Polarization Control in High Gain Free Electron Lasers

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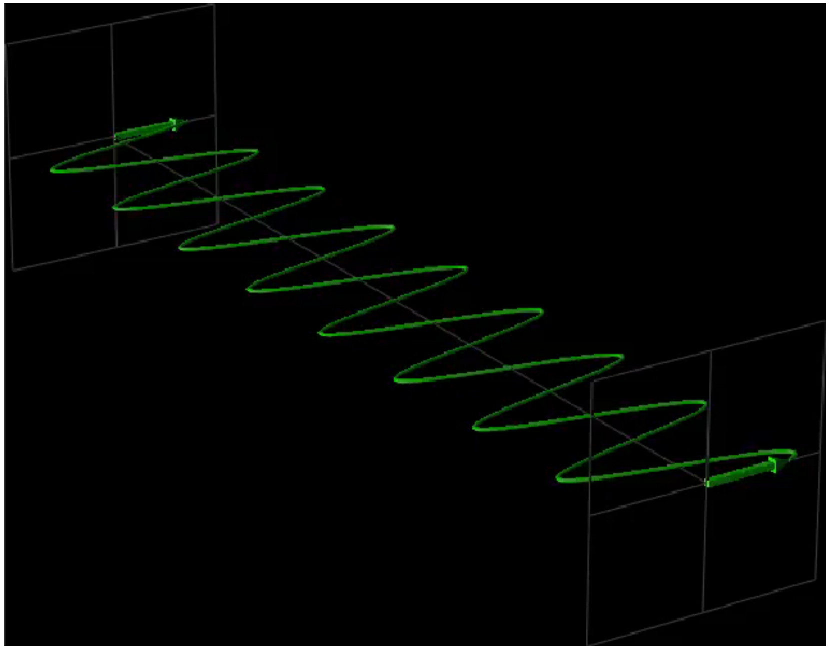
Outline

- Light **polarization** and polarization control in FELs
- Crossed polarized undulator schemes
- **Implementation** of the crossed polarized undulator scheme at FERMI
- **Model** for the experimental results
- Strategies to **improve** the degree of polarization of the output radiation

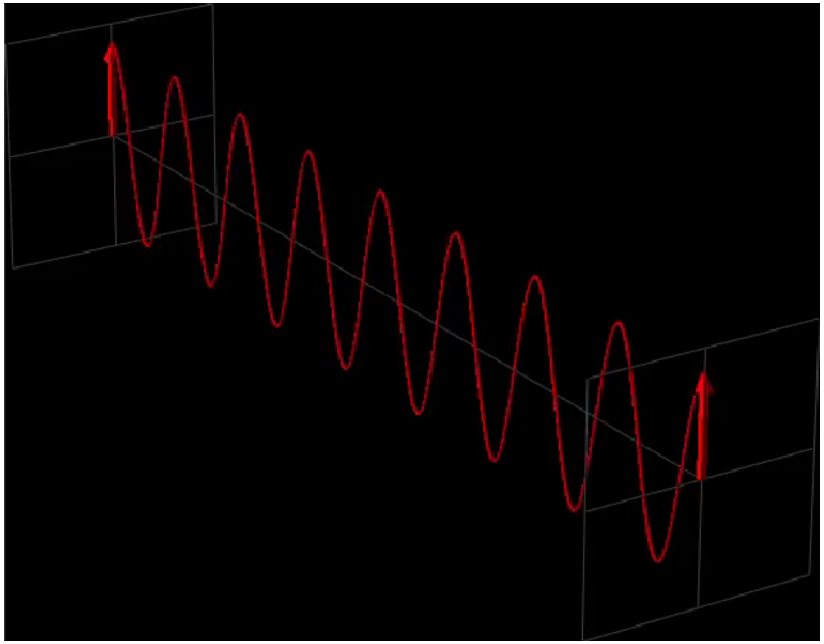
Polarization of Light

The **polarization** of the light describes the way in which the electric field of an electromagnetic wave is oscillating.

If the oscillation is along a single direction, the light said to be linearly polarized



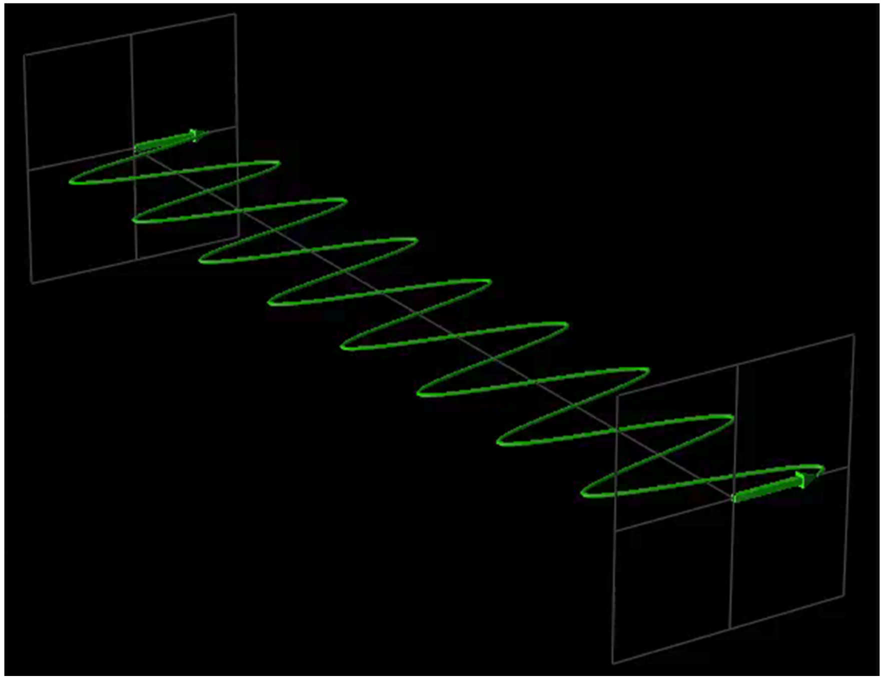
Linear Horizontal

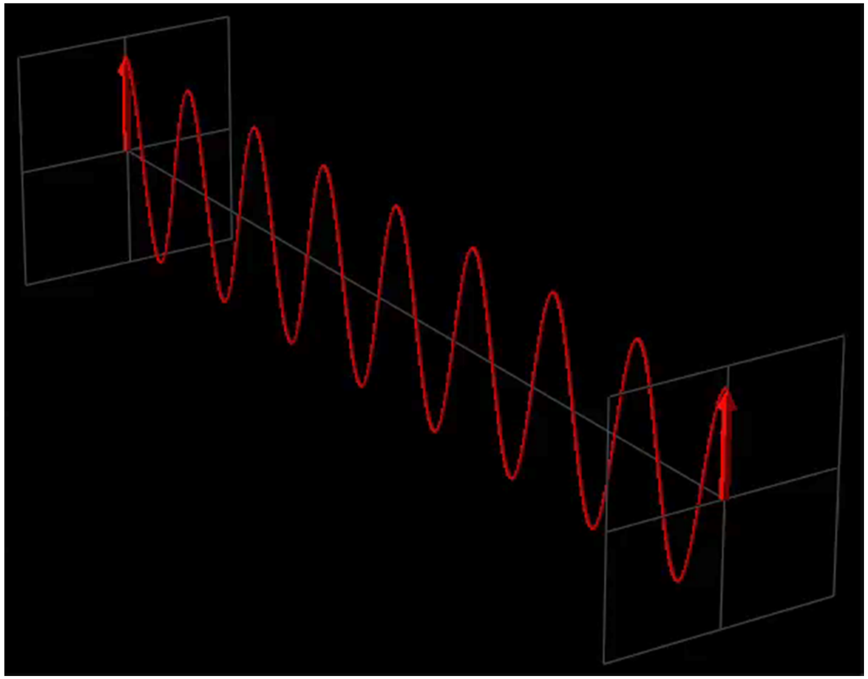


Linear Vertical

Animations from **EMANIM**: http://www.enzim.hu/~szia/emanim/emanim.htm

Polarization of Light

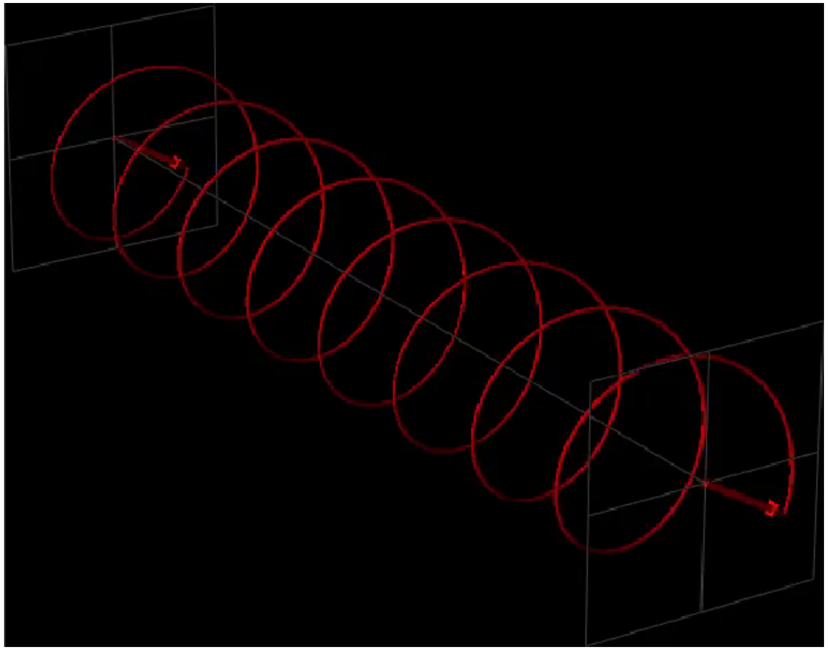




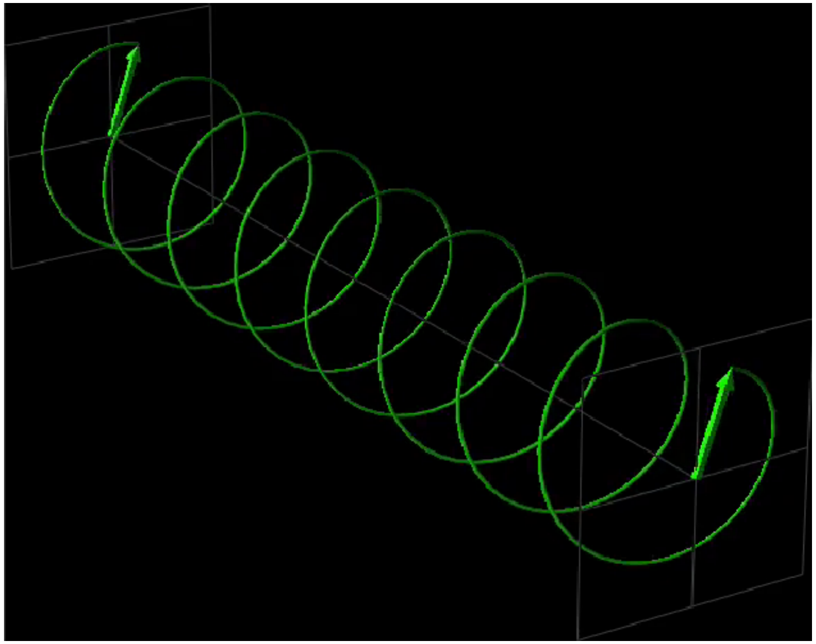
Polarized light is naturally produced by FEL sources as they utilize undulators. "Normally" with linear polarization

Polarization of Light

If the oscillation of the electric field is rotating, the light has an elliptical or circular polarization.



Circular Left



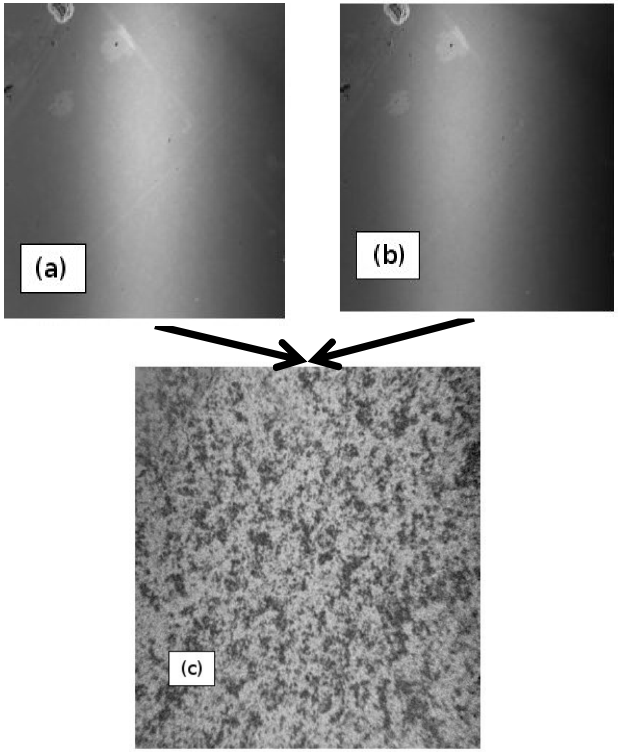
Circular Right

Why considering polarized light?

For the Experiments:

e.g.: dichroic studies

Cobalt film
(Curtesy C. Spezzani)



Visualization of magnetic domains

For the FEL:

Larger field-electron coupling

E.g., 1D gain length (E.L. Saldin)

$$L_{g0} = 1.67 \left(\frac{I_A}{I}\right)^{1/2} \frac{(\epsilon_n \lambda_{\rm w})^{5/6}}{\lambda_r^{2/3}} \frac{(1+K^2)^{1/3}}{K A_{JJ}}$$

$A_{JJ} = J_0(K^2/2(1+K^2)) - J_1(K^2/2(1+K^2))$ Planar und.

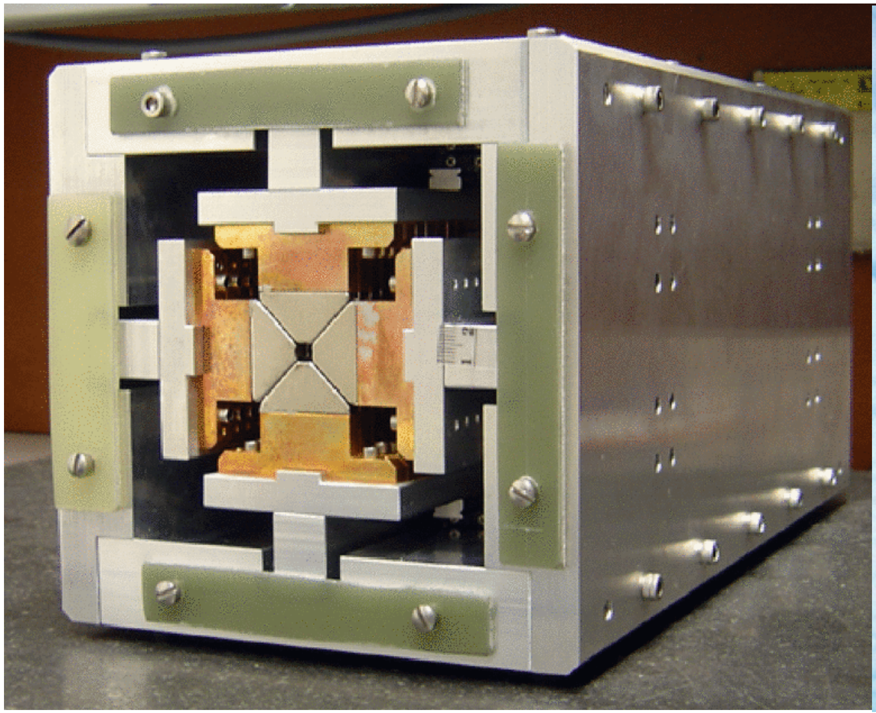
$A_{JJ} = 1$ Helical und.

