Very large emissive foil detectors for the tracking of low energy heavy ions

Authors

A. Drouart[1*], C. Mazur[2], Ph. Bourgeois[2], E. Bougamont[2], A. Gillibert[1], V. Lapoux[1], L. Nalpas[1], E.C. Pollacco[1], M. Riallot[2]

[1] CEA Saclay, DSM/DAPNIA/SPhN, 91191 Gif/Yvette Cedex, France.

[2] CEA Saclay, DSM/DAPNIA/SEDI, 91191 Gif/Yvette Cedex, France.

PACS: 29.40.Cs, 29.40.Gx

Keywords: Emissive foil; gas detector; heavy ion tracking

*Corresponding Author:

antoine.drouart@cea.fr

Tel : +33 1 69 08 73 52 Fax : +33 1 69 08 75 84

Addr.: CEA Saclay
DSM/DAPNIA/SPhN
Bat 703
91191 Gif/Yvette Cedex
France

Abstract

We present the development of a thin large area tracking detector. The thickness of matter intercepted by the ions is approximately 0.25 mg/cm² of low mass material (aluminized Mylar). It is designed to detect low energy heavy ions with a minimum of energy and angular straggling. We use a secondary electron emission foil coupled to an innovative large area gaseous electron detector. The electrons are guided toward the detector by an electric and a magnetic field. We achieve good time (300 psec FWHM) and two dimensional position (1.4 mm FWHM) resolutions over a large area (10x40 cm²).

Introduction

The VAMOS spectrometer

VAMOS (Variable Mode Spectrometer) [1] is a magnetic spectrometer designed for the study of reactions with SPIRAL beams at GANIL [2]. It consists of a quadrupole-quadrupole-Wien filter-dipole spectrometer. VAMOS allows a focusing and M/q selection with a large angular (90msr) and momentum (10%) acceptance. The focal plane of VAMOS is 40x10cm². When used in its dispersive mode, the trajectories of the reaction products must be reconstructed in order to calculate their momentum and scattering angle. Therefore 2-dimensional position measurements are needed at the focal plane of the spectrometer. Moreover, the identification of the reaction products in atomic number Z and mass A requires energy and energy loss measurements, as well as a time of flight.

For this latter point, an ionization chamber and a plastic scintillator give ΔE-E correlation. The scintillator can also give a time measurement with 300 ps (FWHM) resolution. It can be coupled to the high frequency of the cyclotron to obtain a full time of flight, but this limits the final time resolution to 2ns.

For the tracking of the ions, two position sensitive detectors are placed in front of the ionization chamber. VAMOS is designed to cope with a large array of incoming ions, ranging from light particles with energy around 10 MeV/A (e.g. coming from direct reactions with the target), to heavy particles, having energies less than 1 MeV/A, (e.g. from fusion reactions). Due to this diversity of ions and their wide range of energy loss in matter, two kinds of position sensitive detector were designed for VAMOS. For the lightest (Z<15) ions with high energy (2-20 MeV/A), low pressure drift chambers were developed. The chambers give x and y positions with resolutions of 0.3 mm and 1 mm (FWHM), respectively.

VAMOS also deals with heavier and slower (E<2 MeV/A) ions. The energy and angular straggling caused by the drift chambers significantly increases the straggling and deteriorates the resolution. It is therefore necessary to use thinner detectors. Moreover, for such low energies the ions may be stopped in the ionization chamber and may not reach the plastic scintillator. Therefore another time measurement is required.

Due to these considerations we decided to use emissive foil detectors. They are known to be the thinnest possible, since they involve only one thin film on the ion trajectory. In this paper, we present an original use of a low pressure gas chamber to detect the secondary electrons emitted by the foil. This detector meets the requirements for VAMOS:

- 2D position measurement with 1 mm resolution (FWHM)
- Time measurement with 300 ps resolution (FWHM) for A/q resolution
- Large size to cover the 40x10 cm^2 focal plane.

Emissive foil detectors

The basic principles of emissive foils detectors have been known since the sixties [3]. Their main advantage is that only the emissive foil is on the trajectory of the ions. The foils are thin and therefore induce minimal energy and angular straggling. They may thus be considered as the least interceptive detectors developed to date (carbon foil of a few tens of $\mu g/cm^2$ thickness are readily available). The device is in two distinctive parts:

- The emissive foil: a thin layer of material (usually carbon, Mylar…) which lies on the ion trajectory. The incoming ion sputters secondary electrons (Se^-) out of the foil [4]. These electrons are electromagnetically accelerated and guided towards a detector.
- The secondary electron detector that gives the time and position of the Se^- shower and thus those of the ion traversing the detector.

