Direct Conversion of D-^{3}He Protons Using a Silicon PIN Junction Diode

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Project Goals

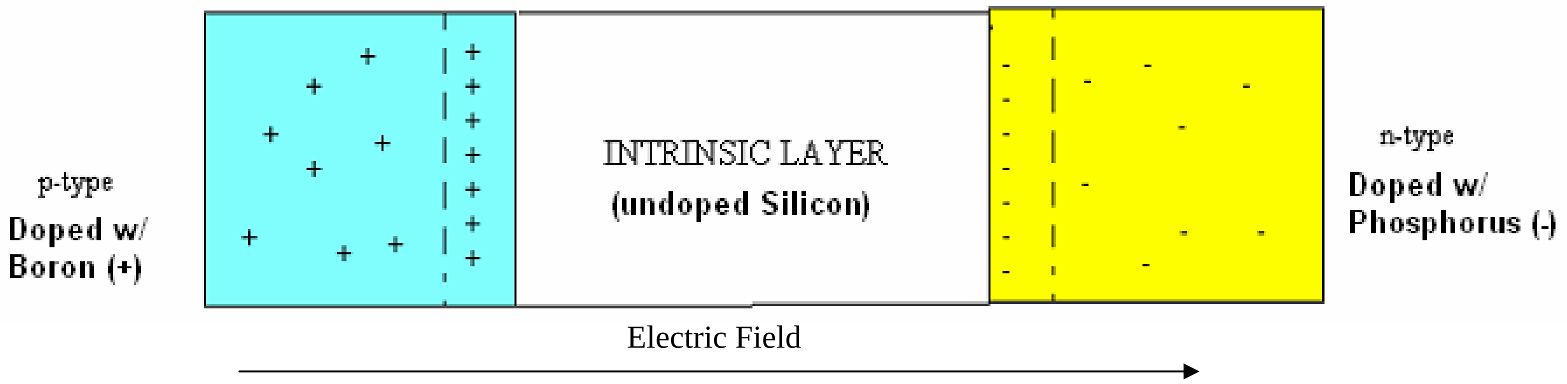
- Proof of principle for using a solid state device as a means to convert D-^{3}He fusion protons to electric power

- Measure the efficiency of such a device and compare with theoretical predictions

- Characterize the damage induced in such a device under proton fluxes similar to those in a power reactor.

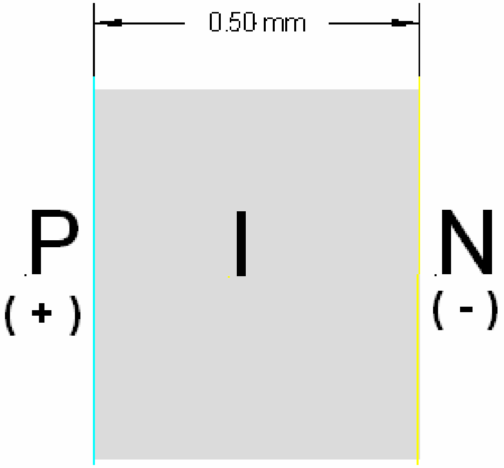
Direct Conversion Theory

- Semiconductor devices have a inherent voltage drop due to p-type and n-type dopant. Charge carriers (e- / holes[+]) induced in the semiconductor will move in



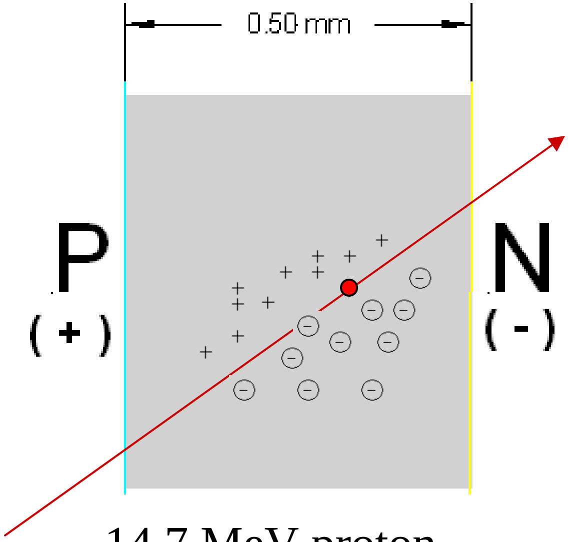
Inherent Voltage drop creates a built in Electric field which creates an electric current from any charge carriers created from incoming radiation.

