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PLASMA PHYSICS LABORATORY

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

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Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

ABSTRACT

In 1981, the joint ORNL/PPPL PDX neutral beam heating project succeeded in reliably injecting 7.2 MW of D^0 into the PDX plasma, at nearly perpendicular angles, and achieved ion temperatures up to 6.5 keV. The expeditious achievement of this result was due to the thorough conditioning and qualification of the PDX neutral beam ion sources at ORNL prior to delivery coupled with several field design changes and improvements in the injection system made at PPPL as a result of neutral beam operating experience with the PLT tokamak. It has been found that the operation of high power neutral beam injection systems in a tokamak-neutral beam environment requires procedures and performance different from those required for development operation on test stands. In this paper, we review the installation of the PDX neutral beam injection system, and its operation and performance during the initial high power plasma heating experiments with the PDX tokamak.

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In 1978, the Princeton Large Torus (PLT) achieved a record ion temperature of 6.5 keV using 2.4 MW of D neutral beams injected tangent to the plasma axis.[1] At that time work was already in progress at PPPL and ORNL on the much larger injection systems for the Poloidal Divertor Experiment (PDX). The PDX is a tokamak designed to study impurity control via magnetic divertors in high density, high temperature plasmas[2] using neutral beam sources developed at ORNL.[3,4] In 1981, the joint ORNL/PPPL PDX neutral beam heating project succeeded in reliably injecting 7.2 MW of D° into the PDX plasma, at nearly perpendicular angles, and achieved ion temperatures up to 6.5 keV at plasma densities about 1.5 times greater than those of the PLT conditions.[5] The expeditious achievement of this result was due to the thorough conditioning and qualification of the PDX neutral beam ion sources at ORNL prior to delivery coupled with several field design changes and improvements in the injection system made at PPPL as a result of neutral beam operating experience with the PLT tokamak. It has been found that the operation of high power neutral beam injection systems in a tokamak-neutral beam environment requires procedures and performance different from those required for development operation on test stands. In this paper, we review the installation of the PDX neutral beam injection system, and its operation and performance during the initial high power plasma heating experiments with the PDX tokamak.

SYSTEM DESCRIPTION

The PDX neutral beam injection system consists of four beam lines. Each beam line is used to inject H° or D° beams of up to 50 keV and accelerating currents of up to 100 A, for pulse lengths of 0.3 sec, at power levels of 1.5 MW H° or 2 MW D°. Figure 1 shows the location and near perpendicular injection angles of the PDX beam lines (a tangency radius of 35 cm; 9° normal to the outer port).

Figure 2 shows a schematic of a PDX neutral beam line. Shown is the circular 30 cm duopigation ion source without its magnetic and electrical safety shield, the 1.2 m neutralizer cell, the ion dumps, the 270 kl/sec LHe cryopumps, and the retractable water cooled calorimeter. The forward cryopanels shown in Fig. 2 were removed and are not presently installed (see below). Table 1 gives the beam line specifications.

The power, vacuum, and auxiliary systems for each beam line are monitored and controlled by an industrial-type programmable controller (ISSC-IPC 300) which is augmented by some "hard-wired" analog and digital signal interlocking to provide fail-safe operation.[6] Figure 3 gives an elementary electrical diagram of the neutral beam power system. Figure 4 shows the instrumentation and layout of the beam control room.

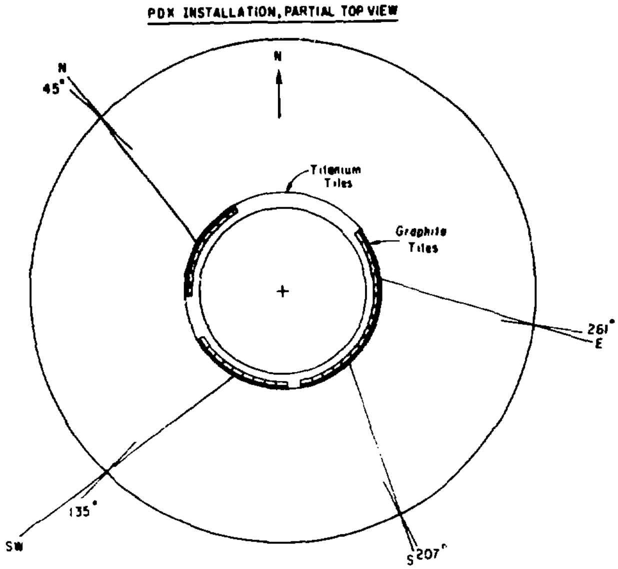

Fig. 1 The location and injection angles of the PDX neutral beam system. Shown also are the locations of the coated graphite and titanium inner wall armor.

