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Study of RF Source Ignition System with Impedance Matching Network for RF Driven H^- Ion Source

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ABSTRACT: This paper presents study of a 6.78 MHz RF source with impedance matching network based inductively coupled plasma generator ignition system for an H- ion source. Two types of 10 turn RF antenna (solenoid coil) were developed, to couple the RF power to the ignition plasma chamber. The antenna's electric parameters were measured using Vector Network Analyzer (VNA). A copper conductor of 3 x 4 mm size with 10 turn solenoid coil was selected for simulation and experimental prototype antenna. Two L-types of (CCL and LCL C-capacitor and L-inductor) matching network were selected for impedance matching network for RF antenna. Initial simulations are carried out using ELSIE and LT-spice for frequency range from 5 to 8MHz. The matching network along with RF antenna was matched to ~ 50 Ωimpedance at 6.78 MHz with capacitive nature. An experimental prototype RF power source, 10 turn antenna (coil) and a matching network was developed to validate the simulation results. The prototype ignition system along with impedance matching network L-type with CCL was tested for inductively coupled hydrogen plasma generation and experimental results presented. Hydrogen plasma generation starts at minimum antenna coupled RF power of 150 watts, once initiated hydrogen plasma maintains to a minimum RF power of 10 watts.

KEYWORDS: Inductive coupled hydrogen plasma, Impedance matching network, Ignition system, LT spice, RF source and antenna.

I. INTRODUCTION

Initial seeding of electrons and hydrogen ions is achieved through an ignition plasma system. The electrons and ions are generated in the ignition chamber, which diffuses to the main plasma chamber due to drift and/or diffusion. This is required for high current H^- ion source to enable high power RF arc discharge in the main plasma chamber and reliable starting and to enhance the hydrogen plasma density [1-9]. Conventionally a high voltage based glow or arc discharge ignition is used [2, 3]. This is very simple type of ignition system, but it suffers from continuous erosion and sputtering of electrodes and need frequent cleaning or may need replacement after few days of operation. An electrode less, external RF antenna based ignition system was developed; here RF antenna needs to couple the RF power to the hydrogen plasma chamber through inductive coupling [9-15, 18-25].

Two types of RF antenna of different shape conductors, each with 10 turns in single layer was developed and their electrical parameters were measured using VNA. The measured parameters are given in table-I. The RF antenna with3x 4 mm copper conductor was selected for simulation and experimental prototype. L-type impedance matching network was chosen and design procedure was carried out using ELSIE simulation package [16], and selected a series capacitor (C_S) in series with RF antenna and parallel capacitor (C_P) across the RF source. These selected capacitors were used in LT-spice [17] steady state simulations and results obtained were presented in details in this paper. An experimental laboratory prototype developed and presented to validate and testing of inductive coupling plasma (ICP) generation based ignition system for RF driven H^- ion source.

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II. RELATED WORK

The design and results of computational modelling of a high-power RF based H^- ion source featuring an aluminum nitride plasma chamber is discussed in [1]. The paper [2] describes negative hydrogen ion source used worldwide for accelerators and their ignition system, along with the physics of surface and volume H^- production. The article [3] describes a RF ion source with a back-streaming electron dump. The book [4] describes various ways to produce hydrogen plasma and the negative hydrogen ion production. The paper [5] describes the RF based negative ion source operating in continuous mode, with RF frequency 11 to 27.12 MHz for RF power of maximum 1400 W with planer spiral antenna. The article [6] describes RF driven external antenna multicusp ion source with plasma ignition system, using a separate 13 MHz antenna. The paper [7] describes an RF driven multicusp source, operated in both CW and pulsed mode to generate H^- and various types of positive ion beams and production of metal ion beams, as an alternative to the arc-discharge sources. The paper [8] describes the RF based negative ion for H- production. In order to make clear the condition for the discharge initiation of the RF source, they developed a numerical model using the finite difference time domain Monte Carlo method to analyze the electron energy distribution function in RF field. The article [9] describes the various types of principle of RF coupling, power absorption, skin effect, discharge, electron temperature, energy loss. The paper [10] describes design and implementation of highly efficient, low cost 13.56 MHz, 1.5 kW RF source for inductively coupled plasma, for atomic emission spectroscopy. In paper, [11] an inductively coupled pulsed plasma source with an operating frequency of 29 kHz was described. The paper [12] describes, in detailed the inductively coupled plasma generation and their application for spectroscopy and their applications. The thesis [13] is written on the diagnostics and modelling of an inductively coupled RF discharge in hydrogen. The presentation [14] explains a different type of ion sources and the capacitive and inductively coupled RF plasma generation along with simulation and development of inductively coupled RF plasma ion source for different applications. The presentation [15] is on low pressure RF plasma sources for industrial applications, simulation and experimental results. The [16] is simulation software for RF network/circuit to generate Smith chart, input/output impedance, real and imaginary plot etc. for different frequency. The [17] is general purpose P-spice type simulation software for circuit analysis. The [18] paper is on the automatic frequency controller for power amplifiers used in bio-implanted applications. The patent [19] describes a compact matching network couples an RF power supply to an RF antenna in a plasma generator. The [20] paper explores some unique techniques and models for simulating amplifiers running in class C operation. The paper [21] gives the details of a new matching network with two tunable capacitors has been built and tested. The paper [22] gives the details on a FEM model was built to estimate the equivalent circuit parameters of the exciter. The chapter in [23] describes the three types of plasma generation for semiconductor industry (1) capacitive coupled plasmas (2) inductively coupled plasmas and (3) helicon wave sources. The thesis [24] is written on plasma thrusters and the performance characteristics of a compact electric thruster utilizing helicon plasma source is investigated. The book [25] incorporates a cutting-edge perspective on RF plasmas. It also covers basic plasma physics, including transport in bounded plasmas and electrical diagnostics.

