# Development of Neutral Beam Injection System for KSTAR Tokamak

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## Abstract

The design results and the developmental status of the KSTAR NBI system are described. The KSTAR Neutral Beam system shall provide ion heating, current drive, core fueling, profile controls for pressure and current by injecting energetic neutral particle beam, and support diagnostic requirements. The facility shall initially be configured to provide 8 MW of deuterium neutral beam power to the plasma per beam line. It can be achieved by a modification of one TFTR beam line with 300-s pulse lengths. The facility shall be capable of accommodating 14 MW of deuterium neutral beam power to the plasma (one co-directed TFTR beam lines plus one counter-directed TFTR beam line modified for 300-s pulse lengths). The beam line shall be oriented with a tangency radius for the central beam trajectory of 1.486 m. The beams shall inject at fixed angular positions.

## 1. Introduction

Two Neutral Beam(NB) systems are planned to be installed in KSATR tokamak[1] to provide heating and current drive until the start of the upgrade phase. The needed deuterium beam power per beam line is 8 MW with an energy of 120 keV. In order to develop the required NB system, all of the NB components, ion source, and related power supplies should be developed to cover a distinctive KSTAR parameter of 300-second operation time on the bases of the proven technology within the limited period. Ion source, acceleration power supply, and hypervapotron as a cooling component are the critical ones in developing this system.

The basic beam parameters of the KSATR NB system, namely particle energy, power, and pulse duration, were chosen on the basis of proven technologies used in conventional positive ion sources, related beam technologies developed by KAERI, and physical goals of KSTAR tokamak. The NB system shall initially be configured to provide 8 MW of deuterium neutral beam power with 120 kV of accelerating voltage for pulse lengths up to 300 s(20 s in the baseline) to the plasma with one beam line. The expected full energy component is 5.5 MW. It can be achieved by modifying TFTR beam line design to 300 s pulse length. The beam line shall be oriented with a tangency radius of 1.486 m for the central beam trajectory. The second beam line shall be installed during upgrade phase.

## 2. System Layout and Design Calculations

The designed NB system is shown in Fig. 1. The whole components of the system, such as ion sources, neutralizers, a three gap bending magnet, beam dumps, calorimeters, and cryopanels are all assembled in a 3m(W) x 4m(H) x 5m(L) vacuum chamber. Two large cryocondensation panels are lined up on the side of the vacuum vessel for vacuum pumping. A three gap bending magnet separate ions from the mixed beam leaving the neutralizers and direct them to an ion dump installed on the top of vacuum vessel cover. A calorimeter is provided for beam conditioning and for measuring the energy of neutral or mixed beams. Scrapers located along the beam paths define the beam size, and various protective plates protect beam line components from reionization losses and reflected beam power.

The distance from the exit grids of the ion sources to the NB port of the vacuum vessel of KSTAR is 10 m. The results of the particle transport calculation shows that among 24 MW of total input power into three ion sources, 8 MW is transferred to the plasma by neutral beams. Other 16 MW should be transferred finally to cooling water along the beam line. The pumping system for the vacuum chamber is required to maintain the line density integral from the bending magnet to the torus below $5 \times 10^{-5}$ torr-m for 2 % re-ionization. It is necessary to divide the vacuum chamber by baffles into three rooms pumped differentially. In order to control the pressures of each chamber at $P1 = 9 \times 10^{-5}$ torr, $P2 = 2 \times 10^{-5}$ torr, and $P3 = 3 \times 10^{-6}$ torr, the required pumping speeds for each chamber are $S1 = 5.9 \times 10^{5}$ l/s, $S2 = 5.4 \times 10^{5}$ l/s, and $S3 = 6.2 \times 10^{5}$ l/s. Total pumping speed for the NB system is about $2.0 \times 10^{6}$ l/s, which can be achieved by using in-vessel cryopump.

## 3. Component Design and Construction

### Ion Source

The prototype of KSTAR ion source is based on the LPIS[2] (Long Pulse Ion Source) bucket source which has been developed by LBL (Lawrence Berkeley Laboratory), and used in TFTR and DIII-D for more than a decade. The source was originally designed and developed for operation up to 30 s, but has not been tried longer than 10 s. Some modifications for 300 second capability with appropriate tests are required for use in KSTAR. This source has accelerator grids made with slit apertures for the extraction of high current beam.

