

## THE SPEAR3 RF SYSTEM\*

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### Abstract

SPEAR2 was upgraded in 2003, to a new 3<sup>rd</sup> Generation Light Source (3GLS) – SPEAR3, enabling users to take better advantage of almost 100x higher brightness and flux density over its predecessor. As part of the upgrade, the SPEAR2 RF system has been re-vamped from its original configuration of one 200 kW klystron feeding a single 358.5 MHz, 5-cell aluminum cavity; to a 1.2 MW klystron feeding four 476.3 MHz, HOM damped copper cavities. The system installation was completed in late November 2003 and the required accelerating voltage of 3.2 MV (800 kV/cavity) was very rapidly achieved soon after. This paper details the SPEAR3 RF system configuration and its new operating requirements, highlighting its installation and subsequent successful operation.

### INTRODUCTION

The SPEAR3 project at SSRL is a major upgrade of the original SPEAR2 synchrotron radiation source [1], which significantly enhances both the photon brightness and flux density for its users. Beam currents will increase from 100mA up to 500 mA, with an order of magnitude reduction in beam emittance down to 18 nm-rad. An accelerating voltage of 3.2 MV is required to sustain the 3.0 GeV operation and to replenish almost 1 MeV/turn of lost energy due to synchrotron radiation. The original 358.5 MHz RF system of SPEAR2 has been replaced with a new system operating at 476.336 MHz (harmonic number  $h=372$ ). The experience gained at SLAC since 1996 running many 476 MHz RF stations in unison to provide stable electron and positron beams for collision analysis on the BaBar detector for PEP-II, has led to the adoption of a 4-cavity PEP-II HER RF station for SPEAR3.

### THE SPEAR3 RF SYSTEM

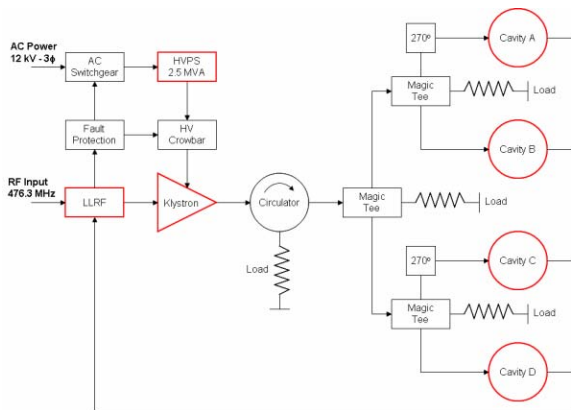


Figure 1: SPEAR3 RF System Layout.

The SPEAR3 RF system consists of a single Marconi 1.2 MW CW klystron, operating at 476.3 MHz. This feeds RF power through a network of WR2100 waveguide, via an AFT circulator. The waveguide system is pressurized with dry air (@ 1/4 psi) and interlocked for personnel protection against possible RF power leakage from waveguide flanges and/or removed sections, whilst also keeping moisture out of the system. The single waveguide feed splits into four individual feeds which power the HOM-damped cavities in the SPEAR3 tunnel. Figure 1 shows a schematic layout of the SPEAR3 system from its klystron through to the cavities, highlighting the LLRF feedback controls for the klystron. The cavities are equi-spaced in the storage ring tunnel, separated in RF wavelengths by  $-90^\circ$ . The waveguide lengths for each cavity then removes this  $90^\circ$  offset, so that a 'synchronous particle' arrives at the same RF phase in each cavity as it is accelerated.

### The RF Cavities

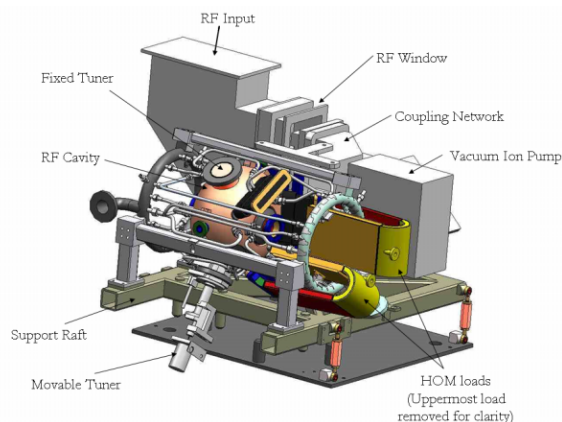


Figure 2: SPEAR3 HOM-Damped Cavity Assembly.

