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NANOSECOND ELECTRON BEAM GENERATION AND INSTRUMENTATION AT SLAC*

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Introduction

Much of the SLAC injector system including some beam chopping equipment is described in the book, The Stanford Two-Mile Accelerator.[1] Fig. 1 shows an updated diagram of the present SLAC injector including the latest beam chopping equipment. Two off-axis guns can each be grid-modulated with trains of pulses as short as 5 nanoseconds. An initial 39.667 MHz beam deflector has sufficient deflecting field to reject adjacent electron bunches of the 2856 MHz prebunched beam, thereby loading one RF bucket of the accelerator every 12.5 nanoseconds. Fast pulse amplifiers can be used in conjunction with the chopping system to produce any spacing which is a multiple of 12.5 nanoseconds. After the first accelerator section (35 MeV) a quarter wave resonant balanced deflector chops beams to 1 nanosecond for SPEAR injection. A second reverse traveling wave deflector is used in conjunction with the upstream deflector to generate 25 or 50 nanosecond spaced single bunch beams.

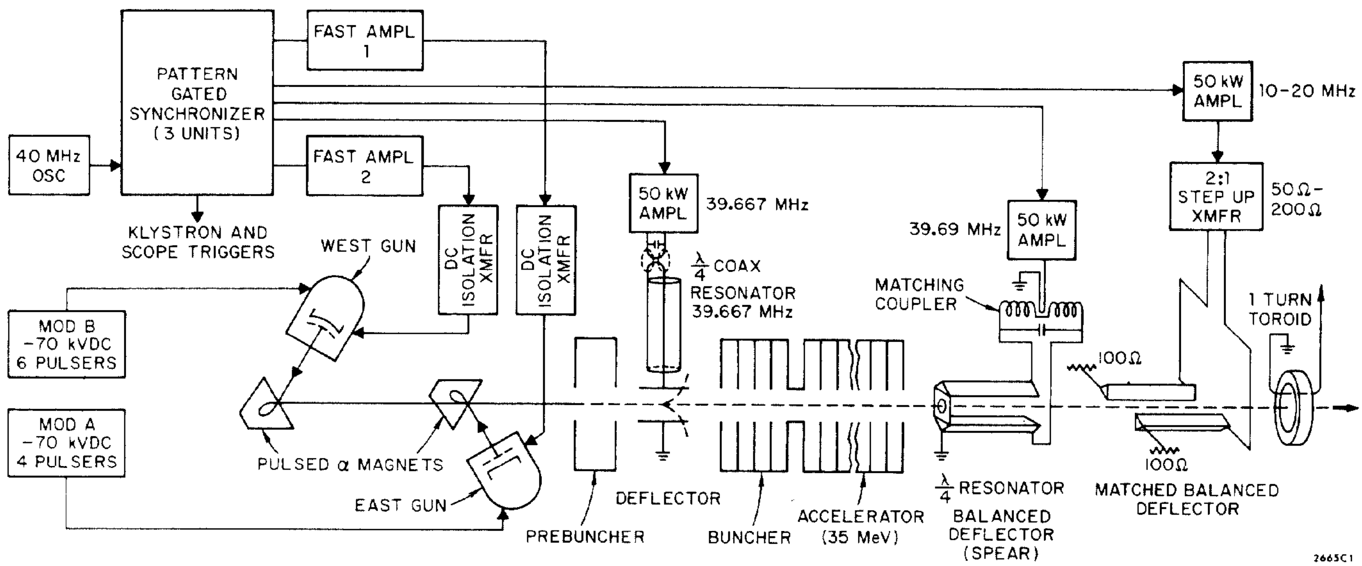

FIG. 1--Elements of fast beam generating system at SLAC.

The machine RF accelerating frequency, 2856 MHz, and the SPEAR cavity accelerating frequency, 358 MHz, provide subharmonics to which the various beam generation systems are synchronized. Synchronization is pattern-gated so that each beam of a multiple-beam complement receives correct synchronization and chopping.

