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BUNCH SCHEDULES FOR THE FCC-ee PRE-INJECTOR

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Abstract

The latest design of the Future Circular electron-positron Collider (FCC-ee) foresees a luminosity per interaction point above 2×10^{36} cm^{-2}s^{-1} for operation at the Z-pole. The filling from zero current occurs in collision to profit from the bunch lengthening due to beamstrahlung (so-called bootstrapping). At any time when new e^+ and e^- buckets or bunchlets are injected into the collider, they will collide instantly. For this reason, we may prepare the charge in each injected bunch in a way to pre-compensate for anticipated beam loss, and to reach the target luminosity as soon as possible after the first injection. In this way, we optimise the injection schedules for Z-mode so as to reach the peak luminosity in less than 20 minutes by interleaved injection of the two species at some portion of full bucket charge. Filling from zero the injector should allow accumulating 1.7×10^{11} particles in one collider bucket within at least 10 injections, assuming a total transmission above 80%. In steady-state operation, the injector chain continually produces and accelerates lower bunch charges so as to maintain nearly constant bunch currents and constant peak luminosity.

INTRODUCTION

The FCC-ee is being designed to furnish high luminosities for Z, W, H, and $t\bar{t}$ particles. All injector parameters for initial fill up and top up are presented in Table 1. The main idea of top-up injection is to sustain the luminosity at the peak by recovering the charge missed in the collider buckets due to collisions. The most challenging operation mode for the pre-injectors is Z-mode since it requires the highest total current accumulated in the collider. Thereby, it will be the focus of this paper for the calculations and simulations. The main effort of the pre-injectors at the Z-mode will be to foresee the charge loss in a bucket since the injector cycle is 51.7 seconds and we can inject once into the same bucket in 2×51.7 s. This time interval stems from the fact that the collider will have two beam pipes, one for each species, yet the rest of the pre-injector synchrotrons can accumulate and accelerate solely one kind. On the other hand, the beam lifetime is short due to high collision rates, plus the collider will be filled by interleaving the species, while keeping the current of two species within a ±5% asymmetry. Therefore, a bunch schedule assisted by a simulation code has been developed to operate such a complex scheme within given constraints, including short beam lifetime, asymmetry limit for the charge of species, bootstrapping, and pre-compensation of the charge loss.

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BASELINE FOR THE PRE-INJECTORS

The recent baseline of the FCC-ee is to accelerate both species alternatively in a linac up to 6 GeV by using a damping ring at 1.54 GeV for emittance cooling [1], then utilize the slightly modified Super Proton Synchrotron (SPS) of CERN to accelerate the particles to 20 GeV [2]. This is followed by the 98 km top-up booster to reach the operating energy of the collider [3]. The layout of the FCC-ee can be seen in Figure 1.

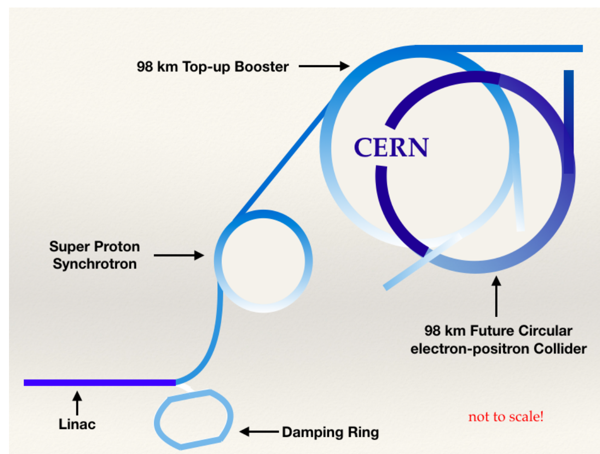

Figure 1: FCC-ee main layout

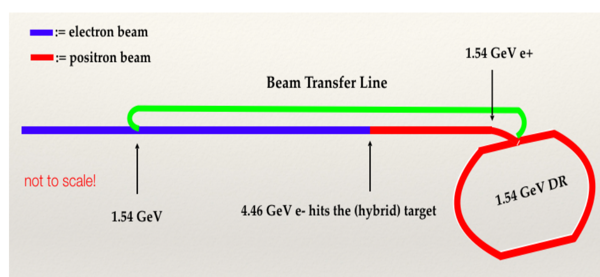

Figure 2: Positron flow scheme using the same linac as for the electrons. Notice that the positrons will be transferred back to the linac, drawn green.

The 1.54 GeV damping ring (DR) will be at the end of the linac and electrons will be transferred from a branching point in the linac at 1.54 GeV (Figure 2). We may tilt the DR just by a small angle in order not to bend e^+ beam noticeably. In this way, the beam transfer lines can share the same tunnel as the main linac.

High luminosity reduces the beam lifetime, hence it requires fast cycling injectors to fill up and top-up. The FCC-ee requires 200 Hz linac repetition with 2 bunches per RF pulse particularly for Z-operation mode, as tabulated in Table 1.

