RPDL: Control of Ion Beams

Independent Study Report

Tripp Hyde
May 6, 2003

Table of Contents

I. Introduction:

The RPDL's Helicon (see Figure 1) is used as test equipment for the Madison Symmetrical Torus (MST). It has been discovered that x-rays given off by the created plasma excite electrons off of the metal in the Helicon. One particular place this occurs is on and around the sweep plates used for controlling an ion beam shot. Electrons excited off of the negatively biased sweep plate will jump across to the positively biased side creating a short circuit (a voltage across the plates for steering cannot be maintained). This problem disrupts any measurement occurring on the sweep plates as well as their ability to control the ion beam. Having thought about various ways to fix this problem, it was decided that if a magnetic field were created to pass through the sweep plates, the electrons would follow a path according E x B rather than jumping across the sweep plates.

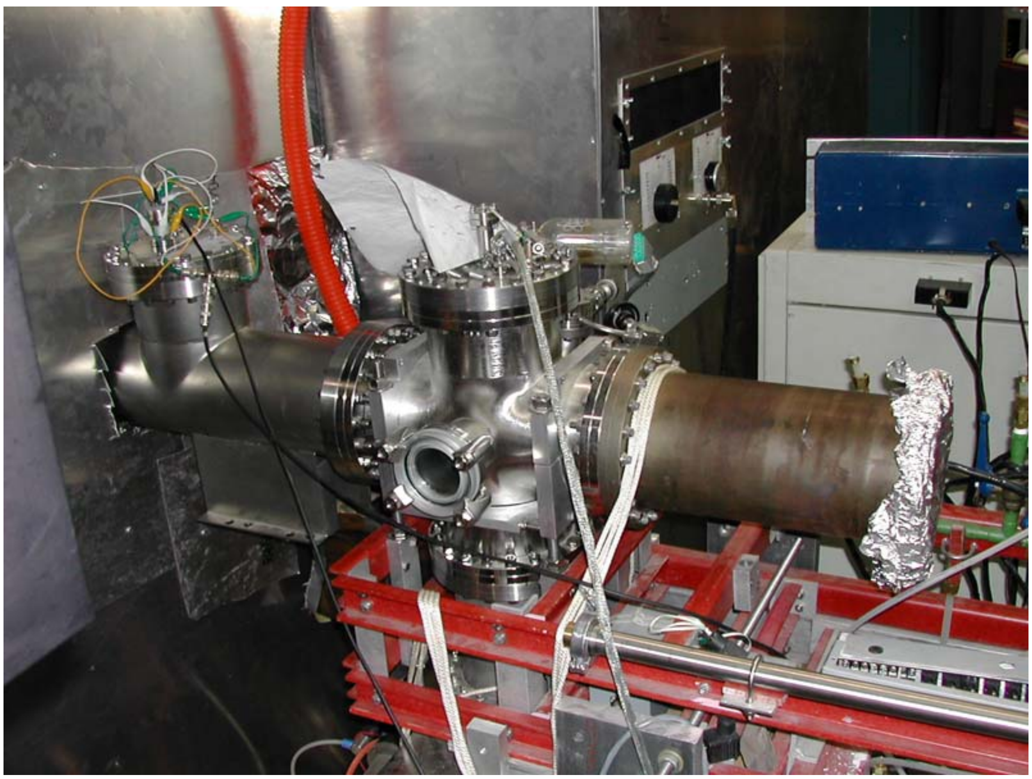

Figure 1. Helicon.

II. Objective:

To design and build an effective mechanism to create a magnetic field parallel to the sweep plates and across the Helicon. Also we must measure the effects to discover if the electrons are, in fact, pushed away. This is best done by observing the current flowing between the two plates and how it changes as we apply the magnetic field. See Figures 1 and 2 below for an idea of how this should work.

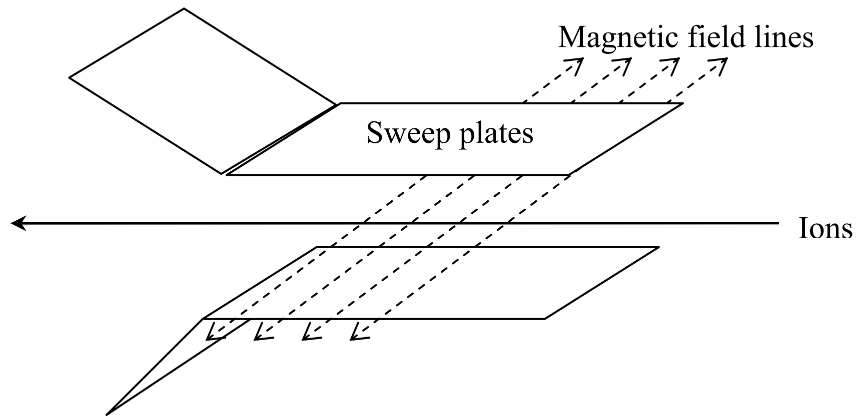

Figure 2. Sweep plates with ion beam and applied magnetic field.