III. RF ANTENNA DEVELOPMENT AND PARAMETER MEASUREMENTS.

A 10 turn single layer RF antenna (coil) developed using two types of copper conductors, first using a 4 mm outer diameter tube and another using 3x 4 mm solid copper conductor, the inner diameter of solenoid shape antenna is ~ 41 mm. The electrical parameters were measured using VNA (Model: E5061B). The measured Smith chart graphs are shown in figure 1 (a) and (b), for 4 mm diameter tube and 3 x 4 mm rectangular conductor respectively. The physical dimensions and measured electrical parameters are given in the table-I. An RF antenna was made with 3 X 4 mm copper conductor selected for simulation and experimental prototype, since it shows lower Equipment Series resistance (ESR) of 333.95mΩ, higher inductance of ~ 3.03 µH and compact in size (short in Length ~ 38 mm).

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TABLE: I

RF ANTENNA PARAMETERS

S. No.	Parameters	Round conductor Antenna (4 mm)	Rectangular conductor (3 x 4 mm) antenna
1.	Inner diameter	41mm	41 mm
2.	Outer diameter	48 mm	51 mm
3.	No. of turns	10 turns	10 turns
4.	Over all width	~ 42 mm	~ 38 mm
5.	Conductor size	4 mm diameter tube	3 x 4 mm rectangular
6.	Series inductance at 6.78 MHz	2.86µH	3.03µH
7.	Equivalent series resistance at 6.78 MHz	455.10mΩ	333.95 mΩ
8.	Inductive reactance at 6.78 MHz	121.85 Ω	129.21 Ω

Fig. 1(a). RF antenna made of 4 mm diameter round conductor with 10 turn.

Fig. 1(b). RF antenna made of 3 x 4 mm rectangular conductor with 10 turn.

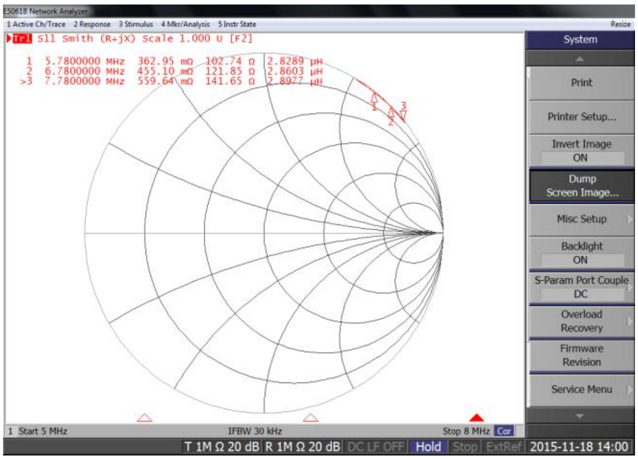

Fig. 2(a). Experimentally measured Smith chart and parameters of RF antenna made of 4 mm diameter round conductor with 10 turn, using VNA.

