FIRST RESULTS OF BEAM DYNAMICS SIMULATION IN ELECTRON INJECTOR LINAC FOR FCC-EE

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Abstract

New high-energy frontier project FCC is now under development at CERN. It is planed that all three modes as ee, hh and eh will be available for FCC. New injection system for FCC-ee is planned to consist of new ~ 2 GeV electron linac and electron-positron converter. Two possible layouts for further beam acceleration are discussed. The high-energy 14 GeV linac is the first layout and the booster synchrotron is the second one. Pre-injector linac design will have two regimes: ~250 pC bunches for injection and ~6 nC bunches for e^-/e^+ conversion. In the second case we will have extreme parameters: bunch charge up to 6 nC in 10 ps, up to 10 bunches per pulse and the pulse repetition rate up to 100 Hz. Such beam parameters lead to significant design difficulties caused by very high influence of Coulomb field in the near-cathode region and high peak beam loading. First results of beam dynamics simulation in FCC-ee injection linac and near-cathode dynamics problems are discussed in the report.

INTRODUCTION

New injection system for FCC-ee [1] is now under discussion by FCC collaboration [2-3]. A number of different injection schemes are discussed: linac (from 2 to 7 GeV) with booster synchrotron, high energy linac (up to 14 GeV) and reacceleration in main collider ring, top-up injection. It is obvious that linac should include the first stage (about 2 GeV) and the electron-positron converter with damping ring to generate the necessary positron flux. Beam intensities for two regimes (electron beam acceleration for injection and for e^-/e^+ conversion) will differ very significantly: it is necessary to have up to $1.65{\cdot}10^9$ e^-/bunch (~250 pC) for injection mode [2-3] and up to $4{\cdot}10^{10}$ e^-/bunch (~6 nC) for e^-/e^+ conversion mode; 10 ps bunch duration is the same for both cases. It is planned to have 10 bunches/pulse with distance between bunches of 25 or 50 ns. The pulse repetition rate will be up to 50 Hz. The separated bunches regime facilitates RF system design and operation because of low beam loading influence compared to the bucket of bunches mode. Note that 6 nC regime is very complex and limited number of linacs are operating with such currents.

The general scheme of the CLIC linac or the new SuperKEKB injector linac [4] could be proposed to use as the base of FCC injector. New SuperKEKB injector consists of the modern RF gun commissioned in 2013-14 and traveling wave regular sections. It is very interesting idea to combine thermionic RF gun for high-intensity high-emittance drive bunch for 5 nC mode and high-quality beam generated by photogun for injection into synchrotron.

The choice of operating frequency is very important too. It is proposed to use 2000 MHz structures which will have higher acceptance compared to conventional 3000 MHz band. Two notes should be done here: i) exactly 2000 or 3000 MHz structure can give 25 (or 50) ps of bunch separation (conventional 2856 MHz can not) and ii) there are no high-power RF sources for 2000 MHz (but they are available for 1816 and 1860 MHz and can be scaled). It is important because 10 bunches/pulse regime is planned. Current pulse duration will be 250 or 500 ns, SLED or other RF pulse compression scheme can be used to reduce necessary peak RF power and RF feeding system cost. Low average pulse current (but peak is very high) give us possibility to use a standing wave structure (biperiodic accelerating structure BAS, or side-coupled one), but it should have very high coupling coefficient (10-12 %) to realize low power filling time.

Two possible layouts of linac are presented in Fig. 1. Let us discuss first results of the beam dynamics simulation and RF gun and regular section electrodynamics study.

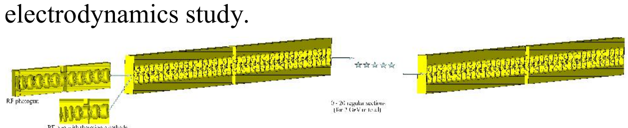

Figure 1: Two possible schemes of linac layout (RF gun with thermionic cathode is option for high intensity drive bunches production for e^-/e^+ conversion).

