DESIGN CONSIDERATIONS FOR PHASE REFERENCE DISTRIBUTION SYSTEM AT ESS

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Abstract

Coaxial cable based solution and optical fibre based solution are discussed in this note for PRDS (Phase Reference Distribution System) at ESS. Some possible schemes in each of these two distribution solutions are introduced and comparisons among these schemes are made. Some efforts have also been made in this paper to try to figure out the requirement and find a reasonable design for PRDS at ESS.

INTRODUCTION

PRDS (Phase Reference Distribution System) will be serving as the phase alignment line for RF cavities and beam instrumentations with high phase stability, i.e., with low phase noise and low phase drift. At ESS with preliminary design of individually RF source powering for most cavities, phase reference distribution system should provide the reference signals for totally 34 LLRF systems at 100 meters long low-frequency section (for all 352.21 MHz cavities, including RFQ, DTL, bunching cavities and spokes), and for totally 180 LLRF systems at 342 meters long high-frequency section (for all 704.42 MHz cavities, including medium beta and high beta elliptical cavities) [1]. A detailed linac layout and RF sources distribution can be seen in Figure 1 [2, 3].

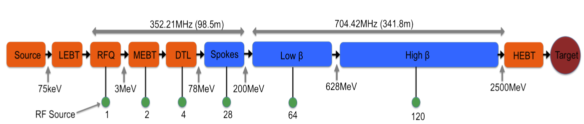

Figure 1: ESS Linac Layout and RF sources distribution.

The system will provide phase reference signals also for beam instrumentations such as BPMs and BSMs. There is much in common between phase reference signals for RF cavities and beam instrumentations. Detailed design for beam instrumentation is carried out at ESS now and will be introduced in later work.

DESIGN CONSIDERATION

There are a variety of approaches to distribute the RF reference signals and many new technologies are being applied worldwide. As coaxial-cable-based distribution and optical-fiber-based distribution are the two most commonly used solutions for PRDS in Linac accelerators, we will therefore focus in later sections on possible schemes based on these two distributions and try to make a reasonable design for PRDS at ESS.

COAXIAL CABLE BASED DISTRIBUTION

System Topology

Coaxial cable is a very conventional medium to distribute the RF reference signal, by which RF signal can be transmitted directly from source to destinations. For a linac with multiple LLRF systems, a bus-like topology is preferred with a main cable line running the RF power and many tap points along the line delivering required signals to each of LLRF systems. The bus-like topology distribution has the advantage of less volume, less power attenuation and easier to implement compared to star topology. Directional couplers are the most-commonly used components at tap points to extract the RF power due to that they provide good isolation between adjacent systems [4].

Phase Drift Control for Main Reference Line

Temperature Control As phase drift in cable is mainly caused by temperature change, an obvious way to reduce phase drift is to control the temperature around cable within a small range. For 704.42 MHz section, phase drift due to temperature change is ~ 3°/° C over the whole line (assuming temperature coefficient of the cable is 10 ppm/°C). Therefore, to maintain the phase stability within ±1° over the whole linac, the temperature range of the cable should be controlled within ±0.3°. Temperature can be controlled in different ways such as cooling water at JPARC [5] and PID temperature controllers at SNS [6].

Phase Averaging Instead of controlling the temperature range of the cable, in phase averaging method it combines reflected and forward signals along cable and takes their averaged phase as reference phase [7]. Figure 2 shows a possible schematic diagram of phase averaging scheme for PRDS at ESS.

