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ABSTRACT

A brief review of fast electronics is given, leading up to the present state of the art. Cherenkov counters in high-energy physics are discussed, including an example of a velocity-selecting Cherenkov counter. An electronic device to aid in aligning external beams from high-energy accelerators is described. A scintillation-counter matrix to identify bubble chamber tracks is discussed. Some remarks on the future development of electronics in high-energy physics experiments are included.

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Introductory Review

Electronics has played an exceedingly important role in the advance of nuclear science--it would be difficult to imagine how nuclear physics could have progressed to its present state of development without the art of electronics. It seems that as physicists needed better electronic devices, the devices became available from parallel advances in other fields of application. For example, when nuclear physics needed electron tubes with faster pulse-handling capabilities, they became available because of apparatus manufactured for radar and television. I am going to suggest that nuclear science deserves more work on development of devices designed specifically for its needs.

Let us review for a moment what we mean by "fast" electronics. "Fast" is a relative term (and not even a very good one). My remarks now apply to highly efficient apparatus for general use in particle counting. In the year 1940 ionization chambers had a resolution time of about 10^{-3} sec. By employment of certain pure gases and by collection of electrons, the resolution time was reduced to 10^{-6} sec in 1942.

The next significant advance was the technique we are using today, the scintillation counter,--although it had existed in a primitive form for 50 years, it underwent such revolutionary improvements in 1948 as to open entirely new possibilities. By using multiplier phototubes already developed and electron tubes borrowed from radio and television, we could achieve a counting resolution of about 10^{-8} sec. Certainly in 1948 10^{-8} sec would have been called "fast" electronics. You can see that in about 8 years we progressed from 10^{-3} to 10^{-8} sec (5 decades) in time resolution. However, the next decade of years has advanced us only about one more decade in counting speed. Perhaps this is quite to be expected, as we are approaching limitations imposed by the speed of light. This year finds us with resolution times of about 10^{-9} sec. Please remember that I am thinking only of counting charged particles of all kinds with nearly 100 °/o efficiency—especially in connection with high-energy accelerators. I am aware that resolution times even shorter than 10^{-10} sec can be achieved under certain special conditions.

The identification of particles generated by the giant accelerators is one of the principal needs for which we still wish to develop fast electronics to shorter and shorter resolving times. One of the ways to distinguish particles bearing a particular characteristic, such as mass, is by time of flight in a momentum-analyzed beam. For this application we need the shortest possible resolving times in an array of counters subjected to high instantaneous counting rates, and as particles approach the speed of light, the requirements for sorting them become more and more stringent.

Present Status of High-Resolution Scintillation Counters

In discussing the present status of scintillation counters, I rely very much on the equipment in use at the Bevatron in Berkeley; I understand that quite similar work is being done in many other high-energy laboratories, including CERN, Saclay, Brookhaven, and Liverpool, and in the USSR.

The development of high-current-output photomultiplier tubes such as the RCA types 6810 and 7046 has proved to be a significant advance. The 14-stage tubes eliminate amplifiers when they are used with scintillators, and decrease the amount of additional amplification necessary for use with Cherenkov counters. The recently available RCA developmental type C7251 and Radiotechnique 56 AVP multiplier phototubes represent the latest models for good resolution in time-of-flight identification of particles.

Figure 1 is a schematic representation of a typical circuit. I point out some of the precautions that must be taken on account of the high instantaneous counting rate during a burst of beam from an accelerator. The pulse current output of the multiplier amounts to about 1/10 ampere, which will generate a practical working voltage across a 100-ohm matched transmission line. In some experiments 10^7 pulses per second will be the counting rate during a time of 1/10 sec. In order for the current output per particle pulse to remain substantially constant, we must supply adequate charge reservoirs to maintain the working voltage between dynodes and last dynode and anode. This can conveniently be accomplished by capacitors as indicated on the circuit.

Another effect that should be avoided is the shift in operating bias on the grid of the coincidence circuit input tube, which is inevitable if conventional coupling capacitors are used. Probably the simplest way to avoid this effect is to use a direct connection from photomultiplier anode to grid.

Figure 2 shows a resolution curve obtained by employing two 1/4-inch-thick plastic scintillators coupled to RCA C7251 photomultipliers. The anodes were connected directly through transmission lines to the grids of E180F pentode limiters feeding a simple Rossi-type diode coincidence circuit.(1) Clipping lines 1 nanosecond in electrical length (clipping time 2 nanosec.) were used

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(1) W.A. Wenzel, Millimicrosecond Coincidence Circuit for High speed Counting, UCRL-8000, Oct. 1957

at the plates of the limiter tubes. The counting efficiency is seen to decrease by a factor of 100 in 1 nanosecond, on the steepest parts of the delay curve.

