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Experimental Characterization of FEL Polarization Control with Cross Polarized Undulators

Eugenio Ferrari on behalf of the FERMI Polarization Task Force

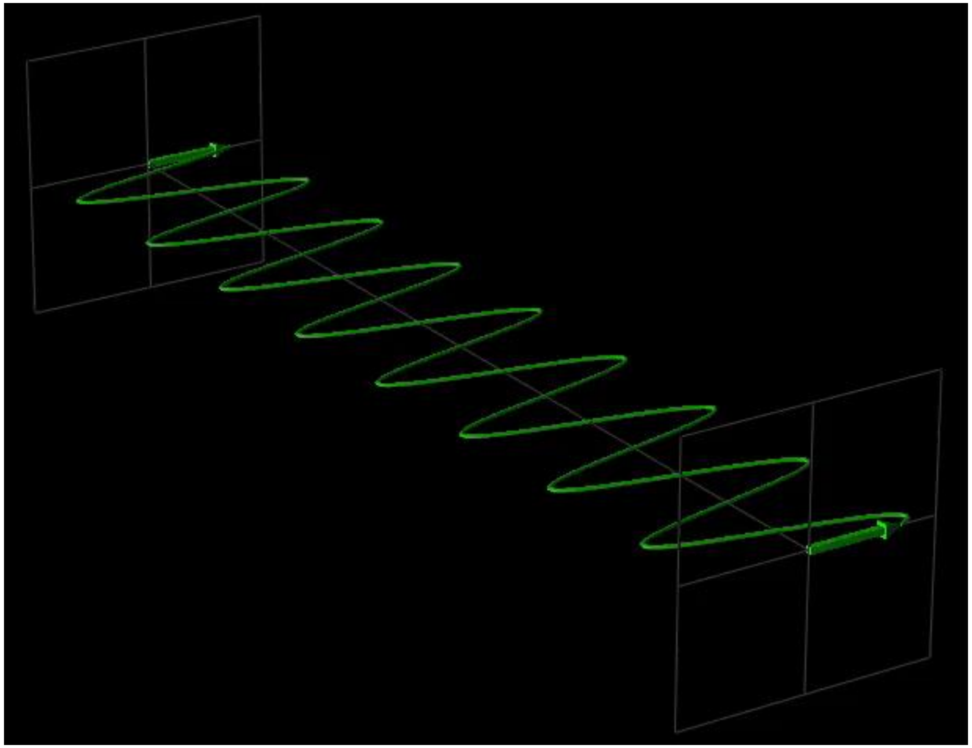
Outline

- Light **polarization** and polarization control in FELs
- Crossed undulator schemes
- **Implementation** of the crossed undulator scheme at FERMI
- **Model** for the experimental results
- **Improve** the degree of polarization in a crossed undulator scheme

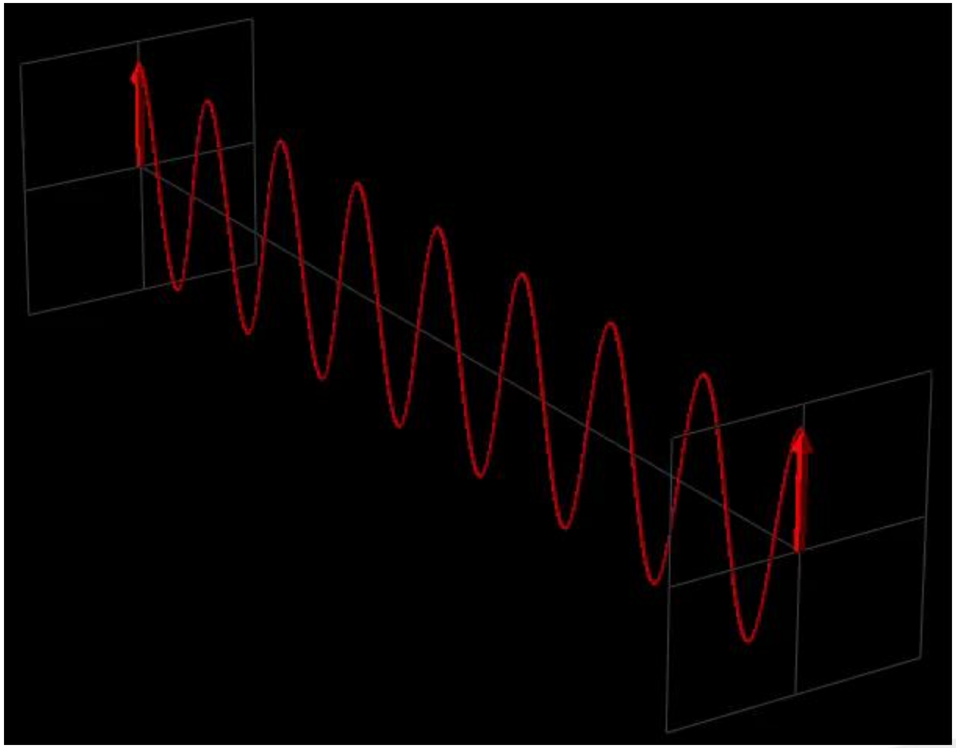
Polarization of Light

The Polarization of the light describes the way in which the electric field of an electromagnetic wave is oscillating over one period.

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



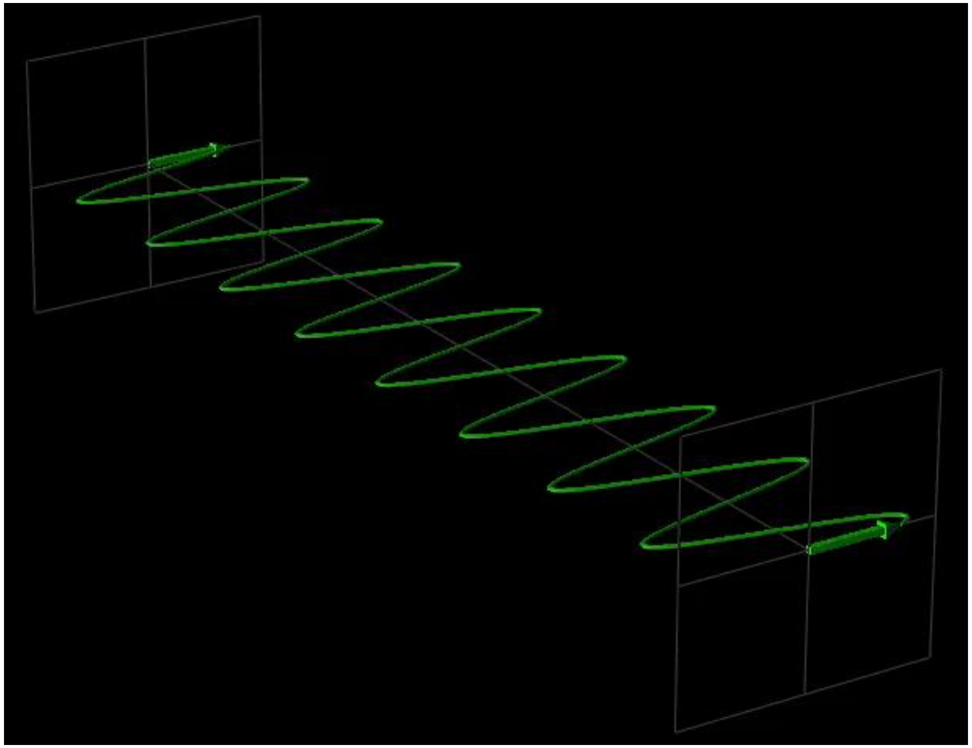
Linear Horizontal

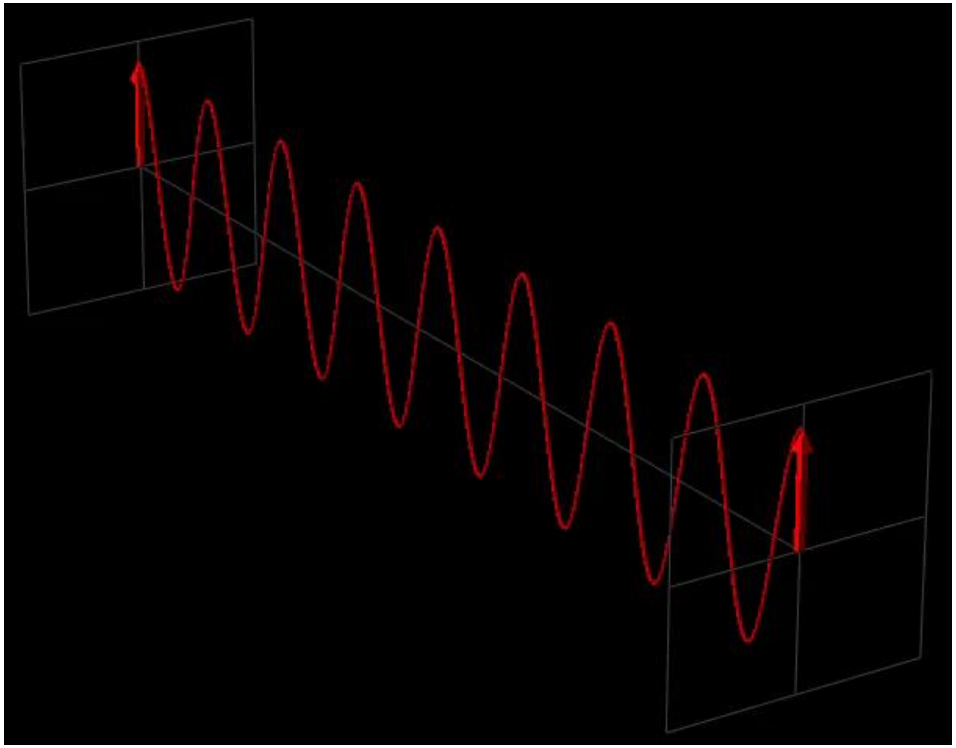


Linear Vertical

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

Polarization of Light

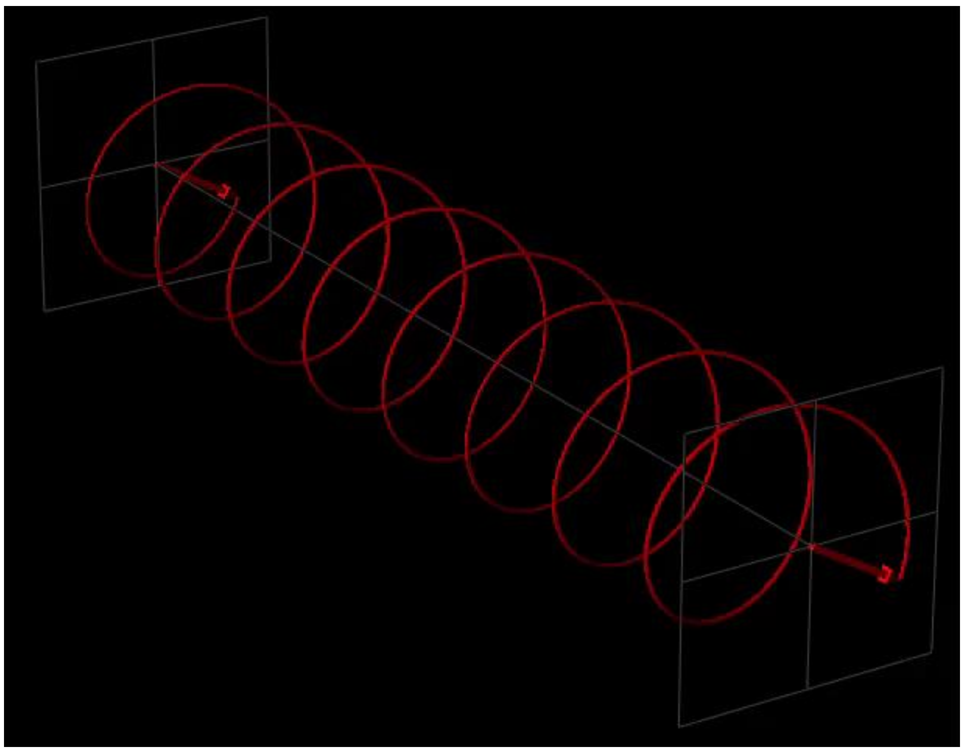




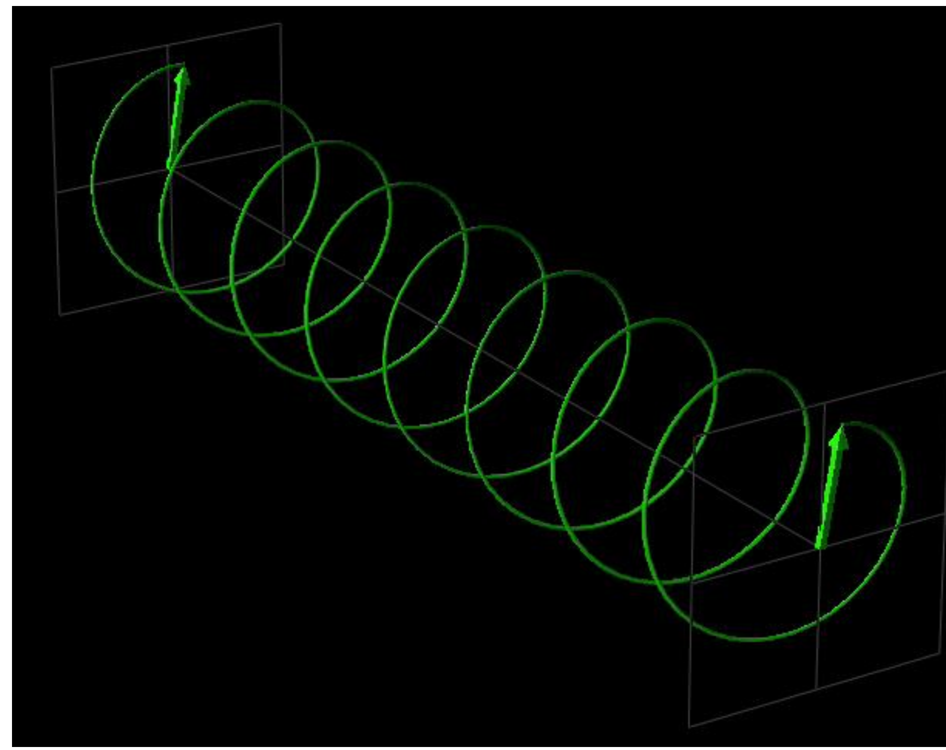
Polarized light is naturally produced by FEL sources, normally with linear polarization

Polarization of Light

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



Circular Left



Circular Right

Variable Polarization Undulators for short wavelength, high gain FELs

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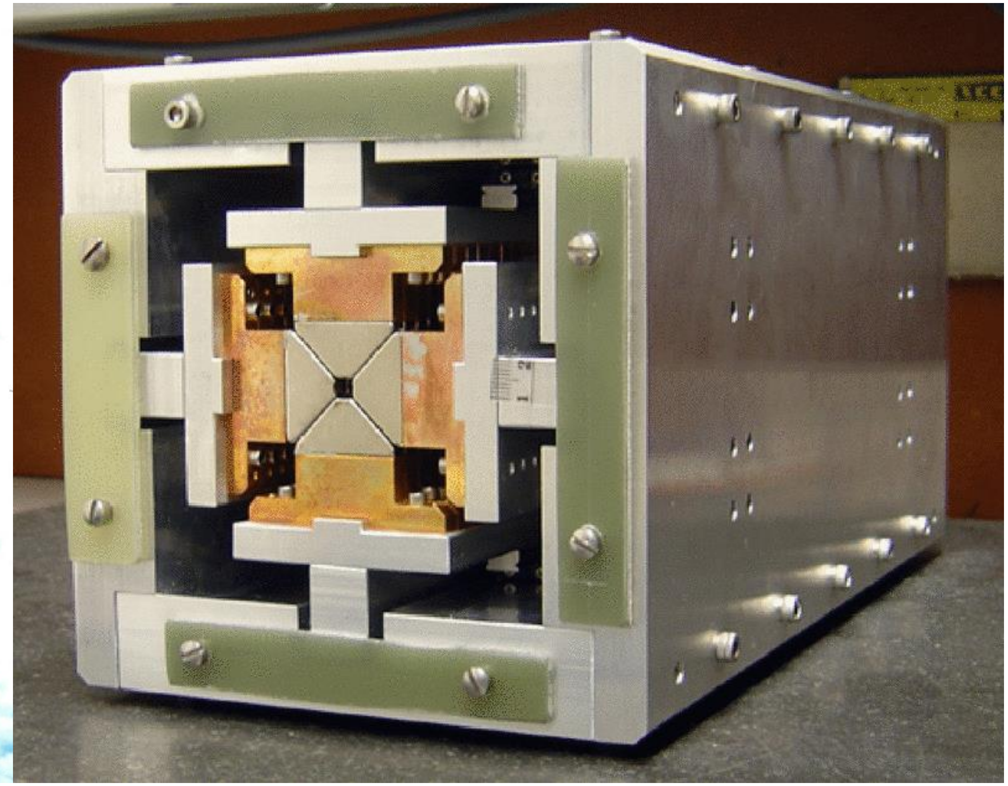
APPLE-II Undulator

Delta Undulator



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

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))

