

FIRST RESULTS ON FAST ION INSTABILITY IN THE FCC-ee INJECTOR COMPLEX DAMPING RING

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Abstract

The FCC-ee injector complex design includes a dedicated damping ring (DR) to significantly reduce the transverse beam emittance of the incoming positron beam at 2.86 GeV prior to injection into the high-energy linac, where it is accelerated up to 20 GeV for the main booster ring. The DR is also foreseen for the electron beam to mitigate possible emittance growth due to alignment errors and collective effects in the electron linac. Ionization of residual gas molecules due to interactions with the circulating bunches can lead to ion trapping in the beam's potential well. These ions may accumulate over many turns and oscillate around the bunch train centroid, potentially causing fast ion instabilities (FII) and degrading beam quality in the damping ring. This study investigates the impact of FII on the two considered FCC-ee DR options: the six-fold symmetry (baseline) and the three-fold symmetry (alternative). A range of vacuum conditions, gas compositions, and bunch parameters are explored to identify the operational regimes in which fast ion instabilities may become significant. In this context, we evaluate the trapping mechanism and its impact on each lattice option based on analytical estimates and tracking simulations performed with the PyHEADTAIL code.

INTRODUCTION

The Future Circular Collider e^+e^- (FCC-ee) is a proposed high-luminosity precision frontier accelerator aimed at comprehensively investigating the Higgs, W and Z bosons, and the top quark. The FCC-ee injector complex relies on a 2.86 GeV damping ring (DR) to achieve low beam emittance prior to subsequent acceleration in the high-energy linac and the booster synchrotron to meet the stringent luminosity requirements of the collider ring [1–8]. The fast ion instability (FII) is one of the effects that must be evaluated before finalizing the DR design. The interaction of the dense circulating electron beam with residual gas molecules such as H_2 , He, CH_4 , N_2 , CO, O_2 , and CO_2 leads to collisional ionization in low-emittance rings. The resulting positively charged ions are attracted towards the center of the beam by the electromagnetic fields of the electron bunches and can become trapped in the potential well of the beam. As the bunch train passes, these trapped ions accumulate turn-by-turn, forming an increasingly dense ion cloud. The coupled interaction between the ion cloud and the subsequent bunches in the train can induce instabilities [9–11]. A detailed analysis of the

specific lattice design is needed to understand the dynamics of ion accumulation, as variations in optical functions, beam sizes, and magnetic fields along the ring strongly influence the ion trapping conditions. Accurate estimates of the critical mass, instability rise times, the resulting beam offset and emittance evolution are necessary to define the design specifications for the vacuum and feedback systems. Ionization cross section (σ_{ion}) is one of the crucial parameters required for the analytical estimates and simulations. Thus, these cross sections for common ions that can be present in the vacuum pipe for the working energy of DR are calculated based on Bethe theory by using the following expression [12, 13]:

$$\sigma = 4\pi Z^2 \left(\frac{\hbar}{mc}\right)^2 \frac{1}{\beta^2} (M^2 x + C). \quad (1)$$

where M^2 and C are experimental constants depending on the gas species, $x = 2 \ln(\gamma) - \beta^2$, c is the speed of light, m is the mass of the electron. The calculated values for several ions together with their mass numbers (A) are listed in Table 1.

Table 1: Ionization cross sections at 2.86 GeV

Gas species	Mass number (A)	σ_{ion} [Mbarn]
H_2	2	0.436
He	4	0.445
CH_4	16	3.109
N_2	28	2.688
CO	28	2.678
O_2	32	3.011
CO_2	44	4.199

ION EFFECT CALCULATIONS

Beam Parameters

The purpose of the DR design is to accept the 2.86 GeV positron beam from the positron linac, damp the beam emittance, and provide the required beam parameters for injection into the high-energy linac where both positron and electron beams are accelerated up to 20 GeV. The DR is primarily required to reduce the geometrical emittance of the incoming positron beam from 2.36×10^{-6} m-rad to about 1.8×10^{-9} m-rad. In addition, the DR is also foreseen for electron beam emittance cooling to mitigate possible growth due to alignment errors and collective effects in the electron linac. Two alternative DR designs are considered: six-fold

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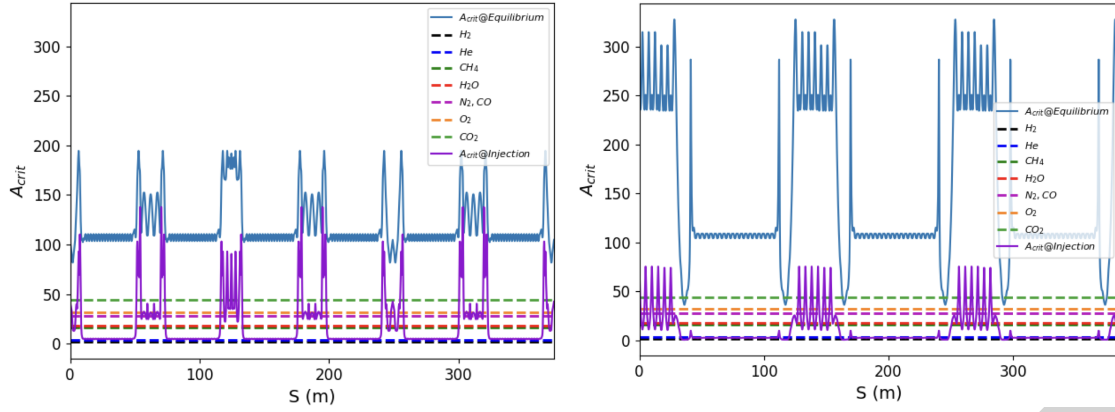


