Polarization Control of Storage Ring FELs Using Cross Polarized Helical Undulators

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Acknowledgment:

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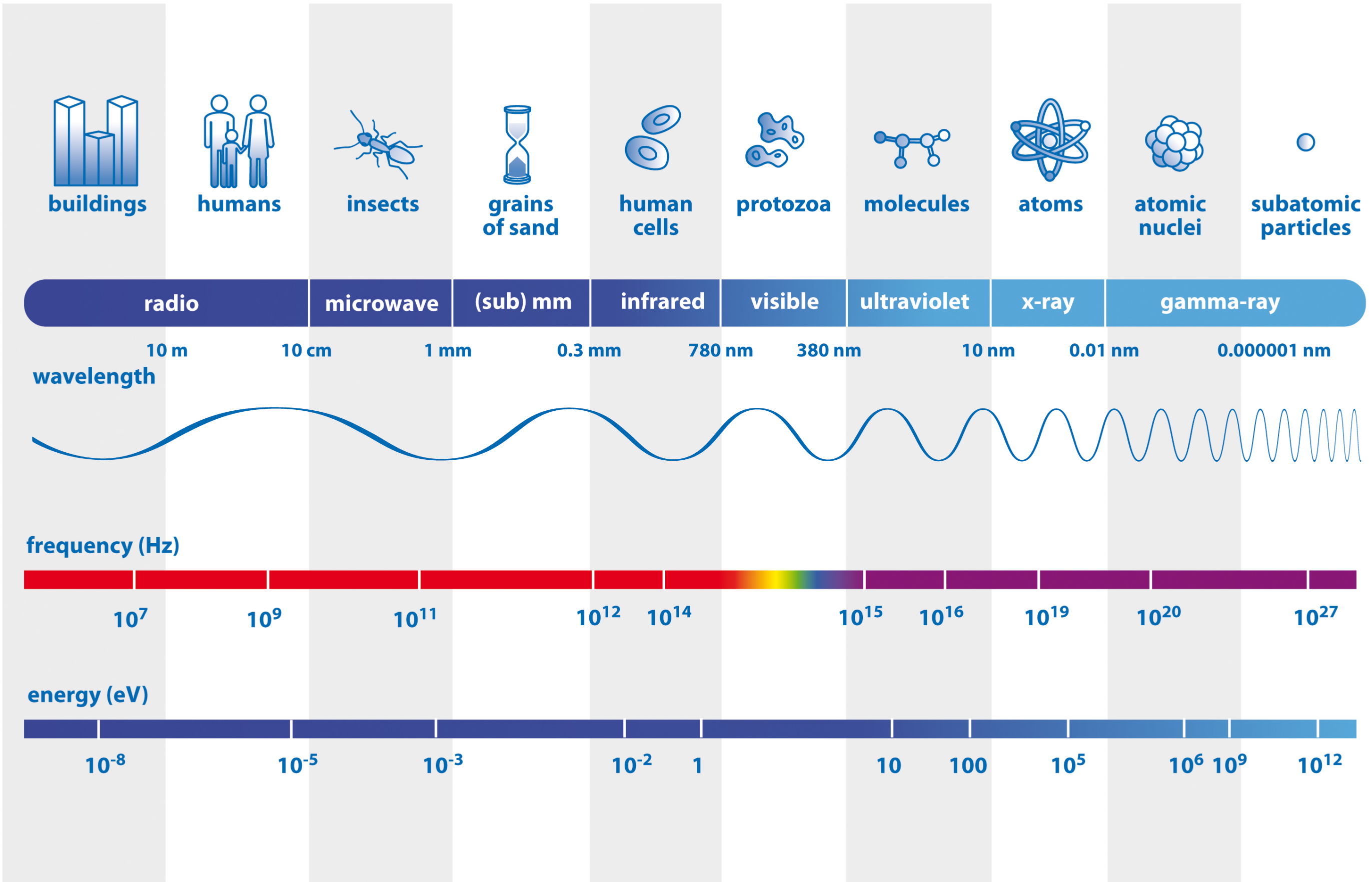
Outline

- **Introduction**
  - **Development of FEL Polarization Control**
  - **Duke Storage Ring FEL: Configurations with multiple undulators**
- **Controlling FEL Polarization at Duke**
  - **Helicity switching of circularly polarized FEL beams**
  - **Precision measurement of linear polarization**
  - **Generation of linearly polarized FEL beams using crossed helical undulators**
- **Controlling Compton γ-ray Polarization at HIγS**

Short wavelength: x-ray FELs



Soft x-ray

FLASH

FERMI

SXFEL

Hard x-ray

LCLS SACLA

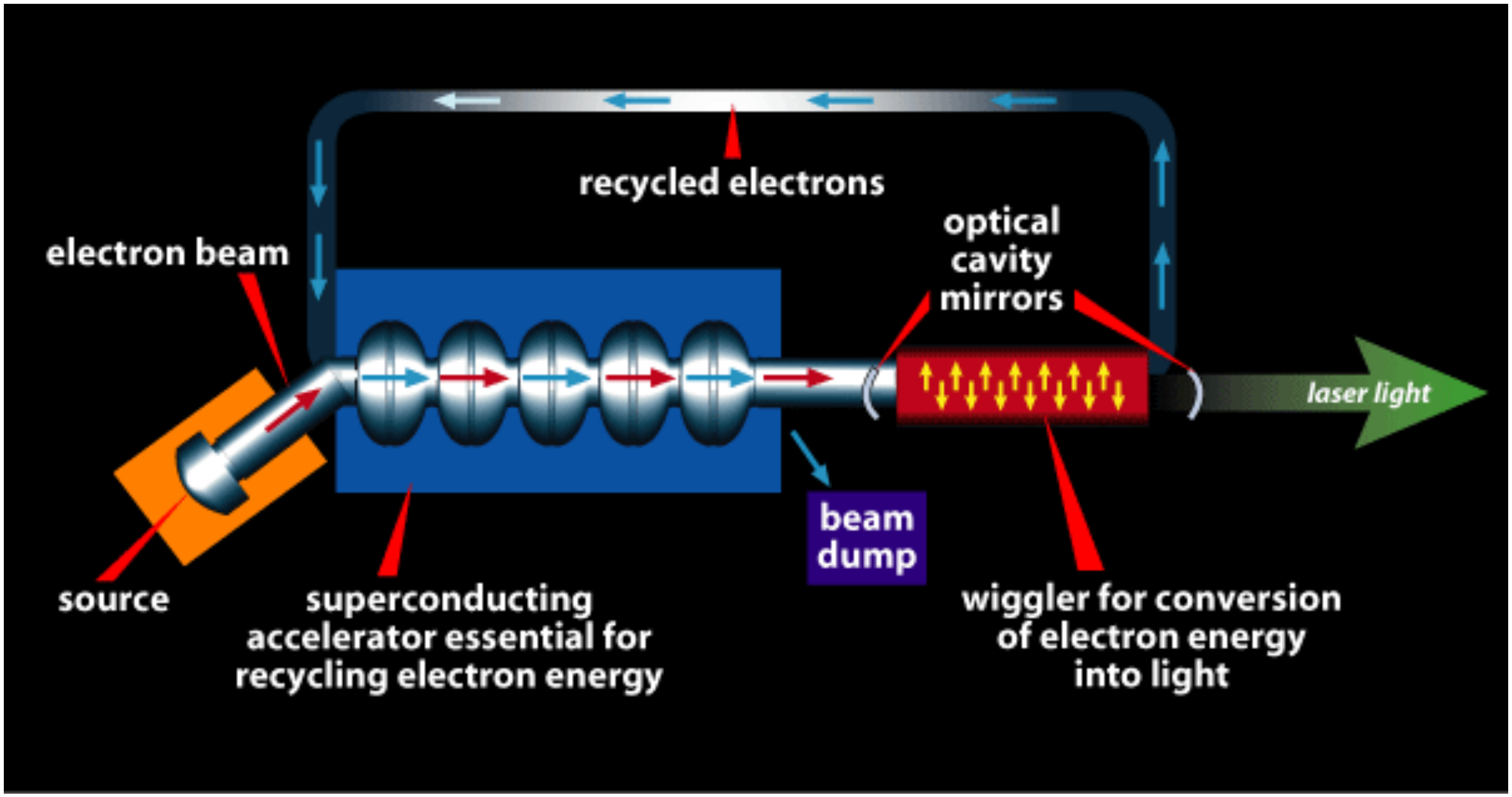
PAL-XFEL European XFEL

SWISSFEL

http://solar-center.stanford.edu/about/electromagneticspectrum.jpg

High Extracted Power (Average)

