Design Considerations for Phase Reference Distribution

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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 note to try to figure out the requirement and find a reasonable design for PRDS at ESS.

1 Introduction

PRDS (Phase Reference Distribution System) will be serving as the phase alignment line for all cavities with high phase stability, i.e., with low phase noise and low phase drift. The system starts at the output of the master oscillator and ends at the inputs of the LLRF systems. 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 352.21MHz cavities, including RFQ, DTL, bunching cavities and spokes), and for totally 180 LLRF systems at 342 meters long high-frequency section (for all 704.42MHz cavities, including medium beta and high beta elliptical cavities). A detailed linac layout and RF sources distribution can be seen in Figure 1[1, 2].

Timing system, local oscillator signals and clocks for special purposes such as for ADC, DAC and digital signal processing will be included in other systems and they will therefore not be considered in this note.

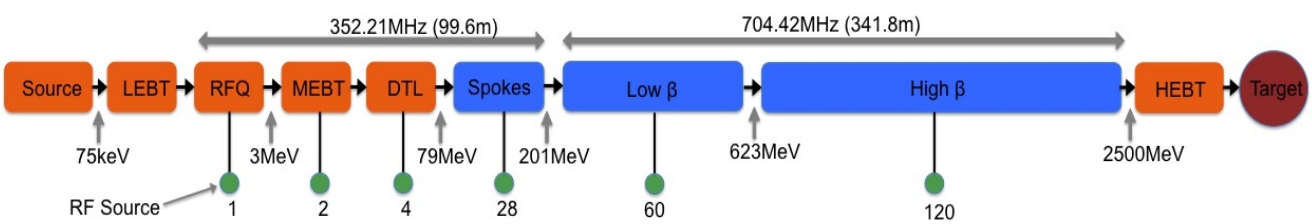

Figure 1: ESS Linac Layout and RF sources distribution

2 System Requirements and Design Considerations

To keep required beam energy spread in ESS linac, RF accelerating field error of each cavity in linac must be maintained within ±1% in amplitude and within ±1° in phase. The phase error budget in PRDS is expected to be more stringent since we have to keep enough margin for other error sources and uncertainties. Our goal at the moment is to achieve a phase error ±0.1° in short term (during beam pulse) and ±1° in long term (hours to days) in PRDS. The short term error comes mainly from the phase noise in master oscillators and other active components, while the long term error results mainly from the phase drift along the reference line due to ambient temperature changes. Apart from the field stability requirement, many other requirements and issues have to be considered as well in PRDS when making a design. The main ones are listed below:

- Delivery medium
- Topography
- Frequencies to be delivered
- Input and output power level
- The number of stations to be delivered
- The length from master oscillators to each station

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.

3 Coaxial Cable Based Distribution

3.1 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 system[3].

A phase reference distribution scheme based on coaxial cable has been investigated at ESS and an overall system topology diagram is shown in figure 2. As the linac length is of the order of several hundred meters, the same rf frequencies as the ones run in cavities are chosen to deliver in order not to introduce additional components such as frequency multipliers and dividers in local LLRF system. MO (Master Oscillator) is considered to place in between 352.21MHz section and 704.42MHz section to reduce the reference cable length in both sections. It should be noted that MO will be located in

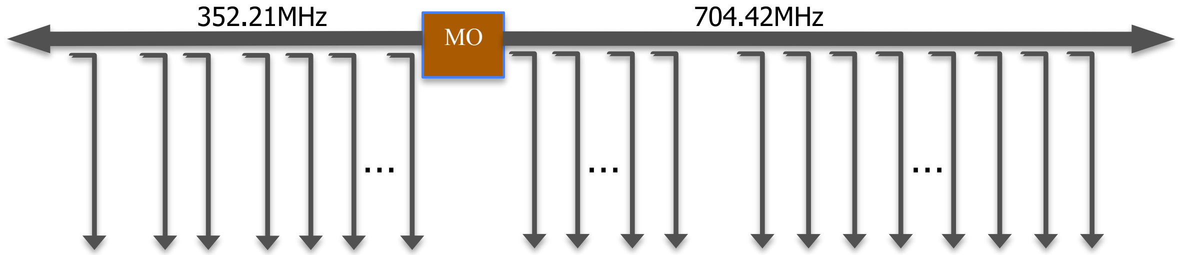

Figure 2: System topology diagram for coaxial cable based distribution scheme

klystron gallery due to radiation in tunnel, while reference lines are expected to be in tunnel to get close enough to the cavity probe signals. The reference lines will cover both around 100-meter 352.21MHz section (including RFQ, DTL, bunching cavities and spokes), and around 342-meter 704.42MHz section (including medium beta and high beta elliptical cavities).