K~2 ➔ A_{JJ}~0.75

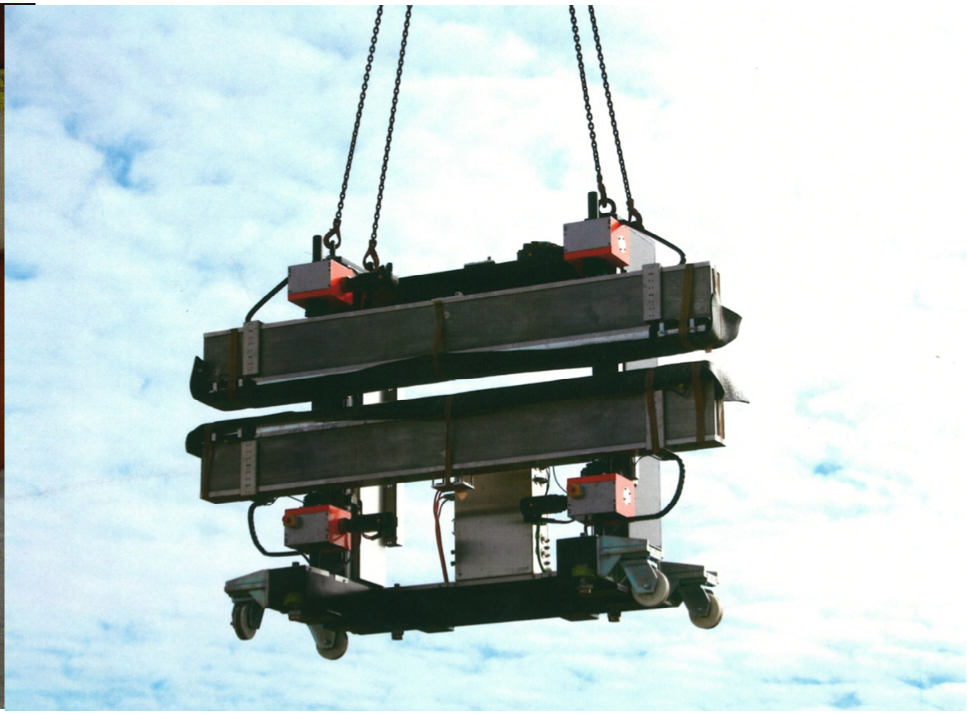
Gain length is ~25% shorter for helical undulators.
For SASE machines the typical undulator length is ~100 m

Variable Polarization Undulators for short wavelength, high gain FELs

Delta Undulator

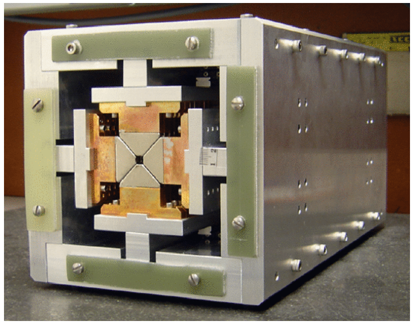


APPLE-II Undulator



Capable of producing linear, circular and elliptical polarized light.
“Slow” switching between different polarization states

Delta undulator at LCLS



Installed at girder 33, work as variable polarization “afterburner”
The ratio between linearly and circularly polarization is about 5 (20 with reverse taper)


nature photonics ARTICLES
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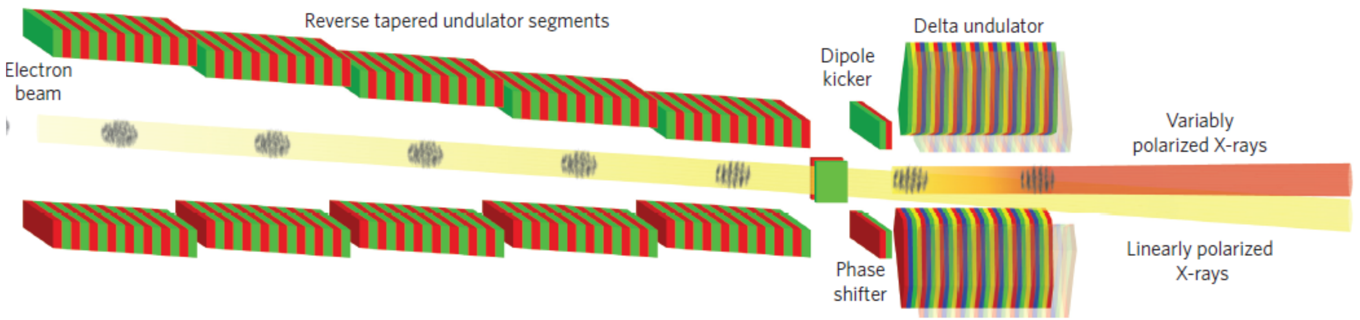
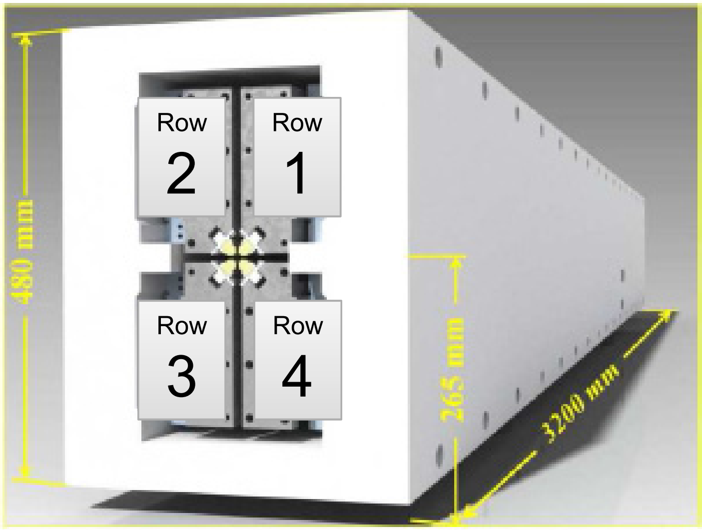
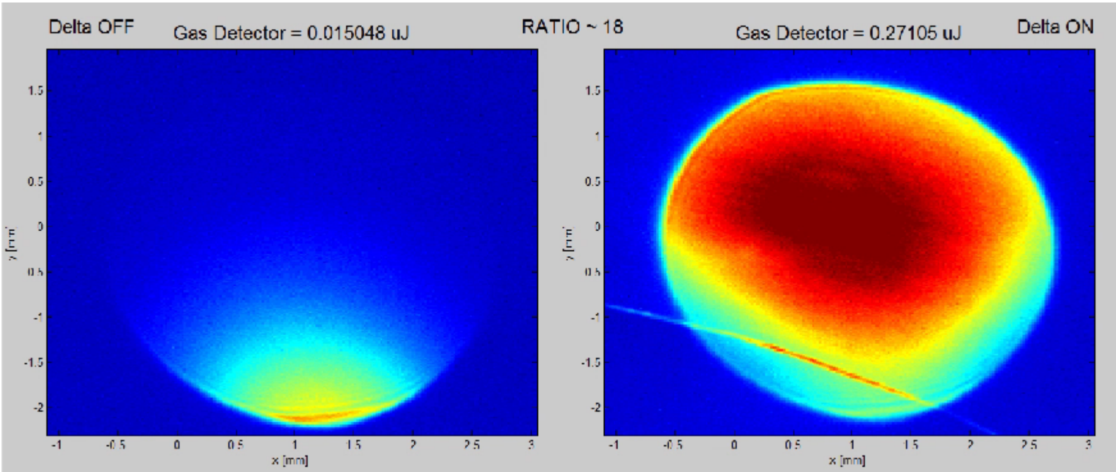
Polarization control in an X-ray free-electron laser

Alberto A. Lutman[1*], James P. MacArthur[1], Markus Ilchen[1,2,3], Anton O. Lindahl[3,4], Jens Buck[2], Ryan N. Coffee[1,3], Georgi L. Dakovski[1], Lars Dammann[5], Yuantao Ding[1], Hermann A. Dürr[1,3,6], Leif Glaser[5], Jan Grünert[2], Gregor Hartmann[5], Nick Hartmann[1,7], Daniel Higley[1], Konstantin Hirsch[1], Yurii I. Levashov[1], Agostino Marinelli[1], Tim Maxwell[1], Ankush Mitra[1], Stefan Moeller[1], Timur Osipov[1], Franz Peters[1], Marc Planas[2], Ivan Shevchuk[5], William F. Schlotter[1], Frank Scholz[5], Jörn Seltmann[5], Jens Viefhaus[5], Peter Walter[5], Zachary R. Wolf[1], Zhirong Huang[1,3] and Heinz-Dieter Nuhn[1]







Curtesy A.A. Lutman

+ Collimating Jaw, optimal ratio > 200

Elettra Sincrotrone Trieste

Delta undulator at LCLS

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Polarization control in an X-ray free-electron laser

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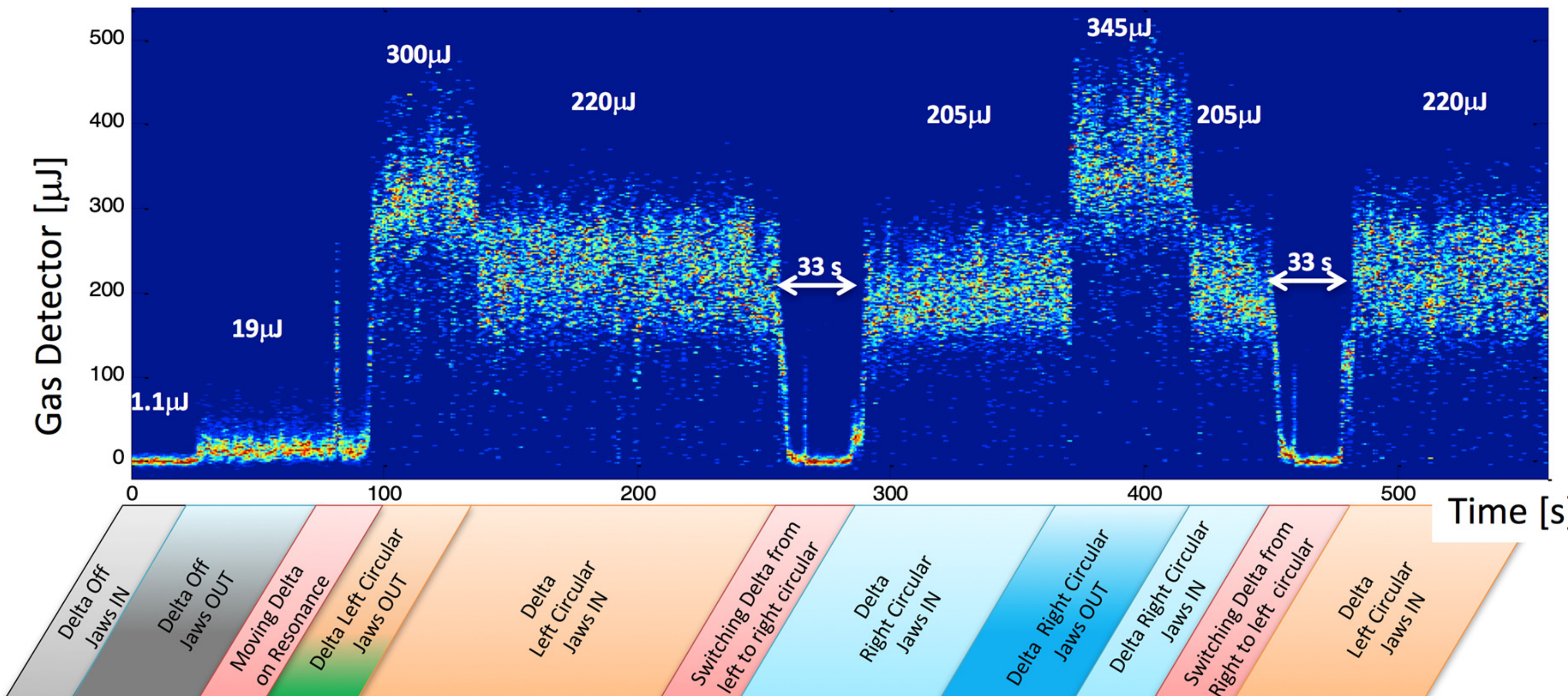
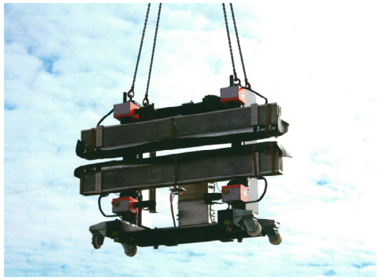
Polarization control over 10 minutes

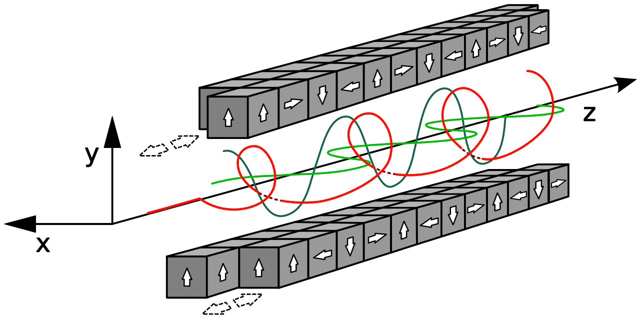


Curtesy A.A. Lutman

APPLE-II undulator at FERMI



FERMI is based on **variable polarization** APPLE-II und.
They provide VUV and soft X-ray radiation with linear, elliptical and circular polarization.
All undulators **normally tuned** to the same polarization



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Control of the Polarization of a Vacuum-Ultraviolet, High-Gain, Free-Electron Laser

Enrico Allaria *et al.*
Phys. Rev. X **4**, 041040 – Published 2 December 2014

photonics MDPI

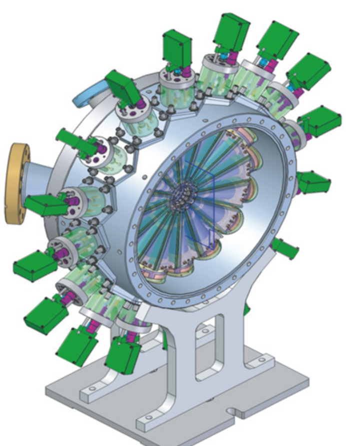
Article

Polarization Characterization of Soft X-Ray Radiation at FERMI FEL-2

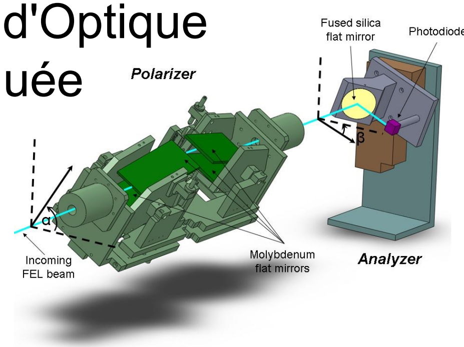
Eléonore Roussel [1,*], Enrico Allaria [1], Carlo Callegari [1], Marcello Coreno [1], Riccardo Cucini [1], Simone Di Mitri [1], Bruno Diviacco [1], Eugenio Ferrari [1,2,†], Paola Finetti [1], David Gauthier [1], Giuseppe Penco [1], Lorenzo Raimondi [1], Cristian Svetina [1,‡], Marco Zangrando [1,3], Andreas Beckmann [4], Leif Glaser [5], Gregor Hartmann [5,§], Frank Scholz [5], Joern Seltmann [5], Ivan Shevchuk [5], Jens Viefhaus [5] and Luca Giannessi [1,6]

Measurement of the polarization with three independent setups:

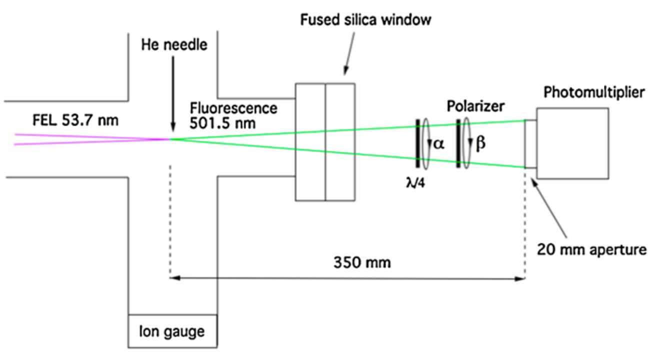
Cookiebox
DESY



Polarizer + analyzer setup
Laboratoire d'Optique Appliquée

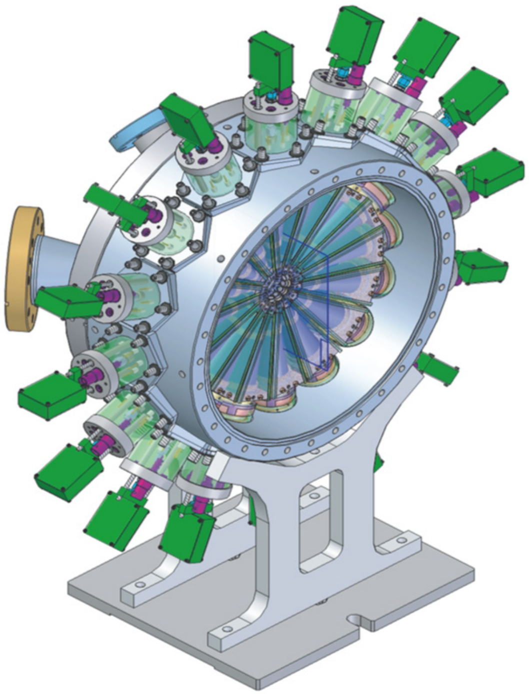


Fluorescence polarimeter
Low Density Matter (FERMI)



