Laboratory Directed Research and Development

Project Final Reports

FY2018 – FY2020

Princeton Plasma Physics Laboratory

Princeton, NJ 08540

SEPTEMBER 2021

Tables of Contents

Introduction

The U.S. Department of Energy's (DOE) Princeton Plasma Physics Laboratory (PPPL) is a collaborative national center for fusion energy science, basic sciences, and advanced technology. The Laboratory has three major missions: (1) to develop the scientific knowledge and advanced engineering to enable fusion to power the U.S. and the world; (2) to advance the science of nanoscale fabrication for technologies of tomorrow; and (3) to further the development of the scientific understanding of the plasma universe from laboratory to astrophysical scales.

PPPL's Laboratory Directed Research and Development (LDRD) program supports and encourages creativity and innovation and contributes to its long-term viability. New scientific and technical research areas emerge and are nurtured through the program. Furthermore, new capabilities are developed to enable the Laboratory to meet its and DOE's missions.

The program is used to systematically diversify the Laboratory's programs and mission. In the last few years, the program has started projects in nanomaterial synthesis, microelectronics, advanced x-ray spectroscopy, high-energy-density physics, superconducting magnet technology, machine learning and artificial intelligence, 3D magnetic fields to optimize fusion plasmas, integration of permanent magnets with simple high-field magnets to reduce the cost of producing complex 3D magnetic fields, advanced computational methods for predictive understanding and control of fusion plasma, development of quantum computing algorithms for plasma physics, liquid metal plasma-facing components for fusion reactors, virtual engineering, and plasma-based space propulsion.

The program is also the vehicle to recruit and train talented scientists and engineers with the new skills needed to perform the Laboratory's mission. Many of the new hires through the program go on to become world-class scientists and engineers in their fields.

This report provides descriptions and accomplishments of those LDRD projects that were completed during fiscal years 2018 through 2020.

Predicting and Mitigating Runaway Electrons in Tokamaks

Principal Investigator: Amitava Bhattacharjee

Project Period of Performance: February 2, 2015 – January 31, 2018
Project Number: PPPL-045

Project Description

The prediction and mitigation of runaway electron (RE) generation in tokamaks is one of the most important problems in tokamak physics. For present operating tokamaks (such as DIII-D, Axially Symmetric Divertor Experiment upgrade (ASDEX-U), and Joint European Torus (JET)), there is now a wealth of data awaiting theoretical interpretations. Even the simplest and fundamental predictions regarding the threshold electric field (by J. Connor and R. Hastie) for runaway generation have been questioned by recent experiments. For large tokamaks to operate in a regime of high plasma current (International Tokamak Fusion Reactor (ITER) and burning plasma devices beyond ITER), the so-called "avalanche effect" is predicted (by M. Rosenbluth and S. Putvinski) to convert nearly the entire equilibrium current to RE current with electrons of MeV energies. There is an urgent need for theoretical and computational research to answer questions relevant to mitigation techniques pertaining to runaway electrons.

Accomplishments

Based on a newly developed simulation code, several critical remaining questions on runaway electron research are answered. The code is based on existing simulation methods of runaway electrons and focuses on self-consistent wave-particle interactions between runaway electrons and plasma waves. In addition, synthetic diagnostic tools are developed to better interpret the results and benchmark with experiments. It is found that the excitation of plasma waves such as whistler waves plays an important role in runaway electron avalanche and can affect the critical electric field for the avalanche onset. The critical electric field predicted by the simulation code is very close to the observation from experiments. In addition, the plasma waves are found to be connected to the abrupt growth of electron cyclotron emission (ECE) power from runaway electrons, which has been observed in several tokamaks. These results are very helpful for understanding runaway electron physics and developing novel mitigation techniques for ITER. In addition to wave-particle interactions, other critical problems on runaway electron research were investigated. A new test-particle simulation model was developed to remedy the errors of classical guiding-center model when applying to runaway electrons. A new set of equations, which couples a kinetic model of runaway electrons with a magnetohydrodynamic (MHD) plasma, was developed including the generation and loss of runaway electrons.

Simulations of Plasma Turbulence with Lithium or Other Walls

Principal Investigator: Gregory Hammett

Project Period of Performance: February 2, 2015 – January 31, 2018
Project Number: PPPL-046

Project Description

This project extended a new full-F edge gyrokinetic code (full-F means no assumptions of small amplitude fluctuations are made) to study the important problem of edge turbulence in fusion devices and how it depends on divertor materials. Solid high recycling divertor targets like tungsten are the standard assumption, which might be sufficient for the international ITER tokamak that the US is participating in but not higher-power demonstration power plants. Lithium coated divertor targets are an intriguing alternative, for their potential to achieve a low-recycling, high edge temperature regime (which should improve the fusion gain Q), for their self-healing robustness, and their potential for handling large amounts of power (perhaps through vapor shielding). While there is a lot of experimental evidence of strong improvements with solid and liquid lithium coatings, and there is a qualitative understanding that reduced recycling can lead to a significantly improved temperature, the detailed mechanisms by which performance improves in experiments are not well understood. Furthermore, though raising the edge temperature does reduce temperature-gradient driven turbulence, lowering the edge density may enhance density-gradient driven turbulence.

Predictions of how much lithium can improve performance will require edge simulations that can predict the formation of edge transport barriers and the height of a density pedestal. The general feasibility and usefulness of advanced Discontinuous Galerkin (DG) algorithms for edge turbulence has been demonstrated in our recent work. In this LDRD project, we proposed to build on this new edge gyrokinetic code Gkeyll, extending it beyond its initial capabilities to add plasma-wall-sheath interaction models to its 5D capability to simulate the scrape-off layer (SOL) region of the National Spherical Torus Experiment Upgrade (NSTX-U) or other machines. It would also be extended to include simple models of plasma-wall processes such as recycling, etc., to study how different walls (lithium, tungsten, carbon) affect the plasma. This code could operate both in an axisymmetric mode with models of radial diffusion (and thus be like a gyrokinetic version of the UEDGE or SOLPS fluid codes), and in a full simulation mode with 5D (3 spatial and 2 velocity dimensions) for self-consistent calculations of turbulence. One of the broader goals of this project is developing a more comprehensive computational tool that can help make the case for next steps in fusion experiments (at both small and large scales).

Accomplishments

This LDRD project started with a new full-F gyrokinetic code employing discontinuous Galerkin algorithms that has the full 5D capability (3x/2v) needed for gyrokinetics. The code also has a Lenard-Bernstein collision operator and had demonstrated stable and efficient performance for a 1D SOL (scrape-off layer) test problem with a logical sheath. This project was building on this code and extending it to be able to study the possible benefits of lithium walls.

We began work on simple models of recycling and secondary electron emission. The main differences between flowing lithium and solid metal walls in their impact on turbulence is probably because of major differences in the recycling coefficient R, which affects things as 1/(1-R) (thus small changes in R near 1 have a huge effect). Another effect is secondary electron emission. Most metals have secondary electron emission coefficients that exceeds 1 if the electron temperature gets too high, which causes a collapse of the sheath that floods the plasma with cold electrons, thus putting a limit on the edge electron temperature. But lithium has the lowest secondary electron coefficient of all metals, staying well below Furthermore, in related work studying secondary electron emission, our collaborators eventually concluded that it will be strongly suppressed by a grazing-incidence magnetic field for typical parameters. Thus, we focused on recycling and sputtering as the next step processes to include in Gkeyll. We worked on merging the SOL capability of the code with the 3D/2V capability of the code, modifying the Poisson field solver for the SOL, to carry out simulations of turbulence in the SOL.

Two major advances achieved as a result of this LDRD project include: (1) the first successful gyrokinetic simulations of turbulence on open field lines with a continuum code (documented in a paper simulating the LAPD device at UCLA, E. Shi et al., J. Plasma Phys. 2017, which the editors selected as a Featured Article, and (2) the first successful continuum gyrokinetic simulations in a tokamak scrape-off layer (SOL) region with a model helical SOL geometry including the bad-curvature drive (E. Shi et al., Phys. Plasmas 2019, submitted in 2018). The LAPD (straight field) and NSTX (toroidal field) results, and a number of important algorithmic details and physics results, are presented in E. Shi's 2017 thesis. Some initial recycling studies are reported in Shi's thesis, and this work lays the groundwork for more detailed studies of how much performance can be improved with lithium.

A lot of challenging problems had to be overcome in achieving these results. There have been several previous attempts around the world to develop codes for simulating edge turbulence with continuum algorithms over the past decade. Part of this difficulty is because there are numerical difficulties in dealing with large amplitude fluctuations in the edge region of tokamaks, and with constructing stable ways for gyrokinetics to interact with sheath boundary conditions. (Algorithms often used in magnetic fusion research or in core gyrokinetics can have "ringing" behind blobs or regions of steep gradients which can cause negative density overshoots in the particle distribution function, which can cause difficulties with sheath boundary conditions or collision operators.) XGC is the only other gyrokinetic code at present that can do turbulence in the SOL (using PIC, not continuum algorithms). XGC can also handle the X-point (that is a high-priority future extension for Gkeyll). It is very important to have independent codes to cross-check against each other, which helps build confidence in both codes.

The Efficacy of Lithium Conditioning and Liquid Lithium Surfaces in Devices with Metallic Plasma Facing Components

Principal Investigator: Rajesh Maingi

Project Period of Performance: February 2, 2015 – January 31, 2018
Project Number: PPPL-048

Project Description

The purpose of this activity was to investigate the use of lithium (Li) in devices with metallic plasma-facing components (PFCs). The International Tokamak Fusion Reactor (ITER) and other future devices have identified tungsten as the leading candidate material for PFCs, owing to low hydrogen retention and reduced activation, as compared with other materials. The use of tungsten PFCs in present day devices has, however, reduced the edge plasma temperature and overall performance of those devices, e.g., the Joint European Torus (JET) and the AxiSymmetric Divertor EXperiment (ASDEX)-Upgrade (AUG), while coating those PFCs with low-Z elements, like boron or with nitrogen gas seeding, partially or completely restored performance. The use of lithium wall conditioning has improved the edge and global plasma performance in a number of devices, notably the National Spherical Torus eXperiment (NSTX). The issue to investigate here is if those improvements can be extended to devices with metallic PFCs with high power (e.g., AUG) and long pulse (the Experimental Advanced Superconducting Tokamak [EAST]).

Accomplishments

The main elements of this project were collaborative work for impurity injection on AUG and flowing liquid Li limiters on EAST. On AUG, PPPL staff participated in Li pellet injection experiments. It was found that Li pellet injection had a short-term conditioning effect, similar to boronization, but had otherwise no impact on H-mode and pedestal performance. A Li powder dropper was built for AUG, but never installed per their priorities. However, PPPL R&D in parallel to change the design of the Li powder dropper to make it capable of injecting other non-spherical, sticky compounds, like boron and boron-nitride, was successful. This new dropper was collaboratively installed on AUG. The first set of experiments were supported by FES, i.e., not under this LDRD scope, but demonstrated beneficial effects of wall conditioning due to B injection and enhanced power exhaust and confinement improvement due to BN injection. On EAST, design for a lithium limiter base plate made entirely out of Mo for improved material compatibility was performed. FES directly funded continued work on EAST and, hence, the remaining EAST work was removed from the LDRD project. The EAST effort has resulted in several Nucl. Fusion papers and talks at major conferences.

