SIMULATIONS OF ULTRA SHORT SINGLE BUNCH OPERATION ON 150 MEV MICROTRON

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Abstract

Sub-picosecond electron pulses play a substantial role when we are planning to generate femtosecond X-ray pulses by inverse Compton scattering. Racetrack microtron (RTM), the usefulness of which as an injector for small SR ring is quite confirmed by its excellent beam characteristics, is one of the most promising for such the purpose. However, RTM has been kept using on the condition of long pulse mode so far, which meant the machine was operated under the steady state of beam loading. We have investigated for the first time by numerical simulation that the principles of RTM is well conserved even on the condition of short pulse mode, which means RTM is under a transient state of beam loading. Thus a single-pulse electron beam is comfortably accelerated from 4.5 MeV to 150 MeV.

1 INTRODUCTION

High quality X-ray beam of the pico- to femtosecond pulse width is an indispensable tool for the investigation of various phenomena in the same time scale. Inverse Compton Scattering between electrons and laser beams is considered to be the most promising to generate such the excellent X-ray pulses [1,2]. For such the purpose, it is inevitable to produce ultra-short pulses for both laser and electron beams. One candidate to obtain such the ultra-short electron pulses is RTM by reason of its outstanding beam characteristics, that is, low emittance of the order of 0.1• mm·mrad and small energy spread of 0.1%, in the case of our 150 MeV RTM [3,4]. Its compactness is also an essential point to carry out those experiment.

The design of RTM has been established after long-range excellent performance as the injectors of compact SR rings, AURORA-1 and -2 [5]. The already-existing design is, however, optimized for the output beam having medium pulse length at about a few microseconds and relatively low peak current, 10 mA at the maximum. This means that we have been using RTM not under the transient state but under the steady state of beam loading.

When we adopt new technology of RF gun with photo cathode [6,7] in the injection system of conventional RTM as shown in Fig. 1, sub-picosecond electron pulses will be extracted as an output beam with no other sophisticated technologies such as the bunch compressing magnets. We need to investigate the behaviors of beam on the condition of transient beam loading when considering the acceleration of a single bunch, the period of which is shorter than the filling time of accelerating cavity. We first simulated a single-bunched electron beam how it could preserve the synchronous condition required from the principles of RTM. The effects of space charge and coherent synchrotron radiation while acceleration would next be taken into account.

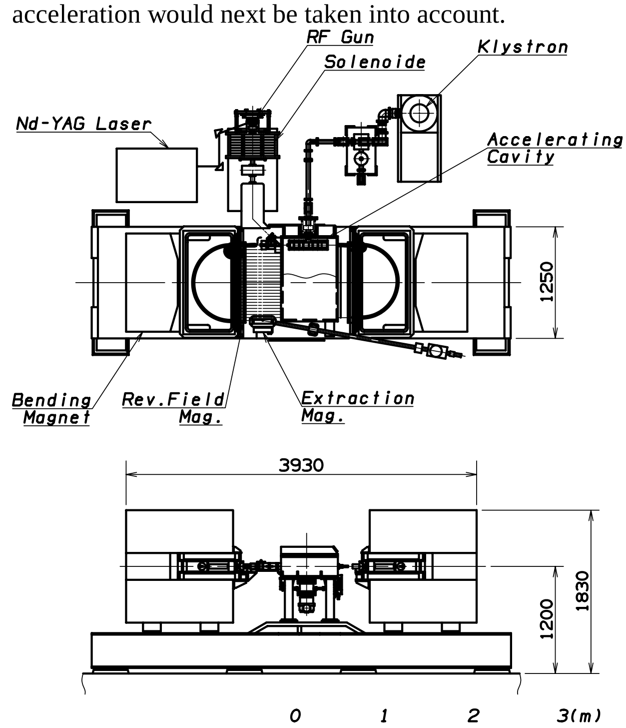

Figure 1: Top view of 150-MeV RTM with RF gun in injection system.

2 RTM WITH RF GUN

As seen in Fig. 1, major components of RTM are two 180 degree bending magnets placed on both end-sides with reverse field one in front of each, one S-band accelerating cavity of 0.5-m long placed on the mid-portion of the first orbit near the injection point, and the new 4.5-MeV injection system adopting an RF gun with photo cathode. Except the new injection scheme, other sub-systems are precisely the same as the normal 150-MeV RTM.

