contributed the same delay. It may be presumed that if the shutter could be moved as fast as the timepieces, the amplifier-delay errors would be reduced. However, it is not possible to use this shutter at such a high velocity.

ACCURACY

The absolute accuracy of the instrument is limited by the accuracy with which the slits are set out. In the present apparatus, the distance is known to be 25 cm to within 1 part in 10 000. The biasing arrangements and circuit design are such that the error in recorded velocity will rarely be worse than $0 \cdot 2\%$ and will usually be about $0 \cdot 1\%$.

TESTING OF APPARATUS WITH HOPKINSON PRESSURE BAR

A tandem arrangement for measuring the velocity of the timepiece was set up. The mechanical contactor was placed first in the line of flight, the front foil being 5 cm from the timepiece, and the front light beam being 15 cm beyond the second foil contact, that is, 45 cm from the timepiece. It was arranged in this manner to facilitate adjustment of the foil height early in the trajectory.

The apparatus was carefully alined so that, with the axis of the pressure bar perpendicular to the planes of the light beams, at least half of each beam was obscured by the timepiece in flight.

Tests were made using seven different types of detonator on three types of pressure bar. Timepiece velocities ranged from 700 to 3000 cm/s. In all cases a higher velocity was recorded by the photoelectric apparatus, the average difference being 4 cm/s. There is every reason to believe that this approaches very closely to the true velocity because it has been shown that the mechanical arrangement would give velocities consistently lower by up to $0 \cdot 4\%$. In general, the coefficients of variation were slightly lower for the photoelectric apparatus.

OTHER APPLICATIONS

The primary function of this device was to measure the time of flight of pressure bar timepieces, but it may be used for measuring the velocity of other objects. Its frequency response has permitted its use for the measurement of the velocities of spheres rolling in a glass tube (where the velocity has been as low as 200 cm/s) and of cylinders projected from an air gun (at velocities up to 10 000 cm/s).

FUTURE IMPROVEMENTS

A unit fitted with four photoelectric cells arranged in two pairs each slightly offset from the tunnel centre is being built to give duplicate readings. Amplifying systems will not be made interchangeable, but provision will be made for testing each photocell system by means of a rotary light chopper.

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High energy, high current synchrotron injector

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The construction and testing of a pulsed 450 keV injector for an electron synchrotron are described. High voltage is obtained with a spark gap and pulse transformer. The electron-optical system consists of a series of electrodes connected to a voltage divider programmed so as to approximate the field in a space-charge-limited plane diode. Quadrupole lenses are used to optimize the shape of the beam spot and to counteract space-charge spreading. Details are given of the dependence of beam current on energy and on filament power.

In electron synchrotrons which make use of betatron action during the early part of the acceleration cycle, it is usually sufficient to inject electrons at an energy of 100 keV or less.(1) The Michigan race-track synchrotron, however, employs frequency modulation of the radio-frequency accelerating oscillator, the frequency being increased continuously from injection time until the circulating electron beam has become strongly relativistic. In such an accelerator a rather higher injection energy is desirable in order to reduce (*a*) the amplitude of the phase oscillations immediately following injection, and (*b*) the frequency range required of the radio-frequency system. In addition, the acceptance time is comparatively short (approximately 1 μs). Consequently, the injection requirement is for a short, high-current, high-energy pulse of electrons.

The injector described herein is capable of operating at 450 keV and delivering a maximum pulsed beam current of 1 A. A pair of quadrupole magnets permits adjustment of the shape of the beam cross-section to the optimum for synchrotron acceptance.

GENERAL DESCRIPTION

(*a*) *Design considerations.* Ideally, in order to produce a parallel beam of electrons limited in intensity only by space charge (within the thermionic emission limit of the cathode), it is necessary to provide a field distribution of the infinite planar diode form. Thus for a direction of motion z, $E_z = kj^{2/3}z^{1/3}$, where E_z is the z-component of electric field intensity, k is a constant and j is the current density.

(Relativistic considerations have been deliberately ignored in the design of this injector. In principle, a more nearly uniform gradient is required relativistically. However, use of the classically-calculated gradient results in a slight constriction of the beam toward the end of the accelerating column, and this was felt by the authors to be a desirable effect.)

This is exactly as in the Pierce electron gun.(2) In the present application, the use of only two electrodes would be inconvenient because of the correspondingly large diameter needed for a reasonable aspect ratio. Accordingly, the ideal distribution is approximated by means of a stepwise arrangement, in which a larger number of plates is used. The separations of these plates decrease suitably as z increases, so that with equal increments of voltage across each pair the field increases approximately in accordance with the above requirements. The cathode electrode is conically shaped according to the Pierce specification, since the flat plate approximation would be poor in this most important region.

