Abstracts

16th US-Japan Workshop on Fusion Neutron Sources for Nuclear Assay and Alternate Applications

30 September - 2 October 2014
Madison, Wisconsin

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

Agenda: 2014 US-Japan Workshop at UW-Madison

Tuesday, September 30, 2014 (Union South, 328 A&B Industry Room)			
7:00-9:00 PM	*Registration & Reception*		
Wednesday, October 1, 2014 (Union South, 328 A&B Industry Room)			
7:30 AM	*Registration & Continental Breakfast*		
8:00 AM	*Opening of Workshop (Jerry Kulcinski)*		
Session 1 (Keynote) Jerry Kulcinski, Chair			
8:10 AM	Jaeyoung Park	EMC2	Polywell - A Path to Electrostatic Fusion
Session 2: Joe Khachan, Chair			
8:50 AM	Kai Masuda	Kyoto University	Active Interrogation of Special Nuclear Materials by Use of IEC Fusion Neutron Generator
9:15 AM	Jerry Kulcinski	University of Wisconsin	Experimental and Theoretical Program Highlights from the University of Wisconsin IEC Program
9:40 AM	George Miley	University of Illinois	Comments About Varied IEC Approaches to Fusion Power
10:05 AM	Joe Khachan	University of Sydney	Progress in inertial electrostatic confinement at the University of Sydney
10:30-10:55 AM	*Posters / Break (Union South, 318 A&B Agriculture Room)*		
Session 3: Kai Masuda, Chair			
10:55 AM	Masami Ohnishi	Kansai University	D-T Burning in IECF
11:20 AM	Ross Radel	Phoenix Nuclear Labs	Recent Progress at Phoenix Nuclear Labs
11:45 AM	Greg Piefer	SHINE	An Innovative Neutron Source and Low-Enrichment Uranium System for the Production of Mo-99
12:10 PM	Yasushi Yamamoto	Kansai University	Prepare for the D-T Burning in IECF – relocation, remote operation, and tritium handling
12:35-1:45 PM	*Lunch (Union South, 318 A&B Agriculture Room)*		
Session 4: George Miley, Chair			
1:45 PM	John Santarius	University of Wisconsin	Polywell Physics Modeling Considerations
2:05 PM	Devlin Baker	Convergent Scientific	Rapid Parametric Study of Polywell Devices
2:25 PM	Dan Barnes	Coronado Consulting	Penning traps as neutron sources
2:45 PM	Gil Emmert	University of Wisconsin	On Including Electron Effects in VICTER
3:05-3:30 PM	*Posters / Break (Union South, 318 A&B Agriculture Room)*		
Session 5: Masami Ohnishi, Chair			
3:30 PM	Hodaka Osawa	Kansai University	The parallel running of multiple IECF devices
3:50 PM	Gabriel Becerra	Phoenix Nuclear Labs	Neutral-particle analysis in IEC devices
4:10 PM	Hiroshi Horibe	Kurita Manufacturing	Transfer IEC Equipment
4:30 PM	Rich Bonomo	University of Wisconsin	Preparing for 300 kV DC Operation – System Stability Studies and Component Selection
4:50 PM	*Adjourn*		
6:00 PM	*Reception (Wisconsin Institutes for Discovery)*		
6:45 PM	*Banquet (Wisconsin Institutes for Discovery, Steenbock's on Orchard formal dining room)*		
8:00 PM	*Bob Hirsch, Banquet Speaker*		

Thursday, October 2 2014 (Union South, 328 A&B Industry Room, except Wisconsin Institutes for Discovery for reception and dinner)			
7:30 AM	*Continental Breakfast*		
8:00 AM	*Announcements (Jerry Kulcinski)*		
	Session 6: Jaeyoung Park, Chair		
8:10 AM	John Hedditch	University of Sydney	IEC simulation via a Relativistic Particle Code
8:30 AM	Drew Chap	University of Maryland	Simulations for Multi-grid Inertial Electrostatic Confinement
8:50 AM	Kazuki Nanjo	Tokyo Institute of Technology	Characterization of the discharge plasma in Cylindrical Inertial Electrostatic Confinement Fusion device
9:10 AM	George Chen	University of Illinois	Plasma Flow from the Helicon into the IEC
9:30 AM	Matt Michalak	University of Wisconsin	Expanding the D-D Voltage and Current Operating Space between 0.1 to 1 mTorr in the UW IEC Device HOMER
9:50-10:30 AM	*Group Photo / Posters / Break (Union South, 318 A&B Agriculture Room)*		
	Session 7: Eiki Hotta, Chair		
10:30 AM	Rehan Bandara	University of Sydney	Nonlinear saturation of the ion-electron Buneman instability in a spherical positively pulsed gridded IEC device
10:50 AM	Ryota Nakamatsu	Kyoto University	Study on the Delay Time of Current Rise in Pulsed Glow-Discharge-Driven IEC
11:10 AM	Andrew Seltzman	University of Wisconsin	Measurement of Ion Bombardment Heat Load Distributions on the Central Grid of an IEC Fusion Device
11:30 AM	Aaron Fancher	University of Wisconsin	Design and Testing of a High Voltage Feedthrough for Extending IEC Operations to 300 Kilovolts
11:50 AM-1:00 PM	*Lunch (Union South, 318 A&B Agriculture Room)*		
	Session 8: Gil Emmert, Chair		
1:00-1:45 PM	*Awards, Workshop Summary & Closing Remarks*		Joe Khachan, *Workshop Summary*
1:45-2:45 PM	*UW IEC Lab tour*		
3:00 PM	*Bus to SHINE & PNL*		
3:30-4:30 PM	*SHINE Medical Technologies & Phoenix Nuclear Labs tour*		
4:45 PM	*Bus to Union South*		
POSTERS: Wednesday & Thursday, October 1-2, 2014 (Union South)			
1	Drew Ahern	University of Illinois	Experimental Advances and Next Steps in the Helicon Injected Inertial Plasma Electrostatic Rocket (HIIPER)
2	Hiroki Konda	Kansai University	Gas supply/exhausting system with getter pump for D-T Burning in IECF
3	Kenji Miyamoto	Kansai University	Decontamination of Tritium from exhaust gas of IECF device
4	Marcos Navarro	University of Wisconsin	D-D Neutron Production Optimization in a Linear IEC Device
5	Jeff Kollasch	University of Wisconsin	Simulation of enhanced fast electron confinement in multi-cusp geometry due to flux exclusion
6	Benjamin Bercovici	University of Illinois	Experimental and Numerical Validation of Ion Extractor Grids
7	Yosuke Kawahira	Kansai University	Discharge characteristics of multiple IEC device
8	Karla Hall	University of Wisconsin	Effects of Multiple Energy 4He+ Bombardment on Cathode Materials Such As W at High Temperatures
9	Matt Jasica	University of Wisconsin	Investigations of Helium Ion Damage to IEC Cathode Materials at the University of Wisconsin
10	Aaron Olson	University of Wisconsin	Design of a Heat Exchanger for the Extraction of Lunar Solar Wind Volatiles
11	Dan Knapp	Medical University of South Carolina	Finite Element Method Simulation Studies of a Prototype Planar Geometry IEC Fusion Device

Alphabetical Order				
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Talks

Rapid Parametric Study of Polywell Devices

Devlin Baker

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A particle-in-cell (PIC) plasma simulation code optimized for deployment on general purpose GPUs has been developed which uses a dynamic particle list sort to accelerate parallel particle-to-grid operations. The sorted particle approach lends itself to extremely fast particle-geometry intersection, making possible the modeling of particle interactions with complex geometry. This is particularly attractive for study of Polywell devices due to the suspected dominance of electron losses to internal surfaces in considerations of device power balance [1]. A client-server-node system utilizing Amazon Elastic Compute Cloud (EC2) was developed to allow hundreds or thousands of instances of the simulation code to be run concurrently within the EC2 framework. Using this system, a simultaneous study of virtual cathode formation by electron injection into Polywell type magnetic traps was undertaken wherein a plurality of EC2 nodes each simulated a different set of initial values, and returned their respective results to the client.

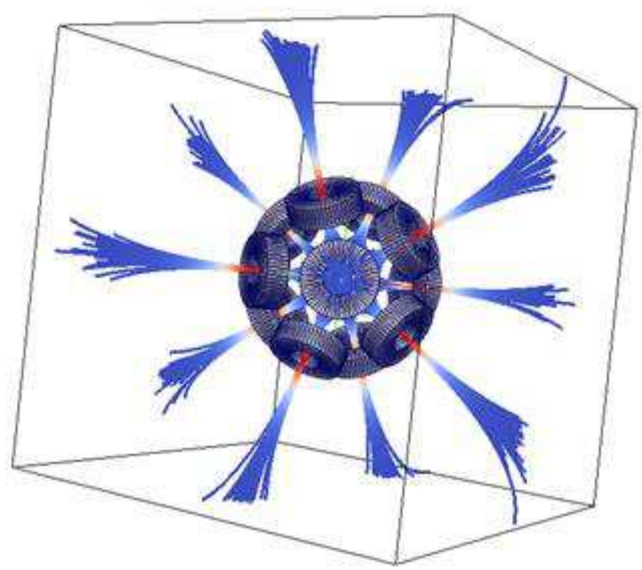

Figure 1. Electron escape trajectories in a dodecahedral Polywell device

Large relative values of traverse electron injection velocity were found to result in comparatively lower loss current for initial virtual cathode formation, though resulting in lower values of resultant virtual cathode potential. A scheme for varying the degree of electron traverse velocity over the duration of startup and operation is suggested based on these observations.

[1] Bussard, Robert W "The Advent of Clean Nuclear Fusion," *57th International Astronautics Congress,* Oct 2-6, 2006.

Nonlinear saturation of the ion-electron Buneman instability in a spherical positively pulsed gridded IEC device

Rehan Bandara and Joe Khachan

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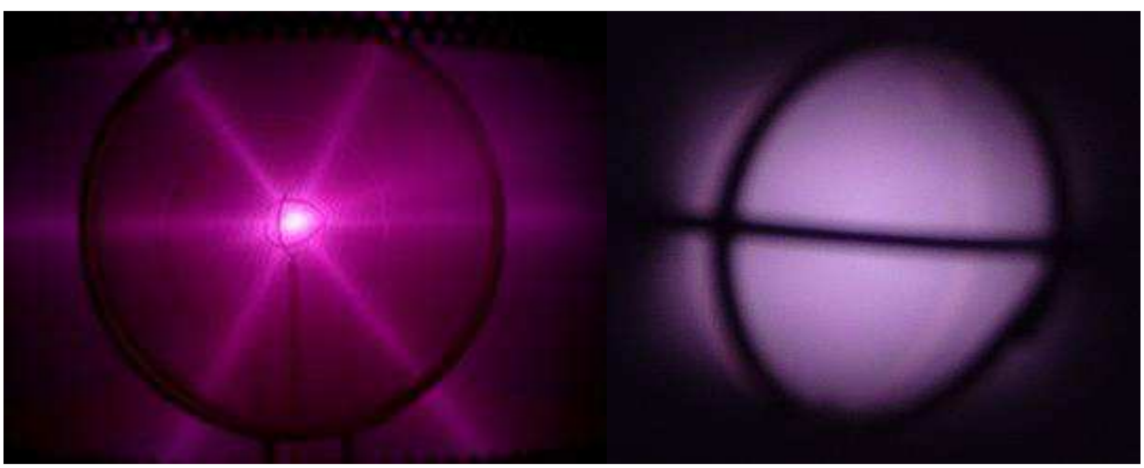
A pulsed, positive polarity gridded inertial electrostatic confinement device has been investigated experimentally, using Doppler broadened spectra and current and voltage traces as primary diagnostics. In the high current and energy regime explored in this paper, large amplitude oscillations in the plasma current and potential were observed within 100ns of the discharge onset. These oscillations are a result of a modulation of the plasma resistivity between the lower Spitzer resistivity and higher Buneman anomalous resistivity resulting from the Buneman instability. Removal of the series ballast resistance from the external biasing circuit drove the oscillations into a nonlinear and saturated Buneman regime, characterised by a locked oscillation frequency as a function of increasing anode potential. The saturated Buneman instability is known to exhibit ion mass independent behavior and cause electron trapping, resulting in a transient spatio-temporal virtual cathode and ponderomotive ion confinement, as evidenced by Doppler broadened spectra when operated at large peak anode potentials.



