OP Shutdown Lecture on the RF System

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gratefully acknowledging
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Basic physics behind operational quantities

- What do phase, frequency, and voltage do to the beam?
- How to regulate the bunch length?
- How do blow-up and flattening work?
- What quantities can actually be controlled on the HW?

Diagnosing problems

- Where is the limit between low-level and high-power RF?
- Which piquet to call?
- What is the switching-on sequence of the RF?

Challenges for near and further future
RF INSTALLATIONS IN THE LHC

THE HARDWARE
All RF cavities are placed in SS of Point 4

- 2 modules/beam
- 4 cavities/module
- Up to 2 MV/cavity
LHC Point 4, UX45 cavern

- Cryogenic station (behind)
- Cavities (under the concrete)
- Klystrons (RF power generation)
- Faraday cages
- HV bunkers
- High-power controls
Faraday cages for the LLRF

- Low-power level RF loops are control electronics that act on-line on RF voltage, phase, and frequency in order to
  - Monitor and correct the applied RF w.r.t. the designed RF
  - Correct for noise or collective effects
  - Stabilise the beam by damping collective oscillations

LHC Faraday cage
LONGITUDINAL BEAM DYNAMICS

THE BASICS...
RF frequency

Synchrotron

Magnetic field and RF frequency $\omega_{rf}$ are synchronised to the design ("synchronous") energy of the beam $E_s$

- Frequency: synchronous to design energy & revolution period $T_0$

$$\omega_{rf} = h\omega_0 \quad \text{(RF frequency on harmonic h)}$$

$$\omega_{rf} = \frac{hR_s}{\beta_sc} \quad \text{(RF frequency determined by the design radius and relativistic beta)}$$
RF phase

Synchrotron

- Phase: gives the correct accelerating kick when the bunch arrives

\[ \frac{\Delta E_s}{T_0} = qV \sin \varphi_s = qV \sin(\omega_{rf} t_s + \varphi_{rf}) \]

\[ V = \text{cavity peak voltage} \]
\[ \omega_{rf} = \text{RF frequency} \]
\[ \varphi_{rf} = \text{RF phase} \]

\[ \Delta E_s \text{ determined by magnetic field} \]

**Condition for RF acceleration:**

\[ qV \sin \varphi_s = \Delta E_s > 0 \]

\[ \therefore \varphi_s \in (0, \pi) \]

Stationary energy: \( \varphi_s = 0 \) or \( \pi \)

\( \varphi_s \) can be shifted due to SR and intensity effects: induced voltage and e-cloud

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Synchrotron frequency shift

Phase shift due to e-cloud can be visibly measured

- Shift due to induced voltage is difficult to measure

Bunch phase measurement
Beam stable phase during ramp

From the equations of motion, a condition for the particles to stay bunched emerges:

\[ \varphi_s \in \left[ 0, \frac{\pi}{2} \right] \text{ if } \gamma < \gamma_T \]

\[ \varphi_s \in \left( \frac{\pi}{2}, \pi \right] \text{ if } \gamma > \gamma_T \]

Stable/synchronous phase during the LHC ramp, for linear voltage ramp from 6 MV to 10 MV
The RF voltage creates the potential well that keeps the beam bunched

\[ V_{rf} = V \sin(\omega_{rf} t_s + \varphi_{rf}) \]

- Bound and unbound trajectories are separated by the **separatrix** in the phase space of the particle coordinates \((\Delta t, \Delta E)\)
- The length of the **RF bucket** is determined by the RF period \(\frac{2\pi}{\omega_{rf}}\)
- Hole between stationary buckets \(\Delta \varphi = 2\sqrt{\pi} \sin \Delta \varphi_s\), where \(\Delta \varphi_s\) is the phase shift due to impedance, e-cloud, or SR
For constant emittance & energy, the bunch length scales as

\[ \tau \propto V^{-1/4} \]

- Ratio btw. bunch emittance and bucket area = bucket filling factor
  If the bunch is too small w.r.t. bucket, it can become unstable
  If the bunch is too big w.r.t. bucket, losses can occur
Typical feedback loops used

Keep the cavity voltage and phase as programmed
- Cavity loop: slow feedback
- One-turn-delay feedback to compensate for beam loading
- Feed-forward (optional): to reduce the errors in the correction

Keep the bunch centred
- Synchronisation loop: synchronises RF with magnetic field
- Radial loop: corrects transverse position

Correct differences between RF and beam phase
- Beam phase loop: damp injection oscillations, phase noise, etc.

