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The effect of a Bragg reflector on the spectral stability of the Twente Raman free-electron laser

P. Zambon[a], W.J. Witteman[a], P.J.M. van der Slot[b,]*

[a] *Department of Applied Physics, University of Twente, P.O. Box 217, 7500 AE Enschede, Netherlands*
[b] *Nederlands Centrum voor Laser Research, P.O. Box 2662, 7500 CR Enschede, Netherlands*

Abstract

The spectral distribution of the Twente Raman FEL has been studied as a function of the interaction length for an amplifier configuration. A stable spectrum was found for the minimum required interaction length necessary for the RF signal to be detected. Large variations in total emitted energy are observed however. With increasing interaction length the spectral distribution not only evolves but deviations are also observed, i.e. for some shots distributions are found which do not conform to the average distribution. For even longer interaction lengths the spectra can be grouped in a few different patterns. The influence of the feedback on the spectral distribution has been studied by changing the configuration to an oscillator using a Bragg reflector. For all settings investigated, the oscillator showed a more stable spectrum, i.e., less spread in total emitted energy as well as less spread in spectral distribution. For some settings operation on a single frequency in the K_a band was observed. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

The Twente Raman FEL (TR-FEL) can be operated as an amplifier by mounting a low reflecting outcouple horn on the end of the waveguide. Alternatively, by inserting a Bragg reflector [1] before the outcouple horn, the laser can be configured as an oscillator. The Bragg reflector has a reflection of 30% at 30 GHz for the TE11 mode with a bandwidth of approximately 1 GHz (FWHM). A Hamming window has been applied to the corrugation height to suppress side-lobes. The TR-FEL has been thoroughly described elsewhere [2] and only the main parameters are repeated here for convenience. The helical undulator has 40 periods of 3 cm each, with a cosine taper of 6 periods at the entrance. The central part of the electron beam, produced in a cold field emission diode by a 500 kV voltage pulse of 100 ns duration, is used for the FEL interaction and has a radius of 3 mm. The current is approximately 190 A.

The experimental setup for measuring the spectral distribution is as follows. The radiation

* Corresponding author. Tel.: +31 53 4893969; fax: +31 53 4891102; e-mail: p.j.m. vander slot@tu.utwente.ul.

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transmitted into free space by the outcouple horn is picked up by two standard K_a-band receiving horns, each mounted on a standard rectangular waveguide. These waveguides transport the radiation pulse towards a shielded room where each pulse is divided into three pulses using a three-way power divider. On each output port a cut-off waveguide filter is mounted with a crystal detector (HP R422C). The six output signals are measured using a fast digitizing two-channel oscilloscope by delaying two signals with 150 and 300 ns, respectively and combining them with a third signal for each oscilloscope channel. Low dispersion, low attenuation coaxial cables were used to provide the delay and a three-way matched resistive power divider/combiner was used to combine the three signals on one oscilloscope channel. The dispersion in the rectangular waveguide between the receiving horn near the laser and the detectors in the shielded room can be quite large. Therefore, for each filter the output signal is converted from voltage to power and integrated over time, thus giving the total energy passed through the filter. By subtracting successive filter signals the energy emitted in a wavelength band is obtained. The resolution obtained with this method was limited to 1 mm wavelength bands (determined by the cut-off wavelengths of the filters). Using a kicker magnet the electron beam could be stopped within 2 cm at different positions along the undulator.

As the TR-FEL uses some components which have an intrinsic stochastic character (like the field emission diode and gas switches in the Marx generator producing the voltage pulse) small variations in experimental parameters are unavoidable. When analyzing the data usually only shots are taken into consideration which fulfill certain selection criteria. In the following analysis only shots were taken into account for which the beam voltage amplitude was within 1.5% of 500 kV and the ripple was less than 1.5%. For all shots the current was approximately the same within 10% unless otherwise stated.

2. Amplifier configuration

It was demonstrated that in the amplifier configuration the total energy in the laser pulse reached its maximum for an interaction length, L, of about 75 cm [3] when the laser starts from noise (i.e., SASE). For longer interaction lengths the total energy slightly oscillates. Decomposing this into wavelength bands of 1 mm width with the waveguide cut-off filters, it was found that the spectrum was quite broad and the different bands have different growth rates and the energies in each band maximizes at different interaction lengths. As a first analysis of the data the measurements were summarized by averages over many shots. Information about the spectra of individual shots could only be extracted under the assumption that, for constant experimental parameters, the laser pulses all have the same spectral distribution. In view of the stochastic character of some of the experimental parameters and the fact that the system starts from noise this assumption may be questionable. Through the method described above, a rough estimate could be made of the spectrum belonging to a single emitted radiation pulse by simultaneously registering the output of six cut-off waveguide filters.

