INTENSE, NANOSECOND ELECTRON BEAMS

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Summary

Pulsed radiation sources of higher intensity and shorter duration are desired to broaden the scope of experimental studies of radiation-induced phenomena. For this purpose, a family of generators has been developed which can produce intense pulsed beams of electrons. The highly reproducible beam is extracted from the accelerating tube through a thin window and can be injected readily into other experimental apparatus.

Available pulse durations range from 3 to 50 nanoseconds. The maximum electron energy can be adjusted continuously from 150 to 600 keV, or from 500 keV to 2 MeV, depending on the specific generator. Available peak beam currents range from 1,000 to 10,000 amperes, and the electron output can be varied from 10^{13} to 2×10^{15} electrons per pulse. When desired, the output beam can be concentrated magnetically to energy densities in excess of 100 cal/cm^2, creating shock waves and permitting study of materials under intense transient stress.

The basic design concepts, and diagnostic techniques developed or adapted for reliable measurement of the beam characteristics, will be discussed.

Design Features

The successful performance of the electron accelerators described herein rests on the design of the two main components, an efficient Marx-surge generator and high vacuum, kiloampere field emission electron source.

Marx-surge Generator

The Marx-surge generator was chosen because it is capable of producing a pulse of moderately high voltage (up to a few megavolts) at low impedance and hence at extremely high peak power level (up to 10^{10} watts) as desired for the acceleration of intense bursts of electrons. Other advantages of the Marx-surge design include:

1. By use of a large number of stages, for instance 160 stages in the 2 MV generator, the required dc voltage supply can be kept to a relatively low voltage (for instance 30 kV) and current, hence it is compact and economical. The high voltage exists during the shortest possible time, increasing insulation strength and reducing the size of the equipment. Spark gap switching is distributed among a large number of high pressure gas gaps, minimizing the voltage and energy per gap for maximum reliability and life. By careful enclosure of the Marx-surge generator and gap column in a well grounded metal tank, the RF noise created by the pulser in the experimental region is kept to a minimum.
2. Very fast voltage rise time and good control of pulse duration and waveform can be achieved through good design of the basic energy storage elements.
3. The energy of the output electrons can be varied readily and continuously over a large range of values (for instance, from 2 MeV down to 500 keV for one model, or from 600 keV down to 150 keV for another) by panel adjustment of the dc charging voltage.
4. Repetitive pulsing at fairly high rates, for instance 100 pulses per second, is feasible, at least for a limited train of pulses; of course, sustained pulsing at this rate would result in extremely high average power levels which would be difficult to handle.

High Vacuum Field Emission Tubes

Multiple needle field emission cathodes are used to provide the kiloampere currents desired. Advantages of this design approach include:

1. The use of a large number of sharp needles reconciles the desired high current capability with long cathode life and minimal jitter in pulse timing (5 ns).
2. The use of high vacuum sealed-off tubes permits control of tube impedance, yielding high reproducibility of the output beam characteristics from pulse to pulse and from tube to tube (± 3% rms for the electron dose) and insuring the good impedance match of tube to pulser which is desired to improve output voltage waveform.
3. The cathode dimensions and needle density can be controlled to provide the maximum beam density compatible with adequate life of the tube window through which the beam is extracted for use.

These basic design principles have been

incorporated in two electron beam generators, with maximum electron energy of 2 MeV and 0.6 MeV respectively, which are further discussed below.

2 MeV Electron Beam Generator

Output Power Waveform

The 2 MeV, 10^{10} watts, 50 ns generator and its control console are shown in Figure 1. An electromagnet is used to confine the electron beam inside the accelerating tube for more efficient extraction through a 3 cm diameter vacuum window. The time duration of the electron beam power pulse can be changed from 20 to 40 ns by panel control of the magnetic field. Figure 2 shows the corresponding waveforms. The peak power is the same for both values of the magnetic field. The shorter pulse length may be preferred when high time resolution is desired, whereas the longer pulse length provides maximum electron fluence and absorbed dose.

Charge and Energy in the Transmitted Electron Beam

Figure 3 shows the dependence of the total output beam energy per pulse (in joules) and the total output beam charge per pulse (in microcoulombs) on pulser charging voltage. At the maximum recommended dc charging voltage of 35 kV, the beam output energy is 450 joules and the beam charge per pulse is 320 microcoulombs, corresponding to a total of 2×10^{15} electrons extracted per pulse. The electron density on axis is approximately 5×10^{14} electrons per cm^2, corresponding to a peak flux of 10^{22} electrons/cm^2 sec. From an alternate point of view, the output beam just outside the window has an energy density of 30 cal/cm^2 and can produce a surface dose of 20 megarads, i.e. 50 cal/g.

