FCC week, Amsterdam

# Longitudinal beam dynamics and RF requirements

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# Main input ring & beam parameters

- Ring
  - Circumference: ~ 100 km (97.75 km)
  - Energy: 3.3 TeV → 50 TeV
  - Transition gamma: $\gamma_t$ = 99 & 71
  - 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: $1.0\text{x}10^{11}$
  - 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 qp = 0.9 during ramp and qp = 0.8 in physics (qp = $2\sigma_p$/bucket height)

- Longitudinal emittance on the flat top:

  → in 2016 was based on loss of Landau damping threshold for $N = 1\mathrm{x}10^{11}$

  and longitudinal effective impedance ImZ/n = 0.2 Ω (for LHC calculated and measured ImZ/n = 0.1 Ω).

  → in 2017 was based on maximizing transverse stability (TMCI) at 50 TeV

- Longitudinal emittance during ramp:

  → in 2016 scaled $\sim E^{1/2}$ from the top value for $(\mathrm{Im}Z/n)_{th}$ = const

  → in 2017 optimized for transverse beam stability

# Beam stability limits

- Loss of Landau damping (F. Sacherer, 1973)

$$|\mathrm{Im}Z|/n < \frac{\mathrm{F}|\eta|E}{eI_{\mathrm{b}}\beta^2}\left(\frac{\Delta E}{E}\right)^2 \frac{\Delta\omega_s}{\omega_s} f_0\tau$$

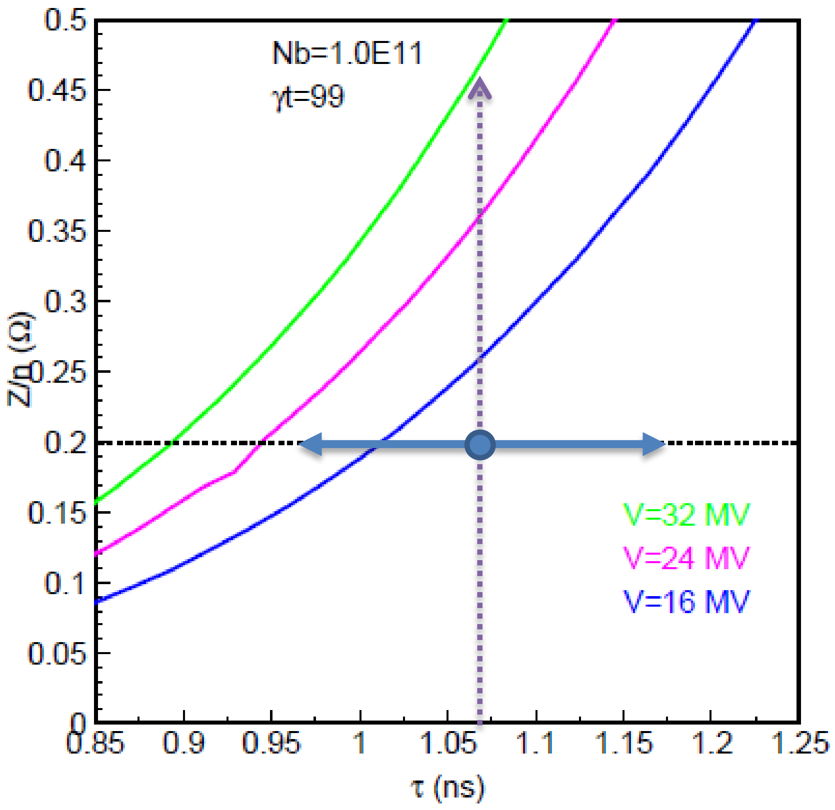
- TMCI threshold for short bunches (B. Zotter)

$$\beta_\perp Z_\perp < \frac{2E\tau\omega_s}{eI_b}$$

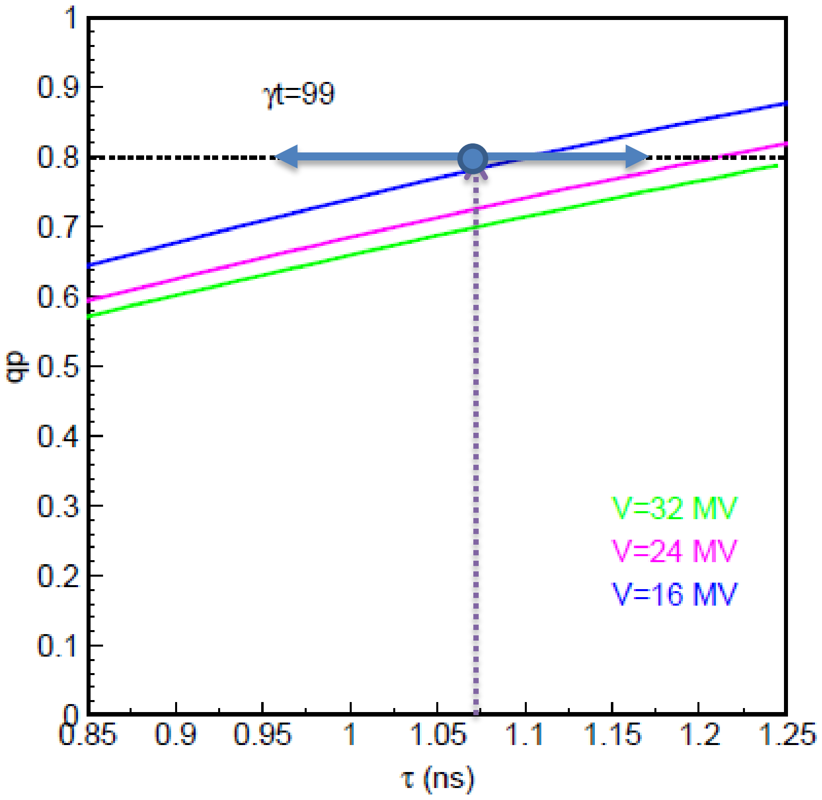
$E$ – beam energy, $I_{\mathrm{b}}$ – bunch current, $\omega_s$ – synchrotron frequency, $\tau$ – bunch length, $f_0$ – revolution frequency, $\eta$ – slip factor, $\mathrm{F} \sim 1$ – form factor, $\beta_\perp$ – beta function

