Development of a large beam facility

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Abstract A large beam facility for the application of high power ion beams has been developed at the Korea Atomic Energy Research Institute (KAERI). The primary usage of this facility is to develop an 8 MW neutral beam heating system for a tokamak, but other applications using a large beam would also be possible in the near future. The facility is composed of a bucket ion source (120 kV, 65 A), related beam line components including a large vacuum chamber (3 m × 4 m × 5 m), power supplies for the ion source, control and DAS (Data Acquisition System), beam diagnostics system, and a water circulation system (2 MW) for cooling of the beam line components. The maximum beam parameters at present are a beam energy of 87 kV and a beam current of 17.5 A with a beam size of 13 × 45 cm^2. A maximum pulse length of 10 s could be achieved with a 1 MW beam power. The beam power with a hydrogen ion will be increased up to 7.5 MW during 5 s.

Key words beam facility • high power ion beam • neutral beam • beam line component • cryosorption pump

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Introduction

High power and/or large ion beams have a big potential to be applied to various areas such as fusion energy generation, material sciences, surface physics, semiconductor processes, intensive heat flux engineering, and others [6]. A large ion beam facility, which has been designed and constructed at the Korea Atomic Energy Research Institute to test the Neutral Beam Injection System for KSTAR tokamak [3], could be applied to other areas with little added efforts at any time.

The beam facility consists of an ion source, beam line components, power supplies, cooling circuits, control & DAS system, and beam diagnostics system. The ion source was designed to extract 120 kV and a 65 A deuterium beam with a rectangular beam size of 13 × 45 cm^2 at the exit grids. Beam divergence is limited to less than 1°. Beam line components include a vacuum chamber, a neutralizer, a bending magnet, ion dumps, a calorimeter, and cryosorption pumps. They limit the beam size to less than 20 × 55 cm^2 at a distance of 5.2 m from the ion source. Depending on the experimental conditions a neutral beam could be made by filling hydrogen gas into the neutralizer and activating the bending magnet. A cryopump is also necessary to minimize the re-ionized ions during a beam transport, and to maintain the pressure of an ion source as

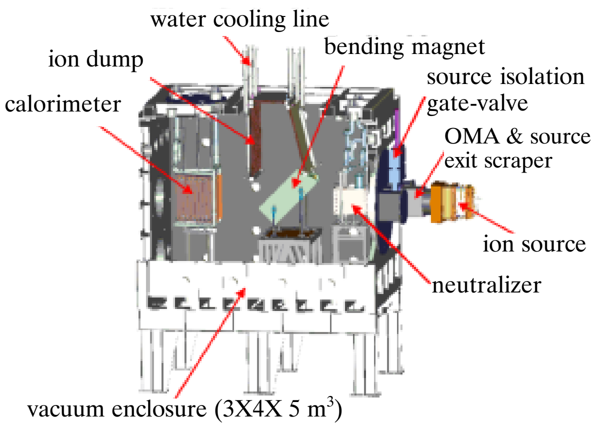

Fig. 1. Schematic diagram of the large beam facility at KAERI.

constant. An acceleration power supply, an arc power supply, a filament power supply, and a deceleration power supply make the needed powers in proper timings for the ion source. OMA (Optical Multi-channel Analyzer) system is used for measuring the beam divergence and ratio of the beam species (H^+:H_2^+:H_3^+), and an IR camera is used for measuring the beam profile and temperature distributions in the target. Water flow rates and water temperatures at the points of the inlet and outlet of all the components are measured to calculate the dissipated energies within them. Also there are many thermocouples on every beam line component to measure the temperature profile on the target surface. PXI (personal computer based VXI system) modules controlled by LabView acquire the data from the thermocouples and flow meters. The capacity of the cooling system is 2 MW during a continuous operation. Figure 1 shows a schematic diagram of the layout of the vacuum components including an ion source.

The recent activities have been concentrated on high power beam extraction experiments and related upgrades for the completion of the beam facility. A long pulse of 60 kV and 14 A hydrogen beam during 10 s, and a short pulse of 87 kV and 17.5 A hydrogen beam during 0.5 s have been reached. The long pulse limit was created by a calorimeter problem, and the short pulse limit was created by ion source problems. The final beam power will be upgraded to 80 kV and 30 A without a time limit, and 120 kV and 65 A during 5 s. The maximum beam power is limited by the cooling capacity of the facility. In this paper, facility descriptions including the required information, which is important for the users of a large beam, have been described.

