DESIGN OF THE NIJMEGEN HIGH-RESOLUTION THz-FEL

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Abstract

In 2006, the Radboud University in Nijmegen received approval to realize a THz Free-Electron Laser (FEL) system and a 45 T hybrid magnet system. The THz-FEL system will be used in material science at high (30–45 T) magnetic fields, and applications e.g. in the field of biomolecular spectroscopy.

We here present the conceptual design of the Nijmegen THz-FEL. The FEL covers the 100–1500 μm spectral range and will operate in either a "spectroscopic mode" (spectral resolution better than 10^5) providing 100 Watt bandwidth limited pulses of several microsecond or "pump-probe" pulsed mode providing macropulses consisting of 3 GHz micropulses. Technical challenges are in achieving the required coherence for the narrow-band operation and in the 3 GHz operation of the source.

INTRODUCTION

At the Radboud University in Nijmegen (the Netherlands) a new THz-FEL facility will be constructed. The THz frequency range is highly relevant for biomolecular physics, solid state physics in high magnetic fields and security issues but lacks powerful and flexible sources. Although several FELs in the THz (mm-range) regime are operational [1, 2, 3, 4], the Nijmegen FEL is unique as it provides the ability to generate intense band-width limited pulses both with picoseconds duration and with microsecond time duration. The project was outlined previously [5] and is funded via the National (NL) Programme for Investments in Large Scale Facilities. Science drivers for the THz-FEL are:

- spectroscopy and dynamics of solid state materials in high magnetic fields, using pulse-echo's techniques e.g. following electron spin excitations or cyclotron resonances.
- dynamic nuclear polarization (DNP) experiments, potentially enhancing the sensitivity of NMR significantly, although it is realized that technological and system specific hurdles are enormous for a realization with a wide scope of applications.
- molecular spectroscopy of bio-organic molecules, biomimetics (analogues of biomolecules), and smart organic molecules, providing information on the structure of these molecules and on slow intra- and intermolecular motions related to their functionality.

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The THz-FEL and associated laser laboratory will be located in a new building adjacent to the already existing High Field Magnetic Laboratory. This paper summarizes the conclusions from the conceptual design study.

FEL SYSTEM REQUIREMENTS

It should be possible to run the Nijmegen THz-FEL in two distinct operating modes: a narrow-band "spectroscopic mode" (with spectral resolution $\lambda/\Delta\lambda > 10^5$) for high-resolution solid state and molecular spectroscopy, and a high-power "pump-probe" mode for non-linear experiments (employing high peak power and/or 5–80 ps time-resolution). Basic requirements for both operating modes are summarized in Table 1.

Table 1: General requirements of the Nijmegen THz-FEL for the "spectroscopic" and "pump-probe" mode

FEL parameter	spectr.	pump-probe
Spectral range	0.1 - 1.5 mm	
Bandwidth	10^{-6}–10^{-5}	0.5%–2%
Micropulse rep. rate	–	3 GHz
Macropulse rep. rate	10 Hz	
Macropulse duration	10-15 μs	
Macropulse power	100 W	>3 kW
Micropulse power	–	100 kW

The spectroscopic mode demands coherence of all micropulses, generating a 3 GHz frequency comb by a pulse train of phase-locked light pulses [6]. Extra-cavity filtering selects a single mode out of the frequency comb providing bandwidth limited narrow-band radiation. The effect of this technique on the spectral distribution of the FEL output is illustrated in Fig. 1. Figure 1A shows the typically 0.5–2% bandwidth (dashed-line) of the FEL as well as the longitudinal cavity modes (solid line) for a single incoherent micropulse. The mode spacing (20 MHz in our case) reflects the length of the FEL cavity, and typically 200-4000 modes are present within the FEL spectral profile. The macropulse averaged spectrum will show a similar mode-structure, although with strong intensity variations due to variation in

