Project of CW Race-Track Microtron-Recuperator for Free-Electron Lasers

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Abstract—**The project for a race-track microtron—the beam source for a FEL—is considered. The beam, utilized in a FEL, returns to a microtron where it decelerates and releases its energy to an RF system. The design energy of electrons is 35 MeV and the average current ranges from 0.1 to 1 A.**

THE research being conducted at the Institute of Nuclear Physics, Novosibirsk, on the creation of a race-track continuous microtron-recuperator at 35 MeV electron energy, is intended to be employed in a free-electron laser (FEL). Utilized in the FEL, the beam will liberate its energy to the RF microtron system when, being decelerated, it passes along the same microtron orbits in inverse sequence. The layout of the microtron is depicted in Fig. 1. Its overall dimensions are limited by a room where the microtron is to be accommodated. The microtron comprises an injector (1), two magnetic systems of a 180° separating bend (2), a common straight section with RF cavities (3) (the section is common to electrons of different energy), magnets for the injection (4) and extraction systems (5), and solenoidal magnetic lenses (6), four separated straight sections with magnetic quadrupole lenses (7), a FEL magnetic system (8) placed in the fourth straight section, and a beam dump (9).

A 300 kV electron gun of the injector (see Fig. 1, 1.1) generates 1 ns electron bunches at a repetition frequency of 45 MHz. The first RF cavity is identical with all RF cavities of the machine. It is used not only for acceleration but generally for electrons energy (and velocity) modulation. Then the modulated electron bunch is longitudinally compressed in the bunching straight section (1.2) down to 150 ps. Two RF cavities with 1.6 MV amplitude of energy gain accelerate electron beam up to the final 2.1 MeV injection energy. The equilibrium phase in those cavities is $\varphi_o = 29°$. The electrons are injected into the common straight section of the microtron using a 180° magnetic mirror and two identical 65° bending rectangular magnets opposite in sign (4). This magnetic system of 180° bend is achromatic, and its horizontal and vertical optical matrices are mutually coincident and look like the matrix of the empty straight section.

The working-voltage amplitude of RF cavities in the common straight section of the microtron is 800 kV for one cavity and, hence, 9.6 MV for 12 cavities, with the transit time factor taken into account. These RF cavities are half the wavelength, $\lambda = 165$ cm, distant from each other, which corresponds to their resonance frequency $f = 180$ MHz.

A separating 180° bend (2) for the first three tracks of the microtron is completely similar to the magnetic injection system considered above, i.e., this is a 180° magnetic mirror with two 65° bending magnets on each track. Variation in the orbit length in going to the next microtron track is one wavelength of its RF system. The choice of this type of bend and its achromaticity are due to the necessity for the beam to pass round RF cavities of the common straight section, the necessity to reduce the horizontal beam size, and to simplify the matching of β functions on three isolated straight sections where there are quadrupole lenses (7).

The fourth straight section is intended for the FEL magnetic system (8). To lengthen it, a 180° achromatic bend on the fourth track comprises two 90° bends. The distance between 90° magnets are such that the length of the fourth track differs from the length of the third track by about 2.5 of the wavelength of the microtron RF voltage. At the exit from the FEL magnetic system there are two RF cavities to compensate for the average losses in electron energy in the FEL.

The RF cavities and a detector of horizontal beam displacement, installed behind a 90° bending magnet stabilizes the electron energy at the exit of the fourth straight section. Entering again the common straight section from the fourth track, but now in the decelerating phase of RF voltage, the electrons release their energy to the RF system during the passage in the same direction through the same three microtron tracks. Emphasis should be made that in this case their sequence is inverse. After that the electrons are extracted using the magnets of the extraction system (5) (identical to the magnets of the injection system) and are directed to the beam dump (9).