Ion source and beam experimental results

The ion source developed for the KSTAR NB (neutral beam) system is composed of a plasma generator [4] and a beam accelerator. The type of plasma generator is a multi-cusp chamber where the arrangement of the magnets is set to form magnetic cusp fields to contain the plasma. The multi-cusp source is capable of producing large volumes of uniform, quiescent and high density

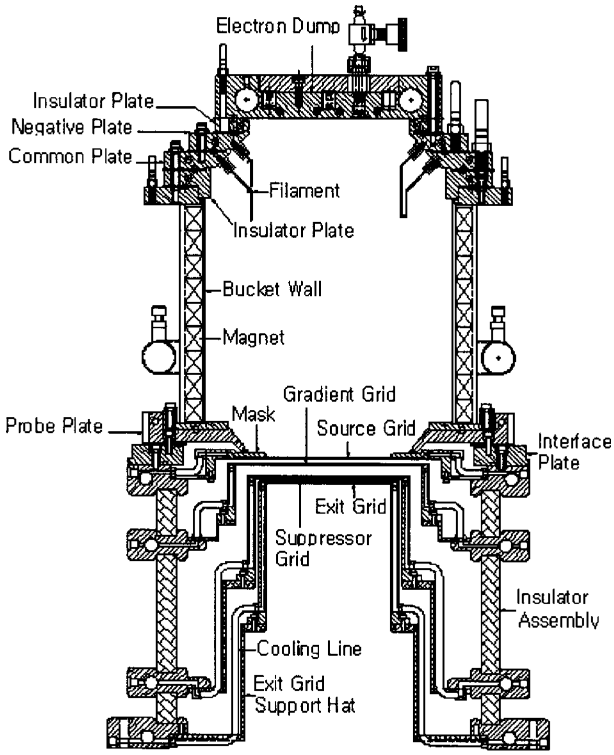

Fig. 2. Developed bucket ion source.

plasmas with high gas and electrical efficiencies. The plasma chamber has a cross section of 26 cm × 64 cm and 32 cm deep, and axial arrays of Sm-Co permanent magnets (4.65 kg ± 2%) spaced between the cooling channels which are lined up on the wall to make the cusp field around the inner wall of the chamber. An array of 32 tungsten filaments (1.2 mm diameter) is used as a cathode. Three kinds of different filament shapes are used in order to obtain a plasma uniformity throughout the chamber. The filaments are mounted on the water-cooled filament assembly, which contains one positive and one negative filament plate. Precisely aligned four sets of circular aperture grids extract the high energy and high current ion beams from the plasma generator. The schematic drawing of the assembled ion source including the four accelerating cupper grid modules is shown in Fig. 2. There are 586 circular apertures (7.2 mm diameter) on every set of grids. For the long pulse operation cooling channels (1.8 mm diameter) are aligned well between the aperture layers.

Figure 3 shows typical beam extraction results [1] with the developed ion source, when a beam of 87 kV and 17.5 A during 0.5 s beam was created. Designed currents of the ion source depending on the beam energy are shown with a solid line, and the achieved values with a dotted line in Fig. 4. It shows that the critical problem at present is a lesser beam current than the designed one. An OMA system is used for estimating the quality of the extracted beams by the values of the ion ratio and beam divergence. The measured ion ratios (Fig. 5) are 41.1%, 18.2% and 39.7%, and the divergences (Fig. 6) are 1.45°, 1.70° and 1.68° for a beam of H^+, H_2^+, and H_3^+, respectively. The OMA spectrum was obtained for a 60 kV accelerating beam during a full

