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Design of power supply system for the prototype RF-driven negative ion source for neutral beam injection application

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HIGHLIGHTS

- A supporting power supply system was designed in details for a RF-driven prototype negative ion source at ASIPP.
- The RF power supply for plasma generation adopts an all-solid-state power supply structure.
- The extraction grid power supply adopts the pulse step modulator (PSM) technology.

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ABSTRACT

In order to study the generation and extraction of negative ions for neutral beam injection application, a prototype RF-driven negative ion source and the corresponding test bed are under construction at Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP). The target of the negative ion source is extracting a negation ion beam of 350 A/m^2 for 3600 s plasma duration and 100 s beam duration. According to the required parameters of test bed, the design of power supply system is put forward for earlier study. In this paper, the performance requirements and design schemes of RF power supply for plasma generation, impedance matching network, bias voltage power supply, and extraction voltage power supply for negative beam extraction are introduced in details. The schemes provide a reference for the construction of power supply system and lay a foundation for the next phase of experimental operation.

1. Introduction

As a well-established technique for plasma heating and current driver, the neutral beam injection (NBI) is a promising option for future fusion devices, such as ITER [1], JT-60SA [2], and DEMO [3]. Because a long penetration distance of neutral beam is required in these large devices, an initial negative ion beam is necessary to attain an acceptable neutralization efficiency. According to the previous experimental results [4–6], one of the largest challenges is to increase and maintain the production efficiency of negative ions (extracted ion current density >300 A/m^2) in a long pulse operation (plasma pulse >3600 s).

For the research and development on the generation and extraction of negative ions, a prototype RF-driven negative ion source [7] (shown in Fig. 1) and the corresponding test bed are under construction at Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP). The main parameters of the prototype RF-driven negative ion source are listed in Table 1. Such concept of RF-driven negative ion source for NBI application has been demonstrated on several test beds [8–10], and it is chosen for the final design of ITER-NBI negative ion source. The application of RF driver is beneficial to steady state operation and Cs surface production of negative ions without tungsten pollution [1,6]. The plasma from the RF driver diffuses into the bucket chamber for further collisions to generate negative ions. A magnetic filter is used to cool down the electron temperature in front of plasma grid [11]. Because the high energetic electron will destroy the negative ions. The magnetic filter may also reduce the co-extracted electrons. The negative ions are extracted and accelerated through a multi-aperture grid system [12]. Rows of magnets are embedded inside the extraction grid to deflect the co-extracted electrons. Moreover, in order to suppress the co-extracted electron, the plasma grid is positively biased against the source [13].