The SLAC Linear Q system[2] displays integrated charge in beams in the machine and switchyard. It is useful for chopped as well as unchopped beams although it becomes marginal for single bunch beams because of the small charge content. Fast monitors capable of reproducing time structure down to 100 picoseconds exist in the machine and switchyard for looking at these single bunch beams.

Beam Generation Equipment

Guns

All electron beams at SLAC, with the exception of the polarized electron source originate in one of two oxide cathode, grid controlled guns. The cathode accelerating potential is - 70 kV dc. Two distinctly different gun designs are now in use. The first design is a wholly SLAC-developed and constructed unit using a spherical cathode and grid with a peak current output of about 1 amp. Grid drive for full output is in the range of 500-1000 volts with a cutoff bias voltage of -50 volts. A number of these guns have been built at SLAC over the last nine years. The design[3] has been computer-analyzed for beam trajectory, perveance, and potential distribution. The oxide cathode in this design is used at moderate current density, less than 1 amp per cm^2, and hence has very long life in the accelerator vacuum system, six months to two years. On the whole it has been a very satisfactory gun design, having experienced only one failure during nine years of machine operation that caused the machine to be shut down for gun repair.

The limited peak current output and large grid drive requirements led us to develop a new gun design for high peak current fast beam pulses. This second design made use of the technology of UHF planar triodes. Both Eimac and Machlett manufacture these tubes in large quantities. Current output of a typical cathode is in excess of 10 amps and the grid-cathode mutual transconductance is 30,000 μmhos. Cutoff voltage is less than -40 volts. Neal Norris at EGG wes being supplied with green cathode-grid assemblies from production runs of these tubes. He had incorporated this structure into a gun design for the EGG accelerator at Santa Barbara. We borrowed the idea and designed our own gun, mounting this structure in our standard ceramic gun enve-lope. We have achieved peak currents in excess of 4 amps with grid drive levels of only 200 volts. Lifetime of the three cathodes we have used on the machine to date has been only two months each, but we expect this to improve as our fabrication methods are perfected. Beam from the new gun

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seems to be contained in a phase space smaller than that of the old gun although computer calculations show similar computed phase space. Beam transmission from the gun to the accelerator input increased from 70% to 90% with the new gun design. With pulsing techniques to be described we have achieved in excess of 2 amps output in a pulse less than 5 nanoseconds full width at half maximum. It is possible to reduce this pulse width even further, but other requirements of multiple beam generation make this difficult. We have accomplished the same end by using a variety of beam chopping techniques.

Grid Pulsers

Normal rise time (30 nanoseconds) conventional length (1.6 μsecond) electron beam pulses are obtained from either gun by pulsing the gun cathode from one of a matrix of six variable height hard tube pulsers mounted on the -70 kV floating deck. The very fast, short pulses are coupled directly to the gun grid through a 100 kV wide band isolation transformer. The fast pulsers are in the injector control room at ground level. The original fast pulser design came to SLAC as a modification of a design used at Santa Barbara accelerator of EGG. Over the last several years at SLAC we have modified this design to make it more stable and long-lived. In the process we did much study of UHF planar triodes, broadband coupling transformers, and interstage matching techniques. We now have a pulser design that can amplify a 10-volt pulse to 1,400 volts driving a 50-ohm load. Pulse width can be as short as 5 nanoseconds. The pulse repetition rate during the 1.6 μsecond accelerating time available from each machine pulse can be as high as 40 MHz.

