Timing, Synchronization & Longitudinal Aspects I

H. Damereau
CERN

CAS Course on
Beam Injection, Extraction and Transfer

13 March 2017
Outline

• Introduction

• General concepts
  • Signals with noise, transmission of RF signals
  • Phase detectors and dividers

• Beam transfer
  • Fundamental periodicity
  • Transfer between circular lepton accelerators

• Transfer between hadron accelerators
  • Beam phase loop, bucket numbering
  • Transfer process: Synchronization, transfer triggers
  • Longitudinal matching

• Summary
Introduction
Introduction

• Two or more people must be synchronized to meet
  → Calendar item: date, time and location
  → Typical uncertainty: some minutes

• Slightly more precision required to have a meeting with a particle beam
  → Typical uncertainty: some nanoseconds down to femtoseconds

→ To be at the right time in the right place

→ Set conditions and generate timings and RF signals with a given time relation with respect to the beam
→ Make beam feel comfortable in its new accelerator
Timescales

Proton bunches in low energy synchrotrons

Hadron colliders

Electron storage rings

Plasma wakefield experiments

→ Geometrical size: few meters to some km
Synchronization for beam transfer

• How to get the beam through the accelerator?

Source \[\rightarrow\] Exit

• How to transfer beam from accelerator A to B?

Accelerator A \[\rightarrow\] Accelerator B

• Beam passes many elements on its way:
  \[\rightarrow\] RF structures \[\rightarrow\] Must be in phase
  \[\rightarrow\] Septa, bumper and kicker magnet \[\rightarrow\] Trigger
  \[\rightarrow\] Fast beam instrumentation \[\rightarrow\] Trigger
  \[\rightarrow\] RF systems in source and target accelerator \[\rightarrow\]
  Correct phase with respect to beam
Particle velocity

• Particle velocity depends on its type:

\[ \beta = \frac{v}{c} = \sqrt{1 - \left(\frac{E_0}{E}\right)^2} \]

- Old television set (30 kV):
  - Electrons at 30% of \( c_0 \)
  - Protons just at 0.7%

- Small synchrotron (500 MeV):
  - Electrons at 99.99995%
  - Protons at 75.8%

→ Many electron accelerators at ‘fixed’ frequency
## Synchronization needs for particle types

<table>
<thead>
<tr>
<th>Lepton accelerators</th>
<th>Hadron accelerators</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Velocity $v \approx c$ in high energy accelerators</td>
<td>• Slow, even velocity change relevant to the multi-GeV range</td>
</tr>
<tr>
<td>• Synchrotron radiation <strong>damping</strong> (mainly circular accelerators)</td>
<td>• Negligible or small damping from synchrotron radiation</td>
</tr>
<tr>
<td>• Short bunches</td>
<td>• Long bunches</td>
</tr>
<tr>
<td>• Storage rings: $\sim 10...100$ ps</td>
<td>• Synchrotrons: $1...1000$ ns (depends on RF frequency)</td>
</tr>
<tr>
<td>• Linear free electron lasers: $50...200$ fs</td>
<td>• Linear accelerators: typically <strong>few ns</strong></td>
</tr>
</tbody>
</table>

→ Fixed frequencies
→ High precision

→ Variable (sweeping) frequencies
→ Moderate precision
Bunch-to-bucket transfer

• Bunch from sending accelerator into the bucket of receiving

Advantages:
→ Particles always subject to longitudinal focusing
→ No need for RF capture of de-bunched beam in receiving accelerator
→ No particles at unstable fixed point
→ Time structure of beam preserved during transfer to the next
Noise on signals
Degradation of signal quality due to noise
- Amplitude and/or phase jitter
- What is the difference between a coherent signal and noise?

- Amplitude of **coherent**, quasi monochromatic signal (at 200 MHz) is independent of observation bandwidth

- Incoherent noise power (dominated by spectrum analyzer front-end amplifier/mixer) is proportional to bandwidth

- Thermal noise power \( \frac{P}{\Delta f} = k_B T = 1.38 \cdot 10^{-23} \text{ J/K} \cdot 296 \text{ K} \approx -174 \text{ dBm/Hz} \)
Analysis of phase noise

• Compare noise power with carrier power as reference

\[ \text{Ratio of carrier to noise: } \text{dBc} \]

\[ \Delta f = 1 \text{ Hz for normalization} \]

• Noise power density

\[ \mathcal{L}(f) = \frac{\text{Power density}}{\text{Carrier power}} \left[ \frac{\text{dBc}}{\text{Hz}} \right] = \frac{1}{2} S_{\phi}(f) \]

→ Its integral is the phase jitter and using \( \Delta t = \frac{\Delta \phi}{2\pi f_c} \)

the jitter in time becomes

\[ \Delta t_{\text{rms}} = \frac{1}{2\pi f_c} \sqrt{\int_{f_1}^{f_2} S_{\phi}(f) \, df} \]
Typical phase noise plots

