# SPEAR3 BOOSTER RF SYSTEM UPGRADE: PERFORMANCE REQUIREMENTS AND EVALUATION OF RESOURCES*

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## *Abstract*

The SPEAR2 accelerator system originally had 3 RF stations (2 for storage ring, 1 Booster) operating at 358.5 MHz. SPEAR3 now operates at 476.3 MHz with the PEP-II type RF system, while the Booster RF frequency remains unchanged. For top-off operation, the Booster injects single 3.0 GeV electron bunches into SPEAR3 at 10 Hz every 5 minutes to replenish lost charge. Due to the frequency mismatch between SPEAR3 and the Booster, only one SPEAR3 bucket can injected per shot limiting injection rate and overall system flexibility. The aging high-power RF subsystems of the Booster pose a reliability issue as well. In order to remove these constraints, studies are underway to replace the Booster RF system using the PEP-II type RF system as a baseline. The new Booster RF system will be tuned to 475.036 MHz, and phase-locked to the SPEAR3 RF system. The project calls for ramping the Booster cavity gap voltage to 0.80 MV at 10 Hz, each with a 40 ms acceleration interval. With very low beam loading and low average RF power, there are many subsystems that can be operationally simplified. In this paper we present the results of analysis leading to a new Booster RF system.

## INTRODUCTION

The dedicated 3.0 GeV SSRL injector synchrotron, or Booster, started its operation in November 1990 [1] [2]. Its RF system shared the same RF source with, and phase-locked to, SPEAR2 at 358.54 MHz. While there were 2 RF stations – one in operation and the other idle – at the storage ring, the Booster had one RF station to ramp up the 120 MeV linac beam to 3.0 GeV for injection to the storage ring. At each of the three stations one klystron powered one 5-cell cavity of the SLAC PEP-I style. SPEAR2 and Booster ring circumference ratio was 7 to 4 with 280 and 160 RF buckets each.

In March 2004 the newly commissioned SPEAR3 started user service. Its RF system is a close copy of the PEP-II high-energy ring RF station where one klystron rated at the maximum RF power of 1.2 MW drives a set of four single-cell cavities for up to 3.2 MV gap voltage. A 2.5 MW rated DC high-voltage power supply is the source of the klystron beam power.

When SPEAR2 was upgraded to a third generation light source, the RF frequency $f_S$ was set at 476.316 MHz with the harmonic number of 372 so that the beam circumference and thus the beamline positions remain unchanged, allowing a savings in construction cost and schedule.

While the SPEAR3 storage ring underwent an upgrade there were no basic changes made to the RF gun, Linac or Booster synchrotron. Phase-locked to SPEAR3, with its beam circumference unchanged, the new Booster RF frequency was set at $f_S*280/372 = 358.517$ MHz. One Booster bunch is thus injected to one target SPEAR3 bucket by a programmed RF phase-shift in the Booster, which is derived from SPEAR3 RF master oscillator [3].

## OPERATIONAL CONSIDERATIONS

From November 1990 through May 2010 the Booster injected every 8 hours to SPEAR2, or every 6 hours to SPEAR3. During this period the 500-kW rated booster klystron was turned on for about 2 hours a day at a reduced output power of 33 kW. Since June 2010 the Booster injection was increased to every 5 or 10 minutes in top-off mode to maintain the SPEAR3 stored current within 1% of the authorized maximum current.

Since the RF gap voltage must match the energy of the beam, the gap voltage set points are computed from $E^4 + dE/dt +$ offset, where $E$ is the Booster beam energy. The first 2 terms counter the synchrotron radiation and provide the beam acceleration, and the offset is to keep the system tuned, as well as to maintain the RF acceptance for the incoming linac beam. The RF power over the 100 millisecond duration of the 10 Hz injector cycle is shown in Figure 1 below.

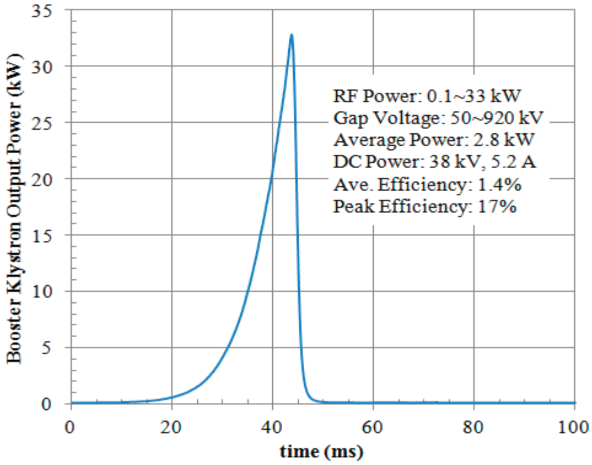

Figure 1: Booster klystron output power waveform.

For top-off, the injector White Circuit is turned on for about 45 seconds before the scheduled injection, and turned off once injection is complete. Since the RF power waveform is linked to the White Circuit, the klystron generates about 0.1 kW at all times as set by the "offset" value.

