

PROGRESS IN THE BUNCH-TO-BUCKET TRANSFER IMPLEMENTATION FOR FAIR*

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Abstract

The transfer of bunched ion beams between various synchrotrons is required for the multi-accelerator complex FAIR, presently under construction at GSI. To avoid a dedicated distribution infrastructure for Radio Frequency (RF) signals between each source and destination synchrotron, a new approach has been developed to transmit bunch and bucket phase information using synchronous Ethernet. This allows to locally regenerate all reference signals needed for the RF synchronization prior to a Bunch-to-Bucket transfer, as well as the triggers to the kickers. The modular and configurable hardware implementation based on the White Rabbit network [1] progresses towards a proof-of-principle demonstrator.

Besides the synchronization of revolution and RF frequencies, the bunches in the source accelerator must be aligned in azimuth with respect to the buckets in the receiving synchrotron. To validate the feasibility of this azimuthal steering, measurements have been performed with protons in the CERN PS to evaluate the longitudinal emittance growth. They are complemented with tracking simulations using the BLonD code [2].

INTRODUCTION

The campus at GSI is equipped with a very accurate absolute time frame called the Bunch-Phase Timing System (BuTiS) [3]. It is based on a 5 ns period clock signal with a jitter of 100 ps per km and of a 10 μ s synchronization marker. Additionally the White Rabbit network enables high speed point-to-point deterministic Ethernet packet exchange.

The accelerators of the FAIR project will handle a large spectrum of ion species from protons to uranium ions to various energy levels. In order to develop a Bunch-to-Bucket transfer topology applicable to every transfer between synchrotrons at FAIR project, two main synchronization strategies were considered: the frequency beating, as a passive synchronization strategy and the phase shift, which is detailed in the next section of this document.

PHASE SHIFT METHOD

Moving a bunch in azimuth with respect to an external reference can be performed by modulating the RF drive signals of the corresponding synchrotron's cavities. Knowing the

azimuth correction value $\Delta\Phi$ to align the first bucket of the source synchrotron with the targeted bucket of the receiving synchrotron, a modulation can be defined deterministically according to

$$\Delta\Phi = 2\pi \int_0^T \Delta f(t) dt, \quad (1)$$

with the shift duration T and the modulation profile $\Delta f(t)$. The constraints on the frequency modulation with respect to the beam orbit length, the beam pipe aperture and the time budget for synchronizing the beam are discussed in [4].

Adiabaticity

To avoid longitudinal emittance blow-up during the synchronization procedure, the phase shift must remain adiabatical. Adiabaticity is usually specified by the quantity [5]:

$$\alpha_{ad} = \frac{1}{\Omega_s^2} \frac{d\Omega_s}{dt}, \quad (2)$$

with the synchrotron frequency Ω_s defined according to

$$\Omega_s^2 = 2\pi f_r^2 \frac{h\eta Q \hat{V} \cos \varphi_s}{\beta c_0 p_s} = \Gamma^2 \cos \varphi_s. \quad (3)$$

The ratio $\beta = v/c_0$ is the relativistic velocity factor, c_0 the speed of light, f_r the revolution frequency, h the harmonic number, φ_s the synchronous phase, Q is the particle charge, \hat{V} the RF peak voltage and p_s the momentum of the synchronous particle [6].

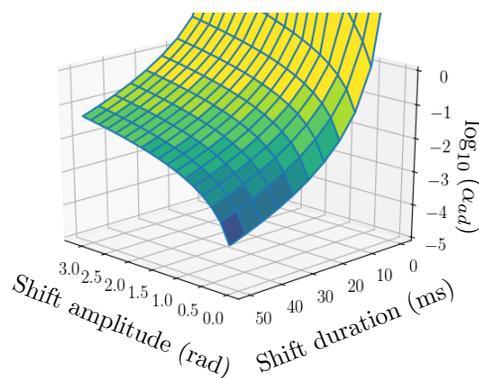


Figure 1: Maximum adiabaticity factor magnitude ($\log_{10} \alpha_{ad}$) for a 4 GeV proton bunch at SIS 18 as a function of the shift duration and the shift amplitude, second phase profile.

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A logarithmic derivative of Eq. (3) assuming constant RF voltage leads to

$$2 \frac{d\Omega_s}{\Omega_{s,R}} = 2 \frac{df_r}{f_{r,R}} + \frac{d\eta}{\eta_R} - \frac{d\beta}{\beta_R} - \frac{dp_s}{p_{s,R}} - \tan \varphi_{s,R} d\varphi_s. \quad (4)$$

The R index marks the reference value corresponding to a phase shift of 0° .