Micro-channel plates (MCP) are commonly used as Se^- detectors [5]. They give good time resolution and localization. Nevertheless, they suffer from definite drawbacks for our application:

- limited size
- low durability, a critical characteristic in a vacuum chamber containing other gas detectors.

For these reasons we investigated an alternative to MCP: low pressure gaseous detectors.

Gaseous detectors at low pressure are commonly used in nuclear physics experiments as ionization chambers, beam tracking detectors or drift chambers. The low pressure allows thin retaining windows and of course a low number of atoms/cm² in the gas. The ions pass through the detector and are detected via the ionization of the gas. In the case of a multi-wire proportional counter, the ionization is amplified during the avalanche regime and it is possible to obtain both time and position measurements [6]. The Se$^-$D described in the present work has a similar configuration but it is not on the trajectory of the beam. Instead, it detects the cloud of secondary electrons emitted from an emissive foil. Therefore, the ions do not traverse the full detector but only a minimal thickness of matter.

The basic principles of the Se$^-$D were described for an initial small size prototype [7]. The first tests with a full scale prototype were presented in [8]. In this paper, we make a thorough description of the final detector. We report its performances obtained in different tests and experiments. Figure 1 shows a photograph of the detector as installed at the VAMOS spectrometer at GANIL.

[Include figure 1]

Description of the detector

Emissive foil

The emissive foil is inclined at 45° relative to the beam direction (see full scheme on figure 1). The width of the foil is 40 cm and its height 15 cm. This covers the whole focal plane of VAMOS. It is a 0.9μm (120 μg/cm^2) thick Mylar film, aluminized (30 μg/cm^2) on both sides. Taking into account the 45° angle, the total effective foil thickness is 250 μm/cm^2. We think it is still possible to use thinner material if available, but there are two limits concerning its resilience: the foil has to sustain Al evaporation and it has to be manipulated during the setting-up of the detector.

Guidance system

The Se$^-$ are focused towards the detector by two longitudinal electric and magnetic fields. The first is primarily used to accelerate the Se$^-$. They must obtain sufficient energy in order to cross the entrance foil of the detector, a 0.9 μm aluminized Mylar foil. Range calculations [9] and tests show that the minimum energy is 7 keV. The Se$^-$ have to be accelerated as quickly as possible to minimize their dispersion. We use here an electrostatic grid of 10 μm gold coated tungsten wires with 1mm spacing. The distance between the grid and the foil is 9 mm. The grid is grounded while the emissive foil is at -10 kV. This value is a compromise between the amplitude of the signal of the detector and the spontaneous emission noise. Our tests have shown that both increase from 7 kV to 12 kV. The noise also critically increases with the vacuum quality. A pressure below 10^{-5} Torr is necessary to reach good operating conditions.

In addition to the electric field, a parallel magnetic field is mandatory to focus the Se$^-$ and have good position resolution [10]. It has no significant influence on the time resolution. It is generated by a current through two copper coils on both sides of the Se$^-$ drift zone. These coils are made of rectangular x-section tubes, cooled by cold water. The uniformity of the field is assured by soft iron plates. Figure 2 shows the coil plus iron plate assembly. A nominal field of 110 Gauss is reached for a current of 70 A. In the centre of the zone, the operating magnetic field value is 110 Gauss. A field chart was simulated in 3D with the TOSCA software and verified with a precise B measurement at the magnetic measurement bench at GANIL. Simulations of the Se- trajectories have been performed and they show good agreement with the observed results. The simulations were based on a Runge-Kutta integration of the electron trajectories in the magnetic field calculated from a linear interpolation of the measured field map. The magnetic field is not uniform and variations of up to 5% are observed in the outer parts. Therefore, it is necessary to “map” the detector with a reference mask at the foil position. This procedure and the effects on the position measurements are detailed in the performance chapter.