Figure 3. Pictures of sweep plates from inside (left) and outside (right) the Helicon.

III. Coil Design:

It was decided that the best way to create a magnetic field between the plates would be to wind two large coils and form the field lines in the manner of a large solenoid. This way a current could easily be applied and a measured as well as an estimation of the field created. It was originally decided that a field strength of approximately 150 Gauss would be suitable for the situation. One of the biggest factors was trying to fit these large coils into the proper area where they would be aligned with the sweep plates. In order for this alignment to occur correctly the coils had to be approximately 20 inches in diameter. It was originally intended for the setup to be governed by the Helmholtz equation (where the distance between the coils is equal to the coils' radius) because this makes for simpler measurements and is scalable for other applications, like if the coils were to be used at MST. However, because of the strength of the field required and the space constraints, the coils ended up being 20 inches apart across the Helicon, rather than 10 inches as the Helmholtz equation would have.

There was an abundance of 3 gage solid copper wire so this is what was used to wind the coils. With this amount (although on a large spool this was estimated by its weight), the coils came out be approximately 85 turns (±2 turns at about 135 m). One coil turned out to weigh about 77 lbs while the other weighed about 80 lbs, so their turn totals were very close. The two were suspended from a standard 2x4 and held together with tape and plastic strapping. Figures 4 and 5 below show the ideal setup and a picture of the actual coils.

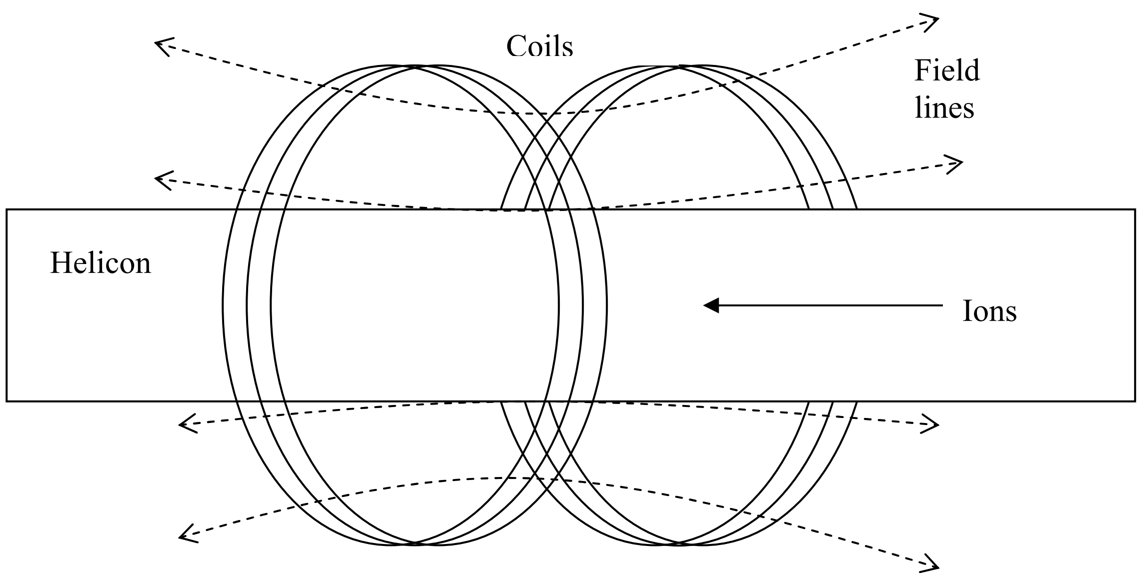

Figure 4. "Hanging coils" with field lines and Helicon.

