SPS RF: Proton LHC Operation
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Introduction

Programme

- pLHC cycle, RF point of view relevant for OP
- TWC 200 MHz and cavity loops: differences with respect to Fixed Target Beam
- TWC 800 MHz and cavity loops
- step through cycle: loops, signals and diagnostics
  - longitudinal damper
  - controlled longitudinal emittance blow-up
  - rephasing
Proton LHC Beam

Single and Multi Bunch Beams

- $1 \times 10^9 \leq N_Q \leq 4 \times 10^{11}$
- up to 4 batches of 72 (82) bunches
- bunch spacing 25 ns or more
- batch spacing 225 ns
TWC 200 MHz

Power

Travelling wave cavities (1)

- 4 cavities as for pFT beams
- structure parameters, $Z_1$, $Z_2$, counterphasing

(1) OP Shutdown Lectures 2017-02-23, Note-2017-01
The RF power limits of the travelling wave cavities under consideration are given by

\[ P = v^2 + i_b^2 + 2v_i_b \cos \alpha \]

where

- \( v \) is the axial voltage produced by the RF generator current,
- \( i_b \) is the beam current vector,
- \( \alpha \) is the beam loading angle.

This equation can be visualised in a vector diagram, Fig. 1, shown for a case above transition energy.

**Note:** 2017-03 OP Shutdown Lecture 2017-03-02 6/42
TWC 200 MHz

Power

Example

- 72 bunches, 25 ns bunch spacing,
- MD_SCRUB_26_L26400_Q20
- $N_Q = 1.7 \times 10^{11}$, $I_{pk} = 2.1$ A
- cosine-squared bunches of 1.5 ns ($f_{shape} = 0.92$), $I_b = 1.9$ A

4 Sections

5 Sections
TWC 200 MHz

Power

Example

- 1 batch, 72 bunches, 25 ns bunch spacing
- $N_Q = 1.3 \times 10^{11}$
- $V_{RF} = 1.2$ MV, 5 section structure
TWC 200 MHz

Cavity Loops

Cavity loops for pFT and pLHC operation
- cavity loop (1)
  - amplitude loop
  - phase loop
- 1-Turn Delay Feedback (1)

Additional loops for pLHC operation
- Feed-Forward (one per TWC)
- Longitudinal Damper (TWC200-1, TWC200-3)
### Cavity loop block diagram

**Diagram Details:**
- **LO (Local Oscillator):** $f_{LO}$
- **RF (Radio Frequency):** $f_{RF}$
- **VCO (Voltage-Controlled Oscillator):** $\Phi_{VCO}$
- **MOD (Modulator):** $\Delta V$
- **DET (Detector):** $f_{XTAL 10.7}$
- **BPF (Band-Pass Filter):** $f_{RF}$
- **TWC 200 MHz:**
- **Beam:** $f_{LO}$
- **Wall Current:** $f_{200 MHz}$

**Connections:**
- $f_{LO}$ connects to $f_{RF}$
- $f_{XTAL 10.7}$ connects to $\Phi_{VCO}$
- $\Delta V$ connects to $\Phi_{VCO}$ and DET
- $f_{200 MHz}$ connects to TWC 200 MHz and Beam

**Annotations:**
- Simplified TWC200 Cavity Loops
- T. Bohl, U. Wehrle, 2017-02-17

**Additional Notes:**
- Note-2017-03
- OP Shutdown Lecture 2017-03-02
TWC 200 MHz
Cavity Loops

1-Turn Delay Feedback (one per TWC)

- delay and feedback gain
- comb filter, 
  \[(h \pm n)f_{rev}, \ f_{RF} = hf_{rev}, \ \{h, n\} \in \mathbb{N}\]
- \(\sin x/x\)
- limitation: \(Z_1 \neq Z_2\) (1)