The RF cavities employed on SPEAR3 are identical to those used successfully on PEP-II since 1996 [2] and are manufactured by ACCEL Industries GmbH in Germany [3]. The beam induced HOM impedances are damped by way of three intersecting waveguides which couple out the HOM power, which is then dissipated in in-vacuum high power, water-cooled loads. Figure 2 shows the layout of the cavity raft assembly.

### The 1.2 MW Klystron

The klystron employed on SPEAR3 was procured from industry using the same operational specifications as those used for the PEP-II klystrons. This made the spares availability for each accelerator more cost effective as the same klystron could be used for both. The specified requirements for the 1.2 MW klystron is a 43 dB gain (min), over a 5 MHz bandwidth with an efficiency exceeding 60%. For LLRF feedback control, the group

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delay through the klystron is limited to <150ns. The Marconi K3512S Klystron currently employed on SPEAR3 had originally been utilized on PEP-II during 2001, only to suffer a failure due to a vacuum leak at its collector after only 1,300 hours operation. A repair was performed at CPI and a new electron gun and re-designed collector assembly were installed. The tube was then high power tested at SLAC in September 2003. Figure 3 shows the klystron installation on SPEAR3, with the high power circulator and waveguide feed clearly visible.

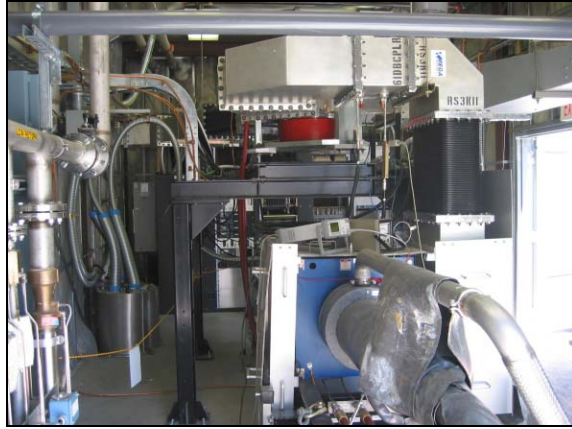


Figure 3: SPEAR3 Klystron Room Installation.

### The High Voltage Power Supply (HVPS)

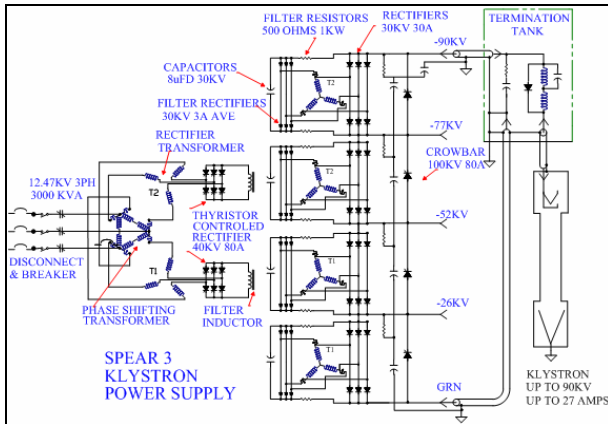


Figure 4: SPEAR3 Klystron Power Supply System.

The 2.5 MVA power supply for the klystron (see Figure 4) employs a primary SCR-controlled rectifier operating at the existing site-wide distribution voltage of 12.47kV. This control choice reduces the size of the power supply in comparison to a conventional VVT-adjusted power supply. Furthermore, the control provides for fast voltage adjustment and fault protection. Arrangement of the SCRs as a star point controller with the filter inductor in the primary is a configuration commonly used in European fusion research [4]. The configuration is ideally suited for an inductor-capacitor filtered supply where dissipation of the filter inductor stored energy is important. The power supply employs novel optically triggered SCRs in a fast crowbar circuit to reduce the possibility of arcing or damage to the klystron tube under fault conditions.

