T.1: Development of hydrogen ion sources for proton accelerators at RRCAT

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Abstract

RRCAT has a long-term plan to build high energy proton accelerators for research, industrial and medical applications. Ion source is one of the critical components that creates the initial beam for further acceleration and utilization in varieties of societal applications, including radioisotope production for medical diagnostics and cancer therapy, material research, ion implanters for manufacturing of semiconductor chips, cleaning of dirty water and polluted gases, etc. Towards indigenous development of ion sources for these accelerators, a significant progress has been made and three types of hydrogen ion sources viz., cold filament arc discharge based negative hydrogen ion source, radio frequency (RF) based negative hydrogen ion source, and electron cyclotron resonance (ECR) ion source have been developed. The filament arc discharge based ion source is our country's first indigenously designed and developed high current negative hydrogen ion source (12 mA, 50 keV with 0.5 ms pulse duration at 2 Hz repetition rate). This source is coupled to low energy beam transport (LEBT) system for beam characterization and transport studies. A multi-cusp free external antenna-based RF negative hydrogen ion source has been developed and 26 mA negative hydrogen ion current at 50 keV energy with pulse width of 2 ms has been successfully extracted at 50 Hz repetition rate. An ECR type proton ion source, based on 2450 MHz RF, has also been developed, and tested for continuous wave (CW) proton beam current of 10 mA at 35 keV energy. To operate this source in pulse mode, the CW magnetron has been replaced with an indigenously developed solid state based pulsed amplifier having 1-5 ms pulse width and duty factor up to 10%. With this, the hydrogen plasma has been successfully generated and the source has been operated at 0.4% duty factor, with extraction of 10 mA pulsed beam current of 2 ms pulse width, up to 35 keV beam energy. This theme article presents the detailed design, simulation, development, technological challenges, test results, etc. of these negative hydrogen ion and proton sources.

1. Introduction

Ion sources are key components of high intensity proton accelerators required for different types of applications. For example, the Spallation Neutron Source (SNS) accelerator system is comprised of negative hydrogen ion source, low energy beam transport line, radio frequency quadrupoleaccelerator and a series of high energy linear accelerating components to produce up to 1 GeV beam for injecting into proton accumulating ring. The arc and RF based volume production type high duty factor (~10%) negative hydrogen ion sources are the most promising candidates for this application. Accelerator Driven Subcritical (ADS) reactors require proton/deuteron ion beam current. Generally, for this, ECR based ion sources are used, which are capable of delivering CW beam current in the range of 10 mA to 100 mA with energies varying from 50 keV to 100 keV.

This theme article gives an overview of the design, development and test results of negative hydrogen ion sources based on arcing [1-4], RF [5-9], and ECR proton ion source [11-14] developed at RRCAT.

2. Cold filament arc discharge-based negative hydrogen ion source

A cold filament arc discharge negative hydrogen ion source has been developed as shown in Figure T.1.1. This is a pulsed arc based multi-cusp ion source and uses an innovative cold cathode high voltage low current glow discharge as an ignitor for sustainable arc discharge inside plasma chamber [1-4]. The multi-cusp geometry for plasma confinement consists of alternating rows of 12 magnets to generate a line cusp configuration so as the magnetic field is maximum at plasma chamber surface and reduces to minimum at the axis of the chamber. Hence, most of the plasma volume is confined virtually in the magnetic field free central region, with strong field existing near the plasma chamber wall inhibiting the plasma loss and leading to increase in plasma density and uniformity in the central region. It has been designed and developed to operate in pulse mode (pulse width 0.5-1 ms, pulse repetition rate 2-25 Hz). Negative hydrogen ion beam, up to 12 mA beam current at 50 keV beam energy, has been successfully extracted from this source. The arc deposited power is ~40 kW (100 A at 400 V pulse mode). In order to get collimated beam, a 3D design simulation study of 6 and 12 permanent magnets based multi-cusp cylindrical plasma chamber having length 140 mm and inner diameter 110 mm was performed. Optimization of three electrode extraction system was also carried out. The results of these studies and optimization are shown in Figure T.1.2. Simulation [10] results of multi-cusp magnetic field have shown good agreement with the measured values. Effect of multi-cusp magnetic field and filter field on extracted negative hydrogen beam has also been studied along with the effect of magnetic field of steering magnets, kept inside the extraction electrode of a triode negative hydrogen ion extraction system. Simulated value of magnetic field of dipole filter magnet (used for negative hydrogen ion formation through volume process), with variation of gap between two permanent dipoles magnets, has been matched with the measured value. From experimental results shown in Figure T.1.3, it is clear that these cusp-magnets generate field strength of about 0.2 T at the inner wall of the plasma chamber shown in Figure T.1.4(a) and a field free region of diameter 12 mm and 28 mm where magnetic field value reduces to about 10 gauss for 6 and 12 magnets configurations, respectively. The cold cathode filament with oval shape is shown in Figure T.1.4(b).

