# BOOSTER SYNCHROTRON RF SYSTEM UPGRADE FOR SPEAR3*

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*Abstract*

Recent progress at the SPEAR3 includes the increase in stored current from 100 mA to 200 mA and top-off injection to allow beamlines to stay open during injection. Presently the booster injects 3.0 GeV beam to SPEAR3 three times a day. The stored beam decays to about 150 mA between the injections.

The growing user demands are to increase the stored current to the design value of 500 mA, and to maintain it at a constant value within a percent or so. To achieve this goal the booster must inject once every few minutes. For improved injection efficiency, all RF systems at the linac, booster and SPEAR3 need to be phase-locked. The present booster RF system is basically a copy of the SPEAR2 RF system with 358.5 MHz and 40 kW peak RF power driving a 5-cell RF cavity for 1.0 MV gap voltage. These requirements entail a booster RF system upgrade to a scaled down version of the SPEAR3 RF system of 476.3 MHz with 1.2 MW cw klystron output power capabilities.

We will analyze each subsystem option for their merits within budgetary and geometric space constraints. A substantial portion of the system will come from the decommissioned PEP-II RF stations.

## INTRODUCTION

The SSRL Booster was commissioned in December 1990. The injector linac system has a thermionic cathode 1.5-cell RF gun, an alpha magnet, a travelling wave chopper and three sections of 10-foot S-band linac sections. It was initially powered by three XK-5 klystrons. From 1997 one SLAC 5045 klystron powered the entire injector linac system that produced 3~5 electron bunches at a nominal 120 MeV beam energy. The repetition rate was, and still is, 10 pulses per second to match the Booster White Circuit.

The Booster RF system[1] is a copy of SPEAR2. Both systems were phase-locked at 358.54 MHz. The harmonic numbers were 280 at SPEAR and 160 at Booster for the circumference ratio 7 to 4. The 3~5 linac bunches are coalesced into a single Booster bunch, boosted in energy from 0.12 to 2.3 GeV, and then injected to the SPEAR2 storage ring, where the beam energy was ramped up to 3.0 GeV. The RF station has a 5-cell standing wave cavity and a PEP-I type klystron operating at 358.54 MHz and rated at about 500-kW maximum cw RF power.

Since the SPEAR3 was commissioned in January 2003, the Booster injected to SPEAR3 at 3.0 GeV. While the system upgrade was extensive in the SPEAR3 RF, the Booster RF system remains unchanged for the last 20 years; even the original klystron stays in service to date.

The 358.516 MHz for Booster RF power is derived from the 476.314 MHz for the SPEAR3 RF through $\div 93\times 7\times 2\times 5$. To align the Booster RF bucket to the targeted SPEAR bucket N, the Booster RF reference signal $\cos(\omega_{RF}t)$ is I/Q modulated to $\cos(\omega_{RF}t+\phi_m(t))$, $\phi_m(t)=\int\omega_m dt=2\pi N$, $\omega_m/2\pi=$ 13 kHz where the range of integer N is $-185 \le N \le 186$, and is the number of cycles sent to the I/Q modulator to advance or delay the Booster RF phase. It coves the entire 372 buckets of SPEAR3. This modulation is done after the Booster beam is ejected to SPEAR3 and the klystron output power is at its minimum and thus the reflected RF power has minimal effect to the klystron.

## EXISTING BOOSTER RF SYSTEM

The existing Booster RF system consists of a klystron, a HV power supply, a 5-cell standing wave cavity and low-level RF system. The cavity RF coupling and the WR-2100 size waveguide network are configured in such a way that the RF power reflection from the cavity is minimal and thus there is no circulator. The details of each subsystem are as follows.

The klystron is a PEP-I type running at SPEAR2 358.516 MHz, which is within the design bandwidth of (358.54 ± 0.1) MHz. The parameters are shown below:

Table 1: Booster RF Klystron Performance

| | | | | | |
|---|---|---|---|---|---|
| Beam Voltage | 37.6 | 50.0 | 60.0 | 63.0 | kV |
| Beam Current | 5.80 | 8.52 | 11.02 | 11.80 | A |
| RF Power | 40.0 | 210 | 361 | 424 | kW |
| Efficiency | 18.3 | 49.3 | 54.6 | 57.0 | % |
| μperveance | 0.796 | 0.762 | 0.750 | 0.746 | μperv |
| Gain | 36.0 | 41.7 | 43.4 | 44.0 | dB |

At the Booster RF station, the operating beam voltage is fixed at 37.6 kV. While the gain and efficiency are much lower than the design values at higher beam voltage, the klystron still provides sufficient peak RF power to the cavity for it to deliver enough peak gap voltage for the Booster beam energy ramp from 0.120 to 3.00 GeV.

The test data listed in Table 1 above at the higher beam voltages have been taken at the SLAC Klystron Test Lab in 1986 when the klystron was built there.

