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Design and development of pulsed electron beam accelerator *'AMBICA – 600'*

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Abstract. Short duration, high power pulses with fast rise time and good flat-top are essentially required for driving pulsed electron beam diodes. To attain this objective, a dual resonant Tesla transformer based pulsed power accelerator 'AMBICA-600' has been developed. In this newly developed system, a coaxial water line is charged through single turn Tesla transformer that operates in the dual resonant mode. For making the accelerator compact, in the high power pulse forming line, water has been used as dielectric medium because of its high dielectric constant, high dielectric strength and high energy density. The coaxial waterline can be pulsed charged up to 600kV, has impedance of ~5Ω and generates pulse width of ~60ns. The integrated system is capable of producing intense electron beam of 300keV, 60kA when connected to impedance matched vacuum diode. In this paper, system hardware details and experimental results of gigawatt electron beam generation have been presented.

1. Introduction

In the last few years, pulsed beam technology has reached to very sophisticated level. The growth of interest in the intrinsic behavior of intense relativistic electron beams and its utilization in various fields has also been grown very rapidly. Intense electron beams can be used for variety of applications like – high power microwave generation, heating of plasmas to high temperatures, plasma confinement, collective acceleration of ions, short pulse gas lasers, controlled thermo-nuclear fusion, flash X-Ray generation, material modification studies etc.

The basic structure of an electron beam accelerator for all mentioned applications consists of prime power source, high voltage generator, pulse forming line and a field emission (FE) diode. The sequential integration of these major constituents is shown in Fig. 1.
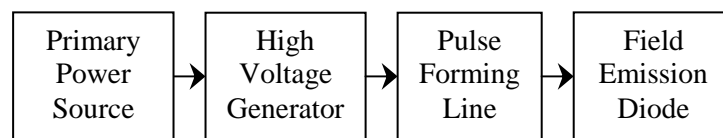
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┌──────────┐   ┌──────────┐   ┌──────────┐   ┌──────────┐
│ Primary  │   │  High    │   │  Pulse   │   │  Field   │
│ Power    │ → │ Voltage  │ → │ Forming  │ → │ Emission │
│ Source   │   │Generator │   │  Line    │   │  Diode   │
└──────────┘   └──────────┘   └──────────┘   └──────────┘
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Fig. 1. Basic structure of a pulsed electron beam accelerator.

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The DC charging of a high voltage energy storage capacitor provides primary power source to the system. Then a high voltage generating system is needed to transform the few ten's of kV in the primary power source to values in the range of several hundreds of kilo-Volts. Such high voltages can be produced either by using Marx generator or Pulse transformer. While utilizing Pulse transformer technique for voltage amplification, by tuning the parameters (LC) of primary (L_1C_1) and secondary (L_2C_2) circuits such that frequencies of free oscillations in the primary and secondary circuits become identical; the system operates in Tesla transformer mode. The main advantages of the Tesla transformer generator as compared to the Marx generator are [1]: (i) Possibility to work with rather high pulse-recurrence frequency (ii) Lower cost due to a small number of used high voltage capacitors that reduces weight and system dimensions and (iii) More reliability in the performance because of the absence of large number of sparkgap switches. The transient behavior of Tesla transformer is analyzed using simple equivalent circuit as shown in Fig. 2.
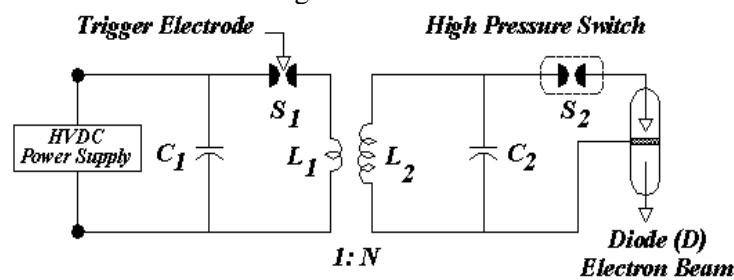

Fig. 2. Equivalent circuit of Tesla transformer based accelerator.