Low Temperature Magnetized Plasma for Synthesis and Functionalization of Graphene

Principal Investigator: Yevgeny Raitses

Project Period of Performance: February 2, 2015 – January 31, 2018
Project Number: PPPL-051

Project Description

This project is aimed to study a new transformative application of low temperature magnetized plasmas for nanotechnology – functionalization of nanomaterials. The focus of the proposed research was on the use of the magnetic filter effect to produce a non-equilibrium plasma with spatially separated regions of hot and cold electrons suitable for synthesis and functionalization of complex thin films of graphene (and its derivatives), respectively. The successful implementation of this technique could potentially lead to the development of revolutionary methods of synthesis and functionalization of nanomaterials, including but not limited to graphene, carbon nanotubes and similar nanostructures. In addition, this technique could be also applicable for new and emerging plasma processing technologies of semiconductor materials such as atomic layer etching and deposition. The main deliverable of this project is a new concept of the plasma-based functionalization of large-area graphene films.

Accomplishments

Parametric studies of ExB plasma and its effects on graphene samples were completed. The focus was on investigations of effects of hydrogen additions on different samples of graphene immersed in the plasma. These studies included characterization of magnetic filter plasma with hydrogen gas mixtures, using available laser-induced fluorescence (Xenon) and probes diagnostics. Samples were characterized using ex-situ material evaluation diagnostics (Raman, scanning electron microscopy, X-ray diffractometer) available at the Princeton Institute for the Science and Technology of Materials (PRISM) and Physics Department of Princeton University. Experiments devoted to the feasibility studies of combined synthesis and hydrogenation of graphene in the magnetic filter plasma were performed. We demonstrated that the Penning RF-DC system enables a mild plasma for a long duration of hydrogenation. The hydrogen coverage was shown to be engineered by modulation of the parameters such as RF power and DC power, magnetic field, sample location, and process duration. The Raman spectra and a high resolution XPS spectra investigation demonstrated that cold plasmas provide a promising way to achieve higher hydrogen coverage than conventional chemical methods and existing plasma methods.

Investigation of a Plasma Mass Filter

Principal Investigator: Nathaniel Fisch

Project Period of Performance: April 13, 2015 – April 12, 2018
Project Number: PPPL-055

Project Description

To elucidate plasma separation, differential confinement will be studied in open field geometry. The aim is to retire uncertainties associated with a variety of plasma mass separation approaches, in addition to the leading method that we have been advocating theoretically. New ideas on how to produce rotation will be tested. Methods of preparing impurities for separation will be studied. This project also has as its goal to actually measure mass separation.

Accomplishments

This LDRD project investigated the theoretical and experimental bases for plasma mass separation, which the eventual goal of developing valuable practical applications. Several new theoretical ideas, experimental results, and assessments of potential applications were published during project. A tutorial paper reviewing the experimental aspects of this field was published at the end of the project period.

Theoretical calculations were made of ion separation effects in rotating plasmas. The desired rotation may be obtained by either electrical biasing or wave-driven momentum input. The effect of collisions was analyzed in detail for a relevant experimental condition, and the beneficial effect of high ion temperature ($T_i \geq 5$ eV) on mass throughput was discovered. The centrifugal instability was found to be a limiting factor in highly rotating plasmas.

Three potential applications of plasma mass separation technology were investigated; nuclear waste remediation, spent nuclear fuel reprocessing, and rare earth recycling. For each of these, conventional chemical or physical separation methods are difficult or expensive, and plasma separation may eventually provide a cost-effective solution. An upper bound for the energy required for plasma separation was estimated to be ~2 GJ/kg (or ~$65/kg). Beyond these practical applications, the study of differential confinement in plasmas would likely benefit other fields in which plasma rotation effects manifest, including fusion (such as through impurity removal), space propulsion with Hall thrusters, plasma processing with magnetron discharges, or the astrophysics of accretion disks and dynamos.

Experiments were performed on the Plasma Mass Filter Experiment (PMFX). The main result was a reproducible control of the plasma potential and rotation using biasing of the end electrodes, which is favorable for ion mass separation. Although some radial ion separation of the krypton/argon mixture was observed spectroscopically, the collisionality was too high to allow separation based on the ion gyro-orbit mechanism.

The existing experimental configurations for plasma mass separation were reviewed. These include ion gyro-orbit separation, drift-orbit separation, vacuum arc centrifugation, steady-state rotating plasmas, and several other geometries. Generic physics issues were discussed such as the ion charge state, neutrals and molecules, collisions, radiation loss, and electric fields and fluctuations. Generic technology issues were discussed such as plasma sources and ion heating. The tutorial also described criteria for evaluating separation mechanisms, options for small-scale experiments, needs for theory and simulation, potential experimental diagnostics, and general directions for future research.

Large-Data Statistical Approach for Predicting Disruptions in Tokamaks Using a Joint European Torus (JET) Disruption-Relevant Database

Principal Investigator: William Tang

Project Period of Performance: April 13, 2015 – April 12, 2018
Project Number: PPPL-056

Project Description

The goal of this project is to deliver validated predictive software from a machine learning (ML) application on Joint European Torus (JET) data that represents advancement toward future disruption avoidance capability involving multi-dimensional data. Working with the current zero-dimensional time-dependent APODIS capability, we will contribute to ML-based analysis of ITER-like tungsten wall disruption studies on JET. The leadership at JET has agreed to allow us to have direct access to their large disruption-relevant data base. In addition, JET's machine-learning Centre for Energy, Environment and Technology (CIEMAT) team has provided PPPL with the key Support Vector Machine (SVM) component of their APODIS software that has now been installed on PPPL clusters.

Accomplishments

All project objectives were achieved including delivery of predictive software from a machine learning application which were validated on experimental data from the Joint European Torus (JET). This achievement was well recognized as a significant advancement toward future disruption avoidance capability involving multi-dimensional data. Comparisons of our results with those from the zero-dimensional time-dependent APODIS code developed at JET yielded very favorable results. For example, our work contributed to ML-based analysis of ITER-like tungsten wall disruption studies on JET. In addition, JET's collaboration with the machine-learning CIEMAT team in Spain provided PPPL with the key SVM component of their APODIS software that helped facilitate efficient cross-benchmarking of our predictive software. Overall, our own Machine Learning software based on a powerful new Deep Learning approach proved to operate with much greater accuracy and speed when deployed on modern GPU clusters at Princeton University and on the Titan supercomputer at the Oak Ridge National Laboratory.

Construction of Nb3Sn Superconducting Magnets at PPPL

Principal Investigator: Yuhu Zhai

Project Period of Performance: August 12, 2015 – August 11, 2018
Project Number: PPPL-058

Project Description

With recent advances in the development of high temperature superconductors (HTS), there is a growing interest of designing higher field (>13 T) superconducting magnets for the next–step fusion devices beyond ITER. The design and optimization of a fusion magnet system has many unique challenges not well acknowledged in high energy physics and the applied superconductivity community. We propose a superconducting magnet R&D initiative at PPPL.

The goals of this initiative include 1) to review fusion magnet system design for next-step devices and evaluate state-of-the-art HTS conductor options for optimizing the Toroidal Field (TF) and Central Solenoid (CS) coil shape and coil winding pack design. 2) to develop in-house superconducting magnet design and coil fabrication procedure with available PPPL resources and validate the procedure by 1-2 small coil fabrication and coil performance testing at the cryogenic temperatures.

Accomplishments

We established in-house design, fabrication and cryogenic testing capabilities for novel low cost, simplified superconducting magnets using Nb3Sn wires. We completed coil construction and testing to achieve a 3 T central magnetic field in a subscale small prototype solenoid coil.

Our work attracted collaborators from industry and other national laboratories and resulted in a DOE Small Business Innovative Research (SBIR) Phase II award to develop high current cables for compact fusion magnets.

Advanced Centrifuge Development of Industrial Applications

Principal Investigator: Erik Gilson

Project Period of Performance: November 1, 2015 – September 30, 2018
Project Number: PPPL-059

Project Description

The proposed research is centered on the preliminary design, building, operating, understanding, and optimizing of a dedicated Advanced Annular Couette Centrifuge (AACC) device for the separation of sub-micron-diameter particles in water.

Accomplishments

During the first year, ANSYS simulations were performed to help guide the preliminary design of an AACC variant which explored the ability of different inlet and outlet geometries to modify and control the secondary flows in the system. It is important to understand whether the flow is significantly altered as compared to the case of the standard AACC where the annular rings that modify the secondary flows are only on the upper and lower boundaries and there is no forcing of the flow. Results demonstrated that axial inlets and outlets at the mid-radius, between end rings were feasible. New optical laser diagnostics enabled the simultaneous measurement at multiple radii of sub-micron-sized test particle concentrations. The AACC was presented at the first PPPL/Princeton Innovation Discovery Event and received positive feedback from the panel of reviewers.

In the following year, the AACC variant design was completed. The design allowed for the inflow of water with titanium dioxide particles that serve as prototype sub-micron-diameter particles. The design included two outlets, one for a clean phase and one for a dirty phase. Due to the limited speed of the apparatus, overall separation was improved by recycling the dirty phase effluent back into the inflow reservoir for further separation. The separation and recycling were done in a continuous, steady-state mode of operation. This type of operation is similar to a centrifuge cascade in which the outlet of one centrifuge in the cascade is connected to the inlet of the next centrifuge in the cascade. This mode of operation in AACC was dubbed "pseudo-cascade" operation since the outlet was redirected back into the one centrifuge. A numerical model was developed and used to optimize the flow rate and recycling fraction. Modifications to the upper manifold were completed and a dual-port rotating fluid coupler was procured.

In the final year, modifications to the lower manifold were completed and the dual-port rotating fluid coupler was modified to work with the apparatus' motors and was installed. Initial operation tests, without any test particle separation attempt, were successful in operating the system in pseudo-cascade mode. The flow rates in the inlets and outlets were adjusted to achieve the desired overall flow rate (0.5 gallon per minute) as well as the desired fraction of recycled flow (50%) and fraction of rejected flow (50%).

Establishing the Feasibility of the Lithium Vapor Box Divertor

Principal Investigator: Robert Goldston

Project Period of Performance: November 1, 2015 – September 30, 2018
Project Number: PPPL-060

Project Description

It has long been recognized that volumetric capture of the plasma heat efflux from a fusion system is preferable to its localized impingement on a material surface as a means to mitigate the anticipated very high heat flux and intense particle-induced damage. This is the fundamental motivation behind the "gas-box" divertor concept, in which recycling deuterium-tritium (DT) fuel is to provide momentum balance with the upstream plasma, through charge-exchange and collisional friction, allowing the divertor plasma to detach from the material target. Here we investigate the possible use of lithium vapor, rather than recycling DT fuel for this purpose. This requires very aggressive differential pumping to localize the cloud of lithium vapor away from the plasma. This LDRD will develop a computational model describing the vapor transport in the vapor-box concept as well as experimentally validate those solutions using similarity experiments based on water vapor.