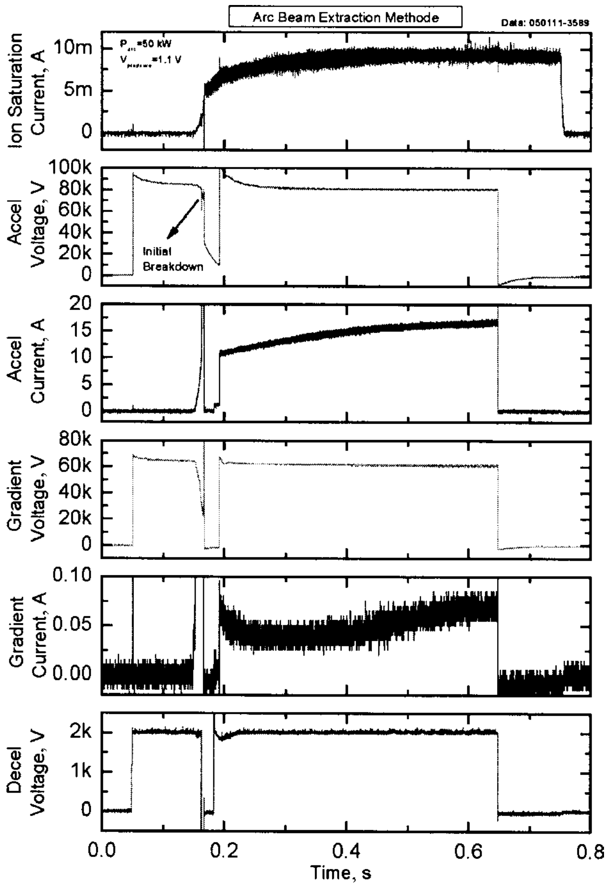

Fig. 3. Recent beam extraction results.

extraction time. The goal for the H^+ ratio is more than 80%, and the beam divergence is less than 1.0°.

The new grids are being fabricated with a new design to get obtain beam currents and high voltage holding characteristics. Minimization of the fabrication and assembling errors to within 50 μm and an improvement of the high voltage holding characteristics in the accelerator are the main topics of this upgrade. Depending on the experimental objectives, other ion beams could also

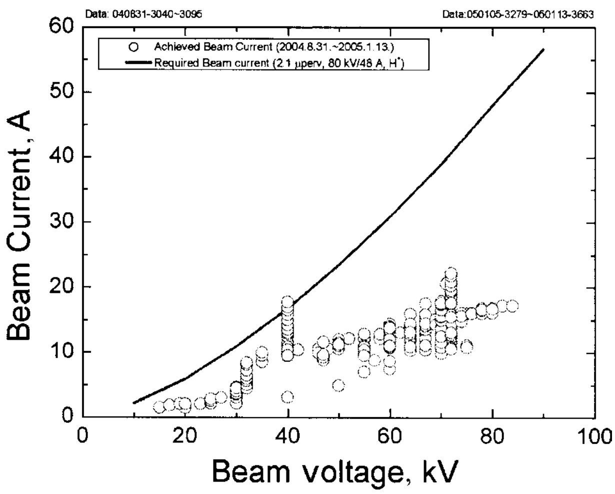

Fig. 4. Designed and achieved currents of the prototype ion source depending on beam energies.

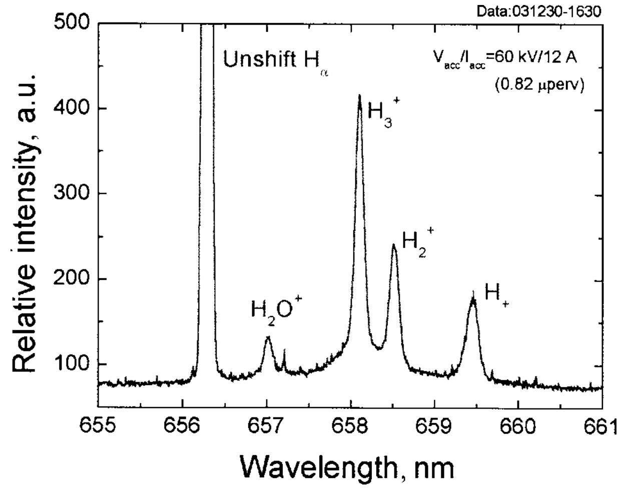

Fig. 5. OMA data for a calculation of the beam ratio.

