# Direct Conversion of High Energy Protons Using a Solid State PIN Junction Diode

*David R. Boris, Zhenqiang Ma, Hao-Chih Yuan, Robert P. Ashley, John F. Santarius, Gerald L. Kulcinski, Clayton Dickerson, Todd Allen*

*Fusion Technology Institute*

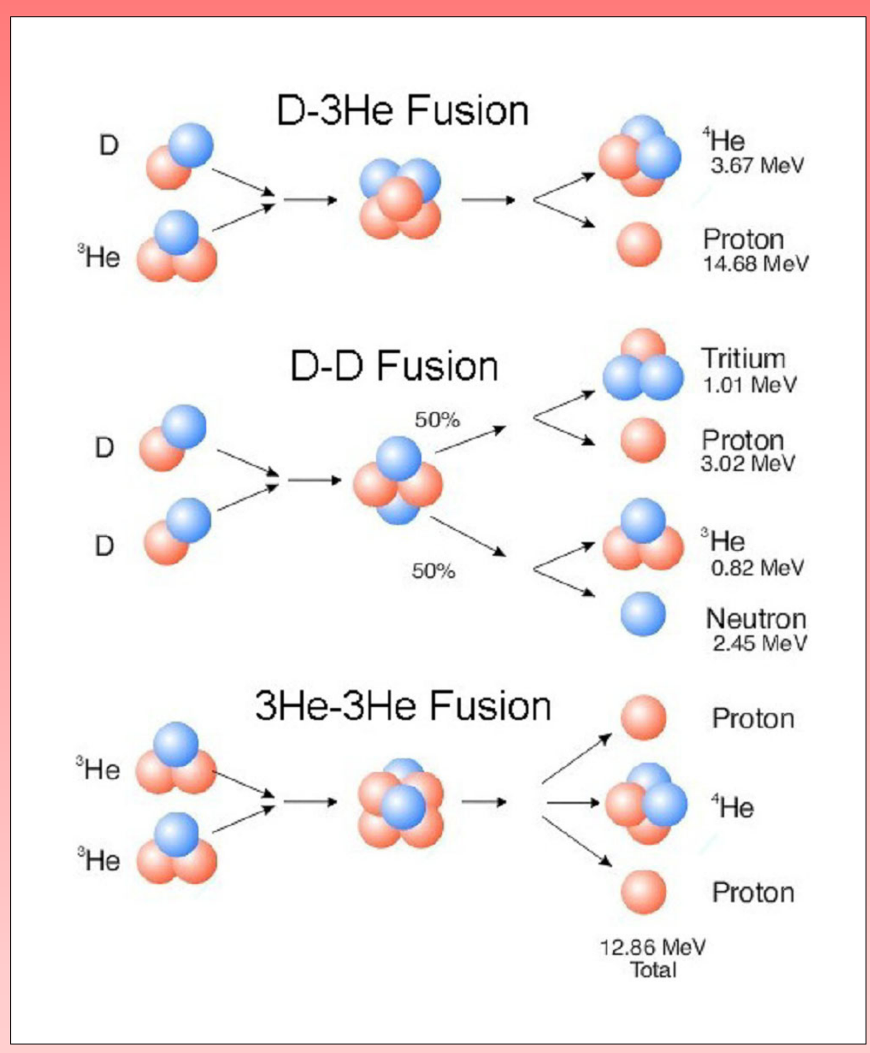
THE UNIVERSITY of WISCONSIN MADISON

## Abstract:

*Using a single junction PIN (p-type, intrinsic, n-type) diode made of silicon and doped with boron and phosphorus high energy protons have been converted to electricity, through ionization from electronic stopping in the silicon, at an efficiency of 0.2%. The 3.02MeV D-D protons were simulated using a 3MeV linear accelerator. Proton fluxes of ~$3x10^{10}$ protons-$cm^{-2}s^{-1}$ were incident on a PIN diode with 0.7$cm^2$ of surface area facing the incident protons. Losses in efficiency as a function of proton fluence are compared with dpa (displacements per atom) rates calculated using the Monte Carlo ion transport code TRIM (Transport and Ranges of Ions in Matter).*