A rough approximation for a 4 GeV proton bunch shifted in the SIS 18 by half its circumference within 10 ms with a second order phase modulation profile shows, that the synchronous phase term dominates the synchrontron frequency variation by at least one order of magnitude.

Under this assumption, introducing Eq. (3) into Eq. (2) results in an iso-adiabatic condition for the phase shift profile

$$\int \alpha_{ad} dt = -\frac{1}{2\Gamma} \int \frac{\tan \varphi_s d\varphi_s}{\sqrt{\cos \varphi_s}} = -\frac{1}{\Gamma} \left[\frac{1}{\sqrt{\cos \varphi_s(t)}} \right]_{\varphi_{s0}}^{\varphi_s(t)}. \quad (5)$$

Regarding the averaged energy gain of the synchronous particle per turn, one can derive the synchronous phase as a function of the frequency variation for $\dot{B} = 0$

$$\sin \varphi_s = \frac{1}{\eta_R} \frac{C_R p_R}{Q \hat{V} f_{r,R}} \dot{f}_r, \quad (6)$$

with C_R the length of the beam reference orbit. The frequency modulation and the synchronous phase drift are coupled [7]. The modulation pattern used to shift the beam is an important synchronization optimization factor.

Phase Shift of a Proton Beam at PS

Beam tests have been carried out at the CERN Proton Synchrotron (PS) in August and November 2016, aiming at validating the adiabaticity of moving a bunch in azimuth over an arbitrary large portion of the synchrotron circumference. A single 26 GeV proton bunch on harmonic 84 was considered and $V_{RF} = 100$ kV. Deterministic particle bunch shifts over an arbitrary large part of the synchrotron circumference have been validated.

Figures 2 and 3 show the impact of the shift duration on the synchronous phase drift predicted by Eq. (6). The experiment was performed using a second order (parabola) phase modulation profile, in red.

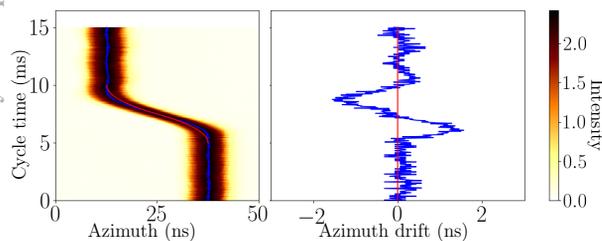


Figure 2: A proton beam shifted in the PS by one bucket at $h = 84$ within 5 ms (left) and the corresponding measured bunch phase deviation (right).

In spite of the strong correlation between the shift duration and the synchronous phase drift, the measured relative

emittance growth remained under 10%. This corresponds to the BLonD-based simulation results, except for very fast phase shifts, in which case the model did not agree with the measurements, due to important particle losses of the real beam.

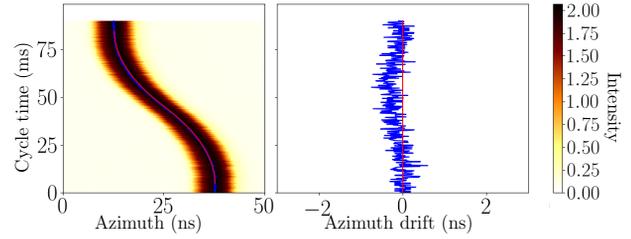


Figure 3: A proton beam shifted in the PS by one bucket at $h = 84$ within 80 ms (left) and the corresponding measured bunch deviation (right).

IMPLEMENTATION

Figure 4 shows the functional flow of the new Bunch-to-Bucket transfer topology for FAIR. The azimuth of the source and receiving synchrotron's first bucket is asynchronously measured by means of a Digital Signal Processor (DSP)-based phase measurement system [8]. The Phase Advance Prediction (PAP) module makes use of the measured phase values to extrapolate a BuTiS-consistent phase value and time-stamp it prior to share it through a separated Virtual Local Area Network (VLAN) of the White Rabbit network by means of a Scalable Control Unit (SCU).

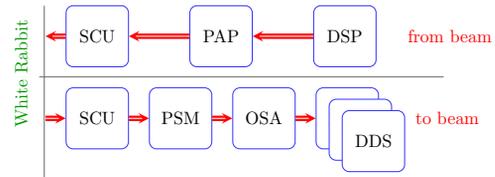


Figure 4: Functional flow of the future Bunch-to-Bucket transfer topology for FAIR.

