REALIZATION OF THE NIJMEGEN TERAHERTZ-FEL

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Abstract

In 2006, the Radboud University Nijmegen received funding to realize a narrow-band terahertz (THz) laser system and a 45 T hybrid magnet system to establish a center for advanced spectroscopy. The Nijmegen THz-FEL will combine a pump-probe pulsed mode with a spectroscopic high-resolution mode. After completion of a feasibility and system predesign study early 2008 and a technical design study early 2009, the review committees recommended to enter the realization phase. We here present the status of the design of LINAC system, cavity and optical distribution system.

INTRODUCTION

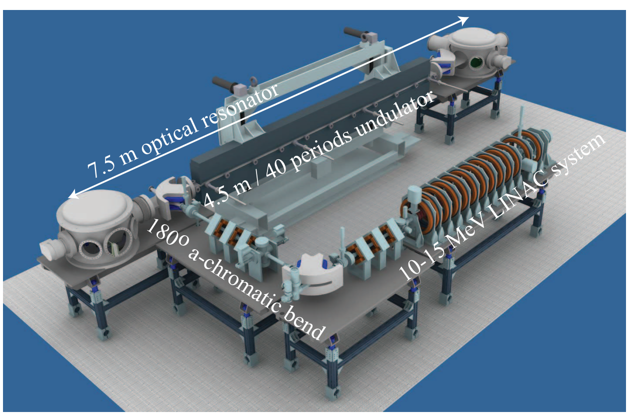

Figure 1: 3D design of the Nijmegen THz-FEL, showing LINAC, electron beam transport system, and optical cavity including 4.5 m long undulator.

The Nijmegen THz-FEL was funded in 2006 [1] based on only a preliminary system description. Its main specifications are summarized in Table 1. The FEL system, illustrated in Fig. 1, will provide output in the 100 μm to 1500 μm spectral range, while its most prominent feature is that it combines 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 10–200 ps time-resolution). The combination of the two operating modes, but especially the availability of the spectroscopic mode will make the Nijmegen THz-FEL a unique light source. Implementation of this operation mode will also be most demanding on accelerator specifications and optical cavity design. A more detailed analysis of the spectroscopic mode is presented in another contribution to this conference [2].

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Table 1: Main Specifications of the Nijmegen THz-FEL

General specifications	
Spectral range	0.1 - 1.5 mm
Micro-pulse frequency	3 GHz
Micro-pulse duration	10-200 ps[a]
Macro-pulse duration	10–15 μs
Repetition rate of macro-pulses	10 Hz
Electron beam energy	10–15 MeV
Undulator period	110 mm
Number of undulator periods	40
Undulator parameter K_{rms}	0.7–3.4
Optical cavity length	7.5 m
Short pulse mode	
Bandwidth	≈1 %
Micro pulse energy	> 3 μJ
Macro pulse energy	> 60 mJ
Narrow band, long pulse mode	
Bandwidth	10^{-5}–10^{-6}
Max. power	100 Watt

[a] Bandwidth limited

During the last few years, a feasibility study translating the desired system specifications into a realistic instrument concept was performed. This study, completed early 2008, determined the main instrument parameters on LINAC system, undulator, and cavity geometry [3]. The production of the LINAC system and electron beam transport system is commissioned to RI Research Instruments GmbH (a former ACCEL Instruments GmbH activity). The undulator is commissioned to DanFysik. The detailed design studies will be completed in fall of 2009 after which the production phase will commence. This paper describes the current status of the main system components: LINAC system, optical cavity, and optical distribution system.

LINAC SYSTEM

The LINAC system for the Nijmegen THz-FEL will be a normal conducting 10-15 MeV system consisting of electron source, single cell pre-buncher, (β-matched) buncher, and (fixed β) final accelerator section and is derived from the system developed and built for PTB-Braunschweig (Germany). The complete system, including the source, will operate at 3 GHz to allow generation of a frequency comb with large "tooth" spacing in the frequency domain, which will be beneficial for the spectroscopic mode [3]. For sufficiently high gain the use of high micro-bunch charge - in our case at least 200 pC at the entrance of the undulator - is required to reach saturation within the macro-pulse over the complete spectral range.

