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Electron emission characterization of laser-induced gaseous plasma

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Laser induced hydrogen plasma has been investigated as a source of electrons. The energy, temperature and flux of the electrons have been determined by using two different temporal detectors; Faraday cup and Rogowski coil. The energy, temperature and flux were measured from the electrons extracted from laser induced hydrogen plasma. The Rogowski coil has been used for measurement of flux and current whereas Faraday cup has been used to determine the current density in laser induced plasma. The energy and temperature of the electrons are measured by the time of flight method in the range of 1.23 - 5.04 keV and 2516.26 eV, respectively. The flux of the electrons has been measured $\approx 10^{15}$ by Rogowski coil and the maximum current has been measured to be 39.6 kA. The current density has been measured by the Faraday cup ranges from 20 Am^{-2} to 23 Am^{-2}.

Keywords: Laser-induce plasma, Hydrogen plasma, Faraday cups, Rogowski coil

1 Introduction

Pulsed laser induced plasma is transient in nature and has a very short temporal existence but it is rich in characteristics. This dense and hot plasma is a source of electrons, ions, neutral particles and various radiations[1-3]. The generation of the electrons by the interaction of the high power pulsed laser heavily depends upon incident laser intensity, pulse duration, focal spot size, gas composition and gas pressure[4]. Due to high density, plasma can be used as a source of energetic electrons. The electrons are accelerated either by the interaction of the electrons with the laser directly called "Direct Laser Acceleration - DLA" or by the interaction of the electrons with the wake field of the high power lasers termed as "Laser Wake Field Acceleration- LWFA". The electric fields inside the plasma also accelerate the electrons[5,6]. Laser induced plasma emits radiations in different regions of the electromagnetic spectrum and this emission phenomenon is related to the plasma temperature and electron density in the plasma[7,8]. This emission is caused by the electron energy loss due to the attraction of the ions behind those electrons. The energetic electrons can be used in applications of physical sciences such as welding[6], lithography[9], processing[10] sterilize medical and food products[11], particle accelerators[12], low energy electron diffraction[13], reflection high energy electron diffraction[14], electron microscope[15], optical microscope[16], free electron laser[17], cathode ray tubes[18] and vacuum tubes[19]. Researchers have applied several diagnostic techniques to determine the number density, flux and energy of the bunch of the electrons inside the plasma which includes Langmuir probe[20], Thomson scattering[21,22], plasma spectroscopy[23] and laser interferometry[24,25]. The earliest technique to diagnose plasma was Langmuir probe[26], but its results are not reliable because it is to be immersed in the plasma plume, which disturbs the plasma.

Laser generated plasma has ability to emit electrons, ions, molecules, clusters and light which consists of discrete lines, bands, and an overlying continuum. Such discrete lines, which depict the material, have three main characteristics; intensity, wavelength, and shape. These parameters depend on both the structure of the emitting atoms and their environment. The wavelength of the line is always characteristics of atom (as each kind consist quantized energy levels) whereas the intensity and shape of the line strongly depend on the environment of the emitting atom. Both the natural broadening (due to Heisenberg's uncertainty principle) and the Doppler broadening (due to the thermal motion of the emitters) for not too high plasma densities govern the linear shape[27].

In high density plasma the energy levels of atoms are affected by charged species (ions and electrons) present in plasma and hence there is splitting and shifting of energy levels known as Stark effect. These perturbations broadened the intensity and shape profile and also dominate the linear shape. The broadening, intensity and shape even the radiation continuum can be useful to determine the plasma parameters like electron temperature, density and

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pressure. These parameters are very important to determine the physical state of plasma[27].

The band emission always depends on both temperature and density of the plasma and are too high in the initial stages of plasma, especially in the ignition. For this reason, some delay is provided to acquisition window to avoid the continuum. For a nanosecond laser the atomic emission occurs after a microsecond whereas molecular emissions occur later from recombination in plasma. These results strongly indicate that the nature and pressure of the ambient atmosphere is one of the controlling factors of the plasma characteristics.

Recent progress in this field has generated significant interest due to the observation of quasi mono-energetic features in the electron energy spectrum produced due to wave breaking in a laser wakefield accelerator. However the control and stability of these electron beams remains a serious concern. All groups report a degree of shot to-shot variation in the measured electron beam parameters including beam charge, beam energy and beam energy spread, that is unacceptable for use in most applications. Most of the fluctuation can be attributed to variations in the laser parameters, including focal spot intensity distribution, pointing, pulse energy and pulse duration[28].

The most important parameters that influence laser ablation properties include laser wavelength, pulse width, spot size, and laser intensity. Apart from laser properties, the target material as well as background gas nature and pressure also affect plasma plume kinetics[28]. To our knowledge, there have been no published works on quantifying the effect of ambient pressures on the laser plasma electron characterization such as for nanosecond 1064 nm radiation.

In this paper, we explored the kinetics of electron emission generated from Hydrogen plasma created using Nd: YAG laser operated at the wavelength of 1064 nm under ambient pressure 150 Torr. Two detectors (Rogowski coil and Faraday cup) are used which give the temporal behavior of the electron characteristics in the plasma. A Faraday cup was used as an ion collector for determining the ion flux as well as kinetic energy distributions. Moreover, Time of Flight method is employed to determine the electron energy.

