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THE DESIGN PHILOSOPHY AND USE OF HIGH VOLTAGE POWER SYSTEMS FOR MULTI-MEGAWATT ION BEAM ACCELERATORS*

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The requirements for a neutral beam high voltage power system are derived from the characteristics of the ion source. High voltage system component characteristic requirements and choices are described.

CONF-771029--68

The Ion Source

The ion source of a modern neutral beam plasma heating system imposes special requirements on its high voltage power supply system. Typical current is 40-100 A and typical voltage is 45-120 kV. At present, pulse width of 100-500 msec is typical. In the near future, we will operate developmental ion sources for several seconds. As with other high voltage gas-filled devices, the ion source has a tendency to arc occasionally.

The structure of a typical ion source and its associated electrical systems are shown in Fig. 1. The high voltage systems accelerate the ions which emerge from the apertures in the plasma electrode and, in focused beamlets, pass through the openings in the extraction and ground grids. When the ion generator conditions and source geometry are proper, the loss due to beam interception on the grids is only 1-2%.

An important consideration in the design of the high voltage system is the amount of fault energy the source structure can withstand (without damage) during an arc. This source characteristic determines the measures which must be taken to protect the source (during an arc) from the stored- ($1/2\ CV^2$ and $1/2\ LI^2$) and follow-through energy of the high voltage system. The grid structure used in typical Oak Ridge National Laboratory (ORNL) sources consists of heavy (0.06" thick), multihole, water-cooled copper plates (Fig. 2). It has been our practice to design systems which limit fault energy to approximately 50 J. We have not experienced source arc damage in systems designed for the 50 J level. Furthermore, the ability to allow fault energy of this magnitude accelerates the process of "seasoning" a source in order to develop its full voltage hold off capability. In the "seasoning" mode of operation a source is caused to arc by raising the accelerating voltage so that surfaces are polished and cleaned.

Since we are concerned with the development of neutral beam systems, we often operate sources which are built to study specific features but do not necessarily include all the features required to optimize voltage hold off characteristics. As a result, the high voltage system must be capable of withstanding repeated source arcs and of meeting the reliability requirements of a successful experimental program.

The ORNL ion source's performance is sufficiently independent of the magnitude of the accelerating voltage to tolerate voltage variations of 2-4%. These include variations which occur during a pulse (after the turn-on transient) and from pulse to pulse (Fig. 3).

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High Voltage System Requirements

The preceding section illustrates explicitly and implicitly the reasons for the high voltage system requirements listed below. These requirements are for a high voltage system to be used in the development of neutral beam systems. A high voltage system for an operational neutral beam system would have reduced voltage adjustment range, arcing frequency, and overvoltage requirements.

1. Voltage adjustable from 15 to at least 125% of required voltage level.
2. Fast (20-30μs) shut off if current exceeds a level (selected by operator) between 10 and 150% (typical) of required operating current.
3. Limit energy delivered to an arcing source to 50 J maximum.
4. Protect against major source and system component damage even if some system components arc.
5. Provide maximum operating time despite frequent source arcing.
6. Provide adjustable pulse length and interpulse interval.
7. Withstand (without damage) the fast ($<10^{-6}$ sec) transients characteristic of low pressure arcs.
8. Exclusive of front of pulse turn-on transients, limit voltage variations to <5%.

High Voltage System Specifics

Experience with sources from the 30 kV 10 cm source used on the Oak Ridge Tokamak (ORMAK) through 50 kV 22 cm developmental devices has led to the system shown in Fig. 4. This is basically the system which is used on our Medium Energy System Test Stand (MESTS) and will be used in the ISX-B experimental tokamaks's 2 MW neutral beam systems. The special requirements of the ORNL High Energy Test Stand (HETS) — 150 kV, 50 A plus power for a gradient grid — have led to an adaptation of this basic system. It consists of three high voltage transformers (rectifier units in series), three series-connected tetrode switch tubes, and a separate gradient grid modulator. The HETS is currently undergoing final system tests.

Input Circuit

Primary power is fed from available circuits. The MESTS if fed with 2300 V three-phase power from a 3.8 MVA 7.5% impedance transformer. The HETS and ISX-B neutral beam high voltage systems are fed with 13.8 kV three-phase power from a 50 MVA 15% impedance transformer.

The master circuit breaker (MCB) is provided so as to interrupt the current from a short circuit anywhere in the input circuit. The disconnect switch is used to isolate the high voltage system whenever maintenance is required.

