Neutron Imaging of Inertial Confinement Fusion Implosions

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Abstract.

During an inertial confinement fusion implosion, energy is produced as the kinetic energy of neutrons that are released from the deuterium-tritium (D-T) fusion reaction. Neutron imaging techniques indicate neutron producing and non-producing regions of the compressed target, allowing a spatial map of target conditions. Primary neutrons from the D-T fusion reaction, at 14.1 MeV, leave the target, some hitting a neutron imager producing an image. Others leaving the target enter dense regions, scatter from the unburned fuel, and are ejected from the core with reduced energies. Two-dimensional hydrodynamics simulations of direct-drive implosions have been postprocessed to calculate neutron images. While imaging the primary neutrons does not give much information about the core, imaging the scattered neutrons can be useful in determining core characteristics. These images can provide information about core distortions, and subsequently about the implosion. This will enable a deeper understanding of why certain implosions fail and why others succeed, aiding in the development of more successful implosions at the OMEGA laser facility, and eventually ignition at the National Ignition Facility.

Introduction.

Nuclear fusion power is one of the most important alternative energy sources. Nuclear fusion is the process by which lighter atomic nuclei combine to form a heavier nucleus. This process involves the release of energy. The most common form of fusion is the deuterium-tritium fusion, in which a deuteron, an isotope of hydrogen, and a triton, a heavier isotope of hydrogen, combine to form a helium nucleus and a neutron as defined by the formula: ${}_{1}^{2}H+{}_{1}^{3}H\rightarrow{}_{2}^{4}He+{}_{0}^{1}n$ [1].

At the University of Rochester Laboratory for Laser Energetics, inertial confinement fusion is researched as a way to make fusion a viable energy source. In inertial confinement fusion, a pellet of deuterium-tritium fuel is compressed by a laser pulse so that fusion can occur. The pellet needs to be compressed because the particles that are fusing have positive charges and therefore repel each other. The laser pulse compresses the pellet, ideally shrinking it over thirty times and bringing it to a temperature of 100 million degrees Celsius[2]. The outer layer heats up from the laser pulse, and explodes away. As it ablates the equal and opposite force, directed inward, compresses the target. As the target compresses, the nuclear reactions occur in the hot core of the pellet, releasing energy in the form of high-energy neutrons. For the reaction to be as effective as possible the pellet needs to compress evenly; however in most cases it does not and distortions occur in the target. These distortions limit the amount of neutrons, and therefore energy, produced[3].

For more successful fusion reactions to occur, it is important to study the previous reactions that succeeded, and diagnose those that failed. To do this, imaging techniques are used to make an image of the core of the reaction. Products from the nuclear reactions can be used to study the core region because high energy (multi-MeV) particles produced have the energy to penetrate the core and escape from the center of the reaction[4]. Traditional imaging techniques include x-rays and other light based imaging. However, using neutrons to image would be useful, since neutrons are produced in abundance by the reaction. Also, it is more difficult to image the colder shell around the core of the reaction because fewer x-rays are produced in colder areas. Neutron imaging provides a way to do this successfully, using downscattered neutrons.

In the center of the reaction, there is a hot low density core where the majority of the neutrons are produced. This occurs because in this higher temperature region, at about 10 keV, the reactant particles, the deuterons and tritons, have enough energy to react and fuse when they collide. Surrounding this core, there is a cold high density shell, with temperatures closer to 1 keV, and densities up to 400 g/cc.

