IX. ELECTRONIC INSTRUMENTATION*

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RESEARCH OBJECTIVES

The purpose of the Electronic Instrumentation Group is to fill the gap between state-of-the-art technology in electronics and the electronic instruments now being used in many areas of scientific research. Our group is concerned not only with improving the precision, sensitivity, and ease of operation of present electronic instruments but also with the creation of new instruments.

The present effort is directed toward electronic instrumentation for high-resolution mass spectrography. The specific goals are: to improve the resolution of the CEC 21-110 mass spectrometer by placing it in a controlled environment, and to replace the present photographic plate detection scheme by an electronic interface so that the information contained in the ion-beam output can be read directly into a digital computer for processing. Any improvement in resolution will permit a more accurate determination of unknown chemical compounds, and the electronic interface will eliminate the time now required for removing, developing, and optically scanning the photographic plate.

D. Steinbrecher

A. OPTIMAL SINGLE AND DUAL DETECTOR ARRAYS FOR THE MATTAUCH-HERZOG MASS SPECTROMETER

1. Introduction

The Mattauch-Herzog high-resolution mass spectrometer normally records the mass spectrum of a chemical compound on a photographic plate. It would be desirable to replace the plate by an array of small electronic detectors whose outputs could be counted and stored digitally. Such an array and associated circuitry would provide the mass spectrometer with a digital electronic output.[1]

This report contains a description of a new detector array configuration which "matches" the inherent resolution of the instrument for each mass number.[2] The new array achieves the inherent resolution of the instrument over the entire mass scale with a minimum number of detectors, and typically it requires 64% less detectors than an

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array configuration of equi-spaced elements which also achieves the inherent resolution of the instrument over the entire mass scale. The saving in number of detectors at no expense in resolution also results in savings in counter circuitry and data-storage requirements.

A dual version of the new array eliminates the possibility of a narrow line escaping detection. We shall also discuss possible fabrication techniques for detector arrays.

2. Description of the Mass Spectrometer

In 1936, Mattauch presented the theory of a mass spectrometer that would double-focus simultaneously for all masses.[3] This instrument furnished a specialized application of the general theory of double-focussing presented two years earlier by Mattauch and Herzog. The instrument utilizes a combination of a radial electric field and a homogeneous magnetic field to obtain both velocity and direction focussing over the entire focal plane simultaneously for all masses. The schematic arrangement of the instrument is shown in Fig. IX-1. A detailed description of the ion trajectories and factors determining the resolution has been given previously.[4] For the purpose of this report, it is necessary to know the equation for the point where the ion trajectory strikes the focal plane as measured from 0, the mean entry point of the ion into the magnetic field, ρ,

$$\rho = \frac{2}{B}\sqrt{\frac{mV}{q}}, \tag{1}$$

where m is the ionic mass, q is the ionic charge, B is the magnetic field, and V is the potential through which the ion is accelerated. Equation 1 shows that the mass scale

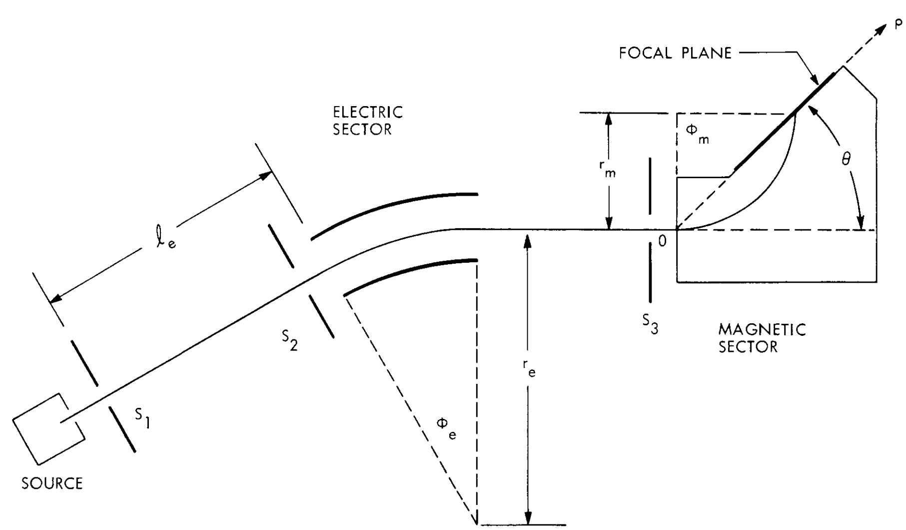

Fig. IX-1. Mattauch-Herzog mass spectrometer.