A comparison between a conventional negatively biased gridded discharge and a positively pulsed discharge.

Penning traps as neutron sources

D. C. Barnes
Coronado Consulting

A harmonic Penning trap may be tuned to produce a spherical well for a single species. Under appropriate boundary conditions of injection and collection, a spherical focus can be produced in such a well. We review the theory and practice of such operation, as described in past literature.[1] In these experiments, electrons were focused to at least 30 times the Brillouin limit in a 3 mm spherical trap at applied voltages up to 30 kV. The over-dense central focus of electrons forms a virtual cathode which can be used to trap hydrogenic ions (D-T) with thermonuclear temperatures, producing a bright source of 14 MeV neutrons. The theoretical efficiency of such a system can approach or even exceed unity, leading to a very small, intense, portable source of fast neutrons.

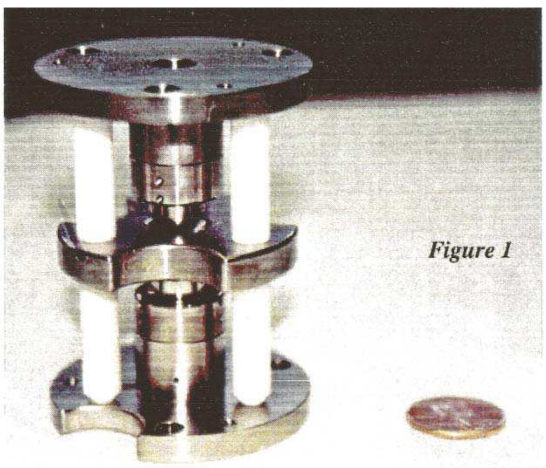


Figure 1

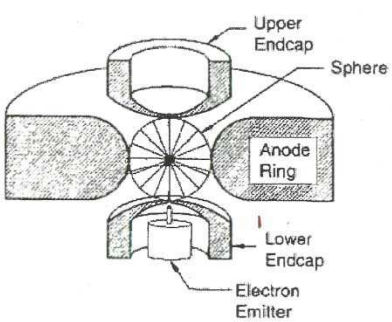


Figure 2

A simple model is developed to describe the non-thermal electron focus. It is shown that under appropriate conditions, a beam-like electron distribution is maintained and that this state is stable to beam-beam modes. The effect of background neutrals is also modeled and conditions for maintaining a high ion temperature within the cathode are derived.

We discuss required conditions and challenges for this approach as a neutron source. It is necessary to sustain large electric fields to maximize the central density. It is also necessary to maintain a rather high vacuum while simultaneously fueling the central cathode with fuel ions. Some potential solutions to problems associated with these challenges are discussed.

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[1] T. B. Mitchell, M. M. Schauer, and D. C. Barnes, *Phys. Rev. Lett.* **78**, 58 (1997); D. C. Barnes, T. B. Mitchell, and M. M. Schauer, *Phys. Plasmas* **4**, 1745 (1997).

Neutral-particle analysis in IEC devices†

Gabriel E. Becerra, Gerald L. Kulcinski, John F. Santarius, Gilbert A. Emmert*

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Direct analysis of escaping fast neutral particles has been performed on inertial electrostatic confinement (IEC) fusion devices for the first time. A new diagnostic setup uses a 10 nm carbon foil as a stripping target for incident neutral particles and cylindrical electrodes with a variable relative voltage for deflecting ions of a specific energy per unit charge into a continuous electron multiplier. The system can be used to study neutral particles with kinetic energies between ~5 and 170 keV, with a measured energy resolution of 2-4% between 5 and 30 keV.

Initial neutral-particle analysis experiments have been performed at cathode voltages up to 60 kV for the HELIOS and HOMER devices in the glow discharge, external-ion-source and filament-assisted source plasma configurations, with both helium-4 and deuterium gas. For experiments with helium-4, with relevance to operation with helium-3, the neutral-particle analyzer yields energy distributions of escaping fast neutral particles produced by atomic and molecular processes between energetic ions and background gas, as well as the line-of-sight-averaged energy distributions of fast ions.

Comparisons between experimentally determined energy distributions and predictions by the VICTER and HeVICTER integral-transport numerical codes on spherically convergent ion flow show that the codes do not capture many details of the relevant physics. For helium-4 experiments in the external-ion-source mode, the energy distributions were confirmed to be significantly harder at 0.2 mTorr than at 5 mTorr, which is essential for the prospects of the configuration for increasing ^{3}He-^{3}He fusion rates.

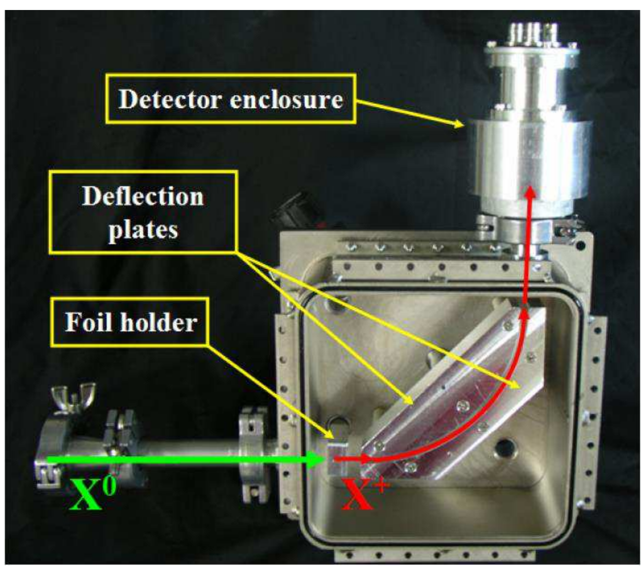

Figure 1. UW-IEC neutral-particle analyzer.

† Research supported by the Greatbatch Foundation and the Grainger Foundation.

UW IEC Group 2014: Preparing for 300 kV DC Operation – System Stability Studies and Component Selection†

Richard Bonomo[1], Gabriel Becerra[2], Gil Emmert[1], Aaron Fancher[1], Lauren Garrison[3], Karla Hall[1], Matthew Jasica[1], Kevin Johnson[1], Gerald Kulcinski[1], Aaron McEvoy[4], Matthew Michalak[1], John Santarius[1], and Craig Schuff[1]*

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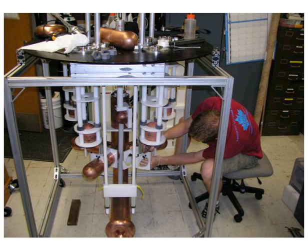
Efforts to upgrade UW IEC Laboratory systems to allow eventual operation at up to 300 kV DC have been slowed by surprising behavior which was reported in previous workshops [1] and by interruptions caused by a very welcome expansion of the space which the facility occupies [2].

Efforts to understand and mitigate system instabilities observed when the high voltage power supply (HVPS) is connected to an IEC device via a switch constructed to allow cold-switching of the HVPS to the various IEC and materials irradiation devices in the laboratory, have resumed.

In the hopes of allowing full and presumably lengthy analysis of the switch itself "offline," that is, without impeding execution of experiments while analysis is in progress, a temporary high-voltage simple resistor array was constructed and placed in the enclosure designed for the 300 kV DC switching apparatus, in place of the switch.

High-potential testing (in vacuum) and testing with plasma demonstrates that though the system with the new temporary resistor array can achieve higher voltages (in the vicinity of 85 kV) stably under high-potential testing than when the switch is in-line, it is not as stable as when the "classic" resistor barrel is in line, with which stable testing well in excess of 100 kV is achieved.

Previous attempts to stabilize the system, with the switch in-line, after system modeling suggested that the cause was likely the increased parasitic capacitance in the system, had failed. Further studies are in progress with varying resistor configurations and placements in an attempt to determine why the system is stable with the "classic" resistor barrel in line, but not stable with either the switch, or the temporary high voltage resistor.



HV Switch (in construction rack)

Temporary HV Resistor Array

[1] US-Japan IEC Workshop 2012, Univ. of Maryland, Collegeville, Maryland, USA: # S5P3
[2] US-Japan IEC Workshop 2013, Kyoto University, Uji, Kyoto, Japan: *Bonomo et al.*

† Research supported by the Grainger and Greatbatch Foundations

Simulations for Multi-grid Inertial Electrostatic Confinement†

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Multi-grid IEC is a method devised to increase the confinement time of ions with the additional positively charged electrostatic grids to focus ion beam paths and limit thermalization [1]. Research at the University of Maryland is also investigating the use of radially magnetized grids to confine electrons to neutralize the IEC core and beam paths.

A hybrid particle-in-cell (PIC) simulation is in development that treats ions using standard PIC methods and models electrons as a fluid [2]. The results from this method on a test problem are shown in Figure 1. In this 2D test problem, electrons are created in the center of the domain and confined by the magnetic fields created by six current-carrying wires. The steady-state for the electrons at each time-step is described by a nonlinear system of equations, the solution of which is found by iterating the Jacobian of the system, solving the electron fluid equation and Poisson's equation simultaneously [3].

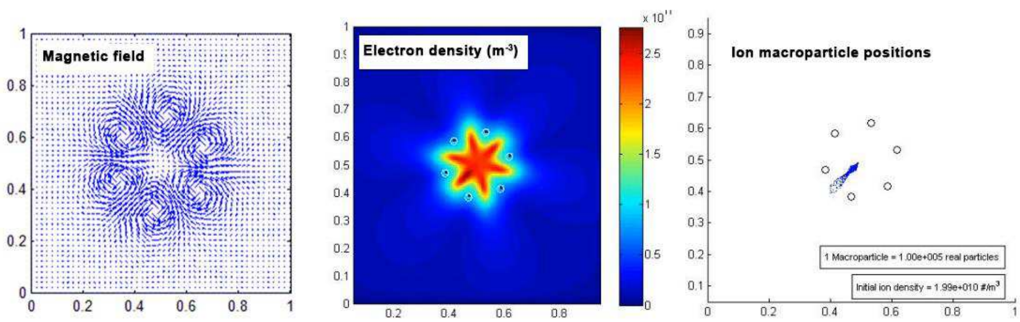

Figure 1. Hybrid particle-in-cell simulation.

