this is the only proven technique for the complete suppression of locked modes, which is a major cause of disruptions, which is one of the biggest concerns in ITER. A discussion offered in this paper and further work carried out under the auspices of ITPA (Sec.5) suggests that the technique will be applicable in ITER.

7) K.E.J. Olofsson, W. Choi, D.A. Humphreys, R.J. La Haye, D. Shiraki, R. Sweeney, **F.A. Volpe**, A.S. Welander

"Electromechanical modelling and design for phase control of locked modes in the DIII-D tokamak"

Plasma Phys. Controll. Fusion, **58**, 045008 (2016)

> All magnetic perturbations discussed so far started in response to a Locked Mode (LM) detector. However, coil-current waveforms were "pre-programmed", i.e. designed in advance and used in feed-forward, rather than adapted in real time to the evolving plasma. Feed-forward sufficed for mode rotation and error-field detection in papers 3 and 5 and to statically control the LM phase and fully suppress the mode in papers 6. However, significant preparation and manual adjustments were required. This motivated the design –described in the present paper- of a feedback controller of the toroidal phase of the island, with the goal of automating the techniques of papers 3, 5 and 6. Note that in conventional feedback -used for example in RWM control- the experimenter prescribes a complex gain by which magnetic measurements are amplified, phase-shifted and fed into the control coils. This *indirectly* affects the island motion. Here, instead, the experimenter *directly* prescribes the desired island phase as a function of time, $\phi(t)$. Based on that request, a proportional-integral-filter controller determines in real time the optimal coil-currents. The controller is robust with respect to island-width and rotation-frequency. It comprises linearizations of a dynamical system description of the problem in infinite aspect ratio. 5 ordinary differential equations are formulated in terms of 5 unknowns: location and amplitude of the island and of the wall-currents, and "velocity" of the latter. Although the equations describe the translation of the island in a cylinder, its actual rotation in a torus is partially retained by way of finite-aspect-ratio corrections to the coefficients. Such corrections, available in the literature, amount to about 40% of the linear coefficients. The model accurately described several experimental observations, such as the deceleration of a LM rotating precursor and the success (or lack thereof) of mode entrainment below (or above) a critical frequency. It also predicted brief, ample oscillations of mode-phase just prior to locking, yet to be observed experimentally.

8) R. Sweeney, L. Frassinetti, P. Brunsell, R. Fridström, **F.A. Volpe**

"Local measurement of error field using naturally rotating tearing mode dynamics in EXTRAP T2R"

Plasma Phys. Controll. Fusion **58**, 124001 (2016)

> Error fields affect the rotation and amplitude-modulation of RWMs (paper 2) and locked modes (paper 3 and 5) forced to rotate by applied magnetic perturbations. In this work they are shown to modulate the amplitude of rapidly, naturally rotating tearing modes (TMs), in the absence of applied rotating fields. This is an even less intrusive technique. The modes rotate at kHz frequencies, and the modulation takes place on a sub-period timescale. Sub-period amplitude-modulation was unexpected and counter-intuitive, before this study, but our first-order solution of the modified Rutherford equation confirmed it to

be possible. Furthermore, such behavior was used to identify intrinsic error fields of $m/n = 1/-12$ in EXTRAP-T2R. In an "active" experiment, a non-rotating resonant magnetic perturbation (RMP) was deliberately applied, and the TM modulation was measured in the presence of the known RMP and unknown EF. Subsequent shot-to-shot scans of RMP phase and amplitude permitted to infer the EF phase and amplitude. The results agreed with other EF estimates (based for example on the best EF-cancelling RMP, resulting in the fastest TM rotation). A "passive" variant of the technique was also presented, where no RMPs are applied and the EF phase was deduced from mere, non-perturbative measurements of spontaneous TM amplitude modulation. It went beyond the scope of the present paper, but the non-uniform TM rotation (phase modulation) could also help characterizing the EF. Together, the two non-perturbative techniques could measure EFs with high temporal resolution, for example in ITER, provided that a detectable (N)TM is present in the plasma.