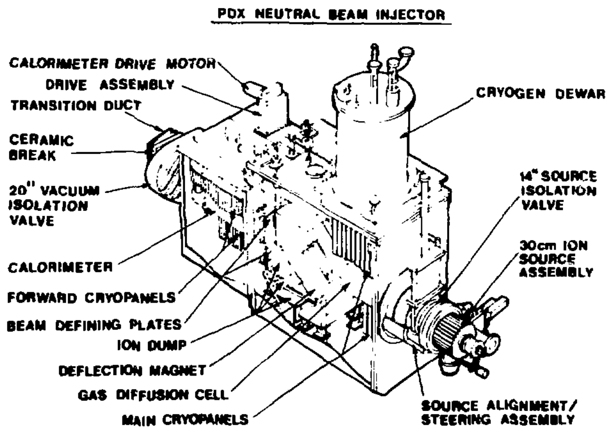

Fig. 2 A partial schematic of a PDX neutral beam line.

Table 1

4 neutral beam lines
Total injected beam power - 6 MW H°, 8 MW D°

Beam energy - 50 keV
Beam current - 100 A
Pulse length - 300 msec
Vacuum system -
    Vacuum enclosure: LHe cryo pumping
        ~ 270 kl/sec - LN_2 shield.
    Secondary system: Mechanically backed turbo-molecular pump.
Ion beam dump - water cooled intertial type.
    ~ 2.5 kw/cm^2 (peak H power).
Valves - 51 cm swing valve for PDX isolation.
    36 cm gate valve for ion source isolation.
Beam defining aperature - water cooled, movable copper plates.
Transition duct - 0.9 m (304SS)
Injection port - 30 cm x 34 cm
Injection angle - 9° off normal at port

Table 1. Specifications of the PDX neutral beam injection system.

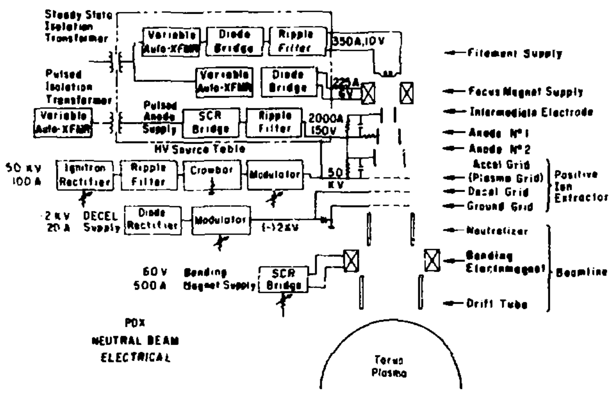

Fig. 3 An elementary electrical diagram of the PDX neutral beam power system.

Fig. 4 Photograph of the instrumentation and layout of the PDX neutral beam control room.

SYSTEM INSTALLATION

The installation of each beam line was preceeded by a fully integrated dummy load power test configured to approximate the full load operating parameters of the PDX ion source, including a triggered sparkdown associated with ion source faulting. These tests provided a thorough check-out of the power control, fault detection, and data acquisition systems prior to using them on an actual ion source.[6]

Figure 5 shows a photograph, top view of PDX and the East and South beam lines. In the right hand corner of Fig. 5 can be seen the East beam line with its ion source magnetic and electrical safety shield removed for source maintenance. On the left side of Fig. 5 can be seen the South beam line with its ion source magnetic and electrical safety shield in place. These enclosures allow personnel to work in the area of beam lines operating with 50 keV H° beams. This feature has aided in the resolution of many beam system problems that occurred during installation and also beam/tokamak/diagnostic electrical interferences that occurred during plasma heating experiments.

