# The design, development and use of a novel Thomson spectrometer for high resolution ion detection

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## Introduction

The traditional Thomson spectrometer[1,2] is a well known diagnostic for observing the energy spectra of different ion species and their various charge states[3,4]. The Thomson spectrometer does this by using parallel magnetic and electric fields to deflect particles, entering a pin-hole at the front, according to their velocities and charge-to-mass ratios. These particles are then deposited on the detection media, usually CR-39, at the back of the spectrometer in parabolic-like patterns. The traditional Thomson spectrometer uses a pair of permanent magnets and a pair of high-voltage electric plates with both pairs being parallel. This design however has limited resolution for multi-MeV heavy ions. The reason for this is that to get high resolution parabola (i.e. making tracks longer and more separated) for multi-MeV heavy ions and their many charge states on the CR-39 media requires much stronger magnetic and electric fields than is needed for protons and the lighter elements such as Carbon. Increasing the magnetic field strength is simple to do by putting stronger magnets in the Thomson spectrometer. However, increasing the electric field strength by either increasing the voltage or decreasing the separation of the electric plates is more difficult as two obvious problems arise. One of these is electrical breakdown which is solved by using a higher quality vacuum for operation. The other problem is that of lighter and slower ions hitting the parallel electric plates due to the much stronger electric field. This is a problem for two reasons, one is that the impact of a large number of charged particles on the electric plates will cause the electric field to fluctuate significantly and the second reason is the lost data that these ions could have provided had they reached the CR-39. This article discusses a novel design for the Thomson spectrometer and its subsequent operation which enables greater resolution of the heavier ion charge states without compromising the slower and lighter ion species.

## Simulations and initial design

The new Thomson spectrometers were designed with the aid of the ion optics computer program SIMION-3D[5]. The simulation consisted of virtual ion optical components, giving rise to electrostatic and magnetic fields, arranged on an ion optics workbench. Ions flown through the system provided ion trajectory data. Figure 1 shows a typical view of the ion optics workbench, and illustrates the final spectrometer design. Several design iterations were required to produce a spectrometer providing optimised electric and magnetic field deflections. The ion dispersion curves extracted from this data for the final spectrometer design compare well with calculated dispersion curves.

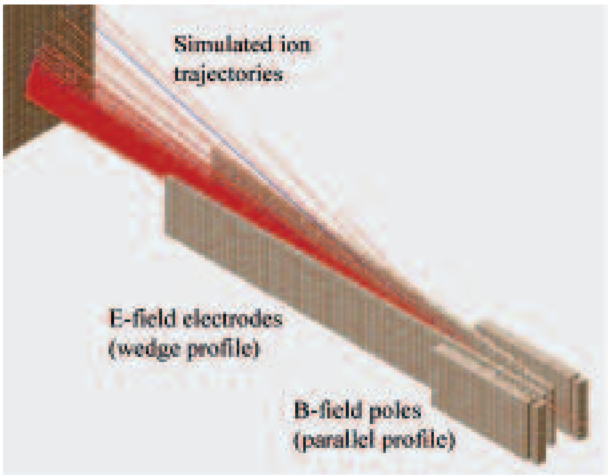

**Figure 1. SIMION-3D simulation image of ion trajectories through the electric and magnetic fields of the new Thomson spectrometer design.**

A schematic of the final spectrometer design is shown in figure 2. NdFeB magnets of standard size 50 × 50 mm were available "off-the-shelf". This was the starting point in the design. The separation of the poles is defined by the dispersion of the ions due to the electrostatic field. By separating the poles at 20 mm a field strength of 0.6 T was calculated. The resulting dispersion of protons and carbon ions at a distance of 200mm downstream is shown in figure 3. The challenge was to produce a similar dispersion due to the electrostatic field. A simple parallel electric field of similar length to the magnet did not produce sufficient dispersion. Increasing the length of the electric field increased the dispersion, but resulted in ions crashing into the Cu plate electrode. A solution was found by titling one of the Cu plates, such that the separation of the plates at the entrance of the spectrometer is 2 mm and at the exit is 25 mm. By applying a potential difference of ~6 kV across the plates, fields of ~3 kV/mm and 0.24 kV/mm are produced at the entrance and exit of the spectrometer, respectively. In this way a similar dispersion is produced, in