Spectral distributions for different interaction lengths are shown in Figs. 1–3. For these figures the energy at a cut-off wavelength of 11 mm is the total energy emitted in the interval $10\,\text{mm} < \lambda < 11\,\text{mm}$ (except for 8 mm where the interval is $\lambda < 8\,\text{mm}$). The error bars indicate the spread in the measured individual spectra. As a general guideline the spread increases with increasing average energy. Care has been taken to check that all spectral distribution were similar before they were averaged. As an example, Fig. 2 shows four spectra obtained for $L = 90\,\text{cm}$. Three of the four spectra are quite similar while the fourth (triangles) has different characteristics and is excluded from averaging. In general the shot to shot variation in the fraction of energy emitted within a 1 mm wavelength range, e.g. from $10\,\text{mm} < \lambda < 11\,\text{mm}$, is found to be of the order of 10% or less when the spectrum is included in the averaging used in Figs. 1 and 3. For an interaction length of less than 60 cm the signals were below the detection limit. The spectral distribution was observed to be very stable at $L = 60\,\text{cm}$ (Fig. 1). Most wavelength bands show maximum gain between 60 and 65 cm where the increase of the total emitted energy

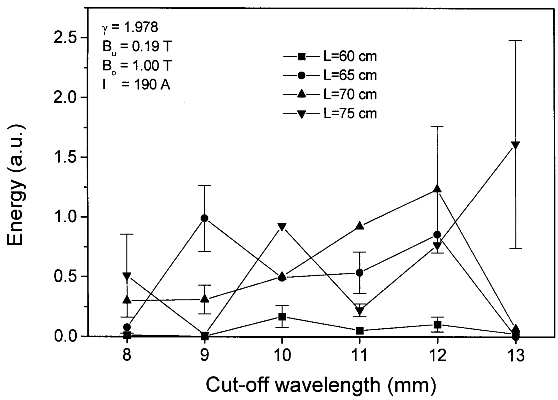

Fig. 1. Spectral distribution for L ranging from 60 to 75 cm. The energy at a specific cut-off wavelength, e.g. 10 mm, is the energy measured in the wavelength interval from 9 to 10 mm.

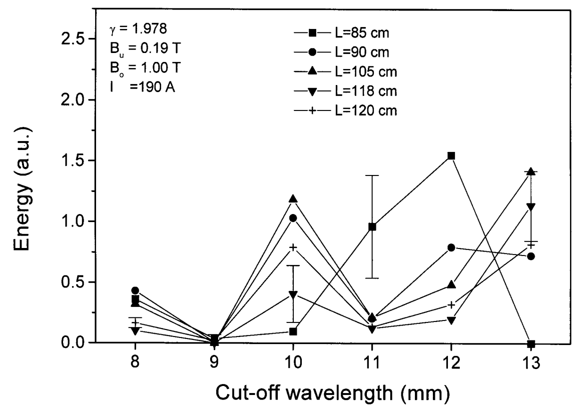

Fig. 3. Spectral distribution for $L = 85$ cm to the end of the undulator (= 120 cm).

corresponds to about 1.8 dB/cm. Only the bands $12 < \lambda < 13$ mm showed a gain of 2.8 dB/cm between 70 and 75 cm and for $9 < \lambda < 10$ mm a maximum gain of 2.1 dB/cm was found between 85 and 90 cm. Increasing the interaction length from 60 to 75 cm one observes that for $8\,\text{mm} < \lambda < 9\,\text{mm}$ the energy reaches a maximum and drops back to zero for $L = 75$ cm, whereas for $\lambda < 8$ mm the emitted energy gradually increases. At the longer wavelength side of the spectrum, $12\,\text{mm} < \lambda < 13\,\text{mm}$, no energy is detected for $L < 70$ cm after which it grows rapidly to a maximum at 75 cm interaction length (Fig. 1). It should be noted that only for $L = 75$ cm an occasional spectral distribution was found which deviates strongly from the averaged distribution shown in Fig. 1. The number

