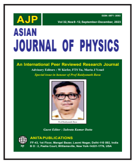

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Large volume plasma device-upgrade: A versatile plasma system for electron emitter, beam and wave based diagnostics

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Dedicated to Prof B N Basu

General classification of vacuum electronic devices are mostly based on their construction and operational principles, associated with generation of waves from low to ultrahigh frequencies comprising of amplifiers, oscillators, electron emitters, etc. The devices are further classified with regard to their operation by applying magnetic field or without magnetic field. Moreover, almost every plasma system requires a proper vacuum device with vacuum requirements typically between ~10^{-2} mbar to ~10^{-9} mbar. Such systems also require a primary electron source (emitter) to initiate the plasma either by field emission or by emission induced impact ionization. In this paper, we describe large volume plasma device-Upgrade (LVPD-U) as a system which produces plasmas with filamentary emission. The plasma is magnetized for electrons and un-magnetized for ions (AR^+) with the scale lengths for electron (r_e) and ion (r_i) Larmor radii and follows the order ($r_e << r_i$, L), L being the system size. The LVPD-U is fancied with several diagnostics viz. electrical and magnetic probes, microwave interferometry, in-vacuum gridded electron beam source, visible spectrometry, RF-based quadruple mass analyzers and thyrotron based exciter for high frequency wave excitation, etc. The system is further being equipped with high-power electron cyclotron resonators and LASER system. The paper highlights on LVPD-U as a large vacuum plasma device and its various diagnostics, coupled to facilitate plasma diagnosis.

Keywords: Vacuum, Plasma, Electron Gun, Microwave.

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1 Introduction

Laboratory based large volume plasma systems have several advantages over small systems in terms of introducing several advanced diagnostics at a time to diagnose the plasmas. Large dimensions provide ample choice to install variety of multiple plasma sources and *in-situ* and/or *ex-situ* diagnostics to examine the plasma. Further, it also facilitates studying small to large wavelength based waves and associated instabilities in the plasma in boundary-less conditions. In general, plasmas in basic devices can be probed with low-cost, easy to make fundamental electrostatic diagnostics like Langmuir probes [1-3], emissive probes [4,5], and magnetic diagnostics probes [6]. These diagnostics measure the plasma density (n_e), electron temperature (T_e), floating (V_f) and plasma (Vp) potentials and their fluctuations. Magnetic probe measurements provide information on magnetic fluctuations in the plasma. However, electrostatic probes despite being robust and capable of providing local measurements of plasma parameters are associated with large statistical error-bars. These statistical error- bars need special attention while interpreting results. In recent times, the plasma diagnostics have made significant advancement in terms of technology, affordability, miniaturization, system

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adaptability, control on parametric variability, detection of wave based modes, neutral ionization, plasma heating, scattering, plasma *in-situ* material heating, wave-excitation and detection of instability, etc. Some of the advanced diagnostics to be named are microwave [7] based plasma interferometry, reflectometry for density and density fluctuation measurements, electron beam [8] diagnostics for plasma heating, wave excitation study of beam broadening in plasmas, wave-number measurements, LASER [9] based diagnostics for wave detection experiments, *in-situ* – in-vacuum material heating for measuring potential and electric field and their fluctuations. Spectroscopy [10] for the understanding of the atomic processes associated with the plasma formation and recombination events, impurity detection and estimation of electron temperature from the line averaged wavelength (λ) – intensity (I) signal ratios. Apart from these, there is a vast number of diagnostics present today to diagnose plasmas not only for low temperature (~eV), moderately dense ($n_e \sim 10^8 - 10^{11}$ cm^{-3}) fundamental plasma systems but also for high temperature (keV), high density fusion plasmas ($n_e > 10^{13}$ccm^{-3}).

In this paper, we shall briefly discuss the results from some of the above mentioned diagnostics implemented in LVPD-U [11].