A second model, a particle-particle discrete-event simulation, has been developed to overcome the computational limitations inherent in field-solving over a large 3D simulation domain and to provide another view of the physics of the multi-grid IEC. This method calculates inter-particle forces directly, so that the electric field over the domain does not have to be calculated at each time-step, providing fast calculation for low density, large domain simulation.

[1] Carl Dietrich, Raymond Sedwick, and Leslie Eurice, "Experimental Verification of Enhanced Confinement in a Multi-Grid IEC Device," *44th Joint Propulsion Conference*, (2008)

[2] G J M Hagelaar, "Modelling electron transport in magnetized low-temperature discharge plasmas," *Plasma Sources Science and Technology* ***16***, S57 (2007)

[3] Andor, Baltes, Nathan, and Schmidt-Weinmar, "Numerical modeling of magnetic-field-sensitive semiconductor devices," *Electron Devices, IEEE Transactions on* ***32***, 1224

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† Research supported by a NASA Space Technology Research Fellowship grant #NNX13AL44H and the University of Maryland

Plasma Flow from the Helicon into the IEC[†]

George Chen, Benjamin A. Ulmen, George H. Miley

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The plasma flow from a high density helicon source to a lower density direct current inertial electrostatic confinement (IEC) device is investigated. Theoretically coupling a high density source such as a helicon to an IEC is beneficial because the high density plasma from the helicon should flow into the IEC. This physical model stems from the fact that the inner IEC electrode grid is often biased negative with respect to ground potential. So the positively charged ions are attracted to the inner negatively biased IEC grid. However this theoretical picture neglects some crucial plasma physics. One of the basic physics the aforementioned physical description neglects is Debye shielding. Plasmas are conductors; the charged species within the plasma move to attenuate large applied electric fields. In this case the electric field generated by the large negative bias applied to the IEC grid electrode has a minimal effect on the motion of the ions "far" away from the IEC grid. The distance from the negatively biased IEC grid in which the large applied electric field has a minimal effect is related to the sheath thickness. This is because most of the voltage drop occurs in the sheath. Due to some fundamental plasma physics, the injection of ions into a low density plasma is not as trivial as it may first appear.

The analysis of helicon plasma injection into the IEC begins first with the energy balance of the helicon. Analysis of the helicon plasma source reveals that most of the energy lost in the helicon is due to electron collisions with the dielectric wall. To tackle this problem, the geometry of the dielectric tube of the helicon should minimize wall surface area, without decreasing the volume of the plasma. By minimizing the surface area of the wall, fewer electrons are lost due to collisions with the dielectric wall. Since most helicons are cylindrical in geometry, a natural idea is to minimize cylinder height and increase cylinder radius. This also has added benefit in that the cross-sectional area with which the plasma flows is greater. Further analysis should focus on the plasma potentials with respect to position in the region where the helicon and IEC are joined.

[†] Research supported by NPL Associates, Air Force Research Laboratory, and NASA

On Including Electron Effects in VICTER†

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The VICTER (Volterra Integral Code for Transport in Electrostatic Reactors) [1, 2] has been under development for several years. The present release version models the transport of energetic deuterium ions (D^+, D_2^+, D_3^+, and D^-), atoms, and neutral molecules. (A separate version for helium plasmas has also been developed.) It focuses on the interaction of the energetic ions and neutral particles with the background D_2 gas and solves kinetic equations for the energy spectra of the fast ions and neutral particles. The code calculates steady-state solutions in one-dimensional slab, cylindrical, and spherical geometry, where the ion and neutral energy spectra are calculated as functions of the "radius" and kinetic energy.

Present code development work focuses on the spatial- and energy-dependent electron energy spectra. A kinetic equation for the electrons has been formulated wherein the electron sources are ion-induced secondary electron emission at the cathode, and ion and electron impact ionization of the background gas in the intergrid region. This kinetic equation is solved self-consistent with the ion transport kinetic equations described above. This work is in progress. Results will be presented for different geometries, background gas pressure, and applied electrostatic potential.

[1] G.A. Emmert and J.F. Santarius, "Atomic and molecular effects on spherically convergent ion flow: I. Single atomic species", Physics of Plasmas **17**, 013502 (2010).

[2] G.A. Emmert and J.F. Santarius, "Atomic and molecular effects on spherically convergent ion flow: II. Multiple molecular species", Physics of Plasmas **17**, 013503 (2010).

† Research supported by the Greatbatch Foundation and the Grainger Foundation.

Design and Testing of a High Voltage Feedthrough for Extending IEC Operations to 300 Kilovolts†

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Progress in advancing the University of Wisconsin Inertial Electrostatic Confinement laboratory to 300 kV operation has been well underway with the testing of a new high voltage feedthrough and stalk design. Upgrading the high voltage feedthrough has been a part of a campaign to equip the HOMER and HELIOS IEC devices to operate at a full power supply capability of 300 kV and 200 mA. The new feedthrough possesses better voltage standoff capabilities and reduced field strength from the previous design [1]. Features of the new feedthrough are presented in contrast to the old design, and results from testing are discussed.

Additionally, an investigation into the manufacturing of IEC HV stalks using borosilicate glass was conducted in brief. Stalk construction using glass is advantageous over boron nitride in ease of manufacturing in addition to being an order of magnitude less in cost. Four iterations of glass feedthrough stalk designs were tested to failure. Glass stalk manufacturing and refinements are briefly presented. Further glass stalk testing has been shelved while other laboratory upgrades are being pursued.

[1] G. E. Becerra, "Analysis of Fast Neutral Particles in Inertial Electrostatic Confinement Fusion Devices" Ph.D. dissertation, Engr. Phys. Dept., Univ. Wisconsin, Madison, WI, 2014

† Research supported by Greatbatch Foundation

IEC simulation via a Relativistic Particle Code

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IEC devices can operate in regimes where the common simplifications to the plasma evolution equations are inappropriate. In particular, in an anisotropic, collisional, charged, non-LTE plasma such as that expected to be found in a Polywell™[1], it is far from clear that even sophisticated Fokker-Planck calculations reflect the relevant physics.

Beginning with Jefimenko's equations[2], we construct a first-principles many-body solver for relativistic charged particles moving under self- and applied EM fields. We present both validation tests and preliminary results of application of the code to exploring electron confinement in a Polywell™.

[1] Krall, Nicholas A. "The Polywell™: A Spherically Convergent Ion Focus Concept." **Fusion Technology** 22, no. 1 (1992): 42-49.

[2] Jackson, John David. "Classical electrodynamics". Vol. 3. New York etc.: Wiley, 1962.

Transfer IEC Equipment †

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IEC equipment in Kansai University was moved to Osaka University. Its aim is to operate using Tritium gas. It was a big job. My aim was electric connection and wiring between power supply IEC chamber and distribution panel.

Not only connecting each component but also improved some of wiring when it have moved to new place.

I talk detail about this how's going this transfer. And some improvement. Ground Bar, High voltage cable support, Corona ring, adding current limit resister and so on.

…

Progress in Inertial Electrostatic Confinement at the University of Sydney

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Work on the Polywell has been in progress, at Sydney University, since 2010. All the work to-date has been focused on the physics of low beta operation since this will at least be a subset of a Polywell operating in high beta mode. We have shown the formation of electrostatic potential wells [1], the geometry of the flux surfaces with analytical equations for the magnetic fields, and corresponding electron loss rate [2]. The electron energy distribution function has been shown to be non-Maxwellian with a small thermalized component superimposed onto a monoenergetic peak [3]. The scaling laws that related electron confinement time with Polywell size and coil currents have been obtained [4].

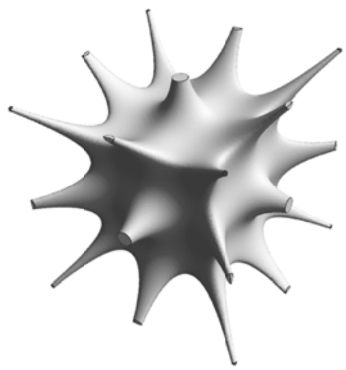

Figure 1. Magnetic flux surface of a Polywell [2] showing point cups when the magnetic field coils touch.

Work has also continued on a pulsed reverse polarity gridded IEC [5] where the aim is to create a virtual cathode from electrostatic confinement of electrons to produce ion acceleration, confinement and fusion. We have identified that oscillations of the electron and ions are related to a Buneman instability that imparts energy to the ions, which we have measured using Doppler shift spectroscopy.

[1] M. Carr and J. Khachan, "The dependence of the virtual cathode in a Polywell™ on the coil current and background gas pressure," *Physics of Plasmas* ***17***, 052510 (2010).
[2] M. Carr, D. Gummersall, S. Cornish, and J.Khachan, "Low beta confinement in a Polywell modelled with conventional point cusp theories" *Physics of Plasmas* ***18***, 12011 (2011).
[3] M. Carr and J. Khachan, "A biased probe analysis of potential well formation in an electron only, low beta Polywell magnetic field," *Physics of Plasmas* ***20***, 052504 (2013).
[4] D. V. Gummersall, M. Carr, S. Cornish, and J. Khachan. "Scaling law of electron confinement in a zero beta polywell device," ***20***, 102701 (2013).
[5] R. Bandara and J. Khachan, "Spherical ion oscillations in a positive polarity gridded inertial-electrostatic confinement device," *Physics of Plasmas* ***20***, 072705 (2013)

Experimental and Theoretical Program Highlights from the University of Wisconsin IEC Program†

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There are 8 main themes of the University of Wisconsin (UW) Inertial Electrostatic Confinement (IEC) program:

1) Theoretical analysis of gridded IEC devices.
2) Experimental physics investigations of IEC plasmas.
3) Near term applications of IEC technology for the detection of clandestine materials.
4) The use of IEC devices for materials surface damage studies.
5) The procurement of ^{3}He from the lunar surface.
6) The study of advanced fusion fuels based on the ^{3}He cycle.
7) Production of PET radioisotopes in IEC devices.
8) Demonstration of IEC as a future fusion power source.

In the Academic Year 2014, significant progress has been made in items 1-5. This overview will set the stage for 9 more detailed papers and posters to follow in this workshop.

† Research supported by the Grainger Foundation and the Greatbatch Foundation

Active Interrogation of Special Nuclear Materials by use of Inertial Electrostatic Confinement Fusion Neutron Generator†

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Since 2010, we have developed an active non-destructive detection system for inspecting special nuclear materials (SNMs) such as ^{235}U in containers at sea ports [1]. This consists of a primary neutron-based interrogation for a rapid screening purpose and a secondary gamma-ray-based stage for isotope identification via nuclear resonance fluorescence method using a quasi-monochromatic gamma-ray beam from laser Compton scattering.

