COMPACT PULSED ACCELERATOR*

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Summary

The formation of fast pulses from a current charged transmission line and opening switch is described. By employing a plasma focus as an opening switch and diode in the prototype device, a proton beam of peak energy 250 keV is produced. The time integrated energy spectrum of the beam is constructed from a Thomson spectrograph. Applications of this device as an inexpensive and portable charged particle accelerator are discussed.

Introduction

To date, the pulse forming lines (PFL) evolved from lumped capacitor circuit systems have been used to produce short, fast rising, high power pulses. Since the energy in these systems is stored in the electric field in the dielectric of the transmission line, the maximum stored energy density is limited by the dielectric breakdown strength. For the most commonly used dielectrics, water and transformer oil, the breakdown field strength is empirically found[1] as $E_{br}\, t^{1/3} A^{1/10} = k$. Typical breakdown strength for a practical system which has an electrode area A = 1000 cm^2, microsecond charging time, and k = 0.5 is about 25 MV/m, thus the corresponding maximum energy densities are about 200 kJ/m^3 for water and 7 kJ/m^3 for transformer oil.

Recently we reported[2] that magnetic field energy can be stored in the transmission line and a rectangular high power pulse can be produced into a matched load. In contrast to electric field energy, the magnetic field energy density is not limited by the dielectric medium. Thus, a very high density device i.e., compact system can be built. The dielectric in this case has to hold off only the output pulse field which is half of the charging field of a conventional PFL and easily an order of magnitude shorter than the pulse charging period. The empirical breakdown field strength formula has been found to be an underestimate for such a fast pulse.[3] Therefore, the energy density of such a device can be increased easily by an order of magnitude over that of a conventional PFL. Furthermore, the bulky and expensive voltage step up device, such as a Marx generator or pulse transformer, employed in most pulsed power systems can be eliminated.

In this paper, we will describe our analysis of pulse formation from a current charged transmission line, a prototype experimental device, and preliminary results of ion beam production and its energy spectrum analysis.

Current Charged Line and Pulse Formation

Analogous to the pulse formation from the (voltage) charged transmission line, one can show that a rectangular pulse can be formed from a current charged transmission line and an opening switch system, by using basic transmission line theory. A simple transmission line of length ℓ and of characteristic impedance $Z_o = (L/C)^{1/2}$, is initially shorted at both ends, and is charged with a constant current I_o as shown in Fig. 1. The current charging can be considered as a superposition of two traveling waves of constant voltage amplitudes $V^+ = -V^- = Z_oI_o/2$ and accompanying currents $I^+ = I^- = I_o/2$, proceeding in opposite directions, each being constantly reflected from the shorted ends satisfying the boundary conditions i.e., reflection coeficient $\rho = -1$. The resultant voltage along the line is zero, while the current is equal to the charging current I_o. When one end is suddenly opened by an opening switch, which is connected in parallel with a transmission line and/or a resistive load of matching impedance, the positively traveling wave no longer reflects and proceeds towards the load forming a rectangular pulse. The resultant output pulse has voltage $V_{out} = Z_oI_o/2$, current $I_{out} = I_o/2$, and pulse length $\tau_{out} = 2\ell\sqrt{\epsilon}/c$.

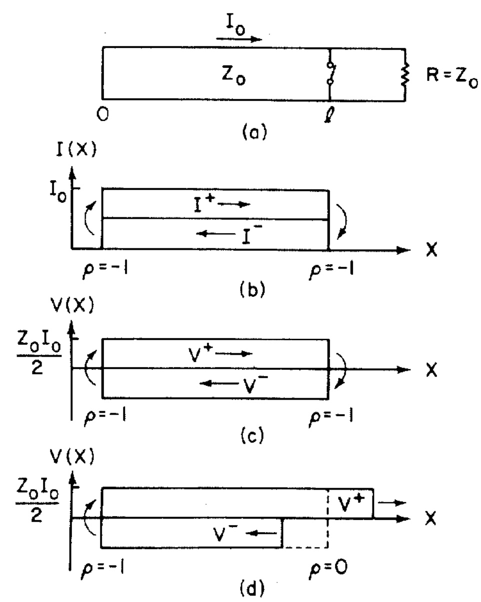

FIG. 1(a). Transmission line initially shorted at both ends and current charged with I_o, (b) Superposition of two waves I^+ and I^-, (c) V^+ and V^-. (d) When the switch opens, $V^+ = Z_oI_o/2$ and $I^+ = I_o/2$ proceeds towards the matched load.

