PAST AND FUTURE OF THE DELTA FREE-ELECTRON LASER*

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Abstract

The storage-ring FEL at DELTA has been successfully operated with different filling patterns and temporal structures following the installation of new mirror chambers three years ago. The modulation depth of the optical-klystron spectrum was used to measure the electron energy spread. The measured FEL output power at high beam currents strongly exceeded the predictions of the low-gain model. This can be explained by the microwave instability being damped significantly by the onset of the FEL interaction. In the near future, the optical klystron will be seeded by external ultrashort laser pulses in order to produce highly coherent, intense and ultrashort VUV pulses by coherent harmonic generation (CHG). Additionally, coherent ultrashort THz pulses will be generated several meters downstream of the optical klystron by the laser-induced gap in the electron bunch.

INTRODUCTION

DELTA is a 3rd generation synchrotron light source with a nominal beam energy of 1.5 GeV and a circumference of 115 m, located at the TU Dortmund University. It comprises three insertion devices, a superconducting asymmetric wiggler (SAW) that provides hard X-ray radiation for three beamlines, the permanent magnetic undulator U55, and the planar electromagnetic undulator U250, consisting of 17 periods of 250 mm length (see Fig. 1). The U250 serves as VUV radiation source during standard user shifts at 1.5 GeV and can be operated as optical klystron for a storage-ring FEL (SR-FEL) at electron energies around 550 MeV. The first laser operation in the visible regime had been achieved in 1999 [1].

Stable and easily reproducable laser operation has been established since fall 2007, mainly due to the construction and commissioning of new mirror chambers for the optical cavity [2].

Starting this winter, the U250 will be used to generate ultrashort, coherent VUV pulses at harmonics of an external Ti:sapphire laser. New power supplies for the undulator allow tuning of the resonant wavelength to the seed laser wavelength (800 nm) during standard user shifts at 1.5 GeV electron energy.

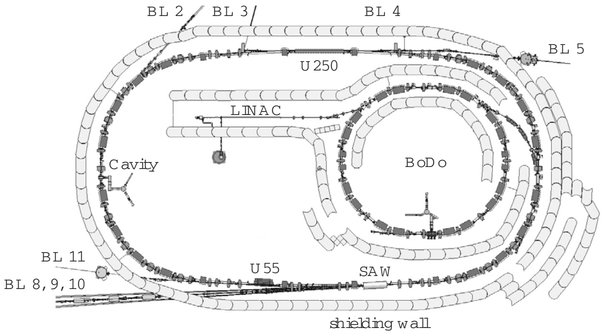

Figure 1: Overview of the DELTA accelerator complex. The electromagnetic undulator U250 is located in the northern straight section of the storage ring.

FEL PERFORMANCE

The storage-ring FEL at DELTA was operated at an electron energy of 550 MeV and a laser wavelength of 470 nm. Lasing was achieved with single-bunch, four-bunch and few-bunch (i.e. a bunch train) filling patterns. The following discussion only refers to single-bunch mode, where lasing was not constrained by coupled-bunch instabilities.

Table 1: FEL Parameters

FEL wavelength	470 nm
K-value	2.54
undulator periods	7+3+7
electron energy	542 MeV
filling pattern	single bunch
lasing threshold	3 mA
threshold gain	3 %
length of optical cavity	14.4 m
mirror reflectivity	99.63 %
mirror transmission	≈ 0.04 %
average output power	< 3 mW
intra-cavity peak power	≈ 13 MW

Temporal Structure

By modulating the frequency of the accelerating RF (499.84 MHz) with an amplitude of up to 2 kHz and a modulation frequency between 10 Hz and 250 Hz, thus periodically varying the orbit length, it is possible to force the laser macropulses into a Q-switch mode with the corresponding frequency. Within the mentioned frequency range, no mea-

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surable change of the outcoupled average laser power was observed.

