

SPECIAL FEATURE: TUTORIAL

Fundamentals of Focal Plane Detectors

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Spatial dispersion of ions in one dimension is a well established means of analysing ion mass and focal plane detectors (FPDs) allow ions of a wide range of masses to be recorded simultaneously. This paper is concerned with the principles governing the performance of FPDs and the types of FPD available. It is focused on magnetic sector mass spectrometry but is relevant to all applications in which spatially dispersed particles can be detected using a microchannel plate electron multiplier, e.g. ions, photons of wavelength <200 nm, electrons and energetic neutrals. Although it has proved possible to produce mass spectra with a high resolution, this has not been matched by an ability to detect them efficiently. Given that highly resolved spectra are available at the detector but are inaccessible efficiently, it is in the development of high-performance FPDs where there are enormous gains in efficiency to be achieved. Limitations of FPD performance of two fundamental types are discussed: the position of impact of an ion on the FPD cannot be measured *exactly*, and the upper and lower count rates of the FPD are both restricted. These limitations are not simply characterized but are sometimes determined by the electron multiplier stage, sometimes by the properties of the array and sometimes by the data acquisition system. © 1997 by John Wiley & Sons, Ltd.

J. Mass Spectrom. 32, 795–806 (1997)

No. of Figs: 20 No. of Tables: 1 No. of Refs: 26

KEYWORDS: focal plane detectors; magnetic sector mass spectrometry

INTRODUCTION

In mass spectrometry, ions of differing mass may be measured by (i) dispersion in space (e.g. magnetic sector) or time (e.g. time-of-flight), (ii) filtering (e.g. quadrupole) or (iii) absorption of electromagnetic energy [e.g. Fourier transform ion cyclotron resonance (FT-ICR)]. Focal plane detectors (FPDs) are used only when spectra are *spatially* dispersed. Electron and photon spectroscopy also normally involve spatial dispersion and have been a driving force in FPD development. Although magnetic sector mass spectrometer design and ion optics have advanced over the years and enabled the production of very highly resolved mass spectra, this capability has not been matched by an ability to detect the dispersed ions efficiently. The basic problem is that the high resolving power of a single-slit detector is incompatible with high collection efficiency. This is illustrated in Fig. 1, which shows that the measured peak profile depends on the slit width (it is the convolution of the incident profile and the slit width). The measured profile more accurately represents the incident profile when the detector slit is narrow [Fig. 1(a)] but clearly a narrower slit means that a smaller fraction of the spectrum is measured at any one time and the entire spectrum takes much longer to measure.

Consider the hypothetical ion beam with the probability distribution $P(x)$ shown in Fig. 1(a). If the dis-

persed ion beam falls across a narrow detector slit of width W_N , a small section of the beam I_N is sampled as shown. The measured ion peak intensity is given to a good approximation by:

$$I_N = W_N[P(x') + P(x' + W_N)]/2$$

When W_N is very small, this gives

$$I_N = W_N P(x)$$

and measurement of I_N gives the beam profile to a constant factor. Note that the probability distribution $P(x)$ has units of counts $s^{-1} m^{-1}$ and I_N has units of counts s^{-1} .

Consider the wide detector slit ($2 \times$ FWHM) in Fig. 1(b). Normally the beam is scanned across the detector slit. For convenience of illustration we imagine a stationary beam with the slit moving from left to right. The

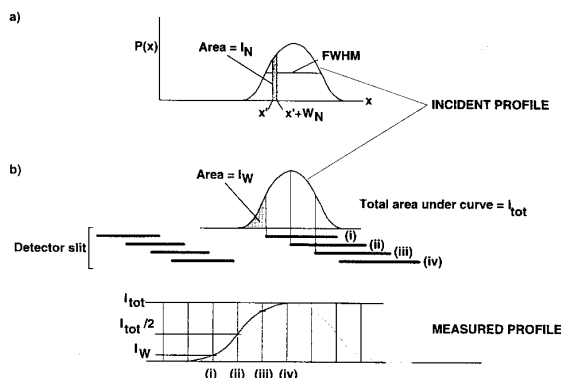


Figure 1. Measurement of an incident particle beam using (a) a narrow slit and (b) a wide slit.

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measured ion peak intensity profile is found by integrating the area under the profile falling above the exit slit. For example, the area I_w represents the section of the beam passing through the slit in position (i). This is plotted at the position of the slit centre along with intensities measured at other positions in the lower part of the figure and it is seen that the measured peak is wider.

Unfortunately, narrow slits sample a mass spectrum very inefficiently. It is the objective of FPDs to detect ions over a much greater fraction of the focal plane than possible with a single slit. It is in the area of FPD development where large gains in efficiency are to be made. The emphasis here will be on one-dimensional multi-event discrete FPDs (see below). These devices have a high data accumulation rate as particles can be detected at many sites simultaneously. Other types of FPD are also mentioned below.

Ion detection

All ion signals result from the combined effects of one or more discrete ion events. Where the flux is low these events may be counted (digital measurement) or their effects may be integrated (integration). For high ion fluxes, direct measurement of the ion current (DC measurement) is possible. In general, non-digital measurements are referred to as 'analogue' measurements.

Digital. In the case of ion (or electron or photon) counting, the occurrences of events are recorded [Fig. 2(a)]. Measurement system noise can be almost eliminated to the point where the fluctuation in the observed count rate is controlled by ion arrival statistics and is random. At low counts the peak height shows a Poisson variation which approximates to a Gaussian variation at high counts with a precision of \sqrt{N} , where N is the number of counts accumulated. Very low ion currents

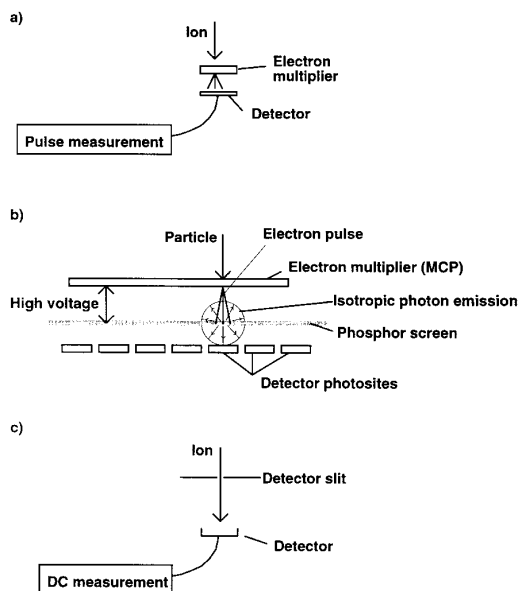


Figure 2. (a) Measurement of an electron multiplier pulse. The electron multiplier may be preceded by a defining slit. If a detector array is used then the electron multiplier is an MCP and there is no defining slit. (b) Measurement of ion flux by integration of free electrons created at photosites by photons emitted at the phosphor screen. (c) Direct measurement of the ion current for large ion flux.

can therefore be measured by counting under conditions where DC current measurements would introduce a measurement error greater than the signal. However, it is beyond the capacity of pulse counting systems to count ions at rates comparable to the switching times¹ of the transistors as the sensing and counting circuitry cannot respond sufficiently rapidly. The upper count rate limit may also be determined by the response time (below) of the electron multiplier (cf. Fig. 2).

