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PRECISION CONTROL OF LARGE RF SYSTEMS*

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Abstract

High luminosities in linear colliders and low energy spread in high energy linacs require precision control of the rf system. The design of the rf system depends on the choice of normal conducting or superconducting technology. Normal conducting technology is usually associated with pulsed operation employing fast feedforward and slow feedback control, while superconducting systems are usually operated in a continuous wave (cw) mode implying use of real-time feedback. A highly stable rf distribution system over large distances is crucial for phase control. Vernier phase and energy control is accomplished using beam derived reference signals. A comparison between the design and performance of existing accelerators such as SLC (SLAC) and CEBAF is given. The rf system related issues for future projects such as NLC and TESLA are discussed. Some examples of issues are field control with one power source driving multiple cavities and pulsed operation of superconducting cavities.

Introduction

Linear accelerators have become an important research tool in high energy and nuclear physics. With energies in the GeV range these accelerators are large facilities. Accordingly the radio frequency systems which are a major subsystem in high energy linear accelerators have grown in size. The SLAC accelerator has the largest rf installation of any pulsed accelerator, operating 960 cavities at a total length of 2 miles to achieve a final energy of 52 GeV. CEBAF, which is designed as a five pass recirculation accelerator with two linacs, has the largest rf system for superconducting cavities in operation. CEBAF's 338 superconducting cavities provide cw electron beam at a maximum energy of 4 GeV.

These two accelerators are used as a reference for the design of future e^+e^- linear colliders which must provide a center of mass energy in the 0.3 to 1 TeV range and a luminosity exceeding $5 \cdot 10^{33}$. Under study are a diversity of approaches to meet these objectives.

The rf system related parameters of SLAC, of CEBAF, and of possible linear colliders are given in Table 1.

The linear colliders under study are:

TESLA (being developed by an international collaboration) is based on superconducting rf. All other designs make use of normal conducting rf.

DLC (DESY/DARMSTADT) uses S-band (3 GHz) rf, where there is extensive operating experience. NLC (SLAC) uses the higher frequency X-band (11.4 GHz) rf in a modulator klystron accelerator configuration similar to S-band linacs.

JLC (KEK) uses a design similar to the NLC. Multiple bunches are accelerated in each rf pulse as in TESLA, DLC, and NLC. VLEPP (INP), employs a single high intensity bunch rather than multiple bunches.

CLIC (CERN) is a "two beam accelerator" with klystrons replaced by an rf power source based on a high-current, low-energy beam traveling parallel to the high energy beam.

The information of the status of the respective activities lies beyond the scope of this paper. The information can be found in the respective status reports. The following chapter focuses on the rf design issues common to all designs. Next, a detailed description of the CEBAF rf system, which has the tightest requirements, is given. Some of the rf control issues at SLC, NLC and TESLA are also discussed.

RF Controls System Design Considerations

One of the major tasks of any rf system for accelerating systems is to maintain the amplitude and phase of the accelerating field within a given tolerance to accelerate the charged particle beam. A typical rf system consists of an rf reference oscillator (also referred to as Master Oscillator), a frequency distribution system, low level controls for cavity field control, a high power amplifier, the accelerating cavity, a cavity frequency tuning system, a power conditioning system, a timing and machine protection system, and an interface for computer control.

Field stability requirements

The requirements for amplitude and phase stability of the accelerating field are derived from the desired beam quality. The major contributions to energy spread are the effects of a finite bunch length, and the amplitude and phase stability of the accelerating field. The dependency of the energy spread as a function of bunch length and of the amplitude and phase stability of the accelerating field has been derived by G. Krafft [1]. The expression is only true for relativistics beams.

The requirements for correlated fluctuations are more stringent than for uncorrelated noise since the fluctuations in a large number of cavities are in synchronism, adding to the total error. If the field perturbations are statistically independent a partial cancellation of the perturbations takes place. The requirements for uncorrelated noise are approximately reduced by $\sqrt{N}$, where N is the number of cavities in the linac.

The future linear colliders demand energy spread to be within the acceptance of the final focus. A typical requirement is an energy spread of 1% or better resulting in correlated amplitude and phase stability requirements in the order of 0.5% and 1° respectively. The goal of rf system design is to exceed this requirement by some factor.

