MULTIPLE BEAM PULSE CAPABILITY OF THE SLAC INJECTOR*

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Summary

The SLAC injector is capable of being programmed for multiple beams of different beam pulse width and intensity on a pulse to pulse basis. Programming is accomplished remotely from the central control building, two miles away. The beam starts at the SLAC gun which is a Pierce triode with cathode operated at -80 KVDC. The gun modulator drives the grid-cathode gap with an 800 volt pulse of selectable pulse width. Selectable grid-cathode bias controls the current output of the gun. These selections are made on a pulse to pulse basis as required for multiple beam operation. For time of flight experiments which require a series of very short pulses, or even a series of single bunches of electrons, a transverse sweeper phase locked to a subharmonic of the bunching frequency is used in the injector to chop the beam accordingly.

Introduction

Early in the design of the accelerator, the problem of full beam utilization by the experimenters was considered. Some experiments such as bubble chambers just cannot use the full repetition rate capability of the machine, (360 pps) while other experiments require large amounts of integrated beam time, but are not concerned with a small percentage of missing pulses. Time is also required for setting up new beam configurations or experiments and this ideally should not represent wasted accelerator time. The outgrowth of these considerations was the beam switchyard with its capability of directing beams on a pulse to pulse basis to the several different target areas where the physics experiments are installed. Along with the capability of directing the beam to different experimental areas on a pulse to pulse basis came the requirement of programming the various beam parameters on a pulse to pulse basis. The significant beam parameters from an experimenters viewpoint are beam energy, beam spectrum, beam intensity, beam duration, beam structure, and beam timing. Of these parameters, the injector has control of all but the first, beam energy. This parameter is controlled by how many klystrons are used to accelerate the beam and the machine control system makes provision for programming this number on a pulse to pulse basis. Beam spectrum is controlled for the most part by the microwave properties of the injector structure and is discussed elsewhere.[1] Of the remaining parameters, beam intensity and beam duration are controlled by varying the output of the gun through control of the gun modulator. Beam structure refers to further intensity modulation within a single beam pulse. Various time of flight experiments require different structuring of the beam, but only one structuring system has so far been constructed at SLAC and is herein described. Additional systems are being studied and designed and in time will become available for experimental use. The last parameter mentioned is beam timing. Control of beam timing and transmission of timing information to the experimenter is accomplished by the machine trigger system. The injector has the requirement of maintaining a stable relationship between machine trigger and the gun output.

Initial Design, Construction, and Testing of Gun Modulator Systems

Gun Characteristics

The Pierce triode gun is discussed in detail in the paper by R.H. Miller, J. Berk, and T.O. McKinney.[2] It's characteristics pertinent to gun modulator design are as follows. It operates at a DC cathode potential in the range of 40 to 100 kV with 80 kV the nominal operating voltage. It requires about 700 volts positive grid drive to achieve a 2 amp peak current output. Grid current is about 10% of cathode current. Grid to cathode capacity is in the range of 20 to 25 picofarads, and the input structure looks like a 50 ohm transmission line terminated in this capacity. Virtually complete gun cutoff (less than 10^3 electrons per pulse) is achieved at a negative bias of 100 volts on the grid.

Prototype Gun Modulator

Early in the design of the SLAC injector, a test stand consisting of prototype injector components was assembled and beam tested. Output of this prototype machine was a 6 MeV electron beam. To supply this beam, a gun and gun modulator were required. Early tests were conducted with a purchased gun and a line type modulator with both grid and cathode pulsing. A procurement was initiated which ultimately delivered two floating deck, hard tube amplifier modulators. The first modulator was installed on the test stand and used to evaluate guns and injector components. This first modulator had no pulse to pulse switching capability. The second modulator delivered had two state switching capability on both the pulse width and pulse height circuits.

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Detailed requirements for final design of a gun modulator suitable for machine use were slow in coming due to the evolution of ideas and the press of other injector hardware construction, so it was decided to modify the second prototype modulator for temporary machine use and to start a development program aimed at producing a new gun modulator meeting the full machine requirements. The modifications to the prototype unit were largely performed by the SLAC modulator group under the direction of C. Olson, with the modifications to effect remote control being done by the injector group. This modified system was installed on the machine and after some initially high failure experience, settled down to become a reliable, if not optimum, source of beam which has been adequate for experiments conducted to date on the machine. The development program for the new modulator is well into the hardware assembly phase and the machine changeover to this new modulator is close at hand.