Direct Conversion Theory Continued



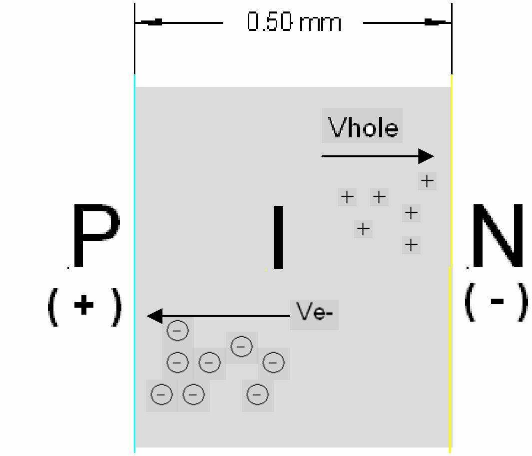
Pre-proton impact

- •P-positive dopant (boron)
- •I-intrinsic (pure) silicon
- •N-negative dopant (phosphorus)



14.7 MeV proton impact

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



Post proton impact

- •Either the inherent voltage across the PIN junction or an applied voltage will cause the electrons and holes to move, inducing a current

Efficiency of Direct Conversion

- The following defines the expected efficiency of the PIN diode energy conversion scheme.
- V_{diode}= Effective voltage drop of diode (max @ inherent voltage [~1V in Si])
  - Typically $V_{diode} \sim 0.7V_{inherent}$
  - Dopant concentration has a significant effect on $V_{inherent}$
- $\gamma \equiv$ proton flux (protons/cm^{2}s)
- $E_{pair} \equiv$ Energy required to create e$^-$/hole pair in Si (3.62eV – Knoll [Table 11.1])

Material	Si	Ge	GaAs	SiC	Diamond
Vinherent(V)	1.1	0.7	1.4	2.4	5.5
Epair(eV)	3.6	3.0	4.7	8.8	16.5
Vdiode(V)	0.7	0.4	0.9	1.5	3.5

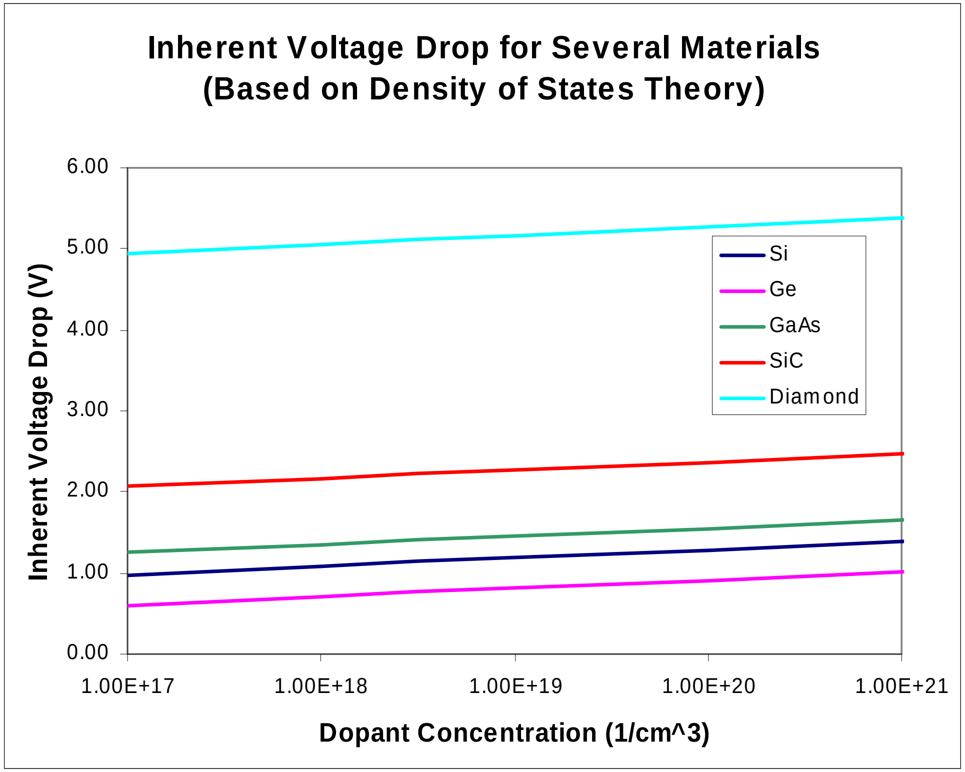
- $E_p \equiv$ Energy of incident proton
- The following calculation is with Si:

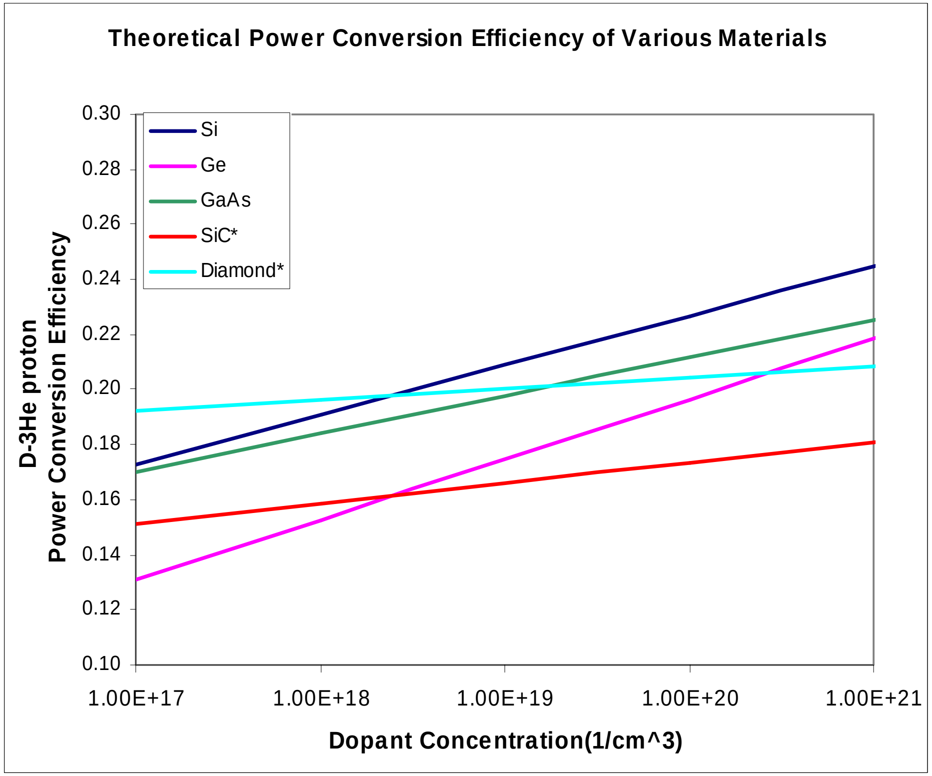
$$P_{in} = \gamma e E_p (eV)$$

$$P_{out} = V_{diode}(Volts)\frac{\gamma e E_p (eV)}{E_{pair}(eV)}$$

$$\eta = P_{out}/P_{in} = \frac{V_{diode}}{E_{pair}} \approx \frac{0.7(Volts)}{3.62(Volts)} = 19\%$$

Direct Conversion Efficiency Depends on "Inherent Voltage Drop" and e^-/hole Pair Creation Energy