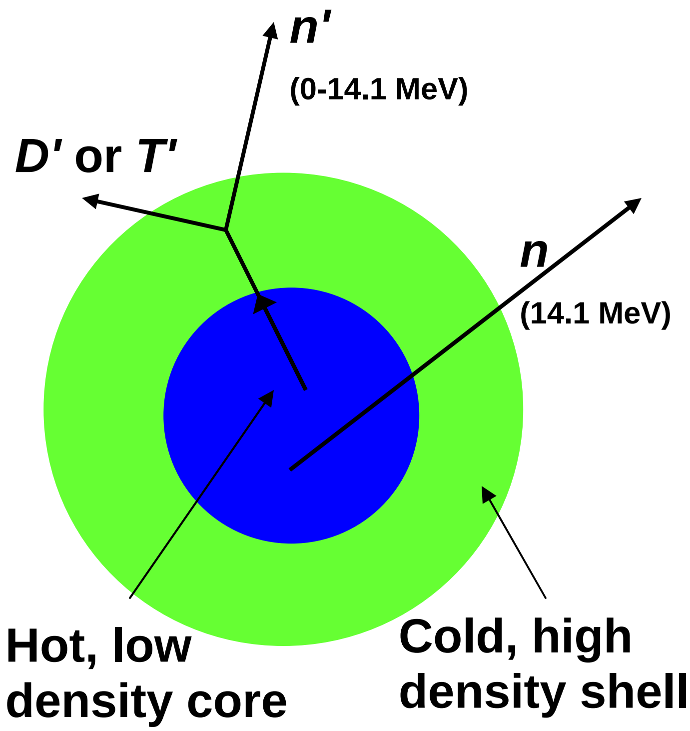

Fig 1. Schematic of a core during fusion reactions.

Primary and downscattered neutrons emerge from the compressed core of a pellet during a fusion reaction (Figure 1). The neutrons generated by the fusion reaction have an energy of 14.1 MeV. These then fly out of the target. While leaving the target, these neutrons travel through the cold shell, and some are downscattered. Downscattered, or secondary, neutrons strike an unburned triton or deuteron and are scattered off in a new direction with a reduced velocity and energy because of conservation of momentum. Since the primary neutrons come from the core they can be used to image it. The downscattered neutrons have a new apparent origin: where they were scattered from. Since the neutrons are most often scattered from regions of high density, the cold shell, they can be used to image it.

