BEAM DYNAMICS ANALYSIS OF AN ELECTRON MICROTRON USING GENERAL PARTICLE TRACER*

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Abstract

Electron microtrons are extensively employed as injectors for tabletop light source facilities. In this paper, a 5 MeV electron microtron is designed, and an external injection scheme is adopted to achieve a large stable longitudinal phase region. We investigated the beam dynamics of this microtron using General Particle Tracer (GPT). After optimization, the width of stable longitudinal phase region is approximately 40°, which is about four times larger than that of conventional internal-injection microtrons.

INTRODUCTION

The concept of resonant acceleration of relativistic charged particles was first proposed by V. I. Veksler in 1944, which led to the development of two major classes of circular accelerators: synchrotrons and microtrons [1]. While synchrotrons employ time-varying magnetic fields to maintain a constant orbit radius during acceleration, classical microtrons operate in a uniform, time-invariant magnetic field, where particles gain a fixed amount of energy each time they traverse a radio-frequency (RF) accelerating cavity.

In a classical microtron, the resonance condition ensures that electrons return to the RF cavity with a constant phase after each revolution, forming a sequence of circular equilibrium orbits with increasing radii [2]. This resonant mechanism enables stable multi-turn acceleration and the generation of electron beams with relatively small energy spread [3]. Owing to their compact structure and reliable operation, classical microtrons have been widely used in scientific research, industrial irradiation, and medical applications, and are particularly suitable as injectors for synchrotron and free-electron laser facilities [4, 5].

According to the injection scheme, classical microtrons can be divided into internal-injection and external-injection configurations. In internal-injection microtrons, electrons are emitted directly within the accelerating cavity and captured into the synchronous acceleration process from the first turn. Although this configuration enables a compact design, the longitudinal capture process is strongly constrained by the RF phase at emission, resulting in a narrow stable phase region and limited capture efficiency [6, 7].

In contrast, external-injection microtrons employ an independent electron gun to generate and pre-accelerate the beam before injection into the microtron cavity. This scheme allows more flexible matching of longitudinal and transverse beam parameters and provides the potential to enlarge the stable longitudinal phase region, thereby improving capture efficiency and operational stability.

Motivated by the demand for compact and reliable injectors for tabletop light source facilities, this work presents the design and beam dynamics analysis of a 5 MeV external-injection classical electron microtron. The beam dynamics of the proposed microtron are investigated using the GPT code [8]. By optimizing the injection parameters and RF phase, a stable longitudinal phase region with a width of approximately 40° is achieved. In the present work, the study mainly focuses on the longitudinal beam dynamics and phase acceptance characteristics of the proposed microtron scheme.

BEAM DYNAMICS SIMULATION

Resonance Conditions

Let the total energy and rest mass energy of an electron in the microtron be U and $U_0 = m_0c^2$, respectively. The corresponding Lorentz factor is defined as $\gamma = U/U_0$. In a uniform magnetic field B, relativistic electrons follow circular orbits with an orbital period given by [3]:

$$T = \frac{2\pi\gamma m_0}{eB} = \frac{2\pi U}{eBc^2}. \tag{1}$$

Each time the electron passes through the RF cavity, it gains an energy increment:

$$\Delta U = eV_{\text{acc}} \cos\phi_s, \tag{2}$$

where V_{acc} is the effective accelerating voltage and ϕ_s is the synchronous phase.

As the electron energy increases turn by turn, the increase in the orbital period must remain synchronized with the RF field. The resonance condition of a classical microtron requires that the period difference between successive orbits equals an integer multiple of the RF period T_{rf}:

$$\Delta T = T_{n+1} - T_n = \frac{2\pi\Delta U}{eBc^2} = nT_{\text{rf}}, \tag{3}$$

where n is the harmonic number.