MASTER

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The current limiting reactor (CLR) is required to protect the vacuum circuit breaker (VCB) and variable transformer (VT) from damage due to excessive short circuit current. The CLR is used on each of the two ISX-B beam lines because the step-switched VT used in these systems has essentially zero impedance. Both the MESTS and HETS use inductrol VTs which have impedance of the order of 10%.

The high speed VCB is used to interrupt fault follow-through energy within two cycles of the occurrence of a fault in the high voltage circuit (Fig. 4). Such a fault will cause the crowbar (CB) to fire within a few μsec. The VCB minimizes the stresses on the transformer rectifier (TR), the CB, and the input circuit. The VCB also includes a step-start circuit to minimize turn-on transients.

The surge arresters (SA) are station-type lightning arresters which are used to control the voltage transients caused by operation of the VCB. Without the arresters, the VT, the TR, and the entire high voltage current would be subjected to potentially destructive transients.

The variable transformer provides a coarse, slow adjustment of the high voltage. In the MESTS and HETS, inductrols are used as the VT. Reliability problems of the MESTS VT associated with damage caused by short circuit stresses led us to specify a step-switched VT for each of the two ISX-B high voltage systems. These will use step-regulator designs proven in power systems to adjust the high voltage within range from 15-100% in 32 equal steps. The HETS high voltage system was designed with an inductrol before our MESTS experience. After two failures during initial short circuit tests the HETS inductrol has passed all specified system over-current tests. Earlier systems for 40 kV 30 A sources used inductrols successfully.

Transformer-Rectifier

The transformer-rectifier uses both a delta and wye secondary unit to provide twelve-pulse rectification. The ripple component of a balanced twelve-pulse rectifier is low enough to make filters unnecessary. The silicon rectifiers are chosen to withstand the systems worst case short circuit currents. A typical TR includes resistor-capacitor transient suppressors on the transformer secondary terminals to protect the rectifiers from commutation transients and fast "spikes" on the power system. Rectifiers are series connected to provide at least 250% inverse voltage capability. The MESTS system TR is a single 60 kV 60 A unit consisting of a delta and a wye in series. The HETS system TR is three 56 kV 50 A, 20 sec units in series; each unit consists of a 28 kV delta and a 28 kV wye in series. This system is designed to allow the delta and wye units to be parallel connected, via balancing reactor, so that either 168 kV 50 A or 84 kV 100 A total output can be obtained. Conceivably, other combinations such as single units or all in parallel could be used; also, either polarity can be off-ground. The HETS TR system provides at little extra cost the kind of flexibility needed for a developmental system. The two 60 kV, 60 A (DC)/100 A (30 sec) ISX-B TR's each consist of two 30 kV (one delta and one wye) units. Because we anticipate using these units for source development in addition to powering ISX-B's neutral beam heating systems, they are arranged so that we can connect them to deliver full 12 MW output at 30, 60, or 120 kV.

The transformers and VTs in an ion source power supply must withstand frequent short circuits. In a typical ORNL ion source high voltage system, the tetrode vacuum tube modulator interrups 90-98% of the source arcs. Even with this capability we have chosen to specify that the TRs be capable of withstanding 50 CB a day. Further, the TR specifications require that the transformers and VTs be subjected to the American National Standards Institution (ANSI) C57.12.90a short circuit tests. The complete units must withstand the severe, fast transients caused by short circuiting them 50 times with a vacuum spark gap at full output. The usual insulation tests, heat runs, etc. are also required as a means of verifying design safety margins. The transformer and VT structural design must be capable of surviving the stresses of such service.

Typically, a 3 MVA transformer such as in the ISX-B TRs under short circuit conditions can have a total force of repulsion between the high and low voltage windings of a quarter of a million pounds. The resultant mechanical stresses in the transformer coil structure require careful design so that mechanical and electrical failures do not occur. The coil bracing structure must contain the electromechanical short circuit forces with a reasonable safety margin but not unduly penalize the size and cost of the overall transformer assembly.

The duty cycle of these power supplies anticipates a crowbarring frequency of 50 times per day. Although the crowbarring current does not subject the power supply to full short circuit forces, the high daily repetition rate demands a rugged structural design for the power supply transformers.