BEAM DYNAMICS IN PHOTOGUN

The beam dynamics simulation was done both for RF gun and regular section. The BEAMDULAC-BL code [5-7] was used for simulations. This code was developed in MEPhI for beam dynamics simulations in RF linacs and transport channels. It has modular structure and number of routines to solve different tasks: initial particles distribution (uniform, Gauss, KV, waterbag, etc.), motion equation integration (4[th] order Runge-Kutta method), beam emittance calculation, post processing and other. The code package has versions that take into account own space charge effects: both Coulomb part and RF part (beam irradiation and beam loading) self-consistently. The excitation equation is solved to simulate RF part of own space charge field using the method of large particles. The Poisson equation is solved on grid by fast Fourier transform (FFT) method and well-known cloud-in-cell (CIC) algorithm is used to represent particles distribution on 3D grid. The BEAMDULAC-BL code

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version is discussed in detail in [7]. It was tested at a number of e-linac designs (see [8, 9] as two examples).

At first we simulated the RF photogun with 300 pC and 10 ps per bunch. Such current is not easy to generate in a photogun, but it is typical for contemporary facilities with semiconductor cathodes. A biperiodical accelerating structure (BAS) with disk-loaded waveguide (DLW) was considered. First (~56 cm in the length) version of photogun ("photogun_v1") consisting of 12 acceleration cells and 10 coupling cells (the first and the second accelerating cells are side-coupled) was presented in FCC Meeting 2016 at Rome. The first and the second accelerating cells should have a side coupling because we haven't got enough space to place it on axis: the first accelerating cell length should be enlarged to have enough space for laser port. The RF-gun accelerating structure should provide: short RF power filling time (high value of the loaded Q-factor is necessary, it can be realized in a structure with high coupling), low transverse emittance growth in first cells (where electrons are non-relativistic and the Coulomb field influence is high), the low energy spread growth (can be achieved by right choice of accelerating field profile). If we try to realize a low energy spread growth and plan to use low field value, we should provide effective capturing into acceleration mode. It was proposed to limit accelerating field by value of 400-600 kV/cm on the axis. Three cells (2nd, 3rd and 4th) having phase velocities β_{ph} =0.91, 0.98, 0.99 were used for efficient recapturing. The last accelerating cell length was enlarged because it has no coupling cell after it. All beam dynamic simulations in RF-guns were done for the operating frequency f=3000 MHz. Other structure parameters were taken for the simulation: channel aperture radius 10 mm, coupling cell length 4 mm (remind that we use side coupling for the 1st and the 2nd accelerating cells), diaphragm thickness 4 mm. The shunt impedance was defined by electrodynamics simulations (discussed below in section 4) and equals ≈80 MOhm/m. The initial transverse emittance of the bunch was taken 20 mm·mrad. The solenoid field of B_{sol} =0.1 T is enough for the effective beam focusing, the envelope of the beam will be less than 4 mm with this magnetic field value. The main beam dynamics simulation results are: capturing coefficient K_T=99.8 %, output energy 9.5 MeV, output beam spectrum FWHM ±3.9 %, bunch length 3.8 mm (initial one is 3.0 mm). Main results illustrated in Fig. 2.

The influence of beam loading was also studied. It was shown that it is not sufficient here: the accelerating field amplitude will drop for less than 0.3% for the 300 pC and 10 ps bunch due to the beam loading. It will not have any sufficient influence on the output energy: the second bunch will have energy of 9.44 MeV compared to the 9.52 MeV for the first one.

