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Air-Core Step-up Transformer

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Further communication about this report is to be sent to the Research Information Center, Institute of Plasma Physics, Nagoya University, Nagoya, Japan.

Synopsis

An air-core step-up transformer with a high coupling factor has been developed to generate a high voltage pulse for charging the pulse forming line of a relativistic electron beam source. A beam source using the transformer was constructed and well operated for the beam injection into a toroidal system.

1. INTRODUCTION

Recently, high current relativistic electron beams have attracted much attention in the fields of researches such as plasma heating[1] plasma confinement[2,3] and heavy ion acceleration.[4,5] Most of electron beam sources have been equipped with a multi-stage Marx generator as a high voltage source[6]. However, the Marx generator needs many stacks of unit element which consists of gap switches, capacitors and resistors. If an efficient and reliable step-up transformer is available, the high voltage source would be much simplified and its maintenance would become easier. In this paper, a relativistic electron beam source "Phoebus-I", which is equipped with an air-core step-up transformer, is described. This source has been successfully operated in experiments[7] on the injection of a relativistic electron beam into a small tokamak device named "SPAC-II"[8]. The next section is devoted to describe the design and the construction of the device. In the third section, characteristics of the operation are to be given.

2. DESIGN AND CONSTRUCTION

The relativistic electron beam source installed with a step-up transformer, Phoebus-I, mainly consists of a capacitor bank for energy source, the step-up transformer, a pulse forming line and a field emission diode. Figure 1 shows its schematic layout. The energy stored in the capacitor bank is transferred to the pulse forming line through the transformer, by which the voltage is increased. In such a system, it is very important to use the transformer with high coupling factor. It is also desirable that the charging time on the pulse forming line is sufficiently short, since the electric breakdown time of the dielectric of the line becomes shorter as the charged voltage is increased. Therefore, the step-up transformer should have high coupling factor in the high frequency region of order of MHz. Materials of high magnetic permeability at a moderate cost can not be found as the core of the transformer, so that an air-core transformer is adopted in Phoebus-I.

2.1 Air-core step-up transformer

The step-up transformer, which is applicable to the relativistic electron beam source, is required to have the following characteristics:

(1) The leakage magnetic flux should be small as much as possible to raise the coupling factor.

(2) The effective stray capacitance should be sufficiently small for the high frequency operation.

(3) The electric breakdown between the elements can be protected easily.

In Phoebus-I, these characteristics are realized by an auto-transformer which has a spiral conducting band as shown in Fig.2. A copper band of 40 cm width is wound on a coil-base of nylon-6 of the outer diameter of 40 cm. Polythene sheets (0.3 mm x 5, 0.5 mm x 3) are also wound as the insulator between the copper band layers. Though the total surface area of the copper band is large in this case, the effective capacitance on the output side is small (300 pF) because the capacity is distributed in series. In the primary winding section, the thickness of the copper band is 1 mm and it is 0.25 mm in the secondary winding section. The primary winding is of 2 turns and the secondary winding is of 31 turns. The outest end of the winding is located far from the ground and the breakdown along the insulator can be easily impeded by elongating the breakdown path as shown in Fig.2.

In order to see the variation of the coupling factor of such a transformer with the geometrical parameters, the self-inductances of the primary and the secondary windings and the mutual inductance are estimated. For simplicity, we assume that the width of the conductor band is very wide. The self-inductances of the primary winding L_p and the secondary winding L_s, and the mutual inductance M can be expressed as follows (per unit length):

$$L_p = \mu_0 \pi a^2 n_p^2 , \qquad (1)$$

$$L_s = \mu_0 \pi a^2 n_s [\, n_s + \frac{1}{6}(n_s - 1)\{2(2n_s - 1)\frac{d}{a} + (n_s^2 - 7n_s + 4)(\frac{d}{a})^2\}] , \qquad (2)$$

$$M = \mu_0 \pi a^2 n_p n_s , \qquad (3)$$

where μ_0 is the permeability of vacuum, a the radius of the winding on the ground, n_p and n_s the number of turns of the primary and the secondary winding, d the radial pitch of the winding (i.e. gap between the neighbouring layers). Then, the coupling factor κ is

$$\kappa = \frac{M^2}{L_p L_s} = n_s [n_s + \frac{1}{6}(n_s - 1)\{2(2n_s - 1)\frac{d}{a} + (n_s^2 - 7n_s + 4)(\frac{d}{a})^2\}]^{-1} \quad (4)$$

Therefore, the ratio d/a should be small so as to get high coupling factor. In case of Phoebus-I (Fig.2), the ratio is 1.5×10^{-2} and κ is 0.76. The reason why the coupling factor is not near unity is that the secondary winding has many turns in order to obtain high voltage or the large step-up ratio. Higher coupling may be attained at lower n_s, so the combination of such a transformer with low n_s with a fairly high voltage capacitor would be very economical for the generation of a high voltage pulse. The assumption made for the calculation would be valid for a high frequency pulse, since the skin depth of the conductive winding becomes very thin and the magnetic field is aligned along the conductor surface.

