Apparatus for Teaching and Research in Electron Physics*

B. R. F. Kendall and H. M. Luther
Department of Physics and Ionosphere Research Laboratory, Pennsylvania State University, University Park, Pennsylvania

(Received 21 December 1965)

A special form of construction for electron devices is described. This construction makes it possible to assemble a wide range of apparatus from inexpensive standard parts, without the use of tools. Modifications can be made with particular ease because the electrodes can be installed, repositioned or removed independently of one another. These features make the apparatus convenient for use in undergraduate and graduate laboratory projects, as well as in more advanced research applications. Examples are given of some typical assemblies, ranging from simple electron emitters to cathode-ray tubes, electron multipliers, and a complete mass spectrometer.

INTRODUCTION

APPARATUS for use in teaching, research, or development work in electron physics should ideally possess a number of special properties which are difficult or impossible to obtain if conventional constructional techniques are used. It should, for example, be possible to assemble the apparatus quickly and with a minimum of tools. Removal, repositioning, and replacement of individual electrodes should be easy, so that the effects of geometrical variables can be studied. The individual components should be reusable and reasonably inexpensive. For teaching applications, the design should be free of details tending to obscure fundamentals, and should be such as to facilitate theoretical analysis by the student before the apparatus is actually assembled.

Superimposed on these special requirements are the more obvious necessities such as adequate electron-optical performance, good vacuum properties, ability to withstand temperatures required for vacuum bakeout and tube processing, and structural rigidity sufficient for accurately reproducible results to be obtained.

Several widely different systems of components for constructing experimental electron-optical apparatus have been described. These range from kits of inexpensive parts assembled in the fashion of conventional vacuum tubes[1,2] to highly complex but very precise systems analogous with the familiar optical bench used for experiments with light.[3,4] An intermediate approach has been described by Crawford,[5,6] who developed sets of reusable components having many useful features, although no special provision was made for simplifying the removal and replacement of individual electrodes.

This paper describes the results of another attempt to devise a standard set of components suitable for use in teaching and research in the general fields of electron and ion physics. Special emphasis was placed on simplicity, low cost, ease of adjusting electrode positions, and self-aligning properties. Various versions of this equipment have been used with encouraging results in undergraduate and graduate-level laboratory projects, as well as in more advanced research applications.

STRUCTURAL CHARACTERISTICS

Figure 1 shows a typical assembly made from the standard set of components, in this case a cathode-ray tube. The 0.030-in.-thick stainless-steel main frame A and sliding support frame B are linked by the four solid $\frac{1}{8}$-in.-diameter ceramic rods C. These rods carry the fixed retaining clips D, a large number of $\frac{1}{4}$-in.-o.d. ceramic spacers E, Inconel X compression springs F and adjustable clamps G. Most of the electrodes, including the filament assembly H,

* Supported in part by NASA Grant NGR 39-009-032.

[1] J. H. O. Harries, Am. J. Phys. 28, 698 (1960).
[2] J. G. King, Am. J. Phys. 32, 473 (1964).
[3] E. B. Bas, Z. Angew. Phys. 6, 404 (1954).
[4] W. C. Nixon and R. Buchanan, *X-Ray Optics and X-Ray Microanalysis*; H. H. Pattee and V. E. Cosslett, Eds. (Academic Press Inc., New York, 1963) p. 441.
[5] C. K. Crawford, in Proc. 22nd Ann. Conf. Phys. Electron. MIT, Cambridge, Mass. (1962), p. 347.
[6] C. K. Crawford, Rev. Sci. Instr. 36, 844 (1965).