RF signal is reflected by a short placed at the end of cable, and a standing wave superposed by forward and reflect signals is formed along the cable. The average phase does not depend on the length changes of the cable since the phase variations due to length changes in forward signal and reflected signal will eliminate each other. One disadvantage of this method is that it employs a long PLL feedback line which might introduce many noise and large delay. A modified phase averaging scheme at Fermilab

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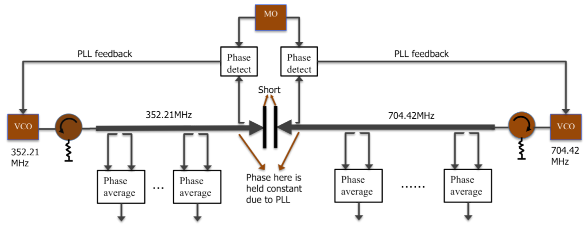

Figure 2: Phase drift control by phase averaging.

can reduce this effect but at a cost of longer main cable and bigger attenuation [8]. Another disadvantage of phase averaging scheme is that bi-directional couplers and additional components in phase average module such as attenuators and combiners have to be employed. Careful design and patient adjustment for cables and components must be taken to obtain good performance in phase averaging.

Active Drift Compensation Active drift compensation refers mainly to an approach in PRDS in which the phase drift of cable is measured by reflectometric method and controlled by active devices such as electrically controlled phase shifters. The concept of reflectometric method is to measure the phase difference between forward signal and reflected signal, which reflects phase drift along the cable. It is an attractive and effective way in maintaining a good phase stability in star topology PRDS system with few LLRF systems. However, in a bus-like topology system with a large number of tap points, it is quite difficult to implement since additional phase drift measurement module and control module are required for every channel from tap point to LLRF system.

Local Distribution

Local distribution refers to the route from tap point of the main reference line to corresponding LLRF system. Due to the radiation environment in tunnel at ESS, it is easier to place down-conversion and other electronics in klystron gallery instead of tunnel. However, it leaves a long cable uncompensated from cavity probe point to LLRF system of a length 20 ~ 30 meters and results in a non-negligible phase drift in long term (~ 0.3°/°C over 30 meters at 704.42 MHz for a cable with temperature coefficient 10ppm/°C). A point-to-point local distribution scheme is then used to compensate this effect, which is shown in figure 3 and has been implemented at SNS [6].

The disadvantage of point-to-point local distribution scheme is that there are a number of tap points along the main reference line and the distance between adjacent tap points is small, which increases the complexity of system and brings difficulties to maintenance. For instance, totally 214 directional couplers are required at ESS linac to implement point-to-point distribution scheme. To reduce the number of tap points, a point-to-multipoint local distribution scheme is proposed. Instead of having individual local reference line parallel to each of cavity probe signals, point-to-multipoint scheme provides a local line for every four probe signals, which is shown in Figure 4. As a result, only around 60 directional coupler are required and the distance between adjacent couplers will reach up to 8 meters in 704.42 MHz section.

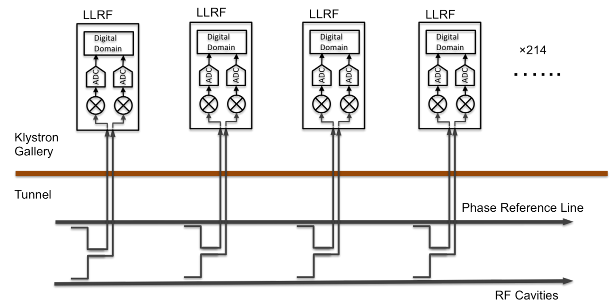

Figure 3: Point-to-point local distribution.

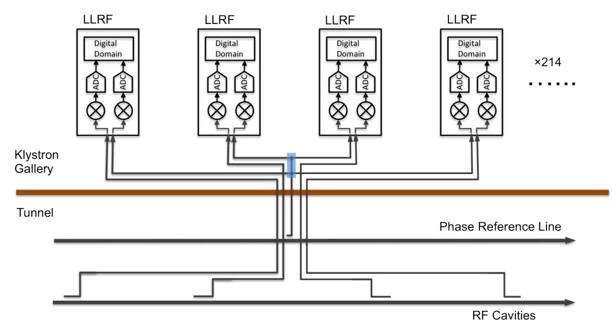

Figure 4: Point-to-multipoint local distribution.

The drawback of this scheme is that the phase drift in cables from cavity probe points to reference line tap point is unable to compensate and an additional power splitter is needed in gallery for every four LLRF systems. As the length of the longest uncompensated cable is not significant (~ 4 meters long, and ~ 0.03°/°C at 704.42 MHz for a cable with temperature coefficient 10ppm/°C), total phase drift could be kept small enough if we choose carefully the cable and the power splitter.