- Measure phase noise of a synthesized lab generator

<table>
<thead>
<tr>
<th>Frequency range</th>
<th>$\Delta t_{\text{rms}}$ [fs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10...100 Hz</td>
<td>12.4</td>
</tr>
<tr>
<td>100 Hz ...1 kHz</td>
<td>5.4</td>
</tr>
<tr>
<td>1...10 kHz</td>
<td>5.4</td>
</tr>
<tr>
<td>10...100 kHz</td>
<td>11.1</td>
</tr>
<tr>
<td>100 kHz...1 MHz</td>
<td>13.0</td>
</tr>
<tr>
<td>Total</td>
<td>31.0</td>
</tr>
</tbody>
</table>

→ Note: jitter values can be added as square root of quadratic sum

$$\Delta t_{\text{rms}} = \sqrt{\Delta t_{\text{rms},1}^2 + \Delta t_{\text{rms},2}^2 + \ldots}$$

→ Convenient split to relevant ranges
Signal transmission
Transmission of reference signals

- Thermal drift of long *coaxial cables* or optical fibres

- Thermal coefficient of delay:
  \[ \text{TCD} = \frac{\Delta\tau}{\tau} \cdot \frac{1}{\Delta T} = \frac{\Delta\phi}{\phi} \cdot \frac{1}{\Delta T} \]

- **Example:** 2 km long RG223 cable with ~10 \(\mu\)s delay
  - \(\Delta T\) of only 1°C (room temperature) changes delay by ~0.5 ns
  - 1.8° at 10 MHz (CERN PS), but 73° at 400 MHz (LHC)
- Optical fibres are typically 10...100 times more stable
- What to do if this is still not sufficient?
Transmission of reference signals

- Measured drift of optical fibres over long distance standard optical fibre
  
  Measured temperature and delay drift of ~6.3 km fiber

- Drift by about 1 ns insufficient for requirements of setup

  → Active compensation of delay
Example: Active drift compensation

- Precise synchronization of proton beam from CERN SPS with plasma wake-field experiment AWAKE

Prototype hardware

→ Expect picosecond precision over several kilometres

D. Barrientos, J. Molendijk
Transmission of reference signals

- Total delay composed of coarse (steps of 10 ps) and fine ~30 ps range: \( \tau = \tau_{\text{coarse}} + \tau_{\text{fine}} \)

\[ \begin{align*}
\tau_{\text{coarse}} [\text{ns}] & \quad 5.05 \quad 5.00 \quad 4.95 \\
\tau_{\text{fine}} [\text{ps}] & \quad 25 \quad 20 \quad 15 \quad 10 \quad 5
\end{align*} \]

- Precision difficult to evaluate without 2\textsuperscript{nd} ‘reference’ link
- Arrival of two beams in AWAKE experiment stable to better ~100 ps over months

D. Barrientos, J. Molendijk
Overview of transmission methods

Various approaches:

1) RF distribution
   \[ f \sim 100\text{MHz} \ldots \text{GHz} \]

2) Carrier is optically
   \[ f \sim \text{GHz} \]

3) Carrier is optically + detection
   \[ f \sim 200\text{THz} \]

4) Pulsed optical source
   \[ \Delta f \sim 5\text{THz} \]
Phase detection
**Frequency and phase**

- Two signals at different frequencies $\omega_1$ and $\omega_2$

$\rightarrow$ Phase difference, $\Delta\phi$, between both signals changes linearly

$\rightarrow$ Ambiguity to distinguish between $\Delta\phi = -\pi, \pi, -3\pi, 3\pi,...$

$\rightarrow$ Saw-tooth in phase means constant frequency difference

$\rightarrow$ Equivalence of frequency and phase

$$\omega = \frac{d\phi}{dt} \quad \leftrightarrow \quad \phi = \int \omega \, dt$$
How to detect phase differences?

- Example: analogue 4 quadrant multiplier and low pass filter

\[
\sin(\omega_1 t + \phi_1) \quad \rightarrow \quad \frac{1}{2} \left\{ \cos[(\omega_1 - \omega_2) t + (\phi_1 - \phi_2)] - \cos[(\omega_1 - \omega_2) t + (\phi_1 + \phi_2)] \right\}
\]

\sin(\omega_2 t + \phi_2)

- Signals:
How to detect phase differences?

- Example: analogue 4 quadrant multiplier and low pass filter

\[
\sin(\omega_1 t + \phi_1) \quad \rightarrow \quad \sin(\omega_2 t + \phi_2) \quad \rightarrow \quad \frac{1}{2} \cos[(\omega_1 - \omega_2)t + (\phi_1 - \phi_2)] \quad \rightarrow \quad \cos[(\omega_1 - \omega_2)t + (\phi_1 + \phi_2)]
\]

Remove ripple \(\rightarrow\) Low-pass filter

- Signals:
How to detect phase differences?

