RF SYNCHRONIZATION AND DISTRIBUTION FOR AWAKE AT CERN

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Abstract

The Advanced Wakefield Experiment at CERN (AWAKE) requires two particle beams and a high power laser pulse to arrive simultaneously in a rubidium plasma cell. A proton bunch from the Super Proton Synchrotron (SPS) extracted about once every 30 seconds must be synchronized with the AWAKE laser and the electron beam pulsing at a repetition rate of 10 Hz. The latter is directly generated using a photo cathode triggered by part of the laser light, but the exact time of arrival in the plasma cell still depends on the phase of the RF in the accelerating structure for electrons. Each beam requires RF signals at characteristic frequencies: 6 GHz, 88.2 MHz and 10 Hz for the synchronisation of the laser pulse, 400.8 MHz and 8.7 kHz for the SPS, as well as 3 GHz to drive the accelerating structure of the electron beam. A low-level RF system has been designed to generate all signals derived from a common reference. Additionally, precision triggers, synchronous with the arrival of the beams, will be distributed to beam instrumentation equipment. To suppress delay drifts of the several kilometre long optical fibres between AWAKE and the SPS RF systems, a compensated fibre link is being developed.

INTRODUCTION

The low-level radio-frequency (LLRF) system for the AWAKE experiment at CERN [1–4] will provide the signals to synchronise three beams with respect to each other. Protons from the SPS accelerator, the light pulse from the laser and the electron witness bunch must arrive simultaneously in the plasma chamber of AWAKE. Additionally, programmable precision triggers are needed for beam instrumentation equipment like streak cameras and fast digitizers.

The LLRF system for AWAKE is mainly distributed over three sites. Its main part is located underground in the AWAKE laser room, about 800 m downstream of point 4 of the 6.9 km long SPS. A GPS-based 10 MHz frequency reference is distributed from a surface building of point 4. The installation to synchronize the proton bunch is situated close to the longitudinal beam control in point 3 of the SPS, one sextant upstream of AWAKE.

CHOICE OF FREQUENCIES

The choices of the frequencies for the RF signals involved in the synchronization is constrained by the hardware requirements of the three beams involved [5]. The fibre ring oscillator of the laser can be designed to operate at a fixed mode-locker frequency, f_{ML}, in the range of 50 MHz to 100 MHz. An integer harmonic of f_{ML} must be equal to an integer harmonic of the RF frequency of the electron gun and the accelerating structure which work in the range of $f_{\mathrm{RF,e}} = 2.9985\,\mathrm{GHz} \pm 1\,\mathrm{MHz}$. To improve accuracy and phase noise, twice that frequency, $f_{\mathrm{LPLL}} = 2 f_{\mathrm{RF,e}}$, has been chosen for the phase locked loop of the laser (LPLL). As the mode-locker frequency of the laser must remain constant, AWAKE cannot follow the frequency sweep during the acceleration cycle of the proton beam in the SPS. Hence AWAKE and SPS can only be locked in phase after the arrival of the proton beam on the SPS flat-top. To reuse existing hardware the same synchronization mechanism for the beam transfer to AWAKE as for the transfer to the LHC [6] has been adopted. The allowed RF frequency window in the SPS at a momentum of 400 GeV/c is limited by the maximum acceptable radial excursion to $f_{\mathrm{RF,SPS}} = 200.394322\,\mathrm{MHz} \pm 500\,\mathrm{Hz}$. This frequency cannot be derived by integer division from any of the signals at 3 GHz or 6 GHz for electron or laser beam. A fractional divider with preferably low division and multiplication ratio is required. Based on these guidelines the mode-locker frequency of $f_{\mathrm{ML}} = 88.173501\,\mathrm{MHz}$ has been selected. The ratio chosen for $f_{\mathrm{ML}}/f_{\mathrm{RF,SPS}}$ becomes $11/25$, with f_{ML} derived directly from $f_{\mathrm{RF,e}}$ or f_{LPLL} by division of 34 or 68, respectively.