## Introduction

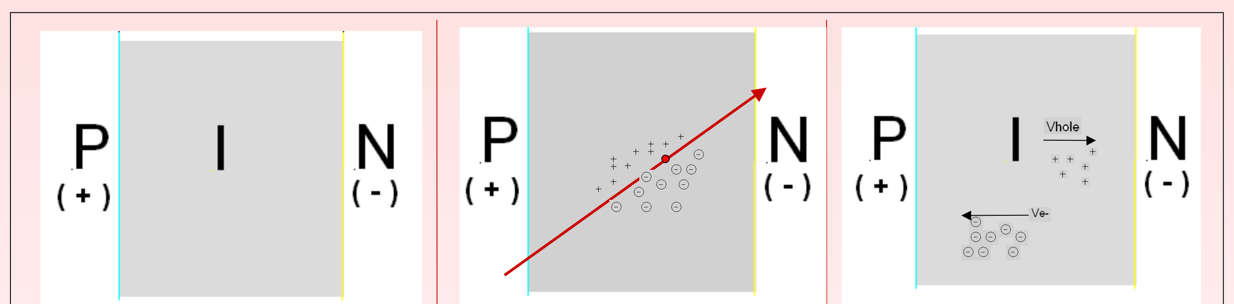
The purpose of this work is to examine the viability of using semiconductors to convert high-energy protons from advanced fuel cycle fusion reactions to electricity.




This figure illustrates the array of high energy proton producing fusion reactions to which solid state energy conversion may be applicable

•A PIN diode acts like a solar cell when irradiated with high energy charged particles (i.e. fusion protons)

•PIN junction diodes are characterized by a large intrinsic region between heavily doped P-type and N-type regions.




Pre-proton impact

•A built in electric field exists due to P and N type dopants (Boron and Phosphorus)

High Energy proton impact

•Electronic Stopping of the proton causes formation of e-/hole pairs in semiconductor

Post proton impact

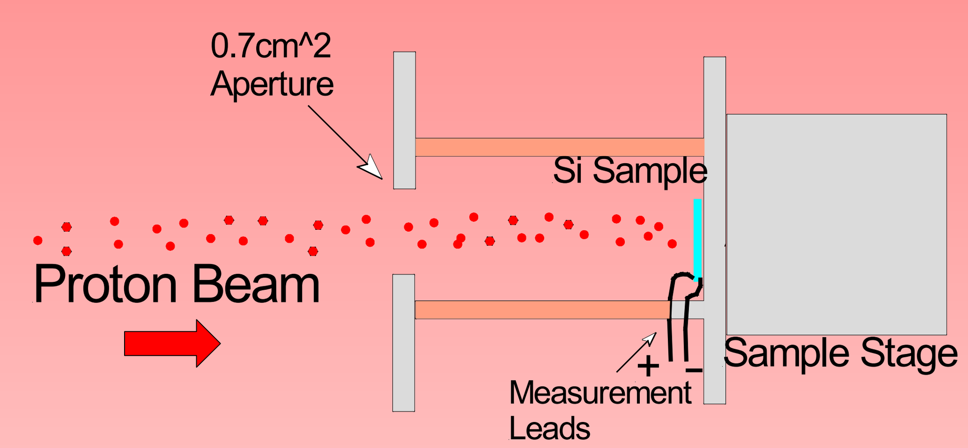
•Either the built in electric field across the PIN junction will cause the electrons and holes to move, inducing a current

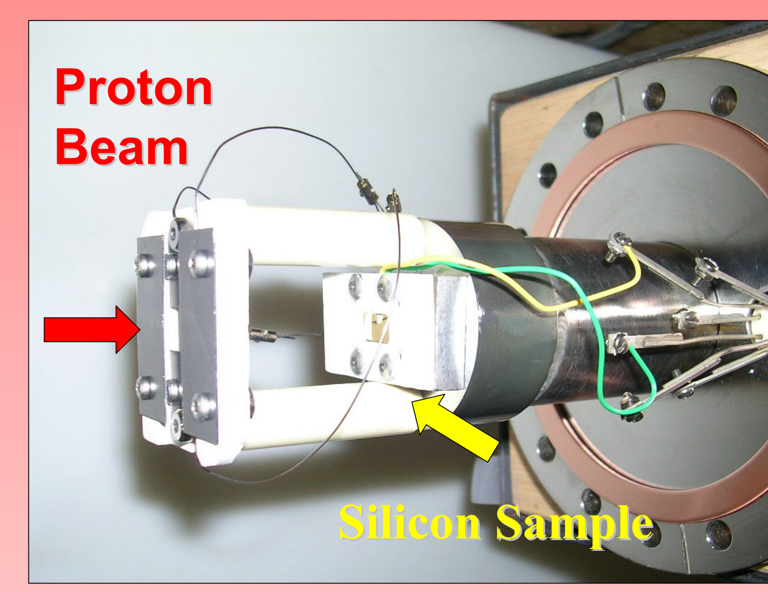
## Experimental Setup

•Experiments performed in the UW Ion Beam Lab will utilize 3MeV protons produced from a linear accelerator, to simulate D-D fusion protons.