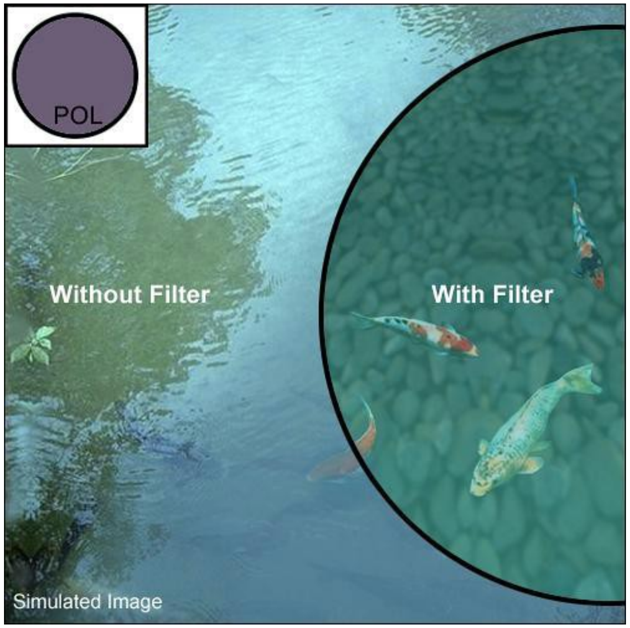
Jlab IR FEL: 14.2 kW cw power at $\lambda = 1.6\ \mu m$



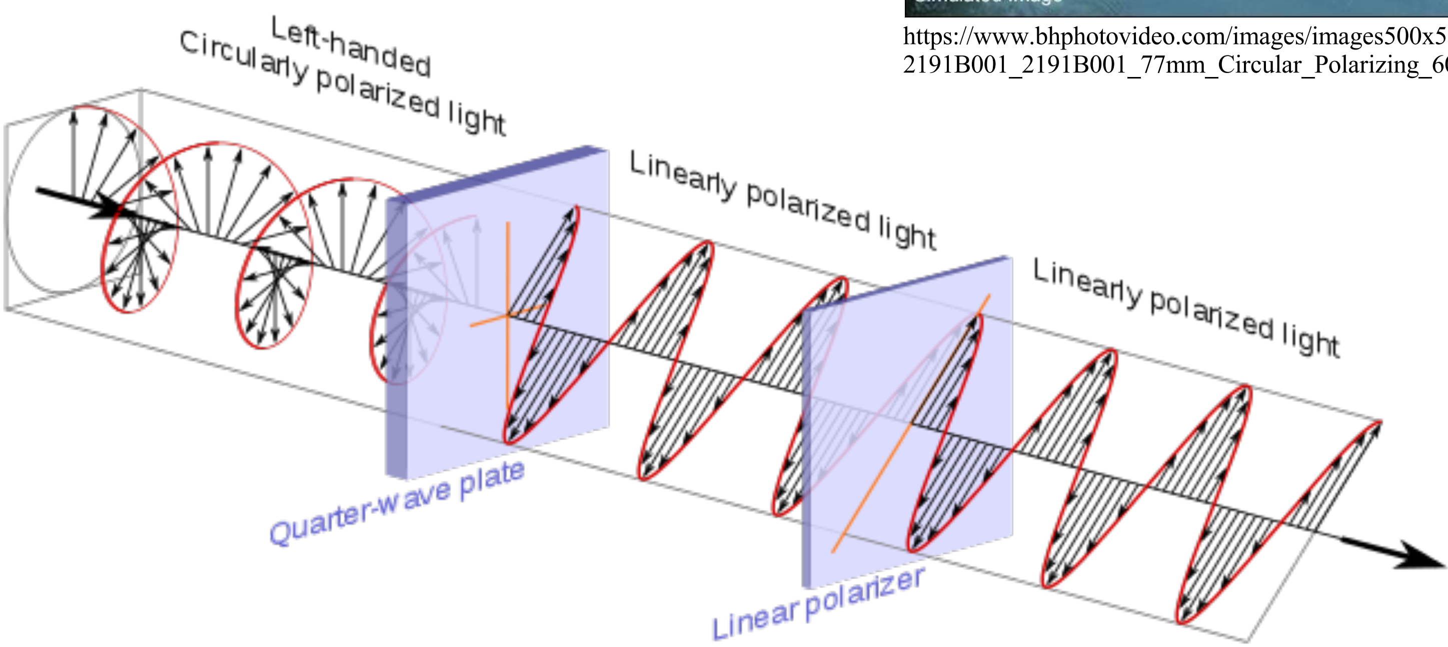
https://www.jlab.org/FEL/images/FELdiagram.gif

Polarization of Light

https://contactsadvice.com/wp-content/uploads/2015/12/PolariodSunglasses.jpg



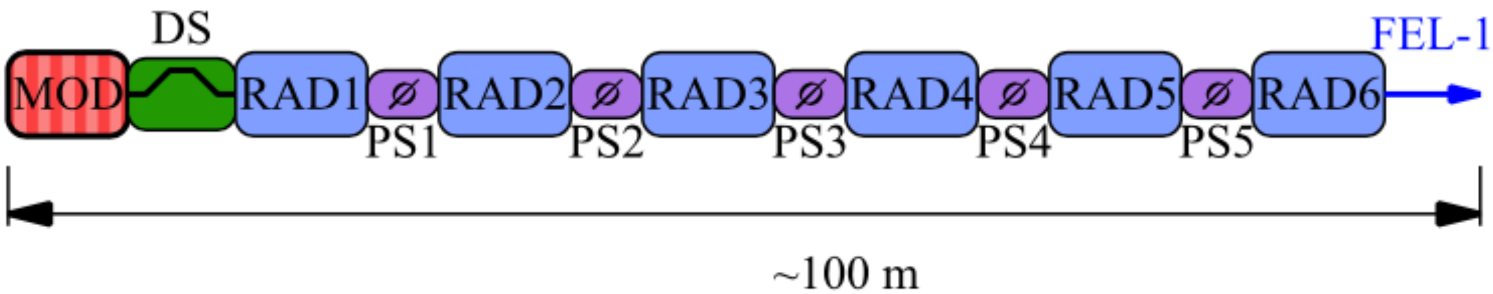
https://www.bhphotovideo.com/images/images500x500/Canon_2191B001_2191B001_77mm_Circular_Polarizing_606825.jpg



http://solar-center.stanford.edu/about/electromagneticspectrum.jpg

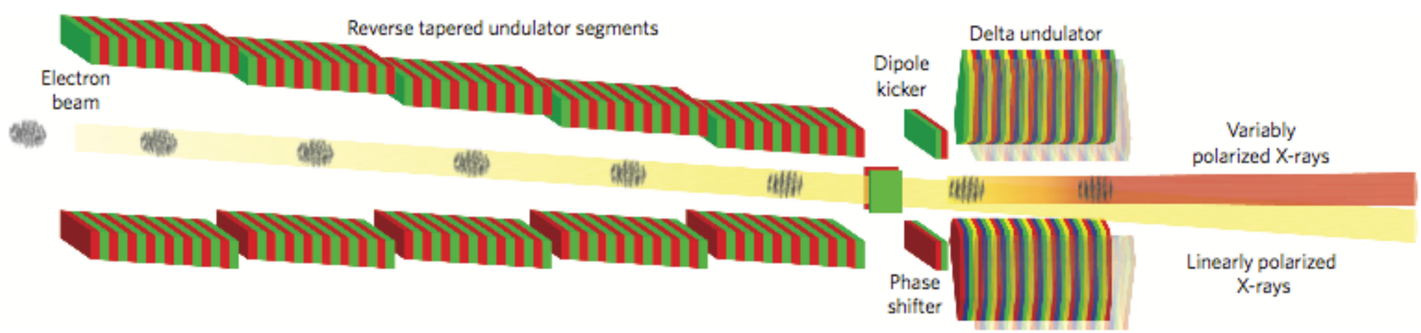
FEL with Variable Polarization (Variable-Pol Undulators)

