THE SPEAR INJECTOR RF GUN AND LINAC PERFORMACE*

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Abstract

In light of the SPEAR3 upgrade project where the goal is to store up to 500 mA of beam current at 3.0 GeV beam energy, the injector RF gun and linac performance must be optimised in terms of reliability and injection rate. The basic linac system layout has not been changed for the last ten years of operation. A thermionic1.5-cell standing wave RF gun is the source of bunched beams at 10 Hz. An alpha magnet then compresses the bunch length to a few picosecond, and a travelling-wave beam chopper then allows only 3 or 4 bunches to reach the linac near the end of the RF pulse. This way the beam loading to the linac is minimized and the linac beam to the Booster synchrotron reaches the maximum energy. Some improvements were made over the past few years to achieve the system reliability and stability. The original three klystrons were replaced by one high-power tube. The modulator is presently charged by a switching power supply. The drive amplifier feeding the klystron was based on thermionic triodes; it is a solid-state amplifier now. The gun cathode assembly underwent several iterations. Some feedback controls stabilise the linac beam energy as needed. In this paper we describe the modifications mentioned above, the present status, and the plans for the future.

1 INTRODUCTION

The SPEAR (Stanford Positron Electron Asymmetric Ring) stores up to 100 mA of beam current to deliver hard X-rays for our users. The injector consists of a thermionic RF gun followed by a 3-section linac operating at 2.856 GHz, pulsed at 10 hertz. This linac beam is boosted to a 2.3-GeV energy by the booster synchrotron running at 358.54 MHz. Once stored in the SPEAR ring, the beam is ramped up to a 3.0-GeV energy.

The SPEAR3 upgrade calls for injection at 3.0 GeV but the linac parameters will remain unchanged in terms of energy, number of bunches per macro-pulse, and the charge per bunch. So far the injection rate was up to some 20 mA/min at 2.3 GeV. Since the upgraded system will store up to 500 mA (up from 100 mA) at 3.0 GeV, the fill time tends to be longer especially after the beam loss. Since the reinforced booster will deliver the beams at 3.0 GeV, some timesaving will be made by not having to ramp the beam energy. Unless the stored beam is lost as a result of some system trip, each injection only need to replenish the beam decay. For example, if the Spear beam has 18-hour lifetime and there are two injections per day, the beam left over at the end of a 12-hour period is 300 mA. The subsequent injection will take (500-300) mA /R = 10 minutes, where the injection rate R is 20 mA/min. In order to maintain high injection rate, the gun and linac must perform reliably with excellent stability. In addition to the shot-to-shot reproducibility, the service life of all the replaceable components must be at least one year or longer so that any unscheduled maintenance is not needed until the annual shutdown. There are 6 major subsystems in the injector linac. They are thermionic standing wave RF gun, alpha magnet, travelling wave chopper, three 10-foot linac sections, one klystron, and a modulator. In this section, alpha magnet and chopper will not be discussed. Some other topics such as transport line and beam dump are also beyond the scope of this paper. Reference to the distribution of rf power and phasing can be found elsewhere [1].

2 RF GUN

The thermionic rf gun was first designed and built by Varian in late eighties [2]. After its successful operation, a number of copies were fabricated with slightly different parameters. One of them has been in service for the last ten years at Spear injector. It takes about 2 MW RF power to produce some 3000 bunches with energies up to 2 MeV over a microsecond pulse length. Unlike a dc gun there is no need for a buncher, resulting in a compact system.

RF Gun Parameters

There are a limited number of thermionic RF guns ever built and used. There are minor differences in geometric dimensions as well as electrical parameters. The Spear RF gun characteristics are listed in the Table below.

Table1. RF gun characteristics

Quantity	Value	Remarks
Frequency	2856.0 MHz	38^{o}C, vacuum
R_S (= V^2/P)	10 MΩ	shunt impedance
Q	14000	unloaded
β	4.2	coupling

The gun body is so stable that those numbers shown above are rarely checked during the normal operation. They are given here for the purpose of future reference in case a new design is considered for an upgrade.

