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PERFORMANCES AND POSSIBLE USES OF FAR INFRARED FREE ELECTRON LASERS

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Abstract

In this paper the advantages of the realisation of a far infrared (FIR) free electron laser (FEL) are shown: it requires an electron beam with less stringent characteristics, less expensive and it is unique source for nonlinearity and coherence in FIR. The dependence of the FEL performance on parameters of the electron beam and undulator is described. For a given beam emittance there is a specific wavelength below which the gain rapidly becomes very low. The important physical phenomena in the FIR and possible uses of FIRFEL are given in broad outline, these studies could be important for the possible development of a THz electronics.

Key words: Far infrared; Free electron laser.

I. Introduction

The free electron laser (FEL), based on stimulated emission of radiation from ultrarelativistic electron beams in an undulator (periodic transverse magnetic field) has caused great interest for its possibilities to extend the range of electron beam devices (travelling wave tubes etc..) to shorter wavelengths than the microwaves (cm-waves) used up to now. Since the first operation of a FEL oscillator in 1976, although slowly (as their construction is not easy), a number of FEL oscillators have been operated, in the range from mm-waves to the visible range. Some of them are beginning or will soon be used as user facilities [1~4]. Efforts are under way to extend the range of FELs as far as possible into the VUV; however their possible actual use is not in the near future.

The Far InfraRed (FIR) region of the spectrum is the range extending approximately from 40 μm to 1 mm wavelength.

In this paper we want to show the advantages of the realisation of a far infrared (FIR) FEL particularly for three reasons:

1) The operation at longer wavelengths is less delicate and requires an electron beam with less stringent characteristics.

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2) As it requires a lower energy machine, a FIR FEL is less expensive than in the near IR.

3) There is a lot of interesting physics to do in the FIR with an intense, short pulse and tunable source, and the FEL is the only source having all these characteristics in the FIR.

First we describe the dependence of the FEL performance on its parameters, and then we indicate some of the fields of application in the FIR.

II. FEL characteristics

Let γmc^2 be the electron energy ($\gamma \gg 1$) and $\hat{I}$ the peak current, λ_0 the undulator period, and $K = eB_0\lambda_0/2\pi mc$ its "deflection parameter". The range of operating wavelengths is defined by[5,6]

$$\lambda = \frac{\lambda_0}{2\gamma^2}(1+K^2/2). \tag{1}$$

The efficiency can be of the order of 1/2 N (N = number of period), but even higher with a tapered undulator. The peak power is then $P_L \simeq \gamma mc^2 \hat{I}/2N$.

The important parameter determining how easily oscillation can be obtained is gain. The dependence of gain on wavelength is of course depending on which parameters we keep constant.

A condition that practically has to be satisfied to have a useful gain is that the electron beam is matched to the (diffraction-limited) mode of the emitted radiation in the cavity. That means that the electron beam transverse sizes are

$$\sigma_x \simeq \sigma_y \simeq (L\lambda/2\pi)^{1/2}, \tag{2}$$

($L = N\lambda_0$ length of the undulator) and the divergences

$$\sigma_{x'} \simeq \sigma_{y'} \simeq (\lambda/L)^{1/2}. \tag{3}$$

In accelerator terms, this means emittance

$$\varepsilon \simeq \lambda/2\pi, \tag{4}$$

and full coupling (equal vertical and horizontal emittances), and beta function of the order of $L/2\pi$. A smaller emittance would give the same gain, but it would be more difficult to get the same current.

Another necessary condition is that the electron energy spread should be small:

$$\Delta\gamma/\gamma \leqslant 1/2N. \tag{5}$$

The gain is also reduced if the electron bunch is shorter than $N\lambda$: so we should have

$$\Delta t \geqslant N\lambda/c, \tag{6}$$

Δt is the sliping time of one optical wavelength for each wiggler period, then it might be useful to use a "debuncher" (or "energy compressor") where $\Delta\gamma$ is decreased while Δt is increased [7].

In case, changing wavelength, we change the beam size and divergence in order to always satisfy the previous conditions, the gain can be expressed in the form

$$g \simeq 5.9 \frac{\hat{I}}{I_A} N^2/\gamma, \tag{7}$$

where $I_A \simeq 17045$ A is the Alfvén current, $\hat{I}$ is the peak current.

More conservatively, taking into account that when in eqs. 4, 5 equalities hold, there is a gain reduction of a factor~ 2, we could put 1 instead of 5.9 in eq. 7.