(1) OP Shutdown Lectures 2017-02-23, Note-2017-01
Feed-Forward (one per TWC)
- same purpose as 1-Turn Delay Feedback
- measure \( i_b \)
- optimal filter for transient (linear/parabolic response, see (1))

- reproduce \( Z_2 \)
- apply inverted beam loading voltage
- limitation: \( Z_1 \neq Z_2 \)
Cavity Loops

1-Turn Delay Feedback, Feed-Forward beam loading compensation, LHC batch of 2 µs

\[ V_{\text{tot}} = \sqrt{V_I^2 + V_Q^2} \]

P. Baudrenghien, Chamonix Workshop 2000
**TWC 800 MHz**

**Power**

- 2 TWC 800 MHz (ppbar switch)
- IOTs: $2 \times 4$, 60 kW each
TWC 800 MHz

Power
TWC 800 MHz

Power

IOT: Inductive Output Tube (Klystrode), 1938
▶ cathode - control grid - drift tube - cavity
TWC 800 MHz
Cavity Controller

Clock Distri
PLL
VCO

SWITCH & LIMIT
Limiter

IOT
4x

VETO
RF Drive

WaveGuide

Phase & Gain control
Polar loop
1-Turn Feedback
Set Point

Functions
(Voltage & Phase)

I/Q mod
DAC
BPF

I/Q demod
ADC
LPF

I/Q demod
ADC
LPF

Σ TWC200

200MHz Quadrupler
Limiter
x4

Σ

TWC 800

G. Hagmann
optimise $f_s$ spread

BS/BL mode, used in BS mode
Beam Control

Overview

Basic steps

- RF on: TWC 200 MHz, TWC 800 MHz
- synchronisation
- injection
- acceleration
- controlled longitudinal emittance blow-up
- rephasing
Beam Control

Overview

SIMPLIFIED RF BEAM CONTROL FOR pLHC OPERATION
T. BOHL, U. WEHRLE, 2017-02-23

FREQ.
PROGRAM

INJ.B-FIELD
RADIAL STEERING
B+ / B-

log ΣVCAV DET
log B°

STABLE PHASE PROGRAM

PHASE LOOP

ΔΦ
S & H
Σ
LOOP AMPLIFIER
LO

SYNCHRO LOOP

ΔΦ

fRF PROG
fRF

fREV

ΣVCAV 200
Φ-PU
BLOW-UP

 susceptors

Note-2017-03
Beam Control

Preparation for Injection

RF on ...

- $t = -410 \text{ ms}$ RF on
- $t = -398 \text{ ms}$ (sampled) Phase Loop on

<table>
<thead>
<tr>
<th>Loop</th>
<th>Meas. Signal</th>
<th>Ref. Signal</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase Loop</td>
<td>$f_{RF}$</td>
<td>$f_{RF,\text{prog}}$</td>
<td>before injection</td>
</tr>
</tbody>
</table>

1.5) Closure of PHASE LOOP ($f_{RF}$ on $f_{RF,\text{prog}}$):

The PHASE LOOP normally locks the beam signal (from the PHASE PICK-UP) to the CAVITY signal. Since there is no beam signal before injection of the first batch, the PHASE PICK-UP signal is replaced by $f_{RF,\text{prog}}$ and the CAVITY signal is replaced by $f_{RF}$.

The phase discriminator output is sampled once per turn. The corresponding trigger unit is controlled by MMI (pLHC PHASE SAMPLING).