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	SLAC	CEBAF	TESLA	DESY/ THD	JLC	NLC	VLEPP	CLIC
Linac energy [GeV]	52	4	250	250	250	250	250	250
Linac active length [km]	3.1	2.0	10	15	8.5	7	3.2	3.3
RF freq. of main linac [GHz]	2.856	1.5	1.3	3	11.4	11.4	14	30
Linac repetition rate [Hz]	12	cw	10	50	150	180	300	1700
Number of particles/bunch [10^{10}]	5	0.00008	5.1	2.1	0.7	0.65	20	0.6
Number of bunches per pulse	3	cw	800	172	90	90	1	1—4
Unloaded gradient	22	5	25	21	40	50	108	80
Section filling time [ns]	830	$1.4 \cdot 10^6$	$5 \cdot 10^5$	825	75	100	107	11.2
Klystron pulse length [μs]	2.5	cw	1300	2.8	1.5	1.5	0.7	0.011
Pulse compression ratio	2	-	-	-	4	6	6.5	-
Number of klystrons/linac	240	320	1264	2450	33424	1945	1300	2
Peak rf power from klystron [MW]	25	0.005	3.3	150	70	94	150	700

TABLE 1
RF System Related Parameters of Large Existing and Future Linacs

Sources of Field Perturbations

The stability of the accelerating field is limited by various noise sources and the system dynamics. In pulsed operation the cavity dynamics is described by the rise time and the settling time of the field. The high power amplifier and associated pulse forming networks for high power pulse generation have their own dynamics which causes the resulting rf power to fluctuate during the pulse. Significant effort is required to reduce these fluctuations below the 0.1% level. Other examples of noise sources are 60 Hz ripple on high voltage power supplies, microphonic noise (vibrations) in superconducting cavities, beam current fluctuations, and Schottky noise in electronics. Most pulsed systems operate at a repetition rate which is a multiple of 60 Hz, thereby reducing the effect of 60 Hz perturbations.

All the above noise sources increase the energy spread of the beam. Some of the errors are uncorrelated, especially if the driving noise sources are statistically independent. Other errors such as beam loading effects or 60 Hz ripple on power supplies are correlated and require more attention.

Field Control

In order to stabilize the rf accelerating field within specified tolerances several methods can be used. The first step is to quantitatively identify all perturbations and to determine by how much their effect must be suppressed. The principal methods for field control are:

1) Reduction of noise sources. Examples are use of filters for power supplies, removal or mechanical isolation of roughing pumps in vibration sensitive environment of accelerators using superconducting cavities, stable AC power.

2) Passive damping of perturbations. Examples are lowering of Q_{ext} of the higher order modes in sc cavities, detuning of higher order modes for wakefield reduction, temperature stabilization of phase and timing signal distribution systems.

3) Application of feedforward. Feedforward is applied when repetitive perturbations are present and can be predicted for the next pulse. The effect of the perturbation can be corrected by compensation techniques in which a correction of the input signal results in a stable output signal. An example of feedforward is the control of the accelerating gradient during heavy beam loading. The cavity drive signal has a slope which counteracts the depletion of the stored energy in the cavity by the beam.

4) Application of feedback. The remaining disturbances which cannot be sufficiently reduced by any of the other methods must be controlled by use of feedback techniques. The signal which has to be controlled is detected, compared to the desired value, and the amplified error signal is used to drive an actuator for the signal to be regulated.

Feedback systems can be implemented in various ways. Hardware solutions require dedicated hardware for signal detection, signal amplification (i.e. processing) and actuators. Digital solutions provide a high degree of flexibility and can be modified easily. A combination of both allows to change parameters in the hardware loop through computer control. A decision has to be made whether to use independent feedback loops for gradient and phase using transfer functions (as, for example, used in PID loops) or application of state space models which allow for superior reduction of the rms errors especially in coupled and/or nonlinear systems.

RF Control at CEBAF

RF control systems for superconducting cavities such as used at CEBAF have to be designed for the specific requirements which high Q cavities impose on such a system. The use of cw operation allows the use of negative feedback control. Microphonic noise in the form of mechanical vibrations, which modulate the resonance frequency of the cavities, causes phase fluctuations up to 20° and associated amplitude fluctuations of up to 5%.

RF Control Requirements

The CEBAF accelerator combines high energy, high current, high duty factor, and high beam quality.

The rf tolerances required to yield an rms energy spread of $2.5 \cdot 10^{-5}$ are listed in Table 2, where σ_A/A is the relative rms amplitude error, σ_f is the fast rms phase error, and σ_s is the slow rms phase error along the linac.

The requirements assume that the linacs are always operated on crest, i.e., the overall linac phase is adjusted for maximum energy gain. This is accomplished by a phase vernier system using the measured beam energy as probe

RMS error	Uncorrelated	Correlated	Measured
σ_A	2×10^{-4}	1.1×10^{-5}	1.5×10^{-4}
σ_f	0.25°	0.13°	0.08°
σ_s	2.6°	∞	1°/day

TABLE 2
Amplitude and Phase Stability Requirements

vernier system using the measured beam energy as probe signal. The requirements for the fast phase error in the uncorrelated case can be relaxed to 0.75°, if the slow phase error is reduced to 0.64°. Fast phase fluctuations have to be suppressed by the control system by a factor of 100 and fast amplitude fluctuations by a factor of 1000.