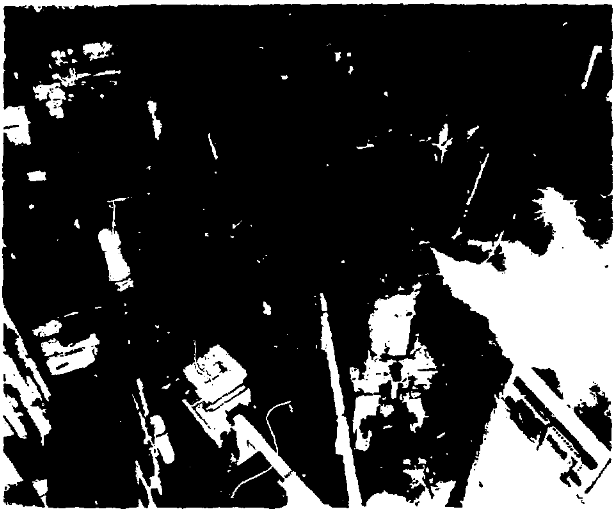

Fig. 5 Photograph, top view of PDX and the East and South beam lines.

Several electrical system improvements have contributed to increased reliability of the PDX beam operations.[6] Modification of the plasma generator circuit has substantially reduced conventional arc faulting.[7] Careful layout of the ion source power cables (see Fig. 6) and the use of metal-oxide type varistors on the ion source assembly help to prevent external arcing between sections of the plasma generator. A new accel rectifier regulator has been added to minimize the voltage drop across the series switch/regulator tube. Improved gas valve driver systems incorporating a high degree of electrical isolation as well as optical coupling for control signals has made these devices highly immune to characteristic ion source electrical noise. The same degree of electrical isolation is used for all the source deck transmitters to protect them from transients typically associated with ion source faulting. Fiber optic links are used to safely decouple all control and data signals between the control room and platform area to eliminate electrical interference and ground loop problems.

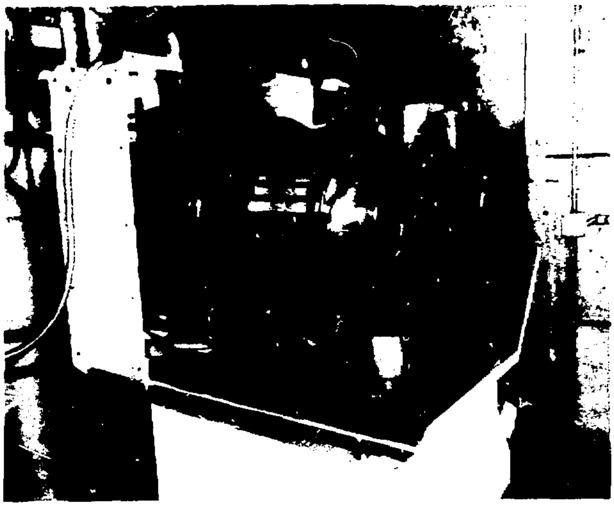

Fig. 6 Photograph of the PDX prototype ion source with magnetic and electrical safety shield removed.

The ion source gas feed systems were installed using metal and ceramic bakeable tubing. At present, the ion source gas has been obtained from conventional gas cylinders without baking the feeder lines. If desired, the gas transport system could be baked to 125°C and connected so as to deliver gas from the same palladium-type hydrogen purification system that provides gas for the PDX plasma. However, preliminary spectroscopic measurements of the PDX plasma do not indicate significant changes in the amounts of oxygen or carbon during neutral beam injection.[8] Hence, the present procedure may be sufficient.

The forward cryopanels (Fig. 2) were originally installed in the first 2 beam lines to lessen the effect of beam reionization losses in the front box and drift duct region (see below).[9] However, a significant improvement in vacuum system reliability and operating convenience was obtained by removing the forward cryopanels. The internal transfer lines used to transport cryogens from the dewar had been a source of inaccessible vacuum leaks, the net LHe consumption had been increased by a factor of 1.7, and the proximity of the cryopanels had created a potential problem of freezing the nearby calorimeter water lines.

Several mechanical system improvements were made as a result of operating experience during plasma heating experiments. Typically, the ion sources are conditioned on a 40 second repetition rate between the PDX heating injections which occur at about a 6 minute repetition rate. This schedule necessitates recycling the beam line calorimeters between heating injections or once every

6 minutes and has caused wear of the motor driven lead screw and internal bellows associated with the calorimeter drive mechanism. This system was rebuilt incorporating a pulley and cable as well as with more extensive interlocking, An external bellows was also retrofitted.