2 System Description

A. Large volume plasma device – Upgrade (LVPD-U)

The LVPD (Fig 1) is a 3m long, and 2m diameter cylindrical plasma system at IPR, Gandhinagar (India) and is among various large plasma devices working across globe dedicated to investigate plasma waves, instabilities and turbulence associated with beam electrons, profile gradients, and plasma parametric fluctuations. The plasma system is recently upgraded to LVPD-U with the addition of a large area multi-filamentary plasma source [11] comprising of 162 tungsten filaments covering a circular diameter of 1.8m.

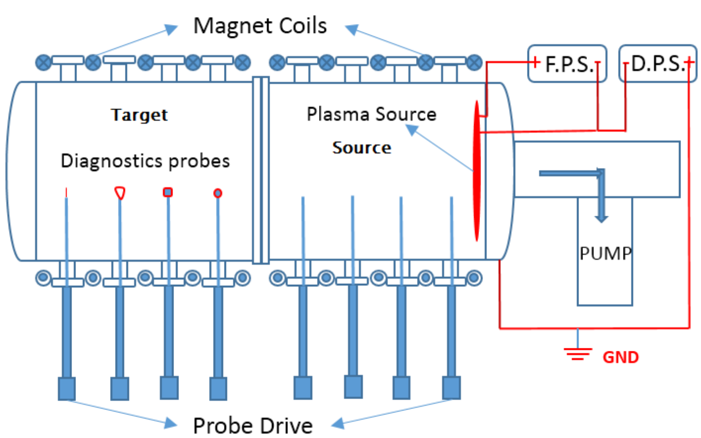

Fig 1. Schematic of LVPD system with the installation of electrostatic and magnetic probe diagnostics in the radial ports is shown.

Apart from these, the system is augmented with magnet power supply (300V, 150A), upgraded filament power supply (FPS) (10kA, 20V), solenoid power supply (2kA, 100V, 55ms) (SPS), discharge power supply (DPS) (1kA, 100V, 55ms), automated probe positioning system [12] and fast data acquisition system (PXIe). The plasma is produced in LVPD-U by electron impact ionization by emitted primary electrons from the heated filaments of LAMPS. The applied discharge potential accelerates the electrons confined in a uniform axial magnetic field ($B_z \sim 6.2$G) thus produces plasma of background Argon gas maintained at a fill pressure (P_{Ar}) of 4.0×10^{-4} mbar. The plasma is pulsed ($\Delta t_{plasma} \approx 55$ms) and produces a density $n_e \sim 3.0 \times 10^{11}$cm^{-3} at typical electron temperature of $T_e \sim 2$eV– 5eV with a standard deviation of 0.5% - 10%. A discharge current

(I_D) of ~ 0.8 – 1.0 kA is produced to sustain the plasma. A rectangular solenoid called as electron energy filter (EEF) is installed at the centre of the vacuum vessel to produce a transverse magnetic field, B_{EEF} which is perpendicular to B_z [13]. The plasma is diagnosed with electrostatic Langmuir probes (LP), centre tap emissive probes (CTEP) [5], magnetic- probes, and combinations of CTEP & LP as diagnostics mounted on automated probe positioning systems. Beside these, diagnostics like microwave interferometry technique, electron beam technique and spectroscopy methods are also used. The data is acquired using national instrument make PXIe 40 channel fast data acquisition system. The data is subjected to digital as well as analog filtering before analysis. MATLAB and FORTRAN routines are made and used for the analysis of the data.

B. Physics of interest in LVPD-U

The LVPD-U is dedicated for investigating plasmas relevant to ionospheric/ magnetospheric and fusion plasma by externally exited or naturally exited energetic electron driven whistler instabilities and electron temperature gradient (ETG) scale turbulence. The cause of the excitation of former is energetic electrons and reflected electrons from a loss-cone (magnetic mirror) distribution whereas later gets excited by gradient in electron temperature profile and is presently identified as a major source of heat flux transport across Scrape-off-layer (SOL) in fusion plasmas. The installation of EEF at the centre of LVPD created three distinct experimental regions (i.e. source, EEF and target) with different plasma characteristics. The EEF also sets up problems concerned to cross field ($\perp B_{EEF}$) plasma diffusion.

