Appl. Phys. B 50, 71–77 (1990)

Applied Physics B Photophysics and Laser Chemistry

Design of a Continuous-Wave Free-Electron Laser Experiment Using an Electrostatic Accelerator with Very High Recovery Efficiency of the Electron Beam

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Received 10 May 1989/Accepted 2 July 1989

Abstract. In this paper the free-electron laser (FEL) experiment SEAFEL in progress at the Legnaro (Padova) INFN laboratory is presented. The accelerator characteristics and FEL parameters are discussed. The laser could sweep the millimeter region up to 2 mm with a power around 15 kW. The main goal is the continuous-wave operation. An existing electron device with some small modifications is used for the experiment.

PACS: 29.15B, 42.55T

The possibility of producing hundreds of kilowatts of tunable and continuous wave (cw) radiation in the centimeter-millimeter region of the electromagnetic spectrum is interesting for varied scientific and technological applications.

We look for an rf source that can be suitable as signal injector of the ELFA (Electron Laser Facility for Acceleration) machine, at Milano (Italy) LASA laboratory [1]. The ELFA Free Electron Laser (FEL) pertains to high-gain FELs which operate as amplifiers with exponential gain, both in steady-state and superradiant regimes [2]. They need a powerful source as signal injector [2, 3].

In the millimeter region, the Gyratron source is not very useful because of its low repetition rate and narrow tunability.

Powerful FEL sources in the millimeter region are also helpful in chemistry and plasma physics.

The cw operation is possible only with an electrostatic accelerator. The high power can be obtained only with the electron beam recovery technique [4, 5]. The cw operation needs a very high efficiency of charge recovery, better than 99%. This efficiency seems possible using an "immersed flow" configuration [4]. This configuration requires a relatively low voltage (1–3 MV).

Owing to high charge recovery, currents higher than 10 A are possible in electrodynamics accelerators as transformer, dynamitron, Cockroft-Walton accelerator; with those powerful electron beams, powerful FEL come along, because the conversion efficiency is $\sim 1\%$ [4].

In the experiment discussed here called SEAFEL (Small Electrostatic Accelerator FEL), a Cockroft-Walton accelerator will provide an electron beam having a current of 3 A at 0.7 MeV energy, with a normalized emittance $\sim 10^{-4}$ m · rad and a relative energy spread $\sim 10^{-3}$. These beam qualities are necessaries for FEL operation in the Madey regime [6].

The main goal of the experiment is to search for cw operation. In the paper, the vacuum system, the gun, the transport channel, the collector and the FEL are described. The accelerator is being assembled at LNL-Laboratori Nazionali di Legnaro (Padova, Italy). The FEL test is scheduled in the next three years.

1. Experimental Apparatus

The system consists of two main parts: the accelerator, providing the laser medium (the electron beam), and the free electron laser set-up. The accelerator is scheduled to operate in the next year and a first electron beam recovery test will be carried out. After the insertion of the parts of the set-up relevant to the FEL, that is undulator, waveguide and diagnostic tools, a new recovery test will be carried out.

The accelerator, has originally been designed for an electron cooling experiment [7]. The electron gun has been redesigned to obtained an electron beam more suitable for our purposes. As shown in Fig. 1, the electrons travel from the gun to the collector in an axial magnetic field ("immersed flow" configuration) to compensate for the space-charge force. The main accelerator parameters interesting our experiment are listed in Table 1.

The undulator will be placed in the drift section of the accelerator. The axial magnetic field has been modified in order to meet the FEL requirements (see below). The "immersed flow" configuration is maintained because it is crucial in order to have very small current leak.

The high voltage terminal is fed by a symmetrical Grainecher voltage generator. The collector is of multistage type to recovery an energy spread electron beam.