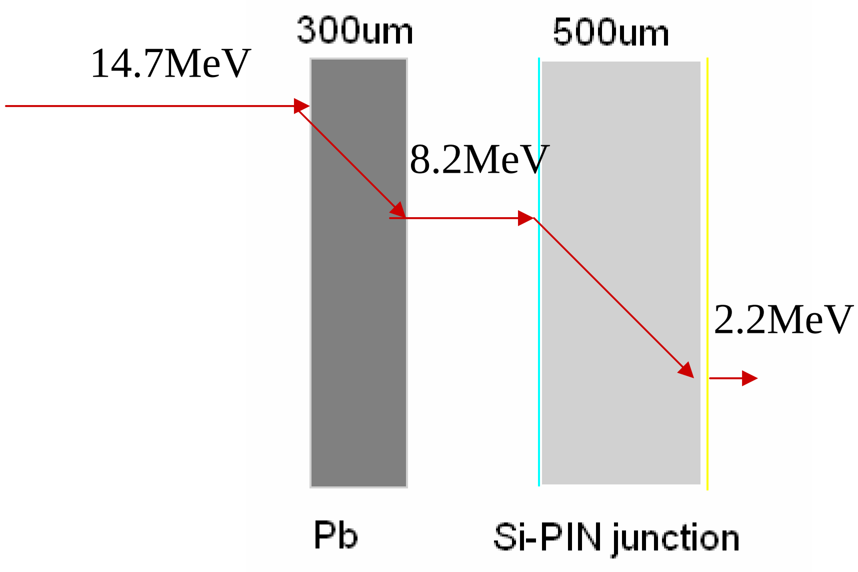




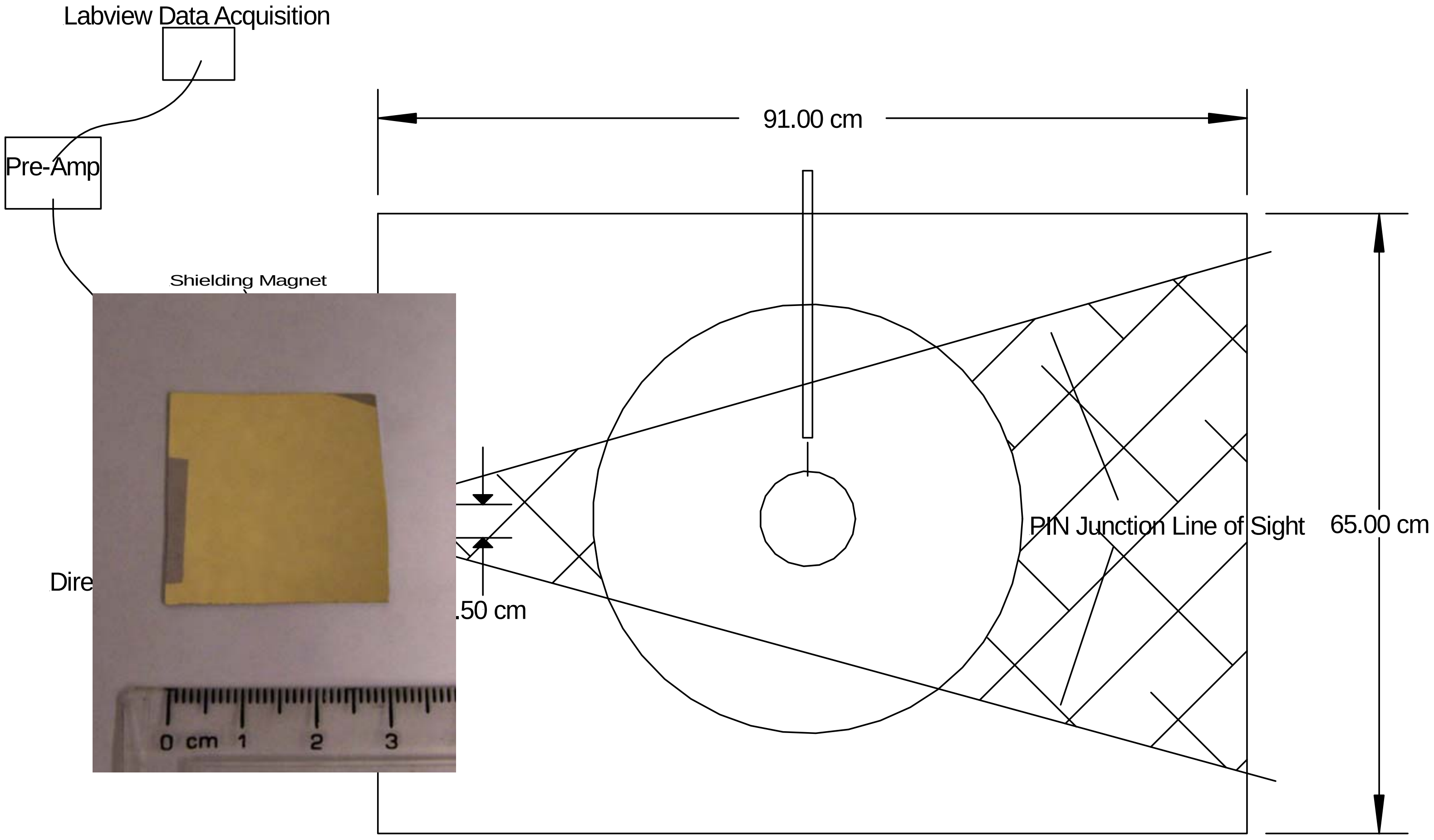
Theoretical Efficiencies for solid state devices range from ~10% - 25% over a range dopant concentrations.