# Loss of Landau damping for $\gamma_t = 99$, 400 MHz RF @ 50 TeV

**Loss of Landau damping**



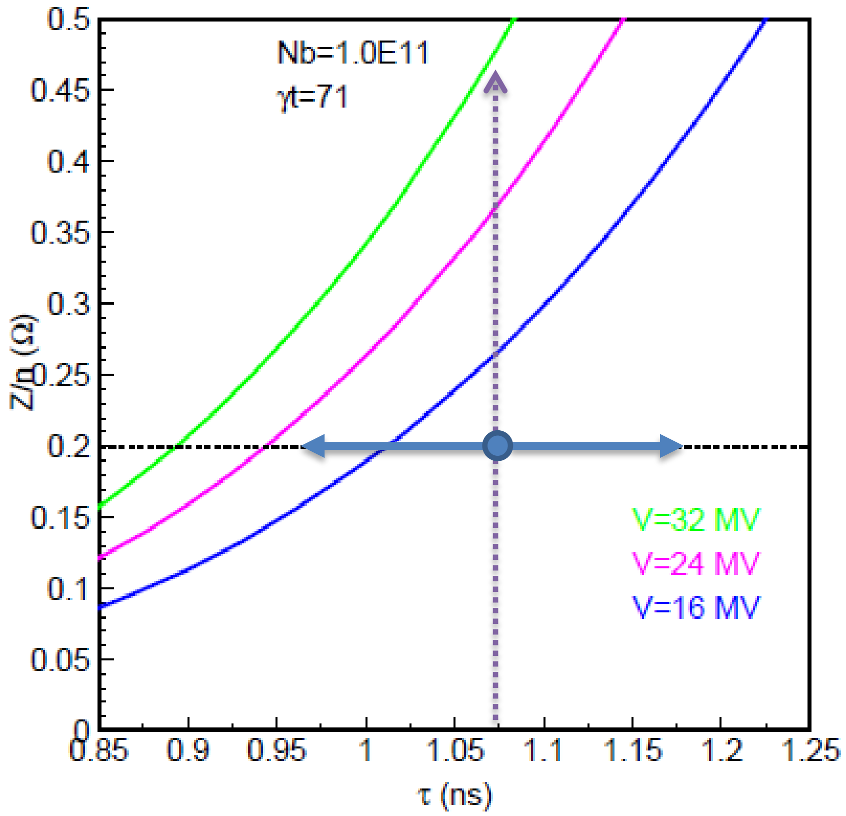

**Filling factor in momentum**



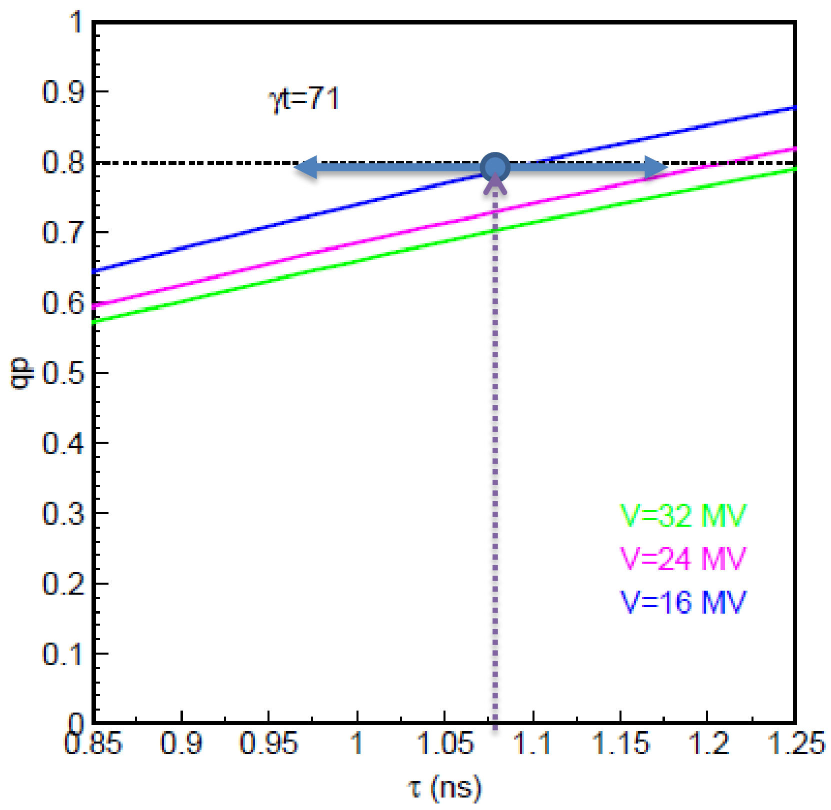

→ V = 24 MV is OK with margin for ±10% bunch length spread and safety factor ~ 3 (in LHC F = 1.8 and HL-LHC impedance ImZ/n = 0.11 Ω)

# Loss of Landau damping for $\gamma_t = 71$, 400 MHz RF @ 50 TeV

**Loss of Landau damping**



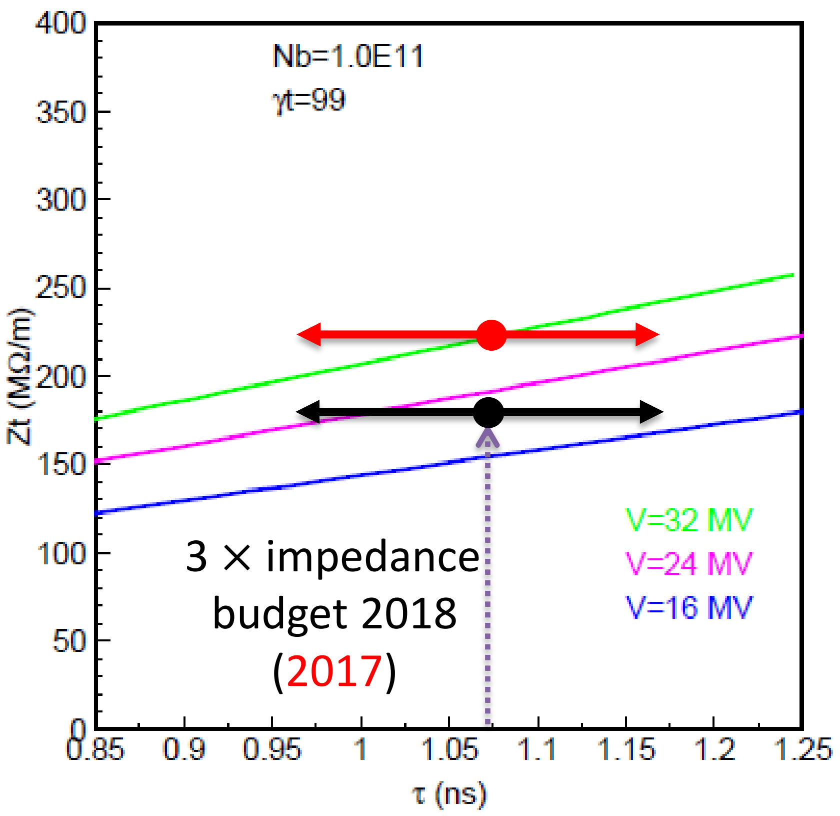

**Filling factor in momentum**



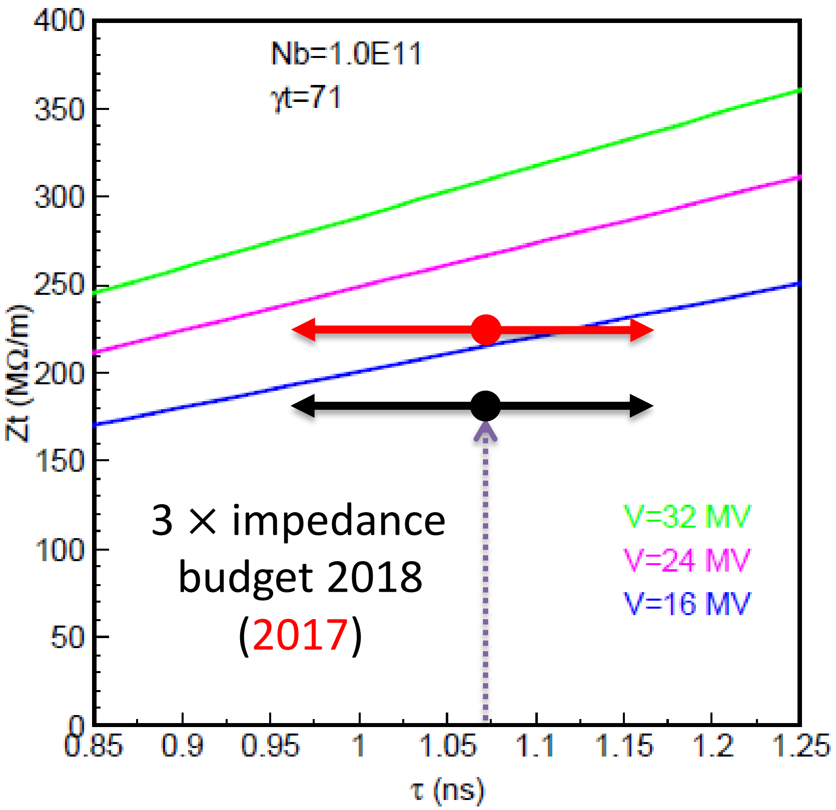

→ V = 24 MV is OK with margin for ±10% bunch length spread and safety factor ~ 3
(in LHC F = 1.8 and HL-LHC impedance ImZ/n = 0.11 Ω)