[Include figure 2]

Secondary e⁻lectron Detector

The Se^-D is a low pressure proportional counter [11]. It allows a 2D position reconstruction and time measurement. Figure 3 presents its basic geometry:

- The gas (here isobutane) is enclosed between the front window (a 0.9 µm Mylar foil supported by a metal mesh) and a printed circuit. The operating pressure is 4 Torr.
- Inside the gas, an anodic wire plane is surrounded by two equidistant cathodes at 1.6 mm. The first cathode is a wire plane and the second is the back printed circuit which is stripped. The first cathode provides the Y position measurement, the second one the X.
- The cathodes are grounded while the anode is at a positive potential (from +500 V to +600V), so that the whole space in between is in a proportional amplification regime.

[Include figure 3]

The entrance window of the detector is a 0.9 µm Mylar foil. Its size is 40x15 cm^2. It is covered with a stretched wire mesh to limit bulging under the gas pressure. This mesh is drawn tight with a pressure of 2.5 bar. It is made of interwoven metal wires 45.8 µm thick with a spacing of 488 µm. Its transparency is 83%. The foil is aluminized on the vacuum side. It is grounded along with the grid. With an energy of 10 keV, the Se^- lose 3.1 keV in this entrance window [9]. After one Se^- crosses the foil, it will lose 290 eV in the isobutane thus creating around 12 electron-ion pairs/electron along the 3.2 mm of the active zone between the cathodes. This is sufficient for a single Se^- to be detected.

The first cathode measures the position along the y axis. It is made of 150 wires of 50 µm diameter, with a spacing of 1 mm. The wires are connected 3 by 3 for the charge measurement. At each end, the last 3 wires are grounded so that 48 channels are available for the measure of the charge distribution and hence the position.

The anode is positioned at 1.6 mm from the cathode. It is made of a 10 µm wire plane with 1 mm spacing. The wires are stretched perpendicular to those of the cathode. There is a total of 402 wires, grouped in 3 independent parts to reduce the entrance capacitance of the fast amplifiers. All parts are raised to a common positive high voltage. They are read separately to provide three timing signals. This anode is soldered to a 1.6 mm thick printed circuit, directly placed on the second cathode printed circuit.

The second cathode is a gold coated stripped printed circuit. Each strip is 3mm wide, with a 0.125 mm interstrip distance. All 128 strips are independently read for the charge measurement.

All the 48+128 charge signals are pre-amplified and shaped by ASICS-Gassiplex [12]. They are coded in two V550 CAEN ADCs. There is no threshold suppression and all channels are read and coded. The 3 fast anodic signals are processed by a fast amplifier with a gain of 200. It has a rise time shorter than 1ns. The time pick-off is a constant fraction discriminator.

Performance

The parameters defining the operating point of the Se^-D are as follows:

- Electric potential on the emissive foil for guiding the Se^-, V_0

- intensity of the magnetic field for focusing the Se^-, B_0
- Pressure of the gas inside the detector, P
- positive voltage of the anode, $V_{Se\text{-}D}$

The energy and atomic number of the detected ions also have a strong effect. We have studied their influence on the efficiency of the detector, on the time resolution, and finally on the spatial resolution.

Efficiency

The efficiency was measured by detecting the heavy ion with a fully efficient detector after the emissive foil. This was a silicon detector for the laboratory test and a plastic scintillator or an ionization chamber for the in beam experiments.

The efficiency of the detector is a function of the number of Se^- emitted by the foil, the loss related to the transmission of the electrons to the active volume of the detector and the amplification process within the detector.

For the first step, the base number of Se^- is directly linked to the nature of the emissive foil and the ion detected. The material of the foil is dictated by practical concerns, as discussed previously. Se^- emission has been studied by several authors [4], but remains a complex phenomenon involving the atomic structure of the solid [13] and its surface characteristics. The number of Se^- is qualitatively linked to the linear energy loss of the ion. This is also confirmed by our different measurements (see table 1).

The Se- are then accelerated with a potential difference of 10 kV. We studied the penetration of the entrance foil of the detector with the Monte-Carlo code of [14]. We calculated that 15% of the Se^- are backscattered from the foil. Moreover, the supporting mesh has a geometric transparency of 83%, giving a global transmission of 70%. This does not mean that the ion efficiency is limited to 70%. Since very heavy ions emit a lot of Se^- (more than 100 for fission fragments), some of them always reach the gas. Thus the ion detection efficiency can still reach 100%. Nevertheless, it does affect the efficiency for light ions which only emit a few electrons.