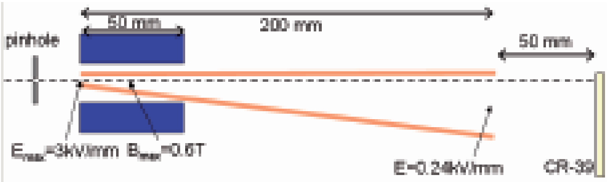

**Figure 2. A schematic of the new Thomson spectrometer design.**

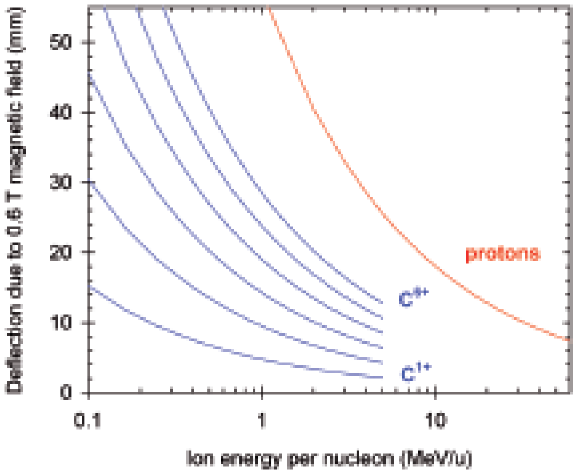

**Figure 3. The dispersion of protons and carbon ions by the magnetic field in the new Thomson spectrometer design.**

orthogonal directions, by the electric and magnetic fields, ensuring good separation of the ion traces. The detection plane was chosen at a distance of 50 mm from the end of the Cu plates such that ions in the energy range of interest are nicely dispersed over the 50 mm × 50 mm area of the CR-39 pieces. The spectrometer design is optimised for the detection of ions above ~0.7 MeV per nucleon. Lower energy ions are deflected into the ‘tilted’ electrode.

The housing for the spectrometers was designed at the Central Laser Facility. A detector mount consisting of a remotely controlled rotating drum was incorporated into the design to enable up to 4 laser shots to be taken before the vacuum chamber is cycled. Figure 4 is a schematic of the housing design showing the CR-39 rotating drum.

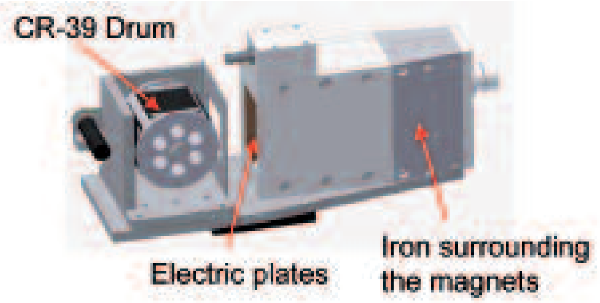

**Figure 4. This shows how the CR-39 rotating drum is incorporated into the design of the Thomson spectrometer.**

## Field characterisation

### *Magnetic Field*

The magnetic field of two of the new Thomson Spectrometers has been mapped out in detail using a Hall probe. It was found that at the centre position between the two magnets for four of the new Thomson spectrometers the magnetic field was between 0.60T and 0.65T. In a plane parallel to the magnets the magnetic field falls away as you move further from the middle of the magnets, as can be seen in Figures 5 and 6. While normal to this plane the magnetic field has a minimum at the magnet gap centre and increases in strength closer to the surface of the magnets, see Figure 7. It should be noted that the plane of the pin-hole is not along the centre between the magnets but is offset to the side by 3.5mm to accommodate the electric plate wedge. The magnets are encased in iron to provide a return path for the field and so reduce fringe fields. The iron is thinner at the front end of the Thomson spectrometer and so gives rise to the longer tailing-off of the magnetic field as seen in Figure 5 at that end of the Thomson spectrometer.

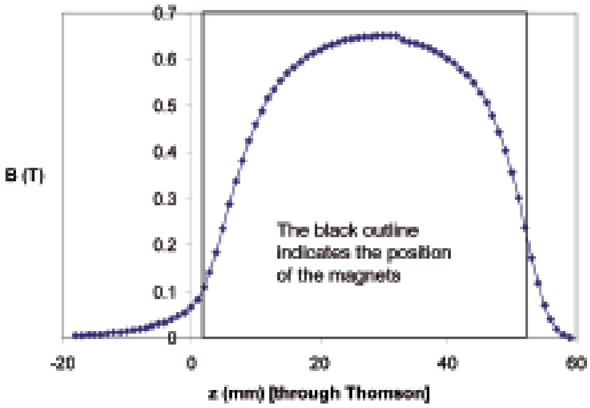

**Figure 5. A cross-section of the magnetic field along the length of the magnets in the Thomson Spectrometer in the plane of the pin-hole (~6mm from the closest magnet).**

