CONCEPTUAL DESIGN OF A NEUTRAL-BEAM INJECTION SYSTEM FOR THE TFTR*

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Summary

The neutral-beam injection requirements for heating and fueling the next generation of fusion reactor experiments far exceed those of present devices; the neutral-beam systems needed to meet these requirements will be large and complex. We discuss a conceptual design of a TFTR tokamak injection system to produce 120 keV deuterium-ion beams with a total power of about 80 MW.

Introduction

The Tokamak Fusion Test Reactor (TFTR) is an experimental tokamak which will be constructed at the Princeton Plasma Physics Laboratory (PPPL); initial operation is scheduled for 1980. Along with demonstrating the production of a magnetically-confined plasma with D-T reaction rates similar to those that will be required for a reactor, this device will provide engineering experience needed to design and construct an experimental power reactor (EPR).

The deuterium neutral-beam system that will be used to heat and react with the tritium plasma in the tokamak requires neutral-injector performance that considerably exceeds the present state of development. The basic requirements were set by PPPL physicists, and were modified by them during the course of several iterations of conceptual design studies carried out during the summer of 1975 by members of the fusion staffs of The Princeton Plasma Physics Laboratory, The Lawrence Berkeley and Livermore Laboratories, The Oak Ridge Holifield National Laboratory, Westinghouse Electric Corporation, and the ERDA DCTR Staff. A summary of the LLL/LBL conceptual design study is presented here; additional details are given in accompanying papers,[1,2,3] and a complete report is available.[4]

Design Basis

A. Tokamak Requirements

The basic PPPL requirement is the injection of 20 MW of 120-keV D^0 atoms in 0.5-sec-pulses at 5-minute intervals. The maximum power available from the flywheel-generator energy storage system is 80 MW. We will see later that the production of the 20-MW, 120-keV D^0 beam requires essentially all of the available power.

The neutral beams, which will be injected through four ports (six if necessary), must pass through the plasma donut approximately perpendicular to a major radius ("tangential injection"). Two different injection radii have been specified: For injection into the TFTR plasma before it is adiabatically compressed the injection radius is 270 cm (Mode I); for injection into the compressed plasma it is 220 cm (Mode II). (The entire beam-line structure will be moved when the injection radius is changed.) Eighty-five percent of the beam power is to be delivered within ± 20 cm of the specified injection radius. The injection port, which is approximately 3 m from the point of tangency, is limited to a width of 40 cm and a height of 70 cm by the equilibrium and toroidal field magnet coils.

The total amount of cold gas entering the torus during the 0.5-sec pulse must be less than 1 Torr-liter.

All parts must be bakeable and, because some tritium will enter the beam-line, everything must be assembled and adjusted with remote handling equipment.

B. Beam-line elements

A schematic diagram of a typical neutral-injection beam system is shown in Figure 1. The basic elements are (1) a plasma generator (ion source), (2) an ion extractor and accelerator, (3) a neutralizer, (4) a sweep magnet, (5) an ion-beam dump, (6) vacuum pumps, (7) power supplies, (8) diagnostics, and (9) controls. The operation is as follows: deuterium plasma is created by a high-current arc discharge. Ions are extracted from the plasma, accelerated in a carefully designed multi-electrode structure and pass through a constricted region containing deuterium gas (the "neutralizer"), where a fraction of the ions become neutralized. Ions that are not neutralized are removed from the beam by a sweep magnet. (Otherwise, the variable tokamak magnetic fields would bend the ions into surfaces near the entrance port, possibly resulting in the release of gas bursts or melting of the surfaces.) This ion beam may have very large power, which must be handled by the ion-beam dump. The vacuum pumps distributed along the beam line remove most of the gas emerging from the neutralizer and the ion-beam dump, and maintain the pressure between the sweep magnet and the tokamak at a sufficiently low value ($\sim 5 \times 10^{-4}$ Pa) that very little of the neutral beam is reionized. Optical, mechanical, and electrical sensors determine the condition and performance of the neutral-beam system and permit the control system to adjust power supply voltages or shut down the system if a malfunction occurs.