Experiments

A prototype experimental device consists of a capacitor, spark gap switch, coaxial transmission line, and Mather geometry coaxial gun[4] which are connected in series as shown in Fig. 2. The energy initially stored in a 20 kV, 3 kJ capacitor is, by closing the spark gap, transferred to the coaxial line in the form of the magnetic field energy. The coaxial transmission line of radii a = 2.54 cm, b = 7.3 cm and length ℓ = 30 cm has total inductance of L = 64 nH. Here, we utilize the plasma focus as an opening switch and also as a plasma diode as the m = 0 instability occurs and pinches off the current carrying plasma column. The coaxial gun electrodes are made of 10 cm long copper tubing of 2.54 cm and 7.7 cm diameter respectively, and are insulated by a 2 cm long pyrex glass tube of 2.54 cm outer diameter with one end flared. Inserted between the transmission line and coaxial gun is a 2.5 cm thick diagnostics ring, in which a Rogowski coil, a $\dot{B}$ probe and a $\dot{D}$ probe are mounted. The Rogowski coil is constructed by winding 30 turns of 3 mm wide copper tape on a plexiglass ring core of 3 mm x 3 mm cross section and mean radius of

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7.65 cm and is mounted inside of the diagnostic ring. The $\dot{D}$ probe is a capacitive probe consisting of 1 cm radius disk separated 1 cm from the inner surface of the diagnostic ring. The slowest time constant for this probe is 1 ns with a water dielectric. The Thomson spectrometer is placed 60 cm downstream from the gun, and is separated by a miniature gate valve which maintains good vacuum for the spectrometer.

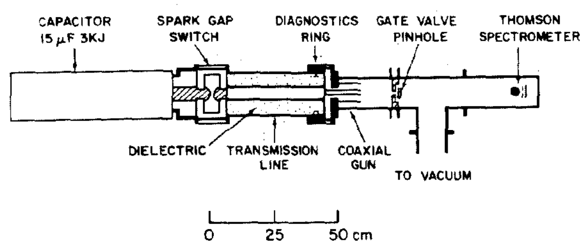

FIG. 2. Experimental setup: Prototype device and diagnostics.

The characteristic impedance of the coaxial line can be varied from 7 to 60 Ohms by using different dielectrics in the coaxial line. The output pulse characteristics strongly depend on the impedance of the transmission line as discussed in the previous section. The maximum current that can be charged through the coaxial line, is found to be 240 kA, assuming an ideal L-C circuit with charging voltage 20 kV on a 15 μF capacitor, 64 nH line inductance and 40 nH internal inductance of the capacitor. We tabulate the output characteristics of the device for reference purposes in Table I, assuming ideal circuit components such as spark gap switch, dielectrics, insulator, plasma focus as an opening switch, and a matched load.

TABLE I. Output pulse characteristics vs. dielectrics.

Dielectrics	Gases	Transformer Oil	Glycol	Water
Dielectric Constant	1	2.2	37	78.5
Characteristic Impedance (Ohm)	60	40	10	7
Output Voltage (MV)	7.2	4.8	1.2	0.84
Output Current (kA)	120	120	120	120
Pulse Length (ns)	2	3	12	18

The system is operated at a typical charging voltage of 18 kV and a fill pressure of 3 Torr hydrogen. The spark gap is triggered by activating a solenoid which opens the gate valve and then closes the trigger contact point allowing the ions accelerated to pass through, while the static filled gas pressure remains almost unchanged and good vacuum is maintained on the other side. The total current through the transmission line and the voltage induced are routinely monitored by the Rogowski coil and the $\dot{D}$ probe. Both signals are integrated by passive R-C integrating circuits with time constants of 50 μs and 2.6 μs respectively. Ions accelerated by the induced pulse voltage pass through the pinhole and the gate valve, drift further downstream, and are deflected by both the electric field and magnetic field of the Thomson spectrometer and recorded on the detector plate.