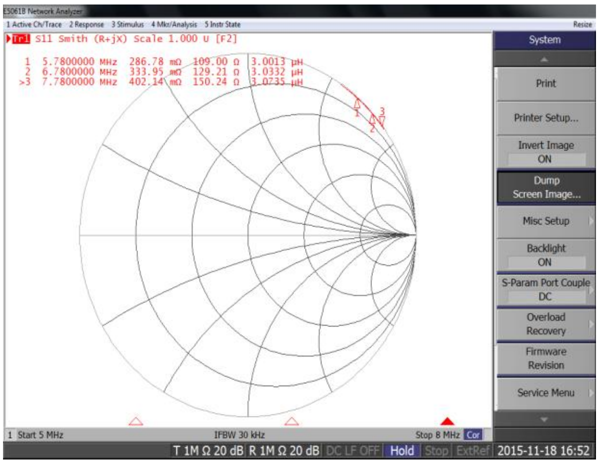

Fig. 2(b). Experimentally measured parameters of RF antenna made of 3 x 4 mm rectangular conductor with 10 turn and Smith chart using VNA.

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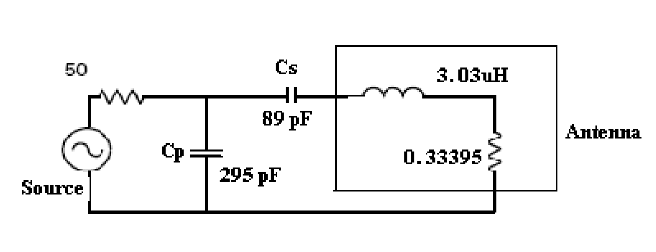

Fig. 3(a) Model for impedance (50 Ω) matching network with CCL for 3 x 4 mm rectangular conductor, 10 turn RF antenna using ELSIE simulator.

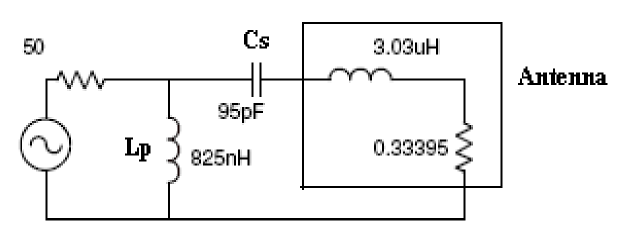

Fig. 3(b) Model for impedance (50 Ω) matching network with LCL for 3 x 4 mm rectangular conductor, 10 turn RF antenna using ELSIE simulator.

IV. SIMULATION RESULTS OF IMPEDANCE MATCHIGN NETWORK USING ELSIE

A simulation model of L-type impedance matching network for a RF antenna (0.33395 Ω and inductance 3.03µH) is shown in figure 3(a). C_P (295 pF) parallel capacitor to the source is greater than C_S (89 pF) a series capacitor to the antenna, the simulated impedance of the network is ~ 50 Ω capacitive at 6.78 MHz. Figure 4(a) shows the simulated Smith chart of matching network impedance of circuit along with RF antenna. Impedance of the network is 63.574 Ω capacitive at 5.78 MHz, and drops to 37.517 Ω capacitive at 7.78 MHz. The phase angle of network impedance is ~ 89.90 degree at 6.78 MHz, is remain nearly constant from 5.78 to 7.78 MHz. The impedance of network drops and transmission power increases as source frequency increases, it is -27.354 db at 6.78 MHz is shown in figure 5(a). The VSWR of network is more than 1000 for 6.78 MHz operating source frequency.

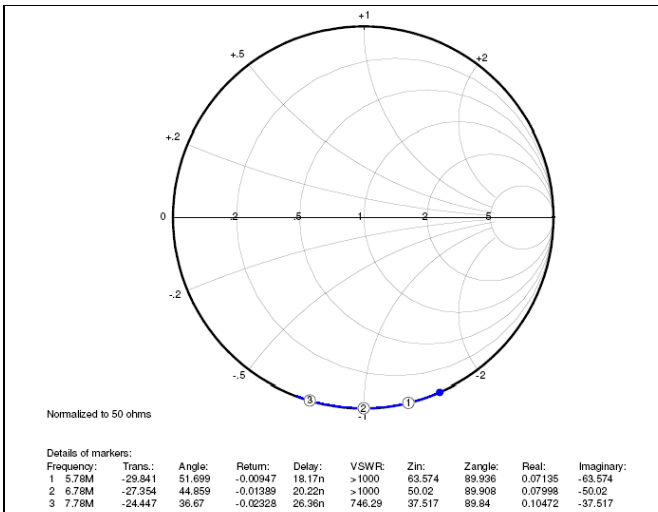

Fig. 4(a) Simulated Smith chart of impedance matching network with CCL using ELSIE simulator.