### The Low Level RF (LLRF) System

The SPEAR3 Low Level RF system is a VXI based system, adopted from PEP-II and provides closed-loop feedback control of the phase and amplitude of the storage ring klystron output signal [5]. All signal processing is done at baseband using in-phase and quadrature (IQ) techniques. A programmable DSP based feedback loop is implemented to control DC phase variations across the klystron and to adaptively cancel modulations caused by klystron HVPS ripple at selected power line harmonics between 60 Hz and 10 kHz. The Direct RF feedback loop re-injects a portion of the cavity field signal back into the klystron drive to accomplish a 15 dB reduction of the drive impedance. A short group delay is necessary to provide 800kHz bandwidths for this loop driving the requirement for a 150 nsec group delay for the klystron (see Figure 5).

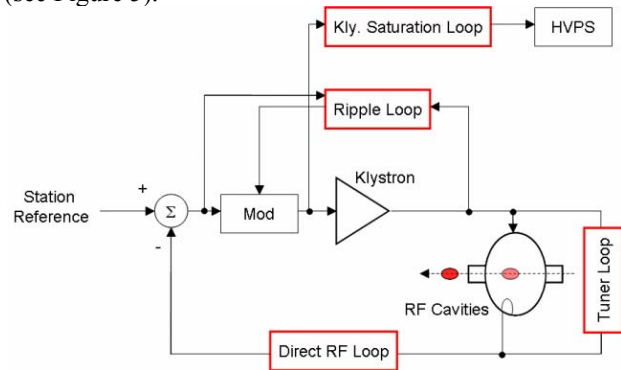


Figure 5: SPEAR3 LLRF Feedback Controls.

### HOM INSTABILITY THRESHOLDS

Table 1: SPEAR3 RF Accelerator Parameters

Parameter	Symbol	Value	Units
Frequency	$f_c$	476.336	MHz
Beam Energy	$E$	3.0	GeV
Beam Current	$I_b$	500	mA
Revolution Frequency	$f_{rev}$	1.280	MHz
Synchrotron Tune	$Q_s$	0.008	
Momentum Compaction	$\alpha$	0.00113	
Longitudinal Damping Time	$\tau_s$	2.87	ms
Transverse Damping Time x,y	$\tau_{x,y}$	4.24, 5.14	ms
Beta x,y (at cavity location)	$\beta_{x,y}$	10.2, 4.7	m
RF Gap Voltage	$V_{RF}$	3.2	MV
Number of Cavities	$n_{cav}$	4	
Cavity Shunt Impedance	$R_s$	3.8	MΩ
Gap Voltage/Cavity	$V_{cav}$	800	kV
Wall Power/Cavity	$P_{cav}$	85	kW
Beam Power/Cavity	$P_b$	150	kW
Klystron Power	$P_{kly}$	986	kW

The HOM impedances of the PEP-II style cavities have been extensively studied and are documented elsewhere [6]. Based on these characterizations a prediction for RF stability, in terms of HOM induced coupled-bunch

oscillations for SPEAR3 in both the longitudinal and transverse planes can be estimated. The formulae for stable beam current thresholds are shown in equations 1 and 2 for longitudinal and transverse planes respectively.

$$\text{Longitudinal } I_{th}^{//} = \frac{2EQ_s}{\alpha\tau_s R_{HOM}^{//} f_{HOM}^{//} n_{cav}} \quad (1)$$

$$\text{Transverse } I_{th}^{\perp} = \frac{2E}{\beta_{x,y} \tau_{x,y} R_{HOM}^{\perp} n_{cav} f_{rev}} \quad (2)$$

Knowing the HOM impedance spectra for the SPEAR3 cavities and equating the HOM growth rates with the SPEAR3 damping times a coupled-bunch instability limit for stored beam current can be made, above which the damping time of the storage ring exceeds the growth rate of the HOM impedance and the system is deemed to be potentially unstable.