Further we tried to simulate the beam dynamics for the 1-6 nC bunch in the same structure with photocathode (we will not discuss the possibility of such charge emission from any cathode). We can simplify the general scheme of the linac (Fig. 1) if the second RF gun (with thermionic gun) is not necessary. It was shown that the current transmission coefficient decreases significantly and the energy spread growth vs. bunch charge and any other RF gun should be proposed. The capturing coefficient vs. the bunch initial current is shown in Fig. 3. It is clear that it will drop fast for high bunch charge case and the photogun has limitations for it to be used at nC drive bunches accelerator. All particle loses are occur at the first cell and are caused by longitudinal Coulomb repulsion leading to the stop of the significant part of the bunch or to the back-current formation. The capturing coefficient can grow for the higher accelerating field E_z=700-1000 kV/cm, but this growth is not higher than 7-10 %.

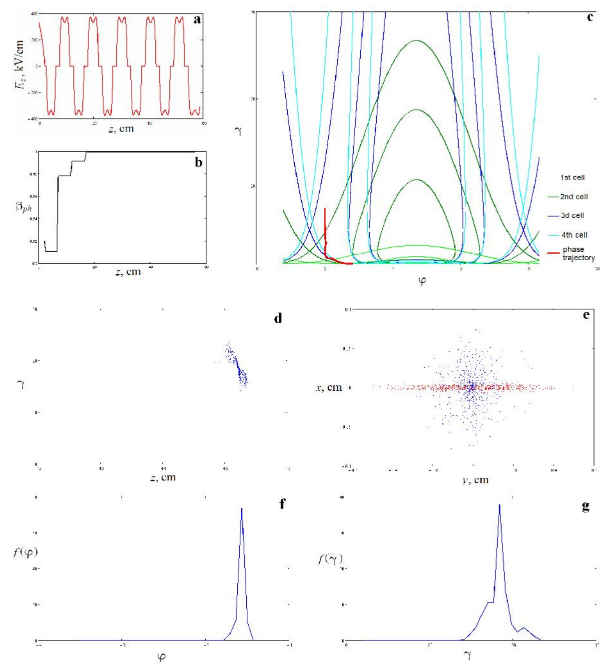

Figure 2: The RF photogun parameters: accelerating field E_z (a) and β_{ph} (b) along the longitudinal axis z; beam dynamics simulation results for the single 300 pC bunch: the center-of-mass trajectory in the (γ, φ) phase plane for first four cells (c), the phase distribution in the (γ, z) phase plane (d); the transverse emittance (e), the energy (f) and the phase (g) spectrums. All initial bunch characteristics are shown by red points and lines, output by the blue.

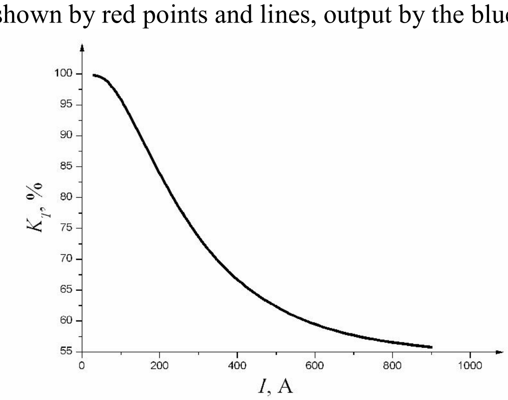

Figure 3: The capturing coefficient vs. bunch peak current for the case of using the photocathode.

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As it was shown, the current transmission coefficient will drop fast for high bunch charge, as an example it will not be higher than 60 % for 6 nC bunches (see Figure 3). The photogun will have current limitations due to such results and cannot be effectively used for acceleration of bunches with population higher than 2 nC. The bunch spectrum is also rapidly increasing vs. the bunch charge. Simulations show that high bunch intensities lead to high back currents. Sufficient Coulomb "head-tail" repulsion was observed. Head-tail difference of RF field amplitude due to high bunch phase size and beam loading effect leads to energy spectrum growth. RF-gun with thermionic cathode was proposed to accelerate nC bunches with high current transmission coefficient and to have high quality bunches. First results of the beam dynamics simulations results shows that for such gun the capturing coefficient can be increased to 90-95 % for 3 nC bunches and to 85-90 % for 6 nC ones. Such studies will be done in future.