in the focal plane is proportional to the square root of the mass for singly charged ions. The mass scale may be expressed incrementally in terms of the fractional change in ρ, $\Delta\rho/\rho$, for a fractional change in m,

$$\frac{\Delta m}{m}. \tag{2}$$

It is important to know that the theoretical resolution of the double-focussing instrument at any mass is only a function of the slit width S_1 and the radius of the electric sector r_e. The resolution is defined in terms of the smallest detectable fractional mass difference.

$$R = \frac{m}{\Delta m} = \frac{r_e}{2S_1}, \tag{3}$$

where m is the mass of the ion, Δm is the smallest detectable absolute mass difference, r_e is the radius of the electric sector, and S_1 is the slit width.

3. Detection Scheme

The detection scheme considered here is a detector array fabricated by using solid-state integrated circuits and film techniques. A solid-state ion-multiplier plate must be developed. The plate must be 25 cm long and 0.6 cm wide. Each detector in the array must have a pulse output proportional to the number of ion impacts on its surface when connected to suitable circuitry.

One approach toward producing the plate might be to grow the structure on a suitable substrate as is done in the manufacture of transistors by the epitaxial method. The plate would then be divided to form an array of ion detectors by cutting partially through the plate with a precision electron beam. Chemical or laser methods would not be suitable because some of the dimensions required may be as small as 1 micron. Electrical connection to the individual detectors in the array would be through deposited aluminum contacts which fan out to allow mechanical connection with the associated circuitry.

An alternative approach may be to use electron-beam deposition methods for the whole manufacturing process. Experimental transistor structures have been fabricated with element dimensions as small as 1 μ through the application of advanced electron-beam technology.[5]

We shall assume that all arrays discussed are to be placed in the focal plane of the instrument and will be 25 cm long, extending from $\rho = 5$ cm to $\rho = 30$ cm. Consequently, a scale along the array, ℓ, will go from 0 to 25 cm and

$$\ell = \rho - 5 \text{ cm} \qquad 5 \text{ cm} \leqslant \rho \leqslant 30 \text{ cm}. \tag{4}$$

It has been shown that with a Maxwell-Boltzmann energy distribution of ions leaving the source, a Gaussian-like mass peak results in the focal plane.[4] This assumption will be used in determining the smallest detectable separation between mass peaks in the spectrum.

4. Resolution and Linear Arrays

The smallest resolvable fractional mass difference, $1/R$, is a constant for the instrument. On the other hand, the smallest detectable fractional mass difference depends on the spacing between the detectors and the size of the detectors. The optimal array is achieved when the smallest detectable mass difference is equal to the smallest resolvable mass difference over the entire mass scale; this means that the array is matched to the instrument, since it is capable of achieving the theoretical resolution of the instrument for all masses. Equation 1 can be substituted in Eq. 3 to yield the smallest resolvable fractional distance between mass peaks in the focal plane.

$$\frac{\Delta\rho}{\rho} = \frac{2}{R}. \tag{5}$$

Equation 5 shows that the smallest resolvable incremental distance, $\Delta\rho$, increases linearly with ρ; therefore, larger mass differences are resolvable for higher mass ions than for lower mass ions. Before presenting the optimal array, the linear arrays will be discussed.

The single linear array is shown in Fig. IX-2a. An equal length is assumed for the width of each detector and the associated space that separates it from the adjacent detector, and the width of each detector-space pair, δ, is constant along the array. The single linear array will not detect narrow spectral lines that strike a space. In order to eliminate this difficulty, a dual linear array as shown in Fig. IX-2c could be constructed. The smallest detectable separation between two mass peaks in the focal plane for the single linear array will be taken as $3\delta/2$ and for the dual linear array as δ; this is a reasonable assumption for Gaussian-like mass peaks. The resolution available from the arrays will then be

	Single	Dual	
Available Resolution	$\frac{\rho}{3\delta}$	$\frac{\rho}{2\delta}$	(6)

Equation 6 shows that the resolution available from the linear arrays increases linearly with distance ρ along the focal plane (see Fig. IX-3). Therefore, the array resolution at the smallest ρ must match the theoretically attainable resolution, R, so that the

