System Integration of RF based Negative Ion Experimental Facility at IPR

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Abstract.

The setting up of RF based negative ion experimental facility shall witness the beginning of experiments on the negative ion source fusion applications in India. A 1 MHz RF generator shall launch 100 kW RF power into a single driver on the plasma source to produce a plasma of density $\sim 5 \times 10^{12}$ cm$^{-3}$. The source can deliver a negative ion beam of $\sim 10$ A with a current density of $\sim 30$ mA/cm$^2$ and accelerated to 35 kV through an electrostatic ion accelerator. The experimental system is similar to a RF based negative ion source, BATMAN, presently operating at IPP. The subsystems for source operation are designed and procured principally from indigenous resources, keeping the IPP configuration as a base line. The operation of negative ion source is supported by many subsystems e.g. vacuum pumping system with gate valves, cooling water system, gas feed system, cesium delivery system, RF generator, high voltage power supplies, data acquisition and control system, and different diagnostics. The first experiments of negative ion source are expected to start at IPR from the middle of 2009.

1. Introduction

Energetic neutral beams have been widely used as heating and current drives in Tokamak devices over the number of years. Though technologically difficult, the basic advantage of such devices finding a wide acceptability is the ease of coupling of power carried by the energetic neutrals to the plasma. The methodology followed in the production of such beams, is the neutralization and transport of accelerated ion beams from the ion source. For beams upto few tens of keV, positive ion based injectors are used where the neutralization efficiency falls with the increasing energy. For large Tokamak devices like ITER and for reactor grade machines, neutral beams with energies of a few hundred keV to a few MeV will be required. For such machines, the use of positive ion source based injectors becomes redundant due to extremely poor neutralization efficiencies. However, negative ion source based injectors are preferred as the neutralization efficiencies for the –ve ion beams are found to be $\sim 60\%$ for the energy range mentioned above [1]. Such negative ion injectors are widely in use in various facilities around the world. Till now, in such facilities, filament driven negative ion sources have been used. Such sources undergo frequent maintenance due to damage to the tungsten filaments. In large machines, such kind of frequent maintenance is not possible due to the radiative environment. As a result the RF driven negative ion sources have been accepted as a base line source, for all the neutral beam lines for ITER [2,3]. Research with RF based negative ion sources has been carried out for nearly a decade in the IPP, Garching [4-6]. Single driver based negative ion sources have been...
designed and developed [7,8]. Studies related to optimizing the source design with respect to various parameters like coupling of RF power, plasma production and its uniformity, beam extraction and acceleration have been carried out. The present optimizations have been done keeping the ITER requirements in mind. It may however be noted that these sources are 1/8th the size of the ITER source. Experiments on half size ITER sources with 4 drivers are underway at IPP to establish ITER plasma production regime and characterize the plasma produced in large size sources. This shall be followed by beam extraction and acceleration studies from half sized sources in a facility called ELISE expected to come up in IPP by 2009. The results from these studies will be used to arrive on a final design for an ITER sized source expected to be ~ 2 m in height and ~ 0.8 m in width and driven by 8 RF drivers.

India shall be collaborating internationally on the activities related to the development of such large area sources. Further, neutral beam lines equipped with RF based –ve ion sources will be necessary to support the future Tokamak related activities in the country. To begin with such a development, it is necessary to have an operational experience on proven systems, like the BATMAN type RF sources [9]. As a first step towards this need, development of an RF driven –ve ion source based source facility similar to the BATMAN facility in IPP, Garching, is underway at IPR. The technology for the manufacturing of the RF driven –ve ion source for this facility has been obtained under an MOU between IPP and IPR and the source is being manufactured at M/S PVA Tepla, Asslar, Germany. The proposed negative ion source test bed shall have a pulse length of about 5 sec. Plasma having a density ~5 x 10^{12} cm\(^{-3}\) is produced through the inductive coupling of ~100 kW of RF power from the 1 MHz RF generator. The source can deliver a negative ion beam of ~10 A accelerated to 35 kV through an electrostatic ion accelerator. The experimental program is divided into two phases. The first phase of the experiments is related to source experiments where the plasma will be generated by the inductive coupling of RF power and characterized. The second phase is related to beam extraction, acceleration and characterization studies.