Cherenkov Counters

I should like now to discuss Cherenkov counters, because they are becoming increasingly important in counting of high-energy particles, and fast electronic techniques apply to them as well as to scintillators. These counters make use of an effect discovered many years ago by P. Cherenkov of the USSR. They consist of a transparent radiator coupled to one or more multiplier phototubes, but their behavior is quite different from that of scintillators.

When a charged particle passes through a scintillator it causes light to be emitted in all directions from its track and the amount of light is, in general, proportional to the energy lost by ionization in the scintillator. The duration of the emission of light depends upon the characteristics of the scintillation material. Cherenkov light is generated by a different mechanism: we can compare it to the shock wave of sound made when a jet plane exceeds the velocity of sound in the surrounding air. When a charged particle exceeds the velocity of light in a transparent medium through which it passes, Cherenkov light is emitted. However, the intensity of the light is at most about 1% of that emitted by a scintillator of the same thickness.

Several good papers have been written on the properties of Cherenkov radiation and counters.[2] I will mention some of them pertinent to this limited exposition:

(a) In order to emit Cherenkov light a charged particle must have a phase velocity greater than that of light in the particular refractive medium through which it

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(2) See CERN Symposium 1956, Vol. 2

passes.

(b) The light is emitted in a definite direction with respect to the direction of motion of the charged particle. The direction of emission is simply related to the particle velocity, v, and refractive index, n, by $\cos\theta = \frac{c}{n\,v}$, where θ is the angle between the direction of motion of the particle and the light rays, and c is the velocity of light.

(c) The light is emitted practically instantaneously from the vicinity of the particle during its traversal of the radiator. Only the refractive index determines its characteristics, not the details of the chemical structure of the molecules which is so important in scintillation.

The first property immediately presents us with a velocity-threshold counter. That is, a particle must be going faster than a certain velocity to be counted.

The second property can be used to measure quite accurately the velocity of a charged particle in the range of velocities from about 0.6 c to c.

Figure 3 (the next illustration) is a schematic diagram of a velocity-selecting Cherenkov counter devised by Owen Chamberlain and the author.[3] It consists of a radiator, a cylindrical mirror, three plane mirrors arranged in an equilateral triangle around the axis of the counter, and three RCA 7046 multiplier phototubes. The diameter of the radiator is 3.5 inches. The incident beam of particles must be very nearly parallel to the axis but not necessarily on the axis (the beam can be 3.5 inches in diameter). Cherenkov light rays generated within the radiator at an angle θ are refracted from the end of the radiator at an angle θ_y, and lie on the surfaces of cones whose apexes are on the end of the radiator and whose axes are parallel to the beam. The light is

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(3) Clyde Wiegand, Cherenkov Counters in High Energy Physics, Trans. I.R.E. Nuclear Sci., NS 5, Nos. 3-4 (1958).

next reflected back toward the axis by the cylindrical mirror, and would fall in an area indicated as a dotted outline of a photomultiplier tube if it were not intercepted by the plane mirrors. The mirrors split the light into three equal parts and cause it to fall on the actual tubes placed at 120° around the principal axis. The purpose of the plane mirrors is to permit the phototubes to be placed out of the beam of particles and to permit the use of a threefold coincidence circuit at the output of the three tubes. The requirement of a coincidence reduces background effects.

The next illustration, Fig. 4, is a photograph of the parts temporarily arranged before being placed inside a black box. The performance curve of the apparatus is shown in Fig. 5. It indicates an efficiency of about 90% for counting protons of the velocity for which the counter was adjusted. The full width of the response curve at half maximum is about 4%.

Insert →

The third property of Cherenkov radiation says that a flash of light can be made to fall upon a photocathode in a time interval that is short compared with that of the light from a scintillator. This effect is presently of limited usefulness in a time-of-flight-experiment because of the small number of photoelectrons ejected from the photocathode by the feeble Cherenkov light. When multiplier phototubes with less spread in transit time and higher cathode efficiency become available, the property could be used effectively. However, the combination of scintillation counters and Cherenkov velocity-selecting counters forms a powerful instrument for identifying rare particles contained in high-energy momentum-analyzed beams from the giant accelerators. For example, it was by this method that antiprotons were discovered at the Bevatron.

Let us consider some electronic devices that can help physicists in their use of the very-high-energy accelerators. We are aware of the great cost in technical manpower and materials necessary for the operation of the giant machines. Therefore, we should take advantage of electronic instruments that will enable us to gather data at a maximum rate.