- adjust OFFSET on 200 MHz PHASE DISCRIMINATOR (RA 9408,B) to the nominal setting 500
- observe the phase of the PHASE LOOP at the output of the SAMPLE & HOLD (RA 9408,B)

- CH2: SAMPLE & HOLD [CH1]
  (PHASE LOOP $\Delta \Phi$) 0.5 V/div

- CH3: VTU $f_{\text{REV PROG pLHC}}$ [TEST SYNC]
  50 mV/div

- CH4: FREQUENCY PROGRAM DDS
  [RF OUT -20 dB] 50 mV/div

- trigger: PHASE LOOP ON [6,7,6]
  (-398 ms)

- time: 1 ms/div

Remarks:
- the beating before closure starts at the START timing of the phase sampling VTU

1.6) PHASE LOOP before INJECTION:

- observe the phase of the PHASE LOOP at the output of the SAMPLE & HOLD (RA 9408,B)
- if there is an offset before injection, fine-adjust the OFFSET on pLHC LOCAL OSCILLATOR (RA 9408,M)
Beam Control

Preparation for Injection

... up to injection

- $f_{\text{inj}}$, $f_{\text{rev}}$ to CPS (Injection Bucket Selector)
- $t = -50$ ms TWC 800 MHz on
- $t = -5$ ms TWC 200 MHz feed-forward on

**SPS RF 2 PS Frequency Measurement (Example LHCPilot)**

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Note-2017-03  OP Shutdown Lecture 2017-03-02  22/42
Beam Control

Injection

First Injection

- CPS Extraction Warning at about $-150 \, \mu s$
- SPS Injection Pulse, RF: $f_{\text{inj,CPS}}$, SYNC: $f_{\text{rev,CPS}}$

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<th>Meas. Signal</th>
<th>Ref. Signal</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchro Loop</td>
<td>$f_{\text{RF}}$</td>
<td>$f_{\text{RF,prog}}$</td>
<td>from injection</td>
</tr>
<tr>
<td>Phase Loop</td>
<td>$f_{\text{RF}}$</td>
<td>$f_{\text{RF,prog}}$</td>
<td>before injection</td>
</tr>
<tr>
<td>Phase Loop</td>
<td>$f_{\text{cav}}$</td>
<td>$f_{\text{beam}}$</td>
<td>after injection</td>
</tr>
</tbody>
</table>

$f_{\text{beam}}$: Phase PU AEP, resonant pick-up
Beam Control

Injection

Phase PU: AEP, BPF, sampled, single bunch example

- adjust the stable phase with the SPS RF Low Level MMI [Beam Control Reference Phase] such that phase error of the SYNCHRO LOOP is minimised after \( \approx 50 \text{ ms} \)
- adjust the injection phase with the SPS RF Low Level MMI [Synchro Injection Phase Shifter] to minimise the transient on phase of the PHASE LOOP at the output of the SAMPLE & HOLD (RA 9408,B)
- if there is a bump on the phase error within the first 5ms, this is due to an error of the injection frequency ask the CCC to adjust the magnetic field (Momentum) at the flat bottom

2.4) Adjustment of PHASE LOOP Sample & Hold:
- observe GATE signal of the SAMPLE & HOLD (RA 9408,B)
- observe PHASE PU signal at the input IN1 of the 200 MHz DUAL LIMITER (RA 9408,B)

<table>
<thead>
<tr>
<th>CH2: SAMPLE &amp; HOLD [GATE]</th>
<th>1 V/div</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH3: 200 MHz DUAL LIMITER [IN1] (PHASE PU) 5 mV/div</td>
<td></td>
</tr>
</tbody>
</table>

trigger: qualified

A \[ : \text{Injection} \]
B \[ : \text{CH3 (beam)} \]

time: 100 ns/div

LHC Beams Phase Sampling

| Top: SAMPLE & HOLD [CH1] (PHASE LOOP \( \Delta \Phi \)) 0.2 V/div |
| Bottom: SYNCHRO LOOP AMPLIFIER [OUT] (SYNCHRO LOOP \( \Delta \Phi_A \)) 0.2 V/div |

trigger: Injection

time: 500 ms/div
Beam Control

Injection

Further diagnostics

- phase loop error, synchro loop error, short/long time scale
  - injection phase
  - stable phase offset (Reference Phase)
  - Imains
  - FT, CO
- MR 1st injection (not well adjusted)