As the primary neutron-based system (see Fig. 1) is required to handle hundreds of sea containers per day, two advanced neutron-in neutron-out techniques are being developed, namely delayed neutron noise analysis (DNNA) [1] and threshold energy neutron analysis (TENA) [2]. Pulsing of the IEC-GD neutron generator is mandatory for the former DNNA method. Another requirement for the neutron generator is as high averaged D-D neutron yield as 10^8 neutrons/sec.

The project outline and the recent results from R&D of the two neutron-in neutron-out techniques as well as the pulsed D-D IEC neutron generator will be presented.

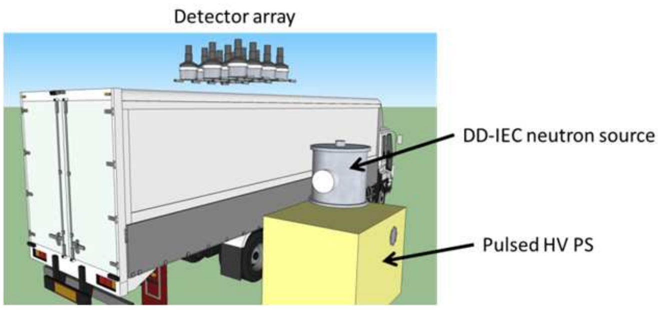

Figure 1. Layout of DD-IEC neutron source and detector array for the active interrogation of SNMs in a sea container.

[1] H. Ohgaki et al., "Non-Destructive Inspection System for Special Nuclear Material using Inertial Electrostatic Confinement Fusion Neutrons and Laser Compton Scattering Gamma-rays", Proc. IEEE Int'l Conf. Technologies for Homeland Security, Waltham, MA, USA, 2012.

[2] Y. Takahashi et al., "Development of Active Neutron-based Interrogation System with D-D Neutron Source for Detection of Special Nuclear Materials", Proc. Nuclear Physics and Gamma-ray sources for Nuclear Security and Nonproliferation, Tokai, Ibaraki, Japan, 2014.

† Research supported by R&D Program for Implementation of Anti-Crime and Anti-Terrorism Technologies for a Safe and Secure Society promoted by Japan Science and Technology Agency

Expanding the D-D Voltage and Current Operating Space between 0.1 to 1 mTorr in the UW IEC Device HOMER [†]

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The University of Wisconsin – Madison Inertial Electrostatic Confinement (UWIEC) Fusion laboratory previously achieved a neutron production record of $2x10^8$ n/s [1]. This record was set in 2006 at cathode electrical settings of 165 kV, 68 mA, and 3 mTorr. The UWIEC laboratory now has a 300 kV, 200 mA power supply, and the lab has been configured to function at higher voltage and higher current.

The focus of recent studies has been to operate at pressures between 0.12 mTorr to 1.3 mTorr (0.016 Pa to 0.17 Pa). A new high voltage feed-through was implemented and has been tested up to a cathode voltage of 165 kV at 30 mA. A meter current of 100 mA has been achieved at 100 kV. Recent results will be compared to higher pressure operation.

[1] R. F. Radel, "Detection of Highly Enriched Uranium and Tungsten Surface Damage Studies Using a Pulsed Inertial Electrostatic Confinement Fusion Device" Ph.D. dissertation, Engr. Phys. Dept., Univ. Wisconsin, Madison, WI, 2007

† Research supported by Greatbatch Foundation

Comments About Varied IEC Approaches to Fusion Power

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IEC Fusin concepts can be broadly categorized as either ion injected or electron injected. Current gridded IEC neutron sources are typically ion injected while Polywell-type concepts use electron injection with magnetic assistance. There are advantages/disadvantages to both, the primary objective being to create a potential well trap with sufficient depth and volume to confine high energy ions at reasonable density and with a good confinement time consistent with the Lawson criterion. In this presentation various IEC concepts intended to achieve these goals will be discussed. The coverage will largely come from Reference [1].

References

[1]. G. H. Miley and S.K. Murali, Inertial Electrostatic Confinement (IEC) Fusion, Springer Press, N. Y. 2014

Study on the Delay Time of Current Rise in Pulsed Glow-Discharge-Driven IEC†

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A pulsed D-D IEC neutron source is being developed for non-destructive detection of special nuclear materials (SNMs) in sea containers. An advanced neutron-in neutron-out method (delay neutron noise analysis; DNNA) is being studied, which requires pulsed flux of probing neutrons.

An issue in pulsing glow-discharge-based IEC is that the rise in electric current tends to delay considerably as shown in Fig. 1. Since the voltage pulse width is limited in the present pulsed power supply, the delay time Δt in Fig. 1 should be shortened to provide required current pulse width of tens μsec. Experimental results show that Δt depends on gas pressure and on applied pulsed voltage. When gas pressure is increased, Δt is shortened, while the pulsed peak current is increased and exceeds the rated current. This study aims to investigate operation of the device with low Δt below the rated current. We discuss effect of the current-limiting resistance in the pulse power supply (see Fig 2), taking into account the experimental dependence of Δt on gas pressure and on applied pulsed voltage.

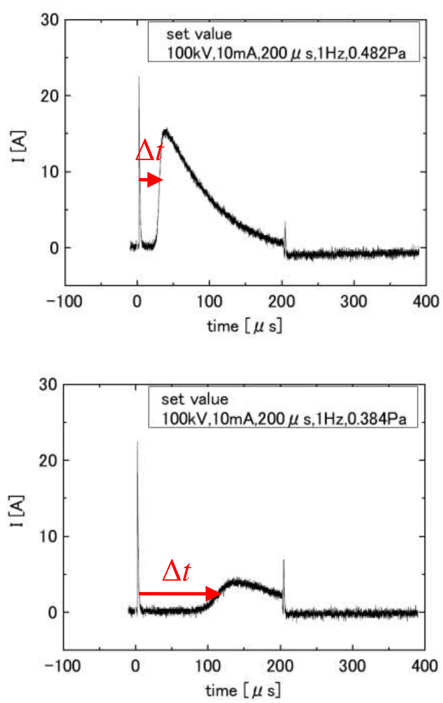

Fig.1. Delay of rise time in pulsed glow discharge current

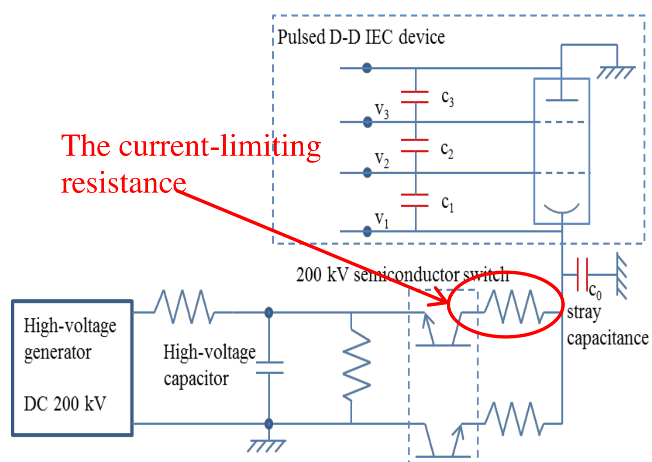

Fig.2. Pulse power supply circuit

† Research supported by R&D Program for Implementation of Anti-Crime and Anti-Terrorism Technologies for a Safe and Secure Society promoted by Japan Science and Technology Agency.

Characterization of the discharge plasma in Cylindrical Inertial Electrostatic Confinement Fusion device

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We developed a Cylindrical IEC device with azimuthal cusp magnetic field [1] [2]. Cusp magnetic field can trap electrons near the anode and they produce ions there. Because the potential is high near the anode and the generated ions may have high energy, thus they can cause nuclear fusion reactions easily. Previous research showed that NPR is 133 % up and predicted that ions are made near anode. We are planning to measure the ion energy obtained in cusp magnetic field configuration by using spectroscopy.

Doppler shift will be used to measure ion energy distribution. Discharge in the chamber generates H^+ et al and the generated ions cause charge exchange reactions such as shown below.

$$\mathrm{H}^+(\mathrm{E}) + \mathrm{H} \rightarrow \mathrm{H}^*(\mathrm{E}) + \mathrm{H}^+$$

The light emitted from excited H undergoes the Doppler shift. The ion velocity which is assumed to be proportional to that of charge exchanged neutral atom, can be obtained from the measured Doppler shift.

The result of spectroscopy will be discussed at the meeting.

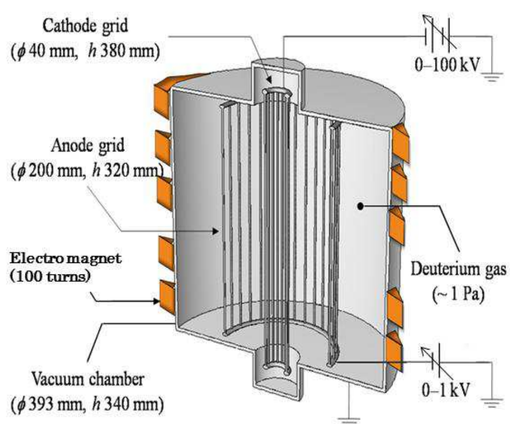

Fig.1 Schematic of cylindrical IEC device with azimuthal cusp magnetic field

This presentation is partially supported by IEEJ International Conference Travel Grant.

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[2] H. Imaji, et al., 14th US-Japan Workshop on IEC (2012)

D-T Burning in IECF

[1]*Masami Ohnishi,* [1]*Yasushi Yamamoto,* [1]*Hodaka Osawa* [1]*Keiji Miyamoto,*
[1]*Masaaki Onishi ,*[1]*Hiroki Konda,*[1]*Takahiro Kato ,*[2]*Kai Masuda,*
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Lots of efforts have been devoted to the increase of the neutron production rate (NPR) in IECF devices. The neutron production rate, 10^7n/s (CW) has been achieved by D-D fusion reactions. The amount of the neutrons is available in the limited area of the application. We can expect the NPR by two hundred times more by using D-T fuels. Then, the application of the neutron by IEC will be broadened in wider fields. The D-T burning project in IECF has been organized by six Universities, and supported by the Ministry of Education, Culture, Sports, Science and Engineering for three years. The IECF device was constructed on December, 2013 and moved in the Subcritical Assembly Laboratory, Osaka University on March 2014 and a preliminary experiment has been made with using deuterium gas. The neutrons in the experiment were produced $7\text{x}10^6$(1/sec) at the discharge of 60 kV and 10mA. The device is intended to work in the completely sealed environment, that is the feed and recover of the gas mixed deuterium and tritium are carried out by the getter pump in which the getter materials are composed of Zr, Va and Fe. The gas pressure is changed 2Pa to 10^{-2}Pa only by controlling the temperature of the getter materials. The tritium of $3.8\text{x}10^9$(Bq) will be used in the preliminary D-T burning experiment. At the end of the D-T burning experiment, the vacuum chamber is cleaned up by a discharge with the hydrogen gas and the exhausted gas is oxidized by CuO and goes through the water bubbler to separate the gas and the liquid such as the release of the gaseous tritium in the air may be less than 70 (Bq/cm^3). The D-T neutron production will be presented at the workshop.
The research is supported by JSPS KAKENHI Grant Number 25289340

The parallel running of multiple IECF devices

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K-PIC(Kansai-particle in cell) code which is designed for studying the discharge of IECF device suggested that the smaller IECF device can be discharge at higher gas pressure and high voltage. The NPR of a small IECF device which radius is 4cm is equal to or greater than original IECF device (r = 15cm) at same current and same voltage. However, the operational current is limited within 5mA by the over heating of ion collide on small cathode.