Figure 1: Critical mass for the six-fold (left, baseline) and three-fold (right, alternative) options in comparison to the thresholds for various molecules.

symmetry featuring a circumference of 373.78 m (baseline) and three-fold symmetry (alternative) with 384.87 m circumference. The beam and lattice parameters utilized for the analytical calculations and numerical tracking simulations for both options are summarized in Table 2.

Table 2: Main parameters for the damping ring options

Parameter	six-fold	three-fold
Circumference [m]	373.78	384.87
Beam Energy [GeV]	2.86	2.86
Eq. Hor. Emit. [nm-rad]	3.37	1.76
Damping time (hor.) [ms]	6.0	6.46
Mom. compaction fac. (10^{-2})	0.16	0.17
Eq. bunch length [mm]	6.83	8.26
Energy spread (10^{-2})	0.08	0.08
Energy loss/turn [MeV]	1.18	1.13
Harmonic number	499	513
Number of bunches	20	20
Bunch spacing [ns]	25	25
Bunch intensity (10^{10})	3.15	3.15
β_x/β_y (average) [m]	3.19/3.02	4.15/5.63
D_x (average) [m]	0.48	0.02

Analytical estimates

The critical mass for the trapping of a singly charged ion is given by [14–18]:

$$A_{\text{crit}} \cong \frac{N_b \Delta T_b c r_p}{2\sigma_y (\sigma_x + \sigma_y)}, \quad (2)$$

where r_p is the classical proton radius, N_b is the bunch intensity, ΔT_b is the bunch spacing, σ_x and σ_y are the horizontal and vertical RMS beam sizes at a given longitudinal position along the ring. Ions with a mass number A greater than the critical threshold A_{crit} are trapped within the bunch train, leading to continuous accumulation. Thus, analytical critical masses (A_{crit}) for both DR ring options have been calculated and presented in Fig. 1 as well as atomic masses of specific ions shown as dashed lines. Both calculations show that ion trapping is expected for heavier ions only at

equilibrium state, while critical masses are lower than almost all ion masses at injection.

Tune shift induced at the end of the train due to ions trapped around the electron beam is given by [14, 17, 18]:

$$\delta Q_{\text{ion}} \cong \frac{N_b n_b r_e c}{\pi \gamma \sqrt{\epsilon_x \epsilon_y}} \left(\frac{\sigma_{\text{ion}} p}{k_B T} \right), \quad (3)$$

where σ_{ion} is the ionization cross section, p is the vacuum pressure, k_B is the Boltzmann constant. For the six-fold option $\delta Q_{\text{ion}} = 0.0005$ and for the three-fold $\delta Q_{\text{ion}} = 0.001$, which are both small, assuming a vacuum pressure of 10^{-9} mbar.

The FII rise time due to accumulated ions is given by [14, 15, 17, 18]:

$$\tau_{\text{inst}} \cong \frac{0.1 \gamma \sigma_x \sigma_y}{N_b n_b c r_e \beta_y \sigma_{\text{ion}}} \left(\frac{k_B T}{p} \right) \left(\sqrt{\frac{8}{\pi}} \right). \quad (4)$$

The FII rise times are estimated to be 30 and 46 revolution times (t_{rev}) for the six-fold and the three-fold options, respectively. Instabilities with such rise times can be compensated with a feedback system for both options, provided that a vacuum pressure of 10^{-9} mbar is achieved.

Simulation results

Estimates presented in the previous section are based on a linear approximation of the beam field. The numerical simulations need to be conducted with full beam field for realistic results in addition to the analytical estimates. The simulations must be performed at different locations of the machine, since the betatron functions vary along the lattice. In this regard, multi-turn tracking simulations are performed using PyHEADTAIL in field-free straight sections (SS) and dipole-dominated arcs, employing the corresponding average betatron functions to analyze beam behavior such as centroid offset and emittance growth. Simulations have been performed with 20 bunches over 50 turns for vacuum pressures ranging from 0.75 nTorr (10^{-9} mbar) up to 100 nTorr for atomic mass number 2 (H_2), 4 (He), 16 (CH_4), 28 (N_2 , CO), 32 (O_2) and 44 (CO_2).