FERMI: Apple Undulators



E. Allaria *et al*., Phys. Rev. X 4, 041040 (2014).

LCLS: Delta Undulator

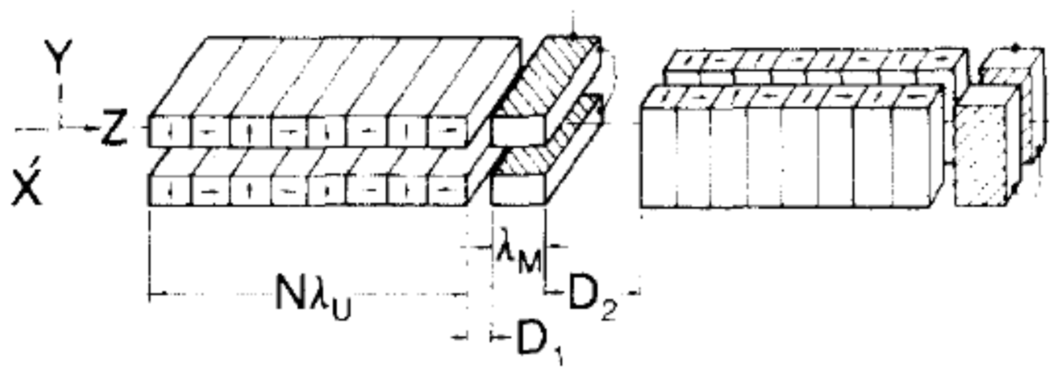


A.A.Lutmanetal.,Nat.Photon.**10**,468(2016).
E. A. Schneidmiller and M. V. Yurkov, Phys. Rev. ST AB 16, 110702 (2013).

FEL Polarization Control Using Fixed-Pol Undulators

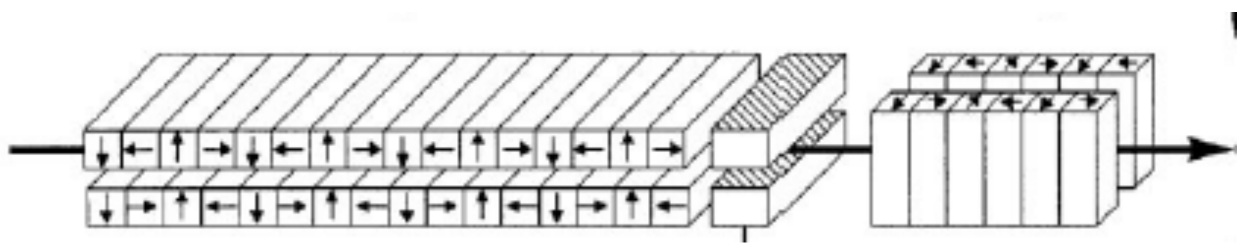
Crossed Undulators

Undulator Radiation:
(Crossed Planar Undulators)



K.J. Kim *Nucl. Instr. Meth. A*, vol. 219, p. 425, 1984.

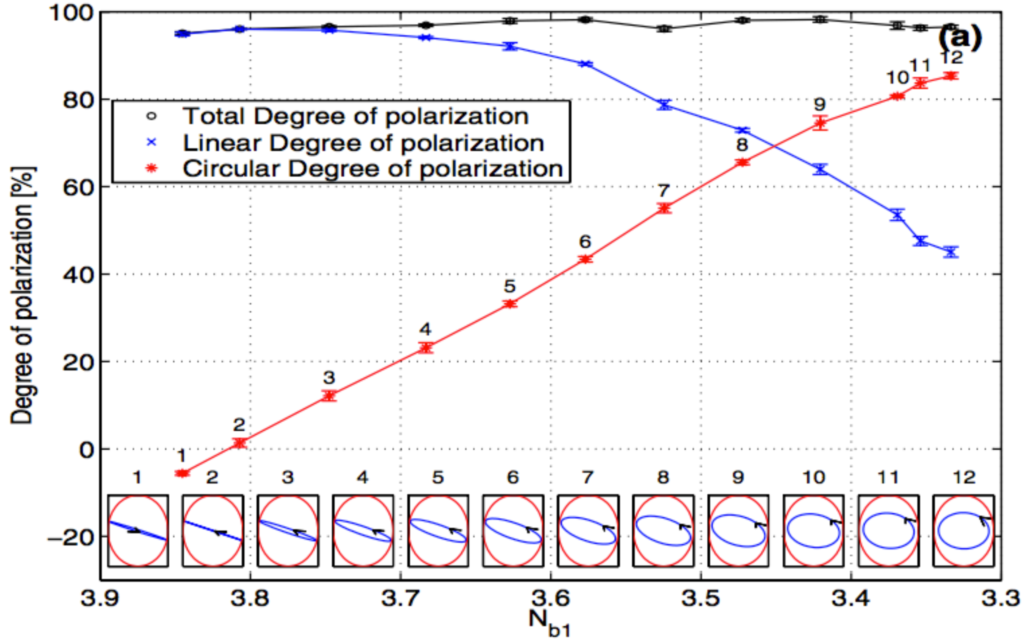
FEL:
(Crossed Planar Undulators)



K.J. Kim *Nucl. Instr. Meth. A*, vol. 445, p. 329, 2000.

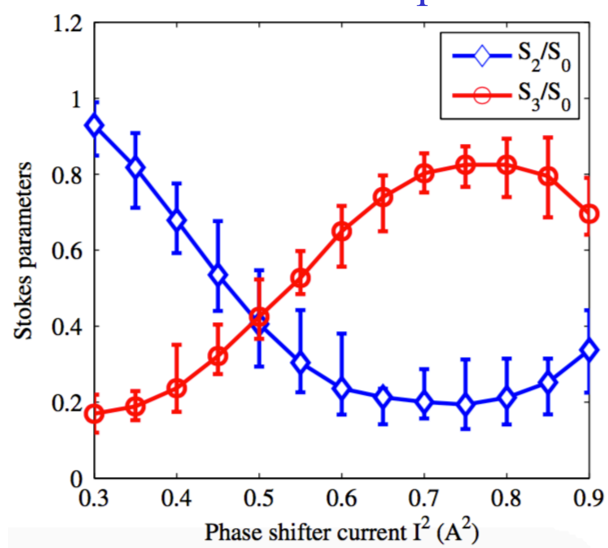
Experimental Demonstration

Duke DOK-1: two planar undulators + two helical undulators



Y. K. Wu *et al*., Phys. Rev. Lett. 96, 224801 (2006).

SDUV seeded FEL: Crossed planar undulators



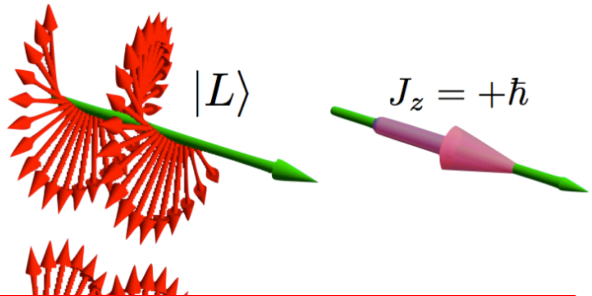
H. Deng *et al.,* Phys. Rev. ST Accel. Beams 17, 020704 (2014).

