FIRST RESULTS OF COHERENT HARMONIC GENERATION AT THE MAX-LAB TEST FEL *

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Abstract

The first generation of coherent harmonic radiation from the MAX-lab test FEL has recently been achieved. The 380 MeV electron beam has been seeded by a 263 nm Ti:Sapphire laser and coherent enhanced radiation in the 1st to 6th harmonic 6 (263 – 45 nm) has successfully been performed in linear mode and the 1st to 4th harmonic in circular polarization mode of the radiator.

Qualitative measurements have been made variating the laser energy and settings of the microbunching chicane.

INTRODUCTION

Under the European project EUROFEL a collaboration was initiated between MAX-lab and BESSY (now the Helmholtz Zentrum Berlin) to study, develop and build knowledge on seeding as a technique for free electron lasers. It was agreed that MAX-lab should provide the linac injector in operation at the lab and a laser system for a photo cathode gun and seeding. BESSY provided the two undulators and a magnetic chicane system. All equipment was installed at MAX-lab and commissioned by MAX-lab and BESSY in collaboration.

THE MAX-LAB TEST FEL

The facility is utilising the MAX-lab injector linac with an upgraded operation of the photo cathode RF gun and the beam transport system with a magnetic chicane for compression. A new laser system for gun and seeding as well as two undulators and chicane have been installed as depicted in Figure 1.

Accelerator and Transport

The accelerator system [1] consists of a RF gun, a linac and a beam transport system. The gun is equipped with a BaO cathode surface that previously has been used only as a thermionic gun for injection into the storage rings; MAX I, MAX II and MAX III. By illuminating the gun with a 10 ps, 263 nm laser pulse, photo electrons are extracted for injection into the FEL. The energy at the gun exit is around 1.7 MeV. The repetition rate is 2 Hz.

The main acceleration is done in two 5.2 m long linac structures each providing 95 MeV. When the electrons have passed both linacs they are bent by a recirculator, and pass through the linacs one more time. This gives a total beam energy of around 380 MeV. The exit from the recirculator is realized in a chicane and the electrons are then transported through a translating achromatic dogleg up to the location of the FEL undulators. The magnetic optics in the recirculator, chicane and dogleg provide enough first and second order momentum compaction for compressing the beam and producing a short spike of high current electrons needed for the FEL interaction. A charge of 25-40 pC is typically achieved inthe FEL.

RF Gun System

The photo cathode RF gun is normally used as a thermionic gun for storage ring injection. It has been adapted to also operate as a photo cathode gun [2] by lowering the temperature of the BaO cathode and introducing the gun laser system described above. Charges up to 1 nC have been extracted, but to reach a lower emittance the extracted charge is reduced by lowering the laser energy towards 25 μJ/pulse. The electron energy is 1.7 MeV at the gun exit.

This pulse is via the linac and transport system

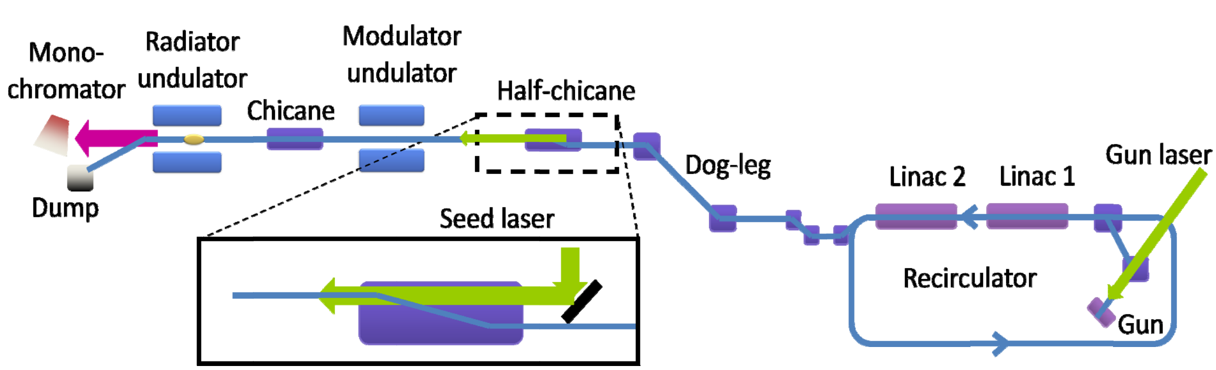

Figure 1: Layout of the MAX-lab test FEL.