The plasma chamber has a cross section of 26 cm x 64 cm and 32 cm deep and is made of "magnetic multi-pole bucket" anode. Axial arrays of Nd-Fe permanent magnets(4.65 kG ±2%) spaced between cooling channels are lined up on the wall to make the cusp field around the inner wall of the chamber. An array of 32 thermionically emitting tungsten filaments (1.5 mm diameter) consists with three kinds of different shapes in order to make a uniform plasma throughout the chamber. The filaments are mounted on the water-cooled filament assembly, which contains one positive and one negative filament plates. The slits are made of specially shaped molybdenium water tubes for beam optics and long pulse operation, but the needed technologies in making the grid structures with such tubes are very hard to follow up. As an alternative of the slit grids, circular aperture grids are under development. The drawing of the fabricated prototype ion source including four accelerating grid modules is shown in Fig. 2.

Discharge characteristics of the ion source has been measured by 6 sets of Langmuir probes. The hydrogen ion densities are around $2.0\text{x}10^{11}$ /cm3 when arc current is 1200 A, and the electron temperatures are less than 4 eV. Also the plasma density which increases linearly with arc power. The plasma uniformity around the bucket was within 20 %, and now trying to improve it.

## Beam Line Components

The beam line includes all hardware items needed to transport the neutral beam from the ion sources to the KSTAR NBI port. For 300 seconds operation, the inertial cooling copper plates are not capable of absorbing the beam power loading for the KSTAR NB pulse, and will have to be replaced with an actively cooled design. While several actively cooled target designs were considered, the hypervapotron[4] elements being used on the JET NBI system were chosen due to their reliable performance and lower cooling water demands. The optical diagnostic chamber is located at the exit of the ion source to obtain diagnostic information on the extracted beam by use of an optical multichannel analyzer. Relative intensities provide an indication of species mix and broadening of the peaks indicates the ion source angular divergence. A gas feed will be installed at the optical diagnostics chamber to provide operational flexibility for the sources while maintaining the maximum neutralization efficiency.

The bending magnet deflects the 120 keV D+ ions upward to the ion dump with 6.8 T-cm. The central field of the bending magnet is 2.3 kG and the magnet is inclined 45 to the neutral beam axis. The ion dump with hypervapotron absorbs the power of the full, 1/2, and 1/3 energy D+ ions that are deflected through the bending magnet. The precise location and orientation of the ion dump will be determined by analysis of the particle trajectories including error fields.

The calorimeter is required to withstand the full neutral beam power from the 3 ion sources for 300 s and the full neutral and ion beam power for 0.2 s which is longer than the response time of the fault protection system. The calorimeter consists of three V sections of stacked hypervapotron panels. The included angle of the V is 16 to reduce the incident surface heat load to 1 kW/cm2. The inner walls of the chamber are lined with cryo condensation panels. The major features of the cryo panels will be active pumping area of 30 $m^2$ and pumping speed of 2.5 M*l*/s for $D_2$ at 4.5 K. Regeneration of the cryo panel will occur either when the cryo panel gas load reaches its administrative limit, or the beam line is brought up to atmospheric pressure for maintenance. With the volume of NB vacuum chamber, the beam line is expected to run for 30 shots before regeneration.

## Power Supply and Control System

The neutral beam power supplies convert the primary power from the MFG to controlled DC power as required to the ion sources and associated auxiliaries. Each ion source has an independent power supply system capable of operation alone or as a group by local control system or remotely by the central I&C system.

