Beam dynamics: RF requirements for the FCC-hh

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Thanks: R. Calaga, D. Schulte, F. Zimmermann

Main input ring & beam parameters

- Ring
  - Circumference: ~ 100 km
  - Energy: (0.45, 1.7, 3.3 TeV) → 50 TeV
  - Transition gamma: γ_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 ($\tau_{4\sigma}$ = 1.07 ns)
  - Bunch intensity: 1.0×10^{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 → n x 200 MHz → 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)

→ 200 or 400 MHz RF

RF harmonic number and ring size

- f_{rf}=400.79 MHz and bunch spacings of 5 ns, 25 ns, (125 ns ?)

  h_{LHC} = 35640 = 2x4x5x9x9x11

  h_{SPS} = 4620x2= 2x3x4x5x7x11

  For example h_{FHC} = 133650 = 2x3x5x5x9x9x11 → 100.2 km

  or h_{FHC} = 132930 = 2x5x7x9x211 → 99.4 km

- Synchronization between different rings:

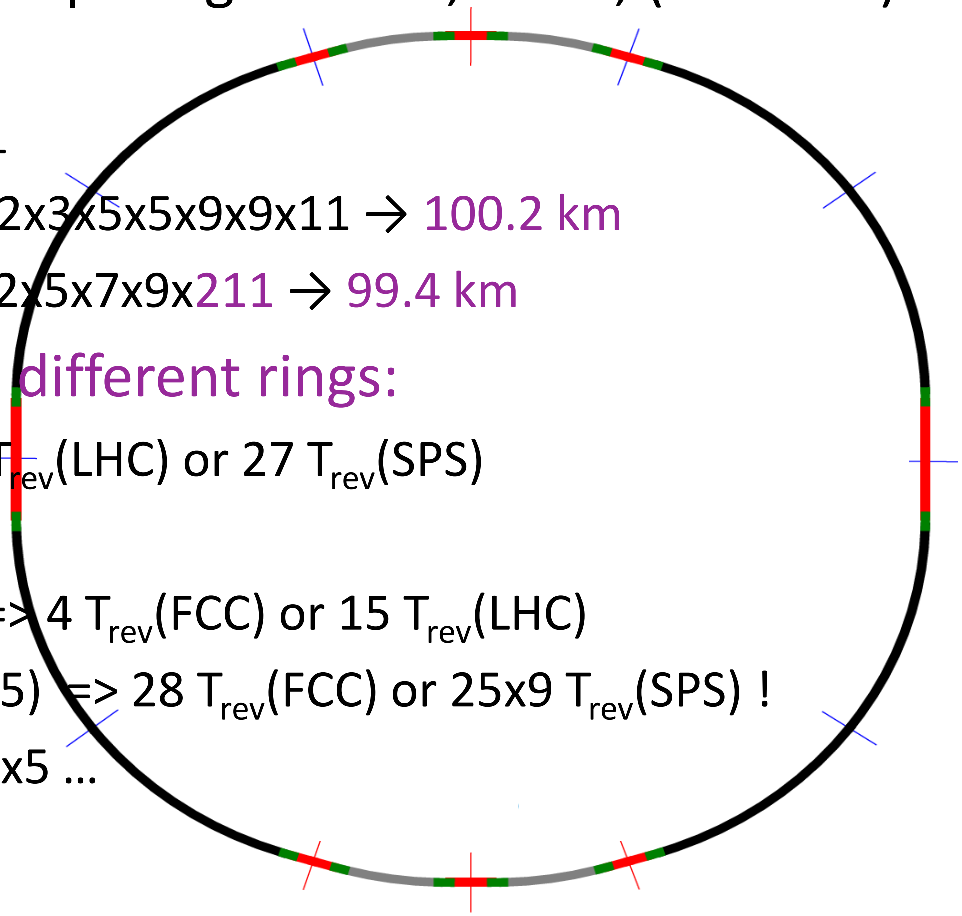
  SPS-LHC: h_{SPS}/h_{LHC} =7/27 => 7 T_{rev}(LHC) or 27 T_{rev}(SPS)

Example for 100.2 km ring

  LHC-FHC: h_{LHC}/h_{FHC} = 4/(3x5) => 4 T_{rev}(FCC) or 15 T_{rev}(LHC)

  SPS-FHC: h_{SPS}/h_{FHC} = 4x7/(9x25) => 28 T_{rev}(FCC) or 25x9 T_{rev}(SPS) !

OK for 125 ns spacing (FHeC): 2x5x5 …



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 $N=1\times10^{11}$ and longitudinal effective impedance ImZ/n= 0.2 Ohm (for LHC calculated and measured ImZ/n = 0.1 Ohm).