1.1. High-Voltage System

The high-voltage (HV) terminal is separated into three stainless steel HV heads (1.4 m diameter, 0.9 m height) connected together through two stainless steel tubes (3 m length, 0.2 m diameter). The heads are supported by three insulating 1.3 m long columns. They contain

Table 1. Main parameters of the accelerator

Beam energy	0.7 MeV
Beam energy spread ($\Delta E/E$)	10^{-3}
Beam normalized emittance (ε_n)	10^{-4} m · rad
Electron beam current	3 A
Max. beam diameter inside the undulator	1 cm
Max. beam diameter	2 cm
High Voltage generator current	5 mA
Multistage collector voltage	3 kV
Number of collector stages	4
Free region length	1.5 m
Vacuum	10^{-9} Torr

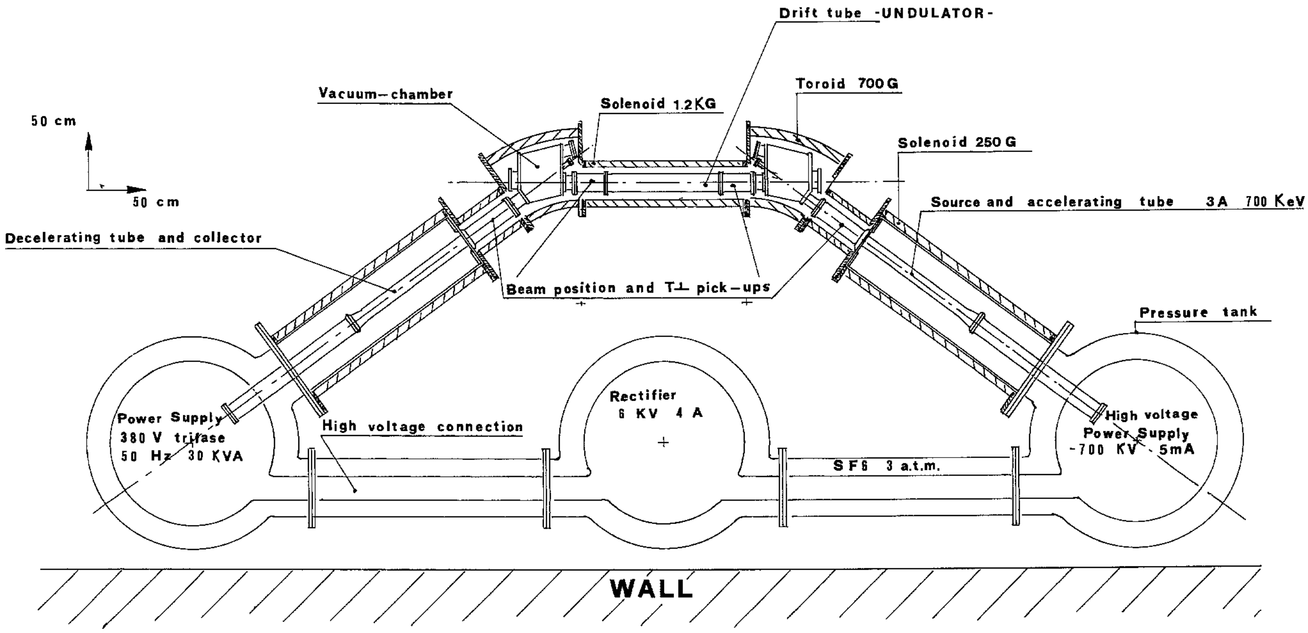

Fig. 1. Overall scheme of the machine. The undulator will be set in the drift region of the machine