Requirements of the Machine Gun Modulator System

Physical

The SLAC accelerator is housed in a tunnel 25 feet below ground level. The moderate amounts of radiation present in the tunnel dictate that electronic equipment, especially that containing semiconductors, be installed if at all possible above ground in the klystron gallery and not in the tunnel. Since the gun must be in the tunnel, the choice must be made whether to install all the gun pulser electronics in the gallery and face the problem of getting the pulser output to the gun by some transmission system, or to mount portions of the pulser electronics in the tunnel close to the gun but in a radiation environment and inaccessible for maintenance.

In the case of the modified prototype modulator, a tunnel location for the distributed pulse amplifier, driver and clipper was dictated by the 300 ohm output impedance of the amplifier and the lack of a suitable transmission system to operate at this impedance level. A large box within a box floating deck structure with standard rack mounting configuration incorporated in the inner box was constructed in the tunnel around the gun with the gun insulator spanning the gap between boxes. The inner box was floated at the DC cathode potential and was connected to the floating deck electronics in the gallery by a specially constructed 100 kV multi-inner conductor cable which contained coaxial cables as well as individual wire pairs. The prototype modulator components previously mentioned were mounted in this box in close proximity to the gun and connected to electronics in the gallery through the multi conductor high voltage cable. The new modulator will have all of its electronics in the gallery as shown in Figure 1, but it is anticipated the deck in the tunnel will be used later to mount fast grid driving pulsers associated with future beam structuring schemes.

Electrical

The new modulator is to be capable of selecting one of three remotely programmable grid bias settings in response to one of three pretriggers. The bias in turn controls the current output of the gun. A pretrigger is supplied in advance of each machine pulse as required by the multiple beam profile of the machine. If no trigger is received, or if two or more simultaneous triggers due to a programming error are received, the bias reverts to a high, but remotely controllable level which either produced no beam at all, or an extremely low intensity beam. The bias control channels are not part of either the personnel or machine protection interlock system, so this fourth channel feature guarantees an experimenter only that he will not receive a damagingly intense beam if a multiple trigger programming error, or missed trigger condition occurs. The fourth channel with its remote control capability also allows experiments which require very low electron densities (10^4 - 10^8 electrons per pulse) to be run while using the bias channel which would otherwise be assigned to this function as a higher current "steering" channel. The low electron density beam is not seen by the machine beam steering monitors, but an occasional pulse on the "steering" channel makes the orbit of the low intensity beam visible on the monitors.

Beam pulse width, or duration is also to be selectable on a pulse to pulse basis. Separately triggered low level pulsers generate three remote width controllable pulses which can be selected as machine beam profile requires. These channels can be triggered in parallel and since each has separate timing control, three current pulses can be accelerator during one machine RF pulse. The pulse width circuitry is part of the machine protection system, so special effort must be made to prevent triggering on noise, or producing output pulses when there is no trigger. The pulse width synthesis circuitry of the prototype modulator was unsuited to the machine requirements, so pulse width synthesis electronics suitable for the new modulator was developed during the prototype modification program and installed in its permanent location on the machine. It performs the functions described and has operated satisfactorily to date.

Since most of the active hardware is installed on the high voltage floating deck, provision must be made for crossing the voltage gap by AC power, status control and analog channels which are narrow band and bias switching and beam pulse signals which are wide band. These functions are accomplished by isolation transformers and electromechanical linkages.

Features of Gun Pulser Design

Pulse to Pulse Bias Control

The switched grid bias electronics consists of a fast regulating power supply and four remotely controlled reference potentiometers which can be switched into the power supply regulator circuitry. This circuitry and the receiving circuits of the deck crossing RF pattern generator are mounted on the gallery floating deck. An RF pattern corresponding to the selected beam intensity profile is generated in ground level electronics and coupled to the floating deck via an isolation transformer. Figure 2 shows a block diagram of the complete bias control system.

One of three pretriggers is supplied to the ground level electronics 1.5 milliseconds before each machine pulse. This causes one of the 2.5 millisecond one shot multivibrators to fire which turns on one of three oscillators. The oscillator frequencies are 4 MHz, 4.5 MHz and 5 MHz. The oscillator outputs are combined and amplified in a 50 ohm line driving output stage. Output level is 10 volts. To prevent simultaneous oscillator triggering by misprogrammed trigger pulses, an anti-coincidence circuit is incorporated. This circuit consists of an adder which samples the output of all three one shot multivibrators and fires a Schmitt trigger when the sum of two or more simultaneous pulses is detected. The Schmitt trigger turns on a transistor in parallel with the amplifier input which grounds the oscillator outputs. Thus, for two or more input triggers, no output ensues and the modulator reverts to the fourth channel bias setting. The modulator also switches to the fourth channel if a trigger is missed, or none is programmed.