GENERAL LAYOUT

Figure 1 shows an overview diagram of the LLRF system for AWAKE. All RF signals are derived from a common mas-

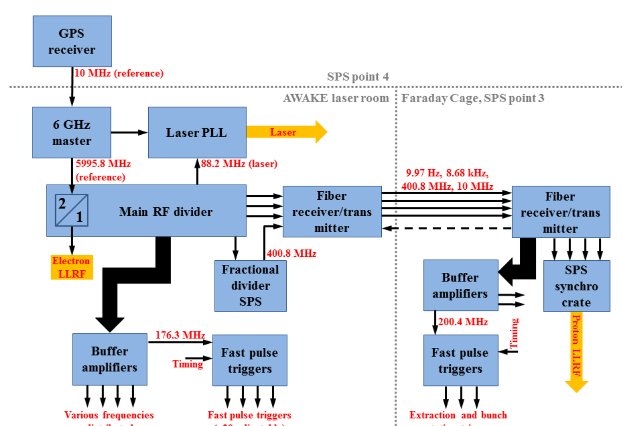

Figure 1: Overview diagram of the AWAKE RF synchronization and distribution.

ter oscillator at $f_{\mathrm{LPLL}} = 5.9958\,\mathrm{GHz}$ which is disciplined in frequency to a 10 MHz reference from a GPS receiver. It serves directly for the synchronization of the laser beam, as well as an input to the main RF divider generating all lower frequency signals in AWAKE. Table 1 summarizes the frequencies delivered by this divider. The signal at f_{c} is

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Table 1: Frequencies of the Main Divider

Signal	Frequency	Division ratio
f_{LPLL}	5.9958 GHz	1, input
$f_{\mathrm{RF,e}}$	2.9979 GHz	$f_{\mathrm{LPLL}}/2$
$2f_{\mathrm{ML}}$	176.347 MHz	$f_{\mathrm{RF,e}}/17$
f_{ML}	88.1735 MHz	$f_{\mathrm{RF,e}}/34$
f_{c}	8.68 kHz	$f_{\mathrm{ML}}/10164$
f_{rep}	9.97 Hz	$f_{\mathrm{c}}/870$

needed for the synchronization with the SPS as described below, and f_{rep} is the fundamental repetition rate of laser and electron beam pulses.

Programmable precision triggers for the beam instrumentation equipment are generated by pulse synchronizers with counters and fine delays (Chopper Trigger Unit, CTU [7]; originally developed for Linac4 at CERN).

A separate fractional divider translates the signal at $2f_{\mathrm{ML}}$ to $2f_{\mathrm{RF,SPS}}$ and is reset by the main divider to assure a fixed phase relationship with respect to the other signals. This 400.8 MHz serves as a phase reference for the re-phasing of the proton bunches in the SPS. The length of the optical fibres between AWAKE and the RF beam control of the SPS is about 3.2 km. To keep the signal delay stabilized to the order of 1 ps, an actively compensated optical link with four fibres has been developed, which also transmits the auxiliary signals, f_{c} and f_{rep}, for synchronization with the SPS.

SYNCHRONISATION OF BEAMS

Laser Beam

The optical fibre ring oscillator of the laser can be electrically tuned by changing its optical path length with piezo elements which allows to lock it to the reference from the master oscillator [8]. While the LPLL at 6 GHz with a balanced optical-microwave phase detector (BOM-PD, [9]) is expected to provide excellent jitter performance down to the 30 fs (integrated from 10 Hz to 10 MHz) level, it would not be sufficient to lock the laser unambiguously to the mode-locker frequency signal provided by the main divider. A two-stage synchronization scheme based on commercial hardware [10] has therefore been adopted. The laser oscillator is first locked in phase at its fundamental frequency, f_{ML}, to the corresponding output of the main divider (Fig. 1). Once locked, the LPLL is then switched to the BOM-PD between reference and the 68th harmonic of the laser oscillator at 6 GHz. This two-stage synchronization combines low jitter with a well-defined phase between the laser oscillator the distributed RF signal at f_{ML} from the main divider.

Electron Beam

The synchronization of laser pulse and electron beam must be on the few hundred femtosecond level [1]. This stability is intrinsically achieved by triggering the photo cathode of the electron gun directly with the light from the laser pulse [11]. Laser and electron injector are both triggered every 100 ms (corresponding to $1/f_{\mathrm{rep}}$) and no dedicated synchronization hardware is required.

