Neutral Beam Injection Requirements and Design Issues for the National Compact Stellarator Experiment

by

H.W. Kugel, H. Neilson, W. Reiersen, M. Zarnstorff, and M. Cole

February 2002
PPPL Reports Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Availability


DOE and DOE Contractors can obtain copies of this report from:

U.S. Department of Energy
Office of Scientific and Technical Information
DOE Technical Information Services (DTIS)
P.O. Box 62
Oak Ridge, TN 37831
Telephone: (865) 576-8401
Fax: (865) 576-5728
Email: reports@adonis.osti.gov

This report is available to the general public from:

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Telephone: 1-800-553-6847 or (703) 605-6000
Fax: (703) 321-8547
Internet: http://www.ntis.gov/ordering.htm
Abstract—NCSX will require 6 MW of 50 keV Neutral Beam Injection with initial pulse lengths of 500 msec and upgradeable to pulse lengths of 1.5 sec. This paper discusses the NCSX NBI requirements and design issues, and shows how these are provided by the candidate PBX-M NBI system.

I. INTRODUCTION

The National Compact Stellarator Experiment (NCSX) will be the primary research tool for understanding the physics of compact stellarators. NCSX will investigate the effects of 3-dimensional plasma shaping, of internally- and externally-generated sources of rotational transform, and of quasi-axisymmetry on the stability and confinement of toroidal plasmas. Auxiliary heating is required to achieve the high temperature, high-beta plasma conditions needed to accomplish the NCSX research goals. A total of 12 MW can be accommodated by the device design, 6 MW of tangential Neutral Beam Injection (NBI) and 6 MW of RF heating. This paper discusses the NCSX NBI requirements and design issues, and shows how these are provided by the candidate PBX-M NBI system.

II. NEUTRAL BEAM SYSTEM CHARACTERISTICS

A. Available Injection Power

NCSX will use the present PBX-M NBI system, consisting of 4 beamlines. This NBI system was used previously for PDX, PBX, PBX-M. The ion sources have 30 cm circular copper grids and a focal length of 440 cm. Each ion source was fabricated, and fully qualified in 1979-1980 on the ORNL NB Test Stand to power levels of 1.5 MW, $^1$H (at 50 KV, 100A, 0.3 sec) for the PDX experimental program[1]. In addition at ORNL, one ion source was demonstrated to yield 2 MW, $^1$D (at 50 KV, 70A, 0.3 sec). As expected, the injected power for a given species was found proportional to the injection energy to the 5/2 power. Subsequent testing after installation on PDX demonstrated the capability to inject with four sources up to 8.3 MW $^1$D in the absence of magnetic fields. In the PDX machine environment, the presence of stray magnetic fields and finite transition duct pressure (~10^-4 torr) reduced the available power to 6.5-7.0 MW $^1$D. This loss of reionization power of 12-18% will be regained in NCSX by reinstalling the 100 kl/s cryopumping capability of the original design. Table 1 shows the NBI system injected power capability and the effects of fringe fields.

<table>
<thead>
<tr>
<th>TABLE 1. NBI POWER CAPABILITY AND REIONIZATION LOSSES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PBX-M Injected Power Capability</strong></td>
</tr>
<tr>
<td>• ORNL Qualification (No Fields)</td>
</tr>
<tr>
<td>$P(H^0) = 6$ MW (4 x 1.5 MW)</td>
</tr>
<tr>
<td>$P(D^0) = 8$ MW (2 x 2.0 MW)</td>
</tr>
<tr>
<td>• PDX Testing (No Fields)</td>
</tr>
<tr>
<td>$P(D^0) = 8.3$ MW (4 NBI @ &gt; 52 KV)</td>
</tr>
<tr>
<td><strong>Neutral Power Reionization Loss Fractions (f)</strong></td>
</tr>
<tr>
<td>in PBX-M Due to Duct Neutral Gas (~1-4x10^-4 T)</td>
</tr>
<tr>
<td>• f (Perpendicular ducts) = 0.88 $P_0$ (12% loss)</td>
</tr>
<tr>
<td>• f (Tangential ducts) = 0.83$P_0$ (17% loss)</td>
</tr>
</tbody>
</table>

