DESIGN OF THE RF PHASE REFERENCE SYSTEM AND TIMING CONTROL FOR THE TESLA LINEAR COLLIDER

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Abstract

The frequency distribution system for the TESLA linear collider must deliver a highly phase stable rf signal to the 616 rf stations over a length of 33 km. At the operating frequency of 1300 MHz a short term and long term stability of the order of 1 degree with respect to the accelerated beam is required. Our solution involves three coherent oscillators, a 9 MHz low loss coaxial cable distribution, 1.3 GHz fiber optics, and continuous calibrations based on beam phase measurements. This system is transparent to beam operation and will continually monitor and correct slow phase drifts.

1 INTRODUCTION

The overall layout of the TESLA linac [1] is sketched in Figure 1. The main elements are two linacs with a length of 2×12 km, the damping rings which make use of the linac tunnel, the source for electrons (laser driven rf photocathode gun), the source for the positrons which is based on the concept of high-energy photon conversion into e^+e^-, and a 3 km region for the beam delivery system in between the two linacs. The photon are generated by the spent high-energy electron beam passing a wiggler. The acceleration system in each linac consists of 9856 superconducting cavities which are powered by 308 klystrons (32 cavities per 10 MW klystron)

The various rf system that must be phase synchronized with picosecond stability over the full accelerator length are:

- the 616 rf systems operating at 1300 MHz in the two superconducting linacs.
- The 433 MHz rf systems for the damping rings
- the 1300 MHz rf system providing power to the photocathode rf gun of the electron source and the associated laser for illumination of the photocathode.

The timing system must guarantee that the bunches which are spaced by 337 ns (3 MHz repetition rate) arrive at the same time at the interaction region.

2 RF DISTRIBUTION STABILITY REQUIREMENTS

The phase stability requirements for the accelerating field in the linac cavities are dictated by the low beam energy spread requirement of $\sigma_E/E < 7\times10^{-4}$ and the timing requirements for the bunch arrival at the interaction point. Assuming that a third of the energy spread contribution originates from phase fluctuations of the accelerating field a correlated phase error of only $\sigma_\phi = 0.4°$ at 1300 MHz corresponding to a timing error of 0.8 picoseconds can be tolerated.

The phase stability of the 433 MHz rf systems of the damping rings determines that arrival time of the bunches at the interaction point. The interaction position error should not exceed one bunchlength (1 mm) resulting in the same timing stability requirements as dictated by the low energy spread.

In addition to the rf phase reference system a timing system with event coding capability is required to allow for real time synchronization of the various rf and other subsystems. The electron and positron bunches must be accelerated in selected rf buckets (every 438^{th} bucket, this number is given by the ratio of bunch spacing and the period of one rf cycle) to guarantee that the collision takes place in the center of the detector. A misplacement by 1 bucket would result in a collision position error of 23 cm (λ=c/f=23 cm). Therefore the timing system for the rf gun must guarantee a trigger signal stability of better than 770 ps. The timing system clock will also be synchronized to the master oscillator and can therefore provide phase stable timing for the digital feedback and rf system monitors.

3 DESIGN CHOICES AND ISSUES

The four basic choices for a phase stable reference system are:

- coaxial distribution system
- fiber optic distribution system
- coherent oscillators
- beam pickup

All systems with the exception of the beam pickup require a beam based calibration scheme since calibrations by measurement of the electrical length of the subsystems is not sufficiently accurate. It is desirable to use a fast coarse calibration scheme for initial start-up of the accelerator and a slow and precise calibrations scheme which is active during accelerator operation and which is transparent to the beam experiments.

The rf distribution system for the TESLA linear collider has been designed as a combination of all of the above options to utilize the advantages of each of the systems thereby maximizing performance and providing some level of redundancy.

The design employs a coaxial distribution system in the linacs. It provides a phase stable 9 MHz signal to all of the 616 rf stations in the linacs and the 433 MHz systems in the damping rings. The signals are locally multiplied by 144 or 36 respectively. Coherent oscillators operating at 9 MHz are located at the beginning of each linac close to the 433 MHz rf systems (also close to rf gun for electrons and auxiliary positron source) and in the experimental hall

