Title
TEST FACILITY FOR THE DEVELOPMENT OF 150-keV, MULTI-MEGAWATT NEUTRAL BEAM SYSTEMS

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DISCLAIMER

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The next generation of CTR experiments, such as the Tokamak Fusion Test Reactor (TFTR), will require neutral-beam injection systems that produce multi-megawatt, 120-keV deuterium-beam pulses of 0.5-second duration. Since present injection systems are operating in the 10- to 40-keV range, an intensive development effort is in progress to meet a 150-keV requirement. We describe the vacuum system and power supplies that make up a test facility to be used in the development of these injectors.

The Vacuum System

The Lawrence Laboratories' "50-Ampere" neutral-beam sources[1] have a deuterium gas flow of about 20 Torr-ℓ/sec, but since they are pulsed on for 0.5 sec at 60 second intervals, the average gas throughput is only 0.17 Torr-ℓ/sec. It is therefore feasible to use a large-volume vacuum chamber to absorb the peak gas load, and to pump out the gas in the one-minute interval between pulses. The test facility has a 6.7-m-diam spherical vacuum chamber with two baffled, 0.9-m oil (Santovac 5) diffusion pumps with an estimated combined pump speed of 18,200 ℓ/sec (air). These are supplemented by two Ti-sublimator pump pods with a combined pump speed of 15,800 ℓ/sec (deuterium). A 70 kW array of quartz infrared lamps suspended in the center of the sphere will allow mild bakeout. The beam-line ports are on the gondola-like cylindrical appendage, 2.3-m diam and 1.5-m long; there are provisions for two separate beam lines. The anticipated pressure resulting from one 0.5 sec pulse is 3.5 x 10^{-5} Torr; the pump speed is adequate to return the chamber to its base pressure of 10^{-6} Torr within the 60-sec pulse rate.

The test facility's 22-ft (6.7-m) diameter sphere that forms the main portion of the vacuum chamber was once used as a storage vessel for gas from the Laboratory's 72-inch hydrogen bubble chamber. It had been built of 0.88-inch (2.2 cm) thick plates, with all welds 100% radiographed. It was moved to its present location, placed upon the support structure, and the lower cylinder was welded into place. This cylinder, 91-in. (2.3-m) o.d. and 60-in. (1.5-m) long, has a 2-ft x 3-ft (.6-m x .9-m) manhole into the vacuum chamber, and 30-in. (.76-m) diam ports for two separate beamlines located 5 ft (1.5 m) above the floor line. The total volume of the chamber is 6000 ft^3 (172 m^3), and the internal surface area is 1760 ft^2 (164 m^2). It is pumped with two 35-in (.9-m) oil diffusion pumps, and two chemisorption pumps. Both diffusion pumps are supported from a single manifold at the equator of the sphere. They were located side-by-side to minimize the number of roof openings, simplify the construction of the building that surrounds the spherical chamber, and consolidate the vacuum piping. (See model of the Test Facility, Figure 1.)

When it was used as a hydrogen storage vessel, the sphere had a thick coating of red lead on its inner surface. Care was taken to remove all of this paint by thoroughly sandblasting and vacuuming the interior. A washdown with 1:1:1 trichloroethane gathered up any dust that may have escaped the vacuum. To help prevent undue oxidation of these walls prior to the time the chamber was evacuated, the air in the sphere was excluded by subliming large blocks of dry ice.