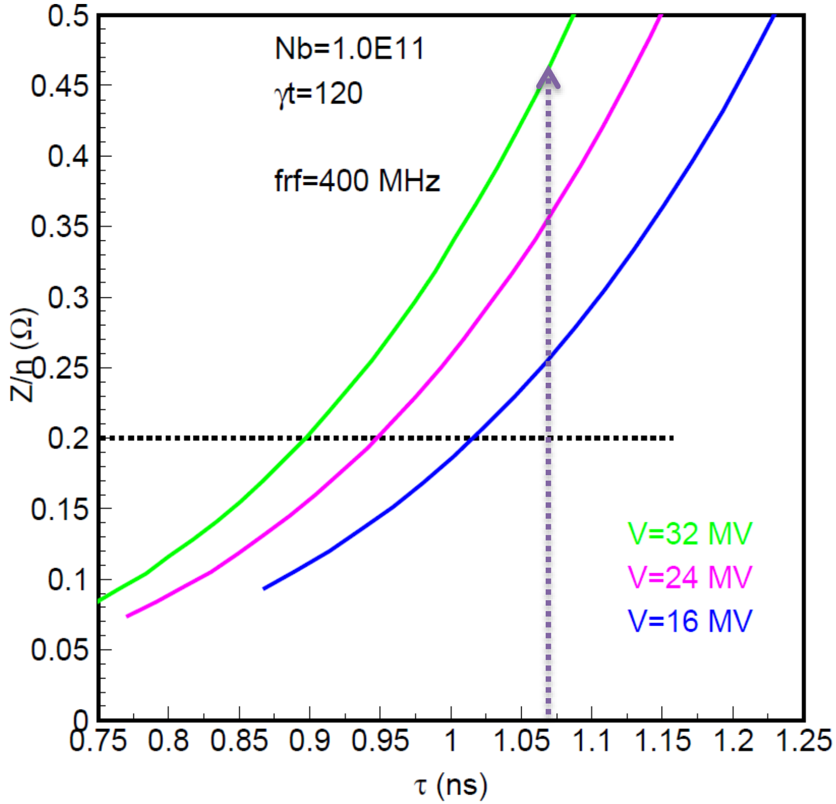
- Longitudinal emittance on the flat bottom:

  → scaled ~ $E^{1/2}$ from the top value (longitudinal beam stability)

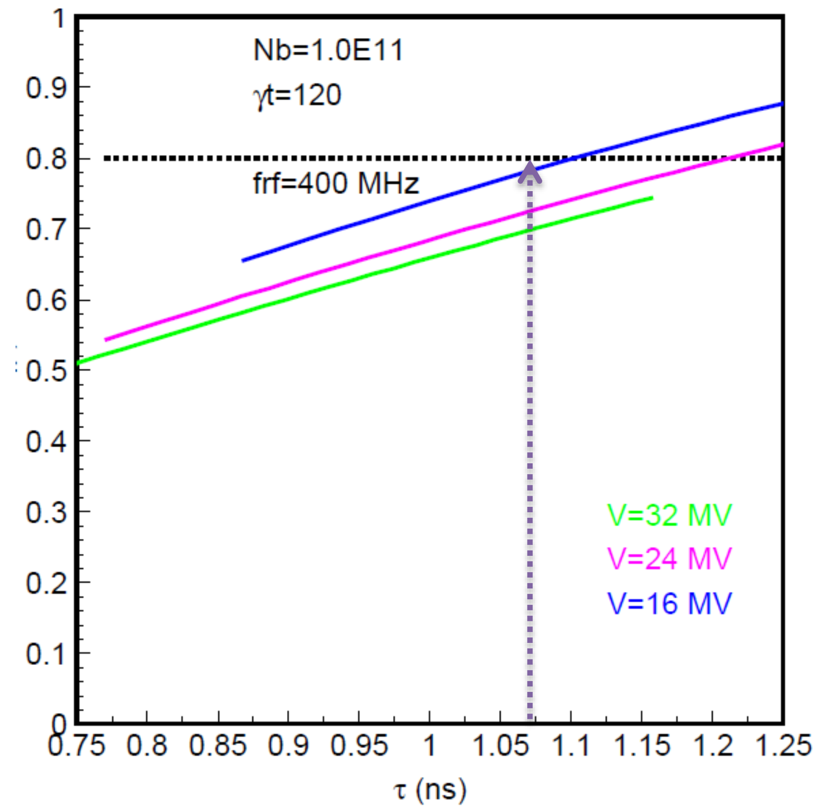
  → maximized for transverse beam stability