Configuration of UW-IEC D-^{3}He Proton Direct Conversion Experiment

- Current PIN junction configuration
  - 300um Pb shield (X-Ray shielding)
  - 500um Si PIN junction diode (to limit damage at end of trajectory)
- This utilizes about 6MeV of 14.7MeV available in the D-3He proton.
- PIN diode face is 10cm^2 → ~1nA of current with IEC proton rates of 1x10^7

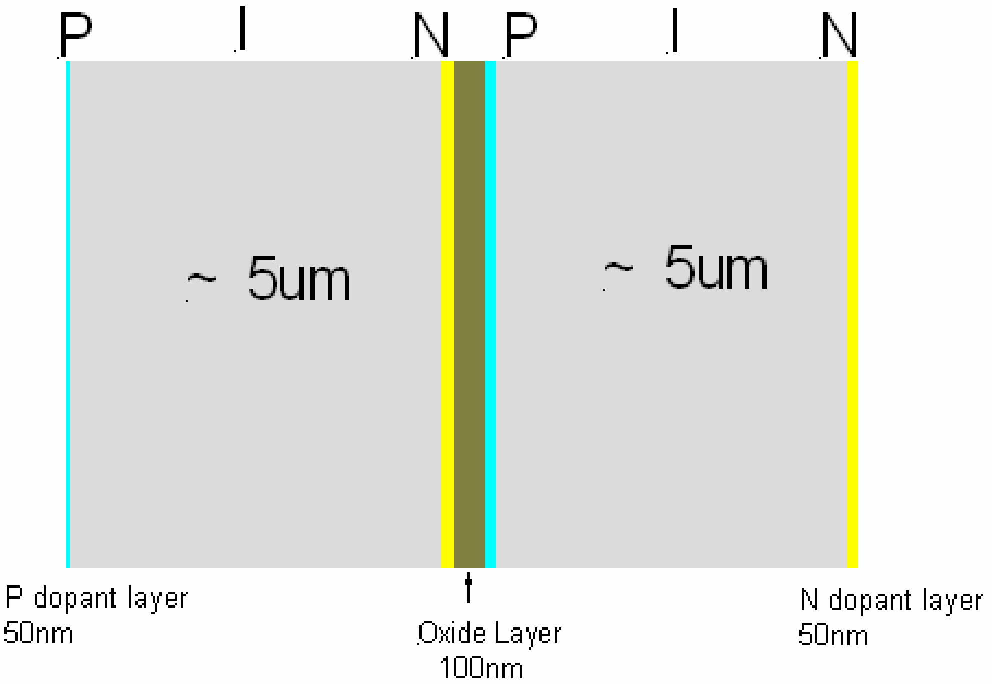


Configuration of UW-IEC D-^{3}He Proton Direct Conversion Experiment



PROBLEM: Charge Carrier Lifetime can Limit the Usefulness of 500 μm Thick PIN Junction Design

- Typical lifetimes of e^-/hole in Si is ~10-100 μs.
- $V_{inherent}$ = 1V → E-field = 2000V/cm (in a 500 μm thick PIN junction)
- In a 2000V/cm E-field a charge carrier spends ~10-20 μs in the junction. (Recombination is possible)



Solution:
By layering smaller junctions in series or in parallel this problem can be avoided.