Accomplishments

1) Established a simple model for the amount of lithium vapor that will be required for extinction of a plasma, based on the concept of cooling per particle. This is always a simple assessment of the required equilibrium vapor density and thus lithium temperature required for detachment. It also permits a direct calculation of the maximum lithium efflux to the main chamber.
2) Established a simple model for the upstream plasma density required for detachment. Remarkably, this provides an explicit prediction of n/n_gw required for detachment, which is in fairly good agreement with current experiments, and projects positive results for lithium vapor.
3) Developed a model for evaporation and condensation in the code OpenFOAM, which is a code capable of calculating vapor transport in the relevant transitional region between molecular and fluid flow and demonstrated operation of the code with this modification.
4) Recognized that we could validate our calculations of lithium vapor efflux using a system similar to the existing National Spherical Torus Experiment (NSTX) lithium evaporators, at the same or lower quantities of lithium and temperature range. This would provide a test of the vapor localization at similar absolute dimensions and lithium vapor density as a lithium vapor box divertor that might be deployed on NSTX-U or a similar scale device.
5) Recognized that a system of this type could also be used at Magnum PSI (plasma surface interactions) to test calculations of the vapor shielding due to lithium vapor.
6) Extended our theoretical model for plasma detachment using the Lengyel formulation, that has allowed a completely new scaling for detachment to be derived. This not only allows a direct comparison between lithium detachment and detachment using other extrinsic impurities, it also provides a general criterion for detachment, that completely upsets prior assumptions. While parallel heat flux scales roughly as PB/R, the difficulty of detachment scales as P/B_pR. This difference arises from the fact that radiated power efficiency scales as the square of the separatrix density, which scales with the Greenwald limit.

7) Developed a model for evaporation, condensation and lithium vapor transport in the Stochastic PArallel Rarefied-gas Time-accurate Analyzer (SPARTA) Direct-Simulation Monte Carlo code. This has a more complete model than is available in OpenFOAM and is easily upgradable. We have developed an importance sampling scheme to reduce the run time by a factor of 10 while also improving particle statistics. With this code we have confirmed the earlier simple box-to-box model based on choked flow and enthalpy conservation for cases without plasma. Furthermore, by adding an absorbing plasma beam in the calculation to model the divertor, we find that we can reduce further reduce the lithium efflux by an order of magnitude.
8) Collaboration with LLNL, in which we were coupling the results from our vapor calculations with UEDGE plasma calculations. We found that we can reduce the lithium efflux to the far Scrape-Off Layer (SOL) by more than an order of magnitude with a single baffle, from 75% of the lithium introduced into the plasma to 5%. We then worked on a system with two layers of baffles.
9) Experiments at Magnum-PSI (performed by the Magnum-PSI group outside of this LDRD project) using a pre-loaded lithium target similar to what is planned for NSTX-U, demonstrated continuous vapor-shielding with lithium for the first time. However, this configuration only causes the plasma to back off from the target by a small distance.
10) Completed construction of a chain of vapor boxes for testing at PPPL. These will be used to compare with SPARTA results, and assure that lithium efflux at Magnum-PSI is acceptable.
11) Working with LLNL and the UEDGE code, we determined that full divertor detachment could be achieved in the high-power Fusion Nuclear Science Facility using an open lithium vapor box divertor. While the upstream lithium density was found to be higher than desirable, this suggested that the original design may have been more constrained than necessary.
12) Using the SPARTA Direct-Simulation Monte-Carlo (DSMC) code we demonstrated that this configuration is quite resilient to changes in power flowing into the divertor, so long as the lithium is injected from the sides of the divertor rather the bottom. With side evaporation, as the plasma retracts vertically the amount of lithium ionized in the plasma drops dramatically, which should cause the plasma to return to its original position. This resiliency had been proposed as a key feature of the lithium vapor box.
13) We made significant progress on the physics design for a lithium vapor box experiment on the Magnum PSI device, outlining the basis features and determining that such an experiment is feasible within the geometrical and physical constraints of the Magnum-PSI device. These calculations were based on simplified models but interpreted conservatively.
14) Performed experiments using the chain of vapor boxes at PPPL, working through the complexities of thermal control, so that experiments could be undertaken with adequate scientific accurately to compare accurately with SPARTA DSMC calculations, and provide a solid physics basis for Magnum-PSI experiments, and to support our other calculations.

Development of Plasma-Surface Interaction Science for Direct Power Extraction Applications

Principal Investigator: Michael Jaworski

Project Period of Performance: November 1, 2015 – September 30, 2018
Project Number: PPPL-061

Project Description

This LDRD project will accomplish two primary tasks based on the DOE/National Energy Technology Laboratory (NETL) workshop meeting on magnetohydrodynamic (MHD) power generation (Arlington, VA, Oct. 2014). The first task is to evaluate the usage of liquid technologies previously developed for fusion for direct power extraction from fossil energy sources, including initial experiments and a modern safety assessment. The second task is to identify key PPPL capabilities in this research line. The key output will be a report on the possibility of PPPL experimental and theoretical work on direct power extraction. Previous research in direct power extraction had indicated electrode lifetime as a critical technological hurdle. Electrodes were developed from solid metal or conducting ceramics but were not adequate to the needs of commercial power plant systems in terms of lifetime. A new concept is the use of liquid electrodes. This suggested the self-healing capabilities of liquid-metal plasma-facing components being established in fusion devices. The chemical reactivity associated with combustion products suggests the use of molten salts which is a new area of application for both PPPL and direct power extraction areas of research.

Accomplishments

Major accomplishments were completed in the first year for further developing this concept area linking Office of Fusion Energy Sciences (OFES) and the Office of Fossil Energy (OFE). In February 2016 the Principal Investigator (PI) visited NETL at the Albany, OR site to hold discussions on the current research on oxy-fuel combustion and direct power extraction. These discussions developed a Big Ideas Summit white paper. The Principal Investigator further developed a multi-color schlieren imaging system for atmospheric-pressure plasma diagnosis. This system was procured, assembled and tested in the summer of 2016 and successfully diagnosed an atmospheric-pressure microwave discharge source at the University of Illinois.

Diagnostic and arc system development included the development of analysis codes for the schlieren imaging system and definition of an infrared spectroscopy system for use in the project. An automated set of analysis routines were developed to more quickly and repeatedly analyze imaging data taken with the two-color schlieren system. This was accomplished with Python code and used to analyze historical data taken in 2016. An arc-model was developed to begin analysis of temperature and composition gradients within the arc itself. This code makes use of a semi-analytic arc model while making calls to the NASA Chemical Equilibrium and Analysis (CEA) code for equation of state and transport properties.

An advanced power cycle featuring an MHD topping cycle combined with a high-temperature Brayton bottoming cycle was analyzed. It was found that overall cycle efficiencies of 50% (including carbon-capture stages) could be achieved assuming an advanced heat exchanger can be developed. The technologies proposed of recent interest in power generation has increasingly deployed smaller-scale generators to meet the needs of variable supply and demand.

Full Wave Calculations in the Scrape-off Layer of Tokamaks

Principal Investigator: Eun-Hwa Kim

Project Period of Performance: November 1, 2015 – September 30, 2018
Project Number: PPPL-063

Project Description

The objective of this project is to adapt a 2D full wave code, which was developed to describe propagation of waves in space plasmas, to examine radio frequency (RF) waves in the scrape-off layer (SOL) of tokamaks, which is the region of the plasma between the last closed flux surface and tokamak vessel. The SOL region is important for RF wave heating of tokamaks because significant wave power loss can occur in this region; for instance, up to 60% of the coupled higher harmonic fast wave (HHFW) power can be lost in the SOL of National Spherical Torus Experiment (NSTX-U).

Accomplishments

The 2D full wave code (FW2D) has been successfully adopted to tokamak geometry. Using the modified FW2D code, we performed simulations of HHFW propagation and collisional power losses in the SOL of NSTX/NSTX-U by adopting realistic vacuum vessel boundary. We particularly investigated the effect of the boundary shape, SOL size, electron density in front of the antenna (N_{ant}), and the ambient magnetic field strengths on the SOL power losses. By adopting rectangular boundary, we compared the wave solution with existing results from the AORSA code. Despite the discrepancy of the methodology between FW2D and AORSA, the numerical results showed that the simulations from two codes have excellent consistency. We then investigated the effect of the boundary shape and SOL size. We showed wave solution dramatically varies along the boundary shape, i.e., SOL size and shape. When we adopted the realistic vacuum vessel boundary, the amplitude of gradually increases as N_{ant} increases. When the FW cutoff layer is closed, or the SOL cavity of the FW mode is narrow, the waves are strongly localized near the antenna and does not propagate into the SOL. Even for the dense SOL case, the standing mode amplitudes in vacuum vessel are not stronger than waves near the antenna, and the wave amplitude in the SOL gradually increases as N_{ant} increases. Then the fraction of power losses in the SOL (P_{abs}) defined as a ratio between total power absorbed to the plasma to power loss in the SOL have been also calculated. Showing consistency with the experiments, lower collisional power losses occur when the density in front of the antenna is similar to the critical density where the fast cutoff is open, when the plasma is strongly magnetized, and when the plasma core located in the lower magnetic field side, thus the distance between the last closed flux surface and the antenna is shorter. We also showed the collisional power losses strongly depends on the SOL boundary shape and the power losses increase as the SOL size increases. As the outer plasma LCFS boundary shifts toward antenna (thus the size of the SOL is reduced), P_{abs} dramatically decreases and finally the maximum (P_{abs}) becomes ~5% for a given condition in the NSTX boundary. Significant reduction of the SOL power losses for lower collisional frequency case in the NSTX SOL boundary suggests that higher power lost to the SOL in experiments might be due to multiple loss mechanisms rather than a single collisional effect.

Development of New Initiatives for Space Instrumentation and Space Plasma Physics Research at PPPL

Principal Investigator: Masaaki Yamada

Project Period of Performance: August 15, 2016 – August 14, 2019
Project Number: PPPL-065

Project Description
The development of unique research plans in the following two areas are proposed: (1) targeted space instruments, such as gamma-ray spectrometers, which could be based on board future space missions and (2) future research concepts for space missions to expand the horizons of space plasma physics research on targeted topics, such as magnetic reconnection and turbulence.

Accomplishments
A comprehensive analysis of a low-thrust electric propulsion mission was carried out with significant analysis of the optimal trajectory of the satellite to maximize fuel use, minimize time in radiation belts, and ensure the solar panels obtain sufficient power generation. While such analyses must eventually happen, an initial pen-to-paper viability check is considered to be very helpful to determine the approximate satellite size and thruster parameters a mission would need.