Without Q-switching and for low beam currents, the macropulses followed the theoretical, natural oscillation frequency [3, 4]

$$f_r = \frac{1}{\pi\sqrt{2\tau_0\tau_\mathrm{s}}}$$

with $\tau_0 = T_0/(G-L)$, gain G, cavity losses L, bunch spacing $T_0 = 384$ ns, and damping time $\tau_\mathrm{s} = 90$ ms. Above approx. 8 mA the spacing between macropulses was consistently 4 ms, dominated by a multiple of the line frequency.

Streak camera measurements revealed an inner structure of the laser macropulses. Attenuating the outcoupled high-intensity laser pulses by a factor of 10^3 with an additional resonator mirror allowed for the simultaneous analysis of laser and electron bunch [5].

Figure 2 shows a series of laser macropulses with the optical cavity slightly detuned. The laser pulses migrate along the electron bunch. It is worth noting that the next laser pulse already starts growing while the previous one has not yet decayed completely.

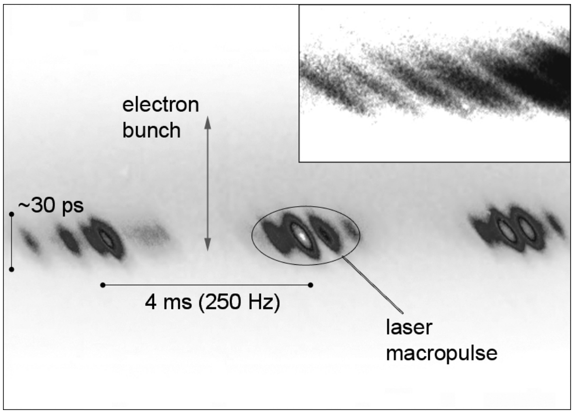

Figure 2: Double-sweep streak camera image of laser pulses with a duration of approx. 7 ps migrating over the 40 ps long electron bunch.

Energy Spread and Gain

An optical klystron can be used to measure the energy spread σ_γ of the electron beam directly, i.e. indepently of the bunch length, by evaluating the modulation depth f_ok of the spectrum [6]:

$$f_\mathrm{ok} \sim \exp\left(-8\pi^2(N+N_d)^2\left(\frac{\sigma_\gamma}{\gamma}\right)^2\right)$$

with the number of undulator periods N and the slippage N_d of the electons in the dispersive section in terms of the laser wavelength. Comparing this with bunch length measurements at varying beam currents confirmed the validity of the Boussard criterion in the turbulent regime above 3 mA (see Fig. 3) [7].

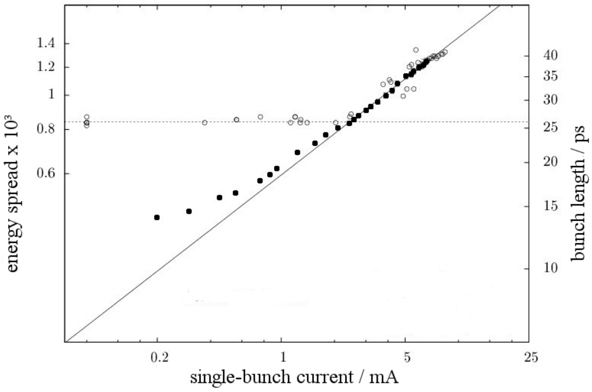

Figure 3: Direct energy spread measurement (circles) and bunch length (black dots) versus single-bunch current.

The initial FEL gain at the laser threshold current of roughly 3 mA (single bunch) just compensates for the cavity losses. The resulting gain value of 3% is in good agreement with the theoretical prediction of the low-gain model:

$$G_\mathrm{0,ok} = 7.4\left(\frac{N_\mathrm{ok}}{N_\mathrm{u}}\right)^3\left(\frac{N_\mathrm{ok}+N_\mathrm{d}}{N_\mathrm{ok}}\right) f_\mathrm{ok}G_\mathrm{0,u}$$

with the modulation depth f_ok of the optical klystron ($N_\mathrm{ok} = 7$) and the maximum gain $G_\mathrm{0,u}$ (see for example [5]) of a pure undulator ($N_\mathrm{u} = 17$).