2 Experimental Setup

A pulsed Nd: YAG laser (λ=1064 nm, τ = 9 ns, E=10 mJ) of intensity ~10^{12} W/cm^2 was employed to produce hydrogen plasma. Laser beam was focused through *IR* lens with 10 cm focal length. The schematic of experimental setup is shown in the Fig. 1(a). Two

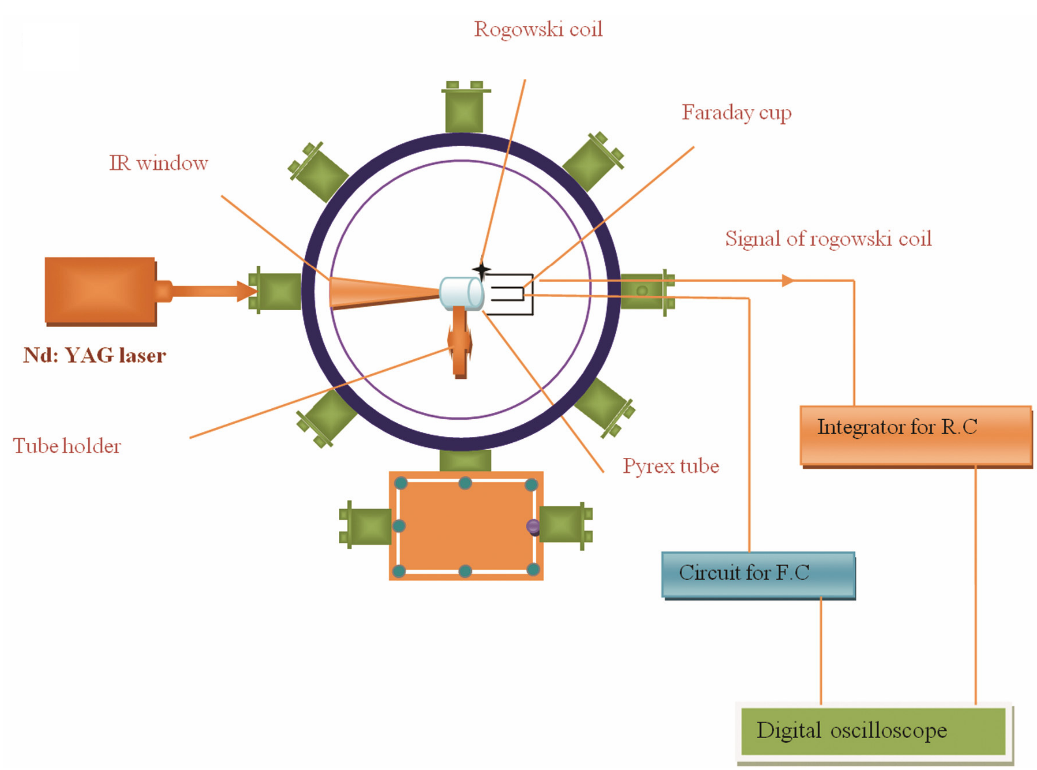

Fig. 1 – (a) Schematic of the experimental setup to measure electron flux using Faraday cup and Rogowski coil

different circuits are used to record the signal for both detectors. The circuit shown in Fig. 1(b) is used for Faraday cup. A positive biasing voltage of 100 V is applied to the inner cup through a resistor of 1 MΩ using a dc power supply to collect the electrons. The biasing voltage is maintained using a capacitor of 0.1 μF. The capacitance of the capacitor is chosen such that the discharge time constant of the capacitor should not be smaller than the time scale of the plasma electrons. Electrons collected by the cup causes neutralization in the positive plate which changes the capacitor voltage and consequently change in the circuit current.

The outer cup is connected with the negative terminal of the battery which is grounded. This cup provides shielding to the inner cup. A 500 MHz digital storage oscilloscope, Yokogawa 7510 is used to record these changes caused by the plasma electrons across the 50 Ω resistor. Coaxial

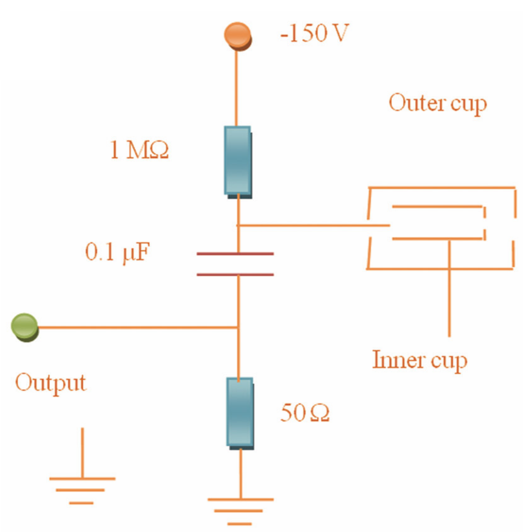

Fig. 1 – (b) Circuit diagram for Faraday cup

cables are used to make electrical connections from the vacuum chamber to the external circuit and from the external circuit to the digital oscilloscope. Resistance of each coaxial cable is 50 Ω that is why output is taken across the 50 Ω resistor to transfer maximum power. External circuit is also shielded from the stray electromagnetic fields using a black sheet of polyethylene. Vacuum chamber and DC power supply are also grounded so that any stray voltage may not affect the output signal of the detectors. Output voltage of the cup is taken across the resistor of 50 Ω as $V_{out} = IR$.