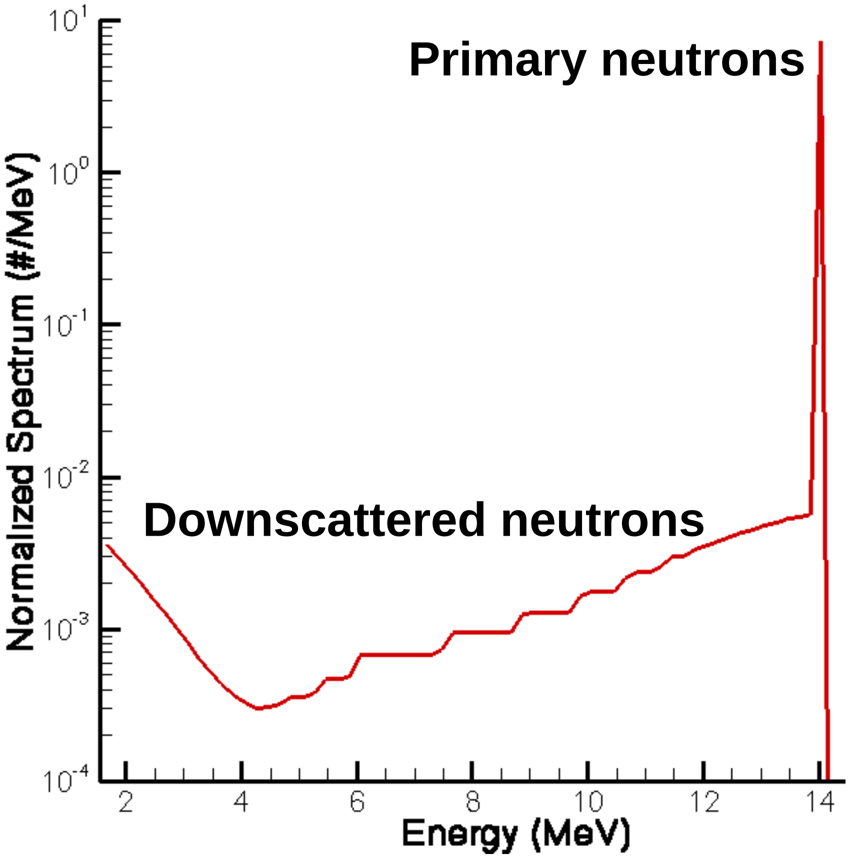

Fig 2. Relative proportions of primary and downscattered neutrons produced

However, neutrons are not downscattered in abundance (Figure 2). Images formed using downscattered neutrons are about two to three orders of magnitude less intense than those formed using primary neutrons[5]. It is thus important to study whether they will be of use as an imaging tool.

Imaging.

Spherically symmetric and distorted profiles were imaged. The spherically symmetric model was used to test the code. It consisted of two regions, an inner core of higher temperature and lower density, and a shell of higher density and lower temperature, both symmetric spheres (Figure 3). This would be characteristic of a 'perfect' implosion, where the pellet would collapse evenly insuring the best reaction. Unfortunately this is not feasible. For a more realistic analysis of the situation, a snapshot of a DRACO simulation of a PDD (polar direct drive)[6] implosion (Figure 4) was used to give a more realistic scenario to test. DRACO[7] is hydrodynamics computer code used to simulate inertial confinement fusion implosions. PDD is one implosion method planned to be used at the National Ignition Facility (NIF). With PDD, the laser beams are not pointed straight at the target center but at angles offset from the center, to compensate for the NIF beams not being arranged evenly around the target chamber. PDD ensures the most uniform compression of the target.

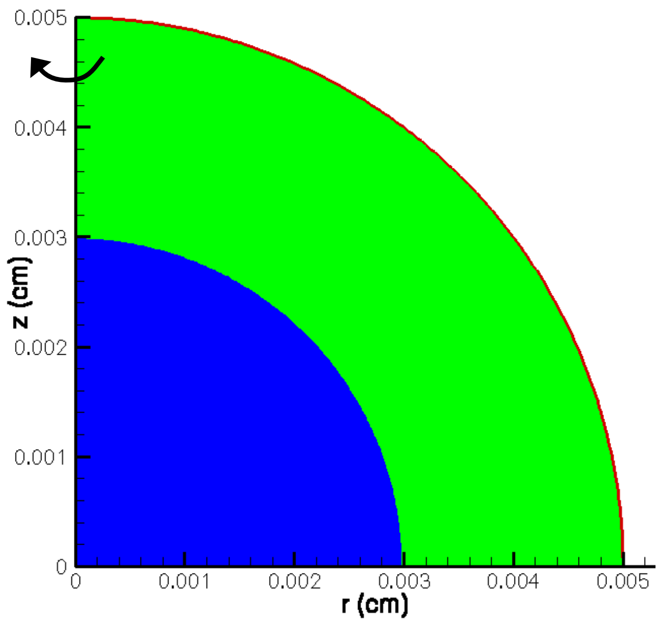

Fig 3. Schematic of a spherically symmetric implosion. The blue area is the hot inner core, and the green area is the cold dense shell.