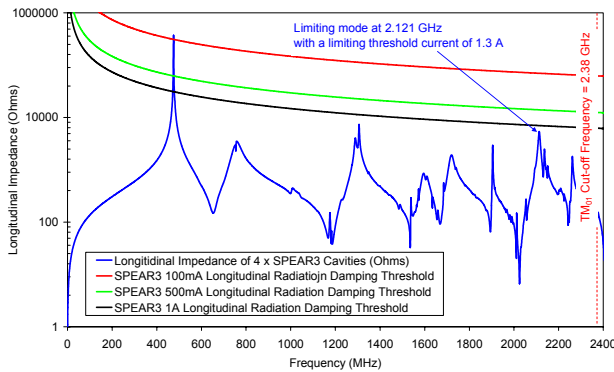


Figure 6: Longitudinal Instability Thresholds.

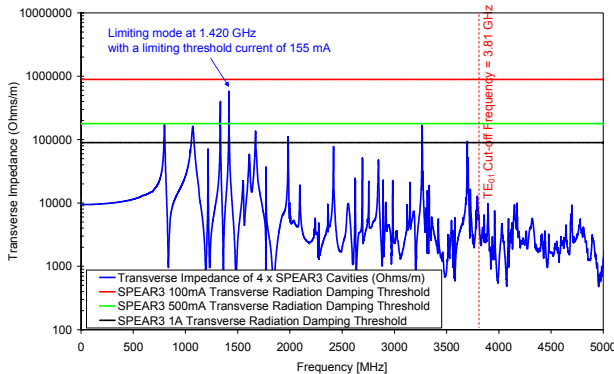


Figure 7: Transverse Instability Thresholds.

For SPEAR3 these estimates are 1.3A longitudinally and 155 mA transversely. Figures 6 and 7 show graphically how these instability thresholds are substantiated. The designed operating beam current for SPEAR3 of 500 mA means that there should not be a requirement for a longitudinal bunch-by-bunch feedback system. However, transversely the operating margins will become much smaller, providing the HOM impedances accumulate optimally as assumed here. Inevitably manufacturing tolerances and differences in frequency tuning will dictate that each cavity HOM spectrum will differ slightly, resulting in a non-optimum accumulation

of HOM impedances and therefore higher threshold currents. Even so, for the transverse case, a factor of 3 increase in threshold current from the prediction would still necessitate the need for some form of transverse feedback control up to 500 mA.

## SYSTEM COMMISSIONING

On the evening of Friday 28<sup>th</sup> November 2003, the SPEAR3 RF system was energized for the very first time. Automated RF processing of the cavities started immediately (see Figure 8), initially in FM-mode whereby the klystron signal is frequency modulated by  $\pm 160$  kHz at discrete sweep frequencies of 400 Hz and 1 kHz, all configurable via the LLRF EPICS control panels. Shortly after midnight on Sunday 7<sup>th</sup> December 2003 gap voltages had reached 850 kV/cavity and processing was switched to CW-mode. The cavities then ran up to their operational requirement of 800 kV/cavity very quickly and except for a HVPS trip and a circulator arc, ran stably for several hours. Gap voltages were then increased further to 850 kV resulting in a number of vacuum trips. Reverting back to 800 kV/cavity, the station ran reliably for almost 24 hours. On Tuesday 9<sup>th</sup> December 2003, the RF system was declared operational and handed over to the operations team for additional processing and commissioning with beam [6].

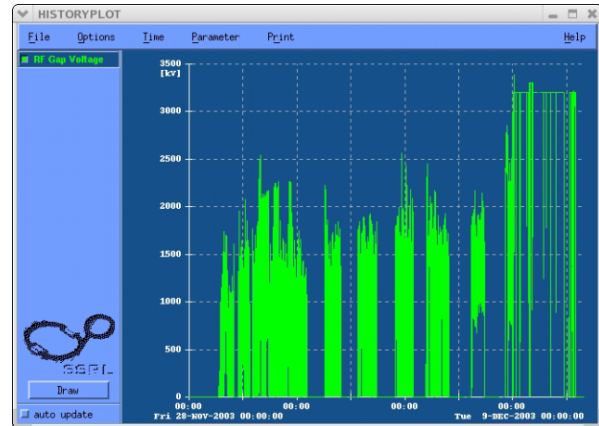


Figure 8: SPEAR3 RF Station Processing.

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