The step-up transformer is housed in a tank. The tank is evacuated up to 10^{-1} torr and then filled with insulating oil of the first class.

2.2 Two-stage 100 kV Marx generator

Two capacitors of 1.9 μF are charged separately up to 50 kV and then connected in series with triggered gaps. The stray inductance of each capacitor is only 30 nH and the pulse feeding to the step-up transformer is made by the use of very wide double copper plates to reduce the additive inductance. At the termination points on the transformer, a resistor of 10 Ω is connected in parallel as a surge absorber. The gaps used are the ones which have been specially developed by Hirano and Kitagawa for high β pinch experiments.

2.3 Pulse forming line and charging on it

A coaxial line with water dielectric is used (Fig.1) as the pulse forming line. The water has specific dielectric constant $\varepsilon/\varepsilon_0$ of 80, the value of which is nearly constant up to 1 GHz[9]. The length of the coaxial line is 40 cm, which corresponds to the pulse width of 24 ns. The aspect ratio of the line is 2, so the characteristic impedance of the line is 4.6 Ω and the capacity is 2.6 nF. The stored energy at the charged voltage of 1 MV is 1.28 KJ. The outer diameters of the inner conical conductor at the ends are 45 cm and 35 cm, respectively. The wall is made of stainless-steel to keep the quality of pure water. For charging the line, a resistive helical wire is used for the connection between the step-up transformer and the pulse forming line. The resistance (4 Ω) helps to damp standing oscillations in the circuits and the helical geometry having inductance of 1 μH serves to increase the impedance against the fast surge from the pulse forming line.

In this charging system, the capacitor and the self-inductance of the primary side are connected to those of the secondary circuit by the mutual inductance. Thus, the transient current includes two characteristic frequencies in general and in such a system the maximum charged voltage on the pulse forming line appears frequently at the second peak. This is called "resonant charging". The waveform of the voltage will be shown in the next section.

2.4 Main gap and transmission line

The pulse forming line is discharged by a main gap which is filled with SF_6 gas. The breakdown voltage is adjusted by changing the gas pressure. To reduce the inductance of the gap, the curvature of the gap is made to be large as 30 cm and, at the center where the spark occurs, copper-tungsten metal tips of the curvature of 10 cm are attached to prolong the gap life. The clearance between the facing tips is chosen to be 6 cm. At low voltage operation (< 500 kV), a mixture of SF_6 and He gases is used to make the breakdown voltage be easily controlled.

The transmission line of the conical shape has the same characteristic impedance as the pulse forming line and it is grounded through a resistor of 20 Ω which is made of the solution of $CuSO_4$. This resistor works to absorb the pre-pulse which is induced at the charging stage of the pulse forming line. The transmission line is water-sealed at the far end by the capacitively grading rings as shown in Fig.1, and this end can be connected with either an another transmission line or a field emission diode.

2.5 Transmission of the pulse

A coaxial transmission line having water dielectric can be attached to the conical transmission line in order to transmit the pulse towards a field emission diode. If the diode impedance is not the same as that of the conical transmission line, an impedance transforming can be made by reducing exponentially the inner diameter of the line, as shown in Fig.1. For the beam injection into the toroidal device "SPAC-II", the diode impedance is about 30 Ω so that the aspect ratio of the impedance transforming line is increased from 2 to 50 over the length of 40 cm of the line.

3. CHARACTERISTICS OF THE OPERATION

In this section, characteristics of each main part of the device are to be described. This device has been operated about 5000 times without maintenance care, but no fatal trouble has occurred.

3.1 Charging and discharging of the pulse forming line

The charged voltage and its waveform of the pulse forming line are measured by an electrostatic probe installed inside the outer conical wall of the line. Figure 3(a) shows a typical waveform of the voltage when the main gap does not work. There exist at least two dominant frequencies. The maximum voltage appears at the second peak, at which the step-up ratio of the step-up transformer becomes about 10 times the output voltage of the two-stage Marx generator in usual operation, though the turn ratio of the step-up transformer is 15.5. This observed step-up ratio depends strongly on the quality of the filled water. The water is deionized by an organic ion exchanger. In the best condition where the specific resistance of the water is greater than 1 MΩ-cm, the step-up ratio becomes 12. In this case, the efficiency of the energy transfer from the capacitor bank to the pulse forming line is 43 %. This value can be said to be fairly high because, even in systems using only Marx generator, the efficiency is about 40 %.

