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DESIGN AND CONSTRUCTION OF THE NEUTRAL BEAM INJECTOR FOR COMPACT HELICAL SYSTEM(CHS)

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Abstract

A 40keV 1.2MW Neutral Beam Injector for the Compact Helical System(CHS) device has been constructed for the purpose of producting high pressure plasma. The beam line consists of one ion source, and is characterised by changeable injection angle for optimising beam deposition, and for investigating confinement of high energy ions. A new technology for manufacturing cooling channels of extracting grids (both copper and molybdenum) is developed. The physical requirement on the neutral beam and the design features of the injector are presented.

Introduction

Compact Helical System[1] is a medium size torsatron/heliotron device (R=0.1m, a_p=0.2m) with ℓ=2, m=8 helical windings. Since the plasma is expected to be net current-free, CHS does not have Ohmic heting coil. Therefore the most reliable way to get high pressure plasma is high power neutral injection into a target plasma produced by ECR or RF. We have planned 1.2MW tangential neutral injection with the beam energy of 40keV, which corresponds to the power density of 1.5MW/m^3 if all the beam is absorbed.

One of the characteristics of CHS device is its low aspect ratio (A_p=5) as for a helical system. The advantage of the low-aspect-ratio machine are its good stability from the physical point of view, and its compactness from the economical point of view. On the other hand, the critical issue on the low-aspect-ratio machine is the loss of the particles which are trapped in the helical ripple mirror field. Heating efficiency of neutral beam is very sensitive to this "loss cone", because fast ions generated by NB are collisionless, and therefore NB is expected to be a good tool of investigating loss cones.

In this paper, physical and technical design of the neutral beam injector is presented. A brief description on the performance of the beam is given.

Physical Requirement

Beam Deposition

The main purpose of neutral injection in helical system is to produce high density plasma as well as to heat it. However the target plasma density is usually very low (1-2x10^{13}cm^{-3}, typically). Therefore the plasma density is widely changed during injection. The beam energy should be as high as realising a peaked deposition profile of the beam at the plasma density of higher than 10^{14}cm^{-3}. On the other hand, the shine through of the beam should be small enough at low density to avoid the wall damage or impurity production. Tangential injection is the best way to cover this wide density variation. As one of the objectives of CHS is to study high beta plasma so that the beam energy is optimised for the case of high density, and chosen to be 40keV, although more than a half of the beam passes through at first. Figure 1 shows the rate of beam deposition as a function of plasma density for 40keV.

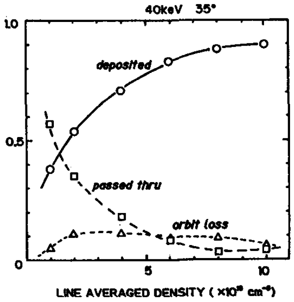

Fig.1
Deposition rate of the beam as a function of target plasma density where parabolic profile is assumed.

Injection Angle

One of the critical issues of the low-aspect-ratio helical device is a loss of trapped particles in helical ripple. As for NBI the absorbed fast ions are immediately lost from the plasma when they are trapped in helical ripple mirrors. This loss not only ruduces the absorbed power but also causes the impurity influx by high energy ions sputtering the wall. The trapping condition depends on the pitch angle and the location of the birth point of fast ion. Therefore injection angle of neutral beam is very improtant especailly in helical system. Figure 2 shows the rate of this orbit loss and shine through as a function of injection angle. In order to choose an optimum injection angle for a plasma with different magnetic axis, and to study the confinement of fast ions, beam line is to be changed from tangenital to normal injection.

Specifications

Taking these physical requirement on NBI into consideration, the specifications of the system are determined as follows:

Beam Energy;	40keV
Number of Beam Line;	1
Number of Ion Source;	1
Ion Current;	60A
Beam Diameter;	20cm
Input Power (port-thru);	1.2MW
Pulse Length;	1sec.
Injection Angle;	R_t=0-94cm

Pulse length of the beam should be larger than any characteristic times to achieve a steady state condition. Here we have chosen 1sec. considering the effect of beam drive current on equilibrium.

