HIGH POWER MODULATOR/REGULATORS FOR NEUTRAL BEAM SOURCES

J. Q. Lawson, A. Deitz

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Summary

From the earliest conceptual fusion machines to the present large tokamak devices there has been a need for auxiliary heating of the confined plasma. In all of the forms utilized at PPPL, pulses of controlled high level energy have been required. These pulses usually have taken the form of video pulses either to drive the anodes of large vacuum tubes for Ion Cyclotron Resonance Heating, or the collectors of klystron tubes to provide Electron Cyclotron Resonance and Lower Hybrid types of heating.

In recent years a third auxiliary heating device, the neutral beam injection gun, has also been used. Because of the high power and voltage levels required in operating each of the three devices, a modulator of some type is generally required for proper isolation from the energy source. In most cases the optimum choice has been a high vacuum tube.

The development of modulator/regulators for use with neutral beam sources is a normal extension of the designs of modulators for high power klystron tubes and many of the components and present configurations are utilized interchangeably.

PPPL has recently completed two new Modulator/Regulators for neutral injection sources used on the ATC machine and is constructing four new ones for use with sources on the PLT machine.

Present ion sources require high voltage pulses (from 20 kV to 50 kV) that should be voltage regulated during the pulse. As a result, hard tube (vacuum) modulators were designed with the capability of microsecond switching response time and closed loop voltage regulation control.

Tetrodes were selected for the modulator/regulator tubes because of their inherent current limiting characteristics and the fact that available units satisfy the other electronic performance requirements.

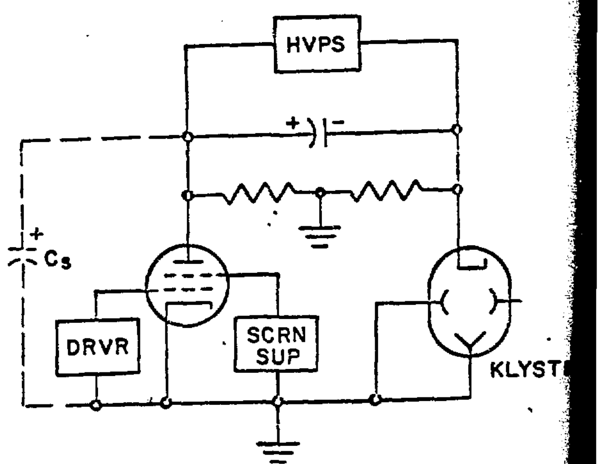
Since one side of the ion source is essentially at ground potential, the switch tube must be configured as a floating deck modulator for which information is transmitted from ground potential up to floating deck potential (20 kV to 50 kV) via optical coupling schemes. Power for deck components is transmitted from ground through low-capacitance high voltage isolation.

Mechanically the units were designed to f tate "production technique" construction, and manufacturing was done at PPPL including print circuit boards, metal fabrication, wiring and testing.

Some interesting circuit and manufacturin techniques are explored in this paper and will serve as guidelines for larger and more powerf devices to be used on the TFTR machine being b at Princeton.

Development of PPPL Modulators

Early in 1964 a decision was made to incr the power of the Etude machine, X band generat from 10 kW CW to 100 kW pulse with a duty fact of .01 and a pulse width of 3 milliseconds. A there were no modulators at PPPL available to accomplish the pulsing, and a very short perio time allotted to the design and construction o unit, a decision was made to build a floating power supply modulator, Fig. 1. This configu permits grounding of the modulator tube catho and the grounding of one side of the screen an supplies.



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The ATC modulator uses the well proven 4CX35,000C tetrode as the main switch tube, while the PLT modulators will be using the new but significantly higher powered X-2170 tetrodes.

Closed loop voltage control provides pulse regulation of better than 1% at 50 kV coupled with fast time response for pulses ranging from 20 to 300 mseconds.

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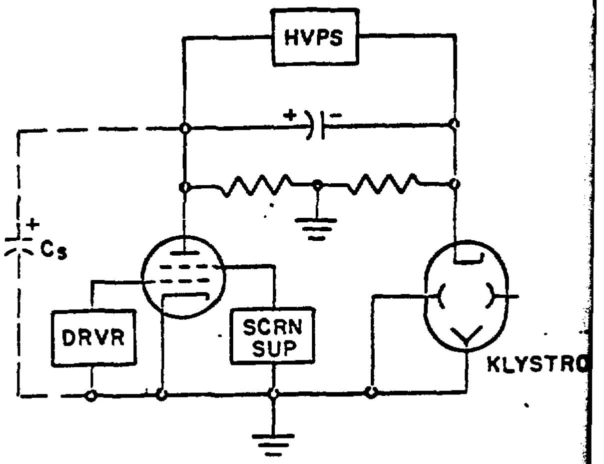

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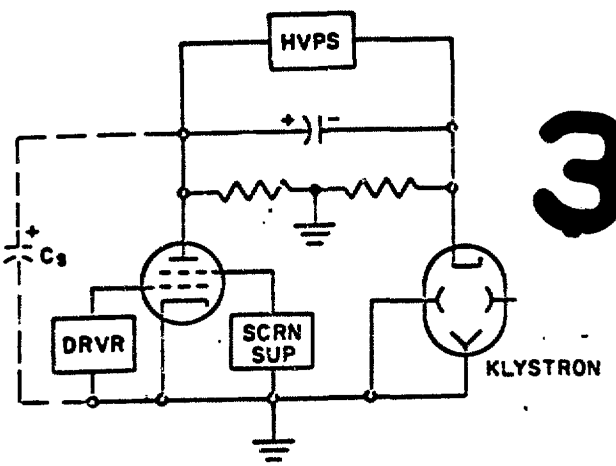

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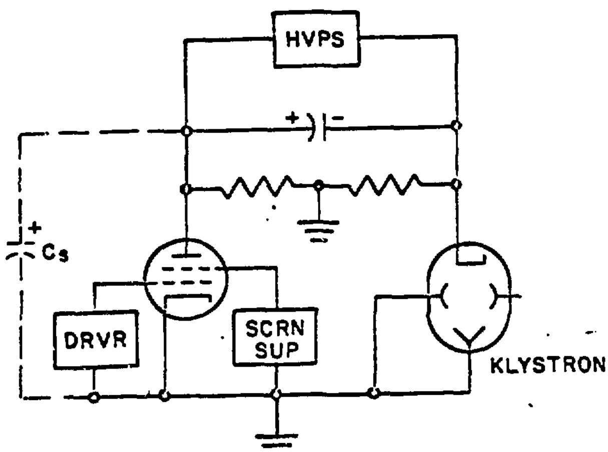

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A second type of modulator, "floating deck", was developed in 1967 to drive either klystron or magnetron oscillators which were used for gas ionization, lower hybrid heating and electron cyclotron resonance heating studies. These units were in the 1 to 5 kW level and a simplified schematic, Fig. 2 shows the major elements of this type of system. The stray capacities C_s in this configuration can be kept to a low level, and rise and fall times relatively short. The major disadvantages of this system is the response time of the modulator grid circuit and the difficulty in linearizing the modulator if it is required. A number of schemes were used to couple drive energy from ground potential to deck potential. These included pulse isolation transformers to trigger multi-vibrators on and off, optical pulse isolators to trigger a multi, and a more sophisticated 2 megacycle rf link and detector which permitted linear operation of the modulator driving source.