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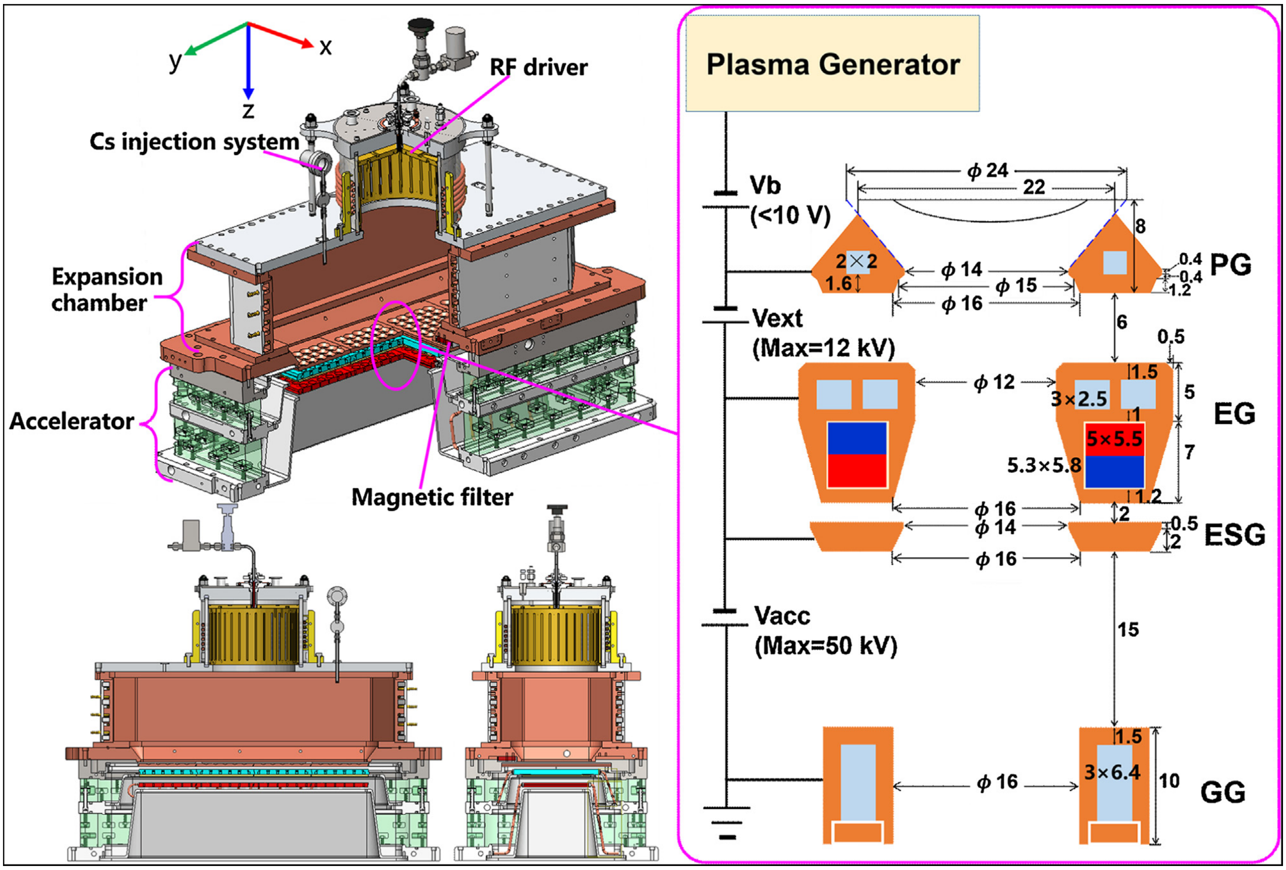

Fig. 1. The prototype RF-driven negative ion source at ASIPP.

Table 1
The main parameters of prototype RF-driven negative ion source.

Parameter	Description
Species	H
Plasma generator	RF driver, 50 kW
Dimension	65cm(L) × 26cm(W) × 19cm(H)
Extraction area	12 × 48 cm^2
Extraction voltage	≤12 kV
Acceleration voltage	≤50 kV
Apertures	5 × 6 each segment, 4 segments, ø14 mm
Ion current	≥350 A/m^2 with Cs-seeded
Electron content (j_e/j_{H-})	<1
Pulse length	≥3600 s negative ions production 100 s negative ions acceleration

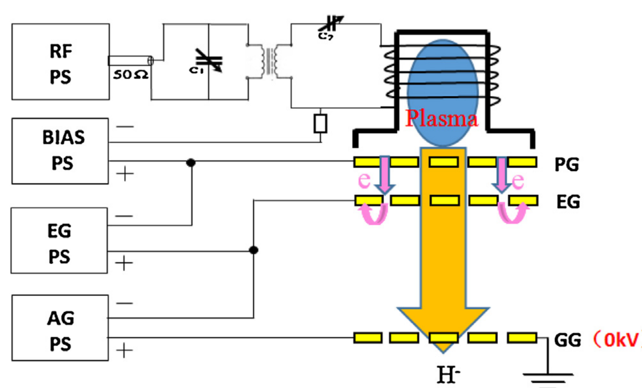

Fig. 2. The power supply system for negative ion test bed at ASIPP.