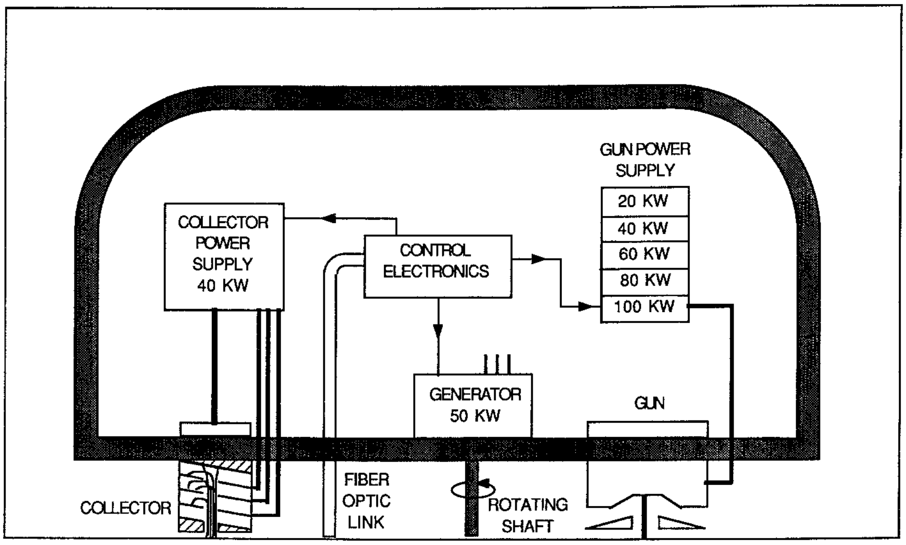

Fig. 2. High voltage heads scheme

all the instrumentation at high voltage (Fig. 2). The first head contains the gun power supplies and the ion pumps; the second one contains the 40 kW power supply of the multistage collector and the latter head contains an alternator (380 V three-phase, 50 Hz, 50 kW) providing all the power at the HV terminal, and the power supplies of the vacuum pump for the decelerating tube and the collector.

The alternator is mechanically driven by a dielectric rotating shaft.

A symmetrical cascade Cockroft-Walton generator of 760 kV nominal voltage allows to accelerate electrons up to 700 keV. It is made up of 19 stages, 40 kV each other, driven by a 30 kHz–20 kV square wave oscillator of 4 kW power. The high-voltage generator can supply a 5 mA current with a ripple of 10^{-4}. All the high-voltage system is contained in a SF_6 tank at 3 atmospheres pressure, because of electric insulation problems.

1.2. Electron Gun

A 3 A–120 keV (5 electrodes) electron gun requires a high perveance parameter. The space charge is counterbalanced by a transverse electric field (due to Pierce focusing design) and by an axial magnetic field (Fig. 1). The plane reserve cathode has an area of $\sim 2\ \text{cm}^2$, heated at 1050°C. The Pierce region is composed of five electrodes; the anode is located at 1.3 cm from the cathode and activated at 12 kV. The other electrodes are spaced 3 cm one another and voltages of 34, 62, 93, and 126 kV are applied, respectively. The calculations have been performed by using the computer code SLACGUN [8] in a version modified by Sedlacek [9].

At the end of the Pierce region a diverging-lens effect exists, which has to be compensated by the axial magnetic field. The magnetic field intensity has to be determined not only by the gun focusing requirement, but also by the requirement of reducing the transverse beam dimension in the undulator (drift region) and to recover the beam energy at the collector (see the collector section). The chosen magnetic field distribution lead to a normalized emittance of $\sim 10^{-4}$ m·rad having properly designed the Pierce electrode.

1.3. The Accelerating Tubes and Beam Optics

The transport channel consists of: the accelerating column, a bendig magnet, a 1.5 m long experimental drift section, a second bending and the decelerating column ended with the beam collector.

The design of the accelerating and decelerating tubes meets the requirements of beam focusing and good uniformity of the accelerating field on the beam volume. The accelerating tube, whose total length is about 1.2 m, consists of a column of 33 constantan electrodes (1 mm thick) spaced by ceramic rings (3 cm thick). A special shape of the electrodes has been studied to shield the ceramics from ion current [10]. The electrodes are polarized through a resistive voltage divider made of special resistances wrapped around the tube and protected by guard rings. We notice that the final part of the decelerating column has been set at a constant voltage gradient (changing the electron cooling design [10]) to maintain the transverse electron-beam dimension at an acceptable value until the exit (Fig. 3). The shape and voltage of the last three electrodes of the decelerating tube have been chosen in order to focus the beam at the collector entrance (Fig. 3).

