Power supply system for Negative Ion Source at IPR

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Abstract. The first step in the Indian program on negative ion beams is the setting up of Negative ion Experimental Assembly – RF based, where 100 kW of RF power shall be coupled to a plasma source producing plasma of density ~5 x 10^{12} cm^{-3}, from which ~ 10 A of negative ion beam shall be produced and accelerated to 35 kV, through an electrostatic ion accelerator. The experimental system is modelled similar to the RF based negative ion source, BATMAN presently operating at IPP, Garching, Germany. The mechanical system for Negative Ion Source Assembly is close to the IPP source, remaining systems are designed and procured principally from indigenous sources, keeping the IPP configuration as a base line. High voltage (HV) and low voltage (LV) power supplies are two key constituents of the experimental setup. The HV power supplies for extraction and acceleration are rated for high voltage (~15 to 35kV), and high current (~ 15 to 35A). Other attributes are, fast rate of voltage rise (< 5ms), good regulation (< ±1%), low ripple (< ±2%), isolation (~50kV), low energy content (< 10J) and fast cut-off (< 100µs). The low voltage (LV) supplies required for biasing and providing heating power to the Cesium oven and the plasma grids; have attributes of low ripple, high stability, fast and precise regulation, programmability and remote operation. These power supplies are also equipped with over-voltage, over-current and current limit (CC Mode) protections. Fault diagnostics, to distinguish abnormal rise in currents (breakdown faults) with over-currents is enabled using fast response breakdown and over-current protection scheme. To restrict the fault energy deposited on the ion source, specially designed snubbers are implemented in each (extraction and acceleration) high voltage path to swap the surge energy. Moreover, the monitoring status and control signals from these power supplies are required to be electrically (~ 50kV) isolated from the system. The paper shall present the design basis, topology selection, manufacturing, testing, commissioning, integration and control strategy of these HVPS. A complete power interconnection scheme, which includes all protective devices and measuring devices, low & high voltage power supplies, monitoring and control signals etc. shall also be discussed. The paper also discusses the protocols involved in grounding and shielding, particularly in operating the system in RF environment.

1. Introduction
RF based negative ion facility is currently under development in IPR [1]. For the operation of such a facility, various power supplies are required as shown in ‘Figure 1’. Since the negative ion source assembly at IPR is similar to the ion source at IPP, the majority of the specifications are derived from this already existing system.
Plasma is produced by an oscillator-RF generator, which utilizes a separate power supply to drive the oscillator. The power supply for the RF generator is a bought out item and is not discussed in this paper. Regulated High Voltage Power Supplies (RHVPS) with low energy content; fast rise time and various other critical parameters are required for the process of Extraction and Acceleration, which are discussed later in this paper. These Power supplies should be remotely operated and equipped with all necessary protective devices for the safety of the power supply as well as the source. A passive protection scheme (Snubber) will also be incorporated, which will provide protection against the grid breakdowns. In addition to this various other isolated low to medium power, heating and bias power supplies are required for beam production and control. This includes Filament Bias, Filament Heating, Grid Bias and Grid Heating power supplies. The Filament circuit assists in plasma generation; Plasma Grid and Bias circuit is used for electron suppression. The input power to these power supplies will be fed through MCB based sub-distribution panels housed with necessary electrical protection devices. A 50kV DC isolation transformer will be used to feed the AC power to the power supplies, which are floating at the source potential. To avoid grounding problems like the ground loops and the noise pickups, a star point based grounding scheme has been designed. A complete power interconnection and integration scheme is designed, showing all the power supplies, protecting & measuring devices and all the control and monitoring signals.

2. Ion source High Voltage Power Supplies (HVPS)

The high voltage system for the negative ion source consists of the following two power supplies:

- Extraction HVPS for extracting the negative ion.
- Acceleration HVPS for accelerating the beam.

The common characteristics of these power supplies are isolation from ground, regulation, low ripple amplitude, and dynamic response of few milli seconds. Moreover, the HVPS power supplies (accelerator and extraction) should trip within 100µs in case of grid breakdown, which is a common
phenomena occurring frequently during source operation. The typical ratings of the extraction and acceleration HVPS are shown in table 1 and 2 respectively.