The transfer window in which the kickers can be triggered regarding the maximum allowed uncertainty is calculated locally at the source synchrotron and shared with all required actors such as the receiving synchrotron through the White Rabbit system. If required, the Phase Shift Module (PSM) generates the phase shift pattern and sends a correction to the corresponding RF generators (Direct Digital Synthesizers, DDS). Each synchrotron of the FAIR accelerator chain will be equipped with a full Bunch-to-Bucket transfer unit composed of the devices described above and of an injection and extraction kicker trigger system.

New functions such as the PAP or the PSM function require the development of a new FPGA-based Multi-purpose Hardware Unit (MHU), under development in cooperation with the IES Institute at the TU Darmstadt [9].

Data Exchange Through a White Rabbit VLAN

Each set of hardware presented in Fig. 4 will be connected to one end node of the White Rabbit network. End nodes of

the White Rabbit network are connected to a switch of the lowest level, the 4th in Fig. 5.

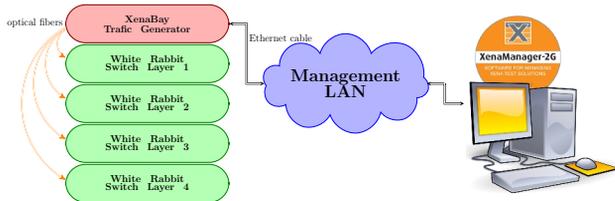


Figure 5: Overview of the emulation setup for the characterization of the White Rabbit network for the Bunch-to-Bucket transfer.

To determine the maximum amount of switch layers of the separated VLAN, an emulation setup using the Xena system as an Ethernet traffic evaluation platform is proposed [10].

According to the latest measurements, The transfer latency between the XenaBay frame generator and the different switch layers takes less than 30 μs per switch layer. The rate of lost and misordered frames introduce additional limitations.

Phase Advance Prediction

The DSP-based phase measurement device developed at GSI delivers phase difference values between an RF signal and a BuTiS-based synchronous reference signal through optical telegrams every 3.22 μs with an accuracy of 0.1 ° [11]. The phase advance measurement concept is designed, such that the maximum absolute frequency difference between these two signals is 50 kHz. The PAP module makes use of this measurement to extrapolate a phase and phase advance value and to re-introduce it into the BuTiS time frame, synchronized with the T₀ synchronization pulse.

Phase prediction algorithms have been developed in Python and tested with real phase measurement data. A moving average is used to reduce the measurement uncertainty. Eq. (7) was implemented and shown to allow converging phase advance measurements:

$$\bar{X} = \frac{1}{M} \sum_{n=0}^{M-1} \bar{X}_n = \frac{1}{MN} \sum_{n=0}^{M-1} \sum_{i=n}^{N+n-1} X_i. \quad (7)$$

Here X_i represents the ith measured value. N represents the maximum amount of samples used for the moving average and M the length of the second average window.

Figure 6 shows the minimum amount of samples (N) required for a phase advance accuracy of 1 ° over the 10 ms synchronization time as a function of the frequency difference between the reference signal and the measured RF signal.

SUMMARY

Significant progress has been made with the development of the future Bunch-to-Bucket transfer topology for FAIR. Experiments concerning the three core functions of the topology, the synchronization data exchange through the White Rabbit network, the phase advance prediction and the phase

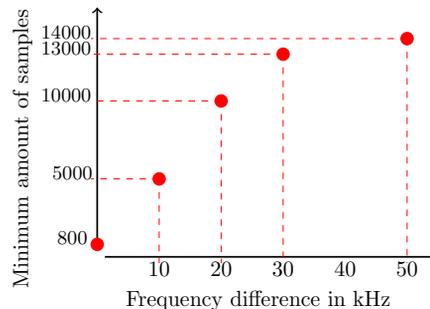


Figure 6: Summarized results of PAP code simulation, minimum amount of samples as function of the frequency difference between the measured and the reference RF signals.

shift of a bunch have been performed towards a final proof-of-principle.

The results obtained at the PS can be scaled to anticipate bunch behaviors at SIS 18 and at other synchrotrons of the FAIR project. The quantitative evaluation of the phase advance prediction, relative optimizations and the real influence of the phase shift modulation profile still remain to be completed.

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