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Development of the TFTR Neutral Beam Injection System*

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ABSTRACT

The TFTR Neutral Beam Lines are designed to inject 20 MW of 120 keV neutral deuterium atoms into the plasma. This is accomplished using 12 sources, 65 amperes each, mounted in 4 beam lines. The 120 kV sources are being developed by LBL and a prototype beam line which will be tested at Berkeley is being developed as a cooperative effort by LLL and LBL.

The implementation of these beam lines has required the development of several associated pieces of hardware. 200 kV switch tubes for the power supplies are being developed by Eimac and RCA for modulation and regulation of the accelerating supplies. A 90 cm metallic seal gate valve capable of sealing against atmosphere in either direction is being developed for separating the torus and beam line vacuum systems. A 70 x 80 cm fast shutter valve is also being developed to limit tritium migration from the torus into the beam line. Internal to the beam line a calorimeter, ion dump and deflection magnet have been designed to handle three beams, and optical diagnostics utilizing the doppler broadening and doppler shift of light emitted from the accelerated beam are being developed by LBL.

The control and monitoring of the 12 sources will be done via the TFTR computer control system (CICADA) as will other parts of the machine, and software is being developed to condition and operate the sources automatically.

The prototype beam line is scheduled to begin operation in the fall of 1978 and all four production beam lines on TFTR in 1982.

I. INTRODUCTION

The goal of TFTR is to achieve reactor grade plasmas with significant D-T fusion reaction rates. To realize this goas will require the attainment of T_e, T_i ~5-10 keV, a maximization of plasma density, energy confinement times corresponding to $n\tau_E \sim 10^{13}$ to 10^{14} sec./cm^3 and the ability to utilize deuterium and tritium as plasma components. The TFTR will have a standard limiter aperture of a=85 cm, at R=248 cm. The toroidal magnetic field is B_t=5.2T and the available plasma currents are I=1.0-2.5MA. The standard discharge duration is 1 sec, but this can be extended to 4 sec. with B_t=4.5T.

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The neutral beam injectors are designed to deliver 20MW of 120 keV neutral deuterium atoms to the plasma. In addition, 12-15MW of 60 keV and 40 keV beams will be injected also. The beam pulse length is presently .5 sec.

II. BEAM PARAMETERS

The TFTR neutral beam lines are being designed to utilize 65 ampere, 120 kV ion sources [1,2] which are being developed by Lawrence Berkeley Laboratory. These sources employ a magnetic field free plasma generator and slotted accelerating grids. There are four grids; the transparency of the accelerating grid structure is approximately 60%. The average current density produced by the plasma generator is .3 amperes/cm^2 and the emitting area is 10 cm x 40 cm. The sources produce an elliptical beam and the measured 1/e half width divergence[3] is ~1.3° perpendicular to the slots and ~.4° parallel to the slots. The area of the source is chosen to give the desired current of 65 amperes when accelerating a deuterium beam to 120 keV. If one were to run hydrogen, the area of the source would be reduced to limit the current to the desired level.

To provide 20 MW of full energy neutrals, 12 sources will be used on TFTR. They will be mounted in four beam lines. Six injection ports are available on the TFTR, four are for co-injection and two for counter-injection. This allows for balanced injection of the four beam lines (2 co- and 2 counter) or all four co-injecting. Also, if necessary, an additional 2 beam lines could be mounted on the machine at a later date. One of these possible arrangements is shown in Figure 1.