Conceptual Design of the TFTR Neutral-Beam System

Figure 2 shows calculated yields[5] of neutrals and ions when a typical mixture of deuterium-ion species (D^+, D_2^+, and D_3^+, as measured in our existing plasma sources) is accelerated to 120 keV and passes through a thick-target D_2 neutralizer. From Figure 2 we infer that if the deuterium ion-species mixture is the same as in the present LBL/LLL 20-kV and 40-kV systems,[6] then about 65 MW of ions must enter the neutralizer with the proper trajectories. Half- and third-energy D^0 atoms resulting from the dissociation of molecular ions contribute to the plasma heating but relatively little to the D-T fusion reaction rate. Because of some inevitable beam losses, the total 120-kV power required to meet the injection goal will be close to the 80 MW available.

Dividing the accelerator power equally among four beam lines gives 20 MW, or about 170 A of 120-keV ions, per beam line. Our present 20- and 40-keV "50 A", 10-msec injectors[6] accelerate about 70 A of ions. To minimize development and maximize reliability we do not want to increase the physical size of the ion sources

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*Work done under the auspices of the US ERDA.

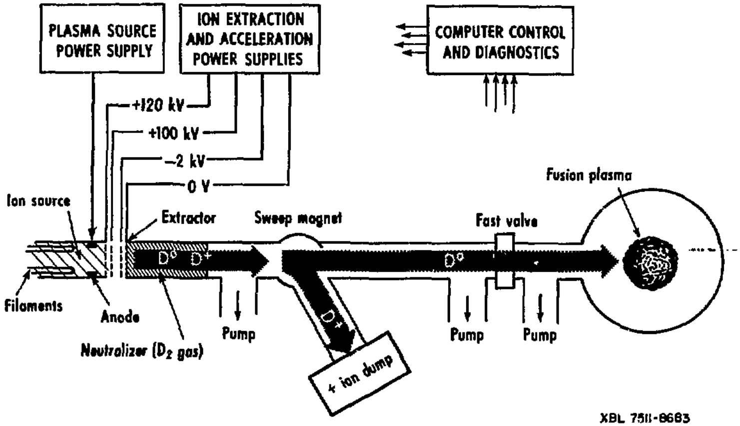

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Fig. 1. Schematic of a typical neutral-beam injection system.

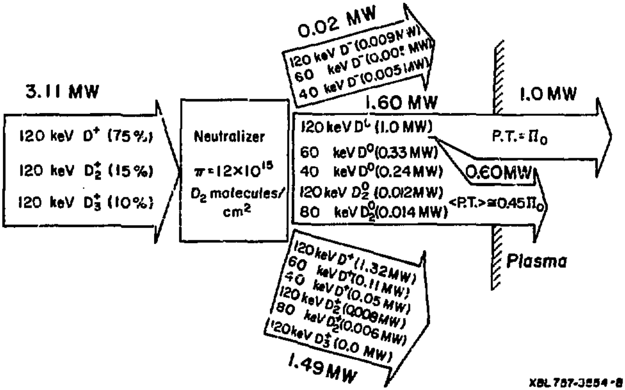

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Fig. 2. Power in initial and final ion- and neutral-beams required to yield 1 MW of 120 keV D^0 atoms. The 75%, 15%, 10% initial ion species distribution is typical of that in present LBL/LLL ion sources. The thickness of the D_2 neutralizer is chosen to give 90% of the (maximum possible) conversion to 120 keV D^0 atoms, which would be obtained with an infinitely thick target.