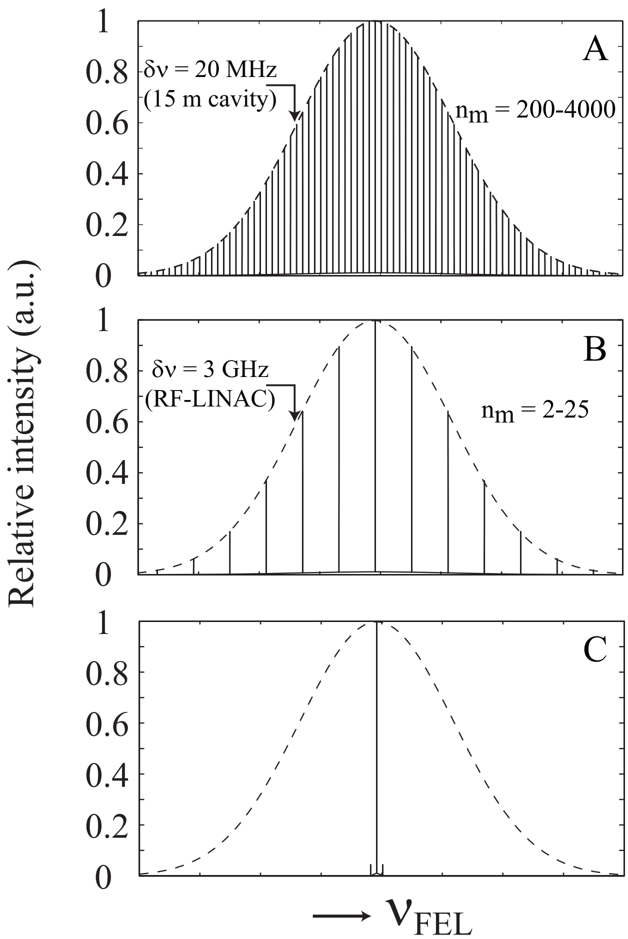

Figure 1: Spectral output of the FEL in case of single incoherent micropulse (A), fully coherent micropulse-train (B), and after extra-cavity filtering of the fully coherent micropulse-train (C). The dashed curve show the FEL bandwidth of 0.5–2% of the average FEL frequency, n_m is the number of modes underneath the FEL profile.

amplitude and phase of the individual micropulses. Figure 1B shows the 3 GHz spaced frequency comb imposed by the micropulse frequency that is realized when the micropulses are fully coherent, reducing the number of modes to typically 2-25, thus increasing the power per mode with more than two orders of magnitude. To obtain narrow-band operation from the coherent FEL output, filtering of a single 3 GHz mode outside the laser cavity is required. Figure 1C shows the expected mode structure after filtering, reducing the number of modes to essentially a single 3 GHz mode, possibly with some nearby low intensity longitudinal cavity modes still present. The output power is typically reduced by a factor of 10 or less while simultaneously the bandwidth is improved by a factor 10^3-10^4 yielding high power light of spectroscopic quality. Note that the high micropulse frequency (3 GHz) is preferred as a lower micropulse frequency increases the number of modes underneath the FEL profile, reduces the power per mode (and thus the power after filtering a single mode), and complicates extra-cavity filtering. Narrow bandwidth FEL operation using this mechanism has been one of the original design ambitions of FELIX [7], and has been realized in practice [8, 9].

CONCEPTUAL DESIGN OF NIJMEGEN THZ-FEL SYSTEM

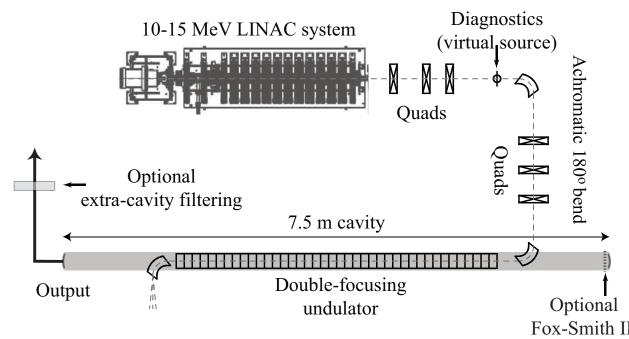

Figure 2: Schematic representation of the Nijmegen THz-FEL setup, showing LINAC system, electron beam transport system, optical cavity including undulator, and optional intra- and extra-cavity filtering required for narrow-band operation.