- Example: analogue 4 quadrant multiplier and low pass filter

\[
\frac{1}{2} \{ \cos[(\omega_1 - \omega_2)t + (\phi_1 - \phi_2)] - \cos[(\omega_1 - \omega_2)t + (\phi_1 + \phi_2)] \}
\]

Remove ripple \(\rightarrow\) Low-pass filter

Relative: arbitrary shift by \(90^\circ\)

- Signals:

- Phase discriminator in approximately \(+/\pm90^\circ\) range
Further phase detection techniques

Multitude of different phase discriminators

<table>
<thead>
<tr>
<th>Type</th>
<th>Range</th>
<th>Behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analogue 4 quadrant multiplier</td>
<td>$\pi$</td>
<td><strong>Sinusoidal</strong>: $s_{\text{out}} \sim \cos \phi$</td>
</tr>
<tr>
<td>Exclusive OR gate</td>
<td>$\pi$</td>
<td><strong>Linear</strong>: $s_{\text{out}} \sim \phi - 3\pi/2$, or $s_{\text{out}} \sim -\phi + \pi/2$</td>
</tr>
<tr>
<td>Sample and hold</td>
<td>$\pi$</td>
<td><strong>Sinusoidal</strong>: $s_{\text{out}} \sim \sin \phi$</td>
</tr>
<tr>
<td>Flip-flop phase detector</td>
<td>$\pi$</td>
<td><strong>Linear</strong>: $s_{\text{out}} \sim \phi - \pi$</td>
</tr>
<tr>
<td>Tri-state double flip-flop</td>
<td>$2\pi$</td>
<td><strong>Linear</strong>: $s_{\text{out}} \sim \phi$</td>
</tr>
<tr>
<td>Balanced optical microwave phase detector (Sagnac loop)</td>
<td>$&lt;\pi$</td>
<td><strong>Sinusoidal</strong>: $s_{\text{out}} \sim \sin \phi$ (clipped)</td>
</tr>
</tbody>
</table>

- **Full phase coverage of $2\pi$ range excludes ambiguity of $\pm \pi$**
  - Avoids locking of phase loop with unwanted offset
- **Measure phase at high frequencies for precision**
Dividers
Frequency dividers

- Generate signals using frequency division from $f_{RF}$

\[ f_{RF} \rightarrow \frac{f_{RF}}{n} \rightarrow \frac{f_{RF}}{n} \rightarrow \frac{f_{RF}}{n} \rightarrow \frac{f_{RF}}{m} \]

- Works (well, on paper), so what is the problem?
  → Dividers are nothing but counters! Initial value?
Synchronizing multiple dividers

- Generate signals using frequency division from $f_{RF}$

- How to fix?
  - Reset from master to slave divider(s) to force initial condition

→ Never more than one divider without reset!
Multiple divider with counting offset

• Counter with programmable offset value

$\frac{f_{RF}}{n}$

$\text{Offset}$

Counter to $n$

$x = 0?$

$x = 0?$

$\frac{f_{RF}}{n}$

$\frac{f_{RF}}{n}$

→ Single counter/divider split in two output branches
→ Impossible to lose relative phase of outputs
→ More complicated set-up allows also $\frac{f_{RF}}{m}$ and $\frac{f_{RF}}{n}$, etc.
Fundamental periodicity
Example: BESSY II booster and storage ring

- Storage ring circumference 240 m, $f_{RF} = 499.6$ MHz
- Circumference ratio of Booster and storage ring: $2/5$

→ Everything repeats with periodicity of
  - 5 turns in booster
  - 2 turns in storage ring

---

Sync. divider

Master: $f_{RF} = 500$ MHz

\[
\begin{array}{c}
16 \\
\downarrow \\
1 \\
\downarrow \\
1/10 \\
\downarrow \\
1/25 \\
\downarrow \\
1/50 \\
\end{array}
\]

- $3.125$ MHz, $f_{rev}$ booster
- $1.25$ MHz, $f_{rev}$ storage ring
- $0.625$ MHz, periodicity

Each gray point represents 4 RF buckets
Example: SLS booster and storage ring

- Storage ring circumference 288 m, $f_{RF} = 499.6$ MHz
- Circumference ratio of Booster and storage ring: $15/16$

→ Fundamental periodicity (super-period)

16 turns of booster corresponding to 15 turns in storage ring
Fundamental periodicity for transfer

- Two accelerators with revolution periods $T_{\text{rev},1}$ and $T_{\text{rev},2}$

$$T_{\text{rev},2} = \frac{m}{n} T_{\text{rev},1} \quad \rightarrow \quad T_{\text{super}} = T_{\text{common}} = T_{\text{fiducial}} = mT_{\text{rev},1} = nT_{\text{rev},2}$$

→ Beam transfer may take place at every period $mT_{\text{rev},1}$ or $nT_{\text{rev},2}$

→ This periodicity is, depending on the accelerator and laboratory, called super-period, common or fiducial period

→ In case of integer ratio of revolution frequencies, beam can be transferred once every turn of the larger accelerator