The first target of prototype RF-driven negative ion source is long pulse (≥3600 s) generation of negative ions in the Cs-seeded RF source. The second target is high current density (≥350 A/m^2) extraction of the negative ion beam. In order to realize these targets, a power supply system for the test bed is in development, which includes RF power supply, bias voltage power supply, extraction voltage power supply, and acceleration power supply. The design of each power supply is analyzed in details in this paper.

2. Overview of power supply system

According to experimental requirements and the other power supply systems for negative ion based NBI [14–17], the power supply system for the negative ion test bed at ASIPP consists of several independent parts (shown in Fig. 2): (1) high power RF power supply (RF PS) and matching network for driving and generating the plasma, (2) extraction grid power supply (EG PS) for extracting the negative ions, (3) bias voltage power supply (BIAS PS) for changing the plasma voltage to increase the yield of negative ion and suppress the co-extracted electron, and (4) acceleration grid power supply (AG PS). As the requirement of acceleration voltage is not high at the present stage, the AG PS adopts the existing acceleration grid power supply of neutral beam test stand at ASIPP [18,19]. The power supply for extraction grid is an independent unit instead of a branch of acceleration power supply.

3. RF power supply and matching network

3.1. RF power supply

According to the research plan of prototype RF-driven negative ion source, the design parameters of RF power supply is the out-

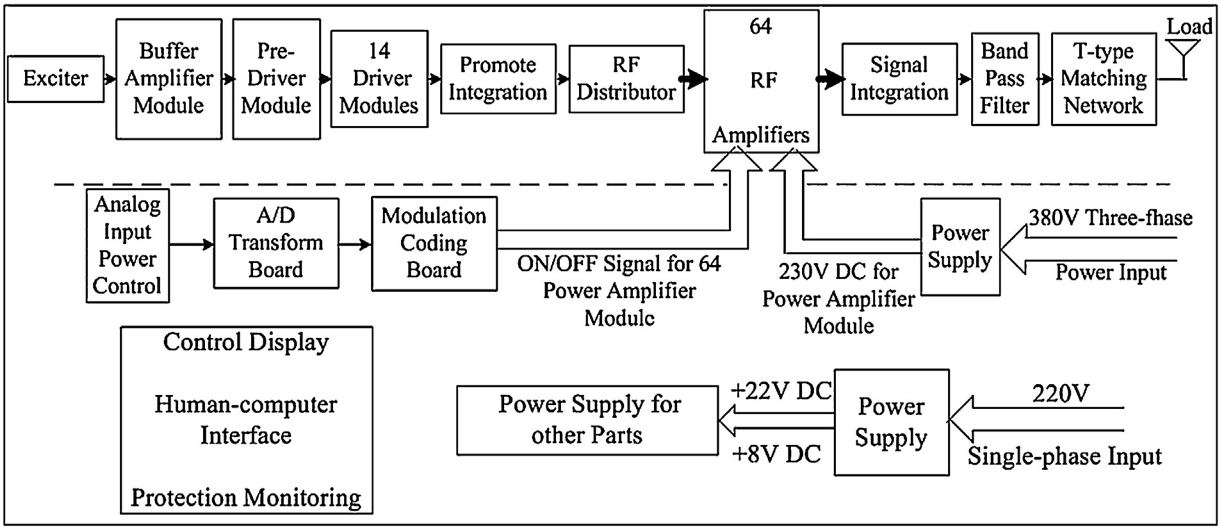

Fig. 3. The structure of RF power supply for the prototype RF-driven negative ion source.

put power of 50 kW and the frequency of 1 MHz. Such frequency becomes a standard value in the high power RF driver for NBI application. It is beneficial to the RF wave cross the copper made Faraday screen into the driver [20]. Comparing the structure of the RF power supply based on the traditional electronic-tube, the power supply with all-solid-state structure [21] has these advantages below: compact size, low cost, modularization design, high efficiency (> 85%) and constant frequency. Therefore, the RF power supply of test bed adopts the all-solid-state power supply structure. Fig. 3 shows the design scheme of RF power supply.