# TMCI threshold @ 50 TeV in two optics

$\gamma_t$ = 99




$\gamma_t$ = 71



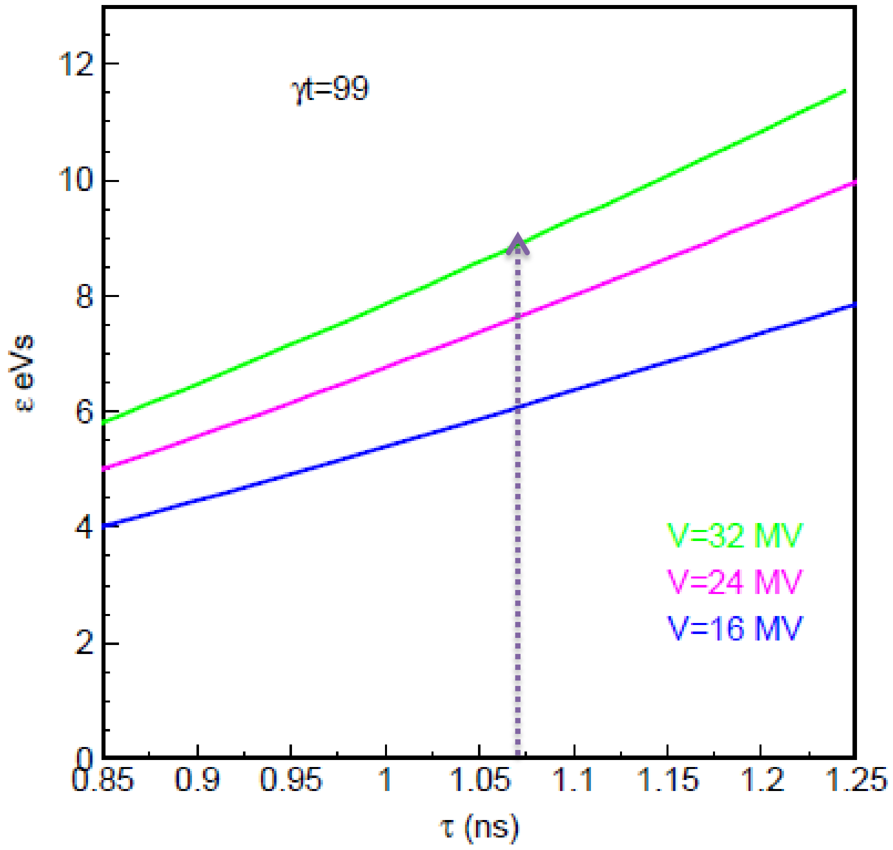

→ Impedance budget at 50 TeV: ~ 60 MΩ/m in 2018 (~ 75 MΩ/m in 2017)

→ V = 32 MV is OK for $\gamma_t$ = 99 with margin for ±10% bunch length spread

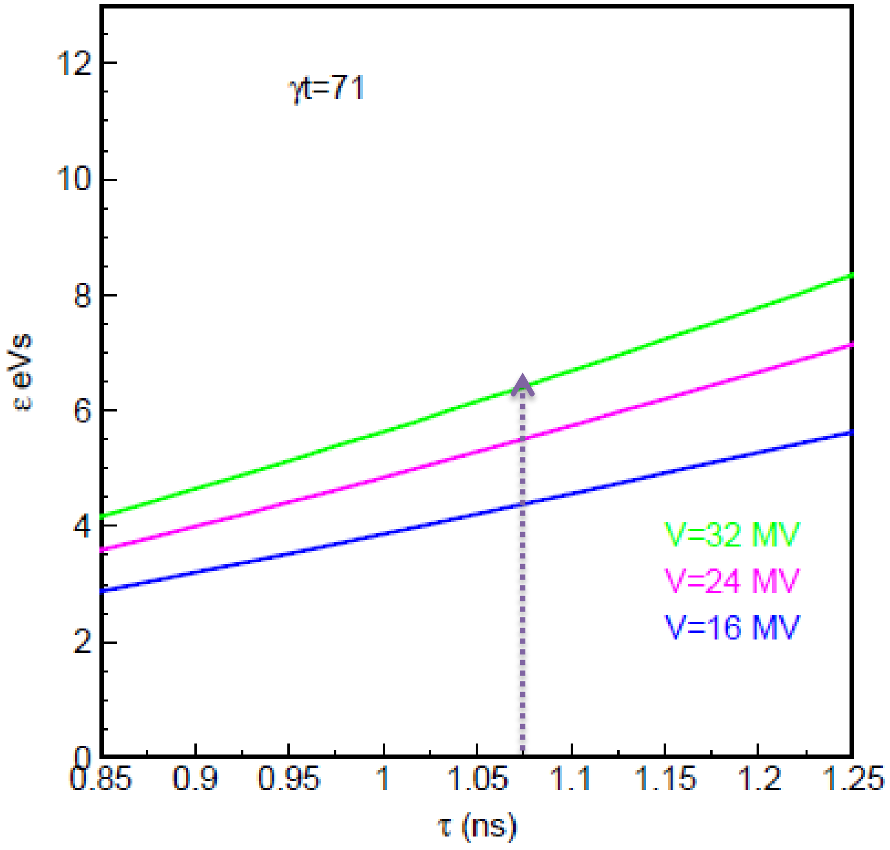
→ For $\gamma_t$ = 71 all voltages are acceptable