The various sub systems of this facility are briefly described in the following sections. Excepting a few, the layout of the major sub systems is similar to that used in IPP, in order to have minimal problems during the erection and commissioning phase of the facility.

2. Layout of the negative ion source lab

A schematic of the negative ion source lab is shown in figure 1. This facility is housed in a space having a floor area of 20 m × 8 m, with a ceiling height of 5.5 m. The proposed space is serviced by an overhead crane of 2-ton capacity. The area is divided into various sections and will house the 100 kW RF generator, RF matching network, the power supplies at high voltage, the RF driven negative ion source, a vacuum vessel, vacuum pumps, gate valves at various locations, various diagnostics and racks for the data acquisition and control systems. The source and the components attached to the source will be at a high potential (source potential). The diagnostics and the modules related to the control and the data acquisition will be at ground potential. The link between the two will be established through fiber optic cables and modules converting voltage to frequency on the high voltage side and frequency to voltage on the low voltage side. Further the equipment and their signals, if any, need to be shielded against the interference from RF signals. The extent of shielding is decided by the value of the field due to the RF at the location of the equipment under consideration. Based on the IPP scheme of operating the equipments in the RF environment, RF shielding with ~2 mm thick screen made of aluminum strips is proposed for the present facility in all its partitions as shown in the figure. Further, in order to avoid formation of ground loops a proper ground scheme is being worked out and shall be implemented during the erection of the facility.
3. RF generator
A 1 MHz, 100 kW, single tetrode tube based self excited oscillator type RF generator is under procurement from M/S Himmelwerk. The important features of the generator include a tunable rise time of the RF output in the range between 300 $\mu$s to 1 ms, a fall time of < 300 $\mu$s and modulation capabilities. A resistive 50 ohm dummy load has been ordered along with the generator to allow for the setting up and testing of the RF generator before its actual operation with the plasma load. The generator will be coupled to the source through a 100 kV isolation transformer having a primary to secondary turn ratio of 3:1.

4. Matching Network
A matching network has been designed for coupling the maximum power to the source. The design of the matching network is such that it ensures matching the 50 ohm impedance of the generator to the 3 ohm (based on experimental experience of BATMAN source) plasma load impedance. The main components of the matching network are:

a. Capacitors in the series and shunt arms of the network
b. A 100 kV isolation transformer in the shunt arm of the network.

The series and shunt arm of this matching network consists of variable and fixed capacitances respectively. The isolation transformer, used in the shunt arm of the matching network, isolates the generator from the source, which floats at a high potential during the experiment. Figure 2 shows the...
schematic of the isolation and matching network set up for IPR’s –ve ion source. The circuit is tuned online when the source is in operation using the variable capacitor C2.

Figure 2. Matching network planned at the IPR –ve ion facility

5. RF based negative ion source
The schematic of an RF based negative ion source is shown in figure 3, which is similar to the source at IPP [7]. The source consists of three sections named driver, expansion region and extraction region. The driver consists of an alumina or quartz cylinder around which a water cooled coil is wrapped. Inside the cylinder, there is a Faraday shield, generally made of tungsten-coated copper with slits parallel to the cylinder axis. Such an arrangement protects the outer ceramic cylinder from plasma and reduces eddy current losses. The coil is coupled to the RF generator through a matching network, to ensure maximum coupling of the power. The back plate of the RF driver houses a filament which is switched on prior to the application of the RF power and assists in plasma production. Magnets arrangement on the driver back plate, the source back plate and the source body help in plasma confinement and reduction of wall losses.

Plasma is produced in the driver region, through the inductive coupling of the RF power to the source gas. The plasma consisting of the H\(^+\) ions and electrons and excited H\(_2\) molecules produced by the interaction of H\(_2\) moeclues with high energy (\(\geq 20\) eV) electrons flows towards the expansion region. A filter field having an \(\mu\)BdL of 500 G-cm between the expansion and extraction regions allows only cold electrons (< 5 eV), H\(^+\) ions and the excited H\(_2\) molecules to flow through. Dissociative attachment of excited H\(_2\) molecules results in the volume production of the negative ions in the source. The source is converted to a surface source by flowing Cs (having a low work function) vapors into the source through a Cs evaporator mounted on the source back plate. Cs deposits itself on the plasma grid and the walls of the source. H\(^-\) ions are produced through atomic and ionic processes by the impinging energetic H atoms, H\(^+\), H\(_2\)^+ and H\(_3\)^+ impinging on the plasma grid. Presence of cold electrons in the region after the filter field helps to reduce the destruction of negative ions where the electron binding energy is \(~ 0.75\) eV.