We performed our first test with alpha and fission fragments from a ^{252}Cf source and with beams of ^{12}C at 10 MeV/A, ^{24}Mg at 12 MeV/A and ^{76}Ge at 2 MeV/A. For light ions like alpha particles, it is necessary to increase the operating voltage $V_{Se\text{-}D}$ to reach an improved efficiency.

[Table 1]

Time measurement

The time resolution of the detector is estimated in conjunction with two other fast detectors. They are another emissive foil detector (Se-D or micro-channel plate) and a plastic scintillator. We measure independently the three time differences between the three different detectors, so we can extract the three time resolutions.

Time resolution is essentially linked to the rise time of the signal and to the signal to noise ratio. Low pressure gaseous detectors are known to have a fast response [15]. The rise time reduces when the pressure is lower. We found an optimum at 4 Torr where the rise time is around 3 ns. The signal to noise ratio is related to the number of Se^-, and the gain of the detector which is directly dependant on the reduced pressure $V_{Se\text{-}D}/P$. Better S/N can be reached through lower pressure (thus also reducing the rise time), or through higher voltage. $V_{Se\text{-}D}$ is limited by the sparking regime, but so far we do not have a quantitative understanding of this limit: it is neither directly linked to $V_{Se\text{-}D}/P$, nor to the maximum electric field in the detector which is reached near the anode wires. When the emissive foil is at V_{0}=-10 kV, the spontaneous electron emission induces a current in the detector. The intensity of this current depends on the vacuum and also affects the maximum voltage of the Se-D. A typical current at V_0=-10 kV and $V_{Se\text{-}D}$ =+520 V is 10 nA.

In fact, as we will show in the next section, the gain is primarily limited by the dynamic range of the front-end electronics for the position measurement. This is why we choose to operate at 520 V. For very light ions, a higher Se^-D voltage gives better results : for alpha particles, the efficiency increases from 40% to 70% and time resolution goes down from 1.5 ns to 1.2 ns (FWHM), when $V_{Se\text{-}D}$ goes from 550 V to 600 V. Nevertheless, for heavier ions the optimum characteristics are reached with 520 V.

As for the efficiency, the time resolution is strongly constrained by the base number of Se^- emitted from the foil as shown on table 1. As underlined previously, the Se^-D is really suited to the detection of heavy and slow ions.

Position measurement

Again, the position resolution depends on the two stages of detection: the transport of Se^- from the foil to the detector, and the reconstruction of the position in the detector.

The Se^- have an initial angular distribution proportional to $\cos(\Theta\text{-}\Theta_0)$ where Θ_0 is the ion direction [16]. From an initial point like source, they will arrive at the detector with a large distribution shifted from the original position. A solution to cancel the effect of this dispersion is to set a magnetic field parallel to the electric field [10]. For a well chosen value of B_0, the trajectories of the electrons are helicoidal with an integer number of turns at the cyclotron frequency between the foil and the detector. In this configuration their arrival point is independent of their initial transverse velocity. It improves the resolution from 3.7 mm (FWHM) with B_0=0 to 1.4 mm with an optimum B_0=110 Gauss in the X direction. The side effect of the magnetic field is a distorted image of the foil as seen in figure 3. Since B is not uniform over the whole drift space, the electrons in the outer part (far from the central horizontal axis or close to the outer perimeter) of the field are deviated. These deviations, as large as 1 cm, are qualitatively consistent with simulations using a field chart, but a calibration of the detector is necessary to have precise measurements. For this purpose, a 0.5 mm thick aluminium mask with calibrated holes of 5 mm diameter is put in front of the emissive foil. The positions are corrected with a bi-dimensional linear algorithm fitted on the centroids of each hole. The calibration is valid for a given (V_0, B_0) couple. These distortions affect the resolutions in a non linear way. At (X,Y) = (-50 mm;0 mm) the resolution is (2 mm,1.8 mm), while at (-100 mm;0 mm) it is (1.9 mm,1.4 mm). Nevertheless, the resolutions are less than 2 mm (FWHM) in the active zone.