Thomson Spectrometer

A Thomson spectrometer used in this work as shown in Fig. 3 is similar in design as reported earlier.[5,6] Two round bar ceramic magnets of 2.22 cm diameter and 2.54 cm long are held together by a 10 cm diameter plexiglass disk maintaining a pole gap of 3 mm. The magnetic field in the gap is measured to be 3.5 kG. The magnets are separately connected to an external HV power supply to produce an electric field parallel to the magnetic field in the gap.

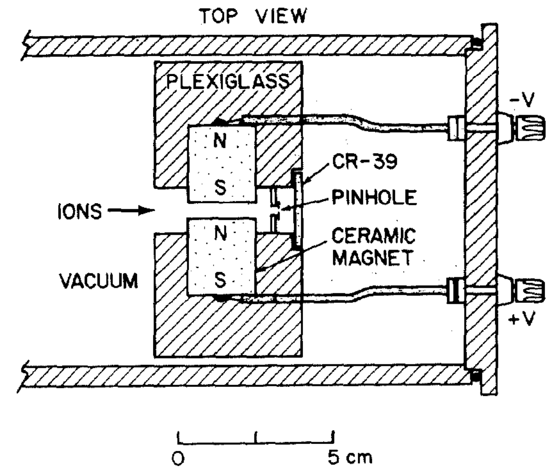

FIG. 3. Cross sectional view of Thomson spectrometer.

Immediately downstream of this field region, a 10 μm diameter pinhole on 10 μm thick nickel disk is placed. The CR-39 detector plate is placed 5 mm downstream of the pinhole. Another pinhole of variable size is placed upstream of the gate valve which is 50 cm upstream of the spectrometer, and serves as an approximate point source of ions with an intensity that depends on the pinhole size. The deflection angles of ions by the electric and magnetic fields of the spectrometer are given by

$$\theta_e = \frac{ZeEL}{2T}, \quad \theta_b = \frac{ZeBL}{\sqrt{2AMT}},$$

and can be used to measure the energy per charge and the momentum per charge respectively, where E and B are electric and magnetic field extended in length L, Z is the charge state, A is the mass number, T is the kinetic energy of the ion, and M is the unit nucleon mass based on C^{12}. The combination of both deflections gives a parabola equation which can be used to determine the charge to mass ratio of ions.

$$\theta_e = \frac{AMEL}{Ze(BL)^2}\,\theta_b^2 .$$

Two shots are needed to complete a Thomson spectrograph: one shot without applied voltage to the electrodes (magnets) deflects all ions vertically, which provides a reference axis (B-axis), and a second shot with electric field by applying a voltage (1 to 10 kV) in addition to the magnetic field which makes a parabola pattern of ion tracks on the CR-39 detector plate. Since the permanent magnets are built into the system, it is difficult to make an E-axis in the horizontal direction, as done in previous works.[5,6] We have found, however, that just enough neutral ions (which may be neutralized by charge exchange or recombination process after the acceleration) are present to mark the origin of the parabola coordinates. This feature not only removes the necessity of the extra shot for the E-axis, but also allows use of small magnets built into the system, thus making operation of the system very simple. After exposure to the ion beams, the CR-39 plate is etched in 6.25 N NaOH solution at 70^0C. The etching time varies depending on the ion species, energies, and the means of reading the tracks. For protons, two hours' etching time is quite adequate for simple optical microscope reading.

Experimental Results

The voltage monitored by the $\dot{D}$ probe at diagnostic ring may be a close representation of the output voltage across the plasma diode, in which both ions and electrons are accelerated. The pulse width is measured to be ~ 20 ns which is consistent with the round trip electrical length of the water filled transmission line.