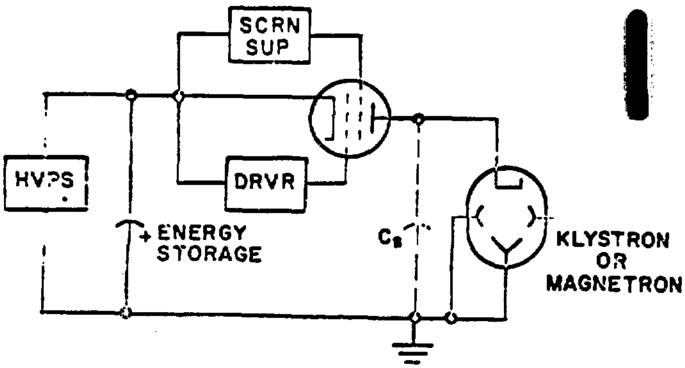
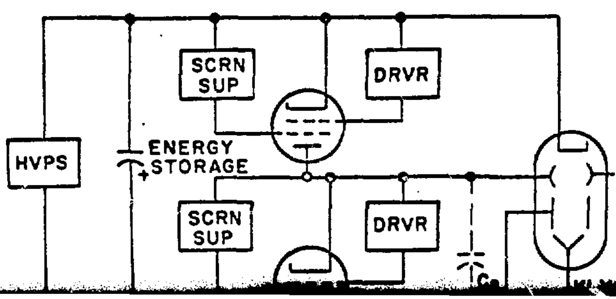


Figure 2 - Floating Deck Modulator

A second floating deck modulator, Fig. 3, was developed for a 200 kW 800 MHz generator for Lower Hybrid Heating[1]. The improvement in this system was not so much that of concept but in improvement of components and manufacturing techniques. The circuits and assemblies developed for this equipment have been the basis for all of the floating deck modulators built at PPPL since 1973.



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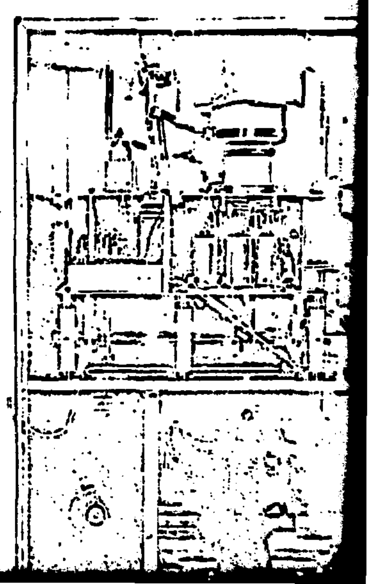

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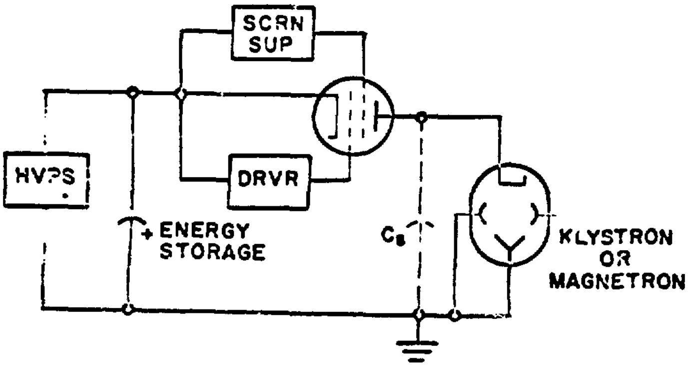

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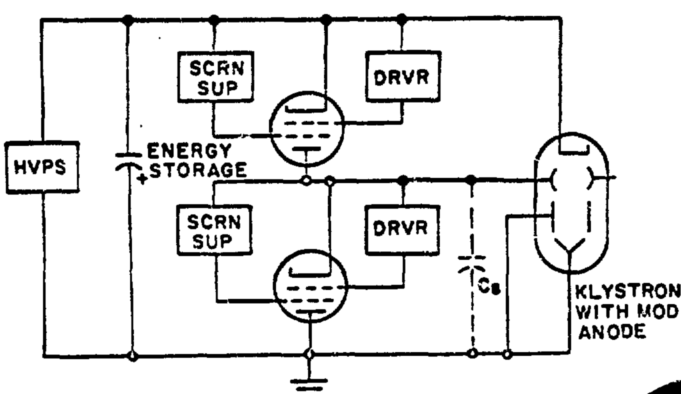

Figure 3 - Floating Deck Modulator and Tail Biter

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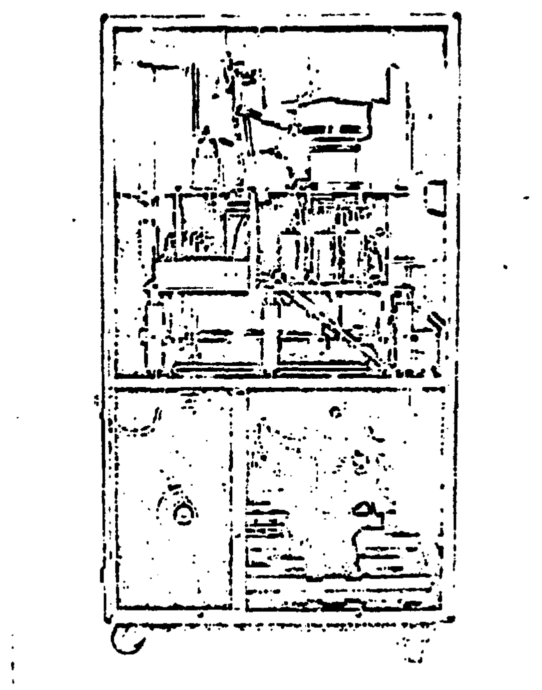

Figure 4 - ATC Modulator/Regulator Utilizing a 4CX35000 Tetrode

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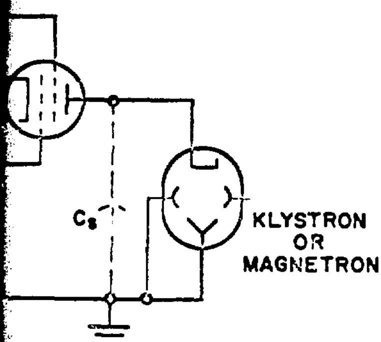