### Table 1. Ratings of Extraction HVPS

| Parameter                      | Value                                      |
|-------------------------------|--------------------------------------------|
| Output Voltage                | 15kV (Floating)                            |
| Output Current                | 35A                                        |
| Output Voltage Rise time      | < 5ms                                      |
| Cut-off time during Fault     | < 100µs                                    |
| “Wire test” clearance value   | ≤ 10J                                      |
| Maximum output allowable ripple at full load | ≤ ± 2% of maximum value              |
| Voltage Regulation            | ≤ ± 1%                                     |
| Normal operating range (NOR)  | 0-100%                                     |
| Best Control Range            | 10-100%                                    |
| DC Isolation level            | 50kV                                       |
| Voltage and current measurement accuracies | < 1%                                |
| Protections                   | Over Voltage, Over Current, di/dt          |

### Table 2. Ratings of Acceleration HVPS

| Parameter                      | Value                                      |
|-------------------------------|--------------------------------------------|
| Output Voltage                | - 35kV (grounded)                         |
| Output Current                | 15A                                        |
| Output Voltage Rise time      | < 5ms                                      |
| Cut-off time during Fault     | < 100µs                                    |
| “Wire test” clearance value   | ≤ 10J                                      |
| Maximum output allowable ripple at full load | ≤ ± 2% of maximum value              |
| Voltage Regulation            | ≤ ± 1%                                     |
| Normal operating range (NOR)  | 0-100%                                     |
| Best Control Range            | 10-100%                                    |
| DC Isolation level            | 50kV                                       |
| Voltage and current measurement accuracies | < 1%                                |
| Protections                   | Over Voltage, Over Current, di/dt          |

Three major power supply topologies are explored to generate the regulated high voltage DC. This include:

- AC thyristorized power controller based topology (‘Figure 2’).
- PWM/PSM based RHVPS (‘Figure 3’).
- Rectifier inverter based topology (‘Figure 4’).

The AC thyristorized based topology (‘Figure 2’) uses a combination of power-controller, followed by a step up transformer and controlled rectifier.

![Figure 2. AC thyristorized power controller based topology with series switch](image-url)
The PWM/PSM based RHVPS (‘Figure 3’) utilizes a multi-secondary step-up, high power transformer. The output of each secondary is rectified and controlled independently with a DC-DC converter operating in PWM/PSM mode. Each DC-DC converter output is connected in series to get the final output. The switching of each module is shifted by 360/n degree; where ‘n’ represents the number of modules.

Rectifier inverter based topology (‘Figure 4’) utilizes a high frequency step-up transformer. The output of the transformer can be single (for 6-pulse) or multi (for 12-pulse). A switching frequency of 2kHz is enough to achieve the desirable parameters [2] and hence amorphous cores can be easily used to form the transformers but the frequency can be raised upto 10-20kHz depending on the ratings and design of the control system.

Technical comparison of the all the three technologies is tabulated in table 3.

| Parameter                        | AC Thyristorized | PWM/PSM Based | Rectifier Inverter |
|----------------------------------|------------------|---------------|--------------------|
| Technology                       | Simple           | Complicated   | Complicated        |
| Control                          | Simple           | Complicated   | Relatively simple  |
| Series switch                    | Required         | Not required  | Not required       |
| Control speed                    | Slow             | Fast          | Fast               |
| Energy content                   | High             | Low           | Low                |
| Transformer design               | Less critical    | Critical      | Less critical      |
| Synchronizing skills             | Less             | More          | Less               |
| HV stresses on                   | Yes              | Yes           | No                 |
| semiconductor devices            | Less             | More          | Less               |
| Inrush current                   | Bulky            | Bulky         | Relatively small   |
| Size                             | Bulky            | Bulky         | Relatively small   |

Based on the preliminary investigation (as shown in table 3), the rectifier-inverter based topology has been proposed; but detailed design analysis and simulations need to be performed before finalizing the topology for its use in the negative ion system at IPR.