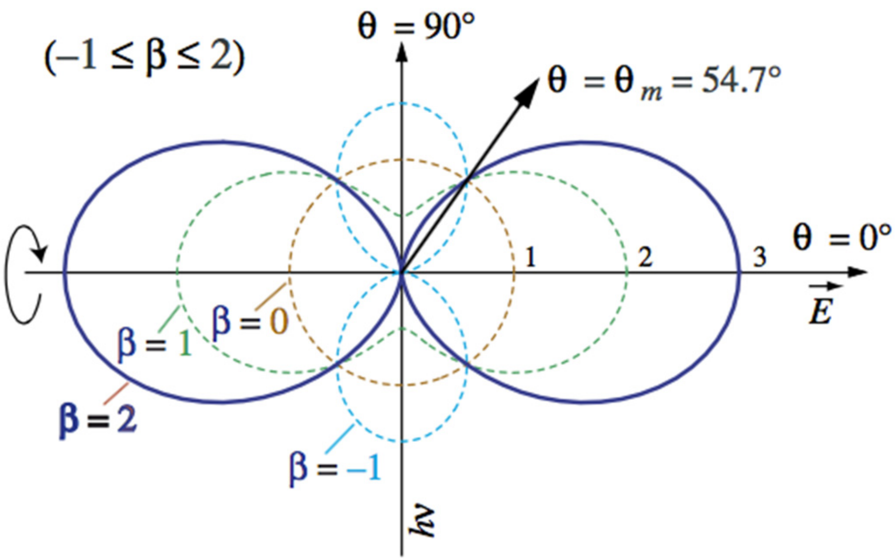
Elettra Sincrotrone Trieste

Cookiebox (DESY)



16-channels electron time-of-flight spectrometer.
Signal from a gas target (e.g., He)
Uses **angle-resolved** electron spectroscopy to determine the degree of linear polarization of the incident light

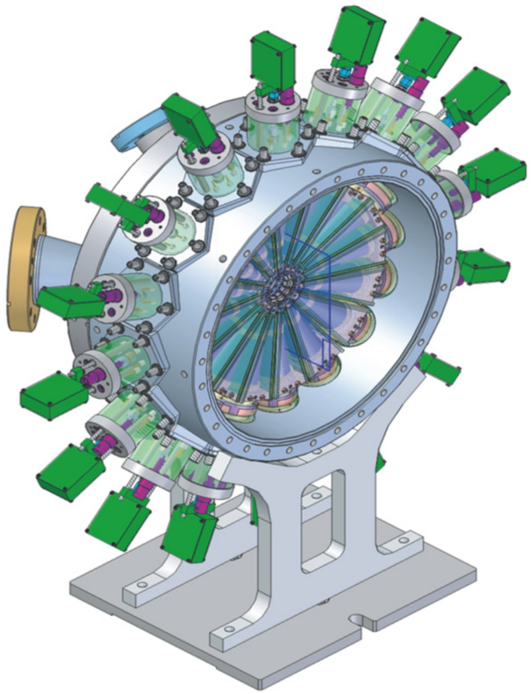
In dipole approximation:



$$\mathcal{P}_2(\cos\theta) = \frac{1}{4}[1 + 3P_{lin}\cos(2[\theta - \lambda])]$$

P_{lin}: degree of linear polarization
λ : direction of linear polarization
β: depends on the gas (=2 for He)

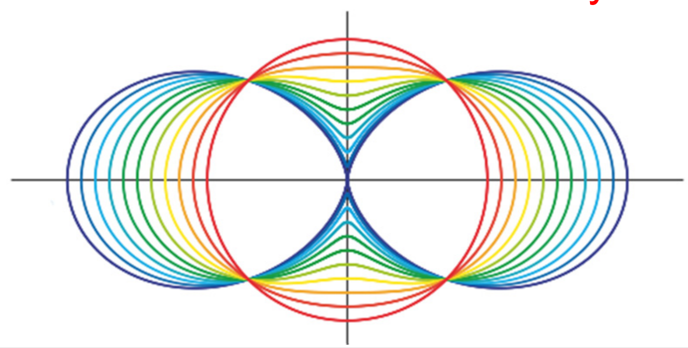
Cookiebox (DESY)



16-channels electron time-of-flight spectrometer.
Signal from a gas target (e.g., He)
Uses **angle-resolved** electron spectroscopy to determine the degree of linear polarization of the incident light

P_{lin} = 1.0/0.9/0.8/0.7/0.6/0.5/0.4/0.3/0.2/0.1/0.0

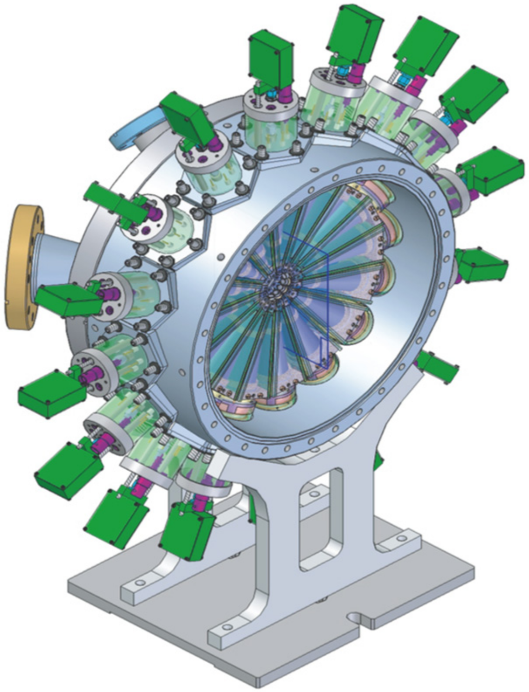
Fully linear polarization — Fully circular polarization*



Wavelength (nm)	FEL polarization	P_{lin}	ψ (°)	S_1/S_0	S_2/S_0	S_3/S_0
26	Linear vertical	0.97 ± 0.02	89.7 ± 1	−0.97	0.01	0.25
26	Linear horizontal	0.94 ± 0.02	0.4 ± 1	0.94	0.01	0.34
26	Circular left	0.11 ± 0.02	50 ± 6	−0.02	0.11	−0.99
26	Circular right	0.11 ± 0.02	127 ± 6	−0.03	−0.10	0.99
32	Linear vertical	0.90 ± 0.02	91.3 ± 1	−0.90	−0.04	0.43
32	Linear horizontal	0.97 ± 0.02	-1.2 ± 1	0.97	−0.04	0.23
32	Circular left	0.10 ± 0.02	124 ± 5	−0.04	−0.09	−0.99
32	Circular right	0.14 ± 0.02	53 ± 6	−0.04	0.13	0.99

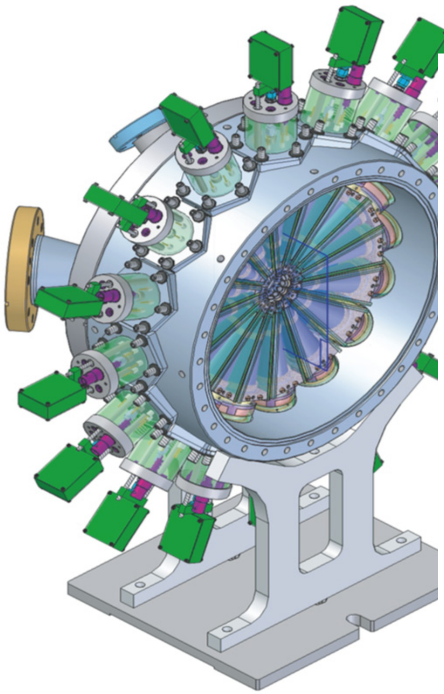
*if light is fully polarized

Cookiebox (DESY)

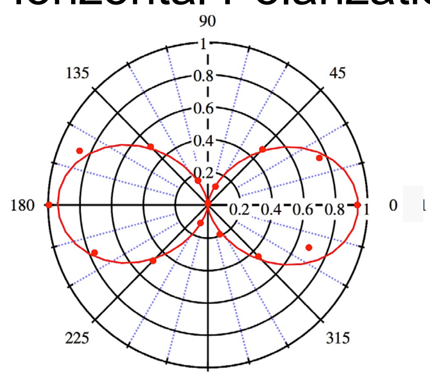


Frau Merkel approved!

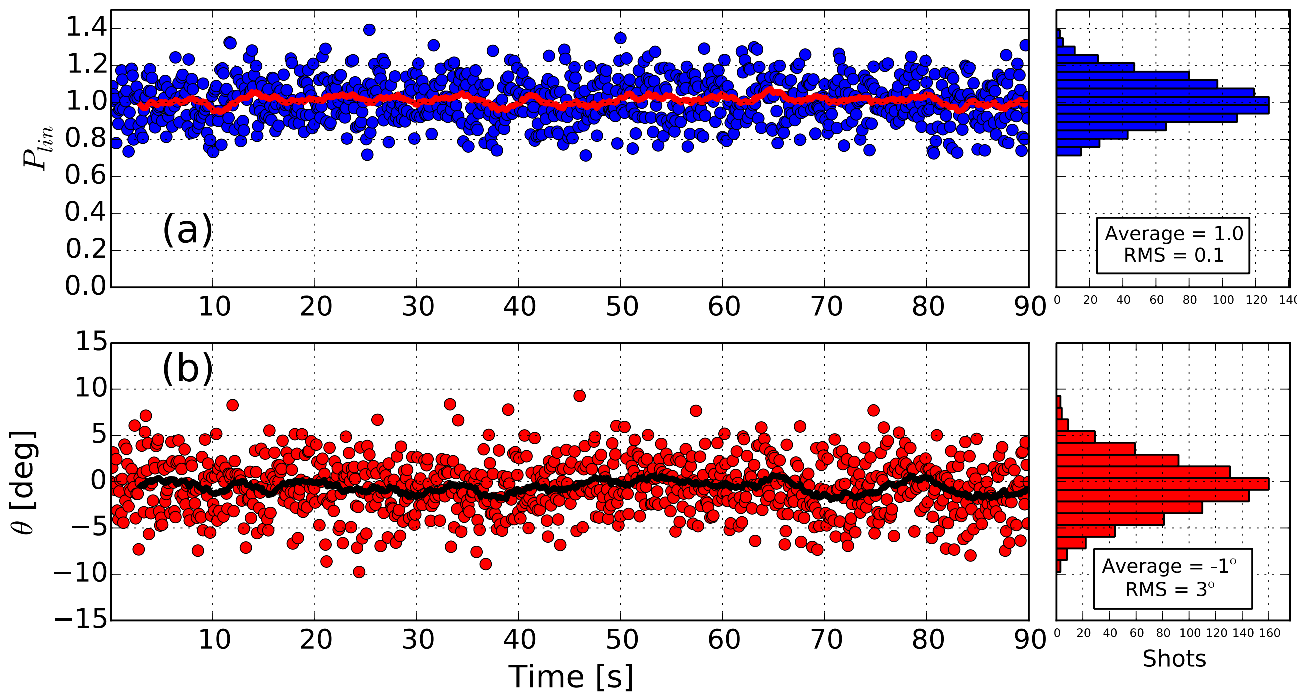
Polarization stability



Horizontal Polarization



The device is capable of measuring the polarization on a **shot-to-shot** basis



The polarization state in the example is **linear horizontal**. The measured stability is dominated by the **statistical fluctuations** on the single e-TOF signals, rather than real fluctuations of the polarization itself

Polarization control via crossed undulators

Crossed polarized undulators emit radiation with orthogonal polarization between each other (e.g., H+V or CL+CR)

Original idea from Kim:

- synchrotron light (K.-J. Kim, NIM 219, 425 (1984))
- FELs (K.-J. Kim, NIM A 445, 329 (2000))

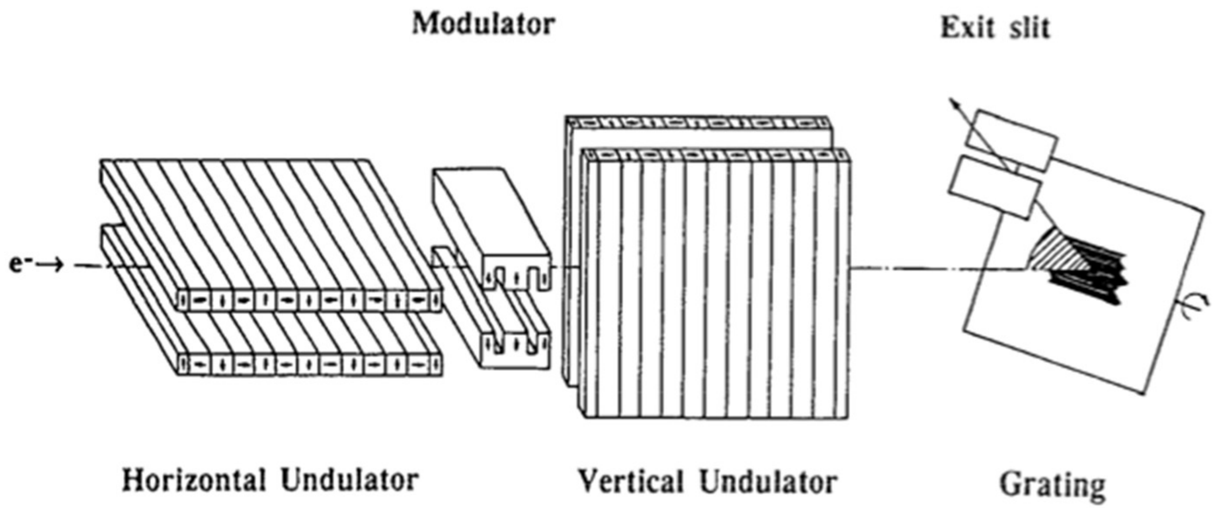
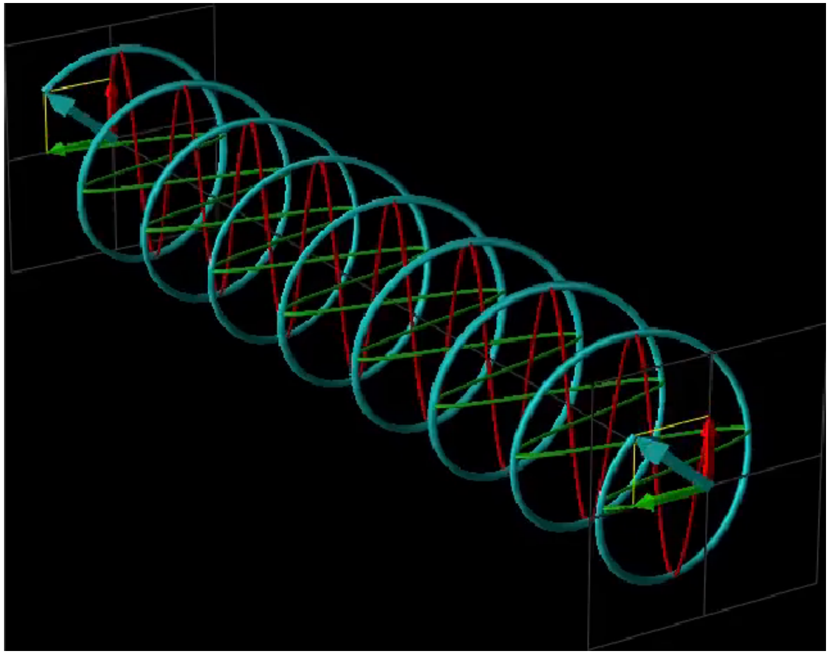
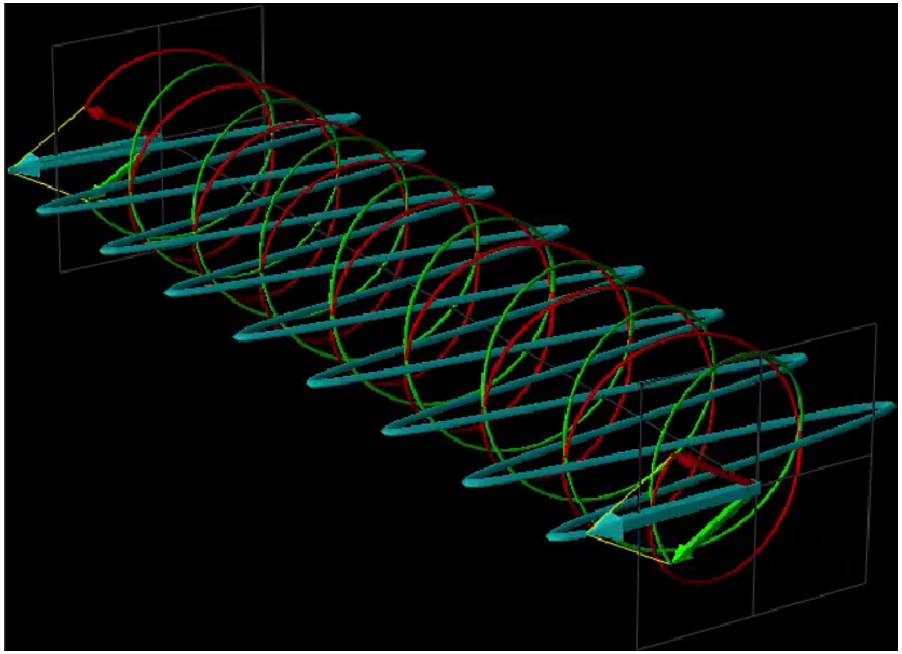


