Hydrogen and Helium Isotope Separation by Permeation Through a Palladium Foil

Brandon Pelc[a] , advised by Professor Cohen[b], Professor Koel[c], and Dr. Buzi[b]
[a] University of Illinois at Urbana-Champaign, [b] Princeton Plasma Physics Laboratory, [c] Princeton University

Abstract

The Princeton Field-Reversed Configuration research experiment is a type of magnetic confinement device that utilizes odd-parity rotating magnetic fields to induce closed field lines, drive current, and heat the plasma. The fuel, D-^{3}He, that would be used in this type of device is aneutronic. However, deuterium (D) atoms in the plasma can fuse with each other to produce tritium (T). The T must be extracted to stop D-T reactions from occurring, which produce high energy (14 MeV) neutrons. Removing T from the plasma will allow for a cleaner and lower radioactivity plasma. One way to separate Hydrogen (H) and Helium (He) isotopes is to utilize a high Z material – permeation barrier – high Z material (ZBZ) configuration. Palladium (Pd) has a high H/He sorption rate and high selective permeability through conversion to a metallic hydride when heated to high temperatures, which increases H/He diffusion. This experiment focuses on how H permeability through a Pd foil is affected by temperature and pressure.

Permeability

- Permeability – the penetration of gas atoms through a solid by diffusion, the product of solubility and diffusion;

$$P = S \times D$$

Where:
S = Solubility Coefficient
D = Diffusion Coefficient

- Dependent on partial pressures of the gas permeate;
- Surface dissociation/association plays a role;

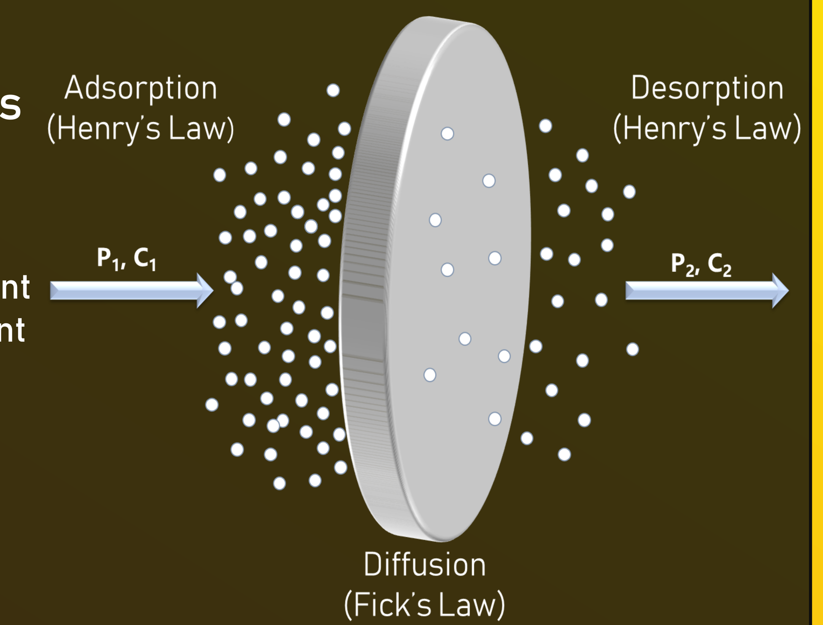
Temperature ↑ ⇒ Diffusion ↑ Solubility ↓

- Generally, every 10 °C increase in temperature causes permeation rate to double;
- Solved using Fick's first and second law.

$$J = -D\frac{dC}{dx}$$

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}$$

Where:
D = Diffusion Coefficient
C = Permeate Concentration
x = Material Thickness