Integration. Two-dimensional semiconductor arrays are widely used in video cameras for visible photon detection. These can be adapted for use in ion detection by first converting ions to photons, as shown in Fig. 2(b). Photons reaching a photosite excite electrons to the conduction band. Electrons in the conduction band are called 'free electrons.' Other events cause the excitation of more electrons and the total number of free electrons is a measure of the number of ion events incident above the photosite. At room temperature free electrons are generated thermally and this introduces *thermal noise*, which can be reduced by reducing the operating temperature. This is in addition to noise introduced during the measurement of the integrated free electrons. These devices can be used to count events, although they are better suited to the integration mode. They can be adapted to measurements in one dimension by averaging the signals in the dimension perpendicular to dispersion.

DC. A sufficiently high ion flux can be regarded as a continuously variable current and measured directly as shown in Fig. 2(c). In the measurement of *continuous* signals the measurement system noise and the signal are added. There is no clear upper limit to the measurement of a DC current. In practice, the minimum current detectable by DC measurement is about 10^{-15} A (about 10^4 ions s^{-1}) but only with a slow (>1 s) response time.² This can be greatly improved using an electron multiplier.

Focal plane detection. Examples of focal plane detectors are presented later. The job of an FPD is to measure a whole section of spectrum simultaneously. Figure 3 shows a multi-event discrete detector FPD consisting of a one-dimensional array of metal strips (detector electrodes) which form the detector inputs. An ion impacting on the MCP initiates an electron pulse at the

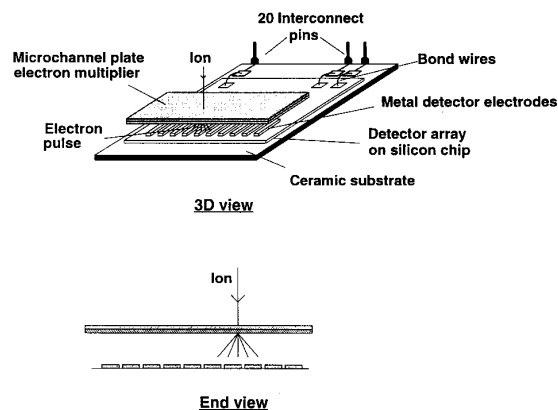


Figure 3. A multi-event discrete detector FPD.

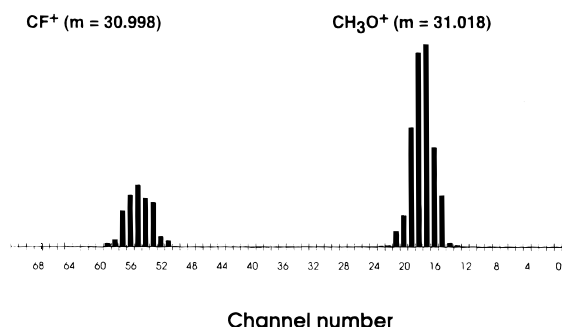


Figure 4. Peaks taken from the spectrum of methyl pentafluoropropionate.

MCP output which falls on the electrodes and is counted. If the electron pulse is wide a single count may be recorded on more than one electrode. A device of this type, an integrated array of 192 detectors on a single silicon chip, has been successfully produced at Aberystwyth.³⁻⁶ It is a small, low-power, high-resolution device which realizes the advantages of a fully parallel detector system. Each detector operates independently and consists of a metal strip (detector input electrode) exposed to the MCP output, a charge sensor, an eight-bit counter, control logic and a bus interface. The detector electrode pitch (the distance between the centres of adjacent electrodes) is 25 μm .

In the 1970s, FPDs were developed following MCP development at a time when custom integrated circuits were not easily accessible. Therefore, arrays were developed which required little electronics. Unfortunately, they were limited to low particle flux where the position of arrival of each ion is computed and registered before arrival of a subsequent ion (see later). Fully parallel particle counting is only possible with a dedicated sensor and memory at each detector site. Timothy and Bybee have produced a one-dimensional discrete detector FPD containing 64 detectors⁷ and a two-dimensional device⁸ containing 100 detectors. Each FPD consisted of detector electrodes deposited on a ceramic substrate and these were connected to external (non-integrated) charge amplifiers and other data-handling circuitry. The number of detectors contained by these FPDs was limited by the large amount of external electronics required. Integration of a small number of detectors at low resolution is today a simple problem but a high-resolution device on a silicon chip requires careful design to accommodate a high density of electronics with high performance and functionality, an acceptable yield and robustness. This has been achieved as discussed below.

Figure 4 shows an example of a mass spectrum measured using the Aberystwyth array. Each bar of the histogram gives the number of counts measured by one of the detectors on the array.

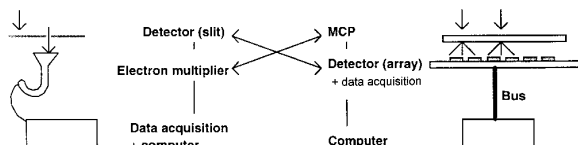


Figure 5. Similarities and differences between a single-slit detector (left) and the FPD (right). The FPD contains no defining slit and therefore detector array sites are exposed to the high-gain MCP output of remote events.

The ideal FPD

An ideal FPD would record the *exact* location of *every* ion in the spectrum. Why cannot this be achieved? There are two reasons: the point at which an ion hits the electron multiplier cannot be recorded *exactly* because of limitations of both the MCP and the array; and both the MCP and the array place limits on the rate at which ion flux can be accurately measured.

In this definition of ideal, we are assuming that the data can be transferred rapidly to the data acquisition and display system. If this were not the case then the data transfer rate itself might determine the upper limit of the flux. We are also temporarily ignoring other issues of importance to a user such as size, complexity and cost. The reason for these omissions is that we are focusing on fundamental performance issues which limit the ideal measurement of the *exact* location of *every* ion in the spectrum.

Currently, single ions cannot be detected without amplification and some form of electron multiplier is essential. Figure 5 shows that in the case of the single slit detector the part of the spectrum to be measured is defined by the slit before multiplication, which is achieved with a conventional single-stage electron multiplier. There is necessarily no slit present when an FPD is used and the spectrum falls directly on a multi-element electron multiplier known as a microchannel plate (MCP). Therefore, there is no definition of the part of the spectrum falling on the multiplier and a detector site of the array is exposed not only to MCP pulses centred directly above it but also to the high gain pulses of more remote events (Fig. 5). This limits the performance in different ways depending on the type of FPD, as will be discussed below.