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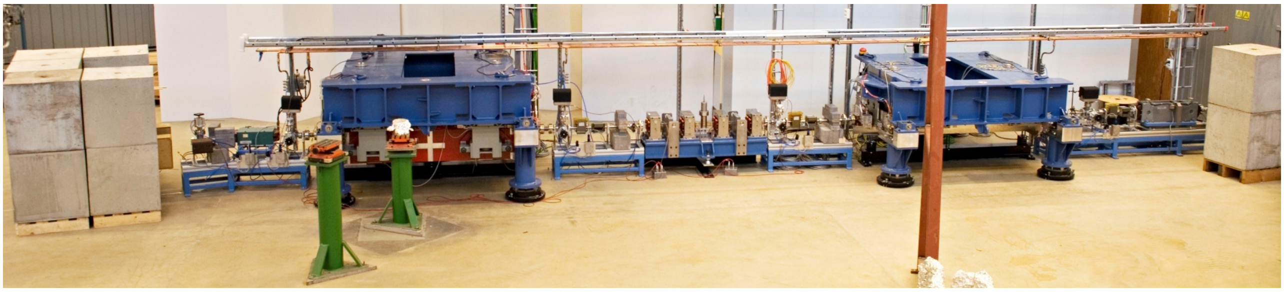

Figure 2: The two undulators (U48, the modulator, right and UE56, the elliptical radiator, left) in the MAX-lab test FEL.

accelerate to 375 MeV and compressed below 1 ps.

Magnet -System

The main component of the test facility is the magnet system [3] which was provided by HZB/BESSY and consists of a modulator undulator (planar type) and a radiator undulator which is an APPLE II type plus an intermediate magnetic chicane. Table 1 lists the properties of both undulators and the intermediate magnetic chicane.

Laser System

The laser system is a combined system which provides both the RF gun pulse and the seed laser pulse for the harmonic generation. The two parts are placed almost 100 m apart and synchronised via a fibre link.

A laser oscillator (Femtolasers Synergy, 93.71 MHz, 790 nm central wavelength, bandwidth 13 nm FWHM) is placed in the gun laser hutch and locked to the 3 GHz signal generated for the RF system (gun, linacs) with a time jitter of 200-500 fs. This jitter level has been achieved by an improved RF generator.

Table 1: Parameters of the undulator section when tuning the radiator to the 3rd harmonic (88 nm) of the seed laser. In parenthesis, the properties for the 5th harmonic (53 nm) are also given.

Modulator	
Period length	48 mm
No. of periods	30
K	2.34
Chicane (4 mag.)	
Length of magnets	12 cm
Length of drifts	40 cm
Magnetic flux density	12(8) mT
Radiator	
Period length	56 mm
No. of periods	30
K	1.05 (0.49)

The pulses of the oscillator are stretched and split in two branches. In the gun laser branch the pulses are shaped in a Dazzler, amplified, compressed and tripled to 263 nm giving up to 500 µJ in a 10 ps pulse.

The other branch is sent through a bow-tie polarization-maintaining optical fiber 90 meters to the seed laser where it is amplified, compressed and tripled to 263 nm in a pulse of 350 fs and ~100 µJ energy. A beam transport system delivers the seed laser pulse into the accelerator system.