3.2 Phase Drift Control for Main Reference Line

3.2.1 Temperature Control

The physical length of a coaxial cable changes as the temperature of cable increases or decrease, resulting in changes in signal phase. The relationship between phase changes and temperature variations can be written as[4]:

$$\Delta\theta = \frac{360 \times P \times L \times \Delta T \times F}{v} \tag{1}$$

where, $\Delta\theta$ is the phase change in degrees, P is the phase-temperature coefficient of cable, L is the length of cable in meter, ΔT is the temperature range, F is the frequency in MHz, and v is the propagation velocity of the signal in cable. The phase-temperature coefficient of a typical coaxial cable is of the order of ~ 10 ppm/°C.

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 special PID temperature controllers at SNS[6].

3.2.2 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. The concept is originally from J. Frisch[7] and proposed as part of phase reference distribution for NLC . Figure 3 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 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.

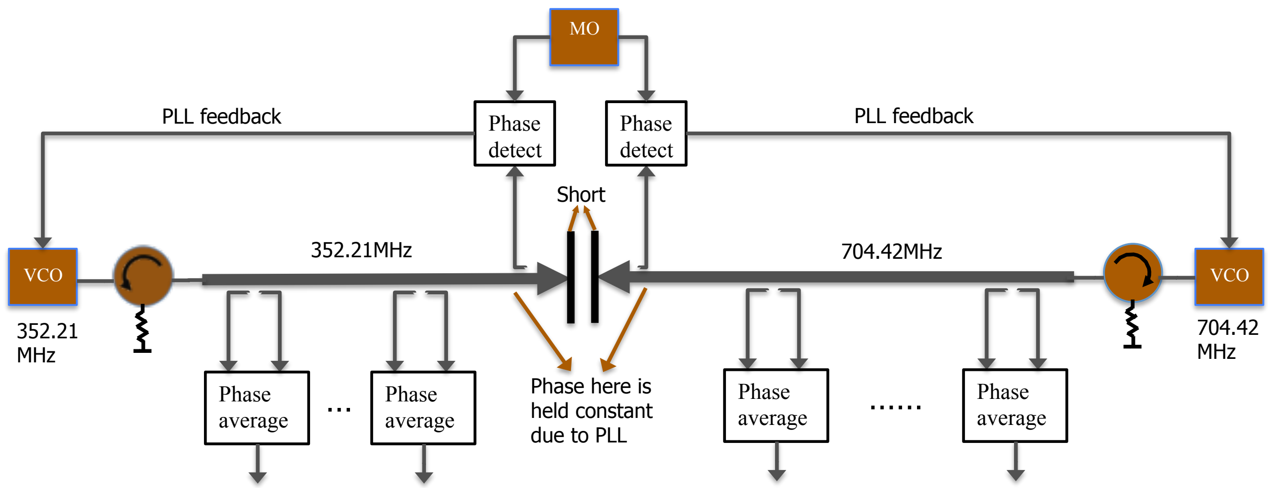

Figure 3: Phase drift control in main reference line by phase averaging

3.2.3 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 is required for every channel from tap point to LLRF system.

3.3 Local Distribution

Local distribution refers to the route from tap point of the main reference line to corresponding LLRF system. In modern accelerators, cavity phase detection is usually done in LLRF system in a way that the cavity probe signal is firstly down-converted by LO (local oscillator) to IF signal and then sampled into digital domain where phase and amplitude information is finally detected. The reference signals have to be sent to each of LLRF systems as well to calibrate long-term phase drift in cable and down-conversion. The LO signals and clocks in LLRF systems could also be generated locally from the reference signal.