During the conceptual design study the main parameters of LINAC system, electron beam transport system, and laser cavity have been defined, initially using simulations based on established models and simulation codes. Finally, the design was verified by the General Particle Tracking (GPT) code [10]. The resulting design is schematically displayed in Fig. 2. It shows the LINAC system, the electron beam transport system, and the 7.5 m optical cavity. The optional intra- and extra-cavity filtering required for narrow-band operation is indicated in the figure as well.

LINAC System

The LINAC requirements are derived from the general system requirements listed in Table 1 and are summarized in Table 2. Clearly, a macropulse/micropulse structure is required. The requirements call for a normal-conducting high-power RF-based LINAC system.

During design of the LINAC system, transport and avoiding break-up of the high current beam received special attention. The LINAC system consists of a 90 kV thermionic electron gun, single cell stainless steel pre-buncher, 4-cell pre-buncher and 60-cell LINAC structure and can be operated using a single high-power klystron (maximum power up to 26 MW). PARMELA [11] beam dynamics simulations indicate a total beam loss of 3% (10 MeV) to 8% (15 MeV).

The beam dynamic simulations showed that in order to reach a good transmission the 3 GHz modulation needs to be performed directly at the electron source. This is the

Table 2: Design parameters of the RF-LINAC system

LINAC parameter	Value
RF frequency	3 GHz
Macropulse rep. rate	10 Hz
Macropulse duration	10–15 μs
Beam energy	10-15 MeV
Energy spread (rms)	0.3%
Beam charge	200 pC [a]
Micro-bunch duration (rms)	3–7 ps
Macropulse current	0.6 A
RF Power[b]	26 MW (10 μs)
	20 MW (15 μs)
Normalized Emittance	≈50 mm mrad
Macropulse Variation	<0.5%
Micropulse Variation	– [c]

[a] At the entrance of the undulator
[b] FEL should work on a single Klystron
[c] Controlled via feed-forward on RF phase and amplitude

biggest challenge for the LINAC system, and is currently being designed and will be tested in the near future.

Electron Beam Transport System

Main considerations for the design of the transport lattice (see Fig. 2) originate from the request of a robust and compact machine design with conservation of the beam quality parameters relevant for FEL operation. To this purpose a 180^o bend was designed which is achromatic in order to conserve the transverse emittance for a relatively large energy spread beam. This is realized by incorporating a quadrupole triplet symmetrically between the two bending magnets. The position of the quadrupoles was chosen to keep the maximum beam diameter reasonably small in both directions.

To keep the optical cavity as short as possible, all electron optics was placed outside the cavity, calling for a (double-)focusing undulator with an off-axis field increase in the dispersive plane. The free design parameters (quadrupole positions, dipole face angles) were chosen to match a virtual source in front of the bend to the undulator, which is a position well accessible for electron beam diagnostics.

The design of the dipole deflecting the beam from the undulator axis towards the dump is not completely finalized yet. A 90^o bend that allows positioning of the dump within one of the walls of the FEL laboratory, thus reducing efforts for radiation shielding, seems feasible. The preliminary design provides a diagnostic position to monitor the energy spread of the electron beam leaving the undulator, thus providing a basic tool for monitoring FEL operation.

Full beam transport calculations using PARMELA [11] corroborate all the results of the first-order calculations.

Optical Cavity

The millimeter wavelength range requires a waveguided cavity. The waveguide will consist of two 10 mm separated parallel plates perpendicular to the undulator magnetic field and extends over the full cavity length, reducing losses due to mode-conversion. The cavity mirrors for a waveguided cavity need to be cylindrical as they have to focus the beam in the wiggle plane only.

