Chapter 9

Component Testing of Linear Transformer Driver LTD-2 Module

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9.1. Introduction

LTD topology is an emerging pulse power technology which can be a replacement of the conventional pulsed power systems used for Flash X-ray (FXR) generation for hydro-dynamic radiographic application, Z-Pinch and inertial fusion energy drivers due to its compactness and modular design structure. An LTD module comprises multiple cavities connected in series for voltage addition and each cavity is made by multiple units called bricks connected in a circular fashion and all are in parallel for current addition. A single brick which decides the pulse width of the output consists of two energy storage capacitor charged in opposite polarity separated by a spark gap switch which can hold the twice the charging voltage and magnetic core that is common to all the bricks in the cavity. It is proposed to develop a 3 MV, 100 kA, 60 ns LTD module for flash radiographic application. The module is proposed to be developed in 3 stages: LTD-1, LTD-2 and 1 MV LTD module. LTD-1 is developed to understand the LTD concept and develop trigger source to synchronize the multiple spark gap switches. LTD-1 having single open air cavity and ten bricks with 34 kV output voltage, 31 kA output current, rise time (10%-90%) ~40 ns & FWHM ~110 ns at charging voltage of ±30 kV. LTD-2 module consists of 3 cavities in series and the total output from the module will be 300 kV voltage, 100 kA current and 60 ns pulse width across critically matched load of ~3 Ω. To achieve this voltage and current, the module's central shaft where voltage addition will be taken place will be in vacuum and the internal chamber of each cavity will be pressurized to 5 bar using dry-nitrogen for insulation purpose. This is a new concept in LTD for insulation using pressurized dry nitrogen as almost all the cavities developed are insulated with transformer oil. The mechanical challenges in the system developments are design of a pressure chamber of ~2 m diameter and also having pressure vacuum interface as the central portion of the module will be maintained at vacuum of ~10^{-5} mbar. Electrical challenges are testing of each components of the module before assembling them in a cavity manner and putting inside the pressure chamber.

9.2. LTD Equivalent Circuit and Working Principle

LTD cavity can be represented by a simple series R-L-C equivalent circuit as shown in Figure 9.1. It consists of a switch and capacitor that is initially charged to voltage V_0. The switch present in the figure is equivalent to all the brick switches which are connected in parallel in the cavity. Capacitor C is equal to the sum of the capacitance of all the bricks as they are connected in parallel. L is the equivalent inductance and equal to sum of inductance of the capacitors, switches and the connecting terminals of each bricks. R is the equivalent resistance which includes the internal resistance of the cavity and residual load resistance.

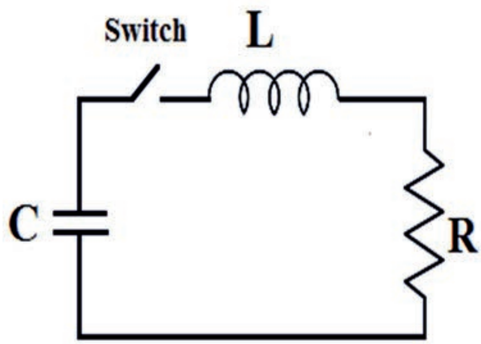

Figure 9.1. LTD equivalent circuit.

The circuit behavior of LTD can be represented by second order differential by the expression:

$$L\frac{d^2i}{dt^2} + R\frac{di}{dt} + \frac{1}{c}i = V_0 \tag{9.1}$$

Where, V_0 is the initially charged voltage. LTD works in two cases as per the voltage and energy requirement at output side [1]. One is the matched case where the load resistance R is equal to the characteristic impedance $\left(\sqrt{\frac{L}{C}}\right)$ of the circuit and other one is the critically matched case $\left(R = 2\sqrt{\frac{L}{C}}\right)$. The time required to reach peak current and voltage (t_{peak}), the value of the load voltage at this peak time (V_{peak})and energy transferred to the load up to this peak time ($E(t_{peak})$) for both the cases can be solved and given by the following expressions:

<u>Case: I</u>

For matched load condition $\left(R = 2\sqrt{\frac{L}{C}}\right)$,

$$t_{peak} = 1.21\sqrt{LC},\ V_{peak} = 0.546293V_0,$$

$$E(t_{peak}) = 0.4031279E_0 \quad (\text{where } E_0 = \frac{1}{2}CV_0^2)$$

<u>Case: II</u>

For critically matched load condition $\left(R = 2\sqrt{\frac{L}{C}}\right)$,

$$t_{peak} = \sqrt{LC},\ V_{peak} = 0.73576V_0,$$

$$E(t_{peak}) = 0.3233E_0 \qquad (\text{where } E_0 = \frac{1}{2}CV_0^2)$$

From the above expression, the rise time is shorter and the peak voltage is higher in case of critically matched load condition. For radiographic applications, where the X-ray output is proportional to higher than quadratic exponent of the electron beam voltage, the critically matched load condition operation is the best choice. Whereas for Z-pinch drivers, where efficient energy transfer to the load at peak time is the main criteria, matched load configuration is chosen in this case [1, 2].

9.3. Component Testing of LTD-2 Module

LTD-2 has been developed to understand the voltage addition with multiple cavities and effect of pressurized air on the breakdown strength of the cavity parameters. Main components of the module are capacitor, Sparkgap switch, magnetic core, charging resistor and trigger resistor. Capacitors and sparkgaps are tested in brick mode which represents a single brick of the module. Other components are tested individually. Numerically, LTD-2 module consists of 30 bricks, 60 capacitors, 30 sparkgap switches, 12 magnetic cores, 60 charging resistors and 30 trigger resistors.

9.3.1. Individual Capacitor Testing

12 nF, 100 kV DC capacitors having peak discharge current of 10 kA, working voltage reversal of 20% are used in each bricks of the LTD-2 module. Oil impregnated paper used as dielectric material in the capacitor and the physical dimension of the capacitor are 190 (L) × 130 (W) × 80 (H). All are in mm. Terminals are placed in the opposite end of height (H) × width (W) section. Capacitors are individually tested before testing them in brick manner. The following steps are followed in the testing of capacitors.

1. **Dimension check:** All the dimensions i.e. length, width and height are checked before and after of step-2 in order to confirm there is no change in dimension.
2. **Pressure Sustain test:** Pressure withstand test of each capacitor is being done at ~5 atm dry air for ~12 hours and checked for no oil leakage or bulging or breakage of the epoxy casting.
3. **Capacitance and Dissipation factor (tanδ) value measurement:** Equivalent circuit and dissipation factor of a capacitor is shown in Figure 9.2 and Figure 9.3. capacitance and **tanδ** values of each capacitors are measured by standard LCR meter at different frequencies (1 kHz, 10 kHz, 100 kHz and 1 MHz) to check the values are as per our requirement and there should not be any change in the values with frequency variation. The capacitance value found to be 12±0.5 nF and **tanδ** value ~0.01. Same thing is repeated after step-5 and step-6 to confirm no change in values due to high voltage stress.

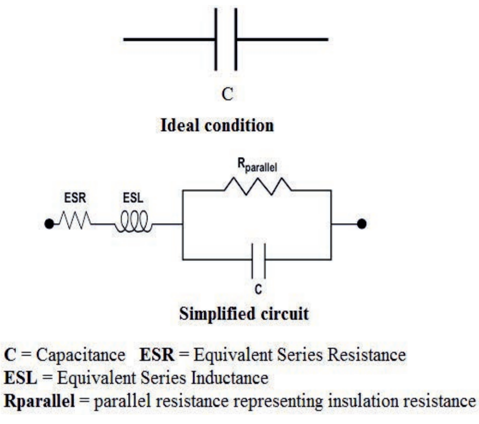

Figure 9.2. Equivalent circuit of capacitor.

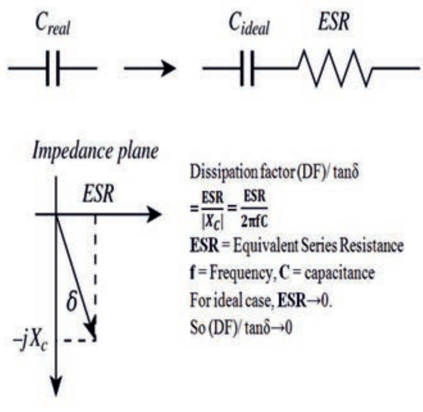

Figure 9.3. Dissipation factor.

4. **Inductance Value Measurement:** The inductance of each capacitor is calculated by short circuit the two terminal of the capacitor at lower charging voltage. Special care has been taken to make the circuit inductance as low as possible.