If the gain is high [8, 9, 6], the single-pass gain increases exponentially:

$$g_h \simeq \frac{1}{g} \exp(2.7\, g^{1/3}), \tag{8}$$

and there is the large accompanying optical phase shift.

But eqs $7 \sim 8$ are applicable only in the conditions (4, 5), while when some value exceeds these, the gain decreases very rapidly. Then for a given beam emittance there is a wavelength below which the gain rapidly becomes very low.

From the point of view of designing a machine for a given output wavelength, its emittance can grow in proportion to λ. If the obtainable current can be estimated to be proportional (for a given duty cycle and bunch length) to

$$\hat{I} \simeq B_e \gamma^2 \epsilon_x \epsilon_y, \tag{9}$$

with B_e depends on the electron gun and is of the order of $10^8 \sim 10^{10}$ A/m^2 (possibly up to 10^{12}).

In practice then eq. 7 can be writtenas:

$$g = AN^2 \gamma \lambda^2 = AN^2 \lambda_0^{1/2} \lambda^{3/2}, \tag{10}$$

where $A \simeq 150\,\mathrm{m}^{-2}$ for $B_e \simeq 10^8$ A/m^2 if we use the factor 1 (instead of 5.9) in eq. 7.

We see that even in the range of wavelength longer than the minimum defined by the beam emittance, the gain tends to increase considerably with wavelength.

Also, the lower value of γ necessary to reach a longer λ make the machine less expensive [10].

A table of examples, for an undulator with $\lambda_0 = 5$ cm, $N = 75$, $K = 1$ and an electron gun with $B_e \sim 10^8$ A/m^2:

γ	60	40	20
$\hat{I}$(A)	1	2.2	9
λ(μm)	10.4	23.4	94
g	0.5%	2%	15%

The effect of energy spread does not edpend on wavelength (see eq. 5): but the availability of a higher gain allows to use a lower value of N, a better tolerance to $\Delta\gamma/\gamma$ can be obtained, at the expense of a decrease in gain by a factor N^2: but the decrease in gain due to energy spread is exponential, so an optimum is found for a value comparable with the condition (5), with a peak current proportional to $1/N$. An "energy compression" could be good both for satisfying eq. 5 and eq. 6 (at the expense of a reduction in peak current).

The temporal structure of the light pulse (as long as the beam length is $>N\lambda$) is equal to that of the electrons, e.g. in linacs this is a few picoseconds. [11]

The linewidth is close to the Fourier transform limit:

$$\Delta\omega/\omega \simeq \lambda/2\sigma_s \tag{11}$$

III. Other FIR sources

1) Up to now, most of the work on FIR has been done with "blackbody" sources with Fourier-transform spectroscopic detection (with a Michelson interferometer). These are very weak incoherent sources and their use is limited to absorption spectroscopy.

2) Information on this spectral region can be obtained by Raman spectroscopy in the visible range. The physical information obtained is oftem complementary to the previous measurements, as there are different selection rules.

3) Several laser sources have been developed in the FIR: methanal, formic acid, etc., pumped by CO_2 lasers. These are coherent continuous-wave sources of many mW [13], and some studies of coherent radiation-matter interactions have been done with them [14]. However, although there are many lines, they are almost not tunable.

4) A widely tunable continuous-wave FIR sonrce can be obtained by mixing two singlemode CO_2 lasers on a point-contact diode [15]. However, the power is in the nano watt (nW) range, and it is not suitable, e.g. for nonlinear spectroscopy.

* In conclusion we see that the FEL offers the possibility of a source with wide continuous tunability, high peak power, short Fourier-transform-limited pulses, that are superior to all other sources.

IV. Physical phenomena in the FIR

The range of phenomena of interest in connection with the FIR spectrum is very wide. For example:[16]

—superconductor gaps have energies corresponding to the FIR.

—"hot" electrons in GaAs/GaAlAs junctions, sub-bands in GaAs/GaAlAs superlattices and quantum wells are phenomena showing FIR resonances and fast decays to be studied with short pulses, and their coherent and nonlinear behaviour is of interest in connection with possible electronic devices.

--plasmons in semiconductors can have all resonance frequencies from the visible to the FIR.

—low-energy electronic excitations of impurities in crystal lattice show narrow atomlike lines.

—molecular gas rotations[17].

—intermolecular vibrations in molecular crystals.

—antiferromagnetic resonances are often in the sub-mm range.

