DESIGN OF A LONG WAVELENGTH FEL FOR EXPERIMENTS UNDER HIGH MAGNETIC FIELDS

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Abstract

At the University of Nijmegen, a novel collaboration has been established that combines a number of spectroscopic laboratories. These laboratories form a centre for advanced spectroscopy and constitute the spectroscopic department of the (Research) Institute for Molecules and Materials combining physical and chemical techniques. As part of the spectroscopic centre, a long-wavelength far-infrared free electron laser (FIR-FEL) operating between 100 μm/3 THz and 1.5 mm/200 GHz will be designed and constucted in the coming years. The FIR-light should facilitate new experiments in the existing high field magnet laboratory (HFML), a large European Rerearch Infrastructure and in the NMR pavillion equipped with NMR instrumentation operating up to 800 MHz, especially for dynamic nuclear polarization technology.

THE NIJMEGEN CENTRE FOR ADVANCED SPECTROSCOPY

The Insitute of Molecules and Materials at the University of Nijmegen houses a number of spectroscopic laboratories. These laboratories combine laser spectroscopy in the European Trace Gas Facility [1], scanning probe technology, employing various forms of scanning tunneling and atomic force microscopic techniques [2], nucelar magnetic resonance (NMR) laboratory [3] and the high field magnet laboratory (HFML) [4]. Existing collaborations between the various laboratories have resulted in experimetns ranging from a 1.277 GHz NMR spectrometer built in a 30 Tesla Bittter magnet to NMR on a chip employing force microscopy to detect the radiofrequency absorption, and experiments exploiting diamagnetism to neutralize gravity in near-zero-gravity experiments inside strong magnetic fields.

In respons to a call from the Netherlands Government named the National Programme for Investments in Large Scale Facilities [5], we have proposed to strengthen existing facilities and to develop two novel instuments, a 45 Tesla Hybrid magnet and a Free Electron Laser operating in the far infrared (FIR).

The frequency window between the microwave region on the low photon-energy side and the infrared radiation on the high photon-energy side is called Far Infrared or THz regime. This energy regime knows many applications and radiation sources with different characteristics are rapidly developed. We believe that at present the most powerful and versatile THz radiation source is a free electron laser. We have proposed the construction of a THz-FEL optimized for the demands of advanced material research in combination with high magnetic fields and for advanced studies of molecular and macromolecular systems. The design aims at generating light between 100 μm and 1.5 mm with a spectral bandwidth of $\Delta\lambda/\lambda<510^{-5}$ while maintaining intensities of the order of 100 Watt during pulses of minimum duration 10 μs and maintaining the possibility of pump-probe experiments at a 10 to 30 picoseconds time resolution. The science driver that resulted in the success of our proposal has been the ambition to bring material research a significant step forward by performing saturation experiments and pulse-echo experiments in magnetic fields above 30 Tesla. In these fields, the relatively high-energy excitations reduce the interference of thermal effects while studying material properties. The total proposal encompassing a 40-45 Tesla hybrid magnet, the FEL and received about 26 M€ (excluding building costs, including some exploitation funds). As the FEL will be a part of an operational large scale facility, and as experience in free electron lasers is still small in Nijmegen, some design specifications will be made conservatively.

SCIENCE DRIVERS AND EXPERIMENTAL LIMITATIONS.

The science call carried the intention to fortify in the Netherlands the number of large scale facilities. It was realized that the Netherlands could not play a sufficiently large role as host country for important international facilities and international researchers. In many other countries the relative number of facilities was found to be significantly larger. In our proposal, we express the ambition that the University of Nijmegen may host many scientific guests using scanning probe techniques, the laser laboratory, and the high field magnets (using the THz radiation source), NMR or the FEL in its own right as versatile spectroscopic light source. The specifications defined above have been formed in collaboration with the FOM Institute Rijnhuizen, which hosts FELIX (free electron laser for infrared experiments). The FELIX staff will not only provide a lot of experience and advice but also forms an example for the management of a highly successful FEL facility. The spectral range chosen for the proposed FIR-FEL complements that of FELIX

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purposefully to optimize the collaboration between the two facilities.

An ideal laser source is easily tuneable in the THz regime, has a flexible pulse structure allowing pump-probe experiments, as well as bandwidth limited in the case of long macro-pulses, and is (quasi-) continuous with an average power of about 1 kWatt. Although the physics does not pose fundamental restrictions, the relative inefficiency of the FEL principle, without energy recovery, and more importantly, technological limitations in the creation of high intensity, relativistic electron beams requires choices optimizing specific aspects.

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Science Drivers

In the following three of the science drivers are identified. An important group of experiments study the spectroscopy and dynamics in solid state materials by observing pulse-echo's following electron spin excitations or cyclotron resonances in magnetic fields. Depending on the effective mass of the electron, FIR-radiation near 1 THz is required in a magnetic field around 35 T. Saturation of these transitions in the form of excitation by a $\pi/2$ pulse within about 100 ns requires powers of about 100 Watt with a bandwidth of $\Delta\lambda/\lambda \approx 2\ 10^{-5}$. Pulse-echo experiments further require the possibility to shape pulses and delay pulses. Atypical experiment requires three of even more of these pulses within a few μs separated at arbitrary time delays ranging from tens of nanoseconds to one microsecond. Hence, we require laser pulses with about 10 μs duration that can be transformed by fast mirrors into the requested pulse train.