The arc & filament power supplies for each ion source are connected to their loads at a high voltage side with the power transmission line, which is terminated in an ion source housing filled with pressurized SF6. The ion source has a large number (32) of tungsten filaments, which are heated by dc current. All filaments of an ion source are powered in parallel by a single filament power supply. Since the arc current is very sensitive to the filament temperature, which is highly dependent on the filament voltage, the filament voltage is regulated within 5%. The filament power supply converts 180 V ac three-phase power from Isolation Transformer to DC for heating the ion source filaments, which operates up to 15 V and 5500 A. The output is isolated from ground and is being referenced to the high voltage accelerator potential of 120 kV. To obtain the stable arc current, the output voltage of filament power supply is altered through a control loop, whose reference is the actual arc current. When the accelerator system malfunctions, the arc current is suppressed by the action of the arc modulator across the output of the arc power supply. The supply can deliver up to 160 V, open circuit, to initiate discharge, and provides sufficient power to sustain the discharge with current limit of 1200 A for the safety.

The acceleration power supply has the feature of step modulation, which consists of an inverter voltage controlled module of up to 30kV and 5 modules of fixed voltage of 20kV. Fig. 3 shows the schematic circuit diagram of an acceleration power supply. All the modules with IGBT output switch are connected in series and make it possible to control the output voltage continuously from 0 to 120kV. The IGBT switch modules are conglomerate in operation to meet such a fast feature as rapid variation up and down of load voltage, high speed current interruption, and stable voltage. The major specifications are:

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|---|---|
| - Voltage | 120 kV |
| - Current | 70 A |
| - Pulse Length | 300 s |
| - Current Rise & fall time | < 25 s. |

A high speed crowbar is connected to the output of the moules to divert fault energy from the ion source and HV current switch in the modulator/regulator. Crowbar firing will take place within 2 to 3 microseconds of detecting a fault. The gradient grid resistor is a tapped voltage divider which provides a voltage to the ion source gradient grid, proportional to the acceleration voltage. The divider consists of 100 resistor assemblies in series with the current capacity of 5A. Each resistor assembly consists of a 5 x 5 array of 250 ohm, 250 W resistors mounted on a water-cooled aluminum plate.

The control system reflects the equipment complexity and technical diversity of the NBIS, requiring approximately 5,000 signal points for the power supplies, 2,000 for diagnostics, and 1,500 for beam line controls and services. Two sets of workstation, one to control and the other to monitor, are entirely committed to NB system. The system software shall be composed in the EPICS(Experimental Physics and Industrial Control

System) environment, and VME bus controlled by VX-works be used as a standard in measurement and control.

Hardwares and softwares are making up with the following logics;

- loosely coupled with main tokamak control system,
- loosely coupled with other beam lines,
- loosely coupled with other ion sources,
- flexibility and expansibility,
- easy system in operation and maintenance,
- operation mode programmable including manual mode,
- safety interlock system for operational errors and device failure,
- self-protective against excessive voltage, current, temperature, and pressure.

## 4. Test Stand Construction

A test stand of the KSTAR NB system is in construction at KAERI for the beam extraction experiments of the developed ion source and for the measurements of the heat removal capability of the developed beam line components. The test stand is almost same as the actual NB system of KSTAR. Therefore most of the components, such as the power supplies of the ion source, neutralizer, ion dumps, bending magnet, and scrapers, developed for the actual one could be used in the test stand.

The calorimeter for the test stand is designed and constructed as shown in Fig. 4 to handle 3 MW of beam power during 20 seconds. A total of 32 beam stopping elements (Hypervapotron unit size; 112 mm x 1001 mm) are arranged in two panels forming a V shape. The opening angle between the panels is 28 degrees and effective aperture size is 430 mm x 1001 mm. To measure the temperatures of each element and beam power profiles 60 thermocouples are distributed on the calorimeter. The vacuum chamber is made with the same size of the actual one (3m x 4m x 5m). There are 81 ports for installing beam line components, vacuum pumps and beam diagnostics tools. The measured out-gassing rate is lower than $1\times10^{-8}$ torr·l/sec/cm2, and the vacuum of $9 \times 10^{-7}$ torr could be earned with 2400 l/sec TMP.

Because of the difficulty of the supply of the liquid helium at KAERI, the cryosorption pumping system is in developing for the usage in the test stand. The desired minimum pumping performance of the needed cryosorption pump is as follows;

- Pumping speed : $2 \times 250000$ l/s
- Pumping capacity : $2 \times 15$ mbar·l/s $\times$ 30 s = $2 \times 450$ mbar·l
- Pumping area : $2 \times 2.5$ $m^2$ .