Image from J. Bahrdt et. al., Rev. Sci. Instr. 63, 339 (1992)

<u>Critical ingredients: coherent, narrow bandwidth source</u>

Examples of Crossed Polarization





linear horizontal + linear vertical
=
circular left polarization

circular left + circular right
=
linear horizontal polarization

Crossed undulator scheme

Studied with SASE FEL based on FLASH, Eu-XFEL and LCLS setup

A nice working point has been found, **just before saturation**, in order to have as **identical** as possible **emission** from the two crossed undulators.

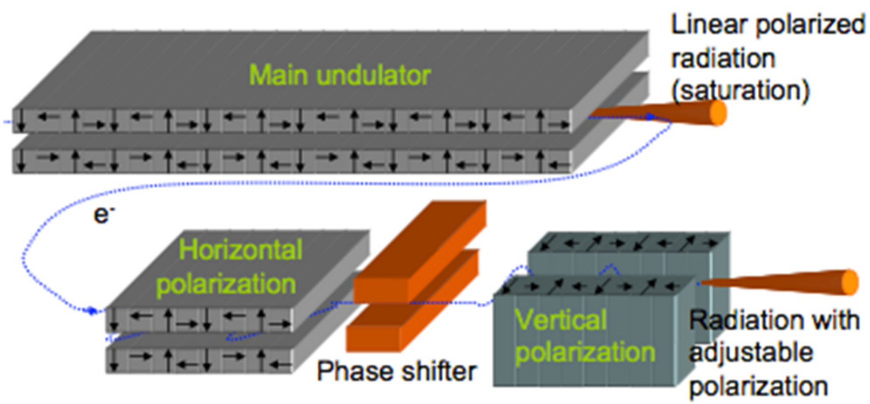


Image from Y. Li et. al, EPAC 08, WEPC118

The **intrinsic spiky** structure and fluctuations of SASE degrade the polarization performances, with a maximum degree of polarization possible of the range **80 – 90%** .

Y. Ding and Z. Huang PR ST-AB **11**, 030702 (2008)

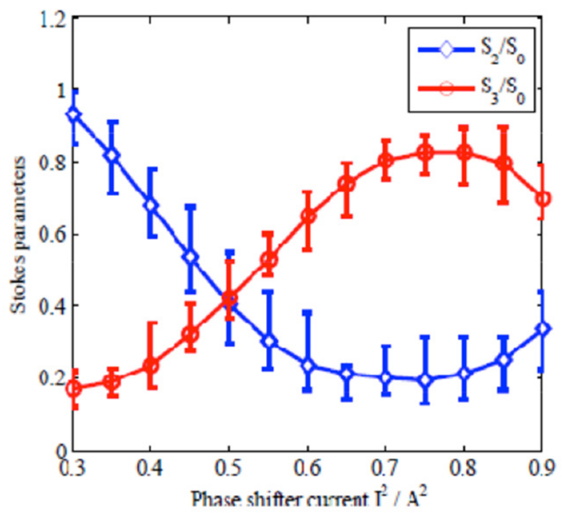
Y. Li et. al, EPAC 08, WEPC118 (2008).

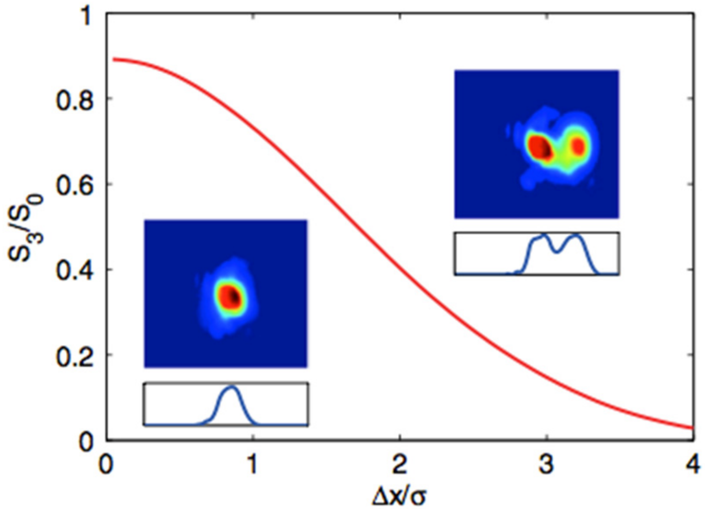
Crossed undulator scheme

Seeded FELs:
The properties of the emitted radiation should be the right ones for the crossed polarized scheme, in particular the **longer temporal coherence** and shot-to-shot stability.

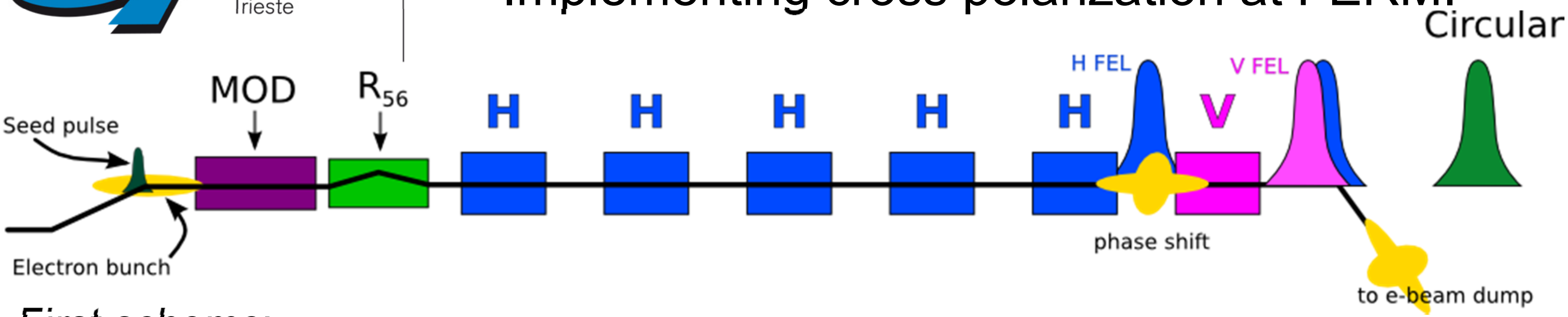
Theoretically, a degree of polarization **larger than 90%** is expected.

Experimentally demonstrated at SDUV FEL.
H. Deng et. al., PR-AB 17, 020704 (2014).

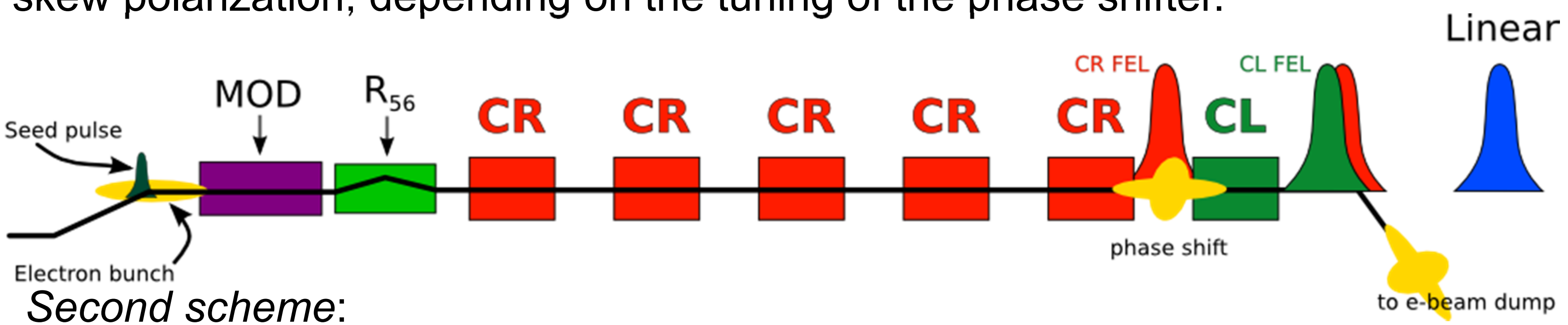




Implementing cross polarization at FERMI



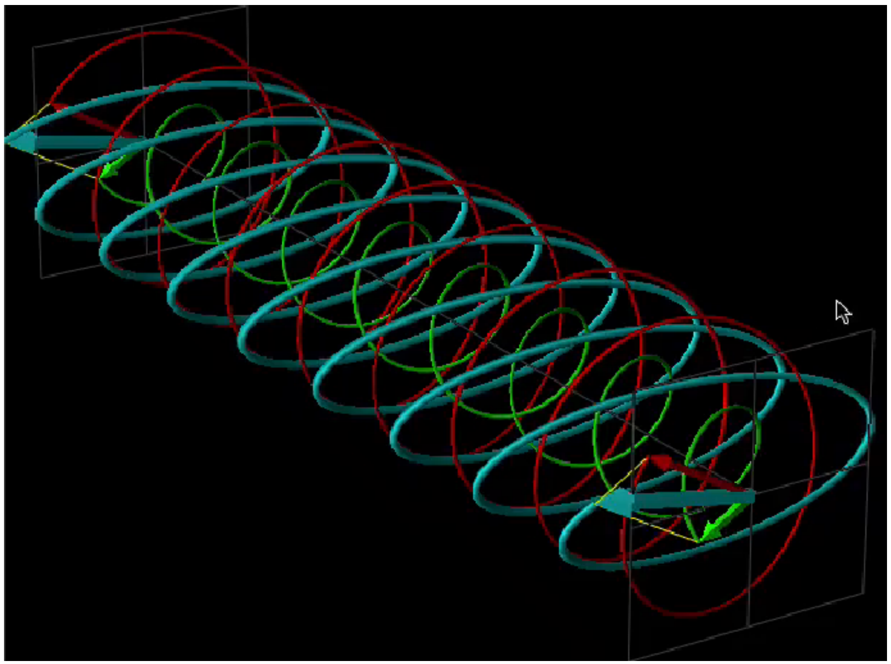
First scheme:
The first part of the radiator emits **Horizontal** polarized light, only one radiator produces **Vertical** polarized light, to produce **Circular** polarization or Linear skew polarization, depending on the tuning of the phase shifter.

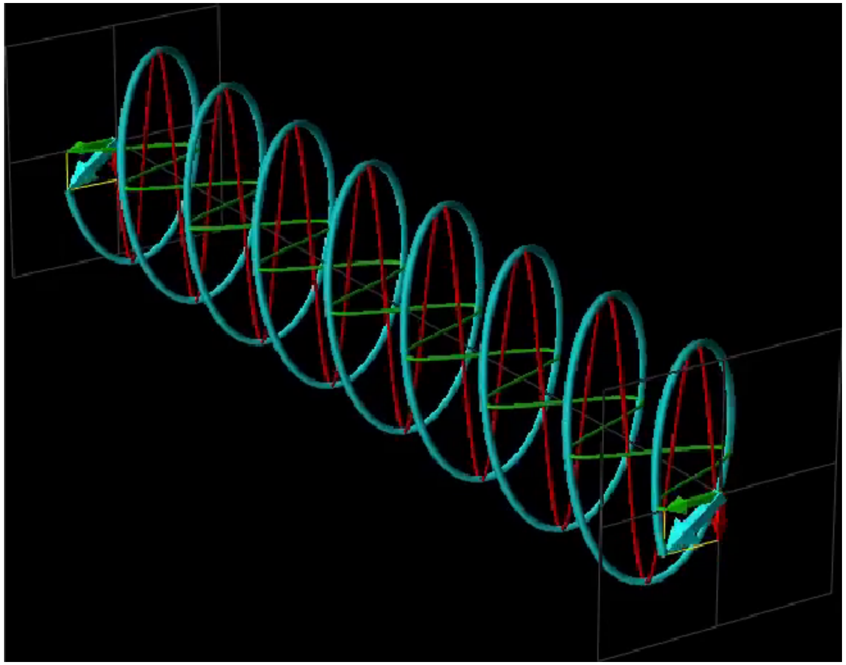


Second scheme:
It is also possible, using the elliptically polarized undulators at FERMI, to perform crossed polarization by using **Right Circular** and **Left Circular** light to obtain **Linear** polarization with adjustable polarization direction.

Useful because the Cookiebox is sensitive to linearly polarized light.

Balancing the emission is critical

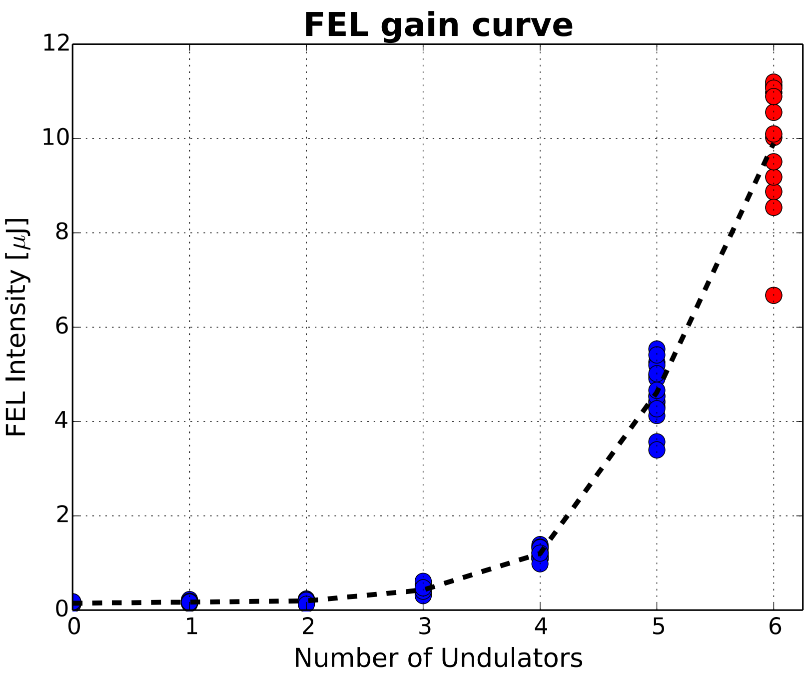


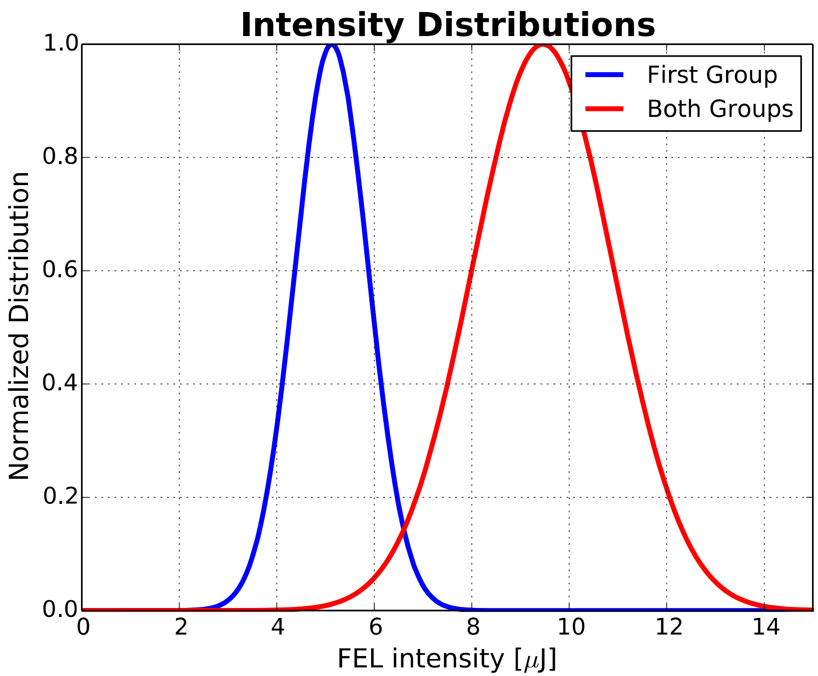


If the two sources are not balanced, the emission exhibits elliptical polarization or there could be loss of polarization

Balancing the emission in presence of gain

It is critical to balance the intensity of the two sources.