OPTICAL FIBER BASED DISTRIBUTION

System Topology

Optical fiber has been popular over the recent years at linac light source and FEL(Free Electron Laser) having long distance linac and very high field stability requirement. Many new technologies are developed to meet these stringent requirements. Optical fibers are preferred for point to point distribution for their small size and low attenuation and a star-topology is usually applied in optical fiber based PRDS. Optical fibers face difficulties to run high power signal larger than 1W, which might be also one of the reasons why it is rarely run in bus-like topologies.

One drawback of fiber based distribution is that additional phase noise is introduced into PRDS due to the use of active components such as optical transmitter (E/O) and optical receiver (O/E).

Phase Drift Control for Optical Fibers

Temperature Control Temperature variation of optical fiber affects changes of both the refractive index and physical length, thereby affecting the time delay in a fiber, which can be written as [9]. Similar to the coaxial cable based distribution, to maintain the phase stability within $\pm 1°$ over the whole linac, the temperature range for a normal optical fiber should be controlled within $\pm 0.3°$.

Active Drift Compensation A star-topology with fibers running from point to point makes it relatively easier to implement active drift compensation compared to coaxial cable based bus-like topology. In such a drift compensation scheme, feedback control by fiber length adjuster or phase shifter is commonly employed to keep a constant phase at output. The short term (seconds) phase stability of this scheme showed in some experiments has achieved up to the level of 1ps [7]. .

Higher precision could be achieved by elegant design or advanced technologies. Some experiments have demonstrated a sub-100 fs precision such as pulsed optical distribution scheme [10] and frequency-offset Michaelson interferometer scheme [11]. However, the level of complexity and the cost of corresponding compensation schemes increase as the precision goes higher.

Local Distribution

Optical fibers and optical receivers at ESS are expected to place in klystron gallery instead of tunnel due to radiation environment in tunnel. Radiation-induced attenuation of fiber is a critical issue to be noted when using fibers in radiation environment. Special attention should be paid and adequate tests are required for radiation-induced effects when applying the optcial fibers and related electronics in radiation environment. Figure 5 shows a possible local distribution for fiber based PRDS system. It can be seen obviously that the phase drift of cavity probe signal from tunnel to klystron gallery cannot be compensated with the method taken in coaxial cable based system. Moreover, phase variation in optical receiver is temperature dependant as well. Therefore, temperature control for the cavity probe signal and optical fiber receiver is required.

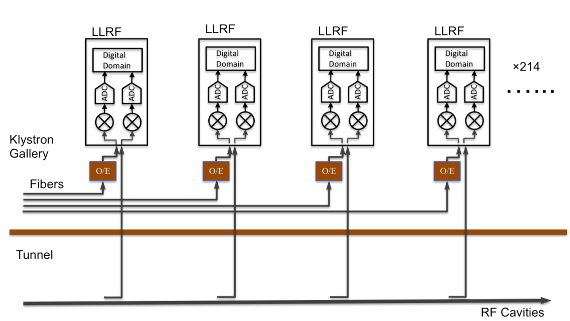

Figure 5: Local distribution in fiber based solution.

CONCLUSION

Both coaxial cable based distribution system and optical fiber based distribution have been discussed and rough comparisons are made based on possible implementation schemes mentioned in this paper. With temperature control for main reference line and point-to-multipoint local distribution scheme, coaxial cable solution seems to be a simpler way to implement and to maintain for PRDS at ESS, but careful design and consideration should be taken on temperature control for both main line and local distribution. On the other hand, optical fiber solution is more flexible for active drift compensation without considering temperature issue for main lines and could achieve better precision, but at a price of increased complexity and cost. At last, even if optical fiber itself is much cheaper than coaxial cable, additional device like optical transmitters and receivers might make the total cost of optical fiber solution with temperature control comparable to coaxial cable solution.

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