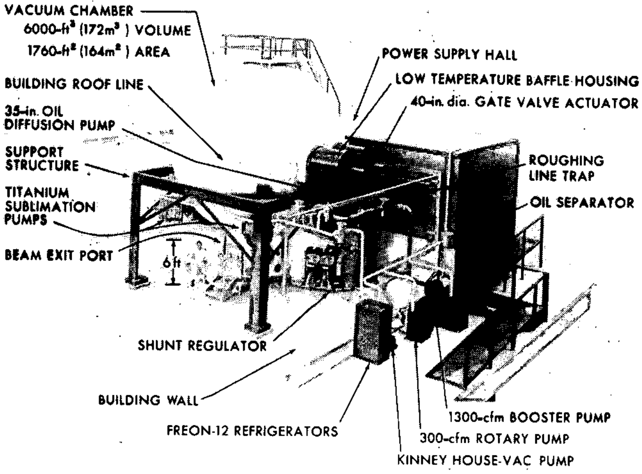

Figure 1. Model of Test Facility

The two 35-in. (.9-m) oil diffusion pumps are Varian Models NHS-35. Although each is rated at 47000 ℓ/sec, it is effectively baffled to 9100 ℓ/sec, calculated at the throat of its 40-in. (1-m) disc valve. Backstreaming of oil from each pump is reduced by a water-cooled baffle in series with a refrigerated chevron. The barrel and forearm, in addition, are cooled by external water coils. The major part of the backstreaming oil is caught on the water-cooled "halo" baffle which fits over the upper jet. The oil caught on this baffle will ooze back into the pump. Any oil vapor which gets through this 18°C baffle will be trapped by the -25°C chevron baffle. The oil caught by this baffle will remain until the baffle is warmed but is not enough to cause any appreciable loss of oil from the pump. This optically-opaque baffle is cooled by a Freon-12 mechanical refrigerator.

The oil used in these diffusion pumps is Monsanto Co.'s Santovac 5, a polyphenyl ether which has an extremely low vapor pressure of 5×10^{-10} Torr at room temperature, low backstreaming characteristics, and is resistant to accidental oxidation. Its primary drawback is its high cost: $1800 to charge 3 gallons into each diffusion pump. However, because there are high-voltage gradients in the extractors of the neutral-beam sources being tested, and because oil vapor may form insulating layers which could lead to voltage breakdown, it was thought that this oil, with its extremely low vapor pressure, would afford adequate insurance against such mishaps. In spite, however, of the many good characteristics of this fluid, the pump must still be effectively baffled against the oil's escape into the chamber. The difference between the manufacturer's rating of 47000 ℓ/sec (air) and the calculated speed of 9100 ℓ/sec (air) at the valve is

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*Work done under the auspices of the US ERDA dramatic illustration of the price that must be paid for such baffling.

The diffusion pumps are supplemented by two titanium sublimation pumps. Each unit has an internal area of 6100 in.^{2} but is conductance limited by the vacuum piping to 7900 ℓ/sec (deuterium). There are two Varian Ti-balls installed on the pump, each with 35 grams of usable titanium, and a maximum sublimation rate of 0.5 gm/hr. One of these Ti-balls will be used at the start-up of the sublimator. Once the pump is operating, the Ti-ball will be phased out, and titanium from an Ultek Model 214 bulk sublimator will be used. This automatic unit can supply 400 usable grams of titanium from a 1¼-inch diam rod, mounted on a linear drive mechanism, at a maximum rate of 1.0 gm/hr. There are two shuttered viewports on the 36-in. diam x 36-in. long (.9 m x .9m) cylindrical vessel. Cooled inner baffles shield the openings to the pump's vacuum gauges and to the 12-in. diam gate valve leading to the main vacuum tank. The heat load from the sublimators is removed from the vessel by external cooling tubes. The interior of the vessel will be cleaned by sandblasting after 3 or 4 bulk rods have been used.

It is planned to pump the gas from the ion source solely by the two titanium sublimators. The two diffusion pumps will only be used to bring the vessel to its base pressure. One diffusion pump will then be shut off and the other used to handle the outgassing load from the vessel walls. This will reduce both the electrical power requirements and chances of oil vapor escaping into the vacuum vessel. The source's pulse repetition rate will be altered to match the pumping speed of the titanium sublimators.

Of the two mechanical pumps used to rough the sphere, one is a Stokes Model 1722 two stage unit: A rotary oil-sealed 300-CFM (142-ℓ/sec) Model 412 vacuum pump backing a 1300-CFM (614-ℓ/sec) rotary lobe dry high vacuum booster. The second vacuum pump is also a Stokes Model 412 300-CFM (142-ℓ/sec) vacuum pump. The roughing line has a trap of refrigerated copper wool used to prevent oil migration from the mechanical pumps.