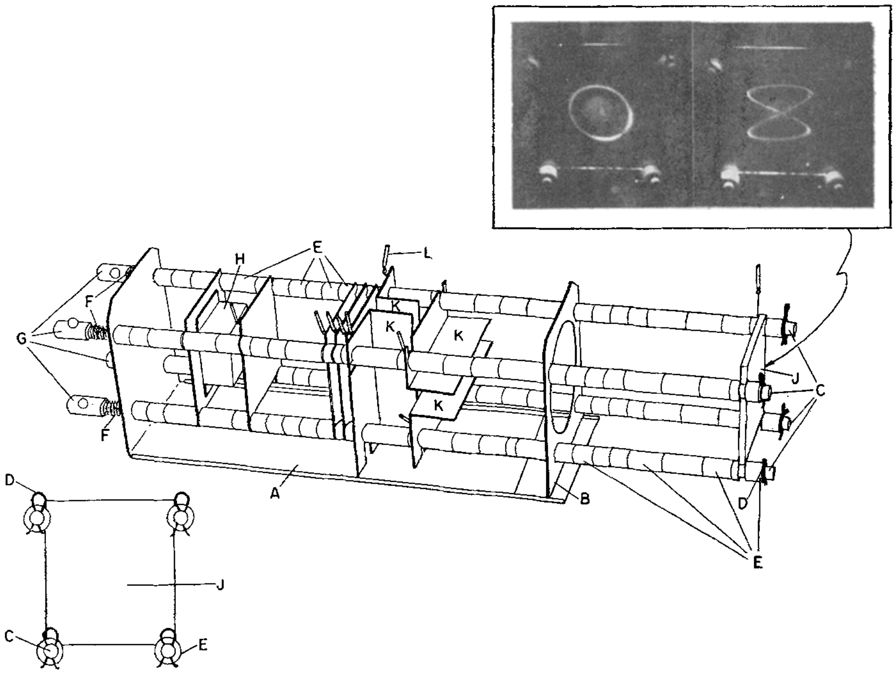

FIG. 1. Cathode-ray tube assembled from standard components. Lower left: Method of supporting $1\frac{1}{2}$-in. square electrodes and screen. Top right: Lissajous figures on screen, photographed through wall of glass vacuum chamber.

are based on identical $1\frac{1}{2}$ in. square, 0.020-in.-thick stainless-steel plates. The $1\frac{1}{2}$-in.-square glass screen J is coated with a P5 phosphor. These electrodes, the filament assembly and the screen are supported by the ceramic rods and positioned axially by the spacers as shown in the detail drawing at the lower left in Fig. 1. The only exceptions to this method of support occur in the case of the horizontal and vertical deflection plates K, which are each supported by only two ceramic rods. Axial positioning for the deflection plates is achieved with spacers, as with the square electrodes. Electrical connections to all electrodes are made through the miniature plug-in connectors L.

This type of construction is self-aligning and the plates are constrained in all but the vertical direction, in which movement is prevented by gravity and friction. Electrodes are easily added, removed or shifted to new positions after compressing the appropriate springs to remove the frictional forces. No tools are required for these operations. The springs and the movable support frames accommodate changes caused by permanent removal or addition of electrodes.

Additional electrodes can easily be made with a simple miniature punch, brake, and metal shear. A small spot-welder is also necessary if grids are to be attached to electrode frames. Photo-etched nickel mesh is a suitable grid material, being inexpensive and available in many sizes.[7]

The ceramic rods (mullite) are readily available from suppliers of thermocouple equipment,[8] while the ceramic spacers, available in a wide range of lengths, are standard steatite insulators of the type widely used in demountable rotary switches.[9]

ELECTRICAL CHARACTERISTICS

The planar construction simplifies accurate determination of the particle trajectories within the apparatus.

Typical emitters and collectors for ions and electrons are shown in Fig. 2. A is a surface-ionization ion emitter with a tungsten filament coated with potassium salts. B is a planar electron emitter of woven tungsten cloth, used as an extended electron source in space-charge experiments. C and D are conventional electron emitters with thoriated tungsten filaments. E is a shielded Faraday cage for collecting either electrons or ions. F is a planar collector with a

[7] Buckbee Mears Co., 245 E. 6th St., St. Paul 1, Minn.
[8] McDanel Industrial Ceramics, Beaver Falls, Pa.
[9] Centralab, Milwaukee 1, Wisc.

TABLE I. Summary of typical experiments based on apparatus assembled from standard components. The apparatus was also used to illustrate practical applications of the phenomena being studied.

Topic of Experiment	Type of Apparatus Constructed	Applications Demonstrated
1. Factors influencing diode, triode, tetrode, and pentode characteristics; space-change effects.	Planar diode, triode, etc.	Rectification, amplification
2. Focusing properties of electrostatic lenses.	Various aperture and slit lenses	Used in experiments (3) and (4)
3. Characteristics of deflection systems; characteristics of phosphors	Cathode-ray oscilloscope	Display of typical waveforms
4. Beam switching and beam current measurement	Modulated beam switching tube	Scan time conversion of repetitive waveforms; improvement of signal: noise ratio by integration
5. Surface ionization	Surface ionization ion source and ion detector	Production of ions with precisely-known energy and mass.
6. Ionization of gases by electron bombardment	Electron bombardment ion source and ion detector	Gas density measurement; also used in experiment (8)
7. Secondary electron emission	Electron multiplier	Detection of electron and ion beams. Also used in experiment (8)
8. Ion velocity measurements; ion bunching; gas analysis	Time-of-flight mass spectrometer	Gas analysis, including observations of transient changes in gas composition in test chamber caused by thermal and electronic desorption processes.