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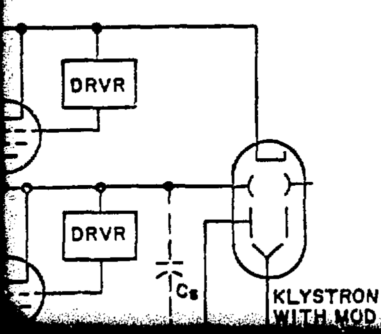

Modulators for ATC Neutral Beam Units

The initial design of the modulators for the ATC neutral beam was based on an expected operating impedance of approximately 2000 ohms at 40 kV. The value was subsequently lowered to 1300 ohms at 30 kV and then to approximately 400 ohms at 20 kV. A paper[2] given at the Fifth Symposium on Engineering Problems of Fusion Research described the mechanical arrangement of the modulator which was totally immersed in sulfur hexafluoride so that the full high voltage capability of the 4CX35000 modulator tube could be realized. In retrospect, the energy expended in making the modulator good for high voltage would have better been directed toward increasing its current capability, and making the electronics more accessible for changes required when working with experimental devices. A decision was made to repackage the modulator, increase its current handling capability, and add voltage feed-back to the unit while new guns were being added to the ATC machine.

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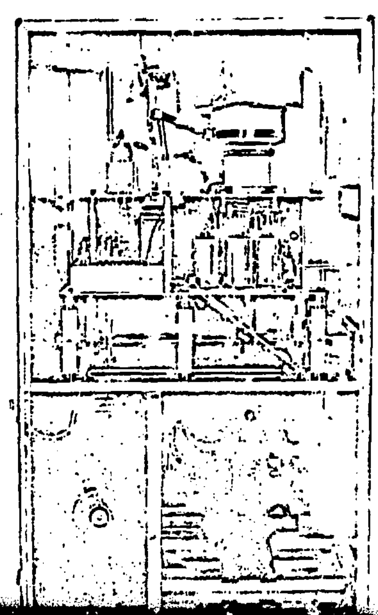

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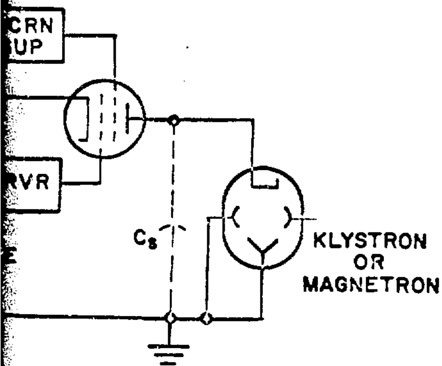

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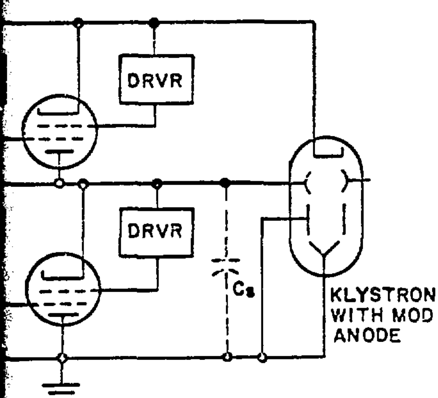

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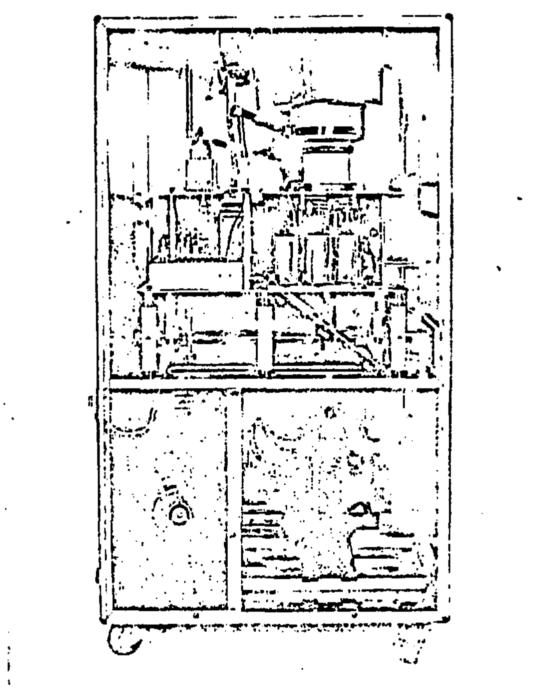

Figure 4 - ATC Modulator/Regulator
Utilizing a 4CX35000 Tetrode

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voltage feedback was added, and an area to install the compensated feedback divider.

In spite of the increased screen supply, it was impossible to achieve the close to 50 amperes required by the new injectors, and maintain a very conservative plate supply (Ebb approximately 2 kV above load voltage). This made it necessary to parallel the two existing modulators to power one Neutral Beam Injector. Figure 5 shows one mod/reg. operating into a 1000 ohm test load shunted by an electronically switched load of 2500 ohms. The top curves show the load voltage variation with and without feedback regulation; and the lower curve the load current utilizing voltage feedback. Figure 6 shows typical neutral beam curves with two units operating in parallel on an injector without feedback regulation and Figure 7 shows units operating with feedback.

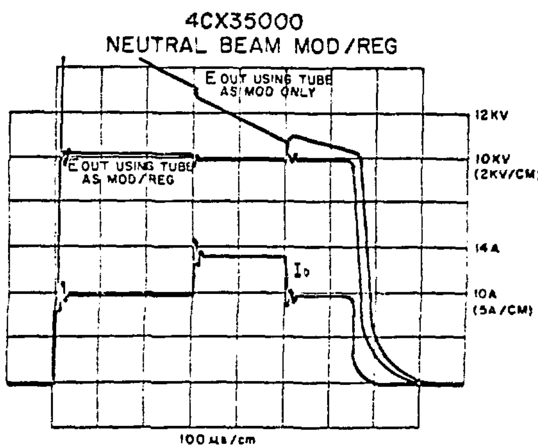


Figure 5 - Voltage and Current of a 4CX35000 Modulator/Regulator into a Test Load

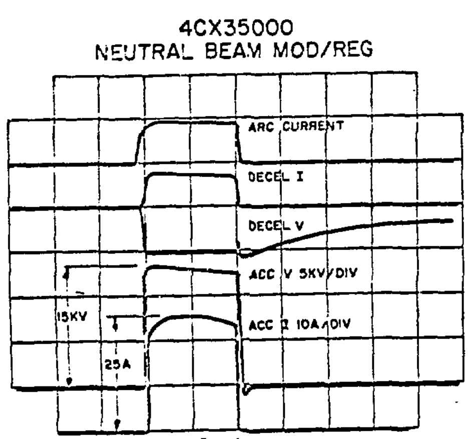
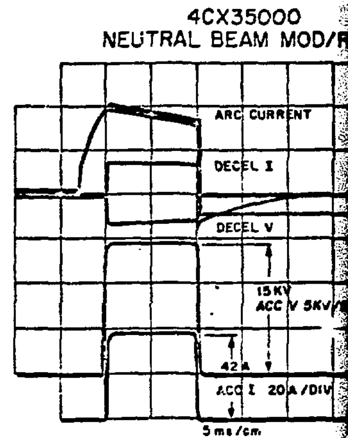