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Table 1: Baseline Parameters for the FCC-ee Injectors

operation mode	FCCee-Z		FCCee-W		FCCee-H		FCCee-tt	
type of filling	Full	Top-up	Full	Top-up	Full	Top-up	Full	Top-up
energy [GeV]	45.6		80		120		182.5	
lifetime [min]	70	70	50	50	42	42	47	47
τ_{inj} [sec]	122	122	44	44	31	31	32	32
linac bunches	2	2	2	2	1	1	1	1
linac repetition rate [Hz]	200	200	100	100	100	100	100	100
linac RF frequency [MHz]	2800							
linac bunch population [10^{10}]	2.13	1.06	1.88	0.56	1.88	0.56	1.38	0.83
SPS bunch spacing [MHz]	400							
SPS bunches/injection	2	2	2	2	1	1	1	1
SPS bunch population [10^{10}]	2.13	1.06	1.88	0.56	1.88	0.56	1.38	0.83
number of linac injections	1040	1040	500	500	393	393	50	50
number of SPS injections	8	8	2	2	1	1	1	1
SPS supercycle duty factor	0.84	0.84	0.62	0.62	0.35	0.35	0.08	0.08
SPS number of bunches	2080	2080	1000	1000	393	393	50	50
SPS current [mA]	307.15	153.57	130.22	39.07	51.18	15.35	4.77	2.86
SPS injection time [s]	5.9	5.9	5.7	5.7	3.93	3.93	0.5	0.5
SPS ramp time [s]	0.2							
SPS cycle length [s]	6.3	6.3	6.1	6.1	4.33	4.33	0.9	0.9
BR bunch spacing [MHz]	400	400	400	400	400	400	400	400
BR number of bunches	16640	16640	2000	2000	393	393	50	50
BR bunch population [10^{11}]	0.21	0.11	0.19	0.06	0.19	0.06	0.14	0.66
BR cycle time [s]	51.74	51.74	14.4	14.4	7.53	7.53	5.6	5.6
booster ramp time	0.32	0.32	0.75	0.75	1.25	1.25	2	2
number of cycles per species	10	1	10	1	10	1	20	1
transfer efficiency	0.8							
no. of injections/collider bucket	10	1	10	1	10	1	20	1
total number of bunches	16640	16640	2000	2000	393	393	50	50
filling time (both species) [sec]	1034.8	103.48	288	28.8	150.6	15.06	224	11.2
required bunch population [10^{11}]	1.70	0.085	1.5	0.045	1.5	0.045	2.2	0.066

In fact, the pulse compressors feeding the cavities can be arranged in a way to accelerate even 4 bunches. This option is considered for the case of FCC-ee positron production only, in which the power pulse [4] would carry 2 e^+ bunches to be injected into the pre-booster, and 2 high charge e^- bunches to hit the target which are directed via a magnetic seperator. The newly created 2 e^+ bunches go through a flux concentrator, an adiabatic matching device, and finally a pre-injector linac surrounded firstly by a focusing solenoid and followed by quadrupole triplets [5, 6]. The positron linac will be embedded into the electron linac by compatible optics. The positrons accelerated up to 1.54 GeV in the last part of the linac will be transferred into the DR for emittance cooling. Then they will be transferred back to the linac at 1.54 GeV part via the bunch compressor [7].

BOOTSTRAPPING

Each ring of the collider will contain 16640 RF buckets filled with $1.7{\times}10^{11}$ (full charge) particles which are either electrons or positrons. The booster will have one beam pipe. It will carry a fraction of the full charge, but will also have 16640 RF buckets filled. The main issue arises when the collider buckets get almost full. If we keep injecting regularly, for example, 10% of the full charge, the asymmetry between the charges may cause the species with the comparatively lower charge to decay faster, and in the end result in a forfeited collider bucket. The beam lifetime of Z-mode operation has been determined with an asymmetry budget of ±5%. However, this limit is approached when the bunch charge gets close to full, but not yet important for the first fill of the collider when injecting from zero. In Table 1, one can see that the injectors are in general optimised to accumulate the collider charge in 10 injections. However, these 10 injections may not necessarily be with the same charge each. For example, the low emittance RF gun of the FCC-ee can provide $4{\times}10^{10}$ electrons in a bunch [8], so that we can start by injecting that charge into the collider, and lower the injection amount later in time. Figure 3 shows an example of such a case starting with a high charge and continuing with lower charge.