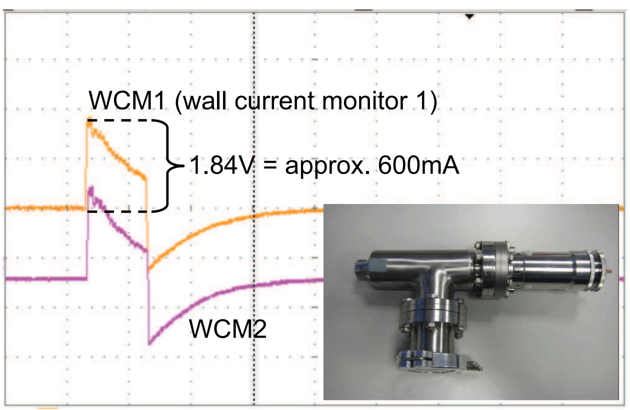

Figure 2: Proof-of-principle experiment: Oscilloscope trace of wall-current monitor signals showing that the 3 GHz modulated source can provide currents of 600 mA. The inset at the lower-right shows a photo of the source with connected matching circuit (right-hand side of the photo).

The combination of high bunch charge and high micro-bunch repetition rate is challenging in particular with respect to the design of the source, which will be modulated at 3 GHz as well. The electron source will consist of a thermionic cathode floating at a -90 kV extraction voltage for initial acceleration. A grid will be used to modulate electron pulses when the system is triggered. During the past year, efforts have been made to implement the 3 GHz modulation of the source. A dedicated matching circuit has been designed, produced, and tested. A photo of the source including matching circuit is displayed in the inset (lower-right part) to Fig. 2. It is demonstrated in Fig. 2 that even under less than optimal conditions (low extraction voltage, large cable lengths), an approximately 600 mA current was generated, providing strong confidence that successful operation with required specifications is feasible. Nevertheless, the complete electron source will be produced first to allow further optimization when required.

The design of the bunching section and final accelerator structure is still under discussion. The use of a β-matched 14-cell bunching section, as previously used for FELIX [4] so far seems to provide the optimal geometry. The requirement on 3 GHz operation of the complete accelerator system and high bunch-charge introduce non-negligible beam-loading effects, while anticipated operation at lower micro-bunch repetition rates (20 MHz operation results in a single optical pulse in the 7.5 m cavity) significantly reduces this effect. For this reason, the use of a low shunt-impedance bunching structure, minimizing the change in beam-loading effects when decreasing the repetition rate from 3 GHz to 20 MHz, is anticipated.

OPTICAL CAVITY

The optical cavity will be 7.5 m long and includes a parallel-plate waveguide (10 mm spacing) over the full length of the cavity. The undulator will be positioned in the center of the cavity, and will be 4.5 m long, consisting of 40 undulator periods of 11 cm length each and K_{rms}-parameter of between 0.5-3.4 [3]. At the upstream side of the cavity a Fox-Smith interferometer for imposing micro-bunch to micro-bunch coherence is optionally included. The realization of the interferometer within the waveguide poses challenges to the mechanical design. The upstream part of the

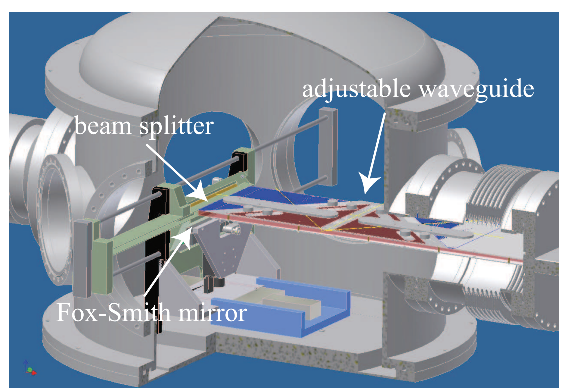

Figure 3: Design of the upstream mirror system, visible through a cut through the vacuum chamber. Left the Fox-Smith interferometer system with removable beam splitter. Right (in blue and red) the adjustable part of the waveguide required to allow cavity detuning over a 2-3 cm range.