The circuit shown in Fig. 1(c) is used to record the signals of Rogowski coil. It is a simple *RC* integrator of time constant ~ 0.1 m·s. Again time constant is compared with the electron frequency. Coil is connected with the integrator through a resistor of 50 Ω to avoid the short circuiting. The *RC* signals are taken on 500 MHz digital storage oscilloscope, Yokogawa 7510.

After these suitable arrangements chamber is air tightened, evacuated using rotary pump and filled with Hydrogen gas at 150 Torr pressure.

Energy of the electrons is determined employing time of flight method using two Faraday cups. The schematic of which is shown in Fig. 2. These cups are arranged in the vacuum chamber in the following way; plano convex lens focuses the laser beam at the distance of 10 cm in the vacuum chamber. Choosing the laser axis as reference axis, first cup is fixed at a distance of 3 cm from the focusing point at an angle of ~ 15° at right from the laser axis. Second cup is fixed at 8.5 cm distance from the first cup along the laser axis. This distance is measured from the collimator of the first cup to the collimator of the second cup. Second cup is

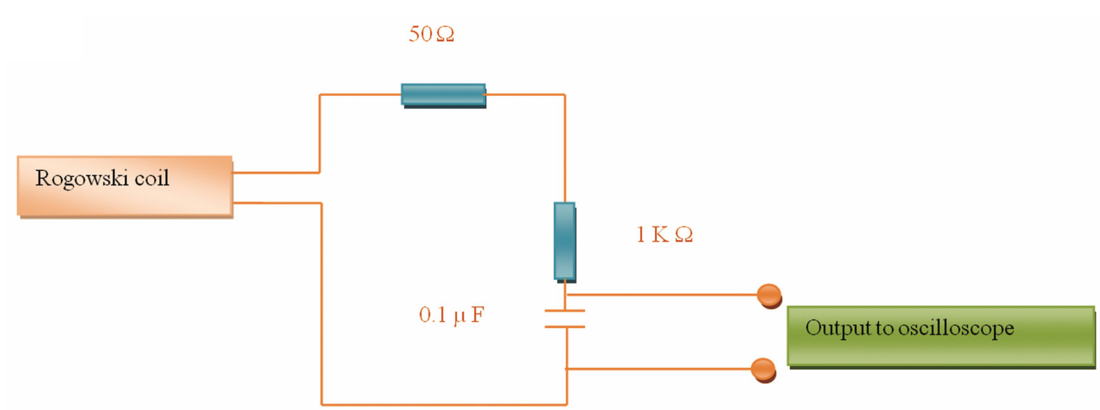

Fig. 1 –(c) Circuitry for Rogowski coil

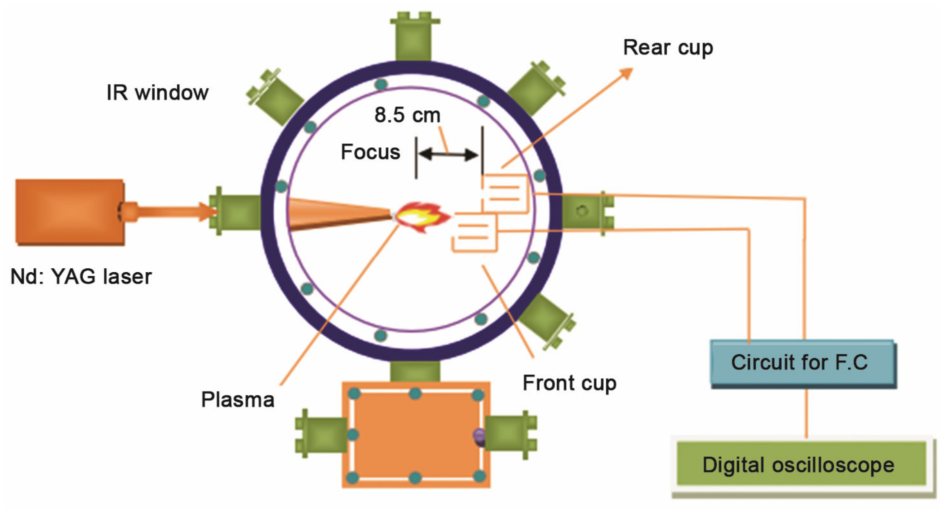

Fig. 2 – Schematic of the experimental setup for TOF arrangement to measure the energy of the electrons from Laser induced Hydrogen Plasma

placed at an angle of 15° left of the laser axis. This angle arrangement between two cups is precisely adjusted so as the rear cup may collect the electron flux. Two channels of digital oscilloscope are used to record the signals of the cups. Time difference between the peaks of the two signals will depict the time taken by the electrons to cover the distance between two cups. From this time difference we are able to measure the velocity and hence kinetic energy of the electrons. After these arrangements, chamber is fixed, evacuated and filled with Hydrogen gas at 150 Torr.