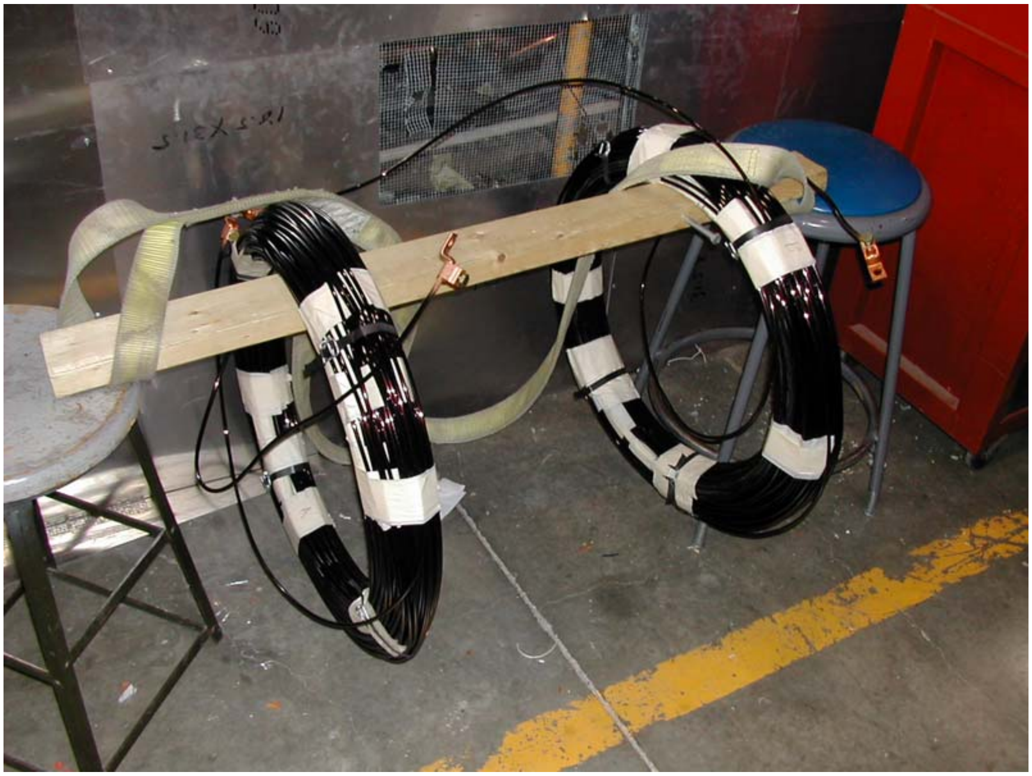

Figure 5. Actual coils suspended from a 2x4.

The following equations express how the size of the coils and the current put through them were determined:

$$B = \frac{\mu_0 I}{4\pi R^2}\oint dL = \frac{\mu_0 I}{4\pi R^2} 2\pi R = \frac{\mu_0 I}{2R}$$

Equation 1. Strength of a magnetic field at the center of a loop.

Equation 1 gives the strength of the magnetic field at the center of one loop. That would be (4πx10^{-7} * 17000) / (2 * (10 in * 0.0254 in/m)) = 0.0421 T = 421 G with a 200 A source (I = 85 turns * 200 A) and 631 G at 300 A. That was well over the goal. However, the following equation gives the strength of the magnetic field at a certain distance, z, from the loop:

$$B_z = \frac{\mu_0}{4\pi}\frac{2\pi R^2 I}{(z^2 + R^2)^{3/2}}$$

Equation 2. Strength of a magnetic field at a distance, z, from a loop.

Equation 2 gives 1x10^{-7} * (2π * (10 in * 0.0254 in/m)^2 * 17000) / ((10 in * 0.0254 in/m)^2 + (10 in * 0.0254 in/m)^2)$^{3/2}$ = 149 G and 223 G at 300 A. These numbers should be doubled because there were two coils, so the final calculated field is approximately 300 G at 200 A and 445 G at 300 A in the middle (10 in away from each) of the two coils (at the center of Helicon where the sweep plates are).

IV. Coil Characteristics:

In order to get a better feel for the coils, several measurements were taken to ensure that they would work in the experiment. Upon measuring the field with the Hall probe a field of about 150 G was discovered just outside the Helicon chamber with the coils in place for the experiment. This number shows that there was some error because the above calculations are for a perfect setup (one single wire, perfectly circular, no other fields in the area, and a "clean" source of current). However, each of the coils had many turns and was not perfectly circular. Also one must consider the effects from the significant magnetic fields created by the American Rectifier that hold the plasma. Finally, a large welder was used to create the current and a welder's foot pedal to control the amount. The ripple was so significant that the coils were physically shaking as more and more current was applied. Eventually a new, rectifying current source was used that provided a smooth 100 A.