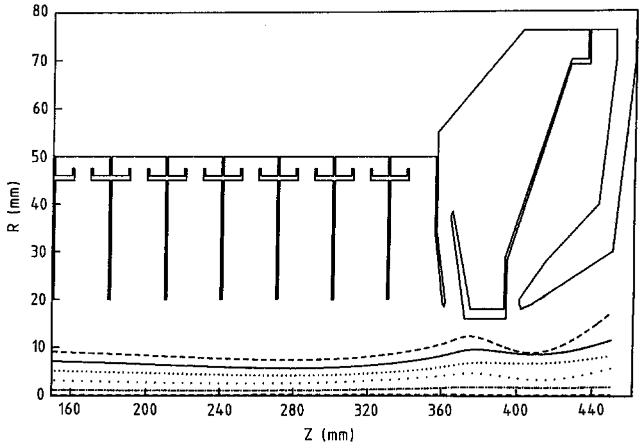

Fig. 3. Computer simulations of a few electron trajectories at the end of the decelerating column before the collector input

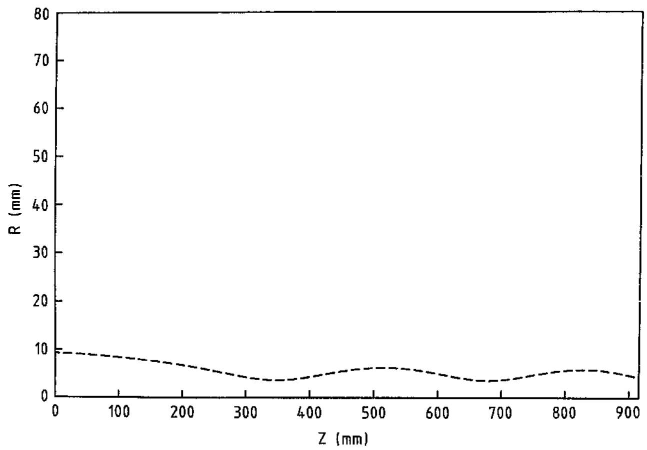

Fig. 4. Computer simulation of electron beam envelope before the entrance of the undulator region. The reduction of the beam size is due to the appropriate axial magnetic field values

Table 2. Parameters of the magnets

Drift solenoid length	1.5 m
Drift solenoid inner diameter	284 mm
Short solenoid length	0.5 m
Short solenoid inner diameter	284 mm
Gun/collector solenoid length	2 m
Gun/collector solenoid inner diameter	520 mm
Toroid bending radius	1.05 m
Maximum current density	13.4 A/mm^2
Maximum current	1920 A
Maximum voltage to ground	320 V
Water cooling pressure	6 kg/cm^2
Maximum magnetic field	3 kG
Magnetic field intensity in:	
accelerating column	250 G
bending toroids	700 G
drift(undulator)region	1200 G
decelerating column	250 G
Total power	750 kW

Since the continuous circulating electron beam has a current of 3 A while the HV power generator supplies 5 mA the charge leak has to be less than 0.17% willing cw operation.

With the aim to keep the high current flow along the transport channel up to the collector without any loss, an "immersed flow" configuration has been chosen. Willing a high current we had to use a large cathode surface which in turn gave a large beam size at beginning. The transverse beam dimension inside the undulator ought be reduced because of the small undulator gap with respect to the initial beam size. This reduction can be accomplished by choosing an appropriate magnetic-field value in the solenoids and toroid preceding the undulator in such a way to get an electron-beam waist immediately before the undulator region where the field intensity is high (Table 2). The beam-size reduction obtained in this way (Fig. 4) can be easily understood by the equations of motion for the electrons in the "immersed flow" configuration (see, for example, [11]). The beam has been followed along all the line with the SLACGUN code and it seems that all the charge recovery is assured. We notice that the undulator effect has been theoretically calculated and added as data input. The bending is accomplished by a section of a toroidal field with a dipole field superimposed [10]. The undulator and toroids effect cannot be taken into account with the SLACGUN code, but further improvements of the simulation are in progress.

We assume that the FEL interaction inside the waveguide does not lead to charge losses because the waveguide dimensions are enough larger than the beam dimensions and, furthermore the emittance is not changed in first approximation because the FEL interaction can be seen as a head-on Compton scattering.

The assembly of magnets is shown in Fig. 1, and the most important parameters are listed in Table 2. A field of 3 kG was required by the cooling experiment. The solenoidal and toroidal coils are surrounded by a soft iron screening tube with the aim to make the field inside the coils independent of the magnetic environment of the device. Solenoids and toroids are bolted together with iron flanges in relative positions defined by dowel pins. Owing to the interruption of the coil the longitudinal field strength in the magnet is slightly reduced near these flanges. In order to compensate for this discontinuity, correction coils are mounted on the flanges.