Damp instabilities
- Longitudinal & transverse dampers: damp corresponding oscillations in a given frequency range
  Longitudinal damper damps only the fundamental impedance, otherwise we rely on natural damping!
Beam phase loop

To correct injection errors, counteract RF noise and phase kicks

- Integrates the phase error and acts on the RF frequency

Beam phase loop only
(no synchro loop)

Injection error: 0.5 ns
PL damping time: 5 turns
(= gain of 1125 in Trim Editor)
Beam phase loop

Phase loop gain

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The synchro loop maintains the desired RF frequency in the long run, typically with a gain 10 times weaker than the phase loop.
Synchronisation loop

Pulls back the bunch to the reference phase and frequency

Beam phase loop and synchronisation loop

Injection error: 0.5 ns
PL damping time: 5 turns
(= gain of 1125 in Trim Editor)
SL damping time: 50 turns
(= gain of 112.5 in Trim Editor)
LONGITUDINAL BEAM DYNAMICS

BUNCH LENGTH REGULATION
Regulating the bunch length

1. Through the RF voltage
   - Adiabatically, preserving the emittance $\tau \propto V^{-1/4}$
   - (Or non-adiabatically, e.g. rotation in the PS prior to extraction, but this is not used in the LHC)

Example:
PS-SPS bunch-to-bucket transfer

Two double splittings followed by a bunch rotation on PS flat top, then flat bottom and start of acceleration ramp in the SPS
2. Controlled emittance blow-up through RF phase noise injection

LHC blow-up during ramp (to 4 TeV)
Emittance increase by a factor five-six using RF phase noise. The phase and synchro loops guarantee the correct frequency & filtering of other RF noise.
Regulating the bunch length

\[ V_{rf} = V \sin(\omega_{rf} t + \varphi_{rf} + \varphi_N) \]

2. Controlled emittance blow-up through RF phase noise injection
   - Target bunch length achieved using bunch-length feedback; this adjusts the amplitude of the noise injected
     
     More bunch length spread for small target bunch length (<1.1 ns)
3. Using sinusoidal RF phase modulation, “bunch flattening”
   - Redistributes the core of the bunch
   - Bunch length increase depends on the modulation frequency
   - Modulation amplitude needs to be above a certain critical value

\[
\varphi_N = \varphi_{mod} \sin(2\pi f_{mod} t)
\]

Bunch flattening in stable beams
17th June 2016 (B2)

Operational parameters:
- Modulation frequency \(0.9875 \times f_s\)
- Modulation amplitude 0.6°, in six trapezoids of 30 s each

\[
f_{s0}(E_s, V) = f_0 \sqrt{\frac{h e V |\eta_0 \cos \varphi_s|}{2\pi \beta_s^2 E_s}}
\]
Regulating the bunch length

\[ \varphi_N = \varphi_{mod} \sin(2\pi f_{mod} t) \]

3. Using sinusoidal RF phase modulation, “bunch flattening”
   - Modulation amplitude adapted to frequency, determined by theory
3. Using sinusoidal RF phase modulation, “bunch flattening”

- Modulation frequency: $0.9875 \times f_{s0}$
- Central synchrotron frequency
  - 450 GeV, 6 MV: 55.09 Hz
  - 6.5 TeV, 10 MV: 18.84 Hz
  - 6.5 TeV, 12 MV: 20.64 Hz
LONGITUDINAL BEAM DYNAMICS

BLOW-UP AND FLATTENING
Controlled emittance blow-up

\[ V_{rf} = V \sin(\omega_{rf} t + \varphi_{rf} + \varphi_N) \]

RF phase noise targeting the core of the bunch
- Phase noise spectrum around the central synchrotron frequency

Phase-space distribution

Synchrotron frequency distribution

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Controlled emittance blow-up

\[ V_{rf} = V \sin(\omega_{rf} t + \phi_{rf} + \phi_N) \]

However, the phase loop damps noise at \( f_{s0} \)

- We pre-distort the spectrum to counteract the phase loop

**Phase loop action on the spectrum**

**Result: round core, no tails**
Bunch flattening

\[ \varphi_N = \varphi_{mod} \sin(2\pi f_{mod} t) \]

Single-frequency sinusoidal phase modulation close to \( f_{s0} \)
- Resonant excitation → frequency determines final bunch length

Result: flattened core, tails untouched, step-like change in FWHM bunch length [1]
DIAGNOSING PROBLEMS

LLRF, HIGH-POWER RF, FESA...
Expert: RF high power control

CCM: LHC Control > LHC Equipment Control > RF > Expert
Expert: RF cavity control loops

High power presence

Klystron overdrive protection

Klystron phase regulation

Clock distribution

Cavity RF feedback

Cavity coupler & tuner regulation

Cavity voltage & phase (from LSA or manual)

Cavity 1-turn feedback
Klystron cathode voltage:
- 50 kV at injection
- 58 kV during ramp & flat top

Klystron cathode current: 8-9 A

If HV or current missing, log failure, try power “RESET” and “ON”

Red “LINE xBx” if interlocks present

If it doesn’t switch on, call high-power piquet
Cathode current missing for 6B1
24 A instead of 30 A
No high-power interlocks => send "RF ON"
High power OK, No interlock

Cavity coupler:
- 20k at flat bottom
- 60k during ramp and flat top

Cavity voltage:
- LSA Total voltage/8
- Power consumption should be similar for all cavities

