THE NEAR-INFRARED FREE-ELECTRON-LASER PROJECT AT DARMSTADT *)

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Abstract

The superconducting 130 MeV electron accelerator at Darmstadt will be modified for FEL experiments. The FEL project is planned with an electron beam in an energy range from 35 to 50 MeV corresponding to wavelengths from 4.9 to 2.4 µm. The planned FEL setup, a high current injection, the design of a hybrid undulator and the results of simulations of the FEL are presented.

I. Description of the accelerator

A layout of the superconducting 130 MeV accelerator which has been described in detail elsewhere [1,2] is shown in Fig.1 and its main parameters are listed in Tab.1.

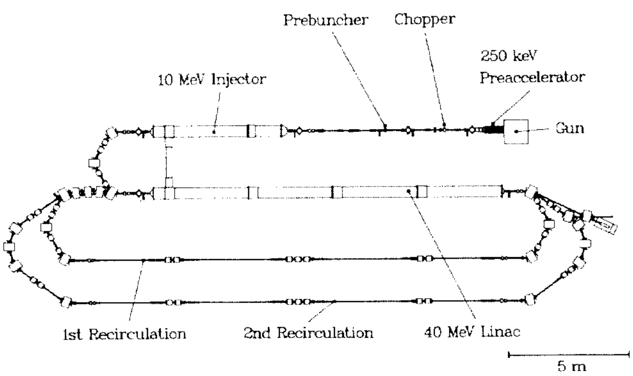

Fig. 1 *Layout of the 130 MeV accelerator*

The electron gun delivers a dc current of I < 2 mA which is then electrostatically preaccelerated to an energy of 250 keV. The dc beam is chopped into segments covering 30° of rf phase at 3 GHz by a system consisting of a cylindrical rf cavity and a water cooled chopper orifice with a 2 mm bore. A prebuncher cavity compresses the bunch to a bunch length of 6° at the entrance of the superconducting capture section.

The superconducting injector consists of one 5 cell 0.25 m long superconducting structure which serves as a capture section and two standard 1 m long 20 cell structures. With an accelerating field of 5 MV/m the beam leaves the injector with an energy of 10 MeV. This beam is then bent isochronously by 180° and injected into the superconducting main linac consisting of eight 1 m long structures. The beam energy is increased by 40 MeV per pass. A two stage isochronous recirculation system, consisting of two 180° bends and a straight section each, recirculates the beam up to two times. Thus the output energy can be varied continuously between 10 and 130 MeV depending on the number of recirculations used.

The 10 MeV injector has been operated successfully for many months and some results of the beam tests are reported also on this conference [3].

Table 1 Design parameters of the superconducting 130 MeV accelerator

General	
Energy / MeV	10 - 130
Energy spread / keV	± 13
Normalized emittance / π mm mrad	2.2
cw current / µA	> 20
Accelerating structures	
Frequency / MHz	2997
Accelerating field / MV/m	5
Q	$3 \cdot 10^9$
Number of structures	11
Beam transport system	
Number of dipoles	22
Number of quadrupoles	34

II. Planned FEL experiment

Figure 2 shows the planned FEL experiment which will be carried out with the beam of the first recirculation in an energy range between 35 and 50 MeV. The bypass containing the undulator magnet consists of six quadrupoles (Q1-Q6 in Fig.2) and four 45° bending magnets (D1-D4 in Fig.2). As reported in [4] this magnetic system is achromatic and the focusing of the electron beam can be matched to the acceptance of the undulator magnet.

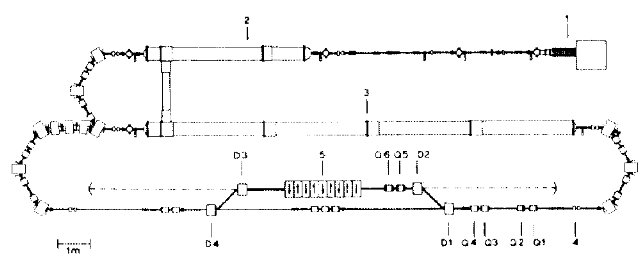

Fig. 2 *Part of the accelerator with the planned FEL experiment (1) electrostatic preaccelerator, (2) superconducting injector, (3) superconducting linac, (4) first recirculation, (5) undulator magnet, (Q1-6) quadrupole magnets, (D1-4) dipole magnets*

In the first stage of the experiment the electron beam will be dumped in a suitable Farady cup which is not shown in Fig.2. In a second step beam energy recovery is planned. For this purpose the bypass has to be isochronous and the beam has to be reinjected into the accelerator with a phase shift of 180° with respect to the rf field in the superconducting linac. The confocal optical cavity as indicated in Fig.2 has a length of 15.03 m and a Rayleigh range of 0.74 m. It will be entirely inside the vacuum.

