SPIE Conference - San Diego - August 2011

SAND2011-5747C

August 9, 2011

Coaxial Microwave Neutron Interrogation Source

Will Johnson[1], Arlyn Antolak[2], Tom Raber[3]
Sandia National Laboratories, California 94551

Ka-Ngo Leung[4]
Nuclear Engineering Dept., UC Berkeley 94720

Abstract

Sandia National Laboratories is developing a compact neutron generator based on deuterium-deuterium (D-D) fusion reactions, using ions extracted from a dipole permanent magnet electron cyclotron resonance (ECR) plasma reactor operated at 2.45 GHz. The deuterium ions extracted from the plasma will be accelerated and collided on a titanium target creating 2.4 MeV neutrons as a result of the D-D fusion reaction. This paper reports on initial simulation results as well as initial experimental hardware setup.

[1]wcjohns@sandia.gov
[2]antolak@sandia.gov
[3]tnraber@sandia.gov
[4]knleung@lbl.gov

Sandia National Laboratories

1 Introduction

Active neutron interrogation has been demonstrated to be an effective method of detecting special nuclear material (SNM), specifically highly enriched uranium [1]. When the neutrons interact with SNM they induce fission, resulting in the emission of neutrons and gammas that may then be detected. We seek to make a compact, hand-portable, neutron source capable of field use active interrogation. The design investigated is based on extraction and subsequent acceleration and fusion of deuterium ions created by a coaxial permanent magnet dipole plasma reactor. The ion source has recently been developed [2][3] for surface physics applications; we seek to take advantage of its small physical size, low operating gas pressure, and minimal power requirements to create a portable neutron generator.

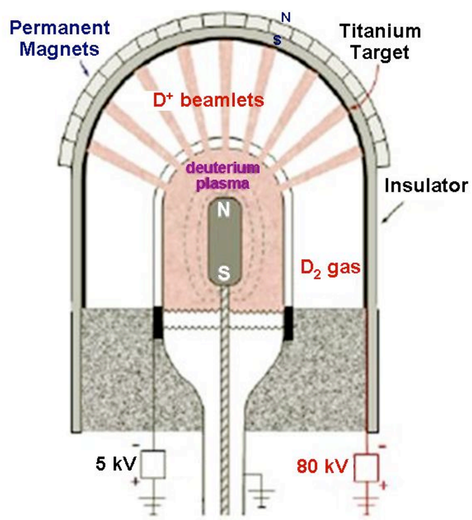
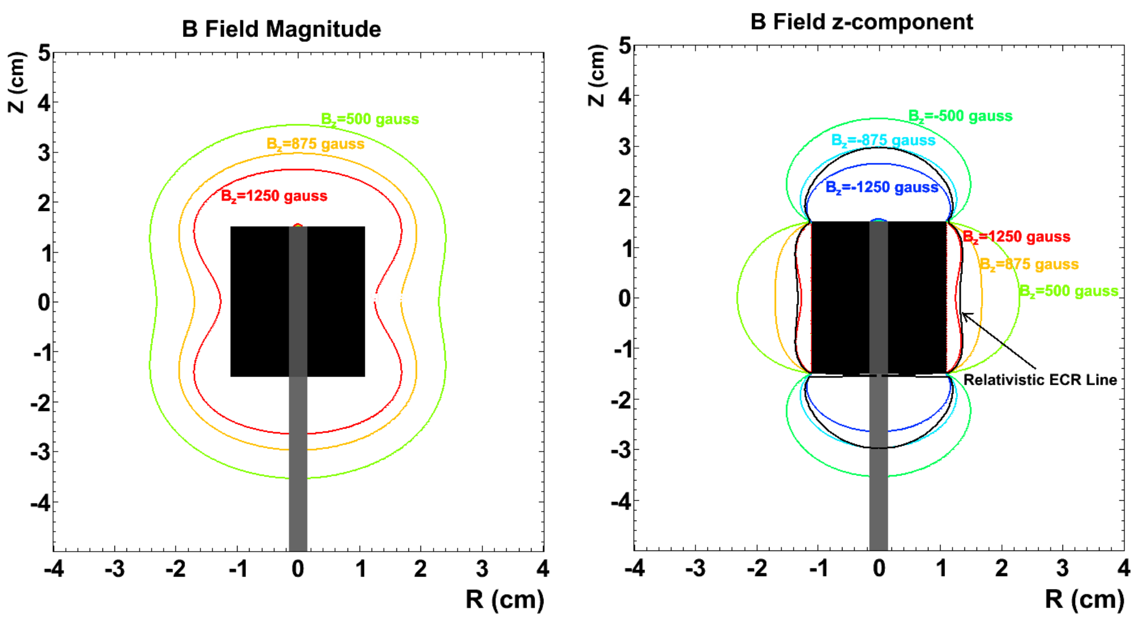