In this study, two small IECF devices which are two sets of a small anode (4cm radius) and a small cathode are used for enhancing the total NPR at parallel running. Figure 1 shows the discharge photo of two devices placed side by side. The electron through the anode is spread the horizontal direction because of the electric field by feed-though which is placed at vertical direction. The two devices help the glow discharge each other in this arrangement, the discharge characteristics (P-V curve) is shifted to the lower pressure area, the NPR becomes lower. Figure 2 is the discharge photo of two devices placed vertically The electron through the anode mesh is spread horizontal direction, will not affect the discharge of another IECF device. Therefore, two small IECF devices in this arrangement (I=10mA) have same discharge characteristics as single small IECF devices (I=5mA). This NPR is almost twice of single operation of small IECF device.

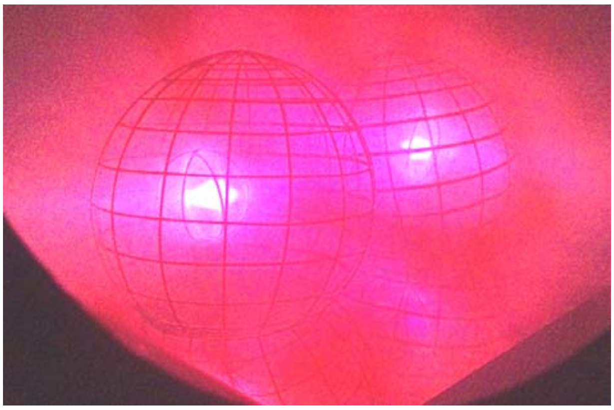

Figure 1. Discharge photo of two small IECF devices placed side by side.

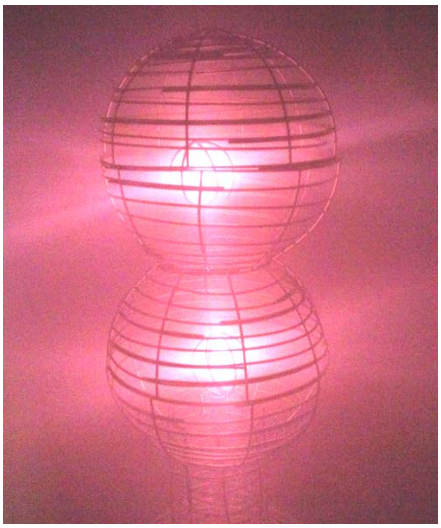

Figure 2.. Discharge photo of two small IECF devices placed vertically

Polywell – A Path to Electrostatic Fusion†

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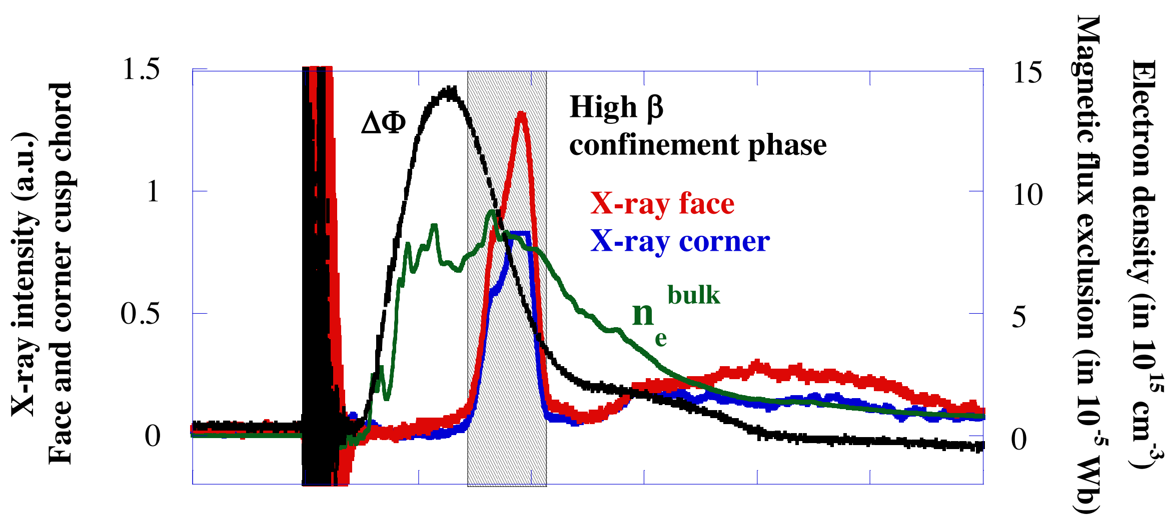
The Polywell fusion concept combines high beta magnetic cusp configuration with electrostatic fusion for a compact and economical nuclear fusion reactor. In this talk, I will describe the basic premise of the Polywell fusion concept and its relevance to electrostatic fusion. In the 1950s, Harold Grad and his team at New York University conjectured (and to some extent calculated) that the plasma confinement properties of a magnetic cusp would be dramatically improved at high plasma pressure. Recent experimental results at EMC2, as shown below, successfully validated this conjecture and open up a path for electrostatic fusion inside a Polywell device. EMC2 is in the process of starting an experimental campaign to demonstrate a stable Polywell equilibrium where high energy electrons are confined by high beta cusp magnetic fields, while fusion relevant high energy ions are confined by an electrostatic potential well formed by magnetically confined excess electrons.



† This work was performed under Contract N68936-09-0125 awarded by the US Department of Defense.

Recent Progress at Phoenix Nuclear Labs

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Phoenix Nuclear Labs (PNL), founded in 2005 by Dr. Gregory Piefer, is an early stage technology design and manufacturing company that has developed a proprietary neutron generator technology. PNL currently operates out of a 14,000 sq. ft. facility located in Monona, WI. PNL scientists and engineers have designed and built several generations of solid target and gas-target neutron generators. PNL's novel neutron generator technology has achieved a D-D fusion neutron yield of 3×10^{11} n/s. A schematic of the PNL gas-target neutron generator is provided below.

This state-of-the-art neutron generator technology is essential for many applications of critical global importance including neutron imaging, medical isotope production, detection of explosives and nuclear material, materials characterization, and others. PNL delivered a prototype neutron generator to the US Army in 2013 that is being used to take thermal neutron radiography images of munitions, and will begin a follow-on contract in late 2014 to deliver a commercial prototype radiography device. PNL has also developed a prototype system for the US Army that uses neutrons to detect explosive material. Additionally, PNL has partnered with SHINE Medical Technologies to develop a PNL neutron generator driven subcritical assembly that will produce Mo-99 and other medical isotopes. SHINE has submitted its construction permit application and plans to have an operating facility in late 2017.

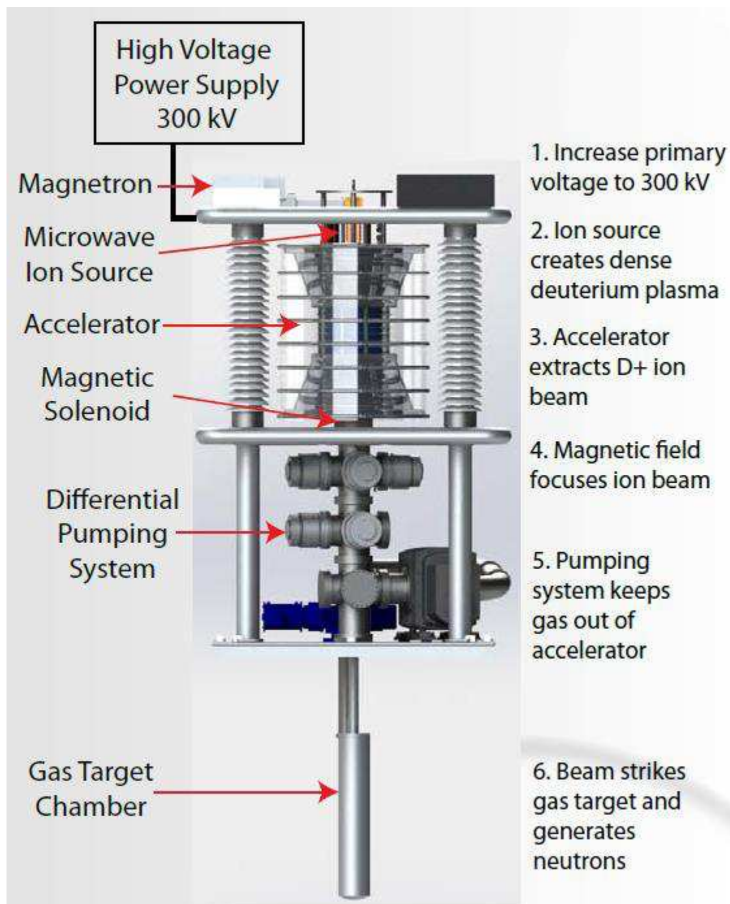

Figure 1. Conceptual schematic of the PNL gas-target neutron generator.

Polywell Physics Modeling Considerations†

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Polywells, shown in Figures 1 & 2, contain features that make them exceptionally hard to model. This talk will discuss a few of the effects listed below and some potential approaches for analyzing them. The complexity of the required physics analysis should not be interpreted, however, as indicating reduced feasibility for Polywell reactors, because this approach possesses excellent engineering features, and the physics design space is flexible.

Modeling Polywells requires taking into account many complicating factors:

- Plasma pressure/B-field pressure (β) ~ 1
- Intrinsically 3D geometry
- Boundary conditions vary with {r, θ, ϕ}
- Space charge
- Electric fields
- Steep gradients
- Plasma flows

In consequence, multiple physics effects play major roles in Polywells:

- Nonadiabaticity
- Collisions
- Sheath physics
- Particle drifts
- Microinstabilities and related plasma transport
- Fuel and power injection details
- Plasma-surface interactions

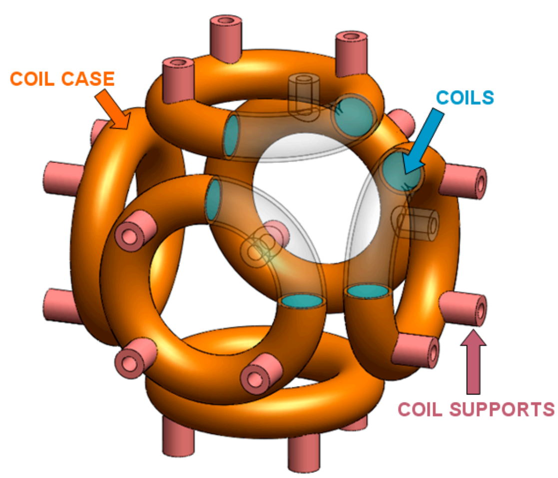

Figure 1. Magnets and supports for a six-sided Polywell. (Courtesy of Edward Marriott, Univ. of Wisconsin)

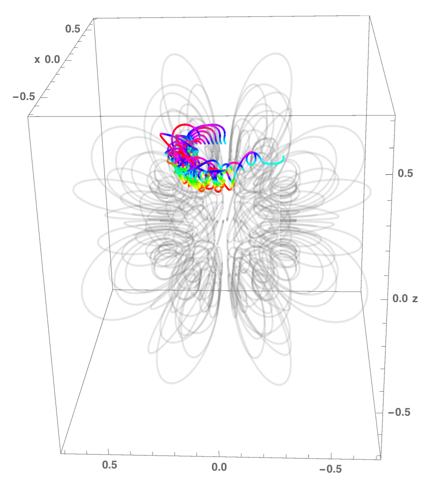

Figure 2. Magnetic field lines (gray) and selected particle trajectories (colors) for a Polywell, showing complicated drifts.