cavity including the Fox-Smith interferometer is illustrated in Fig. 3. The round-trip length in the Fox-Smith interferometer is around 10 cm (corresponding to the micro-pulse distance at 3 GHz operation), because the Fox-Smith interferometer needs to couple the phases of subsequent micro-pulses. The short round-trip distance forces the Fox-Smith interferometer system to be assembled in the vertical plane perpendicular to the cavity axis and does not allow mounting in the horizontal plane, which would eliminate the interruption of the waveguide.

At the downstream-side of the cavity a fraction of the laser light is coupled out. Initially, an adjustable vertical slit (hole coupling) will be used, although in a later stage implementation of a Michelson interferometer is foreseen.

Both options are displayed in Fig. 4. Interferometric output coupling is advantageous as the light that is coupled out of the cavity does not deteriorate the mode-profile inside the cavity, thus eliminating additional intra-cavity losses compared to hole or slit coupling. The appropriate material for the intra-cavity beam splitters has to be selected. The beam splitter material needs to be thin, to withstand the high intra-cavity power, and preferentially to have a reflection coefficient that is wavelength independent.

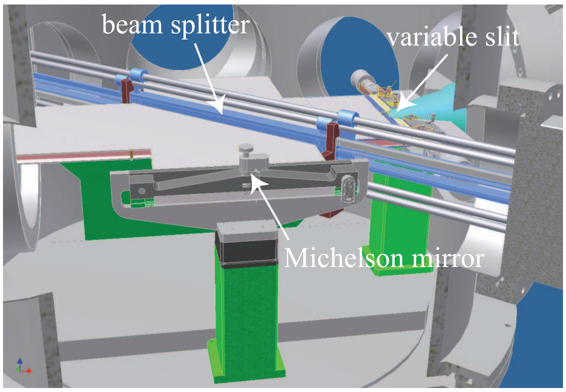

Figure 4: Design of the downstream mirror system. Right: adjustable vertical slit output coupler. Front: Mirror of the optional Michelson interferometer output coupler. The prominent mechanism is for the removable beam splitter of the optional Michelson interferometer.

As the optical distribution system transporting the FEL light to the diagnostics station and user stations starts with a strongly focusing mirror, and thus the distance to this mirror needs to be fixed, it is decided to implement the cavity detuning at the upstream side of the cavity. With the anticipated presence of the Fox-Smith interferometer at this side of the cavity, and the magnitude of the required detuning range (2–3 cm due to the relatively large group-velocity change caused by the presence of the waveguide), it implies that the complete Fox-Smith interferometer system should be part of the cavity detuning mechanism, and that the waveguide is adjustable in length as well. The latter is realized by introducing a wedge-like structure close to the upstream mirror, as illustrated in Fig. 3.

For alignment of both the cavity- and interferometer mirrors as well as the optical distribution system, an alignment laser will be coupled on-axis into the cavity. The cavity length will be monitored during operation using a stabilized HeNe-laser based interferometer system allowing sub-micron stabilization. The latter is of particular importance to reach the required stability during operation in the spectroscopic mode.

OPTICAL DISTRIBUTION

The optical distribution system uses reflective optics to maintain the temporal structure and to ensure a high transport efficiency. The design of the optical distribution system is demanding because of the long output wavelengths, the large spectral range (a factor of 15 between the shortest and the longest wavelength), and the large distances to the diagnostics station and user stations in the dedicated laser laboratory as well as in the adjacent High-Field Magnet Laboratory (HFML); the longest wavelength, 1.5 mm, with the associated strong diffraction effects means that large diameter (vacuum) tubing and mirrors (250 mm effective diameter) need to be used with refocusing elements every 8-10 m. A draft design of a refocusing module is illustrated in Fig. 5. The distribution system is designed to allow implementation of both hole-coupling and interferometric output coupling. The beam envelope for 3.5 times the beam waist (in the Gaussian-beam approximation) is illustrated in Fig. 6 both for a 4 mm slit (to be used for the longest output wavelength) and interferometric output coupling.