The peak symmetrical short circuit forces involved can be calculated from the relationship $F = \sqrt{2}/10\ BI\ell$ where F = repulsive force in dynes, I = RMS short circuit amperes in winding, ℓ = length of wire in the winding, cm, and B = flux density in gausses.

The force vector F can be considered to be acting between the electrical centers of the winding. The amount of tilt of this vector determines the radial and vertical components of the total force.

The first current loop of a short circuit may be nearly 100% displaced from the zero axis. However, the force caused by this asymmetrical current is so transitory that the inertia of the restraining parts acts as a compensating factor.

It is advisable to precompress the coil end to end during the drying process. By removing in advance all coil looseness, that part of the winding movement is eliminated when the short circuit force occurs.

Transformers of circular design typically have rigid end clamps tied to the core framing members. These clamps exert pressure on the coils by means of adjustable jack screws. In addition, solidification of winding the layers into a composite element is accomplished through the use of B-stage layer insulation, the adhesive of which sets up during the coil drying process. The inner winding in particular is protected from buckling by the resulting improved section modulus associated with a thicker member. Further protection against inward buckling of the inner winding is often provided by inserting dowels in the steps of the core leg. Figure 5 shows the core and coil structure of a typical modern transformer.

High Voltage Circuit

The transient snubbing capacitor (TSC) bank provides some energy at the beginning of the pulse (while current builds up in the system inductances) and prevents severe over-voltage transients when the modulator tube interrupts source current. A small amount of resistance is connected in series with the TSC to prvent "ringing." The MESTS and ISX-B systems use a 20 μf TSC. The HETS in its 150 kV configuration has a 9 μF TSC.

The CB is fired by circuits which sense excessive fault currents in the high voltage circuit. The ORNL high votlage systems use series-connected (type 37248) ignitrons as the CB switch. Each ignitron is fired by its own trigger transformer in the newer systems. Conventional globar damping resistors are used to prevent "ringing" of the CB current. The CB is fired only if a fault occurs which the modulator cannot interrupt, i.e., high voltage circuit or modulator tube arcs.

The use of a tetrode vacuum tube as a "modulator" is a basic feature of all recent ORNL ion source systems. A vacuum tube has the fast turn-off capability required to protect the rest of the high voltage system from the frequent arcing which characterizes developmental ion sources. The tetrode's inherent constant current characteristic so far has contributed to making it unnecessary for ORNL to resort to feedback regulation of ion source voltage. The constant current capability also "softens" the current transient caused by a source arc until the grid circuit has time to turn off the modulator (typically 20 μs). This system also has the capability of dynamic control of ion source voltage as required by our experimentalists. To date we have used a high voltage processed version (Y 647) of the 4CW100,000 in 40 kV 20 A service, the X2170 with the MESTS, 60 kV 60 A TR, and three X2170s in series with the HETS 168 kV 50 A system. We will use the X2159 with the ISX-B 60 kV 100 A TRs and two 2062-Js in parallel when the ISX-B TRs are series connected or the HETS TR is connected for 84 kV 100 A. Typical modulator systems are shown in Figs. 6 and 7. The tube(s) and associated circuitry are mounted on an insulated deck. Because our sources can withstand 50 J faults, we are able to tolerate the capacitance of conventional oil-filled transformers to deliver 60 Hz power to the deck. To improve tube life, filament voltage is always run up from zero at start and down to zero on a normal shutdown with a motor driven Variac. All control signals to the deck and pulse signals from the deck are transmitted on fibre optic light pipes.

A standard feature of all of our modulators is a circuitry, which senses output current and removes grid drive from the switch tube if current exceeds an operator-selected level. This circuitry has the capability of turning the modulator back on after over-current trips a preset number of times (3-7 typical) in a pulse. This feature provides approximately 200 μs off time for arc products to dissipate before turning the modulator on again.

Interconnections

Ion source characteristics, particularly their tendency to arc frequently and the broadband noise generated by the ion generator, require that the system designer take special precautions with the high voltage system leads. Without such precautions, nearby instrumentation and computers can be seriously affected; also, damaging voltage transients can appear at the source or elsewhere in the high votlage circuit (Fig. 4).

These special precautions take two general routes. First prevention by proper layout and cable design and second, protection through the use of RC networks, varistors, and spark gaps.