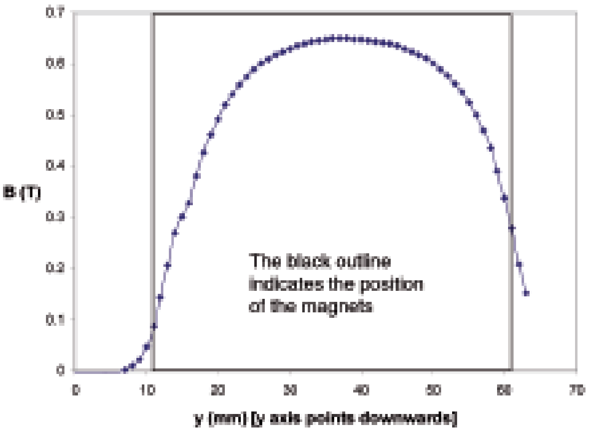

**Figure 6. A scan of the magnetic field in the vertical axis 30mm inside the spectrometer and in the pin-hole plane.**

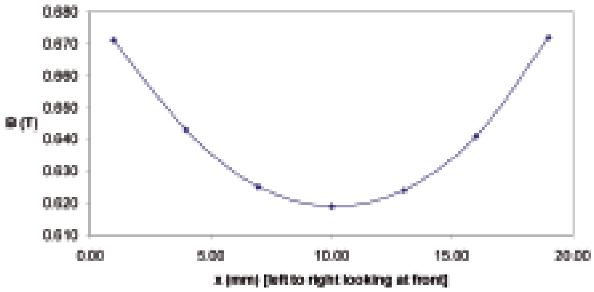

**Figure 7. A scan of the magnetic field across the gap between the magnets. The measurement was made 28mm into the Thomson spectrometer from the front.**

### *Electric Field*

The electric field at any given point between the electric plates as a vector is given by equation 1[6]. The co-ordinate system used for this equation is shown in Figure 8. The origin is defined as where the point of the electric plates wedge would be, its position relative to the front of the electric plates is given in equation 2. It should be noted that as the angle between the plates is small the $E_z$ component of the electric field will be small enough to be ignored as it is likely that the already ignored fringe fields are stronger.

$$\underline{E}(x,y,z) = \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix} = \begin{bmatrix} \dfrac{Vz}{(x^2+z^2)\theta_0} \\ 0 \\ \dfrac{-Vx}{(x^2+z^2)\theta_0} \end{bmatrix} \text{……(equation 1)}$$

$$z_0 = \frac{a}{\theta_0}(1-\theta_0)^{1/2} \text{…………………………...(equation 2)}$$

Where E is the electric field, V is the voltage applied across the electric plates, $\theta_0$ is the angle between the plates, a is the minimum separation of the plates and $z_0$ is the distance between the origin and the front of the plates.

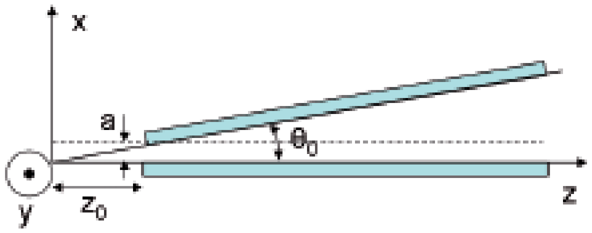

**Figure 8. The electric plate co-ordinate system used to describe the Electric field.**

### First Experimental use of the Thomson spectrometers

The new Thomson spectrometers were first used during the May/June 2005 experimental campaign in the Vulcan petawatt target area, where six were used in total to make angularly resolved measurements of ion emission. Figure 9 is a photograph of three of the new Thomson spectrometers during the experiment. Work on the development of the spectrometers continued in the early stages of this campaign.