RF System Design

The key decision for the CEBAF rf control system is the use of one klystron and control unit per cavity. The major components of the rf control system are shown in Figure 1, and include the high power amplifier (HPA), the power transmission system, the cryostat with the superconducting cavity, and the low level rf control module. A phase stable frequency distribution system provides the control modules with the required frequencies. The detailed description of the CEBAF rf control system can be found elsewhere [2].

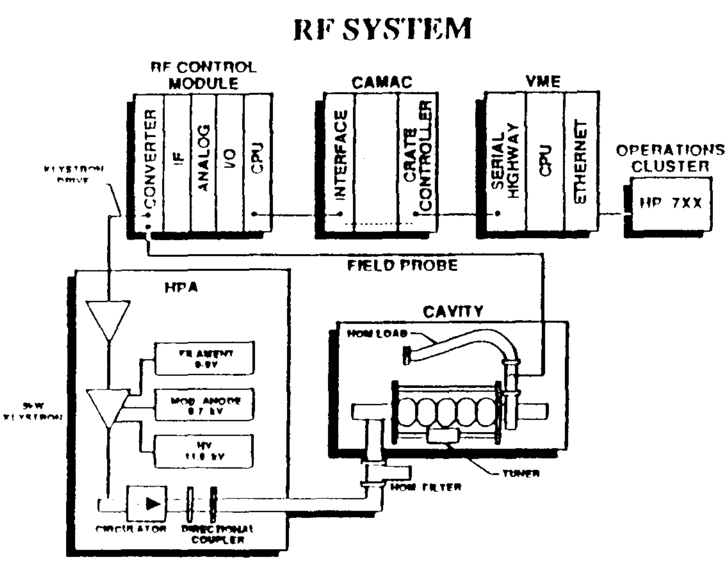

FIGURE 1
CEBAF rf Control System Configuration (one channel)

The control system employs separate feedback loops for gradient and phase control. A heterodyne scheme is used to convert the cavity frequency of 1497 MHz to an IF frequency of 70 MHz. The amplified error signals drive a controller for amplitude and phase operating at 70 MHz. An up converter translates the resulting IF signal back to the operating frequency of 1497 MHz. The phase modulator is designed as vector modulator which has the inverse transfer function of the cavity. This design reduces the gain required for amplitude control due to the coupling between phase and amplitude of the dominating microphonics noise sources.

RF System Performance

The rf control module performance has been extensively tested with a total of 298 operational control modules for the sc cavities in the injector, north linac and south linac. Two cryomodules in the north linac and three cryomodules in the south linac are not operational since they are not yet connected to the control system.

The Central Helium Liquefier provides stable operation at 2.1 K with microphonics noise levels of typically ± 10° but they can be as high as ± 25° as observed in more than 10 cavities. The rf control system has been proven reliable when operating 298 cavities simultaneously. During a typical run less than 10 cavities are turned off for various reasons. Tuner problems lead the list of possible problems.

The rf control system exceeds the requirements for gradient and phase stability except for correlated noise (60 Hz and harmonics) which is 2—3 times larger than required. Slow phase drifts along the linac are less than 1° in a 24 hour period. A slow phase vernier for individual cavities will correct the daily phase drifts.

The spectrum of the residual gradient and noise fluctuations shows a significant contribution in the frequency range from 10 kHz to 100 kHz. There is practically no contribution above 1 MHz. The high frequency noise is dominated by the SSB-phase noise of the master oscillator which is converted to amplitude fluctuations through pm-am conversion in a detuned cavity (only the average detuning angle is maintained to better than 10°). The low frequency and broadband gain have to be optimized for minimum residual gradient and phase fluctuations and to guarantee stability over a wide range of gradients (2—7 MV/m) and beam loading (0—1 mA).

Operational experience

The rf system has been operated during more than 1000 beam hours in 1994 [3]. In June 94 the decision was made to lower the klystron cathode voltage from a nominal value of 11.6 kV to 7 kV for energy saving reasons. This limited the maximum available klystron power to 1.5—1.7 kW compared to the 5 kW design. It is therefore important to ensure that the cavities are tuned closely to the operating frequency.