Each fast amplifier contains 10 UHF planar triodes stages as shown in Fig. 2. Tube lifetime is in excess of

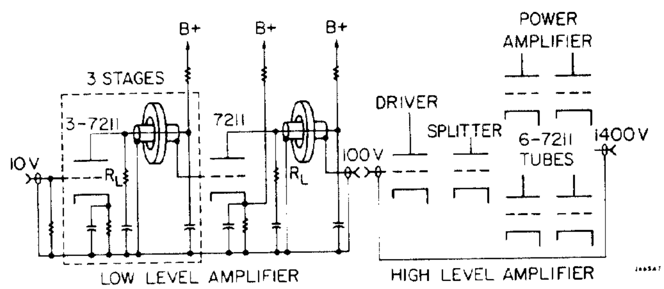


FIG. 2--Fast pulse amplifier.

3000 hours. Although only one tube type is used in the amplifier, distinctly different ranges of operation are used as a function of pulse level. The first three stages operate in a Class A mode which delivers high g_m at low signal levels. The fourth stage does not develop full gain until a minimum pulse amplitude is reached, thereby attenuating baseline noise and small interstage reflections. The last four stages consist of one stage of cutoff biased amplification, a pulse splitter stage, and two stages of parallel high level power driving amplifiers. The plate voltage of the output stage is programmable so the level of the output pulse may be set in accordance with gun current requirements.

The SLAC injector contains two of these amplifier systems. They can drive each gun separately, or both amplifiers can be matrixed onto either of the gun grids for two-channel independent level control. This is the mode normally used for generating SPEAR fill beams. One channel provides an intense electron beam pulse structure for conversion to positrons at the positron source. The other channel provides a more moderate intensity beam for direct electron fill.

Pulse Isolation Transformers

The wideband transmission line type transformer has been discussed in the literature for some years. Two articles, one by C. N. Winningstad[4] and the other by C. L. Ruthroff[5] describe the principles and some embodiments of this class of devices. We will describe here our own designs based on these techniques. First a little review of general principles is in order. Fig. 3 shows a pictorial view of an idealized transmission line inversion transformer.

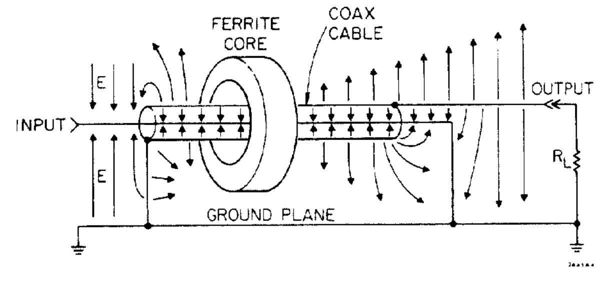


FIG. 3--Transmission line inversion transformer.

Consider the pulse as an electromagnetic wave launched on and retrieved from the transmission line. The entering wave sees two impedances, the coaxial cable impedance Z_0, usually 50 to 95 ohms, plus a complex impedance Z_1 of the space between the ground plane and the outer sheath of the cable which is high and mostly reactive. The input wave divides between these two impedances with most of it entering the cable in the fundamental TEM mode. Once within the cable the pulse is subject only to the normal dispersion and attenuation of the cable itself. A similar situation exists at the output transition. Here, however, the outside of the cable is not grounded, but the center conductor is. This presents a slightly more complex output transition for the wave where the output impedance consists of the real load impedance Z_L in parallel with a complex impedance Z_2 determined by the spatial configuration of the output transition and the impedance of the outside of the cable with respect to the ground plane.

In developing practical transformers two considerations must be kept in mind. To minimize transmission losses Z_0 must be matched to Z_L. Z_1 and Z_2 must be kept large in the active transformer bandwidth. Because these transformers have relatively long signal propagation lengths, care must be taken to reduce mismatches at the input and output transitions to keep portions of the pulse from being reflected back and forth in the transformer, causing unwanted spurious pulses in the output. The design thus focuses on two regions, the high frequency end of the passband where wavelengths in the signal are short with respect to the transformer propagation delay, and the low frequency region where the transformer looks more like a lumped inductance element. In the first region the ferrite core is not necessary for any inductive coupling, but functions as a high dissipative impedance to absorb any portions of the signal that are launched forward on the outside of the cable input or signals that are reflected backward on the outside of the cable output. The geometry of the transitions is carefully designed so that these diversions of the signal are kept to a minimum.