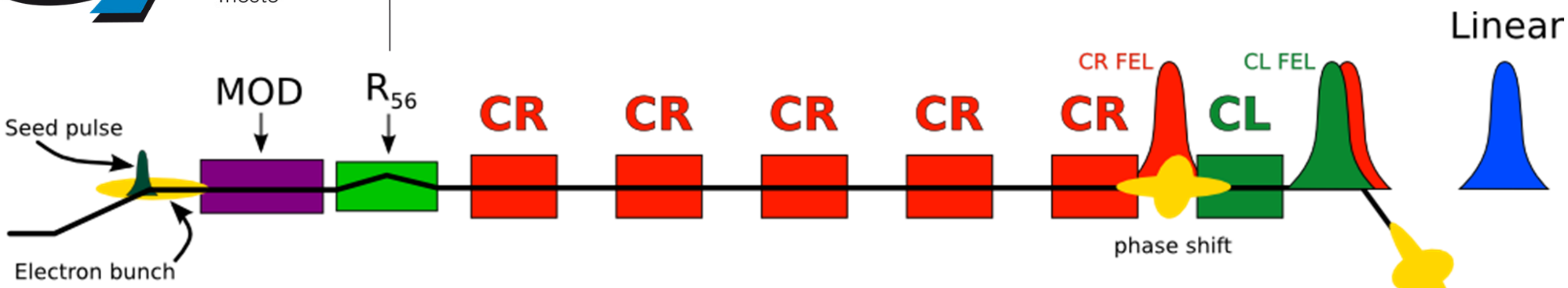


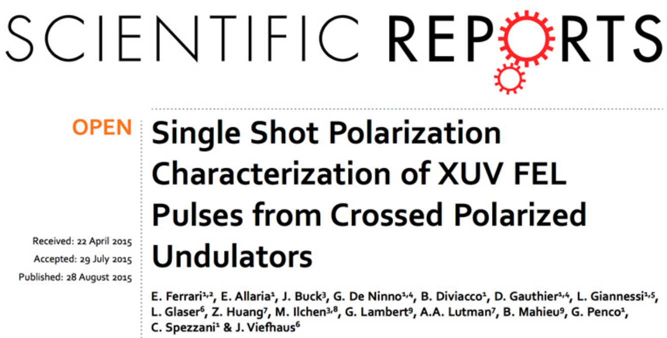


Measuring a gain curve, we can change the **seeding parameters** in order to have that the first 5 undulators emit almost the same intensity as the last undulator alone.

Elettra
Sincrotrone
Trieste

Crossed Polarization Measurements




SCIENTIFIC REPORTS

OPEN

Single Shot Polarization Characterization of XUV FEL Pulses from Crossed Polarized Undulators

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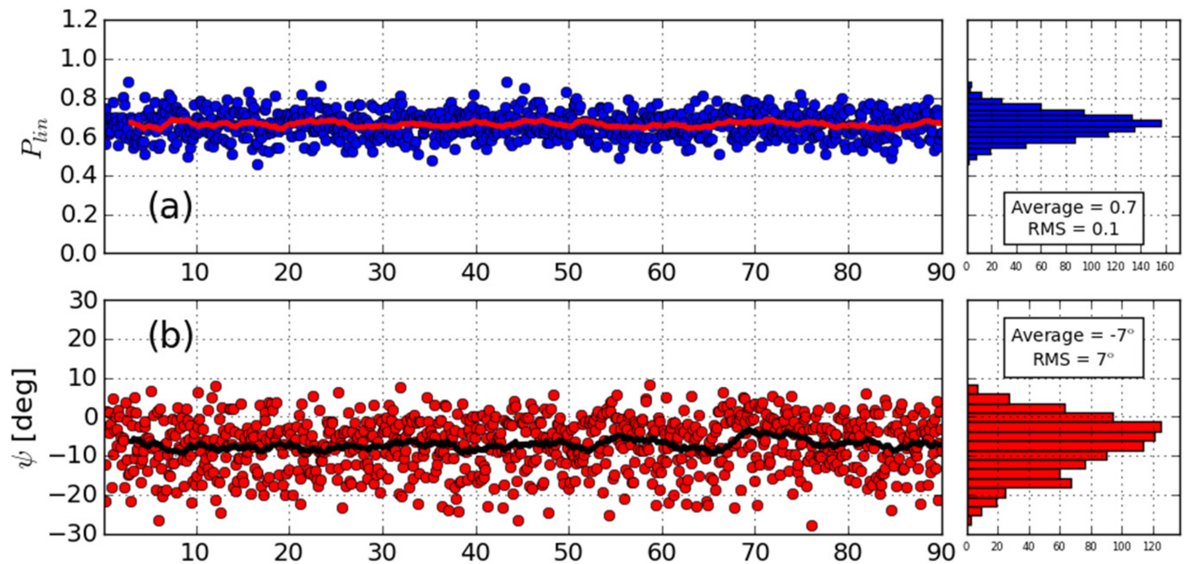
Accepted: 29 July 2015
Published: 28 August 2015

E. Ferrari[1,2], E. Allaria[1], J. Buck[3], G. De Ninno[1,4], B. Diviacco[1], D. Gauthier[1,4], L. Giannessi[1,5], L. Glaser[6], Z. Huang[7], M. Ilchen[3,8], G. Lambert[9], A.A. Lutman[7], B. Mahieu[9], G. Penco[1], C. Spezzani[1] & J. Viefhaus[6]

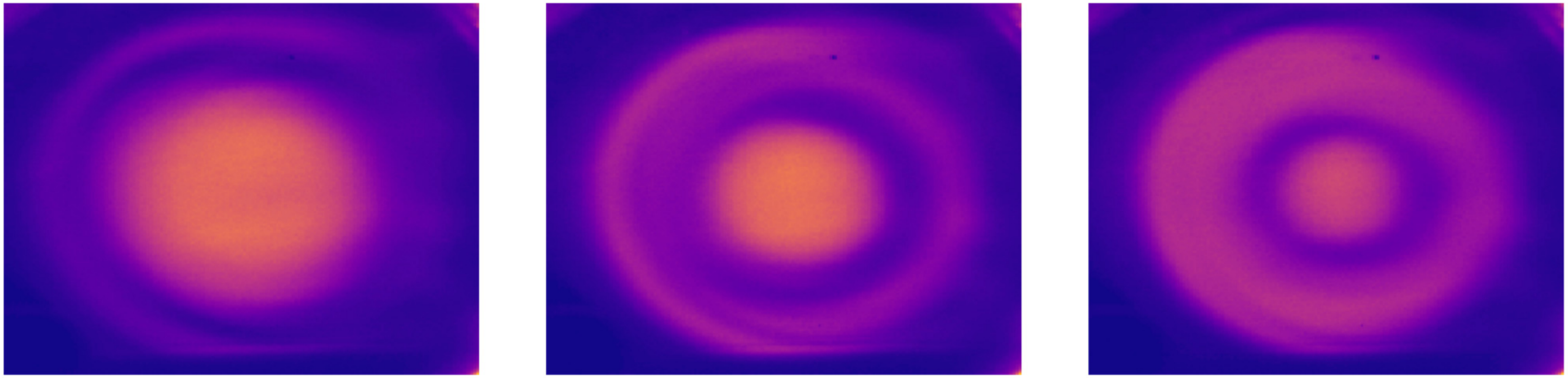


The measured degree of linear polarization is 70%, lower than expected (cfr. H. Deng et. al., PR-AB 17, 020704 (2014), 80% obtained)

How to explain the lower degree of polarization obtained?

Interference effects between different sources

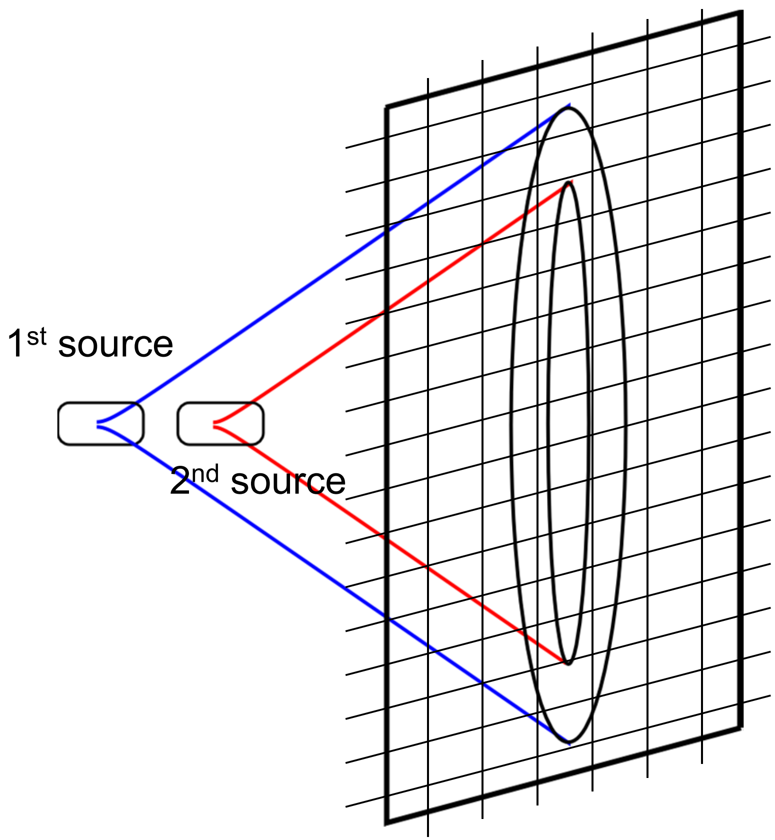
Full radiator tuned at the same polarization



Intensity and FEL transverse mode exhibit interference patterns for different phasing (phase shifter setting) between two undulator groups

Model: interference of two Gaussian sources

Two or more monochromatic Gaussian beams propagating in free space.

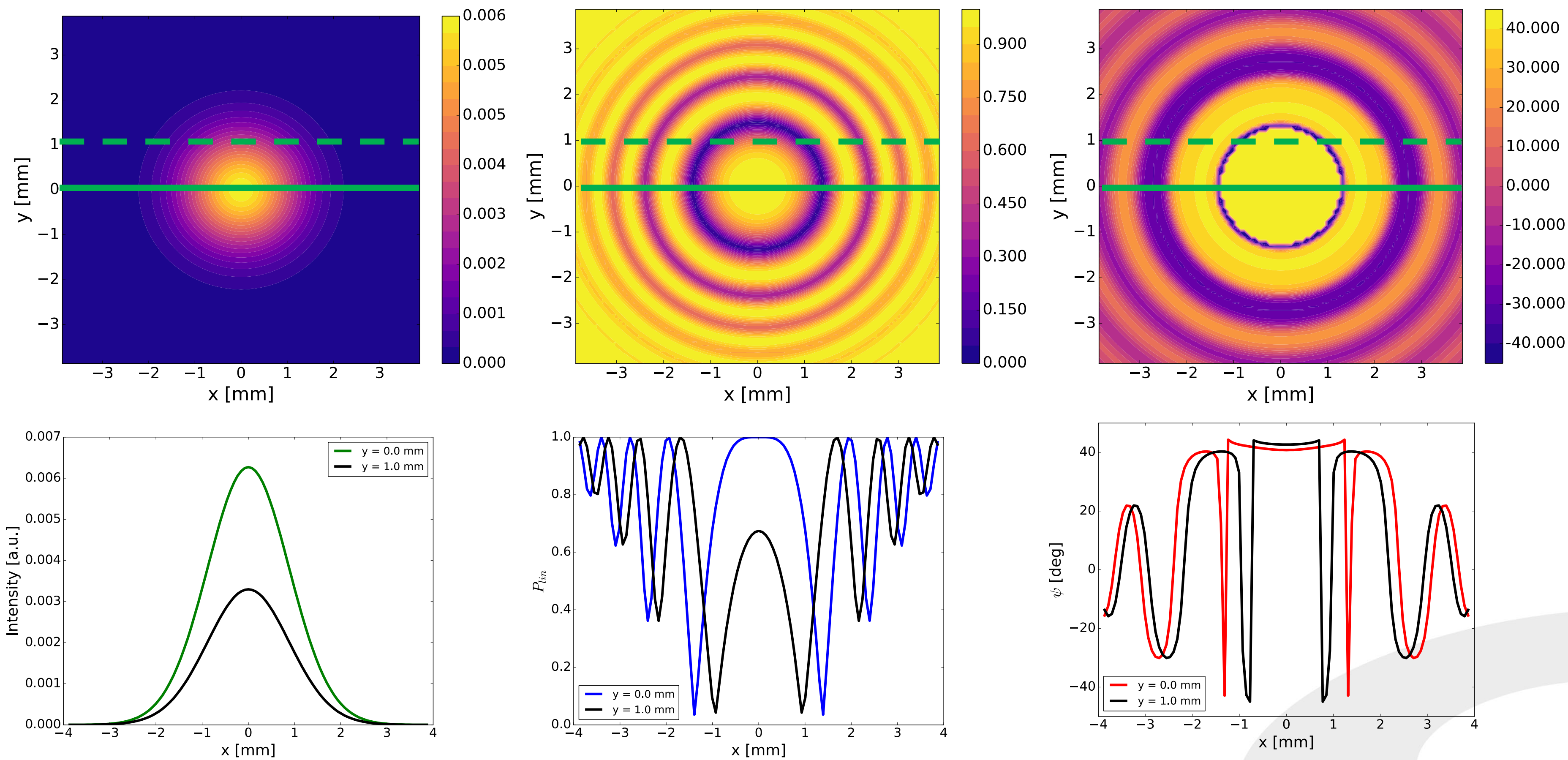


Output: 2D map of the polarization properties of the radiation on a grid.