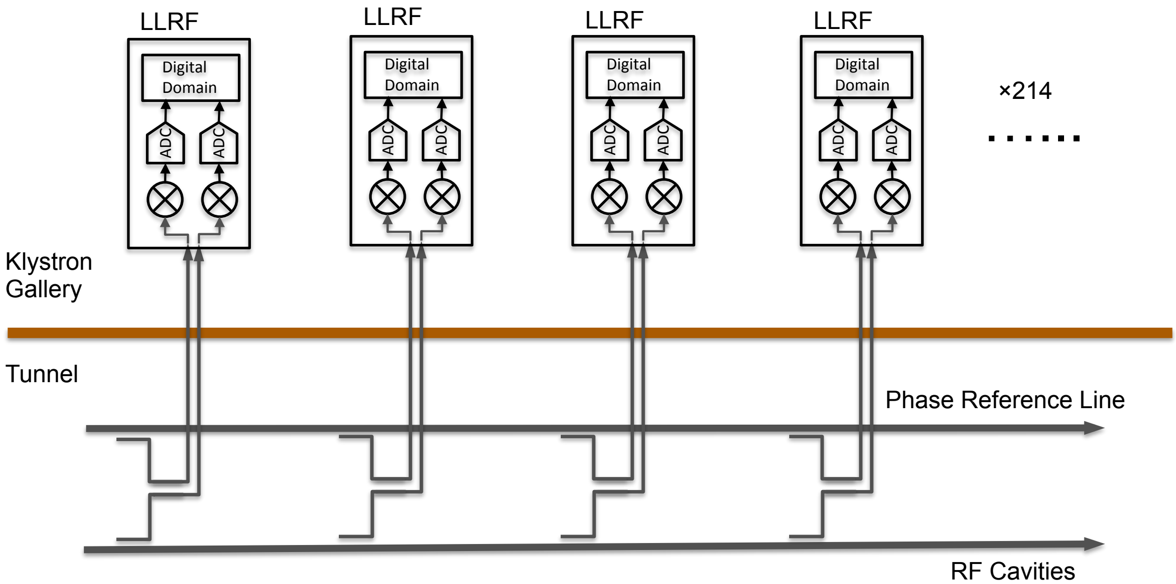

Figure 4: Point-to-point local distribution

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 4 and has been implemented at SNS[6]. At each cavity location point, there is a reference signal close enough to the cavity probe signal and going the same route as the probe signal does. The two signal channels will experience identical phase drift resulting from ambient temperature change and thus the drift could be calibrated in digital domain, if the cables, the connectors, the down-conversion and other related components are identical in these two channels.

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 while the distance between two couplers is less than 2 meters in 704 MHz section.

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 5. 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. 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.

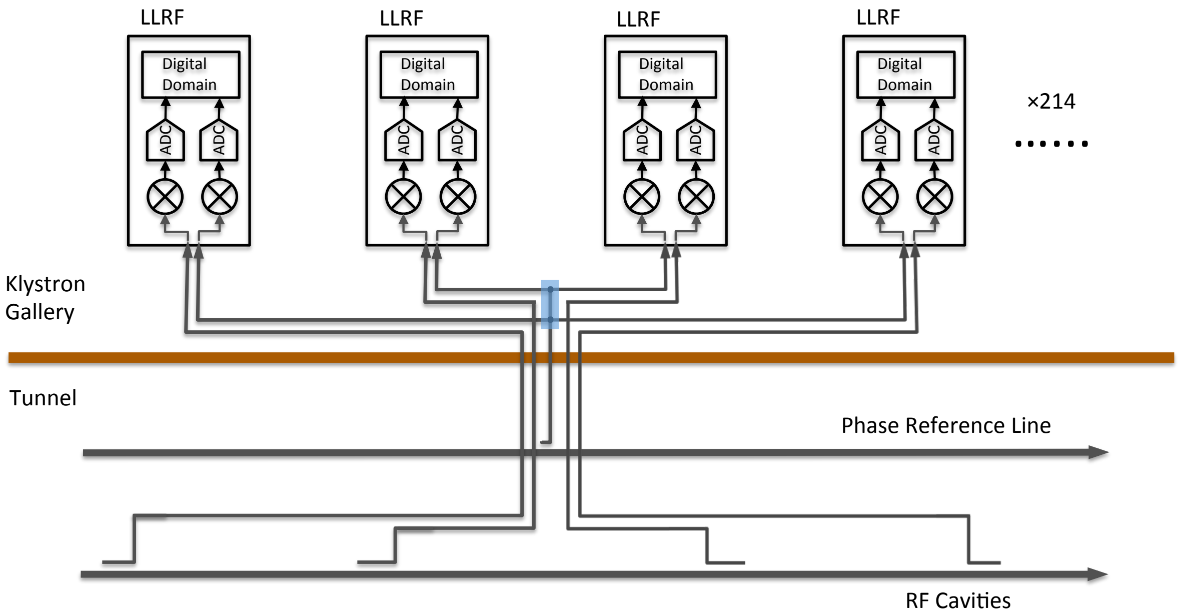

Figure 5: Point-to-multipoint local distribution

3.4 Power Level Assignment

Power level at the tap point is estimated at 15dBm, assuming that 13dBm RF signal is expected at LLRF system (for downconversion, LO and clocks, and probably BPMs) and there is 2dB power loss from tap point to LLRF system. In additional, for the 704MHz section, the power loss is 5 ~ 10dB at a length of 342 meter cable, the pure loss of a typical directional coupler with 10 ~ 30dB coupling factor is around 0.15 ~ 0.25dB (including conductor loss and VSWR loss, but not coupling loss), and the insertion loss of a N type connector is ~ 0.05dB.