The RF cavity is a PEP-I type, 5-cell, standing wave cavity modified for SPEAR-2 operation at 358.54 MHz. It is made of aluminum, has a loop-coupled RF power input, and two movable tuners: one at cell #1 and the other at cell #5. Common mode positioning of the two tuners are controlled to bring the cavity to the RF resonance, their differential movements are to maintain the gap voltage

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balance among the five cells. The RF cavity parameters are shown below.

Table 2: Booster RF Cavity Characteristics

| | | |
|---|---|---|
| Frequency | 358.54 | MHz |
| Shunt Impedance | 25.6 | MΩ ($V_g^2/P_{rf}$) |
| Maximum RF Power | 125 | kW, cw |
| Coupling β | 1.2 | $\beta_{opt} = 1 + P_b/P_c$ |

The RF power is fed to the cavity through a waveguide-to-coax transition. Connected to the inner conductor is a loop coupler at the center cell of the cavity. Depending on the beam loading, the coupling is adjusted by changing the loop orientation with respect to the cavity axis. At the Booster cavity beam loading is small enough to be safely ignored. Since the cavity material is aluminum, it is important to prevent the multipactoring by coating the cavity surface with 10 to 100 nm layer of titanium nitride.

Between the cells the RF power is coupled through the two azimuthal slots in the common-end walls of the cells. For the gap voltage and RF phase control, each cell has an RF pickup loop with 53 dB coupling. The two movable tuners are driven by the phase-lock loops.

The HV power supply for the klystron is a conventional step-up transformer with output voltage-setting taps at the primary and a 6-phase full-wave rectifier assembly with RC- and LC-filtering at the output. The specifications are

Table 3: Booster Klystron HV PS Specifications

| | | | |
|---|---|---|---|
| Output Voltage | -47 | kV | Max. |
| Output Current | 7.0 | A | Max. |
| Primary Voltage | 480 | V | L/L, 3-phase Delta |
| Primary Current | 410 | A | Max. each phase |
| Secondary | 47 | kV | Wye/Delta in series |
| Filters | 15kΩ/30nF | | Across Wye and Delta |
| | 1.0H/0.47μF | | Across HV & ground |
| Voltage Ripple | 0.5 | % | Max. |

The HV output voltage tracks the line voltage without voltage or current regulation, but the LLRF controls the RF output power from the klystron.

When the HVPS is turned on, the primary current is limited by a set of 0.3-Ω resistors for one second, then the Main circuit breaker closes shorting out the resistors. This circuit serves to limit excessive in-rush current.

In the event that any interlock trips and the HVPS is disabled, the energy stored in the filtering capacitor and the HV cable is dumped by crowbar, protecting the klystron from over-current possibly from an arcing.

The low-level RF is entirely an analog system except the gap voltage setpoint, which is set by a computer-controlled function generator. The computer reads in the bending magnets current as the measure of the beam energy. Then it sets the gap voltage that accounts for the beam energy loss due to the synchrotron radiation and the accelerating field needed for the beam energy. Figure 1 below shows the control panel used for set-up of the gap voltage waveform.

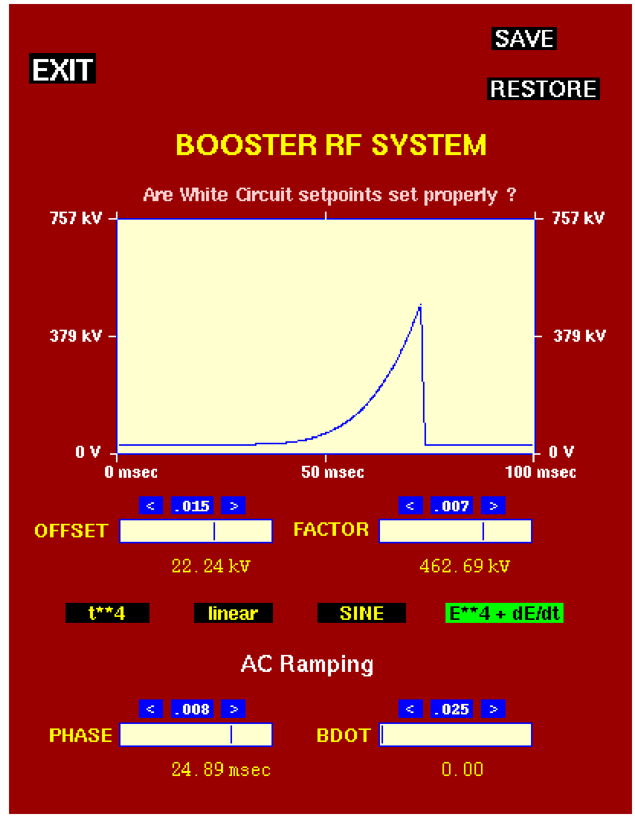


Figure 1: Booster RF gap voltage waveform control page.