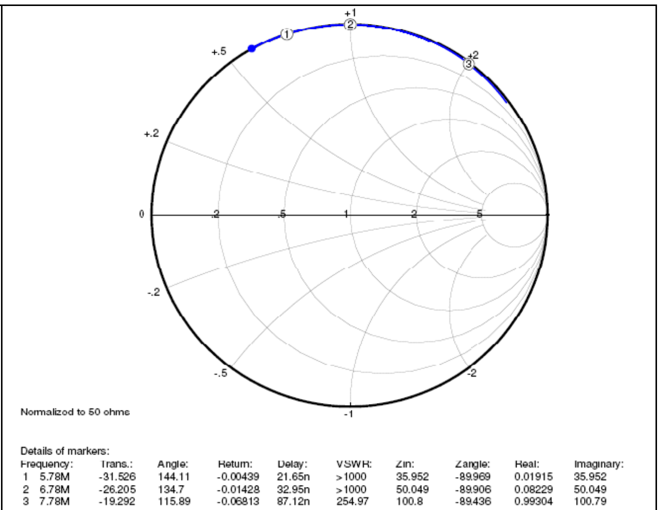

Fig. 4(b) Simulated Smith chart of impedance matching network with LCL using ELSIE simulator.

V. STEADY STATE SIMULATION OF IMPEDANCE MATCHING NETWORK FOR RF ANTENNA USING LT-SPICE.

CCL L-TYPE MATCHING NETWORK: The LT-spice simulation model of RF source, impedance matching L-type CCL network and RF antenna is shown in figure 6(a). The frequency response of current flowing through RF antenna is shown in figure 7(a), the peak current flows through it at 6.336MHz. The bandwidth of current is 8.835kHz.The RF antenna voltage (1.3 kV peak) and current (10 A) flowing through it is shown in figure 8(a). The voltage (1.3 kV peak) generates across the parallel capacitor (C_P) and current (17 A) flows through it is shown in figure 9(a). The RF source peak voltage is 600 V and its supplied peak current is 38 A, is shown in figure 10(a).

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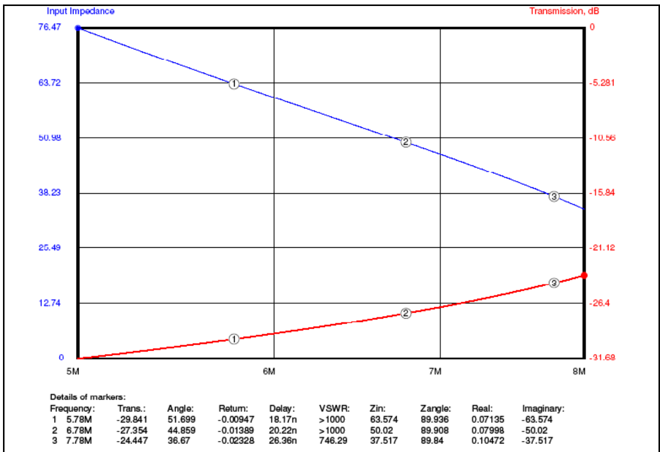

Fig. 5(a). Simulated input impedance (Ω) and transmission power (dB) plot for impedance matching network with CCL using ELSIE simulator.

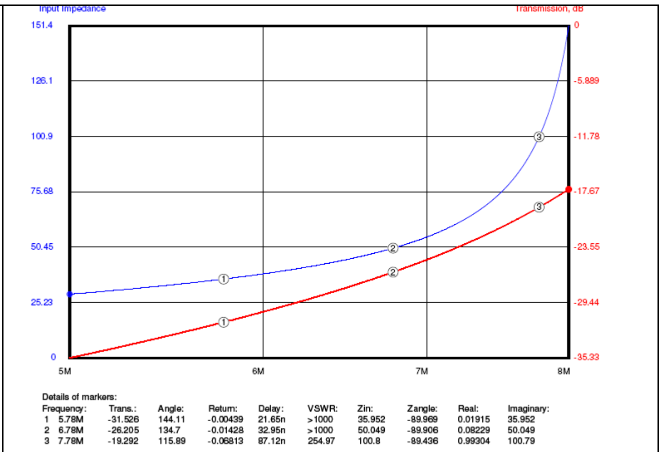

Fig. 5(b). Simulated input impedance (Ω) and transmission power (dB) plot for impedance matching network with LCL using ELSIE simulator.