400 MHz RF @ 50 teV

Loss of Landau damping



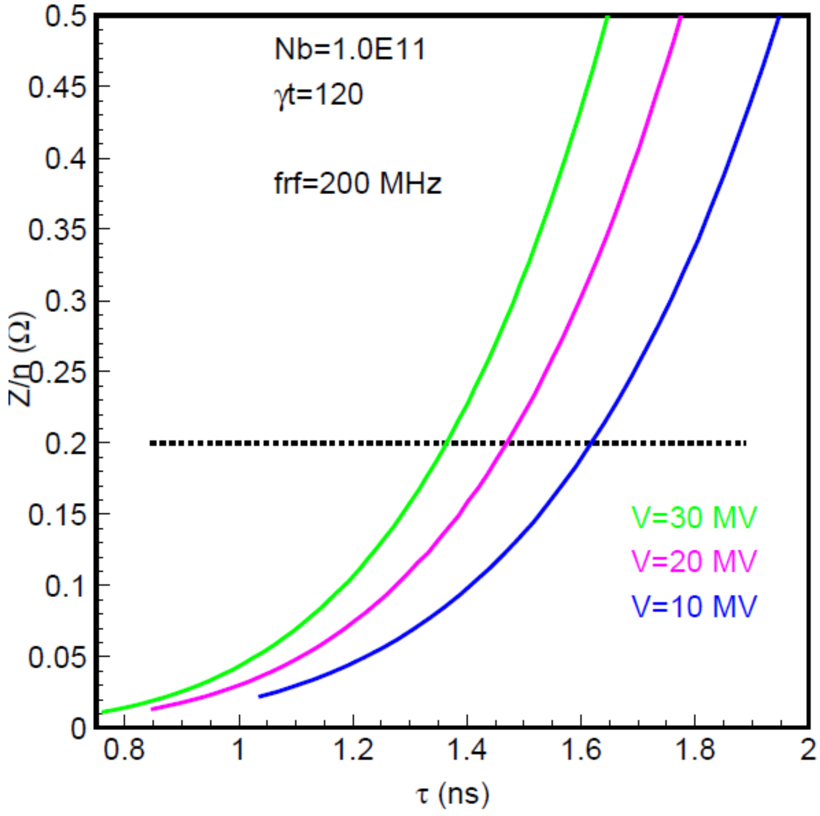
Filling factor in momentum



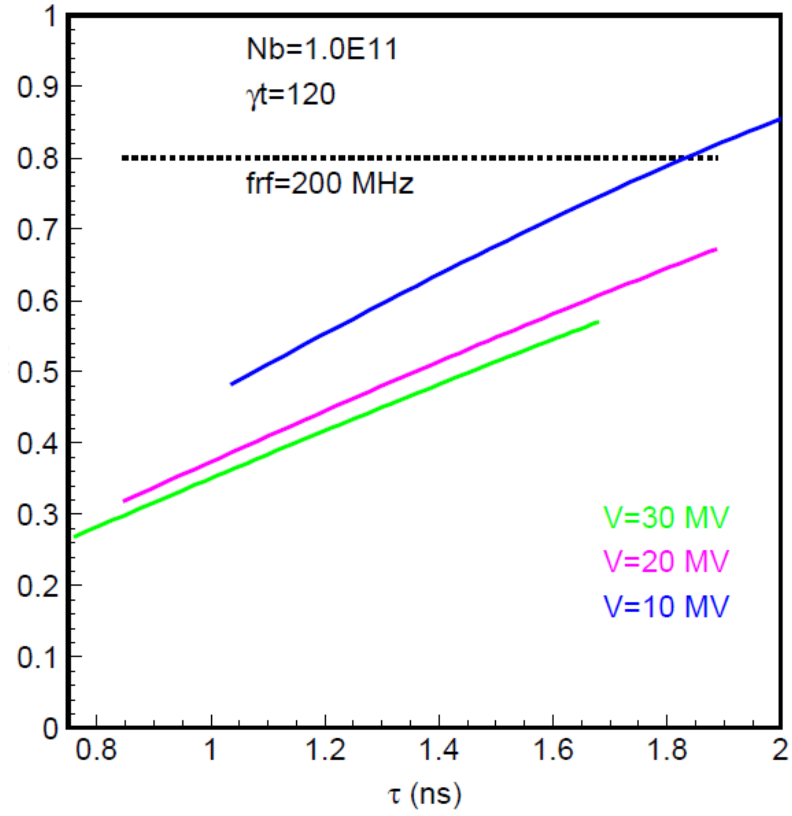
→ Minimum voltage of 16 MV

200 MHz RF @ 50 TeV

Loss of Landau damping