<table>
<thead>
<tr>
<th>Sending</th>
<th>Receiving</th>
<th>Ratio</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>BESSY booster</td>
<td>BESSY SR</td>
<td>2/5</td>
<td>Fixed frequency</td>
</tr>
<tr>
<td>SLS booster</td>
<td>SLS SR</td>
<td>15/16</td>
<td>Fixed frequency</td>
</tr>
<tr>
<td>J-PARC RCS</td>
<td>J-PARC MR</td>
<td>2/9</td>
<td>Profit from ratio for bucket selection</td>
</tr>
<tr>
<td>PS booster</td>
<td>PS</td>
<td>1/4</td>
<td></td>
</tr>
<tr>
<td>PS</td>
<td>SPS</td>
<td>1/11</td>
<td></td>
</tr>
<tr>
<td>PS</td>
<td>AD</td>
<td>3/1</td>
<td>Particle type and energy change at transfer</td>
</tr>
<tr>
<td>SPS</td>
<td>LHC</td>
<td>7/27</td>
<td>$f_c$ as low 1.6 kHz</td>
</tr>
</tbody>
</table>
Synchronous triggers

How to generate beam synchronous triggers?
→ Chains of counters to re-synchronize timings

Each step re-synchronizes with respect counter clock
- ‘Start engine button’ synchronous to nothing
- Complete system of two accelerators periodic with timing #1
- Timing #2 marks, e.g., a delay in number of turns
- Timing #3 counts $f_{RF}$ clocks to fine adjust, e.g., bucket number
Timing counters may use different clocks, as long as the clocks are derived from the same source.

- Reproducible delay between clock #2 and #3
- Tree structures of timings
Circular electron/lepton accelerators

- Simplification for most electron accelerators:
  - Leptons are **practically at speed of light**
  - Synchrotron radiation **damping forces bunches into buckets**
  - Beam synchronous **timing triggers can be derived by counting RF master clock** (or its sub-multiples)
  - Everything is predictable from the beginning

→ Let’s get frequencies moving
Transfer between hadron accelerators
Circular hadron accelerators: master clock sweeps
Need again synchronous timings with respect to beam
    → Kicker magnets
    → Beam instrumentation
RF manipulations require bunches in certain buckets
    → Beating pattern due to multiple RF harmonics
        → Splits behaviour for different buckets
    → Bucket numbering
Need to know longitudinal beam position for transfer
    → Where (in phase/in time) is the beam?
Phase-locked loop

- Frequency re-generation and multiplication
- Voltage controlled oscillator (VCO) locked in phase to input

\[ \frac{d\phi}{dt} = K_{VCO}V_{in} \]

\[ \omega_{VCO} = 2\pi f_{VCO} \]

\[ f_{out} = n \cdot f_{in} \]

\[ \phi_{out}/n - \phi_{in} = \text{const.} \]

→ Fixed phase relationship:
→ Optional divider:
Beam phase loop

- **Phase pick-up**
- **Beam phase**
- **RF cavity**
- **Cavity phase**
- **Power amplifier**
- **Digital synthesizer**
- **Loop corr.**
- **DDS**
- **Precision VFO**
- **RF**
- **Slow signal**
- **$h f_{rev}$**

---

**Beam phase loop with beam phase as reference for RF system**
Benefits of beam phase loop at transfer

- Adapt RF phase to bunch phase **before beam blows-up**
  - Fast compared to timescale of synchrotron frequency, $f_s$

→ Even large transients (injection, transition) can be controlled
→ Small longitudinal emittance blow-up

**Rigid RF, no phase loop**

**With phase loop**
Start counting with injection

\[ f_{RF} \]

- Start of divider/counter?

\[ h \]

→ Get it right from injection

\[ 1 \]

→ Use output from divider as reference for incoming beam

Beam
synchro-
 nous \( f_{rev} \)
Start counting with injection

- **Start of divider/counter?**
  - Get it right from injection
  - Use output from divider as reference for incoming beam

- **Before injection:**
  - Distribute delayed revolution frequency to sending accelerator
  - Bunches are injected synchronously with $f_{\text{rev, delayed}}$
  - **Shifted** with respect to $f_{\text{RF}}$ and $f_{\text{rev}}$
Start counting with injection

- Start of divider/counter?
  - Get it right from injection
  - Use output from divider as reference for incoming beam

- Before injection:
  - Distribute delayed revolution frequency to sending accelerator
  - Bunches are injected synchronously with $f_{\text{rev, delayed}}$
  - Shifted with respect to $f_{\text{RF}}$ and $f_{\text{rev}}$
Beam phase loop without beam?

→ Just replace beam by a simple RF generator!

Beam phase loop

**Beam phase emulator**

Phase pick-up

RF cavity

**Δφ**

Cavity phase

**DDS VCO**

**Power amplifier**

**RF**

**Slow signal**

**h \cdot f_{rev} from B**

**f_{out} = f_{in} \pm Δf**

**Beam synchronous**

**h \cdot f_{rev}**

**φ_{err} \sim Δf**
Synchronization chain for bucket counting

- Incoming beam has reproducible phase with respect to RF bucket, synchronous $f_{\text{rev}}$ and beam phase emulating generator
  → Straightforward switch to beam signals, already locked in phase
Synchronization chain for bucket counting

• Incoming beam has reproducible phase with respect to RF bucket, synchronous $f_{rev}$ and beam phase emulating generator
  → Straightforward switch to beam signals, already locked in phase
  → Beam phase with respect to $f_{rev}$ always known
Bucket numbering
Bucket numbering for RF manipulations