As shown in Fig. 3, the RF power supply contains two parts, one is RF path part (above the dotted line), and the other one is power control part (under the dotted line). The main function of RF path part is to amplify RF small signal generated by exciter to rated power systematically. Firstly, the small RF signal (1 MHz) is amplified by buffer amplifier. Then, it is further converted into a sine wave by pre-driver module and third-stage amplified by 14 driver modules. The amplified signal is transmitted to 64 final-stage amplifiers after synthesis and tuning. The output power of each final-stage power amplifier is about 1 kW, so the total output power of 50 kW is required to switch on 50 modules. The design schemed with 64 amplifier modules takes RF power supply enough load capacity.

Especially, the concept of high frequency transformer is adopted as power synthesis network. Its element is shown in Fig. 4. The transformers $T_1 \sim T_m$ have same turns ratio K, and $R_1 = R_2 = \ldots = R_m$.

When the power synthesis network is in work mode, the RF excitation voltage is fed from the both ends of R_1, $R_2, \ldots R_m$. For the primary coil of transformer, $U_1 = U_2 = \ldots U_m = U$, $I_1 = I_2 = \ldots I_m = I$, $R_1 = R_2 = \ldots R_m = U/I = R_O$, $P_1 = P_2 = \ldots P_m = IU = P$. It can be obtained from the secondary coil that, $U_{L1} = U_{L2} = \ldots U_{Lm} = U/K$, $U_L = U_{L1} + U_{L2} + \ldots U_{Lm} = mU/K$, $I_L = U_L/R_L = KU/R_O = KI$, $R_L = U_L/I_L = mR_O/K^2$. Finally, the synthesis power on the R_L is $P_L = I_L \cdot U_L = KI \cdot mU/K = mIU = mP$. Through this concept of power synthesis network, the power out of the 64 RF amplifiers is combined into a single RF power output.

The functions of the power control part are power-controlling, monitor, protection. Power control part consists of three parts: analog input, A/D conversion, and encoder. The functions of these three parts are listed below: (1) analog input card generate a DC signal varying with the power, (2) A/D conversion card convert the DC signal into the 12-bit digital signal, (3) encoder convert the 12-bit digital signal into the ON/OFF signal of 64 power amplifier modules.

Because the frequency of standing wave is same with that of carrier wave, the reflected power can also transmit in the same

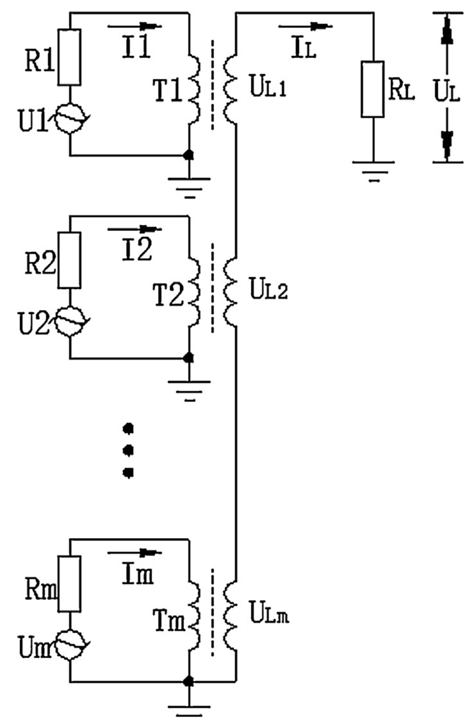

Fig. 4. The power synthesis network of high frequency transformer.

circuit. As a result, the reflected power will deposit on the power tube of RF power supply. Therefore, an allowance of power capacity is considered to accept the reflected power. Here, the maximum allowable reflected power is designed to be 20% of required output power. Thus, the actual capacity of the RF power supply is 60 kW. In addition, an automatic protection will intervene to stop the power supply, when the reflected power exceeds 20% of total setting output power.