Diagnostics and Measurement Systems

The diagnostics system in the transportline of the system consists mainly of screens and current monitors. In the test-FEL itself beam positions are measured by YAG screens. Standard current transformers provide shot-to-shot charge readback. These are not able to resolve the short pulses in time but by calibrating the integrated signal to a Faraday block measurement a correct reading can be achieved. The temporal overlap was originally done in two steps. First a rough measurement based on photo diodes where both the direct hit of the electrons and the light from the seed laser were recorded. The second step is based on an Electro Optical system [4]. After first achievement of CHG the EO system can be used directly.

At the end of the electron beamline the electron beam is bent to a beam dump with a YAG screen placed where dispersion is present to allow for energy spread measurements. Unfortunately it has proven difficult to transport the electrons without significant losses to the last YAG screen while retaining the CHG signal, and thus online measurements have been difficult. We have also utilised a THz system close to the beam dump to collect signals proportional to bunch lengths and probing induced microbunching.

Finally, a photon beamline with a horizontally focusing collection mirror and a spectrometer (2400 l/mm grating) with a liquid nitrogen cooled CCD array is being used to record the CHG signal.

RESULTS

Operation

Coherent Harmonic Generation (CHG) was set up in a multi-step process. The spontaneous radiation from the modulator undulator and radiator undulator was recorded to assure the proper gap settings calibrated to the seed laser wavelength. This was necessary as a precise electron beam energy calibration was not at hand. The electron beam orbit was also optimised for best spectrometer signal. This was followed by transverse overlap where the seed laser was placed on top of the electron beam on two YAG screens placed before and after the modulator undulator. This was repeated a few times to reduce stray light from the seed laser leaking through to the spectrometer, despite an aperture blocking the laser light in the chicane magnet. Temporal overlap was adjusted via

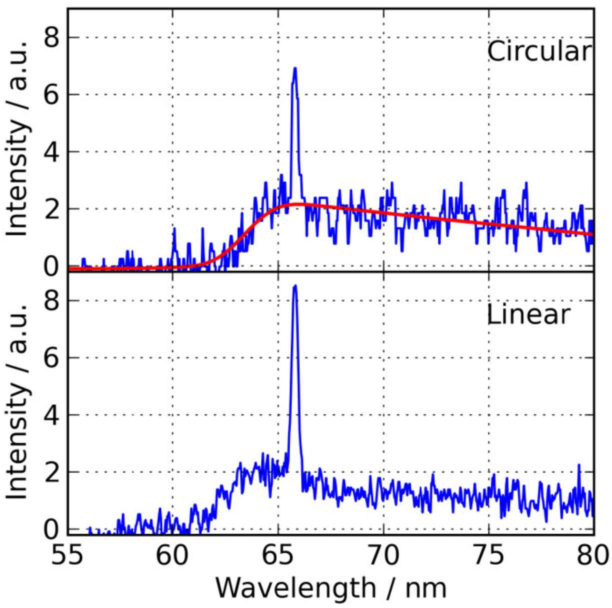

Figure 3. Coherent 4th harmonic signal in both linear and circular mode with fitted spontaneous undulator radiation in circular mode (red solid line).

the Electro Optical system (EO). After this the CHG signal was sought with small adjustments to the temporal overlap by use of the seed laser delay line. This was followed by an optimisation of the CHG signal by adjusting the transverse overlap. Unfortunately, the system has a tendency to drift out of overlap over a 10 minute period. A temporal feed-back system based on the EO signal partly cures the problem [4]. Relative phase drifts between the RF gun and the linac remain though, which makes prolonged operation troublesome without tuning.

Coherent Harmonic Generation

CHG has been recorded from the fundamental (1st harmonic at 263 nm) to the 6th harmonic (45nm) in linear mode (see figures 3 & 4). The 2nd and 4th harmonics (133 nm & 66 nm) have also been recorded in cirular mode (figure 3). The spectra show the spontaneous radiation background and the CHG peak placed at exactly the harmonic of the seed laser. In figure 4 the radiator undulator was put to a fundamental wavelength of 133 nm where the 2nd and 3rd harmonic of the undulator equalled the 4th and 6th harmonic of the seed.