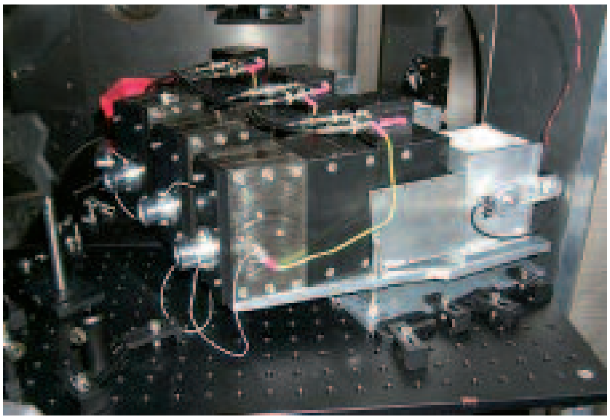

**Figure 9. Three of the new spectrometers being used during an experiment.**

During the experiment it was found that a high pass filter had to be incorporated into the design as the HV cables connected to the spectrometer were picking up noise during the laser shot and so causing the electric field to vary. This resulted in unstable ion trajectories and signature 'wiggles' in the ion trace at the detector plane (Figure 10). The filters considerably reduced this effect.

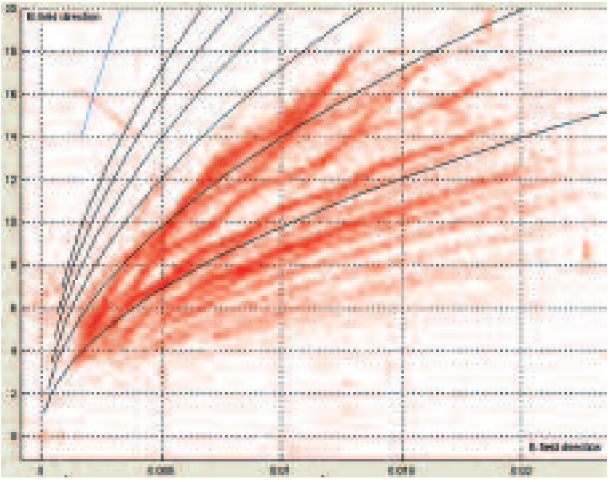

**Figure 10. The effects of cable noise on the electric field can be clearly seen as 'wiggles' in the parabola data above (red). The black lines are the simulated parabolas for Carbon.**

It was found that due to the typical sizes of heavy ion pits in CR-39, a dynamic range of about two orders of magnitude in ion density is measurable. Therefore, the optimum solid angle for the Thomson spectrometers depends on what information is required from the data. If an ion energy spectrum is required for example to calculate the energy conversion efficiency from laser to ions, then a solid angle of ~$5.5\times10^{-9}$sr (equivalent to 50µm diameter pin-hole at ~0.6m) was best as this avoids saturation of the lower energies in the parabolas, but would reduce the maximum cut-off energy that could be resolved for an ion species. However if the maximum cut-off energies for the ion species is required, then a solid angle of ~$2.2\times10^{-8}$sr (equivalent to 100µm diameter pin-hole at ~0.6m) is better, but risks saturation at the lower ion energies where the flux is higher.

The voltage applied across the spectrometers during experiments should be in the 5-6kV range. Going above 6kV is not recommended as the spectrometers have been designed for 6kV and any higher runs the risk of lighter and slower ions hitting the electric plates enough to disrupt the electric field. A 1mm thick piece of CR-39 is enough to detect all heavy ions currently produced in laser-foil interactions and can detect protons up to 11MeV. The lighter ions, such as deuterium and carbon, may pass through the CR-39 if energetic enough. To try and increase the range of proton energies detected by the Thomson spectrometers Fuji-film BAS-MS image plate has been placed behind the CR-39, this has been successful but no detailed analysis has yet been done.

### Extracting ion data from CR-39 and subsequent analysis

To extract data from the CR-39 it first requires etching in a bath of concentrated sodium hydroxide (NaOH). It has been found that etching the CR-39 for about 15 minutes in a 6.25 molar solution at a temperature of 86°C is best for developing the pits generated by heavy ions. This etch time was found to be good as the pits were large enough to resolve using the scanner system, but not large enough that they merged together. The scanning system used is an 'Automated Scanning and Particle Counting Microscope system' that was purpose built for the CLF by Track Analysis Systems Ltd, see Figure 11. It should be noted that proton and deuterium, the lightest ion species, will require longer etch times. The size of the pits depend on several factors, these are the etch conditions[7,8] (temperature, concentration of NaOH and etch time) and the energy and size of the particle creating the pit[9,10]. The scanner system scans the CR-39 and counts the pits it identifies and records the position, the pits elliptical lengths and several other bits of information about the pit in a data file.