The cryosorption pump, shown in Fig. 5, is composed of a cryopanel, a thermal shield and a baffle. The cryopanel, made by 2mm OFHC copper, coated with activated carbon is positioned innermost and is cooled down to below 20 K to pump hydrogen. The cryopanel of 1.75 x 1.75 $m^2$ is installed on the top of the second stage cold head of a GM refrigerator, which is commercially available. The thermal shield including the baffle surrounding the cryopanel to cut off 300 K thermal radiation, composed of 65 angled blades made of pure aluminum(A1090) of 3 mm thickness and a square frame made of A6063 of 10 mm thickness, is installed on the first stage cold head and is cooled down to 80 K using supplementary $LN_2$. On the frame of the thermal shield two parallel $LN_2$ tubes are attached. The baffle is of a chevron type whose blade angle is 120 degree. The test stand will have two cryosorption pumping systems located inside the NBI chamber along the two parallel walls facing each other. The whole cryosorption pump is suspended at a proper position through two titanium alloy support rods of 4 mm$\Phi$ connected to hangers fixed on the side wall of the chamber.

CW 2 MW cooling water system is designed, and is in construction. The designed water flow rate is 100 l/sec in the pressure of 5kgf/cm$^2$. The characteristic resistance of the cooling water will be controlled higher than 1 Mohm-cm. This system will be upgrade up to 6 MW. Also the control and data acquisition system will be tested and upgraded in the test stand during several years before finally installing to KSTAR.

## 5. Conclusion

The design of the KSTAR NBI system has been finished and now in a phase of construction. The construction and installation will be finished until the end of 2005, and the first beam is expected during the middle of 2006. In order to test and upgrade of the developed ion source and beam line components a test facility has been developed in KAERI. It was designed and constructed on the bases of the main KSTAR neutral beam system to testify the completeness of the planned one. Not only ion source and beam line components but also beam diagnostics system, machine control system, and vacuum control system will be tested and upgraded in this facility.

## References

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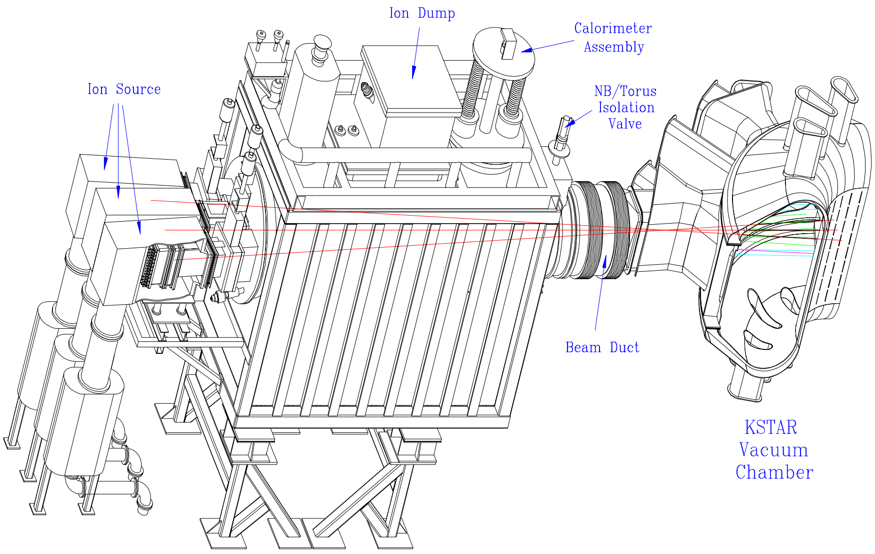