SYSTEM OPERATION

The PDX neutral beam injection system is operated so as to provide reliable neutral beam heating at high power levels and so as to provide the beam related information needed for the study of PDX plasmas. In order to assist us in operating in this manner, a computer is used to manage beam data acquisition, and to help maintain operational safety and system performance. In addition, careful attention has been given to instrumentation for diagnosing the beam properties.

Data acquisition and display is accomplished by a dedicated PDP 11/34 system with CAMAC interfacing.[10] Figure 7 shows a schematic of the computer system layout. This system is presently being developed to provide various levels of operator assisted control.[10] This will optimize the performance of the system by changing source parameters in an overall manner that cannot be done efficiently during manual operation. Also, the gain in operating reliability that has accrued from standarizing ion source manual operation should be extended as each ion source is repeatedly operated in the same optimum manner. In addition, this development effort is contributing to the operating experience needed for the more powerful multi-beam systems of larger experiments such as the TFTR.

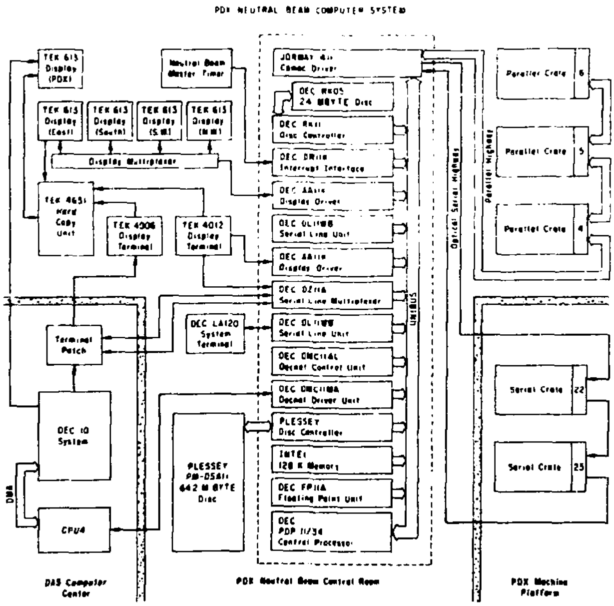

Fig. 7 Schematic of the computer layout for the PDX neutral beam injection system.

Figure 8 shows a computer display that is obtained after each shot. It gives the beam line electrical parameters and waveforms for the accel voltage, accel current, and plasma current. Other displays can be called to give more detailed electrical information. The power is first estimated as the total injected power without a 12% correction for reionized power loss. Special calibration shots produce a calibrated power from measurements of the beam energy deposited on the beam line calorimeter. The transmission factor is computed as the product of the calibrated beam power times the duct efficiency normalized to the particular beam voltage and current. The duct efficiency has been determined at ORNL for each source using a prototype PDX beam line. During heating runs, the power for a given injection is determined using this transmission factor, the measured voltage and current values and a normalization for the neutralization efficiency at the injected beam voltage.

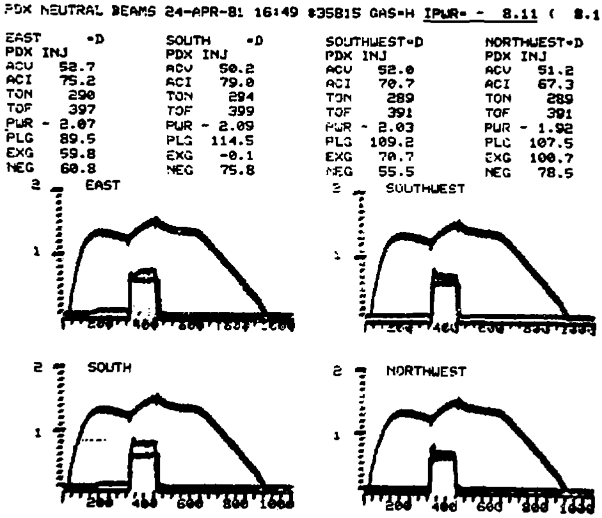

Fig. 8 Computer display of the PDX neutral beam system electrical parameters after an injection.

