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THE TFTR NEUTRAL-BEAM POWER SYSTEM

By

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THE TFTR NEUTRAL-BEAM POWER SYSTEM

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James Forrestal Campus, Princeton, NJ 08544ABSTRACT

The TFTR Neutral Beam Power System (NBPS) consists of the accelerator grid power supply and the auxiliary power supplies required to operate the TFTR 120 keV ion sources. The current configuration of the NBPS including the 11 MVA accelerator grid power supply and the Arc and Filament power supplies isolated for operation at accelerator grid voltages up to 120 kV, is described. The prototype NBPS has been assembled at the Princeton Plasma Physics Laboratory and has been operated. The results of the initial operation and the description and resolution of some of the technical problems encountered during the commissioning tests are presented.

1. INTRODUCTION

The design of the Tokamak Fusion Test Reactor Neutral Beam Power Supply (NBPS) has been completed and a substantial amount of the power supply hardware has been delivered by the various hardware vendors. The NBPS as originally designed and now as delivered (Aydin Energy Division, Palo Alto, California) will provide the 10 cm x 40 cm TFTR Neutral Beam Ion Source with up to 120 kV and 65 A of accelerator power in addition to the prerequisite auxiliary power which includes the Arc, Filament and the Decel (suppressor) power supplies. The Decel Power Supply was provided by Universal Voltronics Corporation, Mt. Kisco, NY. A summary of the prototype test program with a description of some of the problems encountered during commissioning of the prototype and their solutions are described.

2. POWER SYSTEM DESCRIPTION2.1 Configuration

The configuration of the NBPS has been given in other proceedings [1]. However, as a reference for this paper, the NBPS consists of twelve identical power systems, each capable of operation independently of the others. The primary power source for the twelve NBPS are the two TFTR generators, each of which when fully loaded can produce up to 475 MVA. The NBPS can also be operated directly from the public service ac power grid in the event the generators are not operating. An elementary electrical diagram of a typical NBPS is shown in Figure 1, and a tabulation of some of the more important electrical parameters is given in Table I.

Table I.
Characteristics of the TFTR Neutral Beam Power System

Transformer-Rectifier	150 kv, 70 A
Modulator-Regulator	
Accel Grid	24-120 kV, 65 A
Gradient Grid	-5-92% V accel, ± 0.15 A
Decel Power Supply	-3.1 kV, 20 A
Arc Power Supply	80 V, 3000 A
Filament Power Supply	22 V, 6000 A

2.2 General Arrangement

With the exception of the 15 kV switch gear, the Voltage Controller, and the Transformer-Rectifier, all other components of the NBPS are located indoors. Twelve line-ups of these three units are located in the Neutral Beam Power Conversion Yard. Both the Voltage Controller and the Transformer-Rectifier are oil filled and are physically separated from one another to reduce the potential for damage resulting from fire and other similar explosive incidents. The Modulator/Regulator and the surge room equipment are located on the ground floor of the Neutral Beam Power Conversion Building, while the Arc and Filament Low Voltage Power Supplies, the Decel Power Supply, the Power Distribution Center and the Local Control Center are all located on the second floor of the Power Conversion Building. The NBPS water system is in the basement of the Power Conversion Building and the High Voltage Enclosure (HVE) is in the basement of the Tokamak Test Cell immediately beneath the Ion Sources installed on the Tokamak Beamlines so as to minimize the length of the flexible transmission line between the HVE and the Ion Source. This is important as it is required to keep the stored electrical energy to a minimum between the Ion Source Protection Equipment and the Ion Source.

2.3 Special Features of the Power System

In the description of the power system that follows, emphasis is directed to more unusual aspects of the system.