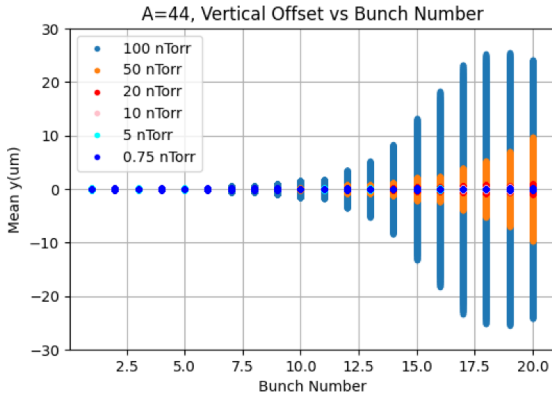


Figure 2: PyHEADTAIL tracking results for the three-fold symmetry option in the straight section for different vacuum pressures. The number of bunches is 20, bunch spacing is 25 ns, $A = 44$ (CO_2).

For the three-fold design option, the beam remains stable up to atomic mass number of 16 even at vacuum pressures up to 100 nTorr; then, a non-negligible beam offset is observed for the higher ions. The vertical offset versus bunch number for $A=44$ is shown in Fig. 2. The beam is stable under the target vacuum pressure of 10^{-9} mbar as estimated by the analytical estimates in the SS. At higher pressures, a beam offset is seen starting from around 20 nTorr after approximately the 10th bunch. A similar behavior is observed in the arc; however, the maximum offset is lower, around $15 \mu\text{m}$. For the six-fold symmetry option, the beam remains stable up to a vacuum pressure of 50 nTorr and at high pressures an effect—a centroid deviation of approximately $5 \mu\text{m}$ —appears at the tail of the bunch train (see Fig. 3). Furthermore, no significant emittance growth was observed during the tracking simulations, suggesting that the FII can be effectively managed for both DR options. Analytical estimates initially predicted that the impact of heavy ions on the emittance would be small, and our macro-particle tracking simulations over 50 turns confirm the result.

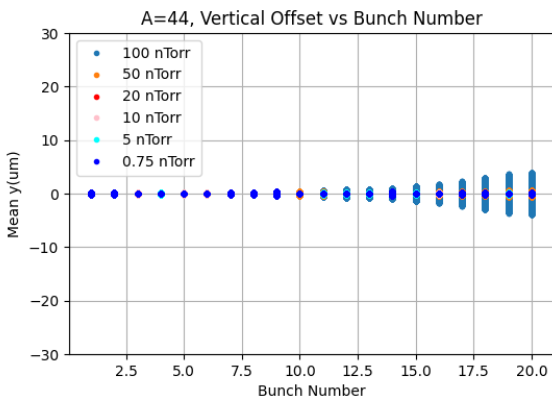


Figure 3: PyHEADTAIL tracking results for the six-fold symmetry option in the SS for different vacuum pressures. The number of bunches is 20, bunch spacing is 25 ns, $A = 44$ (CO_2).

Additional simulations have been performed for the six-fold symmetry option with longer bunch trains of 28 and 45 bunches in order to assess the sensitivity of the FII to the bunch train length. As expected (see Fig. 4), the instability develops more strongly with increasing number of bunches. Further studies are also planned to investigate various bunch spacings, filling pattern, and longer tracking durations.

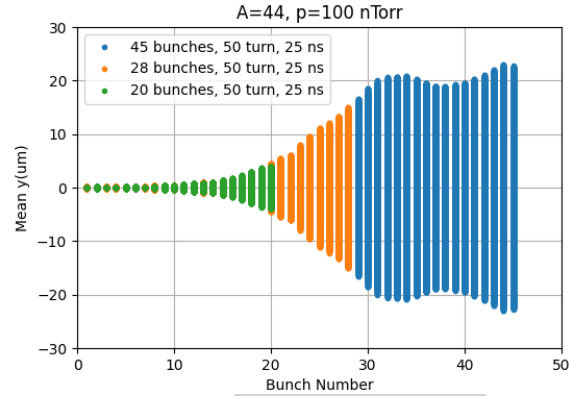


Figure 4: PyHEADTAIL tracking results for the six-fold symmetry option in the SS for different number of bunches. Bunch spacing is 25 ns, $A = 44$ (CO_2).

CONCLUSION

A comprehensive study combining analytical estimates and numerical simulations using the PyHEADTAIL code has been carried out to evaluate fast ion instability (FII) in the FCC-ee damping ring options. Both the baseline six-fold lattice and the alternative three-fold lattice have been systematically investigated. The results show that, although variations in the optical lattice lead to local differences in the critical mass and ion trapping conditions, neither configuration presents a limitation for stable operation at vacuum pressures up to 20 nTorr. The simulations indicate that non-negligible beam offsets appear above 20 nTorr and 50 nTorr for the three-fold and six-fold options, respectively. In both cases, the instability rise times remain within manageable limits, allowing effective mitigation using conventional feedback systems. Future studies will extend the simulations to different bunch patterns, bunch spacings, and longer tracking durations.

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