From the physics of the FEL a number of requirements arise for the electron beam: (1) the peak current has to be of the order of several Amperes, (2) the beam emittance needs to be of the order of the wavelength of the FEL radiation and (3) the energy spread has to be smaller than 1/2N, where N is the number of undulator periods. The requirements (2) and (3) are met by the present design of the superconducting accelerator (Tab.1). The peak current however, amounts to 10.8 mA in the present design, when

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the accelerator is operated in the single pass mode. In order to achieve higher peak currents a new 250 keV injection has been designed which will be described in the following chapter.

III. High current 250 keV injection

The 250 keV injection system consisting of the electron gun, the electrostatic preaccelerator, the chopper and the prebuncher (see Fig.1) delivers a beam with an energy of 250 keV, a bunch length of 6° at 3 GHz and a beam diameter of 2.3 mm at the entrance of the superconducting injector [5]. The charge per microbunch is $7 \cdot 10^{-15}$ C which leads to a peak current of 10.8 mA after the pulse compression to about 2° in the injector. For the high current injection three requirements had to be met: (1) the pulse repetition rate of the micropulses must equal the round trip time of the photons in the optical cavity, (2) the average current is limited to 60 μA due to the available klystron power, (3) the above mentioned beam parameters (bunch length, beam diameter) must be achieved with a higher charge density of the microbunches. The according design was carried out with the program PARMELA [6] which simulates the transport of a bunch of electrons under the influence of external elements and space charge forces. The input parameters for the simulations are listed in Tab.2.

Table 2 Input parameters and results of the injector simulations

Input parameters	
α_x	0
α_y	0
β_x / cm/rad	25.5
β_y / cm/rad	25.5
ε_x / π mm mrad	5
ε_y / π mm mrad	5
$\Delta\varphi$ / ° at 600 MHz	± 40
$\Delta E/E$	10^{-4}
Q / pC	12.5
Output parameters	
ε_x (90 %) / π mm mrad	5
ε_y(90 %) / π mm mrad	5
d_x / mm	2
d_y/ mm	2
$\Delta\varphi$ (6.25 pC) / ° at 3 GHz	5
ΔE / keV	± 4.5

The injector operates on the 5^{th} subharmonic of the accelerator frequency at 600 MHz. The new design of the injector is shown in Fig.3, the details are described in [4]. The electron gun is a high current gun which is normally used in travelling wave tubes. It has a low anode voltage of 1.65 kV and delivers a beam of 24 mA at a control voltage of 0 V. Cutoff is reached at a control voltage of -350 V. The gun has an indirectly heated dispenser cathode with a diameter of 2 mm. The emittance of the beam is about 1.2 π mm mrad which is well within the input data of the simulation. The beam pulse which has a width of 3 ns and a repetition rate of 10 MHz is then accelerated electrostatically to 250 keV. A system consisting of a subharmonic chopper resonator operating at 600 MHz (pos.2 in Fig.3) and a water-cooled chopper orifice (pos.4 in Fig.3) chops the beam into segments of 80° at 600 MHz. The chopper resonator is described in [7]. The charge per microbunch is then about 10 pC. A subharmonic buncher resonator (pos.5 in Fig.3) operating at 600 MHz compresses the bunch so that about half of this charge is contained in 5° at 3 GHz, the beam diameter is then about 2 mm in each direction (see Tab.2).

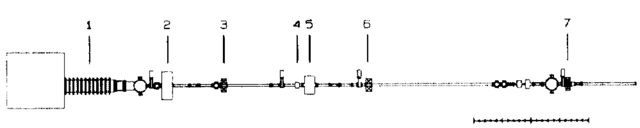

Fig. 3 *Layout of the high current 250 keV injector from the electron gun to the begin of the superconducting capture section (1) electrostatic preaccelerator, (2) subharmonic chopper resonator, (3,6,7) solenoid lenses, (4) chopper orifice, (5) subharmonic buncher resonator*

The subharmonic prebuncher is shown in Fig.4. It is of the single cavity double frequency type as described in [8]. Besides the TM_{010} fundamental mode at 600 MHz the first harmonic at 1200 MHz is excited. The advantage of this type of resonator is that, if properly phasing between these two modes is achieved, the acceptance can be made as large as 220° [8]. A bunch length of 80° as according to the design presented here is well within the phase acceptance of the cavity. For a gap voltage of 10.5 kV at the fundamental frequency, as required according to the simulations about 60 W of rf power will be required.