At higher currents however, both the gain and the measured output power strongly exceed the predictions of the low-gain model and the Renieri limit [8, 9]

$$P = 8\pi\frac{T}{L}(N+N_d)f_\mathrm{ok}\left[\left(\frac{\sigma_\gamma}{\gamma}\right)^2_\mathrm{on} - \left(\frac{\sigma_\gamma}{\gamma}\right)^2_\mathrm{off}\right]P_\mathrm{sr}$$

with the mirror transmission T, the total losses of the optical cavity L, the total synchrotron radiation power P_sr, and the relative energy spread with and without laser activity $(\sigma_\gamma/\gamma)_\mathrm{on/off}$. As illustrated in Fig. 4, according to the low-gain model the gain should drop below the laser threshold above 10 mA, even when assuming the best (i.e. natural) emittance. However, lasing was observed, even with growing output power, up to the accumulated maximum current of 14 mA. This suggests that the onset of lasing reduces the actual energy spread, damping the turbulent bunch lengthening [5]. A direct verification of this behaviour by measuring the energy spread in the vicinity of the onset of lasing was not yet possible due to the limited accuracy and temporal resolution of the measurement equipment, but is planned for the near future.

COHERENT-HARMONIC GENERATION

Many phenomena on the atomic level like chemical reactions or phase transitions take place on the sub-ps time scale. Thus, their dynamics cannot be analyzed by conventional synchrotron radiation pulses with typical durations of 30-100 ps. Ti:sapphire lasers provide coherent

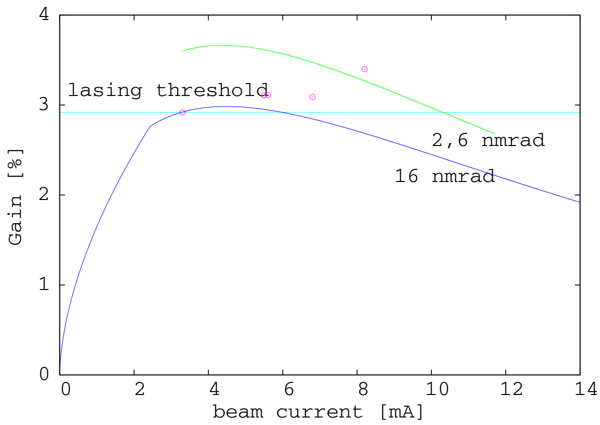

Figure 4: Theoretical gain for different emittances. The lower curve is for an assumed ”effective” emittance, taking into account intra beam scattering and beam oscillations. Even for the natural emittance (top curve) the gain drops below the lasing threshold above 10 mA, but lasing was observed for higher currents. The red dots are measured gain values.

pulses with a duration of less than 100 fs, but operate at a wavelength of 800 nm, whereas many experiments require ultrashort coherent pulses in the VUV regime. An example is the time-resolved photoemission of nanoparticles on surfaces to study the growth and deposition of mass-selected clusters. Unlike conventional synchrotron radiation, highly coherent UV pulses can be used to develop holographic techniques without the limiting apertures that are usually required to create the necessary transverse coherence [10]. Ti:sapphire lasers can provide UV pulses by employing high-harmonic generation (HHG) or radiation from laser-induced plasmas, but the conversion efficiency quickly drops for higher harmonics.

Another technique to generate ultra-short VUV-radiation pulses at synchrotron light sources is to ”seed” the microbunching in an optical klystron with an external Ti:sapphire laser and to tune the second part of the optical klystron, the radiator, to a higher harmonic of the seeding wavelength. The principle of this so-called coherent-harmonic generation (CHG) is illustrated in Fig. 5 and has been successfully demonstrated at e.g. ELETTRA/Italy [11] and UVSOR II/Japan [12].

