EXPERIMENTAL CHARACTERIZATION OF FEL POLARIZATION CONTROL WITH CROSS POLARIZED UNDULATORS

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Abstract

Polarization control of the coherent radiation is becoming an important feature of recent and future short wavelength free electron laser facilities. While polarization tuning can be achieved taking advantage of specially designed undulators, a scheme based on two consecutive undulators emitting orthogonally polarized fields has also been proposed. Developed initially in synchrotron radiation sources, crossed polarized undulator schemes could benefit from the coherent emission that characterizes FELs. In this work we report the first detailed experimental characterization of the polarization properties of an FEL operated with crossed polarized undulators in the Soft-X-Rays. Aspects concerning the average degree of polarization and the shot to shot stability are investigated together with a comparison of the performance of various schemes to control and switch the polarization.

INTRODUCTION

FEL sources naturally produce radiation with precise polarization states as they use undulators. The polarization of light is in fact directly correlated to the symmetry of the electron trajectory in the magnetic device where radiation and electrons couple in the FEL process. Self Amplified Spontaneous Emission (SASE) FELs, which require several tens of meters of undulators, normally use linearly polarized undulators. The choice was mainly driven by the users' request. Moreover, linear undulators ensure high field quality and reduced cost. Otherwise, if different states of polarization are to be provided, elliptical polarized undulators [1,2] have been demonstrated to be suitable for both low and high gain FELs in the VUV and XUV wavelength range [3]. These devices implement a variable arrangement of the magnetic poles such that the magnetic field can assume a circular, elliptical or planar symmetry and so does the emitted radiation. Unfortunately they are not capable of fast variations of the polarization state as requested, for example, by circular dichroism experiments [4].
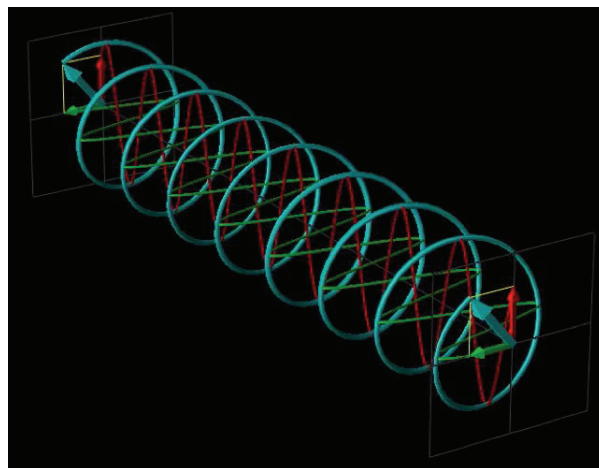

Figure 1: Crossed undulator scheme. One undulator is emitting horizontal polarization (green curve) while the other vertical polarization (red curve) to produce circularly polarized light (blue curve). Image obtained with [5].

CROSSED POLARIZED UNDULATORS

Other possible approaches for fully controlling the output polarization of the emitted radiation have been studied. One is the crossed undulator scheme [6,7].

Synchrotron Sources

Originally demonstrated on synchrotron light sources, the scheme relies on two undulators emitting orthogonally polarized light, e.g., one linear horizontal and one linear vertical undulator, see Figure 1. A suitable phase shifter separates the undulators in order to carefully control the relative phase between the two emitted waves. In this way the scheme is capable of producing linearly polarized light with an arbitrary direction as well as elliptically and circularly polarized light with arbitrary chirality.

In general the source used for this kind of devices must have a high degree of coherence and narrow bandwidth spectrum, so that the two electro-magnetic waves emitted by the undulators can interfere between each other in correspondence of the sample to be studied. In the case of synchrotron light, the bandwidth is too large, so the scheme needs a monochromator to be effective. Still, due to the limited coherence, the maximum degree of polarization that has been demonstrated is in the 40% range [8]. Nevertheless the light has been successfully used to perform experiments [9], demonstrating the viability of the method for full polarization control.

FEL Sources

FEL sources, characterized by a narrow bandwidth emission and high degree of coherence, are most suitable for the crossed undulator setup.

A number of studies have been carried out for SASE, based on FLASH, XFEL [10] and LCLS [11,12] setups. While in the case of synchrotrons the intensity emitted by the two undulators has the same intensity, for FELs the gain determines a possible unbalance between the two undulator emissions. For overcoming this difficulty the scheme can be implemented using a first undulator that acts as a buncher for the electrons that, just before reaching saturation, are injected in the crossed undulators emitting the same intensity for both undulators. In the case of SASE the maximum theoretical limit for the degree of polarization of the output radiation is thought to be in the 80 to 90% range, mainly limited by the spiky structure of the SASE pulse [10-12].