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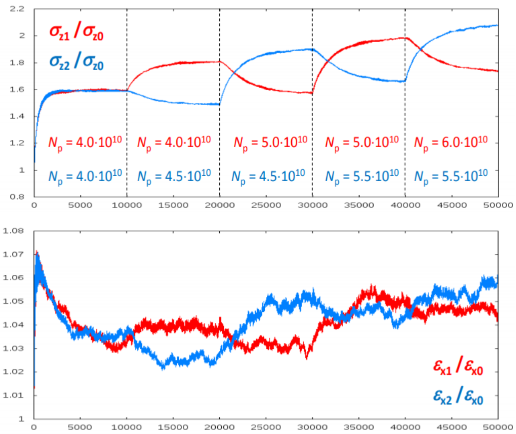

Figure 3: An illustration of bootstrapping, showing the relative bunch length and emittance fluctuations, respectively, while additional bunches are injected, where blue and red colors refer to e^- and e^+ respectively.

BUNCH SCHEDULES

Particles will always collide after the first injection of both species. The amount of surviving particles in collisions can be described as an exponential decay: $N = N_0 e^{-t/\tau}$, where N is the final amount of particles left after a time t, when initially N_0 particles were present with beam lifetime τ. The beam lifetime τ is 70 minutes for Z-operation mode, but τ gets increased when only some fractions of the full charges are available in the collider.

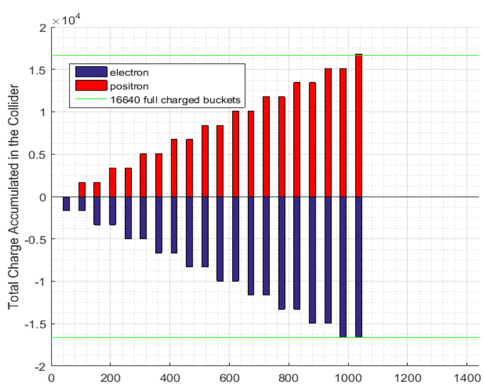

Figure 4: The first fill of the collider is complete after 1035 seconds. The vertical axis shows the total charge accumulated in the 16640 buckets where the full charge is taken as 1.

In Figure 4, the interleaved first fill of the collider is presented. Here, the calculated charge losses in two booster cycles are already added to the preceding bunch while respecting the charge asymmetry limit between the species. The collider bucket is filled in 10 Booster cycles. Since we started with e^-, we include additional e^+ that would be lost within one Booster cycle. For this reason, e^+ surpasses the full charge line (shown in green) in Fig. 4.

As a safety margin, we may send twice intensity of e^- at 4.46 GeV to impinge on the target to yield the required amount of e^+ at the end of linac. Furthermore, the charge available in the SPS should stay within the capabilities of the SPS RF system. Therefore, the charge flux accelerated in the pre-injectors should respect all limitations of the downstream accelerators. To illustrate, if a bunch population of 4×10^{10} is intended in the pre-injectors, 8×10^{10} e^- can be required to get 4×10^{10} e^+. On the other hand, even if the linac can accelerate such a high charge, the current stored in the SPS would become more than 600 mA. All in all, 10 injections with pre-compensation of the charge result in around 2.1×10^{10} particles in a bucket and just above 300 mA in the SPS, which seems to be adequate and sustainable.

On the other hand, the top-up injection will be maintained by injecting 2.4% of the full charge starting with e^- and continuing with alternative charge and so on. Therefore, the charge asymmetry always stays within ±1.2%. Figure 5 shows the top-up injection for Z-mode, the injection repetition is one booster cycle (i.e. ~52 seconds), yet alternating between the species. One can see that the time average of both species is the full charge (i.e. shown as 1), which corresponds to full bunch by bunch luminosity excluding the effect of other parameters on luminosity.

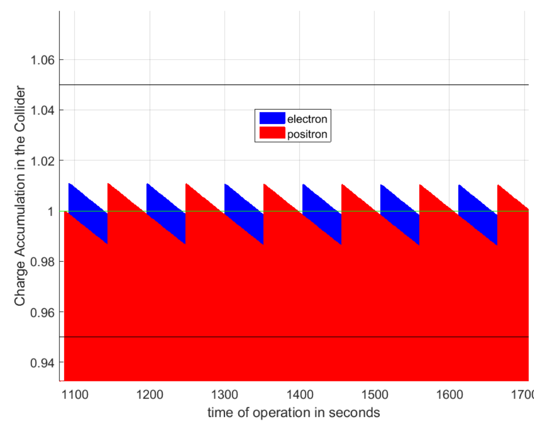

Figure 5: Top-up injection can be arranged to keep the charge imbalance to less than ±5% (shown as horizontal black line). Also, the time average of both charges is kept around the full charge (shown as 1 in vertical axis).

CONCLUSIONS

The recently developed bunch schedules meet the requirements for all FCC-ee operating modes. Depending on the final design of the positron system, the pre-injector schedule will be adjusted to start filling the collider from scratch with the highest charge that can be transmitted through the S-band linac and accumulated in the SPS. A gradual decrease of the charge will be taken into account, such that the top-up is maintained within ±5%. For the final injection schemes, we may need to re-simulate the bootstrapping procedure shown in Fig. 3.

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