From atmospheric pressure, the sphere can be rough-pumped to 100 mTorr in 78 minutes; to 50 mTorr in 84 minutes. After the diffusion pumps are opened to the sphere, the pressure is reduced to 10^{-5} Torr in 20 minutes, 10^{-6} Torr in 1 hour. The pumping time required to achieve this base pressure varies, depending upon the amount of water vapor in the sphere and the length of time it has been exposed to air. To increase outgassing, in an effort to shorten this pumpdown, an array of quartz infrared lamps has been mounted at the center of the sphere. Supplying 70 kW, these lamps will maintain the vessel walls at a temperature of 90°F (50°C) above ambient, after a warm-up time of 2½ hours. So that these pumpdowns are as short as possible, the vessel will always be returned to atmosphere by first letting in a few cylinders of dry nitrogen, followed by air that has been filtered to minimize surface contamination.

The vacuum system is protected by a system of interlocks that protect the chamber and individual vacuum components against serious damage, should there be failure of any of the supplied utilities or any part of the system, or upon any operational error.

Electronics

Figure 2 is a block diagram showing the arrangement of a typical LBL neutral beam (NB) source and the power supply system it requires. Full power supply specifications are given in the following tables.

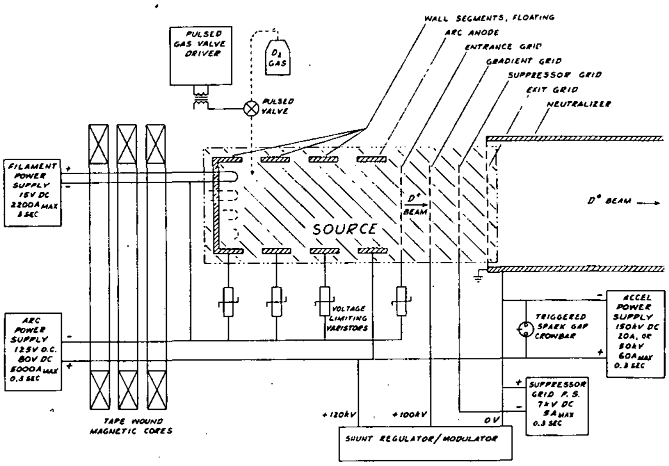

Figure 2. Block diagram of NB source and required power supply system.

Table 1 - Accel Power Supply Specifications

Parameter	Unit	Typical Source Reqmt	P.S. Spec.
Voltage, nominal (series-connected)	kV	+120	variable +15 to +150
Voltage, nominal (parallel-connected)	kV	+50	+5 to +50
Voltage regulation	%	±1	±1
Current, max (series-connected)	A	18	20[1]
Current, max (parallel-connected)	A	54	60
Power, max	MW	2.6	3
Pulse width, operating	msec	300	variable 10 to 300
Repetition Period, minimum	sec	30	30
Current Risetime,[2] max (10-90%)	μsec	20	20
Current Falltime,[3] max	μsec	20	20

[1] Includes 18 A max accel, 1 A max gradient grid, and 1 A max shunt regulator idling or ripple current.
[2] At max output current.
[3] At max output current, or when source sparks.

Table 2 - Gradient Grid Power Supply Specifications

Parameter	Unit	Typical Source Rqmt	P.S. Spec.
Voltage, nominal	kV	+100	+100
Voltage selection[1]	kV	+7 to +120	+7 to +130[2]
Voltage regulation[3]	%	±1	±1
Current, max	A	±1	±1

[1] When conditioning sources over full accel voltage range from +10 to +150 kV, the gradient grid voltage must be varied so as to maintain a constant ratio of accel to gradient grid voltage.
[2] Selectable by coarse and 50 V fine steps, and changing tap point on shunt regulator tube string.
[3] Regulated with respect to accel voltage.