3 Results and Discussion

The aim of the experiment is to characterize the emission of electrons from laser induced hydrogen plasma. Characterization of the electrons involves the beam current, particle flux, energy and temperature. Beam current is measured by both Rogowski coil and Faraday Cup while energy is measured by Faraday Cups employing Time of Flight method.

3.1 Electron flux and current

Electron flux and beam current are determined from the following signal profiles. Each signal profile is recorded at a single laser shot. Current from the Faraday cup is determined from the following relation;

$$V = IR \qquad \ldots (1)$$

where V is output peak voltage and R is output resistance (50 Ω).

The current from Rogowski Coil is determined from the formula;

$$I = \left(\frac{RC}{\mu_0 nA}\right) V_0 \qquad \ldots (2)$$

where V_0 is output peak voltage, RC is time constant of the integrator (0.1 m·s), A is area of each turn and n is number of the turns per unit length.

The number of the electrons can be found easily from the above currents. If N represents the number of the electrons then:

$$N = It/e \qquad \ldots (3)$$

Where the value of e is 1.6×10^{-19} C and t is the time for the maximum output voltage.

These signal profiles obtained from Faraday cup and Rogowski coil. In both the signals, voltage increases with time up to a peak value then it decreases with increasing time. The signal of Faraday cup shows a small dip before it approaches the peak value. This dip indicates the decrease in the electron flux due to the absorption of the electrons by the positive charge or the neutral atoms in the plasma. The maximum value of the signal voltage is 90 mV. This output voltage gives 1.8 mA current, 3.3×10^{8} electrons and 2.6×10^{4} electron flux. Signal (b) in the Fig. 3 is the signal of the Rogowski coil. The output voltage obtained from the signal is

110 mV which gives 36.3 kA current, 5.4×10^{15} electrons and 3.3×10^{12} electron flux.

Output voltage remains constant for 5 ns and then increases steadily up to the peak value of 90 mV. No any dip is observed in this signal. The maximum current obtained in this signal is 1.8 mA which gives 3.9×10^{8} electrons and 3×10^{4} electron flux. An increase in the electron flux is due to the fact that in this shot plasma remains for longer time. Figure 4(b) shows the signal obtained from the Rogowski Coil. A dip is observed in this signal before the signal rises due to the loss of the electrons. Because gas molecules move about in the Pyrex tube, the incoming energetic electrons make ionizing collisions with the gas molecules and lose their energy. Now the produced positive ion moving along the electrons is the responsible for the dip. Output voltage at the peak value remains constant for 5 ns and then it decreases. The peak voltage obtained is 115 mV which gives 37.9 kA current, 7.1×10^{15} electrons and 4.3×10^{12} electron flux.

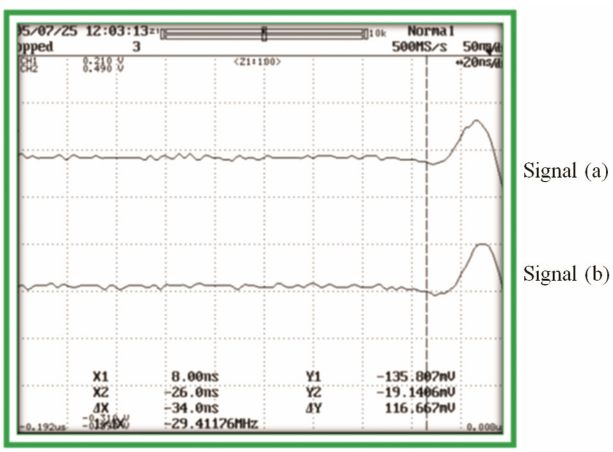

Fig. 3 – Signal profile obtained from (a) Faraday cup (2.6×10^{4} electron flux) and (b) Rogowski coil (3.3×10^{12} electron flux)

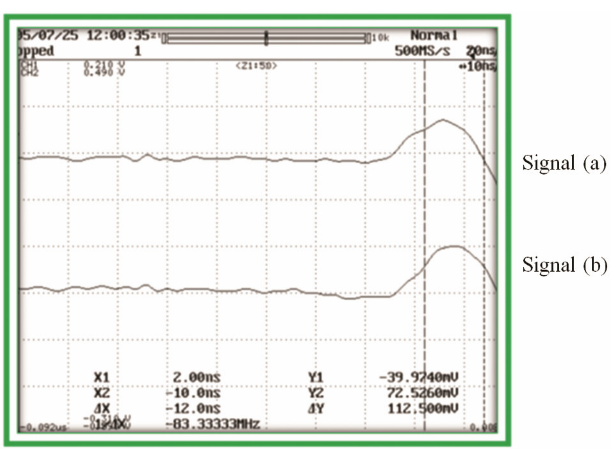

Fig. 4 – Signal profile of (a) Faraday cup (3×10^{4} electron flux) and (b) Rogowski coil signal (4.3×10^{12} electron flux)