A single slit has a significant advantage in that the position of arrival of an ion can be known to an accuracy determined by the slit only. When an event is located from an MCP pulse measured using an array, then the position of arrival cannot be known to better than the MCP channel diameter as all information on the position of arrival of the ion within the channel is lost. However, because an ion peak is an accumulation of many events occurring over the length of one or more electrodes the (normally) random registration of MCP channels above an electrode can result in a measured peak whose centre is given more accurately than the MCP channel diameter.⁹

The high resolving power of a narrow single slit unfortunately means that a small fraction of the spectrum is measured at a given time, i.e. there is a lower collection efficiency. The driving force behind the development of FPDs is the need for a greater collection efficiency. The problem is to achieve higher collection efficiency and match the cost and performance advantages of a single slit.

ARRAYS ON SILICON

Each detector of a discrete detector array requires its own charge sensor and a counter large enough to avoid

overflow before reading. Given the large amount of circuitry needed, it is the case that a high-resolution array of ion counters cannot sensibly be achieved any other way than by integration. It is conceivable that some other semiconductor (e.g. GaAs) or fabrication technology (e.g. silicon on sapphire) could be used, but currently CMOS (complementary metal-oxide-semiconductor) technology is the most cost effective route. Therefore, silicon technology is likely to dominate in high-resolution one-dimensional arrays of event counters because (i) a high resolution array of discrete counters requires a great deal of associated electronics and there is no case for non-integrated electronics, and (ii) continuing high investment in silicon technology will lead to increasingly high specifications and lower costs.

It is normally extremely difficult or impossible to make circuit changes after a chip has been fabricated and therefore all design features must be identified at the outset and incorporated in the design. The major aim is then to achieve all objectives on a single device. The ability to recognize all important design features inevitably requires a multidisciplinary approach. The issues mentioned below represent some of the gross issues involved in the development of a high performance array detector.

Sensitivity

The central issue is whether a silicon chip based detector can be made sensitive enough to detect a single MCP pulse and the answer is a very clear 'yes'. The typical capacitance of a metal layer (from which detector electrodes are formed) on a silicon chip is about $2 \times 10^{-17} \text{ F } \mu\text{m}^{-2}$. The MCP output is around 10^7 electrons ($1.6 \times 10^{-12} \text{ C}$)¹⁰ spread over a circle of radius about $50 \mu\text{m}$ (area about $8000 \mu\text{m}^2$). The voltage induced on a circular metal electrode of radius $50 \mu\text{m}$ by 10^7 electrons is

$$V = Q/C = 1.6 \times 10^{-12} / (8000 \times 2 \times 10^{-17}) = 10 \text{ V}$$

The capacitance can be reduced by introducing a thicker insulating layer to separate the metal electrode from underlying circuitry. An electrode of size $2 \text{ mm} \times 18 \mu\text{m}$ on the Aberystwyth array has a capacitance of around $0.2\text{--}0.4 \text{ pF}$. Thus easily detectable voltage pulses ($>0.2 \text{ V}$) are induced by the MCP pulse. The probability of thermal noise of this magnitude is extremely low, giving essentially zero noise for the array. The MCP itself generates less than three 'dark counts' per cm^2 .¹¹ Given that each detector electrode has an area of about $4 \times 10^4 \mu\text{m}^2$, there are about 10^{-4} counts s^{-1} for each electrode.¹²

Silicon area

The second key issue is whether a high-resolution device with high performance and built-in testability can be accommodated on a small silicon chip. As a detector array is a repeat of many identical units, a single unit must first be designed. For a spatial resolution of $25 \mu\text{m}$ there must be 400 detectors per cm and all the circuitry must fit within the boundary of the

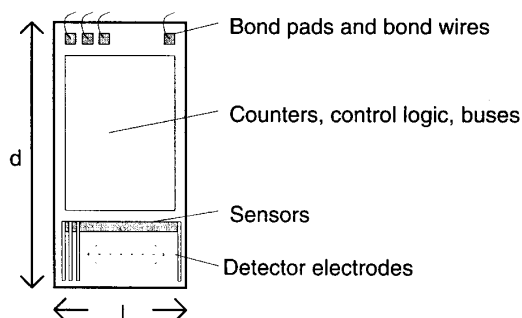


Figure 6. Schematic diagram of the layout of the Aberystwyth detector array.

chip. Figure 6 shows a plan of the array developed on a silicon chip at Aberystwyth. The detector electrodes are arranged along one side of the chip. All associated circuitry is placed as shown.

The dimension d is fixed by the spatial resolution, i.e. the more detector electrodes per unit length (length is in the direction of l) the more circuitry must be accommodated within the distance d . In the case of the Aberystwyth array d was 14 mm and l was 5 mm , giving an acceptable yield.

In spite of the large size and dense circuitry, the energy dissipation is so low that there is no need for cooling even in a vacuum. Low heat dissipation is characteristic of CMOS technology.

Robustness, lifetime

Clearly, an FPD will be of little value if it is extremely fragile or has a short lifetime. The focal plane of a mass spectrometer appears to be in a hostile environment for a silicon chip, especially given the proximity of a high-voltage MCP. The possibility of a high-voltage discharge would definitely pose a potential hazard. This danger to the Aberystwyth array was minimized by adding extra diode protection as an integral part of the chip to short circuit high-voltage fluctuations and by incorporating a high resistance in the high-voltage MCP power line. Most arrays survive numerous discharges.

Apart from an accidental discharge, the only wear and tear on the array is due to impact by MCP electrons. These emerge from the MCP with a kinetic energy of about $30\text{--}100 \text{ eV}$,³ and there is no obvious reason why the bombardment with low-energy electrons should reduce the lifetime of the array. Two arrays have been in intermittent use for over 3 years without a noticeable change of performance.

Physically, the detector array chip is not unduly fragile except in two respects: the surface of the silicon must not be scratched, and bond wires connecting the chip to the ceramic substrate are very fragile. The first problem is avoided by careful handling. Encapsulation of bond wires in a bakeable epoxy resin has proved a successful solution to the second problem.

Technology

Silicon technology is now a major force in electronics, but small-volume devices do not usually attract the

attention of designers and hence the value of this technology is often not exploited as users are unable to design the devices themselves. This is slowly changing and important devices are being produced, such as chemical, physical and medical sensors.

What does silicon have to offer in array design? The first point is that there is no other sensible way to produce a straightforward device containing a great deal of electronics than by integration. However, there are other significant advantages to be had from integration on silicon:

- All sensitive circuitry is an integral part of the array inside the vacuum system in a shielded environment. A low-impedance bus to the outside is insensitive to noise.
- Low capacitance of the detector electrodes. Typical MCP output pulses induce voltage pulses of >0.2 V on electrodes and hence the pulse height discrimination level (PHDL) can be set well above the thermal noise threshold.
- The device allows the elimination of cable and instrument clutter and inherits many of the characteristics (e.g. cheapness, reliability, increased functionality, small size and weight) which have led to the domination of integrated circuits (ICs) in many areas.