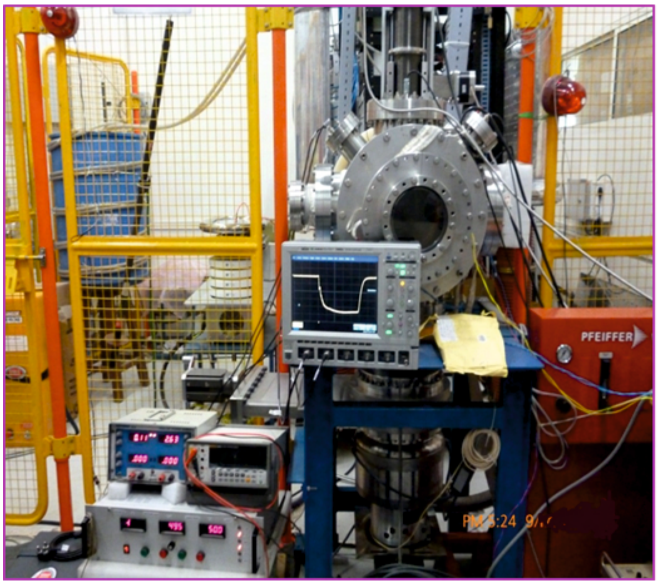


Fig. T.1.1: *Cold filament arc discharge based negative hydrogen ion source.*

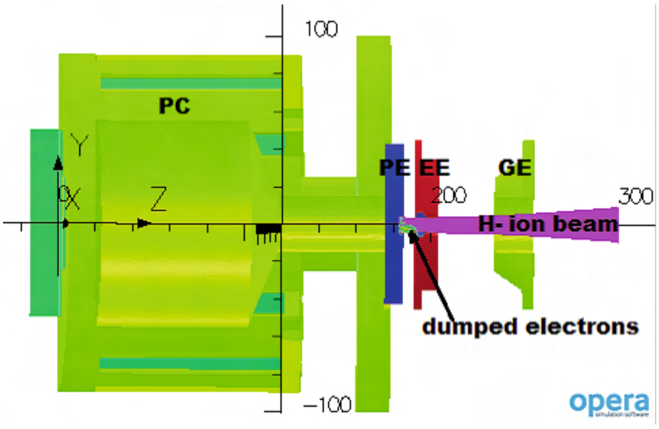


Fig. T.1.2: A 3D model of negative hydrogen ion source with plasma chamber and triode extraction system with 30 mA, 50 keV beam trajectories.

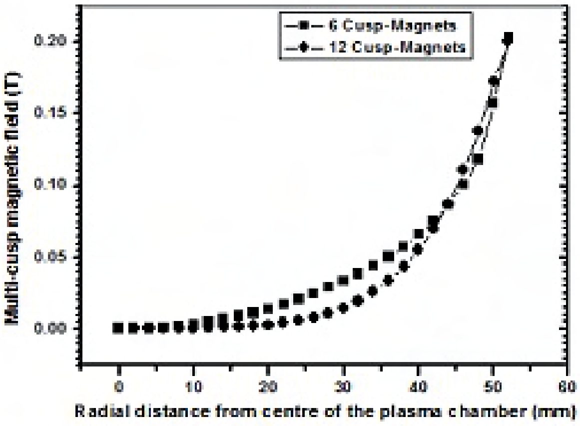


Fig. T.1.3: Measured variation of cusp magnetic field alongradius of plasma chamber for 6 and 12 magnets configurations.

Fig. T.1.4: (a) Multi-cusp plasma chamber and (b) back flange with oval shaped tungsten filament.

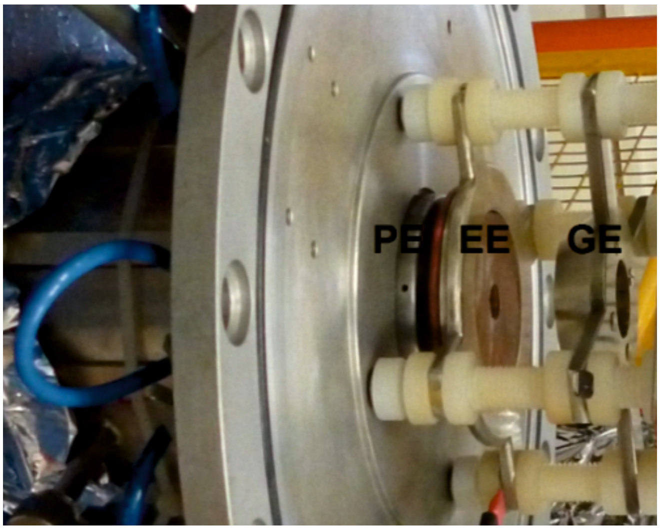


Fig. T.1.5: Triode extraction system (PE - plasma electrode, EE - extraction electrode, and GE - ground electrode).

Negative hydrogen ion extraction system is three electrode extraction systems as shown in Figure T.1.5. First electrode is plasma electrode (PE), second one is extraction electrode (EE) and third one is the ground electrode (GE). The design of negative ion extraction system is very challenging as it involves design of in-built electron dump in a limited space with cooling in the vacuum and high voltage breakdown prone environment. As, in the case of negative hydrogen ions extraction, electrons are co-extracted along with negative hydrogen ion beam, therefore, it has to be separated out from the main negative hydrogen ion beam. Based on the detailed design simulation studies, the separation of co-extracted electrons was done using a pair of dipole steering magnets. These pairs of magnets were chosen with opposite polarities. The first pair of magnet bends and dumps the electrons in the electron dump placed inside the EE and the second pair of magnets with opposite polarity corrects the small angular deviation in the negative hydrogen ion beam along transverse direction, magnetic field along the extraction axis is shown in the Figure T.1.6.