An attempt to illustrate a thruster-selection process is demonstrated in the context of a multi-satellite formation mission currently being discussed in the PPPL. The mission revolves around measuring the phenomenon of magnetic reconnection, which occurs when magnetic field lines reconnect in a plasma, resulting in a transformation of magnetic energy to thermal and kinetic energy of ions and electrons. While this has been studied in an experimental setting, such as the "Magnetic Reconnection Experiment" at PPPL, there is a need to match the theory with reconnection that occurs naturally, notably in the magnetopause between the Earth and Sun. This presents a great challenge, as the magnetopause occurs at an altitude of 63,000+ km above the Earth. A previous mission to measure this region by NASA – the Magnetospheric Multiscale Mission (MMS) – was composed of 4 satellites and had a budget of $1.1 billion. While the data collected made great strides in the theory of reconnection, to fully capture the physics of magnetic reconnection would require a much larger formation for spatial measurements of the plasma properties. This presents an opportunity for small satellites such as CubeSats to lower the cost of a mission sufficiently that a very large formation (up to 100 satellites) may be attempted for an order of magnitude lower cost than MMS.

This orbit design work was split into three parts. The first outlined the basic orbital elements required to create the desired formation at the target orbit, the second considered the orbital perturbations the formation will experience and the corrections to the initial orbital elements to minimize the thrust required as well as the thrust and Delta V needed to maintain the formation. Finally, the third outlined a method to determine the time, Delta V, and the basic cost analysis to use onboard thrusters to transfer from an initial orbit, such as an ISS orbit in LEO, to the target final orbit. This analysis is intended to be a first-stage mission analysis as there is no attempt to optimize any of these parts.

Basic diagnostics for this project have been evaluated and conceptual designs were completed: the feasibility is found to be realistic (B, n, E, fe(E), fi(E)), but the data transfer was challenging and not straightforward.   A new area of research collaboration developed with metamaterials (MMS) researchers regarding electromagnetic and electrostatic fluctuations in the reconnection region. It was realized that to further strengthen the tie between PPPL and the space community, a role in the proposed super-cluster satellite system would be important. To clarify the values of super-cluster system for space physicists, a more intense comparative study has been made with the MMS research groups to compare the recent Magnetic Reconnection Experiment (MRX) data with the MMS data. A paper has been published in Nature Communications.

Permeation Barriers in High-Z Materials used for Fusion-reactor Plasma-face Components (PFCs)

Principal Investigator: Samuel Cohen

Project Period of Performance: February 1, 2017 – January 31, 2020
Project Number: PPPL-066

Project Description

Following ITER's lead, the plasma-facing (first-wall) components (PFC) of future fusion reactors may have high-Z surfaces, in large part to withstand the heat load but also to reduce sputter erosion. PFC components would most likely be in the highest heat load regions, e.g., in the divertor region and at the inter-coil regions at the top/bottom of the machine that is susceptible to fast ion impacts from super-banana-trapped fusion products or to fast electron impacts, from pitch angle-scattered runaway electrons. In these high-heat-load locations and even at the somewhat remote sections of the first wall, PFCs will also experience fluxes of hydrogen (isotope) and helium ions and neutrals, sourced by plasma transport or by charge exchange. The energy of these particles would range from a few eV to over 1 MeV, the latter being promptly lost fusion products. What happens to these atoms once they hit a reactor's PFC is important for issues such as tritium inventory, helium-induced bubble/blister formation, and structural integrity. One way to control these effects is via diffusion barriers built into the near surface of the PFCs. Materials with low diffusivity rates are often ceramic-like materials. Such layers could be formed by thin film deposition.

Accomplishments

A literature search was made of materials that could serve as sputter-resistant first-wall coatings that would promote separation of energetic (300 keV) T and He from low energy (10 eV) H isotopes via differential permeability. An apparatus was constructed to measure the permeation of hydrogen and helium through the materials of choice. Measurements were made of the temperature and pressure dependence of hydrogen and helium permeation through 0.1 cm thick Pd. Favorable comparisons were found between the measured results and published results. Nitrided surface layers were formed by exposure of the Pd membrane to nitrogen plasmas formed by an ECH plasma source. At elevated temperature, above 200°C, the nitride layers no longer formed a permeation barrier. Literature shows that nitrogen goes into solution in Pd above these temperatures.

Proton Beam X-Ray Diagnostics

Principal Investigator: Lan Gao

Project Period of Performance: February 1, 2017 – January 30, 2020
Project Number: PPPL-067

Project Description

Proton Beam therapy is a new treatment of cancer tumors that is an alternative to x-ray and γ-ray radiation therapies. The absorbed beam dose is highest over a 10-20 mm region, making treatment highly localized and lessening damage. The location of the energy deposition is sensitive to the beam energy making it advantageous over radiation treatment where significant damage is along the radiation path, but there is no measurement technique to optimize the beam energy for treatment. To compensate for the uncertainty in energy deposition, treatment uses a multitude of beam energies and therefore it is somewhat excessive in its exposure to the patient and longer facility utilization. As part of the current treatment a gold wire is inserted into the tumor to align the tumor along the beam path using an x-ray CT scan. It became clear to us that when the proton beam hits the gold wire it emits 69 keV X-rays that leave the body and can be easily measured. With this measurement the beam energy can be exactly selected for treatment. This minimizes collateral damage and reduces facility time.

Accomplishments

We performed initial testing at ProCure proton therapy center in NJ using a low efficiency silicon x-ray detector in house and no neutron/gamma shielding and found no usable signals. We then purchased a high efficiency Cadmium telluride (CdTe) photon counting detector and built a steel neutron/gamma shield/x-ray collimator to reduce the background. With this setup we successfully measured the gold K x-rays at ProCure and compared the measured x-ray intensity with theoretical predictions. We also performed testing with lower atomic number fiducials, silver, tin, and tungsten, which could provide much more intense x-ray signals for lower energy protons that are nearer the end point. We compared these measurements to theoretical predictions. In order to increase the gold K x-ray count rate, we moved the detector closer to the gold fiducial using a much smaller steel neutron/gamma shield, where the radiation background became more intense with the smaller steel shield. The data taken from the previous testing was analyzed to obtain absolute count rates with the current experimental geometry. The signals were scaled for a quad Timepix CdTe detector, closer distance of detector to x-ray source, and shorter integration time for faster scanning of the proton beam in a single slice of the tumor, resulting in a factor of 120 increase in signal. This increase would fully ensure the desired signal level at clinical conditions with respect to proton energies, currents and durations and completely remove the possibility of pulse pileup.

Gyrokinetic total-f simulation of edge and divertor transport in stellarators with the XGC codes

Principal Investigator: Robert Hager

Project Period of Performance: May 22, 2017 – May 21, 2020
Project Number: PPPL-068

Project Description

The project proposes to convert the existing global, total-f gyrokinetic edge codes XGCa and XGC1 from tokamak geometry to stellarator geometry, and to perform a systematic study using the converted code to gain comprehensive knowledge of the neoclassical, turbulence and neutral particle transport physics in the edge of stellarator plasmas.

Accomplishments

The basis for enabling simulation of stellarators with XGC is formed by a meshing tool for generating magnetic field aligned, unstructured triangle meshes that was developed as part of this project. Initially the meshing tool was limited to the volume inside the last closed flux-surface (LCFS). Later in the project, the tool was extended to whole-volume meshing by combining a method based on magnetic coordinates with field line tracing.

The second crucial development is the XGC interface for 3-dimensional (3D) magnetic fields, which reads the equilibrium magnetic field data and provides interpolation routines for scatter (charge deposition) and gather (electric/magnetic field interpolation) operations of XGC's particle-in-cell (PIC) algorithm. The 3D geometry interface was refined to be able to trace particle trajectories with high accuracy. This capability was verified against the codes BEAMS3D (a particle tracing code for stellarators) and EUTERPE (a gyrokinetic particle-in-cell code for stellarators developed at IPP Greifswald) and used subsequently to study the collisionless confinement of energetic α-particles in quasi-isodynamic and quasi-axisymmetric stellarators. Both, the implementation of the 3D geometry interface, and the study of energetic α-particle confinement were published in peer-reviewed journals.

To provide flexibility, XGC's 3D geometry interface and meshing tool were extended to support input from three different stellarator equilibrium codes: VMEC, HINT, and SPEC. (For SPEC, only basic support was implemented, and a proof of principle test was exercised.) Only HINT and SPEC allow for including magnetic islands and stochastic magnetic field, whereas VMEC is limited to nested toroidal flux-surfaces inside the last closed flux-surface. Magnetic islands are crucial for realistic whole volume simulation of stellarators.

The adequacy of the finite-element electrostatic potential solver used in XGC for tokamaks was assessed early in the project. Solutions for the radial electric field were evaluated with a one-dimensional potential solver (based on the vorticity equation) and XGC's usual finite element solver for the gyrokinetic Poisson equation and showed good agreement. A successful benchmark between the codes XGC, GT5D and FORTEC-3D was exercised for the collisionless damping of geodesic acoustic modes. The finite element solver proved to be sufficiently accurate inside the last closed flux-surface so that a time intensive implementation of a new 3D solver could be postponed.

At that point, the stellarator version of XGC was capable of running global, nonlinear simulations in delta-f mode with adiabatic electrons, which, placed XGC among the leading stellarator codes at the time. Therefore, it was decided to focus on studying high-impact physics problems with the available capabilities and to postpone the generalization of the total-f algorithm.

To verify XGC's stellarator capabilities, a benchmark of the linear physics of ion temperature gradient driven (ITG) modes was exercised between XGC and the code EUTERPE. Excellent agreement of the linear ITG growth rates was found, and the results were published in a peer-reviewed journal. The benchmark was later extended to include the code GENE3D, also with excellent agreement (unpublished work). In collaboration with a researcher from NIFS, Japan, a benchmark of ITG mode physics between XGC and EUTERPE was carried out using the geometry of the Large Helical Device (LHD). While good agreement was observed, no publication resulted from this project due to some open questions regarding the comparison between simulation and experiment.

Following the verification of linear ITG physics, a study of (nonlinear) global ITG turbulence in the proposed quasi-axisymmetric stellarator QUASAR was conducted. The resulting article published in a peer-reviewed journal is among the first, if not the first, publication of such a study. One of the main findings is that the highly localized mode observed in linear simulations gives way to radially and poloidally significantly broadened turbulence activity.

