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Status report of the Twente University Raman free electron laser

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We report successful operation of a Raman-type free electron laser situated at the University of Twente. It is based on a Marx generator, and uses a transmission line to produce a flat ($\Delta V/V \leq 2\%$) 500 kV voltage pulse of 100 ns duration. The parameters of the bifilar helical undulator are $\lambda_u = 3$ cm, $0 \leq B_u \leq 0.25$ T. The field emission diode and the undulator are immersed in an axial guiding field. The radiation is guided using a circular waveguide with 8 mm inner radius. We estimate the spontaneous power level, and give the calculated growth factor for a TE_{11} mode.

1. Description of the experiment

The Twente Raman FEL, configured as an amplifier (see fig. 1), is built around a Marx generator and uses a coaxial transmission line as a pulse forming network to produce a flat voltage pulse of approximately 500 kV ($\gamma \cong 2$). A low inductance gas switch filled with SF_6 is used to connect the transmission line to the field emission diode (FED). A second coaxial transmission line with the same impedance Z_0 as the first is used to suppress the prepulse on the FED which appears during charging of the first transmission line. The matching resistor is in principle optional, but it has several advantages. It limits the duration of the voltage pulse to twice the transit time of the first transmission line, i.e. 100 ns, since the impedance of the FED, Z_{FED} is higher than Z_0. Also the voltage pulse is less sensitive to the change of the diode impedance caused by the expanding plasma in front of the cathode. A disadvantage of the matching resistor is that the voltage over the FED is only half the loading voltage of the transmission line.

The electron beam produced by the FED is apertured by a hole in the anode and injected into the cylindrical waveguide. The apertured current I_a is transported through the waveguide with the aid of an axial guiding field which confines the beam. A pulsed, bifilar helical undulator with $N_u = 40$ periods (the first seven periods form the tapered entrance) converts the kinetic energy of the electrons into radiation energy. This energy is coupled out of the system using a low-reflectance horn. An overview of relevant parameters of this system is shown in table 1.

2. Spontaneous emission

A free electron laser with axial guiding field produces two kinds of radiation which can both take part in stimulated processes: the transverse electron motion due to the undulator and the electron cyclotron motion about the axial magnetic field lines both produce oscillatory transverse currents, of different frequencies, which are capable of driving different modes of the laser field. The incoherent radiant intensity due to the undulator field B_u is

$$\frac{dP_u}{d\Theta} = \frac{e^4}{4\pi\epsilon_0 m^2 c} \frac{\beta_z^2 B_u^2}{(1-\beta_z)^3} N_e, \qquad (1)$$

where N_e is the number of electrons in the undulator. With our parameters, this takes a value of the order of 1 W per steradian. For radiation due to cyclotron motion,

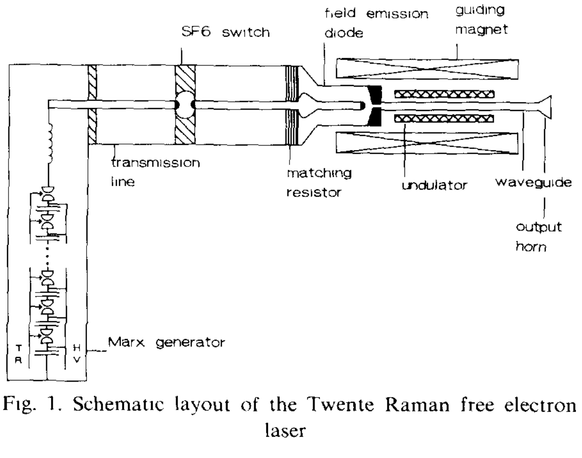

Fig. 1. Schematic layout of the Twente Raman free electron laser

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Table 1
An overview of the relevant parameters of the Twente Raman free electron laser

Field emission diode	
V_d [kV]	500
I_a [A]	600–900
d_{a-c} [cm]	1.0
τ [ns]	100 (matched conditions)
Bifilar helical undulator	
λ_u [cm]	3
N_u	40 (7 tapered)
B_u [T]	0.01–0.3 T
Axial guiding field	
B_z [T]	0.1–1.75
Radiation field	
Waveguide radius [mm]	8
Dominant mode	TE_{11}
λ_s [mm]	7 (FEL instability) 3 (cyclotron instability)
Spontaneous power [mW] (in solid angle of 2×10^{-3})	
P_{FEL}	~1
P_{cycl}	~0.1