Next an LCZ meter was used to measure the inductance of the coils. They had a 17.5±2 mH inductance when in series and situated as they would be hanging across the chamber (20 inches apart). This is an approximate value because the slightest change in the angle or distance of the coils in reference to each other affected the inductance by a few mH.

Finally, a 25 V power supply was used to connect the positive terminal to the input on one coil and the ground to the output of the other so the voltage and amperage could be measured. Data was acquired at several different voltages and amperages and by simply using Ohm's law the resistance was calculated. However, it was also important to do this for the connections to the coil so this resistance could be subtracted from the total resistance first obtained. The data came out to be almost perfectly linear so reproducing the numbers is unnecessary. The final resistances were: both coils – 0.202 Ω, Coil A – 0.105 Ω, and Coil B – 0.101 Ω. The resistances of coils A and B do not add exactly up to the total coil resistance but this could be due to a measurement or environment error.

	Coil A	**Coil B**	**Total**
Inductance	-	-	17.5±2 mH
Resistance	0.105 Ω	0.101 Ω	0.202 Ω
Weight	77 lbs	80 lbs	157 lbs

Figure 6. Calculated and measured coil characteristics.

V. Experiments:

There were two main experiments with the significant differences being that the first was done without an aperature plate and the second was done with the aperature plate. Although the first experiment had no legitimate holding with MST because there was no aperature plate, it was attempted to get some idea if the coils were making a difference. This appeared to be the case. Voltages between 50 and 150 volts were applied to the sweep plates while using the welder current source with approximately 150 to 250 A. The results were promising. With all the x-ray coming from the plasma there was a significant current flowing between the plates and applying the magnetic field this was cut by a factor of 10 or so. The current flow through the coils was applied in both directions with no real effect on the experiment. This particular experiment was run with approximately 10-100 mTorr of argon pressure. MST runs around 0.1 mTorr.

The second experiment was the most important because MST does not run without an aperature plate as was done in the first experiment. Another difference in the experiment was that a new current source was used. Rather than the rippled signal from the welder, a rectified source was used that provided a maximum of 100 A with no ripple. This source also had an accurate control knob so the amount of current being applied was known exactly. Unfortunately, the pressure gage was not available so it is entirely unknown what the argon pressure was during the experiment. It was attempted to keep the pressure low, but the exact pressure was unknown and this may have had an adverse effect on the experiment's results. In fact, the actual results were very poor and, in some instances, the magnetic field made a greater current between the sweep plates.

VI. Discussion of Results:

As mentioned above, the first experiment was really used to just get a feel of how the coils would affect the excited electrons, but no further discussion is necessary. However, the second experiment deserves some in depth discussion. It proved to be a disappointment when the results were first realized. The coils appeared to do nothing and in some cases made things worse. At first there was no idea why this could be. However, greater analysis by Professor Schoch uncovered a few obstacles. In our case, an electron that is excited off of the negatively biased plate will want to move to the positive plate. By creating a magnetic field that flows parallel to plate and is perpendicular to the ion beam (as in Figure 2 above), the excited electrons will move along a similar path as the ions ($F = q(E + V \times B)$, towards or away from the ion gun). They will also move in a helical manner. When the idea of the coils was first born, the fact that the electrons will collide with other particles was not realized. This appears to be what happened in the second experiment. The excited electrons were actually colliding with the argon neutrals and therefore they would lose all energy given to them by the magnetic field and they would then start moving towards the negatively biased plate again from that point in space. Eventually the excited electron would come in contact with the plate again, therefore nullifying any help the magnetic field would otherwise create. Figure 7 below attempts to illustrate this.

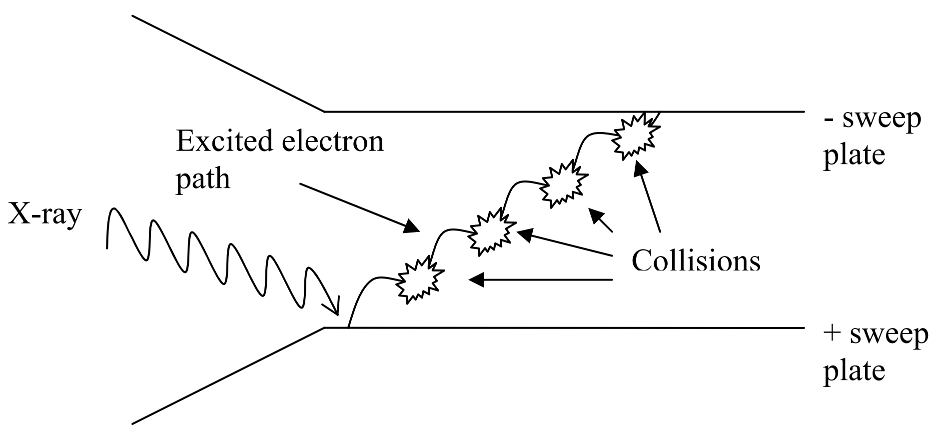

Figure 7. Excited electron colliding with argon neutrals.