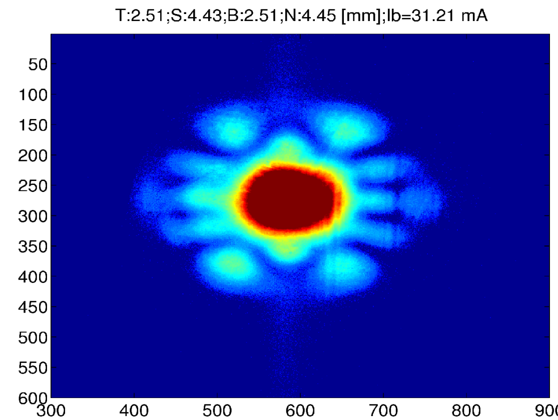
Helical Undulators and Storage Ring FELs

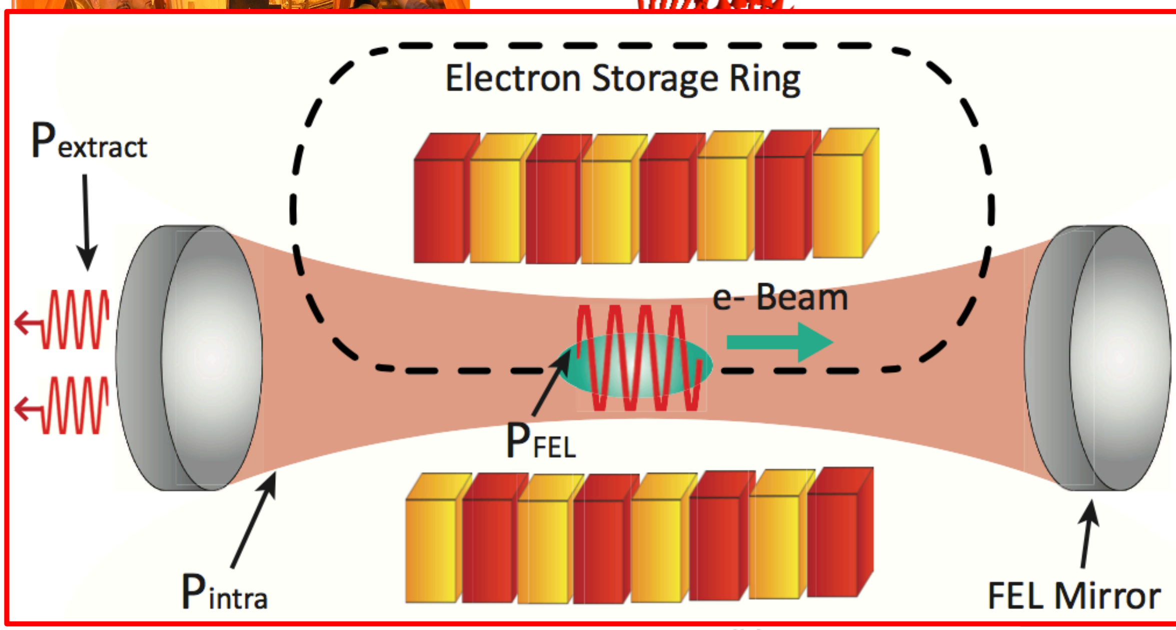
Spin eigenstate of light

Reduce on-axis heat load

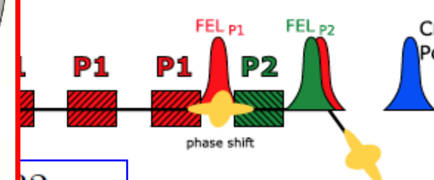
Duke OK-5 Helical Undulator





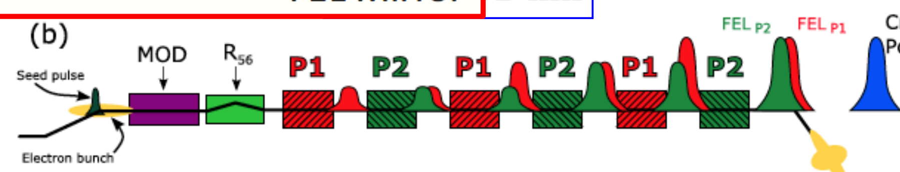


Undulators (Single-pass FEL):