A rough estimate for the total power loss and required power level at input of reference line can be made after knowing the numbers and values above. For point-to-point local distribution scheme, the total power loss along a single 704.42MHz reference line could be up to 60dB since there are 180 directional couplers to be used. Multiple amplifiers or multiple reference lines are required to compensate the power loss. On the other hand, the power loss is much less in point-to-multipoint local distribution scheme, where only around 50dBm is estimated for 704.42MHz reference line and therefore sigle amplifier and single reference line could be capable to provide required power level at LLRF system.

4 Optical fiber Based Distribution

4.1 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. Figure 6 shows a possible star-topology scheme for optical fiber based distribution. 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).

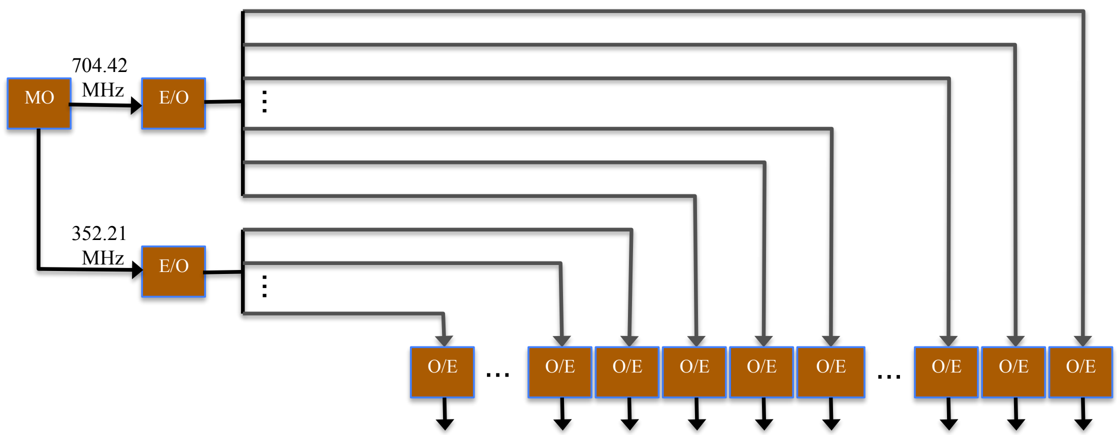

Figure 6: Schematic diagram for optical fiber based distribution

4.2 Phase Drift Control for Optical Fibers

4.2.1 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]

$$t = \frac{NL}{c} \tag{2}$$

$$\frac{dt}{dT} = \frac{1}{c}\left(N\frac{dL}{dT} + L\frac{dN}{dT}\right) \tag{3}$$

where t is the travel time along the fiber, c is the speed of light, T is the temperature, L is the fiber length and N is the refractive index of the fiber glass. The first term in equation 3 describes the contribution from the temperature effect on refractive index, and the second term describes the contribution from the thermal expansion effect on physical length. The second term is much smaller compared to the first term for silica fibers which are most commonly used fibers today. The thermo-optic coefficient $\frac{1}{t}\frac{dt}{dT}$ of a silica fiber is comparable with coaxial cable and is of the order of ~ 10 ppm/°C. In Jparc, a specifically designed phase stable optical fiber has been used with very low temperature coefficient ~ 0.4 ppm/°C, which is coated with a liquid-crystal polymer having an proper thermal expansion coefficient to eliminate the fiber's refractive index change due to temperature variation. However, phase stable optical fiber is rarely used and only produced by one company[5].

Similar to the coaxial cable based distribution, to maintain the phase stability within ±1° over the whole linac, the temperature range for a normal optical fiber should be controlled within ±0.3°.

4.2.2 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. A typical phase drift compensation scheme for fibers is shown in Figure 7, which was a proposed 15km long optical fiber distribution solution for NLC[7]. 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.

