APS Injector Synchrontron Low-Level RF System Design and Test[1]

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Abstract

We describe the control of the RF system for the Injector Synchrotron of the 7-GeV Advanced Photon Source. The RF system consists of one klystron and four 5-cell cavities of the LEP type. A block diagram of the system is shown and the low power rf circuitry is described. Voltage and phase feedback are discussed, along with accelerating the beam to 7-GeV. The accelerating voltage is programmed with a waveform generator. Although the acceleration is constant, the power at injection is almost zero and at extraction it is near 600 kW. The power goes up with beam energy to replace synchrotron radiation losses. Stability of the RF phase between the two sides of the ring are discussed. Control signals are descibed which synchronize the bunch during injection from an accumulator ring and for extraction to the 352-MHz bucket in the Storage Ring. Timing for injection into any bucket in the Storage Ring is accomplished in the RF controls interface located on the VXI cards. There is only one bunch accelerated in the booster at a time, so the beam loading of the cavities is negligible. Operating experience during early commissioning efforts will also be outlined.

I .HIGH POWER RF OVERVIEW

Four LEP five-cell cavities (built by Siemens/Interatom) are powered by a single one-Megawatt LEP-type klystron (Thomson 2089). The power is split by waveguide hybrids with back terminations having 250 kW water-cooled resistors. The cavities are grouped in two pairs, each pair on symetrically opposite sides of the Booster Synchrotron. Since the klystron is located near one pair, there is a motorized waveguide phase shifter in the 150 meter waveguide to the far pair. The shifter compensates for nite-day and winter-summer changes in length of the long run. At the moment, this shifter has no automatic adjusting circuit, but one may be added later by comparing phase between the two pairs of cavities and using that difference signal to drive the motorized phase shifter. See figure 1.

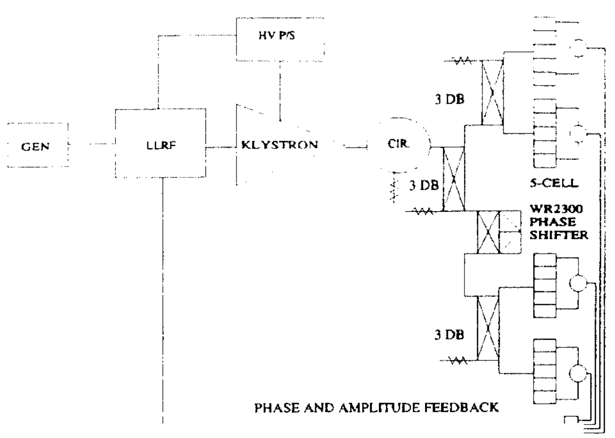

Figure 1: Synchrotron rf block diagram

Injection rf voltage is about 100 kV, enough to capture the 450 MeV beam. Energy gain per turn is 16 keV, but at extraction energy of 7 GeV, the synchrotron radiation is 6.33 MeV/turn, and the rf voltage per turn is 10.4 MV requiring about 480 kW power from the klystron.

Voltage monitors for each of the five cells are summed and this sum is used for tuning of each cavity locally. The sum of the four cavities is returned to the low-power circuitry for processing there.

II. LOW-LEVEL RF OVERVIEW

The low level system generates the RF signal to drive a klystron amplifier. The synchrotron signal generator is phase locked to the storage ring master oscillator. The storage ring RF signal is transmitted to the synchrotron signal generator over phase stabilized cable.

The low level system also includes the analog phase and amplitude regulation systems that maintain the cavity RF voltages. See figure 1, which shows this schematically.

Tuners

The second and fourth cells of the 5-cell cavity are fitted with ports for the piston-type tuners. The cavity tuner port has an 11.5 cm diameter and a 6.0 cm travel. This results in a frequency tuning range of 0.5 MHz to compensate for beam loading, temperature effects, etc.. By adjusting these two both cavity tuning and amplitude balance in the cells are maintainded. The tuner slugs are fitted to worm gears and stepper motors which provide 1 micro-meter of step resolution. A feedback system monitors the phase difference in the cavity and adjusts the tuners in tandem to keep the cavity at the

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resonant frequency with +/- 0.1 ° under RF heating. Also the field amplitude in each of the two cells are detected and the tuners are adjusted differentially to balance the cell voltage to within +/- 1 dB.