3 Diagnostics

In this section, a brief of diagnostics that are implemented in LVPD-U to diagnose the plasma is presented. They are Langmuir probes, emissive probes, coupled centre tap emissive and Langmuir probes (CCTELP), controlled electron beams, and microwave diagnostics and Thyratron based wave exciter diagnostics.

A. Langmuir Probe

Langmuir probes are wires of typical length ~ 5 –10 mm, and diameter 0.5 – 1.0 mm designed according to the prevailing plasma density in the system. The probes are biased to large negative potentials to collect the ion saturation current and by increasing the bias voltage gradually towards electron saturation regime, it passes through the potential where the net current to the probe is zero, i.e. $I_e + I_i \approx 0$. This potential is the floating potential (V_f) of the plasma. Further, enhancement of the bias potential reach to a point where no more electrons can be collected to the probe is called as the plasma potential (V_p). In Maxwellian plasmas, the plasma potential, and floating potential is correlated by the empirical relation, $V_p - V_f = 5.2T_e$ for Argon plasmas. The current is collected across a standard resistance (R = 300 Ω).

The plasma parameters are estimated following the work of Langmuir (Eq 1),

$$I_{i,sat} = 0.61 n_e A_p e\sqrt{\frac{T_e}{m_i}} \tag{1}$$

where, $I_{i,sat}$ is the ion saturation current, n_e is the plasma electron density, A_p is the probe surface area, e is the value of electronic charge, T_e is the electron temperature and m_i is the mass of Argon ion.

The AC component of the plasma parameters are obtained across an impedance (Z) of 1MΩ. Apart from this, double and triple probes are also used to obtain information on electron temperature and its fluctuations.

B. The centre tap emissive probe (CTEP)

The centre tap emissive probe (Fig 2) in LVPD [5] gives information of local floating potential when it is in cold state and when heated provides information on local plasma potential and its fluctuations. The principle of measurement is, the probe is heated enough in vacuum to emit thermionic electron emissions and tend to get float with respect to the plasma potential in space charge limited (SCL) region. Thus, floating potential of the hot probe is the measure of the plasma potential itself. The probe is basically a thin wire (Dia: ~ 0.1 mm) and it gets heated by a DC power supply to make it work at SCL region. The probe provides accurate measurements of plasma potential and fluctuations within the accuracies of T_e/e. The probe data can be analysed in (a) floating point mode, (b) point of separation mode by RAMP at different probe heating currents, and (c) by point of inflection method to efficiently measure the electron temperature. The coupled centre tapped emissive and Langmuir probe (CCTELP) on the other hand gives real time information on electron temperature and its fluctuations [14].

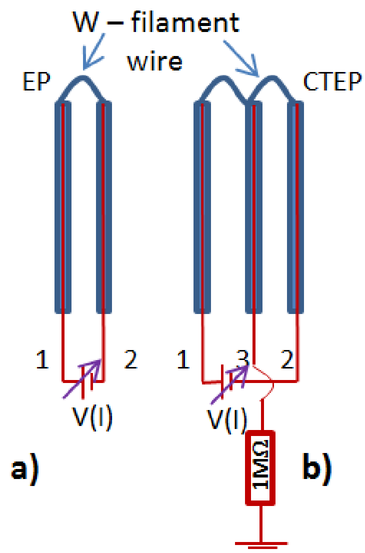

Fig 2. Schematic of emissive probes employed in LVPD is shown (a) general emissive probe (EP), and (b) centre tap emissive probe (CTEP) [5].

C. Pulsed electron beam source

A cathode ray tube (CRT) indirectly heated oxide coated cathode electron beam generator has been used as a source for energetic electrons beams (Fig 3) at fairly low voltage operation (0.1 – 1 kV). The tube grid assembly is suitably altered to introduce controlled, high frequency, high voltage pulses to the extractor grids to generate the beam and is controlled with a TTL (+5 V) circuit synchronised with the rest of the control circuit (Fig 4). The electron beam system was installed at the axial centre of the plasma volume and operated in presence of a background magnetic field and under the influence of an high discharge current (~ 200 A).