$P_{\rm lin} \sim 0.7$

2 nm



$P_{\rm lin} \sim 0.8$

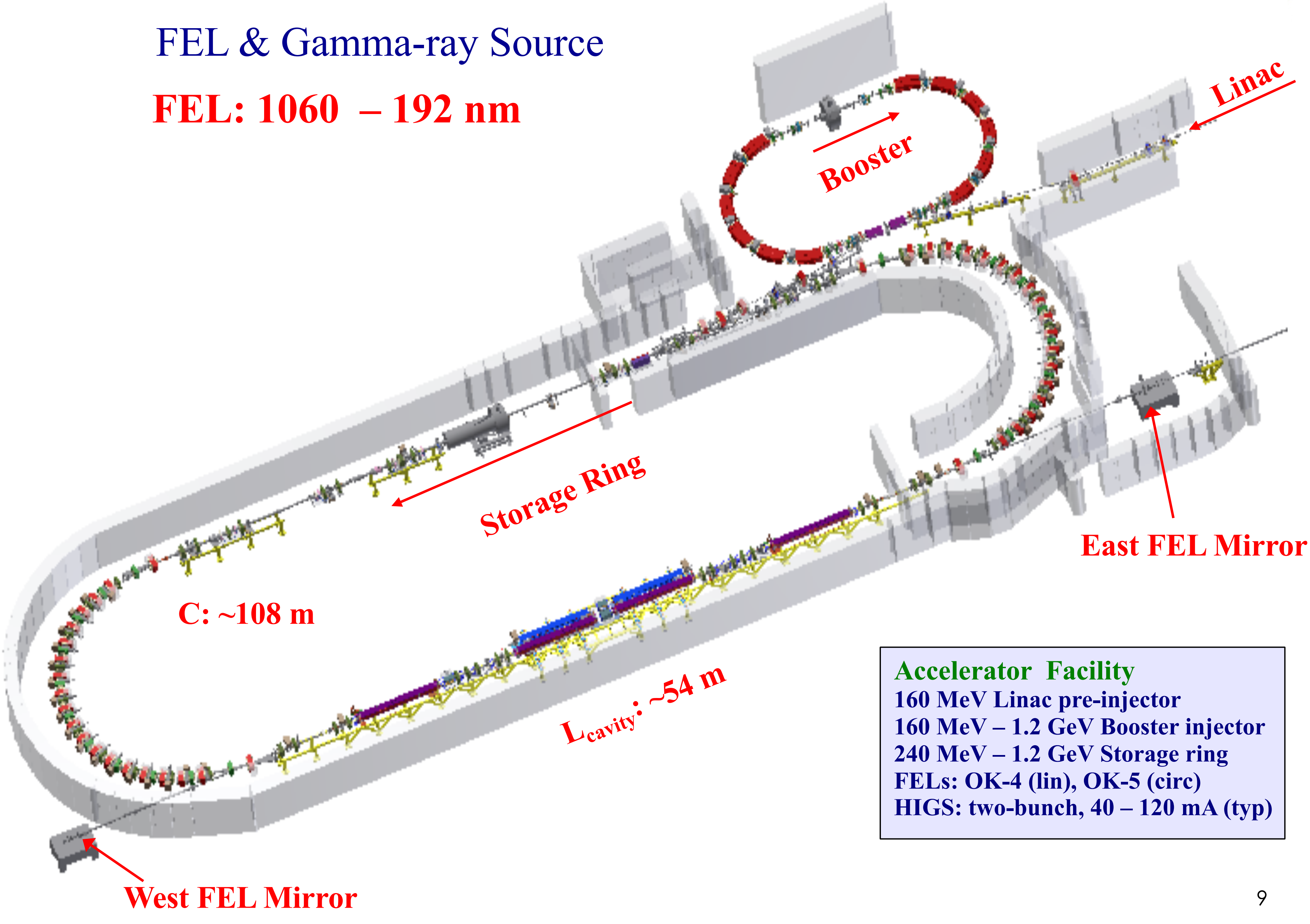
Multi-pass Storage Ring FEL

E. Ferrari *et al.* *Sci. Rep.*, vol. 5, p. 13531, 2015.

Duke

FEL & Gamma-ray Source

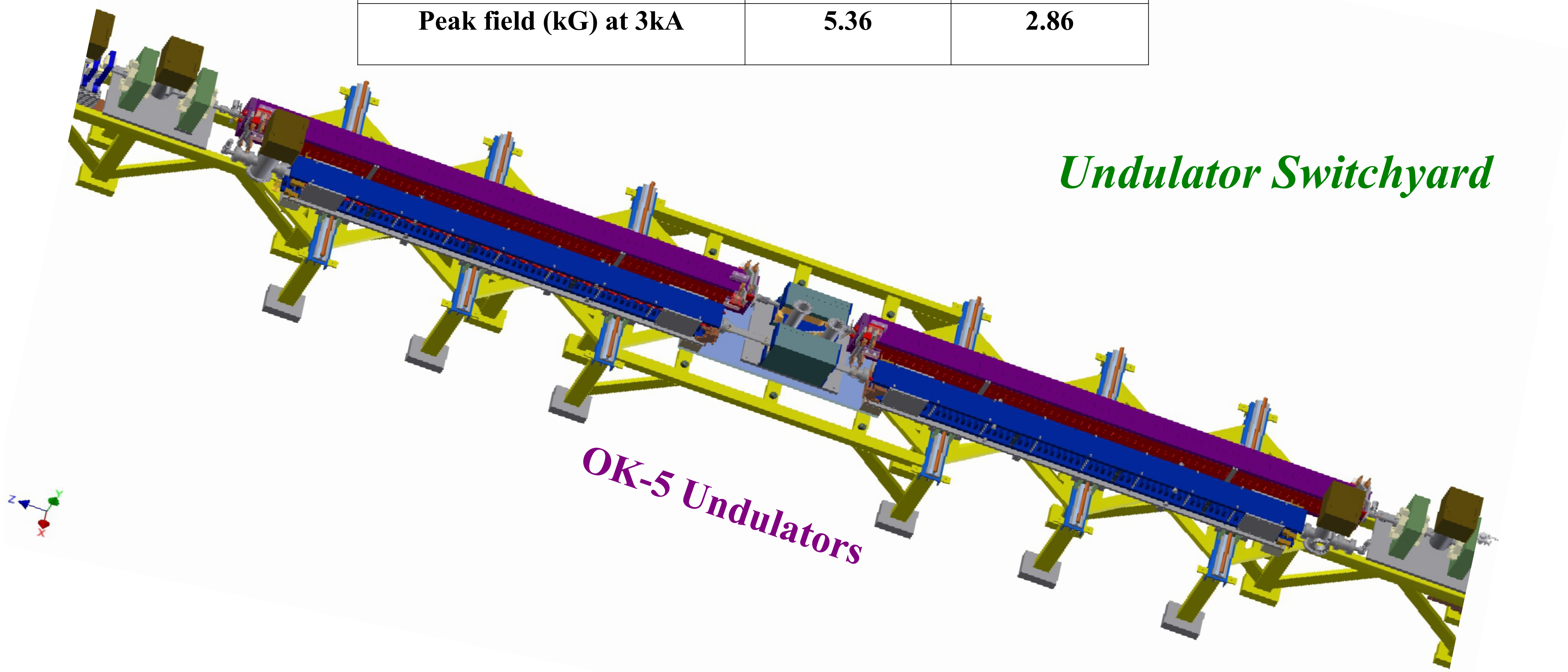
FEL: 1060 – 192 nm



Accelerator Facility
160 MeV Linac pre-injector
160 MeV – 1.2 GeV Booster injector
240 MeV – 1.2 GeV Storage ring
FELs: OK-4 (lin), OK-5 (circ)
HIGS: two-bunch, 40 – 120 mA (typ)

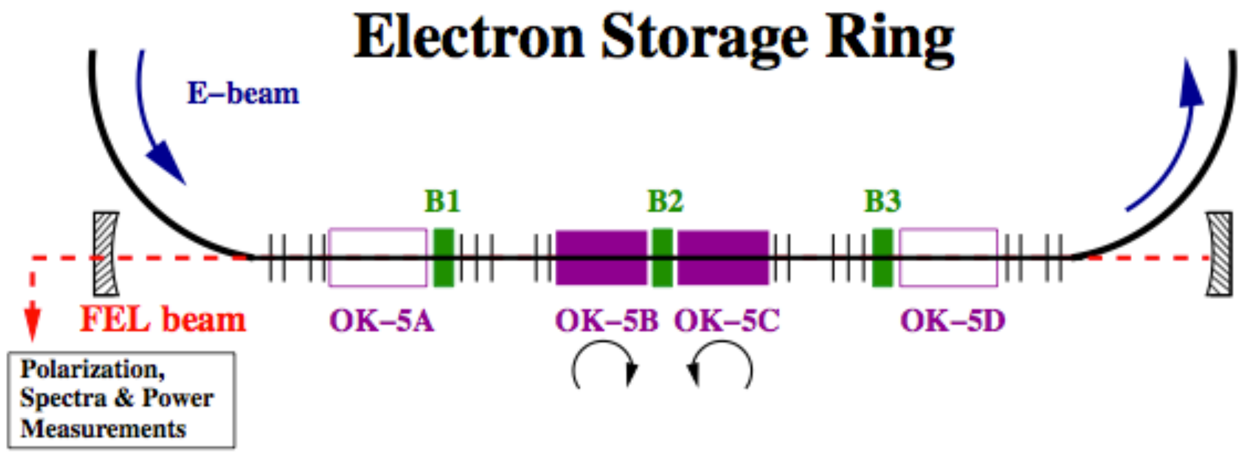
Switchyard for OK-4 and OK-5 Undulators

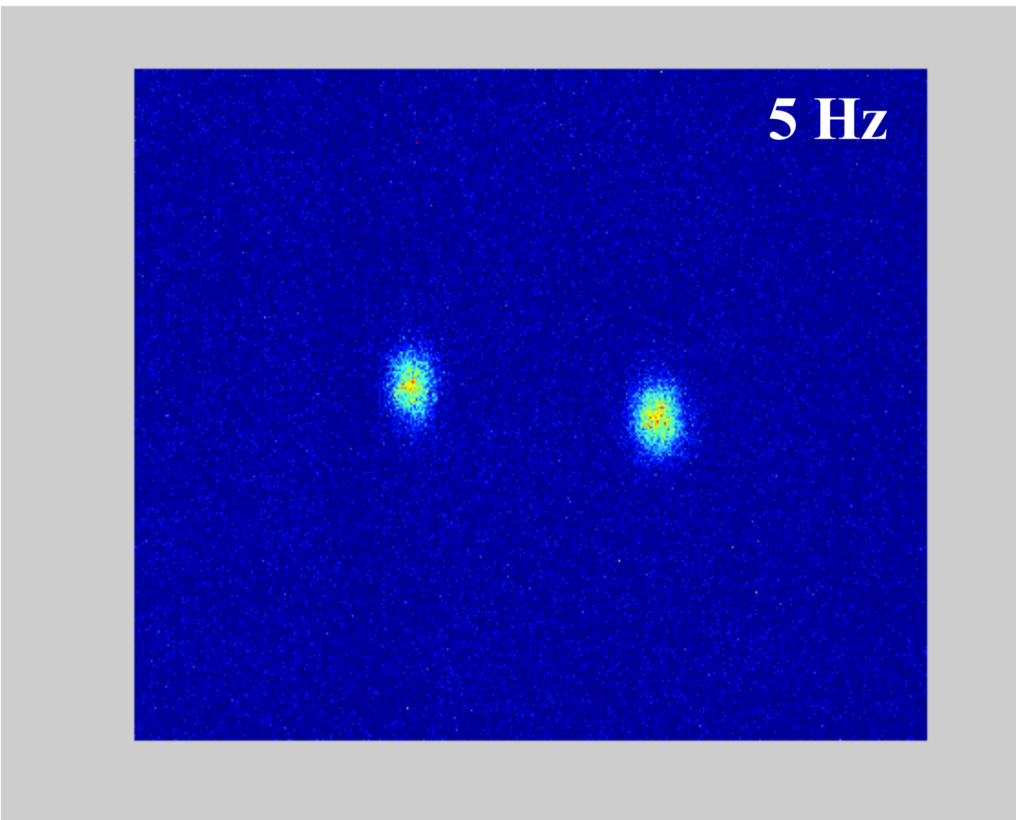
	OK-4	OK-5
Polarization	Linear	Circular
No. of reg. period	33	30
Undulator period (cm)	10	12
Peak field (kG) at 3kA	5.36	2.86

