First Idea on Bunch to Bucket Transfer for FAIR

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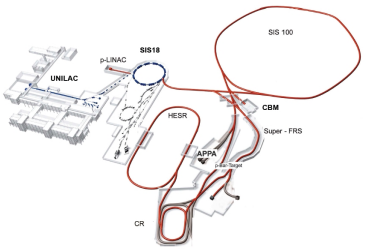
Abstract

The FAIR facility makes use of the Bunch phase Timing system (BuTis) and the General Machine Timing (GMT) system to realize synchronization of two synchrotrons. Under the asssumption of the slightly detuned frequency in both machines, the source and target machine exchange information shortly before the transfer and make use of rf frequency beating pattern to realize synchronization with accuracy better than 1 °. Each involved machines sends data including rf frequency, phase of first harmonics, harmonic number and bunch/bucket position to the other machine at the same time via the timing system. After exchanging information, both machines have the complete information and can calculate the exact transfer time independently and locally.

GSI Accelerator



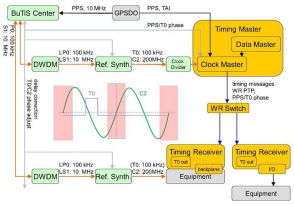
FAIR complex will consist of 12 accelerators
First Stage
■UNILAC
■SIS18
■SIS100
■...

Beams:
■Anti protons
■Protons to uranium

Energy:
■Design ion beam: U^{28+} with 2.7 GeV/u
$5x10^{11}$ Ions/Cycle
■Protons up to 29 GeV/u
■Heavy ion beams up to about 11 GeV/u

FAIR timing system: BuTis and GMT

The GMT and BuTis systems are coupled.

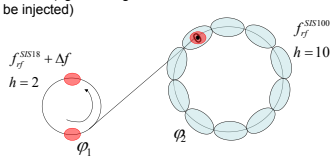


General machine timing system (GMT):
■Control group
■Distributes accelerator events
■Distributes absolute time
■defines time standard for CS
■Sub ns precision / synchronization
■One global timing master

Bunch phase timing system (BuTiS):
■RF group
■Distributes high precision clocks for rf systems
■100ps/km accuracy/ synchronization
■One global BuTiS center

Bunch to bucket transfer

A bunch of particles must be extracted from the source machine to be injected in the centre of a bucket of the target machine.(eg. the figure below shows the U^{28+} transfer from SIS18 to SIS100, eight of ten buckets will be injected)



Synchronization two synchrotrons

RF frequency beating eg. $f_{rf}^{SIS18}+\Delta f$ and f_{rf}^{SIS100}

$(\text{Measured value of SIS18 rf zero - crossing point } t_{18}) = t_{18best}\ (\delta t_{18})$

$(\text{Measured value of SIS100 rf zero - crossing point } t_{100}) = t_{100best}\ (\delta t_{100})$

■$t_{18best} < t_{100best}$

$$t_{100best}+n\times\frac{1}{f_{rf}^{SIS100}}=t_{18best}+(n+1)\times\frac{1}{f_{rf}^{SIS18}+\Delta f}$$

$$n=\frac{t_{100best}-t_{18best}-\frac{1}{f_{rf}^{SIS18}+\Delta f}}{\frac{1}{f_{rf}^{SIS18}+\Delta f}-\frac{1}{f_{rf}^{SIS100}}}$$

$$t_{syn}=\frac{(f_{rf}^{SIS18}+\Delta f)\times t_{18best}-f_{rf}^{SIS100}\times t_{100best}+1}{(f_{rf}^{SIS18}+\Delta f)-f_{rf}^{SIS100}}$$

■$t_{18best} > t_{100best}$

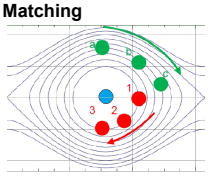
$$t_{100best}+n\times\frac{1}{f_{rf}^{SIS100}}=t_{18best}+n\times\frac{1}{f_{rf}^{SIS18}+\Delta f}$$

$$n=\frac{t_{100best}-t_{18best}}{\frac{1}{f_{rf}^{SIS18}+\Delta f}-\frac{1}{f_{rf}^{SIS100}}}$$

$$t_{syn}=\frac{(f_{rf}^{SIS18}+\Delta f)\times t_{18best}-f_{rf}^{SIS100}\times t_{100best}}{(f_{rf}^{SIS18}+\Delta f)-f_{rf}^{SIS100}}$$

Δf The frequency detuning of SIS18
$f_{rf}^{SIS18}, f_{rf}^{SIS100}$ The rf frequency of SIS18/ SIS100
t_{syn} The best estimation time for synchronization
$t_{18best}, t_{100best}$ The adjacent timestamps of zero crossing point of two rf signals
n The number of rf cycles of SIS100 to realize synchronization

Matching



Stationary bucket in phase space

Matching means:
■Energy matching
The green dots (a, b, c) show the trajectory for an injection energy error.
■Phase matching
The red dots (1, 2, 3) show the trajectory for an injection phase error.
❖The blue dot with energy and phase matching

The phase offset within uncertainty window [t_{syn} - δt_{syn}, t_{syn+} δt_{syn}] is near 1°. which meets the phase requirement.