It is a characteristic of CMOS technology that very little power is consumed. The Aberystwyth array consumes about 5 mW for 192 detectors and could be powered by a 5 V battery with no cooling necessary. The integration of a complete high-resolution discrete detector array system, including computer interface, on a silicon chip is in line with developments in 'smart' sensors, and although the research and development costs are high the production cost of a 192 detector array is low. Therefore, the prospect of disposable arrays exists.

POSITION MEASUREMENT

The objective of finding the location of an event has been achieved in a number of ingenious ways. These have been reviewed by several authors.^{12,14,15} In the following, methods of event location are arranged in classes and an example in each class is discussed. A fuller coverage of individual FPDs can be found in the reviews. It should be noted that many branches of mass spectrometry, such as time-of-flight, quadrupole and FT-ICR, do not rely on position measurement for mass analysis.

Discrete sites

Discrete detector array. It is generally considered that the discrete detector array is the most straightforward, conceptually the simplest and the best approach if counting statistics are required at every site. A 1D discrete detector array can be viewed as many independent single-slit detectors placed side-by-side and events can be recorded at each detector simultaneously.⁶⁻⁸ Such a device may be called a 'multiple-event' array to distinguish it from 'single-event' arrays described below, which can

only measure events sequentially. The barrier to the development of a multiple event discrete detector array is that for particle counting applications there must be a dedicated sensor and counter at each site. Such a large amount of non-integrated electronics is expensive, complex and limits the performance by increasing the capacitance of detector sites as well as site-to-site capacitive cross coupling. However, integration of this circuitry on a silicon chip allows the minimization of complexity, cost, capacitance and cross-coupling in one go. A later section focuses on the performance of the discrete detector array.

Integrating FPD. In this device (Fig. 7) the MCP output pulses are accelerated on to a phosphor screen and the resulting pulse of photons is transmitted to a photodiode array¹⁶ or a CCD^{17,18} (e.g. by channelling down an optical fibre bundle). Resolution is lost at each interface and the photon pulse width measured is a minimum of 100 μm . This resolution combined with a good dynamic range has allowed the use of these devices in mass spectrometers.

A useful characteristic of this type of array is that in applications where bunches of particles arrive at a single detector site in a very short time (e.g. 1 ns) the effect of the resulting MCP pulses would be correctly integrated (assuming the number of particles does not saturate the MCP or the photosite) whereas the discrete detector array would register only one event.

Charge division

Events can be located by charge division by dividing the MCP output pulse between two or more detectors and computing the event position in terms of the charge received by the detectors, as illustrated below. Thus the position of each event is computed and the electronics required are minimized. However, the ion flux must be low enough to ensure that there is little chance of arrival of a second ion before an event location is computed and logged. A high-intensity peak would 'blind' the FPD and would have to be moved off the FPD or reduced in intensity if much smaller peaks are to be measured.

The resistive strip. In its simplest form (Fig. 8) the resistive strip FPD consists of a thin layer of resistive material on the surface of an insulator with electrodes attached to each end. The path resistance seen by an electron pulse to each end of the strip depends on the position of arrival of the pulse and this position can be computed simply from the magnitudes of the charges arriving at each end. A 'spatial location error' of about 21 μm over 25 mm has been obtained with this device.¹⁹

The resistive strip can be represented as a resistor. A pulse landing at a distance x' from the left (Fig. 9)

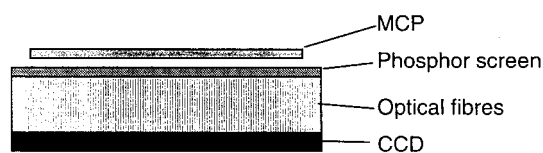


Figure 7. Electro-optical FPD.

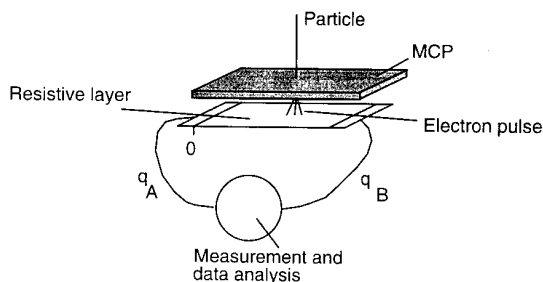


Figure 8. Resistive strip FPD.

induces a small potential and current flows to both ends in the ratio determined by Ohm's law:

$$\frac{i_B}{i_A} = \frac{R_A}{R_B} = c$$

Therefore,

$$i_B = ci_A$$

$$\int_{t_1}^{t_2} i_B dt = q_B = c \int_{t_1}^{t_2} i_A dt = cq_A$$

$$\frac{q_B}{q_A} = c = \frac{R_A}{R_B} = \frac{x'}{x - x'}$$

and

$$x' = \frac{q_B}{q_A + q_B} x$$

Clearly, for accurate event location the resistive layer must be uniform. The main sources of error are in non-uniformities of this layer, electronic noise and thermal noise. Other important devices exist in which the charge is divided by capacitive coupling between discrete electrodes or by varying the dimensions of electrodes across an array such that the charge division is related to the event location.^{12,14,15}

Coincidence

A family of 'multi-anode microchannel arrays' (MAMAs) have been described by Timothy and Bybee⁸ for one- and two-dimensional imaging. The location of an event is determined by the simultaneous detection of a charge pulse on two sets of anodes deposited on a ceramic substrate (Fig. 10). The spatial resolution of the anodes was 25 μm in the device described by Timothy and Bybee.

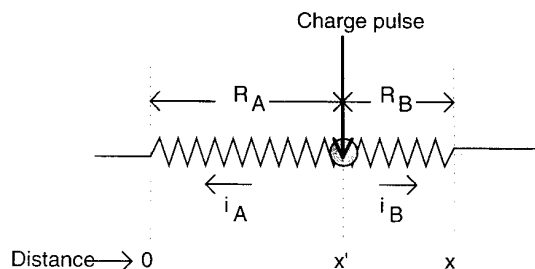


Figure 9. Measurement of the location of an event using a one-dimensional resistive strip.

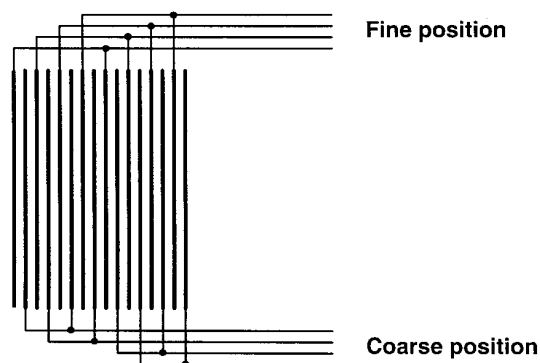


Figure 10. Multi-anode coincidence detector.

Electrodes are connected alternately to coarse and fine position encoding amplifiers as shown. The ambiguity in the location of an event when measured by the fine position encoder is resolved by the coarse position encoder. The final ambiguity of whether the event is closer to the fine position electrode or the coarse position electrode is resolved by determining the electrode receiving the greater charge.