<table>
<thead>
<tr>
<th></th>
<th>Triple splitting</th>
<th>Batch compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection harmonic</td>
<td>[Image]</td>
<td>[Image]</td>
</tr>
<tr>
<td>Periodicity of RF</td>
<td>Every bucket</td>
<td>Only one beating along circumference</td>
</tr>
<tr>
<td>manipulation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection bucket</td>
<td>4 buckets difference between both injections</td>
<td>Both injections into independently defined buckets</td>
</tr>
<tr>
<td>selection</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

→ Must inject into the correct bucket numbers
Example: PS injection bucket selection

- Bunches must be placed into the correct buckets numbers
- Harmonic number change only for even number of bunches

→ Bucket number control during both transfers PSB → PS

→ How to handle changing number of bunches?
Intermediate summary

• Basic techniques of signal synchronizations
  → Beware of dividers

• Beam transfer between circular lepton accelerators
  → Constant frequency
  → Predictable, independently from beam
  → Fundamental periodicity

• Beam transfer between circular hadron accelerators
  → Beam is reference, keep track
Timing, Synchronization & Longitudinal Aspects

II

H. Damerau
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  • Phase detectors and dividers

• Beam transfer
  • Fundamental periodicity
  • Transfer between circular lepton accelerators

• Transfer between hadron accelerators
  • Beam phase loop, bucket numbering
  • Transfer process: Synchronization, transfer triggers
  • Longitudinal matching

• Summary
Synchronization and transfer
# Steps of beam transfer synchronization

1. • Set bending fields in both accelerators to the same magnetic rigidity

2. • Synchronize sending or receiving accelerator

→ **Ready for transfer**

3. • Start counting clock of **fundamental periodicity**
   • Trigger bump and septum elements

4. • Start counting $f_{\text{rev}}$ clock (sending/receiving accelerator)
   • Start counting **bucket clock**

5. • Fine delay
   • Ejection and injection kickers triggers

→ **Transfer**
Match bending field of both accelerator

• Same magnetic rigidity $\rho B$ of sending (1) and receiving (2) accelerators

\[ F_Z = F_L \rightarrow \frac{p}{q} = \rho B \]

\[ \rho_1 B_1 = \rho_2 B_2 \]

→ No rule without exception: Particle type change at transfer

• Proton to anti-proton conversion, e.g.,
  $120$ GeV/c $\neq 8$ GeV/c (Fermilab),  $26$ GeV/c $\neq 3.6$ GeV/c (CERN),

• Charge state change at transfer, e.g. LHC ion injector chain
  Pb$^{54+}$ in LEIR/PS $\rightarrow$ Pb$^{82+}$ (in SPS)
Match RF frequencies

- RF frequencies of both accelerators must have appropriate ratio assuming that the beam velocity is unchanged

\[
f_{\text{rev}} = \frac{f_{\text{RF}}}{h} = \frac{\beta c}{2\pi R}
\]

\[
\beta c = 2\pi R_1 f_{\text{rev},1} = 2\pi R_2 f_{\text{rev},2} \quad \rightarrow \quad R_1 \frac{f_{\text{RF},1}}{h_1} = R_2 \frac{f_{\text{RF},2}}{h_2}
\]

→ Common choice of most circular electron accelerators \( f_{\text{RF},1} = f_{\text{RF},2} \)
→ Harmonic number, \( h \), proportional to circumference, \( 2\pi R \)
→ Again no rule without exception: Production of antiprotons in target in transfer line
Distance between bunches

- Distance of bunches (bunch spacing, $\tau_{\text{bunch}}$) from source accelerator must match distance of buckets

  - Example: $\tau_{\text{bunch}} = 2/f_{\text{RF}}$
  
  - Example: $\tau_{\text{bunch}} = 5/f_{\text{RF}}$

- Common case: $f_{\text{RF,2}} = n \cdot f_{\text{RF,1}}$
  
  - $f_{\text{RF,LHC}} = 2 \cdot f_{\text{RF,SPS}}$ and $f_{\text{RF,SPS}} = 5 \cdot f_{\text{RF,PS}}$

- Several exceptional cases:
  
  - No bunch distance with single bunch $\rightarrow$ more flexibility
  
  - Adjust bunch spacing using multiple RF systems
Exception: double-harmonic RF at transfer

- Was used at CERN PSB-to-PS to transfer 2 bunches at once
- Circumference ratio $C_{PS}/C_{PSB} = 4$

$\rightarrow$ Ratio virtually moved to $2/7$: use $h_{RF} = 2 + 1$

1. Add $h_1$ component such that bunches approach to 245 ns (small spacing) $\rightarrow$ big spacing becomes 327 ns

2. Synchronize on $h_1$ to the PS

3. Trigger extraction kicker in-between the small spacing

4. Eject two bunches per ring at a distance of 327 ns

Spacing larger than $C_{PSB}/2 \rightarrow h_{PS} = 7$, $C_{PS}/7$

Christian Carli
Steps of beam transfer synchronization

1. Set bending fields in both accelerators to the same magnetic rigidity

2. Synchronize sending or receiving accelerator

→ Ready for transfer

3. Start counting clock of fundamental periodicity
   • Trigger bump and septum elements

4. Start counting $f_{rev}$ clock (sending/receiving accelerator)
   • Start counting bucket clock

5. Fine delay
   • Ejection and injection kickers triggers

→ Transfer
Before synchronization

• Even with magnetic rigidity matched: revolution frequencies not at theoretical ratio due to imperfections

→ Bunches and buckets slip in phase

But: important question left unanswered!
Who is the boss?