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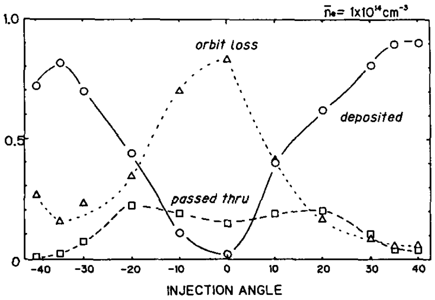


Fig.2 Deposition, orbit loss and shine through rate as a function of injection angle. The beam energy is 40keV and the average density is 1x10^{14}cm^{-3}.

Major Design Features

Ion Source

The plasma source is a cylindrical bucket source of 34cm in diam. and 20cm in depth, which has 34 magnetic cusp lines in parallel to beam axis., and 12 tungsten hair-pin filaments of 1.5 mm in diam. It is designed to generate a dense plasma with ion saturation current of 280mA/cm^2.

The single stage accelerator has 559 holes of 7 mm in diam. in the extraction area of 24 cm in diam., and designed to extract 60A ion beam with the divergence angle of 1 degree.(Fig.3) The plasma grid is made of molybdenum, while others are made of oxygen-free copper(OFCu). Because the beam pulse length is one second, each grid has cooling channels between the holes. These cooling channels (both molybdenum and copper grids) are made by using diffusion bonding technique which has been developed for this purpose.

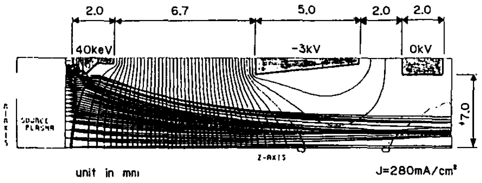


Fig.3 The grid structure, and the optimum result of beam orbit simulation, where the beamlet divergence of 1 degree is obtained.

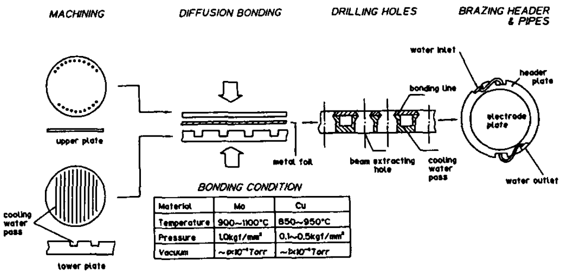
The advantage of this method is as follows:

1)Large area of cooling channel can be obtained; usually a cooling pipe is brazed in the grave of the grid, while in this method the groove itself can be used as cooling channel.

2)Any (two dimensional) shapes of channel can be made. Those facts (1 & 2) can improove cooling efficiency.

3)It can remove brazing metal from the beam extracting area, which may help quick conditioning.

The process of manufacturing the cooling channels is as follows(Fig.4) : put a flat plate on another plate with grooves as cooling channels, between which thin metal (titanium foil) is inserted to quicken diffusion process, and press them for a few hours keeping hot (around 900°C) in a high vacuum. After finishing the bonding, drill the beam extraction holes and braze a header plate and pipes.



Material	Mo	Cu
Temperature	900~1100°C	850~950°C
Pressure	1.0kgf/mm²	0.1~0.5kgf/mm²
Vacuum	~1x10⁻⁴Torr	~1x10⁻⁴Torr

Fig.4 Manufacturing process of electrode plate by diffusion bonding

Beam Line

The beam line is designed on the basis of 180 deg. reflecting system of residual ions (Fig.5). The advantages of this system are:

1)By using a thin magnet, the ion beams diverge under the influence of non-uniform magnetic field. This reduces the power density on the beam dump.

2)The beam dump can be set beneath the neutraliser. This makes arrangement simple, and makes the vacuum chamber compact.

3)By separating the vacuum chamber at the exit of the deflecting magnet, differential pumping is possible. Because the vacuum pressure in upper stream side need not be high, the pumping speed can be small in this side.

The characteristics of this system has been studied in our 10 MW Neutral Beam Test Stand in detail.[2] Consequently, the design of the beam line of CHS-NBI is based on our NBTS.