Until April 1994, the operators had to tune cavities manually. With the implementation of two additional modes for tuner operation the situation improved significantly. The three tuner modes are:

Tracking mode: Maintains detuning angle offset within ±10°. It activates the tuner when detuning angle exceeds 10°, and stops tuner movement when the detuning angle is within ±3°. This mode requires that the detuning angle offset be calibrated better than ± 3°.

Burst mode: Provides coarse tuning capability to better than one bandwidth of the cavity. Generates bandwidth limited (± 5 kHz) pseudo random noise spectrum to drive the cavity. Actual cavity resonance frequency is determined from the 360° phase detector signal. The tuner is activated until the cavity resonance frequency is within ±125 Hz of the operating frequency.

Sweep mode: Provides precision calibration of the detuning angle offset. It measures the transfer function drive frequency is modulated and swept over a frequency range of ±200 Hz around the operating frequency. The three parameters derived from the measured transfer function are the loaded Q factor of the cavity, the phase offset of the 360° phase detector, and the frequency error of the cavity converted to the detuning angle offset necessary for tracking mode which accomplishes the final frequency tuning of the cavity.

All cavities in both linacs can be tuned precisely within 2 hours using the three tuner modes from the control room.

The calibration of the rf control modules ensures interchangeability. It has been demonstrated that the replacement of a control module results in a phase change of the accelerating field of less than 2° and a gradient change of less than 1% therefore reducing downtime due to a control module replacement to less than 15 minutes.

The initial phasing of the cavities has been accomplished using beam induced transients. This method provides a typical accuracy of 5° but can resolve up to 1° if needed. With the beam induced transients it was possible to measure that the overall north linac phase drifted by less than 3° over a period of 24 hours.

During the last week of July 94, a beam with an energy of 600 MeV was delivered to hall C for 60 h with an uptime of 69%. The beam was remarkably stable, verifying the stability of the rf system. At the end of the run the energy was increased to 808 MeV in single pass operation. The stability was then reduced, mainly due to power limitations of some cavities which were not tuned correctly.

RF Control in the SLC Main Linac

The Stanford Linear Accelerator [4] was originally built to support the traditional single beam physics operations of the mid-1960s. While the linac was upgraded over the past several years to support the SLC, with its high-charge, low-emittance, multi-bunch operation, much of the original rf distribution and rf control system is still used.

RF Controls

A computer controlled phase and amplitude detection system is used to measure [5] and stabilize the rf power sources in the SLC. This system measures the instantaneous phase and amplitude of the 1 μs 2856 MHz rf pulse with an accuracy as specified in Table 3.

Sector	Phase jitter (degrees)	Amplitude jitter (%)
2	0.1	0.1
3	0.2	0.2
4–5	0.3	0.4
6–30	0.5	0.5

TABLE 3
Requirements for the SLC rf Phase and Amplitude Error Detection System

Control of the klystron output is accomplished by varying the input drive via a pulsed rf attenuator. The rf attenuator is calibrated in terms of the energy gain of the beam. The ability to control precisely the energy output allows for energy feed-forward as well as energy feedback applications. Most of the SLAC klystrons are operated at full saturation while the vernier klystrons are operated at levels of 5% to 80% of the maximum power output, well below saturation.

Energy and energy spread control

The rf system is designed to allow orthogonal control of both the positrons and the primary electrons in the linac. Linac energy control uses entire sectors of klystrons which are symmetrically counter-phased. This "kinking" of the accelerator sectors allows control of the energy gain, with an adjustment range of several GeV. The use of two sectors allows the control of the energy without affecting energy spread.

Energy difference between the positron beam and the electron beam cannot be achieved with the use of conventional rf controls. The control takes advantage of the 61.2 ns spacing of the electron and positron bunches and the discharge control timing for the SLED energy doubler cavities. The slope of the SLED output pulse allows to change the differential energy gain of the two beams.

The energy spread is controlled by varying the position of the bunch in question with respect to the accelerating rf field. Control of the electron energy spread for the primary bunch is achieved by changing the phase of the Main Drive Line [6] which supplies rf for the sector 2-30. Control of the positron energy spread is achieved by changing the extraction phase control for the South Damping Ring phase feedback. It affects only the positron bunch.

Beam Based Feedback

SLC employs a large number of feedback loops which stabilize the beam. Controlled are x,x',y,y' and beam phase, energy, and energy spread error. In the linac the system is divided between control by a slow feedback system in the central computer, and systems in dedicated microcomputers which attempt to respond on a pulse-to-pulse basis. The energy spread in the SLC has been reduced from 2% to 0.3% by the application of feedback.