Both Extraction and Acceleration HVPS power supplies will be tailored made in Industry. The power supply will consist of the following sub-sections: (1) Power unit (2) Control unit and (3)
Remote control unit. Based on the topology selected, the Power unit will perform the function of AC to DC conversion. The unit will be composed of transformer, rectifier, High frequency/Low frequency step up power transformer, switch mode inverter and filter circuits. The unit will also be equipped with protective sensing devices like current transducers, potential dividers and protection relays. Control unit will form the feedback loop for regulation and control of the power supply. All the essential voltage and current signals will be communicated through FO links, between power and control units, for reliable and isolated signal transfer. The control unit will be composed of a DSP/u-processor based PID feedback control which will generate the control pulses for the switching devices.

'Figure 5' shows a typical integration and measurement scheme of the high voltage power supplies to the source. It can be seen that the Extraction HVPS is floating over the acceleration HVPS and therefore needs special consideration for DC isolation.

![Figure 5. Integration and measurement scheme for HVPS](image)

High voltage coaxial conductor RG-220 is planned for making the HV connections. The cable is rated for 100kV DC and 50A. A 60kV Tri-axial cable is also explored for making the HV connections. The voltage measurements will be performed through 5000x/10000x, 60kV, non-inductive dividers, which will be connected at both - the power supply terminals and before the load, to ensure proper transmission of voltage. The current measurements will be performed through Hall effect type DC current transducers with response faster than 10µs.

Grid breakdown is a common phenomenon in the source when operated with HV. Both HVPS are allowed to pass a definite number of breakdowns before the final trip of the system can occur. During each breakdown, the power supply will be following a typical cut-off scheme as shown in 'Figure 6'. At the occurrence of breakdown, the current rises to the peak value, governed by the total series impedance. The passive snubbers further restrict this to an allowable value close to 1kA. This is followed by a breakdown detection and current quench routine, which should end within 100µs. The power supply is given a rest period of about 15ms. This is followed by the turn-on sequence, which is of the order of few milli seconds (1msec).
A typical grid breakdown and over-current detection scheme is proposed as shown in ‘Figure 7’.

*Figure 7. Typical Scheme for Grid Breakdowns and over-current detection*

The scheme utilizes non-inductive resistor as a current-shunt. The output signal is amplified and compared with a reference to generate a TTL output. The total electronics float at the high potential. The TTL is converted into light through a TTL to Light converter and is transmitted to a breakdown counter. Maximum breakdown count value of 10 is proposed for the HVPS for the operation with ion source. The typical breakdown mechanism algorithm along with the HVPS startup and operational algorithm is depicted in ‘Figure 8’ (a) and (b).

*Figure 8. (a) Startup procedure of HVPS*  
*Figure 8. (b) Operational procedure of HVPS*
3. Heating and Bias power supplies
Various heating & bias power supplies will be required to aid in beam production & beam control. Each power supply is described briefly for its application, typical rating and the start-up/operational procedure.

3.1 Filament heater and filament bias power supplies
Both the power supplies are used for plasma production. Both the power supplies float at the source potential (50kV maximum) and operate in a 100kW, 1MHz RF environment. Table 4 and table 5 shows the typical ratings of these power supplies.

| Parameter                  | Value/Rating                  |
|---------------------------|-------------------------------|
| Input Voltage (Vin)       | 1-phase, 230V                 |
| Input frequency           | 50Hz                          |
| Output Voltage (Vout)     | 0-16VDC                       |
| Output current            | 0-10A                         |
| Output Voltage Ripple     | ≤ 5mV p-p                     |
| Output Voltage Stability  | ≤ 50mV                        |
| Output current stability  | ≤ 1mA                         |
| Regulation for 80-100% Load | ≤ 100µs                     |
| Temperature coefficient   | ≤ 500ppm/°C                   |
| Duty Cycle                | Continuous (100%)             |
| Mode of Operation         | Constant Voltage and Current  |