Each cell of the cavity has a field monitor. The tuner-port cells derive the field-balance signal. The end cell fields are added in phase to derive the average cavity phase and control both tuners in parallel. The resultant signal is compared with a phase meter to the driving signal. For slow tuning, the digital phase information goes to the control computer to vary the water temperature. Since the beam loading is so small, no de-tuning is foreseen to accomodate the "Robinson Stability" criteria.[1]

There are five different control loops. An RF drive control loop is used to set the accelerating voltage in the four cavities. A klystron operating loop is used to set the operating level of the klystron in the linear or saturation region. A cavity tuning loop is used to keep the cavity input impedance real during beam loading and RF heating. The loop moves a tuner piston through a stepper motor which changes the inductance of the cavity. A klystron phase control loop keeps the output phase constant due to changes in voltage and power levels. A cavity phase control loop keeps the phase of the sum of all the cavities constant for proper synchronous phase operation.

The input to the klystron amplifier driver has a computer-controlled rf amplitude modulator and a computer-controlled relative phase shifter. An amplitude comparator compares the sum of the voltages from all cavities to a reference, and adjusts the rf modulator to maintain the required voltage. The phase of the voltage developed in the cavities is compared with the reference, and the phase of the drive to the klystrons are adjusted to maintain the cavity sum voltage phase to < 1.0° with respect to the generator.

The klystron output is monitored and a feedback system is used to eliminate the rf amplitude and phase variations due to cathode voltage variations, typically ac line harmonic ripple. A one percent change in voltage causes a seven degree variation in rf phase. The RF drive signal is modulated in amplitude and phase.

The klystron input power is controlled by a control loop through the modulating anode system, while the klystron operating point is maintained in the linear gain region. In this way the klystron efficiency remains optimum.[2]

controls interface

Each control loop has local operation and diagnostics as well as a computer bus interface for remote operation and diagnostics. This is implemented in a VME and VXI bus architecture.[3]

The computer interface additionally monitors the operating environment of the klystron, circulator, and cavity. This includes water flow, air flow, temperature, and cavity vacuum, and warns of "out of tolerance" operating conditions and shuts off components if necessary.

Rf Waveform

The rf waveform to modulate the rf drive during acceleraiton will be implemented using a Hewlett-Packard 1340A VXI arbitrary waveform generator. The waveform consists of exactly 4096 horizontal points with 12 bits of amplitude resolution. There are 4 memories to store different waveform functions which can be used during consecutive injection cycles.

Timing and Phasing

The cavities are not a multiple wavelength apart and so the waveguide feed between each pair of cavities had to be adjusted to 144 degrees for the beam to see the correct accelerating voltage. Also the sum signal must be phased by the opposite amount to ensure proper combining. The cavities on symetrically opposite sides of the Booster Synchrotron are adjusted to one rf wavelength multiple by the motorized waveguide phase shifter so that the proper accelerating phase is maintained in all four cavities.

III. BEAM LOADING

There is only one bunch of 4.7 mA (average) accelerated in the Booster. The beam induced voltage in each cell is 47 kV (2 x 4.7 mA x 5 MOhms) or 940 kV induced in all four 5-cell cavities. At injection, the radiation loss is small, and for an energy gain per turn of 16 keV, the synchronous phase angle is 9.2 degrees. For a 100 kV ring voltage, the de-tuning angle is 83 degrees. If this large angle becomes a problem, the cavity voltage can be increased to several hundred kilovolts to make the detuning and the beam injection tuning transient smaller. In fact, it may be difficult to operate the Megawatt klystron at this very low power level (50 watts for 100 kV rf ring voltage).

As the beam energy increases, radiation losses increase to 6.33 Mev per turn at 7 GeV and the RF voltage increases to 10.4 MV with a synchronous phase angle of 37.5 degrees. The cavity tuning feedback loop can easily follow this over the 500 mSec booster magnet ramp. There is also provision for an adaptive feedforward programto minimze the tuning error during the booster acceleration cycle.

IV. RF FREQUENCY SYNCHRONIZATION

The booster rf frequency is 352 MHz, while the two PAR frequencies are subharmonics, 9.77 and 117.3 MHz. The present synchronization scheme is to use three synthesizers with resolution to one Herz and a common clock. Preliminary tests indicate that synchronization is within 4 degrees at 352 MHz.

With three synthesizers, the PAR and Booster Synchrotron can be run independently of the Storage Ring, either for physics experiments or for accelerator maintainance and development.

V. OPERATING EXPERIENCE

Currently the synchrotron is operating in a non-ramping mode at injection energy magnet field only. Beam has been injected and coasted beam has been acheieved for 30 msec. Capture in a stationary bucket has been attempted but has been unsuccessful due to the usual timing and phasing problems upon startup. Commissioning of the booster will continue through the end of the year.

VI. REFERENCES

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