Beam dynamics: RF requirements for the FCC-hh

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Main input ring & beam parameters

• Ring
  – Circumference: ~ 100 km
  – Energy: (0.45, 1.7, 3.3 TeV) → 50 TeV
  – Transition gamma: \( \gamma_t = 110 \) (120 previously)
  – Energy loss per turn \( @50 \) TeV: \( U_0 = 4.6 \) MeV

• Beam
  – Bunch spacing(s): 25 ns (5ns)
  – Bunch length during physics: 8 cm \( (\sigma_\tau = 1.07 \) ns)
  – Bunch intensity: \( 1.0 \times 10^{11} \)
  – Large longitudinal emittance on the flat bottom energy (for transverse beam stability)
Output RF & longitudinal beam parameters

– Optimum RF frequency
– Harmonic number (& length of the FCC ring)
– Minimum RF voltage
  • @50 TeV
  • during ramp (depends on ramp rate)
  • flat bottom (depends on energy and emittance)
– Long. emittance & bunch length during cycle
– RF requirements for injectors
RF frequency

- 5 ns spacing $\rightarrow$ $n \times 200$ MHz $\rightarrow$ 200, 400, 800, ... MHz with bucket length = 5, 2.5, 1.25 ns

- Bucket length in the presence of synchrotron radiation is reduced by $\Delta \phi \sim 2(\pi U_0/V)^{1/2}$ (for $U_0<<V$)

- Bunch length of 8 cm ($\tau_{4\sigma} = 1.07$ ns) $\rightarrow$ 200 or 400 MHz RF
RF harmonic number and ring size

- \( f_{rf} = 400.79 \text{ MHz} \) and bunch spacings of 5 ns, 25 ns, (125 ns ?)
  
  - \( h_{\text{LHC}} = 35640 = 2 \times 4 \times 5 \times 9 \times 9 \times 11 \)
  
  - \( h_{\text{SPS}} = 4620 \times 2 = 2 \times 3 \times 4 \times 5 \times 7 \times 11 \)
  
  For example \( h_{\text{FHC}} = 133650 = 2 \times 3 \times 5 \times 5 \times 9 \times 9 \times 11 \rightarrow 100.2 \text{ km} \)
  
  or \( h_{\text{FHC}} = 132930 = 2 \times 5 \times 7 \times 9 \times 211 \rightarrow 99.4 \text{ km} \)

- **Synchronization between different rings:**
  
  **SPS-LHC:** \( h_{\text{SPS}} / h_{\text{LHC}} = 7 / 27 \rightarrow 7 \text{T}_{\text{rev}}(\text{LHC}) \text{ or } 27 \text{T}_{\text{rev}}(\text{SPS}) \)
  
  Example for 100.2 km ring

  **LHC-FHC:** \( h_{\text{LHC}} / h_{\text{FHC}} = 4 / (3 \times 5) \rightarrow 4 \text{T}_{\text{rev}}(\text{FCC}) \text{ or } 15 \text{T}_{\text{rev}}(\text{LHC}) \)

  **SPS-FHC:** \( h_{\text{SPS}} / h_{\text{FHC}} = 4 \times 7 / (9 \times 25) \rightarrow 28 \text{T}_{\text{rev}}(\text{FCC}) \text{ or } 25 \times 9 \text{T}_{\text{rev}}(\text{SPS}) ! \)

OK for 125 ns spacing (FHeC): \( 2 \times 5 \times 5 \ldots \)
Criteria used to define required RF voltage

• Filling of the RF bucket:
  → maximum momentum filling factor of 0.9 during ramp and of 0.8 in physics (LHC experience)

• Longitudinal emittance on the flat top:
  → based on loss of Landau damping threshold for $N=1 \times 10^{11}$ and longitudinal effective impedance $\text{Im}Z/n = 0.2 \ \text{Ohm}$ (for LHC calculated and measured $\text{Im}Z/n = 0.1 \ \text{Ohm}$).

• Longitudinal emittance on the flat bottom:
  → scaled $\sim E^{1/2}$ from the top value (longitudinal beam stability)
  → maximized for transverse beam stability
400 MHz RF @ 50 teV

Loss of Landau damping

Filling factor in momentum

→ Minimum voltage of 16 MV
200 MHz RF @ 50 TeV

Loss of Landau damping

\[ \text{Nb}=1.0E11 \]
\[ \gamma_t=120 \]
\[ \text{frf}=200 \text{ MHz} \]

Filling factor in momentum

\[ \text{Nb}=1.0E11 \]
\[ \gamma_t=120 \]
\[ \text{frf}=200 \text{ MHz} \]

\[ V=30 \text{ MV} \]
\[ V=20 \text{ MV} \]
\[ V=10 \text{ MV} \]

\[ \tau (\text{ns}) \]
\[ Z(\Omega) \]

→ Possible bunch lengths > 1.4 ns
200 MHz RF @ 50 TeV

Loss of Landau damping

Filling factor in momentum

→ Possible bunch lengths > 1.4 ns
Output from analysis at 50 TeV

**RF parameters:**
- $f_{\text{rf}} = 400.79$ MHz
- $h = 132930 \rightarrow C \sim 99.4$ km or ?

**Beam parameters:**
- Min. emittance @50 TeV $\sim 7$ eVs (16 MV)
- Controlled emittance blow-up is required during physics due to bunch length reduction: SR damping time $0.54$ h
  \[ N_{\text{th}} \sim \varepsilon^{2.5} = \varepsilon_0 e^{-2.5t/0.54} \]
  → For $\varepsilon_0 = 10$ eVs stability is lost in 3 min!
  → Better with higher voltage/emittance