The position of an event in two dimensions has been found using a grid of crossed wires. With a grid of $n \times m$ wires the positions of arrival at $n \times m$ points can be found using $n + m$ amplifiers. Coincident signals on the orthogonal wires indicated real events. A resolving power of 10 μm has been achieved using a crossed grid of 100 μm wires on a 200 μm pitch. The device can count at rates up to 10^4 s^{-1} .

THE MCP OUTPUT

In understanding the FPD performance it is essential to understand the factors which influence the gain and the spreading of the electron pulse output by the MCP. The performance of MCPs has been studied extensively.²⁰⁻²³ We divide the FPD into three regions (Fig. 11). In the first region electron multiplication occurs, in the second the pulse widens and in the third the pulse is measured. Measurement of the MCP output is performed in different ways by different arrays. A comprehensive survey is beyond the scope of this paper and the discrete detector array is considered here. The issues raised have relevance for other types of array.

Electron multiplication

The MCP provides amplification and also retains spatial information. A schematic diagram of an MCP is

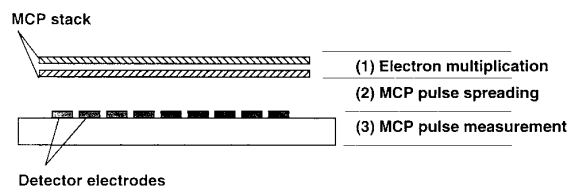


Figure 11. Diagram showing the division of an FPD into regions for discussion purposes.

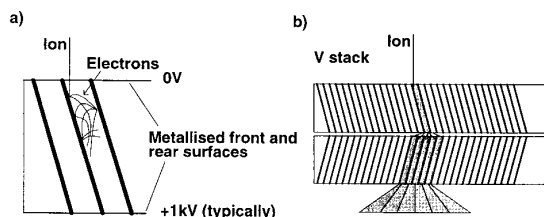


Figure 12. Multiplication of electrons by an MCP. (a) A particle entering an MCP channel emits one or more electrons which are accelerated along the channel to give further collisions and multiplication of the signal. (b) A single event leads to a wide electron pulse at the MCP exit with further spreading on travelling to the array. The channels are arranged to slope in opposite directions to reduce ion feedback and optimize the incident ion detection efficiency.

shown in Fig. 12(a). It consists of a plate typically of thickness 0.5 mm and composed of many small tubes (typically straight tubes of diameter 12 μm) each of which is at an angle of typically 10° to the vertical and has an internal coating of a low work function material. A voltage (typically ≤ 1 kV) is applied between the metallized front and rear surfaces of the MCP. An ion entering a MCP channel causes the release of secondary electrons, which are accelerated down the channel, each electron releasing further electrons resulting in a pulse of G (gain) electrons being emitted at the MCP exit within 1 ns. The firing of an MCP channel is analogous to the sudden discharge of a capacitor and the capacitor must be recharged by current in the channel wall. Typically the recharge time is 10^{-2} s. In order to increase the gain, two MCPs may be stacked together as shown in Fig. 12(b).

Of most importance here is to understand the properties of the electron pulse output by the MCP, as this is the evidence of the arrival of an ion to be measured by the array. Here we will consider the output of a single MCP and the output of a stack of two MCPs.

Pulse gain. Single plate: gain distribution. The gain distribution of a single MCP plate is typically a quasi-exponential decay (average gain about 10^4) as shown in Fig. 13. As the supply voltage is increased the distribution shifts to higher gains but the effect known as 'ion feedback' limits the maximum operating voltage. At high supply voltages (typically > 1 kV), ions formed from residual gas are accelerated back up a MCP channel, collide with the channel wall and initiate secondary electron pulses. This degrades the performance

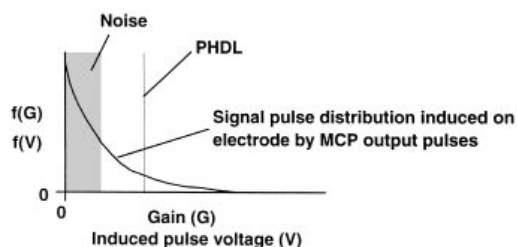


Figure 13. Schematic diagram of the MCP pulse gain distribution $f(G)$ of a single MCP plate. The pulse voltage distribution $f(V)$ induced on the detector electrodes by the MCP electron pulses mirrors the gain distribution and is plotted on the same axes. A pulse is counted by a detector only if the induced voltage on the detector electrode is $> \text{PHDL}$.

and may lead to a continuous discharge. It can be seen that all pulses are counted (i.e. they are above the pulse height discrimination level (PHDL) of the detectors) only if the PHDL is set very low, in which case noise will degrade the data.

MCP stack: gain distribution. If two MCPs are arranged as in Fig. 12(b), ions formed from residual gas in the second MCP are stopped at the interface between the MCPs before they acquire sufficient energy to release secondary electrons, thus reducing ion feedback effects. The input of each channel of the second MCP receives sufficient electrons to drive it to saturation. When the channel output is saturated it is independent of the initiating event and the gain distribution is peaked. The importance of this for event counting can be seen from Fig. 14. The PHDL can be placed above the noise level but below the signal voltage pulse distribution induced by the MCP output. It can be seen that in this case all events are detected (i.e. they are above the PHDL) and that for small fluctuation of the PHDL or MCP gain (which shifts the pulse distribution) there is little variation of the measured signal. This is the *region of stable operation*.

Capacitive cross-coupling between detector electrodes gives an image of the signal voltage distribution on adjacent electrodes. The dotted distribution in Fig. 14 shows such an image. If cross-coupling is low the two distributions may not overlap and the PHDL may be set at a level which detects all events without measuring 'image' pulses on adjacent electrodes or the noise. Thus the measured noise level would be the minimum attainable, inherent in the random time of arrival of the ions, the purely statistical. There would be no region of stable operation if the signal and noise overlap significantly.

Typically the FWHM of the gain distribution is about $\pm 50\%$ of the gain. If the MCP supply voltage is reduced then the peak moves to lower gain and the profile eventually changes to a quasi-exponential fall off.

Pulse spreading

An MCP pulse is output in < 1 ns. The electrons fall on detector electrodes and induce voltage pulses. The first question to be addressed is how many electrons fall on each electrode. This is determined by the gain and the profile of the pulse which overlaps the electrodes.