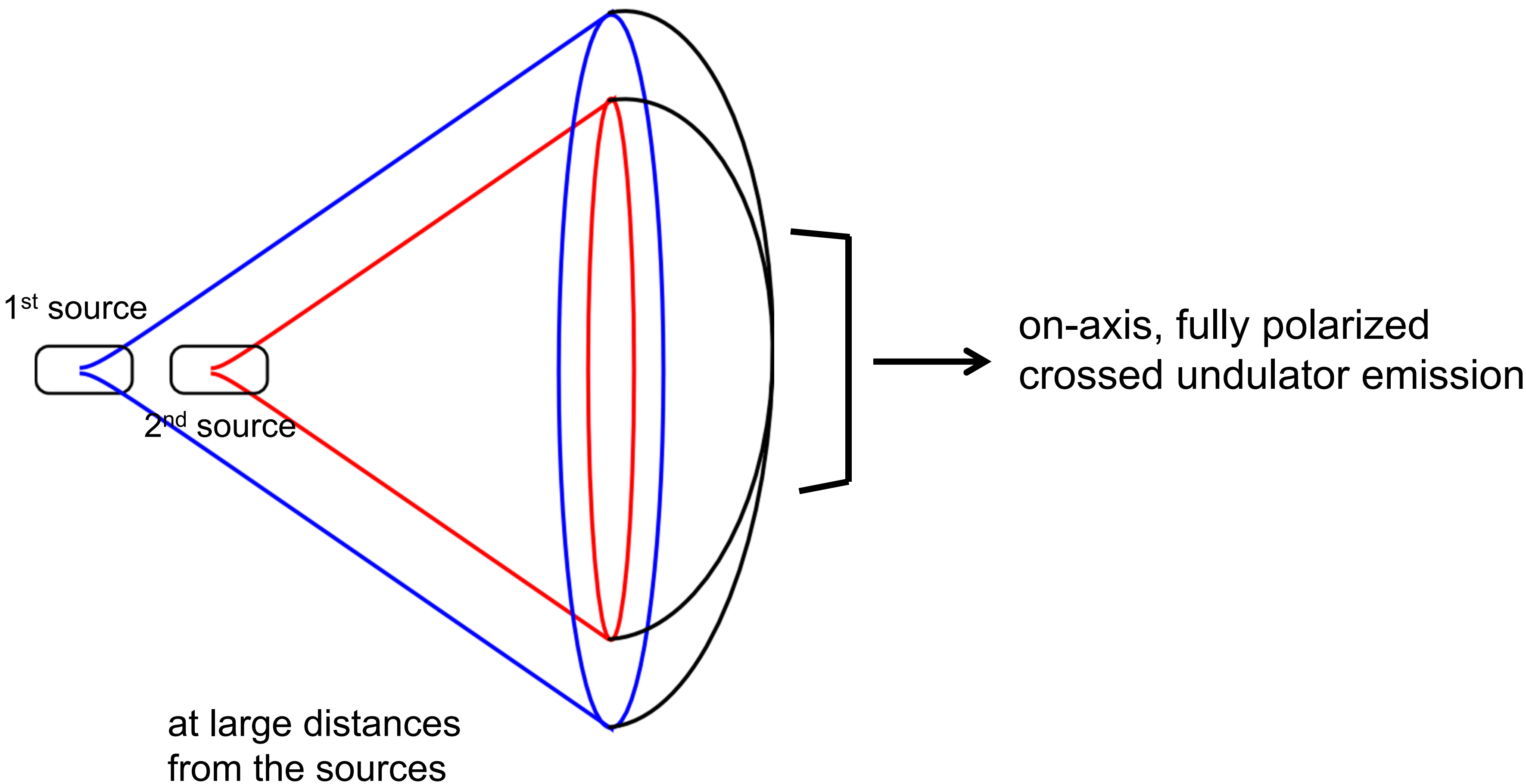
Model: interference of two Gaussian sources

Two sources with **orthogonal polarization**

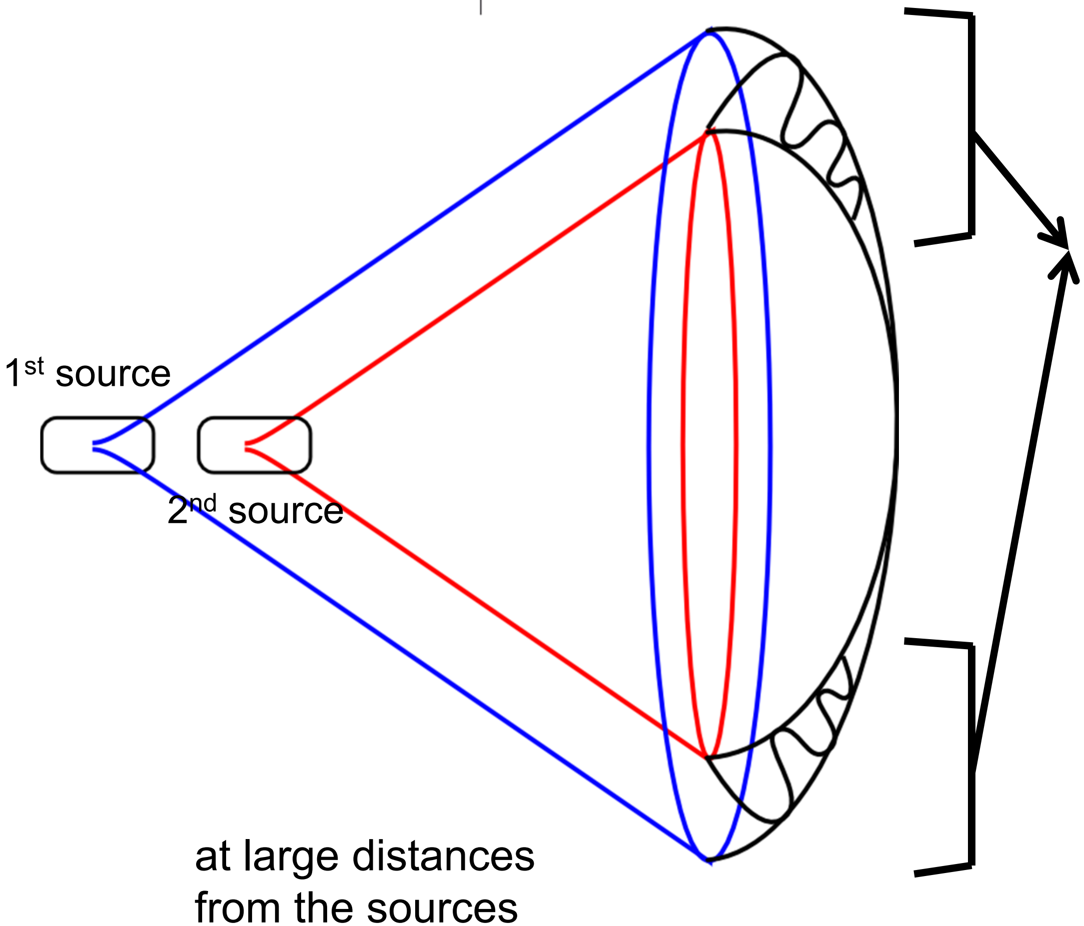
Intensity P_{lin} Angle



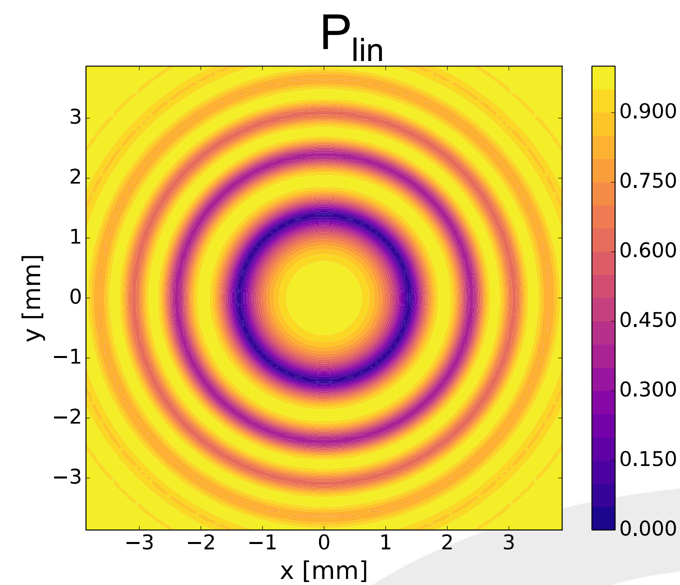
Model: interference of two Gaussian sources



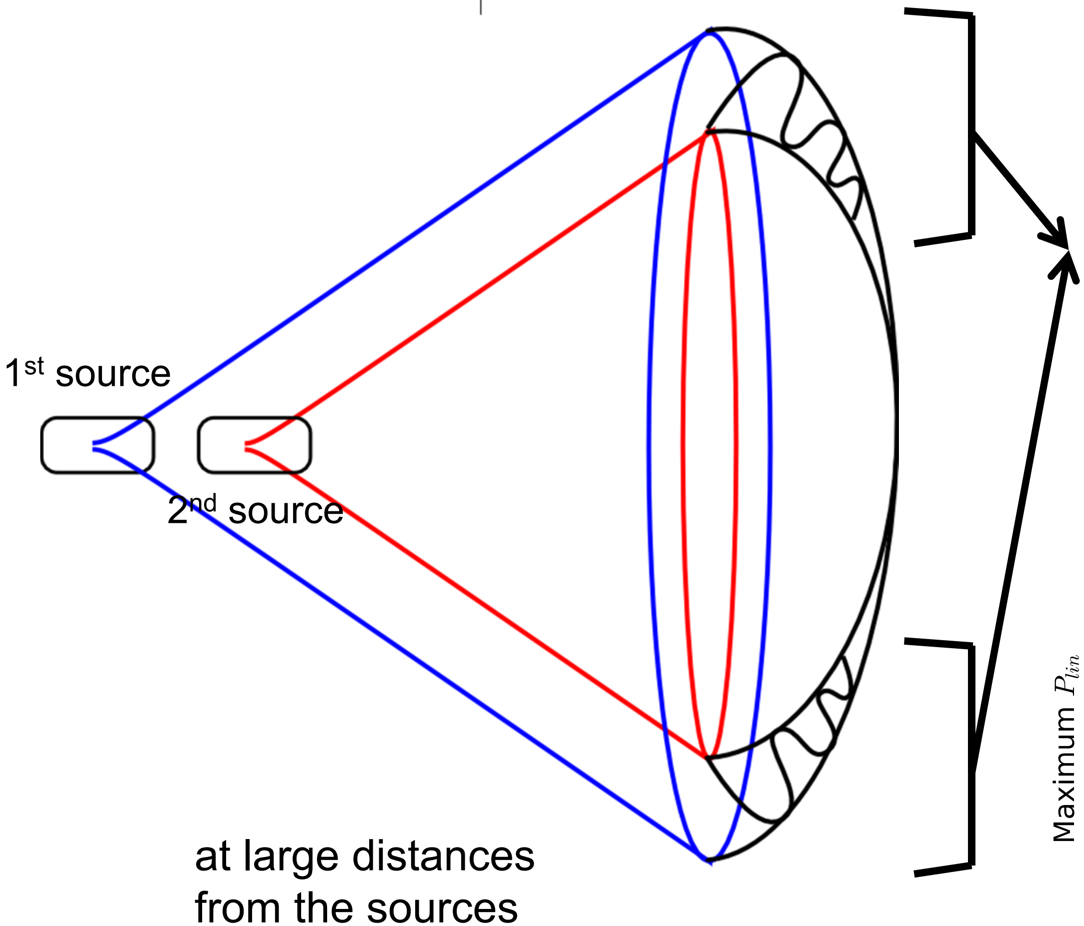
Model: interference of two Gaussian sources



off-axis, the phase of each of the two sources is not constant. The resulting field has strong phase and intensity variations off-axis, inducing a loss of polarization



Model: interference of two Gaussian sources



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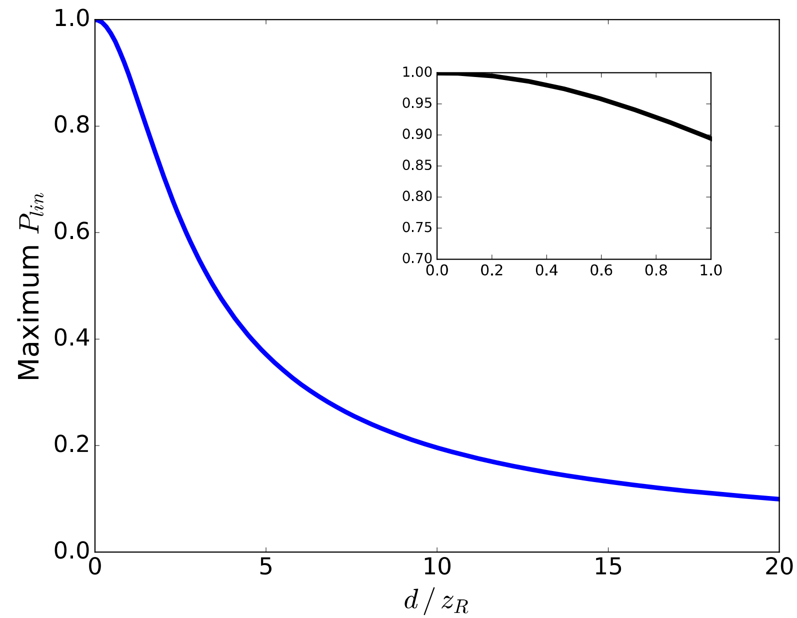

The ratio of Rayleigh range and source distance is the critical parameter

Rayleigh range and crossed undulator distance

Summary of the **Rayleigh ranges** and **undulator distances** for different FEL sources implementing the crossed undulator scheme

FEL source	Wavelength	Rayleigh range	Distance Crossed undulators	Max degree of polarization (from Model)
LCLS like	Hard X	~ 100 m	3 – 5 m	> 99 %
SDUV FEL	Visible	~ 1 m	0.5 – 1 m	> 90 %
FERMI FEL1	EUV	~ 1 m	~ 3.5 m	~ 70 %

At FERMI the Rayleigh range can be smaller (wavelength dependence) than the distance between the crossed undulators, so the maximum degree of linear polarization achievable with the crossed scheme is **~70%**.

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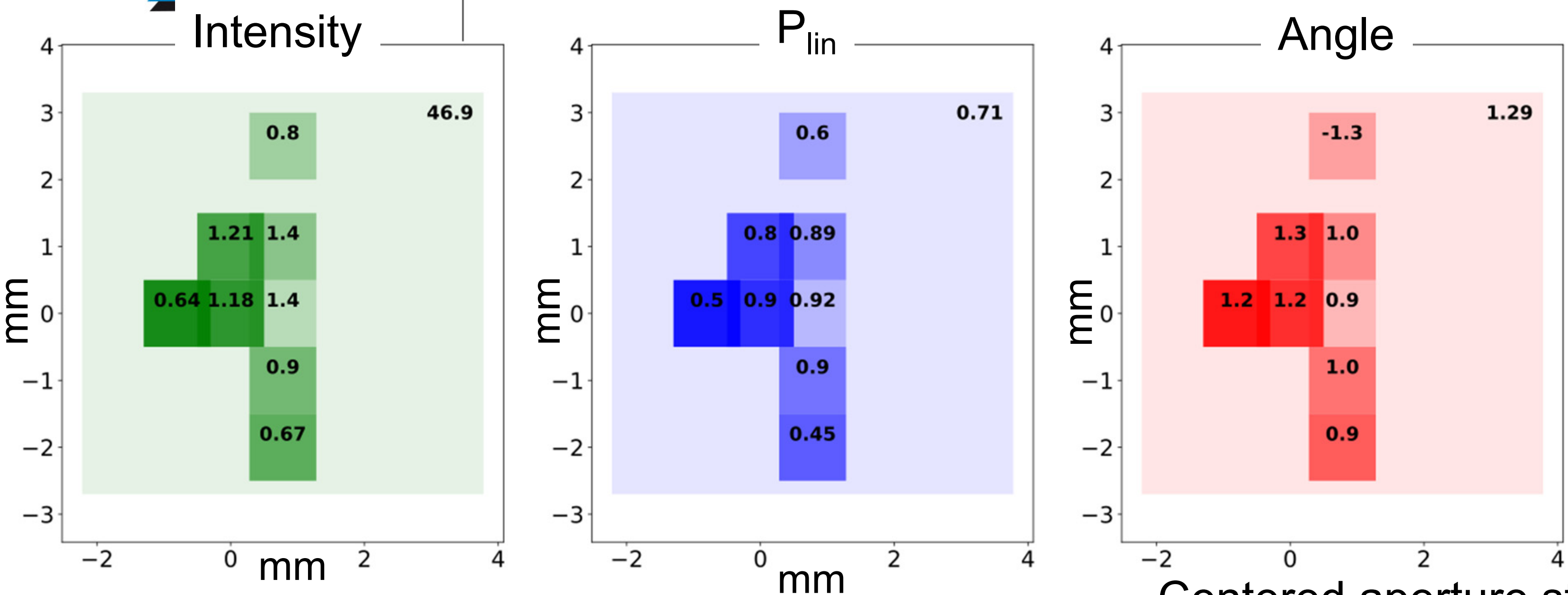
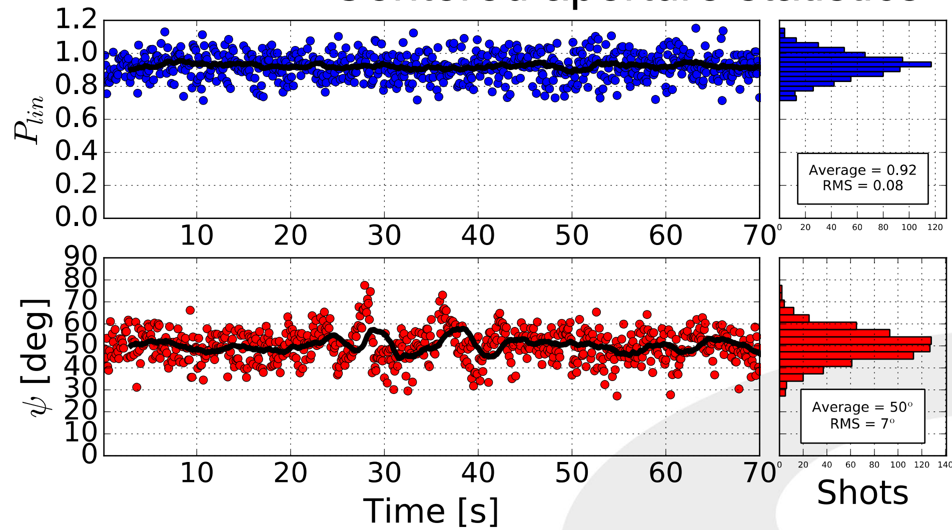
Measure: Polarization through different apertures