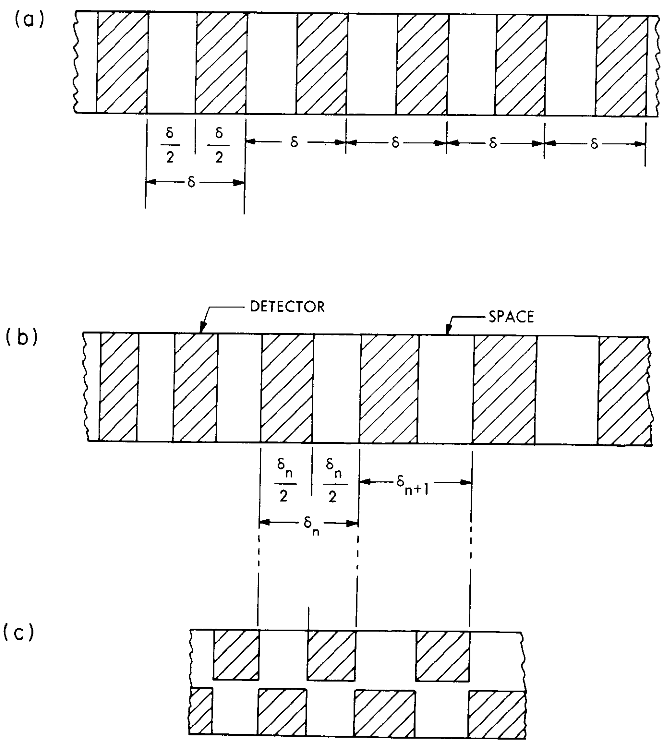

Fig. IX-2. Detector array configurations (not drawn to scale).

theoretical limit is detectable for all ρ (or for all masses). The detector-space width then must be less than a value given by

Single	Dual	
$\delta \leqslant \frac{\rho_1}{3R}$	$\delta \leqslant \frac{\rho_1}{2R}$	(7)

in order that the instrument resolution be achieved for all masses. ρ_1 is the distance from the mean ray entry point into the magnetic sector 0 to the beginning of the detector array.

The minimum number of detectors then required by the linear arrays is

Single	Dual	
$N = \frac{\ell}{\delta} = \frac{3R\ell}{\rho_1}$	$N = \frac{2\ell}{\delta} = \frac{4R\ell}{\rho_1}$	(8)

The number of detectors for the linear arrays as a function of δ is plotted in Fig. IX-4. It is clear that the resolution available from the linear array having a δ given by the equality in Eq. 7 is equal to the theoretically attainable resolution, R, for $\rho = \rho_1$, but

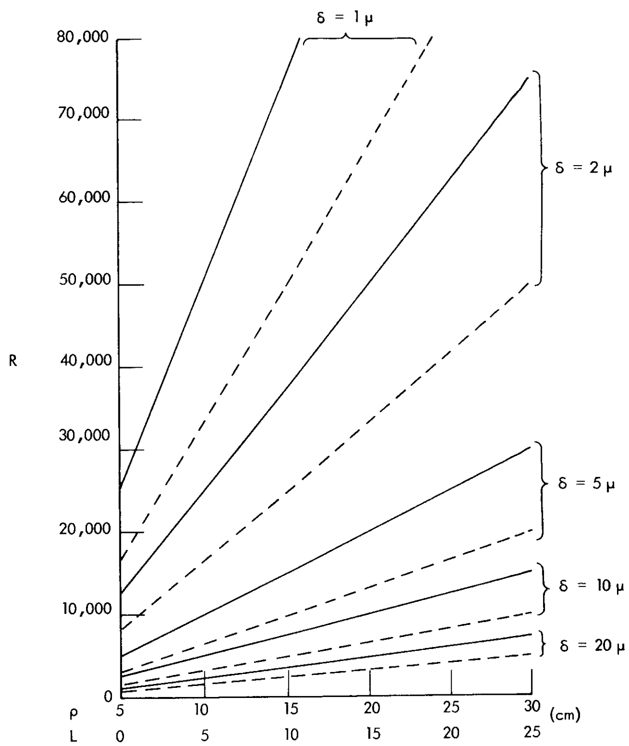

Fig. IX-3.

Linear arrays. Resolution, R, as a function of position along the array for various values of δ.
————, Dual array.
– – – – –, Single array.