Proton Beam

One proton bunch is accelerated in about 4.3 s from 26 GeV/c to 400 GeV/c in the SPS. Depending on the supercycle composition, this may take place about once every 30 s. Bunch rotation prior to extraction shortens the bunch to a 4σ length of about 1.2 ns [12], aiming at a jitter of better than 50 ps with respect to the laser pulse. The 1σ spread of the bunches at SPS extraction was measured to be in the 10 ps range [13] with respect to local reference.

The SPS accelerator and its injectors cycle asynchronously with respect to the 100 ms repetition rate of AWAKE, and the synchronization is only launched once the 400 GeV/c flat-top is reached. The process is based on the re-phasing of the SPS to the LHC [6] so that a copy of the existing hardware can be employed. However, compared to the extraction to the LHC, where the moment of transfer is well known at the beginning of the SPS cycle, the transfer to AWAKE takes place in a window of 100 ms (one period of f_{rep}). With AWAKE being the master of the transfer, in total three signals will be distributed to the SPS: $2f_{\mathrm{RF,SPS}} = 400.789$ MHz, f_{c} and f_{rep} (Table 1). The relevant events prior to extraction from the SPS are illustrated schematically in Fig. 2.

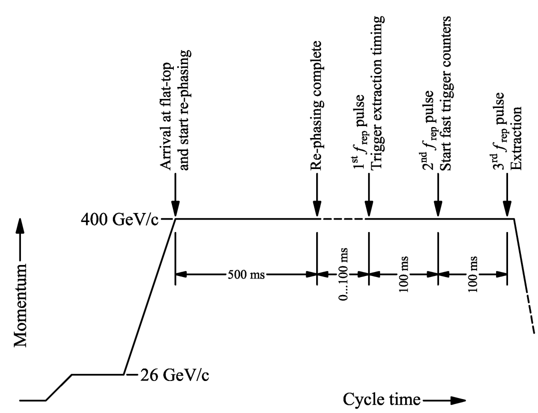

Figure 2: Sequence for synchronization and transfer of the proton bunch from the SPS to AWAKE.

After the arrival on the flat-top in SPS, the proton bunch is first moved to the given phase with respect to the common frequency signal, f_{c}, by a frequency steering. A re-phasing loop is then closed at $2f_{\mathrm{RF,SPS}}$ to lock the RF frequency to the external reference from AWAKE. It is worth noting that the beam phase loop locks the proton bunch to the center of the RF bucket and that the synchronization loop, via the re-phasing, moves the bucket and the phase-locked bunch to the desired phase position. Once the re-phasing process is completed (500 ms after arrival at the flat-top), SPS and AWAKE are synchronous with respect to f_{c}. The transfer can now be initiated at every pulse of the 10 Hz repetition frequency, f_{rep}.

However, to generate the usual extraction warning pulses, triggers for the SPS extraction elements and triggers for the beam diagnostics equipment in AWAKE, the proton beam transfer will take place with the third f_{rep} pulse (Fig. 2) after completion of the RF re-phasing. At the first f_{rep} pulse the main timing generator controlling all warnings for the extraction elements, is triggered. With events distributed via the timing telegram infrastructure it also notifies the trigger equipment in AWAKE of the arrival of the proton bunch at the next but one f_{rep} pulse. The subsequent f_{rep} pulse then starts the counters of the trigger units, counting $f_{RF,SPS}$ on the SPS side and $2f_{ML}$ on the AWAKE side until the final f_{rep} pulse indicates the synchronous transfer to AWAKE.

STABILIZED OPTICAL LINK

Delay drift measurements of optical fibres similar to the links connecting AWAKE with the longitudinal beam control system have shown significantly larger drifts than tolerable for the synchronization of the proton bunch. A compensated optical link to transmit $2f_{RF,SPS}$, f_c and f_{rep} has therefore been developed [14]. It is expected to reach a stability of the order of 1 ps, well below the jitter due to the synchronization.

