# TRANSVERSE COHERENCE AND POLARIZATION MEASUREMENTS OF COHERENT FEMTOSECOND PULSES FROM A SEEDED FEL

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## *Abstract*

We report on measurements of the transverse coherence and polarization of light pulses at 131 nm generated by a seeded free-electron laser. The MAX Test-FEL consists of a 375 MeV linac source with two undulators in optical klystron configuration. The system is seeded at 263 nm and these measurements have been made at the second harmonic of the seed laser frequency at 131 nm. The radiator undulator in the Test-FEL is an APPLE-II undulator [1]. The state of polarization of the radiation can be set to horizontal, circular and vertical polarization by shifting the undulator magnets. The emitted pulses are analyzed with a grating spectrometer. A double slit aperture is positioned in the beam in order to determine the transverse coherence of the light pulses by analyzing the fringe visibility. Furthermore, the generation of circular polarized light is demonstrated. The polarization state of the light pulses is measured with a Rochon prism polarizer.

## INTRODUCTION

The Test-FEL facility at the MAX-lab laboratory is a seeded FEL working with the Coherent Harmonic Generation principle, producing coherent radiation down to the 6th harmonic of the 263 nm Ti:Sapphire seed laser [2]. The electron bunches, which have a charge of 30 pC per bunch and a duration of 1 ps, are taken from the main electron gun of the MAX-lab synchrotron. They pass through a modulator undulator, where they are overlapped in space and time with the seed laser pulse at 263 nm wavelength, with a pulse duration of 500 fs and an energy of about 50 $\mu$J. The laser pulses are produced in a Ti:sapphire system and are triggered at a repetition rate of 2 Hz. The laser field causes an energy modulation of the electrons, which then pass through a dispersive section, where the energy modulation is transferred to spatial micro bunching. In the second undulator, the radiator, the electrons emit light. This undulator is capable of producing linear and elliptical polarization states. However, the pulse energy of the coherent signal is only a few pJ/pulse, which limits the available resolution. Furthermore, the electron accelerator is not dedicated for FEL operation and thus the stability pulse-to-pulse is not excellent [3].

In this report, we measure the transverse coherence and the polarization state of the coherent emission, with the focus on small changes to the existing experimental setup.

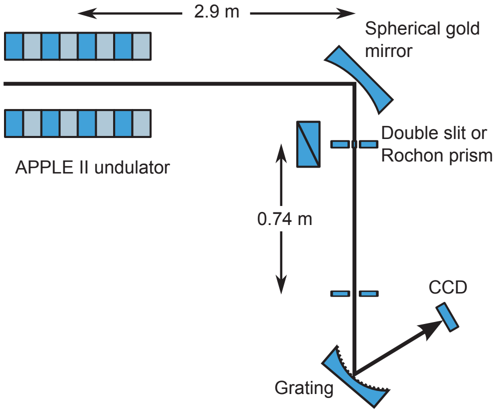

Figure 1: Experimental setup for the coherence and polarization measurements. For the coherence measurement, a double slit is placed between the spherical mirror and the grating. For the polarization measurement, a Rochon prism polarizer is placed in the same position.

## EXPERIMENTAL SETUP

The optical diagnostics system for the produced radiation consists of a spherical mirror and a grating spectrometer, as shown in figure 1. The spherical mirror focuses the radiator emission onto the entrance slit of the spectrometer, and the grating produces a spectrum on the CCD detector. The instrumentation for polarization and coherence measurements were designed for a simple installation on the existing setup. A key feature has been to utilize the non-dispersive plane of the spectrometer where proper imaging of the signal is available. Thus a horizontal double slit will diffract the signal vertically while the spectrometer still provides spectral information in the horizontal plane and disperses residual seed laser light.When measuring the transverse coherence with the slits, the beam intensity was found to be very low, even for the coherent signal. Due to this, recordings of spontaneous undulator emission (with significantly lower intensity per wavelength) were not possible.

The polarization state can be measured by placing a linear polarizer on the beam axis. Here a Rochon prism is used to splits the beam into two orthogonal polarization axes of which only one is transmitted to the spectrometer, while the orthogonal polarization component is refracted and blocked by the spectrometer entrance slit. The polarization measurements reveal a significant rejection of horizontally polarized light by the spherical mirror and the spectrometer grating.