grid to suppress secondary electrons. G is a 6-element annular collector used to determine current density distributions in charged-particle beams. H is a venetian-blind electron multiplier dynode, modified from a commercial E.M.I. unit. Its beryllium–copper active surface makes it relatively unaffected by short-term exposure to atmosphere. All of these components are based on the standard $1\frac{1}{2}$-in. square configuration and

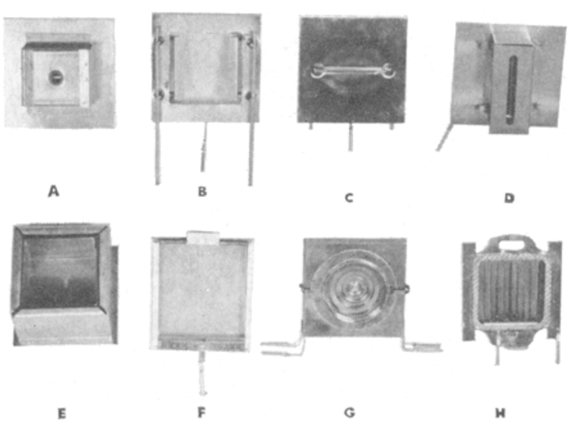

FIG. 2. Examples of emitters (A–D) and collectors (E–H). See text for details.

are installed in the same way as a single planar electrode. Other electron emitters, used mainly in electron bombardment ion sources, provide collimated electron beams perpendicular to the axis of the complete assemblies rather than along the axis.

Breakdown voltages between adjacent electrodes in the completed assemblies are typically greater than 10 kV/cm because of the all-ceramic electrode support structure. This figure is, of course, reduced if the ceramic spacers need to be shielded from stray electrons. In the rare cases where such shielding is necessary, simple detachable metal channels are clipped over the spacers and connected to an appropriate electrode.

VACUUM CHARACTERISTICS AND VACUUM REQUIREMENTS

Assemblies made from the standard components have vacuum properties which make them suitable for operation at pressures down to the ultra-high vacuum range. The manner in which the electrodes are supported ensures release of gases from the enclosed volumes between the