The laser-induced energy modulation of the electron beam is converted into a density modulation by the magnetic chicane (the three central periods of the U250). Subsequently, the bunched electrons radiate coherently in the second undulator. Since bunching occurs on higher harmonics as well, the radiator can be tuned to integer fractions of the laser wavelength to obtain VUV pulses. Even higher photon energies can be achieved by converting the laser pulses to smaller wavelengths (e.g. to the 3rd harmonic) before entering the optical klystron. The restriction to integer fractions of the laser wavelength can be relaxed by employing an optical parametric amplifier. Compared to the seeding pulse, the VUV pulses are lengthened by the number of undulator periods times the seeding wavelength, but typically remain below 100 fs. Thus, the time resolution in pump-probe experiments is improved by three orders of magnitude compared to conventional synchrotron radiation. The essential properties of CHG radiation can be summarized as follows:

- high intensity ∼ (number of electrons)^2
- high degree of longitudinal and transverse coherence
- 50-100 fs pulse length
- perfect synchronization with an external laser system
- typical repetition rate of a few kHz

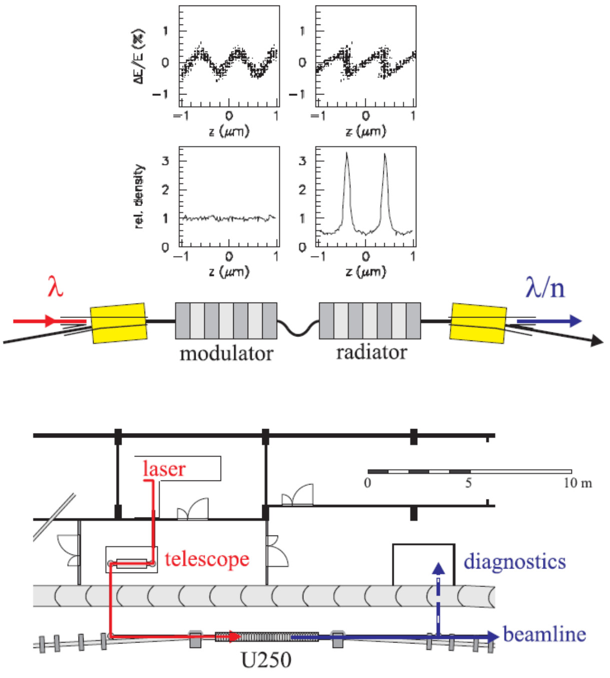

Figure 5: Principle of coherent harmonic generation (top): laser pulses of wavelength λ co-propagating with electrons in an undulator (modulator) cause a periodic modulation of the electron energy, which is converted into a density modulation by a magnetic chicane and gives rise to coherent radiation in a second undulator (radiator). This radiation occurs at harmonics of λ. The setup at DELTA (bottom) comprises a femtosecond laser system, the U250 undulator, diagnostics and a synchrotron radiation beamline.

Terahertz (THz) Radiation

Several meters downstream of the optical klystron, lattice dispersion leads to a longitudinal displacement of the energy modulated electrons, creating a short gap in the electron bunch. This gap gives rise to coherent THz radiation in the subsequent bending magnets. The THz pulses have a duration of only a few 100 fs and are perfectly synchronized to the laser, which makes them ideally suited for time-resolved IR-spectroscopy studies. For example, spin excitations in semiconductors and quantum structures, internal excited states of exciton complexes, or cyclotron resonances of charge-carrier gases can be analyzed. Furthermore, the THz pulses provide a very sensitive signal to detect and optimize the overlap between electron bunches and the laser pulses in the modulator.

It is mandatory that the energy-modulation strength is below the energy acceptance of the storage ring. In the case of DELTA, the energy acceptance is limited by the accelerating cavity to approx. ±0.9%. Simulations show that an energy-modulation strength of ±0.8% can be achieved with laser pulses of about 1 mJ energy and a duration of 40 fs.