- Transfer beam to a downstream machine: **Bunch-to-bucket**
  1. Protons between synchrotrons → **Synchronize accelerators**

2. Move relative phase of RF together with beam between both machines to hit the empty buckets

**Sending accelerator is, the boss?**

**Receiving accelerator is the boss?**
Choice of master for transfer synchronization

- **Sending accelerator is master of transfer**
  - Receiving accelerator adapts to incoming beam
  - Common choice when receiving accelerator has no beam before transfer
  - Interesting for only single beam transfer, e.g., protons from PS → AD for antiproton production

- **Receiving accelerator is master of transfer**
  - Sending accelerator adapts to incoming beam
  - Common choice when receiving accelerator has already beam before transfer (multiple injections)
  - Most common at CERN, e.g., proton injector chain PSB → PS → SPS → LHC
Before synchronization

- Simple test case of circumference ratio 2: \( C_2 = 2C_1 \)

**Source** accelerator is master at transfer

**Target** accelerator is master at transfer
Before synchronization

- Simple test case of circumference ratio 2: \( C_2 = 2C_1 \)

\[ \rightarrow \text{Synchronize both accelerator to force: } f_{\text{rev},1} = 2f_{\text{rev},2} \]
Simple synchronization process

1. Move beam to off-momentum ($B$ const.):
   \[
   \frac{df}{f} = \frac{\gamma^2_{tr} - \gamma^2}{\gamma^2 \gamma^2_{tr}} \frac{dp}{p}
   \]
   → Well defined frequency difference between accelerators

2. Measure azimuth error, when beam at correct azimuth
   → Close synchronization loop
   → Moves beam to ref. momentum

---

1. Move beam to off-momentum ($B$ const.):
   \[
   \frac{df}{f} = \frac{\gamma^2_{tr} - \gamma^2}{\gamma^2 \gamma^2_{tr}} \frac{dp}{p}
   \]
   → Well defined frequency difference between accelerators

2. Measure azimuth error, when beam at correct azimuth
   → Close synchronization loop
   → Moves beam to ref. momentum

---

Bunch should be here

Beam azimuth (from phase loop) → Beam phase (from master)

Act on $f_{RF}$ of slave

Locked!

200 ms
Example: Synchronization of SPS to LHC

→ **LHC is master** for beam transfer from SPS

Arrival at flat-top +30 ms  
Measure $\Delta\tau$ of azimuth SPS-LHC  
Re-measure $\Delta\tau$ of azimuth  
Close fine re-phasing loop at $f_{\text{RF, LHC}}$  
Ready for transfer

Set $f_{\text{rev,SPS}} = \frac{27}{7} f_{\text{rev,LHC}}$
Apply frequency bump
Apply frequency bump

→ Coarse and fine re-phasing to perfectly align bunches with respect to target buckets (400 MHz, 2.5 ns) in LHC
→ Complete synchronization process takes about 500 ms

SPS Phase synchro

SPS turns (10000 turns correspond to 231 ms)
Example: Fast cogging of booster at FNAL

- Rapid cycling synchrotron from 400 MeV to 8 GeV
- Total cycle length is only 25 ms → How to synchronize fast?

1. Measure beam phase early in the cycle and predict azimuth at flat-top
2. Apply radial/frequency bumps already during acceleration
After synchronization

- Simple test case of circumference ratio 2: \( C_2 = 2C_1 \)

Source or target accelerator is master at transfer

\[ \rightarrow \text{Revolution frequencies coupled: } f_{\text{rev,1}} = 2f_{\text{rev,2}} \]

\[ \rightarrow \text{Transfer can be triggered every turn of the target accelerator} \]
Example: Ejection bucket numbering in PS

- Azimuthal position of 1st bunch ambiguous after RF manipulations
  → Number of buckets and bunches changes during acceleration

- But: Synchronous $f_{\text{rev,PS}}$ signal with reproducible phase to beam
  → ‘Re-numbering’ of buckets by shifting reference from SPS

→ Shift of external reference $f_{\text{rev,PS}}$ adjustable in SPS bucket units
  → Synchronize external and beam synchronous $f_{\text{rev,PS}}$
Example: Ejection synchronization chain

→ Multiple ‘batches’ are transferred from PS to 11 times larger SPS

Outgoing beam \( \phi \) const. \( f_{\text{rev,PS}} \) internal \( \phi \) const. \( f_{\text{rev,PS}} \) reference \( \phi \) const. \( f_{\text{rev,PS}}, f_{\text{RF,SPS}} \) for synchro.

