Nuclear Instruments and Methods in Physics Research A304 (1991) 192-196
North-Holland

# A microtron accelerator for a free electron laser *

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A racetrack microtron as a source for a free electron laser is being constructed It will accelerate electrons up to 25 MeV to provide 10 μm radiation in a hybrid undulator with a periodicity distance of 25 mm. The aim is to accelerate 100 A bunches of 30 ps pulse length at 81.25 MHz. This frequency is chosen to minimize cavity loading, by avoiding simultaneous presence of more than one bunch in the microtron cavity. The self-focusing longitudinal action of the microtron assures a small energy and phase spread of the outcoming beam Transverse focusing will be provided by applying edge focusing at valley boundaries in the sector magnets. An analytical theory and computer simulations have been set up and are being further developed for studying the effects of space charge during acceleration. Details of calculations and construction will be given.

## 1. Introduction

Free electron lasers call for excellent properties of the driving electron beam. The required high electron beam quality is expressed by a small emittance, small energy spread and high current, and by a stable timing of the electron bunches when they emerge from a pulsed accelerator. These requirements place strong demands on the design and the performance of the accelerator, and on the electron generating system.

In the TEUFEL project [1] (Twente/Eindhoven University UCN free electron laser) we aim to contribute to the technological and scientific developments of free electron lasers by constructing a FEL with a wavelength around 10 μm. In particular we are interested in the potentials of a pulsed, high current racetrack microtron (RTM) for producing the required 25 MeV electron beam. The microtron will receive beam from a photocathode injector of 6 MeV. A hybrid undulator will be employed, with 40 periods and a wiggler wavelength of 25 mm. It is incorporated in a 1.85 m long optical cavity for trapping the resulting laser beam.

Thus the aim is to achieve the requirements on the quality of the electron beam as mentioned above with the proposed equipment. The photocathode injector, at present being built at the Los Alamos National Laboratory, is a $5\frac{1}{2}$ cell linear accelerator operating at 1.3 GHz and capable of delivering pulses of up to 400 A at a maximum energy of 6 MeV. The photocathode is illuminated by a frequency-doubled Nd:YLF laser, mode-locked at 40.625 MHz, to provide the 16th subharmonic of the linac rf frequency. The 10 Hz macro electron pulses, having a length of 10 μs, consist of micropulses approximately 9 mm long (30 ps). The linac is expected to give a normalized emittance smaller than 25π mm mrad (90%) and a relative energy spread of about 0.5%. Assuming for now that the emittance and absolute energy spread are preserved in the racetrack microtron and in the transfer lines (no beam blowup due to space charge), it can be verified that the conditions imposed on the beam quality in the small gain regime are well fulfilled, i.e. bunch length larger than the laser wavelength times the number of undulator periods $N$, the relative energy spread smaller than $N^{-1}$ and the emittance numerically smaller than the laser wavelength.

Although the photoinjector is capable of producing peak currents up to 400 A, we expect the microtron to be limited to handle a current up to about 100 A. In any case studies of space-charge effects are required in order to predict the increase in beam size and in energy spread; this is done in two ways: by computer simulations using the code PAPA [2] and by analytical methods employing Hamiltonian theory [3].

Various laboratories have applied microtron injectors for FELs, e.g. the NBS cw machine and the pulsed

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* Work supported by Ultra Centrifuge Nederland (UCN), The Dutch Foundation for Technical Research (STW) and the Dutch Foundation for Fundamental Research on Matter (FOM).

RTM of Bell Laboratories and ENEA.

The TEUFEL project will be carried out in two stages. In the first stage the 6 MeV injector will be employed only for producing FEL radiation around 150 μm. In the second stage the RTM will be incorporated in the system.

## 2. Rf power considerations

Table 1 gives some approximate data for the power required by the photocathode injector linac and the microtron cavity at a peak micropulse current of 100 A. It can be compared with the requirements for a separate linac of 25 MeV: for this a reasonable number for the peak rf structure power would be 5 MW, which would be the number for a modern linac operating at 1.3 GHz with an rf structure length of 2.5 m and with a corrected shunt impedance of 50 MΩ/m [4]. However, for this case the emittance and energy spread can be expected to be larger than for the photoinjector/microtron combination.