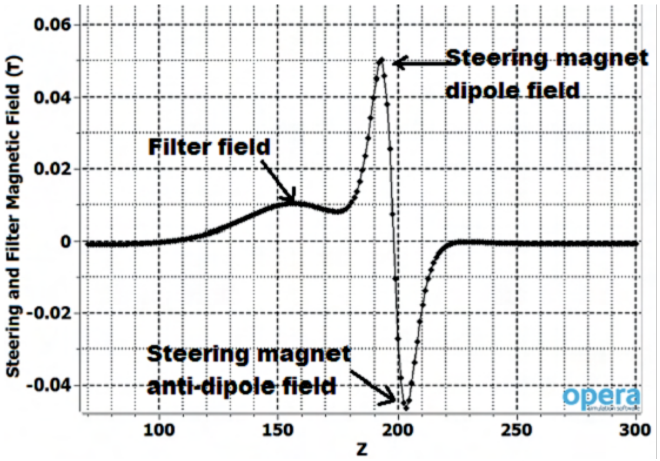


Fig. T.1.6: Variation of transverse magnetic field of filter and steering magnets along z-axis.

This electrode geometry was finalized after a detailed simulation study of the effect of variations in extraction electrode potential, the gap between electrodes and steering magnetic field. Optimized values of these parameters have been used for the operation of the ion source with three electrode extraction system.

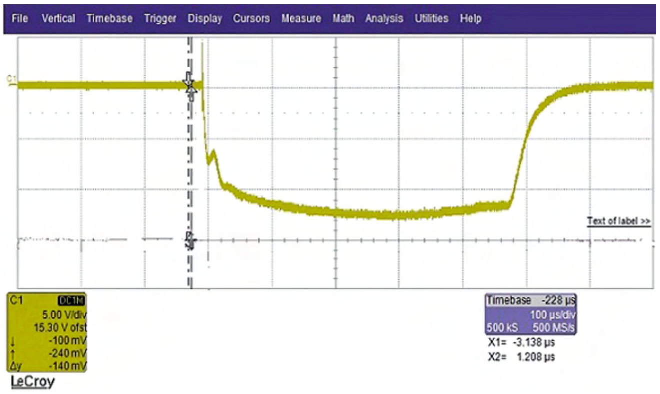


Fig. T.1.7: Negative hydrogen ion beam pulse form of 12 mA current recorded on an oscilloscope (Ch1: 5 mA/div., time: 100 µs /div.).

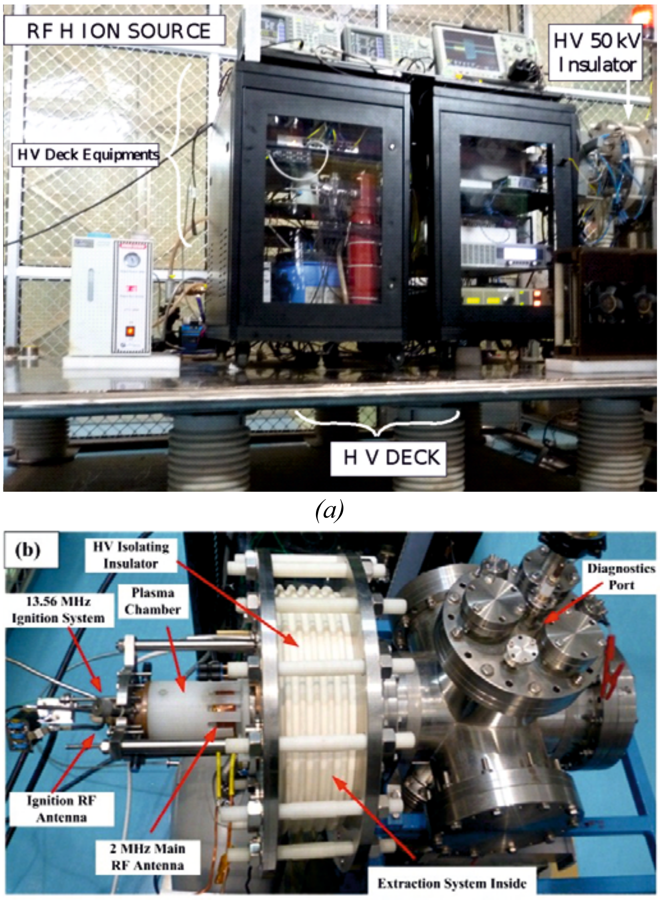
The recoded pulse form of the negative hydrogen ion beam of 12 mA at 50 keV on the oscilloscope is shown in Figure T.1.7 with a pulse width of 0.5 ms at 2 Hz repetition rate.

This arc based ion source can also be used as positive hydrogen (proton) ion source using diode or three-electrode extraction geometry. The electrodes for the three-electrode geometry were fabricated and installed to generate positive hydrogen ion current. This source was tested in the diode mode and positive ion beam current of more than 50 mA at 50 keV of energy was extracted.