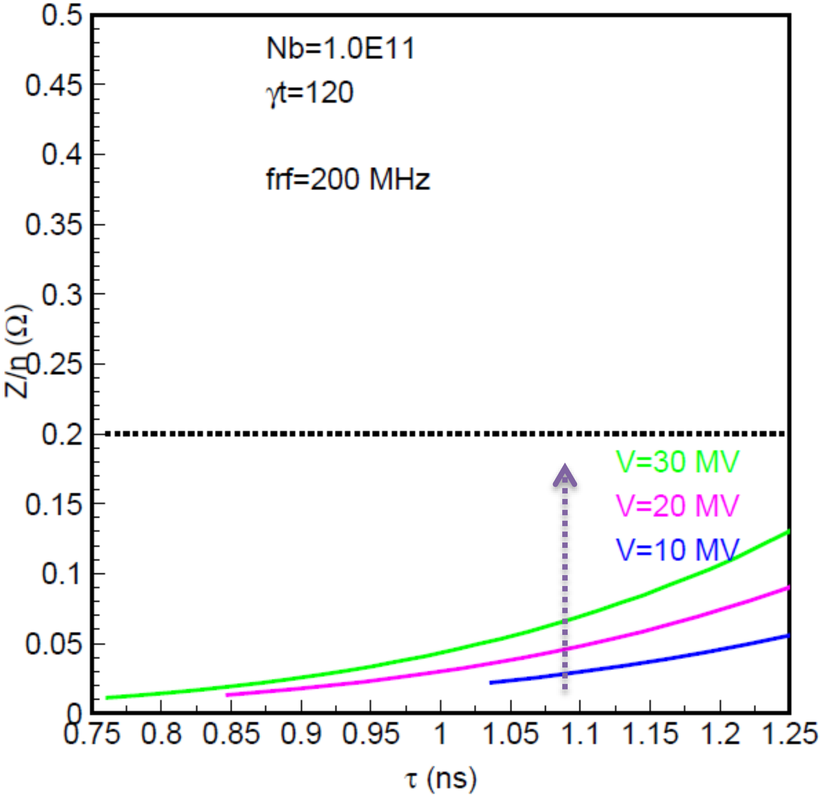
Filling factor in momentum



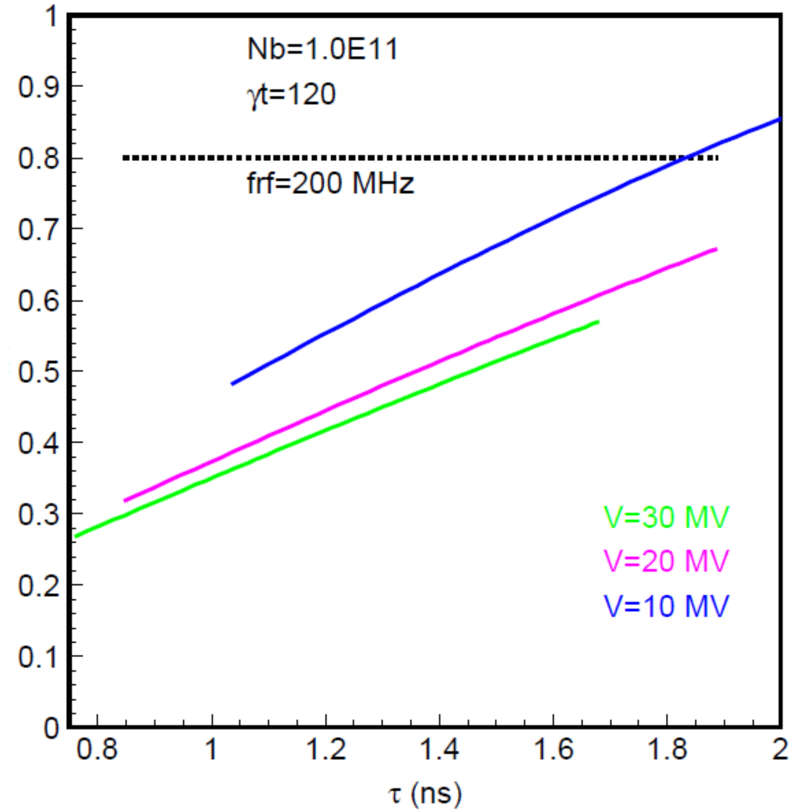
→ Possible bunch lengths > 1.4 ns

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_{rf}= 400.79 MHz
- h = 132930 → C ~ 99.4 km or ?