B. Neutral Species Ratios

Typical species measurements performed at ORNL with equilibrium density neutralizer cells using ion dump yields found ion source species ratios of $H^1(E):H^1(E/2):H^1(E/3) = 63:20:17$, and neutral beam power output ratios of $P^1(E):P^0(E/2):P^0(E/3) = 80:13:7$. On PDX, with $D^0$ at 47 keV, (1.6 MW), Rutherford Backscatter Spectroscopy [2] on the injected neutrals found neutral particle ratios of $D^0(E):D^0(E/2):D^0(E/3) = 53:32:15$, and neutral power ratios of $P^0(E):P^0(E/2):P^0(E/3) = 72:21:7$.

C. Neutral Power Pulse Length

The neutral beamline power handling surfaces are engineered to operate at a maximum of 500 msec pulse lengths at the peak power density of 3 kW/cm^2. In addition to power conditioning each of the ion sources to pulse lengths of 300 msec in 1979-1980, ORNL demonstrated one ion source to operate at 500 msec pulse lengths using $H^1$ at about 50 KV, 90A [1]. Similar results were obtained on PBX-M, where each of the 4 neutral beamlines was demonstrated to operate with $D^0$ at ~40 KV, 1 MW,
to pulse lengths of 500 msec. PBX-M initiated preparations for operation to higher powers at 500 msec for both $^3$H and $^3$D, and this capability should be considered available for NCSX. In addition, the MAST experiment at Culham Science Center, UK, which is presently using similar ORNL style beamlines is planning to upgrade to 1.5-3 pulse length capability. This effort may provide a useful long pulse technology demonstration for NCSX NBI.

D. Ion Source Focal Length, Focusing, and Power Density Profiles

A PBX-M ion source has 3 circular grids, 30 cm in diameter, each containing about 2000 circular holes for producing 2000 circular beamlets. The grids are shaped spherically concave to provide geometric focusing (aiming) with a focal length of 440 cm (the distance to the PDX torus port). Table 2 gives the $^3$H angular divergences for each neutral beam at the torus target horizontal focal plane (440 cm). The results were obtained on the ORNL NB Test Stand from measurements of the respective beam power density profiles measured along the horizontal axis in the focal plane at the torus target using a scanning water calorimeter behind pin-hole apertures [1]. These power density profiles exhibit gaussian behavior down to about 10% of full power. Below the 10% power level, the profiles exhibit "wings" that have been characterized by asymmetric gaussian, or polynomial least-squares fitting.

![Fig. 1. Simulated power density along beam axis from 200 to 600 cm from the ion source. The beam port location will allow adequate duct width to avoid neutral and reionized power impingement on the duct walls.](image)

E. Control and Performance

PDX developed full computerization for the NBI system, including control of filament, arc, and acceleration voltage conditioning, and fault response using an "artificial intelligence" algorithm incorporating "expert rules" [4,5]. One operator monitors all four systems in a "hands-off" manner. The computer control resulted in providing unforeseen benefits in operational reliability, reproducibility, and equipment safety.

III. DESIGN OPTIMIZATION

A. Maximizing Injected Power

The Neutral Beam power injected into NCSX can be maximized by reducing the system gas pressure in the transition duct which causes reionization and loss of neutral particles. A reduction of transition duct neutral gas pressure to the $\sim 10^{-5}$ torr regime can significantly increase the injected power incident on the plasma ($\sim 12$-18%). The design plan for accomplishing this is discussed in Sec.D, below.

B. Maximizing Desired Neutral Beam Species

Typically, neutral beamlines are operated with the neutralizer cell at $\sim 90$-95% equilibrium gas pressure to optimize the yield of the full energy component. The additional gas target through the transition duct can change the fractional ionic yield of the low energy components and produce small differences in the species ratios of injected beam. Small reductions in the percentage of the full energy component have been measured at the edges of beams in a narrow duct. High duct pressure may change the species ratios measured upstream in the beamline and broadens the beam power profile. These effects can be reduced by optimizing the duct design and installing...
additional cryopumping in the front box of the beamline.