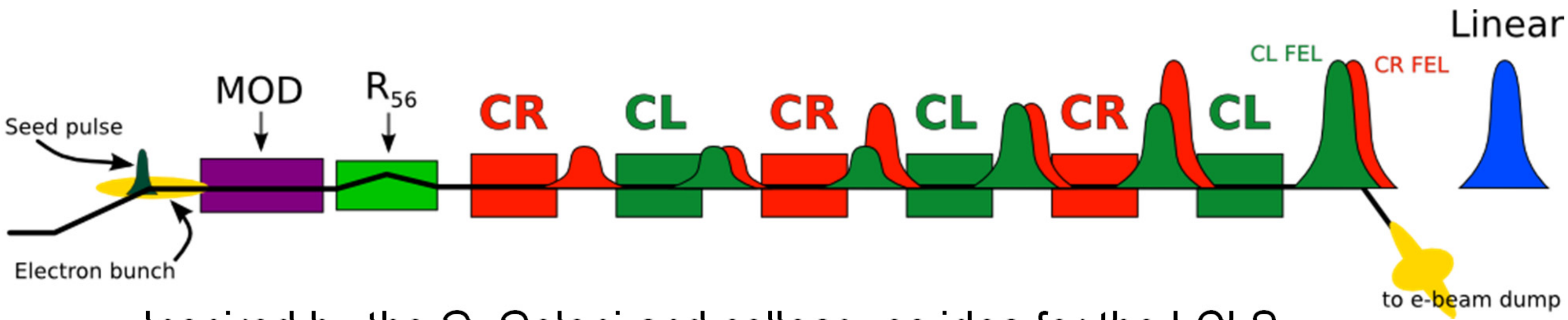
Centered aperture statistics



Experimental confirmation of the model: the polarization state changes along the transverse FEL profile

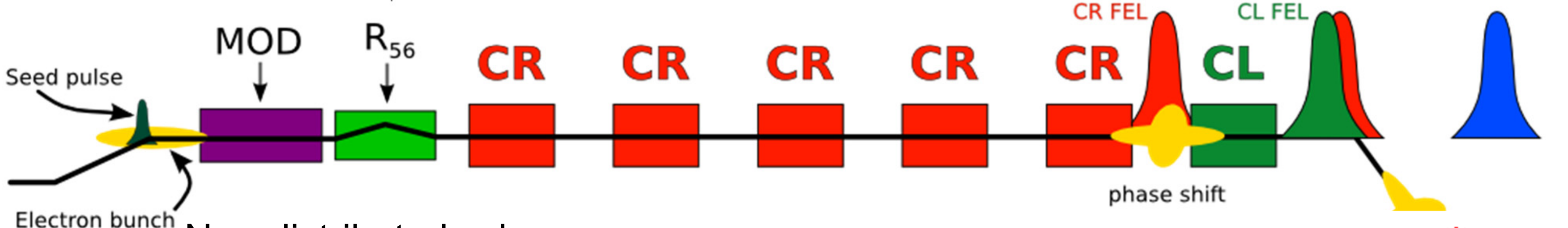
Distributed crossed polarized scheme

Another approach to improved the polarization

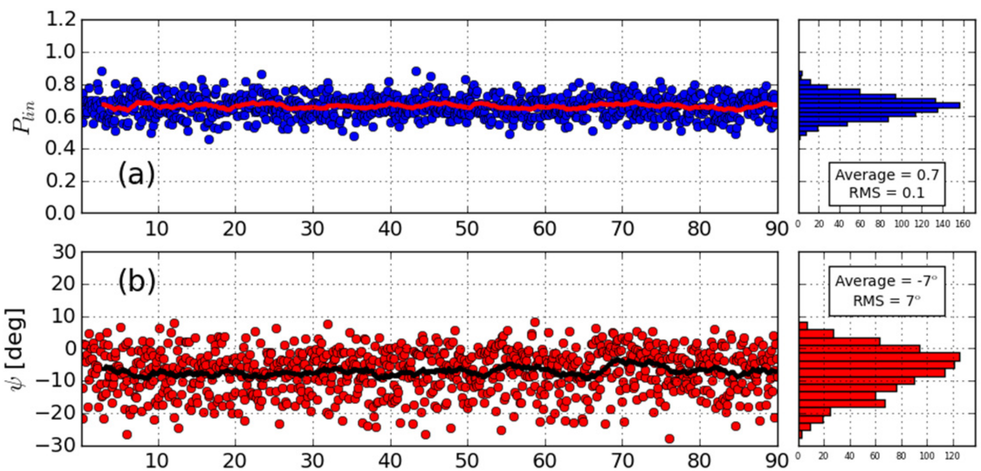


Inspired by the G. Geloni and colleagues idea for the LCLS design (Shanghai FEL2011), to equilibrate the intensities of the two crossed polarization sources in a SASE.
A similar idea was also proposed by T. Tanaka and H. Kitamura, *Improvement of crossed undulator for higher degree of polarization*, AIP Conference Proceedings, 705 (2004) 231.

Distributed crossed polarized scheme



Non-distributed scheme



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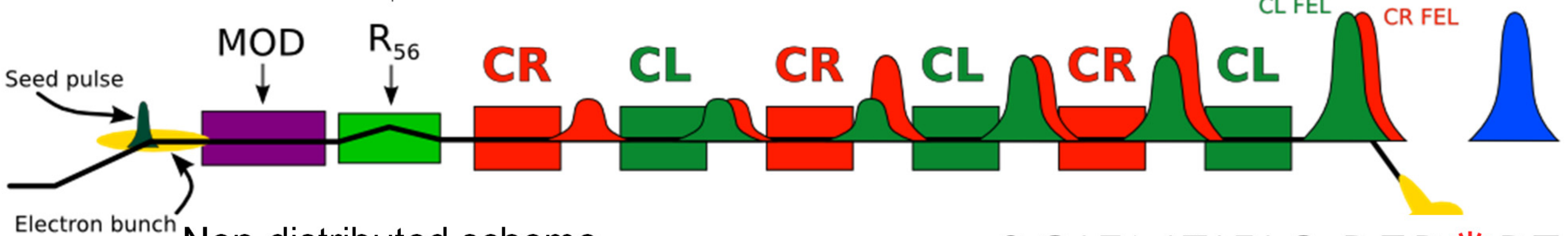
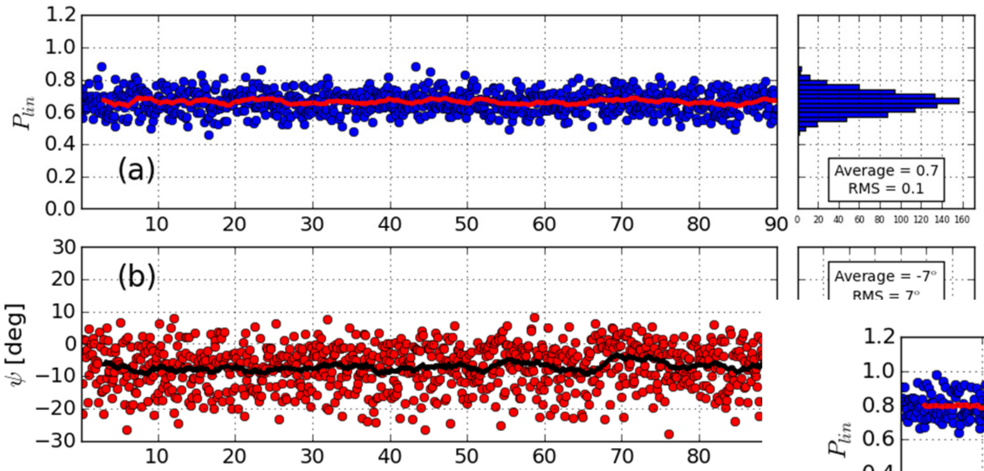
E. Ferrari[1,2], E. Allaria[1], J. Buck[3], G. De Ninno[1,4], B. Diviacco[1], D. Gauthier[1,4], L. Giannessi[1,5], L. Glaser[6], Z. Huang[7], M. Ilchen[3,8], G. Lambert[9], A.A. Lutman[7], B. Mahieu[9], G. Penco[1], C. Spezzani[1] & J. Viefhaus[6]

(Full aperture)

Distributed crossed polarized scheme



Non-distributed scheme



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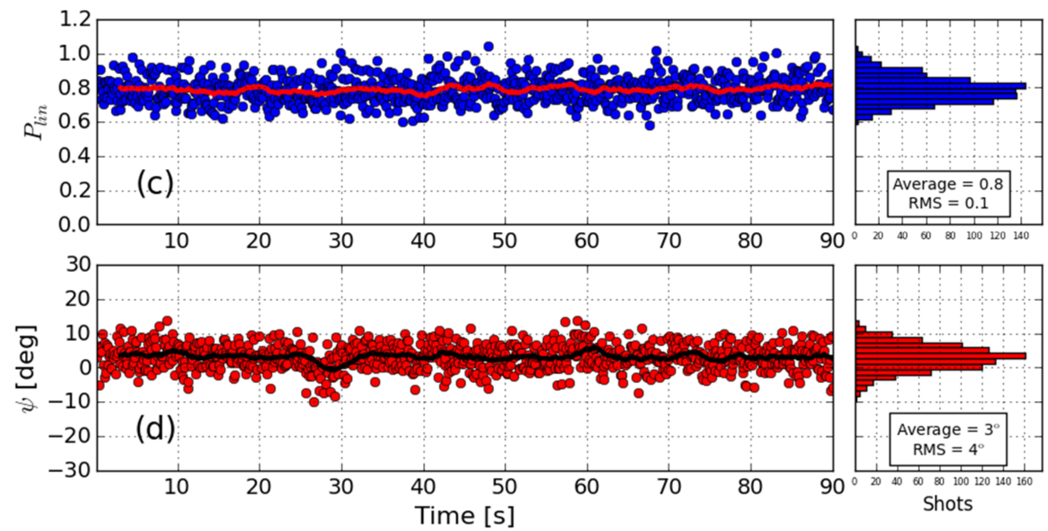
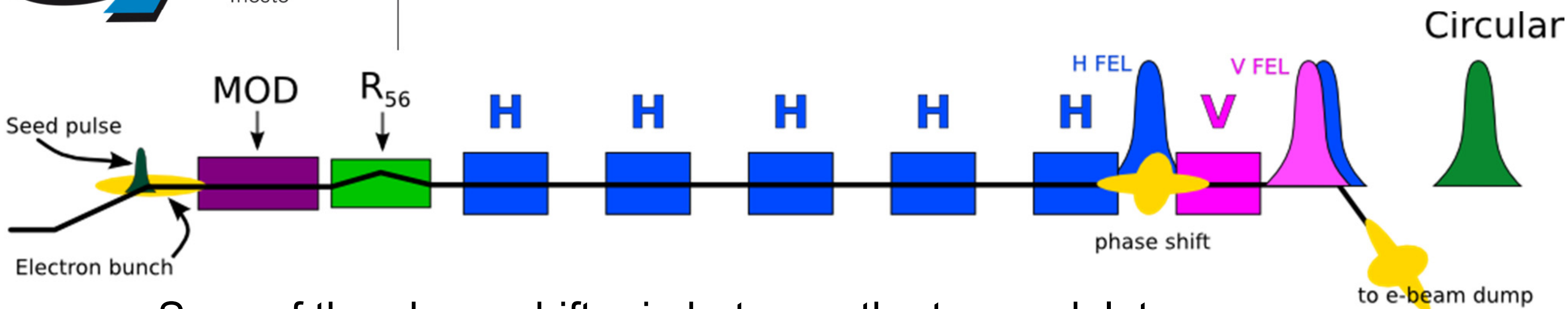
Distributed scheme



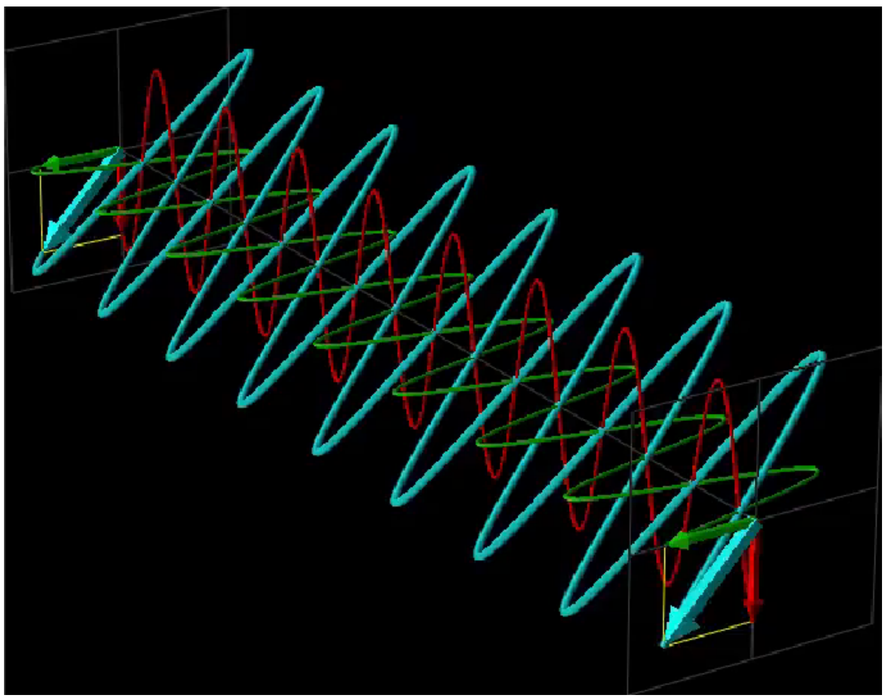
Increase of ~15% of the linear polarization