The spontaneous undulator radiation was calculated using SPECTRA [5] where the gap and opening angles where fitted to achieve the recorded spontaneous signal. Thus the CHG flux could be calculated. The results show that in the 4th harmonic (66 nm) we have 390.000 photons per pulse (at 25 pC in circular mode) which corresponds to 1.1 pJ/pulse.

A modulator undulator gap scan was made (figure 5) and the resulting CHG signal at the 2nd harmonic (133 nm) was recorded. The CHG signal is present within a larger range than the full undulator linewidth which can be explained that the modulation is efficient even if it only works on a shorter part of the undulator, thus an increased linewidth.

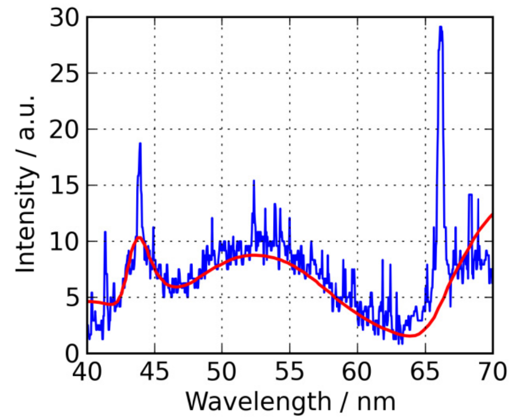

Figure 4: Linear coherent 4th and 6th harmonic signal with fitted spontaneous undulator radiation. (Radiator set to 131 nm and the harmonics are thus 2nd and 3rd of the radiator wavelength).

Pulse Length

The pulse length measurement with the EO system shows an electron beam pulse length around 1 ps. An estimate for the photon pulse has been made by deconvoluting the spectral width of the CHG pulse and making the assumption that the pulse is transform limited. This gives a lower limit on the pulse length of 200 fs (FWHM), far shorter than the electron pulse length. This assumption has two immediate shortcomings. The pulse might well consist of several coherent sub regions, where

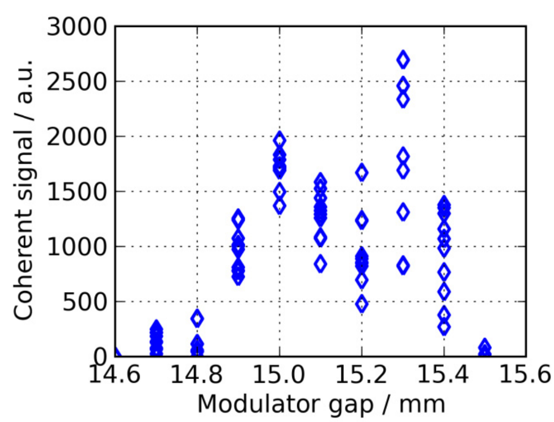

Figure 5. Coherent 2nd harmonic signal as a function of modulator gap.

the indicated length then only refers to one region. Further, the spectrometer resolution is around 0.3 nm, which limits the possibility to resolve the CHG signal linewidth to the lower harmonics (longer wavelengths).

Laser Energy and Modulation

The laser energy and the chicane magnet system strength were scanned. This influences the microbunching in the CHG process. The seed laser energy can be adjusted by a rotatable polariser. It is favourable to induce a large energy spread by the seed laser compared to the natural energy spread in the electron beam. With a larger induced energy spread the microbunching in the chicane will be quicker and a lower strength is needed. Also over bunching will occur quickly. Theoretically the chicane setting should be a sensitive knob to optimise the CHG output. However instabilities and drift in the system makes these kind of optimisations difficult.

In figure 6 the qualitative results of this kind of scans are shown. A stronger chicane (3 A) quickly reaches higher CHG signal when the laser energy is increased. The signal then drops when the laser is further increased, which is a sign of overbunching.

A lower chicane setting (1.3 A) requires more laser energy to microbunch the electrons, but the laser was not intense enough to over bunch the system.