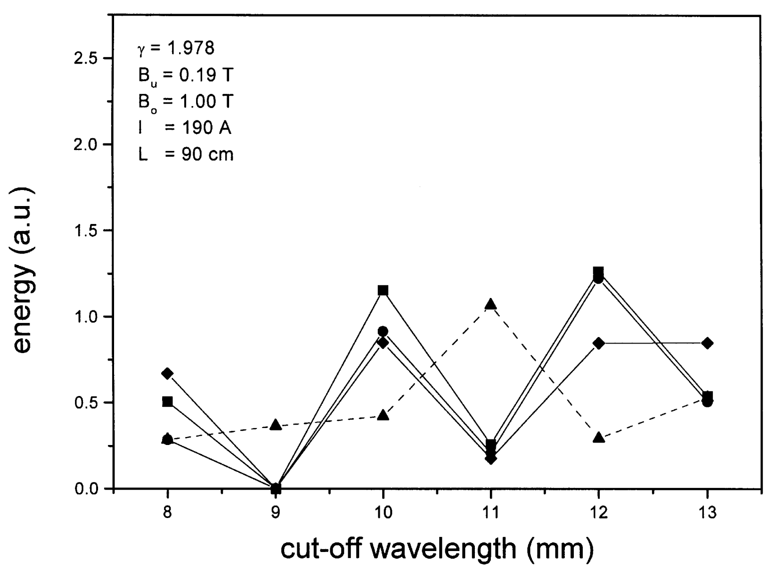

Fig. 2. Typical spectra measured for $L = 90$ cm. Three spectra are considered similar (squares, circles and diamonds) whereas the fourth (triangles) has different characteristics.

of occurrences was too small to determine if more than one stable distribution was present. The corresponding spectra were not included in the averages presented in Figs. 1 and 3. Increasing L to 85 cm results in collapse of energy emitted for $12\,\text{mm} < \lambda < 13\,\text{mm}$ (Fig. 3). This results in a broad line emission from $10\,\text{mm} < \lambda < 12\,\text{mm}$. No emission is observed for $8\,\text{mm} < \lambda < 9\,\text{mm}$ and it remains zero for longer interaction length. For $L > 85\,\text{cm}$ the emitted energy is mainly concentrated in $9\,\text{mm} < \lambda < 10\,\text{mm}$ and $11\,\text{mm} < \lambda < 13\,\text{mm}$. Here, again a very occasional measurement was made which resulted in a spectral distribution with large deviations from those shown in Fig. 3. However, only at the longest interaction length, $L = 118$ and 120 cm the number of occurrences was large enough to establish two other stable spectral distributions with completely different characteristics, i.e., a sufficient number of radiation pulses had similar spectral distributions. The measured spectra were about equally distributed over the three types of spectra. As no evidence was found for several stable spectral distributions at shorter interaction lengths this may indicate that for large interaction lengths the evolution of the spectrum undergoes some kind of bifurcation which may be a sign that the evolution is becoming chaotic. Despite the inherent stochastic nature of the start-up of the laser and of some of the experimental parameters as small variations (in amplitude and ripple) of the accelerating voltage and current the spectral properties of the TR-FEL are quite stable in the sense that, for a specific interaction length, the spectral distributions found are in general very similar. However, the total energy contained in the laser pulses may show considerable variation. Only for the longest interaction lengths it was found that the spectra of almost all laser pulses could be divided into a few different (in our case three) approximately equally populated spectral distributions.

3. Oscillator configuration

By inserting a Bragg reflector before the outcouple horn an oscillator configuration is formed. The other mirror is formed by a flat mirror with a 6 mm diameter hole at the center. Note that the Bragg condition [2] can be fulfilled not only at the design frequency which results in reflection in the TE_{11} mode but also at higher frequencies which results in reflection in higher-order modes. Outside these bands the reflector is transparent. In principle the Bragg reflector can influence the laser properties outside its reflection bandwidth because of line competition. Also this configuration starts from noise.

The effect of the Bragg reflector has been studied by measuring the output spectrum for the full interaction length for an undulator field of $B_u = 0.12\,\text{T}$ and a guide magnetic field B_o varying from 0.95 to 1.05 T for both the amplifier and oscillator configuration. First the total energy in the laser pulse was measured using a crystal detector (i.e., a high-pass filter was present in the form of the K_a-band waveguide). It was observed that in all cases the energy measured in the oscillator configuration was less or equal to those measured for the amplifier. The measurements performed with the oscillator showed however a significant lower shot to shot spread, up to a factor of 4 for $B_o = 0.98\,\text{T}$.