Pulse profile. A key issue in understanding the performance of a multievent discrete detector FPD is the

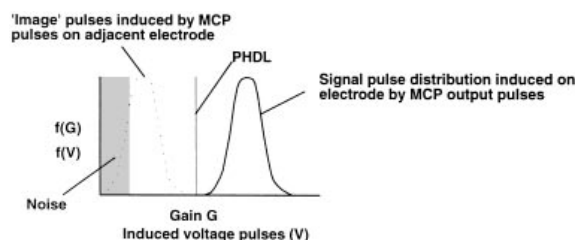


Figure 14. Schematic diagram of the gain distribution of a stack of two MCP plates. The dotted distribution shows pulses capacitively induced on an electrode by MCP pulses falling on adjacent electrodes.

shape of the electron pulse landing on the electrodes. Figure 12 shows that the electron pulse initiated by a single event can become very wide on reaching the array. The profile is not known exactly but should approximate a flat-topped peak with Gaussian fall-off. The factors which influence the width of the measured peak include the following.

Separation between MCPs in a stack. A number of channels of the second MCP are activated by one channel of the first MCP. Even when the plates are in intimate contact, it has been observed²⁴ that the electron pulse emerging from the second MCP has a diameter of about 100 μm , corresponding to the activation of around 50 channels. This may be due to non-planarity of the MCP plates. An electric field between the stacked MCPs helps to reduce the electron pulse spreading.

MCP gain. There is greater spreading for a larger gain MCP output pulse as space-charge repulsion (mutual electrostatic repulsion of the electrons) is greater.

Separation between the MCP and the array. The greater the separation, the greater is the spreading of the electron pulse. This is due not only to geometric factors but also to the increased time during which space-charge repulsion is active.

Field between the MCP and the array. An attractive field will help to confine the electrons and give less spreading.

Capacitive coupling between electrodes. A voltage pulse will be coupled to adjacent electrodes due to capacitive coupling between the electrodes thus spreading the effect of the pulse.

A computer model of the Aberystwith FPD includes all the above factors and has given good agreement with experimental results.²⁴

Curved channel MCPs²⁵ provide a high gain from a single channel, thereby avoiding the need for a stack of two MCPs. An electron pulse of high gain emerging from a single channel would have a small diameter but would experience higher space-charge repulsion. Curved channel MCPs are currently not available commercially except by special order.

Pulse measurement

The voltage pulses induced on the detector electrodes must be measured. If the pulse height on an electrode is above a set threshold (PHDL), then a single count is added to the counter associated with the electrode. In Fig. 15(a), most of the MCP pulse falls on a single electrode and a count is registered at only one site. In Fig. 15(b) a wider MCP pulse gives voltage pulses higher than the PHDL on three electrodes, resulting in the recording of a single count at three sites.

Uniformity

It is immediately obvious that in the case of an FPD an unwelcome factor presents itself which is not an issue for the single-slit detector, namely that any non-

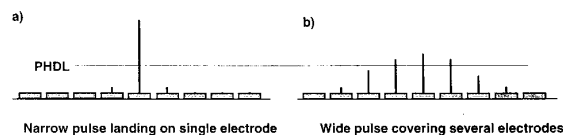


Figure 15. Voltage pulses induced on detector electrodes by a single event. Pulse heights are represented by vertical lines. (a) Charge lands on a single electrode. Small pulses are induced on adjacent electrodes due to capacitive coupling but fall below the threshold for measurements set by the PHDL. (b) A wide electron pulse falls on several electrodes giving voltage pulses $>$ PHDL on three electrodes.

uniformities of the multiplier or array will influence the measured spectrum. The quality of MCPs is generally high. When properly commissioned, low dark counts over the entire MCP are normally observed. Non-uniformities of the MCP quality can take the forms of variations in the channel to channel average gain and non-planarity of the MCP plates. The latter might give a variation of electron pulse spreading (see above) because of the variation of the distance of separation between MCPs in a stack and also the distance between the MCP output and the array. However, as many MCP channels service a single detector electrode, variations of channel to channel performance should be averaged out. On the other hand, the effects of longer range variations in planarity may not be averaged out.

Dynamic range

The duration of a single MCP pulse is of the order of 10^{-9} s and it may appear that a single MCP channel could deliver around 10^9 distinguishable pulses per second. However, as pointed out above, each channel requires a certain time to recover (typically 10^{-2} s) and the maximum pulse rate which can be delivered by an MCP channel without significant gain reduction is therefore of the order of 10^2 s^{-1} . Up to about 1000 MCP channels can service a 2 mm \times 18 μm electrode, giving a maximum count rate of the order of 10^5 s^{-1} .

However, the random time and position of arrival of the ions also influence the maximum flux accurately measurable. Even when the ion flux is below the maximum calculated above, some ions will by chance arrive at channels within the recovery time and may not be counted owing to the reduced gain of the channel. If the total incident ion flux (I_{lim}) on N MCP channels were $N/(\text{recovery time})$, then by chance 26% would fall on unrecovered channels. At a flux of $0.4I_{\text{lim}}$ this would fall to 6% and at a flux of $0.2I_{\text{lim}}$ to 2%.

FPD PERFORMANCE

A complete detector system incorporating an integrated discrete detector array includes the array, an MCP, a computer (a PC) and associated power supplies. The array contains all the sensing circuitry, eight (or more) bit data buffers and a computer interface. A complete specification would be lengthy and therefore only three of the most important performance issues, uniformity,

dynamic range and resolving power, will be considered here. These issues are relevant to all FPDs but for reasons of space the discussion here is restricted to the discrete detector FPD.

Uniformity

Figure 15 shows a uniform PHDL across an array. If the PHDL is not the same for all detectors, then those detectors with lower than average PHDL will on average record more than their fair share of pulses, and the reverse is true for the detectors with higher than average PHDL.

Uniformity is not an issue for a single slit where particles land on the same multiplier with the same measurement electronics. In the case of a discrete detector array on a silicon chip each detector has its own charge pulse sensing circuitry and small differences between the PHDLs of the detectors will arise due to manufacturing tolerances, etc. Non-uniformity is reflected in the accuracy with which peak heights and positions can be found from the quantized position information. Digital signal processing yields both the height and position of peaks and as the PHDL variation across the array can be measured, corrections for this can be incorporated. For the Aberystwyth array processed measurements of a spectrum have shown that a position accuracy of the order of $0.2 \mu\text{m}$ (as defined by the standard deviation of the distance between two peaks as they were swept across the array) is achieved and the relative peak height variation approximately equals that expected statistically.⁹ The raw data used in this analysis are shown in Fig. 16. The larger peak was moved in steps of $12.5 \mu\text{m}$ so that it was alternately directly above an electrode and then between two electrodes hence the alternate high-low variation of peak height. It should be noted that a constant peak height (but lower resolving power) is obtained with a lower PHDL.¹²

Quantization. The location of an event cannot be known *exactly* whether a single slit or an FPD is being used. In the case of a slit, the width limits the position accuracy. In the case of a silicon detector array, the positional accuracy is limited by any non-uniformity of the charge pulse sensor performance and quantization of the positional information. Both the MCP and the array positional information are quantised.