3.2. Matching network

Impedance matching is a state that load impedance is adaptive to the inner impedance of excitation source and transmission line. Because the circuit is in matching state, the RF power of excitation source can be transmitted to the load with no or less

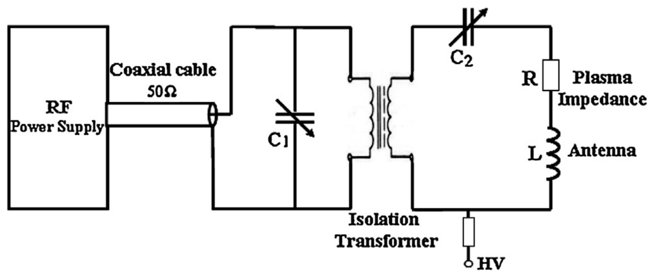

Fig. 5. Matching circuit of the prototype RF-driven negative ion source.

reflected power. In this case, the matching network has the highest transmission efficiency. Conversely, if the circuit is in impedance mismatching, the load cannot obtain the highest power and the reflected power could damage the circuit and electronic bed. The matching circuit of the prototype RF-driven negative ion source is shown in Fig. 5.

The 1 MHz power generated by RF power supply transmits into matching network through the feeder with 50 Ω characteristic impedance. When the LC circuit is in a resonant state, the maximum power can be transmitted. As shown in Fig. 5, C1 and the primary side of isolation transformer form a parallel resonance circuit, C2 and secondary side of the isolation transformer form a series resonance circuit. In order to realize the suitable matching, C1 and C2 are designed to the adjustable capacitor. The measured inductance L of the antenna is 8.55 μH. The reference value of plasma impedance is 2 Ω, which is based on the previous theoretical and experimental works [21,22]. The RF ion sources used in these works have similar structure and geometry with our design. Through a calculation, C1 and C2 are both set to 2–4.3 nF. Isolation transformer insulates the RF power supply and ion source at a high potential during beam extraction experiment. The matching network is installed in a shielding box (shown in Fig. 6).

Comparing with the preliminary design [20,23], the matching box has been optimized as following: (1) in order to meet the requirement of beam extraction, the isolation transformer is inserted into the matching circuit, (2) in order to ensure better insulation, the C1, C2 and isolation transformer are supported with Teflon material, (3) increase the size of matching box and reduce the distributed capacitance impact on the matching performance.

4. Bias voltage power supply

Bias voltage power supply provides a bias voltage between plasma grid and bucket chamber. A positive voltage makes the negative ions in extraction region close to the plasma grid, so it can increase the yield of negative ions. Meanwhile, the electrons are more easily attracted and suppressed onto the plasma grid surface. According to the experimental results of similar source [24], the design value of bias voltage and current is DC 0–30 V and 0–50A for the prototype RF-driven negative ion source, respectively. The bias voltage power supply can operate in two modes of voltage or current feedback, and the alignment accuracy (voltage and current) is less than 1%. The bias voltage power supply is adopted a high accuracy rectifier design.

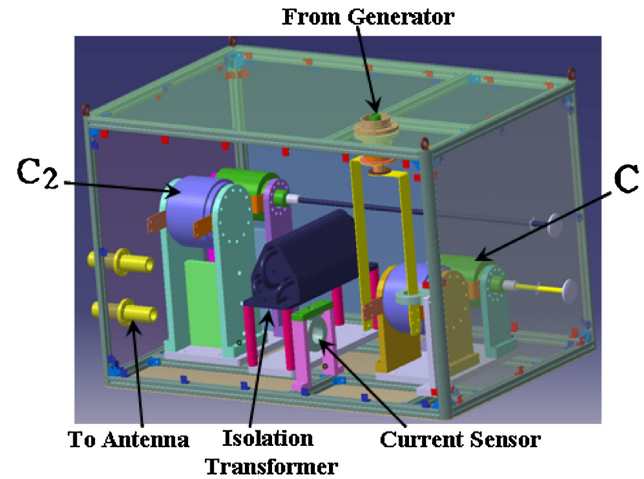

Fig. 6. The matching box for the prototype RF-driven negative ion source.