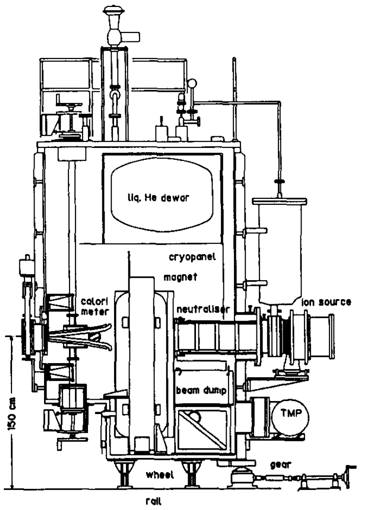


Fig.5 Schematic view of the beam line (side view)

Deflecting Magnet has a pole peace of 25cm x 110cm and a gap of 25cm. Maximum strength of magnetic field is 1.2 kG at the center, which is determined by the condition that the 40/3 keV beam does not go back into the neutraliser. Beam Dump consists of a main dump and sub dumps. The main dump is composed of six OFCu plates of 3cm in thickness, which are inertially cooled and arranged in figure-V shape so that the heat load on it does not exceed 1kW/cm^2. The angle of the dump against the beam is determined by the results of Monte Carlo calculation of beam trajectroies in the deflecting magnet. Figure 6 shows the beam trajectories of three different energy components. As can be seen from the figuer, beams of lower energy deflect over 180 deg. and miss the main dump. Therefore sub dumps are prepared on the upper side of the main dump.

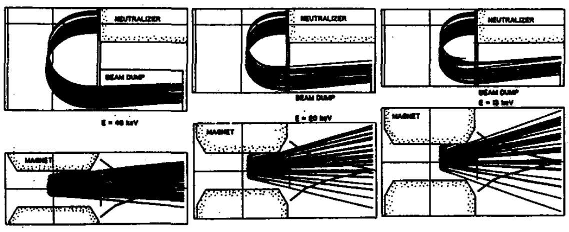


Fig.6 Results of a Monte Calro simulation of the beam orbits in the deflection magnet for (a)40keV, (b)20keV, (c)40/3keV ions.

Cryopump consists of six small cryopanels with radiation shield of louver-blind structure, which has high specific pumping speed of 14 ℓ/s/cm^2, and was developed for 10 MW Neutral Beam Test Stand.[3] The size of cryopump is 2.8m^2. A differential pumping is performed by a buffle plate located at the exit of deflecting magnet. The vacuum pressure in the down stream side should be below 2x10^{-5} Torr in order to make the reionisation loss below 5%, while it can be 1x10^{-4} Torr in the upper stream. The operating temperature of cryopanel is 4.2K, and the pumping speed is 8 m^3/s at down stream side and 23 m^3/s at upper stream side. The pump has a large liquid helium dewar of 0.4m^3 inside the vacuum chamber, and the evaporating rate of stored liq.He is 0.15m^3/day.

In order to change an injection angle, all the beam line is moved at the same time with cables, water cooling pipes and liq.N$_2$ transfer tubes. The vacuum chamber (10 ton, including ion source and other components) is put on curved rails which correspond to arcs of 35 degrees around the pivot point. The pivot point is located beneath the injection port of CHS, where the center pole is set. A large arm from the base-plate of NB vacuum chamber is jointed via bearing. At the back side, a pair of curved gear and wheel is set. So far rotating the beam line is performed manually.

The beam line is connected via bellows to the port flange, to change angle without open the vacuum chamber. The bellows has 335mm inner and 365mm outer diameters, and has 116 convolutions. Inside the bellows there is a drift tube of 20 cm in diam. and 55 cm long, which protects the belows as well as limit the beam size. The latter is important, because the vacuum chamber of CHS is a twisted elipse, and a large beam hits the inner wall when tangentially injected. The location of pivot point is therefore determined by maximising the beam size.(Fig.7) Figure 8 shows a transit efficiency through the tube as a function of beamlet divergence angle.