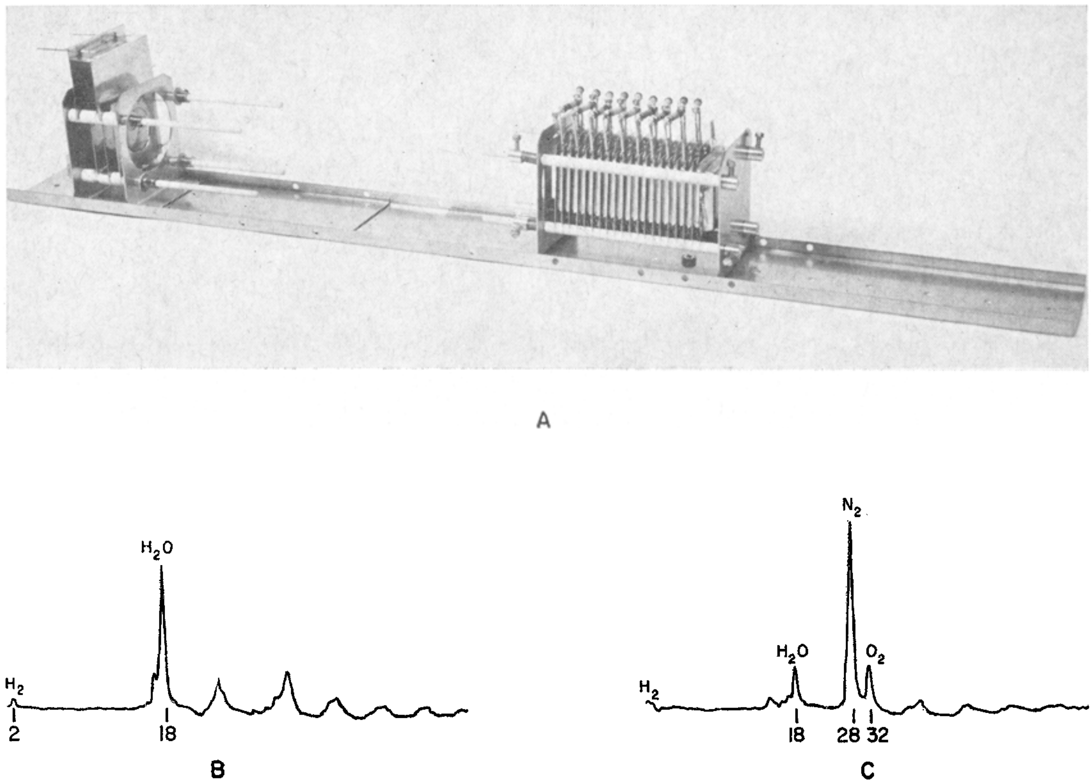

FIG. 3. (A). Time-of-flight mass spectrometer. Electron bombardment ion source (left) and electron multiplier ion detector (right) are mounted in metal channel so that effects of varying flight distances can be studied. (B). Mass spectrum of residual gases in oil diffusion-pumped vacuum system at total pressure of 10^{-6} Torr. (C). Mass spectrum during admission of air to system.

spacers and the ceramic rods, and three small depressions on the undersides of the main and support frames prevent gas being trapped in those regions. The entire structure will withstand temperatures of 300°C–400°C for extended periods.

For experiments involving electron beams, the small dimensions of the apparatus usually make it possible to maintain satisfactory operation up to at least 10^{-4} Torr. For experiments involving ions, the pressure is best kept below about 2×10^{-5} Torr. Pressures meeting these requirements can easily be reached with simple oil-diffusion-pumped vacuum systems.

EVALUATION

Table I summarizes some of the projects which have been carried out in the course of evaluation studies with apparatus constructed from the standard sets of components. The list is intended to be representative of experiments of varying degrees of complexity, rather than to represent a rigid sequence of investigations.

The students involved in the evaluation studies were mostly undergraduates who had completed one term of electricity and magnetism and one term of electronics at the junior/senior level. It was possible to allow them considerable freedom of choice as to the exact nature of their project. Some chose to investigate a particular phenomenon, others to study a particular kind of electron device.

Suitable electrode configurations and spacings in the more elementary types of apparatus were determined by the students with the aid of the theoretical treatments in their standard textbooks. This background information usually proved adequate for the design of simple electron tubes, electrostatic lenses and deflection systems.

For the more advanced projects involving ionization and secondary electron-emission phenomena, a combination of review papers and specialized text-books was used as supplementary reading. Apparatus for these experiments was designed with the aid of information obtained from review articles and original papers.

For the time-of-flight mass spectrometer, the original paper of Wiley and McLaren[10] was used as an introduction to the basic principle, with two other papers[11,12] as guides to the electrode configurations and operating potentials of a suitable low-voltage ion source and electron multiplier ion detector, respectively. Figure 3 shows the completed time-of-flight mass spectrometer with examples of mass spectra obtained with it. These spectra were traced by a chart recorder connected to a Hewlett–Packard 175A oscilloscope and display scanner. They could also have been recorded photographically from the oscilloscope screen. The oscilloscope input was connected directly to the electron multiplier output. No additional amplification was needed.

Towards the end of each project, students were encouraged to set up their apparatus to illustrate one or more practical applications of the devices and phenomena they had been studying. Performance of the completed apparatus was usually satisfactorily close to that predicted theoretically, partly because of the self-aligning construction and partly because the planar geometry simplified theoretical analysis.

In several cases, apparatus constructed with the aid of these sets of electron optical components has been found useful in research applications. One of the two mass spectrometers built during the evaluation studies, for example, is now in permanent use as a gas composition monitor in a space simulation chamber. Another set of the standard components is being used in an investigation of pulse methods for analyzing ions in gases at pressures in the 1–100 μ range.

DISCUSSION

Observation of students working with the new system of components shows that the time required to assemble even quite complicated apparatus is a negligible proportion of the total time devoted to a project. The cathode-ray tube, for instance, takes only about fifteen minutes to assemble after suitable electrode positions have been computed. Analysis of reports submitted by students after completion of the projects suggests that the other goals listed as desirable in the introduction to this paper have also been achieved.

Great advantages resulted from the ability to change individual electrodes, or to move them to new positions, without interfering with other parts of the apparatus. This made it possible for a student to learn from minor misjudgements and his subsequent corrective actions without incurring any appreciable delay. It also greatly simplified investigation of the effect of varying geometrical parameters.