The grid system consists of a plasma grid (PG), extraction grid (EG) and a ground grid (GG). Each grid has 2 halves with each half having 387 apertures. The two halves can be inclined with respect to the vertical axis to obtain a beam focal point. The total extractable area can be varied by masking the grid apertures. The PG is made up of molybdenum whereas the EG and GG are grid made of copper with embedded water cooling channels. In addition, the EG has provisions for mounting the magnets required to trap the electrons co-extracted alongwith the beam. The voltage in the PG-EG gap provides the required extraction field whereas the voltage in the EG-GG gap provides the desired acceleration field. Cooling provisions are provided in the EG and GG to take care of the heat loads due to impinging electrons, co-extracted or stripped.
Figure 3. A schematic view of the RF based negative ion source [7]. The details of the extraction region are shown.

The source can be operated for pulse lengths up to 5 s. Plasma having a density ~5 x 10^{12} cm^{-3} is produced through the inductive coupling of ~100 kW of RF power from the 1 MHz RF generator. The source can deliver a negative ion beam of ~10 A accelerated to 35 kV through an electrostatic ion accelerator.

6. Vacuum vessel and pumping system
A schematic view of the vacuum vessel with support structure along with the schematics for the ion source and the vacuum pumps and different ports is shown in figure 4.

The vacuum vessel is a 15 mm thick cylinder made of SS304. The outer diameter of the cylinder is 1.5 m and length is 2.0 m. One end of the vessel is coupled to the ground support tube of the ion source through a ISO 500 gate valve. The gate valve is specially designed to take a cantilever load of 1.5 ton. The various ports on the vacuum vessel will be used for diagnostic purposes.

The pumping system for the facility consists of a combination of rough and roots pump, a 5000 l/s turbo molecular pump and a 14,000 l/s cryopump. Gate valves of appropriate dimensions will be used between the pumps and the vessels. The combination of rough roots and turbo molecular pumps shall be used during the source operation phase (Phase I) of the experiments, whereas the combination of all the pumps including the cryopump shall be used during the beam extraction and acceleration phase (phase II) of the experiment.

For vacuum pressure measurements, different types of gauges are used. One set of pirani and penning gauge is attached on the vacuum vessel for the measurements from atmospheric pressure to 10^{-7} mbar. Two capacitive manometers or baratrons are attached on the source for absolute pressure measurements. One baratron is attached on the driver whereas other one is attached near the plasma grid. Baratrons are preferred towards the source side as they are less affected by RF signals. Differential baratrons are attached across each gate valve for the safety of the gate valves. Gate valve can be open only when the pressure difference between both sides of the gate valve is less or equal to 10 mbar. As a general implementation policy, the connections of various equipments, like gauges, baratron, gas flow meters, pumps etc. to the vessel or the source shall be done through ceramic isolators to avoid any ground loops or signals getting affected by any noise.
7. Gas feed system

The gas feed system is used to deliver hydrogen gas into the plasma source. It is also used to flush the source with nitrogen or argon gas before the source is opened for any maintenance work. The system is housed inside a rack of ~2.5 m (height) × 1.25 m (depth) × 1 m (width). The gas feed lines from the system are directly connected with the source, which will be at a high potential during the operation. This necessitates, the gas feed system, floating at the source potential, to be isolated from the ground and is implemented using 35 kV isolators. A schematic view of the gas feed system is shown in figure 5.

The system uses a combination of needle valves, pneumatic valves, and solenoid valves to enable remote operations. The needle valves connected to the H₂ main line are calibrated in multiples of 2\(^n\) for a given pressure of the gas to obtain the desired operating pressure in the source. The fifth needle valve is calibrated for 0.8 Pa and is used to supply a gas puff for a short duration during which the plasma is ignited through the coupling of RF power. In future, if it is desirable to add a noble gas, such as argon or neon, with hydrogen gas, provision for a separate line, with a layout similar to hydrogen gas line, is also incorporated in the design.