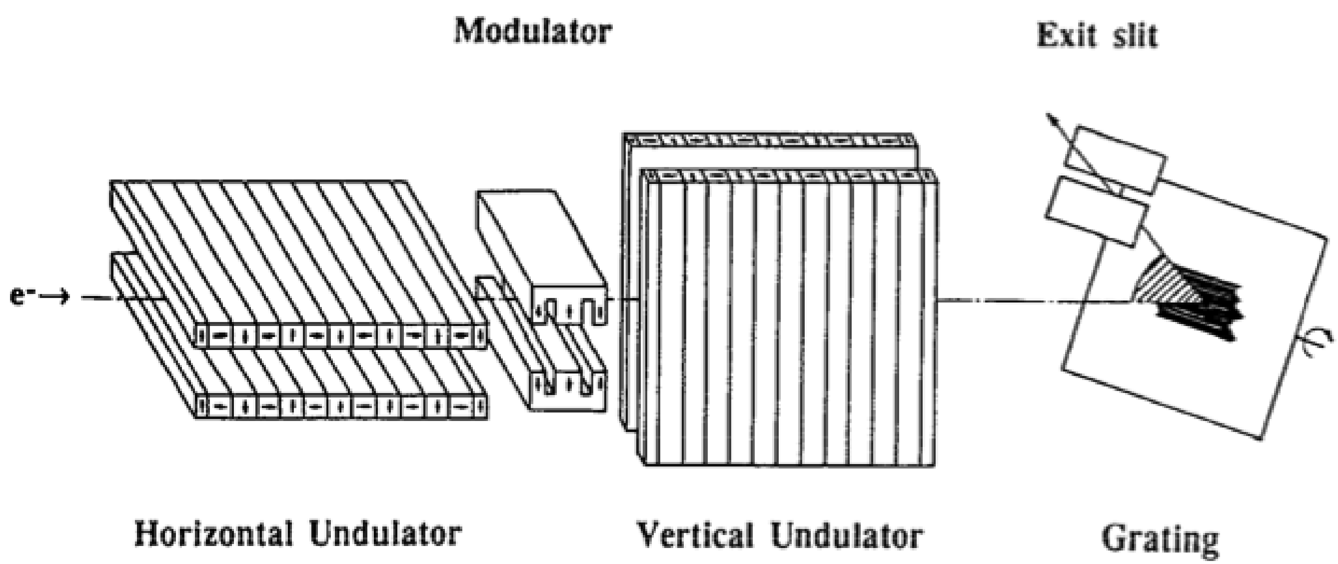
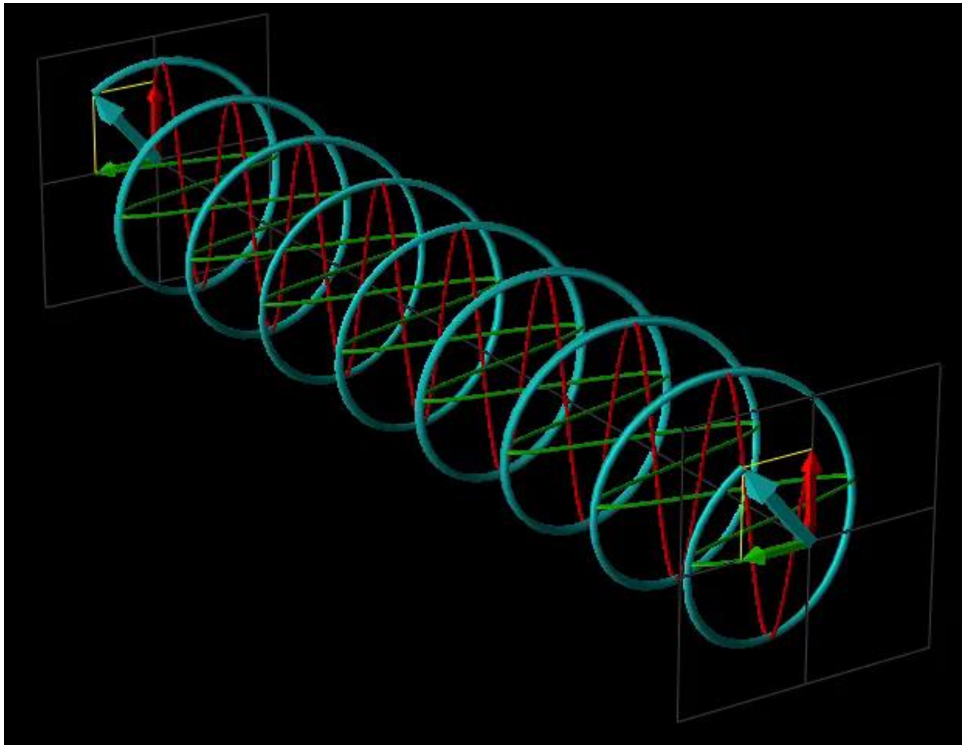
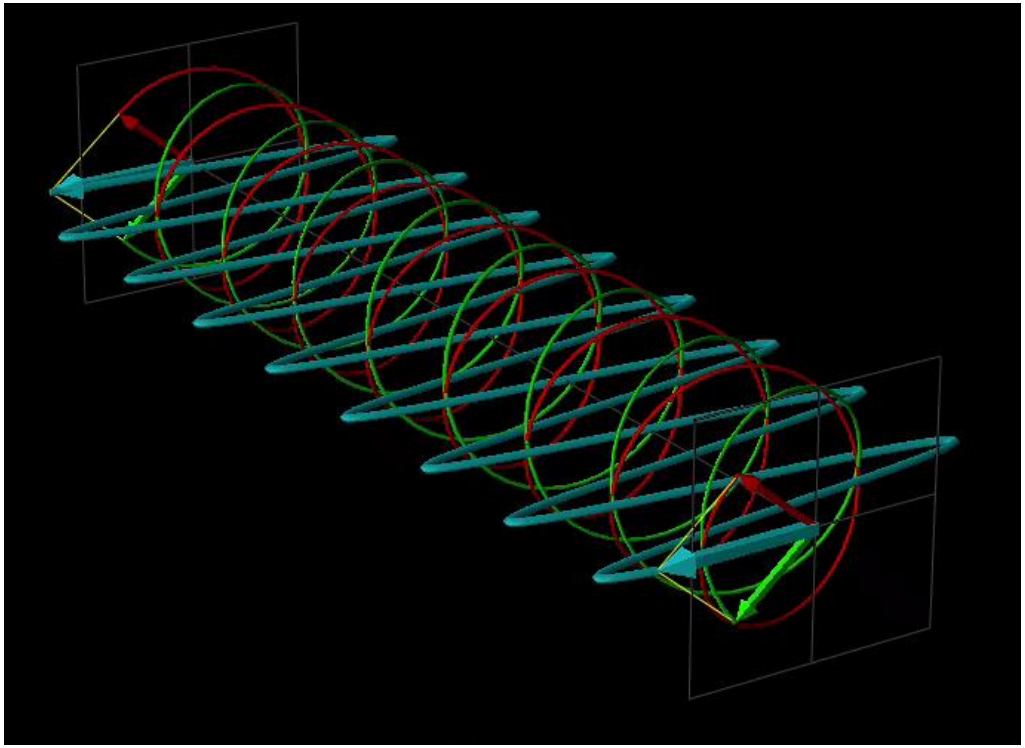


Image from J. Bahrdt et. al., Rev. Sci. Instr. 63, 339 (1992)

<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

First implementation on BESSY synchrotron
(J. Bahrdt et. al., Rev. Sci. Instr. 63, 339 (1992)).

But, the scheme was **not so efficient**, with a polarization degree **~ 40 – 45%**. This was mainly due to low coherence of the source.

Still, it was successfully used for experiments.
(e.g. R. David et. al., NIM A 343, 650 (1994)).

Crossed undulator scheme

Studied with SASE FEL based on FLASH, 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.

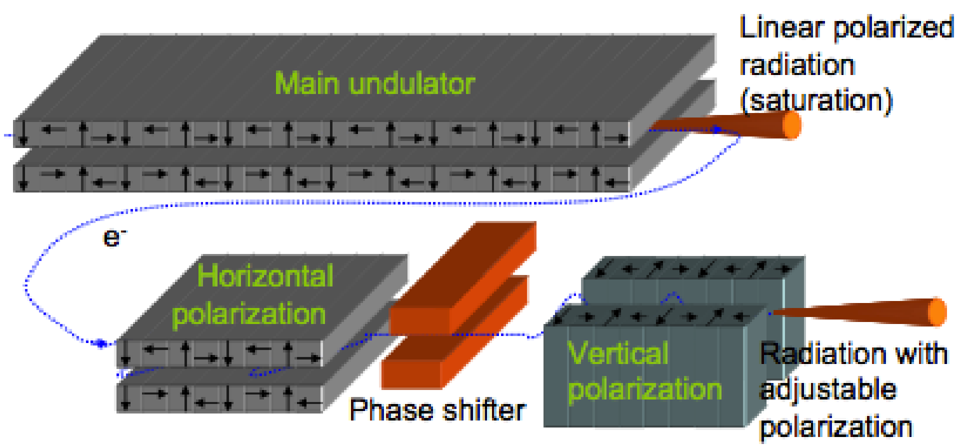


Image from Y. Li et. al, EPAC 08, WEPC118

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)

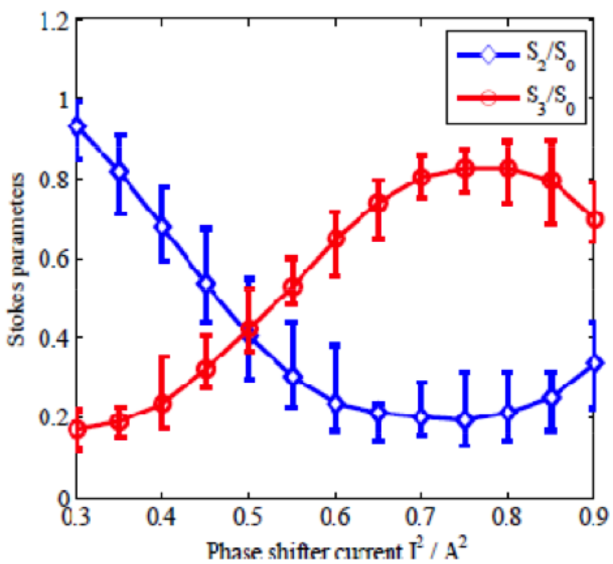
Y. Li et. al, EPAC 08, WEPC118 (2008).

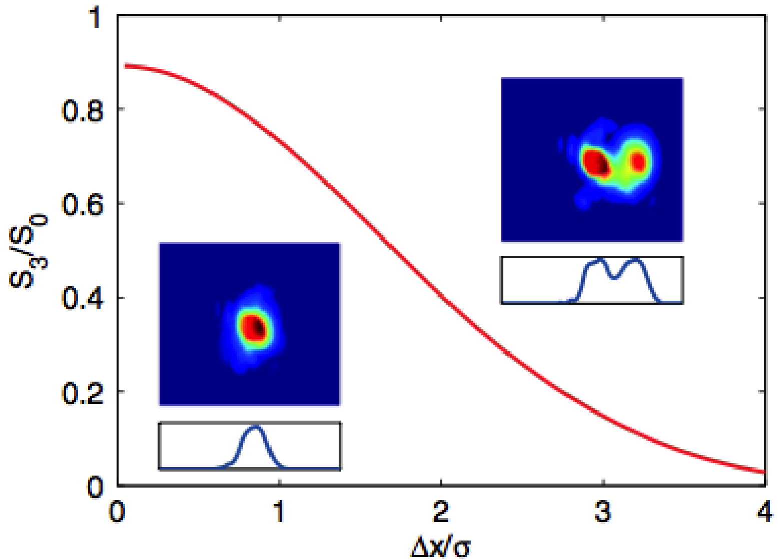
Crossed undulator scheme

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 ST-AB 17, 020704 (2014).





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Crossed undulator scheme

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Today: results at FERMI FEL-1

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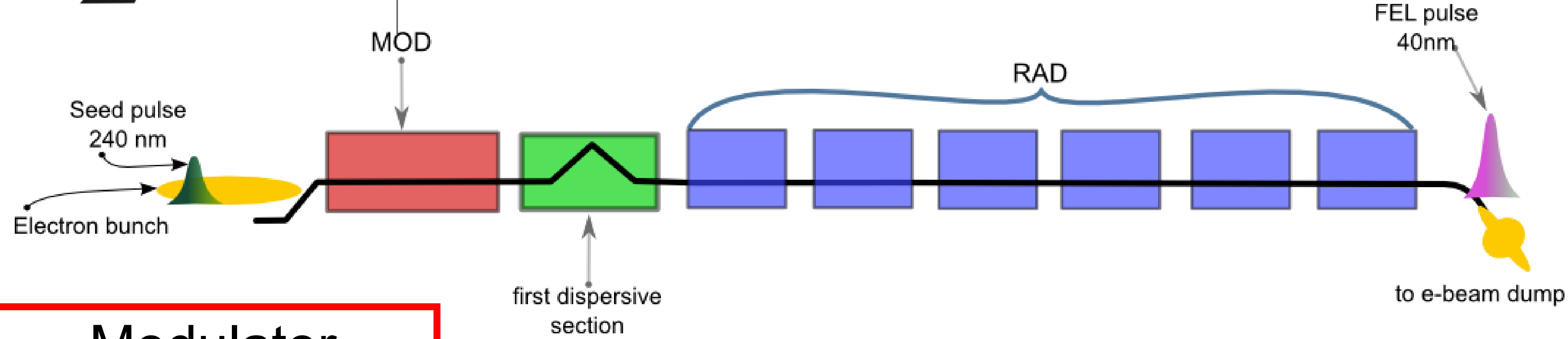
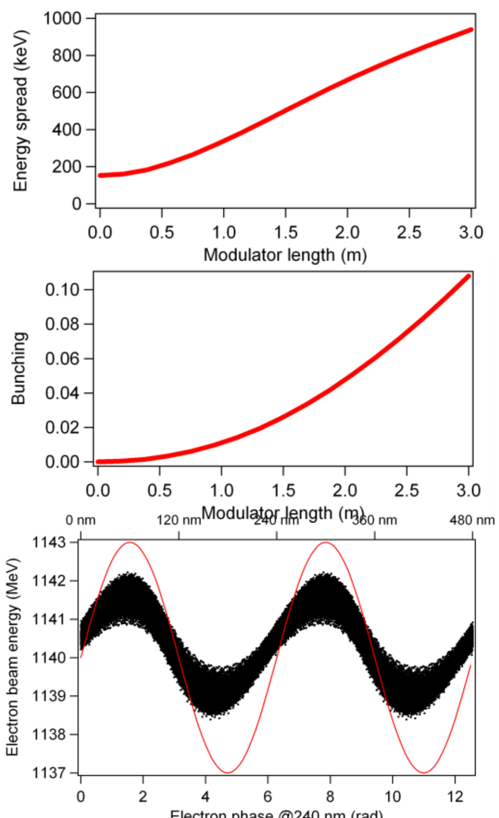
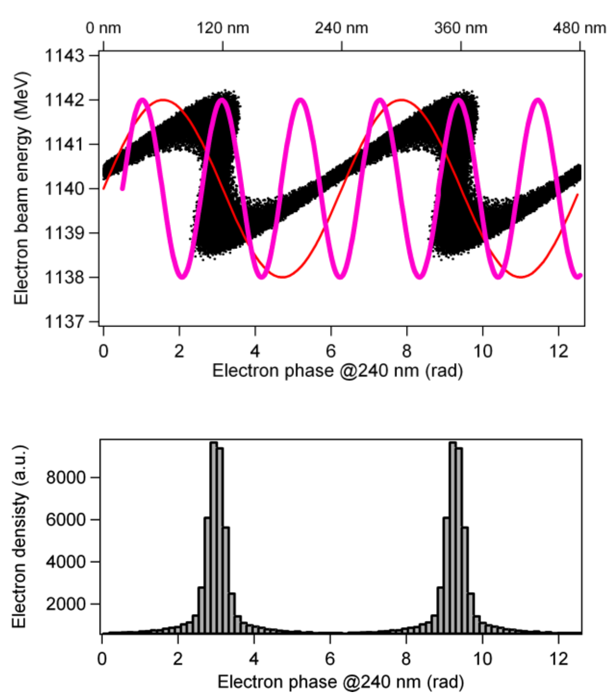
FERMI scheme remainder



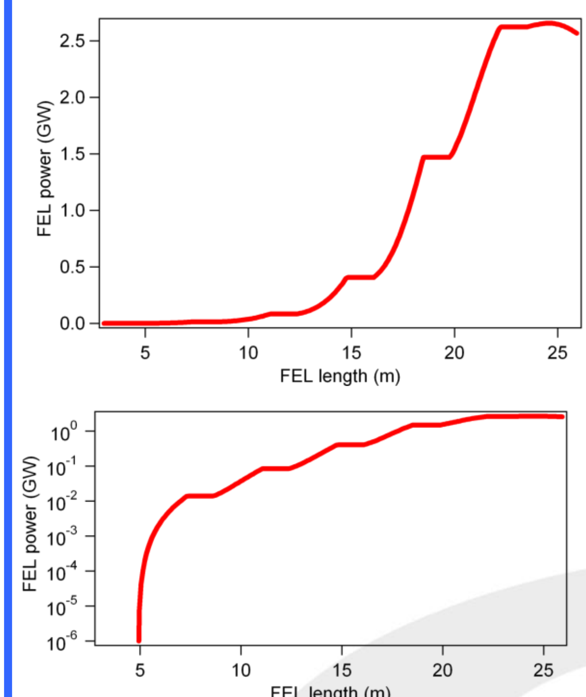
Modulator



Dispersive section



Radiator



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Main peculiarities of the FERMI crossed undulator setup

Cross polarized undulators scheme in the VUV, with the radiation produced by an **high gain FEL**.

Variable polarization **APPLE-II** type undulators are used. Therefore the crossed undulator scheme can be studied with linear, elliptical and circular polarized light.

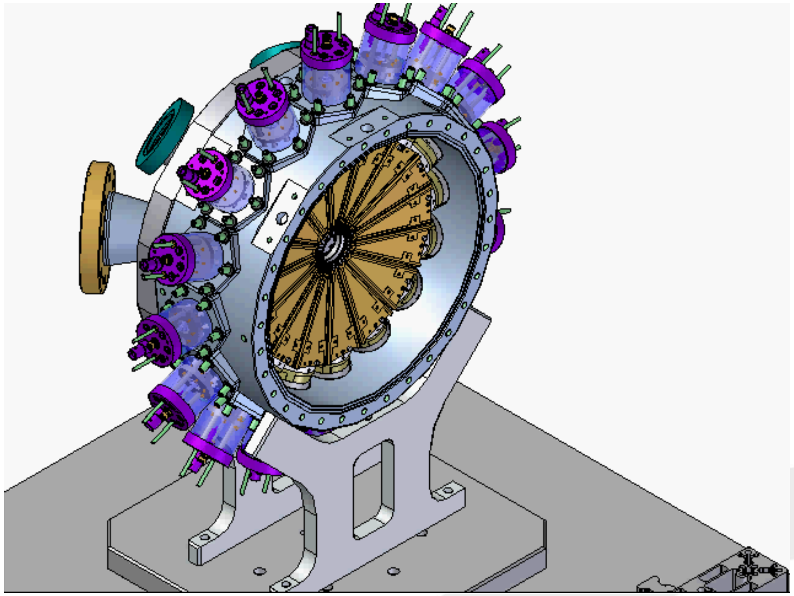
Measuring the polarization at these wavelengths is an experiment itself! ***

*** E. Allaria, et. al., *Control of the polarization of a vacuum-ultraviolet, high-gain, free-electron laser*, accepted.