Figure 6 - Operating Voltages and Currents of an ATC Ion Injector Utilizing <u>Unregulated</u> Parallel 4CX35000 Tetrodes



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Modulators/Regulators

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established that would allow us
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ments are as follows:

1. E output - 5 to 40
2. I output - 0 - 70 a
3. Pulse duration - 30
4. Duty factor - 1% no
   -10% te
5. Rise time - less th
6. Voltage regulation
   from no load t

Having previously built
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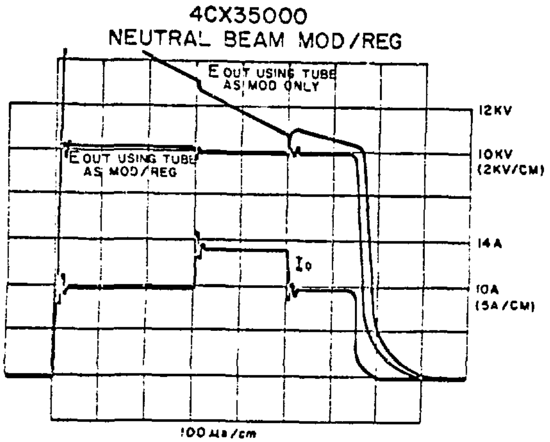

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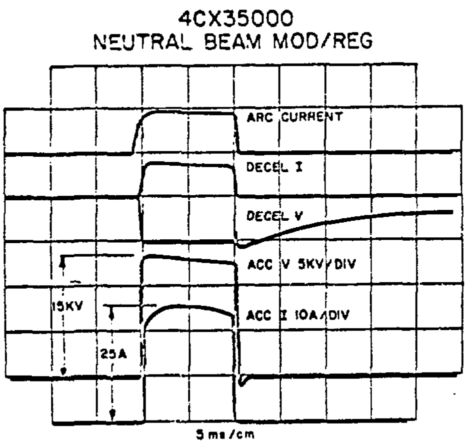

Figure 6 – Operating Voltages and Currents of an ATC Ion Injector Utilizing Unregulated Parallel 4CX35000 Tetrodes

In order to provide accel voltage for the second high power injector, either two more low power units would have to be built or one high power unit could be designed and constructed. The latter choice was made and a 20 kV 50 amp. short pulse modulator/regulator utilizing an Eimac type X2170 tube was completed in a relatively short time. Electronically, with the exception of the tube type and the filament transformer, the higher powered unit uses the same components as the lower powered

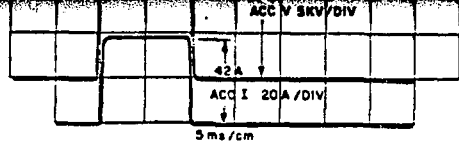

Figure 7 – Operating Voltages and Currents of an ATC Ion Injector Utilizing Regulated Parallel 4CX35000 Tetrodes

units. Mechanically, however, the units are much larger due to higher filament power, larger tube, and the need for water cooling of the tube anode. Development and subsequent operation of this unit has provided us with the basis for the PLT modulator/regulator.

Modulators/Regulators for PLT

When the decision was made to utilize neutra beam injection as the primary supplementary heating for PLT, a set of parameters for the accelerating power supplies and modulator/regulators wer established that would allow use of either the ORNL or the LBL ion sources. The output requirements are as follows:

1. E output – 5 to 40 kVdc
2. I output – 0 – 70 amps. dc
3. Pulse duration – 300 ms max.
4. Duty factor – 1% nominal
   -10% test conditions
5. Rise time – less than 10 μsecs.
6. Voltage regulation – better than 1% from no load to full load

Having previously built and operated a hig current unit utilizing the Eimac X2170 tube, th decision as to what circuitry and tube type to use became relatively simple and straightforwa There were, however, changes dictated by the hi current and voltage and the increase in pulse l The original X2170 modulator used on the ATC hi power injector contained electrolytic capacitor for screen storage, and to increase the size of this bank by 25 to 30 times would have meant a redesign of the modulator deck volume and an in crease in deck to ground capacity which was already approaching the 2500 picofarads budget for the deck. A second consideration for not utilizing energy storage in this circuit is the desire to have the screen voltage at zero poten during the interpulse interval so that a misgui input pulse will not dump the screen supply st energy into damaging screen dissipation. Havi the screen potential at zero during the interp also eases the requirement on the bias supply produce "complete" cut off with 50 kV on the a These considerations dictated that the screen be capable of being turned on only during the and have sufficient capacity to supply 6 kW wi

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creased screen supply, it was
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approximately 2 kV above load
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ws one mod/reg. operating
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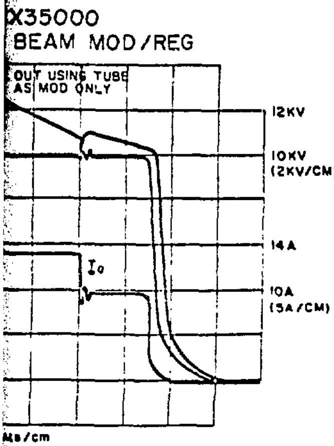
units operating with feed-



and Current of a 4CX35000
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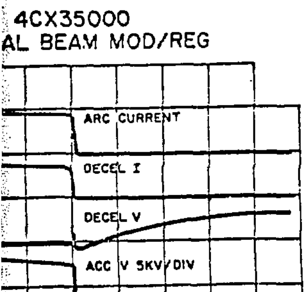

ting Voltages and Currents
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4CX35000 Tetrodes

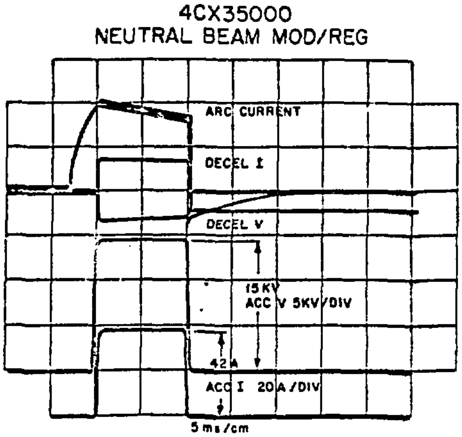

Figure 7 - Operating Voltages and Currents of an ATC Ion Injector Utilizing Regulated Parallel 4CX35000 Tetrodes

units. Mechanically, however, the units are much larger due to higher filament power, larger tube, and the need for water cooling of the tube anode. Development and subsequent operation of this unit has provided us with the basis for the PLT modulator/regulator.