Beam parameters:

- Min. emittance @50 TeV ~ 7 eVs (16 MV)
- Controlled emittance blow-up is required during physics due to bunch length reduction: SR damping time 0.54 h

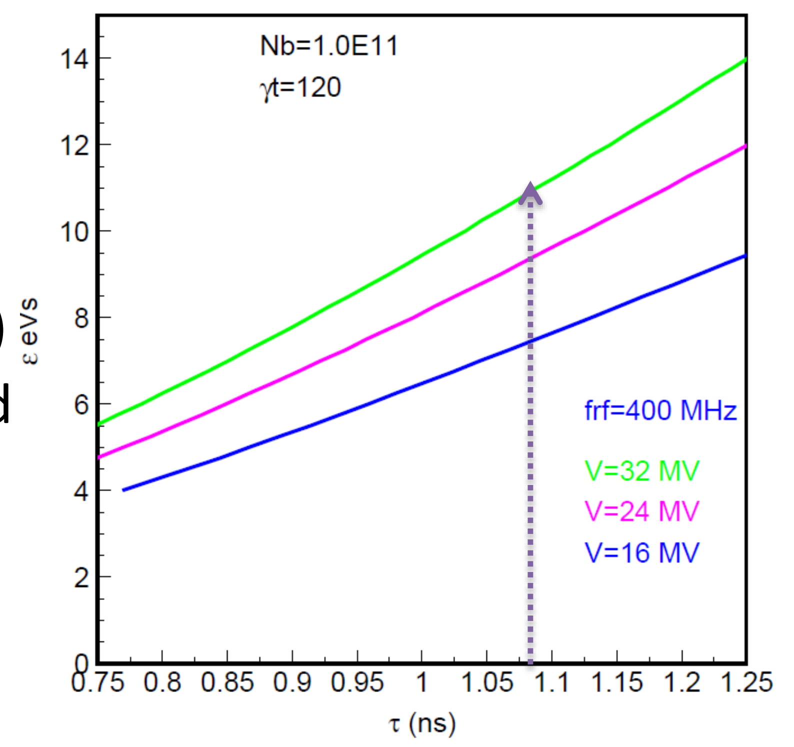
$$N_{th} \sim \varepsilon^{2.5} = \varepsilon_0 e^{-2.5t/0.54}$$

→ For ε_0 =10 eVs stability is lost in 3 min!

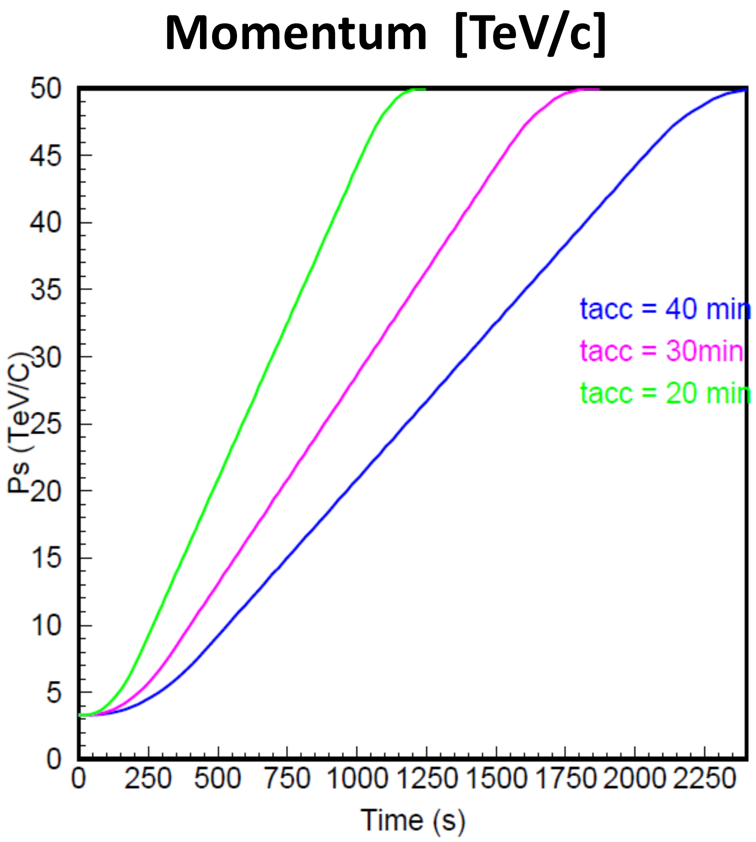
→ Better with higher voltage/emittance

Plus 800 MHz RF system (see talk X. Buffat)?