Energy Spectrum of the Transmitted Beam

Due to the finite rise and fall times of the accelerating voltage pulse the extracted electrons are not monoenergetic. The effective penetration of the electrons at maximum voltage is essentially the same as that of 2 MeV monoenergetic electrons. Since knowledge of the energy spectrum of the output electrons is often required for detailed interpretation of the effects produced by the beam, the spectrum has been derived from the measured attenuation of the output beam current in aluminum foils, as a function of foil thickness and time during the pulse, using an especially designed fast response Faraday Cup to record the transmitted current waveform $I_x(t)$ as a function of aluminum foil thickness x. As shown in Figure 4, most of the beam energy is associated with electrons having an energy near 2 MeV, with a secondary peak observed at 1.1 MeV. The energy and relative amplitude of the peaks can be modified by varying the pulser charging voltage and the beam focusing field.

External Focusing of the Output Beam

The transmitted beam has an energy density of 30 cal/cm^2 on axis near the window. For applications requiring still higher values of the beam energy density or of the dose which the beam can deliver to an absorber, a focusing magnet accessory has been developed to focus the external beam to an energy density greater than the tube window could withstand with an adequate life. Figure 5 shows a self-picture of the focused electron beam propagating in air and made visible through air fluorescence. The beam originates from the tube window at the left and is focused on the slanted steel target at right. The hot center spot on the target, as well as a thin well-collimated jet of material ejected normally from the target center, can be seen. Figure 6 shows a photograph and the section of a steel target after exposure to a single 50 ns pulse of externally focused electrons. The beam energy density and absorption in the target, respectively 100 cal/cm^2 and 300 cal/g, are sufficient to evaporate the front face of the target and to set up internal shock waves strong enough to spall its back face.

Variation of Beam Energy Density and Pulse Duration

The energy density near the window ranges from a few cal/cm^2 to a few tens of cal/cm^2. The natural divergence of the beam in air is relatively slow since ionization of the air by the primary beam produces a dense focusing core of ions. When desired, apertures and scattering foils can be used for controlled variation of the electron flux and dose over several orders of magnitude. Similarly, the beam can be collimated by a set of apertures, and the intercepted electrons used to charge rapidly a set of deflection plates to sweep the apertured beam past an exit slit; in this manner, calculations show that a subnanosecond pulse of monoenergetic electrons may be extracted from the primary beam.

0.6 MeV, 3 Ns Electron Generator

Utilizing a refinement of the basic design principle discussed in the first section, a very compact and economical 0.6 MeV generator has been developed. Figure 7 shows a photograph of the system and Figure 8 shows the output current waveform, recorded with a Faraday Cup with nanosecond time response.

Due to the much shorter pulse duration, the vacuum window can withstand a beam with higher peak current than in the case of the 2 MeV generator (10,000 amperes instead of 5,000); the peak current density is 7,000 amp/cm^2; and the peak electron flux on axis just outside the window reaches the exceptionally high value of 5×10^{22} electrons/cm^2 sec, believed to be the highest ever achieved in a transmitted electron beam directly accessible for use.

High pulse to pulse reproducibility of the output beam energy is retained despite the very high peak current and very short pulse duration. This is illustrated in Figure 9, which shows the total beam energy per pulse over a series of 100 sequential pulses, measured by calorimetry.

Applications

The pulsed electron beam generators just described are relatively recent and their possible applications have not yet been effectively explored. However, the ability to produce short pulse electron beams of extremely high, controlled and reproducible intensity seems attractive.

The main applications to date have been in the study of the effects of very short but extremely intense bursts of radiation on materials and components, using either the electron beam directly or the bremsstrahlung produced by stopping the beam in a tungsten target. The electron beam intensity is sufficient to create large instantaneous temperature and pressure rises, resulting in intense transient stresses and shock waves which may cause spalling. An advantage of the electron beam is that it releases energy in materials at a controlled intensity level and to a controlled depth, both of which can be varied and accurately reproduced from pulse to pulse. One disadvantage, in insulating absorbers thick enough to trap a significant fraction of the incident electrons, is the creation of strong electric as well as mechanical stresses, though this also permits study of the behavior of dielectric under intense transient electrical stress. Other common applications are in pulse radiolysis, for the creation and study of short-lived free radicals in chemical specimens, and also in radiation biology, for the study of fast radiation damage processes and of high dose rate effects.