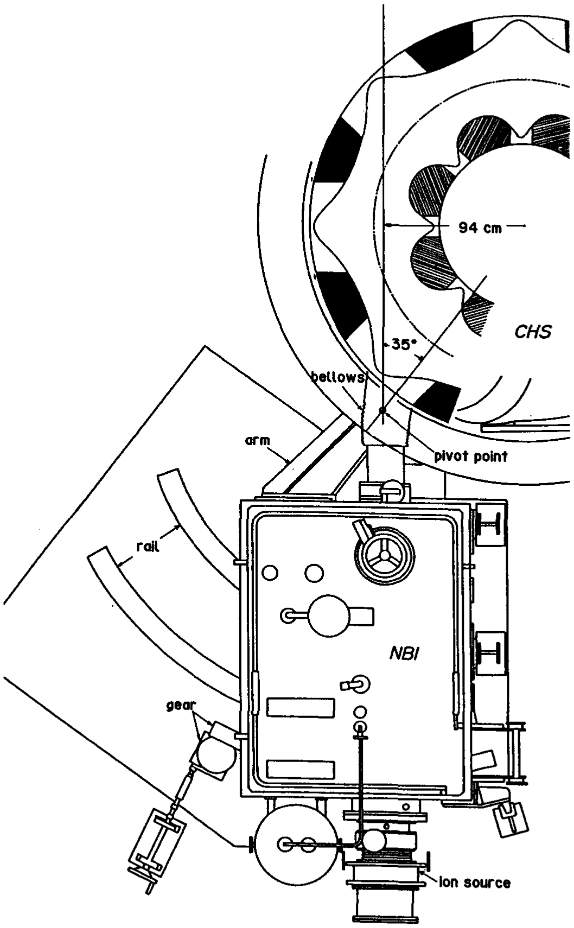


Fig.7 Schematic view of the beam line (top view), and the beam path in the vacuum vessel of CHS.

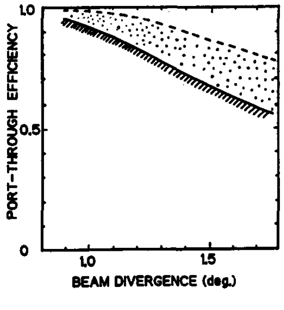


Fig.8
Transmission efficiency of drift tube as a function of beamlet divergence, where dotted area shows a fraction of loss inside the tube and hatched region shows the passing rate.

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Power Supplies

Both accel and decel power supplies are "tubeless", i.e., the output voltage is regulated by thyristors in the primary lines, and the fast switching is performed by series GTO's. This system was first introduced in our 10MW NBTS [4], and is now very popular in Japan. GTO switch consists of 40 GTO's in series, adn three of them have nonlinear resistor in parallel to share the voltage 1kV each. This circuit protects the ion source from a transient high voltage which is caused by overcharging of the filter capacitor after quick switcing off. The arc power supply also has a GTO switch. The specification of the power supplies are as follows:

Accel. :	40kV,	65A,	CV,	1s/180s.
Decel. :	-3.75kV,	6.5A,		1s/180s.
Filament:	12V,	1320A,	CV,	10s/180s.
Arc :	130V,	1000A,	CV,	1.5s/180s.
Magnet :	190V,	80A,	CC,	2s/180s.

Operation

Conditioning of the Ion Source

The conditioning was started from 20kV, and after 500 shots the beam of 20keV, 20A, 0.2sec. was successfully extracted. The pulse length is limited by the heat load on the calorimeter. It took anoter 500 shots to get 35keV, 55A, 0.1sec., and the frequency of break downs in the ion source becomes very low. This conditioning process is quicker than our previous ion source for JIPP-TIIU.

Beam Characteristics

Figure 9 shows the beamlet divergence angle as a function of beam current $(I_{accel}-I_{decel})$, which is estimated by the measured beam profiles at the calorimeter. The minimum divergence is about one degree, which coincides with the design value, but the optimum perveance is about 10% smaller. With a measured neutralization efficiency and with the result of passing efficiency through the drift tube (Figs.8 & 9), the port through power can be estimated (Fig.10). It is noted that the maximum input power does not correspond to the minimum divergence.

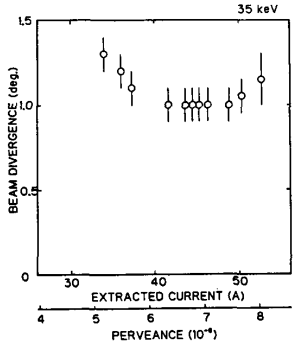

Fig.9 Beamlet divergence angle as a function of extracted beam current. The lower axis shows a corresponding perveance.

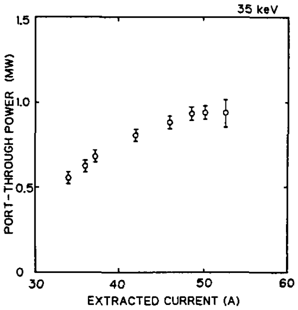

Fig.10 Estimated neutral beam power through the drift tube on the basis of the measured beam profile and neutralising efficiency.

Conclusion

The neutral beam injector for CHS device was constructed and successfully operated. So far 35keV, 900kW, 0.25s beam injection has been carried out at two different injection angles. It takes only ten minuites to move beam line, so that injection angle can be changed even shot by shot.

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