The voltage at the last electrode of the decelerating column must be greater than $V = -700\,\mathrm{kV} + \Delta E/e$, where ΔE is the *eb* energy spread, and e is the electron charge. The energy spread is induced by the FEL interaction and is given by $\Delta E = E/2N$; here E is the electron beam energy, and N is the number of undulator periods (Sect. 2).

1.4. The Collector

The collector design and electrical voltage setting are shown in Fig. 5. The electrons must have enough energy to be focused at the entrance of the collector and collected when their energy is still 1–2 keV to avoid any particles backscattering. It is worth remarking that any secondary emission from decelerating column electrodes (and therefore any electrons hitting outside the collector) must be avoided, otherwise a return beam begins to circulate with an unacceptable energy loss.

After the FEL interaction the electron beam is energy spread ($\Delta E/E \sim 10^{-2}$) and the average energy is down-shifted. Because of this spread, a simple Faraday cup does not permit an efficient beam-energy recovery. Since continuous operation is wanted, a multistage collector [12, 13] has to be used in order to get a much higher efficiency. In a multistage collector several collection stages are connected in series to collect each electron on the appropriate electrode with the minimum energy loss. The principle of operation is to make a spectrometer with the aid of electric [13] or combined electric and magnetic fields [12], to spatially disperse the electron beam.

The "immersed flow" configuration with its stray magnetic field at the end of the decelerating column pushes to a purely electric multistage collector.

The chosen electrode number is four with an applied depressing voltage at each stage of 3 kV. Their spatial orientation and shape have been calculated with the goal to maximize the recovery efficiency [12].

The most serious problem is to launch all the electrons into the hole of the collector. A collector immersed inside the solenoid cannot maintain any dispersive property. Therefore, the solenoid is terminated at the decelerating column, so in the collector only a stray magnetic field is present.

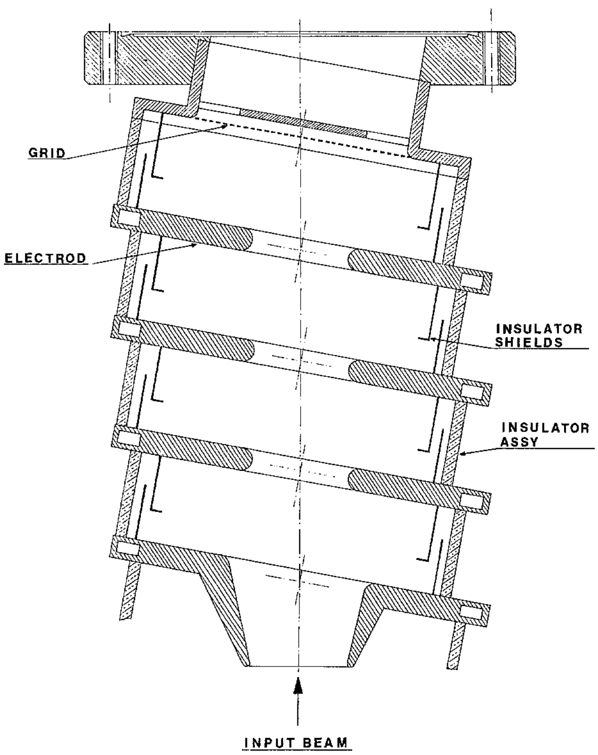

Fig. 5. Multistage collector design. The angle between the electrode normal and the input beam propagation direction is 15°

