BEAM DYNAMICS SIMULATION IN TWO VERSIONS OF NEW PHOTOGUN FOR FCC-EE ELECTRON INJECTOR LINAC

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Abstract

New high-energy frontier project FCC is now under development at CERN. The project includes three modes: ee, hh and eh interactions for FCC. New injection system for FCC-ee is planned to consist of new ~ 2-14 GeV electron linac and electron-positron converter. Injector linac should provide two regimes: ~250 pC bunches for injection and ~6 nC bunches for e-/e+ conversion. Two possible schemes of photogun are comprised and results of beam dynamics simulation in both FCC-ee injection linac photoguns are discussed.

INTRODUCTION

The Conceptual Design Report of new multipurpose collider FCC is now under development [1-3]. New injection system for FCC-ee [4] is now under discussion by FCC collaboration. A number of different injection schemes were proposed: linac (from 2 to 7 GeV) with booster synchrotron, high energy linac (up to 14 GeV) and reacceleration in main collider ring. But the top-up injection scheme into booster synchrotron is preferable. It is obvious that linac should include the first stage (about 2 GeV) before an 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) can differs significantly. It is necessary to have up to $1.65\cdot10^9$ e^-/bunch (~250 pC) for injection mode [1-3] and up to $4\cdot10^{10}$ e^-/bunch (~6 nC) for e^-/e^+ conversion mode; 10 ps bunch duration is the same for both cases. It is also proposed to use ~6 nC bunches both for injection and conversion but such scheme can also require a damping ring for electrons. 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 is interesting and useful because of low beam loading influence compared to the bucket of bunches mode.

Note that 6 nC regime is very complex and very limited number RF-guns were designed for such currents. The general scheme of the new SuperKEKB injector linac [5] could be proposed to use as the base of FCC injector. New SuperKEKB injector includes the photogun to generate comparatively low charged and low emittance bunches and the RF-gun with thermionic cathode for high charged bunches (up to ~5 nC).

Two possible layouts of FCC-ee injection linac are shown in Fig. 1. Let us present results of the beam dynamics simulation for photoguns. The beam dynamics study results in the first version of regular section and RF power requirements will be also briefly discussed.

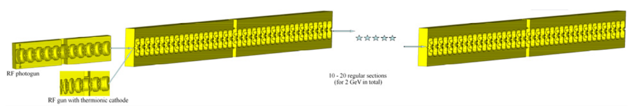

Figure 1: Two possible schemes of the linac layout (RF gun with thermionic cathode is an option for high intensity drive bunches production for e^-/e^+ conversion).

BEAM DYNAMICS IN PHOTOGUNS

The beam dynamics simulation was done both for photogun and regular section using the BEAMDULAC-BL code [6-8]. This code was developed at MEPhI for beam dynamics simulations in RF linacs and transport channels. It has modular structure and a number of routines to solve different tasks: initial particles distribution (uniform, Gauss, KV, waterbag, etc.), motion equation integration (4th 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 BEAMDULAC-BL code version was designed to study the beam dynamics in high-intensity electron linacs, it is discussed in detail in [7] and it was tested for a number of e-linac designs [9-11].

The results of the beam dynamics simulation in the first version of the photogun (called *Photogun_v1*) were discussed in [12]. The main results are the following: a 250-300 nC and 10 ps bunches can be easily accelerated. The current transmission coefficient K_T is close to 100 % and RF field amplitude of E_z=600 kV/cm is quite enough to have W_{out}=10.5 MeV after photogun. Such energy is necessary for effective recapturing by the second section, as it was presented at FCC Meeting 2016. The output bunch energy spread FWHM is $\delta\gamma_{out}$~±3 % (or ±300 keV) here 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: one bunch decreases RF field amplitude less than 0.5 % and such beam loading can be easily compensated by RF feed system. It was shown for 2-6 nC bunches that the current transmission coefficient will drop quickly for high bunch ch arge, as an example it will not be higher than K_T≈60 % for 6 nC bunches (see Fig. 2). Simulations show that high bunch intensities lead to high back currents (it is formed by approximately half of lost particles). 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.

We can conclude that it is necessary to optimize the photogun to decrease the electron's loses. We also need to do more intensive studies. Bunch duration of 10 ps is much higher than relaxation time in metal photocathodes (and may be in semiconductor too) and we can observe an electron depletion for laser exposed volume. Back current influence to beam emission, double layer problems and emission process including possible depletion should be studied in details in future.