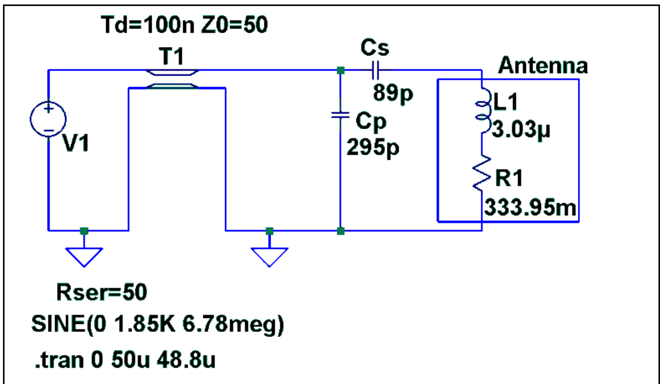

Fig. 6(a). Simulation circuit model at 6.78 MHz RF source with impedance matching network with CCL network (50Ω) for RF antenna in LT-spice.

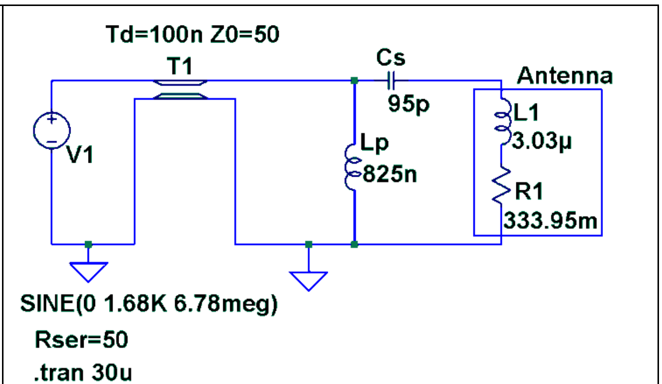

Fig. 6(b). Simulation circuit model at 6.78 MHz RF source with impedance matching network with LCL network (50Ω) for RF antenna in LT-spice.

LCL L-TYPE MATCHING NETWORK: The LT-spice simulation model of RF source, impedance matching L-type LCL network and RF antenna is shown in figure 6(b). The frequency response of current flowing through RF antenna is shown in figure 7(b), the peak current flows through it at 6.336 MHz. The bandwidth of current is 2.05 MHz. The RF antenna voltage (1.3 kV peak) and current (10 A) flowing through it is shown in figure 8(b). The voltage (1.2 kV peak) generates across the parallel inductor (LP) and current (35 A) flows through it is shown in figure 9(b). The RF source peak voltage is 1.55 kV and its supplied peak current is 12 A, is shown in figure 10(b). The bandwidth of LCL L-type matching network is greater than the CCL L-type matching network.

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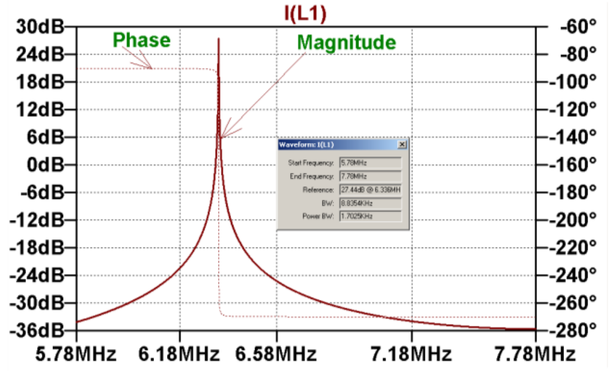

Fig. 7(a). Simulated frequency response in LT-spice for RF antenna current and its phase angle with CCL impedance matching network.

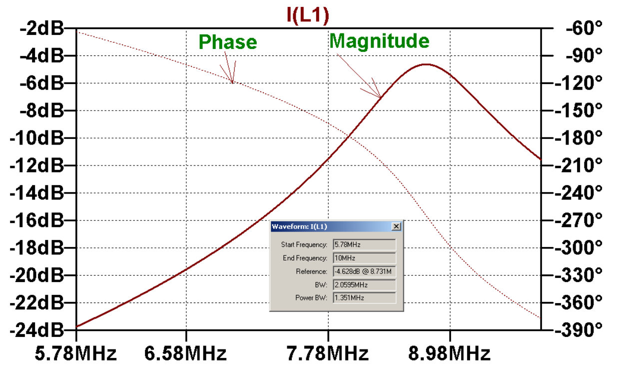

Fig. 7(b). Simulated frequency response in LT-spice for RF antenna current and its phase angle with LCL impedance matching network.