Emittance vs bunch length



Acceleration ramps with 400 MHz RF



Example

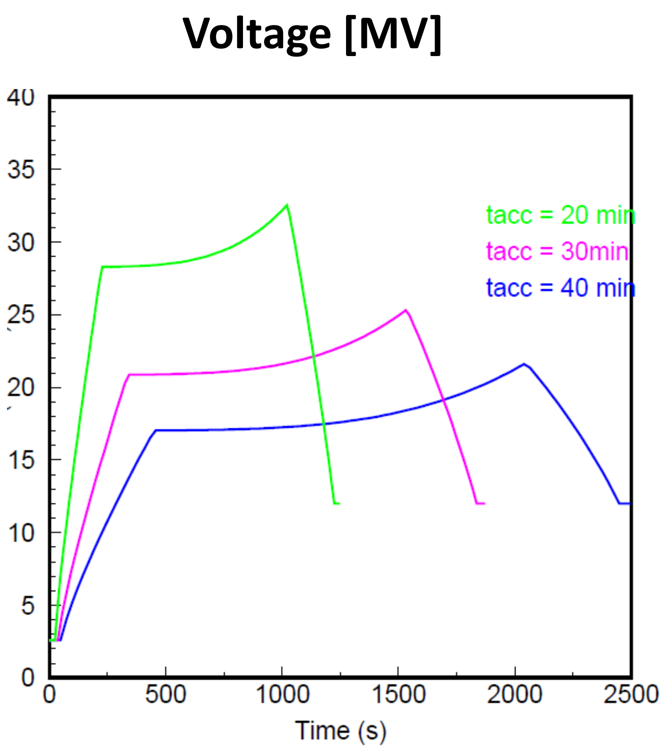
Magnetic ramp composed of

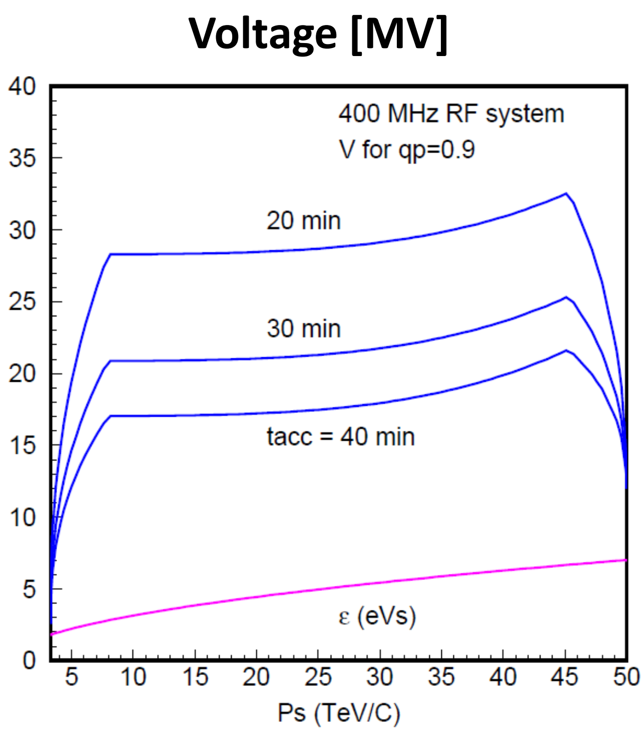
- parabolic part(0.1)
- linear part (0.8)
- parabolic part (0.1)