(b) *Cathode and accelerating column.* The components of the cathode and accelerating column assembly are shown in Fig. 1. The cathode consists of a directly heated filament F

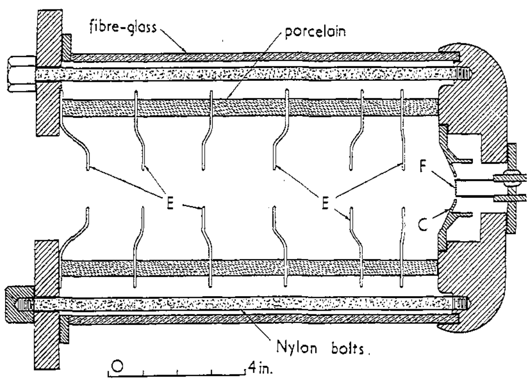

Fig. 1. Cathode and accelerating column

F, filament; C, conical cathode electrode; E, electrodes. Water is circulated in the space between the porcelain insulators and the fibre-glass jacket. Gaskets, screws, etc., are omitted for the sake of clarity.

of 0·020 in. thoriated tungsten wire wound in the form of a flat double spiral, approximately 0·4 in. outside diameter. The two ends of the filament are brought out normal to the plane of the spiral and held in small screw clamps on a mounting plate. Replacement is thus a simple process.

The electrons emitted by the filament are accelerated down the electrode system. This consists of six aluminium plates E separated by porcelain ring-shaped insulators, the assembly of plates and insulators being cemented together. Each plate is $5\frac{1}{2}$ in. in diameter and 0·080 in. thick and has a central hole 1 in. in diameter through which the beam passes. Several smaller holes nearer the edge of each plate facilitate pumping, the interior of the column being maintained under high vacuum of the order of 10^{-6} mm of mercury. The porcelain rings are 5 in. outer diameter, 4 in. inner diameter and either 1·12 or 2·24 in. long according to their position in the column. Thus the cathode, first plate and second plate have single space separation, and the other plates double.

The filament mounting plate is attached to the back plate of the assembly, and so locates the filament in the central hole of the conically-shaped cathode electrode C.

The accelerator column is enclosed by a fibre-glass cylinder so that demineralized water can be circulated around it. This jacket of water serves as a voltage divider for the accelerating electrodes, and at the same time provides cooling of the cathode assembly. The accelerating electrodes are dish-shaped by different amounts in order to provide the required increasing increments of electric field strength along the axis.

This accelerating assembly is supported horizontally in a pressure vessel approximately 4 ft long and 18 in. in diameter which also contains the high-voltage pulse transformer. A mixture of Freon-12 (by Kinetic Chemicals Inc., Wilmington, U.S.A.), nitrogen and carbon dioxide is maintained in the tank at a pressure of about six atmospheres.

(c) *The high-voltage pulse supply.* The pulse transformer system, indicated schematically in Fig. 2, is similar to that generally in use with betatrons; the particular pulse transformer design used here allows operation at 500 kV or more,

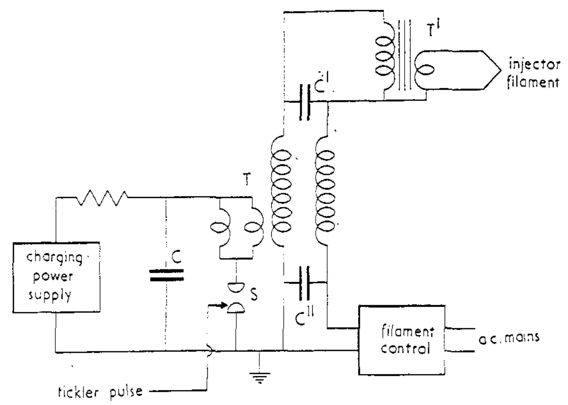

Fig. 2. Schematic diagram of pulse-transformer connexions. In practice, the charging resistor shown is replaced by a vacuum-valve regulating circuit

when used in a suitable insulating medium. Capacitor C, in this case 0·25 μF, is charged to a potential of the order of 20 kV, then discharged through the triggered spark gap S into the primary of the pulse transformer T. (An improved spark gap is described by Hammer and Bureau.[3]) The secondary windings of this transformer are split so that low-voltage a.c. may be applied between them to heat the filament. A filament transformer T' is located within the high-voltage terminal so that the large filament currents need not be passed through the pulse transformer windings. Capacitors C', C'' (of the order of 1 μF) effectively connect the two parts of the pulse transformer secondary in parallel for the pulse.

Construction of the pulse transformer is shown in Fig. 3. A brass tube 3 in. in diameter, slotted lengthwise, serves as

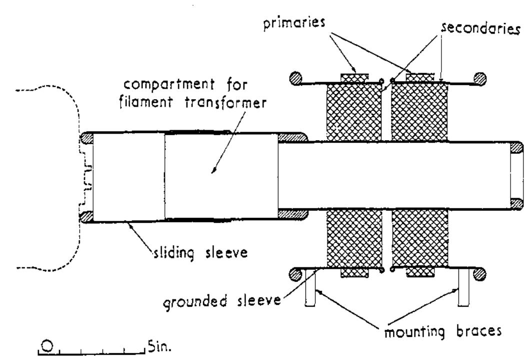

Fig. 3. Section of the pulse transformer. All of the brass tubes used in the construction are slotted lengthwise so as not to act as shorted turns. The sliding sleeve covers the connexions to the accelerating column

the winding former and high-voltage terminal. On this are wound the secondaries, each consisting of 200 turns of flat aluminium ribbon 2 in. wide and 0·002 in. thick. Insulation between turns is provided by three layers of cellulose acetate sheeting, 0·003 in. thick and slightly wider than the aluminium. A primary winding of four turns of copper 0·015 in. thick and 1 in. wide is wound over each secondary, the two primary windings then being connected in parallel.