Figure 1: Schematic design of neutron generator being investigated.

The basic principle of a neutron generator is to bombard an ion beam of either deuterium (D) or tritium (T) onto a target. Neutrons are produced via the D-D, D-T, or T-T fusion reactions if the target surface is loaded with D or T atoms. Current neutron generators have certain intrinsic limitations, mainly related to the ion source. In the case of a Penning ion source, less than 10% of monotonic ion species is produced [4], which is not ideal. Multicusp ion sources may operate at pressures near 10 mtorr, but require higher pressures for ignition; given that the gas pressure also effects the ratio of atomic to molecular ions in the discharge, as well as the necessary pumping equipment, this is also less than an ideal ion source for portable systems. Conventional microwave ion sources produce plasma by applying the microwave electric field along a multi-polar magnetic structure that provides the magnetic field intensity required for electron cyclotron resonance (ECR) coupling. The drawback is that attenuation of a traveling wave along the linear applicator (antenna) leads to non-uniform plasmas that are less than ideal for ion extraction. The production of uniform plasmas requires achieving standing waves with constant amplitude along the linear applicators. In order to obtain a standing wave along a transmission line, a reflected wave is required, i.e., when the microwave power is totally absorbed before the end of the propagation line (no reflection), a standing wave cannot be achieved (only a traveling wave is applied on a part of the line). The microwave power sent to the antenna must be sufficiently high and its absorption by the plasma sufficiently weak to obtain substantial microwave reflection at the extremity of the antenna. Weak microwave absorption cannot lead to high density plasma, and power input cannot be increased indefinitely.

The design we are investigating is shown schematically in Fig. 1, and is based on a single cylindrically symmetric dipole rare-earth magnet, with a 2.45 GHz RF antenna located in the center of, and coaxial to the magnet; this assembly is manufactured by Boreal Plasma [5] and reported in Refs. [2][3]. This design overcomes the attenuation of the RF field difficulties given the field propagates from the center of the magnet directly into the plasma, thus avoiding the problem of attenuation and allowing for a more uniform plasma. The system can also operate and ignite in a decade on either side of ~1 mtorr, meaning bulky pumping equipment is not needed for a sealed design producing a higher monotonic ion fraction given that this is related to the gas pressure. Another benefit of this system is a low power consumption during operation; about 100 watts RF power is required to produce the plasma, and about 100 watts to accelerate the ions. Preliminary estimates indicate that at this power level about 10^8 D-D neutron/seconds can be produced.



(a) Lines of constant $||B||$

(b) Lines of constant B_z, as well as line of ECR coupling when relativistic effects are accounted for.

Figure 2: Magnetic field intensities for a cylindrically symmetric Sm_2Co_{17} permanent magnet with standard properties given by [6]. The magnetic field was computed using the POISSON/SUPERFISH [7] family of codes.