# 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 ($4\sigma_t$ )

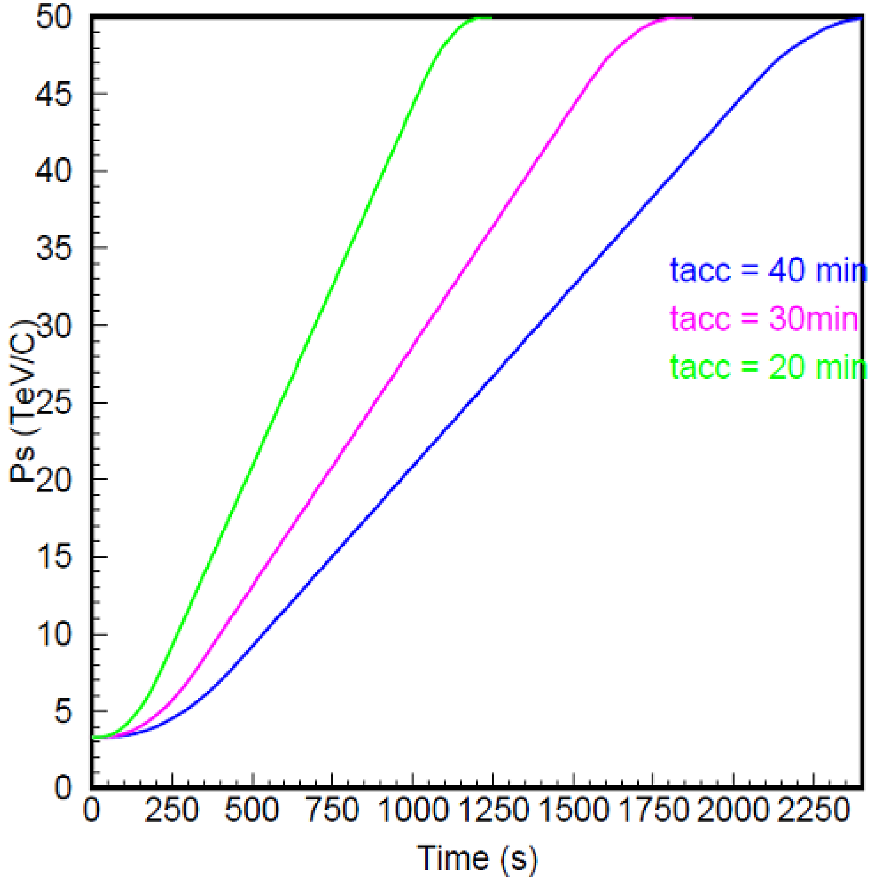
# Output from analysis at 50 TeV

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

- 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

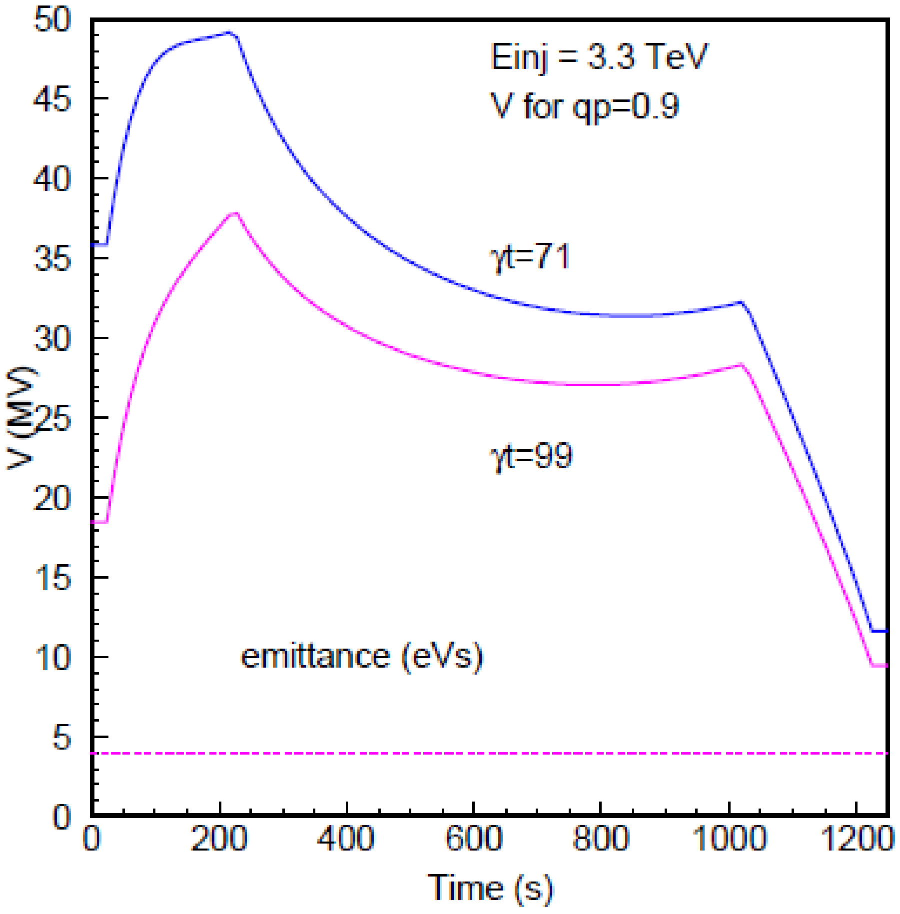
- parabolic part(0.1)
- linear part (0.8)
- parabolic part (0.1)

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

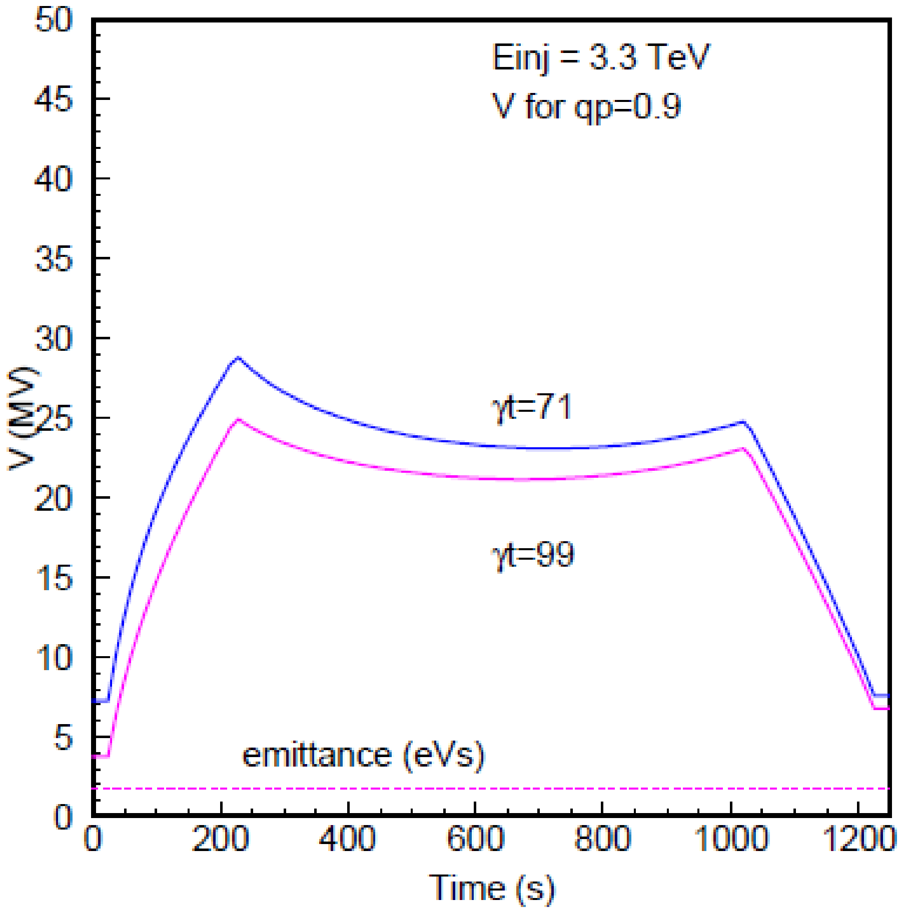
Voltage during ramp depends on acceleration time and emittance
→ 20 min ramp is assumed in following