At the Radiation Laboratory in Berkeley we have constructed a device[4] to aid in setting up the external beams of charged particles emitted by the Bevatron. Typical experiments require beams 20 or 30 meters in length from the primary target in the machine. Such beams are sent through bending and focusing magnets to determine the momenta of their particles and to concentrate the particles onto special targets. A problem is to align the beams along predetermined trajectories with a minimum of time and effort. The intensity of the beams is too low to use the blackening of photographic film or a cluster of ionization chambers. We could expose photographic emulsions, but the time required to develop them and count the individual particle tracks would be prohibitive. We have designed a simple row of 21 scintillation counters, each 1 cm by 1 cm in cross section (Fig. 6). Transistorized circuits are used to amplify, equalize, and integrate the number of pulses from each counter. An electronic commutator allows the accumulated charge associated with each element to be read out and displayed as a histogram on an oscilloscope. With this apparatus we are able to observe the intensity profiles of the beams and to adjust the various magnet currents to optimum bending and focusing conditions.

Electronic control of cloud chambers has been a valuable technique used especially in cosmic-ray experiments for many years. A similar technique has been used in connection with bubble chambers working in beams of the high-energy accelerators. The problem is for the electronics to signal the passage

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(4) H. G. Jackson, D. A. Mack, and C. Wiegand, Beam Profile Indicator, UCRL-8386 Abstract Nov. 1958 Meeting IRE-PGNS.

through the chamber of a particular kind of particle which must be selected out of a large background of extraneous particles. The identity of the desired particle might be determined by time of flight and momentum. Perhaps it is desired to take bubble chamber pictures at every accelerator burst; then electronics could mark pictures of special interest. An obvious extension of this system is to provide a matrix of counters placed directly in front of the chamber and connected in such a manner that the spatial coordinates of a particular particle can be determined. This scheme in conjunction with electronic identification would enable one to say which one of many tracks in a chamber belongs definitely to the particle being studied. In addition to reducing the burden of scanning photographs, the perfection of the technique just outlined would make bubble chambers more effective tools, because at present most of the particles must be identified by their reactions in the chamber, and physicists want to know the probabilities of the reactions and consequently must know how many particles entered the chamber.

We have under construction at Berkeley a scintillation-counter matrix consisting of 176 cells of average size 0.7 cm by 0.7 cm. Transistorized circuitry will be used to indicate through which cell the electronically identified particles enter the bubble chamber.

Physicists have recently become interested in a different type of scintillation-counter matrix: the scintillation-fiber chamber. To achieve spatial resolution of 1 mm and less, we could use a bundle of fibers made of plastic scintillator material. Each fiber would act as a light pipe and carry its light to a small region on a photocathode. If enough light were generated the fibers could be coupled optically to the image tube of a television camera.

Scanning the photocathode would give us a picture of the projection of the tracks of particles through the bundle of fibers. Unfortunately the light intensity from fibers is too low to activate the most sensitive image orthicons. We need a light amplifier of gain of about 10,000 to place between the fibers and the television camera tube. Several American companies have contracts to develop image amplifiers for this purpose. We hope to have a prototype next year (1959). Devices based upon tracking a particle by scintillation would be able to record events in a time of about one microsecond and might therefore record several events during one burst of beam from a high-energy accelerator. Gating and read-out would take place at the command of a external electronics identification apparatus, as outlined in connection with bubble chambers. We hope that a small chamber 10 cm in diameter will be the humble beginning of the technique of electronic track chambers which can be extended to three dimensions.

Future Developments

I shall mention now some developments which physicists would like to have in the near future. I have one persistent request: multiplier phototubes with smaller spread in transit time and more efficient photocathodes. We eagerly anticipate the perfection by Dr. Morton of RCA of his design for an electron multiplier with tremendously increased interdynode acceleration, and invite other makers of photomultipliers to come forth with ideas for improved tubes. Insert Research with the giant machines now under construction needs practical time resolutions of 10^{-10} sec in coincidence circuits. If we assume that phototubes will become available which are capable of such fast pulses, we shall need improved electron tubes to take full advantage of their outputs. I believe that transmission lines are presently available to carry the pulses to the coincidence circuit. Surely better vacuum tubes than conventional pentodes could be designed specifically for coincidence circuits. For example, many experimenters use type 6BN6 tubes. Could not both grids be shielded from each other and from the anode? Also, tubes should be constructed with coaxial inputs so that transmission lines could be matched directly to the grid structures.