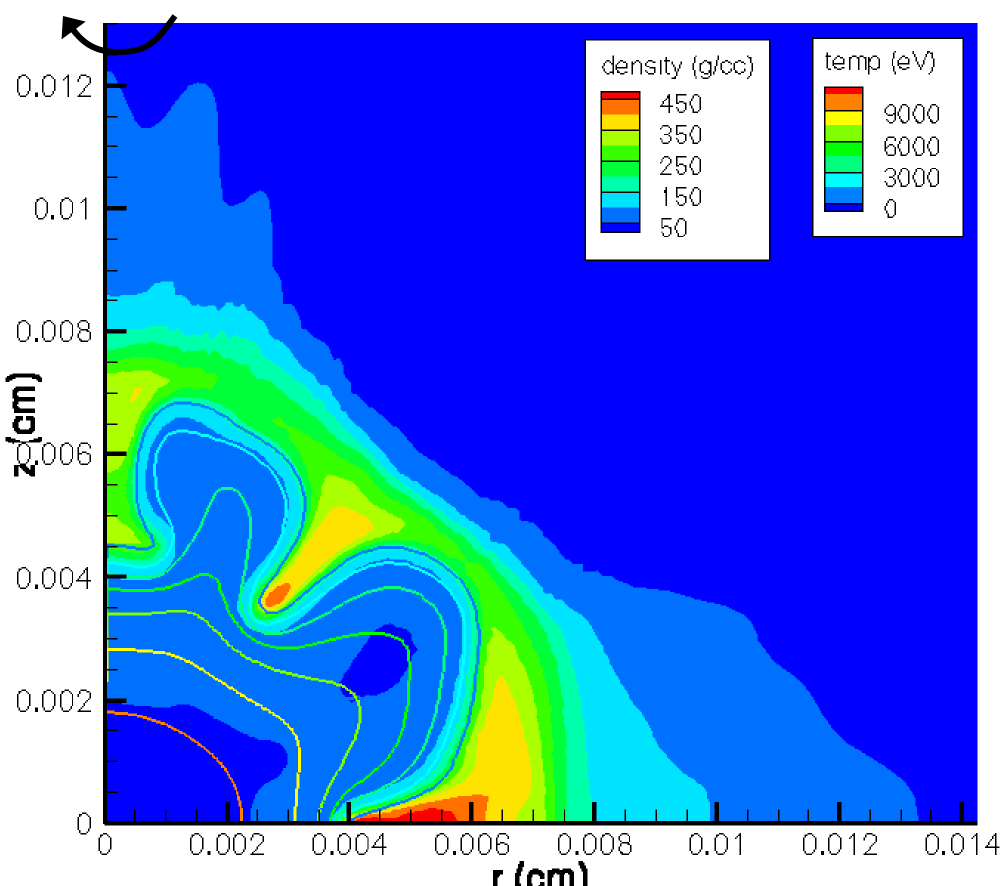

Fig 4. Snapshot from a DRACO simulation of a PDD implosion during peak neutron production. The shaded areas indicate density and the contour lines temperature.