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Dispenser Cathode

The cathode in the gun half-cell is a type M dispenser cathode. Before its installation in the gun, the cathode is heated to 1050°C for about 4 hours in a vacuum chamber for chemical conversion of the coating. This prepares the surface for good emission. Thermal processing is required only once during its service life unless it is exposed to a bad vacuum and chemically contaminated. Unlike a TWT (travelling-wave tube) for which a cathode was originally made, the RF gun produces substantially strong beam that is accelerated toward the cathode since the time-varying field reverses in half-period. This "back bombardment" causes shorter life time of the cathode. Each used cathode taken out of the gun exhibits an elliptic area of cracked surface between its center and the periphery of 0.25-inch diameter emitting surface.

The cracked spot created by overheating from the back-bombardment tends to be worse in case of bad vacuum. It is possible that the beam (forward or backward) creates plasma, from which the ions strike the surface leading to its poisoning. As barium leaks out through the crack, the cathode loses electron emission rapidly. In this case a feedback control can restore beam intensity and stability for a short period of time (up to a month or so).

Feedback Control

There are two gun current toroids (GT1 and GT2) that provide input parameters to the computer to control the heater power supply (PS) as shown in the Fig. 1 below.

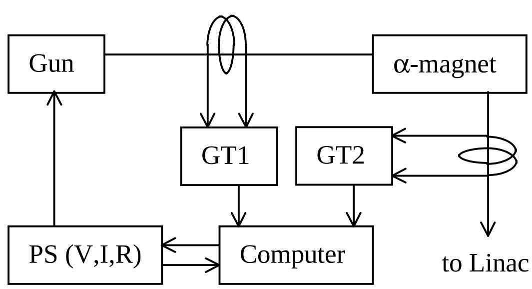

Fig. 1 Gun feedback control block diagram.

Two high-speed (80 MS/s) analog-to-digital converters (ADC) run simultaneously and continuously to read GT1 and GT2. Only a part of the waveform near the chopper pulse (downstream of the α-magnet) is digitally averaged over a number of 10 Hz pulses as determined by the software. Since the beam bunches outside of this window are dumped to the chopper load, they are irrelevant. The computer then controls the power supply (PS) to correct the voltage, current, or cathode heater resistance. The PS is normally voltage regulated without computer. When the cathode temperature fluctuation is suspected (there is no direct temperature monitoring) the PS is run by computer to make it "load-resistance regulated." A robust cathode without heater feedback control performs better than a bad cathode on feedback control.

Heat Dam and RF Short

The cathode temperature is about 1000°C when it emits. Its thermal radiation heats up the half-cell wall near the axis, leading to a detuning. To shield out thermal radiation the original heat dam was made of a ceramic. Later it was replaced by Hastelloy® for better vacuum. It has thermal property similar to a stainless steel that lowers Q value and shunt impedance. For this reason it is copper plated at the front that feels the RF wave.

A narrow gap between the cathode and heat dam gives a good thermal insulation for the cathode to reach emitting temperature. In this arrangement, however, the cathode acts like a center conductor of a coaxial cable allowing the high power RF to leak into the backside of the assembly. This may cause damage to the structure by arcing and/or deform the cathode holder, leading to a detuning. A toroid formed from a helix of thin tungsten wire is inserted from the back to shield out any RF leakage. This toroid also conducts away the heat and cools down the cathode. Therefore there is an optimal number of poloidal turns in the helix that satisfies thermal and electrical requirements. We arrived at 18 turns from the past experience.

3. LINAC SYSTEM

Three or four bunches of electron beam enter the first linac section at about 2 MeV. They are compressed at the alpha magnet and selected by the chopper. All of three linac sections, as well as the gun, are powered by a single klystron. Unlike a multi-klystron arrangement where the beam energy is stabilized by phase feedback control at the low-level RF, the injector linac relies on power saturation and voltage regulation. In this section we will discuss each subsystem that was upgraded.

Solid-State Driver

Until FY2000 a triode-based amplifier produced up to 500 watts input power to the klystron. Starting at 10 mW from a master oscillator, a preamplifier at 2 W is followed by a 3-stage triode tubes. Each stage is housed in a tuned cavity. Like other thermionic devices, the driver's power level declines over time. It was decided to build two units of solid-state amplifier to be cost effective on a long term.