Layout of the circuit and ground return between the TSC (Fig. 4) and the ion source is particularly important both because of the high frequency currents at the front of every pulse and the high frequency currents associated with source arcs and normal ion generator operation which flow primarily in this circuit and its stray capacitances. The multiple conductor cable between the source table and the source is part of this circuit; these cables require special care to keep transients from damaging the low voltage (10-300 V) supplies and instrumentation on the source table.

The cable from the TR to the TSC is subjected to transients caused by CB firing and component arcs. Since this cable is apt to be long (as much as 200 yards at ORNL), long line multiple reflections and ground return voltage drop have to be considered and accommodated.

Layout design minimizes, to the extent allowed by available space, lengths of the critical circuits. In cable design consideration should be given to:

a) provide adequate insulation,
b) minimize the circuit loop inductance and external magnetic fields by running the high voltage and return leads close together,
c) provide shielding to minimize inductive and capacitive coupling to nearby circuits and structures. (The current in structures can conduct noise to sensitive devices.)
d) Provide low inductance return ground leads, including grounds for components with significant stray capacitance (e.g., isolation transformers), and
e) connect the neutral beam system return (ground) circuits to earth at a point which will minimize the voltage between the grounds of the neutral beam systems and adjacent critical equipment.

At ORNL, our practice is to use wide (4-12") individually insulated copper straps as the return lead from each major component to system ground. The return leads are bundled together and run as close to their respective high voltage leads as insulation requirements will allow. Often a separate electrostatic shield around the high voltage cable is provided. Often coaxial cable is used as the high voltage cable; typically the cable shield is used as an electrostatic shield with copper strap return leads provided.

Transient protection, as described above, is used wherever the designer or previous experience dictates. Devices capable of withstanding large energy transients are required, i.e., junction devices are not used often. The low voltage components in the source table and modulator (Fig. 1) are carefully protected. Varistors (MOV and thyrite) are used most frequently.

Conclusion

High voltage power systems for high power neutral beam systems at ORNL are designed to tolerate the behavior of typical ion sources and operate reliably. Our design philosophy provides the flexibility required to accommodate the changing requirements of a dynamic ion source development program with a minimum of both time and costly new major equipment.

We have accumulated thousands of hours of operating experience with systems capable of 40 kV 30 A (ORMAK), and 55 kV 60 A (MESTS). We are now final testing a 150 kV 50 A system (HETS). We are building two 55-kv 100-A systems (ISX-B) and an 80 kV 100 A system (source development). All of these systems are based on the philosophy described in this paper. We expect to use this philosophy (as modified by experience) in our future neutral beam systems.

