BEAM DYNAMICS IN A CW MICROTRON FOR INDUSTRIAL APPLICATIONS

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Abstract

The CW microtron with a 500 MHz RF cavity is proposed for industrial applications. The machine is a racetrack type. The acceleration energy and the beam power are up to 16 MeV, and several tens of kW, respectively. The bending magnets are divided into two subsections to adjust the acceleration phases of all turns. A beam tracking study of a 5 MeV microtron shows that the longitudinal phase stable region is about 30^o and the energy dispersion is about ± 2.2 %. The transverse stability can be obtained using a simple focusing system.

1 INTRODUCTION

High power electron beams are necessary for industrial application: X-rays irradiation, electron irradiation, and defect analysis in semiconductors with a slow positron beam. Required beam energies are about 5 MeV, 10 MeV, and more than 15 MeV, respectively [1]. The beam power is several tens of kW. Development of accelerators operated in a continuous wave (CW) mode is of considerable practical interest for the industrial applications [2][3] because the accelerators require compactness, low cost, and, stable operation.

The CW microtron with a 500 MHz normalconducting RF cavity is proposed to apply for these fields. The essential interests are compactness and low electrical efficiency. A new shaped bending magnet is proposed to adjust beam orbit length of each turn, and appropriate acceleration phases can be selected when an electron beam passes the RF cavity. This paper describes results of the beam dynamics design. Attention will be paid mainly to effects of RF fields on a low energy electron beam. The studies were mainly done with the parameters of the 5 MeV CW microtron.

2 CW MICROTRON

Figure 1 shows a schematic drawing of a 5 MeV CW microtron. An 80 keV electron beam is injected with a chicane magnet from an injection line. In order to match an accelerating RF frequency, the electron gun is pulsed at the RF frequency. There are two solenoid magnets at the injection line for a transverse beam focusing. The RF cavity is a conventional multi-cell cavity with inductive coupling slots, which is frequently used for an electron storage ring. The frequency is selected around 500 MHz that is determined by a capable input power of the RF cavity and the total size of the microtron.

The electron beam after passing the RF cavity for the first time cannot pass by outside the RF cavity after the first bending magnet. Therefore, an inverse-bending magnet (BM3) is situated near the bending magnet. The electron beam crosses the RF cavity for the second time in the inverse direction of the first crossing. A transverse beam focusing is obtained with only edge effects of the bending magnets and QFs near the RF cavity.

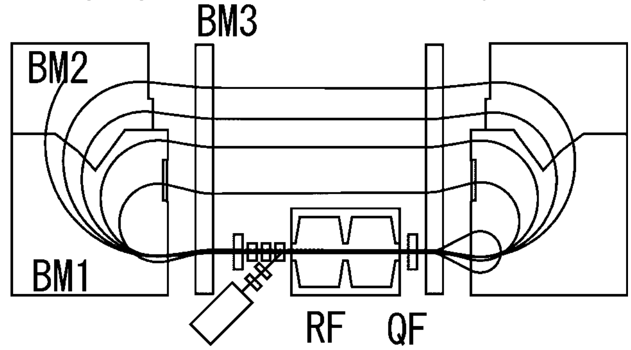

Figure 1: A schematic drawing of a 5 MeV CW microtron.

Table 1: Basic parameters of CW microtrons.

Energy (MeV)	5	10	16
Application	X-rays irradiation	Electron irradiation	Slow positron
Beam Current (mA)	6	9	5.6
The number of RF cells	2	4	4
The number of turns	6	6	8
Wall loss of an RF cavity (kW): ()* rough estimation	40	(90)*	(130)*
Footprint (m×m)	3.5× 1.4	4.2× 1.4	(4.5× 2.1)*

The fixed relation among the magnetic field, the RF frequency, and amplitude of the acceleration electric field is needed for synchronous acceleration in the microtron. As for the proposed microtron, the electron velocity, however, changes with every turn, and the energy gain of each turn changes. The RF acceleration phase slip becomes large, when a conventional bending magnet is used. Therefore, I propose the new shaped bending magnet to adjust beam orbit length of each turn. The bending magnet is divided into two subsections described as BM1 and BM2 in the Fig. 1. The two magnets have different magnetic fields, and a bending angle of each turn is adjusted so that beam orbit length of each turn is appropriate for the acceleration. The parameters are optimised with a computer optimisation program so that an electron beam with the widest acceleration phase can be accelerated. Basic parameters of the CW microtrons are shown in Table 1. The wall loss of the RF cavity is estimated with the SUPERFISH. The wall loss in the Tab. 1 is considered as 88 % of the calculated one.

3 BEAM SIMULATION STUDIES

3.1 Simulation method

The studies were done with a beam tracking. An electron orbit was calculated with a numerical integration of exact equations of motion at the RF cavity section. A 3-D RF electromagnetic distribution was calculated with the SUPERFISH, and took into the equation of motion with a three-dimensional spline interpolation. A conventional linear matrix method was used at the magnet sections. An effect of fringing fields of the bending magnets was approximately considered with the Enge's formula.