Under this synchronization condition, the total energy of the electron at the n-th orbit increases linearly and can be written as:

$$U_n = n\Delta U + U_0. \tag{4}$$

* Work supported by the National Natural Science Foundation of China (No. 12405173) and the Anhui Provincial Natural Science Foundation (No. 2508085QA013, Youth Project, Category C)
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Table 1: Main Parameters

Parameter	Value
Injection kinetic energy	24.5 keV ($\beta \approx 0.3$)
RF frequency	2856 MHz
Magnetic field	0.104 T
Synchronous phase ϕ_s	16°
Harmonic number n	1
Number of turns	9
Final energy	5.2 MeV

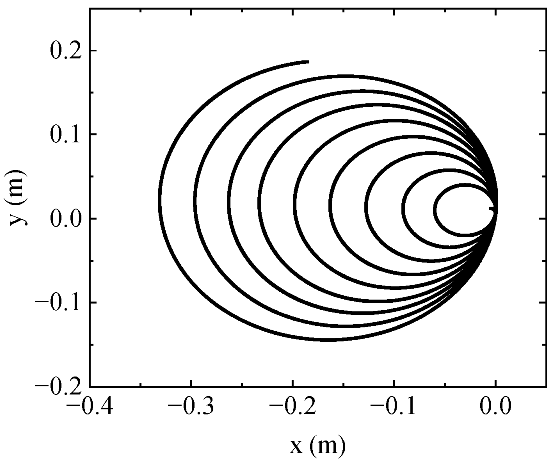

Figure 1: Particle trajectory.

Based on the synchronization conditions derived from the analytical relations, single-particle tracking simulations were performed to verify that the selected magnetic field, RF parameters, and synchronous phase satisfy these conditions. The main design parameters adopted in this study are summarized in Table 1.

Figure 1 shows the trajectory of an electron launched at the synchronous phase. Under the uniform magnetic field provided by the main dipole magnet, the electron follows a sequence of circular orbits with progressively increasing radii and returns to the RF cavity region on every turn. The overlap of successive orbits at the cavity location confirms that the revolution period of the electron remains synchronized with the RF field, demonstrating that the designed magnetic field and RF parameters fulfill the resonance condition of the classical microtron.

The evolution of the particle energy as a function of time is shown in Fig. 2. The electron energy exhibits a characteristic stepwise increase, reflecting the discrete energy gain obtained at each cavity passage. With the chosen synchronous phase and magnetic field strength, the particle completes nine stable turns and reaches a final energy of approximately 5.2 MeV. These results confirm that stable resonant acceleration is achieved at the single-particle level, providing a reliable basis for the subsequent phase acceptance and beam dynamics studies.

Phase Acceptance

After stable resonant acceleration of the synchronous particle was confirmed, the longitudinal phase acceptance was

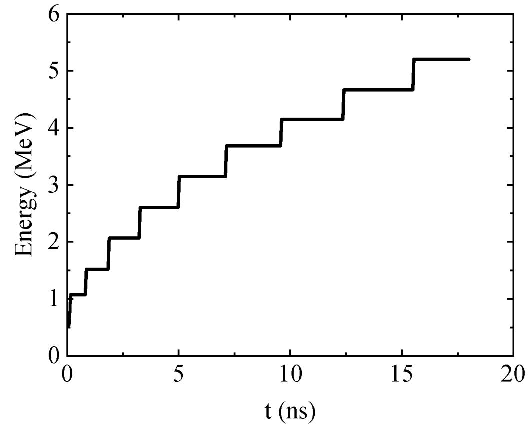

Figure 2: Particle energy gain.

systematically investigated by scanning the initial RF phase. The initial phase was varied from 0° to 360° with a step size of 0.1°. For each phase value, a single test particle was launched with identical initial energy. Space charge effects were neglected in this analysis.

A particle was defined as surviving if its trajectory and energy gain satisfied the conditions described in the preceding sections. The resulting phase-survival distribution is shown in Fig. 3. A continuous stable phase region is clearly observed near the synchronous phase, with a total width of approximately 42°, exceeding 40°. This enlarged phase acceptance is mainly attributed to the decoupling of the injection process from the RF cavity, which allows more flexible phase matching compared with internal-injection schemes.

It should be noted that the scanned phase represents a relative phase parameter used for particle initialization, rather than the absolute RF phase. Therefore, the phase values shown do not directly correspond to the physical RF phase, but indicate the existence and extent of the stable phase region.