The RF bias control signal crosses to the high voltage deck on an isolation transformer consisting of a ferrite toroidal core through which an appropriate corona shielded single turn high voltage secondary is threaded. The high voltage turn is made from the center conductor of RG-17 coaxial cable. A cross section of the transformer is shown in Figure 3. Five copper tape turns are wound on the ferrite core to serve as the primary. With appropriate secondary termination and a single compensation network on the primary, the input to the transformer appears matched to 50 ohms over a band from 100 kHz to 50 MHz. This is quite important since an identical transformer is used to transfer the low level video gun drive pulses to the deck mounted gun cathode driver amplifier. Three of these transformers are mounted in a part plexiglass, part aluminum chassis which spans the high voltage gap of the gallery floating deck. The third unit is a spare and all three are interchangeable.

The RF signal reaching the floating deck is amplified and separated with three simple series resonant filters. A transistor detector conducts when the filter output is above 0.75 volts. When the output of the detector is above 3 volts a Schmitt trigger is fired. The two discrete threshold levels serve to reject noise and adjacent channel leakage, while the Schmitt trigger action provides a constant amplitude pulse output independent of input signal fluctuations above the trigger threshold. The outputs of the Schmitt trigger circuits drive 110 volts hold off gating transistors. The input signals to these gating transistors are derived from three double zener regulated reference voltage potentiometers remotely motor driven from ground level. The three gate outputs, plus a fourth low level reference signal are diode matrixed together in such a way that outputs from any of the gates take presidence over the fourth channel so long as the gated signals call for a higher gun output (lower bias level) than the setting of the low level reference. This combined signal is supplied as a reference input to the fast regulator circuitry. The fast regulator incorporates both series and shunt regulation tubes. A two tube dual triode amplifier drives the feed back loop. The shunt regular tubes are required to rapidly discharge the capacity associated with the grid transmission line and other hardware which rides at the grid potential.

All circuitry associated with the bias control system with the exception of the fast regulator is transistorized and is contained on three PC cards. Low level power supplies up to 150 volts are also constructed on PC card substructures and mount in the card cages. The card cage on the floating deck is constructed integral with the high voltage bias power supply and fast regulator so that the whole deck level bias control system is contained in one quick changeable chassis. It is planned to mount two of these units on the floating deck so that in the event of a malfunction, a switch of input cables will put the spare in operation. The gun pulser circuitry is similarly packaged and spared.

Gun Pulse Circuitry

The ground level pulse synthesis circuitry contains no feed back circuits such as multivibrators, etc. in direct line with the output. Thus, there are no circuits to free run in case of a malfunction. All power supplies are cointerlocked so that loss of one supply removes all voltages from the circuit. These precautions are taken to guarantee that there can be no pulse output without a trigger input since this circuit is a direct series link in the machine protection system. The pulse synthesis circuitry is further designed to ignore noise transients and to generate an output pulse only during the duration of the input trigger pulse regardless of the pulse length programmed. The input trigger pulse is 3 μsec long, occurs 500 nsec before required gun output, and brackets the gun output pulse.

The heart of the pulse synthesis circuit is a three transistor common collector triple gate circuit. Two of the gating transistors are normally conducting while the third is normally cut off. Thus, the common collector point remains at zero voltage. An incident trigger pulse is split three ways. In the first path it is amplified and squared and used to turn off the first transistor of the triple gate. Since the second transistor is still conducting no output of the gate ensues. The second path contains a 300 nsec delay line and a similar squaring amplifier. The output of this amplifier turns off the second transistor and since now all three transistors are off, the collector voltages rises and forms the rise time of the output pulse. During the 300 nsec delay, the trigger signal in the third path is amplified, squared and used to drive an RC charging network. The output charging waveform of this network is added to a zener stabilized remote programmable offset voltage and the combination is used to fire a Schmitt trigger. The output of the Schmitt trigger drives the third gate transistor into conduction, which causes the collector voltage to drop thus generating the fall time of the output pulse. By varying the offset voltage, the Schmitt trigger circuit can be made to fire at any point within 80% of the RC charge curve range and thus provides the variable width control. Since most of the exponential charge curve is used, the width programming rate is non-linear, but non-linear in a most efficient way. At short pulses the programming rate is slow, while at longer pulses, the programming rate is faster. This has the effect of giving a constant percentage programming rate over the whole pulse width range. The range is from zero pulse width (no pulses at all) through a triangular pulse consisting only of rise and fall times contained within 40 nsec to a 2 μsec wide pulse. Pulse width and initiation stability is better than the time resolution of a Tektronix 547 scope.