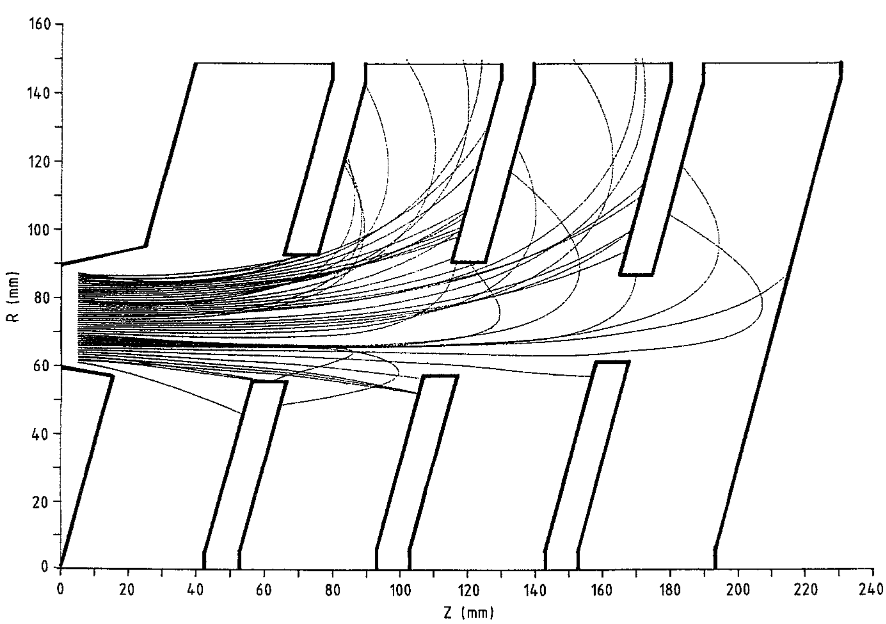

Fig. 6. Electron trajectories in the multistage collector obtained by SLACGUN code. The beam energy spread has been assumed 1%, due to FEL interaction

The convey of the electrons into the collector hole is obtained by the electrostatic lens at the end of the decelerating column and by chosing the magnetic field intensity in order to have the waist of the beam scallop at that hole. In Fig. 6 some computed electron trajectories are shown. All the trajectories end into a collector plate.

The energy-recovery efficiency of the electron beam, defined as $\eta = E_{rec}/E_{in}$ (where E_{rec} is the mean electron energy recovered by the collector, and E_{in} the mean electron energy entering the collector), has been calculated around 80%. The power to be supplied to the beam at the collector is ~ 20 kW. This latter is the sum of the power lost by the beam in the FEL interaction (~ 15 kW), and the power lost in the collector (~ 4 kW). This power is almost uniformly supplied at the four plates of the collector because the beam distribution is a square function of the momentum owing to the FEL interaction [Ref. 14, Fig. 5].

The plate thickness is large enough to allow the cooling by freon circulation.

1.5. Ultra-High Vacuum System

The most serious ultra-high vacuum problem in such a device is to achieve very low pressure while the gas throughout and loads are high with the system active. The gas produced results primarily from thermal degassing and chemistry of the hot cathode of the gun, from the collector, and from impact desorption of gases desorbed from surfaces by the few electrons lost from the primary beam.

While a careful choice of material, cleaning and bulk degassing treatments can help, it is still necessary to provide a very large pumping speed and capacity for the gas species normally desorbed. Moreover, little flexibility exists in the space arrangement, leading to small conductances from the main gas source (gun and collector) to the drift tube where the lowest pressure is required. The argument of rigidity of the boundaries has some consequences in the choice of the principle of pumping.

Given these tight conditions, an analysis of the existing pumping principles while designing the device has led to the choice of cryopumping and sputter ion pumps distributed in the system, providing a strong differential pumping between the gun/collector region and the drift tube.

2. FEL Set-Up

The FEL section must be set in the drift region (1.5 m long). The output wavelength ought to be greater than $\lambda = 2.5$ mm in order to cover the requests of the ELFA project. The resonance condition between the wavelength and the undulator period λ_0 is $\lambda = \lambda_0(1 + a_0^2)/2\gamma^2$, where γ is the Lorentz factor and a_0 the undulator parameter. Since a_0 in our undulator is negligible and the maximum electron energy is 700 keV ($\gamma = 2.4$) the undulator period turns out to be $\lambda_0 = 30$ mm.

A permanent magnet plane undulator with Halbach configuration has been chosen for its easyness. In addition the FEL operates in TE_{01} mode which is requested by the user. However, a convenient quadrupole set of permanent magnet will be added in order to focus the beam on the horizontal plane. Actually, in the plane undulator configuration. the insertion in an axial guiding field originates an outside drift of the off-axis particles in the direction parallel to the horizontal plane, so, to prevent the particles loss, a focusing force in that direction is necessary.