2.3.1 Insulation Systems

The NBPS utilizes several different types of insulation systems to achieve the voltage withstand capabilities required for safe, reliable operation. Special insulation methods were required for the HVE and the Modulator/Regulator. The HVE is a pressurized vessel, about 5 m high and 1.8 m in diameter and contains the Arc and Filament Power Supplies, the Ion Source Protection Equipment (ISPE), and the voltage isolated controls and instrumentation electronics which are used largely for Ion Source diagnostics. Inasmuch as the size of the equipment, limited by the space available beneath the Tokamak, did not permit sufficient clearance for air insulation it was necessary to design the HVE for insulation with pressurized SF₆ (25 psig) to achieve the required voltage withstand levels. The Modulator/Regulator on the other hand is largely an air insulated unit since space was not a main factor; however, the isolation transformer is a SF₆ insulated unit. Unlike the HVE, the required voltage withstand capability in the isolation transformer was achieved with only atmospheric pressure. All other components of the NBPS are air insulated, with the exception of the Voltage Controller and the Transformer/Rectifier which, as previously stated, are oil insulated.

2.3.2 Gradient Grid Voltage Divider

The gradient grid voltage divider must dissipate upwards of 500 kw for five second pulses, and this results in an energy dissipation in the voltage divider of about 2.9 MJ. The equipment vendor chose to remove this energy by using Freon* in the vapor phase. The resistor assembly, consisting of about 8000 wire wound, 10 watt resistors, is immersed in the liquid Freon*. As the temperature of the Freon* rises during the power pulse, the liquid boils, removing the heat from the resistor assembly. The vapor is recondensed by a gas/water heat exchanger, and the heat is removed by the water system.

2.3.3 High Voltage Switch Tube

The Modulator/Regulator utilizes the 200 kV, 2000 kW High Voltage Switch Tube (HVST) developed by RCA (Lancaster, Pennsylvania) as main power control element in the accel/gradient-grid chain of the NBPS. The characteristics of this tube have been described elsewhere in detail /2/. The tube is mounted on an insulated deck in the Modulator-Regulator. Because of the 200kV operating voltage, the anode-cathode ceramic seal is covered with an envelope of SF₆ to provide the required voltage withstand level. The operation of the tube is supported by electronics contained in the deck. The main supporting electronic subsystems include the control grid driver and voltage feedback amplifier, the screen grid power supply, the ion pump power supply, the filament power supply, and other miscellaneous instrumentation and control equipment.

2.3.4 Crowbar

The crowbar for the NBPS is located in the surge room and is connected to the Modulator-Regulator by about 23 m of coaxial cable. The unit consists of six series connected mercury ignitrons that are parallel fired /3/. The firing pulse to each ignitor is coupled by means of a fiber optic cable and optical transmitter and receiver. The tubes are conditioned for high voltage by maintaining a thermal gradient across the envelope through directing heated air to the anode and room temperature air to the cathode.

*Trademark of E. I. DuPont

Fig. 2. Ion Source Protection Equipment-
Elementary Electrical Diagram

2.3.5 Ion Source Protection Equipment

The design of the TFTR-NBPS Ion Source Protection Equipment (ISPE) was patterned after the work of W. Praeg (ANL)/4/ and W. Baker (LBL) /5/. Certain modifications were made to those concepts to make the design suitable for the

needs of the NBPS. An elementary diagram of the ISPE is shown in Figure 2. The maximum let through current during an ion source fault will be limited to 300A by the ISPE, and the current will be completely removed in less than 10 microseconds. All components of the ISPE are located in the HVE so they are as close as possible to the Neutral Beam Ion Source, within the constraints of the general arrangement of the tokamak. Space limitations at the Ion Source Enclosure precluded locating the equipment there.

All the iron of the magnetic circuits of the ISPE, with the exception of the bias reactors (L_1 and L_3), are 50-50 Ni-Fe. The saturated time delay transformer (T_1) contains 4 mil tape, whereas the linear reactor (L_2) contains 1 mil tape. The magnetics of the bias reactors are made from 3% silicon - 97% Fe, each using 2 mil tape.

Both T_1 and L_2 are biased to the reverse saturated flux condition so that the maximum change in flux during the fault can be achieved. The triggered spark gap was added to the T_1 circuit so as to reduce the amount of iron required for T_1 since the capacitance of the interconnecting triaxial cable was larger than anticipated. Although the use of the triggered gap compromises the reliability of the ISPE to some degree, tests conducted indicate an acceptable performance. This is made so by the fact that the gap is triggered by a voltage derived from the fault itself, thus eliminating the need for any external triggering equipment.