•The proton beam has a narrow Gaussian spatial profile when focused into the test section of the beam-line. The beam is then rastered to attain a uniform fluence across the exposed area of the sample.

•The proton flux on the sample was determined to be between $1x10^{10}$ and $5x10^{10}$ protons-$cm^{-2}$-$s^{-1}$.

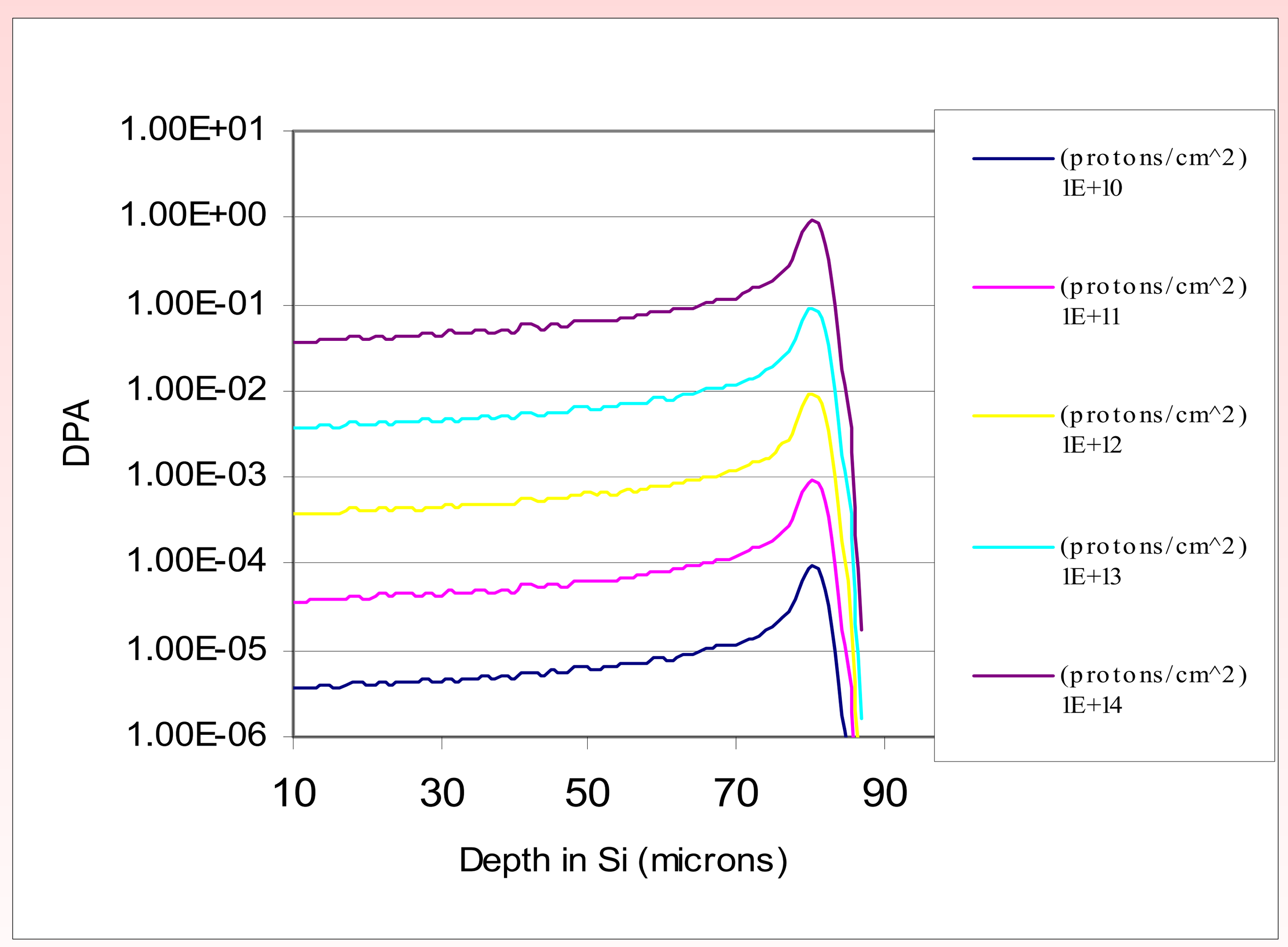



The above figures shows the a diagram of the experimental setup used in the UW-Ion Beam Lab to simulate D-D fusion protons.