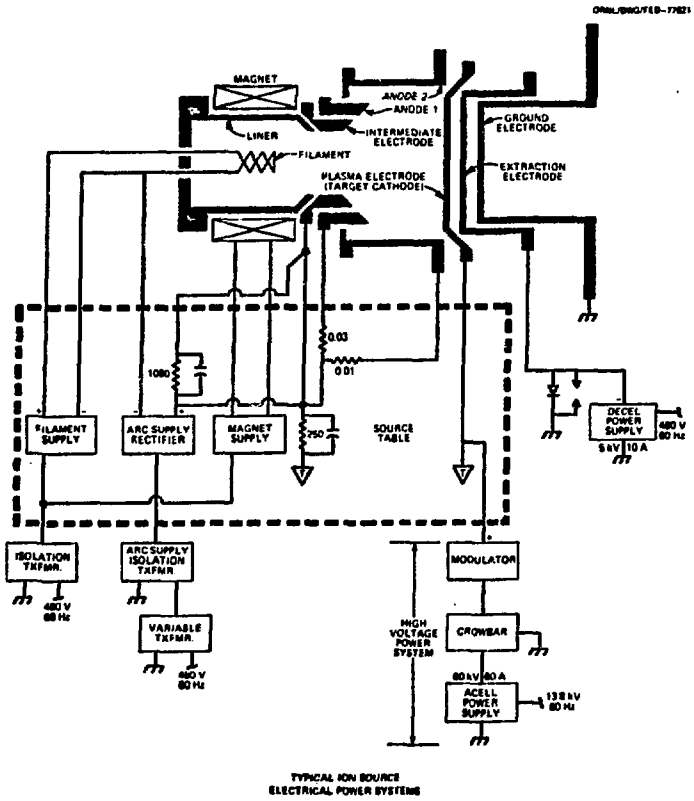


Figure 1

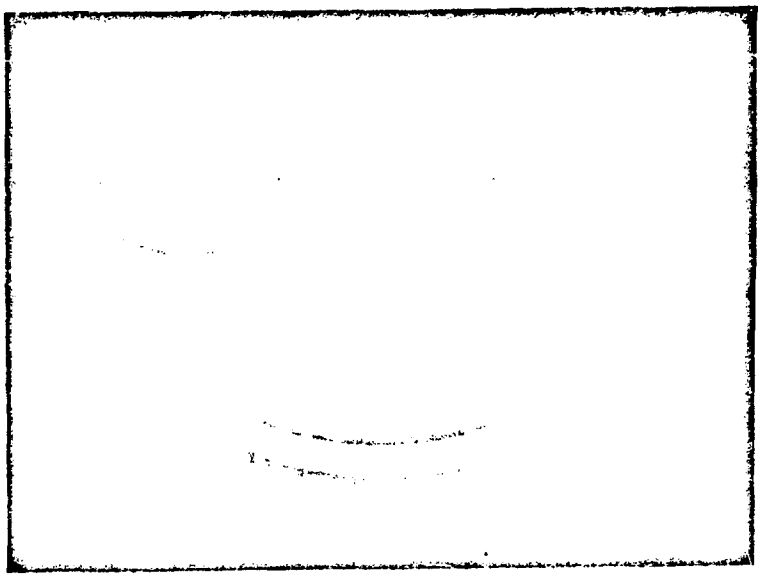
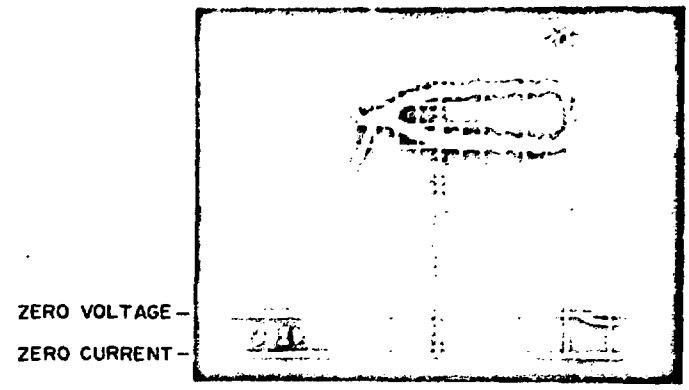