The value of the magnetic field B_0 at the gap centre, for a pure rare-earth-cobalt (REC) undulator with an Halbach configuration is given by [16]

$$B_0 = 2B_r \frac{\sin(\varepsilon\pi/n)}{\pi/n}(1 - e^{-k_0 h})e^{-\frac{k_0}{2}g} \tag{1}$$

with

B_r: remanent field,
n: number of blocks per period,
h: block height,
ε: filling factor, to take account of spaces between the blocks,
k_0: undulator wave number, and
g: gap height.

In formula (1) the horizontal undulator dimension is assumed large enough to make 2-D calculations. In our experiment the relatively low value of the undulator periods number $N_0 = 50$ imposes a gap height g as small as possible in order to get a reasonable value of the magnetic field B_0. The gap dimension is determined in turn by the waveguide dimension. This latter is a rectangular oversized waveguide whose internal dimensions are 60×22 mm^2. The wide dimension depends on the total required field mode volume in order to keep the power losses at a level less than some percents. The vertical dimension is ultimately by the maximum electron beam diameter that comes out to be $\Phi \sim 11$ mm. Since most part of the electrons must be within the radiation intensity pattern and the field has a sine shape for the TE_{01} mode, and the intensity goes like a sine squared, the waveguide height must be $h \sim 22$ mm. The wall thickness is assumed 1 mm and the two wider surfaces facing the undulator are ridged (Fig. 7) in order to be enough rigid against the vacuum pressure. The 1 mm thick ridges fit the slits in the REC magnets array. This means that the undulator configuration has a filling factor $\varepsilon = 0.87$. The peak value of

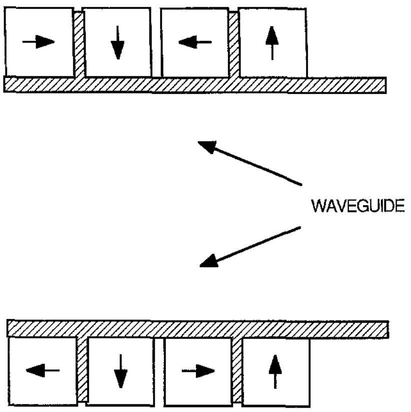

Fig. 7. Scheme of the ridged waveguide supporting the permanent magnet assembly

the magnetic field results $B_w = 900$ Gauss having assumed a remanent field $B_r = 1$ Tesla. Samarium-cobalt is chosen because of its greater stability with temperature. The gain calculated with the simple formula of [17] has a value $\cong 100\%$.

The output and input mirrors, that is the front-end and back-end terminal waveguide sections are corrugated in such a way to make two Bragg reflectors (see, for example, [18]): one with very high reflectivity and the other one with a reflectivity larger than 90%. Those mirrors have the important characteristic of being transparent to the electron beam and to reflect the microwave radiation. This type of cavity does not allow an easy tunability.

In order to reduce the cavity losses the internal surface will be coated with a Cu film. We remark that the power stored inside the cavity can be assessed in 200 kW.

3. Conclusions

In this paper we have outlined the basic physics and properties of our experiment. The Cockroft-Walton accelerator provides an electron beam of $I = 3$ A and $E = 0.7$ MeV and good qualities. The immersed flow configuration ought to warrant a charge recovery of 99.9% up to the collector. The multistage collector from the computer simulation behaves as a black body, so no electron comes back. Collector design assures a calculated electron beam energy recovery of the order of 80%.

The undulator is a pure REC and has a Halbach configuration with a filling factor $\varepsilon = 0.87$. The troughs between blocks fit the ridges of the waveguide. The design allows a small gap and meanwhile the rigidity of the waveguide.

The assessed FEL gain is around 100% thus the losses should be easily overcome.

This machine should be able to provide a continuous-wave radiation in the range of 10–2.5 mm with a power of 15 kW.

Acknowledgement. The authors want to thank Mr. Valentino for providing the drawings.

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