† Research supported by Energy Matter Conversion Corporation (EMC2).

Measurement of Ion Bombardment Heat Load Distributions on the Central Grid of an IEC Fusion Device

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Ion-grid collisions in IEC fusion devices remain a major source of losses of accelerated ions, resulting in grid heating and sputtering, bremsstrahlung x-ray generation and thermionic x-ray emission. Better understanding of ion bombardment distribution on the central grid may be used to better optimize central grid design in order to reduce losses. A previously tested liquid cooled central grid has been used to determine net power dissipation into the central grid as a function of voltage, current, and pressure in an IEC fusion device based on the temperature difference of a flowing coolant of a known specific heat and mass flow rate. The addition of a segmented ion collector array on a sector of the cooled grid is used in attempt to spatially resolve the ion bombardment power density as a function of position on the grid. The ion collector array consists of collector sections, a standoff of known thermal resistance, and a conductive heat sink attached to the cooled grid. The power dissipation into any given collector segment may then be determined by the temperature difference between the collector and the heat sink divided by the thermal resistance of the standoff. The temperature of each collector segment may be measured non-invasively by use of a thermal imager observing the central grid through a ZnSe viewport. Due to the liquid cooled grid remaining at a low temperature (~50C), measurements of the small temperature differential across the standoff between the ion collector and the grid can be obtained with a high signal to noise ratio that would be impossible to achieve on an uncooled grid. Additionally, the feasibility of using a thermal imager as a detector for a CO2 laser interferometer to measure plasma density at the focal point is examined.

Prepare for the D-T Burning in IECF
– relocation, remote operation, and tritium handling -†

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After the construction and preliminary operations at Kansai University, the IECF experiment device (vacuum chamber, power supply, ^{3}He neutron measurement device, and control system) has been transported to the sub-critical assembly building, Graduate School of Engineering, Osaka University in March 2014, for deuterium or deuterium and tritium discharge experiments.

The power supply, water chiller, computer for control and measurement, etc. are located in the main experimental hall. the IECF vacuum chamber is currently placed in same area, but it will be move into the heavy irradiation chamber during tritium experiments which is surrounded with a 1-m thick shielding wall.

As the regulation requires that people must be out of the experiment hall during neutron source is operated expect for a few minute, even for deuterium discharge, we should make it using remote operation. For this purpose, we introduce a KVM extender to operate the computer from a control room, and web cameras to monitor systems. Currently, we control a mass flow controller through computer and control discharge pressure and voltage. A lab view based control system for the power supply is under preparation. For tritium experiment, we have developed gas supply / exhausting system based non-evaporative getter material (SAES Getter St.172/HI/7.5-7). In this case, gas pressure in the chamber is controlled through temperature (heating current) of the getter material.

In September 2014, we plan to make the first D-T experiment using 10% tritium ratio mixture gas (other 90% is deuterium). The total absorbed gas in the getter material will be $40\ \mathrm{Pa} \cdot l = 1.75 \times 10^{-5}\ mol$, and a quantity of tritium is expected to be 3.8 GBq. We expected to obtain 10 times enhancement of neutron compare with pure deuterium discharge.

In the presentation, I will report about relocation and modification of the device, remote operation system, and the tritium handling system using getter pump, etc.

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† Research supported by JSPS KAKENHI Grant Number 25289340.

Posters

Experimental Advances and Next Steps in the Helicon Injected Inertial Plasma Electrostatic Rocket (HIIPER)†

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The Helicon Injected Inertial Plasma Electrostatic Rocket (HIIPER) is an electric propulsion concept under development that uses a helicon to inject ions into a chamber containing an inertial electrostatic confinement (IEC) device. As a space propulsion method, it is advantageous in its simplicity of design and high specific impulse. The IEC grid is electrically biased and constructed with an asymmetry set to induce a jet of ions to form, creating a thrust force (see Figure 1 below). Recently, experimental studies have indicated that the jet with the present experimental setup is dominated by electrons that are created near the asymmetry [1]. This analysis was done using a Faraday cup and a gridded energy analyzer, which showed a negatively charged beam being generated. Computational modeling of the grid was performed in the COMSOL Multiphysics program, which illustrated the electric field inside the grid and provided insight into ion extraction methods. The Faraday cup also provides estimates of efficiencies regarding jet power and input power. Additionally, a thrust plate was constructed to measure the force of the jet, however accurate results have been hampered due to asymmetric heating effects. Work is continuing to refine these measurements.

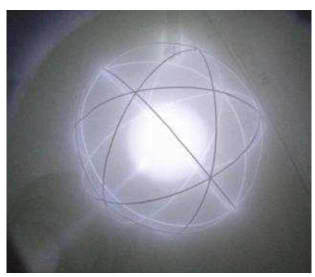

Figure 1. HIIPER in operation, with jet forming in bottom left corner.

Experimental work is ongoing to verify that HIIPER can be a forefront space propulsion method. This primarily entails creating an ion-dominated plasma jet to generate thrust. To do this, experimental methods to draw ions out from the IEC core continue to be studied. These have included biased grids to extract ions as well as concentric grids to change the electric potential well structure. Differential pumping is also being examined to eliminate the presence of neutral particles, which would reduce charge-exchange losses and breakdown effects in the experimental diagnostics. Furthermore, plasma potential probes and modifications to current diagnostics, such as the thrust plate and the GEA, are planned to further define the experiment.

[1] Ulmen, B., "Formation and Extraction of a Dense Plasma Jet from a Helicon-Plasma-Injected Inertial Electrostatic Confinement Device," Ph.D. Dissertation, Nuclear, Plasma, and Radiological Engineering Dept., University of Illinois at Urbana-Champaign, Champaign, IL, 2013.

† Research supported by NASA, the Air Force Research Lab, and NPL Associates of Champaign, IL.

Experimental and Numerical Validation of Ion Extractor Grids†

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The Helicon Injected Inertial Plasma Electrostatic Rocket (HIIPER) is an electric propulsion method being studied for potential use on deep space probes. Experimental studies have shown that with the present experiment, the plasma beam is composed primarily of electrons. However, as a space propulsion device, HIIPER would need to expel energetic ions to produce high thrust. Extractor grids are envisioned as a way to extract these ions from the plasma beam, thus drastically improving HIIPER.

These extractor grids are electrostatic components which can be added to the current experiment.

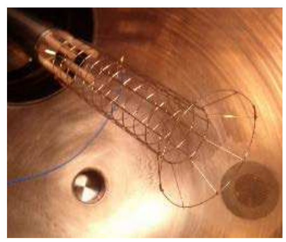
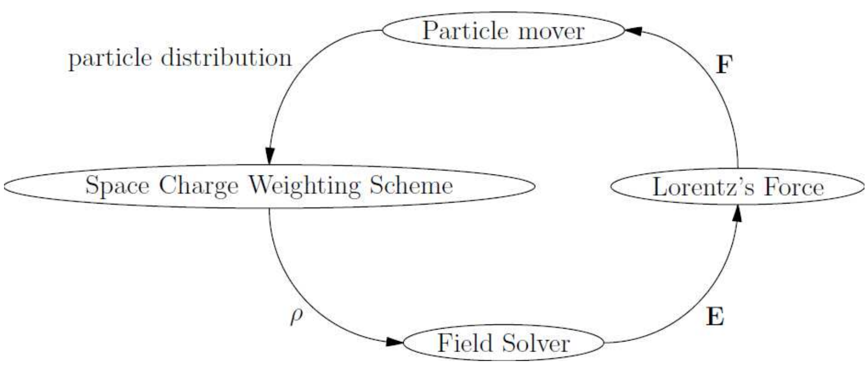


Figure 1 - Cylindrical extractor grid

A Particle-In-Cell[1] simulation is currently being developed and is expected to provide more insight on the system's physics, and also determine how well the different designs of extractor grids perform.



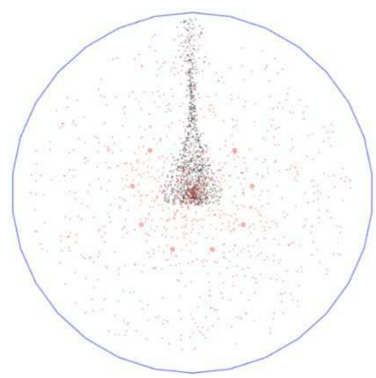


Figure 2. Computational cycle and output of the Particle-In-Cell code

The combination of experimental work and numerical simulations will allow us to validate the concept of extractor grids and choose the design that provides the best overall performance.

The current version of this simulation enables for the study of electron motion only. Upcoming improvements will aim at adding ions to the simulated system, so that a greater extent of the physics can be represented.

[1] C.K. Birdsall, A.B Langdon "Plasma Physics via computer simulations," (1984).

† Research supported by NPL Associates, NASA, Air Force Research Lab, Aerospace Engineering Department, UIUC

Effects of Multiple Energy $^4He^+$ Bombardment on Cathode Materials Such As W at High Temperatures†

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In inertial electrostatic confinement devices, atomic and molecular ions and neutrals of various energies impact the cathode grid wires. As these wires are bombarded, embedded-ion fusion and erosion by ion-impact sputtering of the metal occurs. The $^4He^+$ ions cause subsurface damage to tungsten (W) surfaces and remove some of the atoms off of the top layer. To explore this behavior experimentally, irradiation of W samples is performed with the materials irradiation experiment (MITE-E) in the IEC Laboratory. A 10 mm x 10 mm x 1 mm square polycrystalline W sample (P41) was irradiated in sequence with 10, 20, and 30 keV $^4He^+$ ions to a fluence of 1 x 10^{18} $^4He^+/cm^2$ at 900 °C. The damage the W sample received was more severe than what was seen on previous W samples irradiated with mono-energetic $^4He^+$ ions (see the figure below).[1] What was observed previously were pores, blisters, and ripples; sample P41 exhibited a grass structure on every grain. Early work with W at lower fluences recorded a grass structure on the sample surface as is seen with sample P41. The observed effect with multiple energy bombardment is an even accumulation of He under the sample surface which escapes from the W lattice at high temperatures, leaving a grass structure on the surface. This was seen on all the grains within the polycrystalline structure except for the {111} grain, which was damaged less than the others. Sharp points in a W grid can be created by this surface structure formation. These sharp points can contribute to a high voltage breakdown across the wires, which in turn would lower the maximum cathode voltage achieved and lead to lower fusion rates.