Global numerical studies of magnetic reconnection in rotating plasmas with magnetic and flow shear

Principal Investigator: Fatima Ebrahimi

Project Period of Performance: February 1, 2017 – September 30, 2019
Project Number: PPPL-069

Project Description

This project aims to explore fast magnetic reconnection as well as the effect of shear flows in a global configuration with reversed magnetic shear for the first time. The proposed work will carry out global numerical simulations of magnetic reconnection in rotating plasmas with magnetic and flow shear. Our key physics objective is to investigate the role of rotation and magnetic shear on reconnecting current-driven instabilities in the linear and nonlinear regimes. We will focus on magnetic reconnection due to double tearing modes (DTM) in reversed-magnetic-shear configuration in cylindrical geometry as well as toroidal advanced tokamaks. Using existing extended magnetohydrodynamic (MHD) codes, we propose to explore; 1) the possibility of explosive growth in the nonlinear simulations of DTMs in a reversed magnetic shear configuration, 2) stress-driven zonal flow generation during the nonlinear phase of DTMs. The explosive growth is expected to play a critical role in understanding the sudden onset and fast reconnection events in solar and fusion plasmas. The shear flow, however, usually has a role in suppressing the fluctuations.

Accomplishments

We have examined the onset and nonlinear evolution of coherent current-carrying filaments using global nonlinear three-dimensional resistive MHD simulations in a spherical tokamak (ST). For the first time we have shown that nonlinear coherent filament edge localized structures are formed during full nonlinear 3-D resistive MHD simulations in a tokamak. We also investigated the dependency of onset of peeling-driven filaments on Lundquist number. Similar to fast reconnection due to axisymmetric plasmoids, we find that the growth rate of these edge filamentary structures becomes independent of Lundquist number. We have also investigated the effect of toroidal field on the 3-D stability of edge reconnecting current-carrying filaments using full nonlinear MHD simulations. Complete stabilization of non-axisymmetric fluctuations arising from current-sheet instabilities was found at high toroidal flux.

Definition of a next-step liquid-metal-wall toroidal confinement facility

Principal Investigator: Jonathan Menard

Project Period of Performance: February 1, 2017 – January 31, 2020
Project Number: PPPL-070

Project Description

The purpose of this LDRD activity is to explore possible configurations for a toroidal confinement facility dedicated to the study and development of a range of liquid metal divertor and first-wall concepts. Such a device would build upon past and expected results from liquid metal test-stands, the Lithium Tokamak Experiment (LTX), the National Spherical Torus Experiment Upgrade (NSTX-U), and the Experimental Advanced Superconducting Tokamak (EAST), but the device configuration would be driven primarily by the needs (space, plumbing, thermal insulation, etc.) of liquid metal systems. The proposed studies would also build upon recent low-A High Temperature Superconductor (HTS) tokamak pilot plant studies that incorporated a liquid metal divertor for high-heat-flux mitigation and as a means of reducing poloidal field coil current and simplifying the magnet layout and maintenance scheme. Tokamak aspect ratios in the range of A = 1.8 to 2.5 would be considered based upon recent pilot plant studies indicating this range would be optimal for fusion power production if high-current-density HTS (or Cu) magnets were utilized. This aspect ratio range is subject to change pending the results of the first two years of the study.

Accomplishments

Substantial progress was made on defining the overall liquid-metal divertor geometry and maintenance approach and on the overall device configuration based on expectations for a full-scale fusion power plant. Magnet cable and TF/OH coil layout calculations were completed. Detailed configurations for fast-flow and slow-flow divertors were completed and vapor box divertor concepts were developed.

Initial coil locations and sizes from configuration studies were used to evaluate the first free-boundary equilibria for a R=1.0m device. These studies showed that a range of aspect ratios could be studied in the same device if divertor modules and/or outboard blanket structures were modified. Standard power exhaust parameters such as P/R, P/S, PB/R, and parallel heat flux were computed to evaluate the exhaust relevance to a future pilot plant. Increased q-parallel was found to be accessible if both P and B were increased via an increase in the device major radius. Subsequently, the proposed device major radius was increased to R=1.2m. The understanding and configuration layouts for capillary, vapor box, and fast-flow liquid metal systems were further developed and integration of different liquid metal systems operating simultaneously in the same device was shown to be feasible. In particular, capillary restrained LM (slow flow) surfaces were designed for the inboard and outboard first-wall. A vapor box divertor was located at the top divertor location which also incorporates slow-flow LM surfaces – with no magnetic pumping needed. Lastly, a fast-flow divertor system was defined at the lower divertor where magnetic pumping will occur.

The exploration of TF and OH magnet design implications of new Cable-In-Conduit (CIC) winding techniques under development at Texas A&M University was explored and shown to be favorable for the device magnet system. A 3x3 HTS pancake-wound conductor approach and stacked HTS tape configurations were also explored and offer very compact magnets due to increased effective current density.

Future Stellarator Configuration Investigation

Principal Investigator: David Gates

Project Period of Performance: February 1, 2017 – January 31, 2020
Project Number: PPPL-071

Project Description

The initial plan was to explore the quasi-axisymmetric equilibrium space for a Stellarator configuration with additional optimization constraints beyond those of The National Compact Stellarator Experiment (NCSX) including simplified magnets, turbulent transport optimization, and divertor optimization while including force minimization in the optimization process. The project changed goals substantially following the conceptual development of permanent magnets for stellarator shaping in early 2019.

Accomplishments

The following was accomplished:

1) Completed an elongation scan of neoclassically optimized stellarators at aspect ratio 6 for a 3-period stellarator
2) Validated and incorporated a new version of the terpsichore code into STELLOPT
3) Included force constraints in the COILOPT++ code
4) Incorporated REGCOIL into STELLOPT
5) Incorporated SFINCS into STELLOPT
6) Identified options for incorporating the SPEC code into STELLOPT
7) Incorporated elements of COILOPT++ into the STELLOPT optimization loop
8) Completed turbulent transport optimization of a quasi-helical stellarator
9) Developed a new concept for permanent magnet stellarator shaping
10) Performed coil error analysis using the FOCUS code – results published in Nucl. Fusion
11) Developed codes for permanent magnet optimization (FY2019 milestone)
12) Developed plausible permanent magnet design concept including support structures
13) Codified and published results for permanent magnet design work

A Flowing Liquid Metals Torus - FLIT

Principal Investigator: Egemen Kolemen

Project Period of Performance: March 8, 2017 – March 7, 2020
Project Number: PPPL-072

Project Description

This is a project to develop a toroidal test system to study the technology of fast flowing liquid metal plasma-facing surfaces. The project will focus in the near term on developing a liquid metal divertor suitable for implementation and testing in present-day fusion systems, such as NSTX-U. This project will use liquid galinstan, a commercial non-toxic non-reactive alloy of gallium, indium, and tin.

Accomplishments

The following work was accomplished:

- A Conceptual Design Review (CDR) was held for the full system.
- The coil system was designed and a Final Design Review (FDR) held.
- An FDR for the complete system including the vessel, support structures and jxB pumps was held in September 2018.
- Progress was made on the experimental and numerical understanding of the liquid metal flow stability and heat flux on the Liquid Metal Experiment (LMX) and an upgrade to the system was completed to achieve higher flow rates.
- Experiments were performed on free-surface flow acceleration using jxB force under vertical magnetic field, as well as diagnostic port shape effect on surface quality.
- The results showed that it is possible to overcome the effects of vertical magnetic field induced drag. Furthermore, vertical field in combination with applied currents can be tool to flow the liquid metal at high speeds.
- Many of the chits from the FLIT FDR were answered and closed out.
- A 3D drawing of FLIT was completed by the PPPL Engineering Department and approved.
- Welding techniques for putting together FLIT were decided after discussions with PPPL engineering. This was added to the FLIT drawings.
- Novel liquid metal flowing configurations that might have advantages over poloidal flow were developed.
- 2 papers were published in Nuclear Materials and Energy in 2019.
- One paper was submitted for publication to the Journal Fusion Science and Technology.
- Two presentations were made in FY2019; the first at NIFS in Tokyo, Japan and the second at the IEEE Symposium on Fusion Engineering in Jacksonville, FL.
- We finalized the chits from FLIT FDR and concerns related to FLIT project. We looked at advanced flowing metal configuration ideas (non-linear flow as studied in LMX) and how they can be incorporated into a future reactor. Our LDRD research was successful in obtaining DOE direct funding for the work related to LMX which started in FY2020.

Secondary electron emission from dielectrics and liquids

Principal Investigator: Yevgeny Raitses

Project Period of Performance: October 1, 2017 – September 30, 2018
Project Number: PPPL-074

Project Description

Feasibility studies of measurements of secondary electron emission (SEE) from dielectric thin films and liquids will be performed. There is a strong need for knowledge of the SEE properties of such materials for many emerging applications including, but not limited to, accelerators, fusion devices, neutron tubes, biomedical applications etc. SEE data can help in modeling and design of devices relevant to these applications. There are currently no measurements capabilities in US to conduct measurements of this kind. In the past, PPPL conducted measurement of SEE properties from bulk solid materials, but not from liquids and not from thin films. These measurements established PPPL as a leading authority in the area of SEE measurements. However, for new research frontiers in the above applications, including new materials, we need to 1) upgrade our setup with new capabilities to hold thin films and liquids and 2) explore the feasibility of SEE measurements from these materials.

Accomplishments

We demonstrated the feasibility of SEE measurements for the targeted materials. As a result of these successful efforts, we succeeded in securing funding from the Sandia National Laboratory (Analytical Technologies, Dept. 02576 Component Science, Engineering and Production) and, later, from the DOE Fusion Energy Sciences program as a part of the Princeton Collaborative Research Facility (PCRF).

Development of Magnetic Enhancement Coils for a Fast Time Response Electromagnetic Disruption Mitigation System

Principal Investigator: Robert Lunsford

Project Period of Performance: October 1, 2017 – September 30, 2019
Project Number: PPPL-076

Project Description

This project will develop and test magnetic boost coils to enhance the efficiency of the Electromagnetic Pellet Injector (EPI) concept for disruption mitigation. Research will focus on augmenting a linear rail gun concept with additional high-field magnetic coils to reduce stress on the pellet launching mechanism. PPPL will design and develop the technology and then utilize the rail gun facility currently in operation at the University of Washington (UW) to test its effectiveness at enhancing pellet injection efficiency. This LDRD project will cover fabrication, prototyping and tests of the boost coil concept.

Present disruption mitigation schemes for the radiative quench of high energy H-Mode plasmas are hampered by the inability of the radiative payload to effectively penetrate the edge confinement barrier. The rail gun concept surmounts this obstruction by delivering a solid radiative payload of high sublimation energy through the transport barrier, allowing the majority of the ablated payload to be delivered to the plasma core where it is most effective. However, accelerating the EPI payload occurs through the JxB force resulting from current driven through a pellet encasing device called a sabot. The sabot corrals the pellet and completes the circuit between the two conductors which comprise the rail gun. Because the accelerating sabot needs to have low mass, the energy density deposited within it is large, resulting in a loss of structural rigidity. In addition, at high driven currents, electrode erosion is also substantial, limiting the lifetime between electrode refurbishments. These issues can be overcome by implementing supplemental high field magnetic coils on either side of the delivery rail electrodes to augment the rail gun generated magnetic fields. These additional coils improve system efficiency while reducing the energy deposited on the sabot. It is a quantification of the effectiveness of the boost coils which is the focus of the LDRD project.