[Include figure 4]

The second point is the reconstruction of the position from the charge distribution on the cathode. It is known that good resolution can be achieved with beam tracking low pressure gas detectors (see e.g. [6]). The charge distribution induced on the segmented cathode is known to be centred on the initial ionization track. In our case, this is an averaged value of all the tracks of the Se^-. The charge distribution extends over 8 channels in average in X and 11 in Y if the threshold is set at 10% of the highest signal. The position is calculated by a charge weighted centre of gravity of all the adjacent channels above the threshold. An increase of the threshold does not change the resolution. In the Se^-D detector, the two cathodes are different: the first one is a wire plane (Y direction) and the second one is a stripped printed circuit (X direction). The resolution differs between the two axes: 1.4 mm (FWHM) in the X, and 1.7

mm in the Y with an optimal B_0 field of 110 Gauss. The Y direction is set to 45° relative to the beam, so the effective instrument resolution on the vertical position is 1.2 mm. The variation between X and Y resolution is thought to be related to the electric field shape between the anode and the cathode. While the field between a plane and a wire plane (as for the X position measurement) is well defined [17], the one between two orthogonal wire planes (as for the Y measurement) is less uniform.

While the time resolution might be sensitive to the signal to noise ratio, this is not the case for the position resolution, which remains unaffected from $V_{Se\text{-}D}$= 520 V to 600 V. For heavy ions, where the number of initial electrons is high, the present system is limited by the gain on the GASSIPLEX and the operating voltage must be significantly lower then the maximum sparking limit. Instead of working at around 600 V, the anode is set at 520 V (for a 4 Torr pressure) so as not to saturate the electronics.

Counting rate

In the configuration we use, the Se-D maximum counting rate is limited by the long dead time of the GASSIPLEX electronics and read out. It is of the order of a few 10^3 counts per second. Nevertheless, the intrinsic counting rate is significantly higher. We tested it up to 10^4 ions per second without the position information, but we did not try to reach the upper limit of the detector. Considering our experience with other low pressure proportional counters [6], we can make the reasonable hypothesis of a maximum counting rate of at least 10^5 ions per second. In-beam tests are required to establish this limit and will be performed in the future.

Conclusion

We have designed a very innovative detector for the timing and tracking of low energy heavy ions. It has the following characteristics:

- an effective size of 40 x 10 cm^2
- an effective thickness of only 250 $\mu g/cm^2$ of aluminized Mylar
- a time resolution of 300 ps (FWHM) for heavy ions (Z>30)
- a 2D position resolution of 1.4 mm (FWHM)

This detector couples a thin emissive foil to a low pressure gas chamber as a secondary electron detector. The guidance of the secondary electrons from the foil to the detector is done by an electric and a magnetic field. First and foremost, it has a very large detection area. It is particularly useful on the focal plane of a magnetic spectrometer for the tracking of the ion trajectories, as several successful experiments on VAMOS have shown. The 128 + 48 position channels are treated by integrated ASIC electronics. It is multiplexed for a minimal number of cables. It can be used for lighter/faster ions but its performance is optimal with fission fragment like nuclei. In comparison with micro-channel plates, its durability and insensitivity to X-rays are also advantages.

These characteristics make it very interesting for smaller scale applications, when time and position measurements are needed with minimal perturbation of the ion trajectory. With a smaller size detector the position resolution is better – 1 mm (FWHM) at 10 cm – and the thickness of the foil can be reduced for even less straggling – down to 50 µg carbon foils. The magnetic field is not necessary if only a time measurement is needed.

Thanks

We thank the GANIL engineering team for the simulations and measurements of the magnetic field. The Se^-D are now definitively installed on the VAMOS spectrometer and are taken care of by the VAMOS technical team and the host physicists. We greatly thank them for their help during the first tests and for the installation of the detectors.

References

[1] H. Savajols & al., Nucl. Instr. & Meth. B 204 (2003) 146–153

[2] A.C.C. Villari & al., Nucl. Phys. A693 (2001) 465.

[3] C.W. Williams et al., Rev. Sci. Instr. 35 (1964) 1116.

[4] K.E. Pferdekämpfer and H.-G. Clerc, Z. Phys. A 280 (1977) 155-164.

[5] E. C. Pollacco & al., Nucl. Instrum & Meth. **225**, 51 (1984)

[6] S. Ottini & al., Nucl Instr & Meth A431 (1999) 476-484.

[7] A. Drouart & al. Nucl. Instr. & Meth. A 477 (2002) 401.

[8] E. Bougamont & al. Nucl. Instr. & Meth. A 518 (2004) 129-131.

[9] S. M. Seltzer & M. J. Berger, Int. J. of Applied Rad. 35 (1984) 665.

[10] O.H. Odland & al., Nucl. Instr. & Meth A378 (1996) 149-154.