Table 3 - Suppressor Grid Power Supply Specifications

Parameter	Unit	Typical Source Reqmt	P.S. Spec.
Voltage, nominal	kV	-2.2	-1 to -7
Voltage selection	steps	100V	100V
Voltage regulation	%	±2	±2
Current, max	A	5	5
Current, max, 50 μsec pulse	A	20	20
Pulse width	msec	300	10 to 300
Repetition Period, minimum	sec	30	30
Voltage rise and falltime (10-90%)	μsec	<10	<10

Table 4 - Filament Power Supply Specifications

Parameter	Unit	Typical Source Reqmt	P.S. Spec.
Voltage, adj. range[1]	V	9 to 12.5	1 to 15
Voltage selection	-	continuous	continuous
Voltage ripple, max[1]	%pk-pk	±1	±1
Voltage ripple filter	-	capacitive	capacitive
Voltage regulation[1]	%	±3	±3
Current, max	A	2200	2200
Risetime to full emission, max[1]	sec	1.5	1.5
Inrush/Operate Current Ratio	-	2.8	2.5 to 3.0
Pulse width, max	sec	2	3
Repetition Period, minimum	sec	30	30

[1] At maximum current output.

Table 5 - Arc Power Supply Specifications

Parameter	Unit	Typical Source Reqmt	P.S. Spec.
Voltage, Open Circuit, minimum	V	-	125/250[1]
Voltage Operating, typ.	V	40 to 60	80/160 max
Current, max	A	1200	5000/2500
Current Regulation	%	±1	±1
Current Selection, continuous	% of I_{max}	-	10 to 100
Pulse width, max	sec	0.3	0.3
Repetition Period, minimum	sec	30	30

[1] Parallel or series secondary connection option.

The transformer-rectifier portion of the accel power supply consists of three separate oil-insulated modules. Each of these has a maximum rated pulsed dc output of 50 kV, 20 A for a 0.3 sec pulse occurring every 30 sec. (Undoubtedly, the maximum permissible module current can be somewhat greater than the rated 20 A at some sacrifice in maximum output voltage if the repetition rate is correspondingly reduced. Tests will be conducted to determine the various trade-offs involved.) The secondary ac windings, rectifier system, and transient suppressor networks of each module are fully floating and adequately insulated so that their dc outputs may be connected in series or parallel. These modules were specified and purchased when a conventional 12-pulse transformer-rectifier system was originally envisioned. A shunt-regulated saturable-reactor controlled system is now planned which will use these modules. Even though their configuration would not now be the first choice for this application, they will still perform satisfactorily.

Figure 3 shows a simplified diagram of the portion of the accel power supply that involves the ac power controls and the transformer-rectifier modules. Figure 4 shows a simplified diagram of the shunt regulator-modulator. A detailed explanation of this approach to powering and controlling NB sources has been given elsewhere[2] and will not be repeated here. Because of space limitations, only a few clarifying comments will be made.

The series-connected saturable reactors permit operation of the power supply in a constant current mode where the dc output current is proportional to a dc bias current flowing in the control windings. When a spark occurs in the NB source, the supply can be shorted by the crowbar SCR string long enough to clear the spark (1 to 2 msec). Then the SCR string will be commutated by pulsing on the shunt tube string. Proper control will then permit the current to again be transferred to the NB source with the required risetime. A number of such "interrupts" are permissible before a shutdown is required, i.e., before the dc control bias current is turned off. Accel voltage is regulated during a pulse, while accel power supply current is limited to a value within 10 to 30% of the operating value, when a source spark occurs. For the dc bias supply, we will use an available power supply rated at 0 to 150 V/2000 A or 0 to 300 V/1000 A and which has an electronic contactor. It is desirable to keep the accel power supply output current ripple low to relieve the shunt regulator and maximize the current available to the NB source. A total inductance in the dc bias control circuit of 25 to 50 mH will be required. Higher inductance at low output levels is desirable and will be achieved by a "swinging choke" design. Gradient grid current may be either positive or negative and is generally $\lesssim$ 5 % of the source accel current.

The arc power supply will also be saturable reactor controlled in a constant current mode. It will have a shunt silicon-controlled rectifier (SCR) as a commutatable crowbar so that this power supply can also be interrupted and re-started, if desired, following each NB source spark. The arc and suppressor grid power supplies will be turned on at an optimum time, with respect to the accel voltage at the source, to be determined by experiment. Both the arc and filament transformer-rectifiers are housed in a common SF_6-filled enclosure.