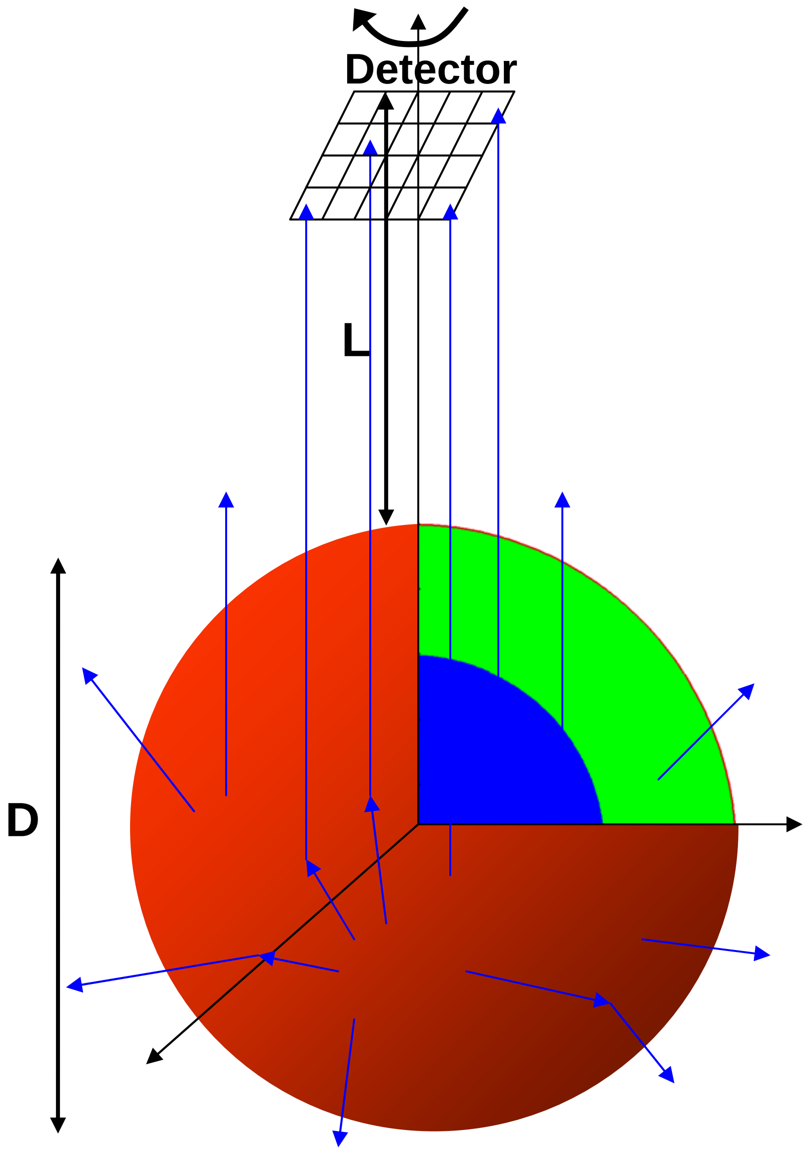

Fig 5. A conceptual schematic of the operation of the IRIS code.

The two dimensional profiles were rotated about the z axis to form a three dimensional profile. Using this profile, three dimensional straight line transport was used to image cores from an IRIS simulation. IRIS[8] is a Monte Carlo code that tracks neutrons and their interactions. In essence it randomly generates a large, statistically significant number of neutrons which it proceeds to monitor and interact with other particles that would be found in a typical implosion scenario. The two dimensional profiles and fundamental variables describing the pellet and core constants were loaded into the IRIS simulation. The simulation then tracked the motion and interactions of the neutrons as they left the target.

IRIS was modified to image the neutrons. It now takes the neutrons that are produced in the ignition scenario and transports them to a detector (Figure 5). The detector is located far away from the target; the distance from the detector to the target is several orders of magnitude greater than the diameter of the compressed target. The detector was an ideal detector: 20 pixels by 20 pixels, each 5 μm in size. IRIS analyzed the movement of the neutrons and recorded their positions when they struck the detector. This data was used to calculate the image of the core as recorded by the neutron detector.

Results.

Imaging primary neutrons provided useful information about the hot core. This makes sense because this is where the neutrons are produced. When the fusion reactions take place the primary neutrons directly leave the core and are not downscattered; thus their position on the detector reveals where they came from in the core. The images of the primary neutrons (Figs. 6 and 7 for the spherically symmetric and PDD models, respectively) show the defined spheres of neutron production. The size of the image is equal to that of its respective hot core in the profiles (see Figs. 3 and 4) and is a little bigger for the distorted profile. Ignoring the higher prevalence of neutrons on the axes of the images, an artifact of the imaging process, the image from the spherically symmetric model (Figure 6) is more uniform, as would be expected. It is not perfectly uniform because of statistics associated with the finite number of neutrons transported. The image of the distorted profile (Figure 7) is less even, and shows neutrons preferentially emitted from a well defined ring.

The images from the downscattered neutrons (Figures 8 and 9) provide useful information about the shell. Downscattered neutrons from within the energy range 6-8 MeV were imaged. In both images the region of the cold dense shell is well defined. In the spherically symmetric case (Figure 8) the region shown on the image is better defined. This is caused by the fact that the spherically symmetric case is unrealistic. The cold shell region is much larger than it would be in an actual implosion, thus the region imaged is much larger. In the more realistic DRACO snapshot, the density of the cold region drops significantly outside of the dense shell, while the shell in the spherically symmetric case extends to the edge of the profile. The image for the downscattered neutrons of the distorted profile (Figure 9) from the DRACO polar direct drive implosion simulation reveals more about the viability of neutron imaging. The most evident feature of the image is the fact that the definition of the shell region is much lower. This is caused because the shell region is much smaller and more distorted. Also, there were poorer statistics for the distorted case. Since there were differences between the two profiles affecting neutron production, the distorted simulation produced less neutrons to be imaged than the symmetric case for the same running time.