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## COHERENCE MEASUREMENTS

Four different double slit apertures were tested, with slit widths of 40 $\mu$m and 100 $\mu$m and slit separation of 400 $\mu$m and 800 $\mu$m. The slits are cut by a laser into a thin steel foil. When the double slit is inserted into the setup, the beam is diffracted along the vertical axis, and the diffraction pattern can be observed on the spectrometer in the spatial direction. The intensity distribution is integrated over the spectral domain in the central part of the coherent signal. The theoretical intensity distribution for far-field diffraction behind a double slit is used for the fit:

$$I(x) = I_0 \frac{sin(\pi dx/\lambda z)}{\pi dx/\lambda z} (1 + \nu cos(2\pi Dx/\lambda z)), \qquad (1)$$

with slit separation $D$, slit width $d$, wavelength $\lambda$, distance $z$ to the double-slit plane and fringe visibility $\nu$. The fringe visibility $\nu$ is used as a fit parameter, and is a direct measurement of the degree of coherence between the two slits. The figure 2 shows the CCD image recorded at the spectrometer for the smallest double slit sample (40 $\mu$m slit width and 400 $\mu$m slit separation) and figure 3 shows the intensity in the vertical direction of the beam together with the theoretical fit. From the theoretical fitting, the fringe visibility is found to be $\nu = 0.67$. However, the beam is expected to have a much higher degree of coherence, and we believe that the fringe visibility is reduced during the measurement. More specifically, long exposure times over many shots are necessary to achieve a good signal-to-noise ratio, and thus stability issues have a pronounced effect on the measurement. Pointing instabilities lead to uneven illumination of the slits, which reduces the fringe visibility in the individual shots, which are then averaged during the measurement. For these reasons, the measured fringe visibility should be considered as a lower limit of the degree of coherence in this case.

Measurements with larger slit width show an even lower fringe visibility of $\nu = 0.41$, yet these measurements suffer from issues with the detector resolution. At the larger slit separation of 800$\mu$m, no diffraction pattern is visible, and the intensity is extremely low. We conclude that the beam size in the diffraction plane is too small to illuminate both slits in this case.

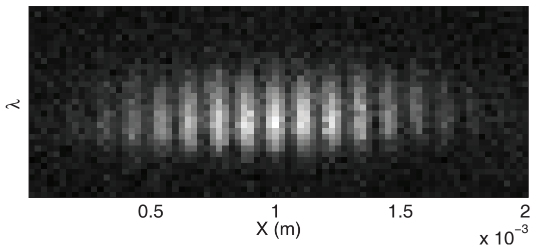

Figure 2: Image of the diffraction pattern behind the spectrometer.

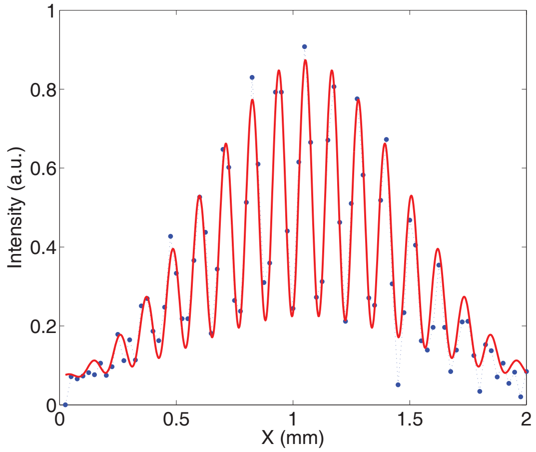

Figure 3: Intensity along the spatial axis of Fig. 2, together with the fit function. The fringe visibility is $\nu = 0.67$.

## POLARIZATION MEASUREMENTS

The polarization state is measured using a Rochon prism polarizer made of magnesium flouride ($MgF_2$), which has a transmission of about 30% at 131 nm. This provides a window for a fairly simple measurement of the polarization at the second harmonic. This kind of prism consists of a birefringent crystal, in which light polarized parallel to the extraordinary axis is refracted under an angle, while light polarized in parallel to the ordinary axis passes straight through. The prism is placed between the spherical mirror and the spectrometer, it is mounted on a rotation stage which allows rotation of the polarizer around the beam axis.