Output signal of the Faraday Cup, Fig. 5(a) shows a dip very near the peak value and there is a sudden rise in the voltage after the dip. This dip is appeared in the signal of the cup due to the absorption of the electrons by the atoms or the positive charges inside the plasma. This positive charge decreases the flux. The output voltage obtained from the cup is 90 mV which gives 1.8 mA current, 3.9×10^{8} electrons and electron flux of 3×10^{4} electrons m^{-2}. Signal (b) is obtained from the Rogowski coil. The output voltage remains constant at its peak value for nearly 5 ns. This indicates that the uniform increase in the current which induces the constant emf across the ends of the coil. The maximum output voltage obtained from the coil is 100 m V which gives 33 kA current, 7.2×10^{15} electrons and electron flux of 4.4×10^{12} electrons m^{-2}.

The signal of the Faraday cup in Fig. 6(a) gives constant peak value for about 15 ns. This shows that for about 15 ns the number of the electrons arriving at

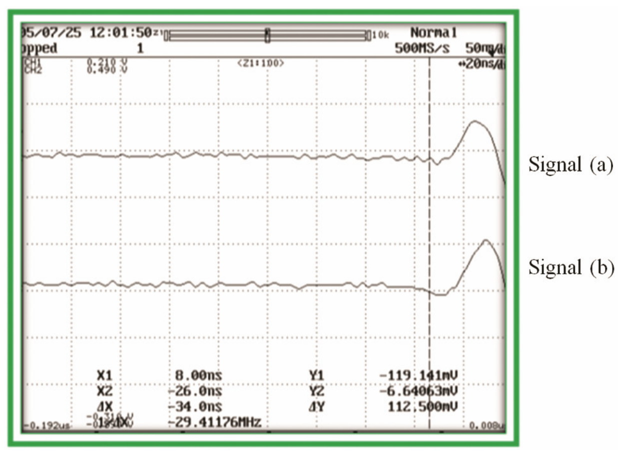

Fig. 5 – Signal profile of (a) Faraday cup (3×10^{4} electrons flux) and (b) Rogowski coil (4.4×10^{12} electrons flux)

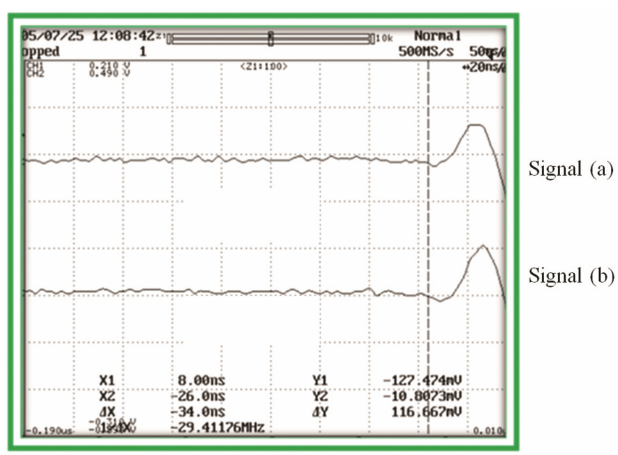

Fig. 6 – Signal profile of (a) Faraday cup (2.4×10^{4} electron flux) and (b) Rogowski coil (6×10^{12} electron flux)

the deep cup is constant. The output voltage obtained is 80 m V which gives 1.6 mA current, 3.1×10^8 electrons and 2.4×10^4 electron flux. The signal of the Rogowski coil gives the maximum output voltage of 120 mV with maximum current of 39.6 kA. This increase in the voltage of the coil is due to the contaminations and the effects of the pre-ionization which reduces the breakdown threshold of the gas. With the decrease in the breakdown threshold of the gas, plasma gains more energy from the laser and growth of the electrons is increased effectively. It gives the 9.9×10^{15} electrons and 6×10^{12} electron flux.

In Fig. 7 the signal of Faraday cup rises positively and reaches at its peak position which shows the equal increase in the number of electrons with the time interval. At the peak value the number of the electrons remains constant for the 5 ns that is why the voltage also remains constant in this interval of time. The maximum output voltage is 80 mV which gives 1.6 mA current, 2.5×10^8 electrons and 1.95×10^4 electron flux. The signal of the coil has a dip before it rises to the peak value. The maximum output voltage obtained is 105 mV which gives 34.6 kA current, 8.6×10^{15} electrons and 5.3×10^{12} electron flux.