V. Possible uses of FIR FEL

Essentially, the whole FIR spectrum can be covered by blackbody sources or CO_2-point contact diode mixers. But there are essentially two aspects that are not studied by these sources, and only in a limited way by FIR gas lasers:

—high (instantaneous) intensities (which need high brightness) of FEL allows excitation of physical systems in the nonlinear regime.

—high intensity coherent (Glauber-state) short pulses allow coherent excitation of physical systems, that is to study phenomena that can not be described by "rate equations" alone, or, in terms used in microwave magnetic resonance, to measure the T_2 (dephasing time) as well as the T_1 (energy decay time).

Then, in thinking about the use of FIR FEL, one should not only think to the materials that have FIR resonances, but to the aspects for which the FEL is unique; nonlinearity and coherence.

It is probably only with the FEL that materials can be studied for their possible use as solid-state FIR sources, mixers, modulators etc..: and this might open the possibility of extending the microwave electronics to frequencies of the order of a tera Herz (1 THz$=10^{12}$ Hz).

In the last two years, some experiments have been done with the Santa Barbara 100~400 μm FEL [1].

VI. Example: the Hefei (USTC) linac FEL

At the USTC in Hefei (Anhui), an experiment is under way to study a linac-based FEL at 10 μm wavelength [18]. At present the linac beam characteristics have still to be improved in order to obtain enough gain for oscillation at 10 μm.

It is interesting to see how operation at 100 μm would give a higher gain and could be obtained with a lower beam quality. The present characteristics are: $\gamma=40\sim80$, $\epsilon=5\pi\,10^{-6}$ m. rad, $\Delta\gamma/\gamma\simeq10^{-2}$.

With an undulator of 98 periods of 3 cm and $K=0.8$, the output at $\gamma=44$ is $\lambda=10\,\mu$m.

The gain is very low because eq. 4 is not satisfied (and some reduction comes also from eq. 5).

At 100 μm eq. 4 would be satisfied, and the gain, with $\gamma=15$, would be more than 20%, which is comfortable. The same could be obtained at $\gamma=30$ with an undulator with $N=75$ and $\lambda_0=10\,\text{cm}$.

VII. Conclusions

It seems not only realistic and less expensive to aim first at realising a FEL in the FIR (before aiming at near IR or UV), but also there is a particular interest in the fact that many nonlinear and coherent phenomena in the FIR can be studied almost only with the FEL (while, e.g. in the near IR and visible there are high peak power, tunable lasers, continuous-wave or short pulse (Fourier-transform limited), as well as mirrors, modulators, fibres,....), and these studies could be important for the possible development of a THz electronics.

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远红外自由电子激光器的性能和可能的应用

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提　　要

本文提出了远红外自由电子激光器(FIRFEL)的现实优点：对电子束质量要求不太苛刻；比较经济；对远红外区的非线性和相干性研究是唯一的合适的光源。分析了自由电子激光器增益与电子束和摆动器参量的关系，指出对给定的发射度存在一特定的波长，当波长比特定波长短时，增益将急骤下降。概述了远红外区的重要物理现象以及远红外自由电子激光器的可能的应用，预期这些研究对THz电子学发展是很重要的。

关键词：远红外，自由电子激光器

（上接706页）

例如：6·5科技规划攻关项目——激光大功率国家基准，专家组鉴定认为该项目达到国际先进水平；美国国家标准局激光大功率测量人士观后认为远远超过他们，并拟1991年6月来人洽谈购买该基准器。

此外，“多孔径干涉扫描拼接检测法”，通过二个小孔径参考波面对被检大孔径表面作扫描干涉采样，以子午干涉图进行转换、拼接，精确测得大孔径表面的波面值，也具有国际水平的论文。

2．科学技术向生产力转化的文章比其它学科多，例如这次学术会议上不少文章是介绍一种实用的测试法或一种参量的基准，充分表现光测试学科的自然特征——生产性的学科。

3．参会少员年轻的科技人员多、博士、硕士研究生多，这说明光测试专业后继有人。

4．不少文章为光测试专业提出了要求，说明科学技术的发展迫使光测试学科开拓新的领域。

在学术交流会期间，光测试专业委员会选出了第二届专委会委员。原主任委员潘君骅研究员坚持让贤，经协商一致选出华东工学院光电子工程系系主任陈进榜教授为二届专委会主任委员。

会议还一致同意五届光测试学术交流会于1993年在山东省曲阜市召开，由副主任委员李国华教授主持筹备。