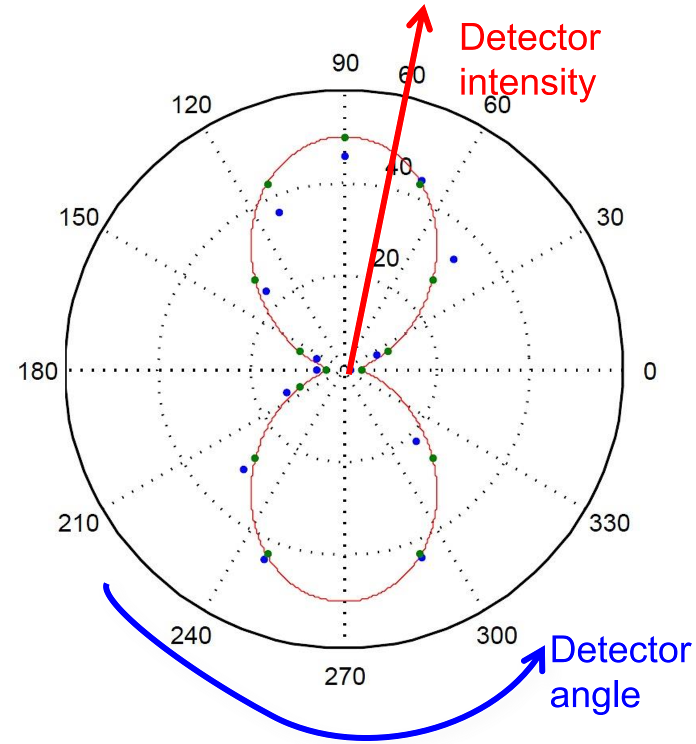
DESY eTOF polarimeter (J. Viefhaus)

Angle Resolving Electron Spectrometer Setup

Uses **angle-resolved** electron spectroscopy to determine the degree of linear polarization of the incident light



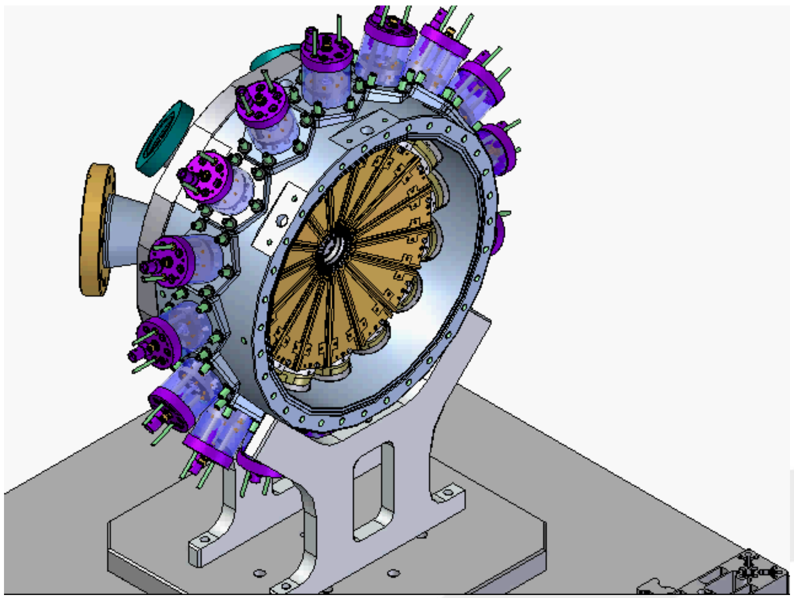
DESY eTOF polarimeter (J. Viefhaus)



Angle Resolving Electron Spectrometer Setup

Detection Scheme

- Record single-shot spectra → High detection efficiency ~4% of 4π
- Energy resolution → Resolution up to 10^{-3}
- Angular resolution → **16 spectrometers** at different angles
- Accessible energy range → 0.02-25 keV (for European XFEL)



Diagnostics

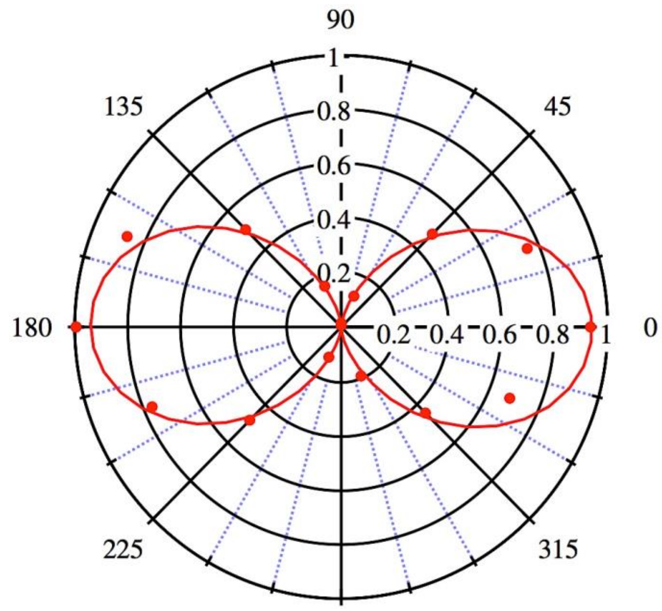
- Versatile online beam diagnostics unit
- Already in use at PETRA III
- Feasible for (X)FEL diagnostics

Characterization of the absolute degree of *linear* polarization **shot-to-shot**

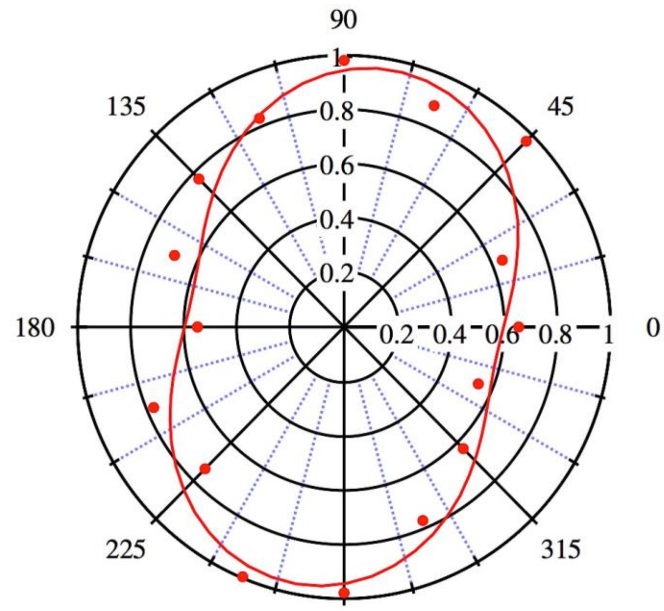
Polarization measurements in the EUV

Pure polarization states at 32 nm

Horizontal Polarization



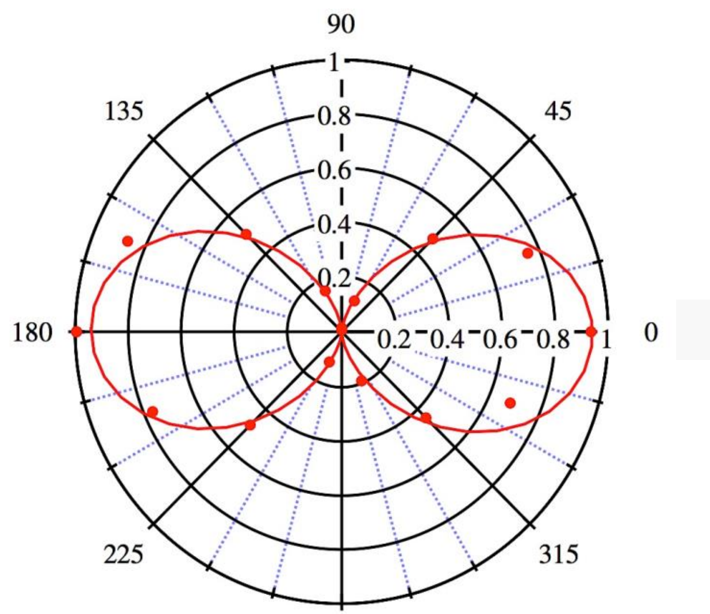
Circular polarization



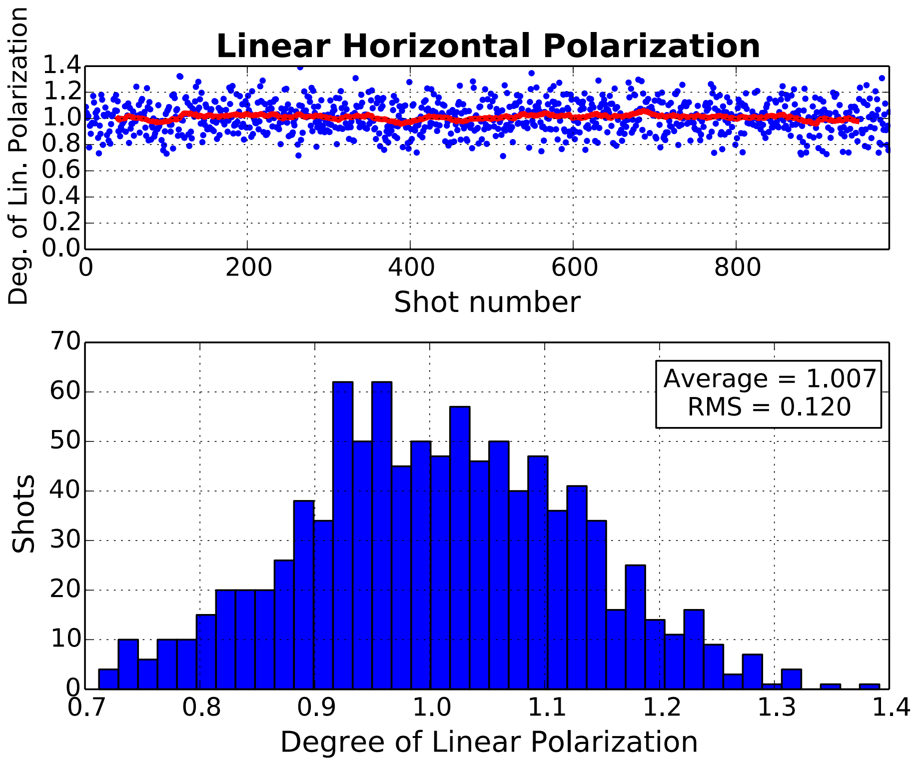
For more, have a look at Poster **MOP078**

Polarization measurements in the EUV

Horizontal Polarization



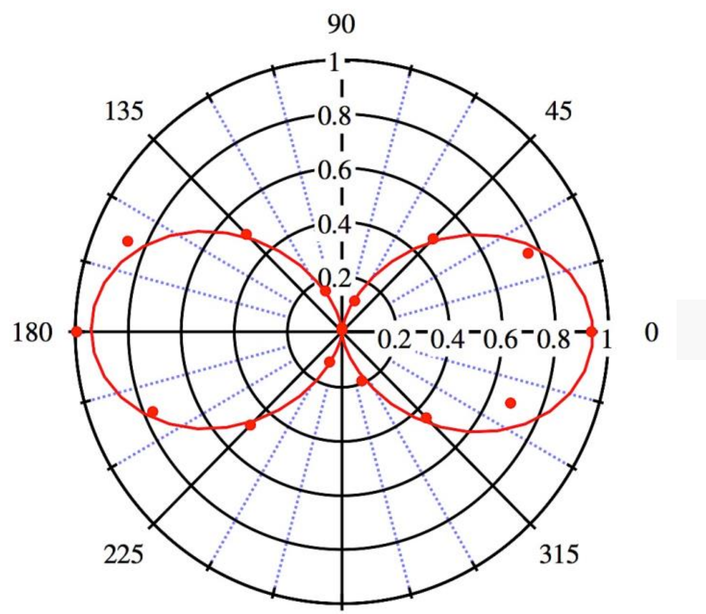
Degree of linear polarization



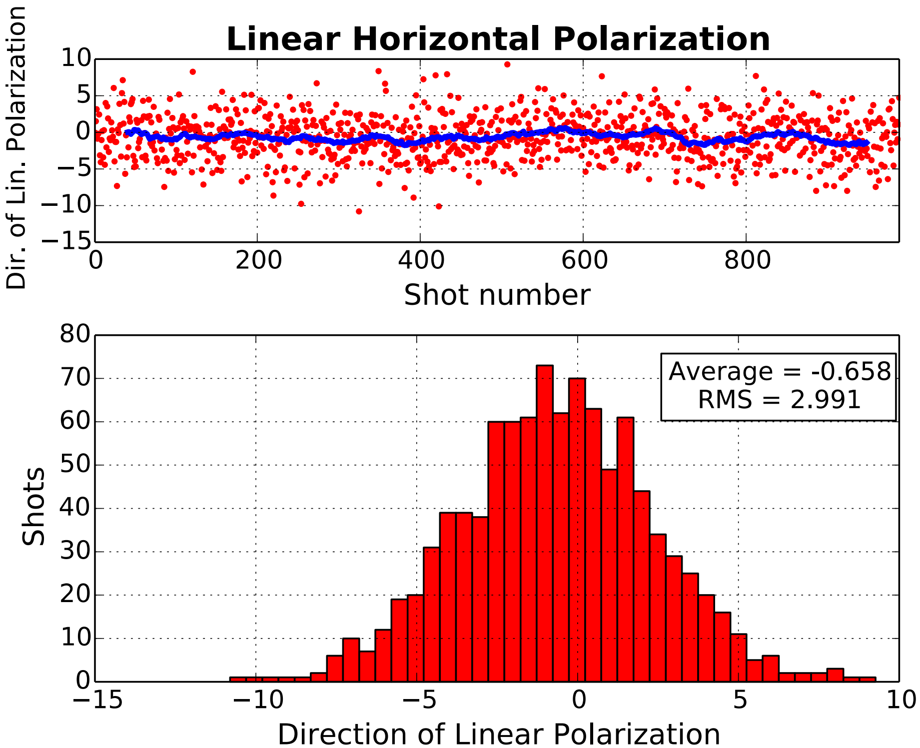
High degree of linear horizontal polarization

Polarization measurements in the EUV

Horizontal Polarization



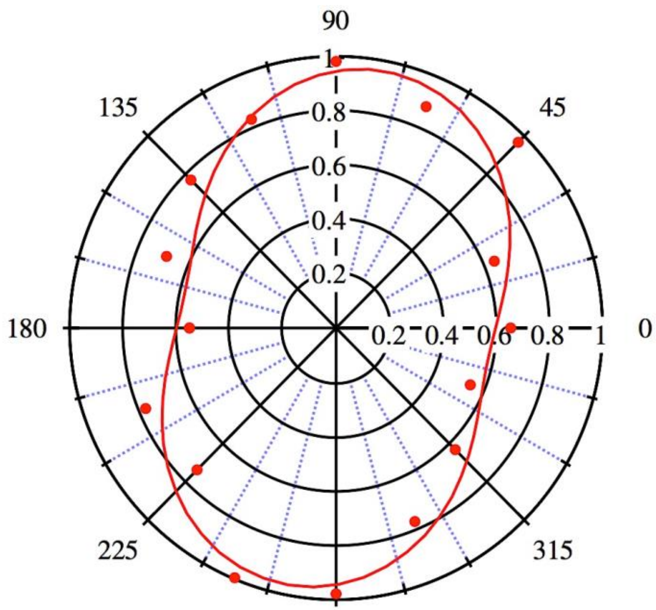
Direction of linear polarization



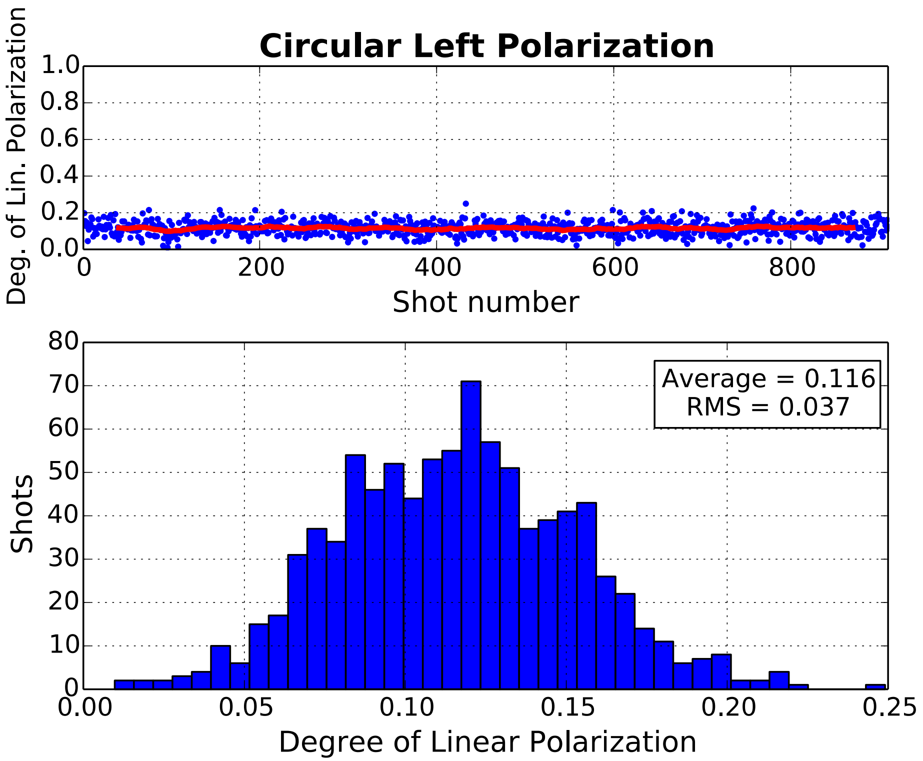
Angle of linear polarization is compatible with the horizontal polarization

Polarization measurements in the EUV

Circular polarization



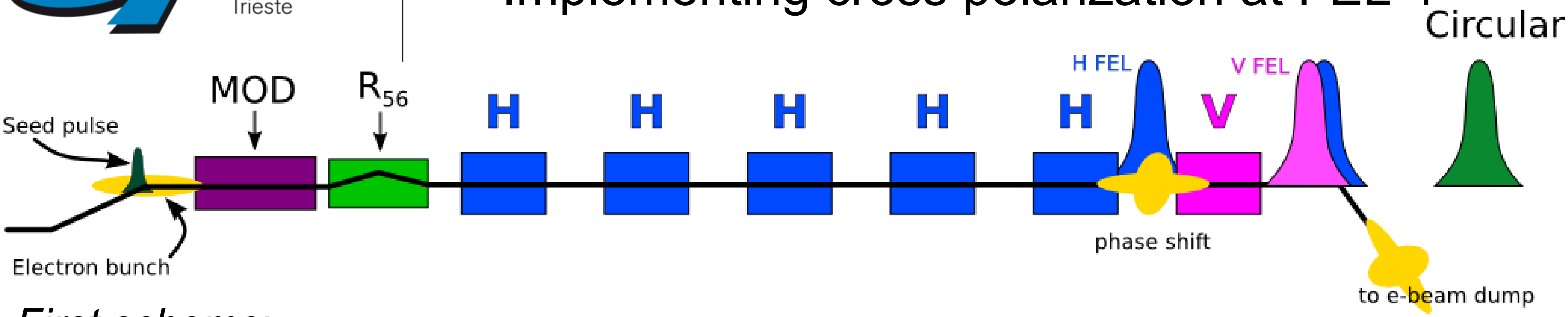
Degree of linear polarization



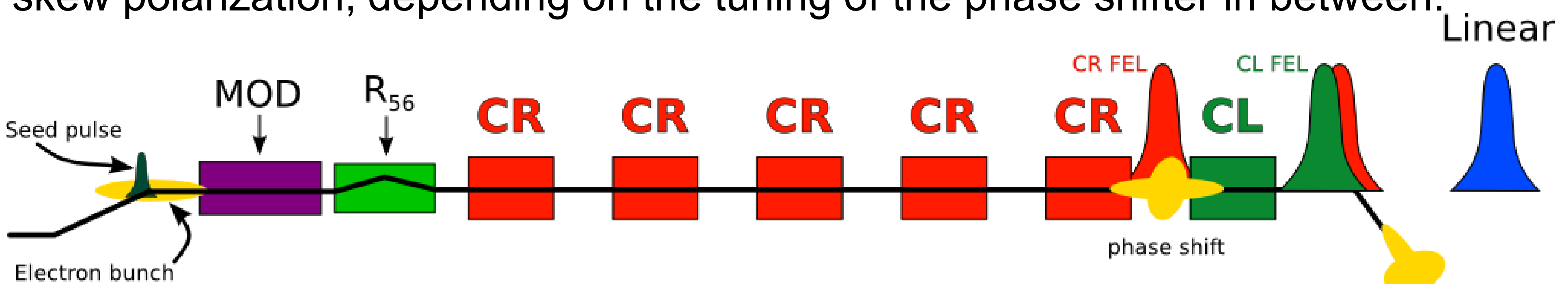
Compatible with a 99% circularly polarized source

The circular polarization signal is instead undistinguishable from the unpolarized one.
It can be inferred by considering a fully coherent source.