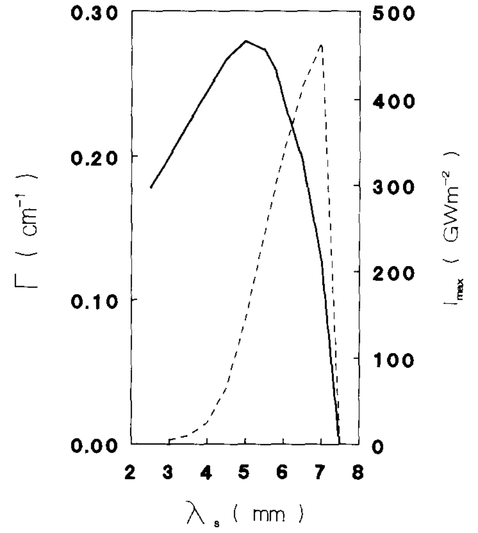

Fig. 2. The growth factor Γ (solid line) and maximum on-axis intensity I_{max} (dashed curve) as a function of free-space wavelength λ_s for a single TE_{11} mode. Model parameters are $N_u = 40$, $\lambda_u = 3.0$ cm, $\gamma = 2$, $I = 750$ A, $a_u = 0.2$, and 100 electrons were used (a_u is the dimensionless undulator vector potential).

$\beta_z B_u$ in the numerator of the above equation is replaced by $\beta_T B_z$, where $c\beta_T$ is the transverse velocity with which each electron enters the guiding field (considered here to be the same for all electrons). This takes a value ~ 0.1 W per steradian.

Feedback from the ECM field bunches the electrons azimuthally about the axial magnetic field lines, in a process similar to the normal FEL bunching mechanism. If the direction of the initial transverse motion is correlated with transverse position, the stimulated ECM process can also be enhanced by longitudinal variations in density [1]. The growth rate for the latter process can be comparable with that for FEL radiation [1].

3. Stimulated emission

Some preliminary calculations have been done to investigate stimulated emission. The model used [2] is

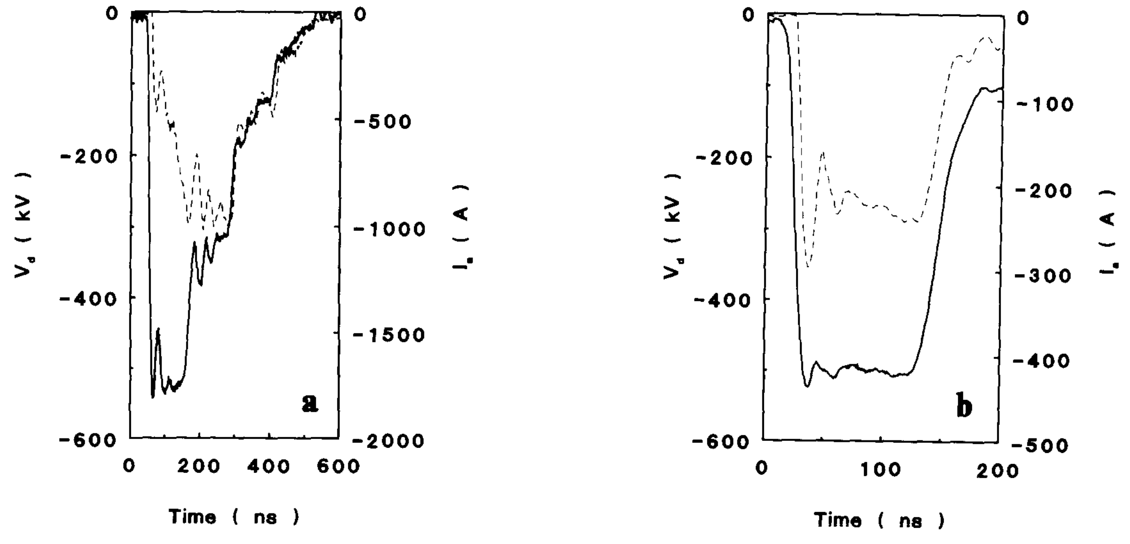

Fig. 3. Typical voltage V_d (solid line) over the field emission diode and the apertured current I_a (dashed line) for (a) anode–cathode distance $d_{a-c} = 1.0$ cm, no matching resistor, and (b) $d_{a-c} = 1.5$ cm, matching resistor installed.

