OVERVIEW OF THE RF SYNCHRONIZATION SYSTEM FOR THE EUROPEAN XFEL

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Abstract

An important requirement for the European XFEL RF system is to assure a precise RF field stability within the accelerating cavities. The required amplitude and phase stability equals $^{dA}/_{A} < 3E\text{-}5$, $d\phi < 0.01$ deg in the injector and $^{dA}/_{A} < 1E\text{-}4$, $d\phi < 0.1$ deg in the main LINAC at an RF frequency of 1.3GHz . To fulfil such requirements for the 3.4 km long facility is a very challenging task. Thousands of electronic and RF devices must be precisely phase synchronized by means of harmonic RF signals. We describe the proposed architecture of the RF Master Oscillator and the Phase Reference Distribution System designed to assure high precision and reliability. A system of RF cable based interferometers supported by femtosecond-stable optical links will be used to distribute RF reference signals with required short and long-term phase stability. We also present test results of prototype devices performed to validate our concept.

INTRODUCTION

This paper covers the RF MO and RF phase reference distribution system concept for the E-XFEL. Current status and updated project concept are described here comparing to preliminary version described in 2009 in [1].

The synchronization system for the European XFEL (E-XFEL) facility consists of four subsystems: the RF Master Oscillator (MO), the RF Phase Reference Distribution System (PRDS), the optical synchronization system with the Master Laser Oscillator (MLO) and the timing distribution system.

The RF MO with PRDS provides the RF reference signals for the E-XFEL machine. The MLO is phase-locked to the RF MO. It uses length stabilized optical fiber links to distribute laser light pulses of approximately 200fs duration. The expected performance of the optical synchronization system is below 10 femtoseconds [2]. Due to high cost of such a system, femtosecond stable optical links have been limited to the most phase critical accelerating sections, arrival time diagnostics, and optical lasers such as the photo-injector laser and the pump-probe laser. In addition, due to the long length of the main linac, four locations have been added to phase lock the RF distribution. Due to optical system complexity a high reliability cannot be guaranteed. Therefore, RF distribution links providing sub-100fs synchronization are used to the most critical subsystems.

The picosecond stable timing system will distribute trigger signals and event information necessary for coarse synchronous machine startup and operation. The timing system is locked to the RF master oscillator.

REQUIREMENTS

Figure 1 shows the subsystems that require RF phase reference signals. Only a few devices are located in the injector area, but their stability requirements are most difficult to fulfil (see Table 1).

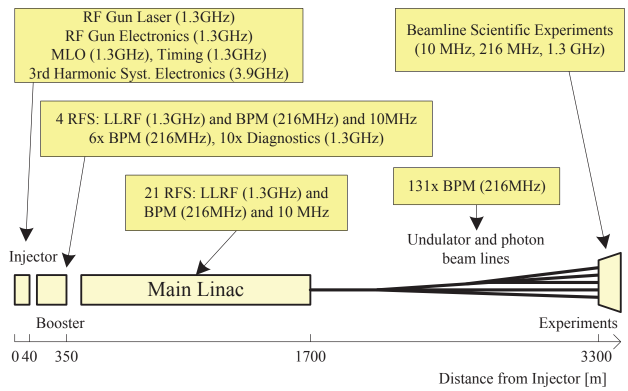

Figure 1: E-XFEL subsystems requiring RF phase reference signals.

Low-Level Radio Frequency (LLRF) controls are located in the injector, booster and at 21 RF Stations (RFS) of the main linac. The LLRF system at each RFS has to process the (forward, reflected, probe signal) from 32 superconducting cavities resulting in 96 signals per accelerating module/RF station. A 1300 MHz phase reference signal has to be distributed to each RF station. The stability requirements for the RF stations are collected in Table 1. Requirements for the other reference frequencies (3.9 GHz, 216.666 MHz = 1/6 * 1.3 GHz) are similar.

Table 1: Stability Requirements at 1300 MHz

Location	Short Term Stability	Long Term Stability
Injector	10 fs	100 fs
Booster Section (L1 and L2)	30 fs	300 fs
Main Linac (L3)	100 fs	<1 ps
Cavity BPM's	60 fs	not specified
Reentrant BPM's	5.8 ps	10 ps

Besides the LLRF system, many diagnostic devices like cavity BPM's require RF phase reference signals too. These devices will be synchronized at 216 MHz which is 1/6 of 1.3 GHz. In the Undulator tunnels the synchronization accuracy for cavity BPM's is less demanding than for the accelerating sections. As the