Implementing cross polarization at FEL-1



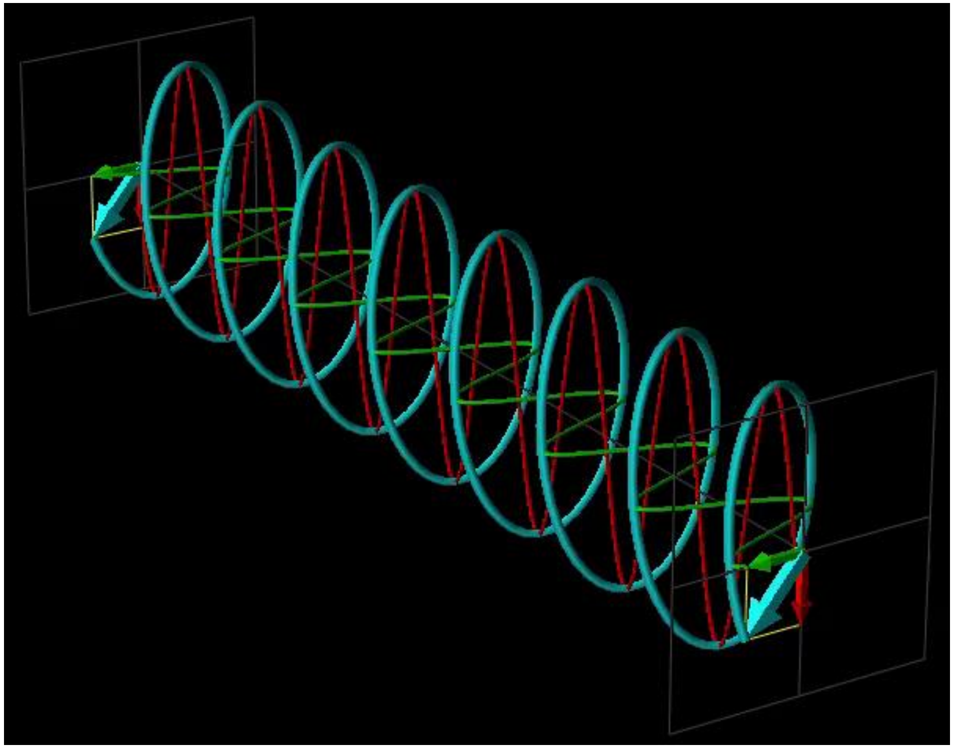
First scheme:
The first part of the radiator emits **Horizontal** polarized light, only one radiator produces **Vertical** polarized light, to produce **Circular** polarization or Linear skew polarization, depending on the tuning of the phase shifter in between.

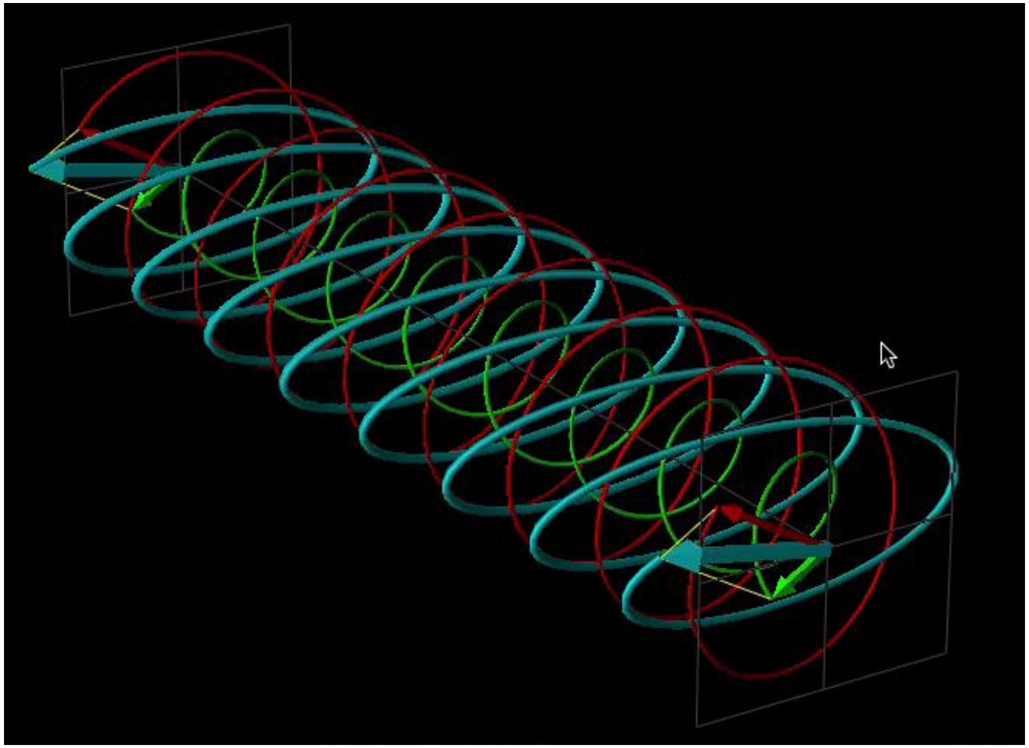


Second scheme:
It is also possible, using the elliptically polarized undulators at FERMI, to perform crossed polarization by using **Right Circular** and **Left Circular** light to obtain **Linear** polarization with adjustable polarization direction.

Useful because the eTOF polarimeter is sensitive to linear polarized light.

Balancing the emission is critical

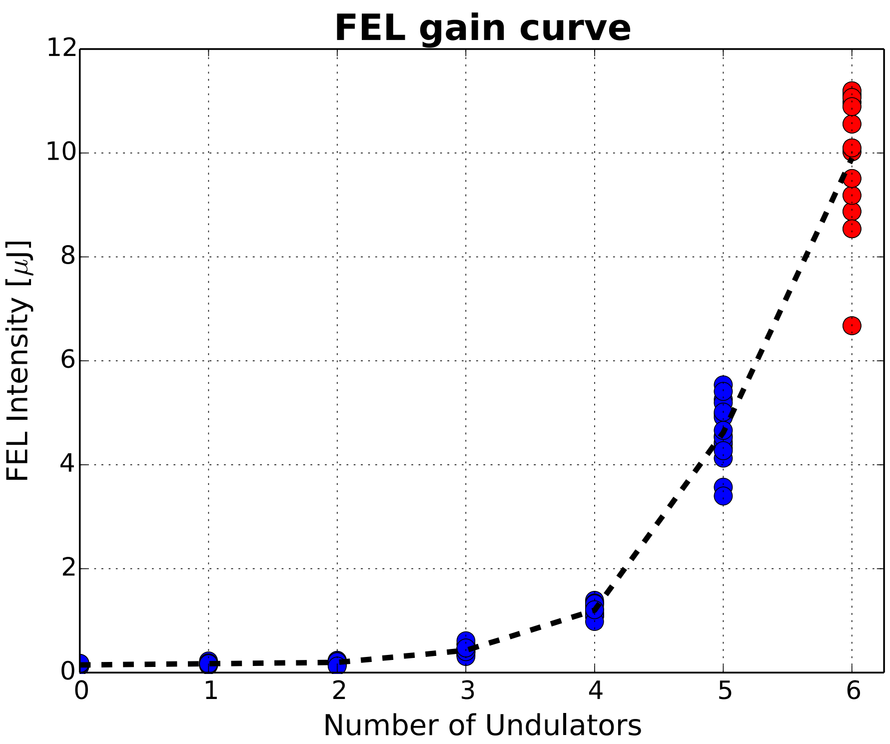


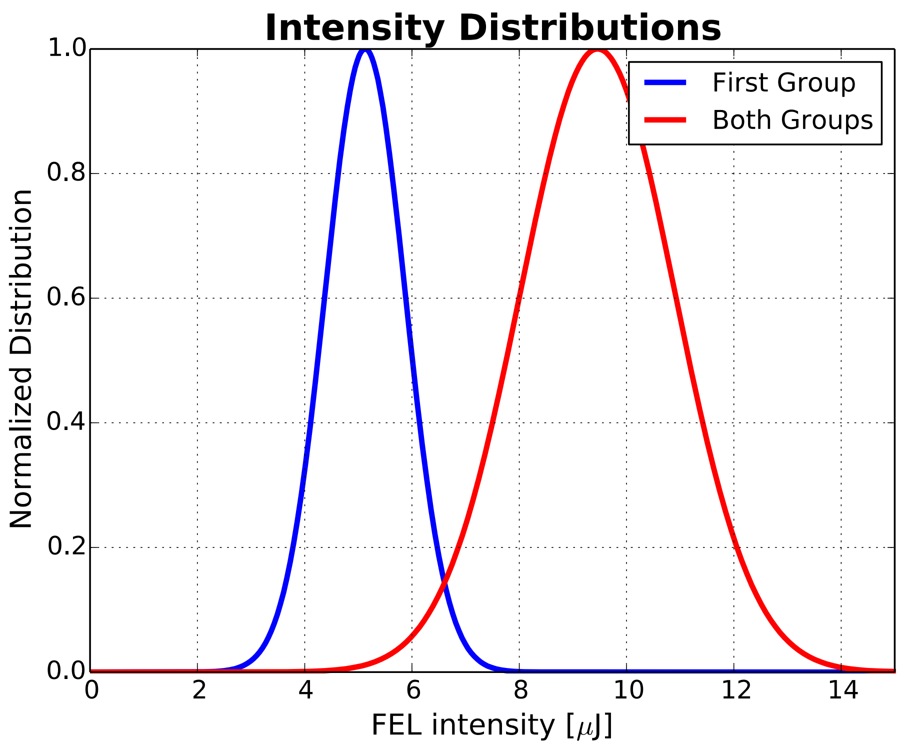


If the two sources are not balanced, the emission exhibits elliptical polarization or it can lose part of the degree of polarization

Balancing the emission in presence of gain

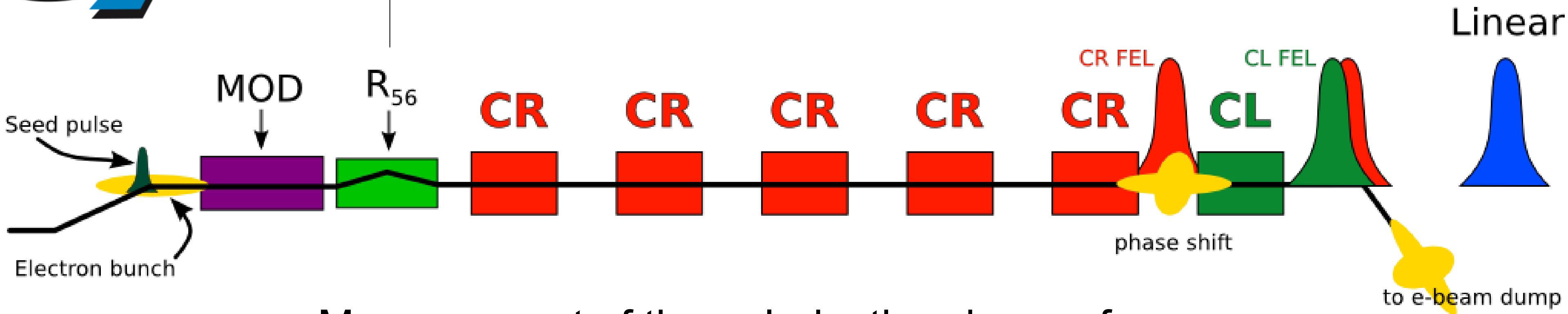
It is critical to balance the intensity of the two sources.



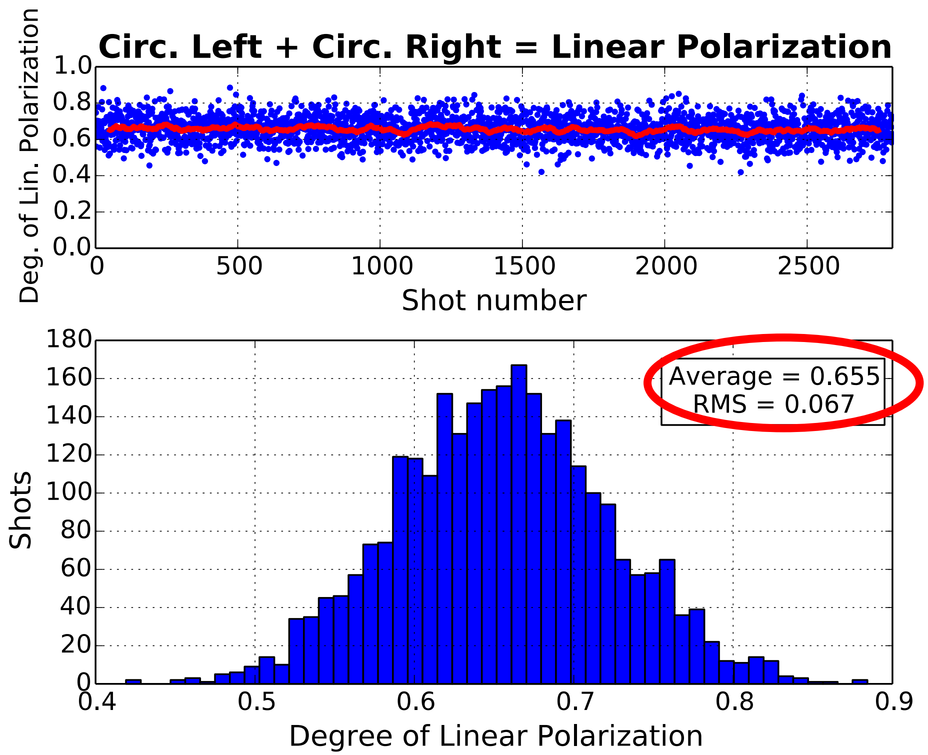


Measuring a gain curve, we can tune the FEL in order to have that the first 5 undulators emit almost the same intensity as the last undulator alone.

Crossed Polarization Measurements



Measurement of the polarization degree for the CR + CL crossed polarization scheme



The average degree of linear polarization is 65.5 %, which is lower than what was thought to be possible.

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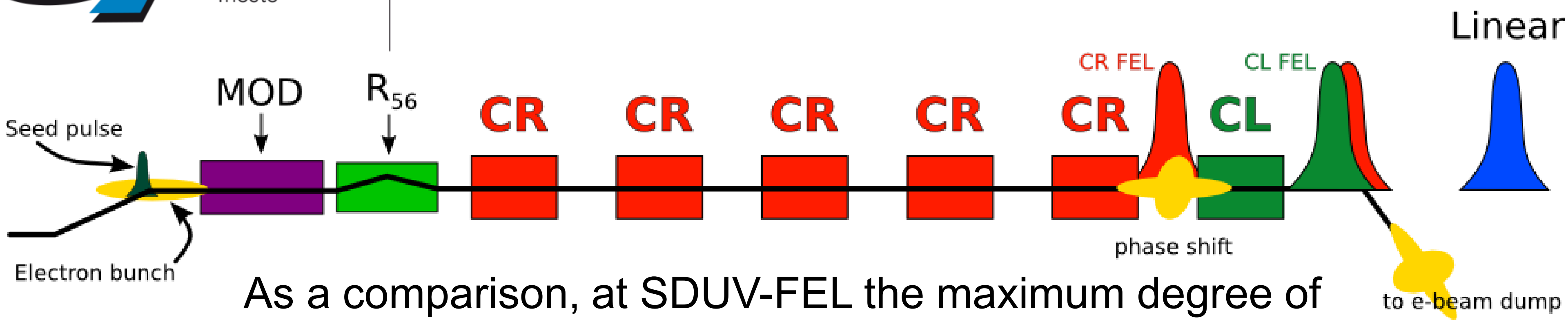
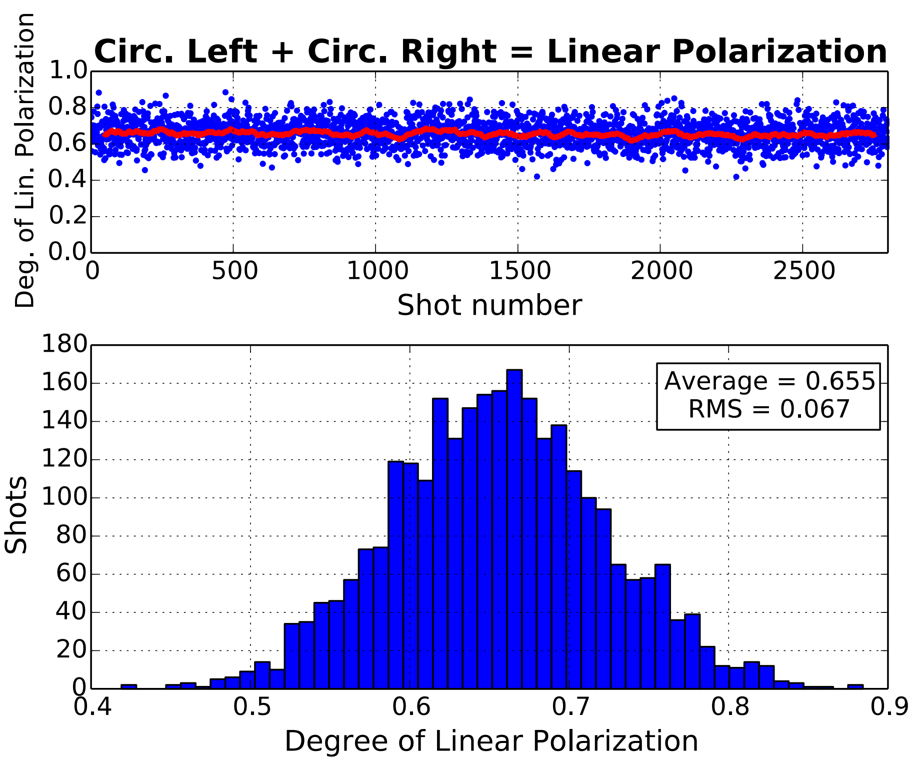
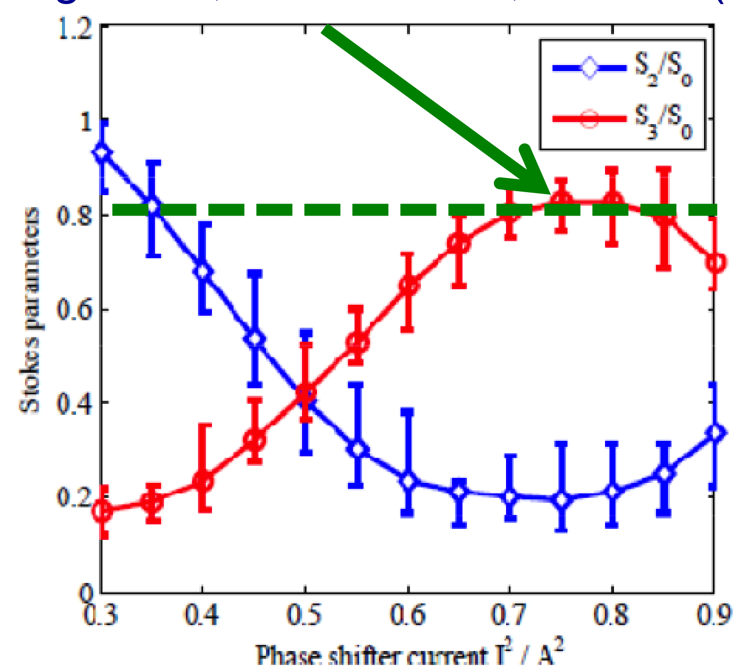
Crossed Polarization Measurements



As a comparison, at SDUV-FEL the maximum degree of polarization observed with a crossed undulator scheme was ~ 0.8 (for linear horizontal + linear vertical = circular)



H. Deng et. al., PR-STAB 17, 020704 (2014).



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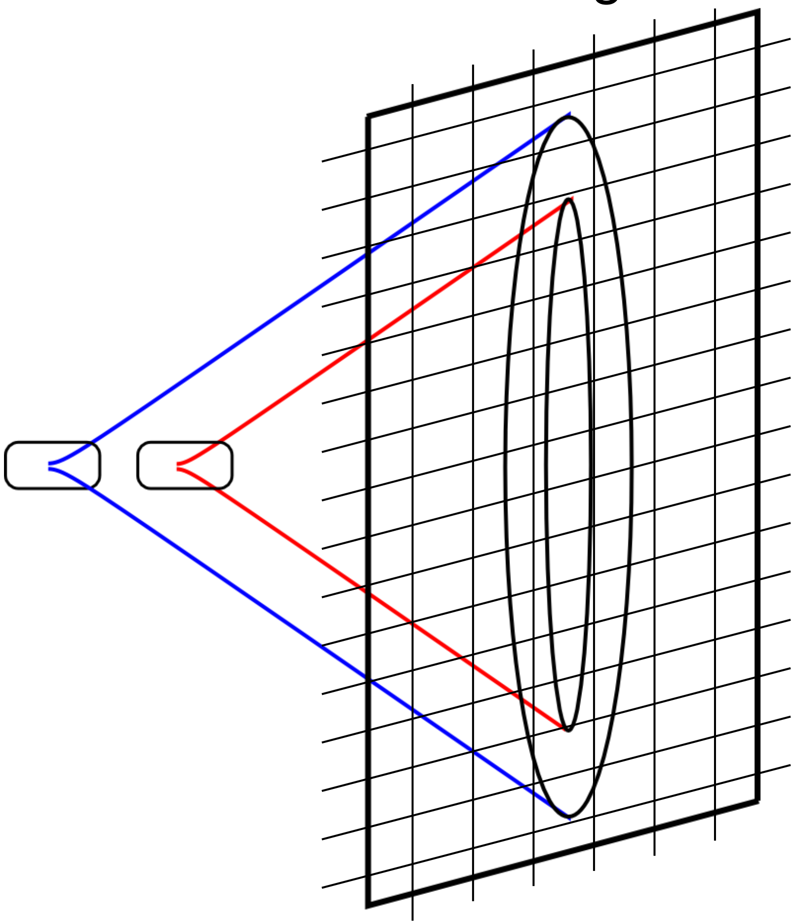
How to explain the lower degree of polarization obtained?