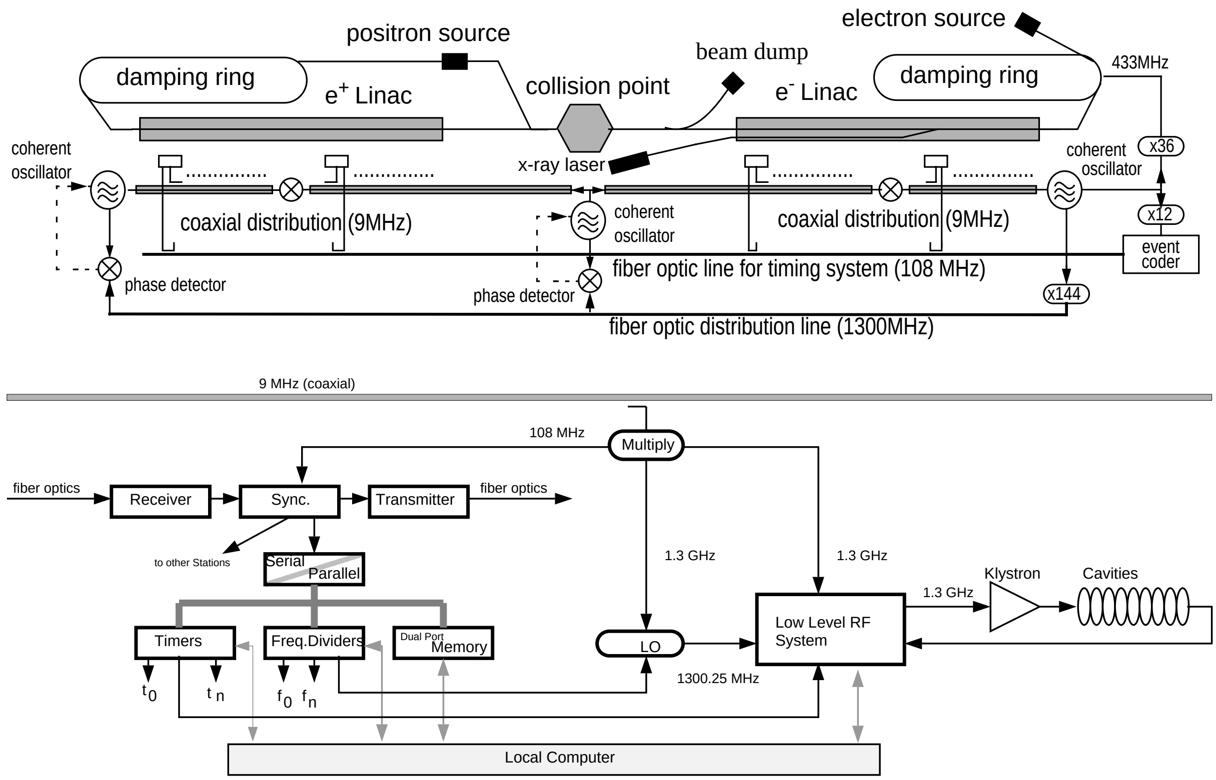

Figure 1 : Overall layout of the TESLA Linac. The phase reference system and timing control distribution are shown.

between the linacs. The three oscillators are synchronized by a optical fiber system. Each of the oscillators provides the reference signal for half of the linac closest to it. All systems are measured against each other and calibrated with reference to the beam utilizing the beam induced transients.

3.1 Coaxial Distribution System

The distribution of rf signals by coaxial cables or waveguides appears to be the most obvious solution since the rf signal can be transported directly to its destination. For the distribution to many rf stations directional couplers are recommended for good isolation between the tap points. This scheme allows for relatively high power levels of up to a few hundred watts at the input of the distribution line and can provide several milliwatts to several watts of rf power to each station. The main parameters that need to be considered for a coaxial distribution system are:

- frequency to be distributed
- distance between signal source and destination
- numbers of destinations to which the signal must be supplied
- power level of signal required at destinations
- power level available at signal source
- attenuation of coaxial cable
- power handling capability of the cable and the directional couplers
- thermal stability (phase stability of cable)
- number of amplifier needed within the distribution system
- sensitivity to microphonics

In the case of TESLA it is advisable to distribute a lower frequency and to convert the frequency locally to the operating frequency by use of multipliers. This method reduces the rf losses in the distribution system significantly. The lower frequency limit is given by the efficiency, noise characteristics, and phase stability of the local frequency multipliers.

For the TESLA accelerator the operating frequency is 1300 MHz but the coaxial frequency distribution along the linac is operated at 9.0278 (= 1300/144) MHz. The signal sources - H^--masers controlled low noise oscillator operating at 9 MHz and boosted by 200 W amplifiers - are located at the beginning of each linac and in the experimental hall between the linacs. For the coaxial distribution system a 1 5/8” (type LDF-50A1-5/8-inch Heliax) cable has been chosen because of its low insertion loss of 0.2 dB/100 m, the excellent phase stability (10 ppm/deg. C) and power handling (42 kW) capability. With a group velocity of 0.88c this results in a phase sensitivity of 177 deg./°C/10 km. The actual sensitivity may deviate from this number since the cable cannot expand freely due to its own mass.