The electron beam produced by the 0.6 MeV generator may also be collimated to produce an intense probe for plasma diagnostics or gas flow density measurements with nanosecond time resolution. The combination of high current density, short duration and variable electron energy (150 to 600 keV) suggests the possible use of the beam as an intense injection source for high energy, high power electron accelerators. Other applications under study relate to electron pumping of lasers, or to the use of the pulser as a fast, high power driver for high voltage deflection systems used in the handling of beams of high energy charged particles.

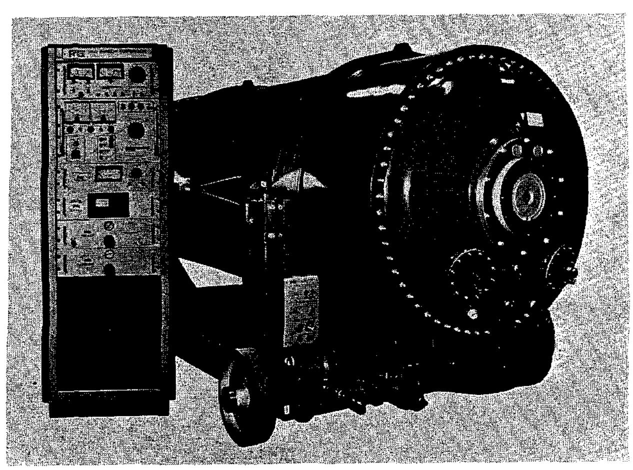

Fig. 1. 2 MeV pulsed electron beam generator, Febetron Model 705, with control console.

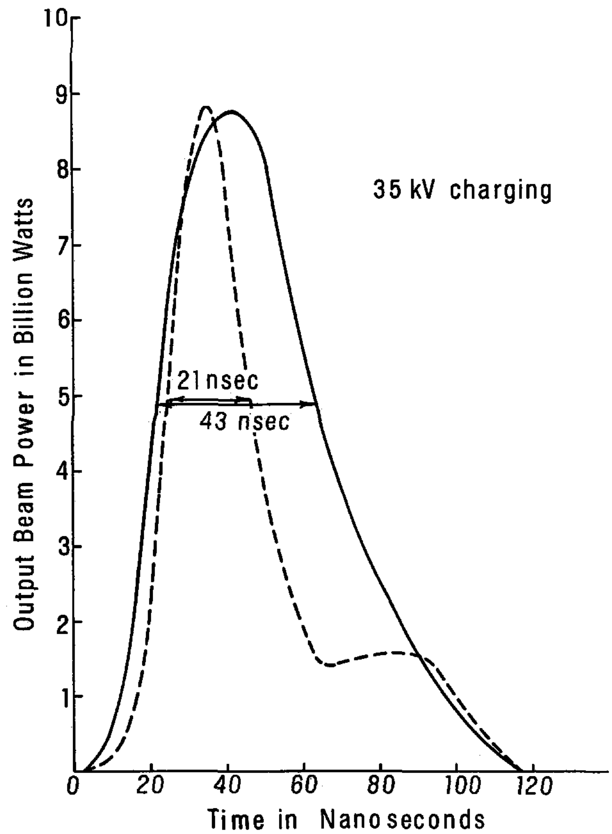

Fig. 2. Effect of focusing field on output beam power waveform, at full output voltage.