As mentioned above, there was no way of measuring the working pressure. If the pressure was high (around 100 mTorr) this would significantly increase the chance of neutral collisions and make the results even worse, as happened in the second experiment. The following calculations of Equation 3 show this relationship:

Gas-kinetic radius of argon, $r_A = 1.9x10^{-5}$ m $= 1.9x10^{-8}$ cm
Argon area (target to hit), $\sigma_A = \pi * r_A^2 = 1.1x10^{-15}$ cm^2

$$\text{Mean free path of argon at 1 mTorr} = \frac{1}{(1.1x10^{-15})(4x10^{13})} = 22.73cm$$

$$\text{Mean free path of argon at 10mTorr} = \frac{1}{(1.1x10^{-15})(4x10^{14})} = 2.273cm$$

Equation 3. Mean free path of excited electrons.

Therefore, with a high pressure (>10mTorr), there is no way that the electrons have a chance to make it out of the sweep plate area before colliding with an argon neutral when the length of the sweep plates themselves is only about 12 cm. Using a lower pressure will allow the mean free path to be much longer, however, the electron moves in an arc so watching how "high" it rises is also important. We can calculate this "height" through the following equations by making a few assumptions:

1. The electric and magnetic fields are uniform.
2. The electric field is in the x direction.
3. The magnetic field is in the z direction.
4. The excited electrons must start at rest.
5. The electrons will have an E x B drift in the negative y direction.

x velocity and y velocity for electron (pick 90° phase angle so the electron is knocked of at t = 0) :

$$v_x = iv_\perp e^{iw_c t}$$

$$v_y = v_\perp e^{iw_c t} - \frac{E_x}{B_z}$$

$$\text{If vx(t)} = \text{vy(t)} = 0 \text{ for } t = 0\text{, then, } v_\perp = \left|\frac{E_x}{B_z}\right|$$

$$\text{The maximum kinetic energy occurs when } w_c t = \pi, v_x = 0 \text{ and } v_y = -2\frac{E_x}{B_z}$$

Setting the maximum kinetic energy equal to the change in potential energy :

$$\frac{1}{2}mv_{\max}^2 = qEl \therefore l = \frac{2mE}{qB^2} \text{ where l is the x distance (or "height")}$$

Equation 4. Electron displacement towards other plate.

In Equation 4 m = $0.9x10^{-30}$ kg, q = $1.6x10^{-9}$, B = 100 G, E = 150V/3cm = 5000 V/m for the second experiment. This gives an *l* = 0.06 cm so it would be potentially safe in this experiment. However this may not always be the case.

VII. Conclusion:

In the end, the experiment did not work as hoped or expected. However, some valuable information was collected. It is now known that a magnetic field cannot be arbitrarily applied to the Helicon (or MST for that matter) without knowing several variables. The most important is the pressure. It should also be noted that the coil idea can still be used. For these experiments, argon was the gas of choice because that is what was readily available. However, a gas with a smaller gas kinetic radius (therefore a smaller target, such as hydrogen) will yield much better results. Equation 5 shows this result:

$$\text{Gas-kinetic radius of } H_2,\ r_H = 0.53\text{x}10^{-8} \text{ cm}$$

$$\text{Hydrogen area (target to hit), } \sigma H = 2\pi * r_H^2 = 1.8\text{x}10^{-16} \text{ cm}^2$$

$$\text{Mean free path of hydrogen at 1 mTorr} = \frac{1}{(1.8x10^{-16})(4x10^{13})} = 138.9cm$$

$$\text{Mean free path of hydrogen at 10mTorr} = \frac{1}{(1.8x10^{-16})(4x10^{14})} = 13.89cm$$

Equation 5. Mean free path of hydrogen.

These numbers are much larger than those of argon, so it appears this would be the gas to use. If hydrogen is used, the experiment may turn out to work quite well.