2 Simulation

When relativistic effects are ignored, conditions for ECR are found by matching the radial acceleration of an electron in orbit in the magnetic field, $a_r = -\omega^2 r$, to the acceleration of the electron due to the magnetic field, $\mathbf{a} = q_e \mathbf{v_e} \times \mathbf{B}$, where q_e, v_e and r are the electrons' charge, velocity, and radius of orbit. When the magnetic field is assumed to be along the 'z'-axis, we find the magnetic field necessary for ECR is $B_z = m_e\omega/q_e$, which for $\omega = 2.45$ GHz gives $B = 875$ gauss. However, when the velocity of the orbiting electron approaches relativistic speeds, the magnetic field necessary for ECR then becomes dependent on the speed of the electron, and hence the radius of orbit. The relativistically correct equation for the the magnetic field necessary for ECR is $B_z = \gamma(v_e)\, v_{e_z} m_e / q_e r$, where $\gamma(v_e) = \sqrt{1/\left(1 - \frac{v^2}{c^2}\right)}$. For a non-uniform or non-analytic magnetic field this equation must then be solved numerically with the magnetic field necessary for ECR then becoming position dependent. It is found for a Sm_2Co_17 magnet with outside radius 1.1 cm, which is similar to the one we are employing and was employed in Ref. [2], the actual magnetic field necessary for ECR at 2.45 GHz is closer to 1250 gauss. The radius of ECR coupling taking into account relativistic effects, and assuming small velocities in the 'z'-direction, is shown in Fig. 2, as well as a number of lines of constant magnetic field intensity. The energy of the electron and radius of ECR ranges from $E_e = 120$ keV and $r_{ECR} = 1.14$ cm ($B_z = 1080$ gauss) near the upper and lower edges of the magnet, to $E_e = 206$ keV and $r_{ECR} = 1.37$ cm ($B_z = 1230$ gauss) near the location of largest radius orbit at $z = \pm 0.87$ cm.

To simulate the electrons involved in the ECR, and obtain expected spacial distributions for the ECR electrons, as well as subsequently produced electrons, we chose to employ the well known GEANT4 [8] library used for the simulation of high energy particle physics to create a C++ program to perform the simulations[5]. The goal of this simulation is to get an idea of the physical location and basic properties of the plasma, to aid in the design of a positive ion extraction system, and to observe effects of outside fields on the electrons in ECR. The code created traces individual electrons using fourth order Runge-Kutta integration, according to relativistically correct equations of motion and Monte-Carlo generated interactions. The magnetic field used is that shown in Fig. 2 and has been computed using the POISSON/SUPERFISH [7] family of codes from magnetic properties given in Ref. [6]. The 2.45 GHz RF field is modeled as a circularly polarized wave with intensity

$$E_0 = \sqrt{\frac{2QP}{0.238\varepsilon_0 \pi a^2, Z_0 \omega}}$$

Where P is the incident RF power, Q is a "quality" factor related to the geometry, a is the radius of the (cylindrical) cavity, and z_0 the length [9]. These parameters are taken as first order estimates to be $a = 2.0$ cm, $z_0 = 6.0$ cm, and $Q = 420$, with input power 100 watts; it was found that most obtained kinematic distributions had little dependence on the value of E_0.

GEANT4 tracks and accounts for physical processes such as: energy loss and secondary electron production due to ionization, scattering, bremsstrahlung, synchrotron radiation, and other less common interactions. cross-sections and various particle production quantities are mainly derived from the G4EMLOW6.19 dataset, which is itself extracted from the Lawrence Livermore National Laboratory provided dataset [10], and was verified to match data given in various plasma literature. Since GEANT4 is typically used to simulate radiation at energies above 1 keV, it was necessary to adjust many default thresholds and parameters, including the energy particles are tracked down to, energies physics processes are

[5]It is beyond the scope of this project to produce a detailed simulation of the plasma properties beyond what is necessary to guide the design of ion extraction.