Table 5. Ratings of filament bias power supply

| Parameter                  | Value/Rating                  |
|---------------------------|-------------------------------|
| Output Voltage (Vout)     | 90VDC (Battery generated)    |
| Output current            | 0.5A                          |
| Auxiliary input voltage   | 1-ph, 230V, 50Hz              |
| ON/OFF Control            | TTL/PFC                       |
| Current Monitoring        | 0-5V for 0 to F.S.            |
| ON/OFF Status             | 0V for OFF, 5V for ON         |

3.2 Grid heating power supply
This power supply is used to electrically heat the plasma grid. This is also floating at the source potential. It should maintain a temperature of 150 °C in the plasma grid, which is controlled by the DAC system through a PID control loop. Table 6 gives the typical ratings of this power supply and ‘Figure 9’ illustrates the typical startup and operational algorithm.

| Parameter                  | Value/Rating                  |
|---------------------------|-------------------------------|
| Input Voltage (Vin)       | 1-phase, 230V                 |
| Input frequency           | 50Hz                          |
| Output Voltage (Vout)     | 0-65VDC                       |
| Output current            | 0-10A                         |
| Output Voltage Ripple     | ≤ 5mV p-p                     |
| Output Voltage Stability  | ≤ 50mV                        |
| Output current stability  | ≤ 1mA                         |
| Regulation for 80-100% Load | ≤ 100µs                     |
| Programmability           | Externally through 0-10V signal |
| Mode of Operation         | Constant Voltage and Current  |
3.3 Grid bias power supply
This power supply is used to bias the plasma grid with respect to the source. This essentially controls the electron current. This power supply also floats at the source potential. Table 7 gives the typical rating of this power supply and ‘Figure 10’ illustrates the typical operational sequence.

| Parameter                        | Value/Rating                      |
|----------------------------------|-----------------------------------|
| Input Voltage (Vin)              | 1-phase, 230V                     |
| Input frequency                  | 50Hz                              |
| Output Voltage (Vout)            | 0-30VDC                           |
| Output current                   | 0-66A                             |
| Output Voltage Ripple            | ≤ 75mV p-p                        |
| Output Voltage Stability         | ≤ 0.05%                           |
| Line and load regulation         | ≤ 0.1% (V) and 0.5% (I)           |
| Programmability                  | Externally through 0-10v signal   |
| Mode of Operation                | Constant Voltage and Current      |
| Voltage monitoring signal        | 0-10V DC for 0 to 100% of V       |
| Current monitoring signal        | 0-10V DC for 0 to 100% of I       |

3.4 Cs oven power supply
This power supply is used to Cs oven power supply feeds the heater coils of the Cs oven. It is typically rated for 40V and 12A AC. It is PID temperature controlled through DAC system. ‘Figure 11’ illustrates the typical startup procedure for this power supply.

4. Typical interconnection scheme for various power supplies
Table 8 gives the description of the output terminal connections for all the power supplies. ‘Figure 12’ depicts this pictorially.
### Table 8. Output terminal connections for all the power supplies

| Power Supply   | Positive Terminal | Negative Terminal     |
|----------------|-------------------|-----------------------|
| Accelerator HVPS | Ground            | Extraction Grid       |
| Extraction HVPS  | Extraction Grid    | Plasma Grid           |
| Filament Heater | Filament lead 1   | Filament lead 2       |
| Filament Bias   | Source            | Filament lead 2       |
| Grid Heater     | Grid heater lead 1| Grid heater lead 2    |
| Grid Bias       | Plasma Grid       | Source                |
| Cs oven PS      | (Connected to the Cs oven) |                  |

5. **Passive protection scheme for grid breakdown**

Grid breakdown in grid system of the source is a common phenomenon, which occur because of many different conditions of the electrode surface, gas pressure and beam optics during the operation [3][4]. This is characterized by the fast discharge of energy stored in the stray capacitance of HV cables etc. The timescale of the breakdown is beyond the scope of any active protection. A suitable passive protection component (Snubber) should be incorporated in the High voltage line in order to protect the load.