Figure 17 is an approximate scale diagram of a section of a discrete detector array preceded by an

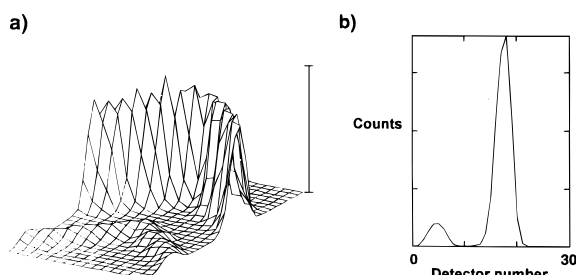


Figure 16. Two ion peaks scanned across the Aberystwyth FPD. (a) The peaks were positioned alternately directly above a detector electrode and between electrodes. (b) The ion peaks at one position.

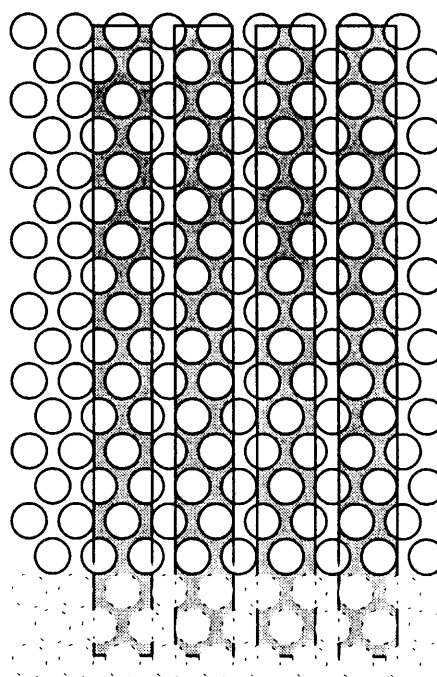


Figure 17. An approximately scale diagram showing relative sizes of detector electrodes and MCP channels.

MCP. The registration of MCP channels and electrodes is normally unknown.

Because many MCP channels service a single detector electrode, variations of channel to channel performance should be averaged out. The peak measured by a discrete detector array is in fact a histogram and although the height and centroid of such a peak cannot be read off by eye as easily as in the case of a continuous outline, they can be rapidly computed using digital signal processing techniques.

Dynamic range

A spectrum often contains many peaks of greatly differing height and one objective is to measure the height of each one as accurately as possible. The dynamic range of an FPD is the range over which the ion flux can be accurately measured. At very low ion fluxes measurements become inaccurate when the noise contribution to the measured flux is comparable to the ion signal. The lower limit of the dynamic range may be defined as the point at which the signal and the noise are equal, i.e. the lower limit is the noise level. At high ion flux the rate of arrival of ions exceeds the limit of a counting system and/or FPD and the measured count rate falls below the incident event rate. The upper limit of the dynamic range is the ion flux above which the measured flux becomes non-linear. This point is somewhat arbitrary as very small deviations from linearity will be present over most of the range of measurement. In some applications a deviation of 5% from linearity would be tolerable. This would imply that the height of a large peak would be underestimated by 5% when the error in the height of a small peak would be random.

The complete detector system can be divided into the MCP, the array and the data accumulation system.

The noise level will be determined by the noisiest component and the maximum count rate will be determined by the slowest component. Table 1 presents a guide to the factors limiting the higher (H) and lower (L) count rates of the various types of array. In the case of the integrating array it is assumed to be operating at room temperature.

Both single-event and discrete detector arrays operate in the counting mode and the main source of noise is MCP dark counts. Thermal generation of free electrons at photosites dominates the noise level for semiconductor integrating arrays at room temperature.

The ability of a single-event array to count events at a high rate (typically 10^5 s^{-1}) is far less than the ability of the MCP to deliver pulses. The dynamic range is limited by the time taken to compute and log the location of events by the data acquisition system. However, for a discrete detector array and for an integrating array, the MCP gain begins to fall before the limit set by the array is reached.¹²

Resolving power

The resolution of a mass spectrometer is a measure of its ability to separate ions of different mass and is usually defined as $M/\Delta M$, where ΔM is the mass separation of two peaks which overlap to give a 10% valley between the peaks (Fig. 18).

For our purposes, we consider the FPD to be separate from the mass spectrometer. The spectrometer delivers the incident ion spectrum and the FPD measures it.

We have seen that in the case of a single slit, the narrower the slit the closer the measured peak profile is to the incident beam profile. The wider the slit, the wider is the measured peak and the lower is the resolving power. When the slit width is about equal to the FWHM of an incident peak there is no point in making the slit narrower as this simply reduces the measured ion flux but does not reduce the measured peak width.²⁶

Figure 5 shows that the position and accuracy of location of an ion using a slit are physically defined by the dimensions of the slit. In the case of a FPD the

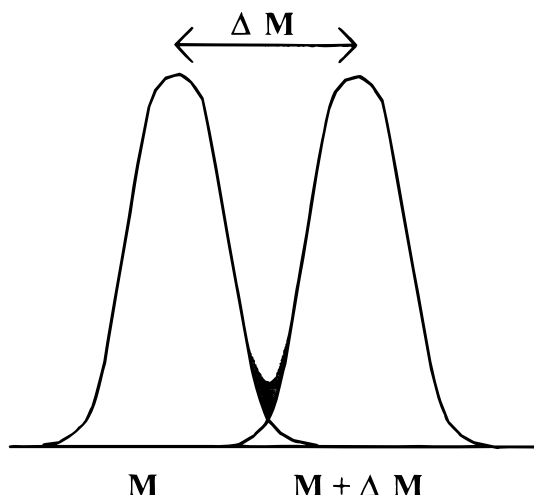


Figure 18. Resolving power is usually defined as $M/\Delta M$, where ΔM is the separation between two ion peaks which overlap to give a 10% valley.

event location must be calculated (i) from the measured charge in the case of a single event FPD and (ii) from the quantized position information in the case of a discrete site FPD. At present the precision with which an event location can be measured using a single slit has not been matched by an FPD. However, the precision of measurement of the centroid of an ion beam can be very high for a discrete detector array.

In order to focus on the performance of a FPD, we define resolving power as the FWHM of a measured peak when the incident beam is narrow (less than the detector electrode width). An insight into the FPD measurement can be gained by recognizing that the measured beam profile is an accumulation of many discrete events. With a multi-event discrete detector FPD a trade-off between dynamic range and resolving power can be made, as explained in the following two sections.

Single-event analysis. If the ion flux is low enough then an ion peak location can be computed from the observation of single events. A single electron pulse activates N detectors (i.e. generates a single count on N detectors) in the vicinity of the event where $N = 0, 1, 2, \dots$. An ion peak is measured by computing and recording the centre of mass of each pulse group. The FWHM of this peak should be about half a detector electrode pitch (distance between electrode centres).¹²

Figure 19 shows single events recorded at a low particle intensity. Each event is recorded as a single count on N detectors where $N = 1, 2, 3, \dots$. Events with $N = 0$

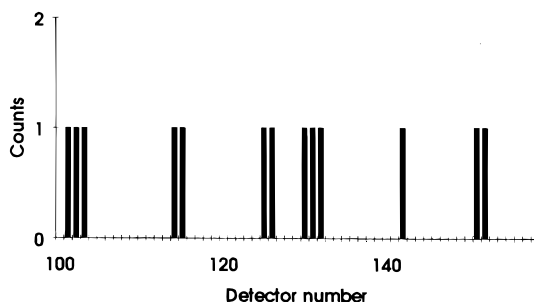


Figure 19. Detection of single events using the Aberystwyth FPD.