Modulators/Regulators for PLT

When the decision was made to utilize neutral beam injection as the primary supplementary heating for PLT, a set of parameters for the accelerating power supplies and modulator/regulators were established that would allow use of either the ORNL or the LBL ion sources. The output requirements are as follows:

1. E output - 5 to 40 kVdc
2. I output - 0 - 70 amps. dc
3. Pulse duration - 300 ms max.
4. Duty factor - 1% nominal
   -10% test conditions
5. Rise time - less than 10 μsecs.
6. Voltage regulation - better than 1% from no load to full load

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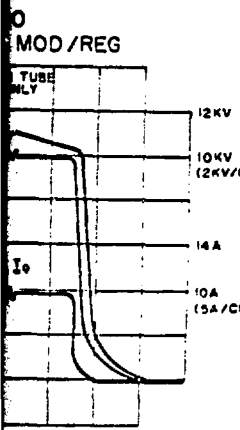

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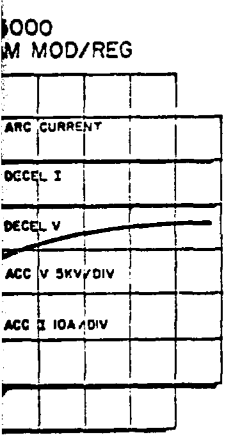

oltages and Currents
Utilizing Unregulated
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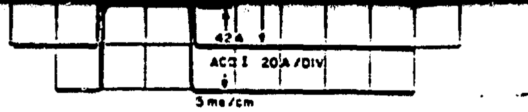

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4

Figure 10 is a schematic of a series modulator/regulator and Figure 11 is a conceptual mechanical layout of this unit. The main tube V_1 shown is a HV tetrode which will require development. As a backup approach, existing tubes can be used in series (Eimac X2170) or in parallel (Machlett LPT17) should the tube development program present too many difficulties to stay compatible with the TFTR schedule.

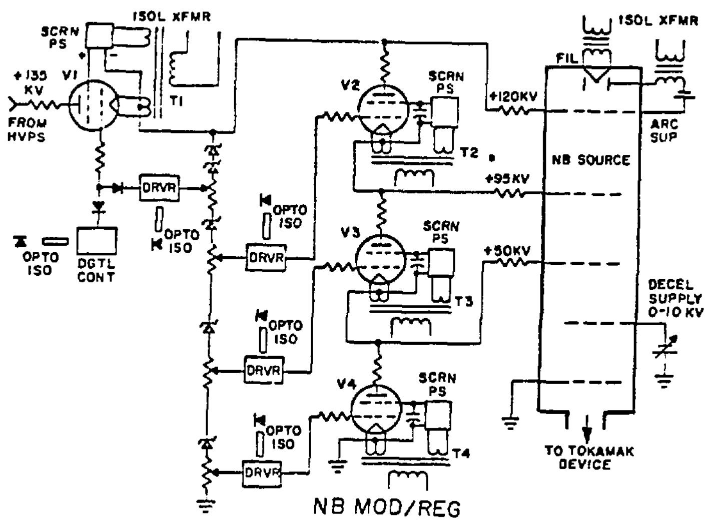

Figure 10 – Simplified Schematic of a Proposed TFTR Modulator/Regulator

V_1 functions as a switch and closed loop voltage regulator in a floating deck scheme. This circuit is quite common in high power radar transmitters. The power for the tube filaments, screen and grid supplies are coupled to the deck via isolation Xfmr T_1. Voltage regulation and feedback is obtained via the combined Zener-resistor string. Since the voltage to grid #1 is regulated, voltage regulation of grid #2 and grid #3 may be slaved to it, thereby requiring the circuits to regulate the voltages between the grids rather than from grid to ground.

Since V_2, V_3, and V_4 are required to carry only the auxiliary grid current plus some bleeder current during the pulse, they will be smaller than the #1 grid switch tube thus reducing size and cost.

The tubes shown in the schematic are all tetrodes and have been selected because of their inherent current limiting characteristics. Should a fault occur in a source grid, current from the power supply would be limited by the HV switch tube until it can open (usec's). Another possible HV switch tube is the high mu triode which can halve the power supply current before opening in the event of a fault, and the tube has the advantage of not requiring a screen supply.

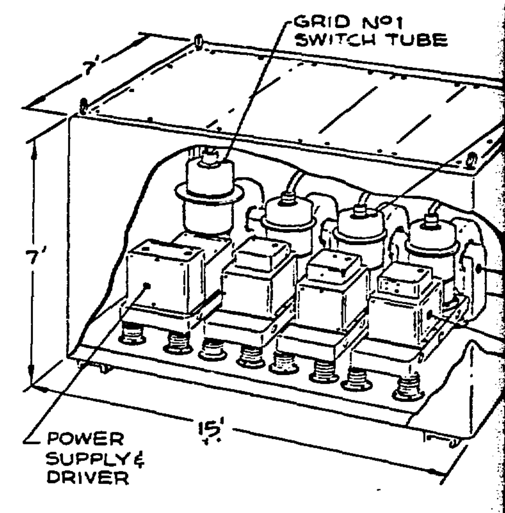

Figure 11 – Conceptual Mechanical
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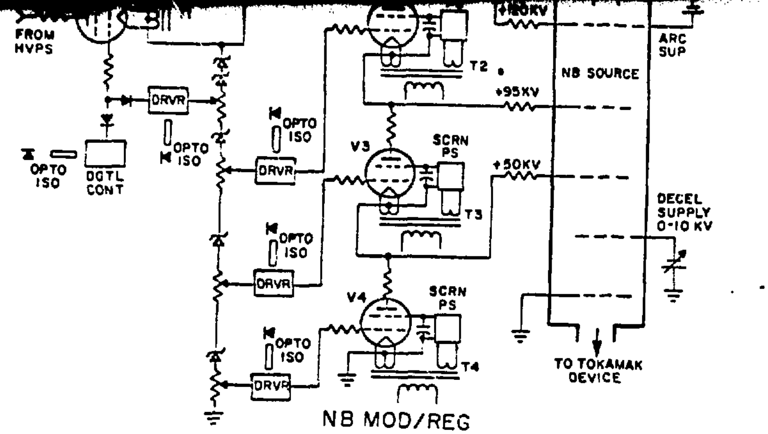

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Whichever tube is finally selected, the scheme presents a positive disconnect from the power supply in the event of a fault and will be used as primary protection for the sources. Should the switch tube fault, an electronic crowbar will shunt the energy from the power system to ground until the high speed disconnect can function removing the AC voltage from the power subsystem. This scheme, however, cannot

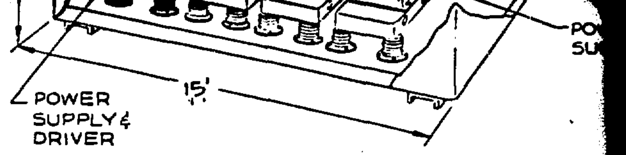

Figure 11 - Conceptual Mechanical Arrange
of a Proposed TFTR Modulator/Regulator

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tion limits fault energy to 50 joules.