**Figure 11. The Automated Scanning and Particle Counting Microscope system used to scan CR-39.**

The data file can then be inputted into an appropriate program to enable analysis of the individual ion parabolas. Figures 12 and 13 are screen captures of the software developed by F. Lindau that we have used to analyze CR-39 data. Figure 13 is also a good example of the higher spatial resolution for heavy ions that the new design has achieved, as the many charge states of gold are easily distinguishable.

It should be noted that some ion species have the same charge-to-mass ratio which will result in overlapping parabolas on the CR-39, e.g. $O^{8+}$, $C^{6+}$ and deuterium. To be able to extract the different parabolas will require looking at the size of the pits as different sized particles produce pits of different sizes. Be aware though that the pit size also depends on the energy of the particle, see Figure 14.

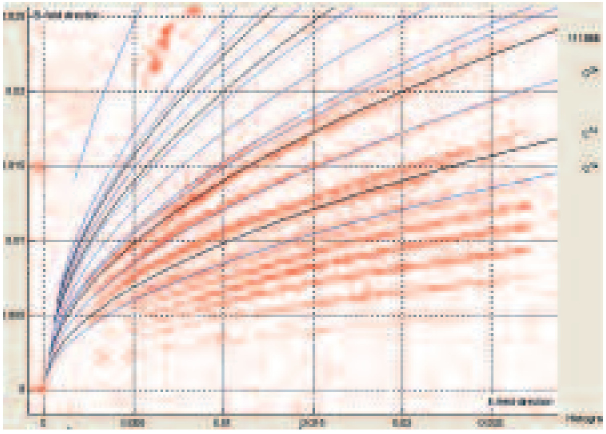

**Figure 12. An example of data obtained using the new design. The red is the real data obtained from scanned CR-39 and the blue and black lines are simulated parabolas of oxygen, protons and carbon charge states.**

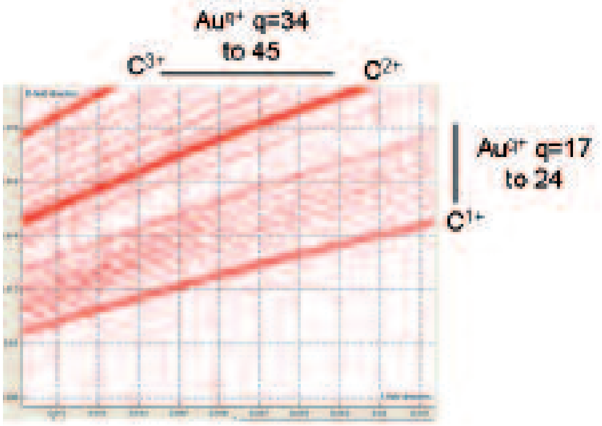

**Figure 13. Example of how the new design allows the many charge states of gold to be resolved.**

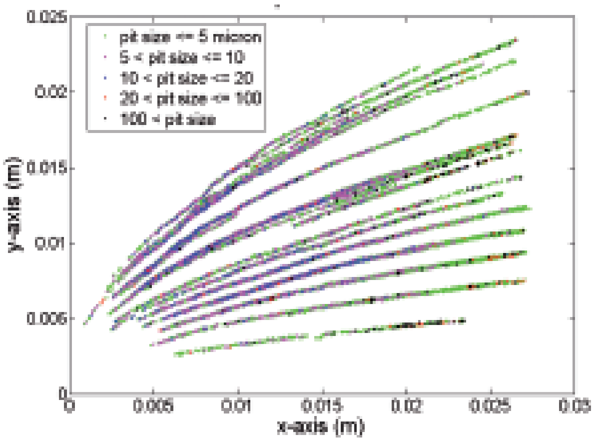

**Figure 14. This is the same data as in Figure 12 but now colour coded for pit size (major elliptical axis of pit). The green pits are the smallest pits and the black pits are the largest, with the other colours in between the two extremes. As can be seen the pit size increases as the particle energy increases (moving left on the graph), the largest pit sizes (black and red) will actually be pits that have merged together.**

## Conclusion

We have designed, developed and demonstrated a novel Thomson spectrometer for high resolution measurement of ion emission from high power laser-plasma interaction. One of the next big steps is developing further the software used to analyze the CR-39 data generated. Another big step is developing other ways of detecting the ions rather than using CR-39 as currently the scanning is time consuming and the Thomson spectrometers are restricted to low rep rate experiments.

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