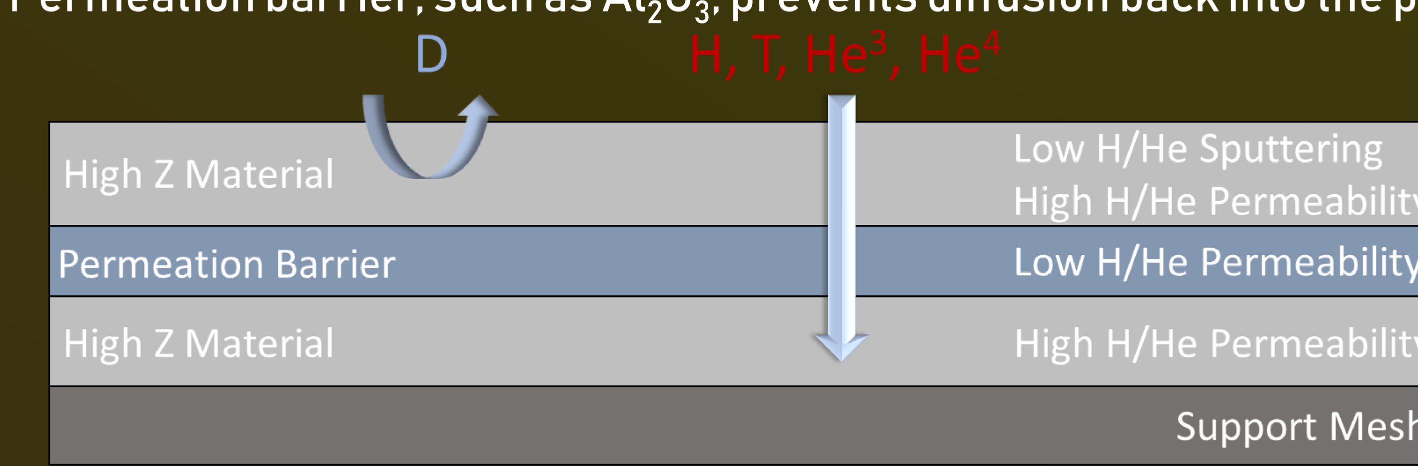
Palladium & ZBZ Configuration

Palladium:

- High Z material with low sputtering yield;
- High H/He sorption and permeability at high temperatures;
- Converts H to a metallic hydride at high temps → increased diffusion;

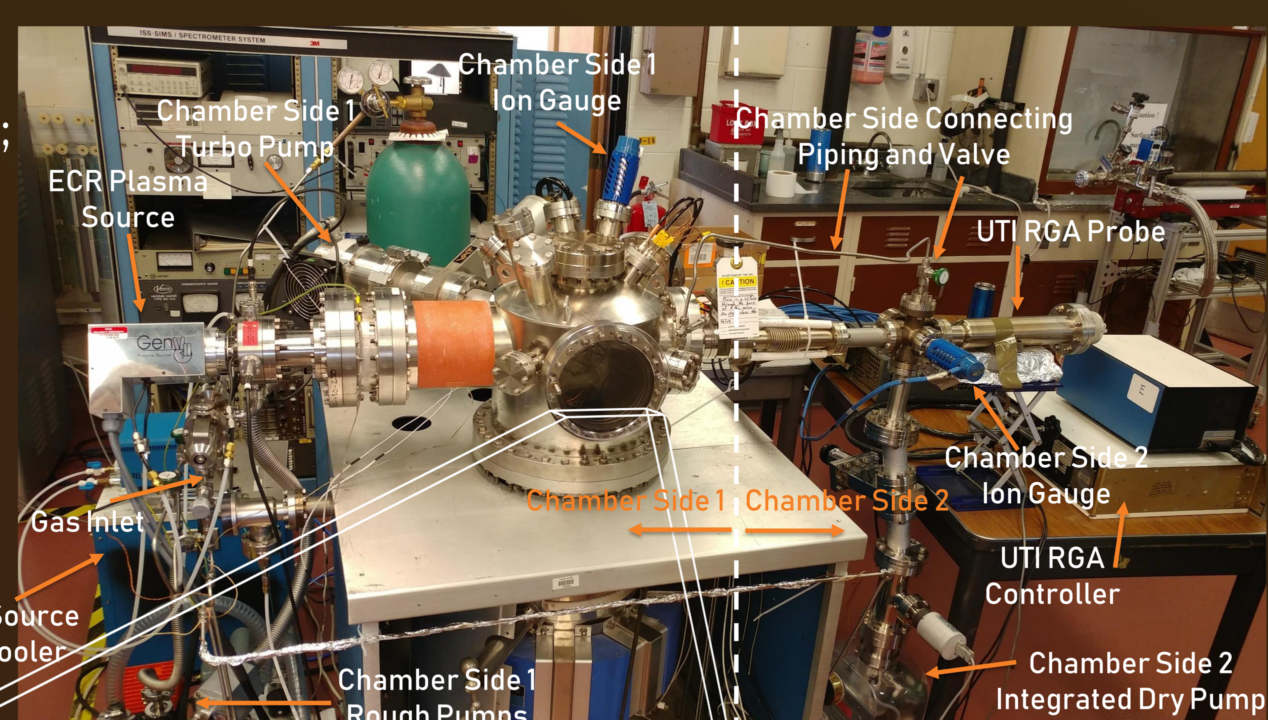
ZBZ Configuration:

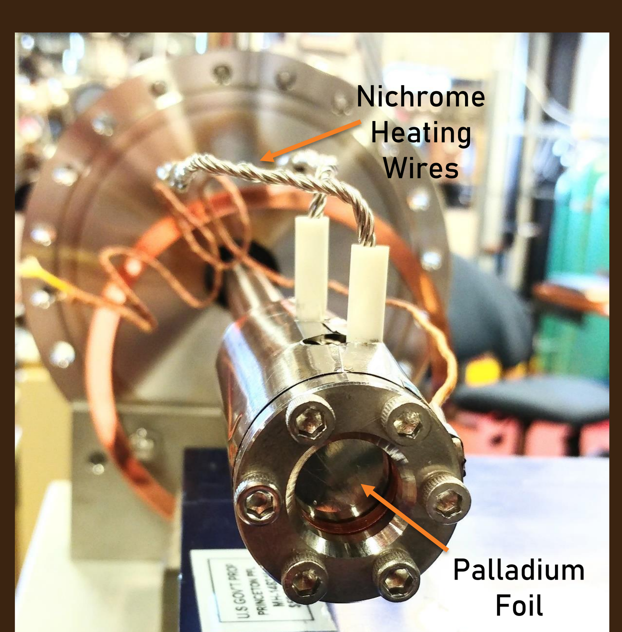
- Permeation barrier, such as Al_2O_3, prevents diffusion back into the plasma.