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The linac klystrons for the thermionic cathode RF gun and the three linac sections also stay on at all times. Their RF pulse length is about 2.5 μs. However, among the ~3000 S-band bunches out of the gun only 3~4 bunches pass the beam chopper before the linac every 100 ms Booster cycle.

### *Reliability Issues*

As mentioned earlier the Booster klystrons and most of the RF subsystems are more than 20 years old. The klystrons were designed and built by SLAC and are not commercially available. There are 2 RF high voltage power supplies rated at 47 kV, 7.0 A. Their output voltage can be reduced down to 37.6kV in 5% steps by changing the taps at the 480 volt 3 phase primary. Once the output voltage is set, however, the actual output voltage tracks the line voltage: There is no active voltage regulation.

The fact that the klystron is left on at all times at low power reduces the thermal cycling stress to the klystron and to the high voltage power supply and contributes to their longevity. Operating the klystron at less than 10% of the rated maximum RF power output also adds to reliability although the efficiency must be raised by some means.

### *Operational Constraints*

The 1-ns long linac bunch train of 3~5 S-band bunches can fill only one Booster bucket. Presently injection to any particular SPEAR3 bucket the Booster RF phase must be shifted by the angle assigned to that bucket. The phase shift is allowed only after the 3.0 GeV bunch ejection.

Because of the single bucket injection scheme the injection rate is relatively low: If the bunch charge at the Booster-to-SPEAR3 (BTS) transport line is 78 pC (present typical value) it translates to (78 pC)/(781 ns) = 0.1 mA stored current at SPEAR3, where 781 ns is the revolution period of the stored beam. If 600 such bunches are injected to SPEAR3 over 1 minute period, the stored current is increased by 60 mA, or the injection rate is 60 mA/min. At this rate the fill time from no beam to 500 mA requires 8.3 minutes.

## SYSTEM REQUIREMENTS

In order to overcome the issues described above, we have been studying a number of requirements and options based on merit and affordability.

The boundary condition for any Booster RF system upgrade is that the Booster circumference must not be changed, to minimize the cost of changing the position of and/or realigning the lattice components. The peak RF gap voltage must also be 800 kV or higher, preferably 900 kV including an operational safety margin, regardless of the RF frequency selected.

### *Selection of RF Frequency*

The original SPEAR2-to-Booster circumference ratio was 7:4, which is still maintained with SPEAR3, where RF frequency $f_S = 476.316$ MHz, the harmonic number $h_S = 372$ buckets, giving the SPEAR3 circumference $C_S = c/f_S*h_S = 234.136$ m and the revolution period $T_{RS} = 780.994$ ns.

If the new Booster RF shares the SPEAR3 frequency, its harmonic number comes out to be 372*4/7 = 212.57, which is not acceptable as a synchrotron. Therefore $h_B$ must be 212 or 213, resulting in the Booster RF frequency $f_B = c/(C_B/h_B) = 475.036$ MHz when $C_B = C_S*4/7 = 133.792$ m and $h_B = 212$. If $h_B = 213$, then $f_B = 477.277$ MHz.

While both cases are valid from the low-level RF point of view, the selection depends on whether it is possible to operate the high-power PEP-II RF system (cavity, klystron, etc). With the PEP-II single-cell cavities designed for 476.000 MHz, they can be modified to accept only the 475.036 MHz by removing fixed tuners and adjusting the movable tuner positions ($h_B$ =212).

### *Booster Frequency Phase-Locked to SPEAR3*

Since $f_B/f_S = 371/372$ when $f_B = 475.036$ MHz, the RF frequency ratio can also be expressed by (7*53)/(2*2*3*31): Dividing $f_S$ by the integer numbers in the denominator and multiplying by those in the numerator yields $f_B$. This is the same method as what is presently being used to phase-lock the SPEAR3-Booster RF systems.

The programmed Booster RF phase shift to target a selected SPEAR3 bucker would not be necessary in the upgraded system: Since the frequency difference is very small there are one-to-one bucket matches over some RF periods during which the phase match slips away.

### *476MHz Multibunch Injection: Possible Benefit*

During one Booster bucket period $1/f_B = 2.1051$ ns, the SPEAR3 RF phase advances by $372/371*2\pi$ radian, which gives rise to the phase slippage of $2\pi/371 = 16.88$ mrad = 0.97 deg, corresponding to 5.67 ps per bucket.

If injection timing is controlled accurately within ±100 ps, then a train of 200/5.67 = 35 Booster bunches could be injected, increasing the injection rate by more than an order of magnitude.

## RESOURCES AVAILABLE

Among the RF subsystems the most critical is the RF cavity. Those at the PEP-II stations are available for this upgrade project. Or they must be designed and built. The PEP-II cavities are for high current (stored current > 1 A) application: Each has high coupling $\beta$ (= $1 + P_{beam}/P_{wall} = 3.6$), rather low shunt impedance ($R_S = V^2/P_{rf} = 7.6$ MΩ) and contain 3 higher order mode (HOM) dampers. They are driven by 1.2-MW-rated klystrons, which are powered by 2.5-MW-rated RF HV power supplies.