[11] A. Breskin & al., Nucl. Instr. & Meth. 196 (1982) 11-21.

[12] J. C. Santiard, CERN ER-MIC, Geneva.

[13] H. Rothard, Phys. Rev. A 41 (1990) 2521-2535.

[14] F. Salvat & al., Computer Phys. Comm. 42 (1986) 93.

[15] A. Breskin, IEEE Tr. Nucl. Sci., Vol. NS-27 No. 1 (1980) 133-138.

[16] L. Bonsten & al., Nucl. Instr. & Meth. A421 (1999) 471.

[17] G. A. Erskine, Nucl. Instr. & Meth. 105 (1972) 565.

Figure 2: Photograph of the definitive detector installed on the VAMOS spectrometer at GANIL

Figure 2: Sketch of the two copper coils and of the soft iron plates for the magnetic field. The emissive foil and the detector positions are indicated for reference.

Figure 3: Basic geometry of the low pressure Secondary electron Detector ($Se^{-}D$)

Figure 4: Image of a mask with B=0 (top) and B=110 Gauss (bottom) (same scale)

Ions	Energy (MeV/A)	dE/dx (MeV/mm)	Efficiency	Time resolution (FWHM ps)
Heavy Fission frag. Average Z~53	0.6	13800	100%	250
Light fission frag. Average Z~45	1	13200	100%	250
^{76}Ge	2	10500	100%	500
^{24}Mg	12	1050	85%	800
^{12}C	10	320	75%	1000
Alpha	1.5	160	40%(70%*)	1200*

Table 1: Efficiency and Time resolution for different ions with the operating conditions: V_0=-10kV, $V_{Se\text{-}D}$=520V (600V*), P=4Torr.

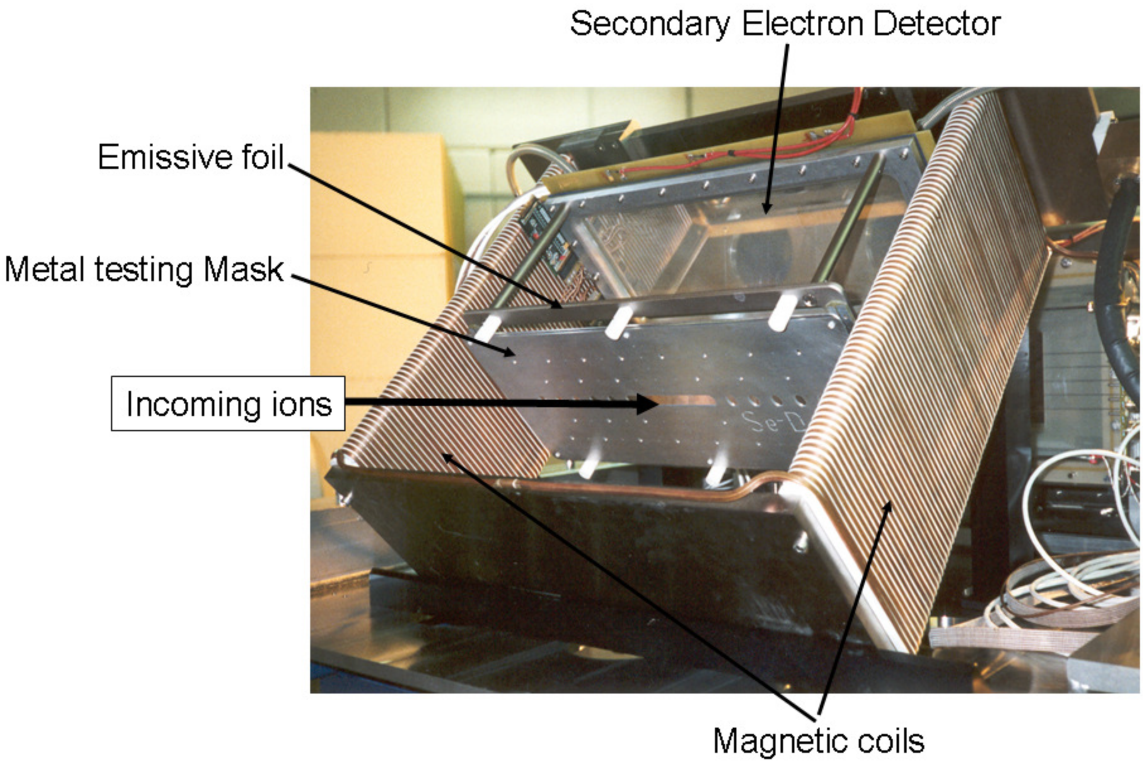
Secondary Electron Detector
Emissive foil
Metal testing Mask
Incoming ions
Magnetic coils