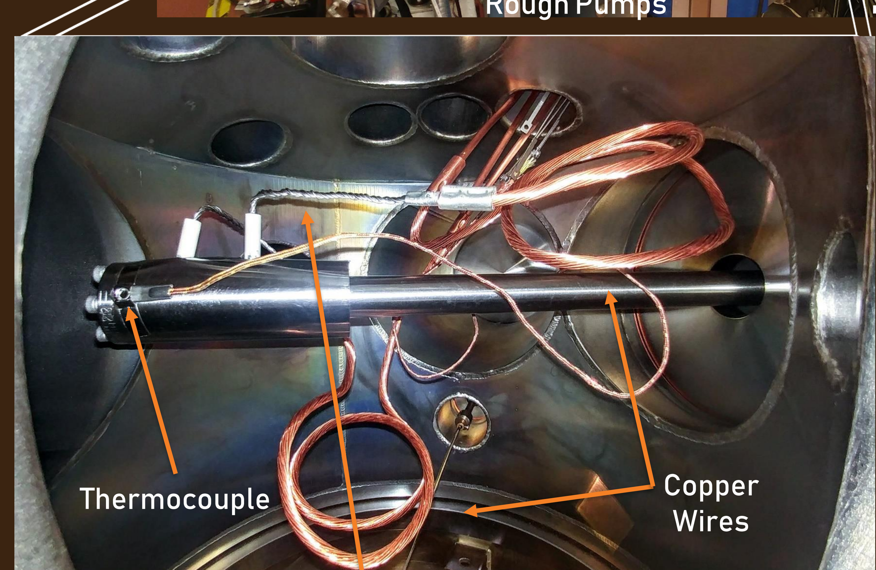


Experiment

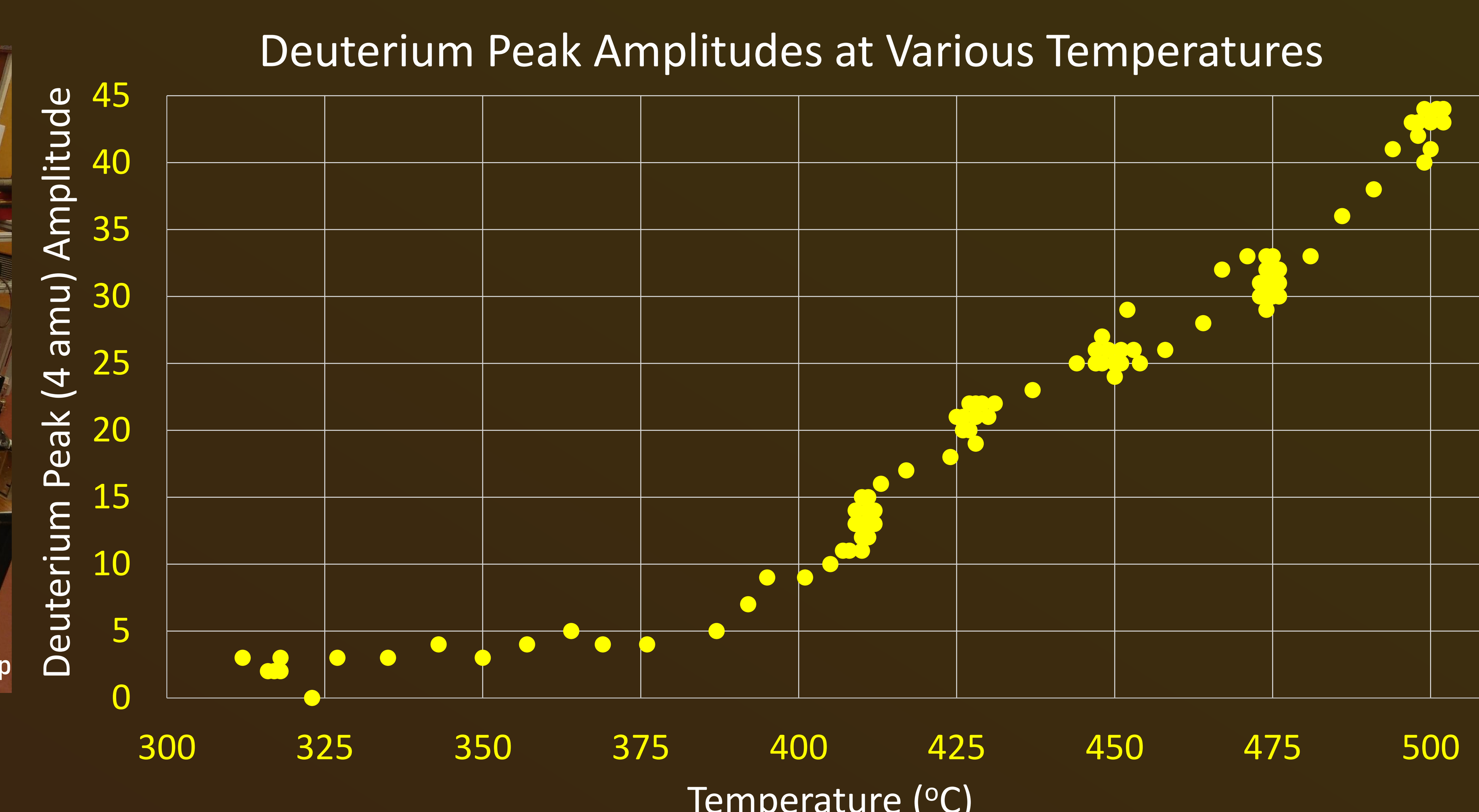
- Assembled experimental chamber;
- 1 mm thick Palladium foil;
- ECR plasma source, argon used;