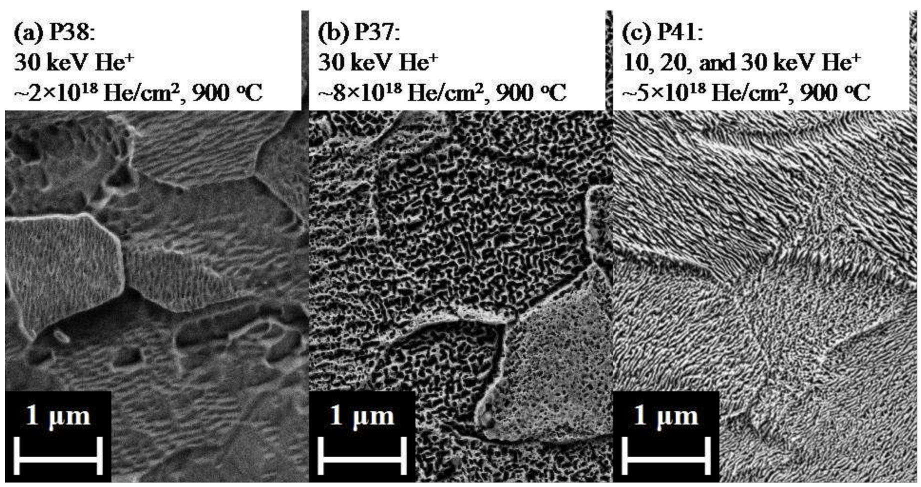

Figure 1: Comparison of the damage of mono-energetic He^+ implantation on samples (a) P38 and (b) P37 with multiple energies of He^+ implantation on (c) P41. The fluences listed are estimates of the local fluence where the SEM images were taken and are based on a Gaussian ion beam profile.[1]

1. **References:** L. M. Garrison, "Improving the Materials Irradiation Experimental Facility and Increasing Understanding of Helium Irradiation of Tungsten," PhD Thesis, University of Wisconsin - Madison, 2013.

† Research supported by the Greatbatch Foundation.

Investigations of Helium Ion Damage to IEC Cathode Materials at the University of Wisconsin

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Extended operation of an IEC device results in high ion fluences impacting experimental components. Previous experiments have shown that high fluences of helium ions accelerated to fusion-relevant energies cause severe microstructural surface and subsurface damage, as seen in Figure 1, which can impact cathode performance [1]. Fluences incurred by the cathode have an additional importance for D-^{3}He fusion rates as fusion with this fuel favors the beam-embedded regime [2]. This poster summarizes the variety of research efforts investigating helium damage in IEC cathode materials, including the various implantation methods, materials, and damage analyses carried out by the UW IEC group.

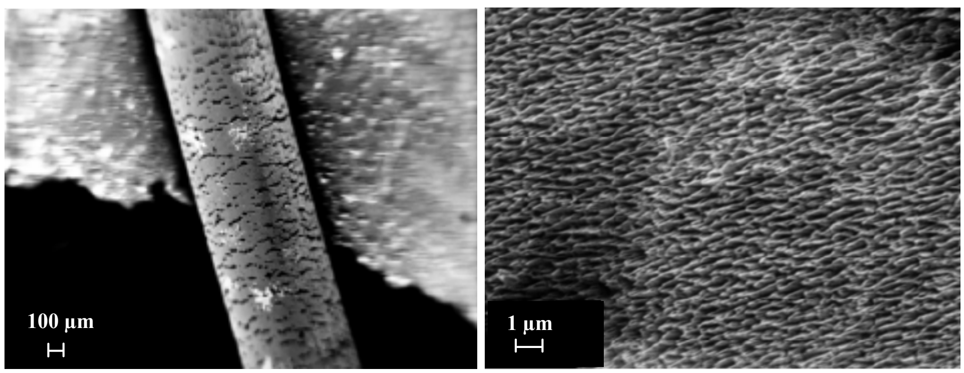

Figure 1. Helium-irradiated W-Re alloy cathode grid wire (left) and magnified cathode wire (right) [1]

To further this research effort a device is being developed that will enable the controlled irradiation of cathode material samples with multiple, simultaneous, individually-controlled ion beams. This will allow effects of operating an IEC fusion device with multiple species of fuel, such as deuterium and helium, to be observed in a controlled environment that is non-destructive to a cathode. This experiment will also have implications for first wall armor of IFE chambers and the divertor region of MFE devices.

[1] G.R. Piefer, “Performance of a Low-Pressure, Helicon Driven IEC ^{3}He Fusion Device,” *PhD Thesis* ***University of Wisconsin, Madison**,* 76 (2006).

[2] B.B. Cipiti, and G.L. Kulcinski, “Embedded D-^{3}He Fusion Reactions and Medical Isotope Production in an Inertial Electrostatic Confinement Device,” *Fusion Science and Technology* ***44,*** 534 (2003)

Discharge characteristics of multiple IEC device

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The Kansai U. s' PIC simulation results showed that electric discharge properties and neutron is improved by using the smaller anode and cathode. Therefore, the 80mm anode instead of 300mm anode and 20mm cathode instead of 80mm cathode are used for experiment of this study. Figure 1 is a photo of the discharges with one small IEC device. The electric discharge with this small IEC device in the low gas pressure domain becomes unstable, and it is difficult to continue. To solve the problem, a wireless camera is equipped for understanding the phenomenon in the vacuum chamber. Then it is found that the electric discharge is occurred between the feed through and the inner wall of vacuum chamber. To defend it the guard fence that surrounds the feed through is attached. In this condition, electric discharge properties are improved and the quantity of neutron is really increased.

The various parallel operations with two IEC devices are tested. The two small IECF devices placed side by side is not applied enough voltage. The two small IECF device placed lengthwise can be applied enough voltage, the neutron production rate of 1.1 x 10E5 which is almost twice of single operation is achieved

Fig.1 Discharge photo of small IEC device

Fig.2 Photo of two small IECF devices placed side by side

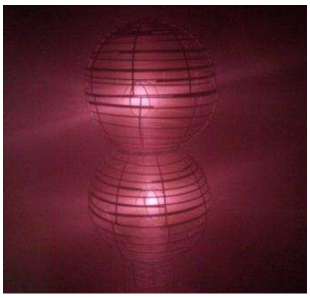

Fig.3 Photo of two small IECF devices placed lengthwise

Finite Element Method Simulation Studies of a Prototype Planar Geometry IEC Fusion Device

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The planar geometry IEC fusion device is a new gridless geometry that offers the potential for greater ion capacity and higher fusion yield via a larger ion turning space region compared to the classic spherical and other previous geometries. Initial studies of ion trajectories in this type of device showed favorable ion trapping behavior [1], and a prototype device has been constructed (figure 1). To further study ion behavior in the device, and in particular simulate the fusion yield, a finite element method model is being developed using COMSOL® multiphysics software. Initial simulations of the prototype device will be presented.

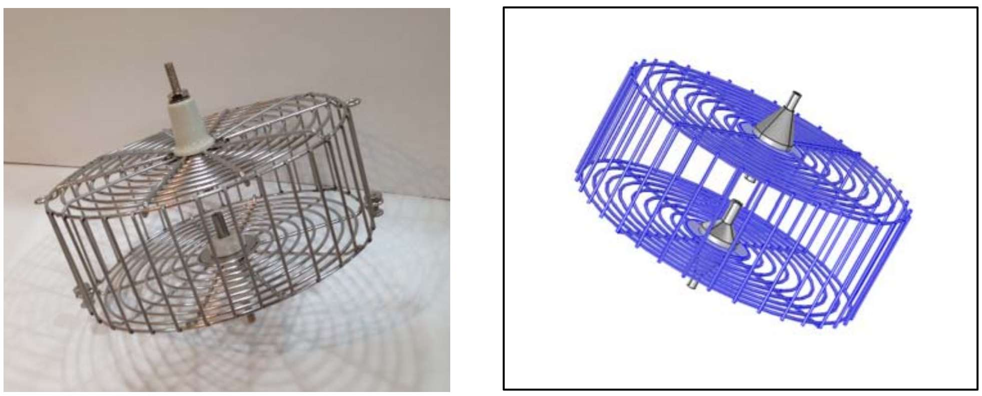

Figure 1. Prototype planar geometry IEC device (left) and COMSOL® model (right).

The first step in the simulation is calculation of the electric potentials in the device. Figure 2 shows an example of an electric potential field plot for -10kV on the pin electrodes with the cage grounded. The calculated fields are then used in subsequent simulations of ion trajectories, collisions, etc. All parameters in the model (dimensions, potentials, etc.) are assigned variable names to facilitate variation of the parameters. The ability to easily simulate variations of the device should significantly expedite refinement of its performance.

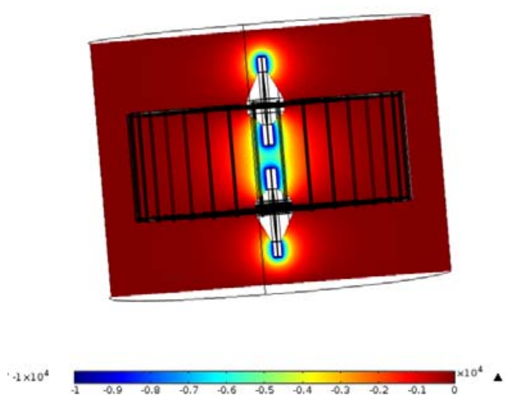

Figure 2. Electric potential field plot.

[1] Daniel R. Knapp, "Planar Geometry IEC Fusion Device," presented at the 15th US-Japan Workshop on Inertial Electrostatic Confinement Fusion, Kyoto, Japan, 2013.

Simulation of enhanced fast electron confinement in multi-cusp geometry due to flux exclusion†

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Early investigations of magnetic cusp configurations for plasma confinement revealed poor confinement due to cusp losses. However, it was predicted by Grad and others that if high beta could be achieved the plasma might exclude magnetic flux from the core of the device leading to a sharper boundary and improved confinement. The company EMC2 has recently reported the first experimental evidence of this hypothesis as well as transient PIC simulations that also demonstrate the effect [1].

In this work we present additional fully kinetic simulations that show the improved confinement due to magnetic flux exclusion in a steady-state system. Two-dimensional slab geometry is considered with cusped fields created by eight out-of-plane wires with current in alternating directions, similar to the mid-plane of the six-coil Polywell(TM). Only one species (electrons) is considered, along with a self-consistent description of electric and magnetic fields due to plasma charge and current density. In order to produce non-negligible diamagnetic currents in a single-species plasma with low enough density not to be expelled by space-charge the permeability of free space is assumed to be much greater than it's physical value. This is equivalent to assuming a much denser two-species plasma with ions neutralizing most, but not all, of the electron charge (note self-consistency is no longer exact in the extrapolated two-species system). Results from these simple, low-cost simulations readily show that flux exclusion occurs in the core and that this can, indeed, lead to improved particle confinement. However, some difficulties in converging to steady-state solutions may reflect experimental challenges during start-up when confinement is poor.