   Initially the capacitor (C) is charged to V_{max}. When the capacitor is shorted by a low inductance switch, voltage across the capacitor will drop from V_{max} and an oscillation will occur having time period of $T = 2\pi\sqrt{L_{total}C}$. Where, $L_{total} = L_c + L_{ckt}$. L_c is the capacitor inductance and L_{ckt} is the circuit inductance. L_c can be calculated from below formula,

$$\frac{V_{drop}}{V_{max}} = \frac{L_c}{L_{total}} \tag{9.2}$$

5. Inductance of the capacitor used in LTD-2 is calculated from the above method and having value of ~45 nH.

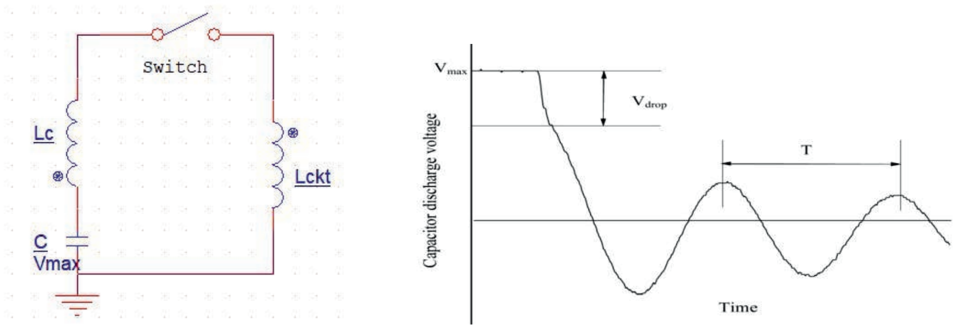

Figure 9.4. Circuit and waveform during short circuit.

6. **High voltage test:** Capacitors are charged stepwise (10 kV in each step) from 80 kV up to 100 kV and 1 minute voltage withstand is tested in each step.
7. **Rated current drawn from capacitor at rated charging voltage:** The capacitors are charged up to 85 kV in a single brick manner and discharged to a resistive load of 10 Ω through triggered spark gap switch and the current through the resistive load is measured ~10 kA. The load value is chosen such that the circuit will be critically matched and it is found maximum of 10% reversal at rated charging voltage as per our specifications.

9.3.2. Spark Gap Switch for LTD-2 Cavity

Non-uniform field distortion three electrode sparkgap switches have been used in LTD-2 cavity. Electrode profile of the switches is hemispherical and each switch has 24 mm gap length in between two main electrodes. Withstand voltage of the switch is tested at 200 kV DC voltage when applied between the two main electrode and at 5 atm pressure of nitrogen. LTD–2 module consists three cavities and each cavity have ten bricks. So in LTD module, there are total thirty numbers of spark-gap switches. Synchronization of these switches plays a vital role in output performance of LTD. In our case the sparkgap switches are to be triggered within a jitter of ~5 ns. For that a high voltage peak of more than 100 kV and high dV/dt of better than 5 kV/ns triggering unit is mandatory.

A seven stage Marx generator has been developed for that purpose. The Marx generator is designed in co-axial geometry. Each stage is consisting of 1.7 nF, 40 kV ceramic capacitors. 2x10 kΩ charging resistors have been used for each stage. The whole system is pressurized at 1.5-2 atmospheres. When charged to 26.5 kV DC, the measured output voltage at the end of a 3 meter co-axial cable whose other end is connected to the Marx generator is >100 kV. Because of the limitation of attenuation of the probe and maximum voltage to be measured in an oscilloscope, we could measure up to ~80 kV and the rise time till that point was ~11 ns giving a dv/dt of ~7 kV/ns. Jitter of <5 ns is measured when the spark gap switches of LTD-2 cavities are tested in brick mode and the capacitors are charged at ±85 kV DC. The switch is triggered externally by the developed Marx generator. Below figures show the Marx Generator and its output voltage.

Figure 9.5. 7-stage Marx generator.