Accomplishments

Magnet prototypes were designed in collaboration with UW personnel. Boost magnet coils were constructed, and initial testing of current response and magnetic field generation was undertaken at the rail gun facility at UW. These experiments allowed us to quantify the low current effectiveness of the boost coils. To extend performance of the boost coils it has been determined that a more robust coil holder needs to be employed. A high strength design for the magnet holder was completed.

The electromagnetic particle injector (EPI) concept is advanced through the simulation of ablatant deposition into ITER H-mode discharges with calculations showing penetration past the H-mode pedestal for a range of injection velocities and granule sizes concurrent with the requirements of disruption mitigation. The present status of the EPI project is outlined, including the addition of boost magnetic coils. These coils augment the self-generated railgun magnetic field and thus provide a more efficient acceleration of the payload. The coils and the holder designed to constrain them have been modeled with the ANSYS code to ensure structural integrity through the range of operational coil currents. These results are reported in the following conference proceedings and publication.

Investigation of Commercial Cloud Services for Research Computing

Principal Investigator: Nate Ferraro

Project Period of Performance: July 11, 2018 – March 31, 2019
Project Number: PPPL-077

Project Description

The goal of this project is to assess whether, and how well, various codes used by PPPL researchers can be run on commercial cloud computing platforms, including Amazon Web Services, Google Cloud, and Microsoft Azure. We will attempt to install and run various codes, such as TRANSP, M3D-C1, GTS, and SPIRAL on one or more of these platforms. We will evaluate the practicality of using these platforms to service PPPL research computing needs by considering the ease of setting up and maintaining the software environment on these platforms, the computing throughput provided by the platforms, and noting other benefits or drawbacks encountered. We will consider this project to be fully successful if we are able to perform tests of at least three codes on at least two platforms. Failed attempts to install or run codes will also provide valuable insight into the possibility of using these services.

Accomplishments

Five research codes—Gkeyll, GTC-Neo, M3D-C1, TRANSP, and XGC—were installed and run on cloud computing platforms in order to test their performance and usability on these platforms. The major findings of this activity are the following:

- **Installation of codes was simple.** These services provide a standard Unix environment to the user, to which the user has root access. However, in this activity we were limited to the use of freely available compilers (*e.g.,* gcc) and libraries. This could be a challenge for codes that require proprietary software (*e.g.,* NAG libraries), and may result in relatively poor performance.
- **Single-node performance was generally good.** The services now provide high-performance hardware, and single-node code performance was generally (but not universally) commensurate with the expected performance given the hardware.
- **Running on multiple nodes was not simple.** Multi-node runs require the instantiation of multiple instances, and manual coordination among these instances. Third-party software or the creation of "containers" may simplify this process, but these possibilities were not explored here.
- **Services lack support for parallel I/O.** This prevents some codes (*e.g.,* M3D-C1) that require parallel-I/O from running on multiple nodes.
- **Multi-node scaling was relatively poor.** Multi-node scaling was poor relative to Eddy or the PPPL cluster, indicating that inter-node communication is relatively slow. This could severely impact the performance of codes that routinely use hundreds or thousands of processors.

These results are primarily based on experiences on the Amazon Web Services (AWS) EC2 instances, on which all of the codes were run and tested. In addition, TRANSP was successfully built on the Google Cloud service, and GTC-Neo was successfully built on the Microsoft Azure cloud service. The computing environment provided by Azure is found to be substantially similar to that provided by AWS, although performance results are not available for Azure due to confusion regarding the approval for the use of that service.

Our overall conclusion is that cloud computing services at this stage might be useful for compute jobs that run effectively on a single node or on a small number of nodes, but cannot be considered at this time as a replacement for larger HPC clusters for more highly parallelized codes or those that require parallel I/O. For smaller use cases, cloud services still may be challenging to use routinely unless solutions can be found to launch jobs through a standard batch system, install proprietary software, and transfer data efficiently and cost-effectively. If the use of cloud computing is to be considered further, we recommend a study to determine whether third-party software, container technology, or other solutions are available to address these issues.

Feasibility Study of a Laser-Based Approach for Diagnosing Deuterium Neutrals in the Edge of Fusion Devices

Principal Investigator: Ahmed Diallo

Project Period of Performance: January 23, 2019 – January 22, 2020
Project Number: PPPL-078

Project Description

In magnetically confined plasmas, neutral deuterium/hydrogen atoms are well-known to play an important role in the energy and particle balance. It became clear that understanding the pedestal density formation is key for performance projections of future devices. There are no direct and local measurements of the neutral density. Typically, measurements of the neutrals are performed using Lyman alpha which is a line-integrated measurement and therefore prone to large uncertainties. This project will explore the feasibility of a laser-based method capable of providing an accurate measurement of both the spatial and absolute magnitude of the neutral deuterium/hydrogen with minimal knowledge of the radial profiles of electron temperatures and densities. More specifically, we leverage the fact that the Thomson scattering cross section is independent of the wavelength of the laser, while the Rayleigh scattering cross section for atoms/molecules is inversely proportional to the fourth power of the wavelength of the laser. We will investigate this approach theoretically and through modeling while exploring other laser-based approaches for completeness.

Accomplishments

Laser two-color scattering is proposed to detect the neutral species in the edge of fusion devices, namely tokamaks. Two-color scattering uses two wavelengths to probe both the laser Rayleigh scattering and Thomson scattering of the neutral-electron bath, with emphasis on neutral density measurements such as that of hydrogen and deuterium. Modeling of the Rayleigh scattering of tokamak neutral species under various plasma conditions (electron density and temperature) show that, with appropriate filtering of the Thomson signal and by going to ultraviolet-region wavelengths, separation of the Rayleigh signal can be achieved. Photon count and signal fractions were calculated in two test cases, one in the midplane of NSTX and one in the divertor region of DIII-D.

Mapping of magnetic field lines in the earth's magnetosphere using electron beam

Principal Investigator: Igor Kaganovich

Project Period of Performance: January 23, 2019 – September 30, 2019
Project Number: PPPL-079

Project Description

Active, space-based particle injection experiments have enabled scientific investigations of space plasmas since at least the 1950s. However, these controlled experiments were mainly based on relatively low-energy electron beams (<40 keV). Controlled experiments with MeV beams injected from a satellite in magnetosphere and observed at earth ionosphere will open up the transformative capability of a laboratory-in-space where key outstanding questions in heliophysics and fundamental plasma science will be answered. In this project we will investigate beam interaction with background plasma in the magnetosphere and ionosphere. The general beam is subject to various beam-plasma instabilities. However, initial studies show that the beam instabilities saturate and do not affect the beam significantly. In this project we propose to perform a study of the beam propagation in the realistic magnetic field structure and study the effect of plasma instabilities on beam emittance.

Accomplishments

Tracing magnetic field-lines of the Earth's magnetosphere using beams of relativistic electrons will open up new insights into space weather and magnetospheric physics. Analytic models and a single-particle-motion code were used to explore the dynamics of an electron beam emitted from an orbiting satellite and propagating until impact with the Earth. The impact location of the beam on the upper atmosphere is strongly influenced by magnetospheric conditions, shifting up to several degrees in latitude between different phases of a simulated storm. The beam density cross-section evolves due to cyclotron motion of the beam centroid and oscillations of the beam envelope. The impact density profile is ring shaped, with major radius $\sim$ 22 m, given by the final cyclotron radius of the beam centroid, and ring thickness $\sim$ 2 m given by the final beam envelope. Motion of the satellite may also act to spread the beam, however it will remain sufficiently focused for detection by ground-based optical and radio detectors. An array of such ground stations will be able to detect shifts in impact location of the beam, and thereby infer information regarding magnetospheric conditions.

Scoping of Facilities in Support of Long-Term PPPL Initiatives

Principal Investigator: Hutch Neilson

Project Period of Performance: April 1, 2019 – January 31, 2020
Project Number: PPPL-086

Project Description

The Fusion Energy Sciences (FES) office has called for community input, through the Advisory Committee (FESAC), to a new ten-year strategic planning activity. The FES call invites proposals for upgraded or new facilities to support research across the FES portfolio. In preparing to contribute effectively to the community activity, PPPL is developing initiatives that are responsive to the FESAC charge and have the potential to gain widespread community support. Initiatives that envision new facilities or facility upgrades, or that involve collaboration in fusion materials and technology development, require strong engineering participation and leadership. The purpose of this project is to carry out the engineering effort needed for conception and preliminary technical analyses of experimental facilities or devices as potential elements of long-term U.S. FES strategy.

Accomplishments

Virtual Engineering: An engineering study was conducted to assess the potential of Virtual Engineering (VE) methodology as one element of a strategy for modernizing the Laboratory's approach to fusion machine design. The basic idea of Virtual Engineering is to develop a modeling framework that could be used to test innovative ideas in simulations and use the results to inform decisions on investing in physical laboratory R&D, which is generally more time-consuming and expensive. A market research and trade study was conducted, resulting in the selection of a commercial tool that would most likely meet the requirements of a VE environment. A use case that can serve as first test of the tool for fusion machine design was developed. The use case considers a few small-scale scenarios and a limited set of parameters, e.g., for plasma, magnets, and divertor/PFCs. It also considers the interactions among system users – plasma physicists, material scientists, and design engineers. Virtual engineering concepts are embedded in the Laboratory's proposal for a national fusion pilot plant design initiative. Such an activity is needed to chart a path to a machine that would generate net electricity at the lowest possible capital cost, as recommended by a recent National Academies study. Simulation must have a central role in such an activity, using models to go as far as possible in predicting the impact of candidate choices on performance and cost, before committing to major physical R&D initiatives.

Innovative Next Step Tokamak: The study focused on the design development of a tokamak device as a candidate for a next-step sustained high power density (SHPD) facility for fusion. The configuration development centered on component areas which were expected to have a major influence on the machine design. This included: the development of a high current density (CD) toroidal field coil winding design and the inclusion of liquid metal first wall and divertor systems. These innovations would enable a device that could test the physics of a sustained high-power density, low aspect ratio (A = 2.4) plasma. The magnet study considered the incorporation of mature low-temperature superconducting material into conductor and winding pack configurations that support high winding pack current densities and thereby reduce the space requirements for magnets. The divertor and plasma facing component study considered two liquid metal (LM) based options: a fast-flowing option and a slow-flow, thin film option. The initial work involved defining a fast-flowing LM system but was expanded to include a combination of a slow flow vapor box upper divertor, a fast flow lower divertor and slow flow capillary pores inboard and outboard first wall system.

Arc-Produced Superhard Materials

Principal Investigator: Yevgeny Raitses

Project Period of Performance: April 1, 2019 – March 31, 2020
Project Number: PPPL-088

Project Description

Recent studies proposed the application of tungsten borides (WB) for radiation shielding (low energy neutrons and gamma ray) of the center column of a superconducting tokamak power plant. There is also a growing interest in the use of tungsten boride materials for various applications requiring mechanically hard materials (e.g., cutting tools). Boron-rich tungsten compounds are predicted to be superhard materials. They are anticipated to be harder than conventional hard materials used for cutting tools (e.g., tungsten carbide) and stable in a broad range of possible processing conditions (pressure and temperature). The latter makes these materials potentially less expensive than diamonds and cubic boron nitride, and thereby, more attractive for industrial-scale applications. In this LDRD project, we seek to conduct a thorough study of the super hardening of the tungsten electrodes exposed to a boron-rich arc. A key question to answer in the proposed research is whether this hardening is due to the formation of WB composites or tungsten phase transitions.