BEAM DYNAMICS IN THE REGULAR SECTION

The long (~3 m) high-coupled biperiodic accelerating structure (BAS) was discussed as a possible regular section. It will have 61 accelerating cells and 60 coupling cells (302.5 cm of the total length) at 3000 MHz. BAS operating at 2000 MHz consists of 41 accelerating and 40 coupling cells (305.0 cm). Two notes should be done here: i) 3m-length BAS is longer that it is conventionally accepted for such structures, but we could accept it because it is commonly used in high-energy travelling wave linacs, and ii) other types of high-coupled structures (disk-and-washer, modified 2π/3 travelling wave DLW, etc.) should be discussed in the future.

We discuss three power feeding scenarios: i) "low-field" scenario with E_z=400 kV/cm which is typical for industrial e-linacs, ii) "realistic" scenario, E_z=600 kV/cm and iii) "optimistic" scenario, E_z=900 kV/cm.

The main results of simulation are summarized in Table 1. Note that 2000 MHz structure has 5 % higher energy gain. It is caused by the larger effective accelerating length of such BAS: 63 mm is the accelerating cell length and 75 mm is period length with f=2000 MHz and 38 mm / 50 mm with f=3000 MHz. But this growth is not sufficient.

The beam envelope can be easily controlled in the regular section, as it is clear from Fig. 4. It was shown that the beam loading effect for 300 pC bunch is not sufficient here: accelerating field amplitude reduction is less than 0.3 % after the first bunch acceleration. Such loading influence can be easily compensated by RF system. The second bunch characteristics are also presented in the Table 1.

The beam loading influence is much more sufficient in case of the drive beam acceleration. The simulation was done for charges equal to 1-3 nC/bunch (for 6 nC it will be done in the future), RF field amplitudes in the regular section decrease is more than 3 % after the 1st bunch acceleration. Such loading must also be compensated by the RF feeding system.

Table1: The Beam Dynamics Simulations Results for One Regular Section, W_{sec} Is The Energy Gain Per Section

E_z, kV/cm	*f*=3000 / 2000 MHz		
	1st bunch		2nd bunch
	K_T, %	W_{sec}, MeV	W_{sec}, MeV
400	98.4 / 98.2	69.9 / 74.2	69.5 / 73.8
600	98.4 / 98.2	104.9 / 111.4	104.4 / 110.9
800	98.4 / 98.3	157.5 / 166.9	156.7 / 166.1

CONCLUSION

As it was shown by the numerical simulations, a 300 nC and 10 ps bunch can be easily accelerated in proposed scheme of the RF photogun. The current transmission coefficient is close to 100 % and the bunch energy spread FWHM is ~±3 % (or ±300 keV) and we can suppose that output energy spread after 10 or 20 regular sections with β_{ph}=1 will not be higher than 0.5-1.0 %. Beam loading effect is not sufficient here. It was shown that the current transmission coefficient will drop rapidly for nC bunch charge (RF-gun with thermionic cathode for example) accelerating structure should be proposed and studied. The first results of the bunch dynamic simulations in the first regular (BAS) section are also presented.

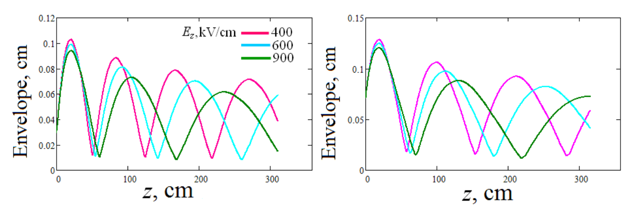

Figure 4: The beam envelope in the first regular section, bunch current is 300 pC and bunch duration is 10 ps, B_{sol} =0.1 T, *f*=3000 (top) and 2000 MHz.

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