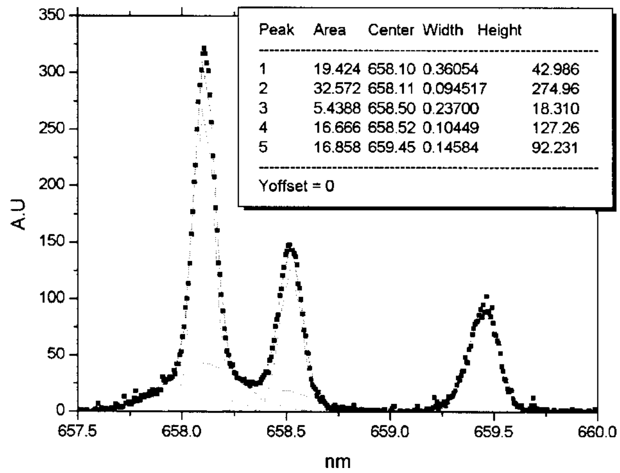

Fig. 6. OMA data for a calculation of the beam divergences.

be created if different gases are supplied to the ion source.

Beam line components

All of the beam line components including a neutralizer, a bending magnet, ion dumps, a calorimeter, and cryosorption pumps are installed in the large vacuum chamber, whose size is 3 m × 4 m × 5 m, and being tested with the beam load. The chamber has 81 ports for installing beam-line components, vacuum pumps, and beam-diagnostic tools. A pressure of 9×10^{-7} torr is usually obtained with a 5500 l/s TMP. An ion source and an OMA chamber, which are isolated from the main chamber by 630-mm-diameter gate valves, are installed to the source ports.

The bending magnet is designed to deflect the 120 kV deuterium beam 60° upward from the beam axis with the magnet current of 750 A. Low carbon steel (S10C) is used for the pole and yoke, and stainless steel is used for the case of the epoxy-molded-coil. Actively cooled pole-protection-plates, an electron dump and pre-magnet scrapers are prepared for the long pulse operation. The ion dump, located above the bending magnet, consists of three sets of plates which are made by swirl tubes. Pipes (inner diameter: 16 mm, thickness: 2 mm) made by 0.2% Ag OFC (oxygen-free copper) and stainless steel swirl tape (thickness: 1 mm, twist ratio 2.0) are used in making the tube. The designed heat flux is 1 kW/cm^2. To measure the ratio of the ion species, each plate has its own calorimetric system in the cooling circuit. Hypervapotrons are used in the calorimeter and neutralizer as a cooling unit. It is also designed to have sufficient thermal capability corresponding to the maximum heat load of 1 kW/cm^2 for the long-pulse operation. The element is manufactured from a copper-chromium-zirconium alloy that is electron-beam welded. The calorimeter is made by a total of 32 beam stopping elements (Hypervapotron unit; 112 mm × 1000 mm) arranged in two panels forming a V shape. The opening angle between the panels is 28°, and the effective aperture size is 430 mm × 1000 mm. It can handle 2-MW beam safely for the long-pulse operation. 64 thermocouples are distributed on the calorimeter to measure the temperature of each element and the beam power profiles.

The cryopumping system consists of four cryosorption pumps, each of which is composed of a cryosorption pump body, a G-M helium refrigerator, and a 150 l liquid N_2 bottle. The G-M refrigerator is installed upside down on the roof of the large vacuum chamber. The baffle and the lower thermal shield are put on the thermally insulated frame fixed to the chamber wall and cooled by liquid nitrogen. The main components of the pump body of the cryosorption pump are an 80 K thermal shield and a 20 K cryosorption panel. The thermal shield is divided into upper/lower circular plates and a cylindrical baffle that allows gas molecules to pass through and to be adsorbed on the cryopanel. The baffle consists of 50 chevron blades of 120° bending angle. The blades are placed regularly at 7.2°, and form as a whole a cylinder of 550 mm O.D., 356 mm I.D., and 1000 mm L. The cryopanel consists of 4 identical AC (activated carbon)-coated rectangular plates of 145 mm × 1000 mm, brazed to a center rod along the long side at intervals of 90°. The surface density of the AC layer is about 500 g/m^2. All the adsorbing surfaces of the cryopanel look directly at the baffle in contrast with the case of a commercial one. Therefore, most gas molecules transmitting the baffle can reach the surface of the cryopanel without additional reflections, and a maximum hydrogen pumping speed can be obtained. Figure 7 shows the temperature variation of the cryopanel when cooling the baffle, and operating the refrigerator. The ultimate temperature is about 18 K, which is attained in about 6 h after the start of cooling. Liquid nitrogen of 150 liter is consumed to cool down the baffle to 80 K in 3 h and to keep the temperature for 2 h, and another 150 liter is spent to maintain the cooling stage for 6 h. This means that it is possible to carry out the beam extraction experiment for at least 5 h under the full pumping speed of the cryosorption pump at the consumption of liquid nitrogen of 300 liter. The pumping speed of the cryosorption pump is shown in Fig. 8 as a function of the cryopanel temperature. The cryosorption pump starts to show its