It may be that we have almost reached the ultimate in resolution using pulses sent over transmission lines to conventional circuits. We should be planning arrangements in which the multiplier tubes themselves perform the coincidence operation. Dr. Morton has succeeded in forming the output current of a multiplier structure into an electron beam. Perhaps such beams at low intensity could be swept over the inputs of slower multipliers at a frequency of about 10^9 per second. Two or more of these devices might be driven by a common radio-frequency generator in such a way that knowledge of the phases differences of the sweeping frequencies would tell the difference in time of events which produced a pulse out of the slower multipliers.

Transistors will be used more in fast electronic circuitry. There are presently available transistors which work in pulse circuits above 100 megacycles.

Finally, at a recent meeting of the American Institute of Electrical Engineers a scaler circuit using non-linear magnetic elements was described which worked at 100 kilocycles. We should watch this technique for its simplicity and reliability.

Some of the work I have mentioned was done under the auspices of the United States Atomic Energy Commission, and I wish to express my appreciation to the United States Office of Naval Research for making possible my attendance at this conference.

LEGENDS

Fig. 1. Schematic circuit for high-speed counting.

Fig. 2. Resolution curve obtained by using 1/4-inch-thick plastic scintillators coupled to RCA C7251 multiplier phototubes.

Fig. 3. Schematic diagram of velocity-selecting Cherenkov counter.

Fig. 4. Photograph of temporary arrangement of the components of the velocity-selecting Cherenkov counter.

Fig. 5. Performance curve of the velocity-selecting Cherenkov counter.

Fig. 6. Photograph of the beam profile indicator, showing the arrangement of scintillators, light pipes, and multiplier phototubes. Parts of the transistorized electronic circuits are also shown.

ADDITIONS

Page 6, after line 13, insert, new paragraph: "The apparatus just described can count particles in a velocity interval from about 0.6 c to 0.9 c. A counter which performs well in the interval from 0.9 c to c has been made and tested by a M.I.T. group (Caldwell, Frisch, Hill, Ritson, and Schluter). Its radiator is a fluorochemical CF-75 at an elevated temperature and pressure. With it particles of velocity 0.98 c have been separated from particles travelling at practically the velocity of light."

Page 9, line 22, insert new paragraph: "For example, at the Westinghouse Company in the U.S. research is in progress on a transmission type electron multiplier structure designed by Dr. E. Sternglass.[5] This structure consists of parallel foils of very thin material. High voltage is applied between the foils. Primary electrons are accelerated onto the first foil and secondary electrons emitted from the opposite side are accelerated to the next foil. Several such stages have been made to work in a single enclosure. I believe the principal problem is to find foil materials which multiply but are not fatigued by the electron bombardment. This type structure is expected to have a small transit time spread because of the high voltage per stage (several kilovolts) and because of the similarity of electron paths. Such structures are also capable of image amplification because they preserve the pattern of the intensity of the original primary electrons.

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[5] I.R.E. Transactions on Nuclear Science NS3 No. 4 Nov. 1956.