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1. A. Deitz, "A New 200 kW, 800 MHz Transmit
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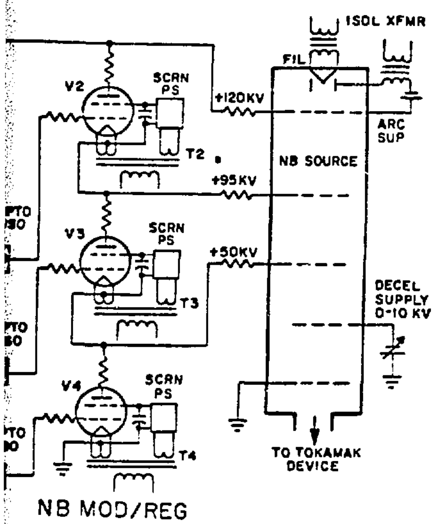

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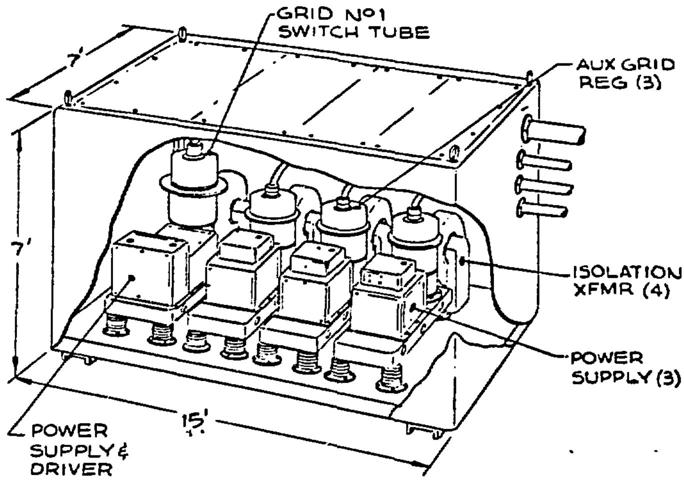

Figure 11 - Conceptual Mechanical Arrangement of a Proposed TFTR Modulator/Regulator

protect a faulted source from the stored energy in all the stray capacity in the system directly connected to the source grids. The source specification limits fault energy to 50 joules.

For a 120 kV source, the capacitance from grid #1 to ground must be limited to approximately 7000 pf in order to meet this specification.

This value is within the realm of the design, assuming the transmission run from the Modulator/Regulator to the source will be kept to less than 100 ft. As an added protection, a small amount of resistance placed in the line (less than 10 Ω) will help to absorb fault energy.

As previously stated, the auxiliary grid voltage regulators will be slaved to the #1 grid voltage. As voltage is applied to this grid the auxiliary grids can derive their voltage from it. It is likely that all voltages can be applied simultaneously which would eliminate the necessity of coupling separate timing signals or gates to the individual decks. Since it is too early in the program to predict this with a high degree of certainty, provision will be made for coupling digital information optically to the decks.

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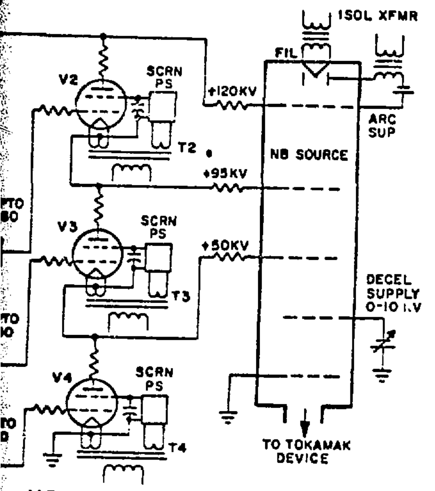

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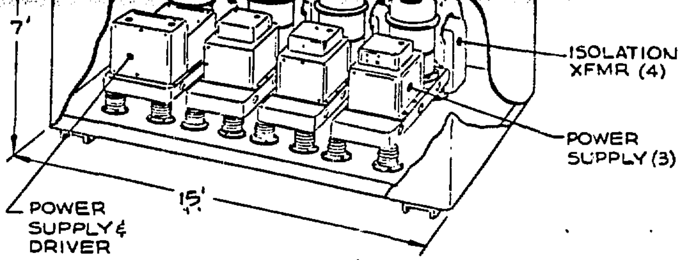

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good regulation during the pulse. The approach decided upon was to provide a power supply that was keyed "on" approximately 100 milliseconds before the pulse by phase controlled thyristors in the primary of the screen supply transformer to give a "soft" start. Isolation from deck potential is built into this three phase transformer which has delta and wye secondaries that provide a low ripple rectified output. Shunt regulators in the output of this supply provide a screen voltage regulated to within less than 1% between zero and four amperes of screen current. At the end of the main pulse the line thyristors are keyed "off" and the screen voltage reduced to zero. A simplified schematic of the complete PLT Modulator/Regulator is shown on Figure 8, and with the exception of the screen changes is identical to the ATC X2170 Modulator/Regulator. The low level pulse shaping and LED Driver are shown at the lower right. The power auxiliaries, filament, isolation, and screen power transformers and rectifiers are at the lower left. The X2170 series regulator tube and all of the "deck" mounted components are in the block at the top.

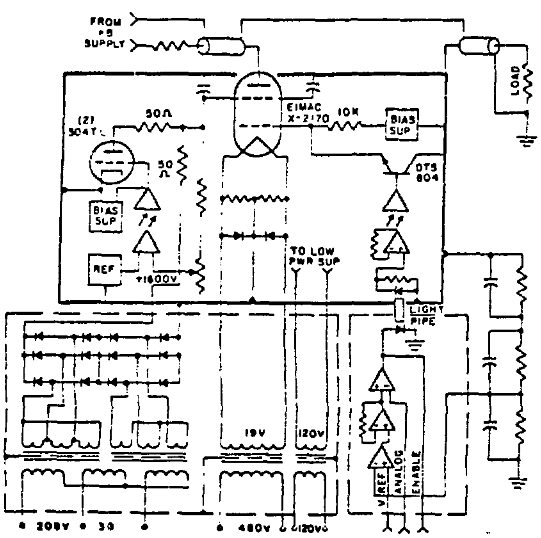

Figure 8 - Simplified Schematic of a PLT Modulator/Regulator Utilizing an X-2170 Tetrode

The pulse forming and LED driver circuits utilize three type 741 linear integrated circuit amplifiers to drive a 2N3507 emitter follower which in turn drives an ME7140 infrared emitter. All of these components except the ME7140 are mounted on a printed circuit board which can be easily changed for trouble-shooting or modification. The power supplies for this unit are also card mounted and readily changed. The LED driver, the photo diode receiver and light pipe are also packaged in a unitized, easily replaceable assembly. The emitter has adequate output to drive an MD2 silicon photodiode through a 16 inch

The third section controls the decay pulse and is known as a "tail biter". Th and its power supplies are also circuit and can be quickly replaced if necessary, and transistors in this amplifier are F9 2N2219A's, and DTS804's.