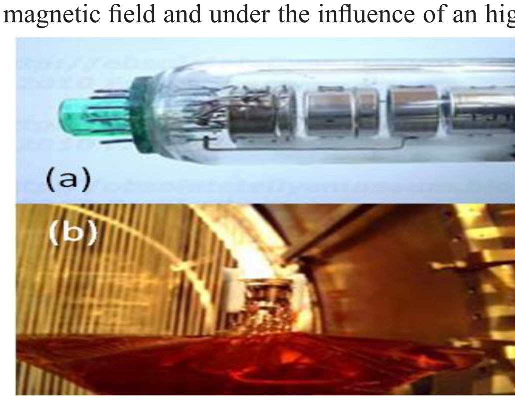

Fig 3. Electron beam source of (a) cathode ray tube (CRT) with (b) grid modifications for pulse biasing the beam extractor.

The pulsar circuit operated at 5kHz switching frequency with 50% duty cycle for 3 ms. This has enabled us in periodic emission of electron bunches upon triggering at different grid excitation potentials. The periodic fast pulsing facility enables us in clear detection and identification of electron beam through digital averaging. The beam current in the plasma is detected by a floating miniaturized Langmuir probe with periodic spatial (radial) scanning at an impedance of 50 Ω. Depending upon the radial location of the electron gun, the extracted electron bunch gets trapped in the axial magnetic field and tends to move along it and get intercepted at a distant location with information of beam spread and typical loss of beam current with plasma interactions.

The electron trajectory provides useful information on the plasma diffusion, transport and shape/configuration of the magnetic field lines. It is a difficult task to control the beaming electrons in presence of a background tungsten filamentary plasma source, however, precise electronics (IC-PA85A) with high signal to noise (S/N) ratio has resulted in beam detection. Detailed control circuit is not discussed here, however, a schematic of the operation is provided for understanding the operation of the coupled pulsar circuit and modified (grid) electron gun (Fig 4).

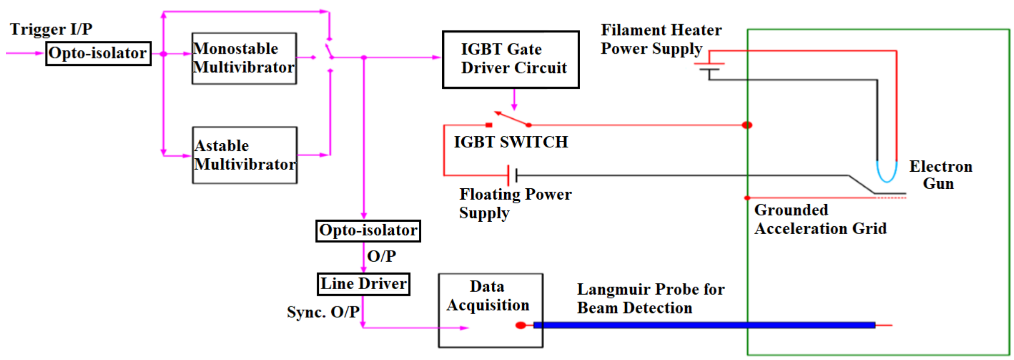

Fig 4. Schematic of the electron gun operation with the high frequency pulsar circuit along with a Langmuir probe.

Figure 5(a) shows the pulse diagram from the high frequency pulsar circuit, Fig 5(b) shows typical beam spread i.e. the beam width detection at an axial location 1.5 m away from the electron gun, and Fig 5(c) shows the beam current control at peak detection with a transverse magnetic field. These figures demonstrate successful operation of the pulsed electron gun in magnetized plasma.