Fig. 7 indicates the block diagram of this power supply. Bias voltage power supply is a high precision rectifier supply. As working on the high voltage of AG (as shown in Fig. 2), the power frequency of AC input at ground potential is isolated from the power output end of AG at the high potential by an isolation transformer. An EMI filter is used to filter the harmonic component from the grid. And the AC input is finally converted into the high precision DC voltage/current by AC/DC rectifier and LC filter. As the power supply work at the high potential of AG, all the control and data signals are transmitted via optical fiber.

5. Extraction grid power supply

Extraction grid power supply provides a certain voltage difference between extraction grid and plasma grid. The negative ions are extracted from bucket chamber by the extraction voltage, and the electrons are co-extracted at the same time. The stability of extraction voltage directly influences the beam optics of negative ion beam. The beam current of negative ion and co-extracted electron will increase with the rise of extraction voltage, but the high-energy electrons are dumped on the extraction grid and result in a high heat load. Hence, the operating range of extraction voltage is below 12 kV. Considering the negative ion current of 350 A/m^2 and an equal election current, beam current of 14 A (including negative ions and co-extracted electrons) will be extracted in the prototype RF-driven negative ion source. For the negative ion test bed at ASIPP, the parameters of extraction grid power supply are listed in Table 2.

The high voltage power supply based on pulse step modulator (PSM) technology [25,26] has been successfully used for the ion source of EAST NBI at ASIPP. It shows a high stability and reliability

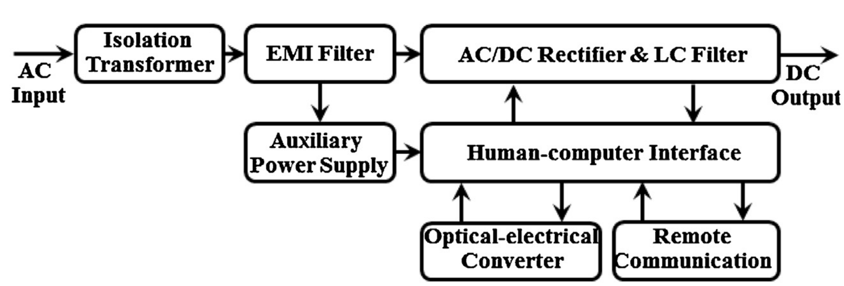

Fig. 7. The structure of bias voltage power supply.