In brief, the principle of the Tesla transformer is based on the energy transfer between the two magnetically air-coupled and perfectly tuned resonating circuits: R_1-C_1-L_1 and R_2-C_2-L_2. R_1 and R_2 are the winding resistances of L_1 and L_2 respectively (not included in the figure). Suppose that, with open switch S_1, V_{DC} is charging C_1. When C_1 is sufficiently charged, S_1 is closed resulting in the discharge of C_1 in L_1. Finally, the primary capacitor C_1 acts together with the primary coil L_1 as a resonating circuit resulting in a damped oscillating wave of a certain frequency f_1. Because of the coupling between the two circuits, the oscillation frequency of the primary circuit appears in the secondary circuit as well. The condition required for the dual tuned circuits to operate in resonance mode is given as [1,2]:

$$f_1 = \frac{1}{2\pi\sqrt{L_1 C_1}} = \frac{1}{2\pi\sqrt{L_2 C_2}} = f_2 \qquad (1)$$

$$L_1 C_1 = L_2 C_2 \qquad (2)$$

The magnitude of amplified output voltage V_{C2} across C_2 depends on the pre-charging voltage V_{C1} at C_1 and the efficiency η of the energy transfer i.e. [2]:

$$V_{C2} = \eta\, V_{C1} \sqrt{C_1/C_2} \qquad (3)$$

For the maximum energy transfer, it is mandatory to have a coupling coefficient between windings of the transformer accordingly as [1,2]:

$$k = M\sqrt{L_1 L_2} = 1; 0.6; 0.385 \qquad (4)$$

Pulse forming line is required for compressing the duration of the high voltage pulse (which is typically in the range of few µs, as an output from high voltage generator) in the range of 30 to 100ns. Another important role of the pulse forming line is to match the driver/accelerator impedance with vacuum diode. The typical impedance of vacuum diode used for various applications is in the range of

5 to 20Ω. Pulse forming/compression along with impedance matching is normally done either by using water or oil as dielectric in the coaxial line of defined length. In our system a high voltage capacitor has been used for primary energy storage, Tesla transformer for high voltage generation and water coax for pulse compression and impedance matching.

2. Experimental Setup

The dual resonant Tesla transformer [2] based AMBICA-600 pulsed power system comprises of primary energy storage capacitor, single turn pulse transformer, coaxial waterline, high voltage holding switch and field emission diode with voltage and current diagnostics. The overall view of the integrated system has been shown below in Fig. 3.
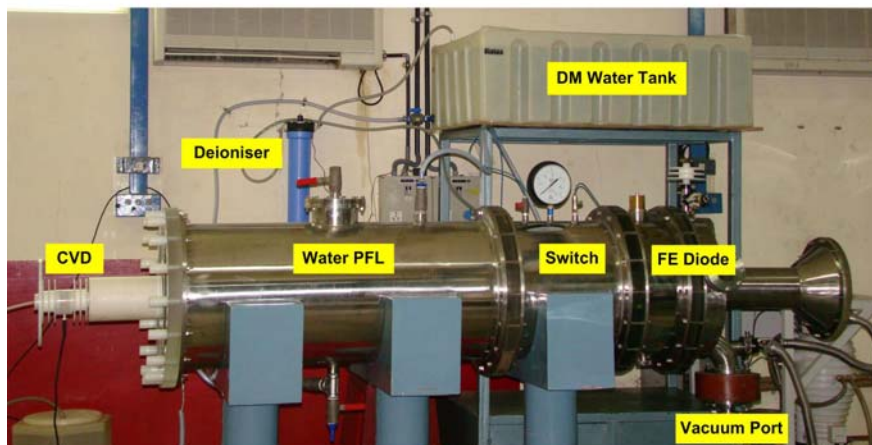

Fig. 3. Overall view of the integrated AMBICA – 600 system.

2.1. Primary energy storage

To energize the primary of the Tesla transformer, a 7.1μF low inductance capacitor that can be charged up to maximum limit of 40kV was used. The capacitor has self- mounted triggerable spark gap on top of it that facilitates direct connection between capacitor and energy transfer switch. The switch is triggerable in the range of 8kV to 40kV by adjusting appropriate Nitrogen (N_2) gas pressure in the gap. Delay and jitter in the main spark gap is minimized by utilizing a trigger voltage of magnitude double the maximum voltage to be switched i.e. ~80kV. The peak current limit of this capacitor for pulsed operation is ~150kA. For making the connection between primary energy storage capacitor and Tesla transformer while keeping the bank inductance low, eight numbers of custom made double braided coaxial cables (equivalent to RG 217 or YK198) have been used in parallel. These indigenously developed cables have impedance of ~19Ω and inductance of ~100nH/m. The material of double layer braid is silver plated copper and Teflon has been used as dielectric in between the layers. These cables have passed high voltage standoff test up to 40kV DC.