3. Inductively coupled plasma based multi-cusp free RF negative hydrogen ion source

The arc based hydrogen ion source has some inherent limitations. The filament gets eroded and sputtered due to high power arcing between the electrodes. The sputtered material gets deposited on the extraction electrodes, internal parts and high voltage insulator. The electrode less RF based inductively coupled plasma generator hydrogen ion source is cleaner and more reliable choice. The RF based ion sources are widely used and accepted by accelerator community as one of the prominent pre-injectors for high power high current Linac for spallation neutron research facilities and proton synchrotron facilities for cancer therapy.

A RF based high current negative hydrogen ion source has been developed for a high-intensity pulsed proton accelerator facility for research and medical applications. This is a Cs-free, inductively coupled 2 MHz RF external antenna-based plasma ion source as shown in Figure T.1.8(a) and T.1.8(b). This source was tested at high duty factor of 10% in pulsed mode with 2 ms pulse duration at 50 Hz, up to ~ 26 mA current and up to 50 keV of beam energy.



(a)

(b)

Fig. T.1.8: (a) Experimental setup of RF based negative hydrogen ion source, and (b) the ion source plasma chamber, high voltage insulator disk and vacuum diagnostics chamber.

3.1 RF based ion source experimental setup

The RF based negative hydrogen ion source consists of 13.56 MHz based ignition system, 2 MHz based main plasma generation system, three electrode extraction system with efficient water-cooling arrangement for plasma and extraction electrodes, 2 MHz high power RF source, Faraday cup for beam current measurement, differential vacuum system, controlled hydrogen gas injection system, etc. A resonant circuit based 2 MHz matching network has been developed for external antenna to deliver 100 A RMS current. The RF power sources, and the electrodes biasing power supplies of ion source are shown in Figure T.1.9. At high current and high duty factor, operation of ion source results in large amount of power deposition in plasma chamber, RF antenna, extraction electrode and Faraday cup, which may lead to failure of these components. Thus, temperatures of these components are kept within limit by providing water cooling arrangement. The inductively coupled hydrogen plasma is having high dynamic impedance varying in the ratio of 1:10.

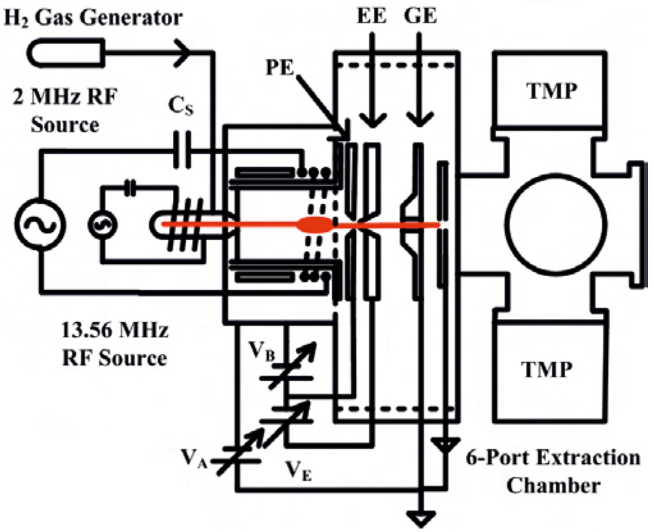


Fig. T.1.9: Schematic diagram of RF based negative hydrogen ion source along with power sources.

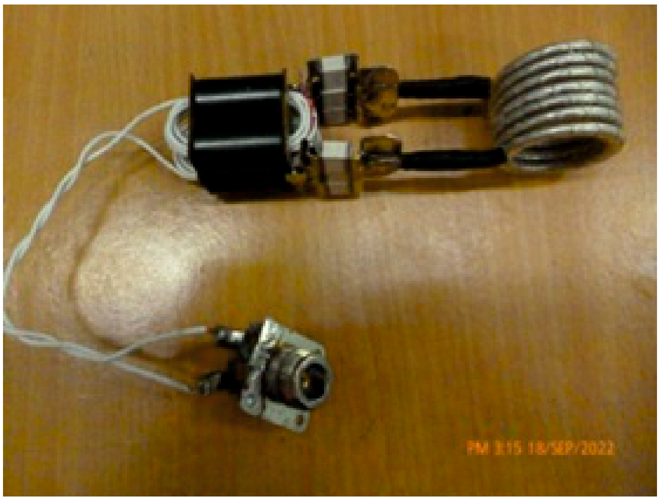


Fig. T.1.10: 13.56 MHz RF ignition antenna and transformer based matching network.

A systematic investigation was carried out to evaluate the dynamic reflected impedance of external RF antenna and its cooling arrangement at high RF power. A highly dynamic variable impedance passive resonant matching network based on LC-C-LC (L-inductance and C-capacitance) was developed for effective coupling of 2 MHz RF power to hydrogen plasma. A high current pulsed extraction power supply has also been developed in-house to dump co-extracted electrons on the extraction electrode. A water cooled, high vacuum compatible biased Faraday cup has been developed in-house for beam current measurement to handle power up to 200 W in vacuum.