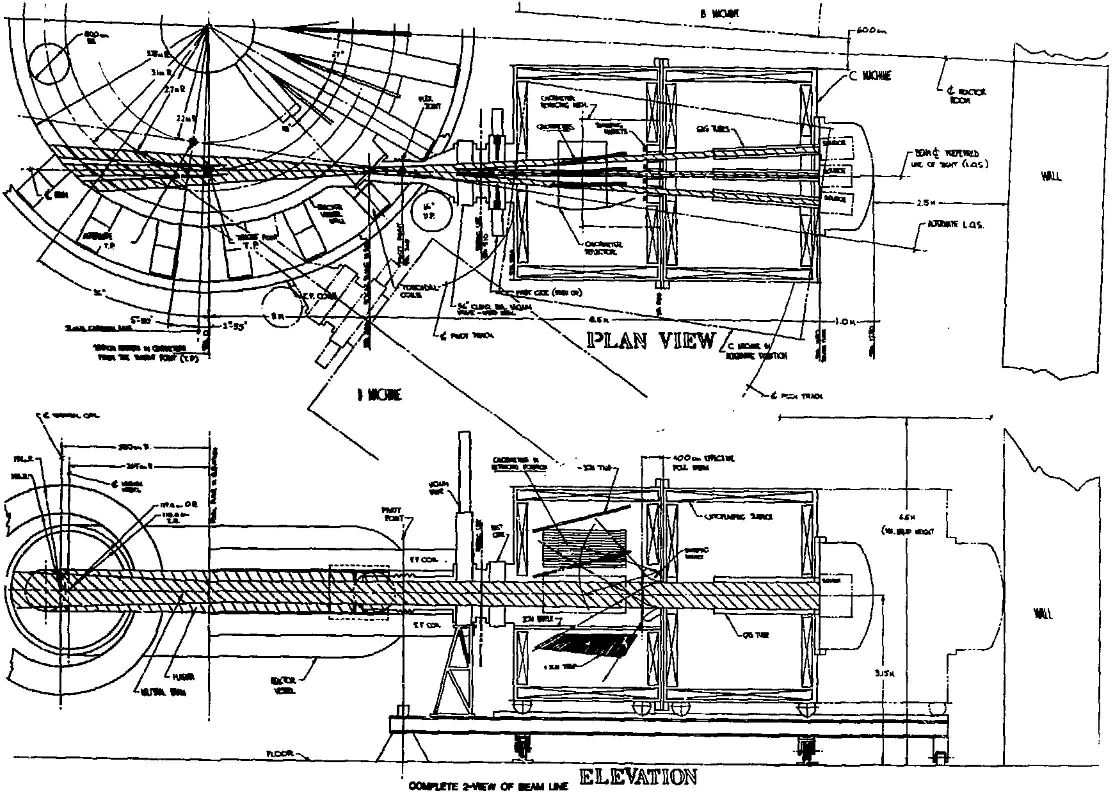


Fig. 3. Plan and elevation views of one of the four neutral-beam-injection lines proposed for TFTR.

appreciably over that of the present ones. For the same reasons, we choose to decrease the density of the current extracted from the plasma from 0.5 A/cm^2 to 0.25 A/cm^2. As a result:

1. Three plasma sources and electrode structures are required for each of the four beam lines (Figure 3). The ions will be extracted from each source over a 10-cm x 40-cm area. Each extractor will require a high-voltage power supply capable of switching about 7 MW of power at 120 kV.

2. The proposed extractor and accelerator structures are of the general type tried in 40-keV sources.[6] About 40 "beamlets", extracted from 0.6-cm x 10-cm slots, will be accelerated in each 4-electrode multislot assembly. Extremely good beam optics are required to maximize the useful fraction of the beam and to minimize primary and secondary power loading in the accelerator structure. The electrode shapes are computed with an optimizing code, WOLF.[6] An example of a plot showing calculated beam trajectories is given in Figure 4. Computed and experimental performance have been in good agreement for our 20-keV and 40-keV sources, providing confidence in the design of the beam-optics of the 120-keV injectors. However, there is not as yet much experience relevant to possible difficulties in maintaining the required voltage gradients.

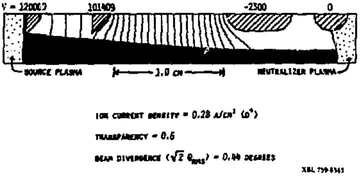


Fig. 4. Computer-optimized four-electrode structure and calculated ion trajectories.

Because of the good optics of each beamlet, it is possible to focus all of the beamlets at a common point by proper shaping of the electrodes or to have different focal lengths in planes parallel and perpendicular to the slots. This astigmatic property is used in the design.

3. The neutralizer attached to each extractor has a cross section of 15 cm x 60 cm, and is 200-cm long. It would be desirable to shorten the neutralizer by increasing the gas pressure, but this would increase the gas flow to the pumps and might adversely affect the ion extraction and acceleration. The line-density of D_2 gas in the neutralizer will be $\sim 10^{16}$ molecules/cm^2 ($\sim$0.5 Pa-m).

4. The iron-core sweep magnet has three 15-cm-long gaps, one for each injector. The path length in the neutral-beam direction is about 25 cm. A gap field of about 0.09 Tesla deflects the 120-, 60-, and 40-keV D^+ beams through slots into the beam dump. The magnet gaps also limit the gas conductance between the relatively high-pressure region at the exit ends of the neutralizers and the part of the beam line that connects to the torus.