# RF voltage for constant emittance and qp in two optics

Constant emittance of 4.0 eVs



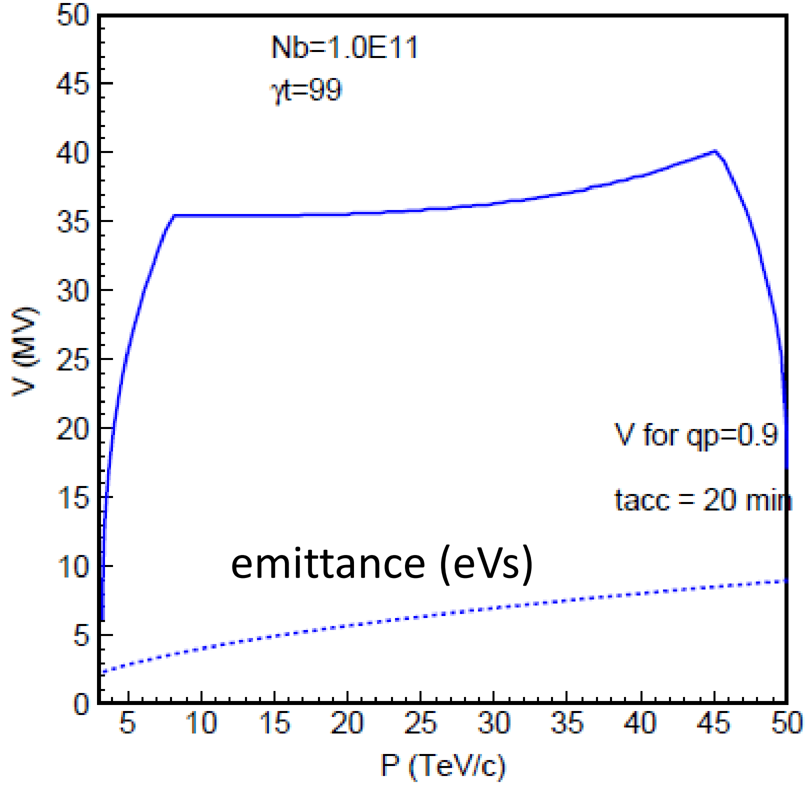

Constant emittance of 1.8 eVs



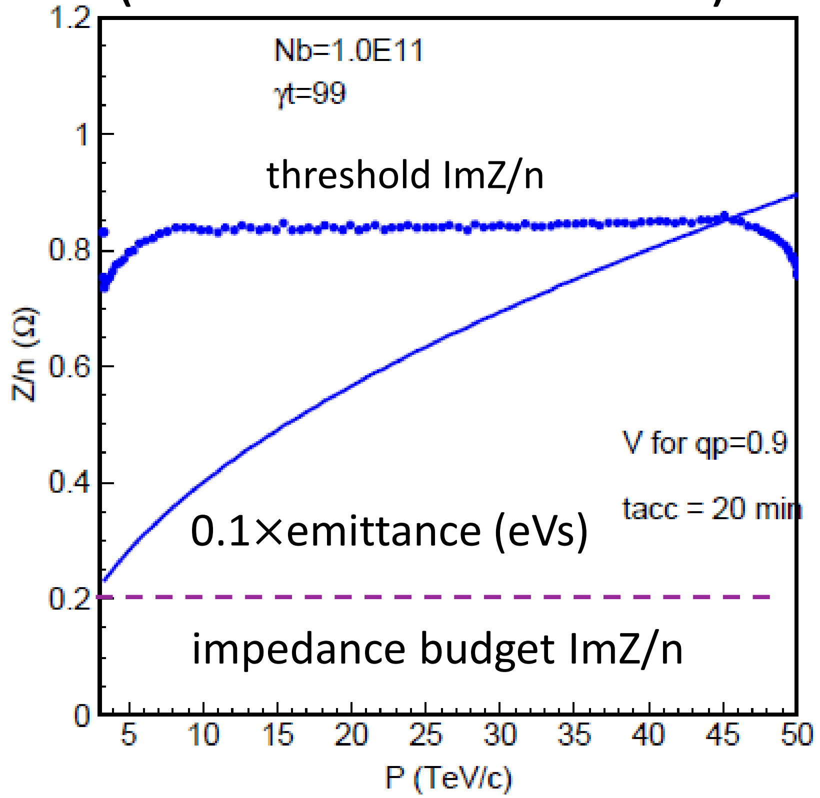

→ Controlled emittance blow up during the ramp is required

# Ramp with emittance blow-up: $\gamma_t$=99

RF voltage program:
emittance blow-up $\propto E^{1/2}$ (2.3→9.0 eVs)




Loss of Landau damping
( ~ constant threshold )




→ Maximum voltage during ramp ~ 40 MV

→ Significant margin for loss of Landau damping during the ramp

# Transverse beam stability limit: $\gamma_t$=99

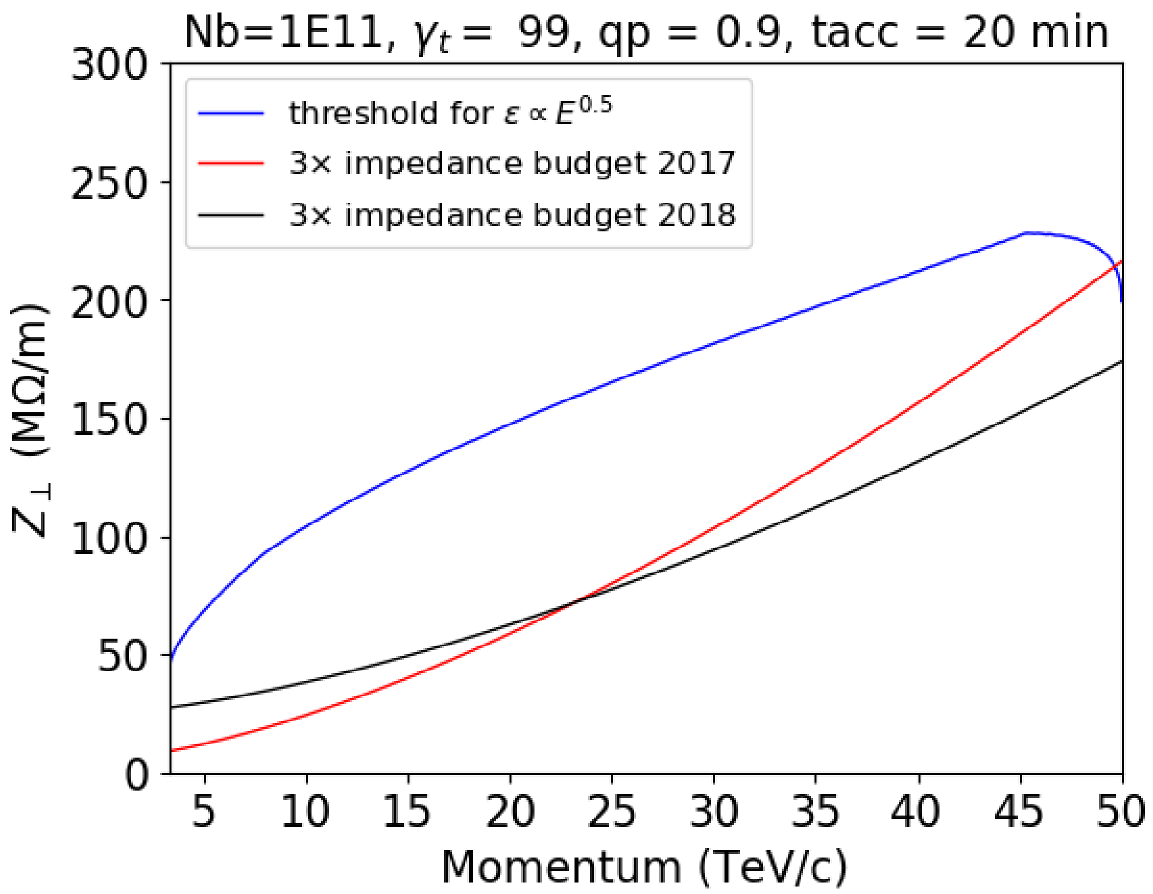
Effective transverse impedance during ramp (impedance database April 2018):