Beam phase loop

Synchronization loop

Ejection divider

→ Beam phase with respect to \( f_{\text{rev}} \) always known
Steps of beam transfer synchronization

1. • Set bending fields in both accelerators to the same magnetic rigidity

2. • Synchronize sending or receiving accelerator

→ Ready for transfer

3. • Start counting clock of fundamental periodicity
   • Trigger bump and septum elements

4. • Start counting $f_{rev}$ clock (sending/receiving accelerator)
   • Start counting bucket clock

5. • Fine delay
   • Ejection and injection kickers triggers

→ Transfer
Synchronous triggers

→ Cascade of trigger counters for fast transfer elements
  • Very similar to transfer with lepton synchrotrons
Steps of beam transfer synchronization

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   • Start counting bucket clock

5. Fine delay
   • Ejection and injection kickers triggers

→ Transfer
Example: Turn count control at extraction

- J-PARC rapid cycling synchrotron and main ring ratio: 4.5
  - Transfer possible once every two turns of main ring
  - Transfer of 4 times two bunches

Counter on $f_{\text{rev}}$ of source (RCS) set normally

Counter on $f_{\text{rev}}$ of source (RCS) delayed by one turn

→ Beam synchronous timing can also be used to control target azimuth (bucket number) of transferred beam
Energy matching
Energy matching of incoming beam

- **Ideal beam** circulates with the expected revolution frequency \((\Delta f = 0)\) on the central orbit \((\Delta R = 0) \rightarrow \Delta p = 0\)
- **Real beam** behaviour is calculated using

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- **Choice of two parameters** from $B, p, R, f$ directly constrains all others

$\rightarrow$ **Example:** at *fixed* magnetic field ($\Delta B = 0$), revolution frequency and radial position are directly linked
Energy matching without RF

• Observe de-bunching (no RF) with periodic trigger at $n \cdot f_{\text{rev}}$

→ Does the beam circulate with the expected $f_{\text{rev}}$?

at the central orbit?

- Changing $B$ alone insufficient, since $f_{\text{rev}}$ and $R$ linked (const. $p$)

→ Change two parameters to fix the others, e.g., $B$ and $p$ or $B$ and $f$

→ All parameters are constrained
Longitudinal matching equations
Recap of longitudinal beam dynamics (1)

For a single harmonic RF system

\[ H \left( \phi, \frac{\Delta E}{\omega_{\text{rev}}} \right) = -\frac{1}{2} \frac{\hbar \eta \omega_{\text{rev}}}{p R} \left( \frac{\Delta E}{\omega_{\text{rev}}} \right)^2 + \frac{qV}{2\pi} \left[ \cos \phi - \cos \phi_0 + (\phi - \phi_0) \sin \phi_0 \right] \]

with \( \phi = \phi_0 + \Delta \phi \) it becomes

\[ H \left( \Delta \phi, \frac{\Delta E}{\omega_{\text{rev}}} \right) = -\frac{1}{2} \frac{\hbar \eta \omega_{\text{rev}}}{p R} \left( \frac{\Delta E}{\omega_{\text{rev}}} \right)^2 + \frac{qV}{2\pi} \left[ \cos(\phi_0 + \Delta \phi) - \cos \phi_0 + \Delta \phi \sin \phi_0 \right] \]

using \( \cos(\phi_0 + \Delta \phi) = \cos \phi_0 \cos \Delta \phi - \sin \phi_0 \sin \Delta \phi \)

\[ \simeq \cos \phi_0 \left( 1 - \frac{1}{2} \Delta \phi^2 \right) - \sin \phi_0 \Delta \phi \]

The Hamiltonian simplifies to

\[ H \left( \Delta \phi, \frac{\Delta E}{\omega_{\text{rev}}} \right) \simeq -\frac{1}{2} \frac{\hbar \eta \omega_{\text{rev}}}{p R} \left( \frac{\Delta E}{\omega_{\text{rev}}} \right)^2 - \frac{1}{2} \frac{qV}{2\pi} \Delta \phi^2 \cos \phi_0 \]
Recap of longitudinal beam dynamics (2)

\[ H \left( \Delta\phi, \frac{\Delta E}{\omega_{\text{rev}}} \right) \approx -\frac{1}{2} \frac{h \eta \omega_{\text{rev}}}{p R} \left( \frac{\Delta E}{\omega_{\text{rev}}} \right)^2 - \frac{1}{2} \frac{q V}{2 \pi} \Delta\phi^2 \cos \phi_0 \]

- In the centre of the bucket, particles move on elliptical trajectories in \( \Delta\phi-\Delta E \) phase space
- Hamiltonian is constant on these trajectories

→ Aspect ratio of the elliptical trajectories must be identical in sending and receiving accelerator
• Compare two particles on the same trajectory