In the waveform of the high-voltage pulse one can easily recognize the oscillations of the coupled primary and secondary circuits. The value of C in Fig. 2 is empirically adjusted for maximum peak output voltage. Since this maximum, with the present transformer, occurs on the second half-cycle, the polarity of the charging supply is so chosen as to make the output voltage positive on the first half-cycle; the negative second half-cycle is the one utilized for acceleration of the electrons. The oscillations decay with a value of Q of the order of five when a load current of several amperes is drawn from the secondary. The duration of a half-cycle is about 2 μs. Should a longer pulse be desired, an iron core may be employed in the transformer, and C may be replaced by a lumped-constant delay line.

A pulse transformer similar to the one described was in use with an earlier injector in this laboratory, and no particular difficulties arose over extended periods of use.

(*d*) *Quadrupole lenses.* To provide focusing and adjustment of the shape of the cross-section of the beam to the optimum for synchrotron acceptance, a pair of quadrupole magnets[4] has been constructed. The four rectangular-hyperbolic pole-pieces on each magnet are 2 in. long, 2 in. wide, and have a minimum separation of $1\frac{3}{4}$ in. Each energizing coil has 1500 turns of No. 25 Brown and Sharpe (26 s.w.g.) insulated copper wire. The field distributions in each magnet were measured with a long rectangular search coil and found to agree closely with those required. To quote typical figures: a field gradient of 75 G/in. is obtained for an energising current of 50 mA through the four coils in series.

PERFORMANCE TESTS

For test purposes, the emergent electron beam, which would in normal service enter the inflector plates of the synchrotron, was deflected by an analysing magnet into a Faraday cup containing a fluorescent screen which could be viewed through a window. The beam current and shape of the beam spot could thus be observed. (A small focusing coil of the type used with cathode-ray tubes is used to counteract the defocusing which takes place when the beam emerges from the accelerating column into a field-free region.) Beam energies were measured by comparison with internal conversion electrons from a ^{137}Cs source.

The dependence of beam current on power supplied to the filament and on energy was measured. Currents recorded were those received through a limiting aperture of $1\frac{1}{2}$ in. diameter at a distance of 40 in. from the filament (without use of the deflexion or strong-focusing magnets). Representative curves are shown in Figs. 4(*a*) and (*b*). At 450 keV, a maximum beam current of 1 A is obtained for a filament power of 200 W [Fig. 4(*a*)]. A reasonable operating point has been chosen as 150 W, for which the emission is approximately 850 mA.

A strong dependence of emission on voltage is found [Fig. 4(*b*)]. This appears to follow a relation somewhere between a linear law and the three-halves power law of the infinite planar diode, and is probably evidence that the device is only an approximation to the ideal case. (Curves in Fig. 4(*b*) have been normalized at 450 keV.)

The focusing behaviour of the quadrupole lenses has also been verified. Beam shapes such as a horizontal or vertical line or intermediate forms, including a round spot, can be obtained. In normal use the lens currents would be adjusted empirically to maximize the circulating synchrotron beam.

On the basis of detailed measurements made in these tests, it is anticipated that the current delivered into the synchrotron doughnut will exceed by a factor of ten the injected beam current at present obtained from a simple two-electrode injector. (The Michigan synchrotron being out of order at the time of writing, installation of the new injector has been considerably delayed.)

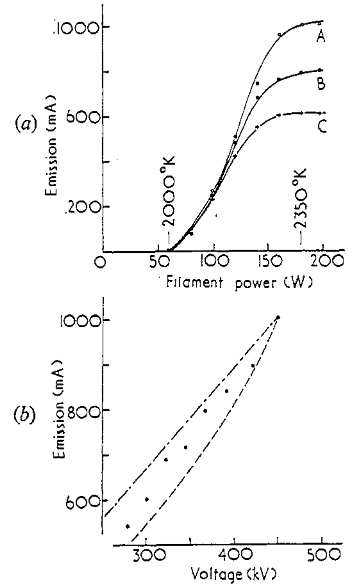

Fig. 4. (*a*) Peak emission current as a function of filament heating power

Curve *A*, 450 keV; curve *B*, 365 keV; curve *C*, 300 keV.

(*b*) Peak emission current as a function of energy or voltoge. Curves of linear and three-halves laws are shown for comparison, normalized at 450 keV

– – – – – $I = KV$. — — — $I = K'V^{3/2}$.

ACKNOWLEDGEMENTS

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