Toy model: Two Gaussian sources interfering

Two or more monochromatic Gaussian beams propagating in free space. We look at the resulting field



Parameters of the toy model:

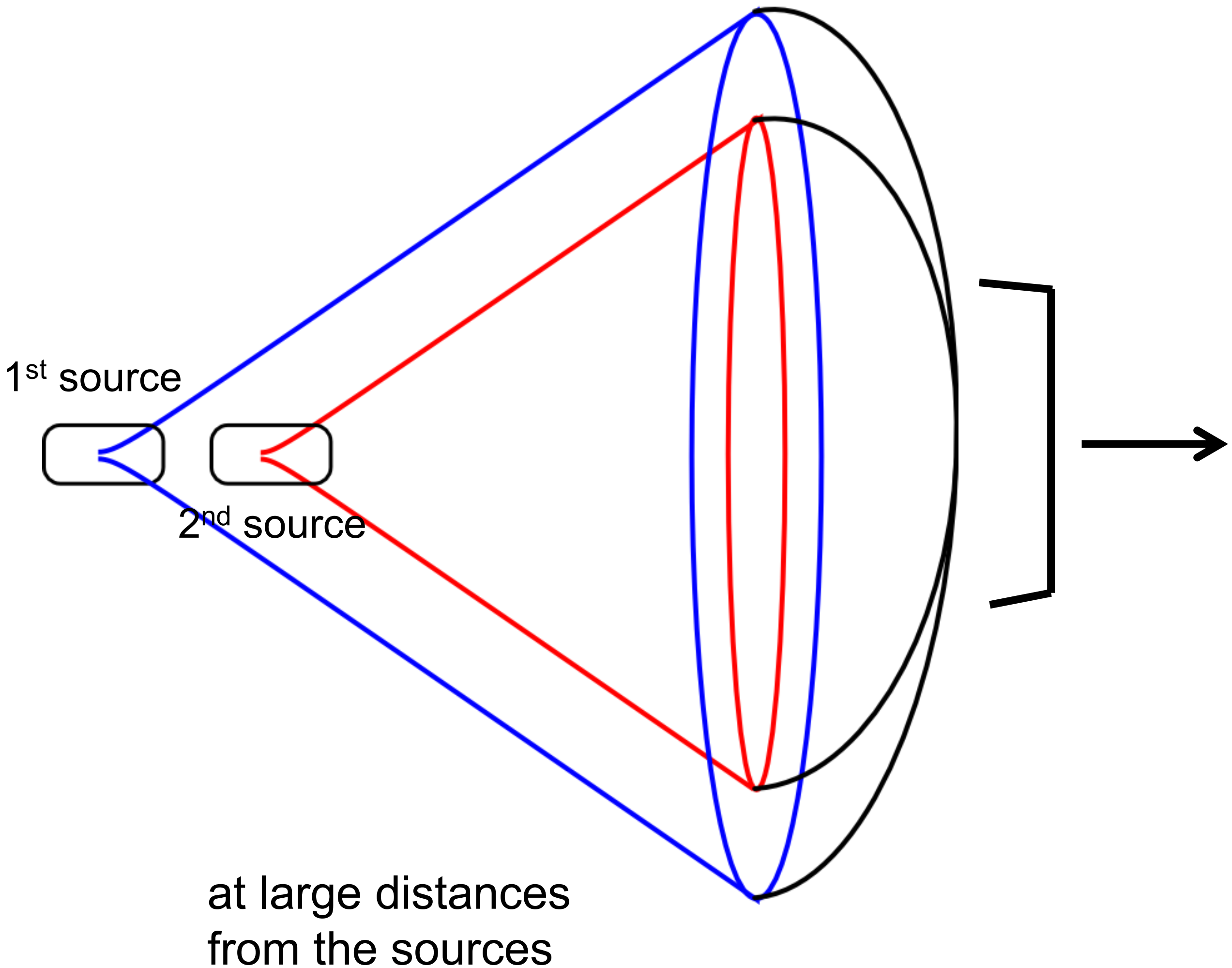
- Distance of the detector from the sources
- Distance between the two sources
- Amplitude and phases of each field
- Phase shift between the sources
- Wavelength of the radiation
- Waist dimensions of the sources
- Aperture of the detector

Stokes parameters of light

$$
\begin{aligned}
I &= |E_x|^2 + |E_y|^2, \\
Q &= |E_x|^2 - |E_y|^2, \\
U &= 2\mathrm{Re}(E_x E_y^*), \\
V &= -2\mathrm{Im}(E_x E_y^*),
\end{aligned}
$$

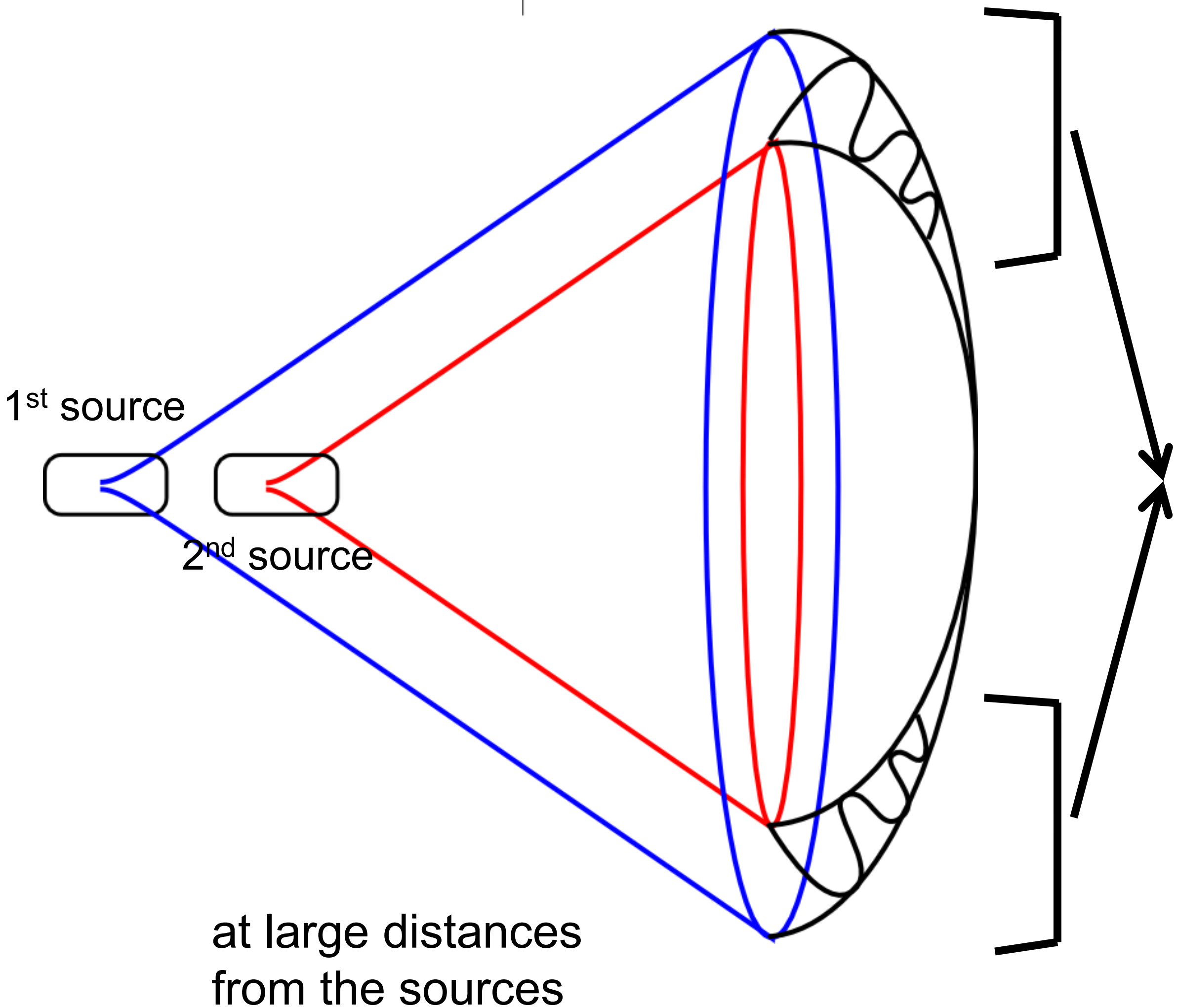
Output: 2D map of the (not normalized) Stokes parameters on a grid. Summing up the Stokes parameters and normalizing to I, we can extract the polarization of the total E field

Toy model: Two Gaussian sources interfering



on-axis, fully polarized
crossed undulator emission

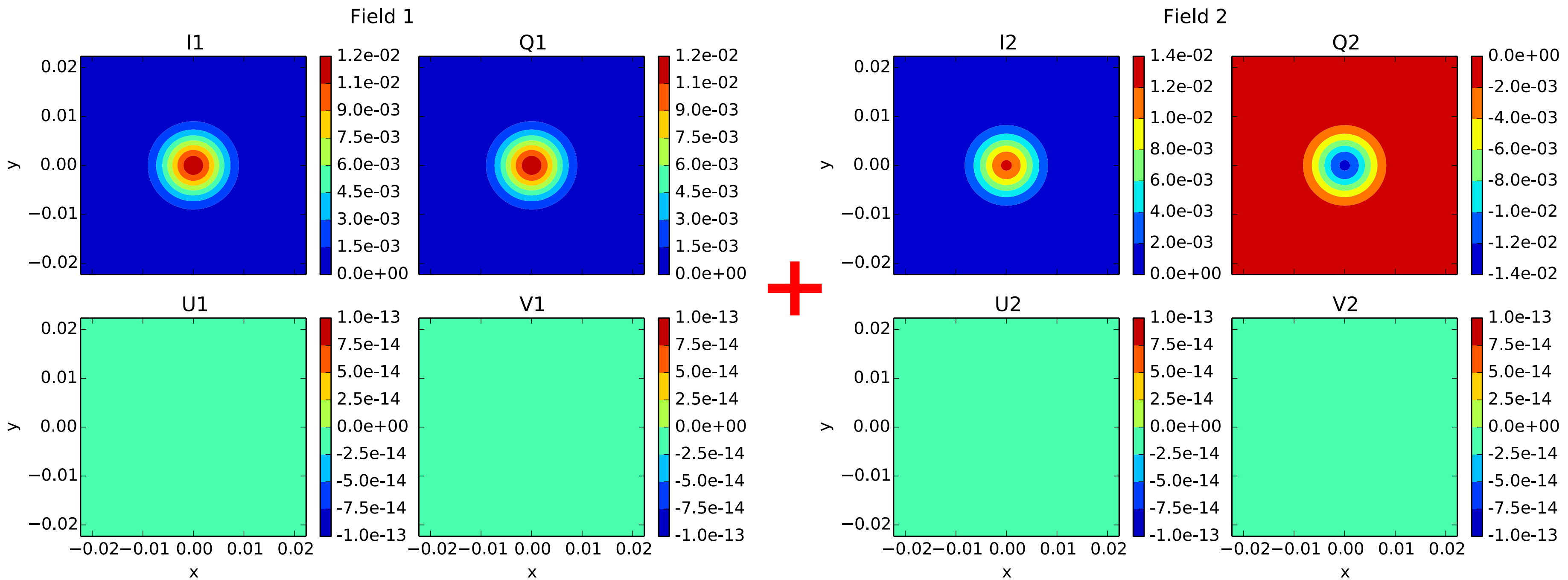
Toy model: Two Gaussian sources interfering



off-axis, the phase of each of the two sources is not constant anymore. For the sum field, strong phase and intensity variations are present off-axis. This induces a loss of polarization

The Rayleigh range is the parameter we have to consider

Crossed polarized fields



+

Linear horizontal Field

Norm. Stokes parameters
(1.0, 1.0, 0.0, 0.0)

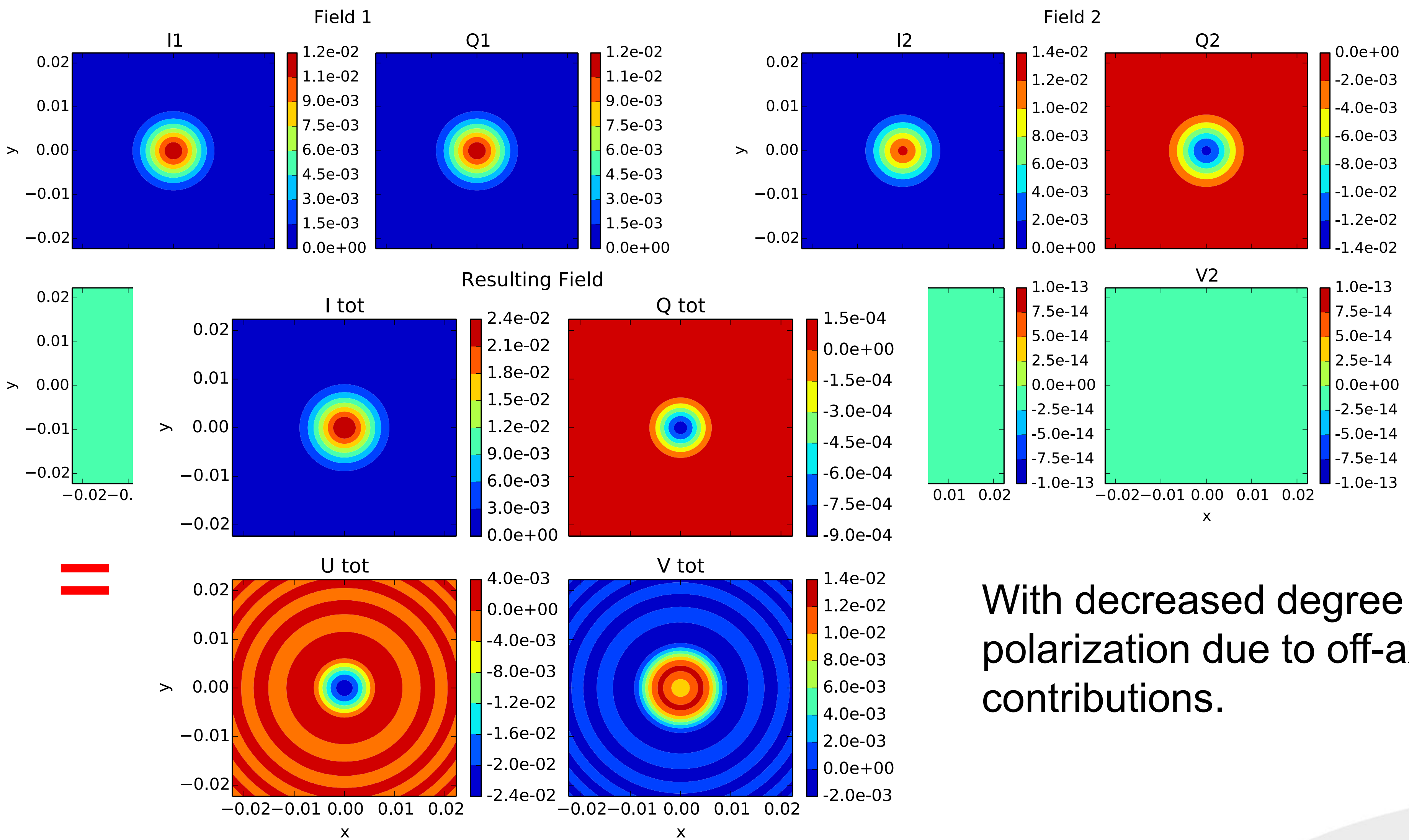
Linear vertical Field

Norm. Stokes parameters
(1.0, -1.0, 0.0, 0.0)

with phase shift = 90 deg
(corresponding ideally to a resulting perfectly circular field)

=

Crossed polarized fields



With decreased degree of polarization due to off-axes contributions.