RF ignition antenna with transformer based matching network is shown in Figure T.1.10. It has seven turns. The antenna is made of copper wire and tuned to the central resonant frequency of ~13.56 MHz. The main 2 MHz RF solenoidal coil type antenna is made of copper tube of 4 mm diameter with 6 turns and series resonantly tuned to the central resonant frequency of 2 MHz. The 3D CAD view of the main plasma chamber and ignition system is shown in Figure T.1.11.

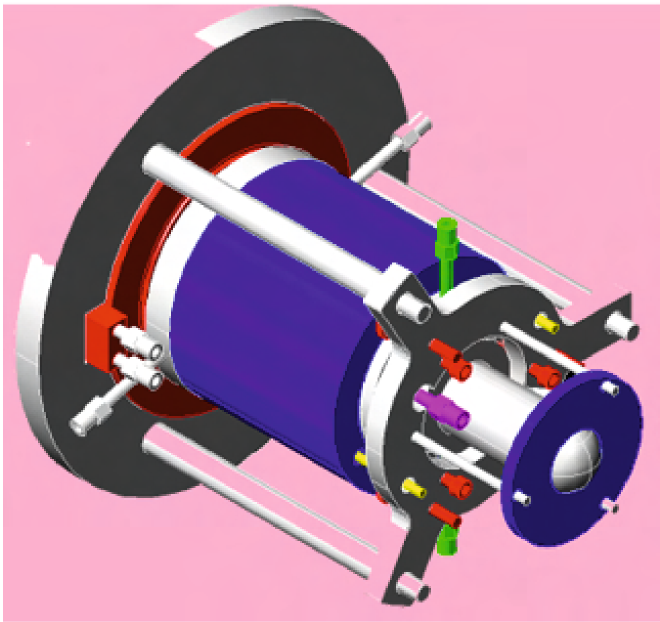
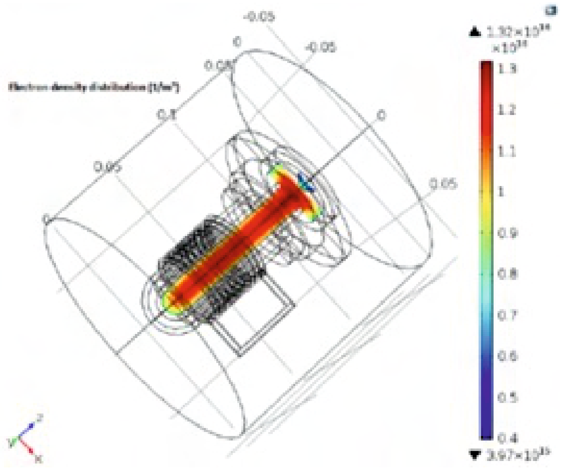
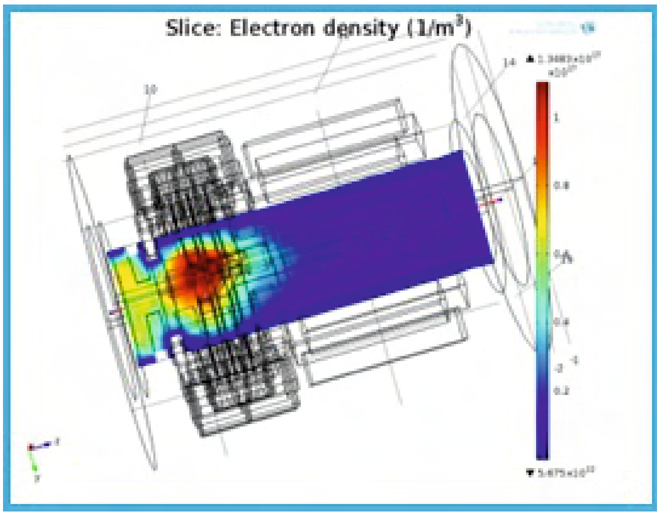


Fig. T.1.11: 3D CAD view of RF based ion source hydrogen plasma generator.



(a)



(b)

Fig. T.1.12: Simulation results in COMSOL for variation of plasma density inside (a) ignition and (b) main plasma chamber.

COMSOL Multiphysics simulation of plasma density variation inside the ignition chamber and main plasma chamber was carried out. The simulated maximum plasma density inside ignition chamber is $1.3\text{x}10^{16}$ /m^3 as shown in Figure T.1.12(a). This plasma density is sufficient to ignite the main RF discharge at 2 MHz frequency in the main plasma chamber connected to this ignition chamber. The simulated maximum plasma density inside main plasma chamber is $1.2\text{x}10^{18}$ /m^3 as shown in the Figure T.1.12(b). To enhance the overall source performance, ferrites are placed over 2 MHz RF antenna as shown in Figure T.1.13. Sufficient water-cooling arrangement has been provided to remove waste heat.