The klystron to be used is a Thomson type TH 2022C, which can deliver 20 MW output for a time duration of 20 μs at 1.3 GHz. With the rf peak structure power given in table 1, it can be seen that enough power is available for the beam.

Table 1
Rf power requirements for injector linac and microtron cavity at 100 A peak current

| General data | | |
|---|---|---|
| Rf frequency | 1.3 GHz | |
| Micropulse length | 30 ps | |
| Micropulse frequency | 81.25 MHz | |
| Microduty factor | $2.4 \times 10^{-3}$ | |
| Macropulse length | 10 μs | |
| Macropulse frequency | 10 Hz | |
| Macroduty factor | $10^{-4}$ | |
| Rf pulse length | 15 μs | |
| Peak micropulse current | 100 A | |
| Average macropulse current | 244 mA [a] | |
| Average current | 24.4 μA [a] | |
| Power requirements | Linac<br>6 MeV | Microtron<br>6–25 MeV |
| Macropulse beam power [MW] | 1.5 | 4.6 |
| Average beam power [W] | 150 | 460 |
| Peak rf structure power [MW] | 2 | 0.5 |
| Total peak power [MW] | 3.5 | 5.1 |
| Beam loading [%] | 42 | 91 |
| Average rf power [W] | 450 | 535 |

[a] This is the output current; in the microtron cavity with 9 orbits the current is 9 times higher.

## 3. Microtron characteristics

The microtron has been described in many papers and in several books (see e.g. Kapitza [5]). Electrons are synchronously accelerated in successively larger orbits. For the RTM two conditions must be fulfilled: the length of the first complete orbit must be an integer $n$ times the rf wavelength ($\lambda_{rf}$) and secondly the difference in path length between successive orbits must be constant, namely an integer ("mode number" $h$) times $\lambda_{rf}$. For "small" microtrons usually the mode number is 1 or 2. For ultrarelativistic particles these conditions can be translated into the following equations, relating the energy gain per turn $\Delta T$ for the synchronous particle with the average magnetic field $\boldsymbol{B}$, and the required injection energy $T_0$ with the separation distance $L$ between the two magnets constituting the RTM,

$$\Delta T = \frac{ehE_0 \boldsymbol{B}}{2\pi m_0 c}\lambda_{rf},$$

$$T_0 = (n - 1 - 2L/\lambda_{rf})\frac{\Delta T}{h} - E_0,$$

where $e$, $m_0$ and $E_0$ are the electron charge, rest mass and rest energy, and where $c$ is the velocity of light. Table 2 gives the main TEUFEL microtron parameters based on these equations. Fig. 1 gives a median plane view of the orbit pattern.

A number of elements has influenced the design of the RTM:

- Space charge may lead to beam blowup: as in AVF cyclotrons a field modulation will be applied in the bending sectors in order to provide sufficient axial focusing. An RTM of this type has been described by Froelich et al. [6].
- The magnetic aperture is taken to be 5 cm for the beam to experience mostly linear effects from the external magnetic field.
- With the presence of the focusing valleys, no attempt

Table 2
Microtron parameters

| | |
|---|---|
| Cavity frequency | 1300 MHz |
| Cavity voltage | 2.22 MV |
| Cavity wavelength | 23.1 cm |
| Dipole field | 0.192 T |
| Dipole length | 140 cm |
| Dipole width | 50 cm |
| Magnet aperture | 5 cm |
| Extraction energy | 25 MeV |
| Mode number | 1 |
| Injection energy | 6 MeV |
| Number of orbits | 9 |
| Orbit separation | 7.34 cm |
| Sector separation | 50 cm |
| Wavelengths in first orbit | 8 |