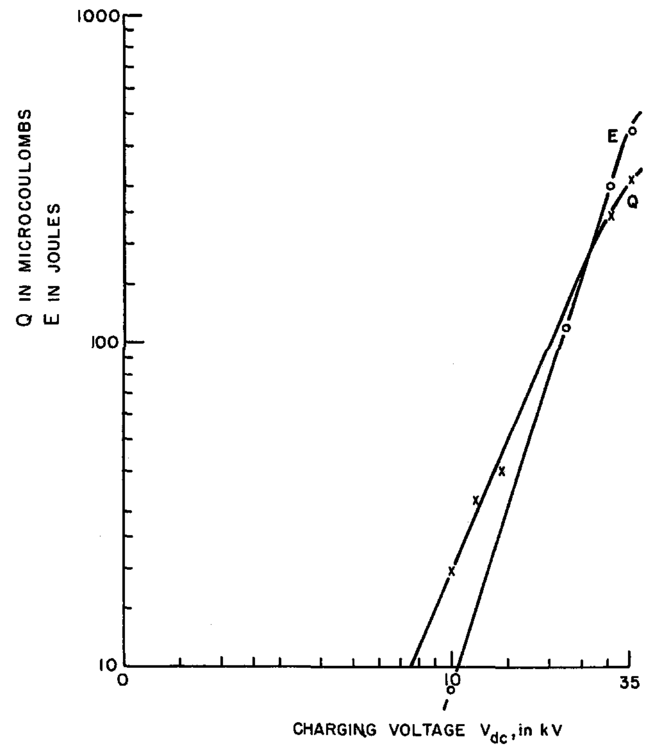

Fig. 3. Output beam total energy and charge vs charging voltage.

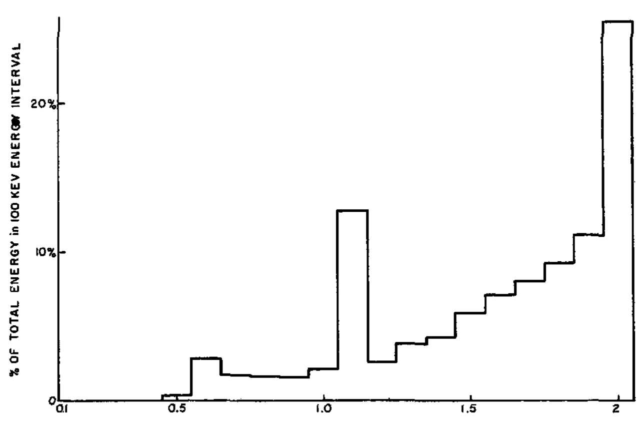

Fig. 4. Differential energy spectrum of output electrons at full output voltage.

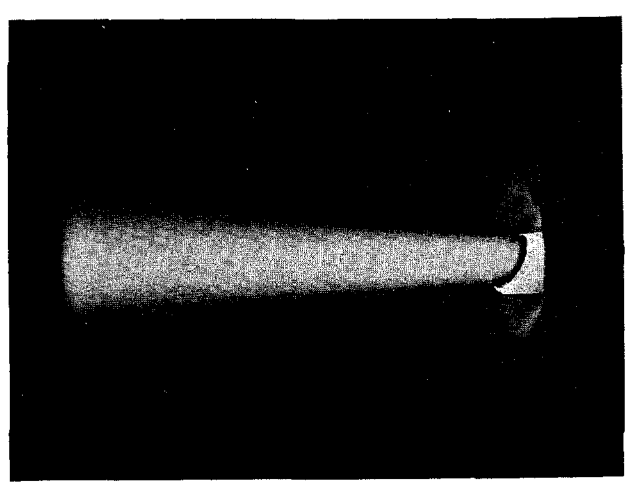

Fig. 5. Self-picture of output beam, propagating in air and externally focused.

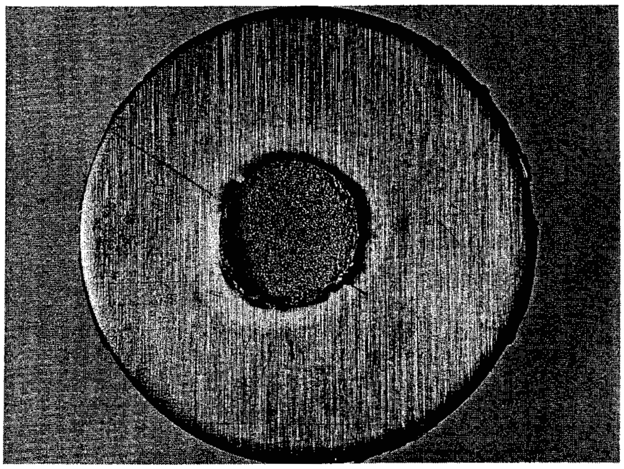

Fig. 6a. Steel target after single pulse exposure to the externally focused beam.