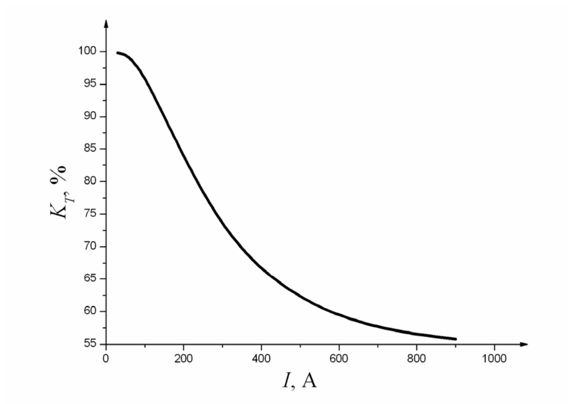

Figure 2: The capturing coefficient vs. bunch peak current for *Photogun_v1*.

After that photogun structure was optimized and current version is *Photogun_v3*. *Photogun-v3* structure and the bunch have the following characteristics: the structure consists of 7 accelerating and 5 coupling cells (the side coupling was used for the 1st and the 2nd accelerating cells), first three cells have the phase velocities of β_{ph}=0.92 (half cell), 0.96, 0.99, last accelerating cell have no coupling one and its length was increased, total section length is ~31 cm, channel aperture radius is 10 mm, coupling cell length is 4 mm, diaphragm thickness is 4 mm, shunt impedance ~80 MOhm/m (f=3000 MHz), solenoid field was varied: B_{sol}=0.05-0.6 T. The simulation was done for bunch charge of 6 nC and bunch duration of 10 ps, the initial transverse emittance is 20 mm·mrad. Normal and Kapchinsky-Vladimirsky (KV) initial phase distribution were studied and the initial energy spread influence was also discussed. The results of the beam dynamics simulations are shown in Table 1 and Fig. 3 for RF fields of E_z=800 kV/cm. It is clear that *Photogun-v3* can provide more effective bunch capturing, but electron's loses of 15-20 % are very high yet. Higher solenoid focusing field give us not only higher capturing coefficient but also the lower energy spread. It should be noted that the phase loses for all simulation variants are close to 15-17 %, other particles loss transversally. For all cases the optimal injection phase δφ is close to 3.4. In the case when δφ =3.0–3.2 the higher energy W_{out}≈12-12.5 MeV is observed, but the energy spectrum FWHM will be more broad and is equal ≈±15-19 %, current transmission coefficient will be the same. For the injection phase δφ=3.5 the energy spectrum is much better ≈±7-8 %, but output energy is W_{out} ≈5 – 5.5 MeV. All results noted above leads to an evident conclusion: beam dynamics of the high-intensity bunch, capturing efficiency and energy spread are defined by the bunch emission process, RF and magnetic field values near cathode and Coulomb effects at the first 2-3 mm of trajectory where electrons are non-relativistic and ultra-relativistic. The electrons losses of 15-20 % are much lower than for previous photogun version (~40 %) but they should be sufficiently neglected because about half of the not-captured electrons form the back-current. We can not assume how the back-current of 600 pC will influences the electron emission but it is clear that it will has a negative influence to the cathode life-time.

Table 1: Beam Dynamics Simulation Results in *Photogun_v3* for 6 nC Bunches, E_z=800 kV/cm, Optimal Injection Phase δφ≈3.4

Injection energy γ_{in} and $\delta\gamma_{in}$	Phase distri-bution	B_{sol}, T	W_{out}, MeV	K_T, %	$\delta\gamma_{out}$ FWHM, %
1.0005 ±0.0005	unif.	0.2	7.37	73.2	±26
1.0005 ±0.0003	unif.	0.2	7.88	74.8	±27
1.0005 ±0.0002	unif.	0.2	8.18	73.7	±18
1.0005 ±0.0001	unif.	0.2	7.76	72.3	±26
1.0005 ±0.0005	KV	0.2	8.01	75.5	±25
1.0005 ±0.0002	unif.	0	6.99	68.7	±23
1.0005 ±0.0002	unif.	0.05	6.75	70.2	±22
1.0005 ±0.0002	unif.	0.1	6.48	72.6	±24
1.0005 ±0.0005	unif.	0.4	8.80	79.2	±15
1.0005 ±0.0002	unif.	0.4	8.60	77.4	±10
1.0005 ±0.0002	unif.	0.6	8.59	80.9	±12
1.0005 ±0.0002	KV	0.6	7.98	84.5	±12
1.0001 ±0.00002	unif.	0.2	8.57	64.6	±21
1.0001 ±0.00002	KV	0.2	9.02	63.8	±12

BEAM DYNAMICS AND RF POWER REQUIREMENTS IN THE REGULAR SECTION

The long (~3 m) high-coupled biperiodic accelerating structure (BAS) was discussed as a start version of the regular section [12]. BAS with two operating frequencies of 2000 and 3000 MHz were studied because the comparison of S-band and L-band structures was stated as one of the FCC CDR tasks. BAS will have 61 accelerating cells and 60 coupling cells (302.5 cm of the