Fig. 1 Schematic Diagram of a NBI Beam Line

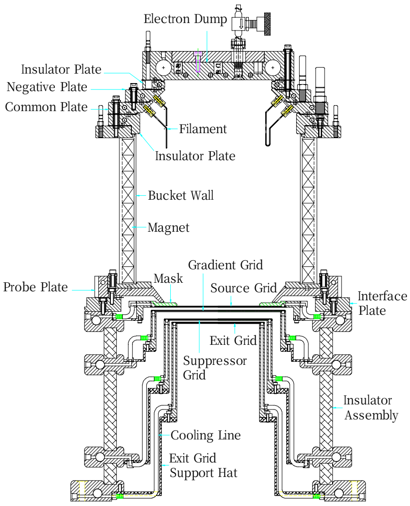

Fig. 2 An Upgraded High Power Ion Soruce

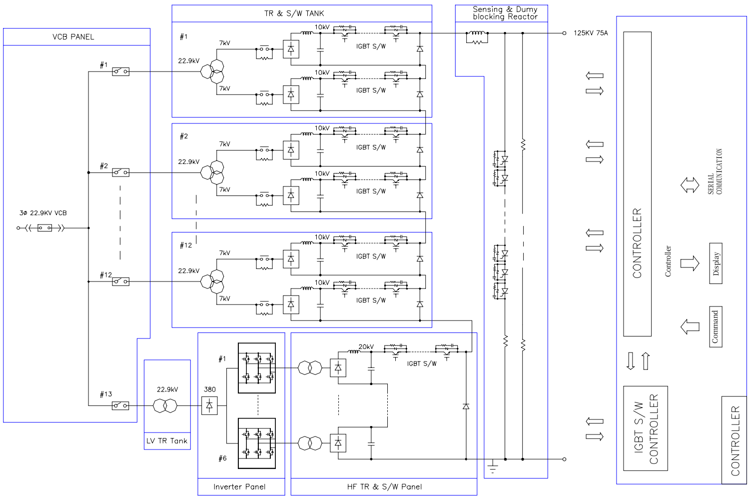

Fig. 3 A Circuit Diagram of an Acceleration Power Supply for the Ion Source

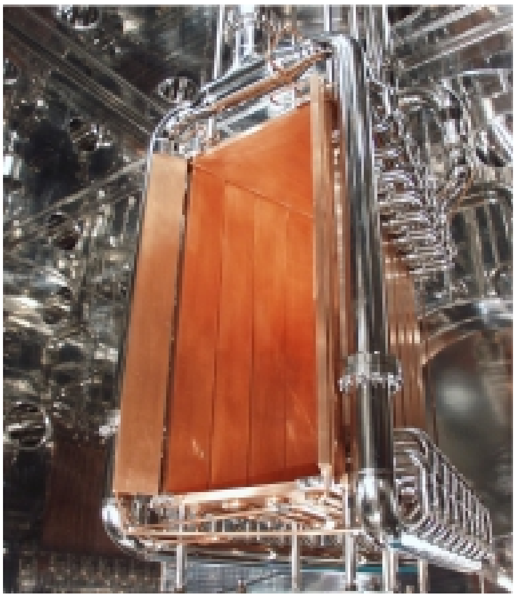

Fig. 4 A Calorimeter for the NBI System

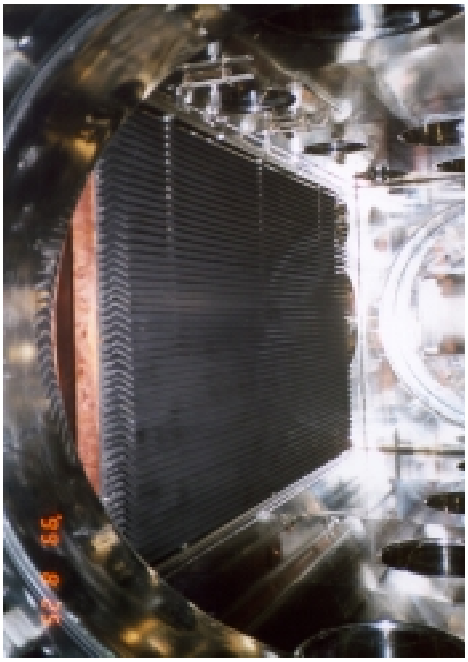

Fig. 5 A Cryosorption Pump