Two of the three accel power supply modules have been installed and acceptance-tested. All other major power supply transformers have been received except the saturable reactors. The dynamics of saturable reactor control have been checked both with low level bench tests and at high level with a 1200 A arc power supply transformer-rectifier system. These tests are just now concluding and will permit the final design of the saturable reactors and dc bias inductors to proceed. The shunt regulator tubes are on hand and the detailed design and layout of that system is underway. Assembly should be nearly complete and initial load tests begun by February or March, 1976. The detailed design of the overall facility controls and diagnostics system has just begun.

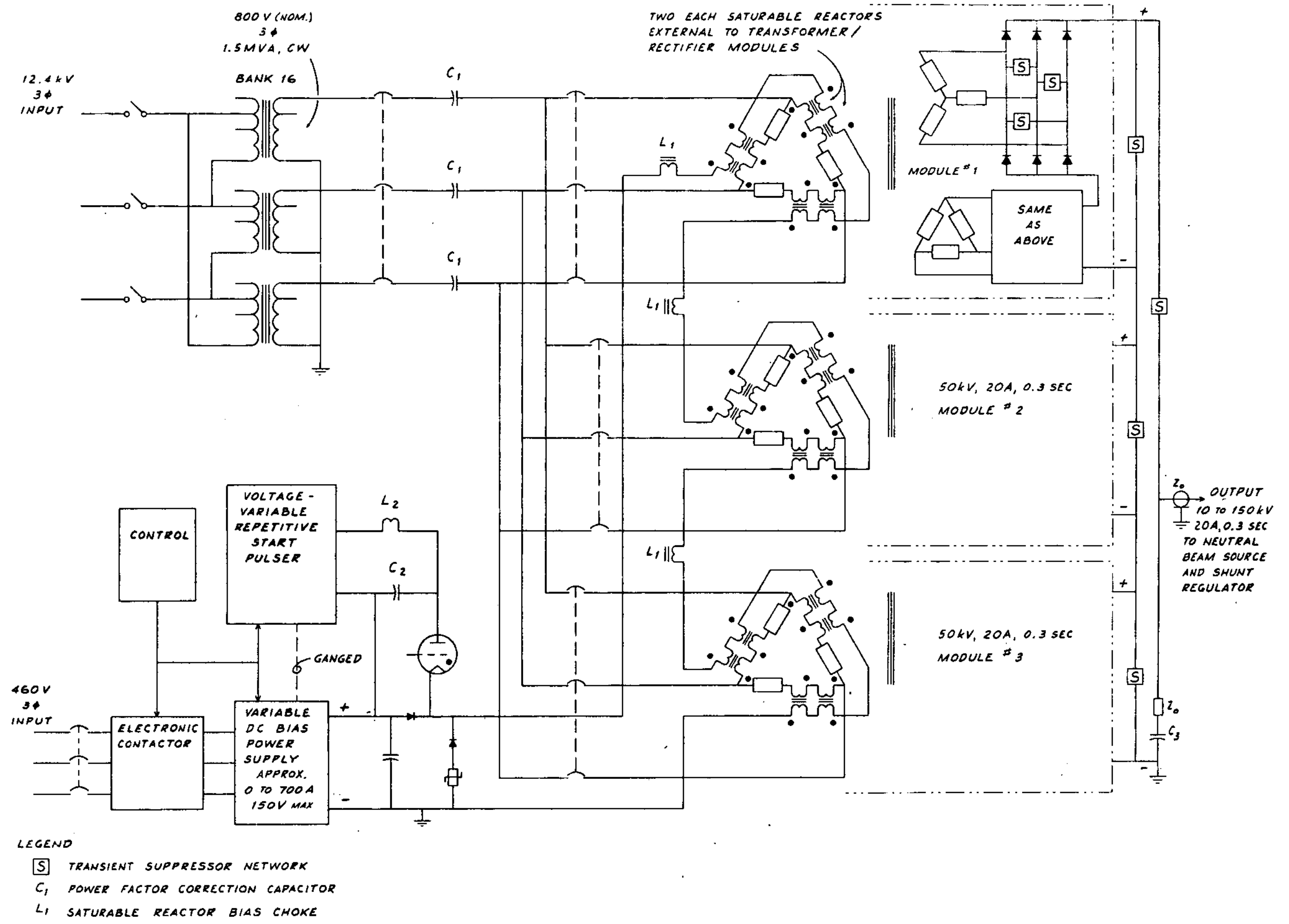

Figure 3. Simplified diagram of accel power supply

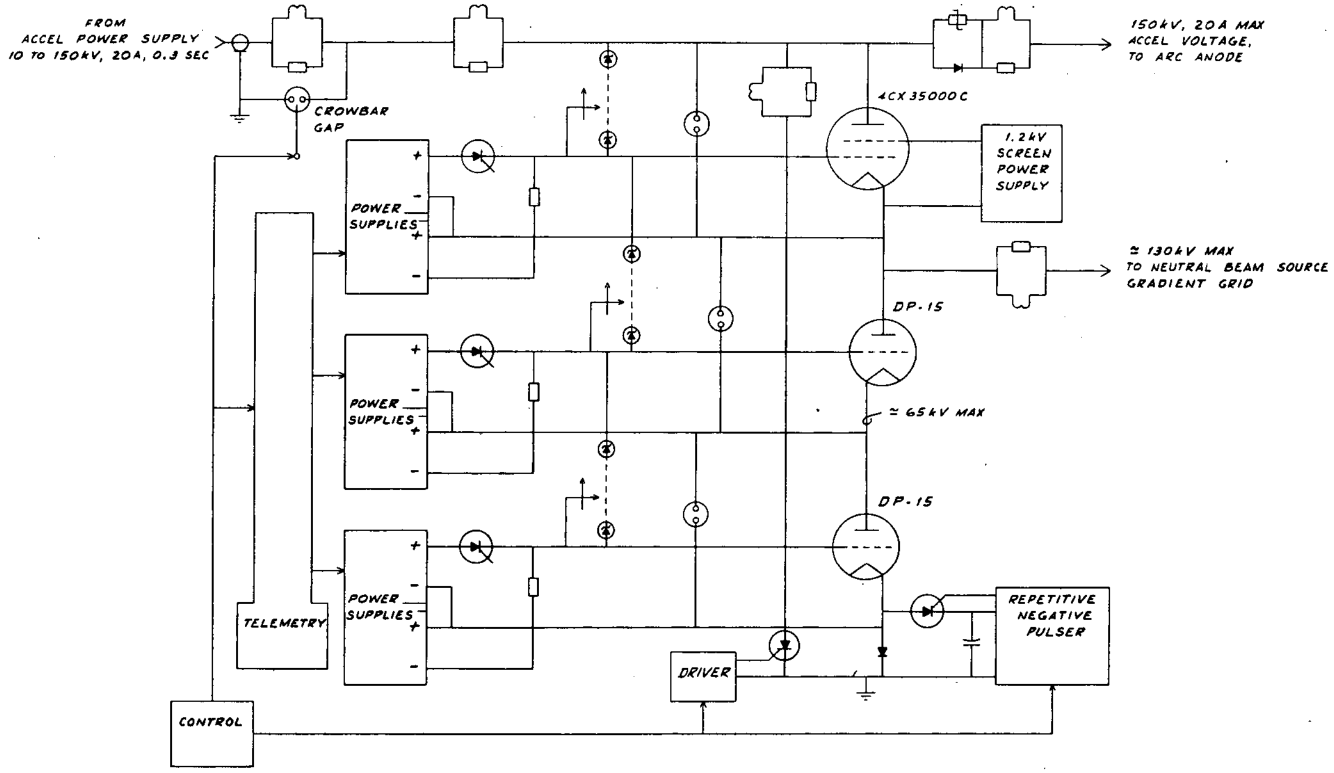

Figure 4. Simplified diagram of the shunt regulator/modulator

Acknowledgements

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