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Section A

Lasing experiments at TEUFEL

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Abstract

The waveguide structure of the resonator of the TEUFEL system has a significant impact on the resonance condition for lasing. The phase velocity of the modes in the waveguide shifts the resonance wavelength to larger values. Although this effect is known in Raman type FELs, it is less known that this mechanism has a severe impact on the resonance condition for Compton-type FELs. Due to this effect, various modes, that differ significantly in wavelength, can be resonant simultaneously. This paper shows that the mode spacing between adjacent modes can be as large as 5%, whereas, the gain bandwidth is not more than 1%.

1. Introduction

The wavelength of the light produced by a free-electron laser depends among other parameters on the relative velocity of the electrons with respect to the phase velocity of the light. It is obvious that for the production of coherent radiation, the phase of the light has to be constant. So, the important parameter is the phase velocity of the light in the medium where the light is generated. In Compton free electron lasers, usually the phase velocity is replaced with the speed of light in vacuum, without making too large errors. However, for the production of FEL light in a waveguide, even a highly overmoded one, one has to take into account the effect of the phase velocity on the resonance condition.

2. Resonance condition

In a simple one-dimensional model for free-electron laser working in vacuum, the resonance condition is normally presented in the following form [1]:

$$\lambda = \frac{\lambda_u}{2\gamma^2}(1 + K^2), \tag{1}$$

where λ is the wavelength of the FEL light, λ_u the undulator wavelength, γ the relativistic factor and K the undulator parameter. This equation is based on the fact that for most FELs the phase velocity of the light v_ϕ is equal to the speed of light in vacuum c. It is known that in Raman-type FELs this is not the case. For this type of FEL, the phase velocity of the light is affected by the collective motion of the electrons and usually the presence of a waveguide [2]. For Compton type of FELs, the effect of a change in the phase velocity due to the presence of a waveguide is less known. If the phase velocity is not equal to the speed of light in vacuum, the basic FEL resonance condition has to be applied, i.e.

$$\frac{\lambda_u}{v_e} = \frac{\lambda_u + \lambda}{v_\phi} \tag{2}$$

with v_e the longitudinal speed of the electrons. Substitution of the speed of light for the phase velocity and the proper expression for the longitudinal velocity of the electrons results in Eq. (1) for $\gamma \gg 1$. Any deviation of the phase velocity from the speed of light in vacuum will lead to a correction factor to Eq. (1). This is not only the case for waveguide modes, but also for finite Gaussian resonator modes.

In case of the TEUFEL system, a circular waveguide is used in the undulator with a diameter of 6 mm. The measured wavelength is around 250 μm. Given these parameters, one finds that the various circular waveguide modes are resonant at distinct wavelengths several micro-meters apart. In Fig. 1, the theoretical wavelengths are presented for the various circular waveguide modes as a function of the relativistic factor γ. The experimental verification is described below.

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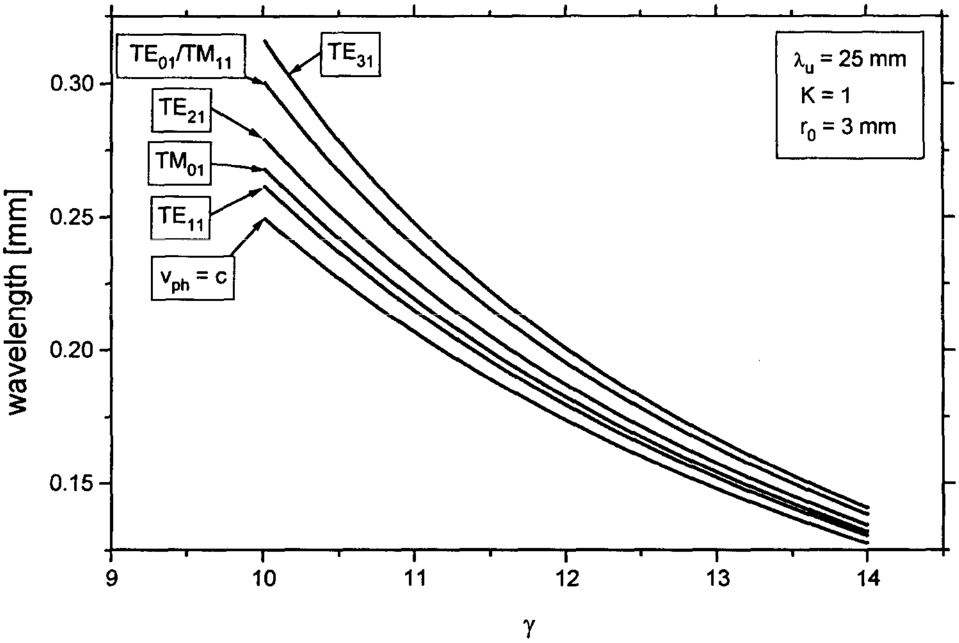

Fig. 1. Calculated wavelength for the various resonant waveguide modes as a function of the relativistic factor gamma.