Examples of the spectral distributions measured for different settings of the guide field are shown in Fig. 4. All measurements are included in the averaging process, however, only for the oscillator configuration all spectra are similar. Fig. 4b shows that for $B_o = 0.98\,\text{T}$ the oscillator produces basically a single line ($10\,\text{mm} < \lambda < 11\,\text{mm}$) whereas the spectrum of the amplifier is much broader for the same setting. The position of the line falls within the reflection bandwidth of the reflector. Fig. 4d also shows single line operation of the oscillator for $B_o = 1.02\,\text{T}$ but now at a wavelength of $11\,\text{mm} < \lambda < 12\,\text{mm}$, which is clearly outside the reflection bandwidth of the Bragg reflector. No measurements are done for the amplifier for this setting. For an intermediate value of the guide field ($B_o = 1.0\,\text{T}$) there is hardly any difference between the amplifier and oscillator (Fig. 4c). In both configurations a broad spectrum is found which includes frequencies falling within the bandwidth of the reflector. For the remaining settings investigated in the range $0.95\,\text{T} < B_o < 1.05\,\text{T}$ the energy emitted in the range $9\,\text{mm} < \lambda < 11\,\text{mm}$ is slightly larger and outside this range it is slightly smaller for

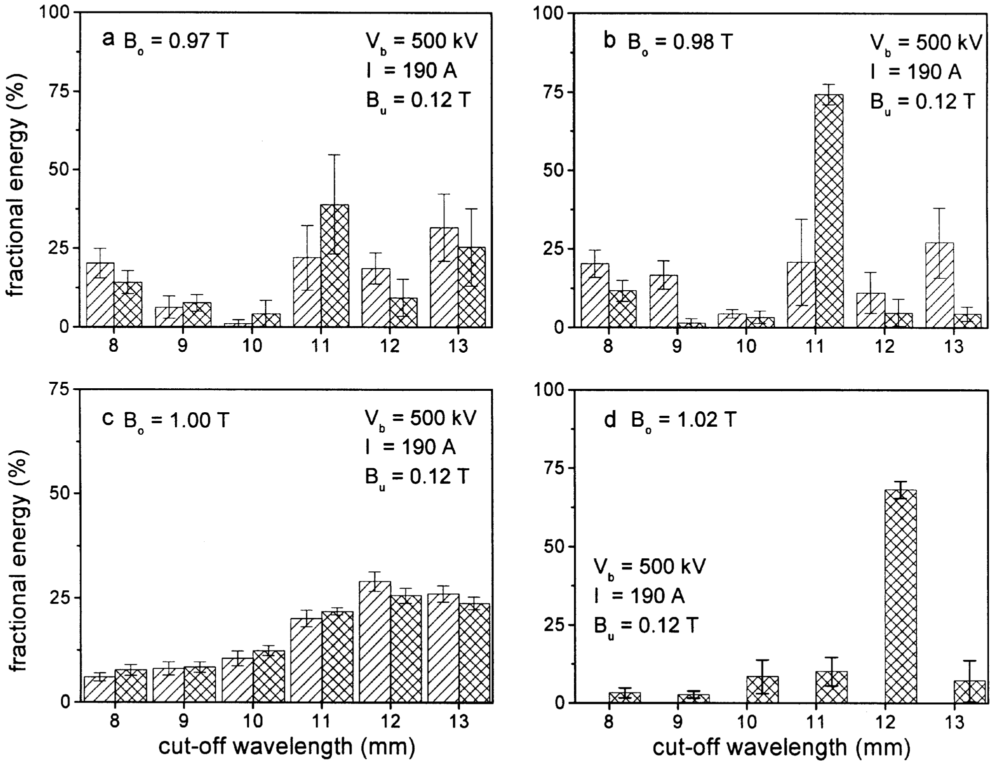

Fig. 4. Spectral distribution for different values of the axial guide field for the amplifier (hatched) and oscillator (cross-hatched) configurations.

the oscillator compared to the amplifier (see e.g. Fig. 4a).