Conversion Efficiency and Proton Damage Effects will be Measured

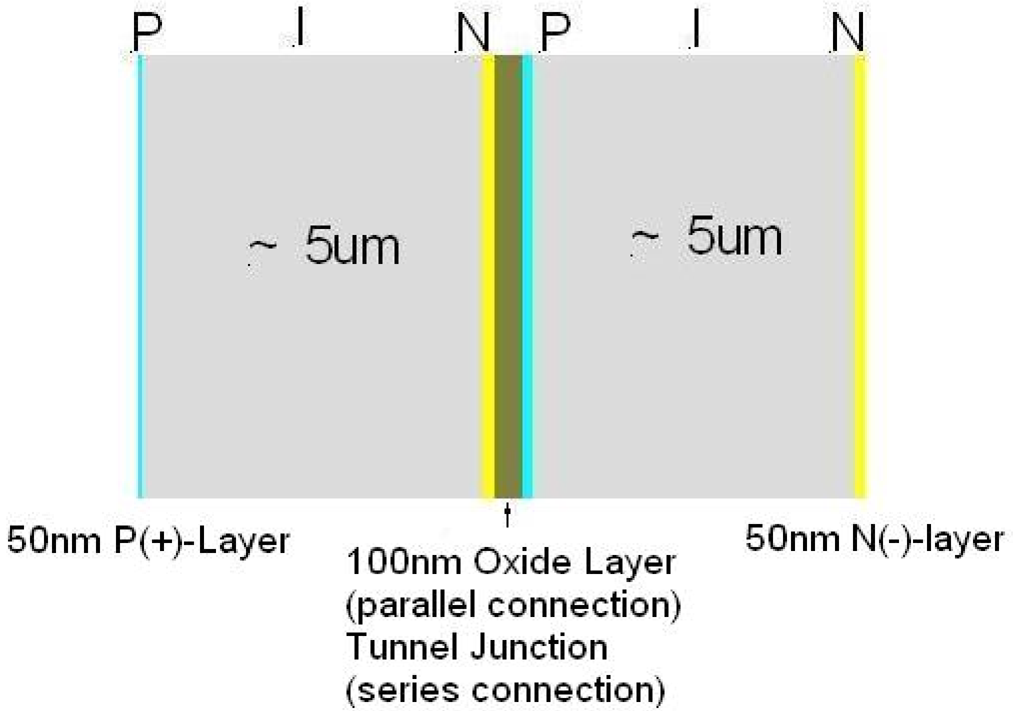
- Once principle has been proven on IEC device a 3MeV linear accelerator will be used for:
  - Measuring the efficiency of PIN junction technique
  - Examining the effect of radiation damage on conversion efficiency and device performance.

Summary

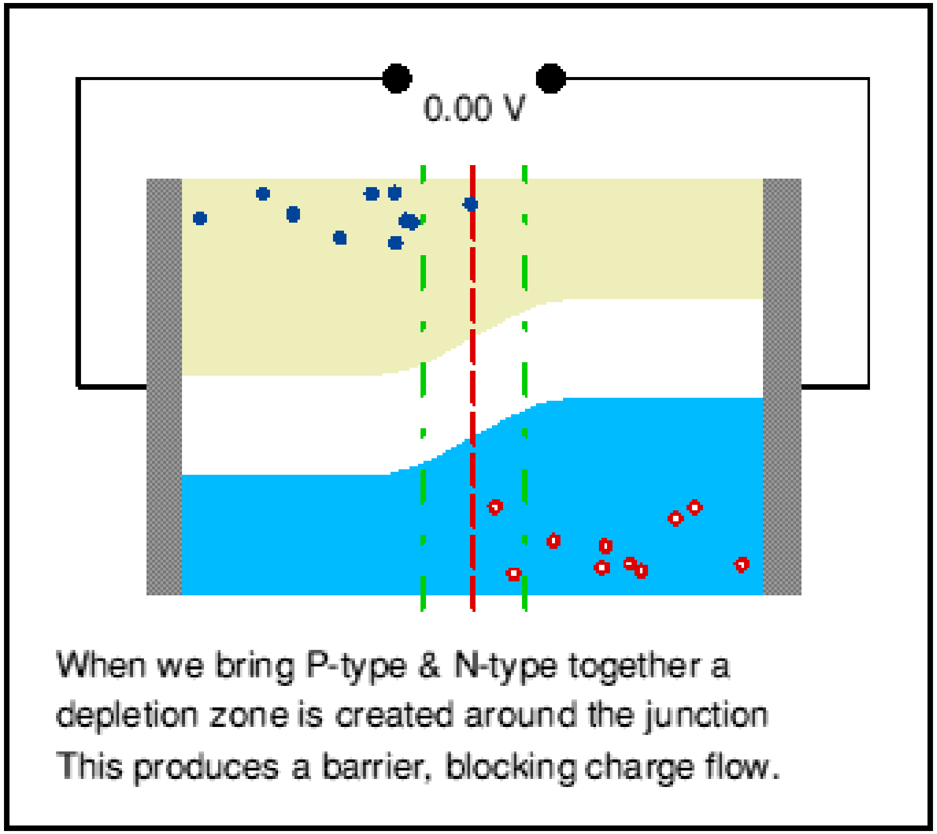
- The theoretical efficiency of a PIN junction direction energy conversion device has been calculated to be ~20%
- An experiment is in progress at the University of Wisconsin to prove the principle of using a PIN junction to convert D-^{3}He protons to electric power.
- Future experiments are planned to measure the efficiency of a PIN junction converter and analyze the degradation of device performance due to radiation damage from protons.