3. PROTOTYPE NBPS TEST RESULTS

3.1 Present Status

The prototype NBPS has been assembled and installed at Princeton essentially as it was delivered by the vendor /6/. However, certain modifications were required in the Modulator-Regulator to improve its electrical noise immunity and the voltage withstand capability of the isolation transformer.

All major components and subsystems of the prototype NBPS were individually tested using specially developed test modules. These modules simulated as closely as possible the actual source and load impedances that the component or subsystem under test would experience in normal operation. Although extra work was involved in building these modules, they enabled us to identify malfunctioning equipment and to correct the problem before the unit was connected into the rest of the power system.

To date, the prototype accel power supply has been operated on a routine basis to voltage levels of 100kV with occasional operation at 120 kV. The primary power subsystem (Voltage Controller and Transformer-Rectifier) has been operated at its rated voltage and current, but not at rated power. Pulse lengths up to two seconds have been achieved. The Arc and Filament Power Supplies have each been operated at their rated voltage, current and power levels. The Decel Power Supply has been operated at its rated voltage and current level. The operation of all the power supplies of the NBPS has been through the Local Control Center.

The Arc and Filament Power Supplies have run the plasma generator section of a full size Neutral Beam Ion Source. This operation has proved informative in that the power supplies functioned properly even with the non-linear ion source load.

The principal effort at this time is to achieve integrated operation of the complete NBPS up to accel voltage levels of 80 kV into a dummy load and having demonstrated the performance of the Power Supply, we will then proceed to operate a Neutral Beam Ion Source with hydrogen. Only hydrogen operation can be undertaken since the radiation shielding requirements necessary for deuterium operation are substantial and they exceed the space limitations of the test site.

3.2 Commissioning

Some of the more significant test results and commissioning problems that have been encountered in the various subsystems and components of the NBPS are described below.

3.2.1 Primary Power Subsystem

The Primary Power Subsystem (PPSS) has been assembled as it was designed by the vendor and has functioned as expected. No significant problems have arisen with PPSS although a rather spectacular failure of the coaxial cable connector at the output of the Transformer-Rectifier gave the protective system of the NBPS a workout earlier than desired. However, the good news was that, in spite of the line-to-ground fault, the damage was confined to the failed component. This result was attributed (although certainly not proved) to the quick response of the crowbar; it fired, diverting most of the follow through energy through it and away from the failed connector.

The adequacy of the speed of response of the crowbar is critical to the protection of the HVST. The crowbar was tested by performing a foil test on the output of the power system. In this rather standard test, the output of the power supply is shorted through a thin aluminum foil (1.5 mils) and the crowbar is required to divert the fault energy away from the foil quickly enough so that only a small hole, no larger than 10 mil diameter, would be made in the foil. The prototype crowbar was tested at voltages through 170kV and with the transient compensation network connected. The foil was not punctured and, by oscilloscope measurements, the crowbar appeared to have been triggered in less than 1 microsecond. The current in the arc through the test foil was cleared in no more than 12 microseconds.

3.2.2 Modulator-Regulator

Testing of the prototype Modulator-Regulator was not completed by the vendor at the factory due to a failure in the HVST which occurred near the completion of the factory tests. Because these tests were being performed using a capacitor bank as the input energy source, resulting in output pulses only of millisecond duration, these tests were of limited value considering the overall NBPS requirements. Accordingly, for that reason and for other programmatic reasons, the factory testing was discontinued and the unit shipped to Princeton. Following its arrival at Princeton, the unit was reassembled, and some of the deficiencies which had been noted during the factory testing were corrected. On operation of the Modulator-Regulator in a long pulse mode from the primary power subsystem, some problems were observed and subsequently corrected which were not noticed in the short pulse testing at the factory. More significant of these problems was the sensitivity to failure of the accel deck electronic components during output load faults. The cause of the failures was in many cases excessive voltage, which may have been generated during the load faults due to the very fast

rate of change in the output voltage. The problem was corrected by adding metal oxide varistors (MOVs) to the ac inputs of all the low voltage power supplies on the accel deck and also to the dc outputs of those supplies when they were located more than about $\frac{1}{2}$ m from the loads they were supplying. Since that time many load faults have occurred without failures in any accel deck electronics.

