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, high 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 transmission lines.
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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 milliseconds.

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

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

Development of PPPL Modulators

Early in 1964 a decision was made to increase the power of the Etude machine, X band generator from 10 kW CW to 100 kW pulse with a duty factor of .01 and a pulse width of 3 milliseconds. As there were no modulators at PPPL available to accomplish the pulsing, and a very short period of time allotted to the design and construction of the unit, a decision was made to build a floating power supply modulator, Fig. 1. This configuration permits grounding of the modulator tube cathode and the grounding of one side of the screen and supplies.

![Figure 1 - Floating Power Supply Modulator](image)

The main disadvantages of this system are the inherent slow rise time caused by large stray capacity C of energy storage and power supplies to ground, the potential hazards of a floating system and the greater volume required by the energy storage. The obvious advantage of this system is the ease with which the grid of the modulator can be driven. This modulator was used on two different klystron generators, requiring -8 amperes dc and -45 kV and 16 amperes dc. These modulators were developed around the operation of the 4 PR250C pulse tetrode and rated most satisfactorily as "hard-on" modula.
HIGH POWER MODULATOR/REGULATORS
FOR NEUTRAL BEAM SOURCES

J. Q. Lawson, A. Deitz

Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08540

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

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Early in 1964 a decision was made to increase the power of the Etude machine, X band generator from 10 kW CW to 100 kW pulse with a duty factor of 0.01 and a pulse width of 3 milliseconds. As there were no modulators at PPPL available to accomplish the pulsing, and a very short period of time allotted to the design and construction of a unit, a decision was made to build a floating power supply modulator, Fig. 1. This configuration permits grounding of the modulator tube cathode and the grounding of one side of the screen and grid supplies.

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some of the confined plasma. Pulses of energy have been required. We have taken the form of video recording of the anodes of large vacuum tubes to provide Electron Resonance Heating, or the Lower Hybrid types of third auxiliary heating. Injection of the anodes of large vacuum tubes to provide Electron Resonance Heating, or the Lower Hybrid types of heating, has also been attempted at PPPL. However, the high power and voltage requirements for each of the three types have been generally difficult to meet. A modulator/regulator for each source is a normal extension of the components and are utilized interchangeably.

Completed two new Modulator/injection sources used on the PLT machine. These require high voltage (50 kV) that should be voltage controlled. As a result, hard tube modulators have been designed. The capability for hard tubes has rise time and regulation control.

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The main disadvantages of this system are the inherent slow rise time caused by large stray capacitance, the potential hazards of a floating supply, and the greater volume required by the energy storage. The obvious advantage of this system is the ease with which the grid of the modulator tube can be driven. This modulator was used on two different klystron generators, requiring 38 kV at 8 amperes dc and 45 kV and 16 amperes dc. Both of these modulators were developed around parallel operation of the 4 PR250C pulse tetrode and operated most satisfactorily as "hard-on" modulators.

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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](image)

A second floating deck modulator, Fig. 3, was developed for a 200 kW 800 MHz generator for Lower Hybrid Heating. 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.

Modulators for ATC Neutral Beam

The initial design of the modulator was based on an expected impedance of approximately 2000 ohms and then was subsequently lowered to 1300 ohms and then to approximately 400 ohms. A paper given at the Fifth Symposium Problems of Fusion Research describes the arrangement of the modulator which was immersed in sulfur hexafluoride so that the high voltage capability of the 4CX35 tube could be realized. In retrospect, it is believed that this design would have better been directed at increasing its current capability, electronics more accessible for change when working with experimental devices, was made to repackage the modulator, current handling capability and add back to the unit while new guns were to the ATC machine.

The modulator was repackaged in cabinets fabricated with aluminum and sheet panel. We have found that fabrication results in workmanlike appearance, and that the allows fabrication in a short time minimum of documentation (rough engineering provided that the work is done by someone capable of resolving minor details of mounting components, etc). We are PPL to have technicians who are capable such work with only rudimentary engineering.

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The modulator was repackaged (Fig. 4) using cabinets fabricated with aluminum corner extrusions and sheet panels. We have found that this fabrication technique results in cabinets with a finished workmanslike appearance, and that the technique allows fabrication in a short time period with a minimum of documentation (rough engineering sketches provided that the work is done by skilled technicians capable of resolving minor details (methods of mounting components, etc). We are fortunate to have technicians who are capable of doing such work with only rudimentary engineering information.

The modification provided the additional requirements for a larger screen supply and energy storage, space for RC compensation required when
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 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 feedback to the unit while new guns were being added to the ATC machine.

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OR
MAGNETRON

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Figure 4 - ATC Modulator/Regulator
Utilizing a 4CX35000 Tetrode
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 (Eeb 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 Unregulated Parallel 4CX35000 Tetrodes

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

1. E output - 5 to 40 kV
2. I output - 0 to 70 amperes
3. Pulse duration - 30 ms
4. Duty factor - 1% nominal
5. Rise time - less than 1 ms
6. Voltage regulation - from no load to full load

Having previously built a current unit utilizing the 4CX35000, the decision as to what circuit to use became relatively simple. There were, however, changes in current and voltage and the need for water cooling. The original X2170 modulator power injector contained elements to store energy, and to redesign of the modulator decrease in deck to ground capacitance. A second circuit utilizing energy storage in the desire to have the screen.
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Figure 7 - Operating Voltages and Currents of an ATC Ion Injector Utilizing Regulated Parallel 4CX35000 Tetrodes

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 µsec.
6. Voltage regulation - better than 1% from no load to full load

Having previously built and operated a high current unit utilizing the Eimac X2170 tube, the decision as to what circuitry and tube type to use became relatively simple and straightforward. There were, however, changes dictated by the higher current and voltage and the increase in pulse length. The original X2170 modulator used on the ATC high 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 increase 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 potential during the interpulse interval so that a misfired input pulse will not dump the screen supply energy into damaging screen dissipation. Having the screen potential at zero during the interpulse also eases the requirement on the bias supply to produce "complete" cut off with 50 kV on the anode.