2.2. High voltage generator

Efficient design of Tesla transformer depends upon parameters like coefficient of coupling, tuning ratio, voltage step up ratio and dielectric strength. The design for a given secondary output voltage and coupling coefficient is an iterative process and was started by assuming values for the step up ratio and the primary input voltage which in turn fixes the ratio L_1/L_2. For attaining high reliability and repeatability, trade off has been made between good coupling coefficient and high voltage stand off. The construction of an indigenously designed single turn pulse transformer has been shown in Fig. 4.
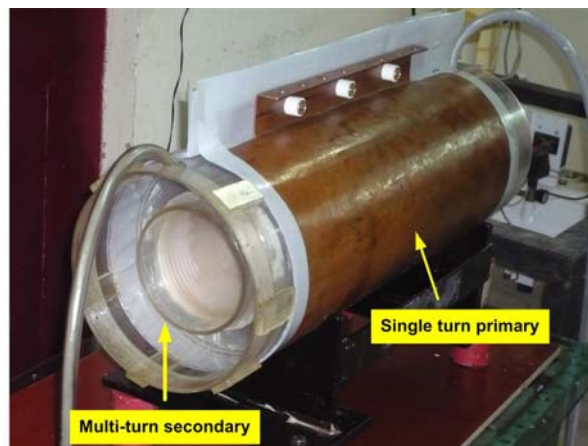
Fig. 4. Constructional view of the indigenously designed pulse transformer.

The single turn primary (outside) is made up of 1mm thick Copper sheet having width ~600mm. It is fixed on insulated Acrylic cylindrical support of mean diameter 250mm. The measured inductance of the single turn primary is ~90nH and the total inductance (L_1) of primary side (including contribution of all connections) is ~220nH. The secondary winding has been concentrically supported inside the primary. It has 70 turns made of polyethylene insulated RG213 inner conductor. The inductance of the secondary winding (L_2) is ~200μH. The mutual inductance (M) and coupling coefficient (*k*) obtained for the Tesla mode operation are 2.42μH and 0.54 respectively. The secondary output of the transformer is connected to the input of coaxial waterline.
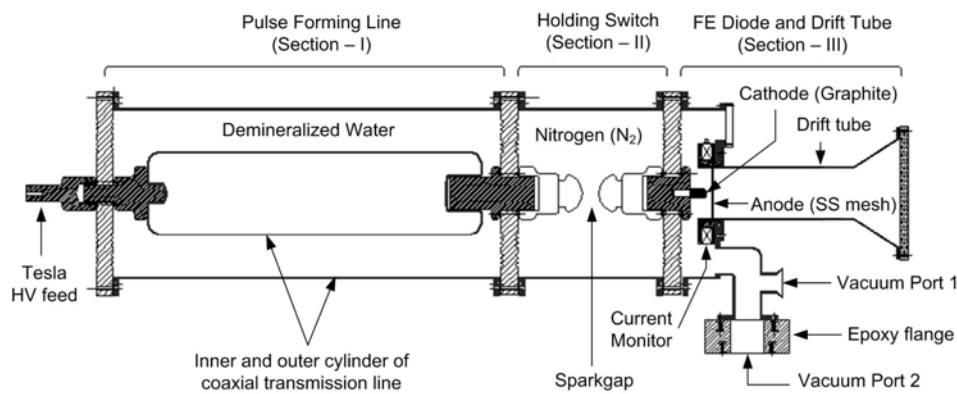

Fig. 5. Constructional schematic of the integrated Pulse Forming Line assembly.

2.3. Pulse forming line and High voltage holding switch

A water line that acts as the secondary capacitor during the resonance charging has been used for pulse compression. Since the dielectric constant (ε_r) of the deionised water is ~80, therefore it facilitates compact construction with high energy density. The constructional layout of the used coaxial waterline along with high voltage holding switching and the vacuum diode assembly has been shown in Fig. 5. The most important consideration in the design of pulse forming line is to choose appropriate physical dimensions (mainly diameter and length) of inner and outer conductors since choice of these parameters decide [3-5] (i) driver impedance (ii) pulse duration of the compressed pulse (iii) electric field stress (across the inner and outer conductors) and lastly but not the least (iv) tuning of the secondary circuit. In the utilized water coax, the inner conductor diameter, outer conductor diameter and their common lengths are 250mm, 500mm and 1000mm respectively. These physical parameters

define pulse forming line characteristics as (i) impedance ~5Ω (ii) duration of compressed pulse ~60ns and (iii) capacitance (C_2) of the pulse forming line (PFL) as ~7nF.