Elliptical Field

(1.0, -2.7E-07, 0.11, -0.72)

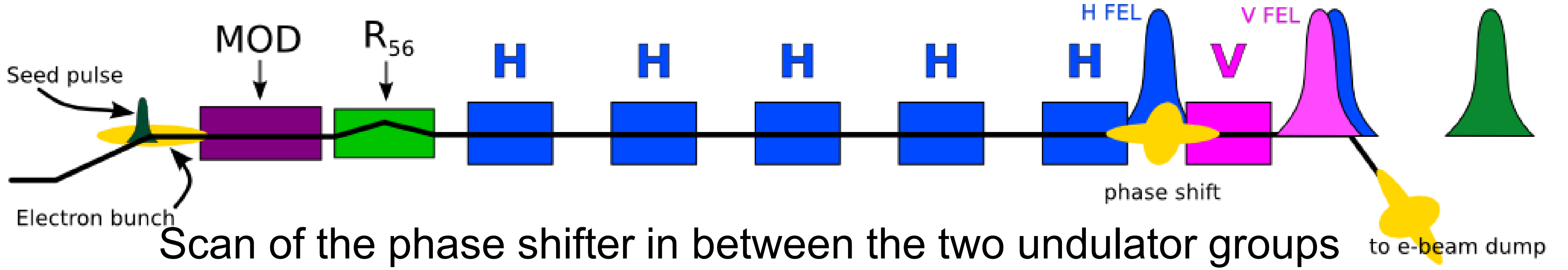
Rayleigh range and crossed undulator distance

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

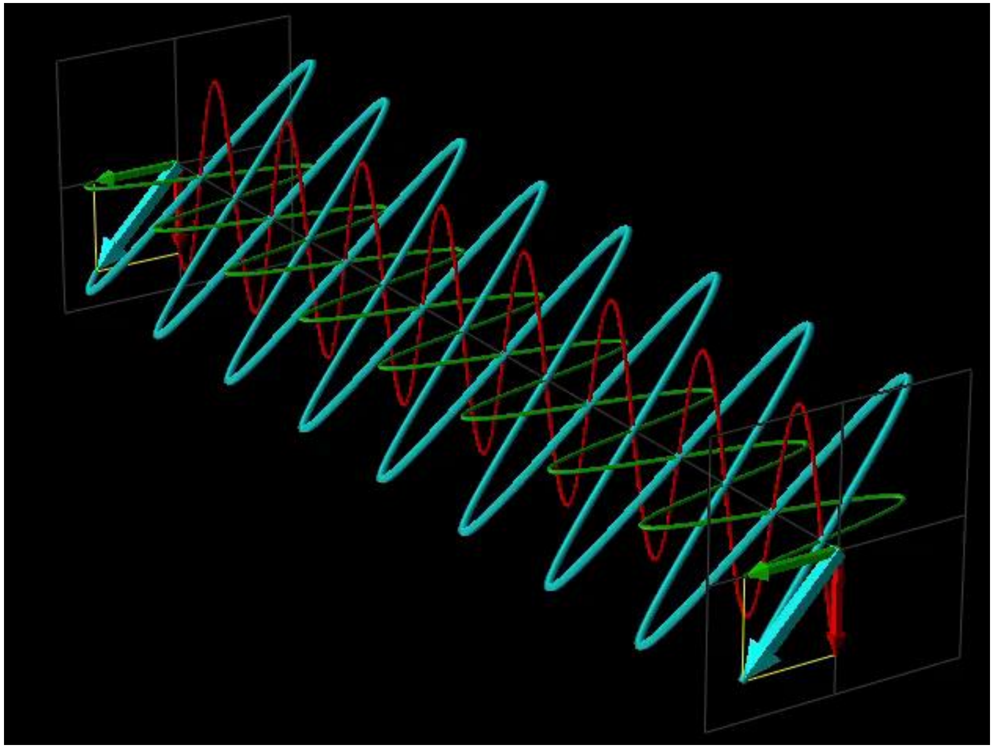
FEL source	Wavelength	Rayleigh range	Distance Crossed undulators	Toy model Max degree of polarization
LCLS like	Hard X	~ 100 m	3 – 5 m	> 99 %
SDUV FEL	Visible	~ 1 m	0.5 – 1 m	> 90 %
FERMI FEL1	EUV	~ 1 m	~ 3.5 m	~ 67 %

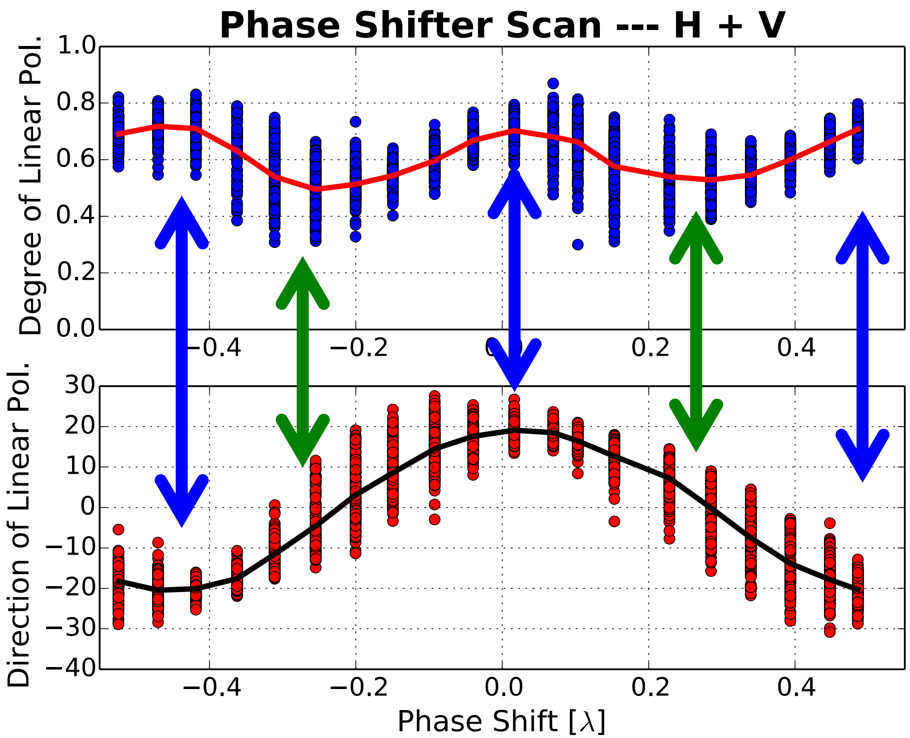
The Fermi problem:
Rayleigh range is (much) smaller than the distance between the two crossed undulators, so the maximum degree of linear polarization is **~67%** in the crossed undulator scheme.

Crossed Undulators to control the Polarization



Scan of the phase shifter in between the two undulator groups





Skew linear Polarization **Circular Polarization**

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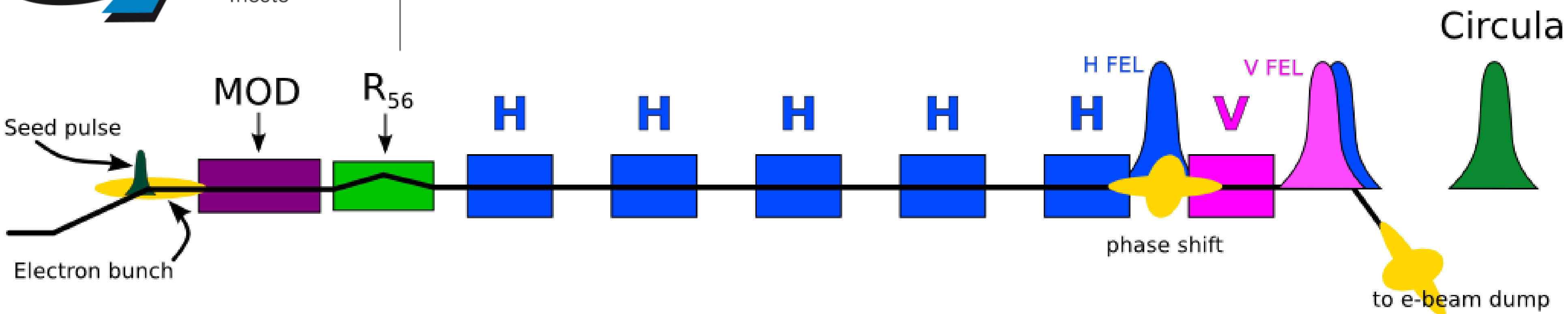
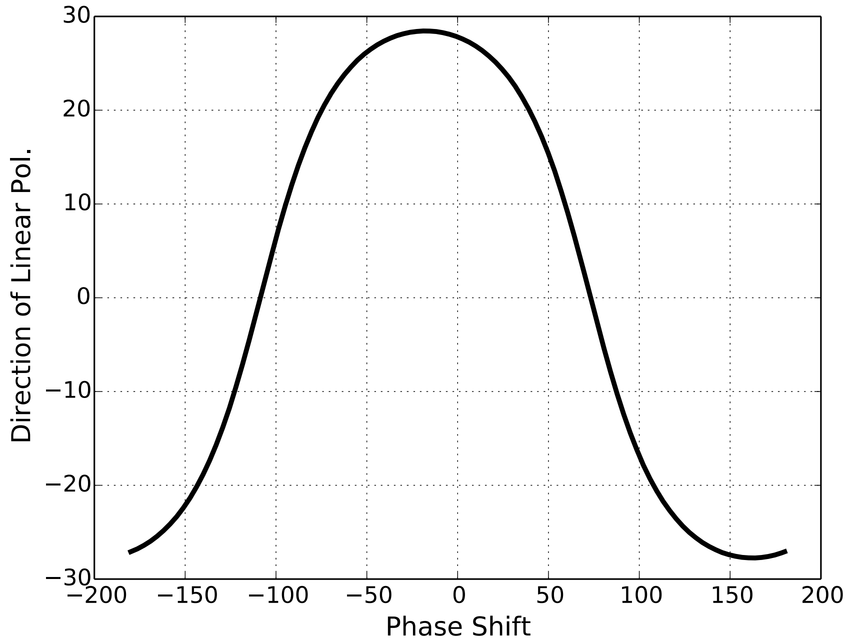
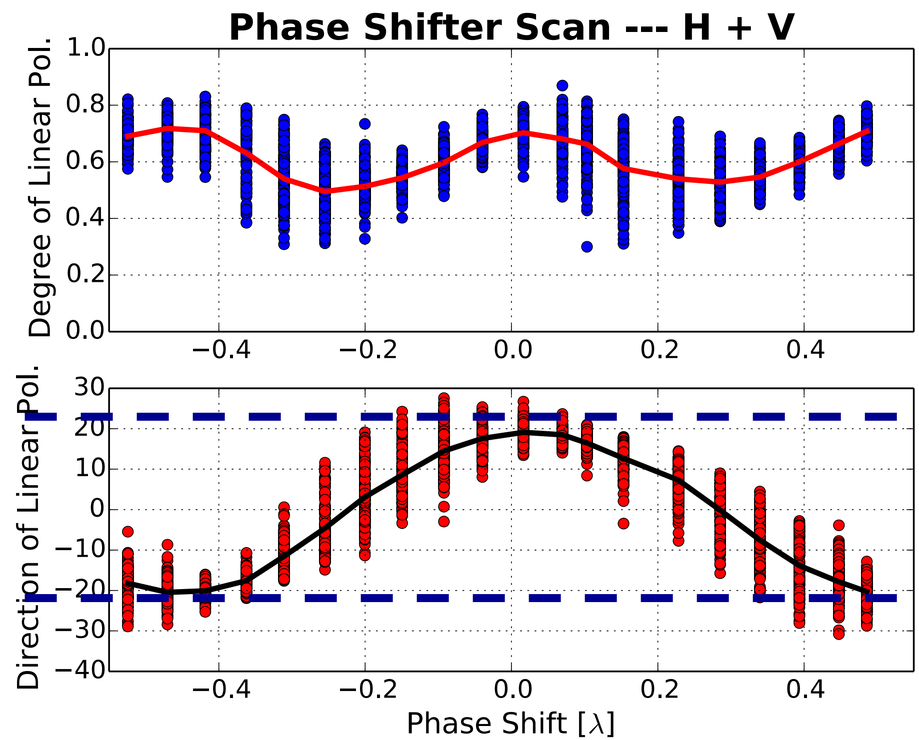
Crossed Undulators to control the Polarization



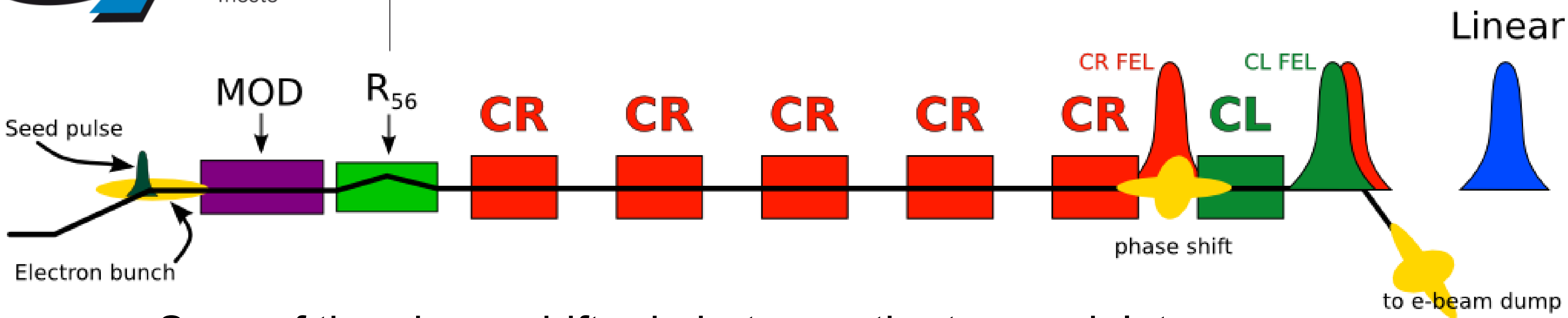
Toy model: Dir. of polarization vs. phase shift





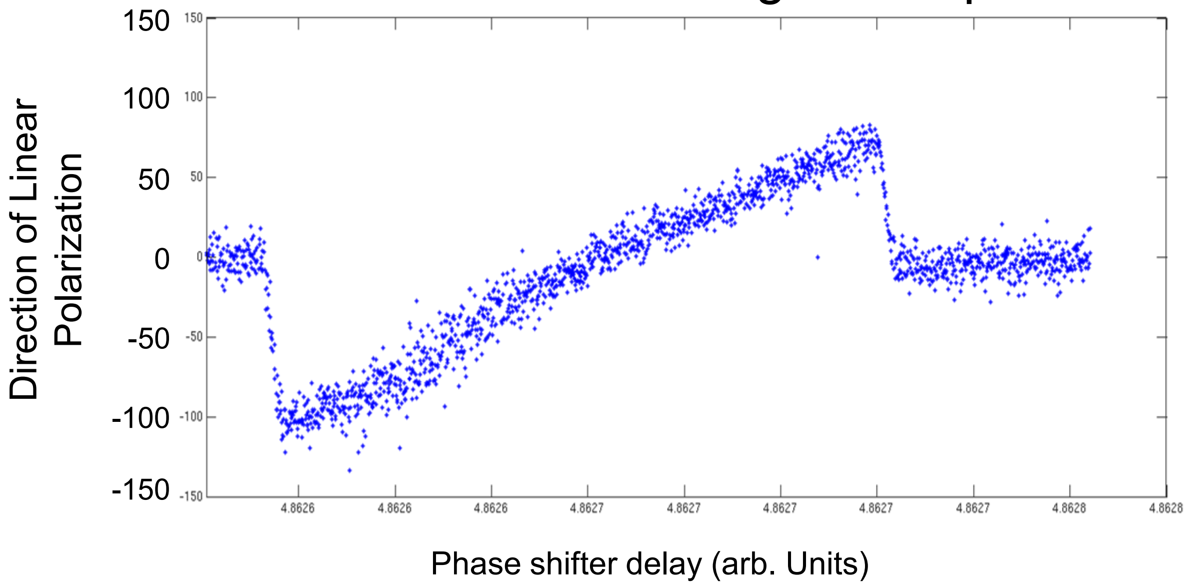
The maximum **direction** of linear skew polarization is lower than the expected 45 deg. This result can be due to a slight unbalance between the intensities of the two sources

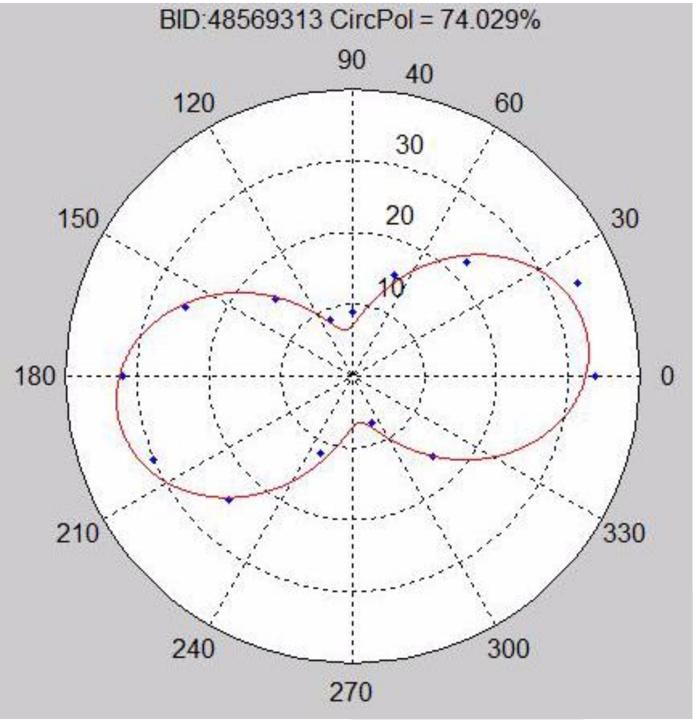
Control of the Polarization Direction



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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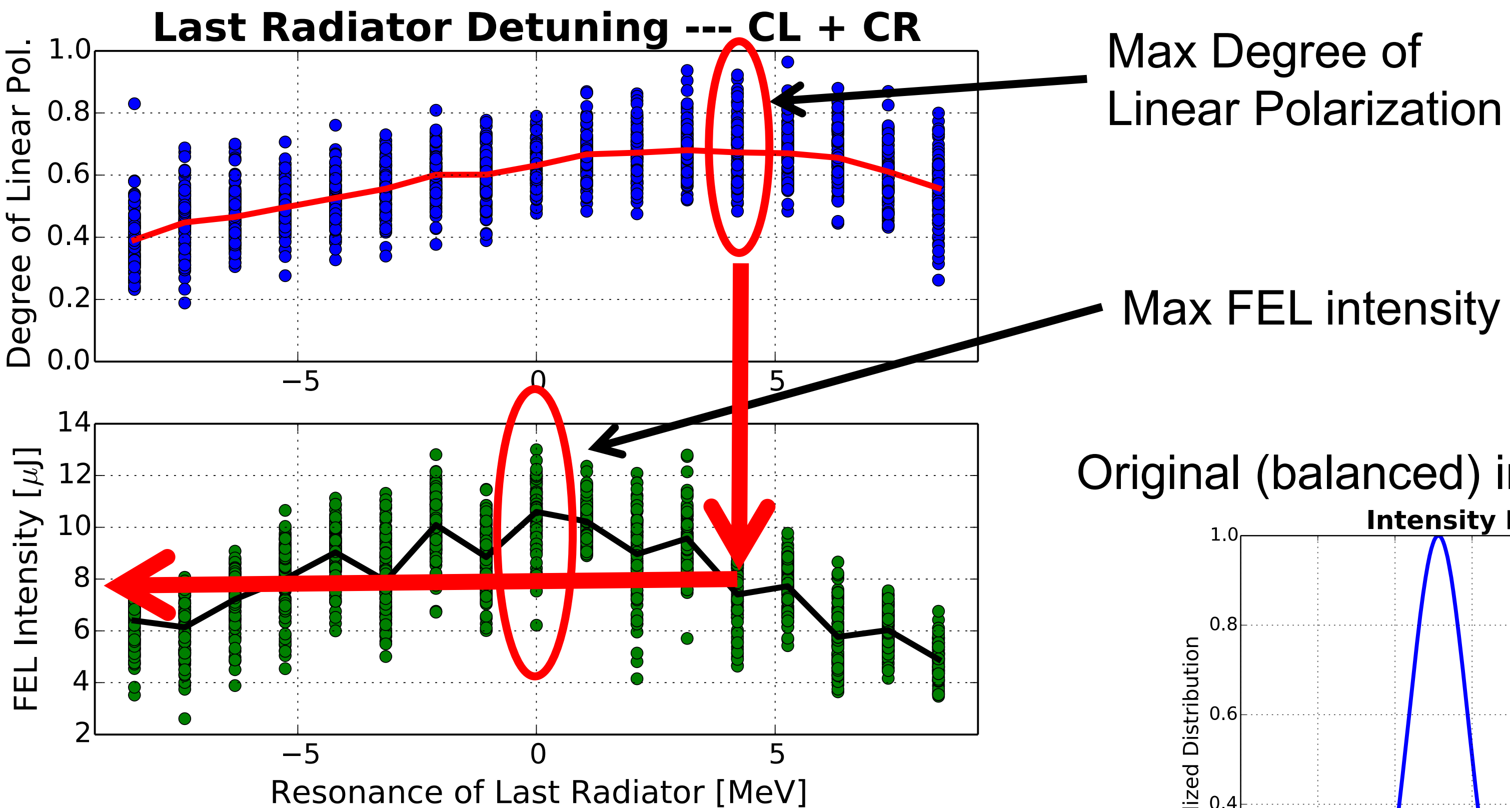
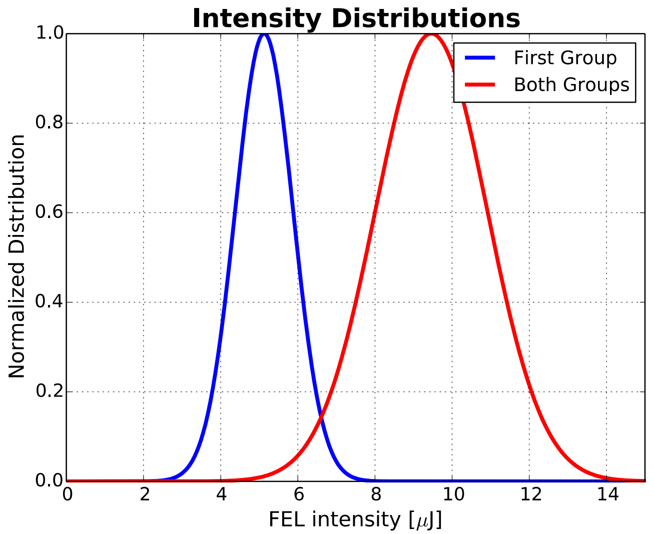
How to improve the degree of polarization?