The principal parameters of RF gun are presented in Table 1. The gun is originally designed in BNL [6] and modified for high repetition rate up to 50 Hz by

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BNL/KEK/Sumitomo's collaboration [7]. The gun has 1.6 cell S-band cavity and can extract 4.5 MeV electrons

RF Gun		
Injection Energy	4.5	MeV
Charge / Pulse	1	nC
(Laser Power / Pulse)	(200	μJ)
Pulse Length (Nominal)	3	psec
(Laser Pulse)	(10	psec)
Max. Repetition Rate	50	Hz
Emittance	<5π	μm.rad
(Type of Laser)	(Nd -	YAG)
150 MeV RTM		
Circulating No.	26	laps
Energy gain	6.0	MeV/lap
Bending Field	1.23	Tesla
Field Gradient	0.14	Tesla/m
Reverse Field	0.3	Tesla
RF Frequency	2856	MHz
Accelerating Gradient	15	MV/m
No. of Accelerating Cell	7 full + half 2	cells

Table 1: Parameters of RF Gun and 150 MeV RTM

at the maximum. According to the BNL measurements, the gun can produce more than 1 nC charge in a bunch within a few μm.rad emittance. We assumed the bunch specifications for the simulation, therefore, that the emittance is 5π μm.rad, the charge 1nC/bunch and the pulse length 3 psec.

The nominal accelerating rate is stayed to 6 MeV /lap, the same as the normal RTM, notwithstanding the far less energy gain at the first lap. After first acceleration, however, the orbits from the 2nd to final laps are un-changed for the convenience of applying the present hardware. While circulating RTM, vertical focusing is generated by the field gradient of bending magnets and horizontal focusing by the only quadrupole placed near the accelerating cavity. Main parameters of RTM are also listed in Table 1. Because the bunch shape rotates in the phase space (E, ϕ) while acceleration, its length varies depending on the lap number. Thus we adopted the lap number 26, increased one from the former RTM's 25, which seemed the best compressed bunch in this calculation as described in the following.

3 SIMULATION RESULTS

In principle, the method of simulation is about the same as used in the calculation of normal RTM operated under the steady state of beam loading. It means the electric field in the accelerating cavity is always regarded as constant and independent of the amount of beam loading. On the other hand, when trying single-bunch acceleration, one must take into account a variable accelerating field depending on the transient beam loading. It takes only ~0.5 μsec for the single-bunch acceleration by 26 laps in RTM which is shorter than the filling time of accelerating cavity. This means the loss of stored energy taken away by the beam is not refilled enough while accelerating a single bunch. The amount of stored energy spent for the beam acceleration is equivalent to the beam loading. The accelerating electric field in the cavity should be decreasing in accordance with the increasing of lap number. The number of electrons per bunch is, therefore, essential in this kind of simulation.

The simulation code was modified to treat the time-dependent acceleration field, where SUPERFISH was used to obtain the field distribution in the cavity. The stored energy before and after the single-bunch acceleration was roughly estimated. Originally, there is about 2 joules of stored energy in the accelerating cavity which consists of 7-full and 2-half cells of side coupled type. On the contrary, a single bunch of 1nC needs 0.15 joule when accelerated to 150 MeV. About 7.5 % of the stored energy is, thus, taken away by the beam which enforces 3.8 % decline of electric field upon the cavity when no refill of RF power is assumed.

Initial x-, y-emittances, about a few μm.rad of rms-εx, -εy was used in this calculation, are shown in Fig. 2. These emittances are slightly larger than the value of RF gun reported from BNL [6], but much smaller than that of the normal RTM. We used this value to check the acceptance of RTM, and found the fact that the vertically focused beam was desirable for the injection (Fig. 2).

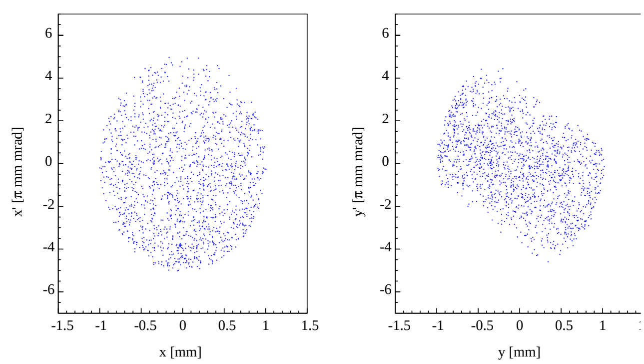

Figure 2: Initial emittance of input beam from RF gun.

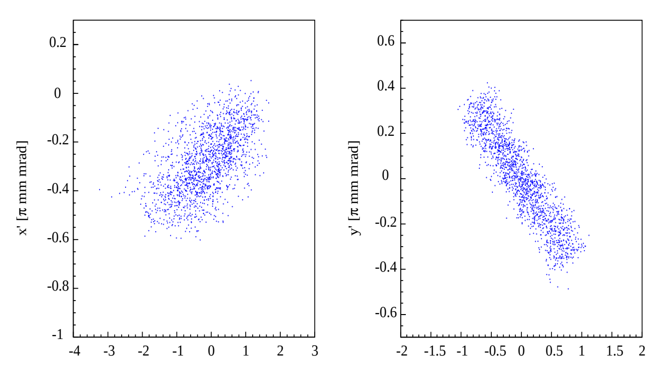

Figure 3: Final emittance of output beam from RTM.