A seeded FEL can therefore be the right choice for the crossed undulator scheme for its higher degree of temporal coherence, inherited by the external seed source used. A theoretical maximum degree of polarization in this case can exceed the 90% [13].

The scheme has been successfully demonstrated at the SDUV FEL [14], using a bunched beam and two orthogonal undulators emitting visible light at 523 nm, corresponding to the second harmonic of the external 1047-nm seed. The balancing of the emission from the two undulators has been achieved by using short undulators in order to have a nearly rigid bunching in both of them.

CROSSED POLARIZED UNDULATORS AT FERMI

Despite of the aforementioned demonstration [14], the demonstration of the scheme in presence of FEL gain in the VUV spectral range was still missing up to now. In the following we provide a description of the measurements carried on at FERMI FEL facility [15], on the FEL-1 beamline.

FERMI is a seeded FEL based on the High-Gain harmonic generation (HGHG) scheme [16]. It features two FEL beamlines, a single stage cascade FEL-1 [17] and a double-stage for FEL-2 [18]. The necessary electron beam for the production of the photons is provided by a normal conducting linac [19].

All the presented results were obtained with FEL-1 tuned at the 8th harmonic of the 260 nm Ti:Sa seed laser, corresponding to HGHG FEL emission at 32 nm. Contrary to the visible spectral range, the measurement of the polarization of light in the VUV and X-ray range is an experiment in itself [20].

FERMI is based on variable polarization APPLE-II type radiator undulators [17]. The polarization of the FEL radiation can be linear horizontal, linear vertical, circular left and right and can be changed arbitrarily. Phase shifters are installed in between each undulator and are used to modify the phase variation of the light emitted by each module.

These features open up the possibility of different implementations of the crossed undulator scheme. We can in fact superimpose a horizontal linear polarization with a vertical linear polarization, in order to produce circular polarization with different chirality and linear polarization
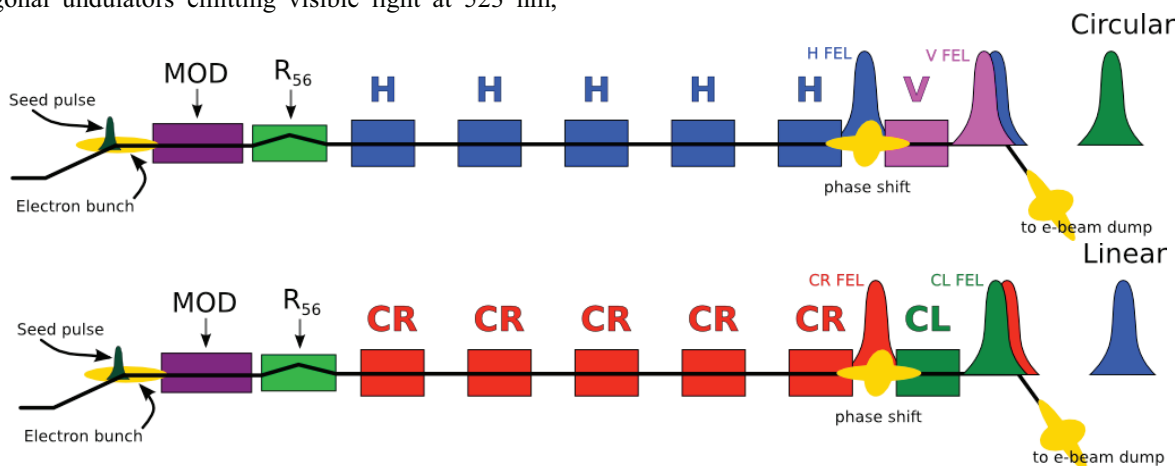

Figure 2: Two different ways to achieve the crossed undulator scheme at FERMI. By taking advantage of the variable polarization undulators, the crossed polarization scheme can be implemented with linear horizontal and linear vertical polarization in order to produce circular or linear polarization with variable direction (top). It is also possible to couple circular right and circular left polarized light to produce linearly polarized light with an arbitrary direction of polarization (bottom).

at an arbitrary direction of the polarization angle depending on the phase shift in between the orthogonal undulators, see Figure 2 (top panel).

Another possibility is to implement the crossed polarization scheme by superimposing two circular polarized emissions with opposed chirality to produce linearly polarized light with arbitrary polarization angle, as shown in Figure 2 (bottom panel).