In the low frequency region the ferrite core serves quite another purpose. Here the impedance seen by the input pulse ultimately becomes dominated by the X_L formed by the cable center conductor and the ground plane return. The ferrite must have as high a μ as possible at frequencies up to the point where X_L no longer dominates the input impedance. For most transformer designs this allows the use of high μ, low frequency ferrites. The high frequency losses actually benefit the high frequency response by attenuating reflections. Using this design criterion we have designed a number of high voltage isolation and interstage coupling transformers which can transform pulses as long as 1 μsecond with rise times of less than 1 nanosecond. The high voltage pulse isolation-inversion transformer[5] used to couple fast pulse trains to the gun grid is pictured in Fig. 4. Making use of the dielectric strength of RG 17 cable the transformer can isolate 100 kV dc. The transformer has a 50-ohm impedance and a rise time of 1 nanosecond. Interstage transformers for the fast amplifier are designed in a similar manner.

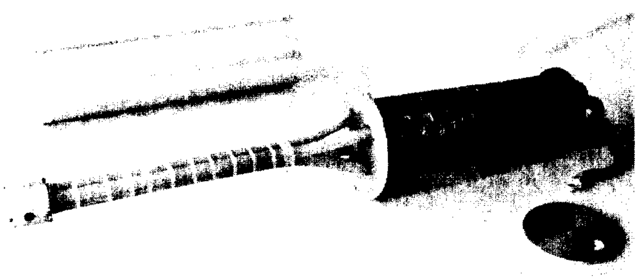


FIG. 4--100 kV dc fast pulse isolation-inversion transformer.

Resonant Choppers

Two resonant chopping systems are used in the SLAC injector. As shown in Fig. 1, the first chopper is located just downstream of the prebuncher. At this point the electron beam is partially bunched, and is still at the -70 kV injection potential. This first chopper is a high power large angle deflector consisting of forked plates 8 cm long with a separation of 2 cm. A scraper aperture located 8 cm downstream at the entrance to the traveling wave buncher serves to eliminate those portions of the deflected beam outside of the accelerator acceptance angle. The resonator attached to this chopper develops a voltage in excess of 50 kV peak RF at the 72nd subharmonic of 2856 MHz, 39.667 MHz. The deflecting fields thus generated are sufficient to dump all electron bunches on the scraper except those passing the deflection plates at zero crossings of the RF. The beam is thus chopped into a series of single electron bunches spaced apart by 12.5 nanoseconds each.

The second resonant deflector shown in Fig. 1 is downstream of the first accelerator section at a point where the beam energy is 35 MeV. Here the beam is fully relativistic so a different deflecting scheme is required. This deflector is a quarter wave resonant balanced stripline device using an external lumped element coupler and inductor to complete the resonator. This deflector is presently being used at a low power to generate 1 nanosecond pulses for SPEAR filling. In this mode it operates at 39.69 MHz, the 31st harmonic of the SPEAR going-around frequency, 1.28 MHz. The fast pulsers previously described inject two 10-nanosecond pulses spaced 800 nanoseconds apart into the accelerator. This deflector system chops them to 1 nanosecond each. The deflector has also been tested at higher power for use as a single bunch chopper. The deflector has sufficient deflecting fields to produce clean single bunches in the machine and without the beam loading effects inherent in the first large angle chopper. In this case there is almost no deflection in the plate region. All the deflected beam is lost in the sector downstream of the plates. The deflecting force of this system is described by the equation