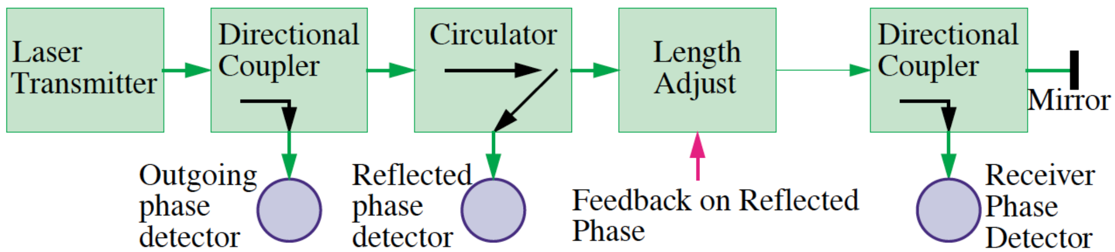

Figure 7: Typical phase dirft compensation scheme for optical fiber[7]

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.

For PRDS at ESS severing a large number of LLRF systems, the disadvantage of active drift compensation is that there are a large amount of additional components and modules (phase detect, feedback control) to be applied in system and it might probably bring into additional phase noise in short term and additional phase drift in temperature-dependant components in long term.

4.3 Local Distribution

Optical fibers and optical receivers 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. The amount of the attenuation depends on radiation condition (total dose, dose rate, temperature, etc.) and varies strongly from a fiber to another. Some data shows that the attenuation of a standard commecial single mode fiber SMF-28 varies from 1dB/km to 20dB/km in different dose rates at a total dose level of 1000 Gy[12]. Another important effect of radiation on fibers for PRDS is radiation-induced refractive index changes. Some experiments indicate that the refractive index changes of single mode fibers under heavy radiation condition are of the order of $10^{-3} \sim 10^{-4}$ (100 ~ 1000 ppm)[13, 14]. 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 8 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

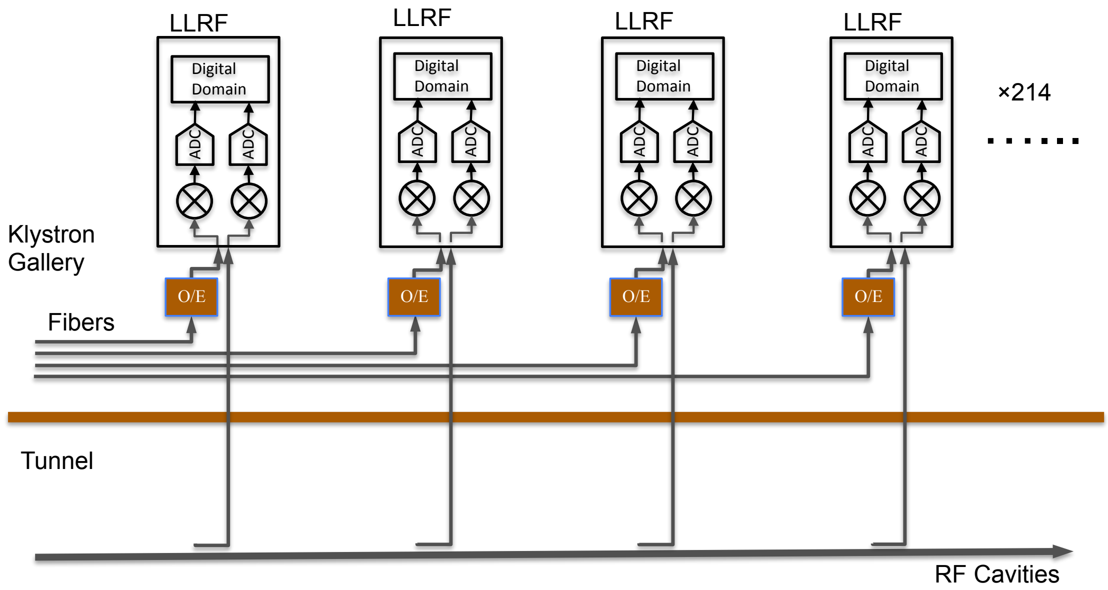

Figure 8: Local distribution in fiber based solution

temperature dependant as well. Therefore, temperature control for the cavity probe signal and optical fiber receiver is required.

A point-to-multipoint local distribution scheme similar with the one in coaxial cable based system could be also implemented in optical fiber system by using optical couplers or dividers. The fiber layout in local distribution changes little but the number of total fibers could reduce significantly.

5 Conclusion

Both coaxial cable based distribution system and optical fiber based distribution has been discussed and rough comparisons are made based on possible implementation schemes mentioned in this note. 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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