5. The ion-beam dump must handle about 10 MW of power. The power density is too high for normal incidence on any material, so the beam will be stopped on molybdenum plates sufficiently angled to the beam to reduce the power density to a tolerable level. The plates are cooled between pulses by low-conductivity water.

6. The vacuum pumps are liquid-helium temperature (4.2 K) cryopanels surrounded by liquid-nitrogen baffles.[2,7] Each beam line is divided into three chambers: (a) the region between the neutralizers and the sweep magnet, (b) the region between the sweep magnet and the torus, and (c) the ion-beam dump. The gas input into (a) is estimated to be 12,000 Pa-liters/sec. The limiting pressure is in region (b) where we have set a maximum on the neutral-gas line-density of $\sim 3 \times 10^{-3}$ Pa-meters to limit the re-ionization of the neutral beam to 1%. A conservative calculation of the areas of 4.2 K panels in the three regions yields 35, 17, and 17 m^2, respectively.

7. Three power-supply approaches have been considered. The first is an extrapolation of our present 40-kV supplies,[8] in which series regulation and switching of the high-voltage supply is used. The other two use shunt regulation, either with inductive energy storage,[9] or operating from AC mains with saturable reactors to limit currents.[1] The latter approach will be used in our 150-kV test facility.[10]

8. Diagnostic signals are obtained from the power supplies connected to the ion sources and from over one hundred other sensors in each beam line (Figure 5). Measurements of the intensity and distribution of the neutral-beam power are very difficult, but essential for the tokamak physics experiments and for protection of the beam line. (The neutral-beam power density at the entrance to the tokamak can have a maximum value of about 100 kW/cm^2.)

When the beam is not entering the tokamak, gross calorimetry can be achieved with thick, water-cooled molybdenum slabs that can be inserted just downstream of the sweep magnet. These are tilted to reduce the surface power density to an acceptable level and extend about one meter along the beam line.

When the neutral beam is injected into the tokamak, solid sensors are not practical, except on the beam periphery. In this case we plan to use arrays of optical sensors that detect the light emitted by the atoms of the D^0 beam and, from the intensity distribution and the Doppler shift of the emitted radiation, deduce the beam profile and composition.

Fast heat sensors will be used to detect hot spots on the walls due to mis-steered or poorly focused beam and initiate beam turn-off before damage can result.

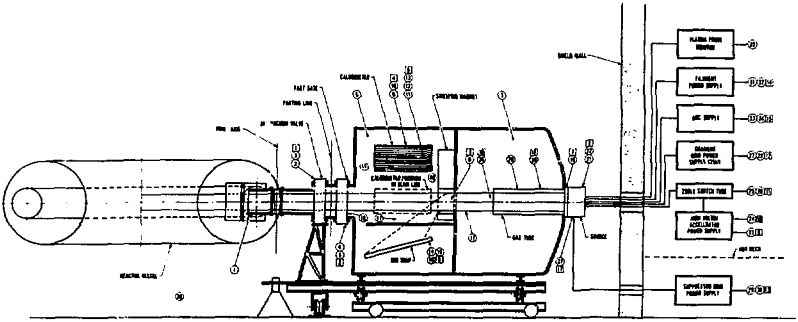
9. Some of the diagnostic signals go directly to the power-supply control circuits. (Because of the enormous power available, ion-source and accelerator structures will be damaged if power is not removed immediately when a fault occurs.) The remaining signals go to a computer that controls the power supplies during normal operation, monitors the status of the beam line, and analyzes diagnostic signals. Many of the computer-control concepts[3] already have been developed and tested at the LBL heavy-ion accelerator (Bevalac).

Conclusion

The conceptual-design of the TFTR neutral-beam-injection system evolved after several iterations in which the interplay of each of the elements described in this paper had to be considered. The length of each beam line, from the ion accelerator to the entrance port of the tokamak, is about 9 m. This was dictated not only by the need to accommodate the neutralizer, sweeping magnet, ion-beam dump, and the necessary cryo-pumping surfaces, but also to deliver 85% of the beam power from three injector modules within ± 20 cm of the specified injection radius. The half-angle of the tokamak entrance port, viewed from an injector module, is only 1.3°. This makes optical design, aiming, and performance of the injectors critical.

Each part of the neutral-beam system is state-of-the-art, or a little beyond. Thus, an intense development effort is required in order to meet the TFTR schedule.

The cost of the entire TFTR neutral-beam system including beam lines, energy-conversion systems, and controls, is estimated to be about 30 million (1975) dollars. This figure includes engineering, fabrication and installation, and contingency. The electrical and mechanical costs are about equal.