RF Control for NLC

A peak power of 200 MW will be required to drive a pair of 1.8-m-long sections of the NLC structure to an accelerating gradient of 50 MV/m. An rf pulse length of 250 ns at the accelerator input will provide 100 ns for filling the structure, 125 ns for accelerating the bunch train, and 25 ns for rise-and-fall-times. The concept of the NLC rf control will be tested in the NLC Test Accelerator (NLCTA) [7].

RF System for the NLCTA

The rf sources will be 50-MW klystrons. Each klystron will be pulsed by an independent modulator to allow flexibility for multi-bunch energy control. Each klystron will feed a SLED-II rf pulse compressor which will compress the 50-MW, 1.5 μs klystron pulse by a factor of six in time to 0.25 μs and will multiply the peak power by a factor of four, to 200 MW.

The compression efficiency will be 67%. Feedback loops for rf control will be implemented within the framework of the SLC control system hardware and software.

Beam-loading compensation

The beam-loading, if not compensated, will reach a steady state value of 25% at the end of the bunch train. The most promising beam-loading energy-compensation strategy for bunch trains of this length is to prefill the structure with rf in such a way that the energy gain of each bunch during the transient period is the same as the energy gain of each bunch in steady state. In one implementation of this scheme, the rf pulse is modulated so that the rf field envelope at the input end of the structure is ramped linearly during one filling time before the bunch is injected. A simulation shows that a stability of 0.1% of the energy gain during the acceleration of the bunch is achievable.

Although amplitude modulation at the klystron input can be used for the appropriate rf pulse modulations of the cavity drive signal, various types of rf phase modulation prior to SLED-II pulse compression are options to be tried.

The fast rf phase and amplitude detection system will be the same as used in the SLC. It will resolve amplitude fluctuations at the 0.1% level and phase jitter of 0.1° with a time resolution of 1.4 ns. The information can be used for intra-pulse and pulse-to-pulse corrections and slow feedback.

RF Control for TESLA

The proposed 250 GeV linear collider TESLA is based on superconducting cavity technology and therefore in some respects is similar to CEBAF. Since TESLA is based on an accelerating field gradient of 25 MV/m, it is necessary to operate in pulsed mode to reduce the 2 K refrigeration needs within reasonable limits. The rf pulse length will be 2 ms from which 600 μs are used to fill the cavity and 1400 μs are available for beam acceleration. The beam pulse consists of 800 micropulses with a spacing of 1 μs. The repetition rate is 10 Hz. The beam loading is heavy with 8.22 mA. For cost reasons it is planned to use one 5 MW klystron to drive 16 cavities in two cryomodules.

RF Control System Issues

The required beam energy spread for the W- and Top-factory is 0.2% demanding gradient stability of better than 0.1% and phase stability of better than 1° for correlated noise. The requirements for uncorrelated noise are much less stringent. Many of the noise terms will be correlated since they are related to system dynamics during pulsed operation.

Lorentz force detuning of the stiffened cavity structures is expected to be the dominating source of field perturbations in the TESLA cavities. The resonance frequency changes with the square of the gradient, resulting in a frequency change of approximately 600 Hz at the design gradient of 25 MV/m. The cavity bandwidth (half width) is 230 Hz; therefore phase changes during cavity filling are significant. It is necessary that the cavity drive frequency track the cavity resonance frequency during the filling process. This can be accomplished by use of a self-excited loop or a phase locked loop using a variable controlled oscillator (VCO). During the beam pulse the drive frequency will be held constant and independent feedback loops for phase and amplitude can be applied. Measurements from A. Mosnier [8] have shown, however, that due to the mechanical properties of the cavity its resonance frequency still changes after the nominal field has been reached. The resulting tuning errors can be minimized to about 6° by introducing a frequency jump of 200 Hz prior to the injection of the beam as shown by Henke and Littmann [9]. Since one klystron drives 16 cavities, it must be demonstrated that the resonance frequencies of the individual cavities are tracking each other sufficiently well to meet the phase stability requirements.

The effects of errors in cavity tuning, microphonics, fluctuations of generator power and phase, and beam loading have been studied [10]. It is planned to apply fast feedback for gradient and phase during the beam pulse using the vector-sum signal of the 16 cavities.

Conclusion

The technology of precision control of large rf systems is well understood. Requirements of 0.1% amplitude and 1° phase stability can be met within rf pulses, pulse to pulse and long-term. Long-term stability control requires a beam based reference signal. Challenging goal is 0.1% amplitude and 0.1° phase stability. The sources of field perturbations are identified. They are different for pulsed and cw machines. Various methods of suppression of perturbations have been developed for future linear colliders and have been successfully tested in dedicated test facilities.

CEBAF has demonstrated that in superconducting rf structures which are operated cw, an amplitude stability of 0.02% and a phase stability of 0.08° can be achieved.

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