When phase spread of the input beam is limited to 3º, almost no beam loss occurred while circulating in RTM.

The emittances after the acceleration are shown in Fig. 3, where rms-εx, -εy are 0.16 and 0.04π μm.rad, respectively. The horizontal emittance looks always larger than the vertical's because of the horizontal beam spread derived from dispersion ηx. These values are close to the measured emittances of the normal RTM, 0.11 for εx and 0.07π μm.rad for εy [4].

The distribution in (E, ϕ) phase space of accelerated electrons within a bunch are shown in Fig. 4 (right), together with the histogram of energy distribution (left). From the figure, the beam energy after 26 laps of acceleration is read as 156.6 MeV and energy spread •E/E as ± 0.064 %. This is quite the same as the measured •E/E, ± 0.06 %, of the normal RTM.

The phase distribution is much more clearly shown in Fig. 5, where the initial and final distributions are compared. The initial phase spread is nominally assumed as 3º, however, its width seems actually 2.5º at FWHM. On the contrary, the phase spread is compressed to 1.3 ± 0.06º after the acceleration, about a half of the initial spread in the result. It is equivalent to 1.3 psec pulse width in the time scale and 0.4 mm pulse length.

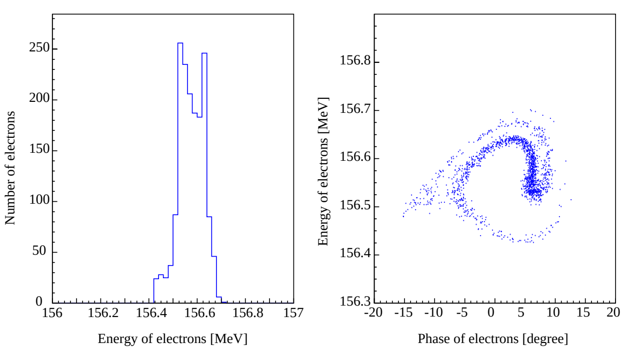

Figure 4: Energy spectrum and (E, ϕ) distribution of accelerated beam.

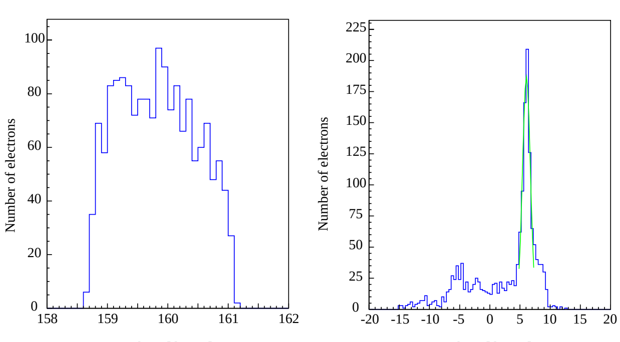

Figure 5:Comparison of initial and final bunch lengths using phase spreads.

In Fig. 4 (right), we see the core portion of the bunch, where a crowd of electrons gather together, lies perpendicular to the horizontal (= phase) axis and parallel to the vertical (= energy) axis. As the electrons rotate in (E, ϕ) phase space, the acceleration to 156 MeV by 26 laps seems one of the optimized case to make a bunch as short as possible, on the sacrifice of energy spread. It means the energy spread, ± 0.06 % of ΔE/E in this case, should be at about the maximum and we will be able to reduce •E/E significantly by selecting a suitable lap number. One simulation shows, for instance, that smaller energy spread, about ± 0.02 % of •E/E, is available when stopped acceleration at 12 laps where the beam energy comes to 73.7 MeV.

These simulations were performed under the assumption that the design of existing normal RTM was applied, except for the injection system. The plan to accelerate a single bunch extracted from the RF gun is in progress directed by Kansai Research Establishment, JAERI.

4 CONCLUSION

It has been proved by numerical simulations that the acceleration of ultra-short single-bunch electron beam emitted from a photo cathode in RF gun at 4.5 MeV was achieved in safety. Assuming 1 nC charge in a bunch of a few picosecond, the existing RTM can accelerate this single bunch to 150 MeV or more, by the time duration ~0.5 μsec. There are no significant differences in the value of emittances, bunch length and energy spread between the normal output pulses (a few μsec) and a short one (a few psec), which means the excellent beam qualities are preserved in both the cases. More precise calculations including coherent radiation and space charge effects are planned in the next stage.

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