Test setup

On each machine, a FAIR receiver node of the timing systemis coupled to the rf-system. When triggered by an event of the timing system, each node measures the rf-phase with respect to the absolute time. By exchanging these two measured values, each obtains the phase difference of bucket and bunch in the two machines.

Example

$f_{rf}^{SIS18}+\Delta f = 1MHz+100Hz \qquad f_{rf}^{SIS100}=1MHz$

$\delta t=\delta t_{18}=\delta t_{100}=1ns \qquad \delta f\approx 0Hz$ when rf signal is derived from Butis

$$\delta t_{syn}=\{\frac{(f_{rf}^{sis100})^2+(f_{rf}^{sis18}+\Delta f)^2}{\Delta f^2}\times\delta t^2+\frac{2\times[(f_{rf}^{sis18}+\Delta f)\times(t_{18best}-t_{100best})+1]^2}{\Delta f^4}\times\delta f^2$$
$$-\frac{2\times[(f_{rf}^{sis18}+\Delta f)\times(t_{18best}-t_{100best})+1]\times(t_{18best}-t_{100best})}{\Delta f^3}\times\delta f^2+\frac{(t_{100best}-t_{100best})^2}{\Delta f^2}\times\delta f^2\}^{\frac{1}{2}}$$

Uncertainty for $t_{18best} < t_{100best}$

$$\delta t_{syn}=\{\frac{(f_{rf}^{sis100})^2+(f_{rf}^{sis18}+\Delta f)^2}{\Delta f^2}\times\delta t_2^{\,2}+\frac{2\times[(f_{rf}^{sis18}+\Delta f)\times(t_{18best}-t_{100best})]^2}{\Delta f^4}\times\delta f^2$$
$$-\frac{2\times[(f_{rf}^{sis18}+\Delta f)\times(t_{18best}-t_{100best})]\times(t_{18best}-t_{100best})}{\Delta f^3}\times\delta f^2+\frac{(t_{100best}-t_{100best})^2}{\Delta f^2}\times\delta f^2\}^{\frac{1}{2}}$$

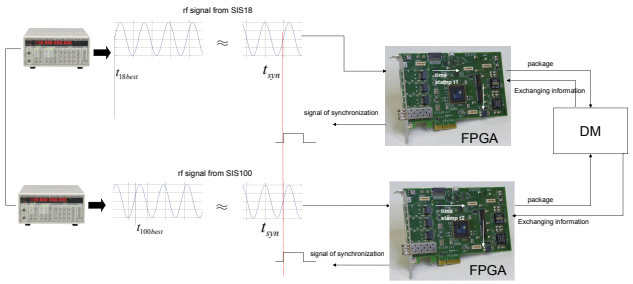
Uncertainty for $t_{18best} > t_{100best}$

$\delta t_{syn}\approx 14.143\ us \qquad \frac{10ms}{360^\circ}\approx 27.\dot{7}us/\deg ree$

```
============================================================
time:0x423c51cdc83
1970-01-01 01:15:51.0.677369475
------------channel 0 timestamp
time:0x423c51cdec5
1970-01-01 01:15:51.0.677370053
**************channel 1 timestamp
============================================================
Beating number:5780
Synchronization time:5.780000ms
Estimate time for alignment :0x423c5750ea3(1ns)
1970-01-01 01:15:51.0.683149475
============================================================
 Error propogation 14.143us
============================================================
Period of synchronization is :10000000.000ns
ECA current time :0x8478f37e1b(8ns)
time:0x423c79bf0d8
1970-01-01 01:15:51.0.719252184
```

Tasks

■Time requirement for synchronization < 20ms
■Linux OS: program latency ≈ 60ms
■Need hard real-time system ➡ Soft-Core LM32 in FPGA



Conclusion

This setup theoretically simulates the synchronization of two synchrotrons, with accuracy of 1°. It paves the way for the further bunch to bucket transfer.