one-dimensional in the electron equations and two-dimensional in the radiation field. Thus it assumes that the scale of transverse electron motion is small compared with transverse variation of the field. In general we can treat the radiation field as a superposition of vacuum waveguide modes and investigate, e.g., optical guiding. For the calculations of the growth factor, however, we used only one mode, the dominant TE_{11} mode. In fig. 2 we plot the intensity growth rate, $\Gamma \equiv \mathrm{d}/\mathrm{d}z\{\ln(I(z)/I(0))\}$, against the free-space wavelength λ_s. Also the maximum on-axis intensity obtained in the undulator is plotted. It can be seen that although a large interval of wavelength shows exponential growth, only a relatively small interval contributes to the final energy in the pulse.

4. Experimental results

We are able to control the apertured current I_a by changing the guiding field strength or the anode–cathode distance d_{a-c}. Both change Z_{FED}, thus changing the total current. It has to be noted that changing the guiding field influences the quality of the e-beam. In fig. 3 two typical shots are shown. The matching resistor was not present in fig. 3a, where $d_{a-c} = 1.0$ cm. Because of the high FED impedance, the voltage diminishes stepwise to zero. The oscillation at the beginning of each step is produced by an impedance mismatch at the connection of the first transmission line to the SF_6 switch. The time-dependent behaviour of the FED is shown by the increase in I_a due to the decrease of