## TRIM Simulations

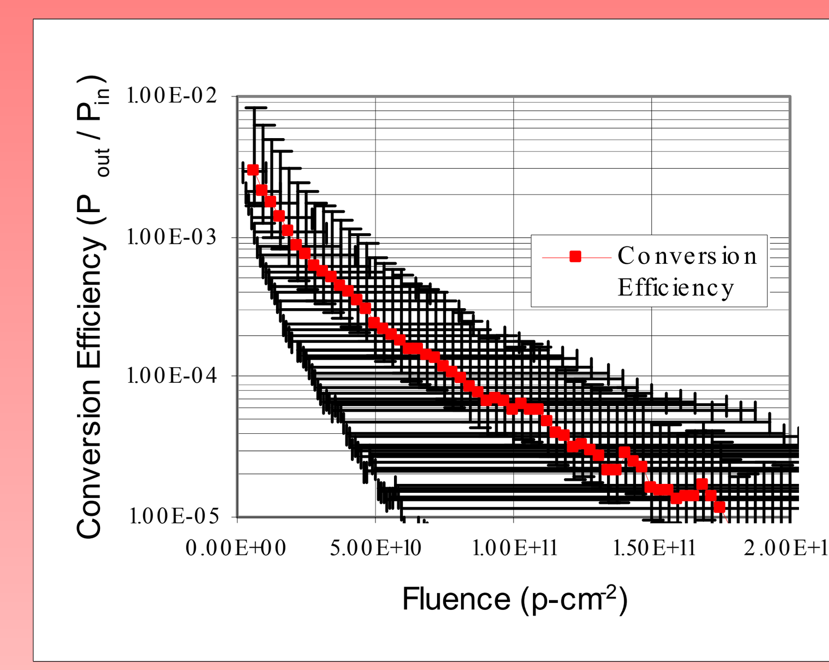
The amount of lattice damage present in the device at different proton fluences was simulated using TRIM. The TRIM simulations were used as a means to correlate proton fluences attained in the experiment with differing levels of damaged attained in the device. The correlation between proton fluence and damage in *dpa*, (displacements per atom) are shown in the figure below.



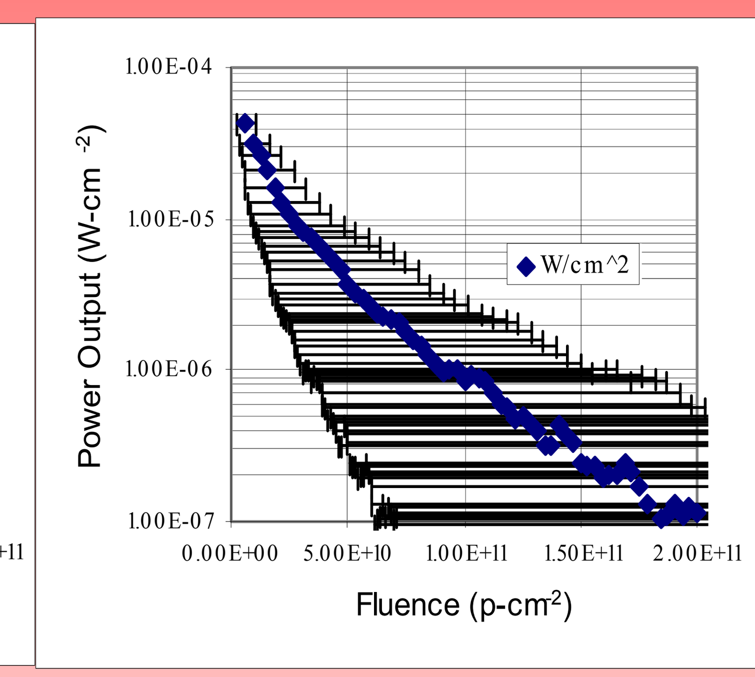

## Experimental Results

•The maximum achieved conversion efficiency for the device was between 0.2% and 0.8%.

•The maximum achieved power output per unit area from the PIN diode was 40μW-$cm^{-2}$.




Conversion Efficiency as a function of proton fluence for a silicon PIN junction diode.




Power output per unit area as a function proton fluence for silicon PIN diode.

## Discussion and Conclusion

•At room temperature the conversion efficiency and power output of silicon PIN diodes decreased by a factor of 100 at proton induced damage levels of $1x10^{-3}$ dpa.

•A solution to the lattice damge involves operating the devices at higher temperatures, and thus annealing out the damage as it is created.

•However, high temperature operation will decrease efficiency significantly in silicon due to an increase in parasitic thermally induced currents.

•Wide band-gap semiconductors (e.g. SiC) are less susceptible to high temperature effects an may be able to operate effectively temperatures necessary for damage annealing

•Application of this technology to advanced fuels fusion reactors would only be practical if high temperature operation can solve the damage problem.

**Contact Information:** **Dave Boris** drboris@wisc.edu **608-265-2937**