Figure 1

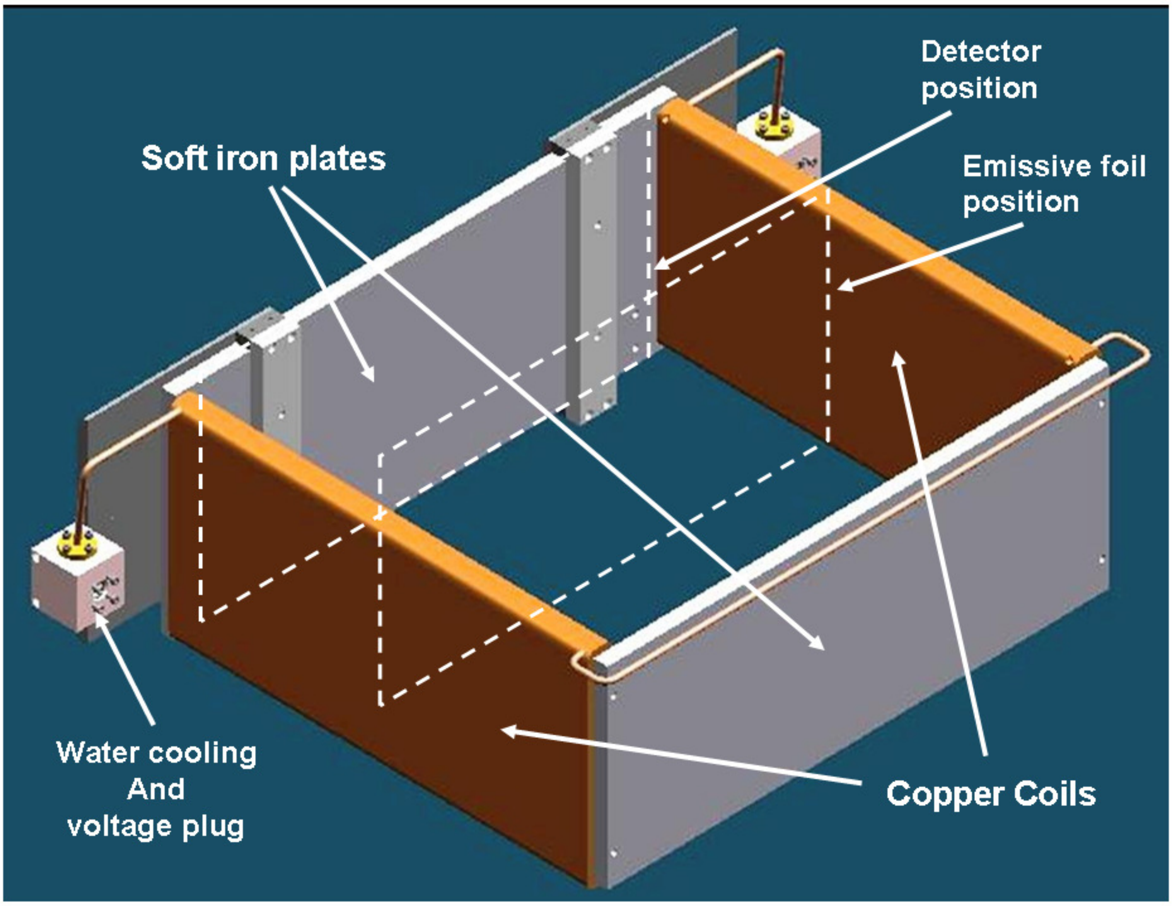
Detector
position
Soft iron plates
Emissive foil
position
Water cooling
And
voltage plug
Copper Coils