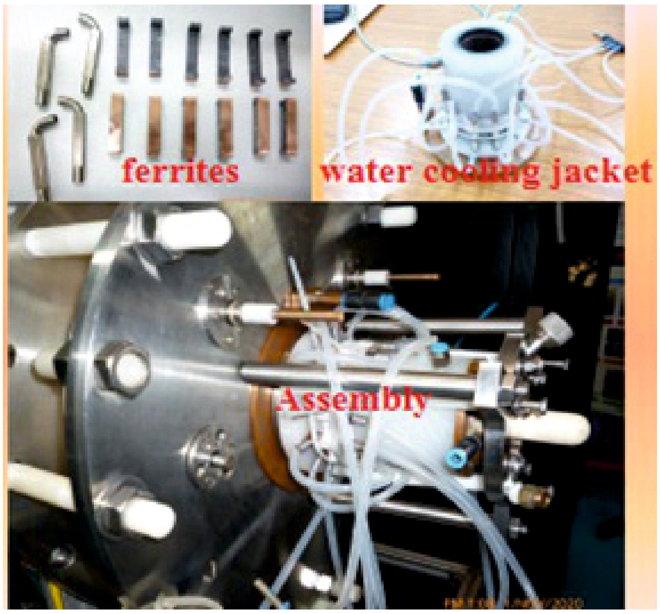


Fig. T.1.13: Main components of high duty factor water-cooled RF based plasma generator.

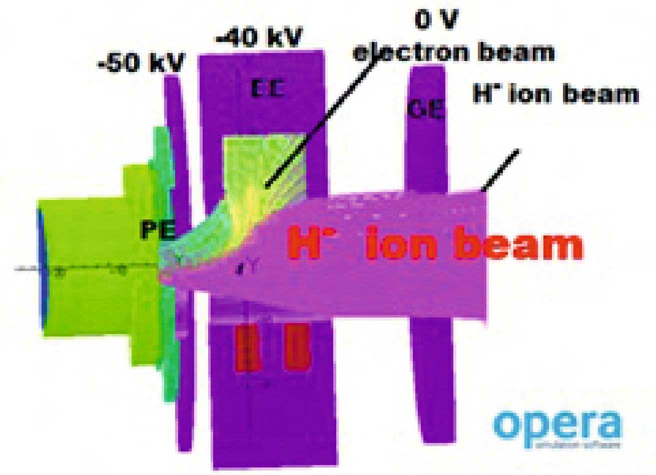


Fig. T.1.14: A three electrode extraction geometry simulation for RF based negative hydrogen ion source.

A simulated beam trajectory for 30 mA negative hydrogen ion beam extraction at 50 keV of energy is shown in Figure T.1.14. This simulation was carried out in OPERA [10].

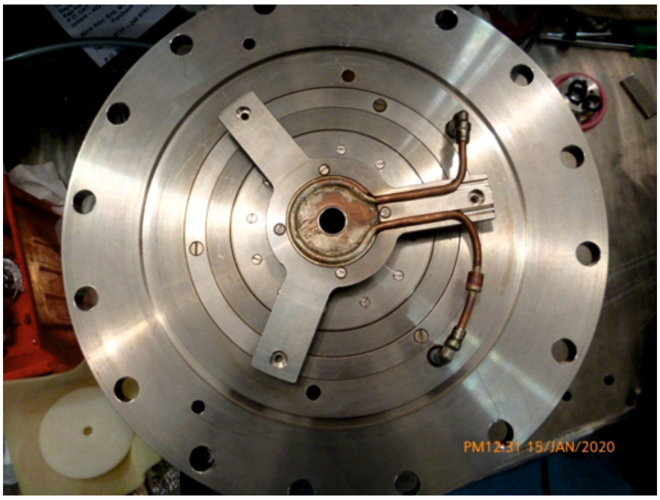


Fig. T.1.15: Assembly of water-cooled high voltage and high vacuum compatible extraction electrode rated for 15 kV DC.

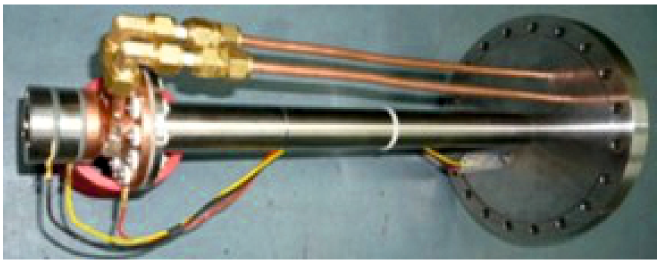


Fig. T.1.16: In-house designed and developed water-cooled, high vacuum compatible Faraday cup for beam current measurement.

Fig. T.1.17: Developed 2 MHz RF source components and their assembly.

All major components of the RF based ion source were developed in-house. The electrical power sources 10 kV, 1.5 A pulsed extraction power supply, 2.4 kW, 13.56 MHz RF source for ignition and 2 MHz, 100 kW pulsed RF source for main plasma generation were developed. The impedance stabilizing network was also developed for electrode biasing and RF matching networks for ignition and main plasma RF coils. The other subsystems are, controlled hydrogen gas injection system, differential vacuum system, three electrode extraction system, de-mineralized (DM) water based cooling system, a high voltage deck rated at 75 kV DC, remote control operation interfacing hardware and GUI based computer controller. The water cooled vacuum compatible extraction electrode is shown in Figure T.1.15, the co-extracted electrons are terminated by this electrode. The ion beam current is measured using biased Faraday cup. A water-cooled Faraday cup was developed as shown in Figure T.1.16. The main hydrogen plasma has been generated using 2 MHz pulsed RF source, developed using SIC-MOSFETs. This is shown in Figure T.1.17.