### *Scaled ILC Positron Injector Cavity Design*

Since 476 MHz range RF frequency is rather unique in the accelerator community it is almost impossible to find a matching cavity among any legacy systems outside PEP-II. However, the ILC positron injector [4] cavity running at $f_P = 1.3$ GHz has been designed that could be

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scaled and adapted for a 475.036-MHz system. The cavity is an 11-cell π–mode standing wave warm structure. It has $R_{SP}$ = (19.3 MV)$^2$/(8.6 MW) = 43.3 MΩ shunt impedance over $L_P$ = 1.27 m total cavity length.

With frequency ratio r = $f_B/f_P$ = 0.365412, the scaled cavity shunt impedance is sqrt(r)*$R_{SP}/L_P$ = 20.73 MΩ/m. Considering 7 cells of $c/f_B/2$ = 0.315546 m length each, then the total length $L_B$ = 2.20883 m, and $R_{SB}$ = 45.8 MΩ. Assuming that the Booster stores 5 mA of current at 3.0 GeV and the gap voltage is 900 kV and the peak RF power needed to drive the cavity is 29.1 kW from the high-power RF source such as klystron, IOT (inductive output tube) or SSA (solid-state amplifier).

If the same conditions are to be met with two PEP-II cavities, the required peak RF power is 83.5 kW. The difference is in part due to the high coupling β as set by the waveguide RF coupler and the cavity iris.

### *Installation Issues*

Each single-cell cavity at PEP-II is assembled on a raft. It is 67.3 inches in transverse direction and 63.3 inches longitudinally. If two such assemblies are installed, it takes a total of 126.5 inches whereas the 358.5-MHz 5-cell cavity presently in service takes up only 103.8 inches flange-to-flange. Its body is 24.0 inches in diameter.

The Booster ring tunnel cross-section measures 96 inches wide and 108 inches high inside. The PEP-II type cavities would take up the walkway space, potentially necessitating a tunnel modification. The 7-cell ILC cavity described earlier takes only 34 inches of transverse space, leaving 64.8 inches on isle side, and 14.2 inches to the outer wall. Its longitudinal extent is only 87.0 inches plus two flanges brazed onto the cavity, each through a short beam pipe leaving 8.4 inch extra space.

### *Low or High Voltage Power Supply*

Unlike klystron or IOT, the SSA takes only up to 50 V. Each module is powered by one DC-to-DC convertor. The PEP-II klystron takes 90 kV, 27 Adc power supply. Along with a switchgear it sits on a 7-ft x 15-ft concrete pad. It weighs 68,400 pounds. Booster klystron takes 37.6 kV, 5.2 Adc power. It also meets HVPS requirements for the IOT, as well as a 500-kW, 476-MHz SLAC klystron.

### *Inductive Output Tube – An Option*

The Booster RF HVPS meets the requirements of the IOT beam power. The tube has sufficient power level and bandwidth for the Booster application. If the RF input to the IOT is turned off, the beam current drops down to less than 0.1 A, from the normal value of 3.5 A. If the RF input is turned on for only a few seconds every 5 minutes, the electric power consumption can be reduced by almost 2 orders of magnitude. At the NSLS-II a 500 MHz 90 kW IOT (Thomson Model L-4444) is used for their Booster RF transmitter system. The tube has sufficient power level and bandwidth for the Booster application.

### *Solid-State Amplifier – An Efficient Option*

High-power SSA systems are in operation at the French light source SOLEIL. The SOLEIL SSA "towers" are bulky but reliable and efficient. Lately RF transistors of 1.5 kW output power have become available. In addition to its long service life (if the transistor junction temperature is kept at 90 °C, the maker claims, the mean time to failure is 10,000 years!) one big advantage is its modularity: The SSA system consists of a number of small identical modules and their individual output powers are combined. There is no need to maintain a complete spare, unlike the case of a klystron or IOT.

## CONCLUSION

Various options available to upgrade the Booster RF system have been reviewed To make the RF system efficient, the cavity shunt impedance must be high. While it is possible that two of the PEP-II type single-cell cavity can establish 900 kV gap voltage at the cost of 90 kW peak RF power, a 7-cell cavity scaled from the ILC positron injector cavity can do the same task with only 30 kW peak power. The design is simple and the fabrication cost-effective. Another benefit is its small foot print.

Considering the high power RF, conservation of energy is mandated by executive orders and agency directives. They are summarized as "Positively discriminate in favour of green schemes with detailed appraisal of all new construction and retrofit opportunities" when decisions are made on project investments. To meet this mandate, the IOT has high efficiency and operates at low duty factor which would conserve electric power. The SSA system has even higher efficiency and the maintenance requirements are very low, which makes SSA highly effective. The PEP-II type SLAC klystron can also be used but efficiency is low in the low-power range.

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