![Figure 12. Power supply output connections](image)

![Figure 13. Typical passive protection scheme (snubber) for grid breakdowns](image)

As shown in ‘Figure 13’, snubber consists of a hollow cylinder of ferromagnetic material, surrounding the high voltage conductor. A resistor may act as secondary winding of the snubber, providing power dissipation. Moreover, a bias circuit can be included to increase the available flux swing before core saturation. In circuit terms, a core snubber is represented by a saturable inductance and a resistance connected in parallel.

The snubber parameters can be calculated from the following mathematical relation:

\[
L = 4 \times R^2 \times C
\]  

(1)
where, $L$ is the snubber inductance (H), $R$ is the parallel snubber resistance (ohm) and $C$ is the stray capacitance (F). The value of $R$ is governed by the maximum system voltage and the peak fault current and is independent of all other snubber parameters. $C$ accounts for the stored energy (capacitance) in the DC cable and the other stray capacitances. As shown in ‘Figure 5’, two snubbers will be used in the HV line for the protection against the plasma grid as well as extraction grid breakdown.

6. Grounding scheme

‘Figure 14’ depicts a typical grounding scheme for the negative ion system at IPR.

![Figure 14. Typical grounding scheme for the negative ion system at IPR](image)

The grounding will be as per IS: 3043-1987 ‘Code of practice of earthing’ and IS: 732-1989 ‘Code of practice for electrical wiring installations’. All the needed ground connections should terminate at one point called the star point or the main ground connection point. Formation of ground loops will to be avoided to the maximum possible extent. This will be ensured by grounding only one end of the ground sheath of the cable at the relevant end. On the other end the ground sheath should be peeled off...
to a certain length and only the central cable should be used for the main connection. All the terminations, hydraulic or electrical, adaptors, vacuum gauges, pumps etc. will be isolated. All the electronics related to the diagnostic set ups including the signal processing modules, various power supplies, gauges etc. at the source end will be isolated from the ground for the reason that they are at the source potential. The ground connection of the racks containing these modules will also be connected to the star point. On the data acquisition end, the racks containing the data acquisition modules, signal-processing modules etc. will be physically isolated from the ground. The ground connection for these racks as well as the modules needs to be routed again from the star point.

7. Shielding scheme
The experimental area housing the RF generator, the matching network, the isolation transformer and source part upto the plasma box in the negative ion system will shielded inside a cage made of aluminum mesh sheets. This is to avoid the radiations of the order ~ 150 V/m from the source, to affect the personnel working in the periphery of the experimental setup. Moreover, such kind of field strengths can completely corrupt the signals and the electronics for measurement and control. As the experimental site at IPR is surrounded by the power supplies of the SST-1, additional shielding using the same Aluminum mesh (4 mm thick strips with 8mm gap between individual strip) is required for the area housing the data acquisition and control racks and computers etc. ‘Figure 15’ depicts the typical shielding scheme, alongwith its grounding, proposed for the negative ion system at IPR.

Figure 15. Proposed shielding scheme for negative ion system at IPR

Measurement using the radiation meter will be performed at the IPR experimental setup, once the RF has been switched on, to ensure that the radiation levels are limited within the allowable value (13.2 V/m near vacuum chamber and 3 V/m near the DAC racks).

8. Detailed power supply interconnection scheme
‘Figure 16’ depicts the detailed power supply interconnection scheme including the measuring equipments, protection devices and auxiliary power supplies. The input isolation transformer connections are also shown. This scheme will ensure reliable connection and easy troubleshooting during the commissioning stage of the negative ion system at IPR.
9. Summary

Power supply system for the Negative ion source programme at IPR is discussed. The system is divided among HV and heating & Bias power supplies. Various parameters of the HVPS along with the integration and measurement scheme have been discussed. A typical breakdown grid breakdown detection scheme is presented along with the operational aspects of the HVPS. Various parameters and operational procedures for the heating and bias power supplies are presented and a typical power supply interconnection scheme is shown for easy understanding. Passive protection schemes and various design parameters are presented. A detailed grounding and shielding scheme is proposed for the negative ion system at IPR is presented. A complete interconnection scheme is presented and discussed which will aid in the error free connections and easy troubleshooting during the commissioning of the system.

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