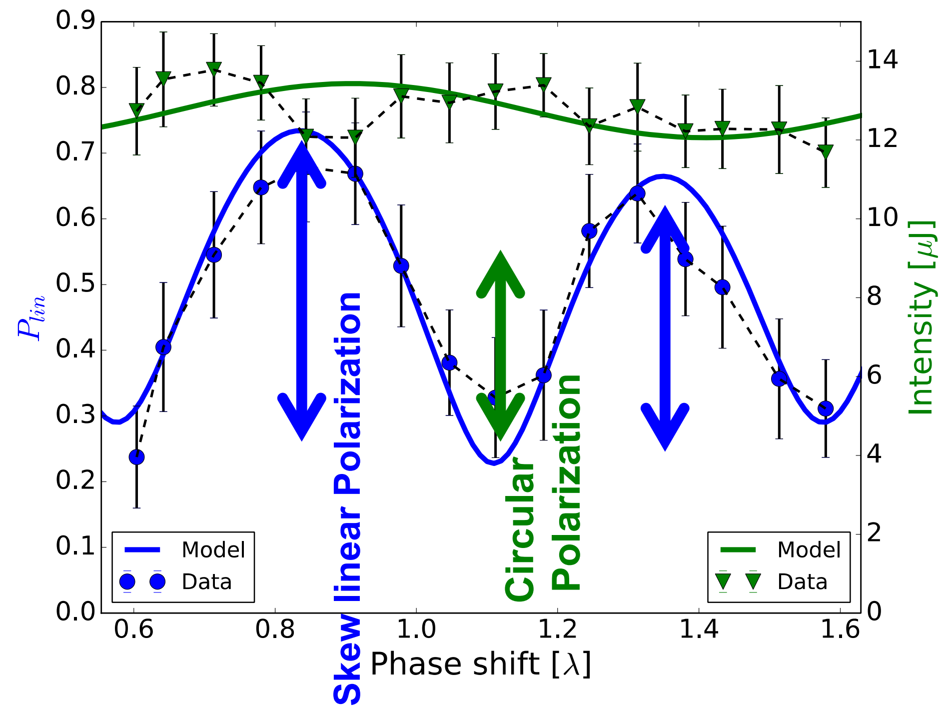
(Full aperture)

Crossed Undulators to control the Polarization



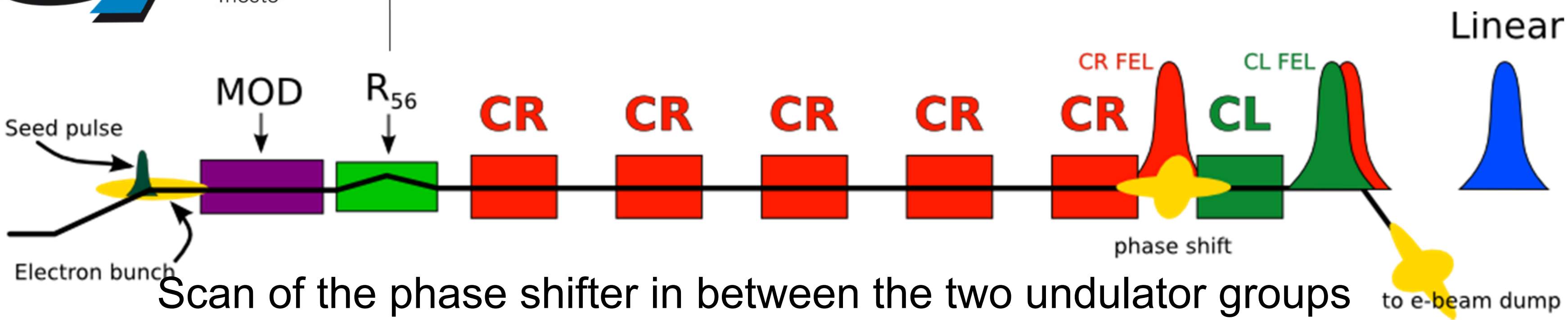
Scan of the phase shifter in between the two undulator groups





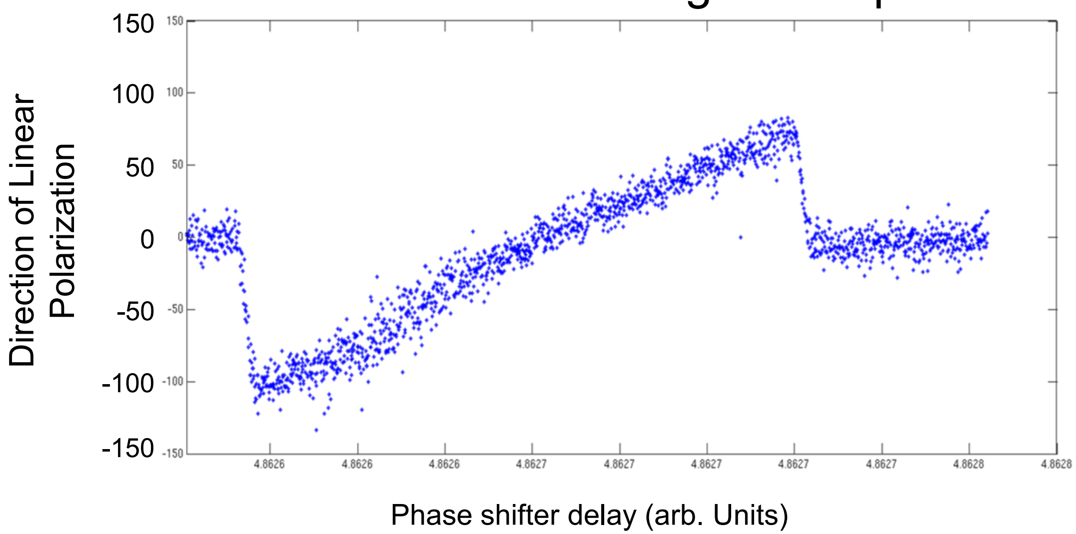
(Full aperture)

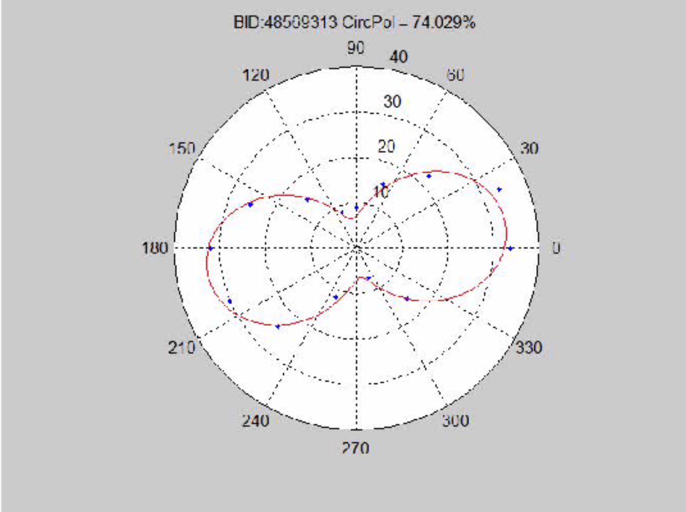
Control of the Polarization Direction



Scan of the phase shifter in between the two undulator groups while recording the polarization

All the FEL shots during the acquisition





The direction of the linear polarization is altered by changing the phase shifter

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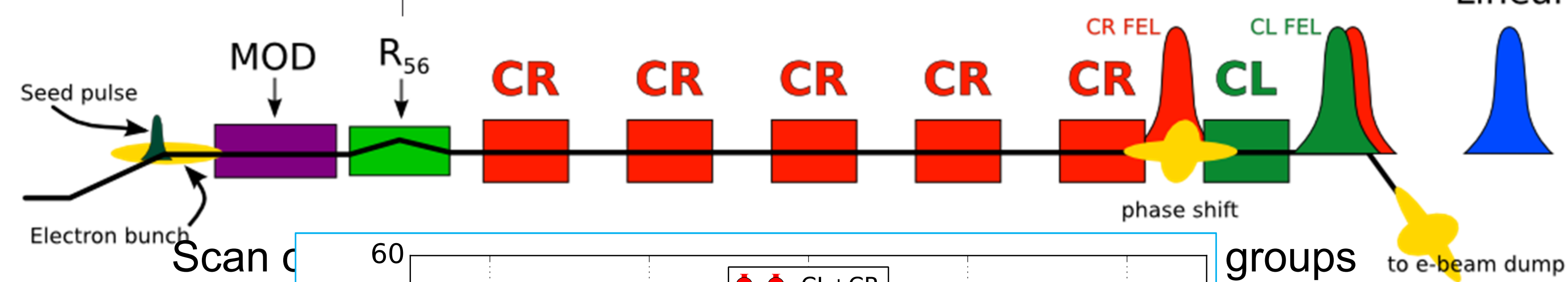
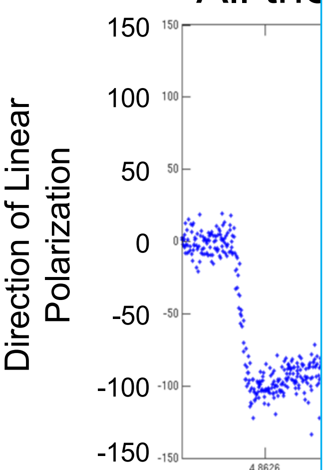
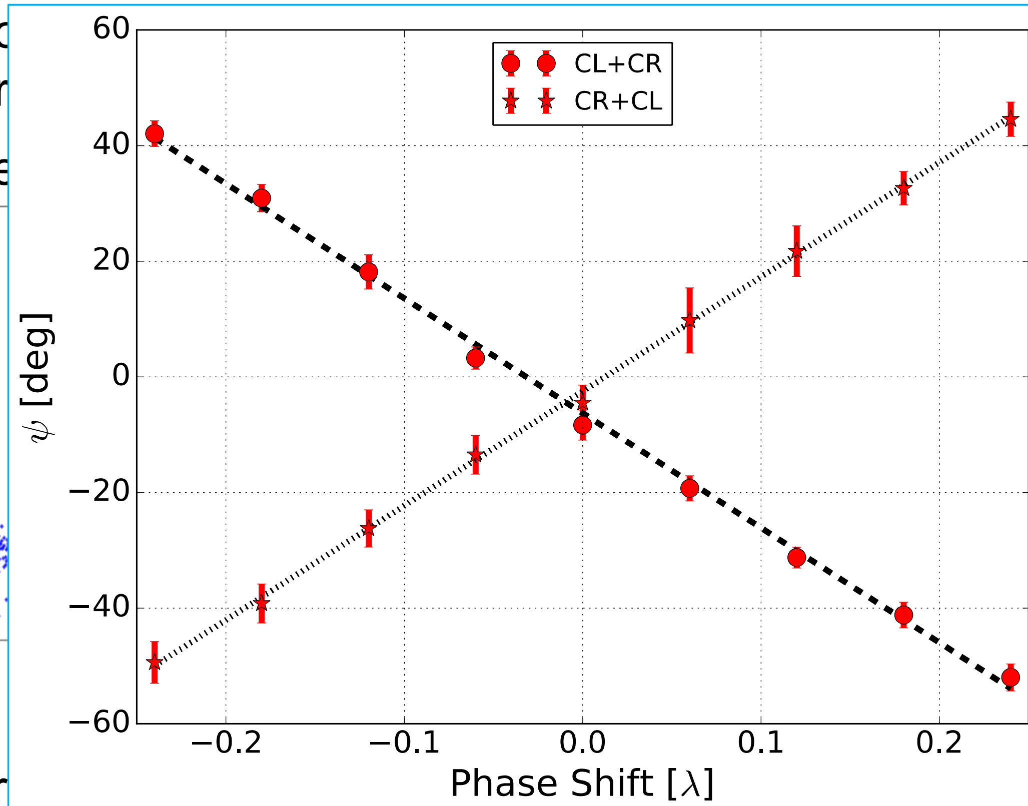
Control of the Polarization Direction

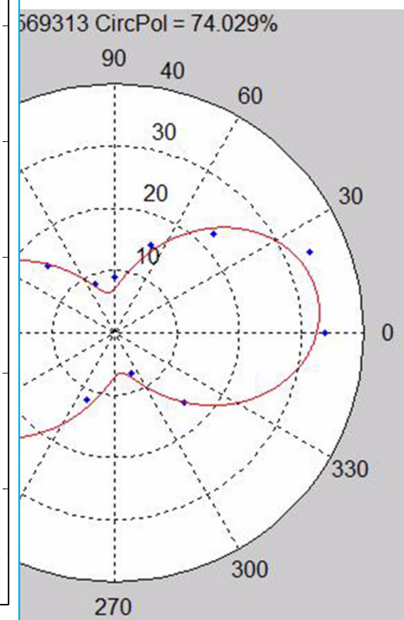


Scan c … groups
while r …

All the …



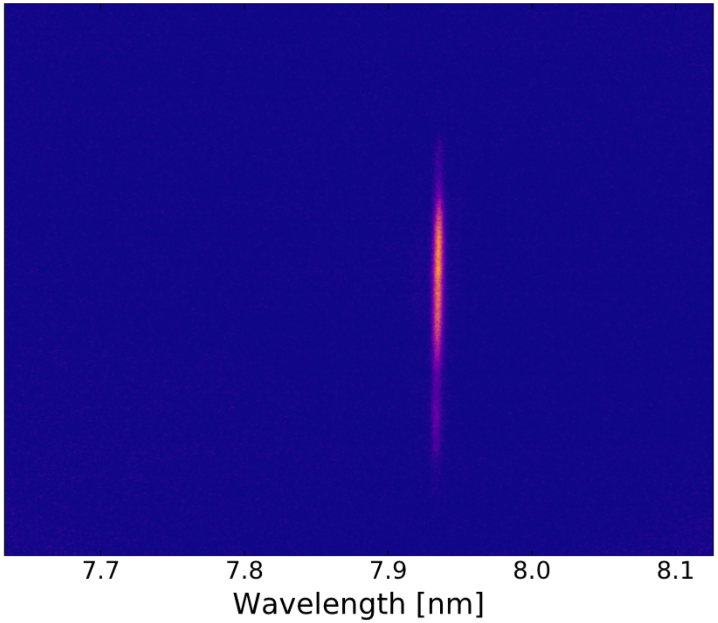




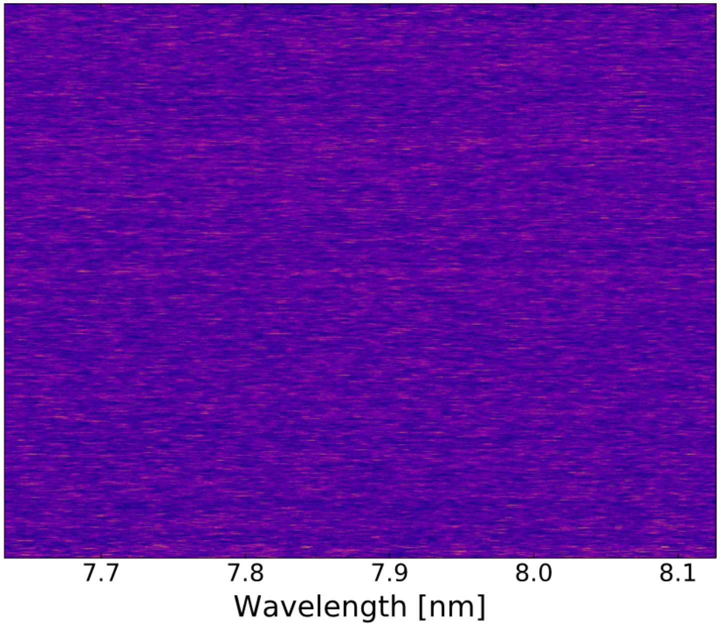
The dir …
altered by changing the phase shifter

Linear polarized light without harmonics

Full undulator in linear polarization at ~21 nm



Crossed polarized undulators (CR+CL)



Third harmonic signal is **suppressed** and radiation is linearly polarized
Critical for experiments investigating e.g. multi-photon resonances

Summary

- FELs produce polarized light with different polarization properties by utilizing variable polarization undulators
- Crossed polarized scheme has been **demonstrated** on a **seeded high gain FEL** in the VUV, with a degree of linear polarization >70% (full aperture) and >90% (pinhole)
- The **distributed scheme** provides an higher degree of polarization for the full beam
- **Full polarization control,** in direction and type of polarization, is possible in all the presented schemes
- Linearly polarized radiation can be produced **without harmonic content**

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A special thank you to many people

FERMI: E. Allaria, M. Trovo', G. De Ninno, P. Rebernik, D. Gauthier, C. Spezzani, B. Diviacco, S. Di Mitri, G. Penco, L. Giannessi, W. Fawley , M. Zangrando, N. Mahne, C. Svetina, L. Raimondi, F. Capotondi, P. Finetti, C. Callegari, M. Coreno, C. Grazioli, O. Plekan, B. Ressel, A. Kivimaki, E. Roussel

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XFEL.EU: J. Gruenert, M. Ilchen, J. Buck, T. Mazza, M. Meyer

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Thank you for the attention!