1. No phase deviation

2. No energy deviation

→ $\Delta \phi$ depends on frequency → use physical duration $\Delta \tau$ instead

$$\Delta \phi = 2\pi f_{RF} \Delta \tau = h \omega_{\text{rev}} \Delta \tau$$

→ Also replacing $pR = \frac{E \beta^2}{\omega_{\text{rev}}}$
Physical aspect ratio of bucket trajectories (2)

→ Hamiltonian equal for both extreme particles, hence

\[
\frac{1}{2} \frac{h \eta \omega_{\text{rev}}^2}{E \beta^2} \left( \frac{\Delta E}{\omega_{\text{rev}}} \right)^2 = \frac{1}{2} \frac{qV}{2 \pi} \frac{h^2 \omega_{\text{rev}}^2}{E \beta^2} \Delta \tau^2 \cos \phi_0
\]

which can be simplified to

\[
\left( \frac{\Delta E}{\Delta \tau} \right)^2 = \frac{qV}{2 \pi} \frac{h \omega_{\text{rev}}^2}{E \beta^2} \frac{\cos \phi_0}{\eta}
\]

→ This aspect ratio \( \Delta E/\Delta \tau \) must remain unchanged at transfer
Matched bunch-to-bucket transfer

\[ \frac{\Delta E}{\Delta \tau} = \frac{qV}{2\pi} E \beta^2 h \omega_{\text{rev}} \frac{\cos \phi_0}{\eta} \]

Equating \( \left( \frac{\Delta E}{\Delta \tau} \right)^2 \) for sending (1) and receiving (2) accelerator gives a general matching condition.

\[ q_1 V_1 E_1 \beta_1^2 h_1 \omega_{\text{rev},1} \frac{\cos \phi_{0,1}}{\eta_1} = q_2 V_2 E_2 \beta_2^2 h_2 \omega_{\text{rev},2} \frac{\cos \phi_{0,2}}{\eta_2} \]

For most cases (fixed energy and no particle type change)

\[ q_1 = q_2 \quad \beta_1 = \beta_2 \quad E_1 = E_2 \quad \cos \phi_{0,1} = \cos \phi_{0,2} = 1 \]

It simplifies to the voltage ratio between RF systems:

\[ \frac{V_1}{V_2} = \left( \frac{R_1}{R_2} \right)^2 \frac{\eta_1}{\eta_2} \frac{h_2}{h_1} \]
Simple matched transfer example

- Transfer between to accelerators with $f_{RF,2} = f_{RF,1}/2$

→ Phase space aspect ratio:

$$\Delta E = \beta \omega_{rev} \sqrt{\frac{qV}{2\pi} E h} \left| \frac{\cos \phi_0}{\eta} \right| \cdot \Delta \tau$$

![Source (1) bucket](image1)

![Target (2) bucket](image2)
Simple matched transfer example

- Transfer between to accelerators with $f_{RF,2} = f_{RF,1}/2$

→ Phase space aspect ratio:

$$\Delta E = \beta \omega_{rev} \sqrt{\frac{qV}{2\pi} Eh \left| \frac{\cos \phi_0}{\eta} \right|} \cdot \Delta \tau$$

→ Obvious case of matched bunch-to-bucket transfer
Longitudinal matching
Longitudinal matching at injection

- Long. emittance is only preserved for **correct RF voltage**

→ **Bunch is fine,**

longitudinal emittance remains constant

→ **Dilution of bunch results in increase of long. emittance**
Longitudinal matching

**Matched case**
\[ \Delta \phi = 0, \frac{V_{\text{inj}}}{V_{\text{RF}}} = 1 \]

**Longitudinal mismatch**
\[ \Delta \phi = 0, \frac{V_{\text{inj}}}{V_{\text{RF}}} = 2 \]

→ **Bunch is fine,**
   longitudinal emittance remains constant

→ **Dilution of bunch results in increase of long. emittance**
Matching of phase and energy

- What is the difference?

-45° phase error at injection
  - Can be easily corrected by bucket phase

Equivalent energy error
  - Phase does not help: requires beam energy change
Example: mismatch at injection to PS

• Deliberate longitudinal mismatch at injection for blow-up

Mountain range

→ Intentional mismatch contributes to controlled longitudinal blow-up

Bunch length evolution

Amplitude [a.u.]

Time [μs]

4σ bunch length [ns]

Controlled blow-up

Mismatch

(Gaussian fit)
No problem with electron accelerators

- Synchrotron radiation damping matches bunches by itself
- Phase and energy oscillations decay

\[ \frac{\Delta p}{p} [%] \]

\[ \phi [2\pi \text{ rad}] \]

\[ \text{Septum blade} \]

→ Mismatched injection can be a useful tool
Summary

• Basic techniques of signal synchronizations
  → Beware of dividers

• Beam transfer between circular lepton accelerators
  → Constant frequency

• Beam transfer between circular hadron accelerators
  → Variable frequency
  → Moving target

• Follow the beam
  → No need to measure → keep track
  → Matching between accelerators
A big Thank You

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this simplifies to

\[ H(\Delta\phi, \dot{\phi}) \simeq \frac{1}{2} \dot{\phi}^2 + \frac{1}{2} \omega_s^2 \Delta\phi^2 \]