EXPERIMENTAL DESCRIPTION

During a dedicated beam time, different polarimeters have been installed and used to characterize the radiation produced by FERMI in the different pure polarization states. In all the cases a degree of polarization up to 99% has been measured at different wavelengths [21]. The machine was then tuned to explore the crossed undulator scheme. One of the concerns for the scheme is its stability from one shot to another, so a shot-to-shot diagnostics was needed.

e-TOF Polarimeter

The only polarimeter capable of characterizing the polarization state of the radiation on a shot-to-shot basis is the e-TOF polarimeter [20]. The device uses angle-resolved electron spectroscopy to determine the degree of linear polarization of the incident light. It is composed of an array of 16 time-of-flight electron spectrometers arranged in a circular symmetry with respect to the photon beam axis.

A 3D rendering of the device is shown in Figure 3. It is capable of detecting the degree of linear polarization as well as its direction, by analysing the angular distribution of electrons photoemitted by a rare gas injected in the centre of the device.

The circular polarization signal is instead indistinguishable from the unpolarized one, but it can be inferred by assuming the source to be fully polarized and subtracting in quadrature the measured degree of linear polarization.
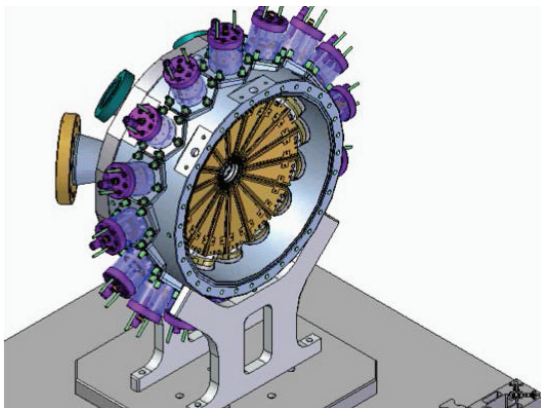

Figure 3: 3D rendering of the e-TOF polarimeter used for the shot-to-shot measurements.

Balancing The Intensities in Presence of Gain

As already mentioned, a key point for obtaining a high degree of polarization in the case of the cross polarized undulators is balancing the intensity of the two sources. This is critical not only to avoid the production of elliptically polarized light, which in principle can be compensated by a proper tuning of the phase shifter between the two sources, but also because unbalanced sources can lead to a degradation of the maximum polarization degree obtainable.
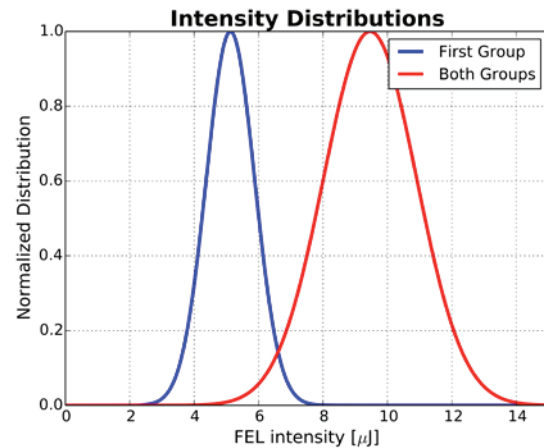

Figure 4: Distribution of the FEL pulse intensities for the first group of undulators (blue curve) and when both groups are emitting radiation (red curve).

While in the case of SDUV-FEL [14] the emission was balanced by using short undulators, so that the FEL gain was not playing any role, in the case of FERMI we wanted to exploit if the balancing of the two crossed sources was possible. This has been achieved by properly tuning the seed laser intensity and dispersive section strength in order to have that the first group of undulators (radiators 1-5 in Figure 2) emits the same FEL energy per pulse as the last undulator alone.

The balancing of the two sources can be fast checked during the experiment either via a gain curve scan or just by recording the intensity distribution with the last undulator tuned and detuned. In Figure 4 the emitted intensities per FEL pulse are reported in the case of all the undulator tuned (red curve) and for the last undulator detuned (blue curve). One can notice that the two groups of undulators are emitting ~5 μJ pulse energy each, for a total emission of 10 μJ.

EXPERIMENTAL RESULTS

In the following the data acquired for the circular left and circular right crossed polarization scheme are presented. This configuration has been chosen in order to take full advantage of the e-TOF polarimeter characteristics, in particular its sensitivity to linear polarization. In the circular left plus circular right scheme, in fact, the output polarization should be linearly polarized, with arbitrary direction of the polarization direction depending on the phase shifter setting. The

machine was tuned as described above in order to have the two undulators emiting similar intensities. The data have been acquired via the FERMI control system and analysed using DART [22].

Direction of Polarization

In Figure 5 the measured direction of the linear polarization, as a function of the shot number (top panel) and the corresponding statistical histogram (bottom panel) are reported in case of zero phase between the two orthogonally polarized sources. One can see that the direction of the linear polarization is compatible with horizontally polarized light, as expected. The rms of the distribution is instead a factor 2 to 3 larger than the one found for the pure horizontal polarization state, cfr. [21]. The obtained result is probably due to shot-to-shot variations of the balance between the intensity of the two sources.