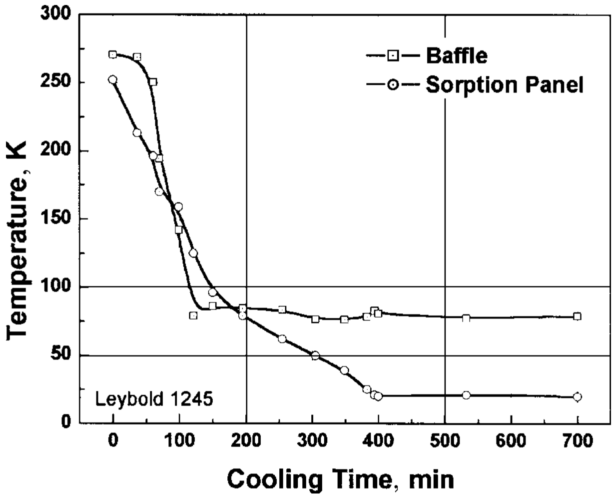

Fig. 7. Variations of panel temperatures with time.

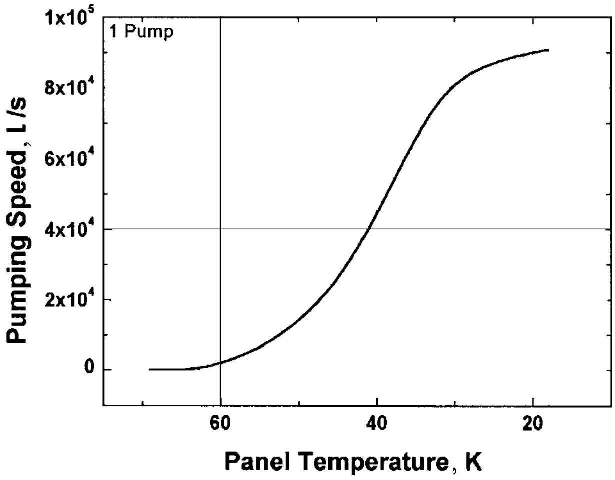

Fig. 8. Pumping speeds of the cryosorption pump for H_2 depending on panel temperature.

pumping capability for the hydrogen gas at a temperature of around 60 K. The pumping speed is steeply increased at a temperature below 50 K and reaches the ultimate level of about 90.000 l/s at below 20 K. The sticking coefficient is calculated by comparing the measurement and the Monte Carlo simulation to be about 0.6 [2, 7], when assuming T_{gas} = 240 K.

Power supplies

The power system [5] for the beam facility consists of an acceleration power supply, a deceleration power supply, a gradient grid potential divider, an arc power supply, a filament power supply, and a snubber bias power supply. Among these, arc, filament and snubber bias power supplies are on the high voltage deck floated at the accelerating potential, and powered via isolation transformer. Figure 9 shows the principal interconnections for the power supplies and how these are connected to the grids and the arc plasma chamber of the ion source. The ratings of the power supplies are summarized in Table 1.

