ZFEL: A COMPACT, SOFT X-RAY FEL IN THE NETHERLANDS

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Abstract

We outline our plans to construct a soft X-ray Free Electron Laser (FEL) located at KVI, University of Groningen, The Netherlands. This new facility will be based on a 2.1 GeV normal-conducting electron linac followed by an undulator and will produce X-ray laser light with wavelengths down to 0.8 nm. The electron linac will be driven by a RF photo-injector and X-band acceleration structures with an acceleration gradient of 100 MV/m. Longitudinal coherence of the laser beam will be established by using appropriate seeding techniques. The entire length of the FEL will be on the order of 100 meters. The facility will primarily be of interest for fundamental research in atomic, molecular and optical physics, material science and (bio)chemistry, but will also be open for other users e.g. from industry.

INTRODUCTION

Since the successful commissioning and startup as user facilities of the soft X-ray FLASH [1] and hard X-ray LCLS [2] lasers in Hamburg and Stanford, respectively, the scientific interest in these new 4th generation light sources has strongly increased. Many recent workshops have highlighted the revolutionary breakthroughs that can be expected in physical, chemical and biological (sub)disciplines by exploiting the unique characteristics of the (soft) X-ray radiation generated by the new FEL facilities. Combined with powerful and new detection, imaging and pump-probe techniques, an entirely new window on the structure and dynamics of the nano world is opened with atomic scale resolution. Because of this the two existing facilities are heavily oversubscribed and new ones are either being constructed, designed or planned.

In addition, contrary to the synchrotron-based light sources which can accommodate several tens of experiments in parallel, the new linac based (soft) X-ray facilities can only serve at most a few experiments simultaneously. As long as the cost of these new facilities is at the level of hundreds of millions of Euros the available beam time will stay significantly behind demand. Access to beam time will therefore be accordingly difficult. There is a real need for reducing the cost of (soft) X-ray FEL facilities, so that they come within reach of university-based institutes serving local and national user communities. Such relatively cheap and small-scale facilities do not primarily aim for the flexibility and wide range of operating conditions available at the large-scale facilities. However, they will provide easier access to (soft) X-ray laser light.

At the University of Groningen we are preparing a proposal to build a low-cost soft X-ray FEL facility on the site of the Kernfysisch Versneller Instituut (KVI). The name of this new facility is coined ZFEL in honor of Frits Zernike, University of Groningen Nobel laureate in physics in 1953 for inventing phase-contrast microscopy. The new facility is primarily intended to serve a strong user community consisting of atomic, molecular and optical (AMO) physics, materials science and structural biology groups, but will also be open for other users e.g. from industry. To establish a timely design and construction phase we will set up several (inter)national collaborations. In this paper we will delineate the linac and FEL characteristics and present a preliminary layout of the facility.

LINAC AND FEL CHARACTERISTICS

The required linac and FEL characteristics are determined by the scientific research that will be carried out at the ZFEL facility and also by site-specific boundary conditions. From discussions with the local, national and international user community and during a recent two-day workshop [3] it was established that ZFEL should be able to generate soft X-ray laser pulses with a minimum wavelength of 0.8 nm, pulse lengths between 1 and 100 fs, full transversal and longitudinal coherence of the laser pulses, a pulse repetition rate of up to 1 kHz with 10^{11} - 10^{12} photons per pulse. To achieve both transversal and longitudinal coherence seeded FEL operation is necessary. A minimum photon wavelength of 0.8 nm can be reached with a 2.1 GeV electron linac that drives an undulator with a period of $\lambda_u = 15$ mm and a K-parameter of 1.2.

Our plan to construct the ZFEL facility on the KVI site sets stringent limits on its total length, which should not exceed 200 m. This means that the linac length has to be minimized by maximizing its acceleration gradient. CERN and SLAC have demonstrated in their CLIC and NLC projects that acceleration gradients of 100 MV/m and even larger can be realized with normal conducting acceleration struc-

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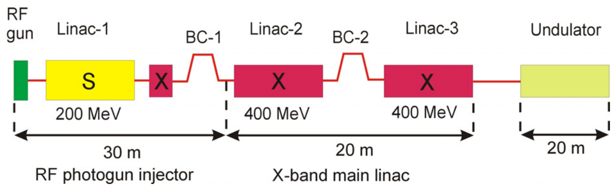

Figure 1: ZFEL machine layout showing major sections.

tures operating at the X-band frequency of 12 GHz. The ZFEL facility will be the first one using a normal conducting X-band RF linac for driving a soft X-ray FEL.