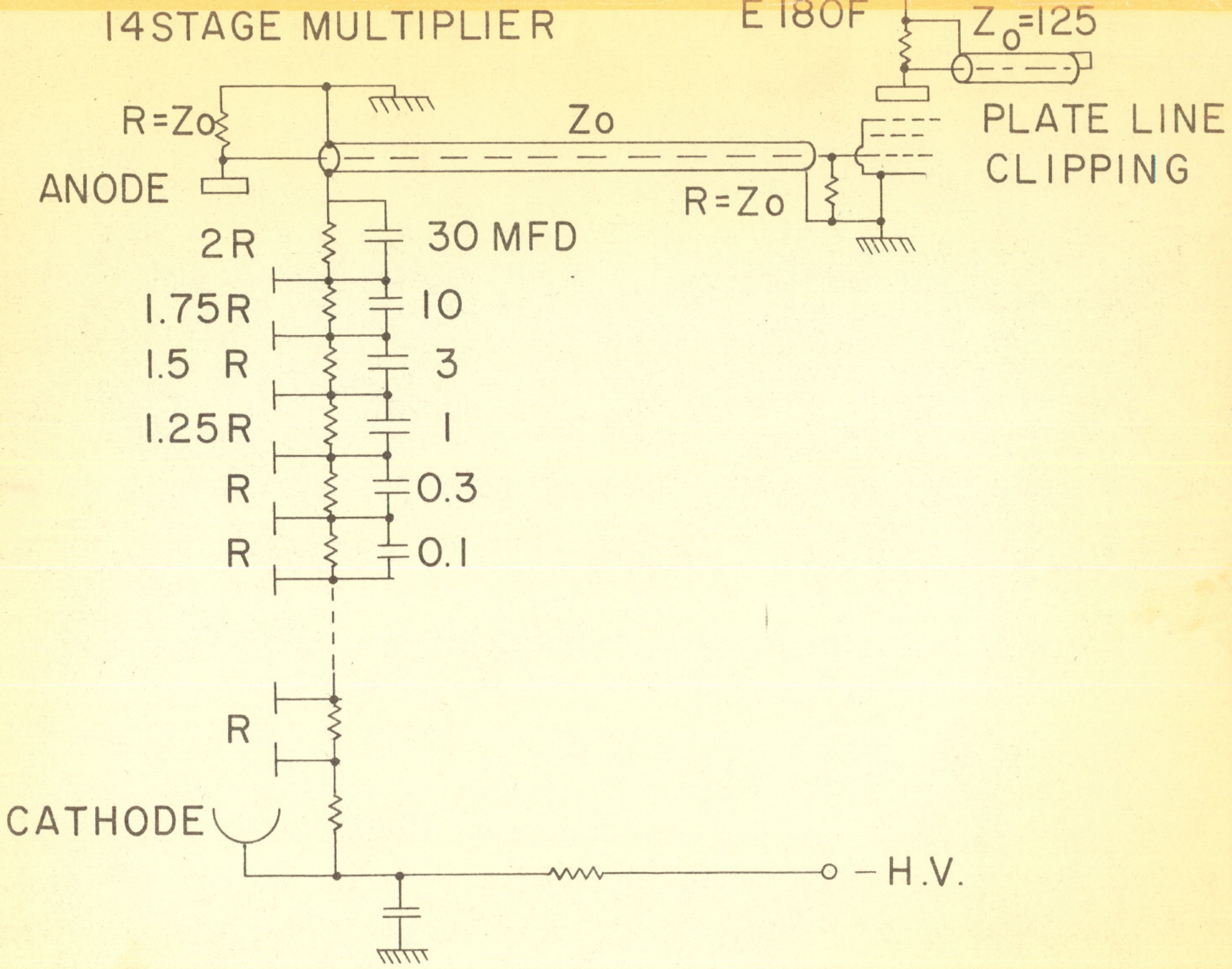


Fig. UCRL-8413