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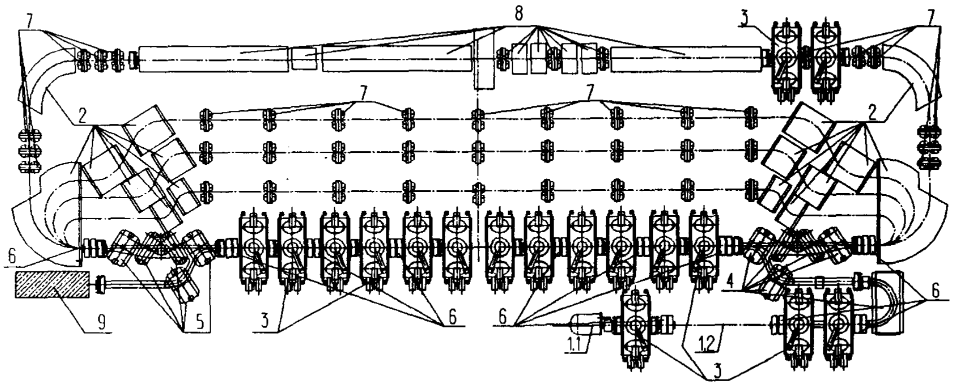

Fig. 1. The general layout of the race-track microtron-recuperator: 1-injector, 1.1-electron gun of the injector, 1.2-bunching straight section, 2-magnetic system of a 180° separating bend, 3-RF cavities, 4-magnets of the injection system, 5-magnets of the extraction system, 6-solenoidal magnetic lenses, 7-quadrupole magnetic lenses, 8-magnetic system of the FEL, 9-beam dump.

To provide the proper focusing of both the accelerated and the decelerated electrons, the magnetic system (except for the fourth track) is mirror-symmetrical relative to the line going through the center of the straight sections. Here the matched β functions are of the same symmetry.

To minimize the length of the electron bunch (maximum peak electron current) in the FEL magnetic system, the longitudinal phase motion of the beam in the microtron was optimized by means of small variations in the values of the equilibrium electron energy on each track (and, correspondingly, the microtron geometry). The equilibrium phases of four passages through the RF system are $\varphi_1 = 21.9°$, $\varphi_2 = 34.6°$, $\varphi_3 = 47.6°$, and $\varphi_4 = 1.6°$. Fig. 2 illustrates the longitudinal phase-energy diagram of the position of the electron bunch on four separated straight sections. The maximum relative spread of the electron energy on the fourth track is $\pm 0.5\%$. The diagram also shows that after the fourth passage through the RF system the second order aberration of the longitudinal focusing is absent. Estimated bunch length on the fourth track is 5.5 ps.

The lengths of the straight sections of the microtron are such that with the injection of electron bunches, in each four periods of its RF voltage (i.e., at 45 MHz frequency), on the common track the accelerated and decelerated bunches are uniformly distributed in the longitudinal direction (i.e., with respect to the time of the passage through cavities) with about an 0.8 m interval. In this case, a mutual influence of the accelerated and decelerated beams at different electron energies is drastically decreased.

Calculations of the longitudinal and transverse beam dynamics show that the microtron-recuperator can operate in a steady mode at an average current higher than 0.1 A. Here the final bunching of electrons occurs only on the last track, thereby contributing to obtaining a high (about 100 A) peak current and small transverse emittances of the beam being conserved.

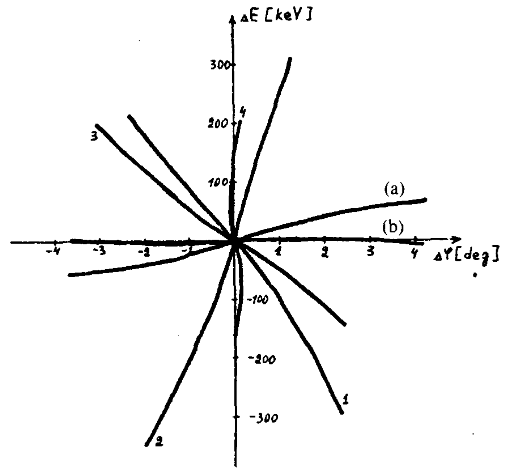

Fig. 2. The longitudinal phase-energy diagram of the electrons (computer simulations): (a) after the bunching straight section, (b) after the injection to the common straight section; 1, 2, 3, 4-at the 1st, 2nd, 3rd, and 4th straight sections, respectively.

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