applicable down to, as well as the lower bound energies that particles may be created. We tracked particles down to 0 eV, as well as applied many physics processes to the lowest energies cross section and production data is available for (for instance, ionization cross-section data go down to 13.6 eV for hydrogen), while the energy threshold for produced secondary particles was set to 0.1 eV. Energy lost from the primary particles, due to particles that would have been produced with less than 0.1 eV of energy is accounted for in a continuous fashion[6]. The `G4EmLivermorePhysics` physics list is used as the base physics list to govern physical interaction, which has only been validated down to 250 eV (GEANT4 users do not typically care about such low energies). However, it was verified from the GEANT4 source code that cross-sections and production spectrums for processes like ionization are interpolated from data, meaning results obtained should at least be approximately correct for energy ranges available. It was also verified for helium gas that the energy spectrum of produced secondary electrons matched that found in the literature [11]. Another issue of concern was numerical accuracy with respect to integration of the equations of motions, especially due to the high frequency nature of the RF field. Integration parameters were adjusted until the expected errors were negligible, and a variety of checks passed (conservation of energy, verifications of simplified trajectories without interactions, etc.).

The basic flow of our simulation program:

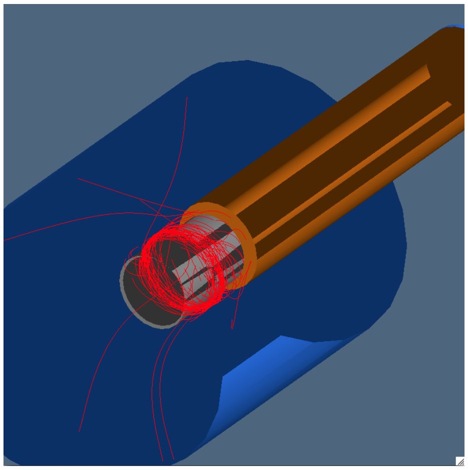
1. Select a random 'z' location and momentum direction according PDF of primary electron positions[7].
2. Find the radius and energies corresponding to ECR coupling.
3. Choose random 'ϕ' and time position of electron (relevant due to RF field).
4. Allow the electron to travel some distance as a 'burnup' period to reduce the biasing of results from starting conditions.
5. Track the electron at every interaction, or every 1 cm to obtain kinematic distributions.
6. Continue tracking the electron until it reaches zero energy, or leaves the region of geometrical interest. Each secondary particle created is placed on a stack for future simulation.
7. Simulate secondary particles created by the primary electron are then simulated, placing their secondary onto the stack for future simulation, and so on.

This approach to simulation mainly targets finding the distribution of electrons in ECR and allows for quick and flexible prototyping to test various scenarios and effects such as externally applied electric fields, ion extraction, etc. However, some particular weaknesses of note to this approach of simulation are that it ignores internal fields created within the

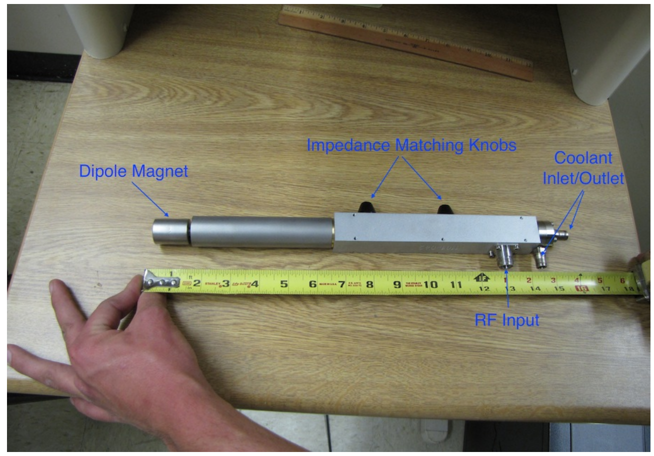
[6]That is, no secondary particle is created; instead, an average energy per unit length is accounted for in the primary particles trajectory. A particularly non-obvious, or rather not well documented, setting to accomplish this down to such low energies was:

```
G4VRangeToEnergyConverter::SetEnergyRange( 0.1*eV, 10.0*MeV );
```

[7]The primary electron position PDF is found iteratively starting with a flat distribution in 'z' and then simulating many particles; then using the resulting electron PDF to seed the locations of the next generation. Only a couple generations were needed to reach steady state.