The gate output is amplified in a transistor line driver stage and the outputs of all three pulse synthesizer PC cards are diode matrixed together to drive the high voltage isolation transformer used to span the ground-floating deck gap. There is no ambiguity in driving all three of these synthesizers during the same machine pulse either concurrently or sequentially and this mode of operation has been used for some machine beam breakup studies to determine time constants associated with the effect.

On the gallery floating deck, the isolation transformer output is amplified and squared in a three transistor driver whose output is a 30 volt pulse at 50 ohm impedance level with rise and fall times of less than 20 nsec. This signal drives the four tube saturated amplifier which produces an output of 800 volts into an impedance of 75 ohms. The four tubes of this amplifier all operate normally cutoff, and the last stage operates with plates referenced to ground potential (cathode operated at -(B+) voltage) so that the amplifier output is available directly between the plates and ground. The polarity of the output is such that it directly drives the gun cathode.

The employment of an all normally cutoff amplifier chain is made possible by the use of coaxial type interstage transformers.[3,4] Figure 5 shows the configuration of these transformers. The operation of these transformers is not easily described analytically and indeed at first glance it looks as if one gets something for nothing. The basic coaxial transformer consists simply of a number of turns of coaxial cable or twisted pair line wraped around a high μ toroidal core. The magic appears when one considers that either side of the output of this transmission line may now be referenced to ground independent of the input side reference. This is true since any ground to ground currents must flow through the toroid and if the toroidal inductance is high enough, they are effectively stopped. Signals on the transmission line being wholly contained within the line, experience no inductive impediment from the toroid. These transformers are inherently wide band being limited on the low frequency side by the toroidal inductance and on the high frequency side by the attenuation and dispersion characteristics of the cable. Two transformer configurations are used in the pulse amplifier. The first transformer consists of two 100 ohm coaxial cable wound toroids with inputs in parallel and outputs in series. This gives a four to one impedance and two to one voltage step up ratio and is used as the input transformer to the amplifier first grid. Three more interstage transformers are used between plates and grids of the four tubes. Because transformer impedance is not a readily altered variable, it is necessary to choose the tube operating points with care. Tube grids also do not present a constant impedance so each grid must be resistive loaded to limit this non-linear load effect on the transformer. The interstage impedance level through the amplifier as dictated by transformers is 200 ohms. The actual impedance as seen by the transformers varies from 400 ohms (resistive load) to 100 ohms (grid and resistive loading combination) during the pulse. Grid saturation effects tend to minimize flat top degradation due to this dynamic impedance mismatch. Voltage gain of the overall amplifier is 20 with stage gains approximately equal. The output of the amplifier is a negative going 800 volt pulse with rise and fall times of less than 20 nsec, and a top flat to within 1%. An intensity range switch is incorporated in the output of the amplifier.

The 75 ohm drive capability of the amplifier is used only on the full drive position of this switch. Reduced range positions present proportionately higher impedances to the amplifier and result in a faster rise time, flater top pulse. In the full drive position of the range switch, low gun output currents are obtained by impressing a large bias signal on the gun grid. This has the effect of using only the top few percent of the drive pulse and the deviations from flatness are considerably amplified by this process. Most of the accelerator operation is in a current range 2 orders or magnitude below the peak output capability of the gun. The range switch provides the capability of proportionately reducing the bias and drive so that the minimum bias setting produces only a fraction of full gun capability. This also has the effect of reducing the programming rate of the intensity controls. They do not have the beneficial non-linearity possessed by the width controls. The range switch, the three pulse width controls, the four intensity controls, and the three pulse timing controls are programmable from the central control room, two miles away.