The remaining components mounted on the "deck" are: (1) The X2170 tube whic mylar ring on top of the deck which form frequency screen bypass capacitor; and (supply regulator, which was discussed ea also located inside the deck.

Figure 9 shows some details of the regulator construction, the modulator de ing in the deck over which the X2170 is filament busses and the AC power isolati rectifier tank.

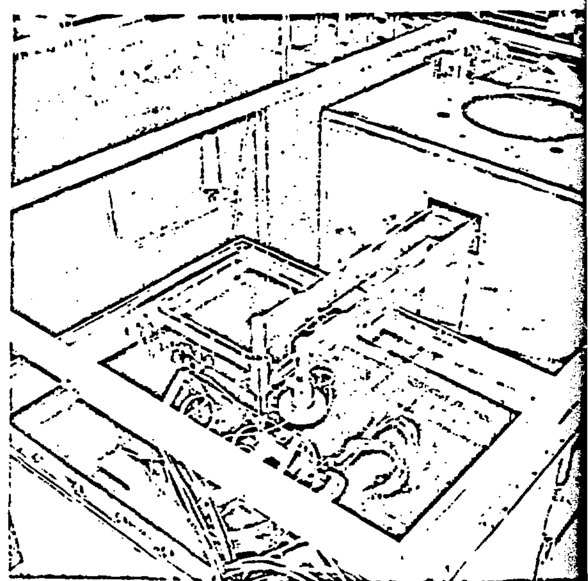

Figure 9 - PLT Modulator/Regulator Deck and A.C. Power Isolation T

Modulator/Regulators for TFT

Several approaches concerning a mo ulator required to apply the pulse volt ion source grids have been investigated

Five specific criteria must be ach Modulator/Regulator. They are:

1. Apply the voltage pulses to th Beam source grids.
2. Limit the energy from the powe should a source fault.
3. Disconnect the power system fr in the event of a fault as ra possible.
4. Reapply energy to the source

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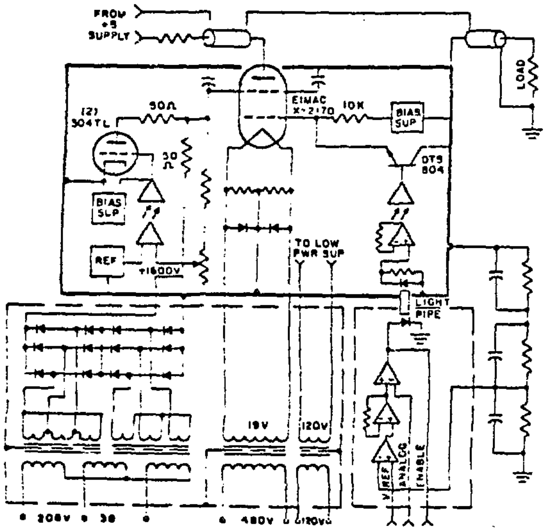

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The complete grid driver amplifier is a solid state unit which varies the grid bias of the X2170 tube. The amplifier has three sections, two of which are in the portion of the circuit that controls the rise and flat top of a square pulse or the pedestal rise and low frequency components of a complex pulse.

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Figure 9 shows some details of the modulat regulator construction, the modulator deck, the ing in the deck over which the X2170 is located filament busses and the AC power isolation and rectifier tank.

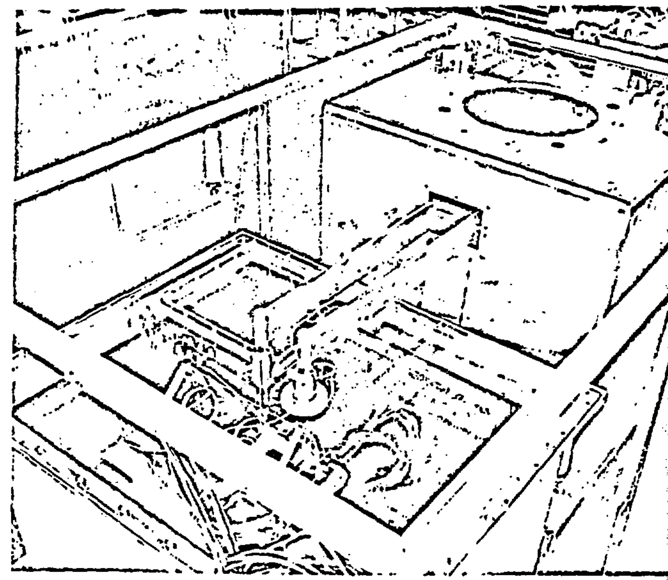

Figure 9 - PLT Modulator/Regulator Showing Deck and A.C. Power Isolation Tank

Modulator/Regulators for TFTR

Several approaches concerning a modulator/ ulator required to apply the pulse voltage to ion source grids have been investigated.

Five specific criteria must be achieved b Modulator/Regulator. They are:

1. Apply the voltage pulses to the Neutr Beam source grids.
2. Limit the energy from the power syste should a source fault.
3. Disconnect the power system from a so in the event of a fault as rapidly as possible.
4. Reapply energy to the source as soon fault clears (less than 1 msec).
5. Regulate the voltages applied to the grids.

The Neutral Injection source requires vol to be applied to the accelerating grid (#1) an auxiliary or gradient grids (#2, #3, and #4). most straightforward method of applying the vo to grid #1 is to use a HV vacuum tube capable holding off the open circuit voltage of the HV This voltage can be as high as 150 kV for a 1 source.

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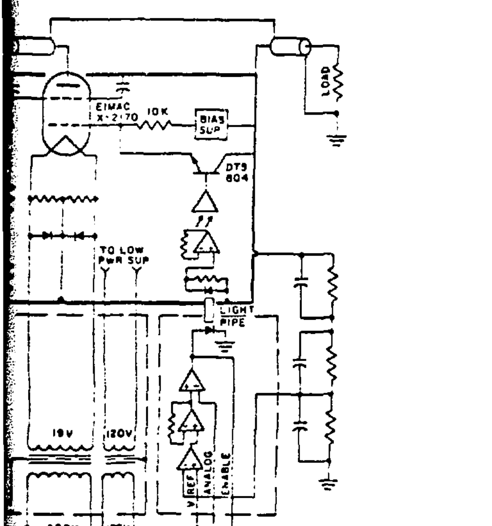


plified Schematic of a r/Regulator Utilizing -2170 Tetrode

ng and LED driver circuits util- inear integrated circuit ampli- 507 emitter follower which in 0 infrared emitter. All of these e ME7140 are mounted on a printed can be easily changed for trouble- tion. The power supplies for ard mounted and readily changed. photo diode receiver and light ed in a unitized, easily replace- emitter has adequate output to photodiode through a 16 inch

The third section controls the decay of the pulse and is known as a "tail biter". This amplifier and its power supplies are also circuit board mounted and can be quickly replaced if necessary. The IC's and transistors in this amplifier are F9601's, 2N2219A's, and DTS804's.