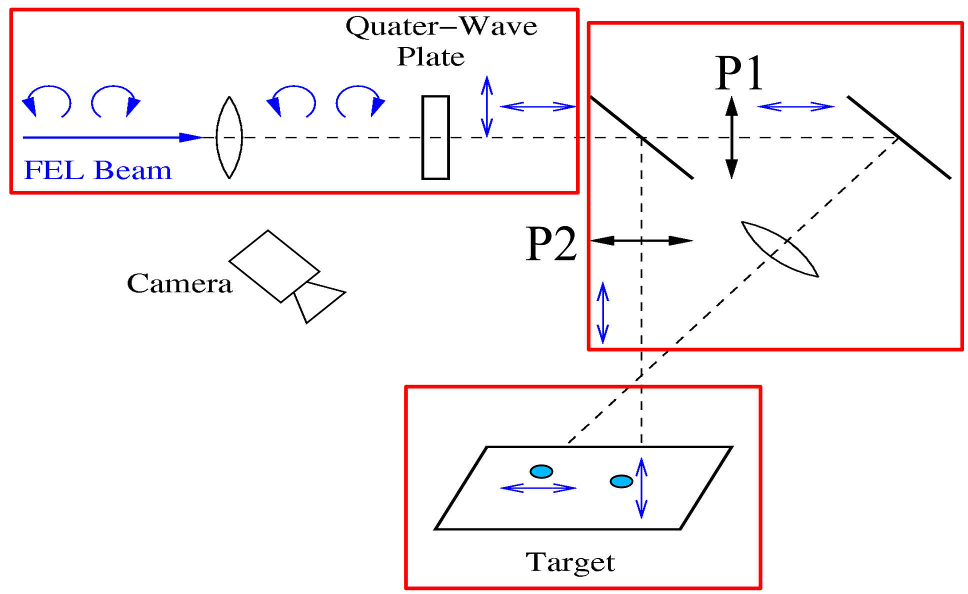


- Polarization Control (Partial): Phys. Rev. Lett. 96, 224801 (2006).
- Two-Color Operation: Phys. Rev. Lett. 115, 184801 (2015).