[1] J. Park et al., "High Energy Electron Confinement in a Magnetic Cusp Configuration," arXiv, *1406.0133* (2014).

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† Research supported by Department of Defense through an NDSEG fellowship.

Gas supply/exhausting system with getter pump for D-T Burning in IECF-†

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Using IECF device, we have been studying to increase the neutron production rate. The amount of the neutron Production rate by D-T fusion reaction can be more expectant than by D-D fusion reaction. This is mainly because the reaction cross-section of D-T reactions is 200 times upper limit as large as that of D-T reaction. We accordingly try to increase the neutron production rate by D-T reaction.

In order to be D-T burning experiment, we should make an effort to keep in a completely sealed state of the vacuum chamber so that leakage of the tritium gas could not be. We therefore try to realize the sealed experiment and hydrogen gas handling system by using getter pump. I briefly show process of the getter pump below.

1. The absorbing the gas mixed deuterium and tritium to the getter pump in which the getter materials (SAES Getter St.172/HI/7.5-7) are composed of Zr,Va and Fe. The amount of them will be 40 Pa $\cdot$ l = 1.75×10^{-5} mol.
2. Control of gas pressure in the vacuum chamber by operating (gas supply/exhausting) of the getter pump. The gas pressure in the vacuum chamber is in the range of 40 Pa to 10^{-2}Pa.
3. Recovery 99% gas of the total by encapsulating them into the getter pump.

The getter pump is operated by controlling the temperature (heating current) of the getter material.

† Research supported by JSPS KAKENHI Grant Number 25289340.

Decontamination of Tritium from exhaust gas of IECF device

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Enhancing the performance of neutron production rate, the IECF device using tritium and deuterium reaction is currently under development. Figure 1 shows the layout sketch of this device. The main pump for the device is the metal getter (St.172/HI/7.5-7, Made in saes co.). After the experiment, the residual tritium gas which can not evacuate by the getter should be removed. So, the recovery equipment with water bubbler tube for residual tritium gas is developed. This equipment can oxygenate the emission gas (T_2 and D_2) from IECF device by using the powder of copper oxide (II). The emission gas becomes water vapor. The vapor is recovered by the water-gas scrubbers. The second scrubber is mounted for trapping the vaporized tritium water from first scrubber.

As the result of the experiment with deuterium gas only, the scrubber equipment can recover the 99.995% of deuterium gas (Lower detection limit of 137U, Kitagawa hydrogen detector tube) by using the heated copper oxide at 300 degree C.

After the experiment at OKTAVIAN in Osaka U., the amount of removed tritium water will be measured by liquid Scintillation. The tritium water will be wasted as diluting water within the regulation level.

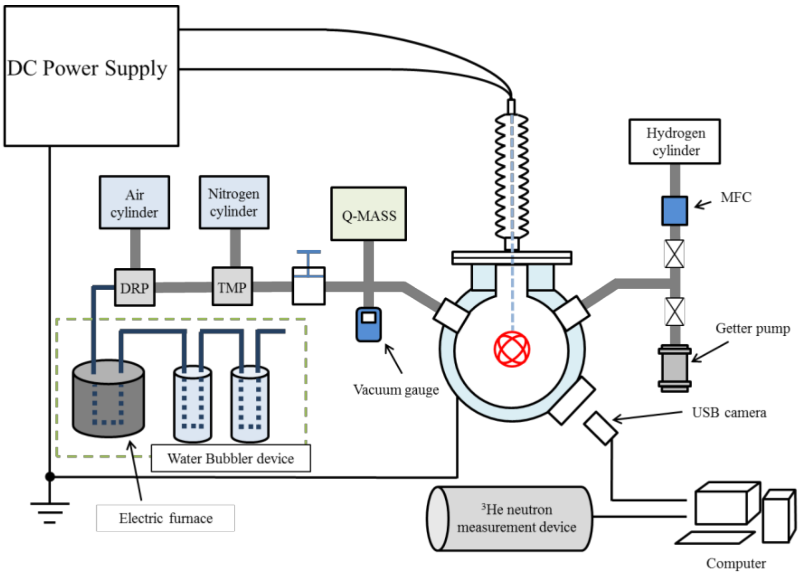

Fig 1. The IECF device

D-D Neutron Production Optimization in a Linear IEC Device

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A need for better detection systems for explosives has arisen in the past few years. Inertial Electrostatic Confinement (IEC) fusion devices, though not yet capable of reaching the conditions needed for a large scale reactor, can serve as very effective and compact neutron sources. The neutrons generated by the reactions can be used for neutron activation, including Thermal Neutron Analysis (TNA) and Fast Neutron Analysis (FNA)[1]; additionally, they can be useful for neutron radiography. A linear neutron source has been proposed for construction by the UW-Madison IEC group in which movable anode-cathode pairs will be used to optimize the production of neutrons in a deuterium plasma-gas mixture. Due to the nature of the configuration, parameters such as pair spacing, gas pressure and high voltage need to be optimized to achieve the high neutron rates required for an efficient source. Using the VICTER code developed by Emmert and Santarius[2], an estimate for these values can be found, and future experimental results will be used to validate its accuracy. Following initial results, an experiment facility will be constructed to fit a neutral gas region, using graphene as a way to maintain a higher pressure in the target region. Though not yet actively studied, this opens the possibility of researching ion bombardment on graphene. This linear device is expected to achieve much higher neutron production rates than the HOMER device housed by the UW-IEC group, which currently holds a record[3] of $2x10^8$ DD neutrons/second.

[1] G.H. Miley, L. Wu, H. J. Kim, "IEC-based neutron generator for security inspection system", *Journal of Radioanalytical and Nuclear Chemistry, **Vol. 263***,159-164 (2005).

[2] G.A. Emmert and J.F. Santarius, "Atomic and Molecular Effects on Spherically Convergent Ion Flow II: Multiple Molecular Species," *Physics of Plasmas* **17**, 013503 (2010).

[3] G.L. Kulcinski, J.F. Santarius, G.A. Emmert, R.L. Bonomo, E.C. Alderson, G.E. Becerra, L.M. Garrison, K.B. Hall, A.M. McEvoy, M.K. Michalak, and C.M. Schuff, "Recent Advances in IEC Physics and Technology at the University of Wisconsin," *Fusion Science and Technology* **64**, 373 (2013).

Design of a Lunar Solar Wind Volatiles Extraction System

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Before 1985, researchers at the University of Wisconsin-Madison Fusion Technology Institute (FTI) and elsewhere knew that the use of helium-3 (^3He) fuel could radically improve the prospect of clean and economical nuclear fusion power. The nuclear fusion reactions below:

$$D + {}^3He \rightarrow p\ (14.68\ MeV) + {}^4He\ (3.67\ MeV)$$
$${}^3He + {}^3He \rightarrow 2p + {}^4He\quad (12.86\ MeV)$$

are promising for future power producing reactors due to their high energy output, low emission of neutrons, higher energy conversion efficiency, increased safety and potential ease of maintenance compared to the more studied deuterium-tritium (DT) fuel cycle. Unfortunately, there is not a sufficient quantity of terrestrial ^3He to support its use for power generation. It was realized in 1985 that there is an estimated 10^6 tonnes of ^3He imbedded in the lunar regolith from over 4 billion years of bombardment from the solar wind. The seminal article tying lunar ^3He to fusion development was published by FTI researchers in 1986. Three FTI designs of lunar ^3He miners have been developed, the Mark-I, II, and III (M-1 through M-3) to collect ^3He. The most recent of these designs was completed in 2006. In general, these designs employed mature terrestrial mining technologies like bucket-wheel excavators and conveyor belts, but also involved key design aspects required for large scale mining operations in the vacuum of the lunar environment. Currently at the FTI, a small scale ^3He and lunar volatiles extraction system research effort is under way. Two devices are being developed to demonstrate the extraction of helium-3 and other volatiles from lunar regolith. The first is an implantation system to embed helium ions into JSC-1A lunar regolith simulant and the second is a counter flow heat pipe heat exchanger for the subsequent diffusion of the helium out of the regolith. This will simulate the previously proposed acquisition of helium-3 from the Moon for use in nuclear fusion reactors on Earth. Preliminary designs of both of these systems are discussed.

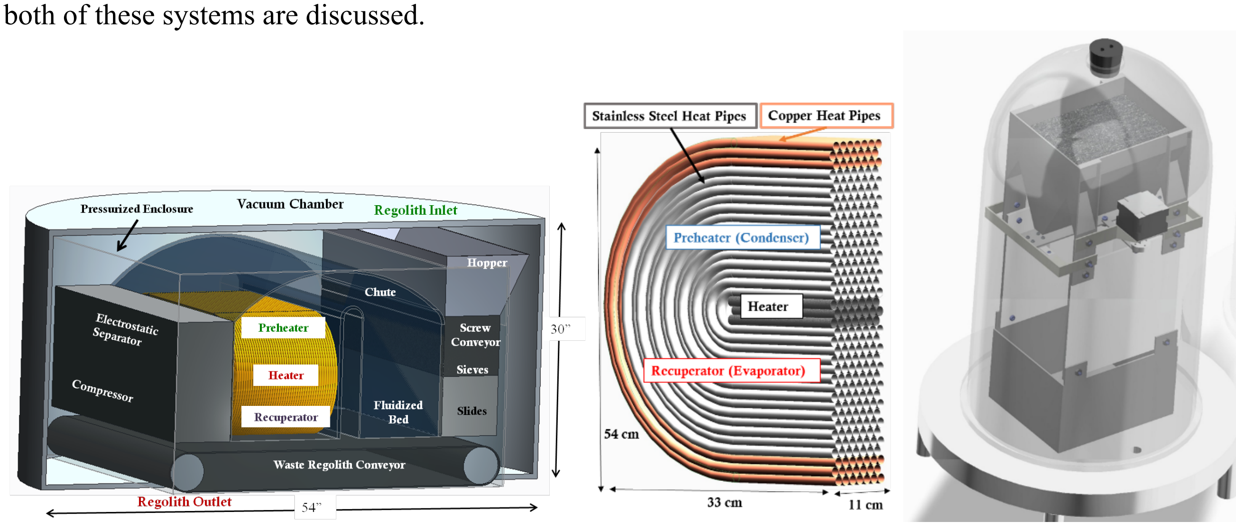

Figure.1. Preliminary CAD model illustrating the prototype lunar volatiles extraction system (left), the heat pipe heat exchanger system within the extraction system (middle) and a conceptual helium implantation system (right)

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[2] Associate Director for Alternate Applications and Concepts, Fusion Technology Institute, Research Professor, Engineering Physics Dept.
[3] Director, Fusion Technology Institute, Grainger Professor of Nuclear Engineering, Engineering Physics Dept.