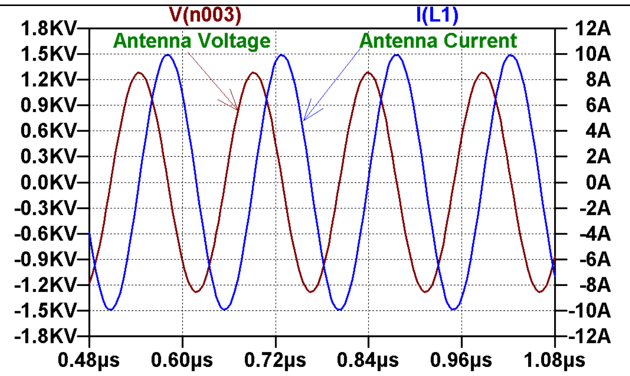

Fig. 8(a). Simulated result in LT-spice for RF antenna voltage and current, for CCL impedance matching network, voltage 0.3 kV/div and current 2 A/div.

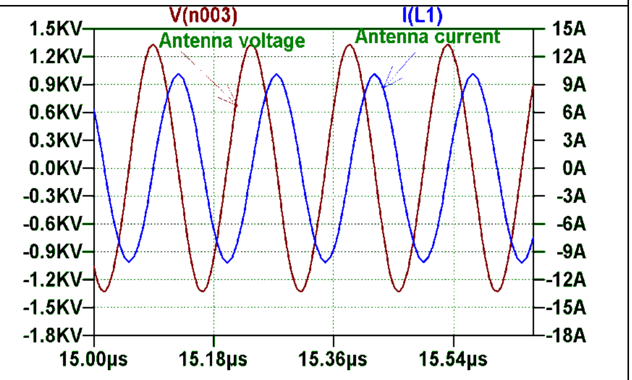

Fig. 8(b). Simulated result in LT-spice for RF antenna voltage and current, for LCL impedance matching network, voltage 0.3 kV/div and current 3 A/div.

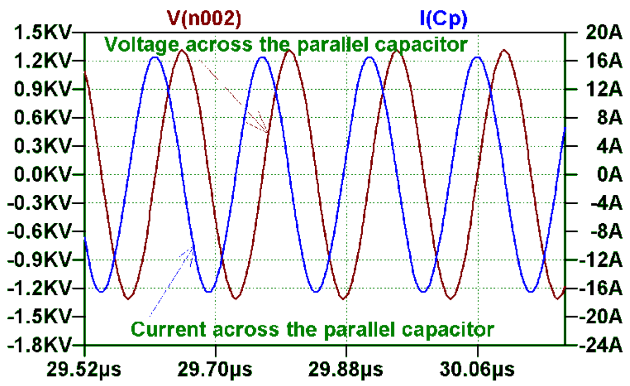

Fig. 9(a). Simulated result in LT-spice for voltage and current across the parallel capacitor (C_P), for CCL impedance matching network, voltage 0.3 kV/div and current 4 A/div.

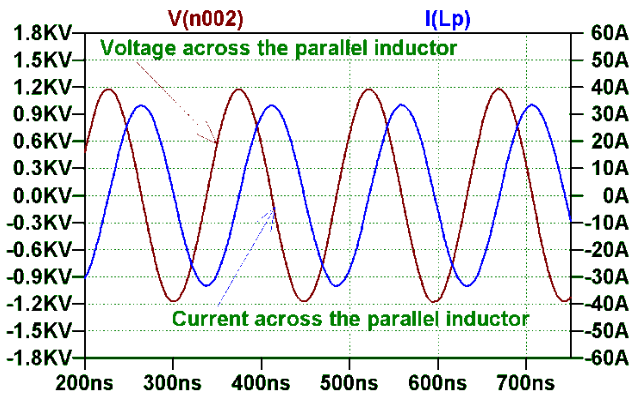

Fig. 9(b). Simulated result in LT-spice for voltage and current across the parallel inductor (L_P), for LCL impedance matching network, voltage 0.3 kV/div and current 10 A/div.