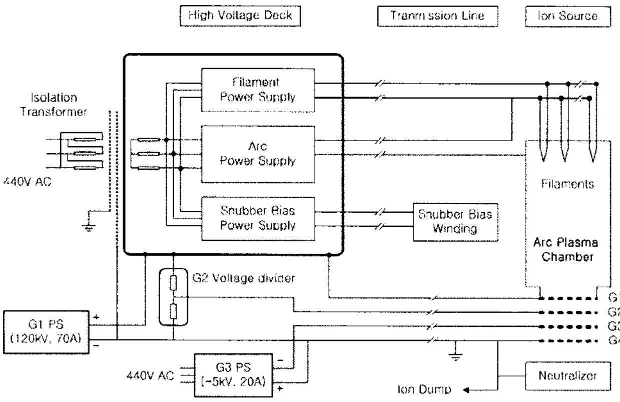

Fig. 9. Basic interconnection diagram for the power supplies.

The acceleration power supply powered from a 22.9 kV 3-phase AC line is made of 6 units of modular high voltage DC sources among which 5 units are of 22 kV fixed (HVTR; High Voltage Transformer & Rectifier) and last one is of variable from 0 to 32 kV with 40 differential steps of 800 V each (LVTR; Low Voltage Transformer & Rectifier), and valve (HVS; High Voltage Switch)/crowbar switches as shown in Fig. 10. The DC link high voltage is set by the active number of fixed high voltage unit of 22 kV and 40 switching power modules. The ions are extracted from the source by an accelerating structure where the electric field is very high (~10 kV/mm): an efficient design requires that the working voltage is near to the breakdown value. Therefore, the breakdown can occur often during beam extraction and must be considered not as a fault but as part of the normal operation of the beam facility. To avoid the degradation of high voltage holding capability, it is very important to interrupt the power very quickly and suppress the breakdown surge into the accelerating structure of the ion source for every breakdown. A high voltage valve switch made of MOSFET is employed to meet the fast switching feature and turn the rated power off within 2 μs. The impact of surge due to the energy stored in the capacitance strayed between HVS and ion source is suppressed by a snubber circuit implemented by amorphous core. As a result, the breakdown surge is finally suppressed to a peak current of less than 1 kA within 1 μs at the rated accelerating voltage of 120 kV.

The oil cooled high power resistive divider of 24 kΩ and 5 A at the rated voltage of 120 kV (600 kW) has 18 taps and provides a potential to the gradient grid of the ion source appropriate to beam

Table 1. Ratings of the power supplies for the large beam facility

	Voltage	Current	Pulse length	Duty
Acceleration P.S.				
1st grid	0 ~ 120 kV	70 A	300 s	1/6
2nd grid	0 ~ 105 kV	5 A	300 s	1/6
Deceleration grid				
P.S.	–(0 ~ 5) kV	20 A	300 s	1/6
arc P.S.	0 ~ 160 kV	1200 A	200 s	1/6
filament P.S.	0 ~ 15 V	3200 A	320 s	1/6
snubber bias P.S.	0 ~ 100 V	100 A	CW	1/1