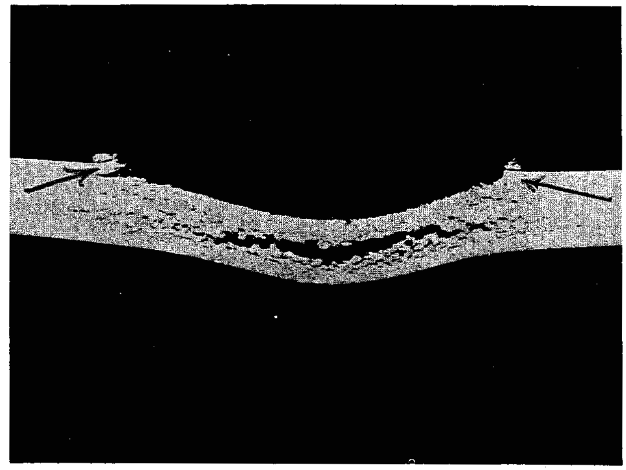

Fig. 6b. Section of steel target after single pulse exposure to the externally focused beam.

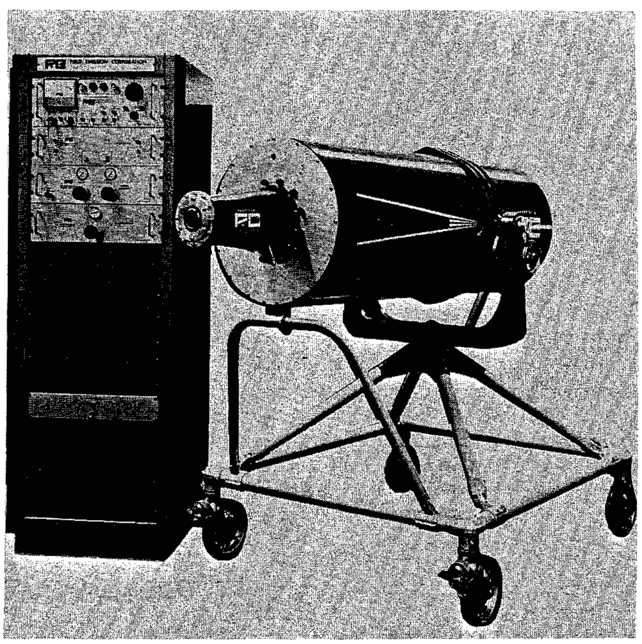

Fig. 7. 0.6 MeV, 3ns electron beam generator, Febetron Model 706, with control console.

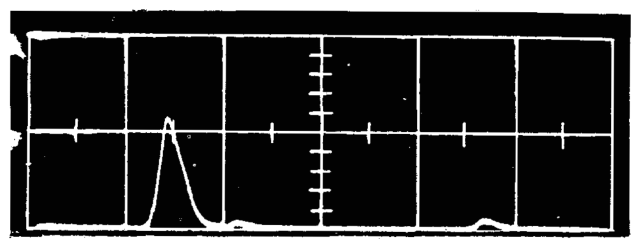

Fig. 8. Output current waveform, recorded with fast response Faraday cup and scope.

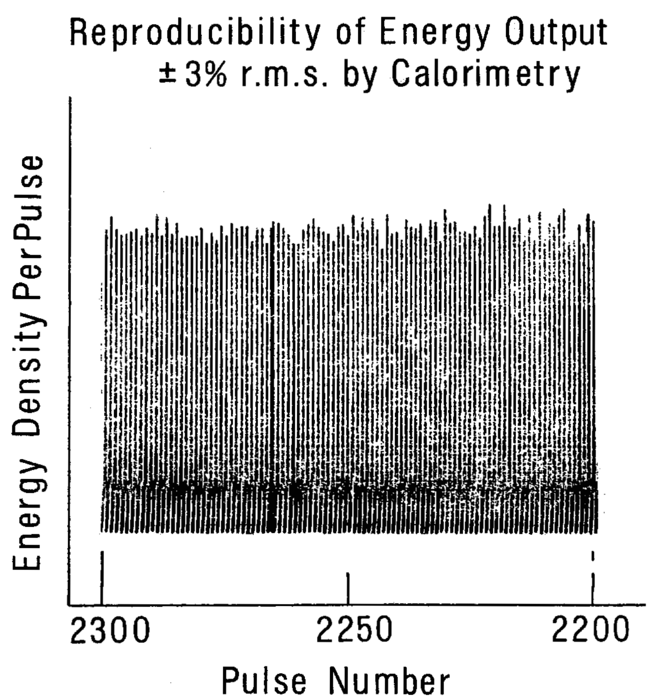

Fig. 9. Calorimetric measurement of output beam total energy for series of 100 sequential pulses, showing $\pm$ 3% rms fluctuation of total energy.