3.3 TeV: $\beta_{H,V}$ = 142.36, 143.63m
8.6 MΩ/m – H
9.7 MΩ/m – V

50 TeV: $\beta_{H,V}$ = 142.32, 143.62m
58.6 MΩ/m – H
57.2 MΩ/m – V

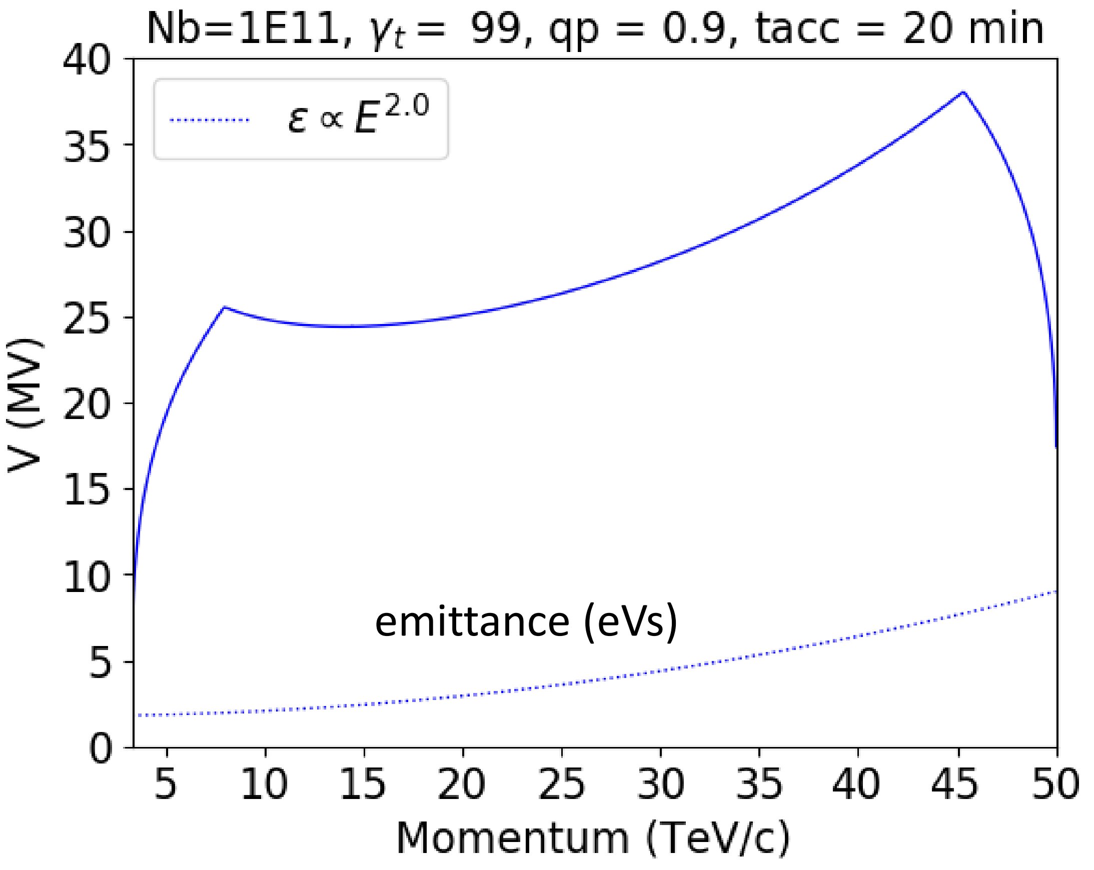
→ $Z_\perp$ = 8.3 + 0.14 E[TeV]$^{3/2}$ [MΩ/m]

**TMCI**

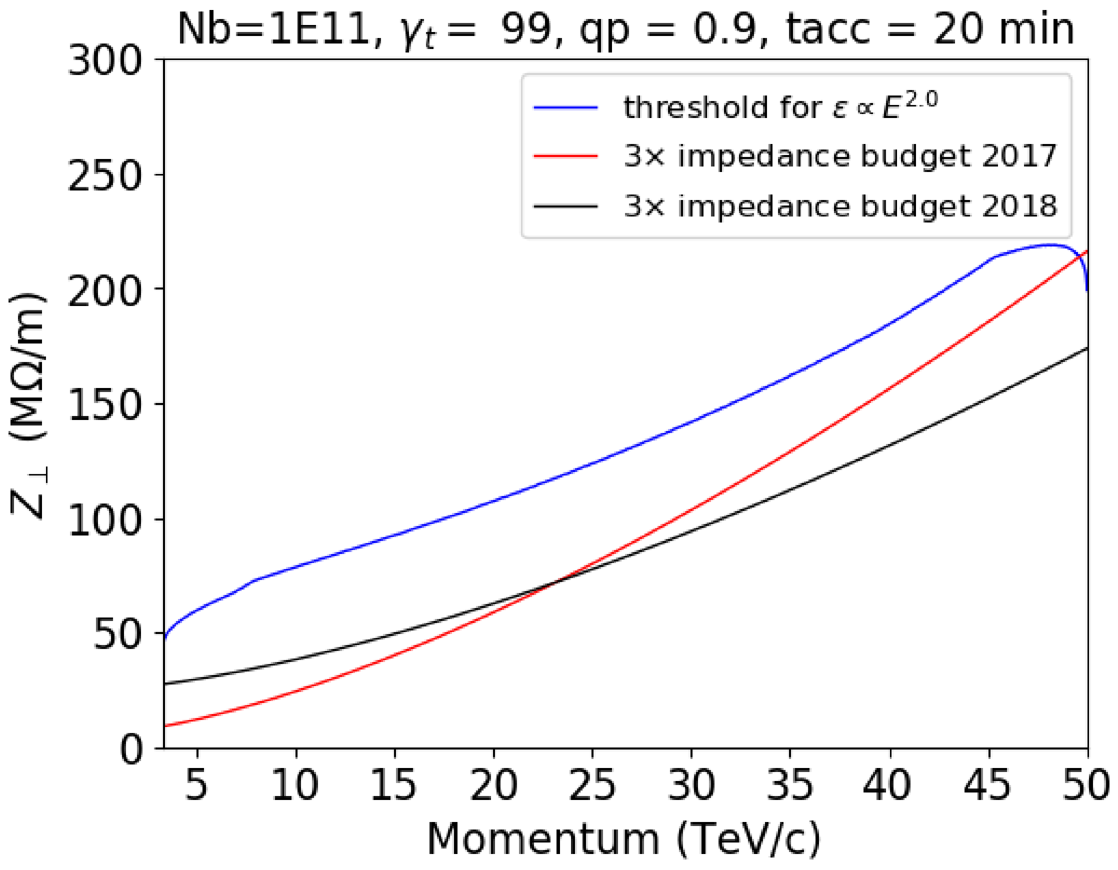


# Ramp with emittance blow-up: $\gamma_t$=99

RF voltage program:
emittance blow-up ∝ $E^2$ (**1.8→9.0 eVs**)