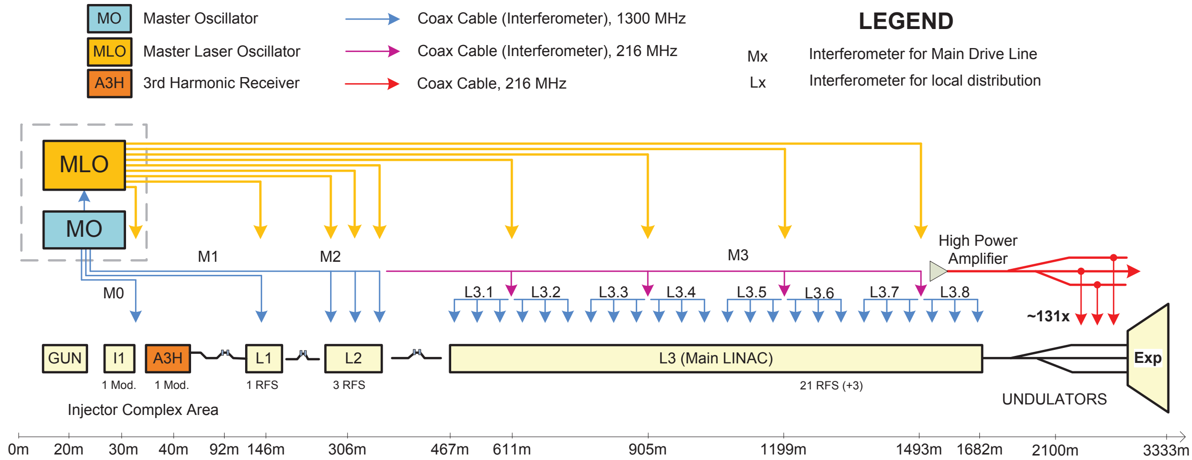

Figure 2: Simplified layout of the RF Phase Reference Distribution System in XFEL.

distribution line is about 1500 m long in 5 parallel photon beam tunnels still makes the design a challenging task

SYSTEM CONCEPT

The simplified layout of the E-XFEL PRDS is shown in Fig. 2. The 1300 MHz reference signal is generated in the MO system. This signal will be delivered to the timing system, to the MLO, to the most demanding accelerator subsystems in the proximity of the injector and further to the RF distribution system.

Master Oscillator

The main function of the MO system is generation of a high performance 1300 MHz signal with a frequency stability of min.10^{-11} by locking the MO to a GPS stabilized reference shown in Fig. 3.

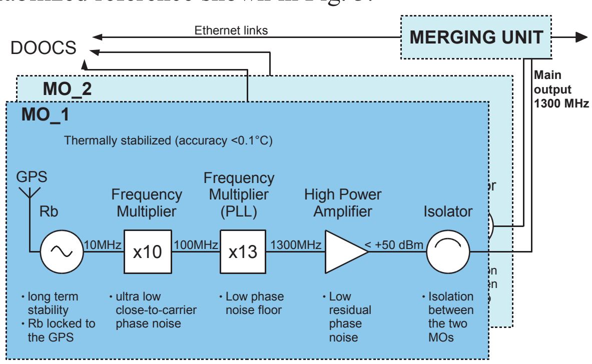

Figure 3: Master Oscillator system architecture.

A GPS disciplined oscillator is considered as primary signal source, which can achieve 10^{-12} stability over 1 day and, doesn't lose the accuracy during the aging process [3]. The required phase noise values are shown in Fig. 4. A prototype of the 1.3 GHz Master Oscillator was assembled using a 100 MHz OCXO and 1300 MHz DRO (see Fig. 3). Tests demonstrated significantly better phase noise performance than required (see Fig. 4). The main challenge in the XFEL MO design is to deliver the reference signal with low probability of interruptions and phase or amplitude transients during the accelerator operation. The operation cost of the facility is significant and an interruption of the RF reference signal may generate significant down time.

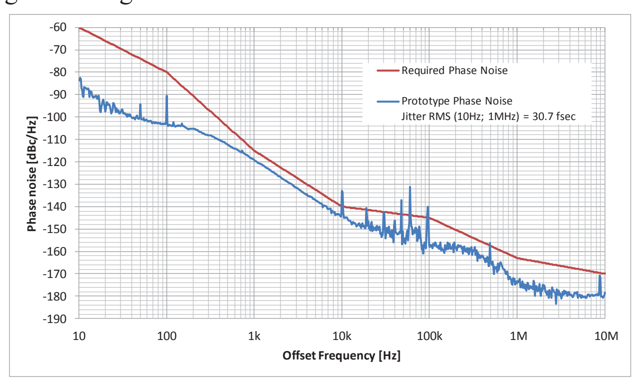

Figure 4: Required and achieved phase noise levels of 1300 MHz signal.