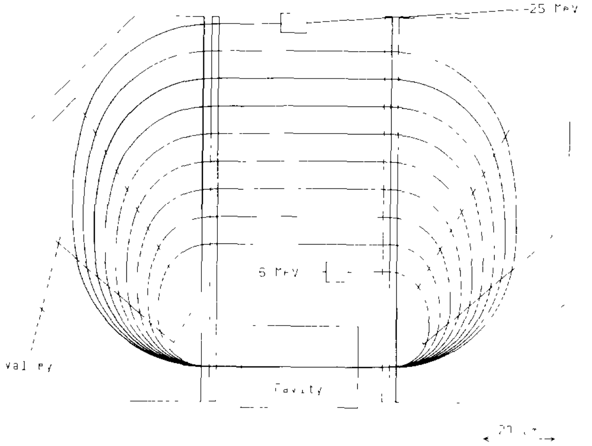

Fig. 1. Median plane view of the 25 MeV racetrack microtron.

is made of homogenizing the bending magnets to such an accuracy as done for many existing microtrons. Rather the field will be measured and correction coils will be provided in order to adjust the isochronism (again as in cyclotrons).

- Field clamps are used for creating a sharper magnetic field boundary than without them. They help in providing extra axial focusing [7], yet are not primarily intended for that, since this is established by the focusing valleys.
- H-type magnets are used with easy accessibility for diagnostic tools. The inherent field variation in the direction perpendicular to the incoming and outgoing orbits, which is not present in the C-type magnets that are mostly adopted for RTMs, is of no concern to us with the presence of the valleys.
- The pulse selection number 1 out of 16 (at 81.25 MHz) for the present microtron parameters prevents overlapping of more than one electron bunch; this would lead to enhanced space charge forces.

In the empty space between the RTM sector magnets, a small vertical injection and horizontal extraction deflection magnet will be placed for handling the 6 and 25 MeV beam. The vacuum system consists of a central aluminum chamber with a turbomolecular pump, connected to the side vacuum chambers in the magnets. Here, the poles of the magnets form a part of the chamber; it is complemented by an aluminum insert piece providing the vertical walls of the vacuum box, with a passage channel to the central vacuum chamber. In the central chamber, a series of corrector magnets will be placed which function together with the valley for correction coils.

## 4. Magnets

The microtron H-type magnets have been constructed in the university workshop. Also the coil wind-