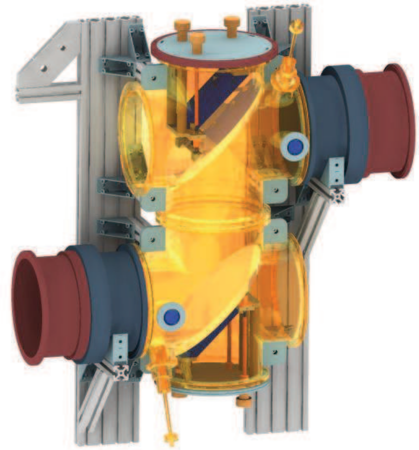

Figure 5: Design of a refocusing module consisting of a focusing and a flat mirror assembly. The vacuum chambers are made (yellow) transparent to show the mirrors and adjustment mechanisms.

The front-end of the beam line creates a demagnified image of the out-coupled beam to allow implementation of a diamond Brewster window separating the vacuum of cavity and optical distribution system. The design of the distribution system is optimized for minimum beam size on the diagnostics table at the locations of the etalon required for extra-cavity filtering to realize the long pulse narrow band output and at the optional power attenuators in the diagnostics station. The remaining part of the optical distribution system to the different user stations will be designed as soon as the lay-out of the distribution system to the diagnostics station is finalized.

CONCLUSIONS

After final choices on the lay-out of the accelerator structure, in particular the buncher, the LINAC for the Nijmegen THz-FEL can be put in production. Design of the optical cavity is challenging mostly due to the combination of the

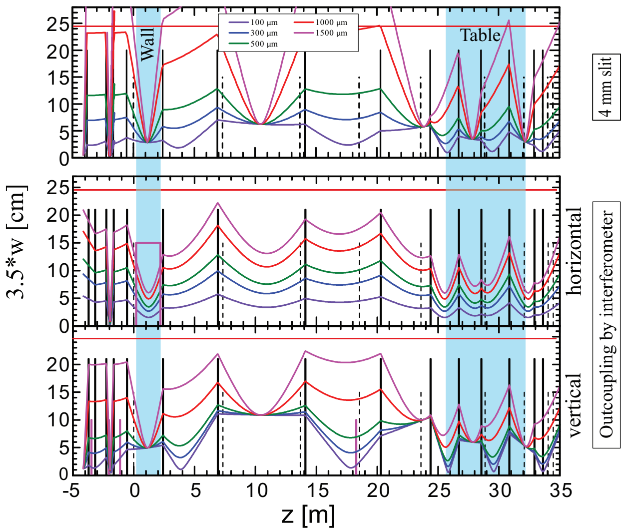

Figure 6: Beam size as a function of distance to the output coupler in Gaussian-beam approximation. Focusing mirrors are indicated by solid vertical lines, flat mirrors by dashed vertical lines. The vertical blue areas indicate the location where the beam passes through the 2 m thick radiation shielding (left), and the location of the table of the diagnostics station (right). Top panel: beam size for 4 mm wide slit output coupler. Lower panels: beam size in horizontal and vertical plane (defined to be directly after the cavity) for the Michelson interferometer-based output coupler.

waveguide over the full length of the optical cavity and the intra-cavity interferometers, but nearing completion. The optical and mechanical design of the optical distribution system is time consuming due to the fact that the spectral range covers the ”Terahertz” gap, and information on systems for spectral calibration and performance of optics at these wavelengths and powers is not abundantly available. Given the current status of the design, commissioning of the Nijmegen THz-FEL is scheduled to be in the fall of 2010. The Nijmegen THz-FEL will be operational in pump-probe mode in the first half of 2011.

ACKNOWLEDGEMENT

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