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2. I output - 0 - 70 amps, dc
3. Pulse duration - 300 ms max.
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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 of a Proposed TFTR Modulator/Regulator

For a 120 kV source, the capacity #1 to ground must be limited to approximately 50 joules.

This value is within the realm of the system's intrinsic inductance and stray capacity. The solution limits fault energy to 50 joules.

As previously stated, the auxiliary voltage regulators will be slaved to the main voltage. As voltage is applied to the auxiliary grids, the voltage on the auxiliary grids may be regulated to the desired level. This ensures a smooth transition from the auxiliary grid to the main grid, eliminating the need for separate timing signals or individual decks. Since it is too early to predict this with high certainty, the hardware will be made for information optically to the decks.

Acknowledgement

The authors wish to thank for their assistance to the various PPL Modulators: O. H. M. Hill, W. G. Newman and A. J. Young. This work was supported by U. S. Energy Research and Development Administration Contract E(11-

References

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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 protect a faulted source from the stored energy 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 #1 to ground must be limited to approximately 0.5 μF in order to meet this specification.

This value is within the realm of the designer, assuming the transmission run from the Modulator 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 ohms) 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 is likely that all voltages can be applied simultaneously which would eliminate the necessity of coupling separate timing signals or gates to 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 deck information optically to the decks.

Acknowledgement

The authors wish to thank for their contributions to the various PPL Modulators: O. N. Bowen, H. M. Hill, W. G. Newman and A. J. Sivo. This work was supported by U. S. Energy Research and Development Administration Contract E(ll-1)-3073.

References


A schematic of a series modulator/ regulator is a conceptual mechanical arrangement. The main tube $V_1$ shown is a plasma tube requiring development. As a plasma tube, it can be used in a switch or in parallel (Machlett tube development program present to stay compatible with the existing tubes). A switch and closed loop voltage regulation and feedback is required to develop $V_1$. The grids, $V_2$, $V_3$, and $V_4$, are required to carry only the switch current plus some bleeder current, which will be smaller than the $V_1$ current, reducing size and cost.

In the schematic, all tubes are tet- tube selected because of their limiting characteristics. Should the source grid current from the $V_1$ grid be limited by the HV switch tube, the grid $V_1$ can carry the required current before opening in the event of a fault.$V_1$ has the advantage of not increasing size and cost.

For a 120 kV source, the capacitance from grid $V_1$ 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 ohms) will help to absorb fault energy.

As previously stated, the auxiliary grid voltage regulators will be slaved to the $V_1$ 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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References

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• NB MOD/REG

**Amplified Schematic of a Modulator/Regulator**

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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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**References**


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.

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 troubleshooting 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 ND2 silicon photodiode through a 16 inch.

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

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

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

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 troubleshooting 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 ND2 silicon photodiode through a 16 inch.

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

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

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

1. Apply the voltage pulses to the beam source grids.
2. Limit the energy from the power source should a source fault.
3. Disconnect the power system in the event of a fault as rapidly as possible.
4. Reapply energy to the source.
Within less than 1 µ second, 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 troubleshooting 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 M22 silicon photodiode through a 16 inch plexiglass light pipe. The output of the photodiode, which has a cutoff frequency slightly above 1 megacycle, feeds an F709C high performance operational amplifier which is the first stage in the X2170 grid driver amplifier.

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.

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

**Modulator/Regulators for TFTR**

Several approaches concerning a modulator 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 fault clears (less than 1 msec).
5. Regulate the voltages applied to the grids.

The Neutral Injection source requires voltage to be applied to the accelerating grid (#1) and 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 HV supply regulator, which was discussed earlier also located inside the deck.

This voltage can be as high as 150 kV for a linear accelerator source.
The pulse. The approach provide a power supply that ultimately 100 milliseconds before controlled thyristors in the a supply transformer to give a tion from deck potential is phase transformer which has varieties that provide a low ripple hunt regulators in the output de a screen voltage regulated to between zero and four amperes of the end of the main pulse the keyed "off" and the screen vol-
A simplified schematic ofulator/Regulator is shown on the exception of the screen to the ATC X2170 Modulator/ level pulse shaping and LED the lower right. The power t, isolation, and screen power tifiers are at the lower left.ulator tube and all of the "deck" re in the block at the top.

![Simplified Schematic of a Modulator/Regulator Utilizing X-2170 Tetrode](image)

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](image)

**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
A simplified schematic of a modulator/Regulator is shown on the exception of the screen to the ATC X2170 Modulator/Regulator is shown on the lower right. The power isolation, and screen power supplies are at the lower left. The modulator tube and all of the "deck" is in the block at the top.

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.