Unbalancing the intensity of the two sources

Detuning scan of last undulator (only CR intensity is changed)



Original (balanced) intensity distributions



It seems that the second group needs to have lower intensity than the first group (10 – 20 % lower intense)

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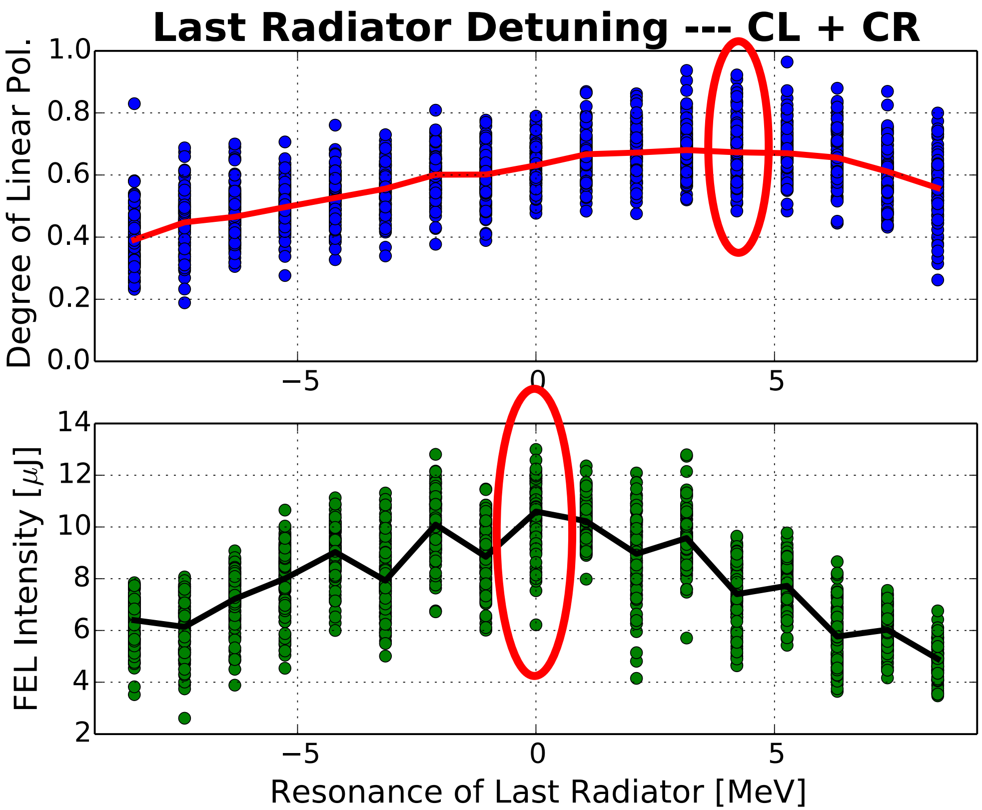
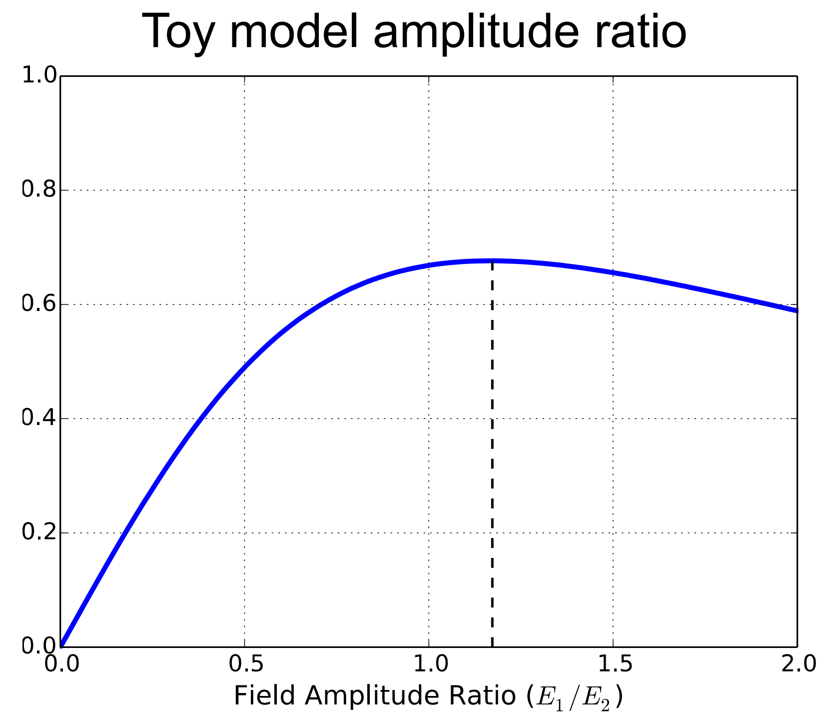
Unbalancing the intensity of the two sources

Detuning scan of last undulator (only CR intensity is changed)



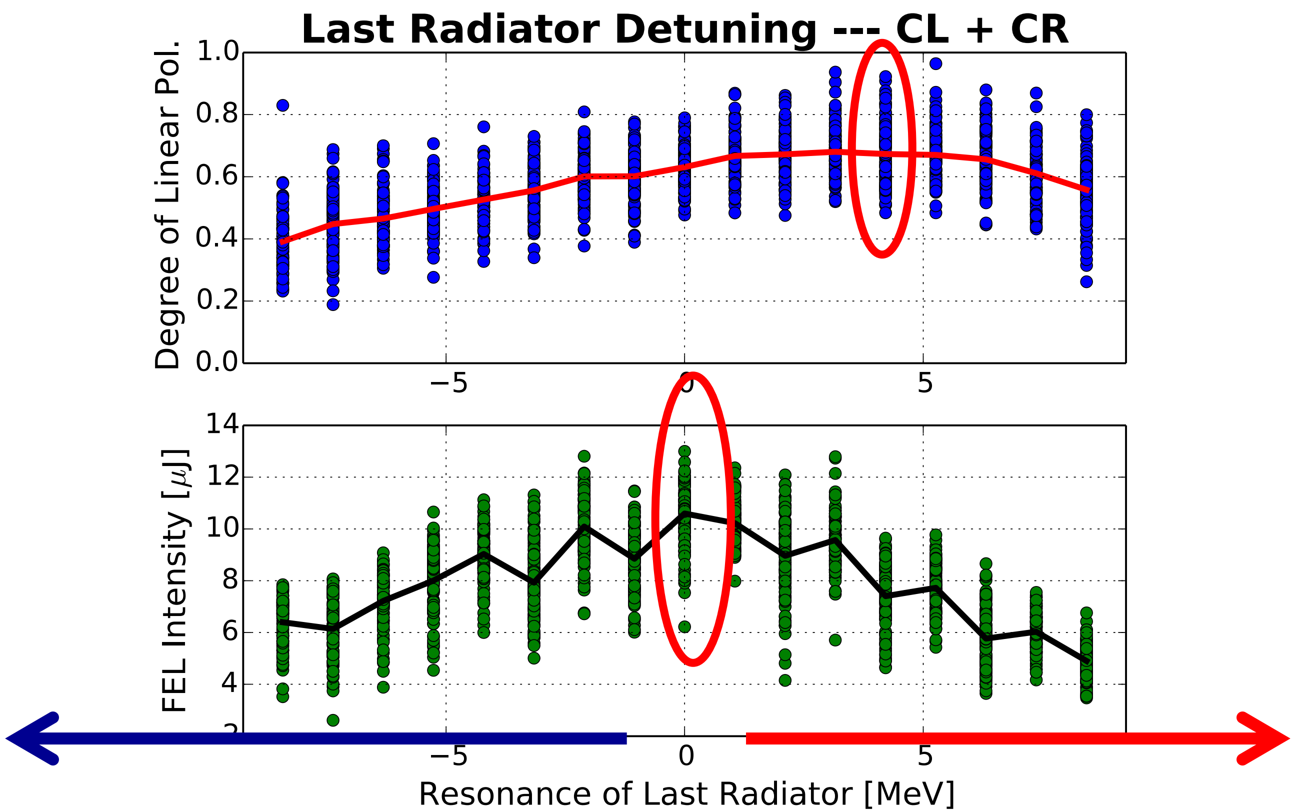


Reproduced by the toy model

By detuning the last radiator (i.e. unbalancing the intensity of the two groups) we can increase the degree of polarization

Why the curve is asymmetric?

Detuning scan of last undulator



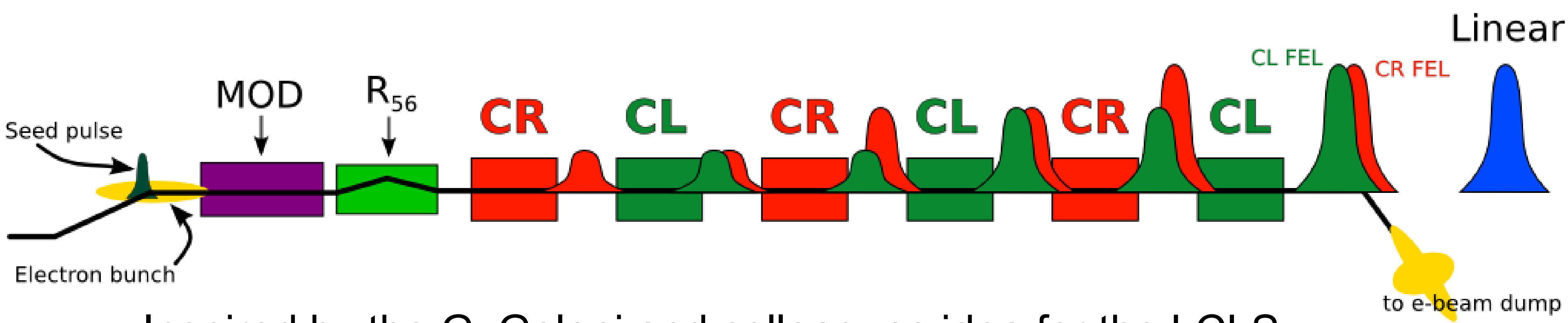
More **off-axis** emission

(lower polarization because of worst compensation of the intensities on-axis)

More **on-axis** emission

(larger polarization due to the better match of the divergences of the two sources)

Distributed crossed polarized scheme



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

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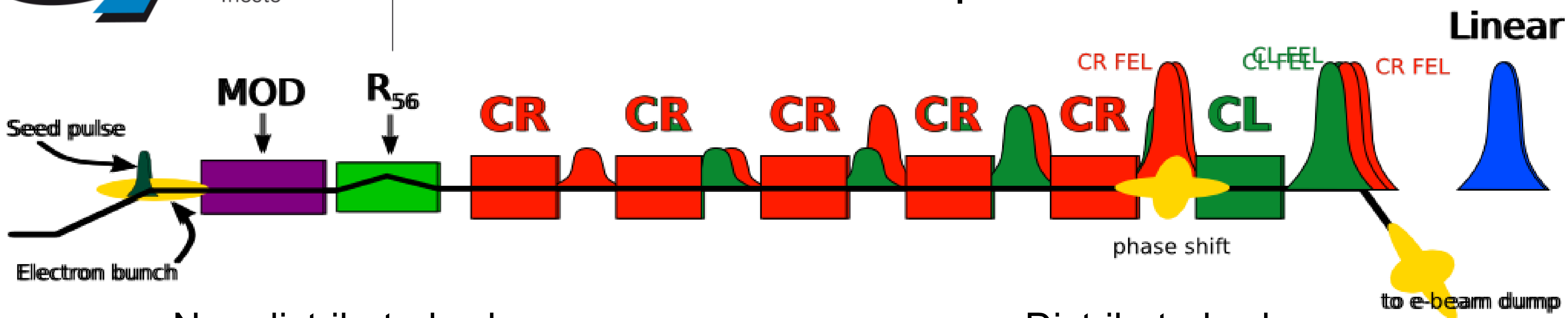
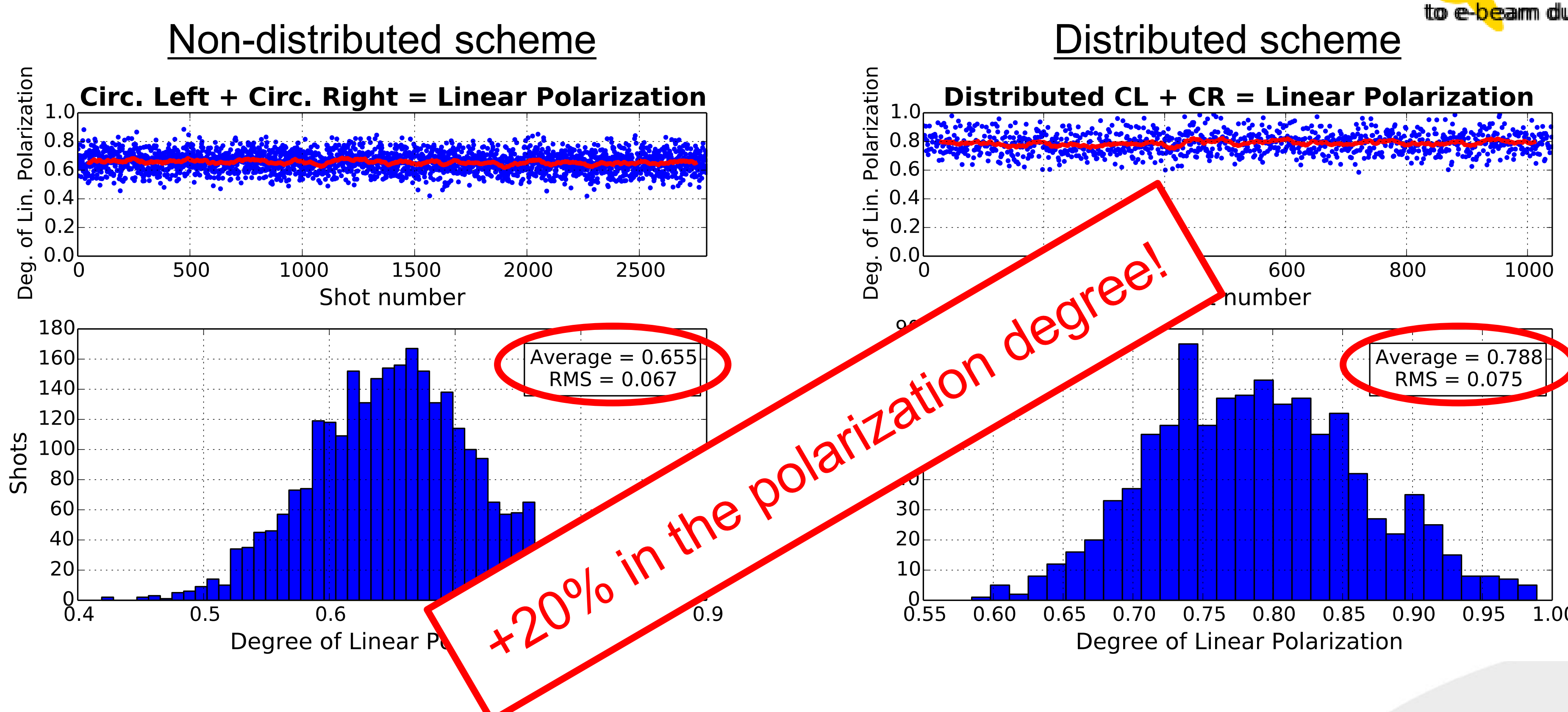
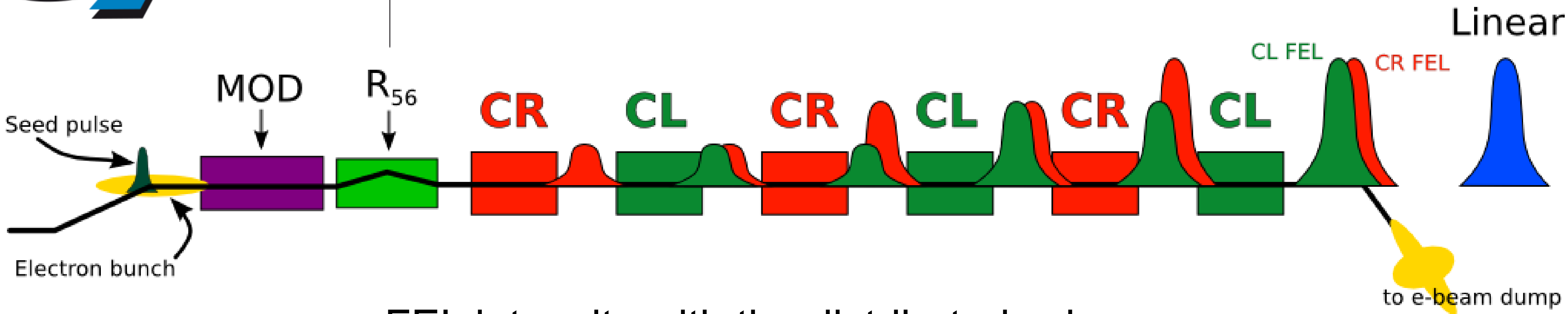