9) R. Sweeney, W. Choi, R.J. La Haye, S. Mao, K.E.J. Olofsson, **F.A. Volpe**

"Statistical analysis of m/n=2/1 locked and quasi-stationary modes with rotating precursors at DIII-D"

Nucl. Fusion **57** 016019 (2017)

A database was developed to study the evolution, effects on equilibria and disruptivity of 2/1 locked and quasi-stationary modes at DIII-D. The analysis of 22,500 discharges showed that more than 18% of disruptions are due to locked or quasi-stationary modes with rotating precursors (not including born locked modes). High values of the ratio of internal inductance to the safety factor at 95% of poloidal flux, l_i/q_{95}, were found to reliably predict whether a locked mode will cause a disruption. The predictor gives ample notice, of up to hundreds of milliseconds before the disruption actually occurs. Good predictive capability was attributed to l_i/q_{95} being a proxy for the classical stability index Δ', but easier to calculate. Within 20 ms of the disruption, the shortest distance between the island separatrix and the unperturbed last closed flux surface, referred to as d_{edge}, performs comparably to l_i/q_{95} in its ability to discriminate disruptive locked modes. Note that the mode can remain locked without causing a disruption for remarkably long times, which correlate well with d_{edge}. Eventually, though, the perturbed n=1 field tends to suddenly, exponentially grow and cause a disruption within 50 ms. In principle, it seems reasonable to attribute this n=1 field growth to the 2/1 island growing larger. However, this is at odds with the fact that disruptivity correlates poorly with the 2/1 island width, except in the last 20 ms before disruption. Further work (paper 10) eventually found that the interpretation is more complex, and involves several n=1 islands of different m. The dynamics of rotating precursors was also statistically analyzed, confirming that higher wall torque results in faster deceleration, and that modes preferentially lock with a certain toroidal phase, likely related to a residual error field. Timescales associated with the mode evolution were also studied, and dictate the response-times necessary for disruption avoidance and mitigation.

The paper also presented and discussed measurements of β_N evolution during a locked mode, the effects of poloidal beta on the saturated island width, and the reduction in Shafranov shift during locking.

10) R. Sweeney, W. Choi, M. Austin, M. Brookman, V. Izzo, M. Knolker, R.J. La Haye, A. Leonard, E.J. Strait, **F.A. Volpe**

"Relationship between locked islands and thermal quench"

under internal review at General Atomics, to be submitted to *Nucl. Fusion*

Locked modes are one of the major causes of disruptions (see for example paper 9). Yet, the physical mechanisms by which locking leads to disruptions are not well understood. To fill this gap, this paper analyzed the evolution of temperature profiles in the presence of multiple coexisting locked modes during partial and full thermal quenches. Partial quenches are shown to be an initial, distinct stage in the full quench. The onset of thermal quenches appears to coincide with the O-points of the various locked islands aligning with each other on the outboard midplane, and/or with the island widths exceeding a threshold. As a result, the field can stochasticize in between islands, and between the outermost island and last closed surface, leading to a partial axisymmetric temperature collapse. This interpretation is supported by nonlinear resistive magnetohydrodynamic simulations, though the simulated temperature profiles exhibit less degradation compared with the experiment. Detailed analysis of a partial thermal quench shows that the lost energy is both radiated in the divertor region, and conducted or convected to the divertor. For values of the minimum safety factor $q_{\min}\gtrsim1.2$, locked modes tend to self-stabilize by inducing a minor disruption, possibly by double tearing modes. The minor disruption modifies the pressure profile in a way that removes the neoclassical drive. At the same time there is no classical drive either, in those high $q_{\min}$ discharges characterized by low l_i/q_{95} (which, as discussed in paper 9, is a proxy for the classical stability index), thus explaining the self-healing.

3. Collaborative journal articles

11) H. Reimerdes, R.J. Buttery, A.M. Garofalo, Y. In, R.J. La Haye, M.J. Lanctot, M. Okabayashi, J.-K. Park, M.J. Schaffer, E.J. Strait, **F.A. Volpe**

"Error Field Tolerance and Error Field Correction Strategies for ITER"

Fusion Sci. Technology **59**, 572 (2011)

Review paper based on a lecture given at the ITER summer school that, among others, presented our error field detection method based on the interaction between locked modes and applied rotating fields.