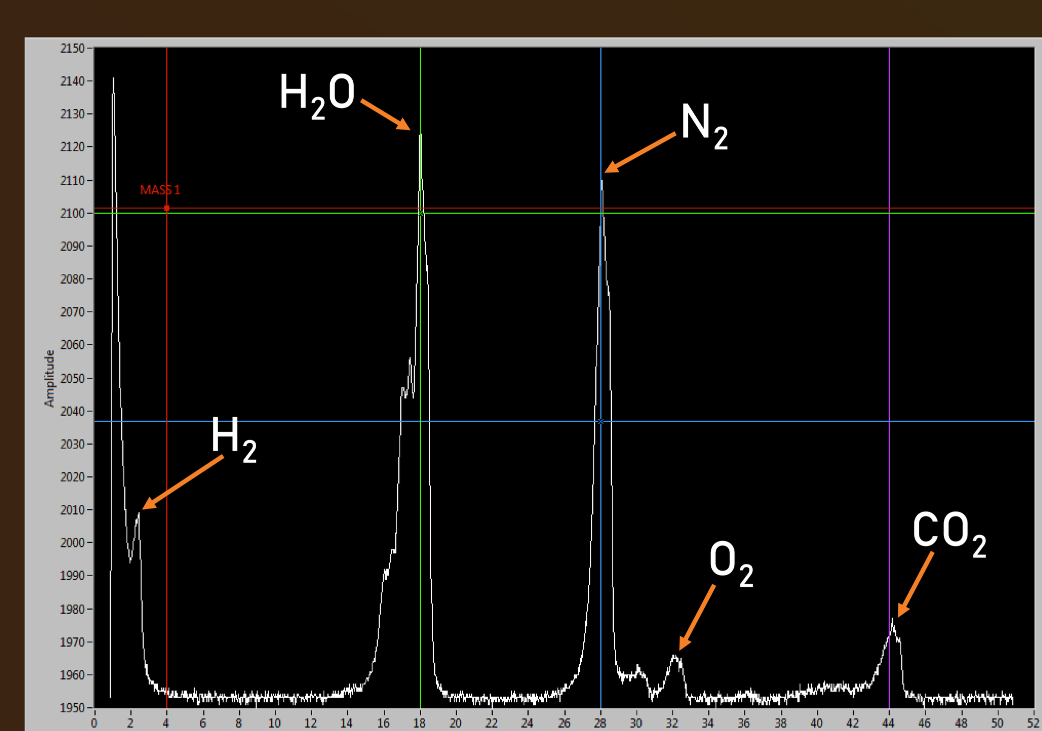




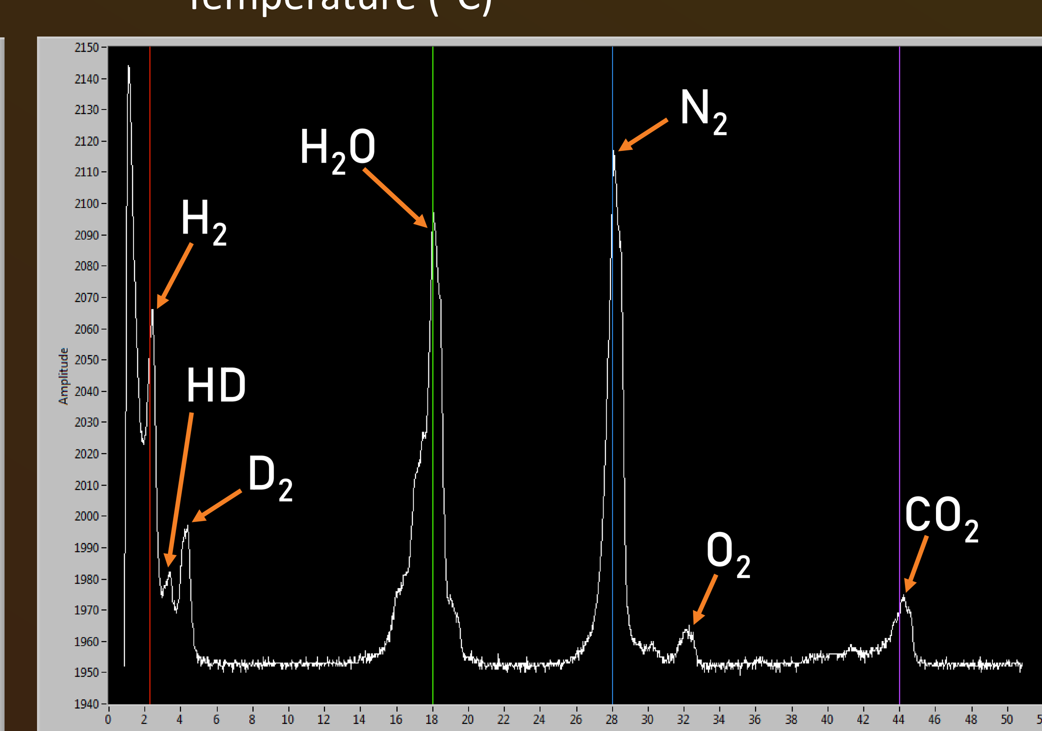


- Hydrogen permeation was seen while heating the palladium attributed to hydrogen already in the palladium;
- Deuterium permeation ranging in temperatures from 300 °C to 500 °C;
- Increase in temperature increased permeation as expected, showing permeation is temperature dependent.





Spectra #1: Chamber side 2 prior to deuterium gas at 200 °C.



Spectra #2: Chamber side 2 deuterium permeation at 500 °C.

$$D = D_o \exp(-Q/T)$$

Where:
D_o = Frequency Factor [m^2/s]
Q = Activation Energy [eV]
T = Foil Temperature [eV]

Experimental Values:
D_o = 2.4E-6 ± 2E-6 m^2/s
Q = 0.30 ± 0.05 eV

- Deuterium peak at 4 amu and HD peak at 3 amu;
- Hydrogen peak increased;
- Water, nitrogen, oxygen, argon, and carbon dioxide peaks remained about the same, indicates palladium has selective permeability and there is no vacuum leak at the foil.

Conclusion

- Palladium has selective permeability to hydrogen isotopes;
- Deuterium and hydrogen were seen to diffuse through the palladium foil;
- Higher temperatures induce quicker and higher permeation;
- Palladium makes a good choice for the first layer in the ZBZ configuration;
- Can be incorporated in fusion reactor exhaust stream to extract tritium to mitigate D-T reactions from occurring and reducing tritium inventory.

Future Work

- Continue data analysis of the collected data;
- The permeation difference of H° and H_2;
- Permeation of H_2^+ and H^+ ions at energies of 1 keV;
- Helium permeation through palladium;
- Examine the role of partial pressures in permeation of H/He;
- Adapt the palladium foil to a ZBZ configuration.

Acknowledgments

The author would like to thank; Professor Sam Cohen, Professor Bruce Koel, and Dr. Luxherta Buzi for guidance and assistance on the experiment; Bruce Berlinger and Anurag Mann for assistance and oversight with the building of the experimental setup; Natalie Cannon for conducting the experiment alongside me; Susanna Belt for preliminary setup and diffusion assistance; and PPPL and the DOE for the Science Undergraduate Laboratory Internship opportunity.

References

[1] Fischer, Joel. "Permeation and Measurement Techniques." Presented at the PLACE Conference, St. Louis, MO., September 2007
[2] Diffusion and solubility of hydrogen in palladium and palladium-silver alloys. Gerhard L. Holleck. J. Phys. Chem. , 1970, 74 (3), pp 503–511.