For the measurement, the radiator undulator is set to vertical, horizontal or circular polarization, and the transmitted intensity through the beamline is measured in dependence on the rotation angle of the polarizer. For linear polarization, such as the vertical and horizontal polarization states, the intensity shows a clear maximum at the matching polarizer angle, and a minimum when the polarizer is rotated by 90 deg. For the case of circular polarization, the measured intensity should be constant, independent of polarizer angle.In the actual setup, the transmission factors for the vertical and horizontal polarization components are not equal, in particular the spherical mirror and the grating reject the horizontal polarization component. The measured intensity curve for the horizontal polarization state reflects this fact by exhibiting only a weak maximum at the corresponding polarizer angle, the measured curve for the circular polarization state is deformed accordingly. In order to map the transmission for different polarization states, we use the incoherent signal from spontaneous emission, which is more stable but much weaker than the coherent signal. The transmission of the light pulse through the spherical mirror, the polarizer, and the spectrometer grating is modeled with a Jones matrix. This matrix is composed of the matrices of the individual components, which are formulated with variables for the attenuation of the horizontal polarization component. The intensity on the detector can be calculated by multiplying the polarization state set in the undulator with the matrix, and the resulting intensity for the vertical and horizontal polarization state is fitted to the respective measurement data (Fig. 4).

For the spherical mirror and the spectrometer grating, the reflectivity for the horizontal polarization component, are found to be 0.85 and 0.53 respectively, normalized to the reflectivity of the vertical polarization component. Using these reflectivity coefficients, the expected intensity curve for the circular polarization state can be calculated and fitted to the measured curve.

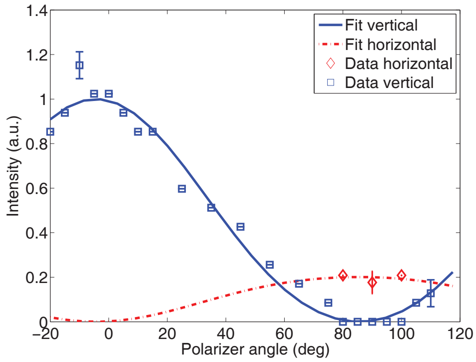

Figure 4: Measurement of the vertical and horizontal polarization of the incoherent beam, together with the fitted functions.

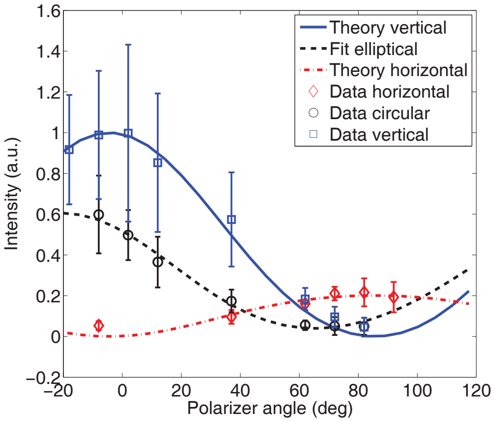

Figure 5: Measurement of the vertical, horizontal and elliptical polarization states of the coherent beam, together with the functions calculated using the parameters found in the measurement of the incoherent beam. The error bars reflect the electron source instability rather than the error in the actual polarization measurement.

Figure 5 shows the measured curves of the coherent signal for the radiator settings for vertical, horizontal and circular polarization as well as the calculated curves. The large error bars, seen especially in the measurement of vertical polarization, result from the intensity instability of the source such as bunch length and arrival time jitter, and arise in any measurement of the coherent intensity. For the circular polarization state, the measured curve was fitted with an elliptical polarization state, where orientation and shape of the polarization ellipse were fit parameters. The curve for the elliptical polarization state can be fitted very well to the measured data. The fitted polarization state is significantly elliptical with an ellipticity of 0.38 and rotation angle of the polarization ellipse of 41 degrees. The ellipticity can be explained by the electron beam not following the axis of the APPLE-II undulator, and thus producing a helical signal in the radiator. The rotation of the ellipse, on the other hand, suggests that phase retardation of the vertical or horizontal polarization components occur in the beamline optics. These are not considered in the Jones treatment described above, and can play a role here.

## SUMMARY

Measurements have been done on the transverse coherence and the polarization of the coherent signal of a seeded FEL. The measurement of the transverse coherence shows a high degree of coherence of $C = 0.67$. However, the measurement is constrained by beam pointing issues of the coherent signal and the true degree of coherence is presumably larger. The measurement of the polarization shows a strong elliptical polarization of the coherent signal when operating the radiator undulator in circular mode. The existing beamline limits the measurements due to a strong rejection of the horizontal polarization component, and likely phase retardation effects, by the beamline optics.

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