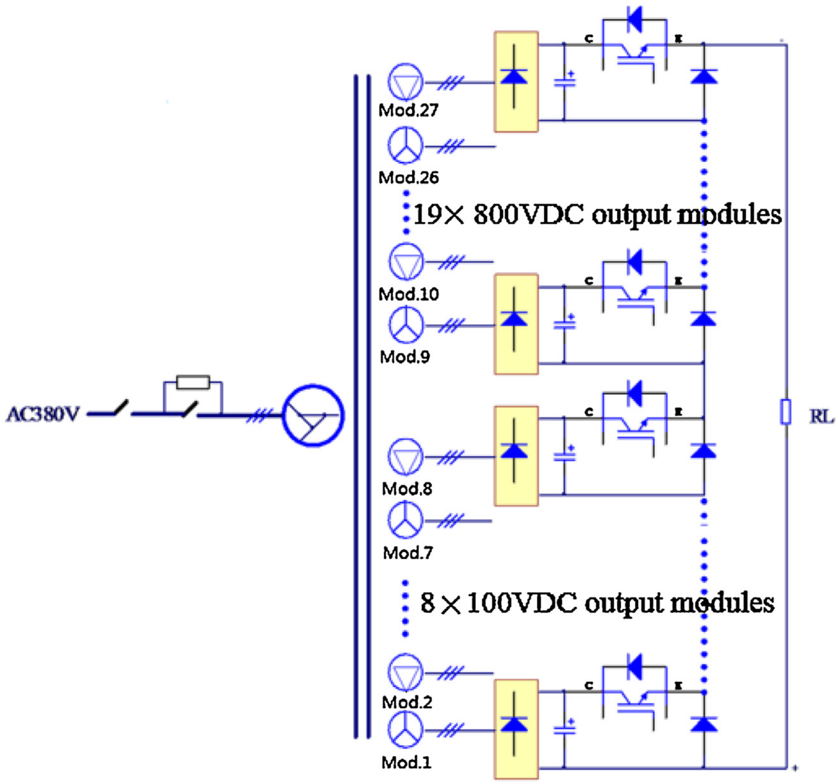

Fig. 8. The electric scheme for the extraction grid power supply.

Table 2
The parameter of extraction grid power supply.

Parameter	Ratings
Output voltage	−16 kV DC
Output voltage range	0–100%
Output voltage resolution	100 V
Rated output current	20 A
switch-on time	50–200 μs
Maximum switch-off time	100 μs
Energy onto breakdown	10 J
Quantity to be controlled	Voltage
Pulse duration	Stable state
Efficiency at full power	>80%

during the EAST NBI experiments. Hence, a similar PSM structure is also applied to the extraction grid power supply, except for the output voltage classes of secondary coil. Its electric scheme is shown in Fig. 8. Three phase AC 380 V is connected to the primary side of the multi-winding transformer in slow start mode. The secondary side of transformer exports 19 sets three phase AC 590 V into 19 power modules (800 V/20 A) and 8 sets three phase AC 75 V to 8 power modules (100 V/20 A). Those power modules adopt the design of three phase uncontrolled rectifier and capacitor filtering. The power output is controlled by the IGBT that connected with power modules in series and the function of the diode connected with IGBT in parallel is freewheeling as the IGBT is off. The output voltage is controlled by means of the number of output module and this scheme can meet the requirements of output voltage control precision and rise time.

The output voltage of 100 V has been considered for each modular, but it will result in the increase of modular. So the different voltage classes for secondary coil of transformer is put forward for extraction grid power supply. The PSM modular with different voltage classes can improve the accuracy of power supply and simplify the power supply structure. However, a new control mode for modular is needed to be developed due to different voltage class modular.

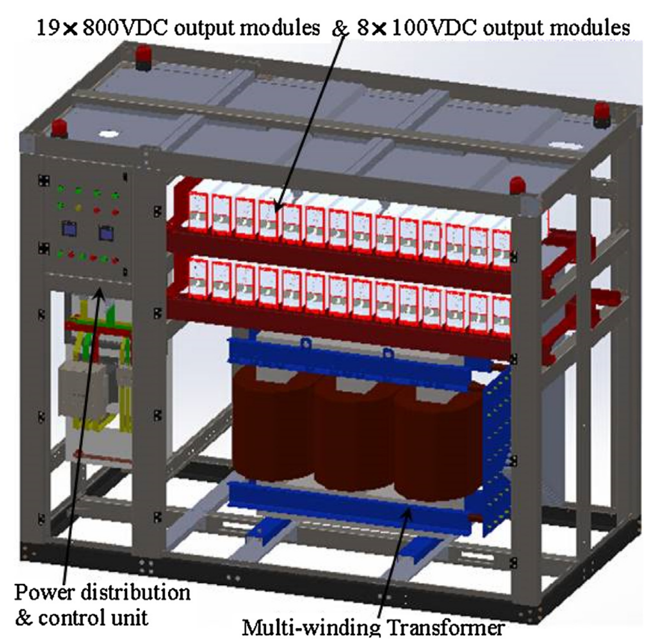

Fig. 9. The prototype extraction grid power supply.

