Beam loading and LLRF considerations for FCC-ee

A. Butterworth, *R. Calaga, I. Karpov, J. Esteban Mueller,*
CERN, Geneva, Switzerland

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Introduction

The FCC-ee is a high-luminosity, high-precision e^+e^- circular collider, envisioned in a new 100 km tunnel in the Geneva area [1].

The FCC-ee physics program defines four stages, each operating at a different beam energy, in order to produce Z and W bosons, Higgs bosons and top quark/anti-quark pairs. The beam current at each energy point is defined by the total power budget for synchrotron radiation which is 50 MW per beam.

A staged installation of RF cavities follows the evolution of the machine energy. For the first stage at the Z, where the total RF voltage is modest but the beam intensity is the highest, 400 MHz single-cell cavities are used to cope with the high fundamental and HOM powers involved. For the W energy point, the single cells are replaced by 4-cell cavities to achieve higher real-estate gradient, and for the H the number of cavities is increased. Finally to achieve the highest beam energies in ttbar operation, the small number of bunches allows the separate RF systems of the two rings to be combined into RF sections common to the two rings, doubling the available RF voltage, which will be further supplemented by the installation of additional 800 MHz 5-cell cavities.

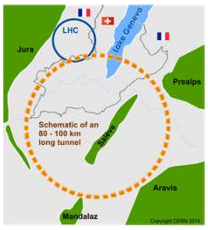


Figure 1: FCC situation plan

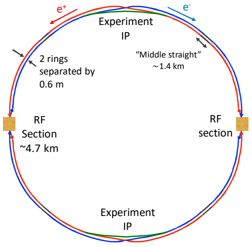
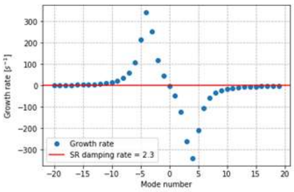


Figure 2: FCC-ee layout

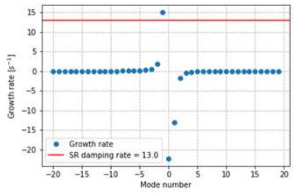
	"High intensity"		"High gradient"		
	Z	W	H	$ttbar_1$	$ttbar_2$
Beam energy [GeV]	45.6	80	120	175	182.5
Beam current [mA]	1390	147	29	6.4	5.4
Number of bunches	16640	2000	393	48	48
Beam RF voltage [MV]	100	440	2000	9500	11000
400 MHz cavities	52 (1-cell)	52 (4-cell)	136 (4-cell)	104 (4-cell)	104 (4-cell)
800 MHz 5-cell cavities				296	376
Runtime [year]	4	1	3	1	3

Table 1: The different FCC-ee operation modes and staging of the RF system installation

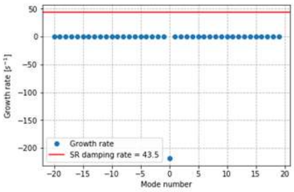
Coupled bunch instabilities



(a) Z machine, $Q_{ext} = 4.4\mathrm{x}10^4$, $\Delta f = 11731$ Hz



(b) W machine, $Q_{ext} = 2.4\mathrm{x}10^5$, $\Delta f = -683$ Hz



(c) H machine, $Q_{ext} = 1.9\mathrm{x}10^6$, $\Delta f = -62$ Hz

Figure 3: Longitudinal coupled bunch mode growth rates. The red line indicates the damping rate from synchrotron radiation.

In the Z operation mode with 1.39 A of beam current, the detuning required to compensate the reactive beam loading is 11.7 kHz, crossing 3 revolution frequency harmonics. Many coupled bunch modes are strongly driven by the cavity fundamental impedance and a number of these have growth rates greater than the radiation damping rate. The most unstable mode has a growth time of 3ms compared with the damping time of 414 ms. Strong RF feedback and longitudinal damping will be required to stabilize these modes [5].

At the W operation point the situation is better: the higher beam energy gives much stronger radiation damping and with the lower beam current the detuning is below the revolution frequency. Only one mode (l=-1) is slightly above the damping limit.

At the H operation point all coupled bunch modes are stable due to the small detuning and the strong radiation damping.

Beam gap transients

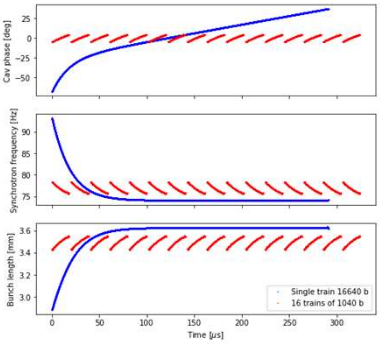


Figure 5: Cavity phase variation, synchrotron frequency and bunch length for different filling schemes in the Z machine. In blue, a single train of 16640 bunches, spacing 17.5ns, single gap 355 μs. In red, 16 trains of 1040 bunches, spacing 17.5ns, gaps each 2.2 μs.

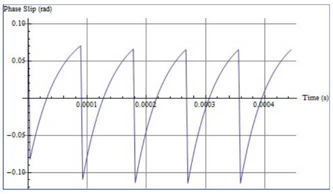


Figure 6: Bunch phase modulation with adaptive setpoint scheme in LHC [7]

Figure 5 demonstrates the effect of transient beam loading in the Z machine with 1.39 A in 16640 bunches and an abort gap of 2 μs minimum. The phase modulation of the cavity voltage without feedback is estimated using the small-signal model of Pedersen [2]. With the bunches disposed in a single train with the widest possible bunch spacing (17.5 ns), the peak to peak phase excursion at the abort gap is an unphysically large 104 degrees. With 16 trains arranged evenly around the ring and a 2.2 μs gap between each, the phase excursion is reduced to 9.4 degrees and the synchrotron frequency and bunch length remain constant to within a few percent.

More effective schemes to reduce transients using fill pattern density modulation have been developed for use in synchrotron light sources [3, 4].

With large gap transients, full compensation with feedback is very costly in terms of peak power. A solution is to relax the requirements on bunch phase allowing bunches at different points in the train to have different phases. Such an adaptive setpoint scheme has been used at PEP II [5] and is adopted as the baseline for LHC operation from 2017 onwards [6].

Higher order modes

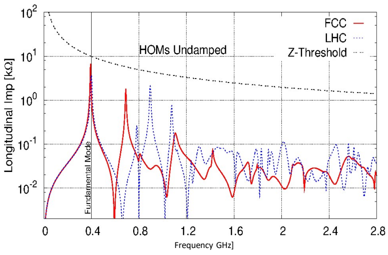


Figure 4: Longitudinal impedance of FCC single-cell cavity compared with Z machine coupled-bunch threshold from radiation damping

Radiation damping gives a limit on the coupled bunch growth rates from which can be derived a threshold impedance for stability. Comparison of the cavity impedance spectrum with this threshold indicates that even for the Z machine the higher order mode impedances are under control and that HOM-driven coupled bunch instabilities will not require active damping.

Conclusions

The most challenging conditions for operation of the FCC-ee are at the 45.6 GeV Z pole, where the beam current is 1.39 A, and high beam loading and higher order mode damping considerations will dominate the RF system design. Separate cavity designs for high intensity and high energy operation are under consideration, and initial calculations of transient beam loading and coupled-bunch stability have been performed. Cavity fundamental-driven coupled bunch instabilities will dominate at the highest beam intensities and will require strong active damping to control them. Beam loading compensation of the gap transients will require careful selection of filling patterns and an adaptive phase setpoint scheme in the cavity feedback to keep peak power to a reasonable level.

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