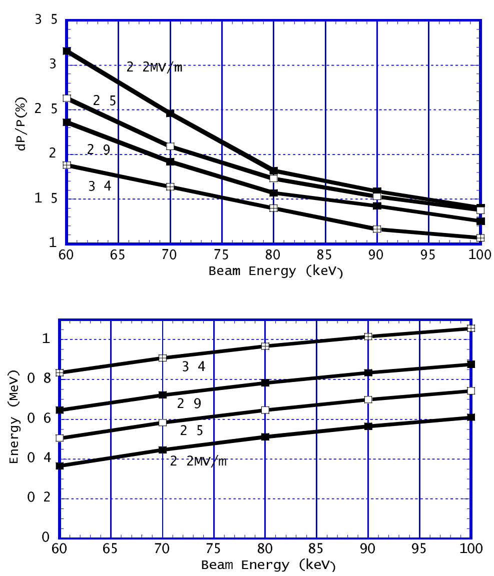

Figure 2: Energy dispersion (upper) and energy gain (lower) after the RF cavity (first turn) as functions of injection beam energy and RF electric field strength (MV/m).

3.2 Effects of a low energy injection

A low RF electric field strength makes a low energy gain and large energy dispersion of a low energy electron beam, when the electron beam crosses the RF cavity. The reason is that the velocity is much slower than velocity of light, and the acceleration phase slip is large. Figure 2 shows energy dispersion and energy gain as a function of the injection energy when the electron beam passes the RF cavity for the first time. An acceleration phase width of the injection beam is 30°. An energy acceptance of the microtron is about 2 %. An injection energy and an RF electric field strength were selected as 80 keV and 2.5MV/m, respectively.

Figure 3 shows horizontal beam orbits, when the beam crosses the RF cavity for the first time. Five electrons were simulated at the same initial position, whose initial acceleration phases are different every 10°. Figure 4 shows horizontal beam orbits on an actual initial beam condition: The initial acceleration phases are -275° (left) and -290 ° (right), respectively. The initial acceleration phase difference produces a difference of transverse beam focusing significantly. Figure 5(a) shows beam energy along the beam axis. The electron beam decelerates at first, and then accelerates. Figure 5 (b) shows horizontal phase space at the exit of the RF cavity. Initial acceleration phases are -260°, -275°, and -290°, and twiss parameter at the entrance of the RF cavity is α=0, β=2. The figure shows that the electromagnetic RF focusing force is thought to be a linear focusing force at the same acceleration phase.

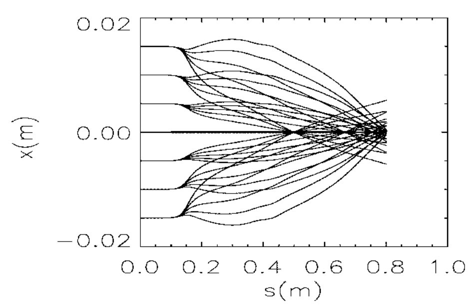

Figure 3: Beam orbits in the RF cavity. Initial RF phases are from -255° to -295°.

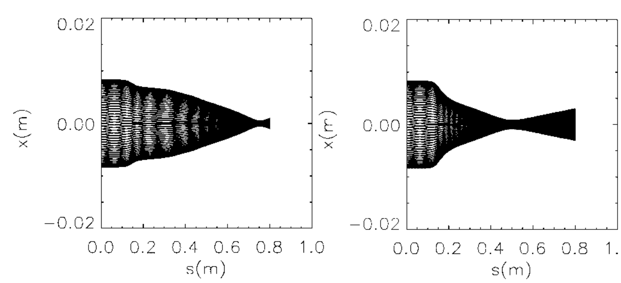

Figure 4: Beam orbits on an actual beam condition. Initial RF phases are -275° (left), and -290° (right).

(a) (b)

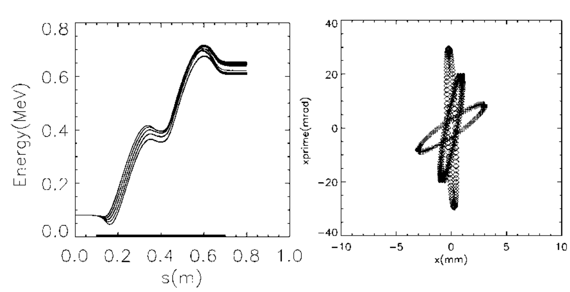

Figure 5: Beam energy along the beam axis (a), and horizontal phase space at the exit of the RF cavity (b).

3.3 Space charge effect

The injection energy is several tens of keV, and space charge effect is thought to be large when a high intensity beam is accelerated. The effect was simulated with a beam tracking. An incoherent space charge effect is approximately considered as effective quadrupole gradients. The tracking was done from an exit of the electron gun to an entrance of the RF cavity. Figure 6 shows horizontal beam emittances at the RF cavity as a function of an average beam current. The emittances were calculated from phase space distributions of 5000 particles. The space charge effect is negligible when an average beam current is around 10 mA, and electron beam energy is 80 keV.