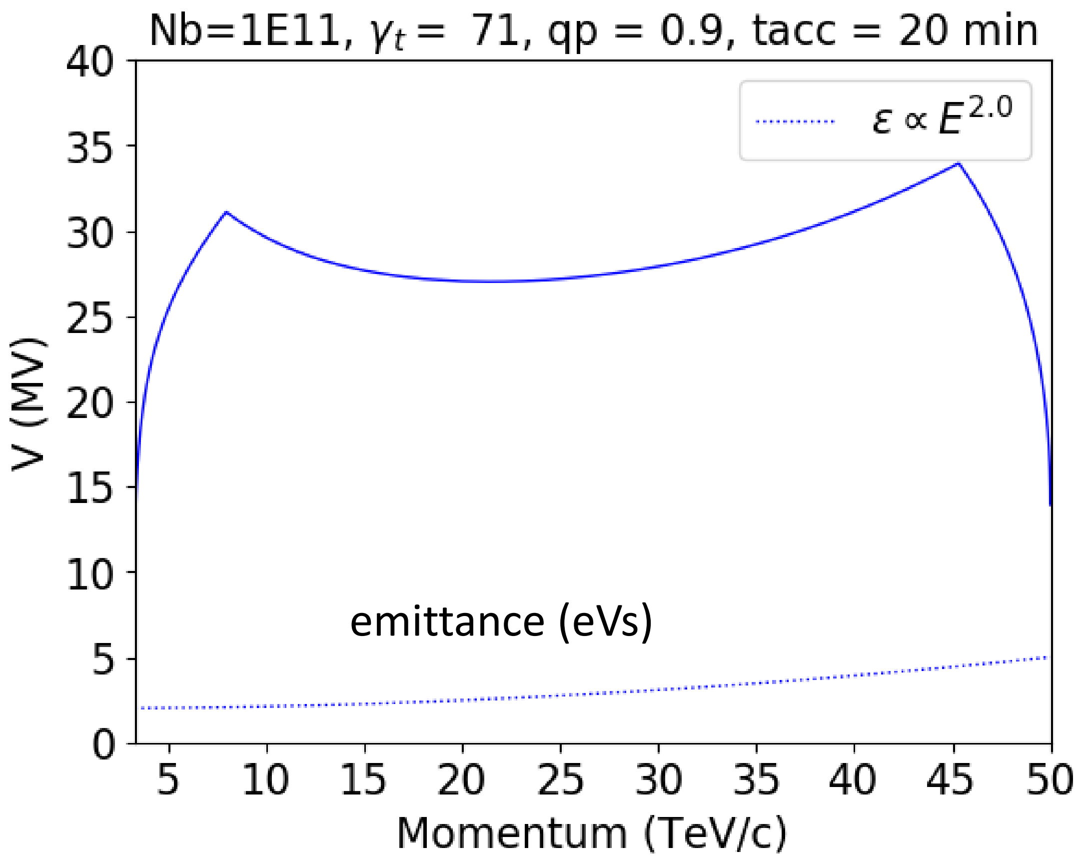

**TMCI**



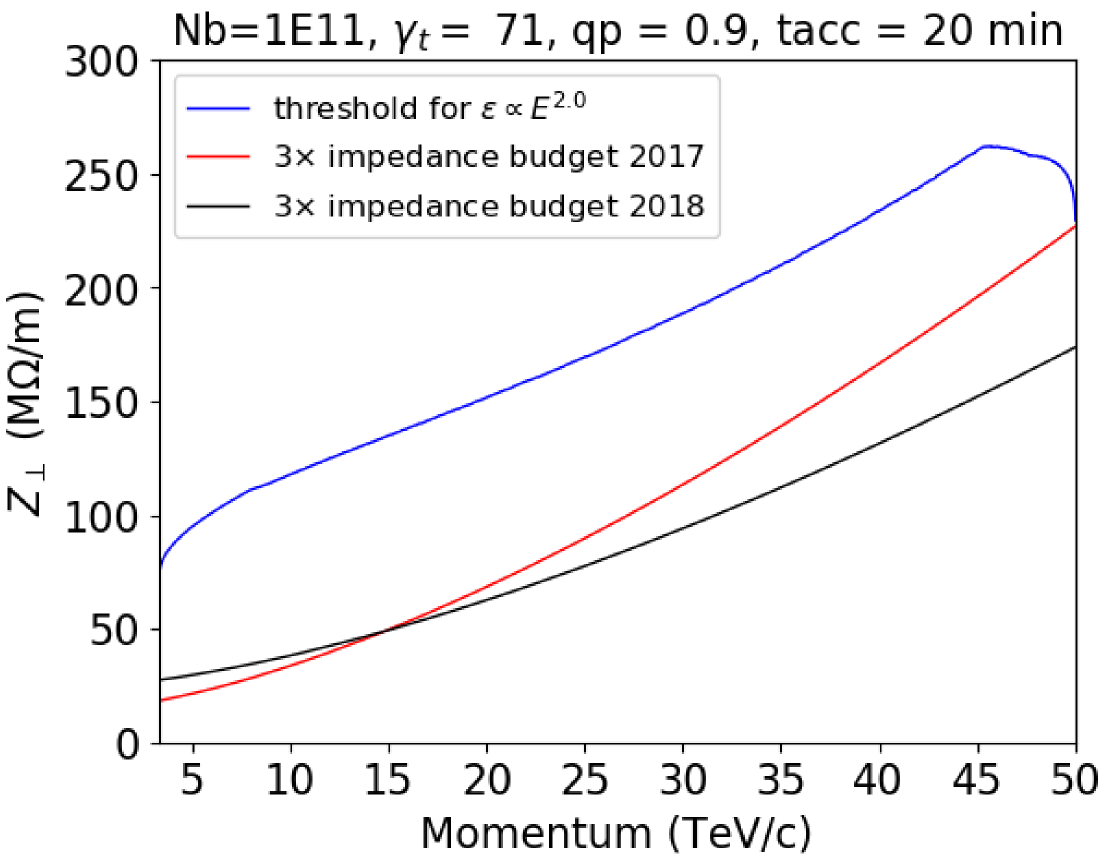

→ Maximum voltage during ramp ~ 40 MV

# Ramp with emittance blow-up: $\gamma_t = 71$

RF voltage program:
emittance blow-up ∝ $E^2$ (**2.0→5.0 eVs**)