C. Power Transmission to the Far-Wall

Neutral Beam power transmission to the far-wall of the vessel ("shine-through") often requires at minimum, sufficient armor to absorb a short full power pulse. If sufficiently robust, this armor could allow short pulse power and position calibration injections in the absence of plasma. Simulations indicate that, for example, ATJ graphite at least 1.3 cm thick or the equivalent will be sufficient for wall armor tiles capable of absorbing the available peak NBI power densities of 3 kW/cm² for 500 msec in the absence of plasma. Thicker tiles with active cooler will be needed as an upgrade for longer NBI pulse lengths. As the design evolves, if sufficient far-wall armor cannot be installed at some locations (e.g., at RF antennas), then suitable interlocks capable of stopping beam injection will be applied, if sufficient plasma is not present.

D. Minimizing Reionized Power Losses and Duct Wall Conditioning

The reduction of duct outgassing by conditioning increases injected power and provides more reproducible results. Outgassing can be reduced by high conductance geometry, with walls far from the beam, appropriate materials, baking, and HeGDC between discharges. The NCSX design will include the installation of high-speed cryopumping in the exit box of the beamlines at the entrance to the duct to significantly reduce or eliminate the effects of duct outgassing. This hardware will also accelerate NCSX pumpdown between discharges.

Fig.2 is a schematic diagram which summarizes the NCSX NB duct and port access requirements discussed above. Shown are the principal elements of a high conductance NBI transition duct. The beam, after passing through the beamline Torus Interface Valve (TIV), enters a rectangular section which is usually connected to a cylindrical section attached to the vessel. In the case of PBX-M, reionized power loss due to residual process gas in the duct is steered to the duct side wall by the predominantly vertical fringe field at the entrance to the duct, and eventually to the top of the duct by the predominantly horizontal fringe field at the vessel entrance. A similar behavior is expected for NCSX and will be simulated as the design evolves. The duct has a ceramic break providing electrical isolation of about 3 kV, and a bellows at the vessel to decouple vessel motion during operation and bakeout. The bellows is shielded with a metal sheet fastened to the vessel and floating on the beam side. Diagnostic ports are provided to provide viewing of the beam in the duct for NBI and plasma related measurements (e.g., Beam Emission Spectroscopy calibrations). Synergies accrue from combining duct requirements of the Neutral Beam and Torus Vacuum Pumping Systems by using the same ducts, and hence, it is desirable to maximize the width W, the height H, the diameter D and the diameter d, while minimizing lengths Lr and Lc. Length S is selected for high conductance reaching a fringe field region comparable to that at the pumps during their PBX-M service. In addition, S is sufficiently long to provide occlusion from beam sputtering. Additional requirements to minimize duct outgassing are electropolished 304-SS walls, and 150°C bakeout capability. Some of these desired requirements are included in the preliminary conceptual design for a NCSX NB transition duct shown in Fig.3.
E. Maximizing Absorbed Power

The NCSX design locates the NBI ports so as to maximize the absorption of injected beam power over the desired plasma region. The absorbed power is determined by the beam focusing (perveance), the distance of the ion source from the deposition region, the aiming angle, and target plasma parameters. Fig. 4 shows the proposed configuration. The vessel has 3 sectors; in each sector, the plasma cross-section changes from bean-shaped to oblate and returns to bean-shaped.

Balanced co- and counter-tangential NB injection are needed to provide control of the neutral-beam driven currents, and to provide control of the driven rotation (and thus electric field) for transport studies. Fig. 4 shows a candidate configuration for 2 Co and 2 Counter NBI systems positioned in the combined PBX-M and PLT Test Cells. The planed site layout will also accommodate beam configurations with three co- and one counter-injected beam.