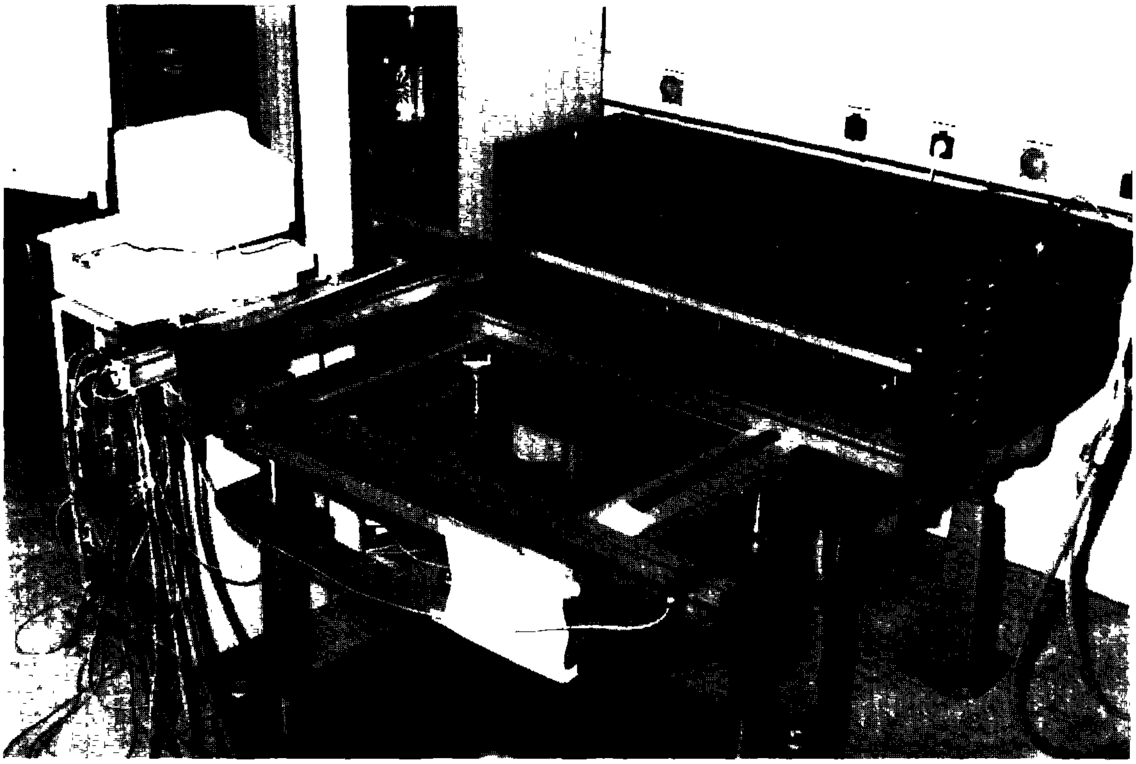

Fig 2. Field measuring equipment at a microtron magnet. The upper field clamp has been removed.

Fig. 3 Magnet coils.

ing has been done there. The pole is maximum 0.50 m wide and 1.10 m long; the total magnet length is 1.40 m. It consist of two iron blocks (approximately 1 ton each) in which the coil channels have been carved out, with small blocks (10 cm width) in between on the return yoke side. Fig. 2 shows a magnet still without a focusing valley on the magnetic field measurement bench. Fig. 3 shows a coil pair, consisting of 36 turns of 6 × 6 mm$^2$ hollow copper conductor. A power supply for both magnets of 120 A and 3 kW is required for a field of 0.2 T. The magnetic flux in the return yoke has been measured and corresponds to an average field of 1 T at 120 A. In the middle of the magnet, a relative field weakening with respect to the field near the pole boundary of 2% was found, in correspondance with POISSON calculations. The effective field boundary is shifted by about 8 mm towards the pole edge when a field clamp is used, again in agreement with POISSON.

The valley shape has been predicted on the basis of 2D POISSON calculations of the field distribution, as well as its effects on the beam dynamics [8]. Since the average field is low (0.2 T) the field is also fairly well described by solving a potential problem. For this, the model field obtained with POISSON was compared with that from RELAX3D [9], and yielded a quantitative agreement better than a few percent. Fig. 4 shows the calculated field in the left magnet. A few iterations of field measurements (fig. 2) and orbit calculations are expected to be required in order to come to the definitive valley shape.

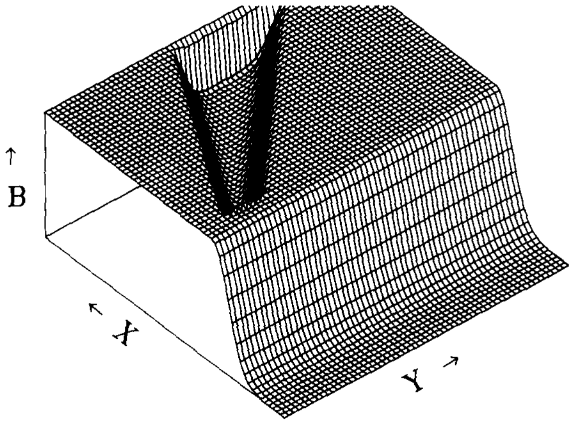

Fig. 4. The calculated median plane field in the left microtron magnet

## 5. Accelerating cavity

The rf cavity for the microtron will be constructed in the university workshop. The 35 cm long cavity will consist of three accelerating cells, operated in the $\pi$-mode. To lower the sensitivity of the electric field amplitude and phase for design errors and beam loading, a biperiodic structure will be made with small coupling cells in between the accelerating cells. To achieve the accelerating voltage of 2.22 MV, a peak power in the order of 0.5 MW is needed. Due to the low duty cycle ($10^{-4}$) the average power dissipation will be small ($\simeq 50$ W) so that cavity cooling should not be difficult. For the numerical design of the cavity, the 2D code SUPERFISH is used. In the future also 3D calculations will be done with the MAFIA codes. An aluminum mock-up (scale 1 : 1) will be made to measure various cavity properties at low power level such as the field distribution on axis, cell-coupling, field asymmetry and higher order modes.