3. Experimental setup

The TEUFEL system [3] consists of a CsK_2Sb photocathode LINAC that is driven by the frequency-doubled light of a Nd : YLF modelocked laser. The laser is operated at a frequency of 81.25 MHz, the 16th subharmonic of the RF-drive for the LINAC. The pulse duration (FWHM) of the laser micro pulses in the green is 21 ps.

The electron bunches are accelerated in the 5.5 cells LINAC to an average energy of 6 MeV. The electron beam is directed to the undulator via three sets of steering coils and two quadrupole triplets. The two quadrupole triplets are essential in order to obtain a matched beam in the undulator. The undulator is a hybrid one with 50 periods of 2.5 cm. The peak field is 0.7 T in order to operate the undulator with a K value of one. In the gap of 8 mm a vacuum tube is present with an inner diameter of 6 mm. Only at the place of the undulator the vacuum tube has this diameter. At the entrance of the undulator, a flat copper mirror with a hole of 2 mm diameter is mounted. At this place also, the diameter of the vacuum tube is reduced from 25 to 6 mm. At the exit of the undulator, a tapered section brings the diameter of the vacuum tube back to 25 mm in 40 cm. At the end of the resonator another flat copper mirror is placed on a translation stage. Also for this, the mirror-hole coupling is used to extract the electron beam as well as the produced FEL-light [4]. The hole in this mirror is optimized to 12 mm in diameter. This is an experimentally optimized value taking the total losses into account and the ratio of outcoupling between the entrance mirror and the exit mirror. The above shows that the resonator is a quite complicated one with respect to the optics. The vacuum tubes act as waveguides, both with their own mode structure. The mirrors act as mode filters due to different transmissions for various modes in the resonator.

The outcoupled FEL-light is extracted from the beam line by a metal mirror after the electron beam is bent down in the spectrometer. The exit window for the FEL-light is made of TPX in order to have minimum losses at 250 μm. At 1 m from the window, a Michelson interferometer is positioned in order to measure the wavelength of the FEL-light. One arm of the Michelson interferometer is scanned over a distance that exceeds the length of the optical FEL pulse. A fast Fourier transform reveals the wavelength spectrum.

4. Wavelength measurements

A typical wavelength spectrum is given in Fig. 2. Three distinct wavelengths are clearly visible. The mode structure in the wavelength spectrum appeared to be quite unstable with respect to the intensity of the individual modes. The relative spacing between the modes, on the other hand, was stable. Mode spacings measured are 11.0 and 10.8 μm. Calculated spacings between the lowest-order modes at 6 MeV are: 5.3, 7.8 and 6.5 μm for the

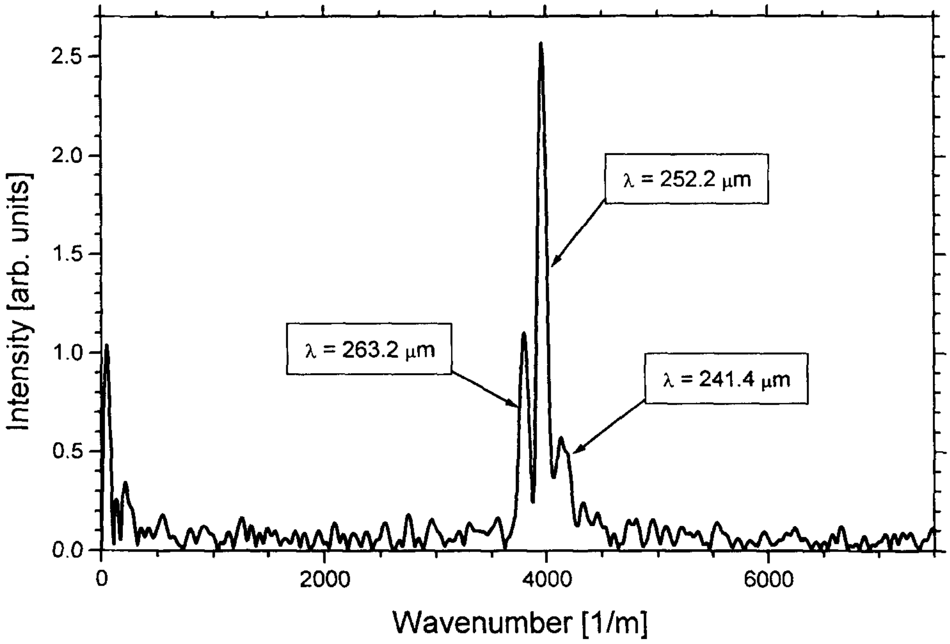

Fig. 2. Measured wavelength spectrum.

TE_{11}–TM_{01}, the TM_{01}–TE_{21} and the TE_{21}–$TE_{01}(TM_{11})$ spacings, respectively.

The fact that the measured spacings are larger than the calculated ones has probably to do with the fact that not all modes are present in the resonator. The presence of the various modes is highly sensitive on the gain and losses of the modes in the resonator. In the present configuration, it is hard to identify the various modes present in the FEL-light.

5. Concluding remarks

The main conclusion from these measurements is that due to the different phase velocities of the various waveguide modes, the resonance condition has to be used in its basic form. In the wavelength spectrum, various modes that are 5% apart can be resonant simultaneously. This was experimentally verified with the TEUFEL system.

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