The remaining components mounted on or inside the "deck" are: (1) The X2170 tube which sits on a mylar ring on top of the deck which forms the high frequency screen bypass capacitor; and (2) The screen supply regulator, which was discussed earlier and is also located inside the deck.

Figure 9 shows some details of the modulator/regulator construction, the modulator deck, the opening in the deck over which the X2170 is located, the filament busses and the AC power isolation and screen rectifier tank.

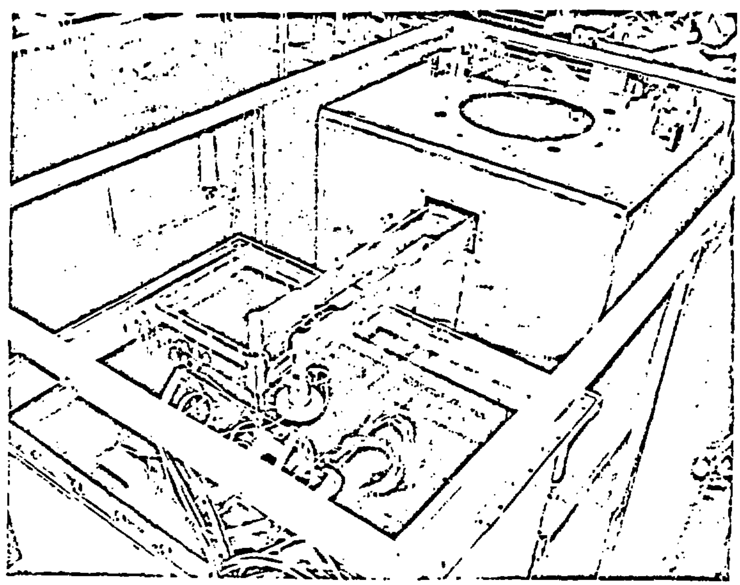


Figure 9 - PLT Modulator/Regulator Showing Deck and A.C. Power Isolation Tank

3

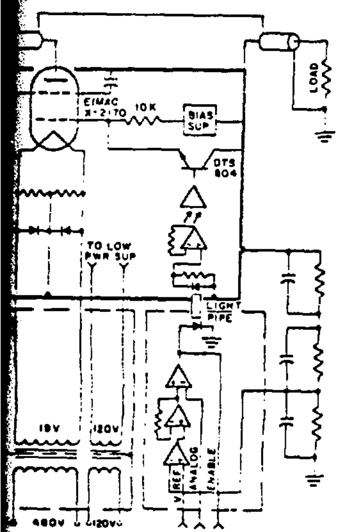
Modulator/Regulators for TFTR

Several approaches concerning a modulator/regulator required to apply the pulse voltage to the ion source grids have been investigated.

Five specific criteria must be achieved by the Modulator/Regulator. They are:

1. Apply the voltage pulses to the Neutral Beam source grids.
2. Limit the energy from the power system should a source fault.
3. Disconnect the power system from a source in the event of a fault as rapidly as possible.
4. Reapply energy to the source as soon as the

end of the main pulse the
yed "off" and the screen vol-
A simplified schematic of
ator/Regulator is shown on
exception of the screen
o the ATC X2170 Modulator/
vel pulse shaping and LED
e lower right. The power
isolation, and screen power
fiers are at the lower left.
ator tube and all of the "deck"
in the block at the top.



lified Schematic of a
r/Regulator Utilizing
-2170 Tetrode

ng and LED driver circuits util-
inear integrated circuit ampli-
507 emitter follower which in
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e ME7140 are mounted on a printed
can be easily changed for trouble-
tion. The power supplies for
ard mounted and readily changed.
photo diode receiver and light
ed in a unitized, easily replace-
emitter has adequate output to
photodiode through a 16 inch
e. The output of the photodiode,
requency slightly above 1 mega-
C high performance operational
he first stage in the X2170 grid

id driver amplifier is a solid
ies the grid bias of the X2170
has three sections, two of which
f the circuit that controls the
a square pulse or the pedestal
cy components of a complex pulse.

supply regulator, which was discussed earlier and is also located inside the deck.

Figure 9 shows some details of the modulator/regulator construction, the modulator deck, the opening in the deck over which the X2170 is located, the filament busses and the AC power isolation and screen rectifier tank.

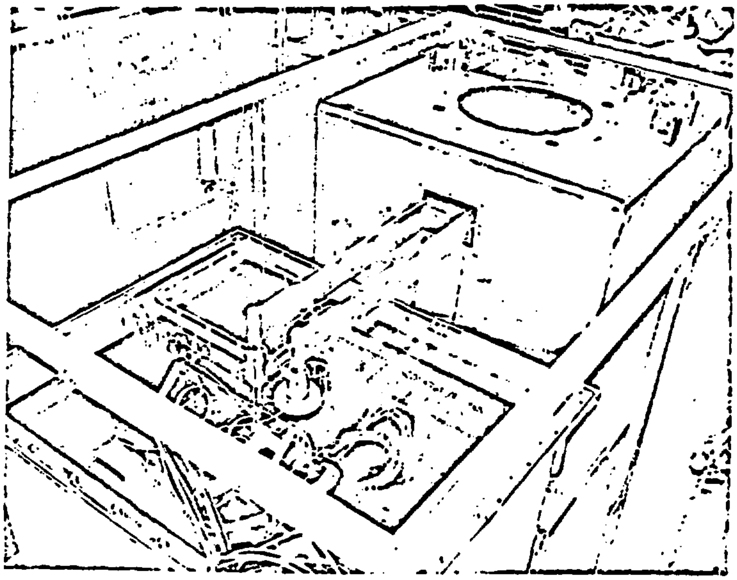

Figure 9 - PLT Modulator/Regulator Showing Deck and A.C. Power Isolation Tank

Modulator/Regulators for TFTR

Several approaches concerning a modulator/regulator required to apply the pulse voltage to the ion source grids have been investigated.

Five specific criteria must be achieved by the Modulator/Regulator. They are:

1. Apply the voltage pulses to the Neutral Beam source grids.
2. Limit the energy from the power system should a source fault.
3. Disconnect the power system from a source in the event of a fault as rapidly as possible.
4. Reapply energy to the source as soon as the fault clears (less than 1 msec).
5. Regulate the voltages applied to the source grids.

The Neutral Injection source requires voltages to be applied to the accelerating grid (#1) and the auxiliary or gradient grids (#2, #3, and #4). The most straightforward method of applying the voltage to grid #1 is to use a HV vacuum tube capable of holding off the open circuit voltage of the HVPS. This voltage can be as high as 150 kV for a 120 kV source.