Beam Structure Equipment

Subharmonic beam sweeper systems are used to impress further structure on the electron beam pulse. The electron beam already has a fine structure corresponding to electron bunching at the machine frequency, 2856 MHz. For time of flight experiments, experimenters would like to eliminate most of the electron bunches and accelerate an equivalent amount of charge contained in a train of single bunches, or bunch groups, spaced apart by the resolution time of their experiments. For single bunches, a deflector system phased locked to the accelerator frequency is necessary to eliminate all but the desired bunches. For bunch groups consisting of several bunches, phase locking is not necessary and the experimenter can vary his group spacing at will by changing the deflector frequency.

A second possibility for producing subgroups within a beam pulse is direct modulation of the gun grid by a short pulse fast rise time pulser. This allows the experimenter to produce single, or nonperiodic electron subgroups during the machine pulse. Space is provided on the tunnel floating deck for just such a pulser. The fast bias regulator is designed to handle the extra capacity that insertion of an additional pulser in series with the grid would entail. The rise time limitation of the grid itself is just the RC time constant of the feed structure impedance and the grid capacitance. This number is about 1 nsec. State of the art in pulsers is approaching this rise time and when a concrete experimental requirement occurs, development of this type of a pulser will be undertaken.

Two requirements which already exist are for a single bunch structured beam periodic at 12.5 nsec and a three bunch structured beam periodic in a range from 25 nsec to 50 nsec. 12.5 nsec periodicity corresponds to a 40 MHz drive frequency. The former requirement is connected with an experiment scheduled early on the machine so the construction of this structuring system was undertaken first and is now just becoming operational. The second system which will use much of the same hardware operates at a lower frequency range, 10 MHz to 20 MHz. Construction is starting on this system now.

The single bunch system just mentioned is shown in Figure 6. It consists of a 50 kilowatt RF amplifier and two resonant beam deflection structures, one close to the gun and one 330' downstream in the accelerator. The operating frequency of this system is at the 72 subharmonic of the machine, 39.667 MHz. The master oscillator of the machine has an output at this frequency and this signal is used to drive a 50 kw peak pulsed RF amplifier. The pulsing is required since in multiple beam operation, the experiment requiring the structured beam may be assigned only a portion of the total machine pulses. The pulsed RF amplifier for this purpose was constructed by the SLAC electronics group with the engineering being performed by W. Tomlin.

Initial Beam Deflector

The first beam deflector is a pair of plates in the beam line following the gun and prebuncher. At this point the beam is not sufficiently bunched for the plates to totally eliminate electrons which form adjacent bunches to the desired bunch, so a clean-up deflector downstream is required. Early elimination of unwanted electron bunches prevents their loading the following buncher and accelerator structures. These loading effects dictated the location of the first deflector. A quarter wave section of RG 220 cable forms the deflector resonant circuit and steps the RF drive voltage up to 40 kilovolts peak. This deflects all but the central bunch and vestages of adjacent bunches into the walls of the deflector structure. The deflector phase is adjusted so that the central bunches occur at the zero crossings of the RF cycle. There are two of these per RF cycle, so 1 out of every 36 bunches is transmitted. A capacitor divider samples the drive phase and transmits this information to the experimenter via the machine master drive line. The machine drive line frequency is 476 MHz and transmission of a 39.667 MHz signal does not degrade its primary function of providing phase coherent drive for the machine sub-boosters, which in turn drive the 2856 mc klystrons.

Initial operation of this first deflector produces chopping rates of up to 40 to 1. Prebuncher excitation and deflector phase interact strongly with these ratios. This indicates the system is deflecting strongly enough to see the granularity of individual electron bunches, and is phase stable enough to preserve coherence during the machine pulse. Testing continues.

Second Beam Deflector

The second beam deflector not installed as yet. Its design is similar to the first deflector but its resonator Q will be higher since beam interception losses are not a factor. This deflector will serve two purposes. It will eliminate the residual adjacent bunches missed by the first deflector. It will also eliminate all random electrons captured and accelerated in the injector and first 330' of the machine. Preliminary measurements of this "dark current" electron count indicate electron quantities of from 10^2 to 10^5 electrons per pulse. Eliminating these "dark current" electrons from the first 330' of the machine effectively eliminates them from the experiment since all electrons captured downstream have insufficient energy to pass through the energy analyzing units of the machine.