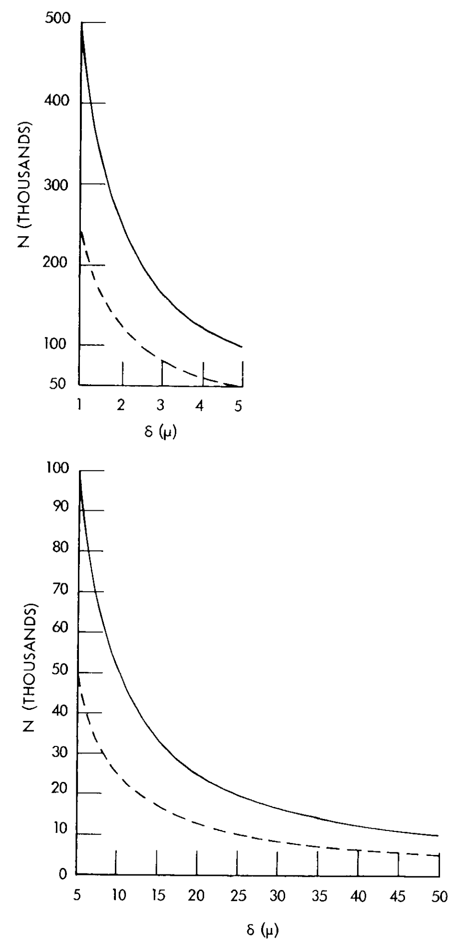

Fig. IX-4.

Linear arrays. N, number of detectors, counters or data storage units as a function of δ for a 25-cm array.
————, Dual array.
– – – – –, Single array.

exceeds R for ρ greater than ρ_1. For this reason, linear arrays are wasteful in number of detectors.

5. Constant Resolution or Optimal Array

The optimal array achieves the theoretically attainable instrument resolution for each mass number by having a detector-space width δ that varies with ρ (or mass number). For this reason, the optimal array is called a constant resolution array. It

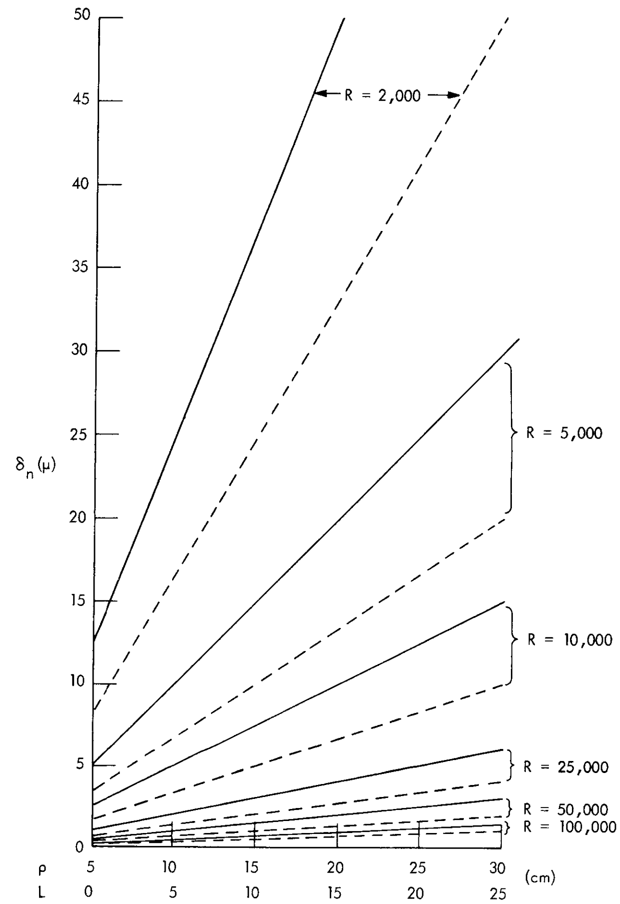

Fig. IX-5. Constant R arrays. Width of detector-space pair, δ_n, as a function of position along the array for various values of resolution, R.
————, Dual array.
– – – – –, Single array.

is called optimal because it achieves the ultimate resolution with the minimum number of detectors. Small detector-space widths compared with ρ_1, the desired incremental spacing for the optimal single and dual arrays, can be obtained from Eq. 6.

Single	Dual	
$\delta = \frac{\rho}{3R}$	$\delta = \frac{\rho}{2R}$,	(9)

where R is the theoretical resolution given by Eq. 3. Equation 9 now defines a constant resolution single and dual array. Equation 9 is plotted in Fig. IX-5 for various values of resolution.

Since the array is made up of discrete elements, as shown in Fig. IX-2b, Fig. IX-5 will only give a close approximation to δ_n. The exact values are obtained from the following relations.