Future Work

- Efficiency and radiation damage measurements on accelerator have yet to be done.
- Multi-junction design would be more useful for power conversion applications. This design is more expensive to fabricate but should eventually be tested.



How a Diode Works



When we bring P-type & N-type together a depletion zone is created around the junction This produces a barrier, blocking charge flow.

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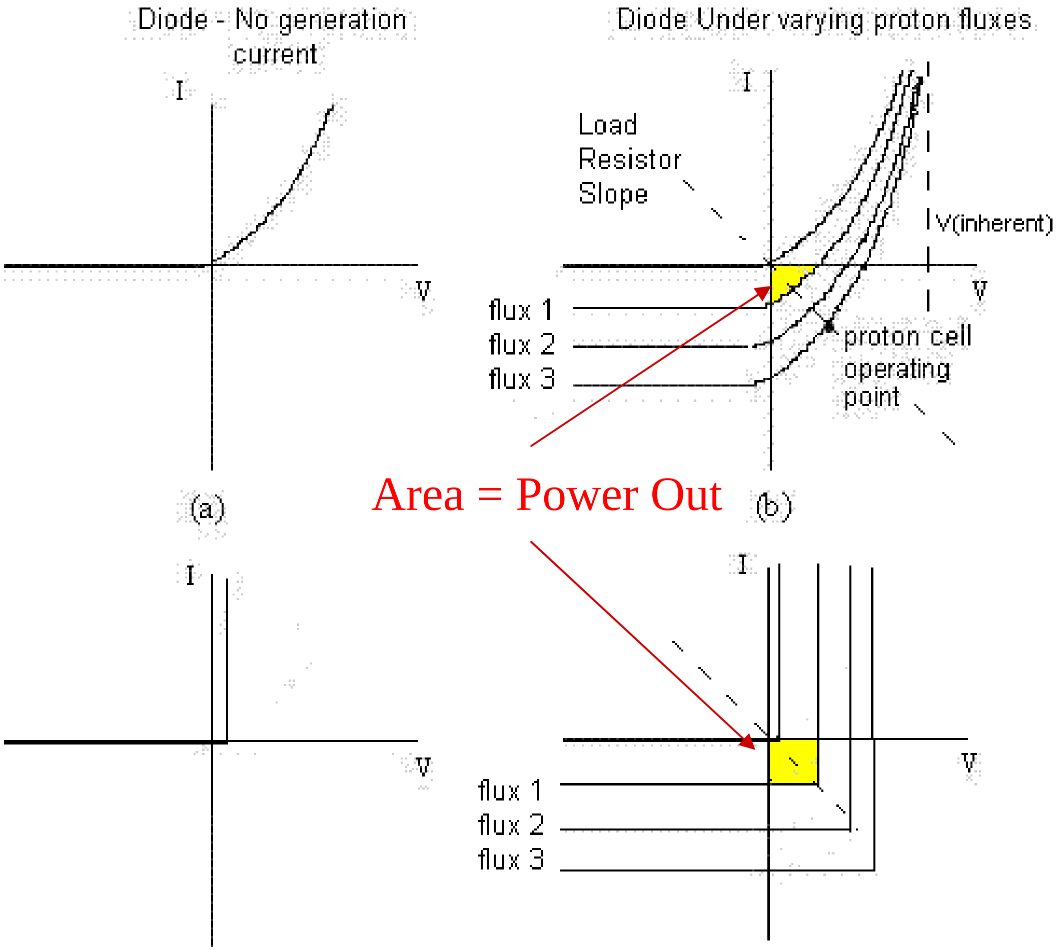
- Proton Detectors operate in reverse bias mode

- Direct Conversion depends on inherent voltage drop with 0V applied.

Theoretical Power Conversion Efficiency is Affected by Real Diode Characteristics

Real PIN Diode Characteristics

Ideal PIN Diode Characteristics



Area = Power Out

$$P_{real} \sim 0.7P_{ideal}$$