The signal obtained from the Faraday cup is shown in the Fig. 8 as signal (a). Output voltage rises steadily and reaches to its maximum value of 90 mV. This peak value remains constant for about 15 ns. The number of the electrons arriving at the collecting cup is constant for the 15 ns and then it decreases with the increase in the time. The maximum current obtained is 1.8 mA, electron number is 3.3×10^8 and electron flux is 2.6×10^4 electrons. The signal of the Rogowski coil is linear to the applied conditions. It gives the maximum value of the output voltage as 100 mV which gives current of 33 kA, electron number of 8.25×10^{15} and electron flux of 5.07×10^{12} electrons. All the results deduced from the experimental observations are listed in the Table 1. The flux and current measured by the Rogowski coil in each signal is greater than the Faraday cup because of its larger cross-sectional area which allows the maximum possible electrons to pass through the coil. Rogowski

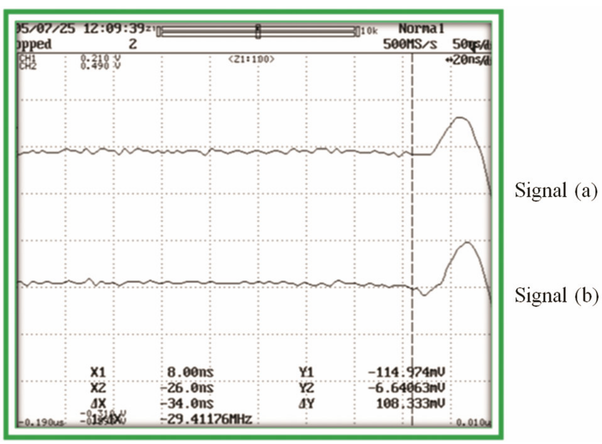

Fig. 7 – Signal profile of (a) Faraday cup (1.95×10^4 electron flux) and (b) Rogowski coil (5.3×10^{12} electron flux)

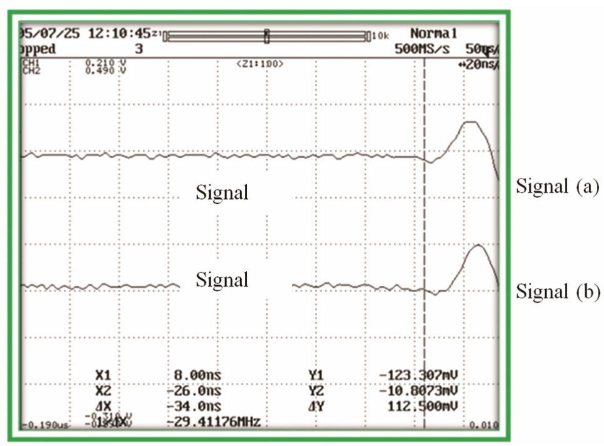

Fig. 8 – Signal profile of (a) Faraday cup (2.6×10^4 electrons flux) and (b) Rogowski coil (5.07×10^{12} electrons flux)

Table 1 – Calculated values of electron flux and electron beam current

Parameters	Peak voltage V_p (mV)	Time factor for peak voltage t (ns)	Current I (A)	No. of electrons N	Particle flux electrons
F.C.	90	30	1.8 m	3.3×10^8	2.6×10^4
R.C.	110	24	36.3 k	5.4×10^{15}	3.3×10^{12}
F.C.	90	35	1.8 m	3.9×10^8	3×10^4
R.C.	115	30	37.9 k	7.1×10^{15}	4.3×10^{12}
F.C	90	35	1.8 m	3.9×10^8	3×10^4
R.C.	100	35	33 k	7.2×10^{15}	4.4×10^{12}
F.C.	80	31	1.6 m	3.1×10^8	2.4×10^4
R.C.	120	40	39.6 k	9.9×10^{15}	6×10^{12}
F.C.	80	25	1.6 m	2.5×10^8	1.95×10^4
R.C.	105	40	34.6 k	8.6×10^{15}	5.3×10^{12}
F.C	90	30	1.8 m	3.3×10^8	2.6×10^4
R.C.	100	40	33 k	8.25×10^{15}	5.07×10^{12}

coil offers the cross-sectional area of 6.15 cm^2 to the electrons while Faraday cup offers only 0.78 cm^2. This large difference between the entering areas makes the value of flux and current measured by the cup smaller than the coil. However cup is placed ~ 2 cm behind the coil position and electrons reaching at the opening face of the cup starts avalanche due to the electrostatic field of the cup. Although there is a probability of the losses due to diffusion and attachment but these losses are made negligible due to the field of the cylindrical cup which attracts, collimates and accelerate the electrons. These accelerated electrons ionize the hydrogen atoms in their paths and develop a cascade growth. In this way the expected very large difference between the flux and current of the two detectors becomes smaller but even it is of considerable amount. In most of the signals of Rogowski coil, a dip is observed before the signal rises. This is due to the presence of hydrogen atoms inside the hollow Pyrex tube. These atoms cause loss of electrons by attachment or ionizing collisions. Ionizing collisions produce hydrogen ions which also move in the forward direction causing a dip before the signal rise. Also some positive hydrogen ions are accelerated by the laser itself along the laser propagation and in this way these ions cause a loss of electrons. The current measured by the coil is in kA while the current measured by cup is only in mA. It is due to the same reason that coil offer larger area and maximum possible number of electrons can pass through the coil while cup offers very small area. Faraday cup can effectively measure the current density. The values of current density are tabulated against each output voltage in Table 2. Though Faraday cup is incapable to measure the beam current but it is efficient in determining the current density.