In coaxial configuration, the electric field stress E_r at a radius r is given by the relation:

$$E_r = \frac{V/r}{\ln(b/a)} \qquad (5)$$

Here a and b are the diameters of the inner and outer conductors respectively, and V is the voltage between two conductors. For the maximum charging voltage of 600kV, the estimated electric field stress is ~70kV/cm close to the surface of inner conductor and ~35kV/cm near the surface of outer conductor. The resistance of the water line is estimated using expression:

$$R_w = \frac{\rho}{2\pi d}\ln\left(\frac{b}{a}\right) \qquad (6)$$

For the utilized de-ionised water resistivity ρ of 1MΩcm, the total resistance of the coaxial line corresponds to ~1.1kΩ. For maintaining resistivity >1MΩcm, water is continuously kept in closed loop circulation though a large capacity monobed deioniser (Cole-Parmer, model # WW-1503-05).

The high voltage holding switch adjoined to the PFL output, discharges the pulse forming line at peak charging voltage, into the field emission diode that generates intense relativistic electron beam (REB). The sparkgap is made up of brass electrodes and mounted on Acrylic flange having equidistant circular grooves along the radial surface to avoid breakdown. The clearance between the facing tips of the electrodes is kept as 5cm. The breakdown voltage is further adjusted by a controlling the Nitrogen filling gas pressure inside the chamber. The sparkgap is designed to operate in the self-breakdown mode and it can be adjusted to switch voltage in the range of 150kV – 600kV.

2.4. Field Emission Diode

Conversion of high voltage nanosecond pulses into electron beam requires the use of low impedance vacuum diode. The diode assembly consists of cold cathode and closely spaced from it is the anode. When a fast rising high voltage pulse is applied then due to field enhancement plasma is formed over cathode surface and emission of electron starts [6,7]. The most commonly used materials as cold cathode for 'field enhanced' electron emission are Aluminium, Graphite and Copper. The current density J emitted from the cathode is space charge limited and in the one dimensional case, obeys the Child-Langmuir Law given as [6]:

$$J = 2.33\times10^{-6}\left(\frac{V^{3/2}}{d^2}\right) Amp/m^2 \qquad (7)$$

Here, V is the accelerating voltage and d is the anode cathode gap spacing in MKS units. The effective gap spacing d tends to decrease with time as the cathode plasma expands towards the anode with velocity, typically of the order of 3cm/µs. This phenomenon is called 'plasma gap closure' and causes the current to grow with respect to time until the diode completely shorts. For planar diode consisting of cylindrical cathode of radius r_c and distance between the anode-cathode (AK) spacing d, impedance of the diode Z_d is given by relation [6-8]:

$$Z_d = 136\times\frac{(d/r_c)^2}{\sqrt{V}} \qquad (8)$$

Here, V is the voltage applied across field emission diode in MV. In our case, the diode consists of a planar graphite cathode (of 40mm diameter) and stainless steel anode mesh (of 240mm diameter). The

typical impedance of diode for cathode-anode spacing of 3mm, at 200kV is ~6.84 ohms. It may be noted that, impedance of the pulse forming line is ~5Ω and the actual voltage that appears across the diode depends on the division ratio of impedance of the pulse forming line and the dynamic impedance of diode.