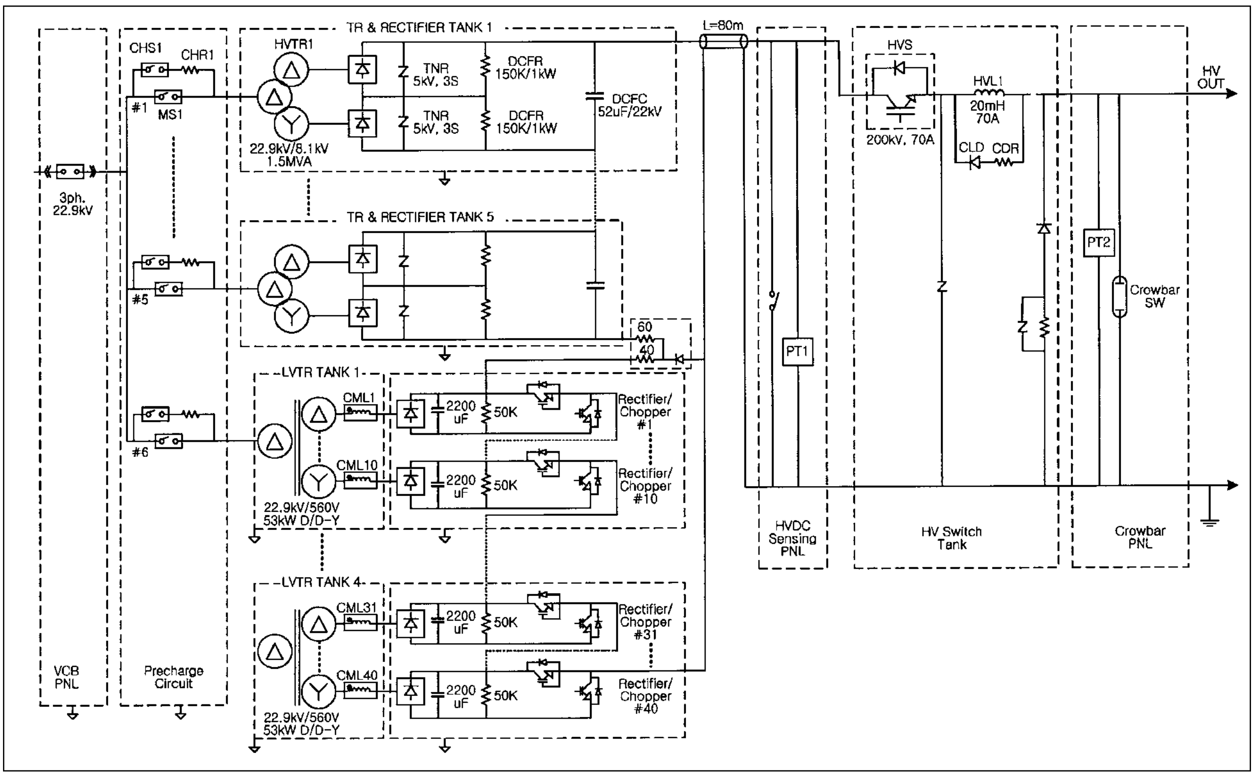

Fig. 10. Schematic circuit diagram of the acceleration power supply.

optics in 18 steps in the range from 90% to 64% with a differential step of 1.5% of the accelerating voltage. The deceleration power supply is equipped with the voltage of –5 kV and the current of up to 20 A for the deceleration grid of the ion source to block the backstreaming electrons from the neutralizer and synchronized with the accelerating voltage pulse. The operation sequence and timing of all the power supplies are managed by a central timing/interrupt controller so as to initiate the beam by the arc discharge plasma all the time.

Other systems

The machine control and DAS system consist of two PCs. One for a power supply control including a timing, and the other for data acquisitions. Labview and PXI modules are being used in the system, which cover 10 kHz 20 channels for a fast sampling, and 10 Hz 206 thermocouple channels for a slow sampling. The angular divergence and the neutral species converted from ion beams can be simultaneously measured using Doppler shift spectroscopy of the H_α spectral line at an OMA chamber (upstream location of the neutralizer) of KSTAR NBI system [8]. Doppler-shifted H_α lines, which originate from different ions, such as H^+, H_2^+, H_3^+, and H_2O^+, are spectrally well separated on the measured spectra. The ratio of mixed species is estimated from the intensity ratio of each peak by using a fully developed emission model, and the angular divergence of each ion beam component is determined from the line widths of the fitted Gaussian. The calorimeter is used for measuring the beam profiles of the ion source on the target. IR camera could also be used for measuring the beam profile on calorimeter or ion dumps. Small water leakage into the vacuum chamber can be detected by using a residual gas analyzer system. A CW 2-MW cooling water system has been prepared for cooling the beam-line components. The cooling system has a water-flow-rate capability of 100 l/s at a pressure of 5 kgf/cm^2. The water quality is controlled by chemical treatments to maintain the resistivity within 1 MΩ-cm.

Conclusion

A large beam facility, which includes an ion source, related power supplies, high power beam line components, a fast vacuum pumping system, and a 2 MW cooling system, has been developed at KAERI. The test results at present are a hydrogen beam of 87 kV, 17.5 A, which could be upgraded up to a beam energy of 120 kV. The OMA system and IR camera system are installed to check the beam quality and beam profile on the target, respectively. High heat flux experiments and large beam applications could be made in the near future.

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