A critical element in this configuration is the transition duct region. Each transition duct region is partially shared by 2 beamlines, and nearby walls receive power from an oppositely directed NBI. The neutral beam is incident on a bean-shaped plasma cross-section which changes gradually to an oblate cross-section as residual beam reaches mid-sector. Fig. 5 is a schematic diagram which shows the envelope of the oblate target plasma section. The large circle encloses ~96% of the injected power from the most poorly focused NB (IS#1, HWHM =1.5°); the small circle encloses ~47% of the injected power.

F. Far-Wall Armor to Absorb Beam Shine-thru

The NCSX design locates the NBI ports so as to minimize beam power deposition on ports on the opposite wall. The design goal is to mount far-wall armor to absorb shine-through so as to allow of plasma for calibrations while not oculting ports needed for RF Antennas and special diagnostic requirements.

III. Conclusions

The NCSX Neutral Beam design adopts the high performance NBI system of the PDX, PBX, and PBX-M projects which provided automated, reliable, economical operation. The design has the required heating power and pulse length. The design has power density profiles that can transit the available ports and heat the oblate target plasma. The design has co- and cntr- NBI for beam balance studies, and control of beam driven currents. The NCSX NBI design will provide an effective high power neutral beam system for the NCSX experimental program.

REFERENCES


*This work is supported by U. S. DoE Contracts DE-AC02-76CH030 and DE-AC05-00OR22725.
External Distribution

Plasma Research Laboratory, Australian National University, Australia
Professor I.R. Jones, Flinders University, Australia
Professor João Canalle, Instituto de Fisica DEQ/IF - UERJ, Brazil
Mr. Gerson O. Ludwig, Instituto Nacional de Pesquisas, Brazil
Dr. P.H. Sakanaka, Instituto Fisica, Brazil
The Librarian, Culham Laboratory, England
Library, R61, Rutherford Appleton Laboratory, England
Mrs. S.A. Hutchinson, JET Library, England
Professor M.N. Bussac, Ecole Polytechnique, France
Librarian, Max-Planck-Institut für Plasmaphysik, Germany
Jolan Moldvai, Reports Library, MTA KFKI-ATKI, Hungary
Dr. P. Kaw, Institute for Plasma Research, India
Ms. P.J. Pathak, Librarian, Institute for Plasma Research, India
Ms. Clelia De Palo, Associazione EURATOM-ENEA, Italy
Dr. G. Grosso, Instituto di Fisica del Plasma, Italy
Librarian, Naka Fusion Research Establishment, JAERI, Japan
Library, Plasma Physics Laboratory, Kyoto University, Japan
Research Information Center, National Institute for Fusion Science, Japan
Dr. O. Mitarai, Kyushu Tokai University, Japan
Library, Academia Sinica, Institute of Plasma Physics, People's Republic of China
Shih-Tung Tsai, Institute of Physics, Chinese Academy of Sciences, People's Republic of China
Dr. S. Mirnov, TRINITI, Troitsk, Russian Federation, Russia
Dr. V.S. Strelkov, Kurchatov Institute, Russian Federation, Russia
Professor Peter Lukac, Katedra Fyziky Plazmy MFF UK, Mlynska dolina F-2, Komenskeho Univerzita, SK-842 15 Bratislava, Slovakia
Dr. G.S. Lee, Korea Basic Science Institute, South Korea
Mr. Dennis Bruggink, Fusion Library, University of Wisconsin, USA
Institute for Plasma Research, University of Maryland, USA
Librarian, Fusion Energy Division, Oak Ridge National Laboratory, USA
Librarian, Institute of Fusion Studies, University of Texas, USA
Librarian, Magnetic Fusion Program, Lawrence Livermore National Laboratory, USA
Library, General Atomics, USA
Plasma Physics Group, Fusion Energy Research Program, University of California at San Diego, USA
Plasma Physics Library, Columbia University, USA
Alkesh Punjabi, Center for Fusion Research and Training, Hampton University, USA
Dr. W.M. Stacey, Fusion Research Center, Georgia Institute of Technology, USA
Dr. John Willis, U.S. Department of Energy, Office of Fusion Energy Sciences, USA
Mr. Paul H. Wright, Indianapolis, Indiana, USA