Longitudinal beam dynamics and RF requirements

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With input from S. Arsenyev, R. Calaga, D. Schulte
Main input ring & beam parameters

• Ring
  – Circumference: ~ 100 km (97.75 km)
  – Energy: 3.3 TeV → 50 TeV
  – Transition gamma: \( \gamma_t = 99.0 & 71.0 \)
  – Energy loss per turn @50 TeV: \( U_0 = 4.6 \) MeV

• Beam
  – Bunch spacings: 25 ns & 5 ns
  – Bunch length during physics: \( \sigma_z = 8 \) cm (\( \tau_{4\sigma} = 1.07 \) ns)
  – Bunch intensity: \( 1.0 \times 10^{11} \)
  – Maximum longitudinal emittance (for transverse beam stability)
RF and longitudinal beam parameters

✓ Optimum RF frequency → 400 MHz
✓ Harmonic number (ring size) → h=130680 (97.75 km) from synchronization with injectors

– Minimum RF voltage
  • @50 TeV
  • during ramp

– Longitudinal emittance and bunch length
Criteria used to define RF voltage

• **Filling of the RF bucket:**
  → **maximum** momentum filling factor $q_p=0.9$ during ramp and $q_p=0.8$ in physics ($q_p = 2\sigma_p$/bucket height)

• **Longitudinal emittance on the flat top:**
  → previously was based on loss of Landau damping threshold for $N=1\times10^{11}$ and longitudinal effective impedance $ImZ/n= 0.2$ Ohm (for LHC calculated and measured $ImZ/n = 0.1$ Ohm).
  → now based on maximizing transverse stability (TMCI) at 50 TeV and during ramp

• **Longitudinal emittance during ramp:**
  → previously scaled $\sim E^{1/2}$ from the top value for $(ImZ_L/n)_{th}=\text{const}$
  → now **optimized** for transverse beam stability
Beam stability limits

- Loss of Landau damping (F. Sacherer, 1973)
  \[ |\text{Im}Z|/n < \frac{F|\eta|E}{eI_b\beta^2} \left( \frac{\Delta E}{E} \right)^2 \frac{\Delta \omega_s}{\omega_s} f_0 \tau, \]

- TMCI threshold for short bunches (B. Zotter)
  \[ \beta_{\perp} Z_{\perp} < 2 \frac{E}{e} \tau \frac{\omega_s}{I_b} \]

- $I_b$ - bunch current, $\omega_s$ - synchrotron frequency, $\tau$ - bunch length,
  $f_0$ – revolution frequency, $\eta$ - slip factor, $F \sim 1$ - formfactor
Loss of Landau damping for $\gamma_t = 99$
400 MHz RF @ 50 TeV

$\rightarrow$ $V=24$ MV is OK with margin for ±10% bunch length spread and safety factor ~3 (in LHC F=1.8 and HL-LHC impedance $\text{Im}Z/n = 0.11$ Ohm)
Loss of Landau damping for $\gamma_t = 71$

400 MHz RF @ 50 TeV

→ $V=24$ MV is OK with margin for ±10% bunch length spread and safety factor ~3 (in LHC $F=1.8$ and HL-LHC impedance $\text{Im}Z/n = 0.11$ Ohm)
TMCI threshold @ 50 TeV in two optics

\[ \gamma_t = 99 \quad \text{and} \quad \gamma_t = 71 \]

→ Present impedance budget at 50 TeV: 75 MOhm/m \((x3=225\ \text{Mohm/m})\)
→ Need in margin for ±10% bunch length spread
Longitudinal emittance @50 TeV in two optics

$\gamma_t = 99$

$\gamma_t = 71$

→ Significantly smaller longitudinal emittance for beam stability in 32 MV $\gamma_t = 71$ optics for 1.07 ns bunch length ($4\sigma_t$)
Output from analysis at 50 TeV

- Longitudinal emittance and minimum voltage at 50 TeV (defined by TMCI threshold):
  - $\sim 9$ eVs (32 MV) in $\gamma_t=99$
  - $\sim 5$ eVs (24 MV) in $\gamma_t=71$

- Controlled emittance blow-up need during physics due to fast bunch length reduction since longitudinal bunch stability can be quickly lost (better with higher voltage)

  \[ N_{th} \sim \varepsilon^{2.5} = \varepsilon_0 e^{-2.5t/0.54} \]

  → the 800 MHz RF system for longitudinal beam stability?
Acceleration ramp

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

Injection at 3.3 TeV from LHC: max emittance of 4.0 eVs

Voltage during ramp depends on acceleration time and emittance
→ 20 min ramp is assumed in following
RF voltage for constant emittance and qp in two optics

Constant emittance of 1.8 eVs

Constant emittance of 4.0 eVs

→ Controlled emittance blow up during the ramp
Ramp with emittance blow-up: $\gamma_t = 99$

**RF voltage program:**
\[
\text{emittance blow-up } \sim E^{1/2} (2.3 \rightarrow 9.0 \text{ eVs})
\]

**Loss of Landau damping**
\[
\sim \text{constant threshold}
\]

→ Maximum voltage during ramp $\sim 40$ MV
→ Significant margin for loss of Landau damping during the ramp
Transverse beam stability limit: $\gamma_t = 99$

Effective transverse impedance during ramp (S. Arsenyev):