In the figure above, *OFFSET* determines the gap voltage while there is no beam in the Booster. The gap voltage may be very small, but it must be high enough to let the LLRF phase control loops stay closed, and *FACTOR* sets the margin, or over-voltage factor. The *PHASE* is a time delay from the Booster cycle initiation to the bunch energy ramping. Out of the four available waveforms, *E**4+dE/dt* is commonly used. The first term indicates the compensation for the energy loss due to synchrotron radiation, and *dE/dt* term represents the energy ramping. *BDOT* is for the beam energy calculation but presently it is not implemented.

## NEED FOR CHANGES IN BOOSTER

Since the commissioning of SPEAR3 in 2003, many resources have been allocated to the Booster improvement in stability and reliability. As a result the injection rate is presently about 30 mA/min, so it would take less than 10 minutes to fill SPEAR3 from zero to 200 mA. As long as the existing travelling-wave chopper is in service, only one Booster bunch can be accelerated at a time over a 100-ms period. If a train of many bunches are to be stored and accelerated simultaneously and injected to SPEAR3 filling as many buckets, the 358MHz RF system is a limiting factor.

In order to realize multi-bunch injection, the Booster and SPEAR3 must use the same RF frequency phase-locked to each other, which entails one of the following:

*Change the Booster circumference by -36 or +27 cm
*Change the Booster frequency to 475.04 or 477.28 MHz
*Change both frequencies to 475.04 MHz and keep the Booster circumference unchanged.

There are complexities in LLRF control and in tuning the cavity or klystron in the frequency change options. If the circumference is to be changed, it also will be a quite involved alignment procedure.

In response the Booster RF system must be modified to accommodate the changes. It is assumed that most, if not all, PEP-II RF subsystems are available for use at Booster. The issues to be addressed here are:

* Compatibility in space requirements
* Availability of budget and technical support
* Tests of each subsystem at low and high power.

The most demanding is the space restrictions for the cavity installation. The existing 5-cell cavity takes up about 262 cm of longitudinal space, whereas two single-cell PEP-II cavities occupy 345 cm. A PEP-II type circulator, if used, can be is installed on a frame over the klystron so it does not add much to the footprint on the floor. The existing klystron sits on a support frame that measures 244 cm square, for an example.

## PEP-II FOR BOOSTER RF UPGRADE

At the 358.516 MHz Booster cavity, the klystron output forward power of 40 kW sets up 1.0 MV gap voltage, which must be provided by the new RF system at the 476 MHz. Since the Booster beam current will be no higher than 1 mA (20 bunches of 50 μA), the higher order modes can be safely ignored. Therefore the HOM loads employed by the PEP-II cavities[2] may be removed, and the drift tube can also be taken out making the cavity's longitudinal size that much smaller. Another aspect of the PEP-II cavity is that the coupling factor $\beta$ is set high in order to drive high stored current, in excess of 1 A at the Low Energy Ring. With $\beta = 3.6$, and no stored current, one SPEAR3 cavity takes 48 kW forward power, out of which 16 kW is reflected to produce 0.5 MV gap voltage. For a two cavity system powered by one klystron, it takes 96 kW klystron forward power for 1.0 MV total gap voltage, the same value the existing Booster cavity reaches at its peak. The HV PS must supply 12.5 A to the klystron at 54 kV as seen from the SPEAR3 data. In this case the klystron efficiency is about 14%.

If the entire SPEAR3 RF system is reproduced at the Booster, the set of four single-cell cavities require about 25 kW of klystron power to reach 1.0 MV total gap voltage. The total reflected power would be about 8 kW. Again, the efficiency is quite low and all high-power subsystems will be under-utilized.

## CONCLUSION AND ALTERNATIVES

To optimize the Booster RF system performance and requirements for HV power supply and klystron, total cavity shunt impedance must be maximized. The coupling factor $\beta$ at the cavities must be adjusted to a value slightly larger than one to minimize the reflected power. Then the longitudinal size of the cavity assembly must be made smaller for the restricted space.

Scaling down in frequency of an L-band 5-cell standing wave structure[3] can also be explored. Such a structure has been designed and cold-tested at SLAC. If feasible, it will provide much lower requirement in RF power and make the system installation simpler.

For the high-power RF source, the baseline PEP-II klystron can generate up to 1.2 MW cw. Since the required RF power at the Booster is a few tens of kW, one option is a solid-state amplifier assembly[4]. If employed, there is no need for the large PEP-II klystron, HV PS or circulator: 50 V power supply drives all the amplifier modules. Each has its own circulator built-in. Another advantage is a long service life. Unlike the klystron, there is no need to keep a complete system as a spare: Only 10 or 20% of total modules need to be kept as spares, and each module can be serviced independently.

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