(a) Visualization of simulated device, with some example electron trajectories shown in red



(b) Actual coaxial dipole plasma reactor manufactured by Boreal Plasma

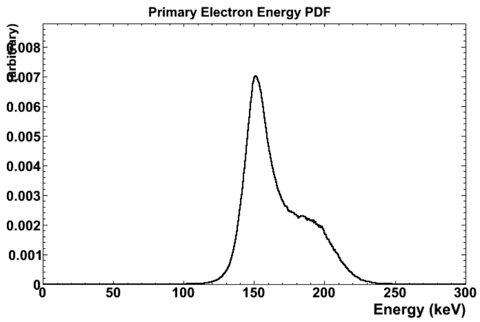
plasma, and can be computationally inefficient to obtain sufficient simulation statistics. We have limited both the path length we will simulate for any one electron to 10,000 m, as well as limited the maximum number of secondary electrons any one electron can produce through ionization to 50,000; this is to help fully sample the possible trajectories of electrons in ECR. Without these limitations the number of electrons on the stack to simulate diverges (e.g. although rare, sometimes electron created through ionization will catch ECR, thus creating many additional electrons through ionization, a run away process).

2.1 Simulation Results

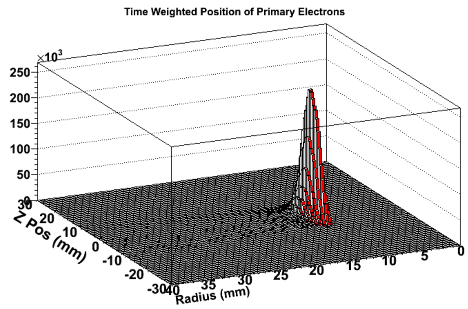
As can be seen from Fig. 3(c), the energy of electrons participating in ECR ranges from about 110 keV to 240 keV, with the most likely energy being about 155 keV. From Fig. 3(d), it is expected electrons in ECR will most likely be found near the lengthwise middle (z=0) of the magnet, and at radiuses very near that of the magnet itself. From Fig. 3(e), 3(f), and 3(g), we can see the locations of maximum ionization, while in 3(h), initial energy of electrons created by ionization is presented.

3 Experimental Setup and Future Efforts

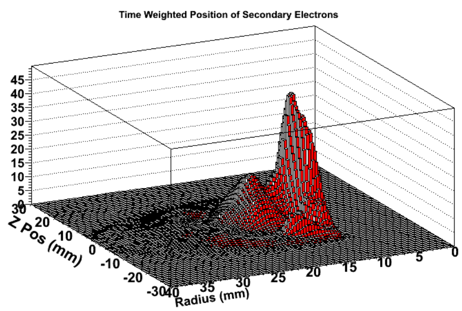
In parallel with the simulation efforts, a laboratory setup is also being constructed with Fig. 3 showing the current progress. A vacuum chamber with the plasma reactor has been assembled and verified to operate and produce plasma. No extensive investigations of the plasma properties has yet been performed, but as can be seen in Fig. 4(b), the physical location of ECR electrons and plasma produced match up to simulation predictions, lending some degree credibility that the simulations may be used to further develop the neutron generator system.