DISCLAIMER

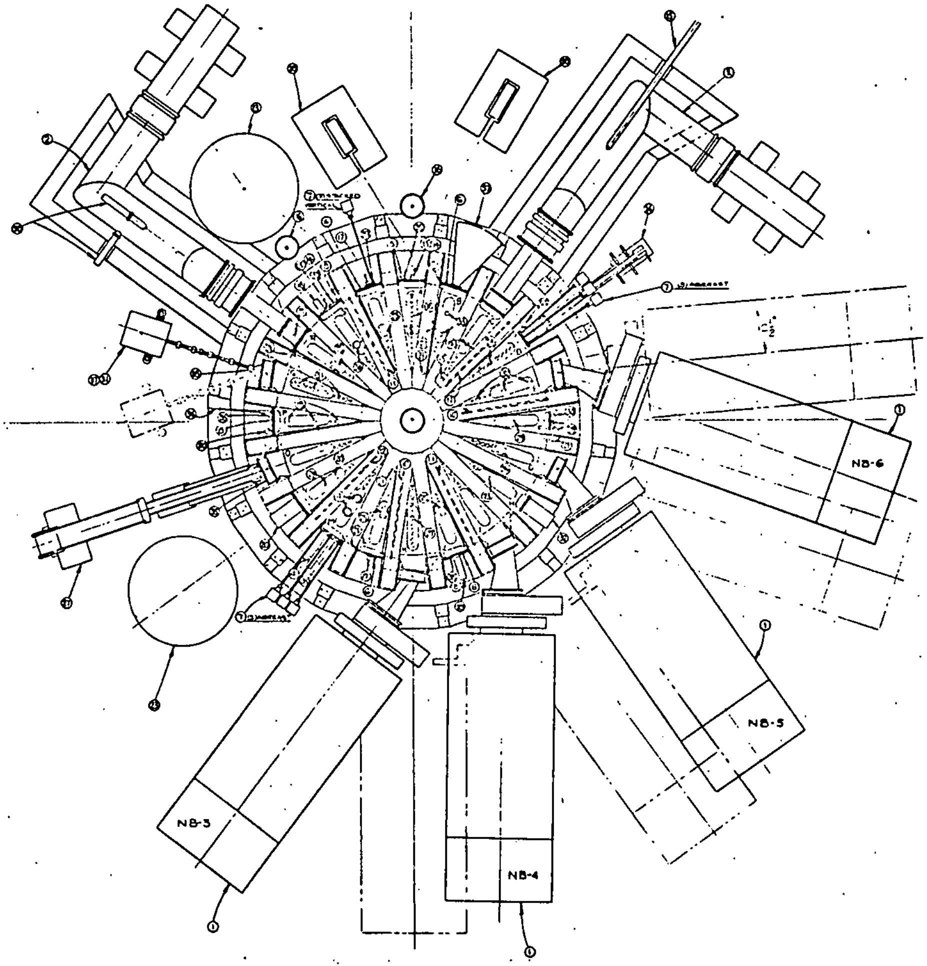

Figure 1 Plan view of TFTR showing various diagnostics positioned about the tokamak and four beam lines mounted for tangential co-injection. The beam lines can be pivoted to any angle between the position shown and perpendicualr injection.

The injection ports are nearly rectangular in shape, 40 cm wide and 80 cm tall. The connecting duct between the beam line and the torus vacuum vessel contains a flexible joint. This joint allows the beam line aiming angle to be changed by 10° without opening either vacuum system. Adapters can be installed to change the aiming angle beyond the 10°, and the injection port is sized such that the injection angle can be changed from perpendicular injection to a tangential injection at a radius of 265 cm, or a total movement of 37°, without restricting the 40 x 80 cm^2.

The large injection port is taken advantage of to reduce the peak beam power density. This is done by eliminating source focusing, or using flat grids, so the emitting surface is flat rather than concave. This reduces the central power density of the beam from 40 kW/cm^2 to 22 kW/cm^2 with only a small increase in the beam size. The calorimeters and ion dumps are angled to reduce this power density to 1-3 kW/cm at the surface.

Using inertial beam dumps at power densities of ~2 kW/cm^2 allow pulse lengths of ~3 sec. The present sources are specified for .5 sec pulses, but it is hoped that this can be extended to 1-3 sec.

III. SOURCE R & D

LBL has successfully operated a 1/4 area test source[4] at 120 kV. This source features a 10cm x 10cm extraction area. The grids used in the test source are identical to those used in a full size source; they are constructed of molybdenum rods machined in specific shapes. They are brazed at one end to a header, and the other end is free to move to accomodate thermal expansion.

The internal insulators on the test source are alumina surrounded by SF_6 (2 atm). The SF_6 is contained in fiberglass vessel which is the external insulator of the source. The ceramic insulators for the full area source are under development and are proving to be somewhat difficult due to their large size and rectangular shape. Both alumina and machineable glass ceramic are being considered for this purpose.

IV. MECHANICAL BEAM LINE

A TFTR beam line is shown in Figure 2. The vacuum chamber is 4.5 m tall, 5.7 m long and 3 m wide. Both sides of the beam line are covered with 4.5°K cryocondensing panels. Their area is ~34 m^2 and the expecting pumping speed is ~3 x 10^6 l/s. All of the components of the beam line are mounted on large flanges and can be removed with the flange to facilitate remote handling requirements. The 3 ion sources and neutralizers mount on a common flange at the rear of the beam line; however, each source has its own isolation valve and can be removed individually without disturbing the vacuum. The three aperture bending magnet and ion dump are mounted from a large flange in the top center of the beam line, and the calorimeters on a similar flange at the front of the beam line. The cryopanels are suspended from the lid of the beam line vacuum chamber, which is removeable, allowing one to lift the entire cryopanel array out of the beam line.