$$\overline{F} = e(\overline{E} + \overline{v}_e \times \overline{B})$$

For a relativistic electron beam and a TEM wave traveling in the same direction, the first term of this equation cancels the second to order $(1 - v_e/c)$, and there is no significant force experienced by the electron beam. If the TEM wave is traveling opposite to the direction of the beam the two terms add and a transverse deflecting force is experienced. Where $\overline{E}$ and $\overline{B}$ are sinusoids as exist in a resonant system the maximum total deflection is experienced when the beam sees a rise in the $\overline{E}$ field of the reverse wave from zero to peak and back to zero as it transits the deflecting region. Because the electron and the wave are traveling in opposite directions at c, this complete cycle takes place in one quarter wavelength of the deflecting RF. This dictates a maximum length of $\lambda/4$ for the deflecting line. Since only the reverse traveling wave couples to the beam, the fact that the deflector is resonant with a matching forward wave present does not detract from the deflection process.

Nonresonant Chopper

A second set of deflector plates is immediately downstream of the resonant deflector just described. The same reverse traveling wave is used for deflection except that the RF is used only once and then dissipated in load resistors at the upstream end of the deflector. This system is useful for beam chopping at any frequency from 5 MHz to 25 MHz but the chopping strength is much less than the resonant system, about 4 nanoseconds at maximum power. This deflector is normally used in conjunction with the upstream deflector to chop the 12.5 nanosecond periodicity into either 25 nanosecond or 50 nanosecond periods by eliminating unwanted bunches.

Synchronization System

The SLAC machine normally operates at 360 pulses per second. These 360 pulses can be allocated to as many as eight experimenters each with different beam requirements. Thus, most beam handling devices on the machine, and particularly in the injector where various beam profiles originate, are programmable on a pulse-to-pulse basis. Where a particular experimental beam profile calls for beam chopping, the need arises to synchronize the machine klystron pulses to a time reference derived from the chopping RF. This RF can be derived from either the accelerator frequency or the SPEAR cavity frequency. In the latter case, SPEAR sends down the machine drive line a complex signal consisting of a pretrigger pulse for synchronization followed by two beam trigger pulses spaced 800 nanoseconds apart which after ampliciation in the fast amplifiers drive the gun grid directly. Superimposed on this signal but at a level 10 dB down from it is a 10 μsecond RF envelope at 39.69 MHz. This signal is recovered and used to drive the SPEAR chopper amplifier previously discussed.

The machine trigger system derives its rough 360 pps timing by sensing zero crossings of the three-phase ac power line. The triggers thus generated form the early pretrigger system used to start various machine equipment needing long pretrigger times. The pretrigger is delayed by 1 millisecond in a magnetostrictive delay line and then goes to the trigger synchronizer electronics in the injector. The synchronizer is a special electronic system having four pattern gated synchronization modes. The heart of the synchronizer is shown in Fig. 5. Gate A combines the machine trigger (1) and the synchronizing RF (2) to form a gated RF signal whose leading edge may be determined by either input. One Shot C triggers on the trailing edge of this gated RF forming a long pulse whose leading edge is stable with respect to the synchronizing RF in all cases except when there is a coincidence between the leading edge of (1) and a trailing edge of (2). In this case a variable height pulse is produced which makes the triggering of C unstable. This ambiguity is resolved by delaying the RF (2) through a gate B and delay D and "anding" it in gate E with the output of the one shot C. This produces a train of pulses whose initial leading edge is always stable with respect to the synchronizing RF. The one shot F converts this into a single RF synchronized trigger pulse which is returned to the

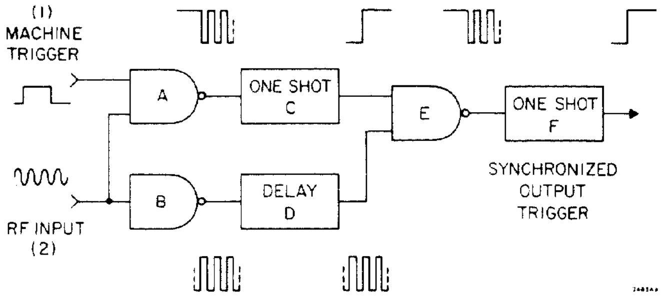


FIG. 5--Trigger synchronizer.

master trigger generator for distribution along the machine. Patterns gate in appropriate synchronization on a pulse-to-pulse basis. In the absence of any pattern input the input trigger is returned to the master trigger generator with a fixed 25 μsecond delay. All scopes, klystrons, gun pulses, and other prompt trigger devices on the machine are triggered from this unit.