The HVST that was installed in the prototype Modulator-Regulator at Princeton was believed to be free of parasitic oscillation. However, when the system was operated at the longer pulse lengths, the sensitivity of the controls in the accel deck of the Modulator-Regulator was apparent and, through the use of a spectrum analyzer, the source of the electrical noise causing the control problem was quickly discovered. The HVST was found to be oscillating at 540 MHz with a second harmonic observed at 1080 MHz. This parasitic occurred at anode-cathode voltages greater than the normal values and, as a result, a simple readjustment of the operating parameters corrected the problem. RCA had observed a parasitic in this frequency range in a tube of later manufacture and has corrected the problem so that the tube is now totally free of parasitics even beyond the normal operating range. Other than the parasitic problem, the HVST in the prototype Modulator-Regulator has performed to our expectations.

The level of the accel voltage from the Modulator-Regulator is maintained at the set value by a voltage feedback loop. The feedback amplifier, which is located on the accel deck, receives the set point voltage through an optically coupled frequency to voltage converter. The feedback voltage (accel voltage) is from a voltage divider between the accel deck and the power supply return lead. The feedback amplifier has a dc gain of about 60dB and an upper cutoff frequency of about 15kHz. The rise time of the accel system power pulse is about 25 microseconds, which is consistent with the bandwidth of the amplifier. The pulse shape appears to be a single-value function up to 95% of its final (flat-top) value, after which the voltage rises to its 100% value, which takes on the order of 20 milliseconds. This behavior is not consistent with the measurements of the feedback amplifier and is being actively investigated.

3.2.3 Auxiliary Power Supplies

The Arc and Filament Power Supplies are 12 pulse diode rectifier units with no active amplitude control except for the voltage variable transformer. Pulsing of these power supplies is controlled through a static contactor in the primary of the isolation transformers (see figure 1). In addition to operating these units at their rated voltage and current, the section of the power supplies located in the HVE that is at accel voltage potential have been hi-potted to a voltage of 200kV, with the tank filled with SF_6 at 25 psig as previously stated. No major difficulties were encountered in making these power supplies operational.

The Decel Power Supply was operated to its rated voltage into a dummy load with no difficulty.

3.2.4 Local Control Center

Of all the electronics in the NBPS, the Local Control Center (LCC) is the most complex. The control functions for all components of the NBPS are integrated and coordinated in the LCC. Due to the fact that the NBPS is a distributed system with components physically located long distances (10 m to 60 m) from each other, the opportunity for false triggering of devices due to noise

within the system was great. However, in our experience to date with the prototype NBPS there has been no false triggering noted, even during the firing of the crowbar and the occurrence of load faults in the accel power supply. Although measurements of voltages in the ground system of the NBPS have not been made, we believe that the single point ground (see Figure 1) in the accel chain was a significant feature in obtaining this result. In addition we have tried to pay attention to the grounding of the equipment to ensure that the enclosures of all components of the NBPS are directly connected together by copper conductors, rather than relying only on the ground grid within the test site complex to conduct the ground currents.

The measurement of all analog parameters in the NBPS, such as the arc and filament voltage and current, is telemetered to the LCC by a combination of fiber optic channels which connect the voltage isolated components and wire channels which connect the optical channels to the LCC. The telemetry system uses voltage-to-frequency and frequency-to-voltage converters to transmit the analog information. The desired bandwidth was to be at least 400 kHz and the noise to be less than 30 mV(rms). The system bandwidth that was achieved was satisfactory; however, the noise in the channels was larger than could be tolerated or expected. This problem was due in part to the fact that the converters were physically separated from the optical transmitters and receivers which raised the sensitivity of the channels to the background electrical noise inherent in the system. This problem is being corrected by combining the electrical and optical functions in one circuit, eliminating the link between the two functions, and the opportunity for the noise to enter the channel. The noise level of the revised channels is less than 5 mV(rms).

4. ACKNOWLEDGMENTS

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