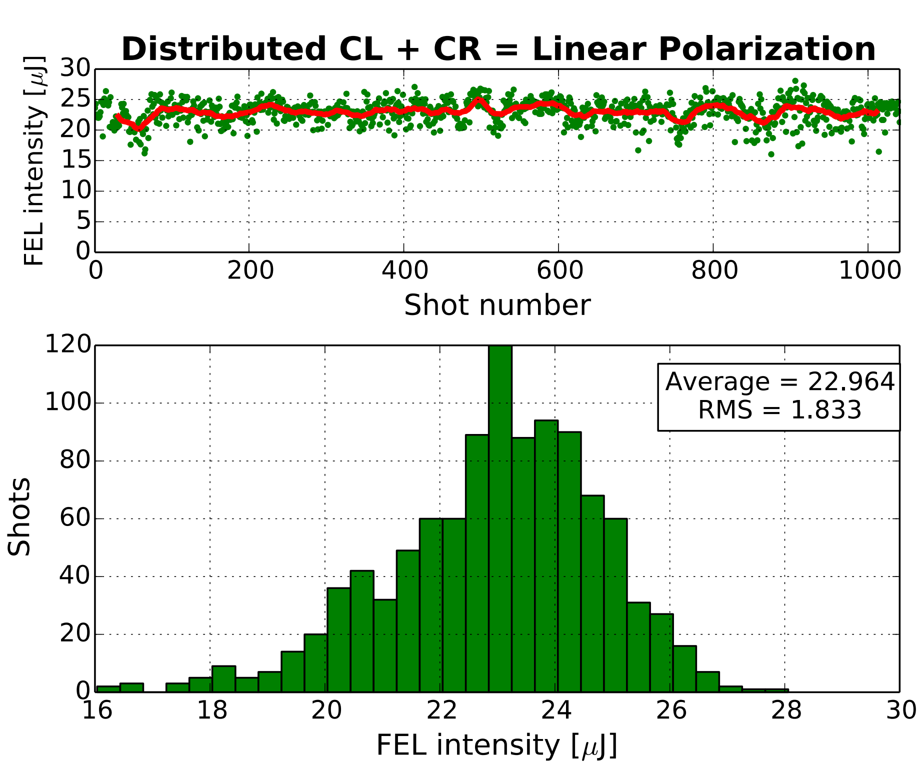


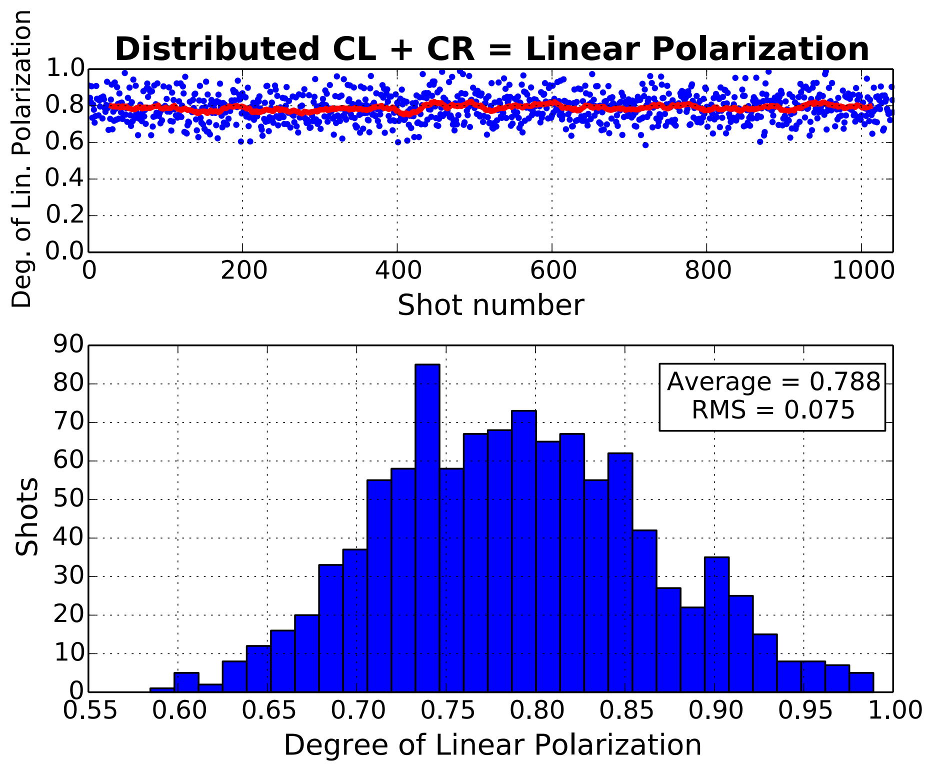
The increase in the degree of linear polarization is also predicted by our toy model

Distributed crossed polarized scheme

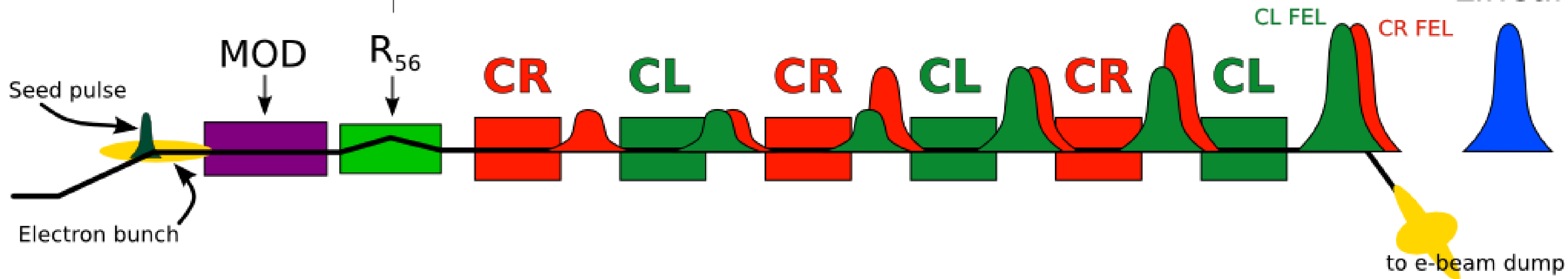


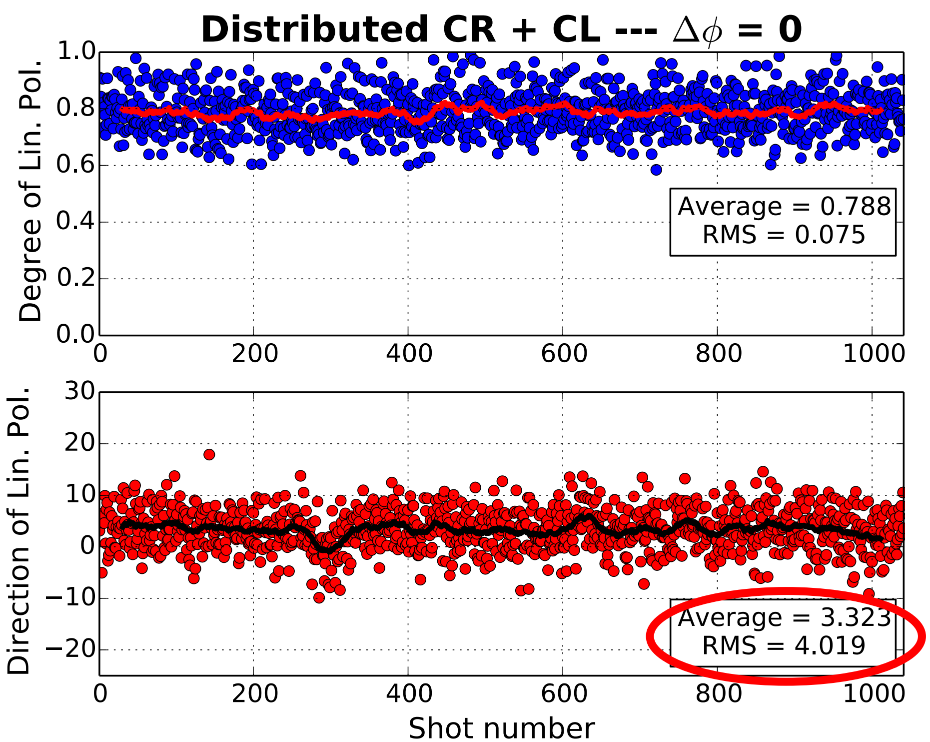
FEL intensity with the distributed scheme





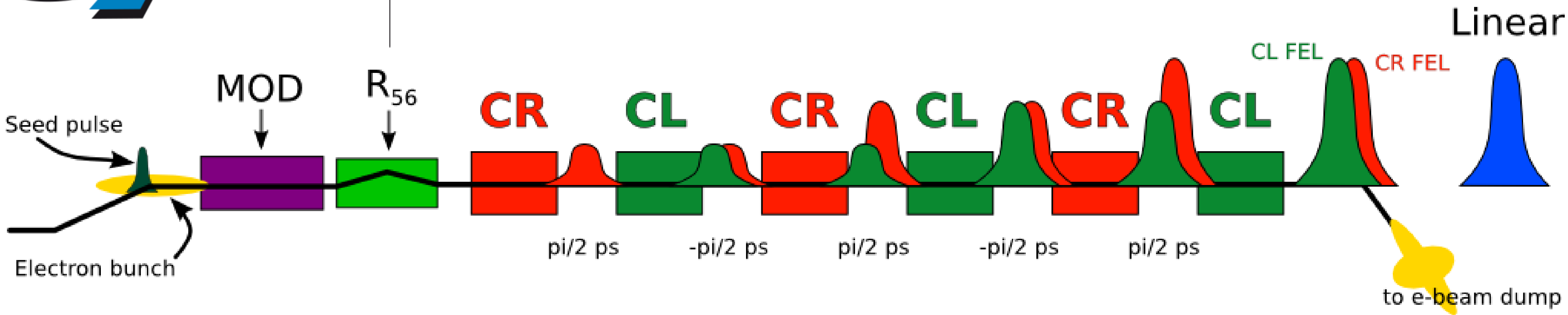
Polarization control in the distributed scheme



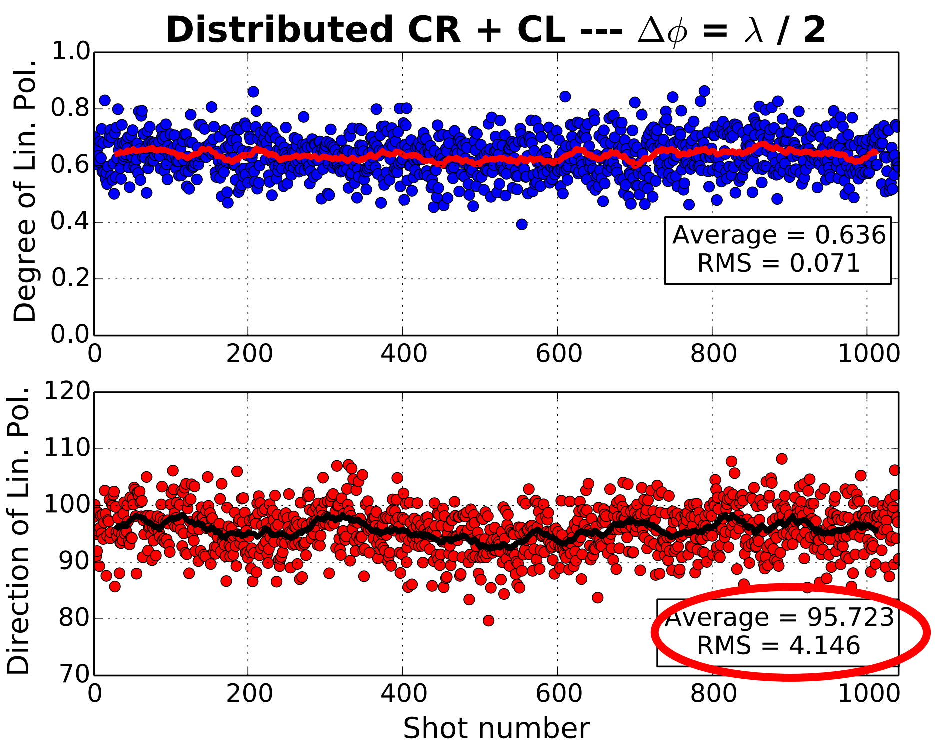


Circular Left plus **Circular Right** gives, with zero phase shift, **Linear Horizontal** polarization

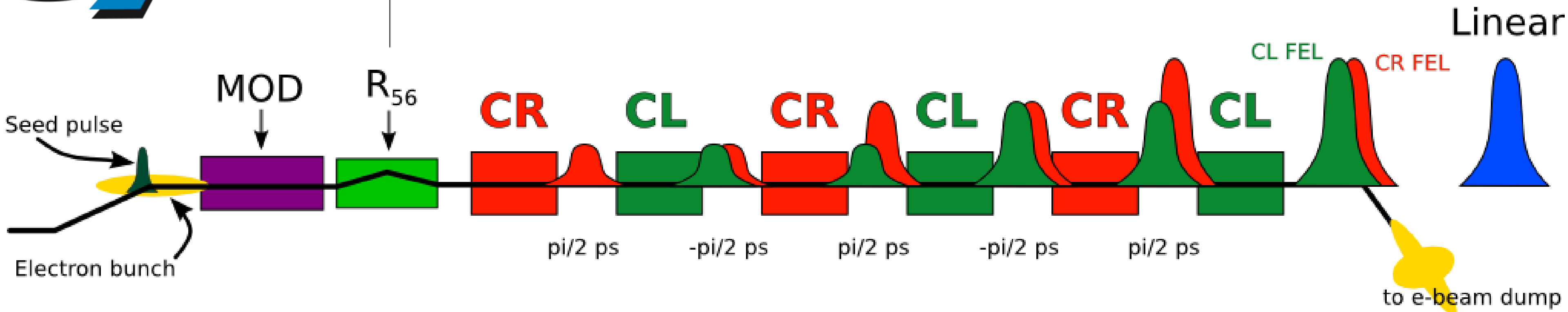
Polarization control in the distributed scheme



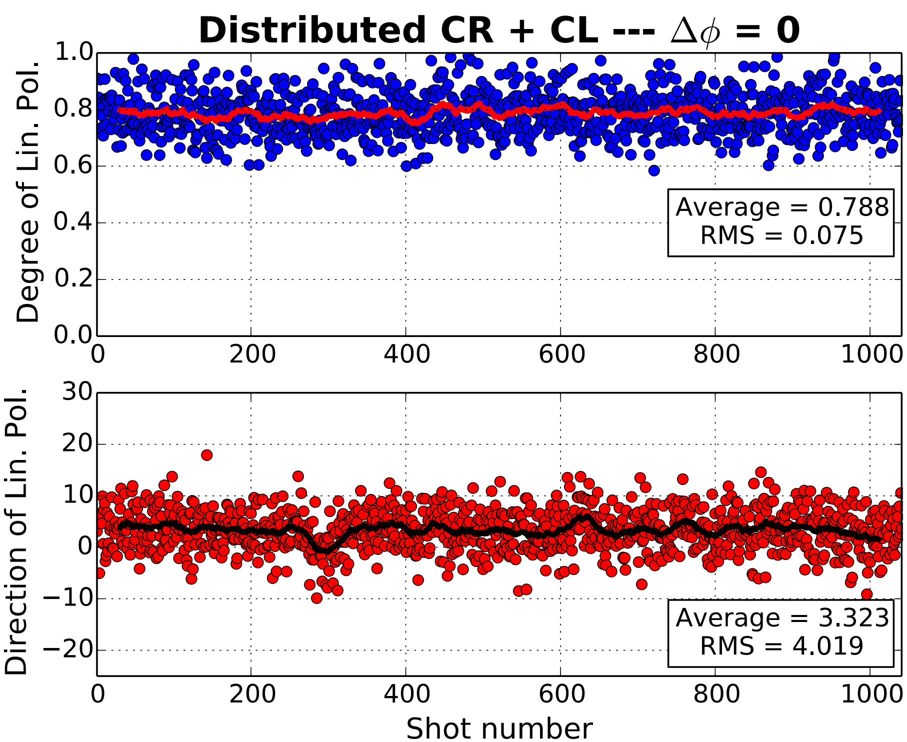
A phase shift of half a wavelength gives **Linear Vertical** polarization.

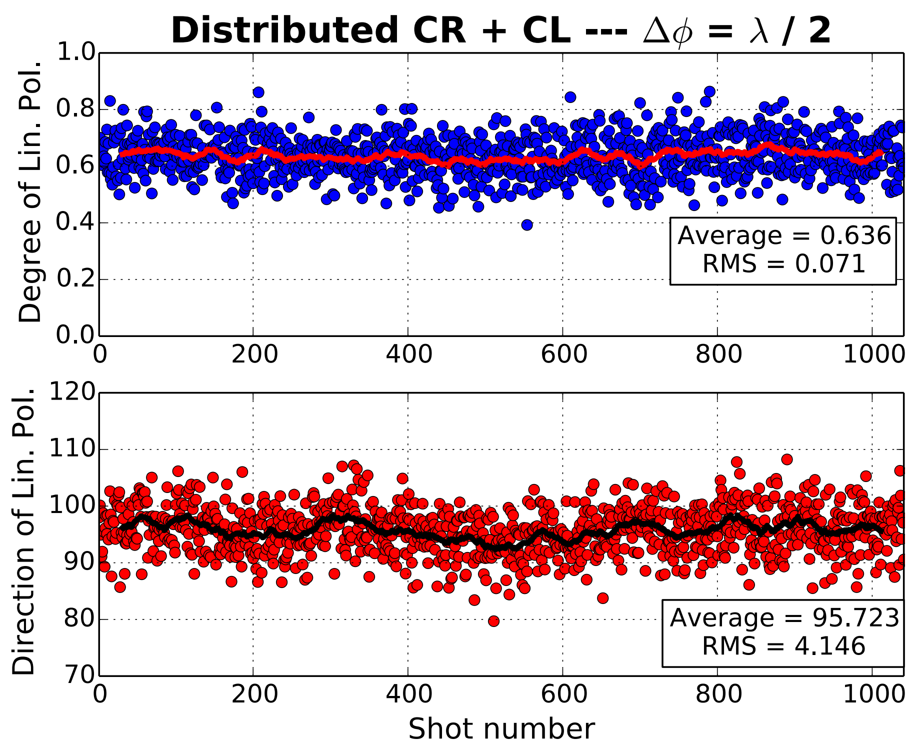


Polarization control in the distributed scheme



The phase shift scheme is **alternated** in order to retain the right phasing between successive CL and CR undulators.





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Future activities

Investigate the possibility of installing an electromagnetic phase shifter to achieve **fast polarization switching**.

Measure the polarization degree as function of the **collection aperture** of the polarimeter.

Study how to **further improve** the output polarization degree beyond the distributed undulator scheme.

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Summary

- Crossed polarized scheme has been **demonstrated** on a **seeded high gain FEL** in the VUV, with a degree of linear polarization > 65%.

- A simple toy model has been studied in order to better **understand** the obtained results

- A **distributed crossed polarized** undulator scheme enables **a significant increase** of the degree of polarization of the output radiation (~ 80%)

- **Full polarization control,** in direction and type of polarization, is possible in all the presented schemes

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

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Thanks for the attention!