The directional couplers (type HDC1460 from HD Communications) exhibit an insertion loss of 0.15 dB /

coupler. The distribution scheme for the linac is shown in Figure 1. Input power for each of the 7 km long sections is 200 W. The number of couplers has been reduced to 50 with a spacing of 120 m. A three way power splitters feeds a subnet consisting of LDF 1/2” cable to the two adjacent stations. The 9 MHz signals are then locally multiplied by 144 in the linacs and 36 at the damping ring rf systems.

3.2 Fiber Optic Distribution

Over the past years, fiber optic distribution links have replaced coaxial cable distribution for phase reference systems [2]. Optical fibers are the preferred medium for distribution because of their low attenuation, immunity to EMI/RFI, and temperature stability.

The thermal coefficient of delay for a typical optical fiber is of the order of 7 ppm/°C and therefore comparable to that of phase stabilized coaxial cables. A LCD coated optical fiber from Sumitomo [3] which has been specifically designed for high thermal stability provides a stability of better than 0.4 ppm/°C at an operating temperature close to 0°C. At a more realistic operating temperature of 30°C the coefficient increases to 1 ppm/°C. The group velocity in this fiber is 0.66c resulting in a phase sensitivity of 23.6 deg./°C/10 km.

The phase noise characteristics of a fiber optic distribution system suffers from the low signal levels retrieved at the individual receivers. The minimum phase noise level at 1300 MHz is expected to be around -100 dBc (> 10 kHz) [2] corresponding to an rms phase error of 0.57 deg. or 1.2 ps timing jitter which is marginal for our application.

3.3 Coherent Oscillators

The timing stability requirements between two remote locations such as the rf stations for the damping rings which are separated by a distance of 32 km could be fullfilled with two absolutely coherent oscillators. Present technology utilizing a H^- Maser allows for a frequency stability of $2x10^{-13}$/s corresponding to a phase stability of about 0.1 deg./s (or 0.2 ps/s) thereby exceeding the requirements for intrapulse and pulse-to-pulse stability. Even oven stabilized crystal oscillators can achieve a stability of the order of 2×10^{-12}/s which might be sufficient.

The coherent oscillators will be synchronized with the fiber optic distribution system with a time constant of 10 - 100 s to ensure long term stability.

3.4 Beam Based Phase Calibration

The ultimate reference for the rf systems in the linacs, the damping rings, and the timing of the bunches at the collission point will be the beam itself. It is therefore foreseen to synchronize all rf systems with respect to the beam. To achieve a measurement accuracy of better than 0.5 deg. or 1 ps, the transient beam loading based algorithm must average over several hundred measurements resulting in a measurement time of up to 100 seconds. Therefore the beam based phase correction can take place at a time scale of 100-1000 s.

4 TIMING CONTROL

The timing system provides various triggers and fixed frequency signals as well as machine parameters in a dual-port memory. A central timing signal source is synchronized with the master oscillator. This signal source generates encoded telegrams and sends them via a fiber optic distribution system to all devices along the linac and the damping rings. Repeaters every 120 meter receive the signals, resynchronize them with the 9 MHz, distribute the data to the local equipment and retransmit the signals to the next stations. The received serial telegrams have to be encoded and converted into parallel data streams. This data stream contains events and data words from the master station. Since the telegrams are synchronized with the main oscillator fixed frequencies with low phase errors can be derived from the telegrams also. The data stream is used to filter events in a timer unit and data words in the dual port memory. Programmable timers are triggered by these events to generate the start pulses for the klystrons or digital signal processors for instance. A timer unit provides several independent output channels. Some machine parameters that change from macro pulse to macro pulse need to be delivered in time to run all digital feedback loops in parallel. The data words from the telegrams are stored in a dual port memory. This information is readable from the local connected computers or signal processors.

5 CONCLUSION

The design of a rf phase reference and timing system for the TESLA linear collider is a challenging task due to the tight timing stability requirements of about 1 picosecond over a distance of more than 30 km. It should be possible to meet these requirements if a combination of coaxial distribution, optical fiber distribution, coherent oscillators and beam based calibration is used. It is planned evaluate the performance of such a scheme at the TESLA Test Facility.

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