The topology of the link is sketched in Fig. 3. After the

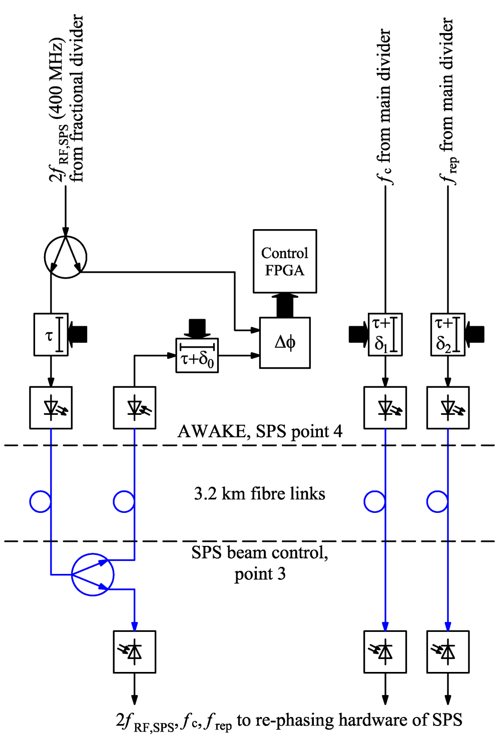

Figure 3: Overview diagram of the stabilized optical links for the synchronization signals from AWAKE to the SPS beam control. The electronic delays are controlled by the FPGA. Optical connections are shown in blue.

re-phasing process the proton bunch in the SPS is phase-locked to $2f_{RF,SPS}$ so that the stability of this 400.8 MHz signal may add jitter and drift of its arrival in AWAKE with respect to the phase reference. The stabilization therefore takes special care of transmitting $2f_{RF,SPS}$ with a constant delay from AWAKE in point 4 to the longitudinal beam control in point 3 of the SPS. The RF reference signal is sent through the 3.2 km long fibre, split optically at the arrival at the SPS beam control and sent back to AWAKE via a second fibre. Original and looped back signals are then compared in phase. Assuming that the delays on forward and return fibres are identical, as they are part of the same bundle, the transmission delay can then be kept constant by adjusting an electrical delay in the forward path.

The other two signals needed for the synchronization with the SPS, at f_c and f_{rep}, are only required for coarse re-phasing and counting of RF periods. Minor drifts on these signals with respect to the signal at $2f_{RF,SPS}$ are not critical as long as they do not get close the boundary of one RF period of 2.5 ns. The electrical delays on their distribution paths are therefore programmed in open loop to match approximately the delay of the regulated RF path.

The noise floor and drift of the digital phase discriminator (Fig. 3) is critical for the performance of the link stabilization. The spectrum of the noise as measured with the prototype hardware is plot in Fig. 4. A delay error of

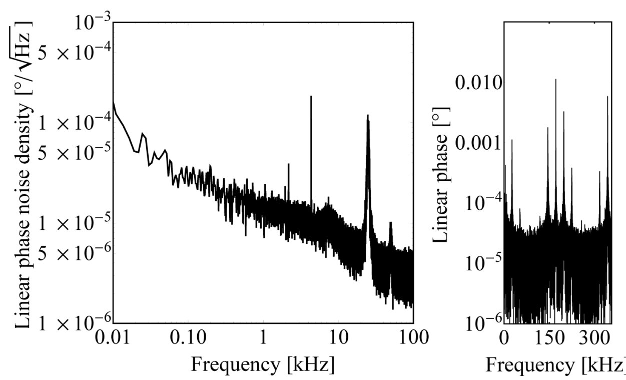

Figure 4: Measured noise density spectrum at the output of the digital phase discriminator (left), together with the linear amplitude spectrum (right). A Hanning window function was chosen for the analysis. The data were recorded at a sampling rate of 0.71 MHz.

1 ps corresponds to a phase of 0.14° at 400.8 MHz and even without averaging the phase measurements have sufficiently low noise. The source of the spurious peaks is being investigated and they are most likely caused by feed-through from the switched-mode power supply regulators.

CONCLUSIONS

The RF synchronization and distribution for AWAKE presently being installed will provide a variety of signals in the frequency range of 10 Hz to 6 GHz for the synchronization of proton, laser and electron beams. It reuses, as much as possible, LLRF hardware from SPS and LHC, but major parts like main divider and the link stabilization required new developments of which prototypes are becoming available. The commissioning with proton beam and laser pulse is planned for August 2016. The development of the LLRF for the electron beam is being launched to be ready for the second commissioning phase in late 2017.

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