The gas pressure of the main gap is adjusted so that the gas breaks down just at the second peak of the charged voltage of the pulse forming line. Figure 3(b) shows the change of the charged voltage where the output terminal of the transmission line is connected with the diode for the beam injection into the torus. Induced high frequency oscillations at the gap firing damps fast, as seen in the figure, owing to the resistive damper set between the transformer and the pulse forming line.

3.2 Generated pulse waveform

The waveform of the pulse generated by the pulse forming line is measured with an electrostatic probe set near a 4.6 Ω dummy load of $CuSO_4$ solution which terminates the coaxial transmission line (Fig.4). The waveform is nearly rectangular and its pulse width is about 25 ns which is almost the same as the designed value.

3.3 Electron beam emission from a diode

In general, a field emission diode for generating a relativistic electron beam changes its impedance during the operation, since the plasmas generated on the surfaces of the anode and the cathode move towards the opposite electrodes and the effective distance between both electrodes becomes narrower with time. As a result, the waveform of the diode current is not rectangular though a rectangular pulse is transmitted on the line. Figure 5 presents a typical current waveform of the diode which is set inside the torus for the beam injection. The diode is made of pure graphite of fine grain, and the anode is tungsten-grid. Here, both the axial transmission line and the impedance transforming line are used as shown in Fig.1. The rise time of the diode current is about 10 ns and the pulse width is about 30 ns in this practical case. The details of the injection into the torus will be reported separately.

4. CONCLUSION

A step-up transformer for a high current relativistic electron beam source has been developed. It has been shown by making a proto-type Phoebus-I that this transformer can effectively transfer the energy stored in the capacitor bank to the pulse forming line with the step-up ratio above 10. An electron beam source using such a transformer is much simplified because many-stage stack of a capacitor-gap-resistor unit is no more needed. Thus, the maintenance of such a source becomes very easy. In fact, Phoebus-I has been successfully operated 5000 times without any fatal trouble.

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Figure Captions

Fig. 1. Schematic layout of the relativistic electron beam source Phoebus-I.

Fig. 2. Step-up transformer used for Phoebus-I.

Fig. 3. Waveforms of the charged voltage of the pulse forming line measured by an electrostatic probe. (a) Oscillatory case when the main gap does not work. The Marx voltage: 48 Kv. Vertical scale: 347 kV/div. Sweep speed: 10 μsec/div. (b) The case when the main gap fires at the second peak. The Marx voltage: 64 kV. Vertical scale: 347 kV/div. Sweep speed 1 μsec/div.

Fig. 4. Pulse waveform with a 4.6 Ω termination resistor of $CuSO_4$ solution at the end of the transmission line. Sweep speed: 20 nsec/div.

Fig. 5. Diode current at the injection of relativistic electron beam into SPAC-II, Vertical scale: 8.4 KA/div. Sweep speed: 20 nsec/div.

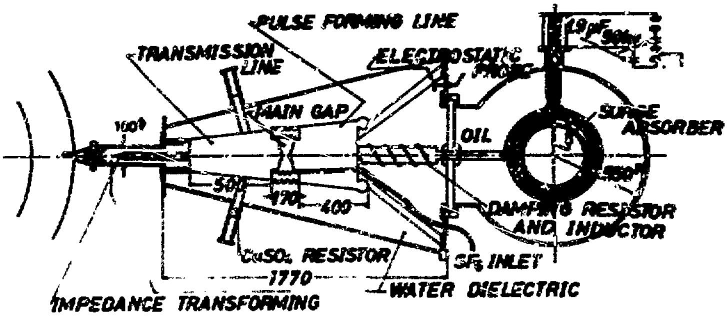

PULSE FORMING LINE
TRANSMISSION LINE
ELECTROSTATIC PROBE
MAIN GAP
SURGE ABSORBER
OIL
DAMPING RESISTOR AND INDUCTOR
CuSO₄ RESISTOR
SF₆ INLET
WATER DIELECTRIC
IMPEDANCE TRANSFORMING
1770
500
170
400
160