Table 2 – Current densities measured by Faraday cup

Number of observation	Output voltage (mV)	Current density ($J = I/A$) (A/m^2)
1	90	23
2	90	23
3	90	23
4	80	20
5	80	20
6	90	23

3.2 Energy of the electron

Energy of the electrons is determined by the time of flight method using two Faraday cups. The arrangement of which is shown in the Fig. 9. Three measurements are made in this experiment at different biasing voltage of the Faraday cups. Kinetic energy is determined by determining the velocity of the electrons. Velocity of the electrons is determined as:

$V = d/t$

Time is taken from the time difference of the two peaks in each signal profile. This time difference is actually the time taken by the electrons to cover the distance between two cups. And kinetic energy is given as:

$K.E. = (1/2)\, mv^2$

This is the energy calculated as we have applied the positive voltage to the cups which accelerate and collect the electrons. To get the energy of the electrons, the energy acquired by the electrons under the biasing voltage of the cups is to be subtracted. This energy is the energy of group of electrons and is treated as the average energy of the electrons.

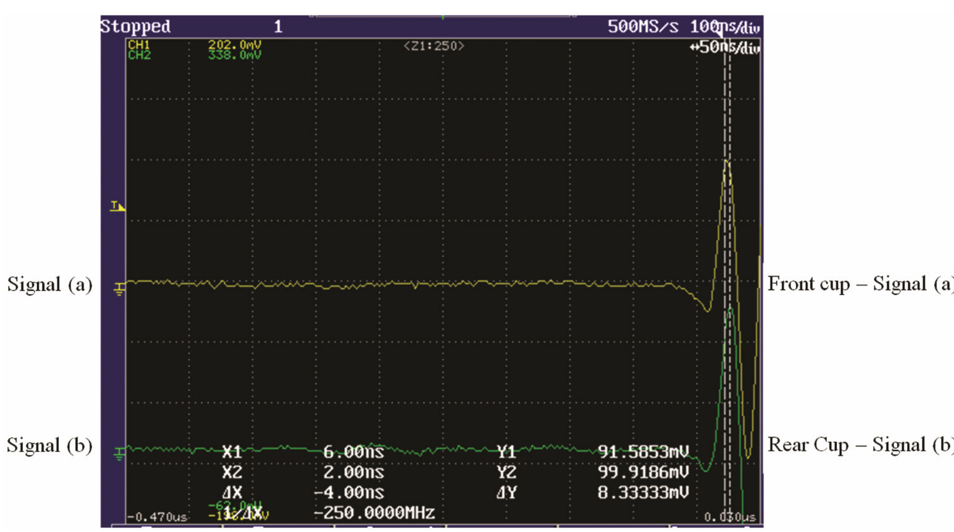

Fig. 9 – Signal profile of Faraday cups obtained at 50 V

Temperature of the electrons can also be calculated using the following relation:

$$\langle E \rangle = (3/2)kT$$

where $\langle E \rangle$ is average kinetic energy of the electrons, k is Boltzmann's constant and T is temperature of the plasma electrons in Kelvins.

The conversion factor of the temperature and electron volt is given as:

$$1 \text{ eV} = 11600 \text{ K}$$

The above formulation is applicable for the Maxwellian distribution only. The experimental signals obtained are discussed as follows;

The signals are obtained at the biasing voltage of 50 V. The time difference measured is 4 nsec while the distance between two cups is 8.5 cm. From these two values the velocity of the electrons is measured as 21.25×10^{6} ms^{-1} and kinetic energy of the electrons is determined as 1.23 keV. Temperature of the electrons measured is 1.43×10^{7} K. The electrons are accelerated by the laser itself and also by the plasma waves. Figure 10 shows the signal profile of two cups. Time difference between the two signals is measured as 4 ns which gives the velocity of 21.25×10^{6} ms^{-1} and kinetic energy of 1.26 keV. Temperature obtained is 1.5×10^{7} K. Although the biasing voltage is 20 V but energy of the electrons is very near to the energy of the first observation. This is due to the presence of the contaminations in the chamber which causes the breakdown threshold to decrease but these offer a lot number of collisions with the neutral and charged particles present in the chamber. These collisions are elastic and inelastic in nature. During inelastic collisions electrons lose energy. But despite all these processes the electrons have energy comparable to the first observation. Figure 11 shows the signals obtained at