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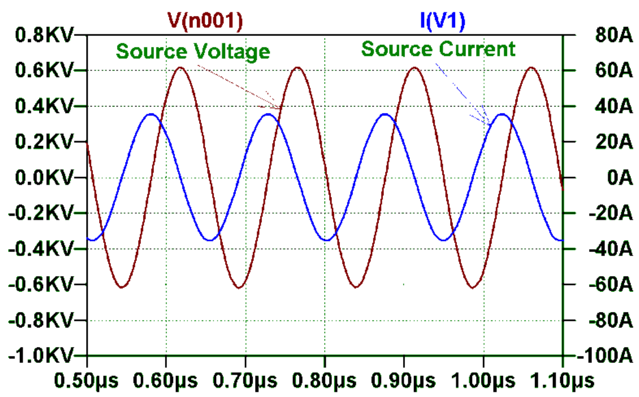

Fig. 10(a). Simulated result in LT-spice for source voltage and current, for CCL impedance matching network, voltage 0.2 kV/div and current 20 A/div.

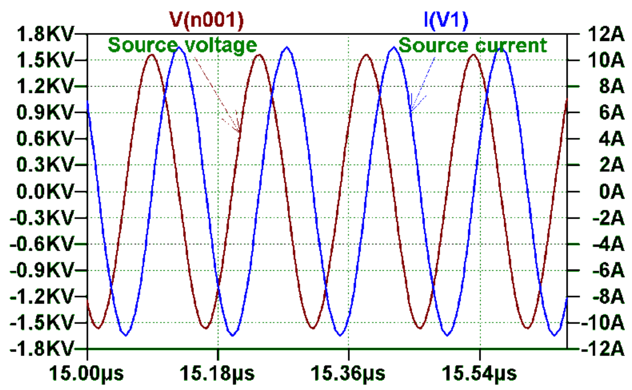

Fig. 10(b). Simulated result in LT-spice for source voltage and current, for LCL impedance matching network, voltage 0.3 kV/div and current 2 A/div.

VI. EXPERIMENTAL PROTOTYPE TEST RESULTS

An experimental prototype test setup block diagram is shown in figure 11. It consists of main components, RF source, amplifier, directional coupler for power measurement and CCL impedance matching L-type network for RF antenna. The main components of these are given in Table-II. The 6.78 MHz RF signal is generated using Arbitrary Function Generator (AFG). This RF signal amplified by 140 W RF amplifiers (AN762-140). The output power of RF amplifier was adjusted by varying AFG signal amplitude. The experimental test setup of ICP generator ignition system is shown in figure 12. The antenna voltage measured using P5100A voltage probe and the current measured using P6021 current probe. Figure 13 shows the typical RF antenna voltage and current through it at 6.78 MHz, recorded at deposited RF power of 51.67 W. The peak voltage and current through it is~ 187 V and the peak is ~ 5.14 A respectively. These results closely match with the simulation results for a RF power of 50 W. The RF power coupled to antenna measured using Oscilloscope power analyzer, is shown in figure 14. The typical deposited power is 51.67 W. The hydrogen plasma ignites at coupled RF power of ~140 W, and once ignited the plasma is able to maintain at minimum RF power of 10 W.

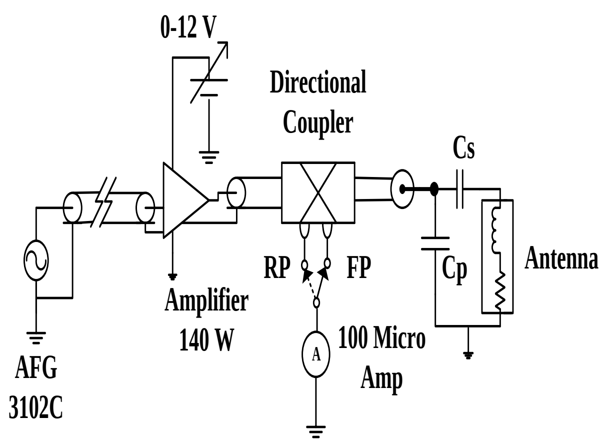

Fig. 11. Schematic block diagram of experimental prototype test setup for a RF frequency of 6.78 MHz.