Single / Dual

$$\delta_1 = \frac{\rho_1}{3R} \qquad \delta_1 = \frac{\rho_1}{2R}$$

$$\delta_n = \frac{\rho_1 + \delta_1 + \dots + \delta_{n-1}}{3R} \qquad \delta_n = \frac{\rho_1 + \delta_1 + \dots + \delta_{n-1}}{2R}, \tag{10}$$

where ρ_1 is the distance from the mean ray entry point into the magnetic sector 0 to the beginning of the detector array. A simple exact expression can be determined for δ_n as well as for the total number of detectors in the array of length

Single / Dual

$$\delta_n = \delta_1\left(1+\frac{1}{3R}\right)^n \qquad \delta_n = \delta_1\left(1+\frac{1}{2R}\right)^n$$

$$N = \frac{\log\left(\frac{\ell}{\rho_1}+1\right)}{\log\left(1+\frac{1}{3R}\right)} \qquad N = 2\,\frac{\log\left(\frac{\ell}{\rho_1}+1\right)}{\log\left(1+\frac{1}{2R}\right)}. \tag{11}$$

For $R > 10$, the number of detectors is given very closely by

Single / Dual

$$N = 3R \ln\left(\frac{\ell}{\rho_1}+1\right) \qquad N = 4R \ln\left(\frac{\ell}{\rho_1}+1\right) \tag{12}$$

Equation 12 is plotted in Fig. IX-6. The actual saving in number of detectors for the constant R array over the linear array for $\ell = 25$ cm and $\rho_1 = 5$ cm is

	Single	Dual	
Linear	N = 15R	N = 20R	(13)
Constant R	N = 5.375R	N = 7.167R	

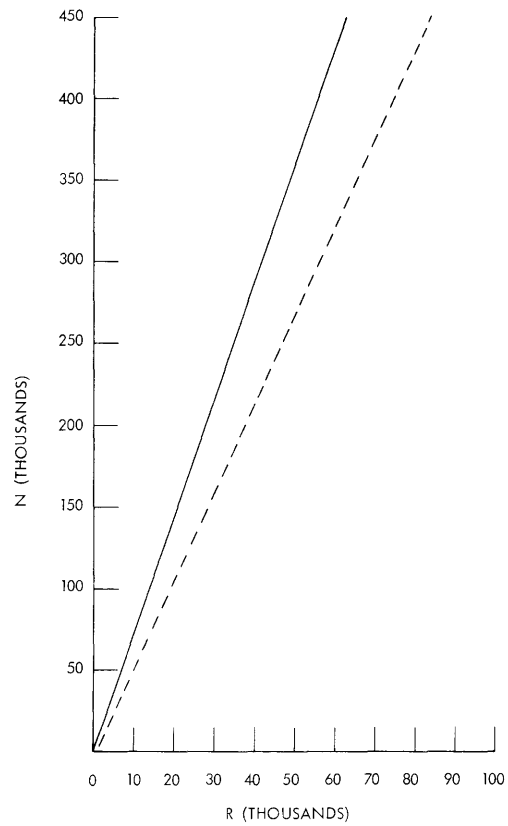

Fig. IX-6. Constant R arrays. N, number of detectors, counters or data storage units as a function of R for a 25-cm array extending from ρ = 5 cm to ρ = 30 cm.
————, Dual array.
– – – – –, Single array.

The constant R array represents a 64.2% saving in number of detectors both for the single and dual arrays.

6. Conclusion

The constant R single and dual arrays have been shown to achieve the theoretically attainable resolution of the Mattauch-type mass spectrometer in an efficient manner when compared with the linear arrays. For example, for an instrument with a resolution of 10,000 the 64% saving translates into 90,000 sets of counters and data storage units for the single arrays and 128,000 sets for the dual arrays.

The dual constant R array has been shown to achieve the theoretical resolution and also eliminate the possibility of a narrow spectral line escaping detection.

J. Glaser

References

1. S. H. Zisk, "Mass Spectrometer Detector," Quarterly Progress Report No. 85, Research Laboratory of Electronics, M. I. T., April 15, 1967, pp. 34-36.

2. This was first reported by J. Hirschel, "An Optimal Detector Array for the Mattauch-type Mass Spectrometer," S. B. Thesis, Department of Electrical Engineering, M. I. T., September 1968.

3. J. Mattauch, "A Double-Focussing Mass Spectograph," Phys. Rev. 50, 617 (1936).

4. J. I. Glaser, "Mass Spectrometer Resolution," Quarterly Progress Report No. 88, Research Laboratory of Electronics, M. I. T., January 15, 1968, pp. 39-40.

5. R. Landauer and J. J. Hall, "Solid State Physics as a Source of Modern Electronics," Science 160, 740 (May 17, 1968).