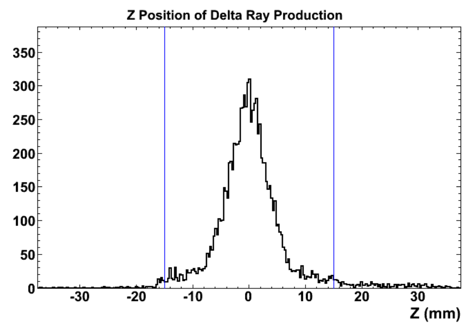
(c) Expected energy distribution of electrons participating in ECR, the blue lines represent the ends of the dipole magnet



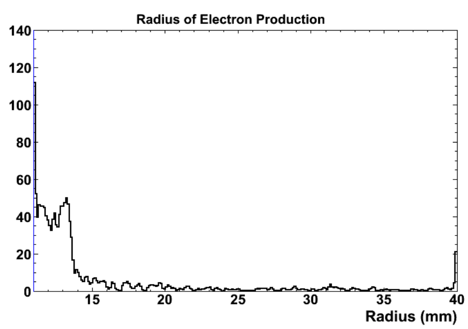
(d) Expected relative probability distribution function of the position of electrons participating in ECR



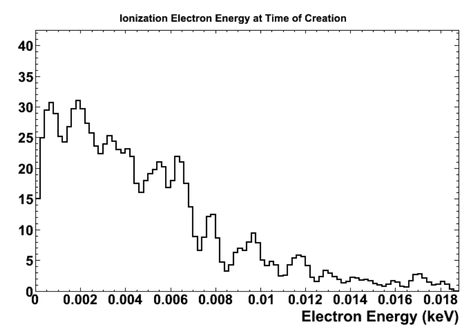
(e) Expected position of secondary electrons not participating in ECR



(f) Expected position in 'z' of electrons produced through ionization



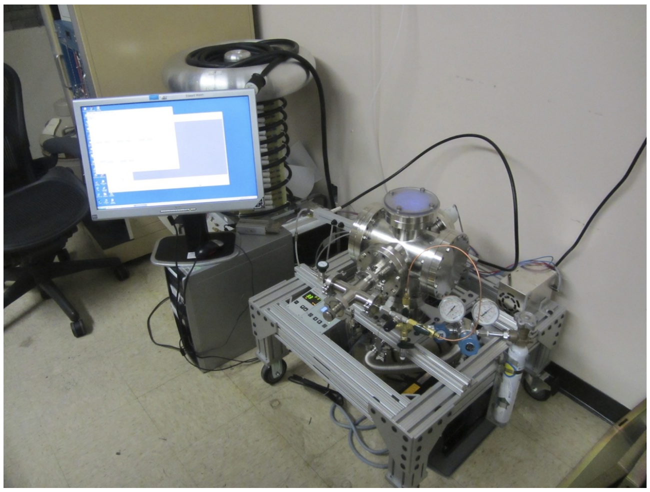
(g) Expected radius from center of magnet, of electron production



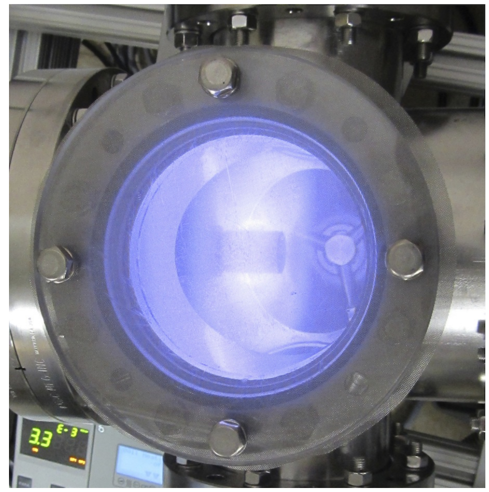
(h) Expected initial energy of electrons from ionization

Figure 3: Some initial distributions obtained from simulation of argon gas at 3.3 mbar pressure.