Accomplishments

We demonstrated and characterized tungsten-boron materials generated in the arc. Materials were evaluated at the Princeton Institute for the Science and Technology of Materials at Princeton University. Results about the cause of hardening were not conclusive due to limited data. Samples were then sent to the Evans Analytical Group for their evaluation. Results confirmed the presence of tungsten (W) and boron (B) but were not definitive on the presence of W-B bounded structures.

An Initial Experimental Study of Plasma Jet Formation Associated with Spheromak Tilt Instability

Principal Investigator: Masaaki Yamada

Project Period of Performance: October 1, 2019 – September 30, 2020
Project Number: PPPL-103

Project Description

Explosive solar activity is observed to be due to the buildup of stressed magnetic flux and free energy in the form of electric currents in the Sun's atmosphere, the corona. Eventually, the flux build-up induces a global Magnetohydrodynamics (MHD) instability that involves fast magnetic reconnection and leads to a catastrophic re-organization of the field and plasma. Recently this process was proposed by as the explanation for the sudden ejection of coronal plasma from Sun in the form of a jet noting that the flux and free energy build-up phase is significantly longer than the reconnection time.

Understanding the mechanism(s) driving coronal jets has long been one of the most important outstanding problems in solar and space physics (e.g., Raouafi et al, Sp. Sci. Rev., 2016). All jets originate from semi-spherical-like, closed magnetic field structures imbedded in a background coronal open field. These magnetic structures appear to sit stably for days before undergoing an explosive burst of energy release along with the ejection of much of the plasma originally within the closed semi-sphere. The particular plasma configuration that we will study is that of a half spherical, line-tied magnetic configuration, which can erupt suddenly from a conducting surface. This configuration is of particular interest due to its central role in storing and sudden releasing magnetic energy in the solar corona, as demonstrated in several numerical models. To study the internal structure of a line-tied half-spheromak in a laboratory setting, a new experiment is proposed using the Magnetic Reconnection Experiment (MRX).

Accomplishments

A new scenario of solar flare eruption in the coronal hole was analyzed and established by using MHD stability concepts for spheromak configuration. The stability properties of a spheromak partially embedded into a conducting surface were studied using three dimensional MHD simulations. In agreement with analytical theory, a large degree of line-tying stabilizes the spheromak's tilt instability while the elongation has a destabilizing effect. High-resolution nonlinear simulations also demonstrate the current sheet formation at the upper surface of the spheromak, where the tilted magnetic field of the spheromak reconnects with the background magnetic field. The calculated stability threshold and the observed magnetic reconnection have verified the project's model of coronal jet eruptions where a dome-like magnetic structure grows through flux emergence on the solar surface, tilts, reconnects, and erupts. Countering the effect from elongation, line-tying strongly stabilizes a spheromak growing from a flux-emergence process, suggesting that for eruptive coronal jets to occur, there must be magnetic reconnection at the bottom of the spheromak to detach the structure from the solar surface. The findings from this research led to a proposal which was funded by NASA for a three-year period of performance.

Publications List

Predicting and Mitigating Runaway Electrons in Tokamaks

Journal Publications

"*Momentum transport and nonlocality in heat-flux-driven magnetic reconnection in high energy density plasmas*", C. Liu, W. Fox, A. Bhattacharjee, A. Thomas, A. Joglekar, Phys. Rev. E 96, 043203 (October

Investigation of a Plasma Mass Filter

Journal Publications

"*Drift and separation in collisionality gradients*", I. E. Ochs, J. M. Rax, R. Gueroult, and N. J. Fisch, Phys. Plasmas 24, 083503 (July 2017).

Construction of Nb3Sn Superconducting Magnets at PPPL

Journal Publications

High Performance superconductors for Fusion Nuclear Science Facility; *IEEE Trans. Applied Supercond., Y. Zhai, C. Kessel, C. Barth, C. Senatore, v27, n4, 2017.*

Numerical stress analysis during cooldown and compressive loading in an imperfect s/c Nb_3Sn wire; *Fusion Sci & Tech., L. D'Hauthuille and Y. Zhai, 2017*

Conceptual Magnet Design Study for the Fusion Nuclear Science Facility, *Y. Zhai, P. Titus, C. Kessel and L. El-Guebaly, Fusion Eng. Des., 2017*

Design, construction and testing of no-insulation small subscale solenoids for compact tokamaks, *Y. Zhai, B. Berlinger, C. Barth and C. Senatore, Supercond. Sci. Technol., 13 August 2021*

Establishing the Feasibility of the Lithium Vapor Box Divertor

Workshops, Conferences, and Presentations

J. Schwartz "Design and measurement methods for a lithium vapor box similarity experiment". High Temperature Plasma Diagnostics / "Vapor flow measurements on a Lithium Vapor Box Similarity Experiment" / San Diego, CA / April 15-19, 2018.

J. Schwartz, E. Emdee, R. Goldston, M. Jaworski "Physics design for a lithium vapor box divertor experiment on Magnum PSI". International Conference on Plasma Surface Interactions in Controlled Fusion Devices / "A lithium vapor box divertor experiment for a linear plasma device" / Princeton, NJ / June 17-22 2018.

Development of Plasma-Surface Interaction Science for Direct Power Extraction Applications

Workshops, Conferences, and Presentations

M. Jaworski "Liquid components as enabling technologies for advanced, high-temperature power cycles". 2017 International Pittsburgh Coal Conference/ Pittsburgh, PA/ Sept. 5-8th, 2017.

Full Wave Calculations in the Scrape-off Layer of Tokamaks

Journal Publications

Kim, E.-H., N. Bertilli, E. Valeo, and J. Hosea (2017) 2D full-wave simulation of waves in space and tokamak plasmas, EPJ web of conference 157, 02005 https://doi.org/10.1051/epjconf/201715702005

Kim, E.-H., N. Bertilli, M. Ono, E. Valeo, J. Hosea and R. Perkins (2019) Effect of wall boundary on the scrape-off layer losses of high harmonic fast wave in NSTX and NSTX-U, under review, submitted to Phys. Plasmas

Workshops, Conferences, and Presentations

Kim, E.-H., N. Bertelli, J. Johnson, E. Valeo, and J. Hosea (2017) 2D Full-wave Simulations of Waves in Space and Tokamak Plasmas, the 22th Topical Conference on Radio Frequency Power in Plasmas, May 30 – June 2 2017, Aixen Provence, France (***invited***)

Kim, E.-H., N. Bertelli, E. Valeo, J. Hosea, and R. Perkins (2017) 2D full-wave simulation of HHFW in the scrape-off layer of NSTX, US-EU-Japan, September 2017, Santa Monica, CA, USA.

Kim, E.-H. et al. (2017) High harmonic fast wave propagation in the scrape-off layer of NSTX and NSTX-U, US-Japan RF heating physics workshop, Japan, Sep 2017

Kim, E.-H. et al. (2018) 2D full-wave simulation of HHFW energy loss in the scrape-off layer of NSTX, KSTAR conference 2018, Muju, Korea, Feb 21-23, 2018. KSTAR Meeting

Kim, E.-H. et al. (2018) High harmonic fast wave propagation in the scrape-off layer of NSTX and NSTX-U, APS-DPP conference, Portland, Nov. 2018.

Bonoli et al. (2018) Overview of Research in the SciDAC Center for Simulation of Fusion Relevant RF Actuators, APS-DPP conference, Portland, Nov. 2018.

Shiraiwa et al. (2018) Development of Petra-M Framework: toward integrated FEM analysis, APS-DPP conference, Portland, Nov. 2018

Kim, E.-H. et al. (2018) 2D full-wave simulation of HHFW energy loss in the scrape-off layer of NSTX and NSTX-U, 2nd AAPPS-DPP conference, Kanazawa, Japan, Nov. 2018. (***Winner, Poster Prize***)

Development of New Initiatives for Space Instrumentation and Space Plasma Physics Research at PPPL

Journal Publications

The two-fluid dynamics and energetics of the asymmetric magnetic reconnection in laboratory and space plasmas, M. Yamada, L/J. Chen, J. Yoo et al, NATURE COMMUNICATIONS, Dec. 2018; DOI: 10.1038/s41467-018-07680-2

Mini-CHT powered Formation Flying Mission for Magnetic Reconnection Research in Space, J. Simmonds, M. Yamada, Y. Raitses: Proceedings of *the 36th International Electric Propulsion Conference University of Vienna • Vienna, Austria, Paper IEPC, 2019-377 September 15-20, 2019*

Gyrokinetic total-f simulation of edge and divertor transport in stellarators with the XGC codes

Journal Publications

T. Moritaka, R. Hager, M. Cole et al., *Development of a Gyrokinetic Particle-in-Cell Code for Whole-Volume Modeling of Stellarators*, Plasma 2, 179-200 (June 2019)

M. D. J. Cole, R. Hager, T. Moritaka et al., *Comparative collisionless alpha particle confinement in stellarator reactors with XGC*, Physics of Plasmas 26, 032506 (March 2019)

M. D. J. Cole, R. Hager, T. Moritaka et al., *Verification of the global gyrokinetic stellarator code XGC-S for linear ion temperature gradient driven modes*, Physics of Plasmas 26, 082501 (August 2019)

M. D. J. Cole, T. Moritaka, R. Hager, et al., *Nonlinear global gyrokinetic delta-f turbulence simulations in a quasi-axisymmetric stellarator*, Physics of Plasmas 27, 044501 (April 2020)

Global numerical studies of magnetic reconnection in rotating plasmas with magnetic and flow shear

Journal Publications

“Nonlinear Reconnecting Edge Localized Modes in Current-Carrying Plasmas”, F. Ebrahimi, Phys. Plasmas 24, 056119, (May 2017).

"Minimalist shear-driven large scale dynamo", F. Ebrahimi, E.G, Blackman (January 2017).

F. Ebrahimi “Three-dimensional plasmoid-mediated reconnection and the effect of toroidal guide field in simulations of coaxial helicity injection ", Physics of Plasmas 26, 092502 (September 2019).

Definition of a next-step liquid-metal-wall toroidal confinement facility

Journal Publications

T. Brown, et al. “A toroidal confinement facility study and eventual experimental device to investigate a range of liquid metal divertor and first-wall concepts” 27th IAEA Fusion Energy Conference - IAEA CN-258, 22-27 October 2018, Contributed Conference Paper and Poster FIP-P7

Workshops, Conferences, and Presentations

Tom Brown presented poster FIP/P7-38 entitled "A toroidal confinement facility study and eventual experimental device to investigate a range of liquid metal divertor and first-wall concepts" at the 27th IAEA Fusion Energy Conference (22-27 October 2018).