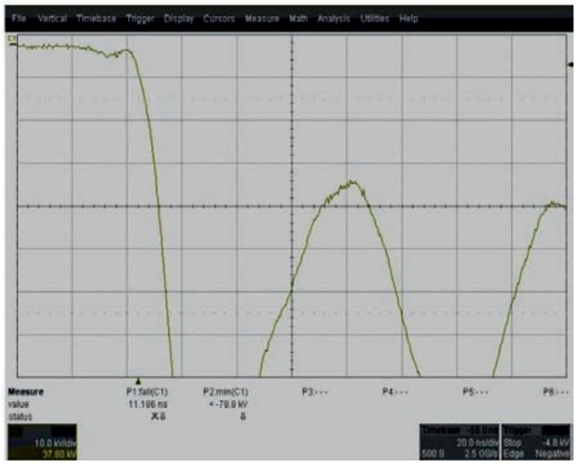

Figure 9.6. Output voltage.

9.3.3. Magnetic Core Testing

Four numbers of Fe-amorphous alloy magnetic cores (two cores in each polarity side) are used in each cavity of LTD-2 module. Individual core has physical dimension of 1070 mm Outer Diameter (OD), 970 mm Inner Diameter and 25 mm height. The cross-sectional area of each core is 10.63 cm^2 and mean magnetic path length of 320.4 cm. Magnetic core can be represented by an inductor (L_m) and resistor (R_c) connected in parallel. Both L_m and R_c will be in parallel to the load R in the LTD equivalent circuit as shown in Figure 9.1. L_m represents core magnetizing inductance and R_c represents core resistance. For slow pulses, the core behaves as a variable inductor and effect of L_m is considered. For fast pulse and single pulse application as in our case, core generates eddy current in the magnetic material. In this case, effect of core resistance R_c is considered and dominant over L_m. R_c should be much higher than the equivalent load resistor R (in Figure 9.1), so that maximum of energy stored in each bricks of the cavity will be transferred to the load.

Magnetic cores are characterized for their core resistance (R_c) in ohm and total change in magnetic flux density (B_s+B_r) in Tesla. To characterize the core, a test setup is made where a capacitor of capacitance 3 µF is charged to ~2 kV and discharged to ten turn winding that is wound over the core. The voltage and current across the winding measured. Before each shot the core is pre magnetized passively to its relative flux density B_r by a DC current of ~17 A for 5 seconds. So the flux density change in each shot will be B_s+B_r. The capacitor is initially charged to 2 kV by a DC power supply. On closing the switch, voltage pulse across the core winding rises sharply thereafter maintain constant value for some time period. After ~ 1 μsec, core voltage starts to fall as core begins to saturate. The current is initially proportional to voltage pulse. When core saturates i.e. when the voltage starts to fall, current increases almost linearly with time, this observation can be explained as under: when the voltage pulse is applied to the core, magnetizing inductance (L_m) provides high inductive path. The current drawn during this time duration compensates the core loss which can be represented by a resistive value (R_c) and hence current is almost proportional to voltage pulse up to the saturation. After ~1 μs, the core voltage falls and current increases almost linearly with time as magnetizing inductance of the core starts reducing and core enters into saturation region. The test setup and the output wave form are shown below.

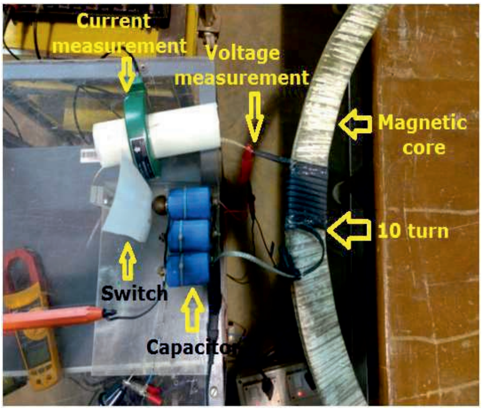

Figure 9.7. Test setup for core characterization.

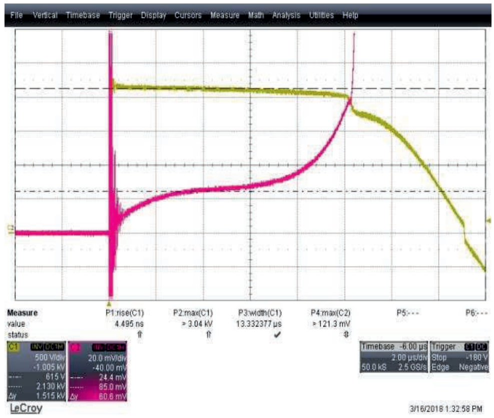

Figure 9.8. Output voltage and current waveform.

