THE ELECTRON ACCELERATOR FOR FELIX

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We discuss the design of the electron accelerator for the Free Electron Laser for Infrared eXperiments (FELIX), which is meant to provide the Dutch science community with a rapidly tunable source of infrared radiation. The first stage of the project will (at least) cover the wavelength range between 8 and 80 μm. The accelerator consists of a triode with a grid modulated at 1 GHz, a 3.8-MeV buncher, and two travelling-wave S-band linac structures, with which 70-A, 3-ps bunches are accelerated to an energy between 15 and 45 MeV. The system has been designed to minimize the energy spread in the electron beam.

Introduction

The FELIX project involves the construction and operation of a rapidly tunable Free Electron Laser facility in the infrared and microwave region. The first stage of the project is intended to cover the range from 8 to 80 μm.

Presently we are finalizing the design of the accelerating system, which utilizes a 3-GHz linac with an adjustable exit energy between 15 and 45 MeV. The system should deliver microbunches with a peak current of 70 A and a duration of 3 ps. The corresponding charge per bunch is Q≈200 pC. The microbunch repetition rate is 1 GHz in order to restrict the average beam current to 200 mA, and hence to keep beam loading within reasonable limits. The high peak current is needed to achieve a gain in the FEL of at least 0.2 over one decade of the spectrum, as is required to reach saturation sufficiently long before the end of the 20-μs macropulse, and to overcome the insertion losses occurring when an intracavity etalon is applied. The latter will be done to achieve phase locking of the individual micropulses, which reduces the number of active modes of the optical cavity. It then becomes possible to provide radiation with a narrow bandwidth and a reasonably high power to external users.[1]

Motivation for the Choice of an S-band Linac

A review of the properties of various types of low energy accelerators in relation to FEL requirements was given by Saxon.[2] For FELIX, the required beam parameters, which dictate the choice of electron source, are challenging in terms of accelerator technology and require a special approach.

Energy considerations alone rule out the VandeGraaff machine, the highest achieved energy of which is 20 MeV at Daresbury. The average beam current requirement also rules out this approach. The conventional microtron might be capable of covering the energy range, but only in discrete steps. It would also be impossible to produce the short length of micropulse, although good energy spread and low emittance might be obtained. The average current requirement has not been achieved in a microtron, nor is it likely to be.

The race-track microtron offers more of a possibility, since the pre-injector allows more control of the injected beam properties. There is little published evidence about the emittance of high-current beams in RTMs. There is only one FEL proposal which used this device, that at Lund,[3] where a 3-A pulse of width 26 ps has been achieved. The energy would be in discrete steps, rather than continuously variable and the complications involved in the RTM structure do not seem justified for the present energy range.

The remaining choice is the linac. In principle this could be L-band, though one would have to choose 1.3 GHz rather than 1 GHz as the modulation frequency because of the availability of power sources. Cost and technical considerations rule out this choice, so one is left with an S-band linac. However, the beam is modulated and bunched at 1 GHz before injection into the 3-GHz structures.

Besides these accelerator related considerations, there is a second motivation for the choice of a linac: the ps-length of the light pulses produced with S-band-linac based FELs makes it possible to do *time-dependent* spectroscopy of, for instance, semiconductor surfaces, a field into which a rapidly growing interest can be observed. At FELIX, we intend to push the maximum wavelength at which ps-pulses can be made to a value far above the present state of the art.

As regards the electron source, the SLAC type of gun has been ordered from Hermosa Electronics.[4] This is partly because of its low emittance, partly because it operates at 100 kV, which is a suitable value for manipulation of the beam, but mainly because it can give direct modulation of the beam at 1 GHz by the application of a signal of this frequency between grid and cathode. By biasing the grid well below the cut-off voltage, it can be ensured that emission only occurs over a 90° phase range. Such an arrangement was used at the UK-FEL project,[5] and is currently in use in the injector for the Daresbury SRS storage ring.[6]

The development of laser-driven cathodes, incorporated in high field rf cavities, has been noted with interest.[7] At FELIX it was felt that the reliable and continuous operation of these devices needed to be demonstrated before they could be considered for this facility, especially in view of the high vacuum in which they must operate.