A second group of experiments is the use of FIR radiation to saturate electron spin transitions within an NMR instrument. By exploiting the coupling between the electron spin with nearby nuclear spin, the saturation of the electron spin population may be transferred to the nuclear spin. This process is called dynamic nuclear polarization (DNP). Although in principle DNP can enhance the sensitivity of NMR by a factor of more than 10^4, technological and system specific hurdles are enormous for a realization with a wide scope of applications. For DNP, the need for a high absolute duty cycle for FIR radiation may establish the largest obstacle for FEL technology to be optimally applicable.

In the first two examples, large magnetic fields play an important role. A third science driver makes optimal use of the flexibility to change the wavelength of a FEL continuously. A research program is anticipated on molecular spectroscopy of bio-organic molecules, biomemetics (analogues of bio molecules), and smart organic molecules often inspired on biological systems. Characterization of the THz response may not only provide spectroscopic information on the structure of these molecules but also on slow intra- and intermolecular motions related to their functionality.

Technological Choices.

The anticipated design for the FIR-FEL is based on experiments performed with the FELIX instrument in The Netherlands. FELIX is a short-pulse Free-Electron Laser operating in the IR from 5 to 250 μm. The spectral width of the output ranges from 0.5 to 7% depending on the frequency. The overall duty cycle is small with a repetition rate up to 10 macro-pulses per second of a maximum duration of 10 μs each. Each individual macro-pulse consists of up to a few thousand micro-pulses each consisting of tens of optical cycles, implying duration of a few picoseconds for each micro-pulse.

In terms of the macro-pulse structure, the duty cycle of FELIX is about $5\ 10^{-5}$ with an average output power of about 1 Watt, implying an average power of 20 kWatt during the macro-pulse. The maximum power in the picoseconds micro-pulses is another three orders higher. From here, we will describe the design for the Nijmegen FIR-FEL. The pulse structure will be similar to the one of FELIX and has the form of a low repetition rate 10 – 15 μs macro pulse structure. The macro pulse will consist of micro pulses with a fixed repetition rate in the range from 1 to 3 GHz. The special property that we aim for is that *all micropulses have a very well defined phase relation.* It is of interest to note that a narrow bandwidth using this mechanism has been one of the original design ambitions of FELIX. Oepts and Colson [6] presented the initial ideas of phase locking otherwise independent micropulses. Also Madey and coworkers started around this time [7,8]. Initial measurements at FELIX were performed by Bakker, Oepts van der Meer and co-workers [9,10], followed by Weits, Oepts and coworkers [11,12]. This research resulted in an experimental scheme to create a pulse train of phase locked light pulses. These authors observed significant phase stability between the micropulses and drew favourable conclusions regarding the bandwidth that may be achieved using external filtering using interferometers.

It is required to have a large number of optical pulses circulating simultaneously in the normally very large FEL cavity (more than 40 pulses in a cavity with an effective length of about 10 meter). As the optical pulses are generated from electron pulses moving at nearly the speed of light, an extra (optical) system has to couple the optical phases in this train of light pulses. An interferometer inside the cavity ensures that photons from a single electron bunch will affect the coherence of the light generated from many electron bunches injected later. The resulting pulse train of coherent and phase coupled micropulses constitutes a frequency comb with narrow FIR lines spaced with the repetition rate of the electron pulses (by the 1 to 3 GHz rf frequency) . These narrow lines have a width that is determined by the quality of the interferometer and by the magnitude of the interpulse phase-coherence. Each line in the frequency comb further consists of one or more longitudinal modes of the large FEL laser cavity, separated by 0.001 cm^{-1} for a 10 m cavity. To achieve really a single longitudinal frequency output, filtering of one interferometer mode outside of the laser cavity is required. This filtering reduces the average power of the macro pulse by factor of at least 50 depending on the quality of the filtering process.

At FELIX experiments have been performed at a fixed wavelength near λ=69 μm, achieving a spectral resolution of 2 10^{-5} using a Fox-Smith type interferometer. Other groups have simulated and employed Michelson type interferometers in the FEL cavity for the same purpose. [9,10] The above specifications have resulted in the expectation that a dedicated design for a FIR-FEL could provide near single mode lasing at the average power of 100 Watt during a macro pulse even when starting with a short pulse FEL instrument. It is realized that it will require a careful design to establish continuous tuning in such a FEL as the timing structure of the RF electron accelerator system and the RF frequency generates strongly preferred absolute frequencies.

DISCUSSION

Many of the specifications related to the science drivers discussed above suggest designing a quasi CW-FEL such as the high quality UCSB FIR FEL operating at the University of Santa Barbara. This long-wavelength output of the FIR-FEL in Santa Barbara combines many of the characteristics required for the experiments planned at high magnetic fields. In fact, the power output of a CW–FEL can be of the order of 1 – 6 kWatt during the macro pulse clearly exceeding the expectations of a pulsed frequency comb FIR FEL as suggested above. The ambition of the Israeli FEL project to improve on the UCSB FEL design such that an *average* power of kWatt may become feasible implying a near CW operation with very high duty cycle while maintaining a large wavelength range seems to bring very difficult experiments such as DNP in NMR experiments more feasible.

At this moment, the extra possibilities to use a pulsed FEL for strongly non-linear experiments employing the very high micro pulse peak powers and to use the FEL for time resolved experiments with 10- 30 picoseconds time-resolution has resulted in the decision to study the possibilities of a pulsed frequency comb type FIR-FEL. The planning of the project involves in the upcoming 18 months design studies and detailed planning of the construction phase of the FEL. Lasing and the opening of a user facility along the lines of the present very successful FELIX facility are foreseen in about five and a half years from now.

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