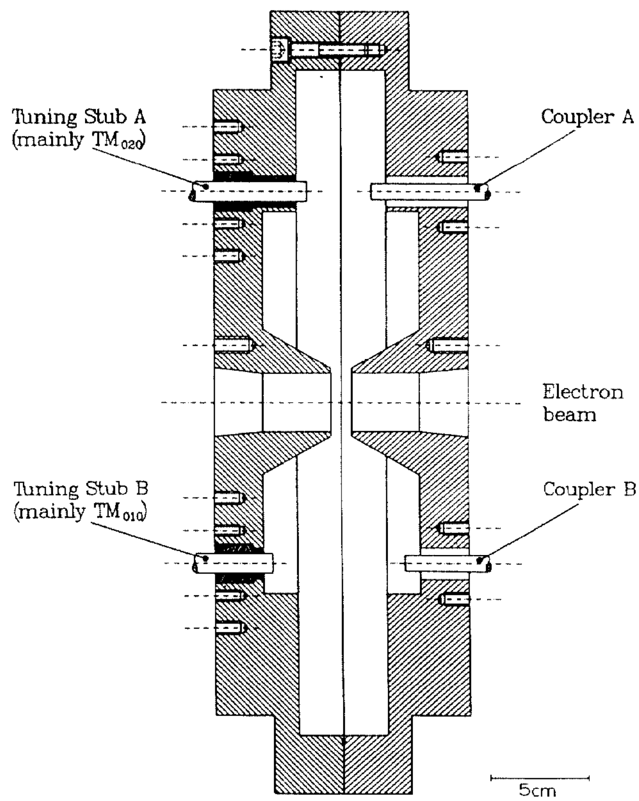

Fig. 4 *Mechanical layout of the subharmonic single cavity double frequency buncher resonator*

The energy spread imposed by the prebuncher is about 9 keV which is within the acceptance of the capture section. Three solenoid lenses (pos.3,6,7 in Fig.3) provide the necessary focusing of the beam. The output parameters of the simulations (Tab.2), which have been made with a higher charge (12.5 pC) and higher emittance (5 π mm mrad), are well within the acceptance of the superconducting capture section. The pulse compression in the injector leads to a peak current of 2.7 A behind the injector. With a repetition rate of 10 MHz this is an average current of 50 μA which is within the limit of the available klystron power.

IV. Hybrid undulator

As an undulator a hybrid system was chosen which is described in [9]. It consists of blocks of rare earth cobalt (REC) permanent magnet material and poles of high permeable material. The poles concentrate the magnetic flux from the adjacent mag-

Table 3 Parameters of the hybrid undulator

Period / cm	3.2
Peak magnetic field / kGauss	3.63
K	1.08
Gap / mm	15
Pole width / mm	30
Pole thickness / mm	5
Number of periods	80
Length / m	2.56

nets on the electron beam axis and it can be shown that a sinusodial variation of the magnetic field in axial direction can be achieved. The advantages as compared to undulators consisting merely of permanent magnets are: (1) the magnetic field tolerances of the REC material do not influence the electron beam as in the pure REC design because the field distribution is mainly determined by the shape and tolerances of the poles thus steering errors are reduced significantly, (2) the field can be tuned externally using tuning studs and thus a higher field homogeneity can be achieved. The results of the design of this undulator which has been carried out with the two-dimensional magnet design code PANDIRA [10] are listed in Tab.3.

The normalized transversal acceptance of this magnet is A_n = 27.6 π mm mrad, the maximum possible energy spread of the electron beam is $\Delta E/E$ = $6.3 \cdot 10^{-4}$ as according to [11]. The design values of the accelerator (see Tab.1) are well within these limits.

V. Expected FEL performance

Two aproaches of calculating the performance of the FEL have been followed: (1) the gain, wavelength and output power were calculated by a standard formula as given in [11], (2) numerical simulations of the FEL have been made with the help of the computer code WIGOPT [12]. A comparison of the results is given in Tab.4. The simulation predicts slightly longer wavelengths than the theoretical calculations. This is due to the fact that the theoretical formula as given in [11] describes the maximum of the spontaneous emission, the radiation wavelength, however, increases when the lasing process sets in. The small signal gain is grossly overestimated by the theoretical formula as given in [11]. The reason is that an unrealistically mode area of the optical mode was used in the formula. The peak output power however is of the order of magnitude as predicted by theory and corresponds to optical cavity losses of 4% at 2.4 μm.

The emittance of the electron beam (see Tab.1) was included in the simulations and leads to a gain reduction of about 10% to 8.4 %/A. The slippage between the optical field and the electron beam was estimated by the formula given in [13] and leads to a gain of 58% of the value given in Tab.4. Another factor of two in gain reduction was assumed to be caused by field errors in the hybrid undulator described in IV. With a peak current of 2.7 A which can be achieved with the new injector described in III., the resulting gain should be 6.6 % which is well above optical cavity losses in this spectral region.

Table 4 Expected FEL parameters

Theory	
Wavelength / μm	2.4 - 4.9
Gain / %/A	62 (2.4 μm) 112 (4.9 μm)
Peak output power / kW	< 800 (2.4 μm) < 400 (4.9 μm)
Simulation	
Wavelength / μm	2.57 - 5.28
Gain / %/A	9.4 (2.57 μm) 13.0 (5.28 μm)
Peak output power / kW	484 (2.57 μm) 321 (5.28 μm)

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