3. Diagnostics and Experimental results

A capacitive voltage divider and self-integrating Rogowski coil have been used to measure the peak charging voltage of PFL and diode current pulse respectively. The most important parameter of the generator is output current. The bandwidth response of self-integrating Rogowski coil was initially confirmed by 60ns duration, 60A square pulse. It was found that the high frequency response was remarkably good while the calibrated factor was 0.01V/A. To investigate the performance of the integrated system, numbers of experiments were performed. The coupling between primary and secondary circuit and charging of the PFL was non-intrusively measured by an indigenously developed capacitive voltage divider installed at the HV feed point of waterline.
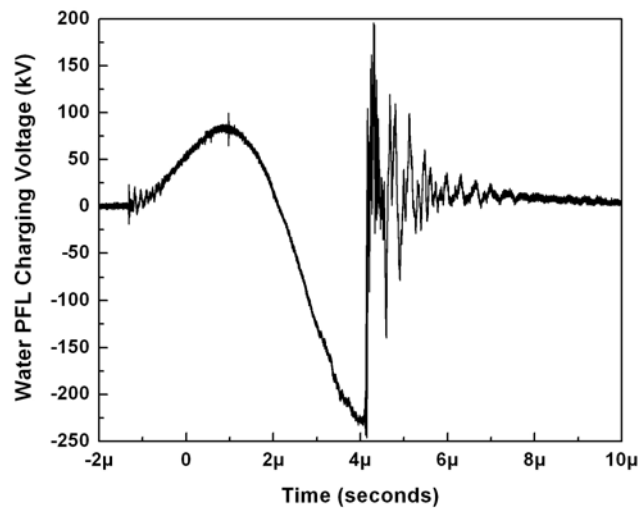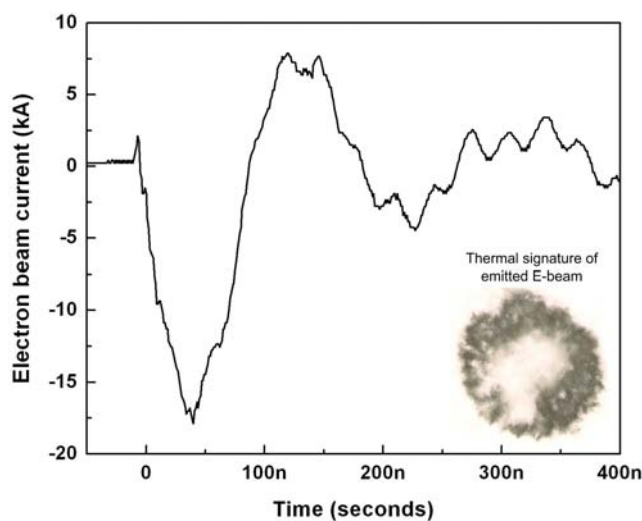

Fig. 6. Oscillogram of the PFL charging voltage.

Fig. 7. Field emission diode current waveform.

The typical oscilloscope trace of dual resonant Tesla output voltage charging the waterline, along with the firing of hold-off switch at the negative peak (at ~230kV), has been shown in Fig. 6. The N_2 gas

pressure and spacing between the switching electrodes of high voltage holding switch is so adjusted that the switch breaks down at the second peak of the pulsed high voltage that charges pulse forming line. The experimentally measured diode current at cathode-anode spacing of 3mm was ~17kA while the duration (FWHM) of the pulse was ~60ns. This value of diode current is in agreement with Child-Langmuir relation. The oscillogram of diode current waveform is shown in Fig. 7. The peak power of emitted electron beam was ~2.4GW. The background pressure in the diode as well as in the drift region was maintained $< 5 \times 10^{-4}$ Torr and no external magnetic field was applied. The signature/impression of emitted electron beam obtained on thermal paper (in a single shot) is also shown in the inset.

From the thermal impression of emitted electron beam it is inferred that in cathodes having flat profile, radial distribution of energy flux is mostly concentrated at the edge because of the high electric field and hence the beam is emitted in annular fashion.

4. Conclusion

A dual resonant Tesla transformer based pulsed electron beam accelerator 'AMBICA–600' has been fabricated and tested successfully. It is remarkable to note that in this system, the length of water based pulse forming line (ε_r ~80) is ~1/4 the length of conventionally used pulse forming line using oil dielectric (ε_r ~4.7), hence new accelerator is relatively much compact. In wide range of experiments electron beams of 100–200keV range with peak current up to 20kA lasting for 60ns have been obtained. The system is presently being used for conducting short pulse high power microwave (HPM) generation experiments using Virtual Cathode Oscillator device as load. Along with the utilization of this newly developed system for various applications, we also plan to study the effect of other candidate cathode materials and their geometries on extracted beam current. Some experiments with various anode mesh transparencies will also be preformed since the extent of transparency may affect the space charge cloud formation considerably.

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