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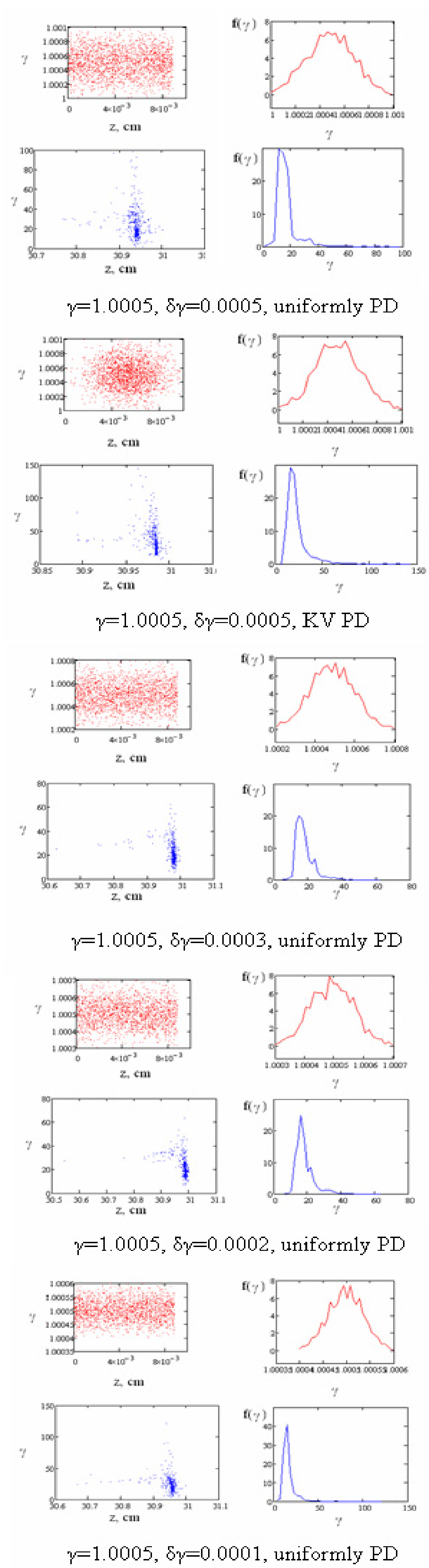

Figure 3: Phase portraits and energy spectrums (initial by red, output by blue) for different initial conditions, E_z=800 kV/cm, the bunch charge 6 nC, uniformly and KV initial phase distributions (PD), B=0.2 T.

total length) at 3000 MHz. BAS operating at 2000 MHz consists of 41 accelerating and 40 coupling cells (305.0 cm). Note that 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. Other types of high-coupled structures (disk-and-washer, modified 2π/3 travelling wave DLW, etc.) should be discussed in future.

The main results of simulation are summarized in [12]. The beam envelope can be easily controlled in the regular section. It was shown that the beam loading effect for 300 pC bunch is not sufficient here: accelerating field amplitude decrease is less than 0.3 % after the first bunch acceleration. Such loading influence can be easily compensated by RF system. The beam loading influence is much more sufficient in case of the drive beam acceleration: RF field amplitude decreases more than 3 % after the 1st 3 nC bunch acceleration.

Three power feed scenarios were discussed: "low-field" scenario with E_z=400 kV/cm which is typical for industrial e-linacs, "realistic" scenario, E_z=600 kV/cm and "optimistic" scenario, E_z=900 kV/cm. Results of RF power requirements analysis are presented in Table 2. It is clear that necessary RF power is two times higher for 2000 MHz structure, but L-band BAS can be further optimized and its shunt impedance can be increased. Clear that a SLED with the boost factor of K_{RF}=4 can be used because of the short current pulse (250 or 500 ns) and low transient time (~200-300 ns which can be realized in a BAS with factor of 10-12 %).

Table 2: RF Power P Requirements for Regular Sections Feed, and a Klystron Power P_{kl} with K_{RF}=4

f, MHz	3000			2000		
E_z, kV/cm	400	600	900	400	600	900
P, MW	61	138	311	99	223	501
P_{kl}, MW	15	35	78	25	56	125

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CONCLUSION

As it was shown by the numerical simulations: 6 nC bunches acceleration using photogun lead to serious problems such as low (<80-85 %) current transmission coefficient and high back-current formation. Energy spread will be also high for 6 nC bunches. It can be proposed to solve such problems by means of a RF-gun with thermionic cathode. Results of the bunch dynamic simulations in the first regular section (BAS) are also presented and RF power requirements are discussed.

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