From the output waveform, the ratio between voltage and current in the flat portion for n = 10 turn winding is,

$$R_{10} = \frac{U(t)}{I(t)} \sim 100\ \Omega$$

Equivalent resistance of the core (R_c) for single winding is equal to

$$R_c = \frac{R_{10}}{n^2} \sim 1\ \Omega$$

From the B-H plot, it is found that total change in magnetic flux density B_s+B_r is ~2.5 Tesla. All cores are individually tested and found all have approximately identical magnetic properties.

9.3.4. Individual Brick Testing

Before assembling the capacitors and sparkgap switches in the cavities of LTD-2 module, they are tested individually in brick manner in a pressurized chamber which is similar to $1/10^{th}$ sector of LTD-2 single cavity. A single brick consists of two 12 nF capacitors whose one end is connected to two terminal of a non-uniform field distortion three electrode sparkgap switch having self-breakdown voltage of >200 kV DC and the other end is connected to two terminal of a matched resistive load (~10 Ω). The capacitors are separated by a 20 mm thick Fiber Reinforced Plastic (FRP) sheet. The complete setup is insulated by 5 atmosphere dry nitrogen pressure. The switch is separately insulated by another line of dry nitrogen of 5 atmosphere pressure. The switch is purged periodically after each shot. The brick assembly inside the pressurized chamber is shown below.

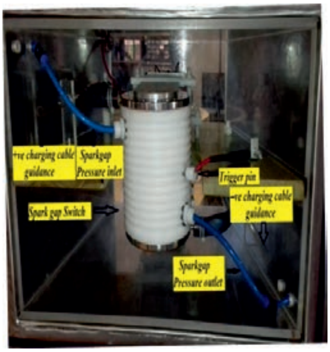

Figure 9.9. Single brick inside pressurization chamber.

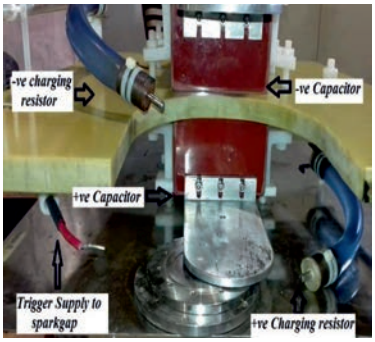

Figure 9.10. Brick assembly without spark gap.

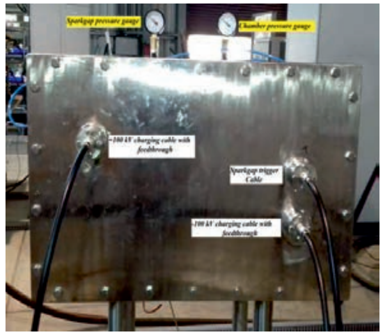

Figure 9.11. Front view of pressurization chamber.

9.3.5. Central Shaft Design of LTD-2 Module

As shown in the Figure 9.12, 1, 2, 3 represent cavity 1, 2 and 3 of LTD module respectively. 4 is the central shaft, 5 is the ring insulator that separate high voltage and ground, 6 is the load chamber and 7 is the pressure chamber where complete LTD-2 module will be kept. The minimum inner diameter of the vacuum chamber or the ID of the cavity is fixed to 774 mm considering all mechanical constraints. Since LTD-2 module has critical matched impedance of 3 Ω, the outer diameter of the central shaft can be calculated as

$$Z = 60\ln\left(\frac{R_1}{R_0}\right)$$

Z = 3 Ω, R_1 is the inner radius of each cavity which is equal to 387 mm. R_0 is the radius of the central shaft where the voltage build-up takes place.

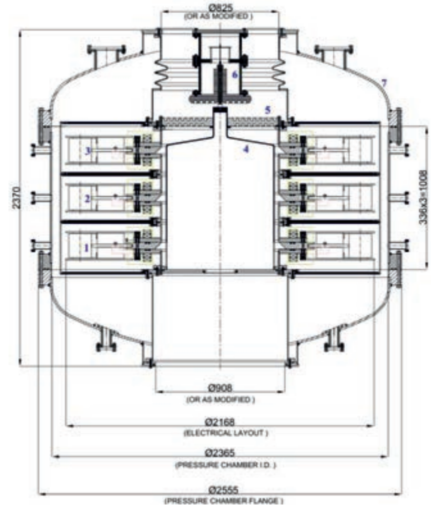

Figure 9.12. Pictorial representation of LTD-2 Module. All dimensions are in mm.