The Injector Philosophy

The injector system is designed to give the required compression of the bunches whilst maintaining a low energy spread. It is shown schematicaly in Fig. 1. As mentioned above, the rf modulated gun is expected to emit only over a 90° phase range, thus giving some phase compression whilst ensuring the needed 1-GHz repetition rate of the bunches. Much more compression is caused by the 1-GHz prebuncher cavity. Since the bunch only has +/- 45° phase spread at the input to this cavity, there is an approximately linear relationship between bunching forces and phase error. However, the degree of bunching is limited by space charge forces, so it is best to use a high field and a correspondingly short drift distance. Present studies centre around an effective peak voltage of 50 kV, given by creating a gradient of 1 MV/m over 5 cm. PARMELA studies, for a bunch of charge 500 pC, show that it is possible to compress the bunches so that over 90 % of the electrons lie within a 10° range, corresponding to 30° at 3 GHz. The optimum drift distance is about 19.5 cm from the centre of the cavity.

The buncher is designed to give a further reduction to 6° whilst accelerating the electrons to 3.8 MeV. The final compression to 3° is expected to take place in the relativistic travelling-wave sections of the accelerator which takes the beam to its final energy. This is ensured by the special buncher design which reduces the phase spread smoothly, that is, particle phase trajectories do not intersect for a wide

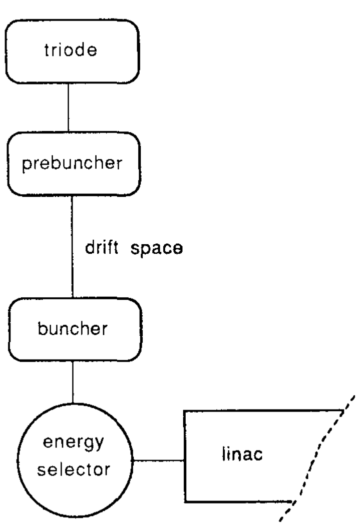

Figure 1. The electron injector.

range of input phase. The output, therefore, has the unambiguous phase-energy relationship needed to give further compression in the later sections.

The buncher employs 14 cells in the $2\pi/3$ mode, and has a total length of 43 cm. Because of the relatively high field gradients it will use the full output of a 20-MW klystron. After traversing the buncher the residual power of 16.5 MW will be used, after suitable power division and phasing, to feed the travelling-wave sections.

It is anticipated that some energy selection will be needed following the buncher. For this reason the calculations have assumed a higher bunch charge than the final specified requirement for the FEL of 200 pC. PARMELA studies are continuing and initial results are encouraging. Of course, the studies include radial effects and the use of solenoids to confine the beam. The low emittance of the beam from the gun provides a good start in limiting emittance growth in the prebuncher and buncher. It is expected that the beam emittance can be kept well within the required value of 50 π mm mrad.

The Accelerating Sections

A schematic view of the layout of the accelerating sections and the undulators is shown in Fig. 2. Two S-band constant-gradient structures with the following properties are used: $2\pi/3$-mode, l=3.15 m, τ=0.41, r=57 MΩ/m. The energy range between 15 and 25 MeV will be covered with the first structure; the required rf power is 3-7 MW (at i=0.2 A). The energy range between 35 and 45 MeV is reached with the second structure. With this twin-structure strategy, a considerably better beam quality can be obtained than with a single accelerating structure; in that case, the electric field at the end of the machine would drop to an unacceptably low value when operating at the lowest required energies. Further, the phases of the two sections can be manipulated in order to minimize the energy spread.

Numerical calculations of the obtainable energy spread were done as follows. The linac is divided into a large number of cells, in which the particle velocity, the particle phase with respect to the rf wave, the bunch length, and the electric field are all assumed to be constant. In the cell at position z, the energy gain of the electron at the center of the bunch is determined from $dT/dz= E_o\cos(\phi)-E_b$, where E_o and E_b denote the no-load field and the beam-induced field *in situ*, respectively. The phase shift is determined straightforwardly from the difference in velocity of the electrons and the wave. The energy gain and phase shift of the electrons at the edges of the bunch are determined in a similar way, where we take into account that the electron at the leading edge feels an extra accelerating field E_s, whereas the particle at the trailing edge feels a decelerating field E_s, due to the space charge in the bunch. The space charge field is determined assuming an ellipsoidal bunch shape. This procedure gives the energies and phases at the exit of the cell in question, which serve as input parameters for the next cell. This way, we are able to determine the energy spread in the microbunch, δT, and the bunch length, $\delta\Phi$, as a function of z, at a constant klystron voltage V_k and beam current i. The influence of a variation of V_k or i is determined by repeating