Fig. 1

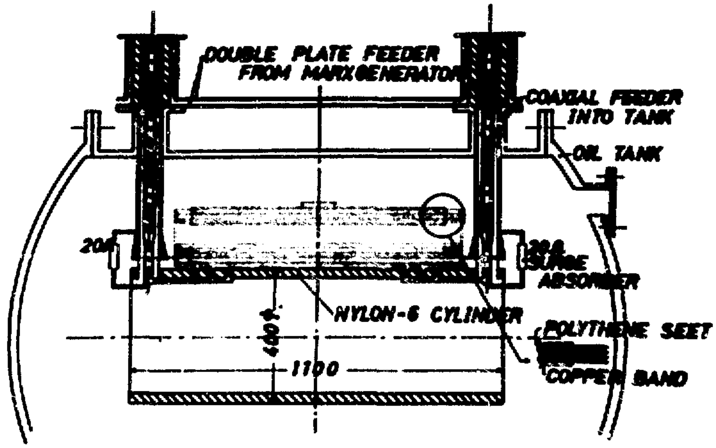
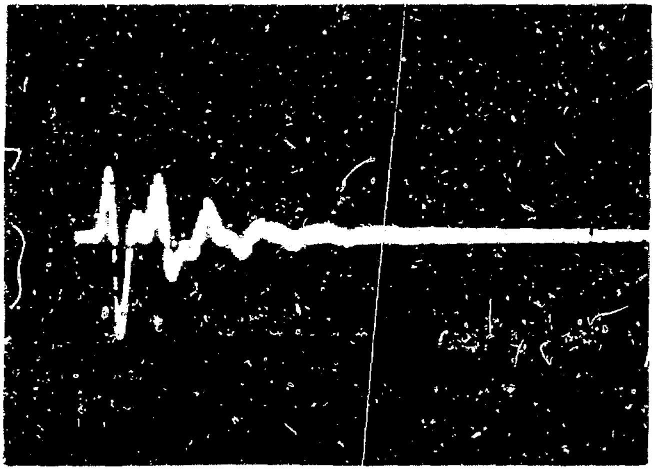
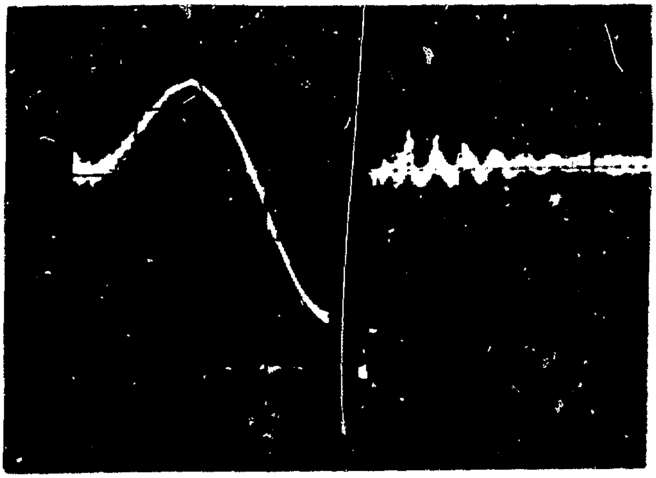

DOUBLE PLATE FEEDER FROM MARX GENERATOR
COAXIAL FEEDER INTO TANK
OIL TANK
SURGE ABSORBER
NYLON-6 CYLINDER
POLYTHENE SEET
COPPER BAND
1100
400

Fig. 2



(a)



(b)

Fig. 3

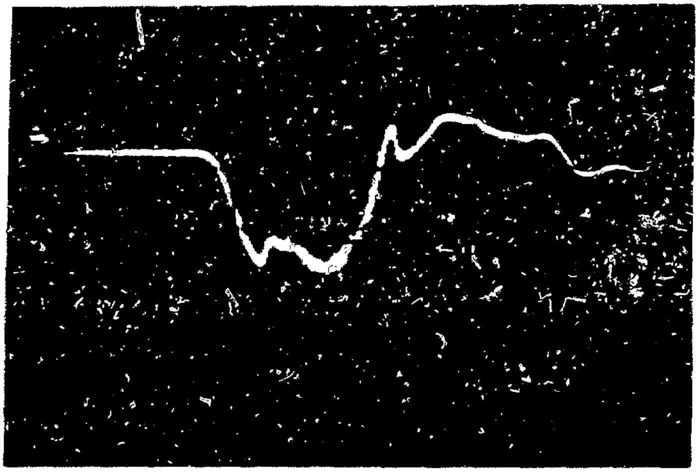


Fig. 4

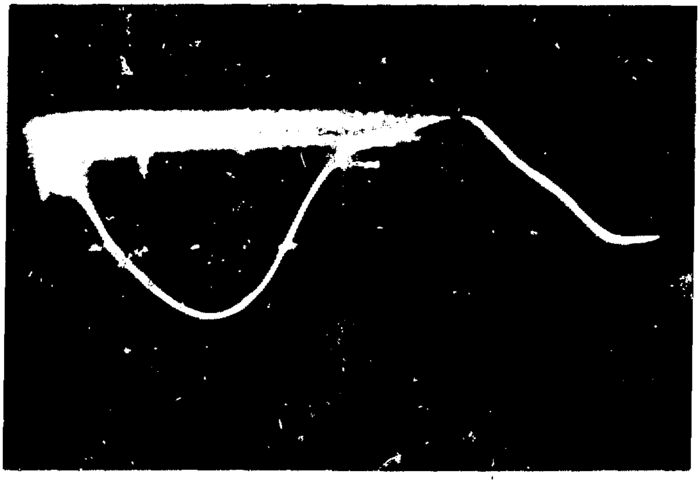


Fig. 5