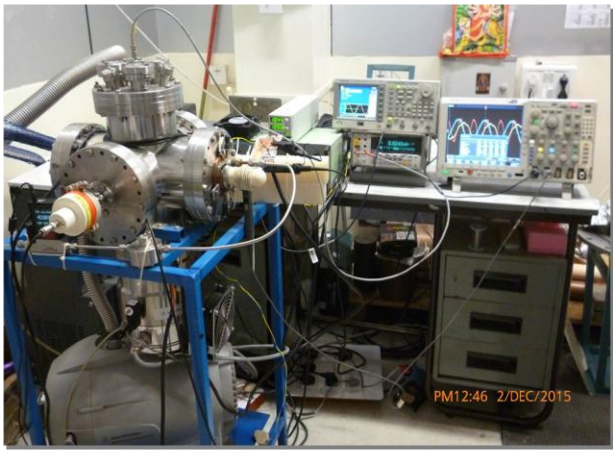

Fig. 12. The Experimental test setup of 6.78 MHz RF based ICP generator ignition system.

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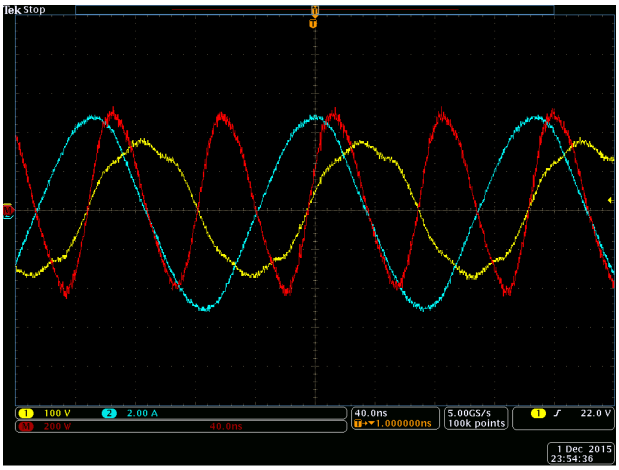

Fig. 13. Experimentally recoded RF antenna voltage 100V/div. and current through 2A/div.

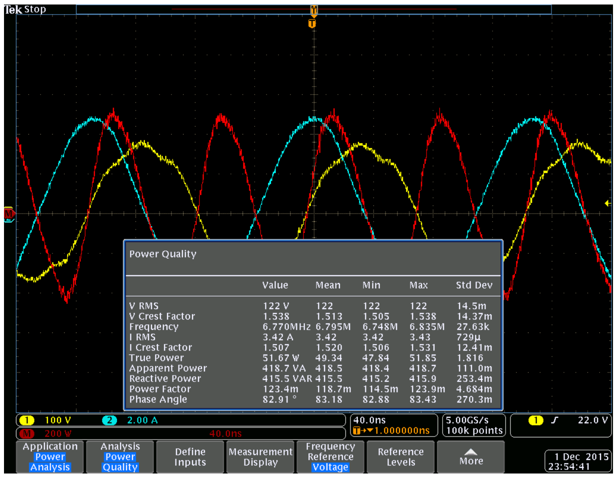

Fig. 14. Experimentally measured RF power coupled by antenna to plasma chamber using Oscilloscope power analyzer, antenna voltage 100 V/div., current through it 2 A/div. and power 200 W/div.

TABLE.II
EXPERIMENTAL PROTOTYPE SETUP MAIN RF COMPONENTS LIST

Serial No.	Component	Value
1.	Function generator (AFG)	Tektronix AFG3102C
2.	2-30 MHz, 140 W RF amplifier	Communication concept, AN762-140
3.	Directional coupler	Bird electronics, DPS 5010B, 100 µA
4.	Series capacitor	85pF
5.	Shunt capacitor	290pF
6.	Connecting cable and connector	RG-58, BNC type connectors
7.	Voltage(V) and current (I) probe (Make : Tektronix)	Voltage probe-P5100A
		Current probe- P6021

VII. CONCLUSION AND FUTURE WORK

Two types of RF antenna (solenoid coil) were developed and their electrical parameters were measured using VNA. The RF antenna made of square 3 x 4 mm copper conductor was selected for simulation and experimental prototype, since it has lower ESR and compact in size, An L-type impedance (50Ω) matching network developed using ELSIE simulator. The impedance matched network steady state simulation was carried out in LT-spice. The bandwidth of LCL L-type matching network is greater than the CCL L-type matching network. An experimental RF source, CCL L-type impedance matching network, and ignition system were developed and tested with actual load of ICP generation. The RF power coupled to antenna measured using directional coupler and oscilloscope power analyzer. The recorded operating RF antenna voltage, current and RF power, closely matches with simulation results for reduced power level. The hydrogen ICP generation starts at minimum RF power of 140W and it maintains for a minimum power of 10 W. In future a compact half-bridge based RF inverter with series resonance (LC) based RF source operating at 6.78 MHz will be developed.

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