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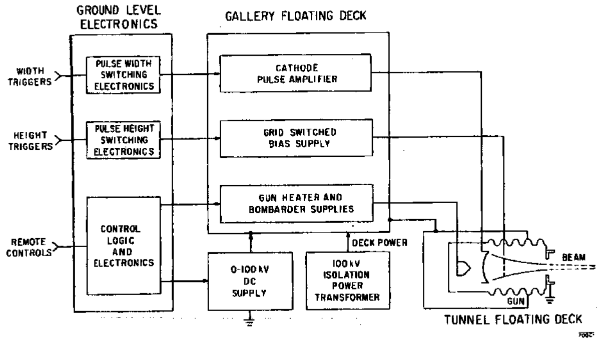

Fig. 1 -- Gun Pulser Block Diagram

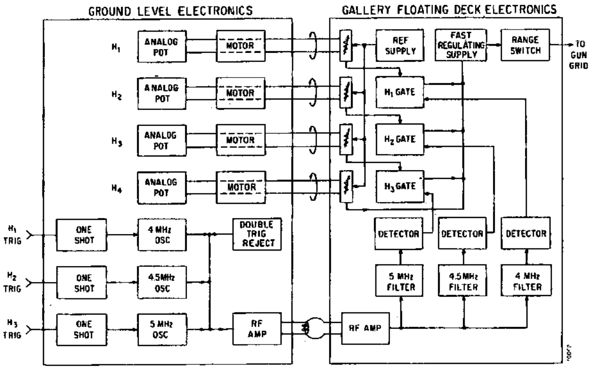

Fig. 2 -- Bias Control Circuitry

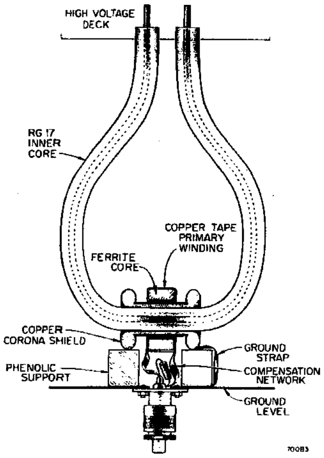

Fig. 3 -- Wide Band Isolation Transformer

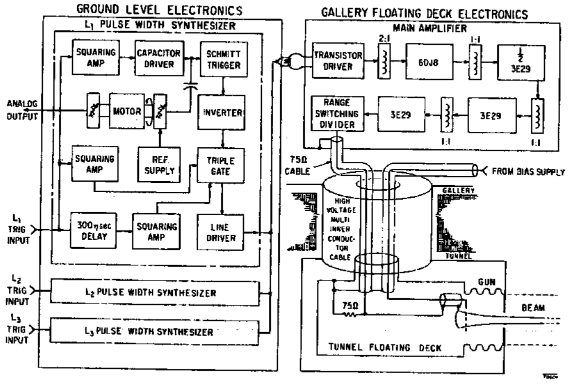

Fig. 4 -- Gun Pulser Circuitry

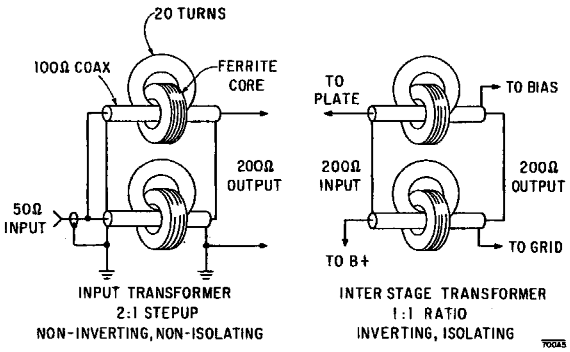

Fig. 5 -- Coaxial Transformer Configurations

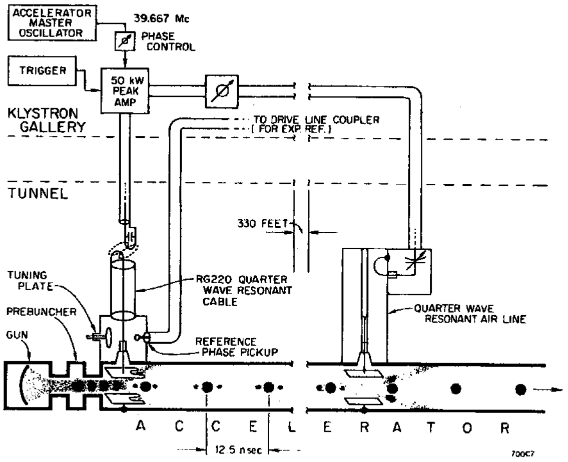

Fig. 6 -- Subharmonic Sweeper System