The hydrogen gas or a mixture of hydrogen and noble gas is supplied to the plasma source when pneumatic valves, adjacent to the needle valves, are open. Solenoid valves control the opening of these pneumatic valves. A flow meter connected in the delivery line measures the flow rate of the hydrogen gas.
A rotary pump, sitting at ground potential, is connected to the gas feed system to initially evacuate the lines before hydrogen is supplied to the plasma source. As a safety feature, an exhaust fan is connected to the gas feed rack to exhaust hydrogen gas out of the lab in case of any leaks. Similarly, safety valve and a pressure switch connected to the plasma source ensure prevention of any damage due to the overpressure inside the plasma source.

8. Water cooling system

The water system for the –ve ion test bed shall consist of two loops, one consisting of a cold water loop and the other a hot water loop. The cold water loop supplies water to the RF generator, dummy load, the RF coil, grid holder boxes in the source, the extractor grid, the ground grid and the calorimeter. The hot water loop supplies water to the source body and the source back plate. The need for the hot water loop arises during the Cs operation of the source in order to prevent Cs deposition on cold surfaces. It has been observed that maintaining the Cs facing components of the source at higher temperatures helps in the optimal performance of the cesiated source in terms of better Cs recycling and larger extracted current densities. The heating unit is a commercially bought out item and has an inbuilt heat exchanger to help regulate the temperature to the desired levels. HV break is provided using rubber tubes compatible to high pressure at high temperatures. An ion exchanger shall be used in the path of the water circuit to provide deionised water to the components. 10% of the water will always flow through the ion exchanger while the system operates to ensure slow but continuous deionization of water flowing in the hydraulic circuit. A conductivity meter placed in the circuit arm provides continuous measurement of the conductivity of the water flowing in the circuit.
conductivity of the water is also maintained at low level to avoid any breakdowns at high voltage. Appropriately long plastic hoses shall be used to isolate the water line from plasma source at high voltage.

The schematics of the cold water and hot water loops are shown in figure 6 and figure 7. Table 1 shows different operational parameters of the circulating water into different components.

**Figure 6.** Schematic of cold-water circuit to cool different components of the negative ion source experimental set up. The water temperature is 20°C.

**Figure 7.** Schematic of hot-water circuit to cool different components of the negative ion source. The water temperature is 40°C.
Table 1. Parameters of the cooling water for different components of the negative ion source experimental set up.

| System                        | Inlet temperature (°C) | Inlet pressure (bar, absolute) | Pressure drop (bar, absolute) | Quality (µS/cm) |
|-------------------------------|------------------------|--------------------------------|-------------------------------|---------------|
| RF Oscillator                 | 20                     | 5                              | 3.5                           | 1             |
| RF power supply, control unit | 20                     | 5                              | 3.5                           | 1             |
| Dummy load                    | 20                     | 5                              | 3.5                           | 1             |
| Plasma grid box               | 20                     | 10                             | 8.5                           | 0.1           |
| Extraction grid               | 20                     | 10                             | 8.5                           | 0.1           |
| Ground grid                   | 20                     | 10                             | 8.5                           | 0.1           |
| RF coil                       | 20                     | 10                             | 8.5                           | 0.1           |
| Heat exchanger of hot water unit | 20                | 10                             | 8.5                           | 0.1           |
| Calorimeter                   | 20                     | 10                             | 8.5                           | 0.1           |
| Plasma box                    | 40                     | 10                             | 5.0                           | 0.1           |
| Back plate                    | 40                     | 10                             | 5.0                           | 0.1           |
| Faraday shield                | 40                     | 10                             | 5.0                           | 0.1           |

The pressure holding system in the return line, as shown in figure 6, helps to maintain the desired pressure difference across each component. Depending on the pressure difference, the flow is automatically distributed in each line and cools the components.

As shown in figure 6 and 7, the temperature sensors are kept at the inlet and outlet whereas flow meters are kept at the outlet of each component. These shall be used to perform calorimetric measurements during source operation to know the actual heat load on each component.