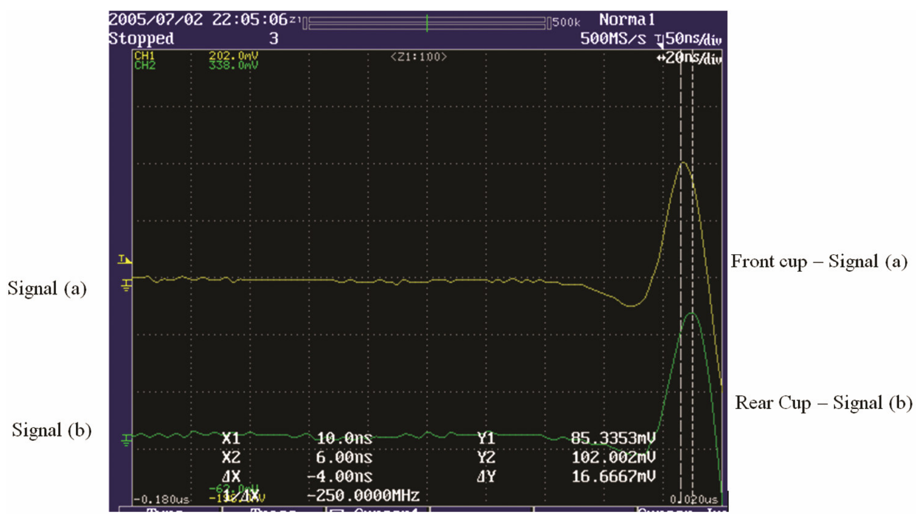

Fig. 10 – Signal profile of Faraday cups obtained at 20 V

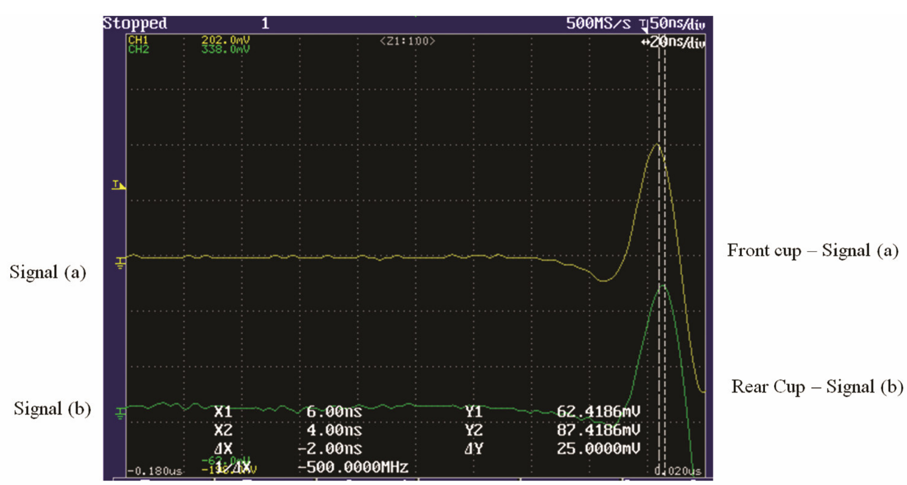

Fig. 11 – Signal profile of Faraday cups obtained at 0 V

Table 3 – Calculations of electron energies obtained by the TOF arrangement

Number of observation	Distance (d) (m)	Time taken (t) (s)	Velocity (m/s)	Kinetic energy $K.E. = ½ mv^2$ (keV)	Biasing energy (eV)	Average energy (keV)
1	0.085	4×10^{-9}	21.25×10^{6}	1.28	50	1.23
2	0.085	4×10^{-9}	21.25×10^{6}	1.28	20	1.26
3	0.085	2×10^{-9}	42.5×10^{6}	5.14	100	5.04

Table 4 – Values of the electron temperature

Number of observation	Energy (keV)	Temperature (K)	Average temperature (K)
1	1.23	1.43×10^{7}	
2	1.26	1.5×10^{7}	2.92×10^{7}
3	5.04	5.84×10^{7}	

100 V. Signal (a) is for the front cup and signal (b) is for the rear cup. The time difference is 2 ns which gives the velocity of 42.5×10^{6} ms^{-1} and kinetic energy measured is 5.04 keV. Temperature of the electrons is 5.84×10^{7} K. At this moment the biasing voltage is quite high which accelerates the electrons at high energies. In all the signals of each cup, a dip before the rise in the signal is observed. This dip is due to the noise. This dip is neglected for the measurements.

Energy of the electrons is gained by the laser direct interaction and also by the plasma waves. Laser provides energy to the electrons by its pondromotive force which accelerates the electrons from the high intensity region to the low intensity region[24]. The observations and calculations are given in the following Table 3. The average energy of the electrons ranges from 1.23 keV to 5.04 keV.

3.3 Electron temperature

Temperature of the electrons can be easily calculated using the above energies. The conversion factor for the conversion of the energy into the temperature is given as follows:

1 eV = 11600 K

Temperatures of the electrons with their corresponding average energy are given in the Table 4. The average temperature of the electrons is 2.92×10^{7} K and it can also be regarded as the plasma temperature because the temperature inside the plasma is due to the fast moving electrons.

4 Conclusions

On the basis of the above results and discussions we concluded that the energy of the electrons from laser induced hydrogen plasma ranges from 1.23 keV to 5.04 keV. The maximum energy is obtained at the first shot. The plasma temperature is calculated as 2.92×10^{7} K. The maximum electron flux obtained from Rogowski coil is 6×10^{12} electrons m^{-2}. The maximum current obtained from Rogowski coil is 39.6 kA. The maximum electron number and current obtained from the Faraday cup are 3.9×10^{8} and 1.8 mA, respectively, with maximum electron flux of 3×10^{4} electrons m^{-2}. Faraday Cup is a good charge collector but it cannot be used to estimate the currents in laser plasmas effectively. On the other hand Rogowski Coil is an efficient detector for the determination of the particle flux and currents in the laser plasmas.

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