Conclusion.

Neutron imaging is a useful tool for diagnosing the compressed shell during an inertial confinement fusion implosion. Traditional imaging techniques, primarily x rays, have a difficult time imaging the cold higher density shell of an ICF implosion because fewer x rays are produced there due to the colder temperatures. Primary deuterium-tritium neutrons at 14.1 MeV and downscattered neutrons (0 to 14.1 MeV) have been studied as an imaging tool. While primary neutrons can image the hot core well, x rays already do this well. Downscattered neutrons, on the other hand, can be used to image the cold shell, because this is where they are scattered from the most easily, and thus their apparent origin is there. While the neutron yield on the OMEGA laser system may not be enough to produce high quality neutron images, the NIF laser system should create a significant yield to allow neutron imaging to be a valuable diagnostic tool.

Images From Primary Neutrons.

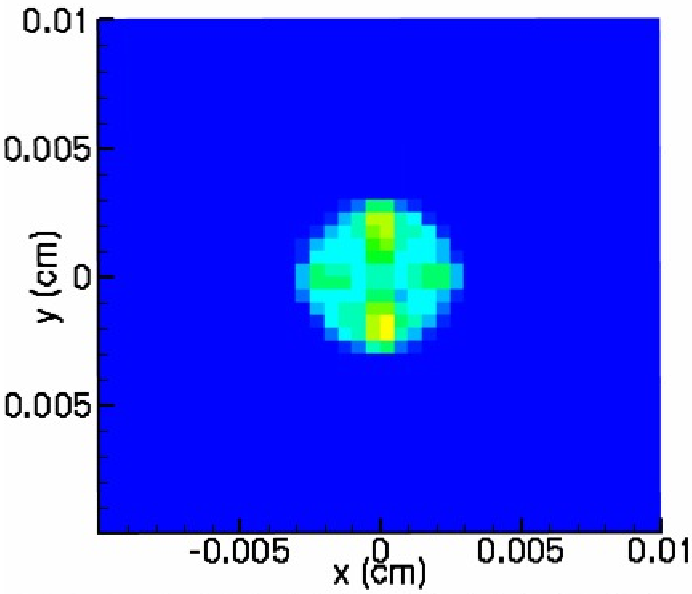

Fig 6. Spherically Symmetric Profile

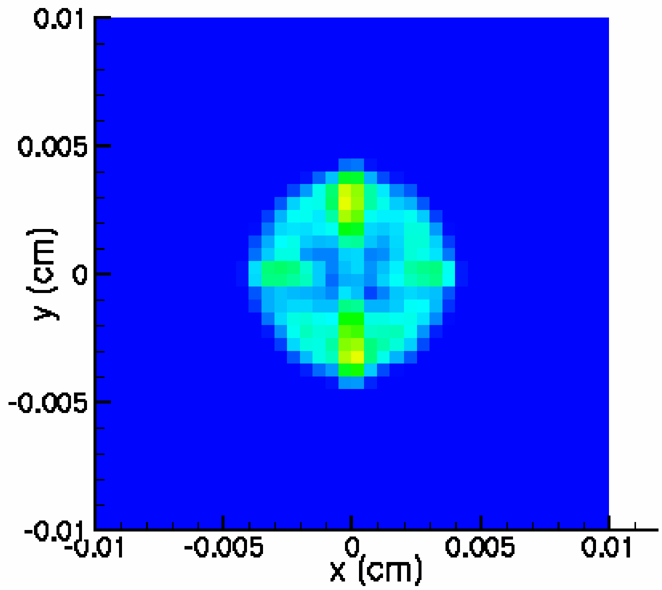

Fig 7. Distorted Profile

Images from Downscattered Neutrons

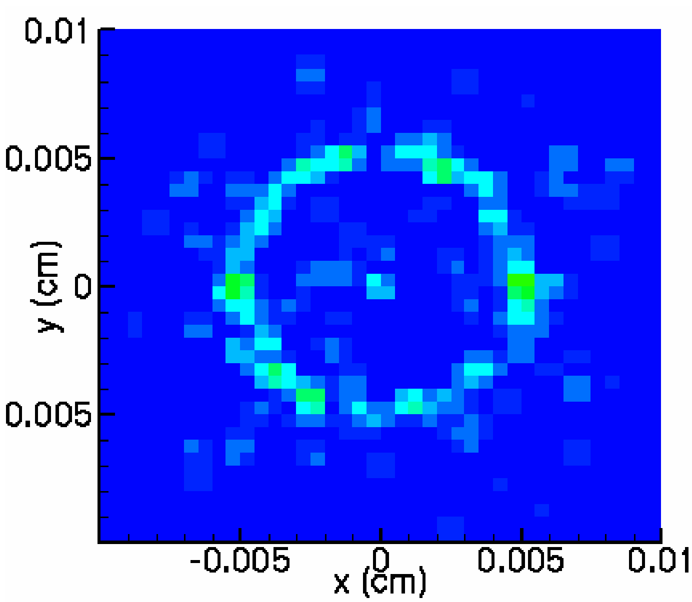

Fig 8. Spherically Symmetric Profile

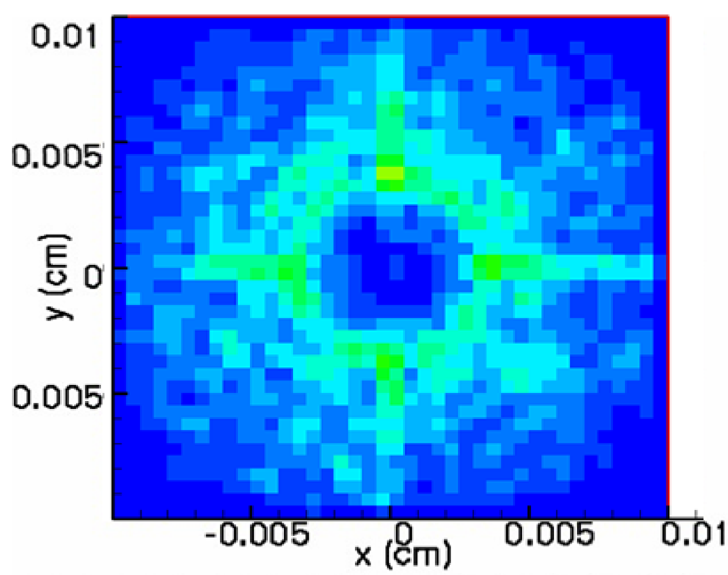

Fig 9. Distorted Profile

Future Work.

Other steps can be taken to expand the significance of this investigation into neutron imaging. The number of neutrons simulated needs to be increased to get better results. Better statistics are needed to determine whether core distortions can be imaged using neutrons. To improve statistics within the imaging simulation, its features, such as axisymmety can be exploited to increase the statistical return of IRIS. More realistic images would give more information about the full viability of neutron imaging. As of now, the images are snapshots; time-integrating the images would lead to more realistic images. In addition, the appropriate scintillators and detectors have not yet been created for proper neutron imaging. However the expected detector response can be folded in to the simulation and imaging process. Other energy ranges and views of the target should be investigated to determine which are the most effective for imaging the core distortions[9]. Assuming that distortions can be imaged to some degree of success, correlating failure modes with images would be an important step for using neutron imaging as a successful diagnostic tool.

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