9. Cs delivery system

As mentioned above, use of Cs in a negative ion source converts the source from a volume production source to a surface production source. Experimentally it has been observed that the extracted current densities are higher in a cesiated (surface) source as compared to a purely volume source [10].

A schematic view of the cesium delivery system is shown in figure 8. The approximate size of the cesium oven is 400 mm (length) × 400 mm (height) × 100 mm (depth). Liquid cesium is stored in a S.S. container, which can store more than 10 gms of liquid cesium. After breaking a 10 gms cesium ampoule, the liquid cesium drops down into the S.S. container through valve V2. After whole of cesium is collected into the cesium container, the valve, V2, is closed.

The cesium delivery system is encased by glass wool thermal insulation and a case of aluminum. The Cs container, the oven body and the Cs delivery tube are provided with separated heater connections. Thermocouples attached to each of these help to monitor temperature during operation.
The cesium container is at the minimum temperature, which controls the vapor pressure of the cesium. The other parts should be kept at higher temperatures (typically 20 to 40°C). Once the desired temperature is achieved, the valve V1 is opened and cesium vapor goes into the plasma source. It may be noted that the operation of the Cs oven and the delivery of Cs into the source are tricky and an online monitoring of the signals is required to make decisions related to the control the various heating circuits in the Cs oven. More details of the Cs oven will be presented elsewhere.

Figure 8. Schematic view of the cesium delivery system. More details can be found in companion paper.

10. Diagnostics
A number of diagnostics are proposed to measure different parameters of the plasma. Most of the diagnostics are located on the filter or diagnostic flange connected to the exit of the plasma box. Some of the important diagnostics are Hα spectroscopy, electrostatic probe diagnostics, cavity ring down spectroscopy, laser photo detachment, Doppler shift spectroscopy, and ion and electron current measurements. The details of these diagnostics will be presented elsewhere.

11. Power supplies
Various types of power supplies are required for the successful operation of this facility. These include filament heating power supply, filament bias power supply, Cs oven heating power supply, bias plate power supply and high voltage power supplies for extraction and acceleration. The power supply requirements and their topology for this facility have been described in a separate publication [12] in this conference.

12. Control and data acquisition
The operation of the source and its subsystems will be controlled by a PLC based controlled system. Approximately 125 Nos. analog and 160 Nos. digital, control and monitoring signals will be required to monitored to ensure the proper performance of the facility. The control logics to be followed for the control of the subsystems independently and in conjunction with the other subsystems have been decided. A schematic of PLC based control system under consideration is shown in figure 9. The
communication between the signals from the modules in the racks (low voltage end) and the source end (high voltage end) is done with fiber optic (FO) modules which act as voltage to frequency and frequency to voltage converters.

Figure 9. Layout of the control system to be implemented on the negative ion test facility at IPR

About 130 essential parameters are required to be stored or acquired for post experimental analysis. This shall be implemented using a PXI based data acquisition system. The philosophy of communication between the HV source end and the low voltage end (modules located in the racks) remains the same as for the control system. However depending on the fast or the slow signals, two types of modules with bandwidths of 1 kHz and 100 kHz have been chosen.

13. Summary
This paper describes in brief the efforts underway towards the establishment of a 10 A 35 kV negative ion beam facility at IPR with a pulse length of 5s. The floor layout of the laboratory, shielding requirements and the configurations of the various subsystems to be used in the set up has been finalised. Various components of the facility are in procurement stages. The facility is expected to be established by the second quarter of 2009 and shall include the commissioning activities of the RF generator and the various subsystems. The source delivery is decided in two stages, with the first stage expected in mid 2009 and comprising of the delivery of the source with a dummy grid to enable plasma production experiments to begin. This shall be followed by the delivery of the extractor and accelerator system to enable beam extraction studies which are expected in 2010. Once established and functional, this facility shall be used as a test bed to learn and operate RF based negative ion sources and extract beams from the source. This is necessary to accelerate the learning process, which
will be required to operate large area source like the ITER source for DNB. The test bed can also be used to perform experiments aimed at improving the source performance and to understand some basic questions related to the physics of negative ion production.

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