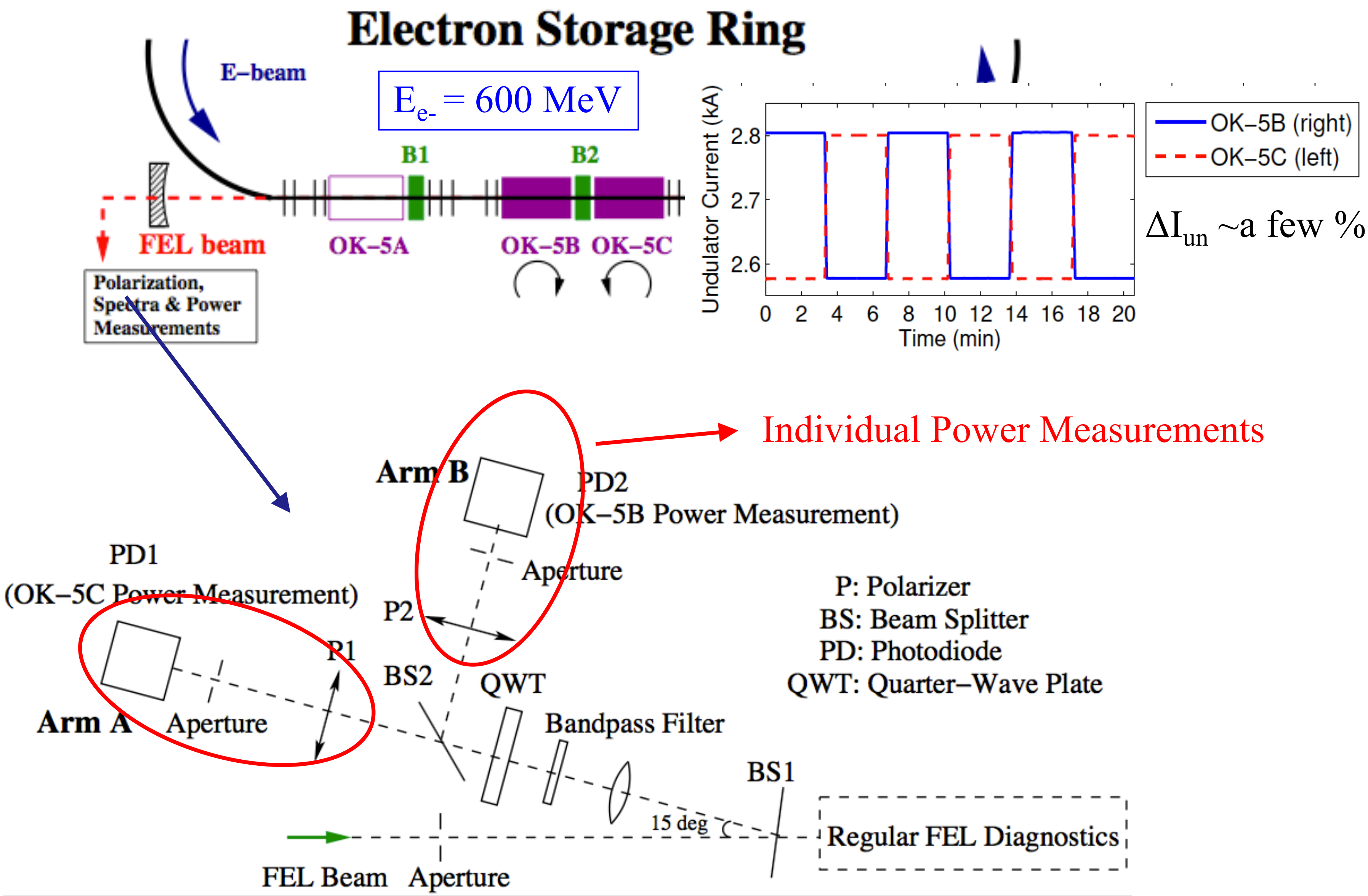
Helicity Switching



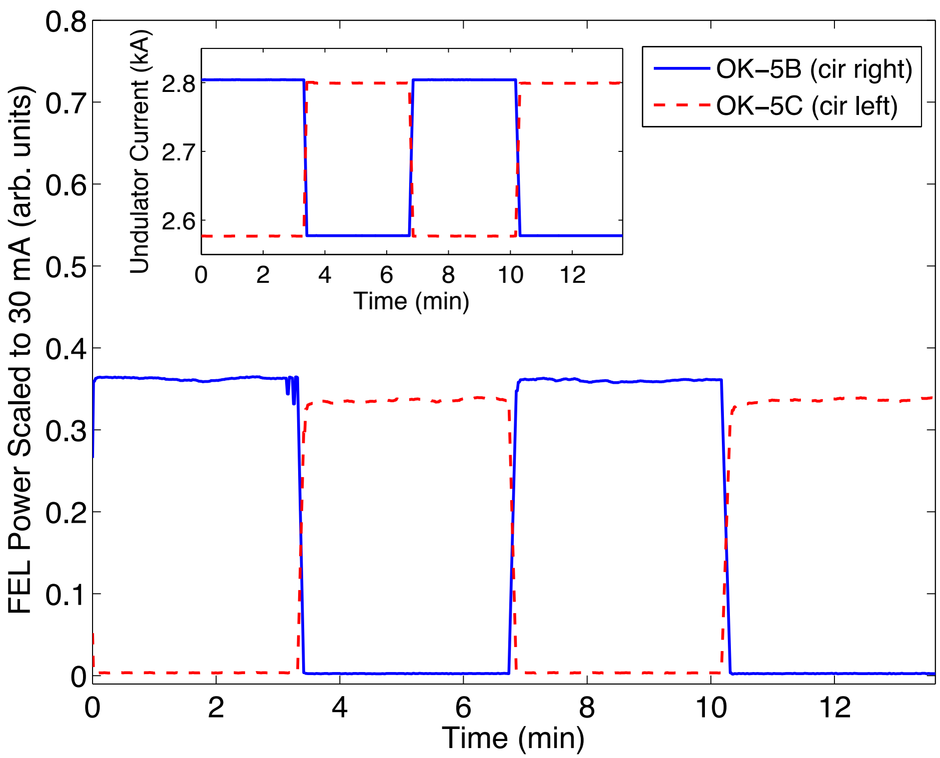


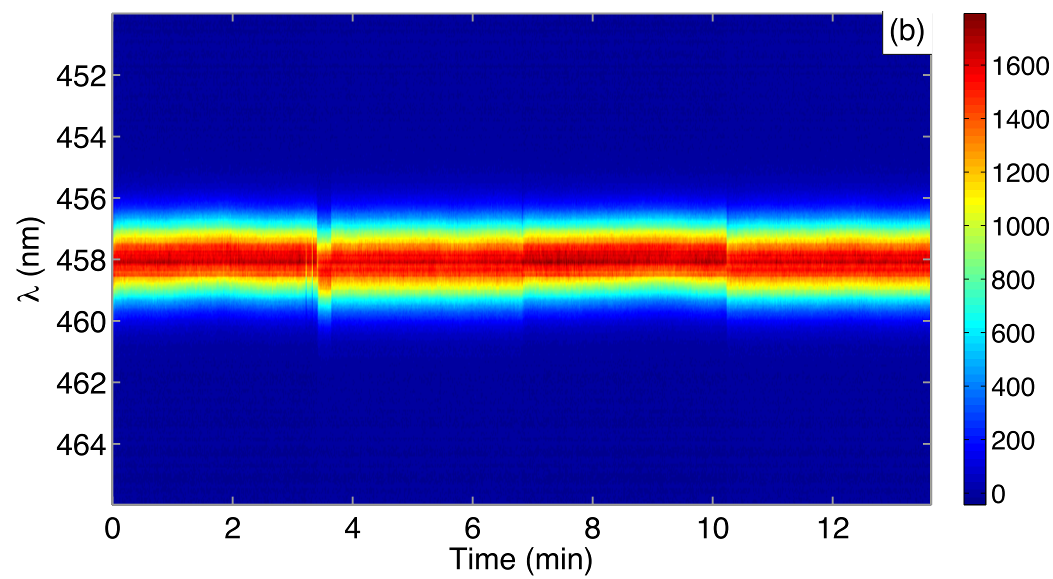


Helicity Switching (Undulator Config. & Optics)



Helicity Switching (2.5 mHz)





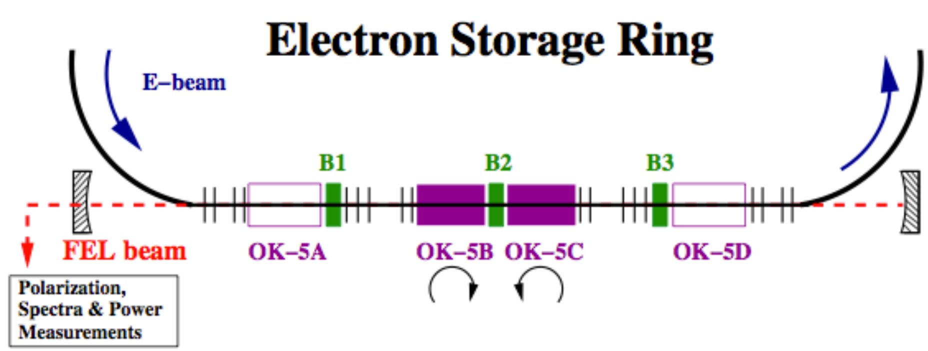
$$\lambda_{\mathrm{FEL}} = 458.06 \pm 0.07\ \mathrm{nm}$$

$$\sigma_{\lambda_{\mathrm{FEL}}} = 0.89 \pm 0.02\ \mathrm{nm}$$

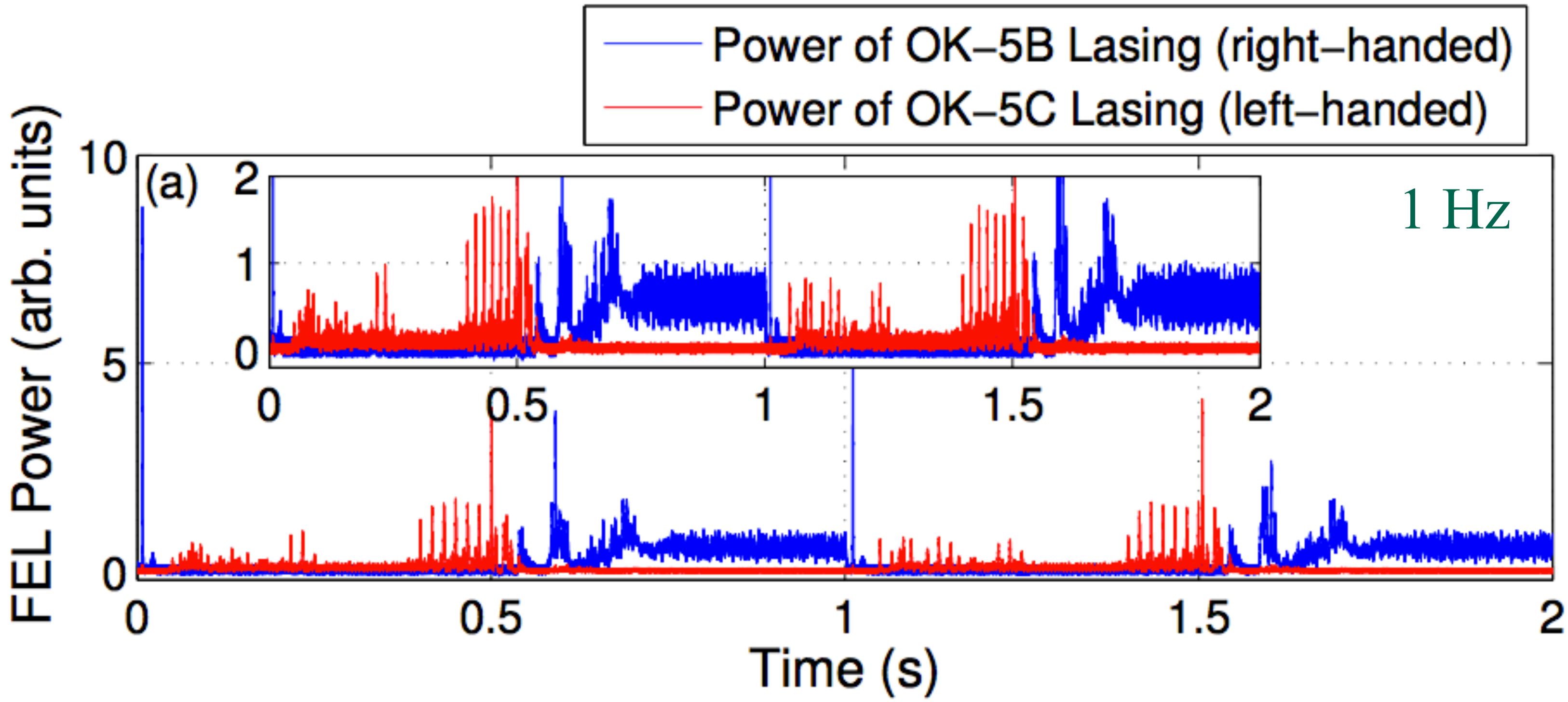
$\Delta I_{un} \sim 8\ \%$

$\sigma_P(\text{OK-5B}) = 0.5\%$

$\sigma_P(\text{OK-5C}) = 0.6\%$



Helicity Switching (Fast Switching)



Electron beam energy damping

600 MeV => $\tau_d \approx 40$ ms

Reasonably stable lasing

→ no faster than ~ 2 - 3 Hz

Polarization Ellipse and Stokes Parameters

Monochromatic wave:

$$E_x = E_{x0}\cos(\omega t - kz),$$
$$E_y = E_{y0}\cos(\omega t - kz + \delta),$$