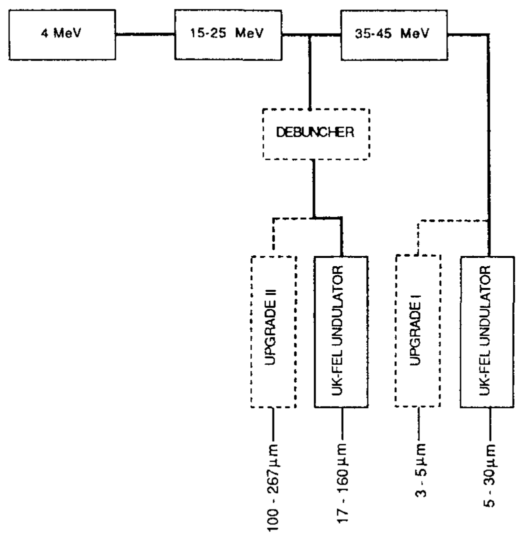

Figure 2. Basic layout of FELIX. Upgrades to be installed in Stage II are shown dashed.

this procedure with a slightly different input phase, rf power, and beam current.[8] This gives the energy spread, <δT>, averaged over all microbunches in the macropulse, where we define energy spread as the difference between the most energetic and the least energetic particle.

Results for exit energies of 15.2, 24.4, 35.4, and 44.9 MeV are presented in Table 1. Each row in this table contains two lines, showing for each of the two sections the input power, P_o, injection phase, Φ, exit bunch length, $\delta\Phi$, exit energy, T, and the energy spreads δT and <δT>. The bunch length at injection is taken equal to 6^o and the injection energy is taken equal to 4 MeV +/- 250 keV, where the 500-keV spread results from the bunching process. The bunch radius is taken equal to 1 mm. In determining <δT>, the jitter of the klystron voltage and of the beam current is taken equal to +/- 0.1 % and +/- 0.5 %, respectively.

Table 1. Results on longitudinal particle dynamics.

P_o [MW]	Φ [^{o}]	$\delta\Phi$ [^{o}]	T [MeV]	δT [%]	<δT> [%]
3.0	-16	4.0	15.2	0.2	1.0
-	-	-	-	-	-
7.0	-8	4.5	24.4	0.4	0.9
-	-	-	-	-	-
5.5	-10	4.4	21.4	0.5	1.0
4.0	-3	-4.3	35.4	0.2	0.9
7.0	-8	4.5	24.4	0.4	0.9
7.0	-3	4.5	44.9	0.3	0.9

It is seen that the bunch length at the exit of the accelerator is reduced with respect to the value at the entrance, due to bunching in the low-energy part of the first structure. Further, the energy spread amounts to <δT>≈1 % in the entire energy range from 15 to 45 MeV.

Expected Gain and Wavelength Range

We intend to use the undulator of the former UK-FEL project in Stage I of our project.[5] This planar undulator consists of 4 sections, each containing 19 periods of REC magnets with a wavelength of 65 mm. The maximum field on axis is B=4400 G. It can be adjusted by varying the gap width.

Two sections of the UK-FEL undulator will be placed behind the second accelerating structure, see Fig. 2. This undulator covers the wavelength range from 5 to 30 µm. Two other sections are planned behind the first structure, covering the wavelength range from 17 to 160 µm. In case our short microbunch length inhibits operation at these long wavelengths (where the slippage of the electrons relative to the optical wave packet might become problematic), a debuncher will be installed in the second stage of the project. With two new undulators, the wavelength range can be upgraded to 3-267 µm.

Our intention is to make wavelength scans via continuous adjustment of the undulator magnetic field, which is believed to be less complicated than continuous adjustment of the electron beam energy. The latter would involve simultaneous scanning of the bending and focusing optics between the linac and the undulator. A limited number of 'working points' for the linac (15, 25, 35, and 45 MeV) suffices to cover the wavelength range from 5 to 160 µm. Calculations of the amplification of the optical wave yield a single-pass gain between 0.2 and 0.5 over this entire range,[1] for the beam parameters in Table 1.

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