**3.3 TeV:** $\beta_{H,V} = 142.36, 143.63$ m
3.5 MOhm/m – H
6.0 MOhm/m – V

**50 TeV:** $\beta_{H,V} = 142.32, 143.62$ m
77.5 MOhm/m – H
76.7 MOhm/m – V

$\rightarrow Z_{\perp} = 4.9 + 0.2 E^{3/2}$ [MOhm/m]
Ramp with emittance blow-up: $\gamma_t=99$

Voltage for emittance blow-up $\sim E^{3/2}$

$1.8 \rightarrow 9.0$ eVs

$\rightarrow$ Maximum voltage during ramp $\sim 40$ MV

$\rightarrow$ Minimum TMCI threshold at the end of the ramp
Ramp with emittance blow-up: $\gamma_t = 71$

Voltage for emittance blow-up $\sim E^{3/2}$

$2.0 \rightarrow 5.0$ eVs

$\rightarrow$ Maximum voltage during ramp $\sim 34$ MV with smaller emittances

$\rightarrow$ Minimum TMCI threshold at the end of the ramp
Voltage during ramp can be reduced with less emittance blow-up, but bunch length will be < 1ns – issues for beam induced heating?
FCC-hh RF system (preliminary)

• 400 MHz single-cell cavity (LHC-type), similar to FCC-ee low energy (high current) machines
• 20 cavities/beam with 2 MV/cavity or 40 with 1 MV/cav.
• frev $\sim$3 kHz, $\frac{1}{2}$ detuning $\sim$ 3 kHz $\rightarrow$ coupled bunch instabilities due to fundamental impedance $\rightarrow$ strong feedback. Full detuning (LHC) for high currents.
• Final RF power requirements depend on
  – total voltage $V$ and power loss (SR)
    • acceleration rate
    • longitudinal emittance (for transverse stability)
  – number of RF cavities (voltage/cavity: 1 - 2 MV)
  – coupling $Q_L$
LHC-ACS, 400MHz

8 SRF cavities/beam (total 16)
- Frequency: 400 MHz
- Voltage: 2 MV/cavity
- Tuning: 240 kHz/mm, t ~ secs
- 4-HOM couplers (1 kW-max)

CW high power variable coupler
- $1 \times 10^4 < Q_{ext} < 1 \times 10^5$
- Klystron driven (up to 300 kW)
Summary

• For the FCC-hh, an optimum main RF frequency to achieve required bunch length and stability at 50 TeV is 400 MHz

• Required voltage strongly depends on optics (for the same emittance and bunch length)

• For 20 min acceleration ramp, $V=38$ MV needed to accelerate bunches with emittance of 2.3 eVs at 3.3 TeV and controlled emittance blow-up to 9.0 eVs during ramp

• At flat top: continuous blow-up needed in physics $\rightarrow$ additional 800 MHz RF system would give more flexibility

• At injection: large emittances with bunch length $< 1.8$ ns are difficult to provide using the SPS as injector $\rightarrow$ 200 MHz RF system (in addition to 400 MHz) would help
Spare slides
RF power: coupling

RF system possibly requires variable coupler (as in LHC)

![Graph showing RF power coupling](image)

R. Calaga
Maximum RF power is required at the end of the ramp (bucket + acceleration + SR) → magnetic ramp can be optimised → 500 kW power coupler (matching RF chain) is required (LHC design 300 kW) → 32 cavities with 1 MV/cavity is a reliable option
Examples of layout

Tapers not included (to go from 300mm aperture to 100mm aperture) \( \Rightarrow \) one should add at least \( \frac{\lambda}{2} \sim 350 \, mm \)

For longitudinal beam stability at flat top (and SR?)

For injection and transverse stability

R. Calaga
Cryogenics for (LHC-like) RF

For FCC ~25W @4.5K, 2MV (dynamic)/cavity & ~45W @4.5K (static + dynamic)/cavity (R. Calaga)
Total ~1.5 kW @4.5K (32 cavities, 2 beams) – very reasonable
RF harmonic number and ring size

For \( f_{rf} = 400.79 \text{ MHz} \) and bunch spacings of 5 ns, 25 ns and with two options for the FCC injector (SPS and LHC):

\[
h_{\text{LHC}} = 35640 = 2 \times 3 \times 4 \times 5 \times 11 \times 3 \times 9, \quad h_{\text{SPS}} = 4620 \times 2 = 2 \times 3 \times 4 \times 5 \times 11 \times 7
\]

From synchronization between different rings:

SPS-LHC: \( h_{\text{SPS}}/h_{\text{LHC}} = 7/27 \rightarrow 7 \ T_{\text{rev}}(\text{LHC}) \) or \( 27 \ T_{\text{rev}}(\text{SPS}) \)

FCC-(LHC/SPS): \( h_{\text{fcc}} = 2 \times 3 \times 4 \times 5 \times 11 \times N = 10 \times 11 \times 12 \times N = 1320 \times N \),

(N is an arbitrary integer).

For the ring size \( C \approx 100 \ \text{km} \rightarrow C = 990 \times N \ \text{m} \) with \( N \approx 100 \)

\( h = 2 \times 3 \times 4 \times 5 \times 11 \times 99 = 130680 \), \( C = 97.75 \ \text{km} \), \( T_{\text{inj}}/T_{\text{fcc}} = 3 \ (7) \) for LHC (SPS)
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.

**SPS**

• **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)
  →200 MHz in the FCChh will help to accommodate large emittances
Voltage programs for different emittances: $\gamma_t = 110$

**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
Voltage programs for constant qp and controlled emittance blow-up for $\gamma_t = 110$

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