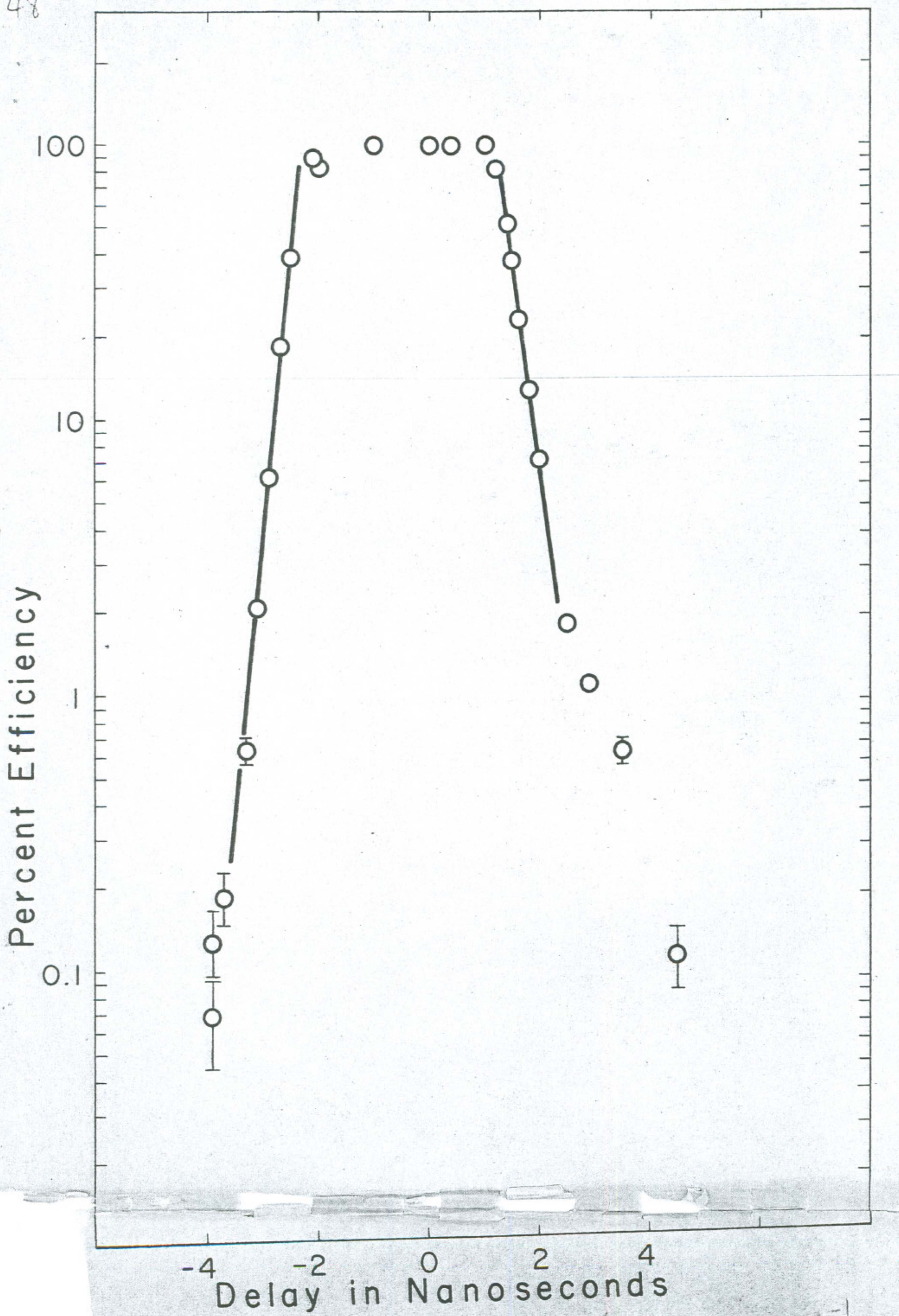
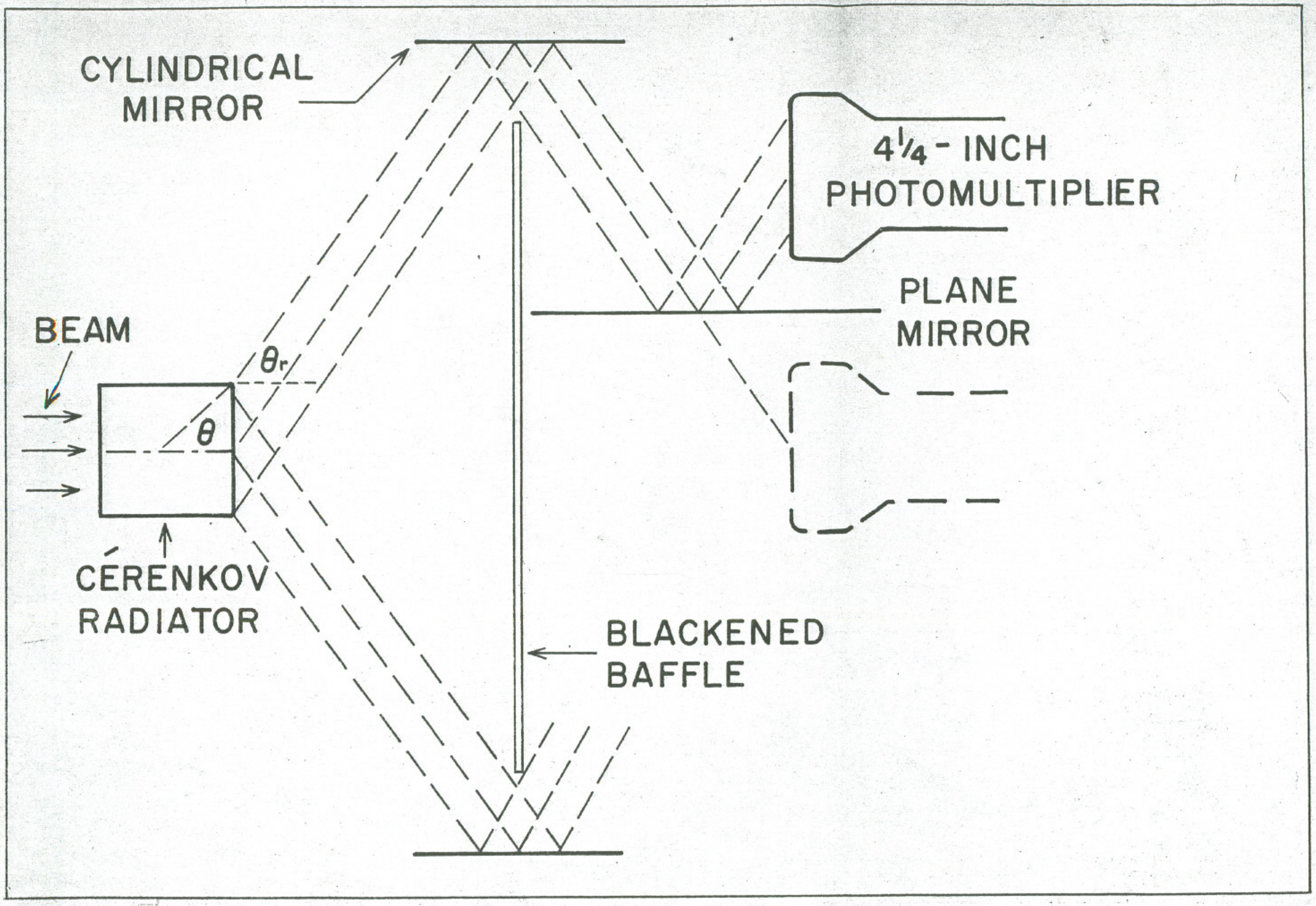