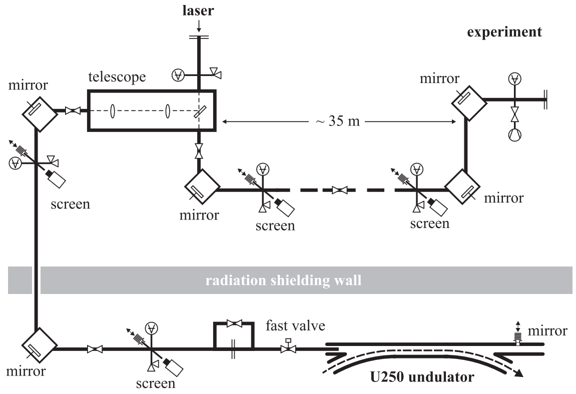

Figure 6: Schematic vacuum concept of the laser beamline. A telescope in medium vacuum creates a laser waist at the U250 undulator. The storage-ring vacuum is separated from the beamline vacuum by a window and protected by a fast valve. A small fraction of each laser pulse is sent over a distance of 35 m directly to the experiment for pump-probe applications. All mirrors inside the vacuum vessel are motorized. Alignment of the beams is facilitated by remotely controlled screens with CCD cameras.

Status

In order to provide ultrashort radiation pulses for users in stable routine operation at the nominal beam energy of 1.5 GeV, new power supplies have been acquired for the U250 to attain the necessary K-value of 10.5. Additionally, both longitudinal and transverse bunch-by-bunch feedback systems will be installed within the next few months in order to reliably enable a stable overlap between the laser pulses and the electron bunches. A fast orbit feedback, based on FPGAs, is developed inhouse.

A Ti:sapphire laser system with minimum pulse durations below 35 fs and pulse energies of several mJ at 1 kHz repetition rate will be installed at the end of 2010. Currently, the necessary infrastructure is upgraded or newly implemented. This includes cooling water pipes, air-conditioning, and a new room to house the telescope (see Fig. 5).

The in-vacuum seeding beamline and the also evacuated pump-pulse beamline are developed and constructed within the scope of two PhD theses (see Fig. 6). The THz beamline, as shown in Fig. 7, is under construction. A THz detector with a high temporal resolution will allow for the analysis of the decaying gap in the electron bunch over several revolutions. This decay is an excellent indicator for optimizing the laser-electron beam overlap in the optical klystron [13].

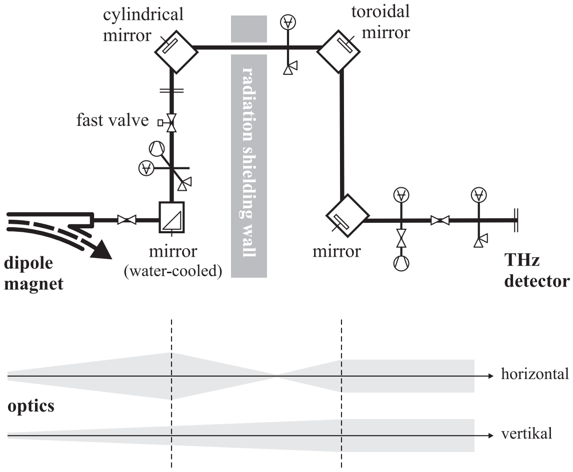

Figure 7: Schematic concept of the THz beamline. Far-IR radiation from a dipole magnet is extracted by a port with large opening angle and a water-cooled mirror. A cylindrical mirror followed by a toroidal mirror, both motorized, provide a nearly round beam at the THz detector, a He-cooled InSb hot-electron bolometer. A fast valve protects the storage-ring vacuum.

The first CHG experiments at DELTA are scheduled for 2011, starting with a seeding wavelength of 800 nm and the radiator tuned to the 3rd harmonic. After optimization of the laser-electron beam overlap, the regime of shorter wavelengths will be explored.

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