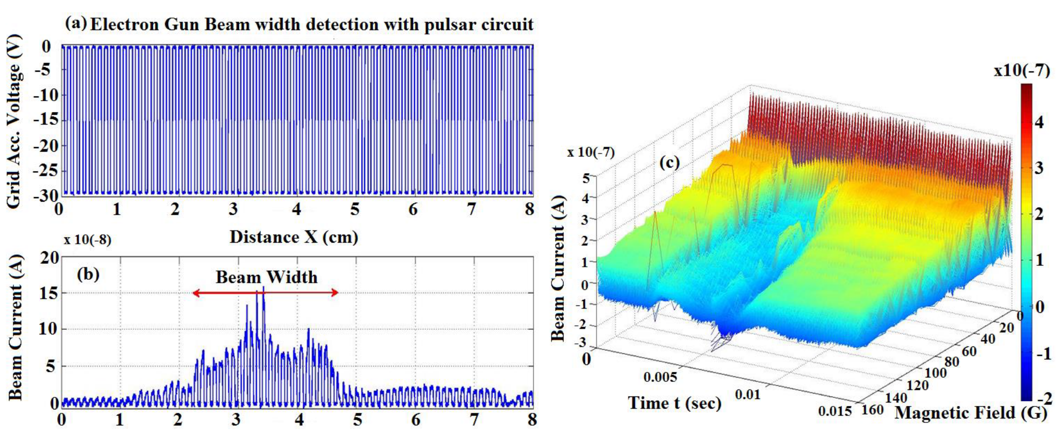

Fig 5. (a) Typical grid acceleration voltage pulse from the pulsar circuit, (b) beam width detection and (c) controlled beam current decay with application of transverse magnetic field.

D. Microwave (µ*-wave*) *interferometry*

We have already mentioned that installation and activation of EEF has produced three distinct plasma regions with different plasma characteristics depending upon the nature of plasma diffusion. In order to make ease of chord averaged density measurements in the diffusion region in a single plasma shot; the microwave diagnostics has been designed and implemented. The operational microwave frequency ($f_{MW} \propto \sqrt{n_e}$) range is considered for typical range of densities. It should be noted that plasma density in LVPD can be controlled either by controlling the filament emission current via ohmic heating or by diffusion through EEF magnetic field. For a confirmation check the data obtained by microwave interferometry is compared to that of Langmuir probe diagnostics.

A beam of microwave is launched by a horn antenna into the plasma through a vacuum window made of glass/Teflon. The condition that, it can propagate through the plasma is $f_{MW} > f_{pe}$, where f_{pe} is the electron plasma frequency, as $f_{pe} \propto n_e$. The interaction of microwave with plasma (while transmitting through it) introduces a phase shift (Θ) that is a function of density ($\Theta \propto n_e$). The phase shift increases with increase of plasma density. The phase shift measures the line integral plasma density. The change in phase shift can be estimated by following Eq (2),

$$\Theta \approx 0.5(k_0 - k_1)L \frac{\langle n_e \rangle}{n_c} \text{ rad} \tag{2}$$

where, k_0 and k_1 are propagation constant in air and plasma, respectively. The average plasma electron density is denoted as $\langle n_e \rangle$, the critical density for cutoff is given as n_c measured over a path length of L. The assumptions to the Eq (2) are as follows; i) the plasma density has a slow variation at the plasma boundary i.e. the microwave – plasma interaction boundary, ii) interference and wave reflection effects are neglected and iii) the plasma volume is considered as a slab geometry.

The experimental setup consists of a Gunn diode based microwave oscillator operating at 22 GHz. It produces an output of +20 dBm and draws +1.15 A at a constant DC voltage of +9V. Figure 6 shows a typical microwave interferometer system installed in LVPD-U for chord averaged density measurements. The microwave source is fed to the plasma with an isolated 10 dB coupler to the transmission horn antenna (TX) via a waveguide and the signal transmitted through the plasma is collected at a port placed radially opposite to the receiving horn antenna (RX).