MONITORS = ○

MONITOR NUMBER	FUNCTION	NO REQ'D	BI STABLE OR ADC	COMPUTER OR AUTO INTERRUPT
1	EXISTENCE OF PLASMA	1	BI ST	BOTH
2	HAND VALVE OPEN	1	-	BOTH
3	HAND VALVE CLOSED	1	-	COMP
4	FAST VALVE OPEN		-	BOTH
5	FAST VALVE CLOSED		-	COMP
6	PRESSURE IN SECOND TANK	1	ADC	
7	PRESSURE IN FIRST TANK	1	-	
8	SWEEP MAGNET FIELD	.		
9	NEUTRAL DUMP IN	1	BI ST	BOTH
10	NEUTRAL DUMP OUT	1		COMP
11	NEUTRAL DUMP WATER IN TEMP	3	ADC	
12	NEUTRAL DUMP WATER OUT TEMP	3	-	
13	NEUTRAL DUMP WATER FLOW RATE	3	-	
14	ION DUMP WATER IN TEMP	1		
15	ION DUMP WATER OUT TEMP	1	-	
16	ION DUMP WATER FLOW RATE	1		
17	HOT SPOT DETECTORS	12	BOTH	BOTH
18	BEAM POSITION DETECTORS	6X16	BI ST	BOTH
19	SOURCE POSITION	6	ADC	
20	BEAM COMPOSITION	3		
21	SOURCE WATER TEMP	3		
22	SOURCE WATER FLOW	3	BI ST	COMP
23	ACCELERATOR RECTIFIER VOLT	3	ADC	
24	ACCELERATOR REGULATED VOLT	3		
25	ACCELERATOR APPLIED VOLT	3	ADC	

MONITORS - ○

MONITOR NUMBER	FUNCTION	NO REQ'D	BISTABLE OR ADC	COMPUTER OR AUTO INTERRUPT
26	ACCELERATOR CURRENT	3	ADC	
27	GRADIENT GRID VOLTAGE	3	-	
28	GRADIENT GRID CURRENT	3	-	
29	SUPPRESSOR GRID VOLTAGE	3	-	
30	SUPPRESSOR GRID CURRENT	3	-	
31	FILAMENT VOLTAGE	3	-	
32	FILAMENT CURRENT	3	-	
33	ARC VOLTAGE	3	-	
34	ARC CURRENT	3	-	
35	PLASMA PROBE VOLTAGE	3	-	
36	MAG FIELD BETWEEN NEUT & MAG	1	-	
37	ARC GAS PRESSURE	3	ADC	
38	FIRE SIGNAL FROM TFTR	1	BI ST	COMP
39	NEUTRALIZER [illegible] PRESSURE	3	ADC	
40	NEGATIVE ION DUMP TEMP	1	ADC	

CONTROLS = □

CONTROL NUMBER	FUNCTION	NO REQ'D	TYPE OF CONTROL
1	HAND VALVE OPEN/CLOSE	1	FWD/REV TO STOP
2	FAST VALVE OPEN/CLOSE	1	BI STABLE
3	SWEEP MAGNET FIELD	1	FWD/REV PROPORTIONAL
4	NEUTRAL DUMP IN/OUT	1	FWD/REV TO STOP
5	NEUTRAL DUMP WATER FLOW	1	FWD/REV PROPORTIONAL
6	ION DUMP WATER FLOW	1	BI-STABLE
7	SOURCE POSITION	6	FWD/REV PROPORTIONAL
8	SOURCE WATER FLOW	3	BI-STABLE
9	ACCELERATOR RECTIFIER VOLTAGE	3	FWD/REV PROPORTIONAL
10	ACCELERATOR REGULATED VOLTAGE	3	STEPPING MOTOR
11	SWITCH TUBE	3	BI STABLE
12	GRADIENT GRID VOLTAGE	3	FWD/REV PROPORTIONAL
13	SUPPRESSOR GRID VOLTAGE	3	-
14	FILAMENT VOLTAGE	3	-
15	ARC CURRENT	3	-
16	MAGNETIC FIELD BETWEEN NEUT & MAGNET	1	-
17	ARC GAS PRESSURE	3	-
18	NEUTRALIZER GAS PRESSURE	3	FWD/REV PROPORTIONAL

Fig. 5. Beam-line controls and monitors.

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