Fast Beam Monitors

When we are chopping beams it is essential to know whether we have achieved single bunch injection into the machine, or whether there are small residual satellite bunches adjacent to the main bunches. This calls for a monitor that has a time resolution of 100 picoseconds. We have found that the Tektronix IS2 sampling plug-in with a resolution of 100 picoseconds is adequate for our viewing needs. The two main design problems then are to construct a beam monitor capable of extracting wideband information from the beam, and then transmitting this information out of the radiation area to a location where the sampling scope can be set up. A simple ceramic gap in the beam line, Fig. 6, propagates a wide band of information outward, the high

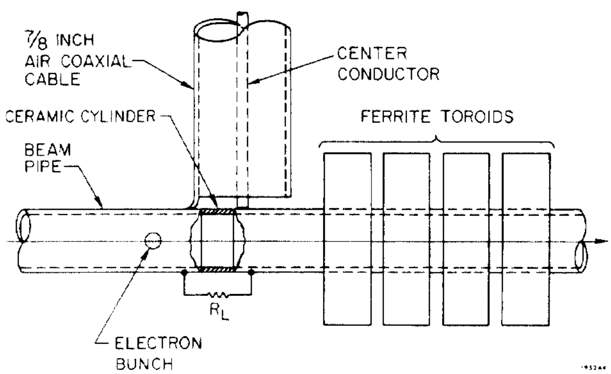
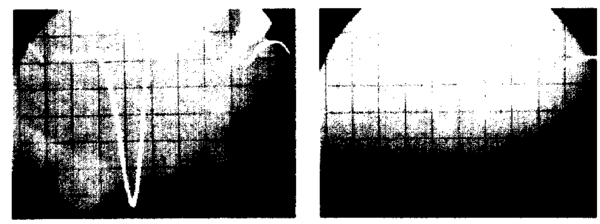


FIG. 6--Nonintercepting fast beam pickup.

frequency limit being the gap capacity. Appropriate resistance loading can make this RC time constant less than 100 picoseconds. The low frequency response is determined by the inductance of the accelerator beam pipe downstream of the gap. This can be made relatively high by loading the pipe with ferrite. A tight coupled air dielectric cable connected to the gap picks up a portion of the radiated signal. What little signal does not enter the cable radiates away or is dissipated in the ferrite loading downstream.

The signal is transmitted from the pickup to the sampling scope in the Klystron Gallery above the radiation shielding through about 75 feet of 7/8 inch Spiroline semirigid cable. This cable has an attenuation of 1 dB per hundred feet at 3 GHz, and so can transmit a signal with 100 picosecond rise time through this distance with little degradation. Fig. 7 shows two pictures of a single bunch chopped



200 psec/cm (SINGLE BUNCH) 200 psec/cm (TWO BUNCHES)

FIG. 7--Sector 10 fast pickup sampling scope display.

beam, one with the chopper properly phased to produce a single bunch, and the other misphased to produce two bunches in the machine. The horizontal and vertical scan outputs of the sampling scope are very low frequency signals, less than 100 Hz. Thus the sampling scope can be positioned close to the beam housing at an appropriate place in the machine and the resulting video information can be transmitted to control rooms and experimental areas via twisted wire pairs. Our fastest monitor is located at the one-third point of the machine and the resulting sampled signal is distributed all over the control and experimental areas.

Conclusion

Work proceeds on optimizing both fast beam generation and monitoring devices for SLAC. The present complement of equipment can produce almost any mix of chopped and single bunch beams for experimenters with a high degree of multiple beam compatibility. Work on new systems to make operation better and more flexible will continue.

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