Table 1. The FPD component limiting the dynamic range; the data acquisition system consists of the electronic system used to read the array and process the data

Array type	Limiting component ^a		
	MCP	Array	Data acquisition
Single event	H		x
	L	x	
Integrating	H	x	
	L		x
Discrete electrode	H	x	b
	L	x	

^a Excessive noise in any component will limit the lower count rate.

^b A longer array requires a longer reading time and eventually limits the upper count rate.¹²

are unobservable. Single-event analysis is, of course, the normal mode of operation for a single-event FPD. A discrete detector FPD working in this mode can measure single events at many positions simultaneously. So far little work has been carried out in the single event analysis mode.

Event accumulation. The detectors *store* the counts generated by each event. A peak is accumulated and information on the location of each event is lost. In this mode the recorded peak is wider than in the single-event mode and hence the resolving power is lower. The dynamic range of the array is greater in the accumulation mode and this is the normal mode of operation.

Resolving power contour diagram. We have seen that the resolving power of an FPD depends on the gain and the spreading of the MCP output pulse. For a given FPD configuration we can plot the resolving power as a function of both MCP supply voltage and PHDL as shown in Fig. 20. This provides a clear and concise means of representing the resolving power of an FPD and also enables a comparison to be made with theory. A model of the FPD has shown satisfactory agreement with the above data.²⁴

Type specific limitations

Each device has its own advantages and its own areas of application. However, for each class of FPD there are fundamental factors which limit the performance. It is useful to examine this list because, although a given FPD may be under development to increase its performance, it is important to recognize the limits beyond which it cannot progress.

Single slit: a very low collection efficiency is inherent. It can currently achieve the highest resolving power but only at the expense of very low collection efficiency.

Single-event FPD: a very low dynamic range is inherent. It is a simple, cheap option for low count rates but is blinded by an intense peak.

Opto-electrical FPD with a CCD: serial readout of pixels of a two-dimensional CCD gives a long readout time. It must be cooled for low-noise operation. The

CCD can integrate the output from events occurring simultaneously and therefore is useful in time-of-flight measurements where bunches of ions may arrive in less than a nano-second. However, such events are not counted.

Discrete detector array: this has a high collection efficiency, a high dynamic range, operates in the counting mode and has a resolving power which at least matches other FPDs. Currently the main feature in need of development is the length in the direction of the ion dispersion, i.e. more detectors should be added in order to measure a greater fraction of a spectrum simultaneously.

THE FUTURE

At the risk of oversimplification, the trends in detector development appear to be as follows.

Counting or analogue

Too high ion peak intensity is not often a limiting problem as there usually exists a simple means of reducing it. Too low ion peak intensity, on the other hand, is often a problem. The low noise levels associated with counting means that ion counting devices will be important in future.

Multiple event or single event

The future for 1D single-event devices does not appear to be rosy. They require relatively little electronics but have a very restricted dynamic range compared with a multiple-event FPD. The electronics could be integrated for a single-event device as for a multiple-event device but there seems to be little point as there would be little improvement of the dynamic range.

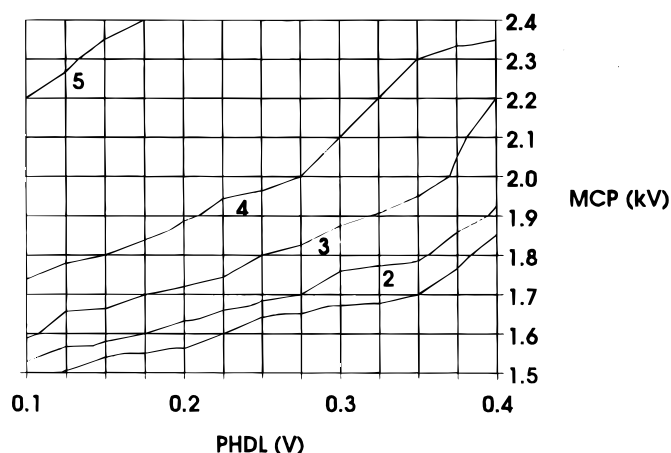


Figure 20. Contours show locations of constant resolving power. The MCP supply voltage and the PHDL are varied. All other variables are held constant.

Miniaturization

The needs of mass spectrometrists are varied but some of the driving forces in mass spectrometer development include miniaturization and portability, performance and, of course, cost. Integrated FPDs can make an important contribution in these areas. A sector mass spectrometer does not require the high-frequency supply of a quadrupole mass spectrometer or the long flight tube of a time-of-flight mass spectrometer and future miniature, low-resolution, portable instruments may consist of small sector mass spectrometers equipped with integrated FPDs.

Integration

There is no alternative to integration if a high-resolution array of ion counters is required. This paper has set out some of the issues concerning high-resolution integrated arrays and the feasibility of these important devices has been established. The focal plane of a mass spectrometer is not as hostile an environment as was feared and the apparent complexity of a discrete detector array on a silicon chip is an illusion. Apart from the MCP, power supplies and the external computer it is a complete measurement system and represents a system simplification. Investment is needed to develop longer devices with even better performance.

DEFINITIONS

A number of terms have been used which are collected defined here.

Array—An array is preceded by a microchannel plate electron multiplier (MCP). The term 'array' is used for the device following the MCP. The term 'position-sensitive detector' (PSD) is a more appropriate description for devices which do not consist of an array of identical detectors. For convenience the generic name 'array' is used.

Focal plane detector (FPD)—A general term for a detector which measures ion flux at more than one point in the focal plane of a spectrometer in one or two dimensions. The term refers here to the combination of the array plus the MCP mounted above it.

Pulse height discrimination level (PHDL)—A voltage pulse on a detector electrode above this discrimination level will be counted. A pulse below this level will not be counted.

Spatial resolution—The pitch (distance between centres) of the detector electrodes on an array.

Resolution—A measure of the ability of a spectrometer as a whole to resolve dispersed particles.

Resolving power—This term is used here when referring to a detector in isolation from the rest of the spectrometer. Assuming a narrow incident particle beam the resolving power is defined here as the FWHM of the measured peak (in units of detector electrode pitch for discrete detector arrays). The highest resolving power is unity.

Particle—A photon of wavelength < 200 nm, electron, ion, energetic neutral or other body which can activate an MCP.

Event—Impact of a particle on the MCP which initiates an output pulse.

Sensitivity—This word is avoided as it means different things when used by mass spectrometrists and electrical engineers. When used here it is used in the sense of PHDL.

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