Figure 2

ORNL/DWG/FED-77830

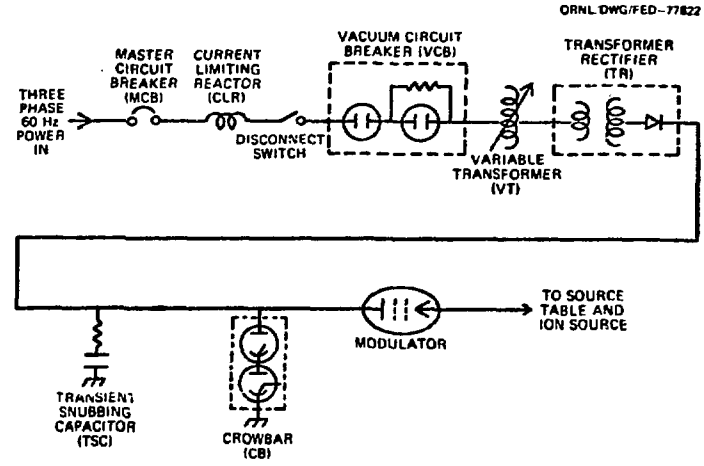


CALIBRATION
VOLTAGE - 10 kV/DIV
CURRENT - 10 A/DIV
TIME - 20 msec/DIV

ORNL Medium Energy Systems Test Stand
High Voltage System Output Pulse

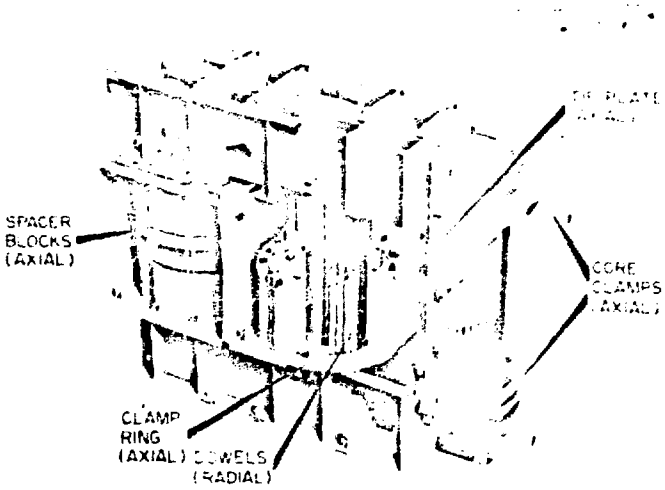
Figure 3

ORNL DWG/FED-77822



ION SOURCE HIGH VOLTAGE POWER SYSTEM SCHEMATIC

Figure 4



Typical Structure of a Modern High Power Transformer
Showing Axial and Radial Blocking and
Bracing Required To Withstand Shortcircuit Forces

Figure 5

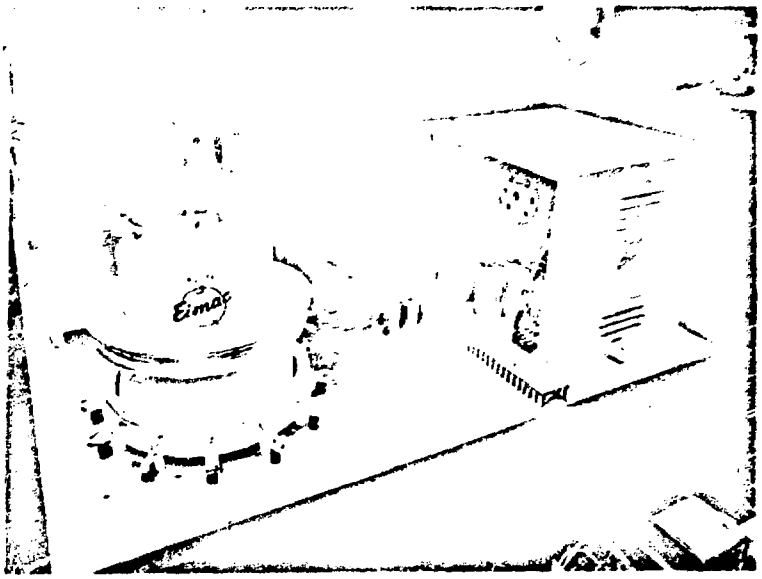
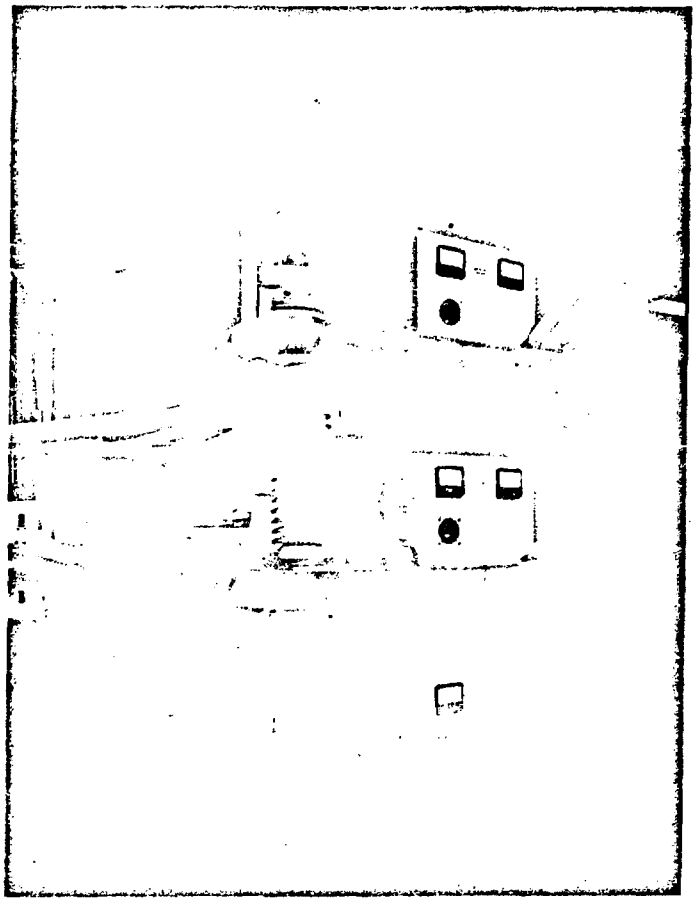


Figure 7



High Energy Test Stand 150 kV, 50A
Modulator System

Figure 7