From the equation, R_0 = 368 mm. So the outer diameter of the central shaft will be 736 mm. Electric field between the annular space produced by central shaft and ID of cavity can be calculated at 300 kV output voltage as

$$E = \frac{V_0}{R_0 \ln(\frac{R1}{R0})} = \frac{300\ kV}{36.8\ cm \ln(\frac{387}{368})} = 163 \text{ kV/cm}$$

The value is less than the vacuum field emission i.e. 200 kV/cm. The central shaft is conically shaped and reduced the diameter from 736 mm to 100 mm at the load end to hold the load as shown in the above figure. A ring shaped placed in between the central shaft insulator and the pressure chamber. It acts as an insulator between high voltage terminal and ground. The insulator is made of acrylic and having corrugated surface having creepage length ~470 mm. Each corrugation is a half circle of radius 10 mm. Relativistic Electron Beam (REB) diode is connected at the end of the central shaft extension as shown in above figure for generation of flash x-ray. The diode configuration is rod pinch having angular graphite disc as cathode and Tungsten rod as anode that extends through the plane of the cathode. The bottom insulator of the diode have diameter ~400 mm and having creepage length 290 mm between anode and ground plane with corrugation as half circle of radius 10 mm.

9.4. Summary

All the components like capacitors, sparkgap switches, magnetic cores, charging and triggering resistors of the module are tested individually at their rated parameters. Capacitors and sparkgaps are tested in brick manner at charging voltage of ±85 kV. Output voltage of 92 kV and pulse width of 60 ns is measured at this charging voltage. Vacuum chamber is tested for vacuum compatibility and no leakage found. Pressure chamber is in procurement stage. Individual bricks are assembled in the 3 cavities along with magnetic cores, charging and triggering resistor. Three external trigger signals required to trigger all 30 bricks. Bricks of LTD -2 module are charged to ±30 kV in open air. After simultaneous triggering of all spark gaps (pressurized to 1bar N_2 pressure), output of 70 kV is generated across matched load (Figure 9.13 and Figure 9.14).

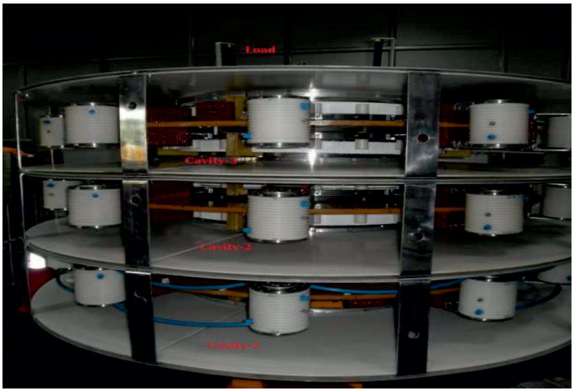

Figure 9.13. Front View of LTD-2 with 30 bricks (without pressure chamber).

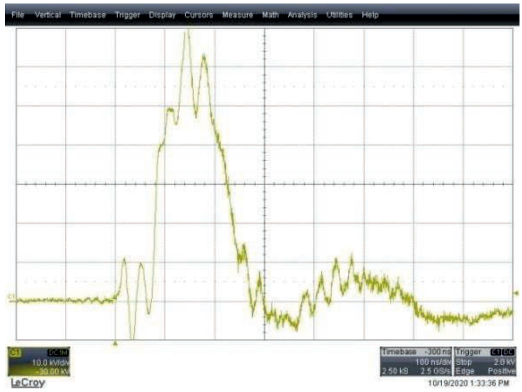

Figure 9.14. Output voltage vs. time of LTD-2 module. (Y-axis, 1 div. = 10 kV and X- axis, 1 div. = 100 nano-sec).

The lower output is due to delay in triggering of spark gaps which can be improved at higher charging voltage when the complete system kept inside pressure chamber [3]. Later the complete cavity will be placed inside the pressure chamber and will be tested at their rated capacity to get 300 kV voltage, 100 kA current and 60 ns pulse width across matched load.

References

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[3] Sukanta Kumar Mishra, Partha Banerjee, B Gowri Sankar, Samir Kumar Sahoo, Ramanand Raman, Archana Sharma, "Electrostatic parameter selection of Linear Transformer Driver (LTD) module" DAE-BRNS International symposium on Vacuum Science and Technology and its applications in accelerators (VSTAA), 2022.