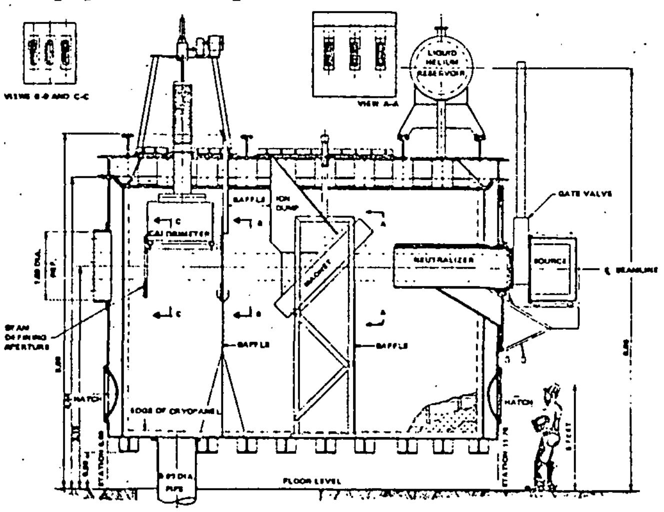

Figure 2 Side elevation of a TFTR Neutral Beam Line. Unspecified dimensions are given in meters. Three sources are mounted side by side at the rear of the beam

Figure 2 (Cont)

line, and seperate neutralizers, magnet apertures and calorimeter sections are provided for each beam.

The cryopanels are constructed from 2 sheets of stainless steel which are edge welded and spot welded at regular intervals across the area of the sheets. The unit is then pressurized to inflate the sheets into a quilted pillow-like form. The back of the LHe filled panel is shielded by a similar structure at 77°K and the front is shielded by blackened copper chevrons also at liquid nitrogen temperatures.

The beam dumps are the inertial type and are constructed of 3/4 in. copper plates with cooling lines brazed to the back side. They are angled with respect to the beam to decrease the incident power density by a factor of ~7.

The ion deflection magnet is a transmission magnet angled at 45° to the beam. The full energy ion component is deflected upward at an angle of 60°. The three apertures are angled with respect to one another to accomodate the 3 converging beams and the field in each gap can be controlled independently. Field clamps are used to reduce the effects of the fringe fields. Edge focusing gives a crossover in the beam near the exit of the magnet and the beams are diverging strongly as they enter the ion dump.

The ion sources are located ~8.5 m from the torus vacuum vessel, and a duct nearly 3m long joins the beam line and torus vacuum systems. In addition to the flexible joint, this duct contains an absolute gate valve, a fast shutter valve, and remotely operable connecting joints. Each of these items are a subject of research and development efforts.

The absolute gate valve is an all metal, bakeable to 250°C, valve capable of sealing against atmosphere in either direction. The specified maximum leak rate is 10^{-9} Torr·l/s and minimum life is 800 closures. It employs a radial or belville spring sealing mechanism and features dual gates with interstitial pumping. The diameter of the aperture is 90 cm.

The fast shutter valve has an aperture 70cm wide and 80cm tall. The purpose of the valve is to minimize the amount of tritium that would drift from the torus and be condensed on the beam line cryopanels. The time required from when the valve aperture begins to be obscured to when the aperture is covered is 50 msec, however, 50 msec are used to start the gates moving and 50 msec are used to decelerate the gates to a stop. Therefore, the total cycle time is 150 msec. The leakage conductance past the shutter valve when in the closed position is 10 l/s. The gates are constructed to prevent eddy current problems and allow free movement in the stray field of the TFTR. They can also withstand a differential pressure of 200 Torr.

V. NEUTRAL BEAM POWER CONVERSION SYSTEM

Each ion source will be powered independently. The arc and filament supplies float at high voltage and are tailored to the Berkeley Ion Source (4000A, 60V arc and 6000A, 13V filaments). The accelerating supplies[5] will employ a series modulator-regulator tetrode, as shown in Figure 3. This is a 200 kV 65 ampere tube being developed by RCA[6] and Eimac[7]. The anode, located in the center of the tube and surrounded by the cathode guns, is capable of dissipating 2MW and is cooled by high velocity high pressure water. The anode segments are angled with respect to the electron beam so that the peak power density is 700W/cm^2.