As for the $B_u = 0.19$ T setting it was observed that for the amplifier the spectra corresponding to a single laser pulse were quite similar with an occasional deviation. However, contrary to $B_u = 0.19$ T, no signs of bifurcation were observed for the $B_u = 0.12$ T setting. With the exception of $B_o = 1.05$ T it was found that for the oscillator the spectral distribution of the laser pulses showed less shot to shot spread and for each setting the spectra of individual pulses were very similar contrary to the amplifier which produced an occasional laser pulse with a different spectrum.

Examples of the temporal structure of the laser pulses are shown in Figs. 5 and 6. Fig. 5 shows three typical laser pulses on the left side corresponding to the spectrum shown in Fig. 4c for the amplifier. For this configuration, occasionally a different spectral distribution was found. For two such pulses the time dependence is shown in the right part of Fig. 5. For the same settings Fig. 6 shows the corresponding time dependence found for the oscillator configuration. For the latter all measured spectra were similar.

4. Discussion and conclusions

Changing from an amplifier to an oscillator configuration has resulted in several improvements of the performance of the laser. For all but one setting investigated, the oscillator produced laser pulses with less shot-to-shot variation and also with a stable output spectrum. The spectrum however depends for $B_u = 0.12$ T strongly on the value of the axial magnetic field as can be seen in Fig. 4. As the central frequency for reflection of an incident TE_{11} mode to a reflected TE_{11} mode is the lowest for a given geometry, i.e. for all other modes the

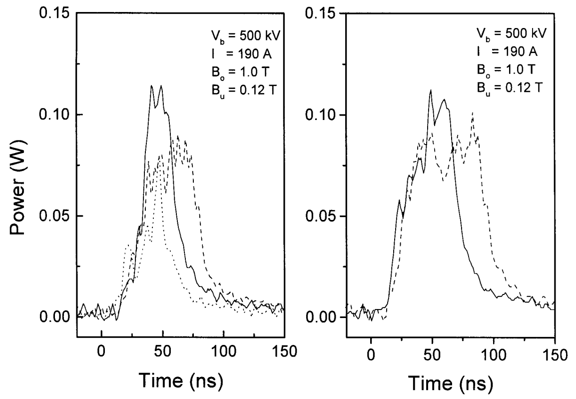

Fig. 5. Typical examples of time dependence of the laser pulse for the amplifier configuration. All curves in the left figure have similar spectral distributions, all curves in the right figure also have a similar spectrum though it is different from the left one.

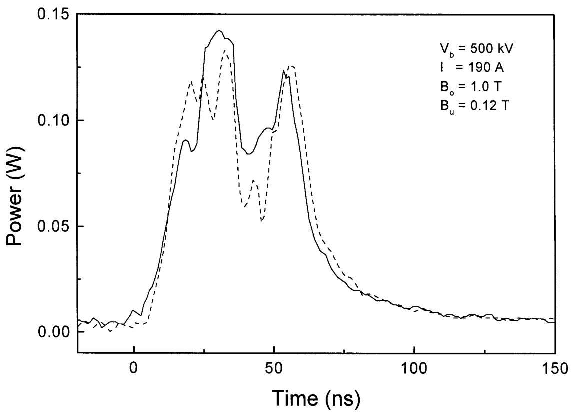

Fig. 6. Two typical examples of the time dependence of laser pulse for the oscillator configuration.

frequency at which reflection takes place is higher, the single line operation at $B_o = 1.02\,\mathrm{T}$ is rather unexpected since the central frequency is below the fundamental reflection band of the Bragg reflector. Unfortunately no data was available for the amplifier at this setting and, therefore, further research is required.

For other values of the guide field investigated the presence of the Bragg reflector seemed to promote emission around the fundamental reflection bandwidth while decreasing the energy emitted at their wavelengths. However, the spectrum still contained several lines. It should be noted that a theoretical analysis of the two configuration requires a true multi-frequency model of the FEL. The output for the full interaction length of the undulator was for the oscillator always less than for the amplifier. For a different setting of the undulator field ($B_u = 0.19\,\mathrm{T}$, $B_o = 1.0\,\mathrm{T}$) the interaction length was varied as well for the amplifier and it was found that the spectrum of the laser pulse was quite stable for interaction length close to the end of the undulator. Near the end of the undulator bifurcation was observed, which probably indicates a chaotic evolution of the spectrum.

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