J. Menard presented an invited talk entitled “Configuration Studies for a Next-Step Liquid-Metal-Wall Toroidal Confinement Facility” at the 6th International Symposium on Liquid Metals Applications for Fusion (ISLA-2019) from September 30 to October 3, 2019 in Champaign, IL

J. Menard presented a poster entitled "Scoping studies for a sustained high power density next-step tokamak facility" at the 61st Annual Meeting of the APS Division of Plasma Physics October 21–25, 2019 in Fort Lauderdale, Florida

J. Menard presented an invited talk entitled "Configuration Studies for a Low-Aspect-Ratio Liquid-Metal-Wall Sustained High-Power-Density Tokamak Facility" at the 20th International Spherical Torus Workshop (ISTW2019) held October 28-31, 2019 in Frascati, Italy.

<u>Future Stellarator Configuration Investigation</u>

Journal Publications

"*Recent Advances in Stellarator Optimization*", D.A. Gates, et al., 2017 Nucl. Fusion 57 126064 (October 27, 2017)

"*Designing stellarator coils by a modified Newton method using FOCUS*", Zhu, C. *et al., Plasma Physics and Controlled Fusion* 60 065008 (April 18, 2018).

"*Hessian matrix approach for determining error field sensitivity to coil deviations*", Zhu, C. *et al., Plasma Physics and Controlled Fusion* 60 054016 (April 4, 2018).

"*Identification of important error fields in stellarators using the Hessian matrix method*", C Zhu, *et al., Nucl. Fusion* 59 126007 (September 20, 2019)

"*Designing stellarators using perpendicular permanent magnets*", C. Zhu, M. Zarnstorff, D. A. Gates, and A. Brooks, *Nucl. Fusion* 60 (June 15, 2020) 076016

Conference paper Oct 2019: A proposed simple stellarator – SAS A proposed simple stellarator - SAS - NASA/ADS (harvard.edu)

<u>A Flowing Liquid Metals Torus - FLIT</u>

Journal Publications

E. Kolemen, M.Hvasta (postdoc), R.Majeski, R.Maingi, A.Brooks, T.Kozub, "Design of the Flowing LIquid Metal Torus (FLIT)", Nuclear Materials and Energy, Vol. 19, pp. 524-530 (2019)

A. Fisher (grad student), M. Hvasta (postdoc), E. Kolemen, "Study of liquid metal surface wave damping in the presence of magnetic fields and electrical currents", Nuclear Materials and Energy, Vol. 19, pp. 101-106 (2019)

M. G. Hvasta (postdoc), G. Bruhaug, A. E. Fisher, D. Dudt, E. Kolemen, "Liquid Metal Diagnostics", Fusion Science and Technology 76 (1), 62-69 (2019)

C. E. Kessel, D. Andruczyk, J. P. Blanchard, T. Bohm, A. Davis, K. Hollis, P. W. Humrickhouse, M. Hvasta, M. Jaworski, J. Jun, Y. Katoh, A. Khodak, J. Klein, E. Kolemen, G. Larsen, R. Majeski, B. J. Merrill, N. B. Morley, G. H. Neilson, B. Pint, M. E. Rensink, T. D. Rognlien, A. F. Rowcliffe, S. Smolentsev, M. S. Tillack, L. M. Waganer, G. M. Wallace, P. Wilson, and S-J. Yoon, "Critical Exploration of Liquid Metal Plasma-Facing Components in a Fusion Nuclear Science Facility", Fusion Science and Technology, https://doi.org/10.1080/15361055.2019.1610685, (2019)

M. Hvasta (postdoc), D. Dudt (grad student), A.E. Fisher (grad student), E. Kolemen, "Calibrationless rotating Lorentz-force flowmeters for low flow rate applications", Measurement Science and Technology 29 (7), 075303 (2018)

A.E. Fisher (grad student), E. Kolemen, M. Hvasta (postdoc), "Experimental demonstration of hydraulic jump control in liquid metal channel flow using Lorentz force", Physics of Fluids 30 (6), 067104, (2018)

M. Hvasta (postdoc), E. Kolemen, A. Fisher (grad student), and H. Ji, "Demonstrating electromagnetic control of free-surface, liquid-metal flows relevant to fusion reactors", Nucl. Fusion 58 016022 (2018)

M. Modestov (postdoc), E. Kolemen, A.E. Fisher (grad student), and M.G. Hvasta (postdoc), "Electromagnetic control of heat transport within a rectangular channel filled with flowing liquid metal", Nucl. Fusion 58 016009 (9pp) (2018)

K. Kusumi, (visiting graduate student), T. Kunugi, T. Yokomine, Z. Kawara, S. Nakamura. E. Kolemen, H. Ji, "Thermal mixing enhancement of liquid metal MHD free-surface flow by optimizing vortex generator arrays", Fusion Engineering and Design. DOI: 10.1016/j.fusengdes.2018.01.067 (2018)

Kusumi, K. (visiting graduate student), Kunugi, T., Yokomine, T., Kawara, Z., Kolemen, E., Ji, H., Gilson, E.P., "Study on thermal mixing of MHD liquid metal free-surface film flow", Fusion Science and Technology, Vol. 72, Issue 4, Pages 796-800 (2017)

"*Application of IR imaging for free-surface velocity measurement in liquid-metal systems",* M. G. Hvasta, E. Kolemen, A. Fisher, Review of Scientific Instruments, 88, 013501, (Jan 5 2017)

"*Experimental calibration procedures for rotating Lorentz-force flowmeters*", M. Hvasta, Slighton, E. Kolemen and A. E. Fisher, Measurement Science and Technology, Volume 28, Number 8, (July 14, 2017).

"*Study on thermal mixing of MHD liquid metal free-surface film flow*", Kusumi, K. (visiting graduate student), Kunugi, T., Yokomine, T., Kawara, Z., Kolemen, E., Ji, H., Gilson, E.P., Fusion Science and Technology, Volume 72, Issue 4, (August 2, 2017).

"*Demonstrating electromagnetic control of free- surface, liquid-metal flows relevant to fusion reactors*", M. Hvasta, E. Kolemen, A. Fisher, and H. Ji, Nucl. Fusion 58 016022, (November 13, 2017).

"*Electromagnetic control of heat transport within a rectangular channel filled with flowing liquid metal*", M. Modestov, E. Kolemen, A.E. Fisher and M.G. Hvasta, Nucl. Fusion 58 016009, (November 13, 2017).

"*Calibrationless rotating Lorentz-force flowmeters for low flow rate applications*", M. G. Hvasta, D. Dudt, A. E. Fisher and E. Kolemen, Measurement Science and Technology, Volume 29, (May 29, 2018).

"*Experimental demonstration of hydraulic jump control in liquid metal channel flow using Lorentz force",* A. E. Fisher, E. Kolemen, M. G. Hvasta, Physics of Fluids, 30, 067104 (June 27, 2018).

Development of Magnetic Enhancement Coils for a Fast Time Response Electromagnetic Disruption Mitigation System

Journal Publications

Modelling of Ablatant Deposition from Electromagnetically Driven Radiative Pellets for Disruption Mitigation Studies, Robert Lunsford1, et al., Fusion Science and Technology, Published online July 15 2019

Workshops, Conferences and Presentations

"Electromagnetic Particle Injector (EPI) as a Fast Time Response Disruption Mitigation Concept" by R. Raman et al., Poster presented at 2018 IAEA Fusion Energy Conference 22-27 October 2018, Gandinghar India

"Rapid Radiative Disrution Mitigation Through Electromagnetically Driven Killer Pellet Injection" by R. Lunsford et al., Poster presented at 2018 Technology of Fusion Energy Conference", 11-15 November 2018 Orlando Florida.

Mapping of magnetic field lines in the earth's magnetosphere using electron beam

Journal Publications

"Relativistic Particle Beams as a Resource to Solve Outstanding Problems in Space Physics" Ennio R. Sanchez Andrew T. Powis Igor D. Kaganovich Robert Marshall Peter Porazik Jay Johnson Michael Greklek-McKeon Kailas S. Amin David Shaw Michael Nicolls, Frontiers in Astronomy and Space Sciences, Published on 27 Nov 2019
https://doi.org/10.3389/fspas.2019.00071

"Evolution of a Relativistic Electron Beam for Tracing Magnetospheric Field Lines"
Andrew T. Powis Peter Porazik Michael Greklek-McKeon Kailas Amin David Shaw Igor D. Kaganovich Jay Johnson Ennio Sanchez, Frontiers in Astronomy and Space Sciences, Published on 14 Nov 2019

"Effect of Field-Line Curvature on the Ionospheric Accessibility of Relativistic Electron Beam Experiments"
Jake M. Willard Jay R. Johnson Jesse M. Snelling Andrew T. Powis Igor D. Kaganovich Ennio R. Sanchez
Frontiers in Astronomy and Space Sciences

Sierra Jubin, Andrew Powis, Daniel Baver, Igor Kaganovich, "Instabilities of a relativistic electron beam in the Earth's magnetosphere", 61st Annual Meeting of the APS Division of Plasma Physics, Volume 64, Number 11, October 21–25, 2019; Fort Lauderdale, Florida,
http://absimage.aps.org/image/DPP19/MWS_DPP19-2019-001309.pdf

Scoping of Facilities in Support of Long-Term PPPL Initiatives

Journal Publications

Hutch Neilson, et al., "National Fusion Design Initiative, v2.0," white paper submitted to the APS-DPP Community Planning Process, Sept. 2019.

Hutch Neilson, et al., "Abridged Pilot Plant Design Initiative," white paper submitted to the APS-DPP Community Planning Process, Sept. 2019.

Hutch Neilson, et al., "National Design Initiative," presentation at the APS-DPP Community Planning Workshop, 22-26 July 2019, Madison, WI.

Jon Menard, et al., "Development of Mission Need and Preliminary Design of a Sustained High Power Density Tokamak Facility," white paper submitted to the APS-DPP Community Planning Process, July 2019.

Jon Menard, et al., "Development of Mission Need and Preliminary Design of a Sustained High Power Density Tokamak Facility," presentation at the APS-DPP Community Planning Workshop, 22-26 July 2019, Madison, WI.

Tom Brown, "Accomplishments of Innovative Tokamak study carried out under the LDRD 7000-R086 account in 2019," report, September 2019.

Peter Dugan, et al., "Using A Virtual Engineering Environment for the Design and Development of a Pilot Plant," white paper, January 2020.

Workshops, Conferences, and Presentations

Peter Dugan, et al., "System Development Using Virtual Engineering in a Multi-Discipline Physics and Engineering Environment," presentation at PPPL Research Meeting, 21 January 2020.

Andrei Khodak, et al., "Liquid Metal Modeling for Plasma Facing Components," presentation at the Third IAEA Technical Meeting on Divertor Concepts, held 4-7 November 2019, Vienna, Austria.