Degree of Linear Polarization

In Figure 6 the degree of linear polarization as a function of the shot number (top panel) and the corresponding statistical histogram (bottom panel) is reported. The rms of the distribution has a value compatible with what found in the pure polarization case, cfr [21], showing that the crossed undulator scheme can be stable enough for performing experiments. The average degree of linear polarization has been found to be ~65%, lower than what expected and reported in [14].

The result can be explained by considering the fact that each of the two crossed polarized sources is diverging due to propagation effects. In Figure 7 a schematic representation of the propagation from the two undulators (red and blue lines) to the detector is provided. At large distances from the sources, compatible with the position of the detector along the beamline, the wavefronts (represented in black) exhibit different behaviours for the on-axis and off-axis regions.
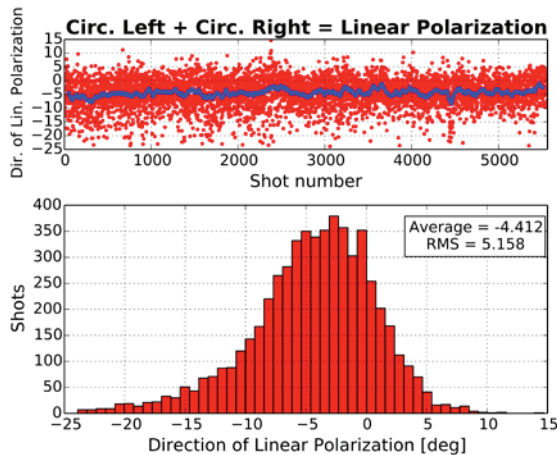

Figure 5: Shot-to-shot distribution of the measured direction of the linear polarization vector in the case of circular left and circular right crossed undulators.
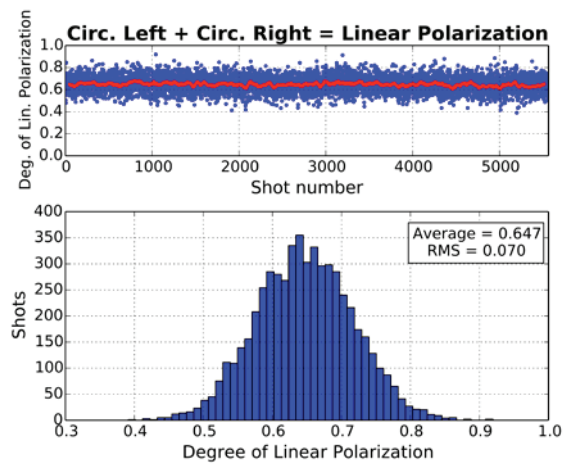

Figure 6: Shot-to-shot statistics of the degree of linear polarization in the case of circular cross polarized undulators that produce linear polarization.
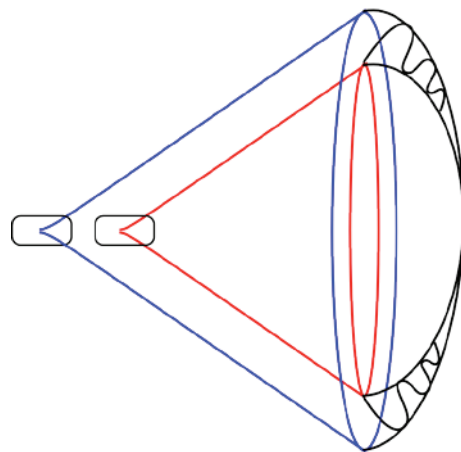

Figure 7: Schematic description of two undulators with different source position (red and blue lines). The wavefronts of the two sources are represented in black.

The on-axis radiation has a smooth phase relation between the two sources, so the resulting field has a definite polarization. Instead, the off-axis emission exhibits rapid phase variations (represented by the oscillating ripples) due to the different divergence of the two sources. This means that, while small regions have a definite polarization state, the latter is changing with the changes of the radiation phase, leading to an overall loss of polarization.

CONCLUSION

Crossed polarized undulator scheme has been demonstrated on a seeded high gain FEL in the VUV. The maximum degree of linear polarization obtained was 65%. Polarization control, both in direction and type, is possible by properly tuning the phase shifter in between the two undulator groups. Other schemes were proposed and have been implemented in order to further improve the degree of polarization obtainable with the crossed undulator scheme [23,24].

A more detailed analysis on the acquired data for the crossed polarized undulator experiment at FERMI is on going [15].

Future activities will focus on studying the possibility of performing fast polarization switching via implementation of an electromagnetic phase shifter.

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