Plus 800 MHz RF system (see talk X. Buffat)?
Acceleration ramps with 400 MHz RF

Example
Magnetic ramp composed of
- parabolic part (0.1)
- linear part (0.8)
- parabolic part (0.1)

Injection at 3.3 TeV

→ Cycle can be optimised for the SR energy loss
Voltage programs for constant filling factor in momentum and controlled emittance blow-up

→ Voltage during ramp depends on acceleration time (magnetic ramp) and controlled emittance blow-up
Other considerations

Instability threshold ImZ/n

Bunch length [ns]

Assumed impedance budget ImZ/n=0.2 Ohm → additional margin → Voltage during ramp can be reduced for smaller emittance blow-up, but then bunch length < 1ns – issue for beam induced heating, transverse stability, ...?
Various injection energies and injectors

- **LHC at 3.3 TeV**: longitudinal emittance of 4.0 eVs with 16 MV (filling factor $q_p = 0.9$) with bunch length of 1.78 ns (4sigma).
  
  → Similar (matched) parameters in the FCC with 16 MV.

- **HEB at 3.3 TeV**: 400 MHz RF system similar to LHC with $V_{\text{max}} = 20$ MV accelerates from 0.45 to 3.3 TeV in 2 min. 60 MV are required for 0.5 min ramp, then larger emittances are possible for FCC injection.

- **Injection at 0.45 TeV from present SPS**: for 1.5 eVs in 15 MV in FCC ($4\sigma_t = 1.8$ ns) → significantly more RF voltage than available in the SPS (even after RF upgrade) is needed.

- **Injection at 1.5 TeV (new ring in the SPS tunnel)**: voltage strongly depends on transition gamma (optics).
Voltage programs for different emittances

**FCC at injection energy:**
in all cases bunch length $4\sigma_t = 1.8$ ns (<2.5 ns)

**3.3 TeV:** 4 eVs injected needs 16 MV

**1.5 TeV:** similar voltage (15 MV) for 1.5 eVs
RF power requirements

- RF power requirements depend on
  - total voltage \( V \) and power loss (SR)
    - acceleration rate
    - longitudinal emittance (for stability)
  - number of RF cavities (voltage/cavity: 1 - 2 MV)
  - coupling \( Q_L \)
- Maximum RF power is required at the end of the ramp (bucket + acceleration +SR) → magnetic ramp can be optimised
- We assume to be below 500 kW/cavity with 12 MW for both beams during physics
The 5 ns beam for the FCC-hh

- The present CERN accelerator complex (PSB-PS-SPS) produces the 5 ns beam in a quite “dirty” way:
  - PS: beam is debunched and modulated at 200 MHz
  - MTE or CTE extraction from PS at 14 GeV/c
  - Beam from the extraction-kicker gap is lost in the ring
  - No bunch-to-bucket transfer
- Studies performed in the past suggest a clean and flexible 5 ns beam production with SPL (Superconducting Proton Linac) replacing the existing PS Booster
Summary

• For the FCC-hh an optimum RF frequency to achieve required bunch length and stability at 50 TeV is 400 MHz
• 32 MV at 400 MHz are sufficient to accelerate in 30 min bunches with injected emittance of 4.0 eVs at 3.3 TeV and controlled emittance blow-up to 7.0 eVs during ramp with some margin for beam stability in physics
• Need for RF synchronisation affects the ring size
• The 5 ns bunch spacing needs a new injector chain
• Bunches with large emittances (TMCl) & bunch length < 1.8 ns are difficult to provide using the SPS ring → 200 MHz RF system (in addition to the 400 MHz) in FCC would help
200 MHz voltage required on the flat top in different SPS options & optics

<table>
<thead>
<tr>
<th>Energy GeV</th>
<th>$\gamma_t$/optics</th>
<th>emittance eVs</th>
<th>bunch lengths ns</th>
<th>voltage MV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present SPS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>450</td>
<td>18.0/Q20</td>
<td>1.5</td>
<td>1.8</td>
<td>52.7</td>
</tr>
<tr>
<td>450</td>
<td>22.8/Q26</td>
<td>1.5</td>
<td>1.8</td>
<td>32.8</td>
</tr>
<tr>
<td>New ring</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1500</td>
<td>18.0</td>
<td>2.5</td>
<td>1.8</td>
<td>44.0</td>
</tr>
<tr>
<td>1500</td>
<td>22.8</td>
<td>2.5</td>
<td>1.8</td>
<td>27.4</td>
</tr>
<tr>
<td>1500</td>
<td>30.0</td>
<td>2.5</td>
<td>1.8</td>
<td>15.8</td>
</tr>
</tbody>
</table>

⇒ In all cases much smaller 200 MHz voltage is required for beam acceleration: < 10 MV
⇒ Much smaller emittance is sufficient for beam stability with $1.1 \times 10^{11}/b$: ~ 0.5 eVs
⇒ Extra voltage is needed only on flat top for beam transfer into 400 MHz RF system of the FCC => additional 200 MHz RF system in the FCC
HEB cycles and beam parameters

**Voltage**

![Voltage Graph]

- 400 MHz RF system
- $V$ for $q_p=0.9$
- $t_{acc} = 0.5$ min
- $t_{acc} = 1.0$ min
- $t_{acc} = 2.0$ min

**Bunch length**

![Bunch Length Graph]

- 400 MHz RF system
- $V$ for $q_p=0.9$
- $\varepsilon$ (eV/s)
- $t_{acc} = 2.0$ min
- $t_{acc} = 0.5$ min
- $t_{acc} = 0.5$ s

=> RF system comparable to the present LHC for 2 min acceleration ramp
=> 30 resonators with 300 kW power for 0.5 min acceleration ramp