Fig 2 UCRL-8413


CYLINDRICAL MIRROR
4¼ - INCH PHOTOMULTIPLIER
PLANE MIRROR
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ĆERENKOV RADIATOR
BLACKENED BAFFLE

Fig 2

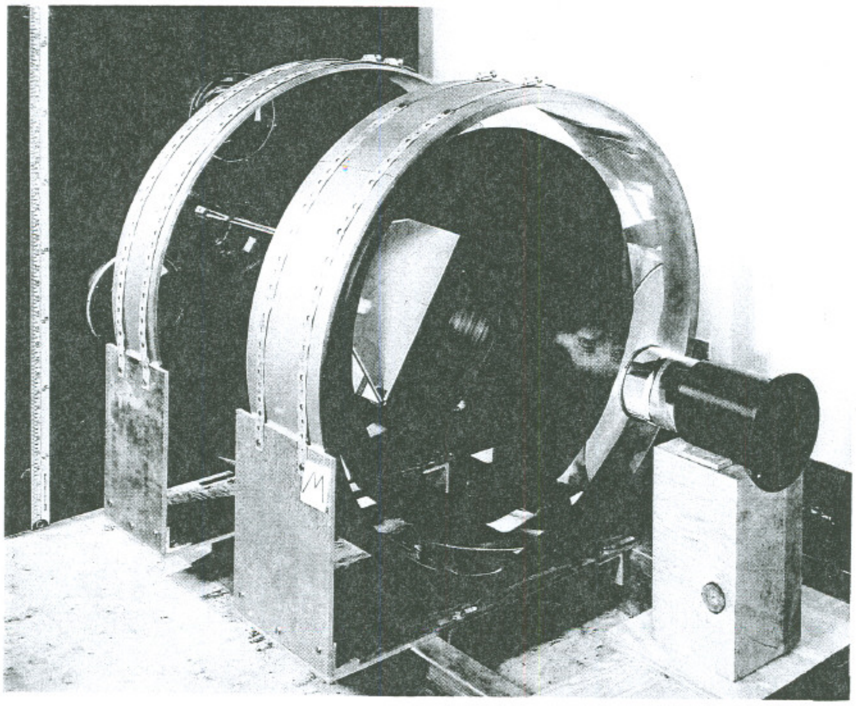

Fig. 4

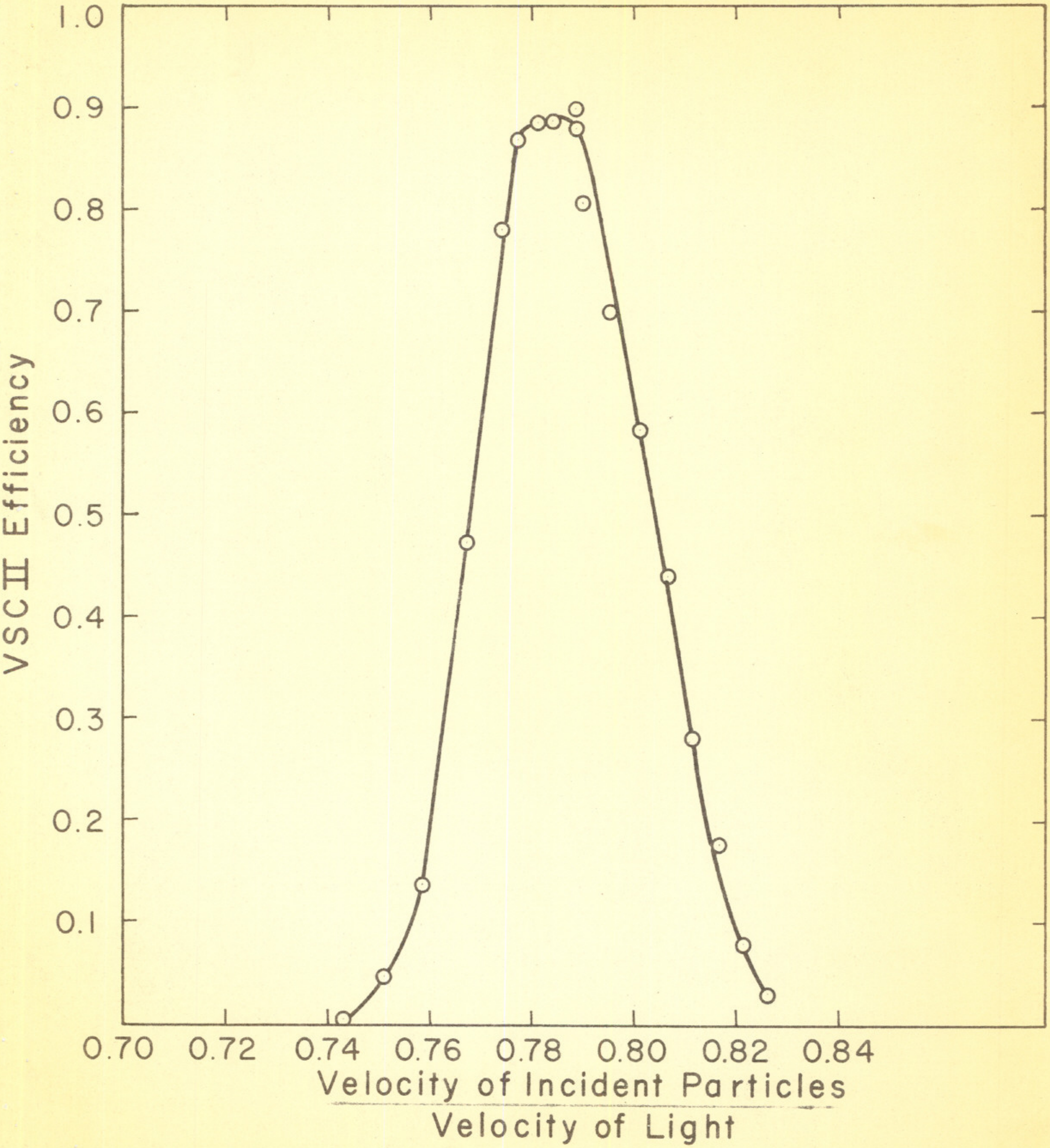

Fig 5 UCRL 8413

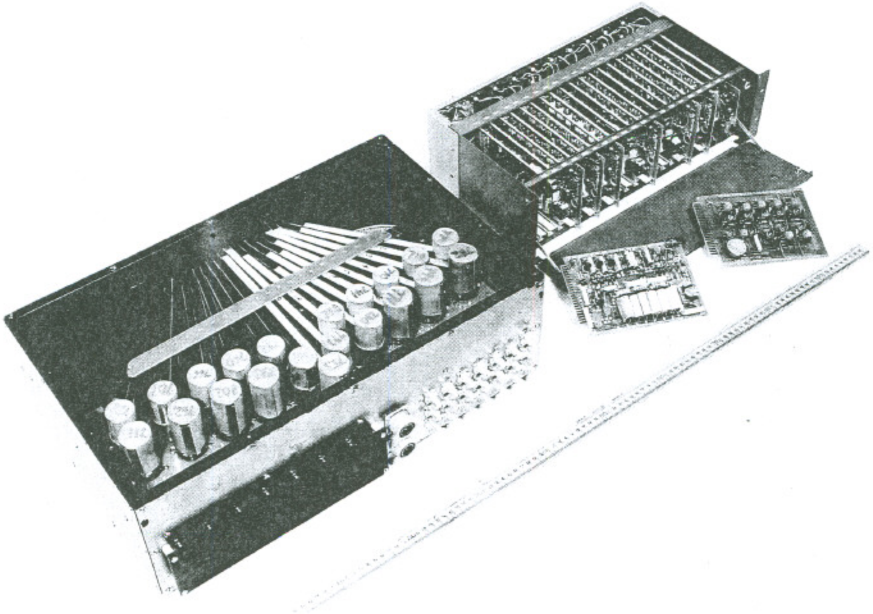

Fig. 6