Fig. 9 displays the prototype extraction voltage power supply of negative ion test bed at ASIPP. As extraction power supply works in the potential of AG (high potential) (as shown in Fig. 2), the multiple winding transformer of EG power supply can isolate the high potential from the AC 380 V power input (the ground potential) as the accelerating voltage is not high in the initial stage of test bed. All the power supply are supported by tailor-made insulator bracket and

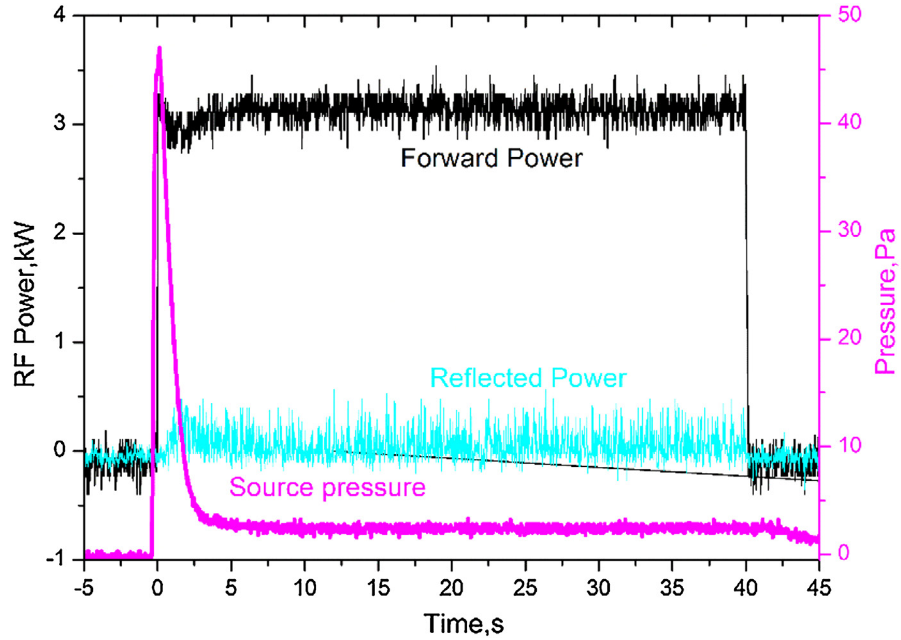

Fig. 10. The preliminary operation results of RF power supply on the RF positive ion source.

Table 3
The key parameters of each power supply.

Power Supply	Parameters
RF P. S.	Solid state design Required output power 50 kW Maximum output power 60 kW RF frequency 1 MHz
Bias voltage P. S.	Rectifier design DC output 0–30 V, 0–50A Alignment accuracy <1%
Extraction grid P. S.	PSM design 19 modular of 800 V/20A 8 modular of 100 V/20A DC output 0–16 kV, 0–20A

the signals, such as control of power supply module, conditional monitor, output voltage and current measurement, are transmitted using optical fiber. As the accelerating voltage need to be increased with the development of test bed, the multi-winding transformer is replaced by the oil immersed transformer with higher isolation level. The total extraction grid power supply will be put on the tailor-made high voltage platform for getting higher isolation level.

6. Conclusion

A prototype RF-driven negative ion source and the corresponding test bed are setting up, aiming to extract a negative ion current density of >350 A/m^2 during the long pulse duration. A power supply system is designed to meet the experimental requirements. It is composed of RF power supply, bias voltage power supply, extraction voltage power supply, and acceleration power supply. The key parameters of newly developed power supplies are listed in Table 3.

So far, the design of all power supplies has been completed. The manufacture of RF power supply was prior finished in 2016, because it will be also applied to the development of RF positive ion source for EAST NBI. The preliminary operation result on the RF positive ion source is displayed in Fig. 10. A stable hydrogen gas discharge was obtained with 3 kW output power. The other power supplies are planned to be finished in the end of 2016. The processing of negative ion source and test bed has been completed 80%. The assembly is planned to be accomplished at January 2017. The commission of all power supplies on the negative ion source is scheduled at February 2017.

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