12) L. Frassinetti, K.E.J. Olofsson, R. Fridström, A.C. Setiadi, P.R. Brunsell, **F.A. Volpe**, J.R. Drake

"A method for the estimate of the wall diffusion for non-axisymmetric fields using rotating external fields"

Plasma Phys. Controll. Fusion, **55**, 084001 (2013)

Experimental realization, at EXTRAP-T2R, of an idea inspired by paper 1, in which rotating fields were applied not to sustain the rotation of a RWM, but rather to measure the wall frequency response and so infer the wall diffusion time, in good agreement with theory and other measurements.

13) E.J. Strait, R.J. Buttery, T.A. Casper, M.S. Chu, J.M. Hanson, A.M. Garofalo, Y. Gribov, R.J. La Haye, H. Reimerdes, M.J. Schaffer, F.A. Volpe

"Measurement of tokamak error fields using plasma response and its applicability to ITER"

Nucl. Fusion **54**, 073004 (2014)

Discussion of various error-field detection techniques based on the plasma response to applied 3D fields. Emphasis is laid on two methods in particular, one of which is our island-based technique from papers 3 and 5. The paper concludes favorably about the usefulness and applicability of both methods to ITER, but raises the question of whether they will be able to isolate individual errors from the outer poloidal field coils, which is left as future work.

14) M. Okabayashi, P. Zanca, E.J. Strait, D. Shiraki, **F.A. Volpe** and 10 coauthors

"Avoidance of Tearing Mode Locking and Disruption with Electro-Magnetic Torque Introduced by Feedback-Based Mode Rotation Control in DIII-D and RFX-mod"

Nucl. Fusion **57**, 016035 (2017)

This work avoided locked mode disruptions not by suppressing the locked mode as in paper 6, but rather by preventing it from locking, and sustaining its rotation by means of applied rotating fields. These fields were applied in feedback to magnetic measurements, using an algorithm originally developed for RWM control, distinct from the algorithm of paper 7. Experiments of this type were carried out with equal success in the DIII-D diverted, highly shaped tokamak and in the RFX-mod, circular cross-section reversed-field-pinch. The results agree well with torque-balance analysis.

4. Invited talks at International Conferences

The PI and his student W. Choi and post-doc D. Shiraki were invited to present their results at international conferences, most prominently at the European Physical Society (EPS) Conference on Plasma Physics. Below is a list of the invited talks. Copies of the slides can be downloaded from http://pl.apam.columbia.edu/mhd-presentations .

1) D. Shiraki, "Error Field Detection and Mode Locking Avoidance by the Interaction of Applied Rotating 3D Fields with Otherwise Locked Modes"

invited to the 18th Workshop on MHD Stability Control, Santa Fe, NM (USA), 18-20 November 2013

2) **F.A. Volpe**, "Using 3D Fields to control Islands, aid ECCD-Stabilization and measure Error-Fields at DIII-D"

invited to the 41st European Physical Society (EPS) Conference on Plasma Physics, Berlin (Germany), 23-27 June 2014

3) **F.A. Volpe**, "Cross-fertilization of magnetic confinement fusion research, nuclear and sub-nuclear physics and accelerator science"

plenary talk invited to the International Conference on Dark Matter, Hadron Physics and Fusion Physics, Messina (Italy), 24-26 September 2014

4) **F.A. Volpe**, "New directions in simplified stellarators, stabilization of plasmas and of liquid walls"

invited to the International Colloquium on New Trends in High Temperature Plasma Physics, Greifswald (Germany), 14-15 October 2015

5) W. Choi, "Analysis of locked mode disruption database in the DIII-D tokamaks"

invited to the 20th Workshop on MHD Stability Control, Princeton, NJ (USA), 22-24 November 2015

6) **F.A. Volpe**, "Prediction, Avoidance and Control of Disruptive Locked Modes in DIII-D and ITER"

invited to the Theory and Simulation of Disruptions Workshop, Princeton, NJ (USA), 20-22 July 2016

5. National and international impact

In addition to giving the international invited talks listed above, in 2013 the PI was asked by the International Tokamak Programmatic Activities (ITPA) to form and lead a Working Group (WG) of international colleagues called “WG11 – Control of Locked Modes”.

The group was asked to identify the coil-current and frequency requirements for locked mode control in ITER. To answer these questions, the PI formed a group of approximately 20 colleagues from 5 tokamaks (Asdex Upgrade, DIII-D, JET, J-TEXT, KSTAR), 2 spherical tokamaks (MAST, NSTX), 2 reversed field pinches (EXTRAP-T2R, MST) and a helical device (LHD) from the US, Europe and Asia. All these devices are equipped with control coils.