- wrong bucket
- bad profile, satellites, no structure
LHC First Bunch Bucket Error

- BQM
  - wrong bucket
  - bad profile, no structure, bunch length, bunch amplitude distribution
- sampling scope
Beam Control

Injection

After 1st injection

- $t = 0.2\,\text{ms}$ 1-turn delay feedback on
- $t = 1\,\text{ms}$ longitudinal damper on
Beam Control
Longitudinal Damper

Longitudinal Damper (TWC200-1, TWC200-3)

- measure bunch by bunch phase (min. 25 ns bunch distance)
- damping of longitudinal coupled bunch instabilities (low order)
- injection damping (2nd and following injections)
- limitations:
  - TWC BW
  - $f_s$ dependence, Q26, Q20
Beam Control
Longitudinal Damper

2nd injection phase error (Long. Damper off/on)

peak detection (Long. Damper off/on)
Beam Control
Longitudinal Damper

Adjustments LSA: damper gain (attention Q20)
Beam Control

Ramp

At Start Ramp
- B-pulses on, \( \Phi_s \) enabled, max \( \dot{B} = 0.35 \) T/s

BQM measurement during ramp

At \( p = 185 \) GeV/c controlled longitudinal emittance blow-up
- for about 2.7 s
- should be finished before start of transverse scraping
Beam Control
Controlled Longitudinal Emittance Blow-Up

no preventive blow-up

with preventive blow-up
Beam Control
Controlled Longitudinal Emittance Blow-Up

bandwidth limited noise, injected into phase loop
Beam Control

Controlled Longitudinal Emittance Blow-Up

Main Parameters

▶ LSA:
  ▶ practically fix
    ▶ MARGIN_HIGH
    ▶ MARGIN_LOW
  ▶ OP adjustable, function of beam intensity
    ▶ AMPLITUDE
    ▶ SCALING
Beam Control
Controlled Longitudinal Emittance Blow-Up

\[ f_s \ (TWC200 + TWC800) \]

\[ f_s \times \text{SCALING} \times \text{MARGINs} = \text{FREQs} \]
Beam Control
 Controlled Longitudinal Emittance Blow-Up

FREQs

AMPLITUDE
Beam Control
Controlled Longitudinal Emittance Blow-Up

VARI_NOISE

[Image of a graph showing waveforms and settings for a data capture system]
Beam Control

Flat Top

Clock Selection

▶ Local Clock
  ▶ $f_{RF,EXT}$, $f_{c,EXT}$
  ▶ setting-up
  ▶ check rephasing
  ▶ check beam quality (BQM)

▶ LHC Clock
  ▶ $f_{RF,LHC}$, $f_{c,LHC}$
  ▶ LHC filling
  ▶ Clock Interlock
Beam Control
Flat Top

Starting at flat top ...

- disable: $B^+/B^-$ pulses, $\Phi_s$, radial steering (LSA)
- set frequency (Freq. Progr. DSP): $f_{RF,SPS}$ to $f_{RF,LHC}/2$
- coarse phasing (TDC): $f_{rev,SPS}$ wrt $f_c$
- fine phasing (PLL): $2f_{RF,SPS}$ wrt $f_{RF,LHC}$
Beam Control
Flat Top

Starting at flat top? No ...

- update BOffset of VTU for $f_{\text{rev,prog}}$ before SYNC with $f_c$
- ms timing (start of ramp) and $f_c$ non-synchronous, FSK
Beam Control

Flat Top

**RECORD mode**

- record B field between B-Start and B-Stop in Freq. Program DSP, i.e. B field as function of time (ppm)

**PLAYBACK mode**

- Freq. Program DSP ignores $B^+$ and $B^-$ pulses and uses recorded B field
Beam Control

Flat Top

- BQM (detailed diagnostics)
- LHC Extraction Bunch Position Error (Extraction Bucket Monitor)

- SPS Warning Pulse, SPS Extraction Pulse
- extraction