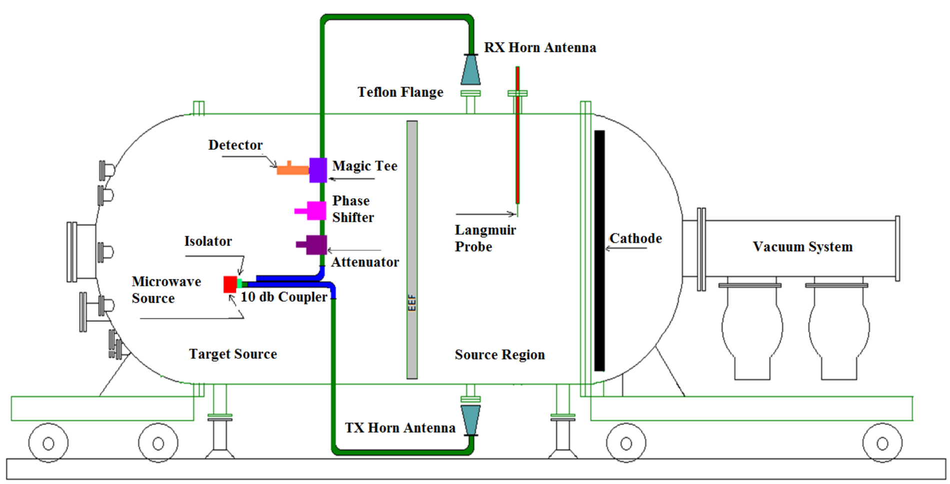

Fig 6. Schematic of microwave interferometry diagnostics in LVPD with k-band components for the measurement of plasma density.

A second signal, which is a reference signal, is transmitted with an attenuation followed by a phase shifter and compared in a magic 'T' finally fed to a detector. The phase change i.e. the fringe counting data is subtracted from the dummy phase shift that might be introduced due to multiple interferences from working electrical sources considered as system noise vacuum shot data.

Figure 7 shows the comparison between the (a) Langmuir probe ion saturation current ($I_{i,sat} \propto n_e$) signal taken at different filament heating currents ($I_F \propto n_e$) and (b) the phase shift in microwave interferometry signals at similar plasma conditions. It is clearly evident that the density change has resulted in the change in the phase shift observed in the plasma coupled microwave signals. Figure 8 shows a comparison between estimated plasma density with Langmuir probe diagnostics and measured plasma density with microwave interferometer phase shift signals for the same plasma shots; and a statistical error bar is shown in the data to mention shot to shot variation in density estimation in LVPD-U plasma. The results are fairly comparable with an exception that the Langmuir probe data might have been influenced by energetic electrons present in the plasma and this might be the reason for higher values of plasma density.

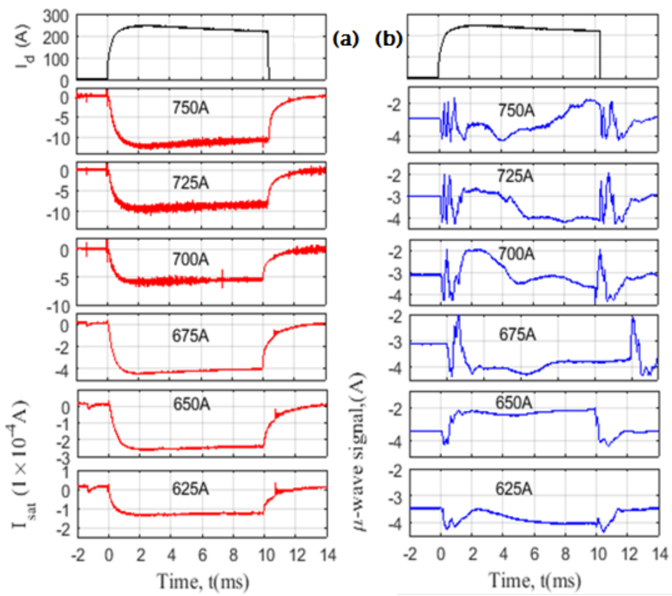

Fig 7. Measured ion saturation current (a) as compared with the microwave interferometry signals (b) for different filament heating currents.