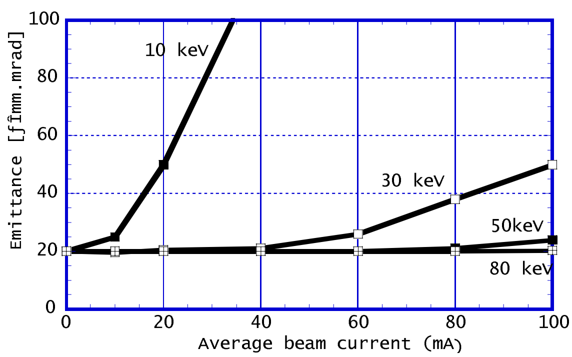

Figure 6: Horizontal beam emittances as a function of an average beam current. Initial beam conditions are $\varepsilon_x = \varepsilon_y = 20\pi mm.mrad$, $\beta_x = \beta_y = 0.023$, and $\alpha x = \alpha y = 0$.

3.4 Transverse beam stability

A beam tracking from the exit of the electron gun to the exit of the microtron was done. Figure 7 shows beam envelopes of the CW microtron along the beam axis. The acceleration phases are –275° (upper) and –290° (lower). The figures show that the transverse stability can be obtained, and the initial acceleration phase has significantly influence on the beam envelope. Figure 8 shows horizontal and vertical phase spaces of 10000 particles at the exit of the CW microtron. Initial acceleration phase width is 30°. The electron beam can be accelerated with practicable beam sizes. The shapes of phase spaces are much different from conventional elliptical shapes. Energy dispersion at the exit of the microtron was calculated to be 2.2 %.

4 SUMMARY

The CW microtron with the 500 MHz RF cavity is proposed and is proved to be practicable. Space charge effect and capable input power of the RF cavity do not restrict the beam current. Therefore, capable beam current is restricted only by the beam quality of the electron gun.

5 ACKNOWLEDGEMENTS

The author would like to thank Drs. S. Nakamura, T. Nakanishi, and many members of our company for helpful discussions.

REFERENCES

[1] H. Tanaka, "Design of CW Microtrons using a 500 MHz RF Cavity for Industrial Application", Proceedings of the 12th Symposium on Accelerator Science and Technology, 107, 1999.
[2] J. Pottier, "A new type of RF electron accelerator: the rhodotron", NIM B 40/41, 943, 1989.
[3]H. Kwon, et al., "Conceptual Design of 10 MeV, 100 kW CW Electron Accelerator for Industrial Application", PAC '1999, 2558, 1999.

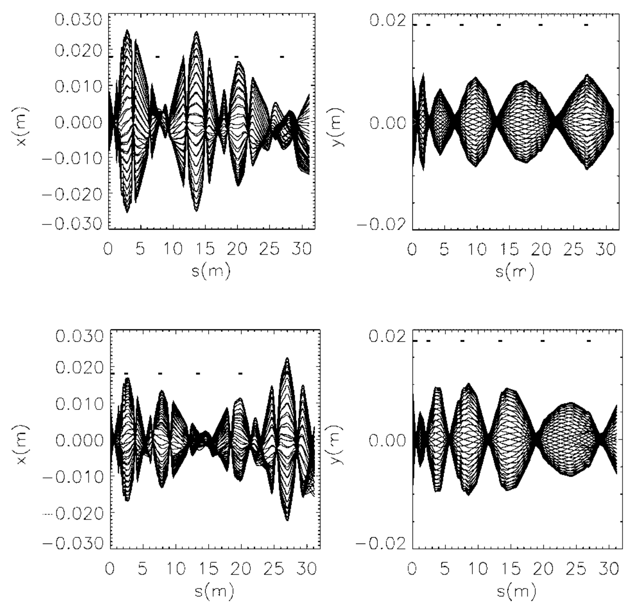

Figure 7: Beam envelopes in the horizontal and vertical coordinates. The initial acceleration phases are -275° (upper) and -290° (lower).

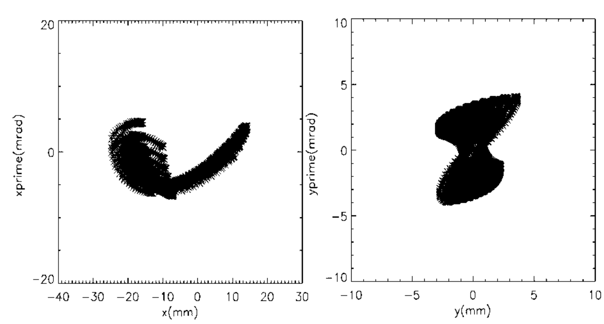

Figure 8: Phase spaces at the exit of the CW microtron in the horizontal (left) and vertical (right) planes. The initial acceleration phases are from -260° to -290°.