We plan to take a two-stage approach to realize the new ZFEL facility, where in the first stage an 1 GeV X-band linac will drive a 15 mm period undulator to produce soft X-ray laser pulses with a minimum wavelength of 3.4 nm using the SASE process. In the second stage the facility will be upgraded to 2.1 GeV and seeded operation. Some relevant linac and FEL parameters for stage 1 and 2 operation are listed in Table 1.

Table 1: ZFEL Machine Parameters

	Stage 1	**Stage 2**
Beam energy (GeV)	1.0	2.1
Bunch charge (pC)	10 - 100	10 - 100
Norm. emittance (mm-mrad)	1.0	1.0
Peak current (kA)	1.5	1.5
Energy spread (MeV)	0.3	0.4
Repetition frequency (Hz)	10 - 1000	10 - 1000
Undulator period (mm)	15	15
Undulator parameter K	1.2	1.2
FEL parameter ρ	$1.1 \cdot 10^{-3}$	$3.4 \cdot 10^{-4}$
Gain length (m)	0.64	2.0
Saturation length (m)	12	34
Photon wavelength (nm)	3.4	0.766

PRELIMINARY ZFEL LAYOUT

A schematic layout of the ZFEL facility is shown in Fig. 1. Very high-quality electron bunches will be produced with an existing RF photo-gun designed and built by the Technical University of Eindhoven [4]. The electron pulses have a peak current of $\approx$ 100 A, a minimum emittance of $0.8\,\pi$ mm-mrad and are accelerated to an energy of 6.9 MeV [5]. After emerging from the RF photo-gun the electron bunches are further boosted in three standard SLAC 3 m long S-band acceleration structures to an energy of 200 MeV. The electron bunches are accelerated off-crest in order to initiate a first bunch compression in the magnetic chicane BC1. A short X-band fourth-harmonic cavity is located in front of BC1 to enhance bunch compression.

After exiting the first magnetic chicane the electron bunches are further accelerated in the X-band main linac. In the first stage two main linac sections are foreseen with a second magnetic bunch compressor BC2 in between. Each main linac section consists of eight 0.5 m long X-band traveling-wave acceleration structures with an acceleration gradient of 100 MV/m boosting the electron bunches with 400 MeV. The gives a total energy of 1 GeV in the first stage. In the second stage we will add another three X-band sections in order to reach a total energy of 2.1 GeV.

After being accelerated to their final energy the electron bunches are injected into a series of 2 m long, 15 mm period, in-vacuum undulator sections. Quadrupoles placed between the undulators will produce the required focusing. We estimate that a total undulator length of 12 m will be sufficient to reach saturation at 3.4 nm with 1 GeV electrons and a length of 34 m to reach saturation at 0.8 nm with 2.1 GeV electrons. The total length of the entire linac and undulator sections will be approximately 70 m for the stage 1 facility and 100 m for the upgraded stage 2 facility.

Many important and essential aspects have not been addressed here including beam diagnostics and control, laser and RF timing/synchronization systems, stabilization and feedback issues and many more. Although very challenging and requiring state-of-the-art technology and instrumentation various solutions to these problems have been developed and shown to work, particularly by the FLASH and LCLS groups.

CONCLUSIONS AND OUTLOOK

We have briefly outlined our plans to design and construct a new soft X-ray laser facility at KVI, University of Groningen. High-gradient, normal conducting X-band acceleration structures combined with a high-quality RF photo-gun and short-period undulators make it possible to build a very compact and cost-effective facility. The facility layout presented here is of course a very preliminary one. In our next step we will perform detailed design and optimization studies and start-to-end simulations leading to a comprehensive design report. At the same time we will already start with installing an RF photogun with its associated laser and RF equipment and to construct various electron beam diagnostic devices. Our plans include an X-band acceleration-structure test facility at the KVI site. This will enable us to quickly acquire experience with these key technologies and to participate in and contribute to existing X-band linac programs.

REFERENCES

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