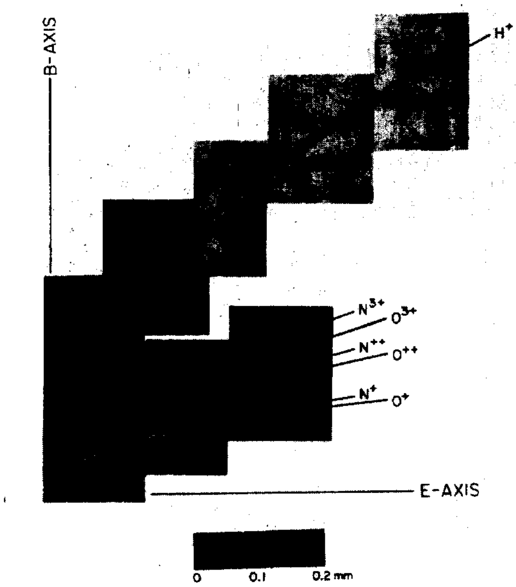

FIG. 4. Optical microscope photograph of a typical Thomson parabola showing protons and impurity ions.

The Thomson spectrometer is particularly well suited for ion beam analysis. A typical Thomson parabola taken with hydrogen filling gas is shown in Fig. 4. The size of the upstream pinhole near the gate valve is adjusted to 0.6 mm diameter which makes the density of ion tracks on the detector plate low enough to be counted by using a simple optical microscope. Each track (dot) corresponding to each ion is well separated as seen in Fig. 4. The uppermost parabola is identified as that of protons by comparing with the calculated parabola and also by track size. A few more parabolas are found below the H^+ parabola. Three distinctive ones correspond to N^+, N^{++}, and N^{+++}. The relatively low number density tracks under nitrogen parabolas correspond to O^+, O^{++}, and O^{+++}. This is attributed to the residual and/or leaked air into the vacuum chamber.

The highest and lowest energies of proton by the electric deflection are found to be 265 keV and 67 keV respectively. The lower limit is due to the narrow pole gap which limits the acceptance angle. A time integrated energy spectrum has been constructed from the H^+ parabola. The parabola is divided into many segments of constant electric deflection angle $\Delta\theta_i$ = 4.4 m rad. The number of tracks ΔN_i in each segment is counted. The mean energy E_i in keV and energy increment ΔE_i in keV of each segment are calculated to find the energy spectrum as

$$\frac{dN}{dE} = \frac{\Delta N_i}{\Delta\theta_i}\,\frac{\Delta\theta_i}{\Delta E_i}$$

and plotted in Fig. 5. The spectrum can be fitted by a power law with two different exponents, $\propto E^{-2}$ and $\propto E^{-3.5}$. It is interesting to note that this power law is similar to that of dense plasma foucs produced deuteron beam reported by Gerdin et al.[7] This spectrum, of course, is representative of the ion beam on axis that passed through the 10 μm diameter pinhole of the spectrometer.

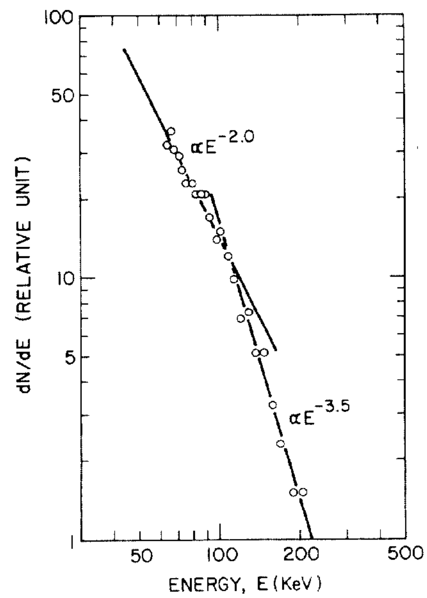

FIG. 5. Proton energy spectrum.

Conclusions

We have shown that high power pulses can be produced by a current charged transmission line and opening switch. A plasma focus, as an opening switch and a diode, has been incorporated with a current charged transmission line to produce energetic charged particles. By analyzing Thomson parabola data, protons and impurity ions have been identified. In addition, the time integrated energy spectrum of the proton beam has been constructed. Although a great deal more effort is required to understand the detailed dynamics of the plasma focus opening switch, it has been demonstrated that the current charged transmission line and plasma focus system is an attractive compact accelerator.

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