To produce electromagnetic radiation in the required spectral range the electron energy and undulator parameters need to be selected appropriately. As the electron beam energy was selected to be in the 10-15 MeV range for optimal electron beam stability, a 11 cm undulator period in combination with an undulator gap in the 24-85 mm range (K_{rms} = 0.5–3.3) yields the appropriate radiation. The optical cavity (see Fig 2) is 7.5 m long, largely determined by the 4.4 m (40 periods) long undulator.

The wavelength range and electron bunch lengths make clear that this is a very high slippage laser (the longitudinal coupling parameter μ_c=5-70, depending on the wavelength). In fact, initial simulations using the GPT code were performed to corroborate that the high slippage does not degrade the FEL-operation. Nevertheless, the short electron bunch length compared to the FEL wavelength implies a large amount of spontaneous coherence. One option for realizing full coherence between subsequent micropulses is to rely on spontaneous coherence [12]. Disadvantage of the spontaneous coherence option is the limited wavelength tunebility, only harmonics of the 3 GHz RF clock are expected. The wavelength can be tuned continuously, however, when it is enforced by an intra-cavity interferometer, such as a Fox-Smith interferometer as suggested in Fig. 2. As both sources of coherence will compete, spontaneous coherence needs to be reduced.

FEL PERFORMANCE SIMULATIONS

In the first stage of the design study, the FEL performance simulations concentrated on gain, start-up dynamics and saturation power. We have concluded that achieving full coherence between micropulses possibly will depend on details that require tests at the FEL system. Nevertheless, a simulation program concentrating on the coherence properties will be started. FEL performance simulations have initially been performed [13] using established FEL models [14] to verify the compliance with system requirements. Calculations demonstrate that the requested spectral range can be covered using the selected parameter set with sufficiently high single pass gain and saturation power, the latter being displayed in Fig. 3. The figure indicates that the saturation power easily exceeds the 3 kW minimum requirement for all combinations of electron energy and undulator parameters K_{rms}, both for a 3 ps and 6 ps electron bunch, with even higher saturation powers for the shorter bunch over the full wavelength range

With the parameters of the above-defined instrument concept full performance calculations using the GPT code

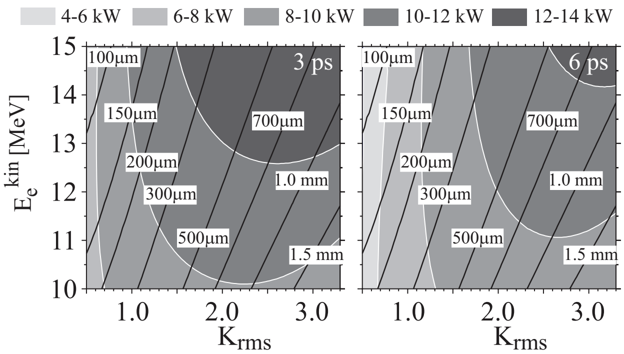

Figure 3: Calculated saturation power for 3 ps (left) and 6 ps (right) rms electron bunches

have been performed as well. An important measure for the performance of the system is the start-up time required to reach saturated output. These numbers have been determined for the extremes of the spectral range (100 μm and 1.5 mm) and for minimum and maximum coherent spontaneous emission (CSE), selected by proper choice of the cavity detuning δL_c. The simulations are performed with a 22% power loss per pass, including 7% outcoupling. Results of these simulations are visualized in Fig. 4 for a varying number of undulator periods. The figure shows that