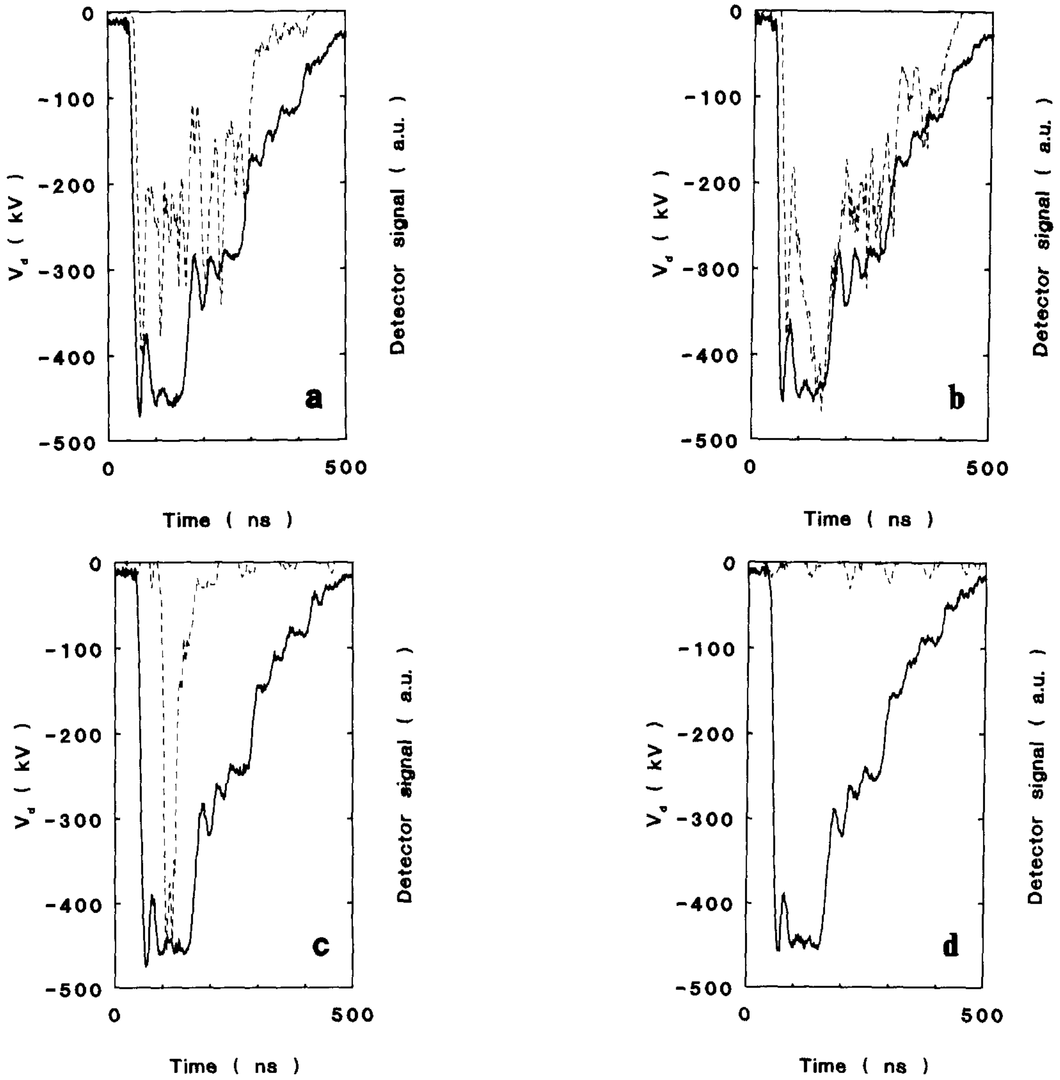

Fig. 4. Typical shots above magnetoresonance. Shown are the voltage V_d (solid line) over the field emission diode and the millimeter wave crystal detector signal (dashed curve) for the following combinations of guiding and undulator fields: (a) $B_u = 0.18$ T, $B_z = 1$ T, (b) $B_u = 0.28$ T, $B_z = 1$ T, (c) $B_u = 0.28$ T, $B_z = 0.3$ T, and (d) $B_u = 0$ T, $B_z = 0.3$ T.

Z_{FED}. At the end of the pulse a current of approximately 1 kA is obtained. In fig. 3b a matching resistor was installed and the oscillations at the beginning of the pulse have almost disappeared (note that the matching is not perfect). The change in I_a is less than in fig. 3a because the fractional change in Z_{FED} is reduced by the larger value of $d_{a-c} = 1.5$ cm ($Z_{FED} \propto d_{a-c}^2$). The current I_a dropped down to approximately 200 A. From the time dependence of $Z_{FED} = V_d/I_t$, where V_d is the FED voltage and I_t the total current in the FED, we estimated the velocity of the expanding plasma in front of the cathode to be approximately 1.1 cm/μs at $V_d \cong$ 500 kV. Fig. 3b shows that it is possible to produce a voltage pulse with $\Delta V_d/V_d \leq 1.5\%$ for 80 ns if the FEL is operated under matched conditions, i.e., the matching resistor is installed.

Very recently we have obtained successful operation of our FEL. Fig. 4 shows four typical shots done under unmatched conditions. In a FEL with an axial guiding field as well as an undulator one can distinguish two operating regimes, one below and the other above magnetoresonance [3]. For our experimental parameters magnetoresonance occurs near $B_z = 0.62$ T ($B_u = 0$), 0.26 T ($B_u = 0.18$ T) and 0.16 T ($B_u = 0.28$ T). Thus figs. 4a–4c apply to the regime above magnetoresonance. Calibration of the detector used (HP R442A crystal detector) has not yet been possible, but the measured signal levels are at least four orders of magnitude larger than the spontaneous power levels, which are ~ 1 mW at the position of the detector. In figs. 4c and 4d all experimental parameters are kept constant except the strength of the undulator field which was turned off in the case of fig. 4d. The power levels and the difference between figs. 4c and 4d indicate that we have obtained stimulated FEL radiation. It is not possible to determine from figs. 4a and 4b which part of the radiation is due to the FEL and which part to the cyclotron instability. Planned measurements of wavelength may give the answer.

The simulations mentioned above also show that saturation occurs well before the end of the undulator. This makes the interpretation of the measured signals as presented in fig. 4 difficult, so spatial growth and saturation will also be investigated in the near future.

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