The intermediate chicane settings give intermediate results, but only qualitatively.

There is no definite sign of a higher CHG signal using more laser energy. This is an indication that the natural energy spread is not a limiting factor at the 2nd harmonic (133 nm).

Stability

The stability of the system has a couple of shortcomings (figure 7). There is a clear shot-to-shot instability originating mainly from the klystron/linac system giving energy and thus position as well as temporal variations. There is also a long term (10 min) drift mainly from temperature effects.

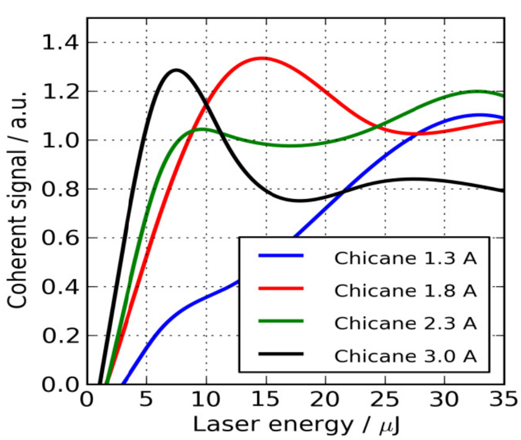

Figure 6: Scan of the laser energy (in the undulator) for different excitations of the microbunching chicane.

In figure 7 the result of the shot-to-shot variations can be seen with 25 recorded spectra at 133 nm.

The shot-to-shot instabilities have been addressed by stabilising the klystron system, locking the trigger phase to the grid 50 Hz and by a feedback system for the seed laser timing [5]. The long term drift induced by the optical fibre was a factor considered initially in the project, but to reduce the budget it was decided to compensate for the drifts using cheaper means since the system was not intended for routine user operation.

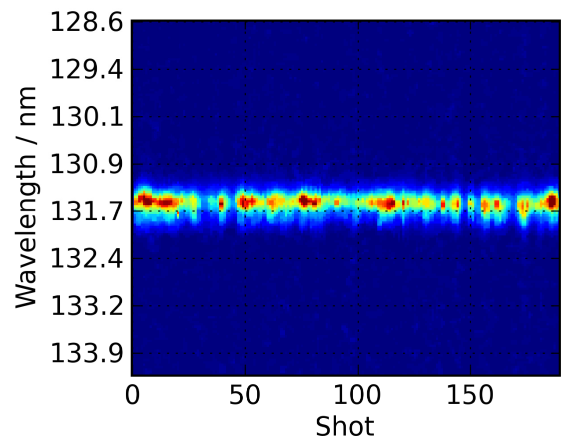

Figure 7. Stability of 133 nm CHG signal. 25 single pulses (wavelength vs. sweep number)

SUMMARY

The collaboration between MAX-lab and HZB/Bessy has successfully built and commissioned the test FEL at MAX-lab for Coherent Harmonic Generation. An existing linac system has been upgraded and CHG in linear mode in the 1-6th harmonic (263-42 nm) and (2nd and 4th harmonic (133 and 66 nm) in circular mode has been achieved. We believe that circular polarised coherent radiation at 66 nm has never been observed from an accelerator source before.

The main goals of the system have been achieved and some features even beyond the goals. One of the main purposes of the facility was to gain experience of operation, diagnostics and FEL technology to build a base for a future FEL facility within the MAX IV project.

REFERENCES

[1] S.Werin et al., ``Commissioning of the 500 MeV Injector for MAX-lab", EPAC 2004, Luzerne, Switzerland 2004..

[2] S. Thorin et al., Nucl. Instr. and Meth. A, 606 (2009) 291

[3] J. Bahrdt et al., ``Undulators for a Seeded HGHG-FEL at MAX-lab", EPAC 2006. Edinburg, Scotland 2006.

[4] N. Cutic et al, THOA4, these proceedings.

[5] T. Tanaka and H. Kitamura, J. Synchr. Rad. 8(2001)1221