The RF based negative hydrogen ion source was tested for high duty factor operation and at 10% duty factor (pulse width 2 ms @ 50 Hz), it is able to deliver a beam current of up to ~ 26 mA current at 50 kV DC acceleration voltage. The recorded beam current form is as shown in Figure T.1.18.

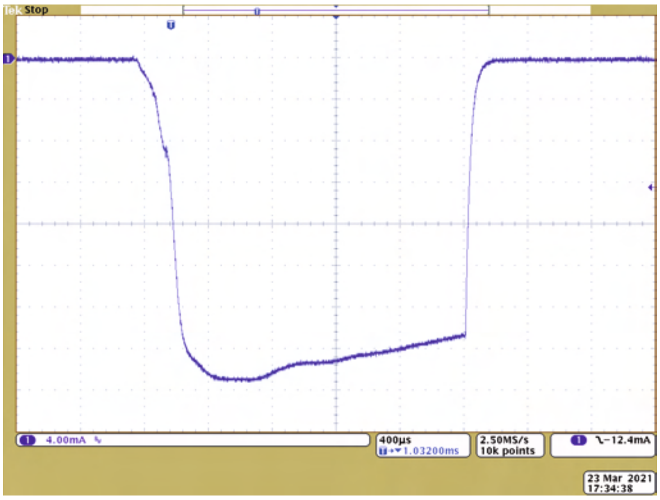
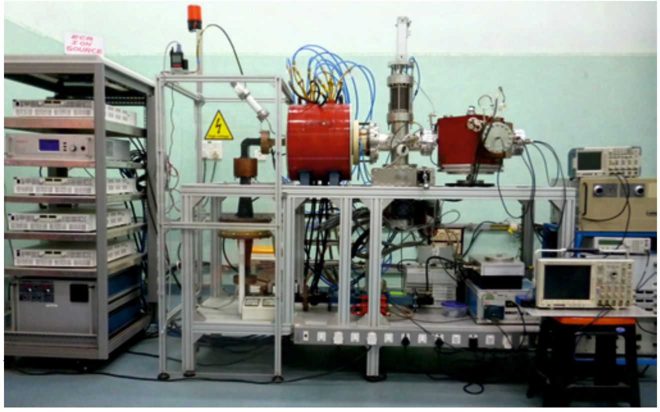


Fig. T.1.18: Recorded negative hydrogen ion beam current form (~ 26 mA) on a digital oscilloscope at 50 kV DC.

4. ECR hydrogen positive ion source

ECR ion sources (ECRIS) are being widely used for the production of light/heavy as well as multiply charged ions. The advantages are, it is a clean source and there is no limitation on life time because it does not use any filament and electrode. This source is most popular in accelerator community due to their stability, durability, reproducibility of low/high charge states, low-cost of operation, longer life time, high ion beam current power ratio and good beam emittances. The ECR proton source has been developed with 10 mA CW proton current up to 35 keV beam energy using a magnetron as a source of microwave power. To operate this source in pulse mode, the CW magnetron has been replaced with an indigenously/ in-house developed solid state based pulsed amplifier having 1-5 ms pulse width and duty factor of up to 10%. With this, the hydrogen plasma has been successfully generated and 10 mA pulsed current has been extracted at 35 keV beam energy with 2 ms pulse width and at 2 Hz repetition rate.

The experimental setup of ECRIS is shown in Figure T.1.19 [11-13]. The major components of the ECRIS to produce CW and pulsed beam are microwave source (CW and pulsed) and its power supply, microwave system (isolator, directional coupler, triple stub tuner, high voltage DC break, microwave window, microwave feed structure), resonant plasma cavity, vacuum chamber cum beam extraction chamber, vacuum system, gas feed system, beam extraction system, Faraday cup, mass analyzing magnet, etc. The microwave system is used to feed the microwave power to the plasma cavity, where plasma is generated. The high voltage DC isolator is used to isolate plasma chamber, which is floating at high voltage from ground potential and transmit the RF power from grounded microwave source. The directional coupler is used to measure forward and reflected RF power. A triple stub tuner is used to match the plasma impedance to keep the reflected power minimum. A differential vacuum system consists of turbo-molecular pump backed by dry pump. The desired operating pressure in the plasma cavity for the generation of plasma is maintained by regulated hydrogen gas injection rate. A three-electrode extraction system is used to extract positive hydrogen ion beam. Water cooled Faraday cup is used for the measurement of the beam current.