Experiments involving magnetic lenses and magnetic sector-fields have not yet been attempted, but there is no reason to expect any special difficulties to be encountered. It has been established that ordinary Alnico and ferrite magnets have acceptable vacuum properties for such applications.

Although it has been found feasible to run two or three sets of apparatus simultaneously in a conventional belljar vacuum system pumped by an oil-diffusion pump, larger laboratory classes would obviously require fairly extensive vacuum facilities for efficient operation. An inexpensive (and unconventional) laboratory high-vacuum system with a very short pumpdown time is currently being developed here for this and other more general applications. Details will be reported after development is complete.

It can be concluded that, by using sets of standard components similar to those described in this paper, it is possible to offer a challenging and effective laboratory course in electron physics. The same components can also be used to construct a wide range of permanent research equipment. It is hoped that a similar approach may prove equally useful in other institutions.

ACKNOWLEDGMENTS

The work on which this paper is based had its origins in a brief investigation of simplified elec-

[10] W. C. Wiley and I. H. McLaren, Rev. Sci. Instr. **26** 1150 (1955).
[11] B. R. F. Kendall, J. Sci. Instr. **39**, 267 (1962).
[12] B. R. F. Kendall, J. Vac. Sci. Technol. **2**, 1 (1965).

tron and ion gun construction carried out several years ago by one of us (BK) in the Electron Physics Laboratory of the National Research Council of Canada. This earlier investigation proved a useful starting point for the development of the present apparatus, which includes several fundamental improvements in design. Grateful acknowledgment is made of the assistance of D. R. David, W. L. Brown, L. R. Kost, C. Rockwell, P. Hennessey, and others who helped to evaluate different versions of the apparatus.

Mach's Critique of Newtonian Mechanics

MARIO BUNGE*
Institut für theoretische Physik der Universität Freiburg/Br.
(Received 1 December 1965)

Mach's reinterpretation of Newtonian mechanics is examined and found ambivalent. His criticism of absolute time and absolute space was sound whereas his attempt to replace Newton's whole theory by an allegedly empirical statement and a definition was logically untenable. The whole program of reducing mechanics to kinematics is found to be unfeasible for logical reasons. The impossibility of deriving masses and forces from observations alone is discussed in detail. The driving force behind Mach's ideas on the foundations of mechanics is shown to be his empiricist philosophy which, while allowing him to impugn inscrutables, also suggested him to minimize the role of ideas. It is recalled that the discussion of the foundations of mechanics proceeds nowadays in a way far removed from Mach's operationalistic approach, namely via the axiomatic reconstruction of classical theories on the basis of undefined but meaningful concepts.

INTRODUCTION

A DISTINGUISHED experimental physicist and psychophysiologist, Ernst Mach (1838–1916) was an influential worker in the foundations of physics. His main contributions to the latter were critical rather than constructive, yet important because they were concerned with certain fundamental ideas. Many of Mach's criticisms, particularly those of atomistics and Newtonian mechanics, have had a profound influence. While the former was entirely negative, Mach's work on the foundations of mechanics was ambivalent.

On the one hand, Mach made a correct criticism of the concepts of absolute space and absolute time. On the other, he tried to minimize the role of mechanical theories and, indeed, of all theory. These two aspects of his work were as many consequences of the empiricist theory of knowledge he adopted and popularized. In fact, for a radical empiricist, every inscrutable idea is damnable and, moreover, no idea is to be accepted unless it concerns experience. By the first token, untestable assumptions are discarded from factual science, and rightly so. By the second, every theory is distrusted, or even condemned, because theories proper overreach experience and do not refer to it; and this was wrong.

Faithful to his empiricist philosophy, Mach attempted to cleanse physics from untestable hypotheses by the simple technique of eliminating hypotheses altogether—in fact by keeping only "experimental propositions" and definitions. Thus, his criticism of Newtonian mechanics was more of a criticism of theoretical physics than a criticism of classical physics—so much so that he attempted to replace that theory by a single empirical statement and a definition, and that he sanguinely opposed every attempt to go beyond classical physics, particularly relativity and atomic theories.[1] By criticizing Newtonian me-

* Alexander von Humboldt Research Fellow (1965–66). The draft of this paper was written during a stay at the Departments of Philosophy and Physics, University of Delaware.

[1] See, e.g., E. Mach, *The Principles of Physical Optics* (1913; Dover Publications, New York, 1953), p. viii. For the opposite opinion, that Mach prepared the way to modern physics, see K. D. Heller, *Ernst Mach, Wegbereiter der Modernen Physik* (Springer-Verlag, Wien, 1964).