There are pulsed high power S-band transistor modules commercially available for radar applications. The output power is 5 to 240 watts at the pulse length up to 100 μS. The drive amplifier has six 240-watt modules at the output stage. The combined power is in excess of 1 kilowatt. Although 500 W is sufficient for a SLAC 5045 injector klystron, the two XK-5 klystrons used at GTF (Gun Test Facility for photocathode RF gun R&D) require much higher power. The GTF driver is a hot spare for injector. Without a cathode to deplete over time, the solid-state driver rarely needs maintenance or refurbishment.

Switching Power Supply for Modulator

At 10 Hz repetition rate the injector modulator charging supply needs only 6 kJ/s capacity. During the last several years the switching power supplies at high voltage have been commercially available. At 25 kV rating, the voltage regulation is better than 0.01%. The klystron beam current is proportional to $V^{3/2}$ and beam power to $V^{5/2}$. The linac energy depends on the klystron beam voltage, which is set by the capacitor charging supply voltage, by $V^{5/4}$ if the efficiency is constant. At 0.01% regulation, the linac beam at 100 MV has energy stability of ~13 keV, which is well within the acceptable range of $\pm$0.1 MeV.

RF & Beam Diagnostics

Unlike the Spear storage ring where all the RF data are logged every 2 seconds, the linac system at 10 Hz requires additional consideration for data acquisition and storage to monitor the long-term drift. A simple solution is S&H in analog fashion. This was rejected because the clock is not adequately precise to determine the sampling window of less than 1 μS in every 100 mS. A better scheme is to use a high throughput (~100 MS/s) ADC controlled by micro-processor. All the salient aspect of the pulsed signal is summarised by the processor’s computation. The results are logged at much less than 10 data per second. By using the self-contained DAC the system can feedback control hardware components, and act as an elaborate interlock. A study is underway to set up a prototype module and test the concept.

4. INJECTOR OPERATION

As mentioned earlier, the upgraded Spear3 commissioning in 2003 [3] calls for improved injector performance. System stability is one aspect of it, fast recovery from failure is the other. In this section we discuss klystron saturation for the former, then vacuum and RF power handling for the latter.

Klystron Saturation

Assuming that the klystron beam power is steady, the klystron power gain is a constant at low power regime. As the driver power is increased, the gain is reduced. At some drive power level, the slope of the P(out) vs. P(in) gain curve is essentially zero. In the vicinity of this drive power level, the klystron output power is practically fixed. Then small fluctuation in drive power doesn’t degrade the stability of RF power to the linac, which translates into the beam energy stability. The klystron is saturated. If the drive power is raised further, the klystron output power begins to decrease.

If gain curves are plotted on one frame at equal beam voltage intervals, the spacing between the curves is about the same. There is no way of stabilising the klystron RF power in the presence of the beam voltage fluctuation. As the beam voltage is raised, as it is required to produce higher RF power, the drive power for klystron saturation goes down, perhaps due to the increase in efficiency. One can find the drive power at which the klystron saturates as follows. Set the charging supply voltage fixed. Then continuously increase the drive power. The klystron is saturated when its output power begins to decrease.

Waveguide Vacuum

Whenever the waveguide is vented to dry nitrogen, it must be high-power processed after restoring the vacuum. If the gun was opened up to replace the cathode, it must be baked for about 24 hours. The RF loads, especially Kanthal loads, outgas more after the pumping down and during the RF processing. Spear injector has eight loads: 3 at the linac sections, the rest at the waveguide network. In 1997 four SiC loads replaced old Kanthal types. This year we will replace two more. The remaining two Kanthal loads will be isolated by ceramic window. The space beyond the window is to be kept in vacuum at all times. The SiC load outgassing is much lower than Kanthal type in the same circumstance. The new arrangement will reduce pumping time. It is important when unscheduled maintenance is needed in the middle of the user run since shorter recovery provides more beam time for the users.

High-Power Processing

The high-power processing of the gun, linac, and the waveguide network is to bring up the system to the full power in the shortest possible time. One conventional way is to increase the RF power gradually at the full pulse length. A better method used at the injector is to increase the pulse length. The modulator is charged up for full power operation. Delay the drive power pulse until the modulator pulse is completely over. Decrease the driver pulse by 0.01 μS at a time. The overlap of the two pulses in time goes up, and the klystron RF power increases in pulse width and amplitude. When the two have complete overlap, then processing is over and the system is up to a full power operation. The process takes about 2 hours compared to more than 8 hours by old method.

5. ACKNOWLEDGEMENT

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