Figure 2

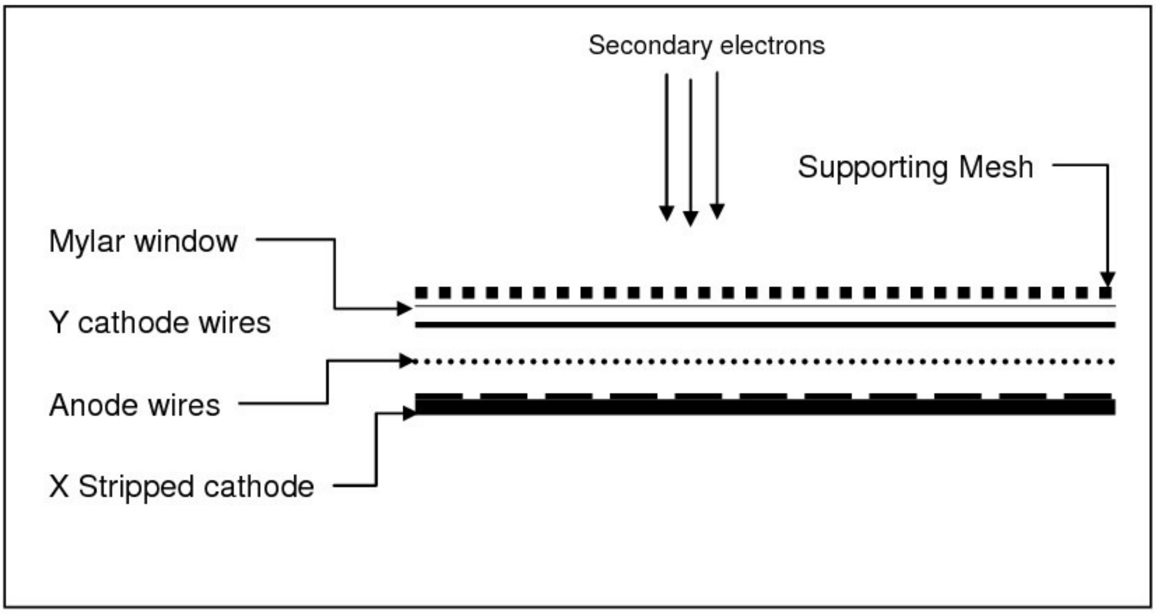
Secondary electrons
Supporting Mesh
Mylar window
Y cathode wires
Anode wires
X Stripped cathode

Figure 3

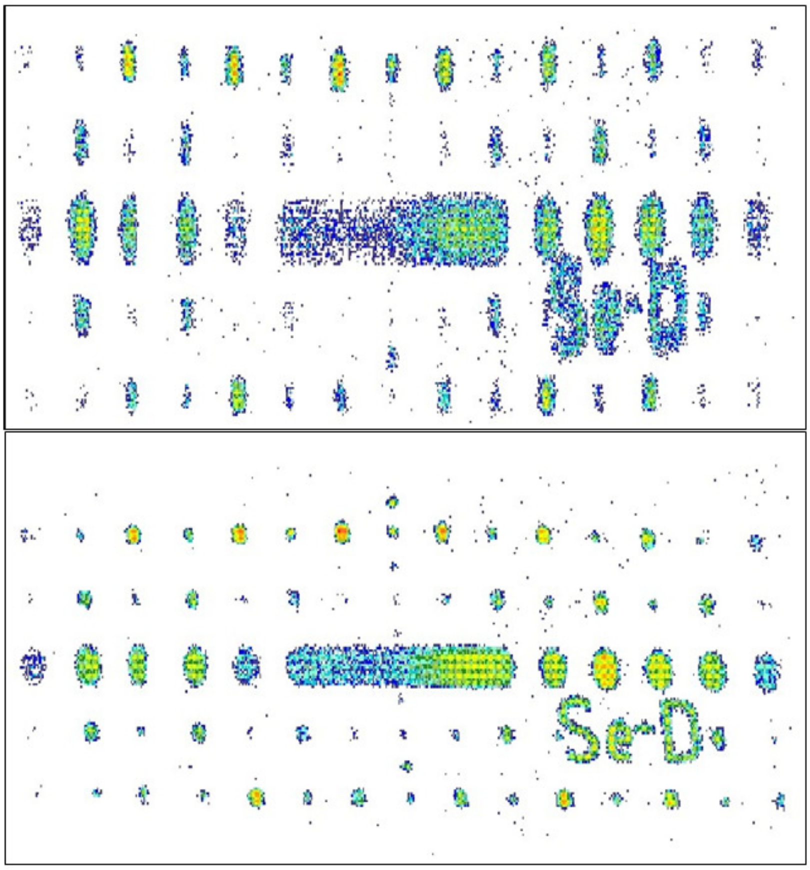

Figure 4