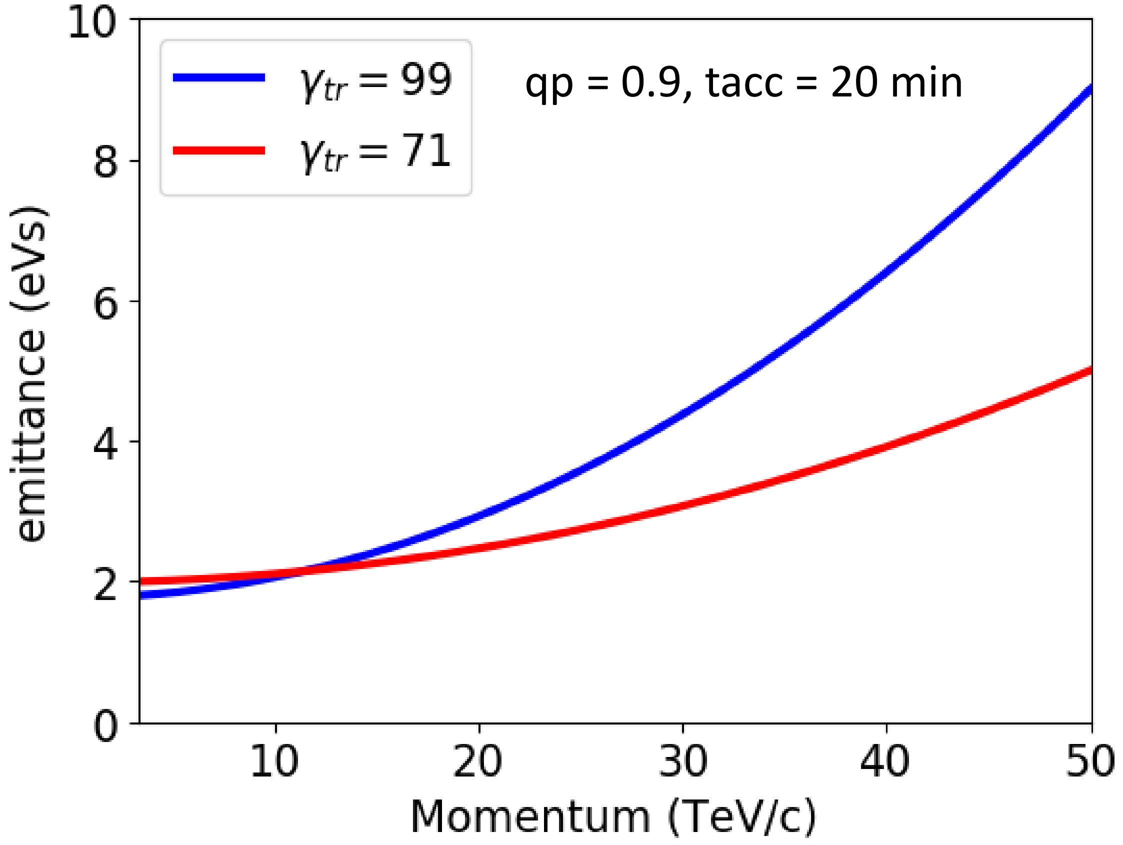


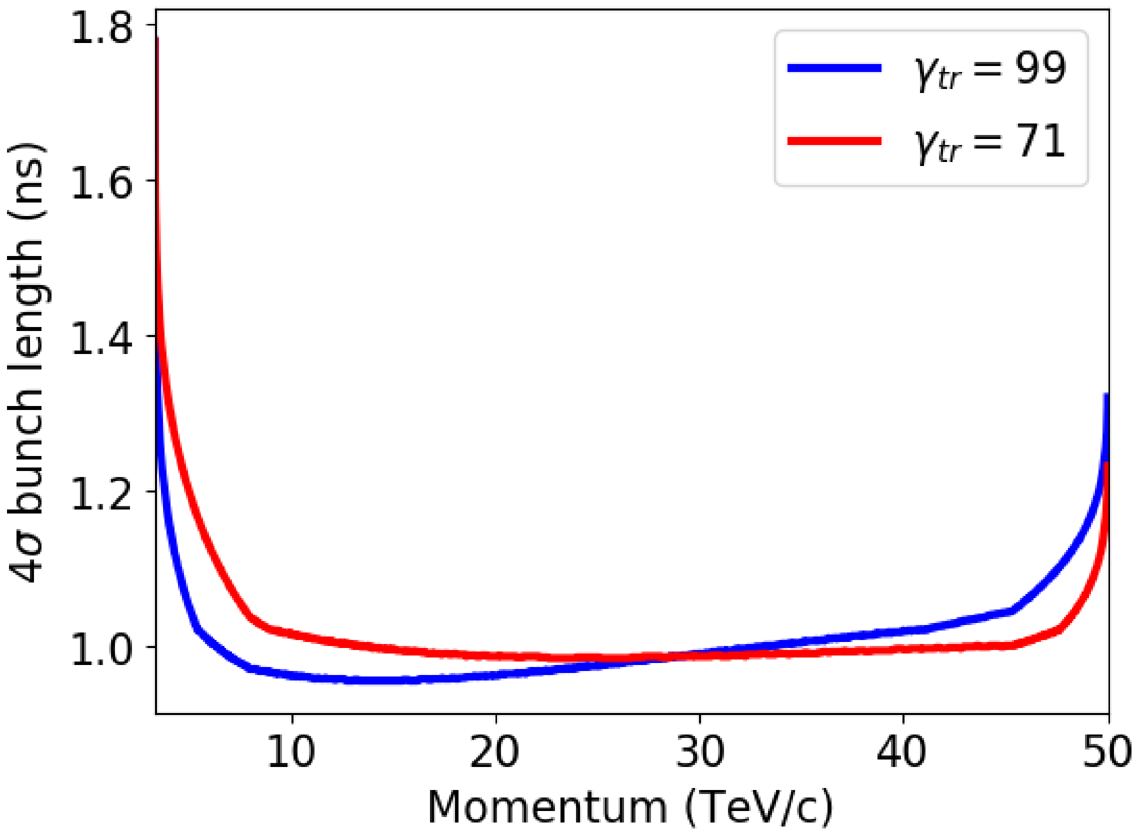

**TMCI**




→ Maximum voltage during ramp ~ 34 MV with smaller emittances

# Bunch parameters during 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)

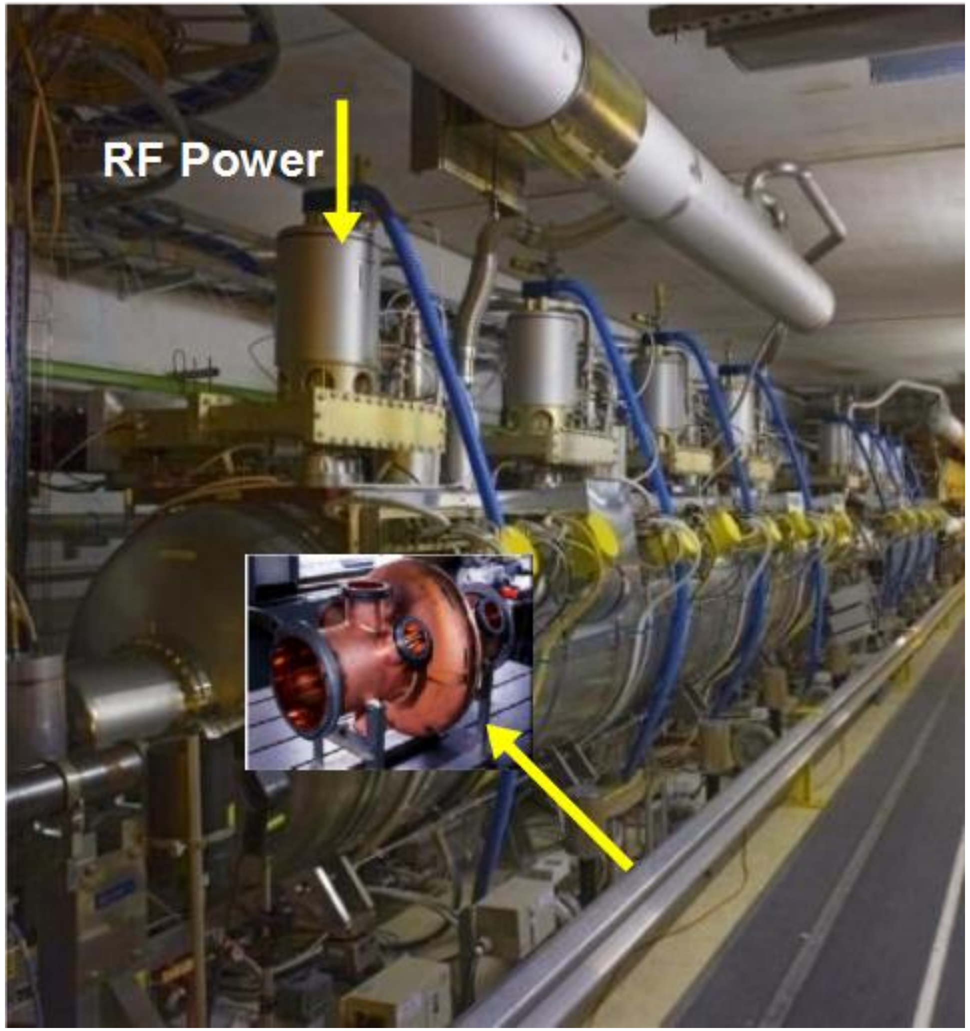
- 400 MHz single-cell cavity (LHC-type), similar to FCC-ee Z machine
- 20 cavities/beam with 2 MV/cavity or 40 with 1 MV/cav.
- $f_0 \sim$ 3 kHz, ½ detuning or optimum detuning $\sim$ several kHz → coupled bunch instabilities due to fundamental impedance → strong feedback.
- Final RF power requirements 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
- $1x10^4 < Q_{ext} < 1x10^5$
- Klystron driven (up to 300 kW )

400 MHz(Nb-Cu)



# 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 1.8 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 → additional 800 MHz RF system would give more flexibility