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

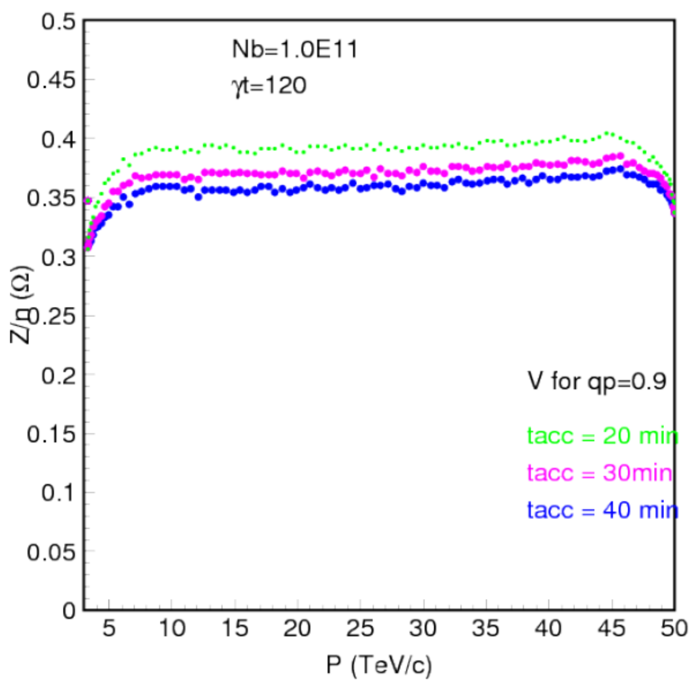




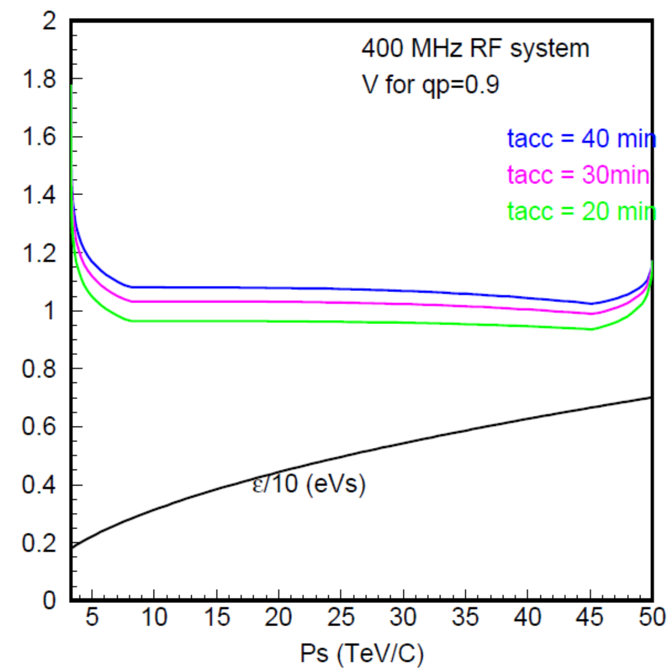
→ Voltage during ramp depends on acceleration time (magnetic ramp) and controlled emittance blow-up

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 qp= 0.9) with bunch length of 1.78 ns (4sigma).

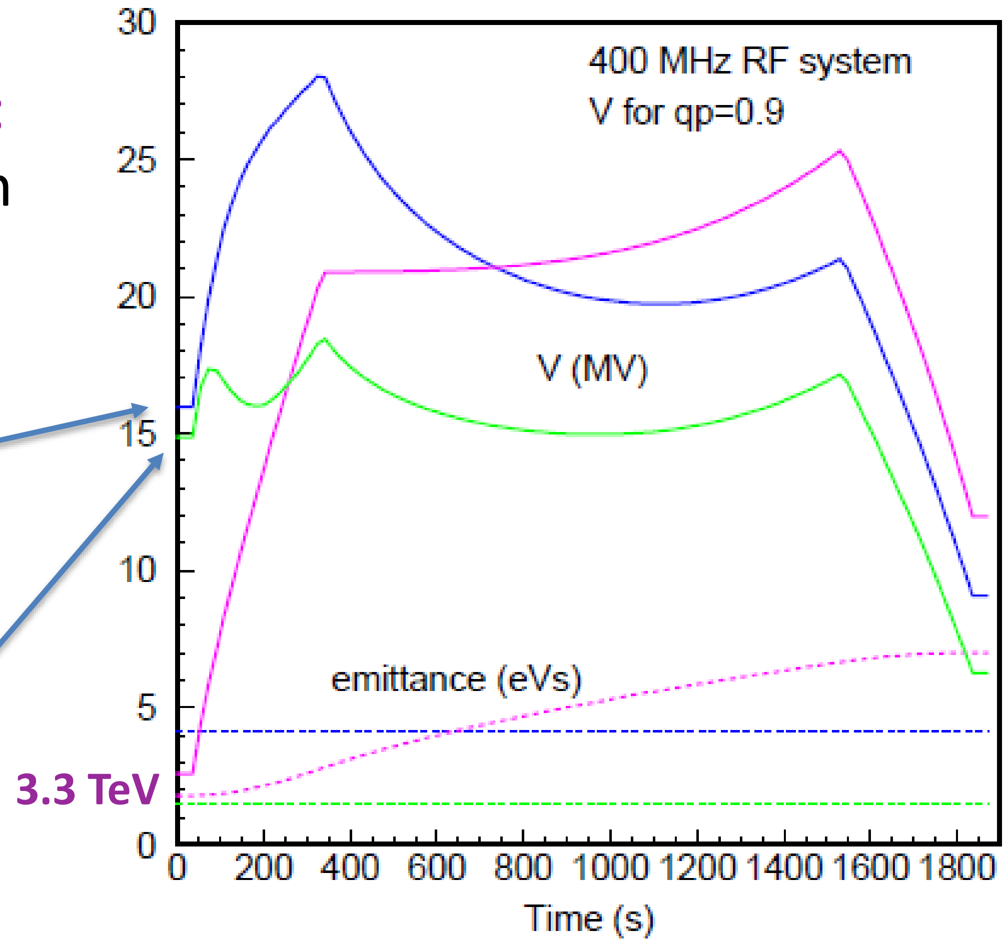
  → Similar (matched) parameters in the FCC with 16 MV.
- HEB at 3.3 TeV: 400 MHz RF system similar to LHC with V_{max}=20 MV accelerates from 0.45 to 3.3 TeV in 2 min. 60 MV are required for 0.5 min ramp, then larger emittances are possible for FCC injection.
- Injection at 0.45 TeV from present SPS: 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 (TMCI) & 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