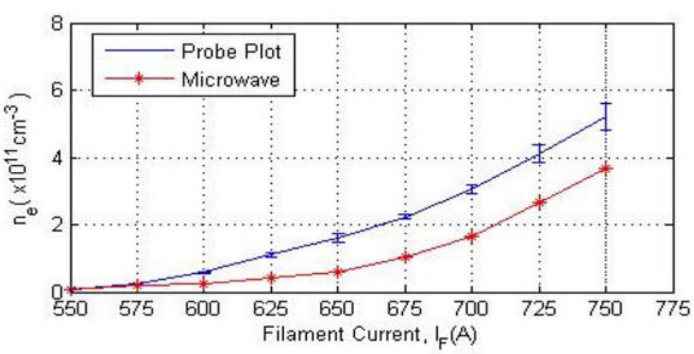

Fig 8. Comparison of electron density estimation with Langmuir probe measurements and microwave interferometry data at different filament heating currents.

E. Thyratron based exciter system

Whistlers are electromagnetic waves found in abundance in earth's magnetosphere bouncing to and fro between the magnetic poles. It is good diagnostic tool which provides information on magnetosphere plasma density and magnetic field conditions. This information is very important for ground based high frequency communication system (TX & RX) that uses plasma as a reflecting boundary for electromagnetic whistler waves ($F_{WH} \cong f_c\,(n_e)$). The wave can also propagate at oblique angles with respect to the background magnetic field ($k.B_z \cos\theta$) and are highly dispersive in nature, as expressed by (Eq 3),

$$F_{WH} = f_{ce} c^2 \frac{k.k_{II}}{f_{pe}^{\ 2}} \cos\theta \tag{3}$$

where, $f_{ce} = e\ B_z/m_e$ is the electron cyclotron frequency, k_{II} is the parallel wave number, $f_{pe} \propto \sqrt{n_e}$ is the electron plasma frequency and θ is the angle between the propagation wave vector (k) and the background magnetic field. From Eq (3), it is evident that the whistlers can be effectively used to probe plasma as a diagnostics wave.

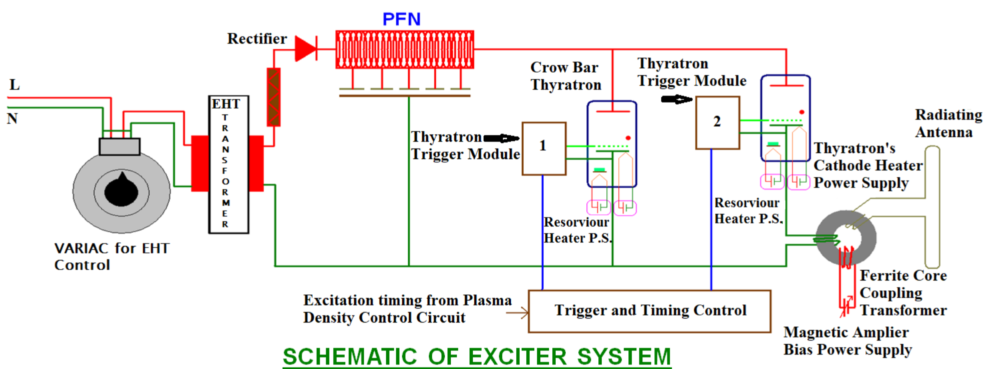

Fig 9. Schematic of Thyratron based electromagnetic wave excitation system.