Reionization losses were studied using pressure gauges, phototransistors, thermocouples, surface shielding, and surface sample analysis. Considerable outgassing of conventionally prepared 304SS ducts occurred during initial injections and gradually decreased with the cumulative absorption of beam power (see Fig. 9). Reionization power losses are presently about 5% in the ducts and about 12% total for a beam line including the duct. Present duct pressures are attributed primarily to gas from the ion source and neutralizer with much smaller contributions from residual wall desorption. Physical mechanisms for the observed duct outgassing are discussed elsewhere.[11]

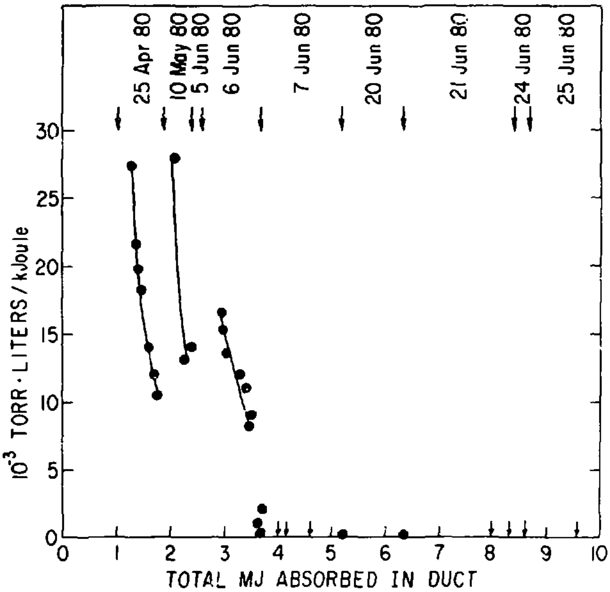

Fig. 9 PDX East neutral beam duct outgassing per kJ of absorbed power per injection versus the cumulative power absorbed.

Since it has been shown experimentally that beams of this power can easily melt 1.27 cm thick stainless steel, it is necessary to protect the inner wall of PDX from direct full power neutral beam exposure. This protection was achieved by installing a neutral beam armor system on the inner wall of PDX.[12] It consists of 1.27 cm thick POCO graphite tiles which are coated with a thin layer of titanium carbide (see Fig. 10). The tiles are held in water cooled stainless steel and copper backing plates. The heat load on the armor during full power injections in the absence of the plasma can be determined from changes in the circulating water temperature. During high plasma density conditions, the power transmission is not sufficient to give a water temperature change that is observable using simple techniques. An array of 14 to 16 themocouples in the graphite armor opposite each beam is used to measure the beam location, power density, and transmitted power. Figure 11 shows a computer display which lists the output from the inner wall thermocouple diagnostic. Shown are the results of a bi-gaussian least-squares-fit to the power density distribution.

Fig. 10 Photograph of the PDX inner wall neutral beam armor and inner limiter system.

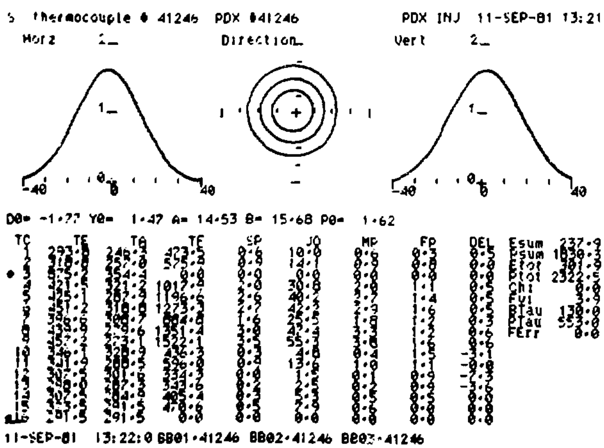

Fig. 11 Computer display of the PDX inner wall armor thermocouple diagnostic.

The PDX inner wall armor system, in addition to its armor and beam diagnostic functions also acts as a toroidal inner limiter. Initial thermal load measurements have been made during 450 kA OH heated discharges for which this inner limiter was in contact with the plasma. Preliminary results suggest the feasibility of operating in this mode using high power neutral beams and these experiments will be attempted. The results of these experiments should make a direct contribution to the data base needed for design of large beam heated reactors such as TFTR that will employ toroidal inner limiters.

In conclusion, we have oriented the procedures of PDX neutral beam operation toward optimizing the experimental goals of PDX and contributing data and experience to the development and reliability of the more powerful neutral beam injection systems needed for TFTR and future devices.

ACKNOWLEDGMENT

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