For a microbunch current of 100 A the peak power transferred to the beam will be close to 10 times the peak power dissipated in the cavity. Therefore, beam loading effects will be important. A complication in this respect is that only one klystron is used to drive both the injector linac and the microtron cavity. Independent phase and amplitude control of the microtron cavity field yields a severe complexity.

## 6. Space-charge effects

The semi-analytical space charge calculations are based on the root-mean-square approach as has been developed by Sacherer [10]. The linear part of the space charge forces as determined by a least-squares method is taken into account and ellipsoidal bunches are assumed. The longitudinal-transverse coupling in the microtron magnets destroys the symmetry of the bunch with respect to the reference orbit and therefore the ellipsoid is allowed to rotate around its vertical axis. The transverse focusing, the transverse-longitudinal coupling and the longitudinal focusing in the microtron

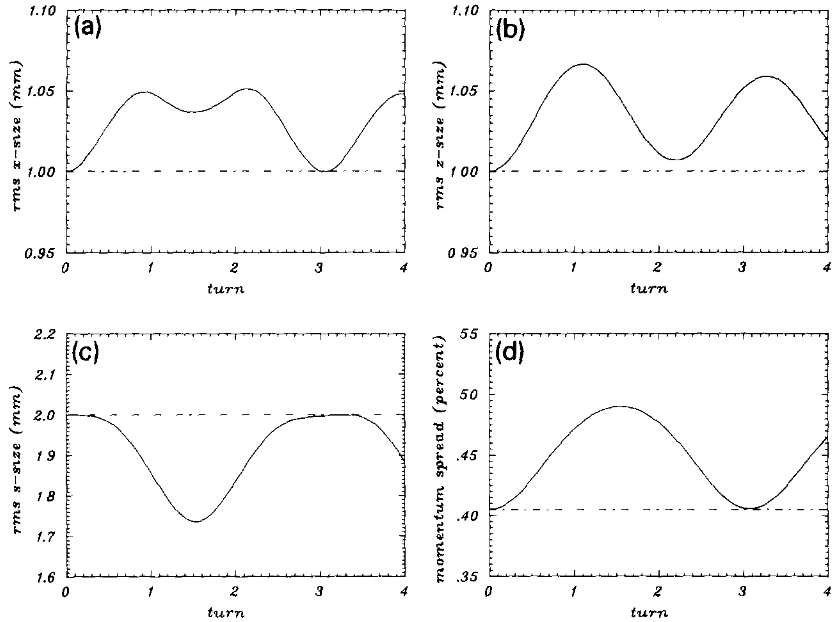

Fig. 5. Preliminary calculations on the time evolution of the rms bunch dimensions (a) horizontal, (b) vertical, (c) longitudinal and (d) of the rms momentum spread during four revolutions

are properly taken into account by a smoothing procedure. In fig. 5 a typical example is shown of the calculated bunch properties during 4 turns starting at 5 MeV with a peak current of 100 A [3]. In this case the initial conditions were chosen such that the bunch properties would be stationary in the zero-current limit. These preliminary calculations show a 5% effect on beam size and a 25% enhancement of the momentum spread.

## 7. Conclusion

An RTM with a photocathode injector system seems to be an economical candidate as an electron source for a free electron laser, to deliver the required high quality beam. Its performance as such will be investigated experimentally and theoretically on the described system which is currently being built. Handling the high peak current is an important issue in these studies.

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