To excite whistler waves using a loop antenna (~ 4 µH) in a quiescent plasmas having a typical $\delta B/B$ ~ 1–40 %, an exciter system is developed with a high voltage pulse power system. The system is based on discharging a 50 Ω pulse forming network (PFN) capable of storing up to 12 C of charge at 20 kV through a triggered Thyratron to a loop antenna. The PFN is made up of 12 sections of lumped 12.5 µH inductors and 5 nF capacitors. An inductor is formed with a dimension of length 55 cm and diameter 65 mm. High frequency capacitors (5 nF/30 kV) are tapped along the inductor and spaced after every 12.5 µH on the solenoid to make the PFN. Two hydrogen Thyratrons (FX2519A, E2V Technologies) are used as switch and crowbar to obtain the desired pulse width. Reservoir heater current control ensures reliable and uniform switching of PFN over a range of 500 V to 20 kV. The PFN output is coupled to a loop antenna through a ferrite core transformer. Impedance matching between the PFN and the load is done by biasing core of the transformer with a DC current. The optically isolated trigger to the exciter is generated with a trigger capacitor (1 µF/2 kV) discharged through a silicon controlled rectifier (SCR) (10RIA100) coupled to a high voltage pulse transformer. TTL IC (74LS121) is used for delay and pulse width control of the trigger circuit. The controlled pulse width produced between 500 ns to 4.5 µs with a pulse repetition frequency of 1 Hz, current amplitude of 10 – 200 A, with having rise and fall time of 100ns at 50 Ω with a maximum peak power of 2.0 MW. Figure 9 shows the Thyratron based exciter system for the excitation of electromagnetic waves. The developed pulse exciter has been tested on three types of antennas i.e. loop antenna, linear antenna and multi wire antenna. Figure 10 shows typical output pulses from the exciter system (a) without and (b) with the crowbar and fine-tuned PFN system.

4 Conclusion

In this paper, we briefly described the LVPD-U plasma system as an advanced vacuum electronic device capable of handling and incorporating various class of diagnostics to investigate plasma efficiently. However, its diagnostics implementation scope is not limited to this report. We broadly discussed plasma *in-situ* placed Langmuir probe, emissive probe, CCLTEP, high-frequency pulsed electron beam diagnostics, μ- wave based interferometer system and Thyratron based EM wave exciter system and described their successful operation for the measurement of plasma electron density in LVPD-U. The diagnostics up-gradations are still underway with implementation of 10.6μm, CO_2 LASER for potential measurements, multi-channel microwave interferometer system and a microwave reflectometry setup for density fluctuation measurements. An electron cyclotron resonance based (ECR) plasma source is being procured for plasma-plasma, wave-plasma interaction studies. A high power electron beam system for wave (scattering) studies and CMOS chip based high speed camera system for turbulence imaging and advanced plasma spectrometry in LVPD-U is planned. We have measured different plasma parameters in LVPD-U by making use of some of the above mentioned diagnostics. In the background of these, we propose LVPD-U plasma system as an efficient and versatile vacuum plasma system capable for accommodating the testing and implementation of various plasma diagnostics for their compatibility to advanced vacuum electronic devices (VED).

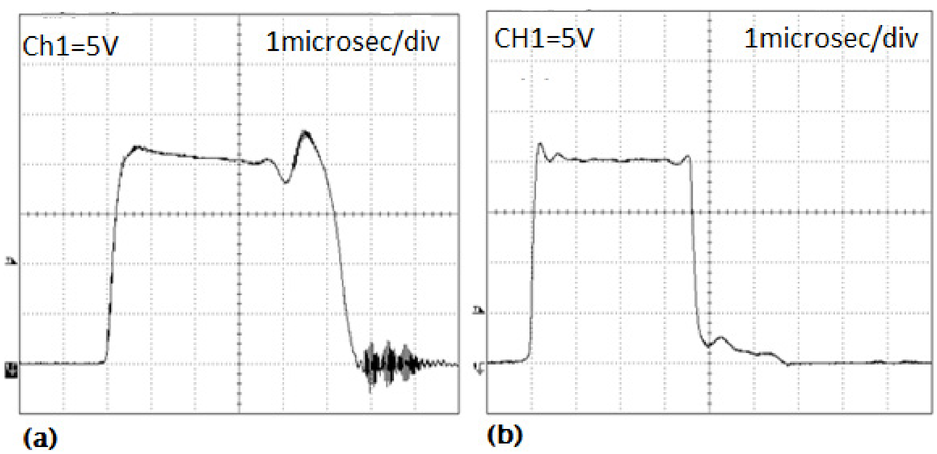

Fig 10. Output pulse of exciter system (a) without and (b) with the crowbar and fine-tuned PFN.

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