In the interest of time, the approach was to rely on existing data as much as possible. However, new experiments were also realized, for example at Asdex Upgrade, J-TEXT and KSTAR, and their results published. We analyzed magnetic measurements of the amplitude and phase of magnetic islands in the presence of applied RMPs (static and/or rotating). We then adapted our DIII-D model (see paper 7) to the other devices. Good agreement was found with the experimental results despite the variety of conditions (internal or external coils, angularly broad or narrow coils, dense or sparse arrays with partial or full poloidal or toroidal coverage, in circular or elongated devices of different sizes and aspect ratios). This built confidence in our model, and motivated its deployment for ITER. Simulations confirm that mode entrainment at up to 10 Hz will be possible in ITER, given the available power supplies.

WG-11 recently closed its activities; a report is under preparation and might result in a publication. Some presentations are available at http://pl.apam.columbia.edu/mhd-presentations.

Papers 1-14 were cited in several other papers on locked modes, outside of WG-11 activities. One example is the recent work on the avoidance of and recovery from locked modes in Alcator C-Mod without external momentum input, by means of Ion Cyclotron Resonance Heating. Other citations to our work can be found at http://www.researcherid.com/rid/D-2994-2009 and http://scholar.google.com/citations?user=FUndNhkAAAAJ.

Another measure of impact of this research is the ~50 citations to a seminal work [Volpe *et al.*, *Phys. Plasmas* 2009] that inspired the DOE grant proposal in 2010 that resulted in this Award in 2011.

Finally, magnetic islands and other structures are now routinely entrained at DIII-D, for instance for the sake of characterizing them toroidally (or, possibly, in 3D) by moving them in front of a fixed diagnostic (or camera). Shot-to-shot scans of the toroidal phase of locking are also routinely performed at DIII-D. Toroidal scans of the locked island O-point relative to the location of massive gas injection are reminiscent of similar scans, relative to the location of ECCD deposition.

6. Training of young physicists

At any given moment the group consisted of the PI F. Volpe and of two young post-docs or graduate students. The PI was based at Columbia; the post-docs were based at GA; the students were initially based at Columbia and then moved to GA after finishing their classes and exams. Video-conferences between the Columbia-based and GA-based part of the group were held twice a week.

The two post-docs trained under this Award were:

Daisuke Shiraki (2012-13) – formerly a graduate student at Columbia. Daisuke analyzed the interaction of locked modes with error fields and developed several synthetic diagnostics. He first-authored papers 3 and 5 and gave invited talk 1. He went on to carry out an additional post-doc at DIII-D under N. Commaux (ORNL), on the interaction between locked modes and massive gas injection (e.g., radiation asymmetries). He is now an ORNL scientist based at GA, and an appreciated, active member of the DIII-D group.

K. Erik J. Olofsson (2012-14) – formerly a graduate student at KTH Stockholm. Erik developed the EIGSPEC code (paper 4) and the island phase-controller (paper 7). After his post-doc at DIII-D, sponsored by this Award, he was directly hired by GA as a scientist in the Control group, where he kept making contributions to mode analysis, locked modes, NTM control, ECRH/ECCD and error field studies, and expanded his interests to profile control and RWMs.

The two students trained under this Award are:

Ryan Sweeney (2012-16) – He first-authored papers 8, 9 and 10. His main contribution consisted in developing and analyzing a database of disruptive and non-disruptive locked modes at DIII-D, and in extracting and interpreting empirical criteria to predict locked mode disruptions. Shortly before completing his PhD he was awarded a prestigious Monaco Post-doctoral Fellowship at ITER, where he is continuing his research on disruptions with P. De Vries, M. Lehnen *et al*.

Wilkie Choi (2013-17) – He experimentally demonstrated feedback control of the island phase using the algorithm of paper 7, in a number of entrainment experiments with and without modulated ECCD (paper under preparation). He also contributed significantly to the database work, which he presented in invited talk 5, and modeled entrainment in several international devices, under the auspices of ITPA WG-11 (Sec.5). Thesis defense expected in Spring 2017.