Current work is focused on the design of a positive ion extraction and acceleration mechanism. The ion extraction system is being developed using both the current C++/GEANT4 based simulation, as well as using the Ion Beam Simulator (or IBSimu) [12][13] package. We will initially design, prototype and test a single extraction slit for positive ions, to allow progression to a 3-dimensional extraction and acceleration system that will allow us to maximize current on target for maximum neutron flux. Using a 3-dimensional extraction system minimizes beam power per target area, thus avoiding target overheating issues. Additionally, to enhance active interrogation capabilities, the neutron production will be "pulsed" to allow the use of delayed fission product detection without background from the neutron generator itself.



(a) Current experimental setup.



(b) Plasma produced in argon at $\sim 3.3 \times 10^{-3}$ mbar and 50 watts of RF power, with effectively 0 watts of reflected power.

4 Conclusion

Initial modeling work and construction efforts towards a compact coaxial microwave ECR neutron source have been presented been presented. Using a permanent magnet dipole ECR plasma reactor, along with a 3-dimensional ion extraction and acceleration system, will allow building a sealed, hand-portable, D-D neutron generator which may be operated on only $\sim$200 watts of power. The small physical size, relative low cost of components, expected high flux of neutrons, ability to switch neutron generation off, as well as pulsed mode of operation makes the system being investigated an ideal source of neutrons for active interrogation of SNM, industrial, and research purposes where a portable size is desired.

References

[1] Dennis Slaughter *et al.* Detection of special nuclear material in cargo containers using neutron interrogation. Technical report UCRL-ID-155315, Lawrence Livermore National Laboratory, Livermore, California 94550, August 2003.

[2] S. Bchu, O. Maulat, Y. Arnal, D. Vempaire, A. Lacoste, and J. Pelletier. Multi-dipolar plasmas for plasma-based ion implantation and plasma-based ion implantation and deposition. *Surface and Coatings Technology*, 186(1-2):170 – 176, 2004. 7th International Workshop on Plasma-Based Ion Implantation.

[3] A Lacoste, T Lagarde, S Bchu, Y Arnal, and J Pelletier. Multi-dipolar plasmas for uniform processing: physics, design and performance. *Plasma Sources Science and Technology*, 11(4):407, 2002.

[4] E.J.T. Burns and G.C. Bischoff. Ion sources for sealed neutron tubes. *IAEA*, 28(043), 1996.

[5] Boreal plasma. http://www.borealplasma.com/, 2007.

[6] Standard specifications for permanent magnet materials. Technical report 0100-00, Magnetic Materials Producers Association, 8 SOUTH MICHIGAN ANENUE / SUITE 1000 / CHICAGO, ILLINOIS 60603.

[7] Los Alamos Accelerator Code Group. Reference manual for the poission/superfish group of codes. Technical report LA-UR-87-126, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, jan 1987.

[8] J. Allison *et al.* Geant4 developments and applications. *Nuclear Science, IEEE Transactions on*, 53(1):270 –278, feb. 2006.

[9] R Geller. *Electron Cyclotron Resonance Ion Sources and ECR Plasmas*. Institute of Physics Publishing, Philadelphia, PA 19106, 1996.

[10] Llnl nuclear and atomic data. https://wci.llnl.gov/codes/tart/nuclearatomic.html, February 2011.

[11] Tom Burnett, Steven P. Rountree, Gary Doolen, and W. Derek Robb. Differential cross sections for electron-impact ionization of helium. *Phys. Rev. A*, 13(2):626–631, Feb 1976.

[12] Taneli Kalvas. Ion beam simulator, ibsimu. http://ibsimu.sourceforge.net/, 2011.

[13] T. Kalvas, O. Tarvainen, T. Ropponen, O. Steczkiewicz, J. rje, and H. Clark. Ibsimu: A three-dimensional simulation software for charged particle optics. 81(2):02B703, 2010.

[14] H-G Mathews, H Beuscher, and C Mayer-Bricke. Status of ecr-source development for isis at jlich. *Physica Scripta*, 1983(T3):52, 1983.

This work was funded by the Sandia Laboratory Directed Research and Development (LDRD) program.. Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Company, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia National Laboratories