This stable phase region is significantly wider than the typical longitudinal acceptance of about 10° reported for conventional internal-injection microtrons [9], demonstrating the clear advantage of the external-injection scheme in enhancing longitudinal capture efficiency and relaxing the RF phase requirements at injection.

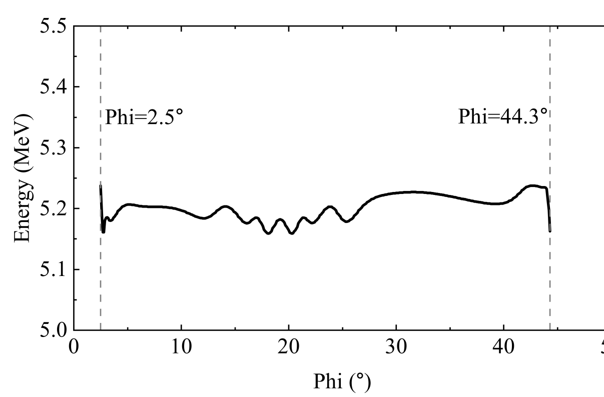

Figure 3: Longitudinal phase acceptance.

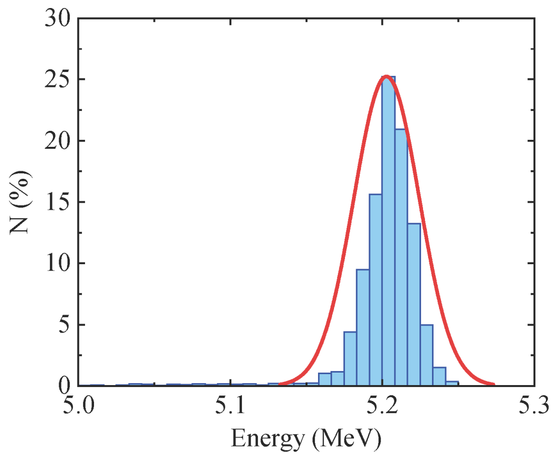

Figure 4: Particle energy spectrum.

Multi-Particle Beam Dynamics

Based on the identified stable longitudinal phase region, multi-particle tracking simulations were carried out to evaluate the collective beam dynamics and final energy spectrum. The initial beam was generated with a longitudinal phase width of 40°, corresponding to the stable phase acceptance, and a uniform transverse distribution within a radius of 2 mm. Space charge (SC) effects were included in this simulation. The simulations were performed using 10000 macro-particles with a total bunch charge of 500 pC. The inclusion of SC effects introduces a slight broadening of the energy distribution, but does not significantly affect the overall beam quality.

The particles were tracked through the full acceleration process, and approximately 40.88% of the injected particles successfully completed all acceleration turns and survived. The final energy spectrum of the surviving particles is shown in Fig. 4. The mean beam energy is 5.2 MeV with an rms energy spread of 21.6 keV, corresponding to a relative rms energy spread of approximately 0.4%. The energy distribution exhibits an approximately Gaussian profile, indicating that the beam energy quality is preserved even with a relatively large longitudinal phase acceptance.

These results demonstrate that the proposed external-injection microtron combines a significantly enlarged longitudinal phase acceptance with favorable beam quality, confirming its suitability as a compact injector for tabletop light source applications.

CONCLUSION

In this work, a 5-MeV classical electron microtron employing an external-injection scheme has been designed and systematically analyzed. Single-particle dynamics simulations verify that the selected magnetic field, RF parameters, and synchronous phase satisfy the resonance and synchronization conditions required for stable multi-turn acceleration. The longitudinal phase acceptance is subsequently evaluated through phase-scanning simulations, demonstrating a stable longitudinal phase region of approximately 40°, which is approximately four times wider than that typically achieved in conventional internal-injection microtrons. Multi-particle simulations including space-charge effects further show that the accelerated beam maintains a near-Gaussian energy distribution with limited distortion.

These results confirm that the external-injection scheme significantly enhances the longitudinal capture capability and relaxes the requirements on injection phase control, making the proposed microtron a promising injector for compact tabletop light source applications. Future studies will include detailed transverse beam dynamics optimization and more realistic electromagnetic field modeling.

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