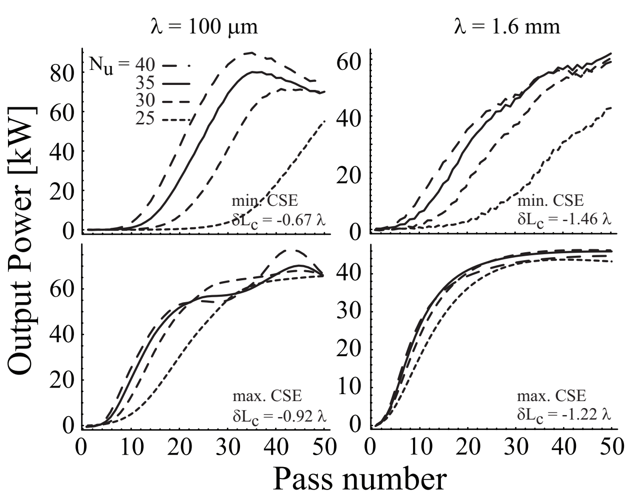

Figure 4: Start-up time calculations for minimum (left) and maximum(right) wavelength, both for minimum(top) and maximum (bottom) CSE conditions. Calculations are performed for 25, 30, 35, and 40 undulator periods (line-styles are indicated in the legend).

even for minimum CSE conditions, saturation is reached in about 50 cavity round trips (2.5 μs) at power levels readily exceeding the requirement, and thus confirms the feasibility of the conceptual design. Clearly, start-up for minimum CSE conditions takes longer than for maximum CSE. As at long wavelengths the start-up at maximum CSE is very fast even for N_u = 25 and single-pass output power (without mirrors) is comparable to the power requirements listed in Table 1, it can even be considered to not use the resonator at all and operate the system as a single-pass laser.

CONCLUSIONS

The Nijmegen THz-FEL will be combining a LINAC system based on proven RF-technology, an elegant electron beam transport system, and compact fully waveguided cavity. Performance simulations confirm that the system in high-power pump-probe mode operation will readily meet the requirements, and that single-pass, mirror-less lasing could even be considered for the longer wavelengths. Realization of narrow-band operation is most challenging, as it remains unclear if coherence of the micropulse train can be successfully realized during routine operation with continuous wavelength tuning.

ACKNOWLEGDEMENT

The Nijmegen THz-FEL is funded via the National (NL) Programme for Investments in Large Scale Facilities. RTJ and WJvdZ like to thank Dick Oepts from the FOM Institute for Plasma Physics "Rijnhuizen" for fruitful discussions on coherence.

REFERENCES

[1] U. Bizzarri, F. Ciocci, G. Dattoli, et al. Nuclear Instrument & Methods in Physics Research 208, (1983) 177

[2] G.Ramian, L. Elias, Nuclear Inst. & Meth. Phys. Res. A 272, (1988) 81

[3] A. Abramovich, A. Arensburg, D. Chairman, et al., Nuclear Inst. & Meth. Phys. Res. A 407, (1998) 16

[4] M. Yokoyama, F. Oda, K. Nomaru, H. Koike, M. Sobajima, H. Miura, H.Y. Hattori, M. Kawai, and H. Kuroda, Nuclear Inst. & Meth. Phys. Res. A 475, 38 (2001).

[5] W.J. van der Zande, F. J.M. Harren, A. P.M. Kentgens, J. C. Maan, T. H.M. Rasing, Proc. FEL 2006, Berlin, Germany, (2006) 485.

[6] Nobelprize 2005 shared by Hänsch, Hall and Glauber

[7] D. Oepts, W.B. Colson, IEEE J. Quant. Electr. 26, (1990) 723

[8] D. Oepts, A.F.G. van der Meer, R.J.Bakker, and P.W. Amersfoort, Phys. Rev. Letters, 70 (1993) 3255

[9] E.B. Szarmes, E.D. Madden, and J.M. Madey, J. Opt Soc. Am. B, 13 (1996) 1588

[10] http://www.pulsar.nl/gpt

[11] L.M. Young, J.H. Billen: Los Alamos National Laboratory, LA-UR-96-1835 (1996)

[12] D. Oepts, D.A. Jaroszynskis, H.H. Weits, P.W. van Amersfoort, Nuclear Inst. & Meth. Phys. Res. A 358, (1995) 72

[13] P.J.M. van der Slot, E. van Geijn, K.J. Boller, J. Jalink, W.J. van der Zande, Proc. FEL 2007, Novosibirsk, Russia, (2007) 163

[14] S.V. Benson, CEBAF TN#94-065