Energy GeV	γ_t/optics	emittance eVs	bunch length ns	voltage MV
Present SPS				
450	18.0/Q20	1.5	1.8	52.7
450	22.8/Q26	1.5	1.8	32.8
New ring				
1500	18.0	2.5	1.8	44.0
1500	22.8	2.5	1.8	27.4
1500	30.0	2.5	1.8	15.8

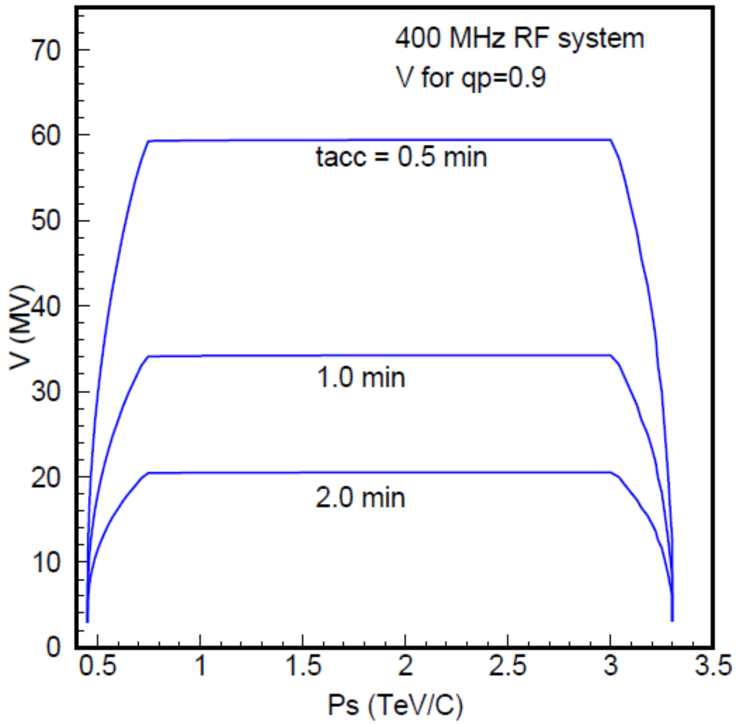
⇒ In all cases much smaller 200 MHz voltage is required for beam acceleration: < 10 MV

⇒ Much smaller emittance is sufficient for beam stability with 1.1×10^{11}/b: ~ 0.5 eVs

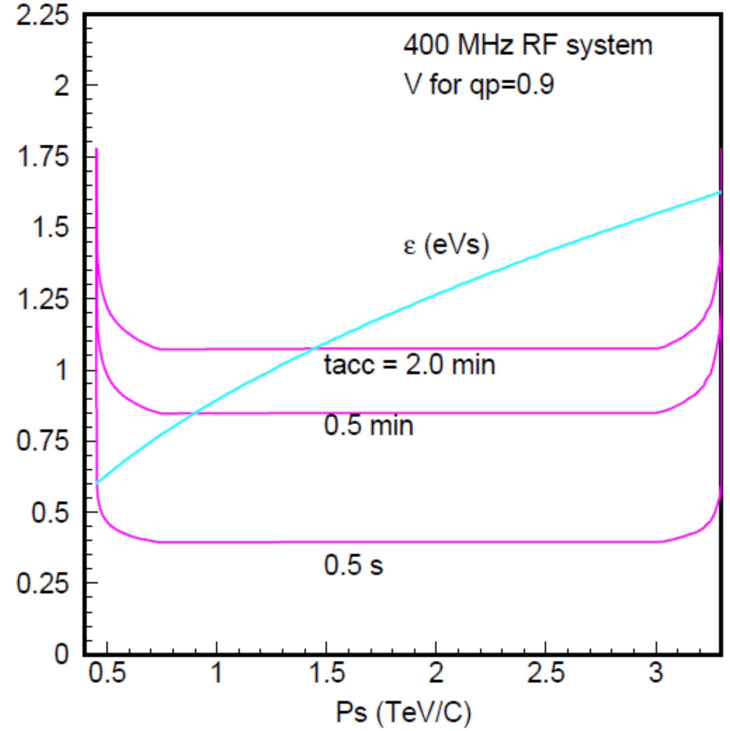
⇒ Extra voltage is needed only on flat top for beam transfer into 400 MHz RF system of the FCC => additional 200 MHz RF system in the FCC

HEB cycles and beam parameters

Voltage



Bunch length



=> RF system comparable to the present LHC for 2 min acceleration ramp

=> 30 resonators with 300 kW power for 0.5 min acceleration ramp