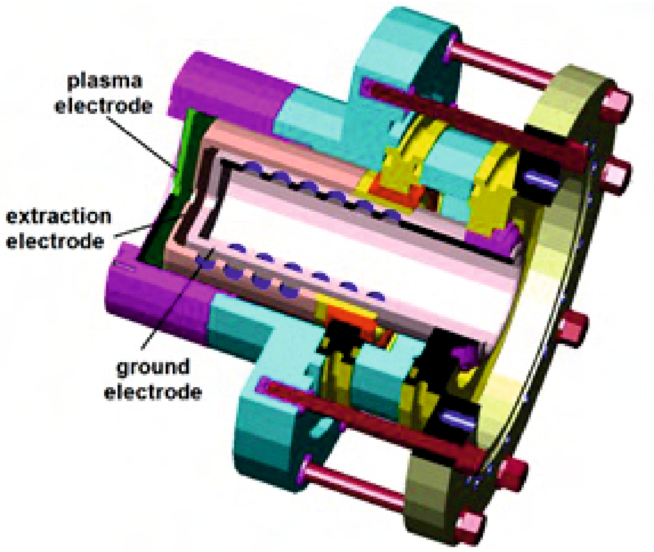


Fig. T.1.20: A 3D cross-sectional view of three-electrode extraction geometry.

4.1 Ion beam extraction system

Ion beam extraction system having triode-based geometry has been used for proton beam extraction. It has three electrodes namely, plasma electrode (PE), extraction electrode (EE) and ground electrode (GE). The PE is floated at high voltage, equivalent to beam energy for singly charged ions, EE is biased at negative potential to control the beam emittance and to suppress the accelerated electrons and GE is biased with zero voltage. The PE, SE and GE have apertures of 5, 8 and 10 mm, respectively. The spacing between the electrodes PE-EE, EE-GE is 22 mm and 3 mm, respectively. The 3D CAD view of electrode geometry is shown in Figure T.1.20.

4.2 CW mode operation of ECR ion source

To feed the microwave power in CW mode, magnetron is used as a source of microwave power at 2.45 GHz frequency and 2 kW adjustable. The output of the magnetron is connected to isolator, directional coupler, triple stub tuner, high voltage DC break and then microwave window. The microwave power is coupled to the plasma cavity via rectangular open-ended waveguide (WR-284). The water-cooled solenoid is used to produce and to confine the plasma. The source is operated in resonance mode to satisfy the ECR resonance condition inside the plasma cavity. The extracted beam current is measured using standard water cooled 1.5 kW Faraday cup.

4.3 Pulsed mode operation of ECR ion source

In order to operate the ECRIS in pulsed mode, the CW magnetron is replaced with a solid state RF pulsed amplifier of 1 kW peak power, 2.45 GHz frequency, pulse width of 1-5 ms, and duty factor of up to 10%. The microwave power to microwave system was fed through waveguide to coaxial adapter. The mass flow controller is used to feed the hydrogen gas. The source was operated by varying pulsed power from 10 W to 850 W and hydrogen gas flow of 0.5 to 5 SCCM. The pulsed current was recorded on a digital oscilloscope. The source was biased at 35 kV DC, and electron suppressor electrode voltage applied was approximately negative 1 kV. The directional coupler was calibrated for the forward and reflected power measurements, and the RF power signal was recorded using digital oscilloscope. The recorded waveform of beam current of 10 mA from ECRIS, operated in pulsed mode, on a digital storage oscilloscope is shown in Figure T.1.21.

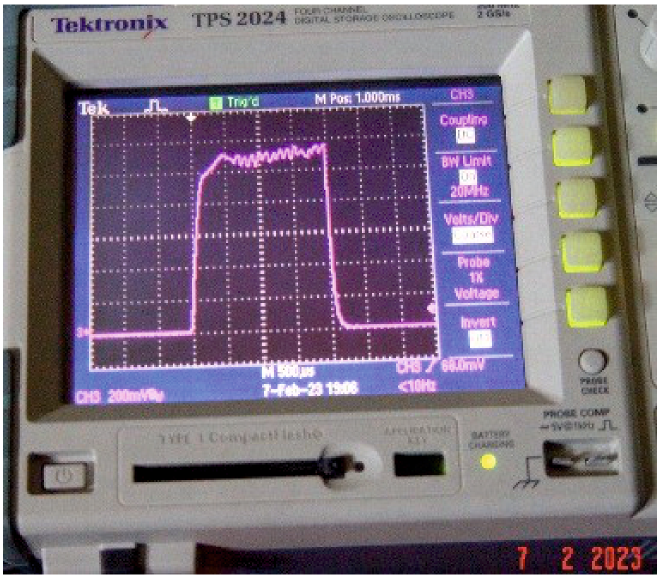


Fig. T.1.21: Recorded beam current from ECRIS, operated in pulsed mode, on a digital storage oscilloscope.

5. Conclusion

This article presented an overview of the R & D activities related to hydrogen ion sources, carried out during recent years. Cold filament arc discharge negative ion source is working well, with limited current up to 12 mA in pure volume mode and is coupled to a magnetic LEBT. A RF based negative ion source is also developed for higher current up to 30 mA in pure volume mode of negative ion production without using Cs and for operating at high duty factor of up to 10%. This has been successfully tested for extraction of ~26 mA beam current at 50 kV DC acceleration and is in the advanced stage of coupling with the newly designed and developed magnetic LEBT. The prototype ECR proton source has been successfully operated in CW and pulse mode. The measured current in CW mode is 10 mA at 35 keV beam energy and in the pulsed mode, it is 10 mA at 35 keV beam energy with pulse width of 2 ms at 0.4% duty factor.

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