Therefore a redundant concept (shown in Fig. 3) is proposed. In case of a failure the backup unit will take over the operation. However, the challenge of such a system is to provide sufficient small phase and amplitude transients during the switch process. Signal transitions with large glitches or sudden phase jumps could cause the PLLs to loss lock. This would require time-consuming resynchronisation of subsystems in the accelerator. A way of merging the two units is still in the concept stage and several options are investigated currently. The most favourable concept is to use a signal combiner with power level adjustments of both main and redundant MO systems followed by high-quality factor filter to suppress sudden amplitude and phase transitions.

Phase Reference Distribution System

The Phase Reference Distribution System is based on a coaxial cable distribution links for the reference signals. With proper selection of the RF distribution components signal phase noise degradation can be neglected. The most demanding challenge is to overcome the phase drifts and RF cable loss in the system.

A list of cables that could be used for the long distance distribution is limited (due to loss and E-XFEL fire protection regulations) to low-loss corrugated cables of CELLFLEX® or similar type. Cables of $1\,^{5}/_{8}$" and 7/8" diameter with attenuation of 2.6 dB and 4.5 dB per 100 m @ 1300 MHz signal frequency were considered. It is feasible to distribute a 1300 MHz signal directly from the MO to the end of L2 accelerator section with a distance of about 350 m (see Fig. 2). Further distribution has to be carried out at 216 MHz with frequency upconverted locally to 1.3 GHz within the L3 section. This concept is feasible, due to reduced stability requirements in the L3 section comparing to the Injector and L2. One power amplifier (+40 dBm) at the exit of L3 is sufficient to cover the 216 MHz signal distribution within the Undulator section.

The phase-drift origins from electrical changes with temperature. Cables installed in the accelerator tunnel will be exposed to temperature variations due to RF power redistribution, climatization variations after maintenance and show-down periods. The tunnel temperature variations along the accelerator tunnel have been simulated during normal machine operation, after a warm-up period. The temperature exhibits a profile along the tunnel varying between 25 ^{o}C and 35 ^{o}C, with a stability of about ±1 ^{o}C over hours at subsequent locations.

Phase drifts of various cable types (both thick for long distance and thin for local distribution) have been investigated [4]. Fortunately, within the required temperature range, cables selected for long distance distribution exhibit temperature coefficient of phase changes of about 20 to 30 fs/ ^{o}C/m. Cables used for local signal distribution can be selected with coefficients changing down to 0 fs/^{o}C/m and even negative values to compensate for long distance cable drifts.

An analysis of the proposed distribution scheme shows that assuming a temperature change of 2 ^{o}C we expect a total phase drift of about 70 ps at the end of L3. This is approximately 70 times larger than required. Due to cost reasons cable temperature stabilization over such long distance is not feasible. Therefore interferometer links were designed according to idea of J. Frisch, D. Brown, and E. Cisneros [5]. See Fig. 5 for a basic conceptual diagram with 3 outputs. Experiments performed at DESY show that phase drift suppression factors values of 50 to 100 are easily achievable. Higher suppression factors could be achieved with greater effort and probably cost. A suppression factor of 100 is sufficient to fulfill E-XFEL phase drift requirements.

The following numbering of the links will be used in the accelerator tunnel (see Fig. 2). Links named M0, M1 and M2 will cover the distribution requirements of the Injector and Booster sections. Long link with 4 tap points at 216 MHz will deliver reference signals to 8 section distribution links (L3.x) working at 1300 MHz. Link L3.8 is planned for possible future accelerator upgrade of 3 more RF stations.

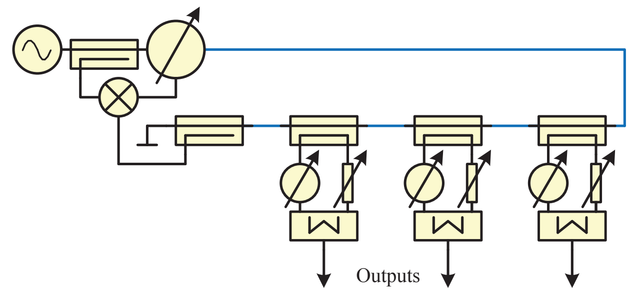

Figure 5: Conceptual diagram of interferometer link.

The RF synchronization distribution links are complemented by 12 optical fibre links of 10fs stability from the MLO (9 of them are shown in Fig. 2). A concept of electro-optical system was developed [6] that can be used to correct phase of electrical signals to highly-stable optical pulses. By such combination of interferometer and optical links we expect to reliably fulfil all requirements on the RF synchronization, while maintaining the high reliability for large scale infrastructure at moderate investment costs.

CURRENT ACTIVITIES AND PLANS

Currently the E-XFEL PRDS design is being finalized. Link and other distribution devices prototypes are being prepared. First MO prototype and distribution links in the Injector area will be installed in E-XFEL in second half of 2013. More detailed installations and tests of long distance distribution are planned in 2014..

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