A case for LLRF or RF controls piquet
LLRF front-ends in DIAMON

DMN2 console [PROD] 1.6.9 - UNKNOWN as HTIMKO - dbrf

Events Module Check Services Processes Config MOTD CLIC State Problem Logs

General Metric

name seq description

ALLAnalogDemod_M 120 FESA Server and Real-time for class ALLAnalogDem...
ALLAnalogDemod_R 170 FESA Real-Time task
ALLBlowup_M 220 FESA Server and Real-time for class ALLBlowup
ALLClockDistr_DU_M 190 FESA3 mixed server/rt deployment unit
ALLCrateMan_DU_M 200 FESA3 mixed server/rt deployment unit
ALLOTFdbk_M 130 FESA Server and Real-time for class ALLOTFdbk
ALLOTFdbk_R 180 FESA Real-Time task
ALLRFFeedback_M 80 FESA Server and Real-time for class ALLRFFeedback
ALLRFFeedback_R 150 FESA Real-Time task
ALLSetPoint_M 100 FESA Server and Real-time for class ALLSetPoint
ALLSetPoint_R 160 FESA Real-Time task
LTIM_M 70 FESA Server and Real-time for class LTIM
timService 5 Startup timing services
LLRF front-ends in DIAMON
Which piquet to call?

In summary

1. Check for error messages and log them to have a trace!
2. If cathode voltage or cathode current missing, or there is a red line around the “LINE xBx” box, can try to do “POWER RESET”, then “POWER ON”
   If it doesn’t help ⇒ call the high-power piquet
3. Check if all FESA processes are up and running on the front-ends cfv-ux45-acsc1b1-t and cfv-ux45-acsc1b1-f
   If some processes are missing ⇒ call the RF controls piquet
4. If FESA classes are running, but cavity voltage still missing, can try to do an “RF OFF”, “RF ON” sequence
   If it doesn’t help ⇒ call the LLRF piquet

If problems with Beam Control or re-phasing, call LLRF piquet
SWITCHING-ON SEQUENCE

DIAGNOSING PROBLEMS
Main bullet points:

1. Switch on the high-power RF
   - Power mode “ON” → coupler position in “automatic” mode (read from LSA)
   - Power mode “ON_LOCAL” → coupler position in “manual” mode

2. If power is on, switch the LLRF to “operation” mode (in “Switch and Protect”) and limit clamp level to safe value
   - Ensures clamping of RF power not to drive the klystron beyond saturation

3. Test the LLRF with some test point values (in “Modulator” and “Set Point”)
   - Close the klystron polar loop that regulates the klystron phase
   - Automatic cavity tuning on
   - Closing digital & analogue RF feedbacks
   - Checking vacuum pressure and RF clocks

4. If vacuum pressure and RF clocks are OK, clear faults and wait for tuner lock
Main bullet points:

5. Remove the “Modulator” test value and put nominal clamp level in “Switch and Protect”

6. Iteratively increase klystron forward power level through increasing the voltage test value in “Set Point”, while checking loop stability (stability of power level)
   • In power mode “ON_LOCAL”, with manual coupler position

7. If stable, switch mode to “ON” definitely and receive RF voltage & coupler position values from FESA
CHALLENGES FOR THE NEAR FUTURE

WHAT TO EXPECT IN 2017 AND AFTER?
Loss of Landau damping

Single-bunch loss of Landau damping in long fills observed according to measured single-bunch threshold [2].

- Threshold at constant energy scales as $Jm \frac{Z}{n} \propto \frac{\tau^5 V}{N_b}$

Sensitive to bunch length

Loss of Landau damping results in a very slow blow-up
Controlled emittance blow-up

In 2016, the blow-up was close to the limit of stability as the target bunch length was decreased from 1.25 ns to 1.1 ns [3]

- Modified initial target bunch length for better convergence
- With higher intensity, divergence is expected with longer target bunch length; studies to be continued...

Before: spread 410-450 ps

After: spread 120-160 ps
Klystron forward power is limited to about 270 kW (LDR: 300 kW)

- The longer the batches, the stronger the beam loading
- Half detuning, 2015: close to the power limit with 144 bunches
Full detuning

Power reduction demonstrated in MD & physics in 2016 [4,5]
- Half detuning: voltage amplitude constant, phase modulus constant
- Full detuning: cavity voltage amplitude constant, phase modulated

Effect on experiments
- Modulation of collision time w.r.t. bunch clock (all IPs)
- Modulation of z-vertex (IPs 2&8)

Klystron forward power in MD

Modulation of collision time (ALICE, courtesy of R. Shahoyan and S. Foertsch)
References


All animations were done with the BLonD Beam Longitudinal Dynamics code [http://blond.web.cern.ch](http://blond.web.cern.ch)
Operation of the LHC RF system

• The hardware behind
• The meaning of physical quantities
• Beam-based feedback loops
• Means of regulating the bunch length
• Controlled blow-up and flattening
• Diagnosing problems
• Switch-on sequence
• Future challenges

So let’s keep on bunching... Thank you for your attention!