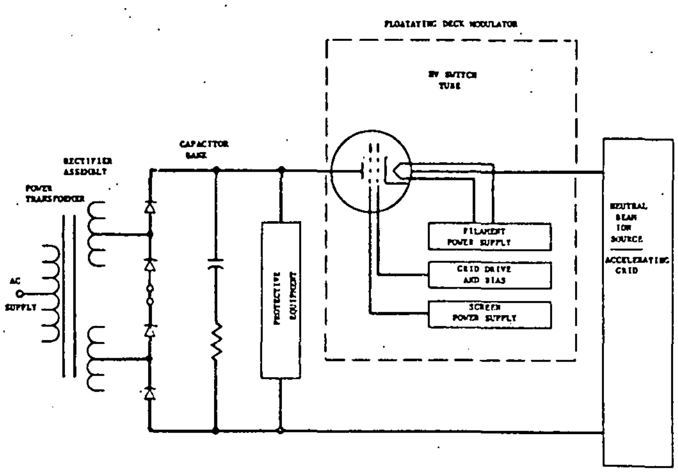

Figure 3 A simplified diagram of the TFTR Neutral Beam Power Conversion acceleration supplies. Modulation and regulation is accomplished by a 200kV, 65 A series tetrode presently under development.

In addition to the 120 kV, the supply also provides ~100kV for the gradient grid of the ion source. A separate supply is used for the suppressor grid and the fourth grid is maintained at ground potential. To increase the flexibility of the accelerating supplies, they will be capable of running with either a positive or negative ground. The supplies are capable of 5.0 sec pulses at a duty cycle of .033.

The plasma source supplies will be located in the basement directly under the ion sources. The distance from these supplies to the source is ~20 ft. The accelerating supplies will be located in a building adjacent to the test cell at a distance of ~100 ft. from the ion sources. This arrangement minimizes the stored energy in the capacitance of sources, supplies and transmission lines within the constraints imposed by buildings and availability for maintenance. This stored energy, if not kept to a minimum, can seriously damage a source during a sparkdown.

To additionally protect the source, a series impedance in the form of a transformer core snubber[8] will be employed near the source. By passing all source leads through such a core stack, the stored energy can be absorbed in the cores during a spark and damage to the source prevented. The volt seconds of the core should be large enough to accommodate the stored energy than can be delivered to the source in the event of a spark.

Some of the most difficult problems to eliminate in a neutral beam power supply are fast transients which occur during source sparks. It has been found that after running a supply satisfactorily on a dummy load the interactions with a source reveal new problems which must be solved. Likewise, the problem of crosstalk between adjacent supplies and sources complicate this problem.

VI. CONTROLS AND DIAGNOSTICS

The TFTR Neutral Beam Lines will be computer controlled by the TFTR control system, CICADA. The beam line devices interface with local CAMAC hardware, and where needed local microprocessors will be provided. The CAMAC crates in turn are linked to subsystem computers of which one (or more if needed) will be dedicated to the neutral beam lines. The subsystem computers in turn are linked to four large central computers. The subsystem computers handle real time monitoring and control; the central computers provide servicing for the operating consoles and off line data analysis and program preparation. One of the four, the operations computer supervises the activities of the total system. A shared memory will be used with the central computers for the data pool and for intercomputer communication.

In addition to controlling and monitoring the beam line subsystems, a number of beam diagnostics will be processed by CICADA. These include arrays of thermistors embedded in the calorimeters and ion dumps for measuring beam power and profiles, and optical diagnostics[9] for determining beam divergence, aiming and species. The divergence can be determined by measuring the doppler broadening of D_α light emitted by the beam. Similarly, the doppler shift can be used to separate the differnet energy components of the beam and the relative light intensities coupled with the proper cross sections can be used to calculate the ratio of D^+ to D_2^+ to D_3^+ contained in the beam.

These systems provide redundant means of measuring the beam properties and will provide valuable information for beam injection experiments on TFTR.

VII. SUMMARY

The TFTR beam lines, which are scheduled to operate in 1982, will employ a large number of items which are presently in the research and development stage. These include, but are not limited to, the sources themselves, 200 kV switch tubes, 90cm metal seal gate valves, fast shutter valves, beam dumps and various types of beam diagnostics. To a large extent, future beam lines will be affected by the problems and promises of the TFTR neutral beam injection system and the development projects it is based on.

One can assume that future beam lines will look for greater power and higher energies as TFTR in itself is a significant extrapolation over existing machine beam capabilities. The operating experience with the prototype beam line and then the production units will provide valuable information as to what future beam lines may be like.

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