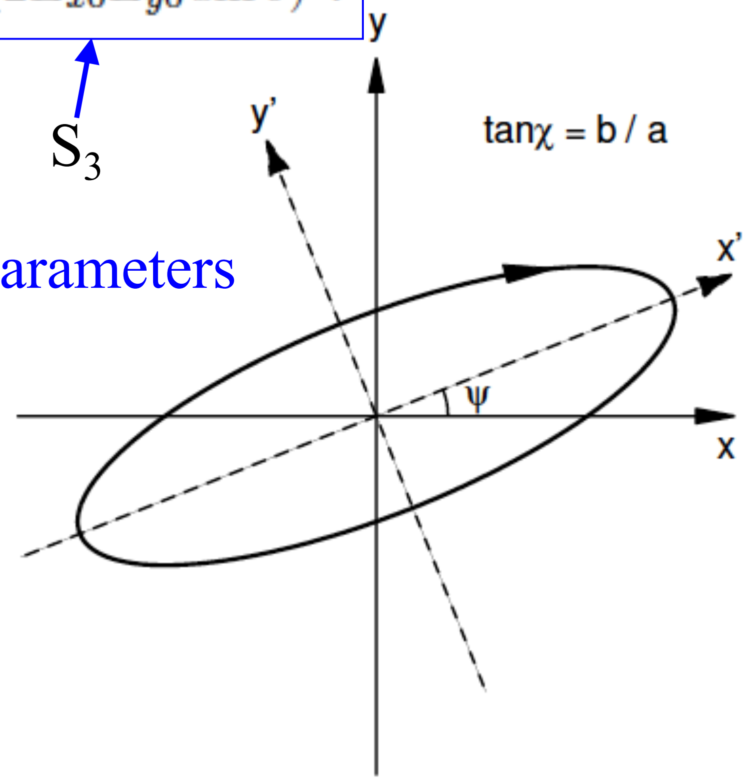
$$\left(\frac{E_x}{E_{x0}}\right)^2 + \left(\frac{E_y}{E_{y0}}\right)^2 - 2\cos\delta\frac{E_x E_y}{E_{0x}E_{0y}} = \sin^2\delta.$$

$$(E_{x0}^2 + E_{y0}^2)^2 - (E_{x0}^2 - E_{y0}^2)^2 - (2E_{x0}E_{y0}\cos\delta)^2 = (2E_{x0}E_{y0}\sin\delta)^2.$$

S_0 S_1 S_2 S_3

$$\vec{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} I(0^\circ) + I(90^\circ) \\ I(0^\circ) - I(90^\circ) \\ I(45^\circ) - I(135^\circ) \\ I(\mathrm{Cir_{right}}) - I(\mathrm{Cir_{left}}) \end{pmatrix}$$

Stokes parameters



$S_1^2 + S_2^2 + S_3^2 = S_0^2$: Completely Polarized

$S_1^2 + S_2^2 + S_3^2 = 0$: Unpolarized

$0 < S_1^2 + S_2^2 + S_3^2 < S_0^2$: Partially Polarized

$$P = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0}$$

Degree of Polarization

Polarizing Optics (Mueller Matrix)

$$\vec{S}^{(o)} = M\vec{S}^{(i)}$$

(1) Polarizer

$$E_x^{(o)} = t_x E_x^{(i)},$$

$$E_y^{(o)} = t_y E_y^{(i)}, \qquad 0 \leqslant t_y \ll t_x \leqslant 1,$$

t_x^2/t_y^2 : Extinction Ratio

$$M_P = \frac{1}{2}\begin{pmatrix} t_x^2+t_y^2 & t_x^2-t_y^2 & 0 & 0 \\ t_x^2-t_y^2 & t_x^2+t_y^2 & 0 & 0 \\ 0 & 0 & 2t_xt_y & 0 \\ 0 & 0 & 0 & 2t_xt_y \end{pmatrix}.$$

(2) Quarter-Wave Plate (ideal)

$$E_x^{(o)} = E_x^{(i)} e^{i\phi/2},$$

$$E_y^{(o)} = E_x^{(i)} e^{-i\phi/2}, \qquad (\phi = \frac{\pi}{2})$$

$$M_{QWP} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix}.$$

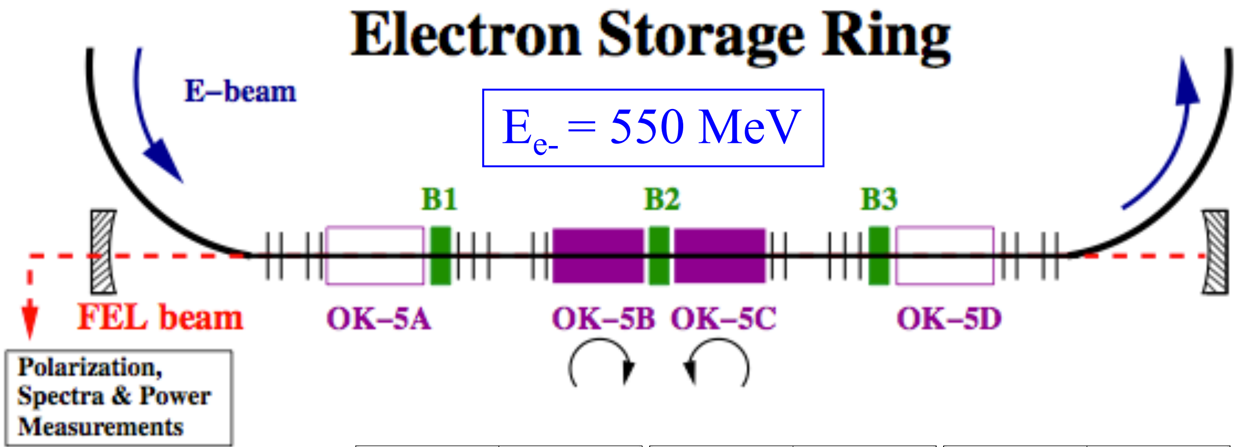
(3) Rotated Polarizing Optics

$$M_P(\theta) = M_R(-\theta) M_P M_R(\theta),$$

$$M_{QWP}(\theta) = M_R(-\theta) M_{QWP} M_R(\theta),$$

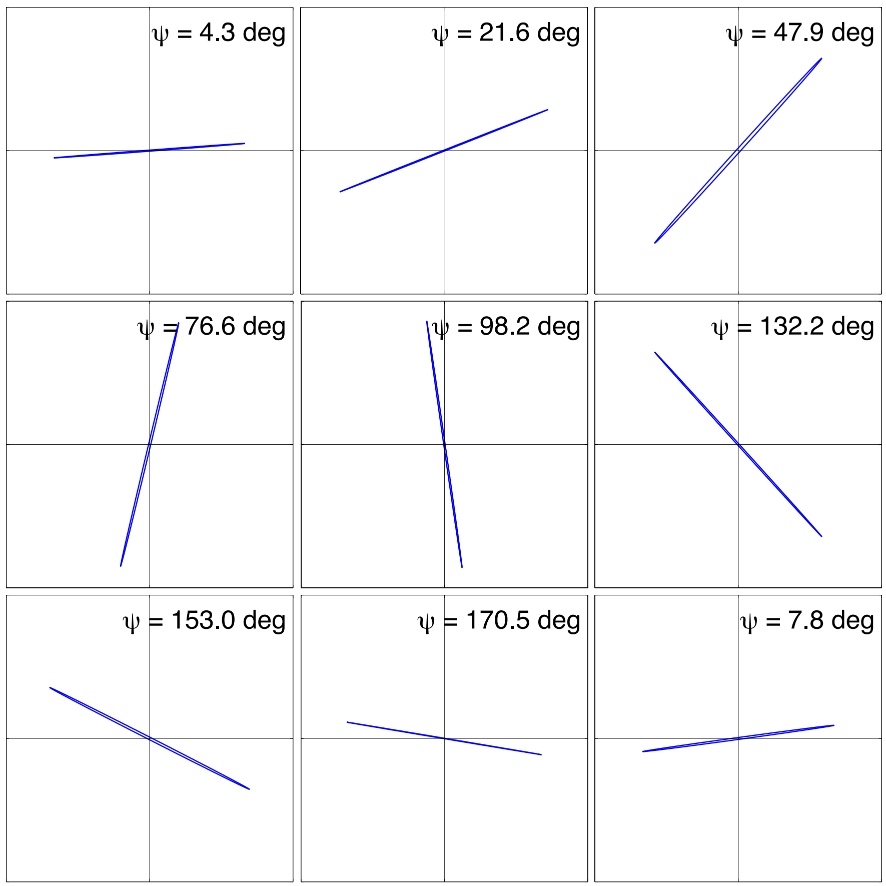
$$M_R(\theta) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(2\theta) & \sin(2\theta) & 0 \\ 0 & -\sin(2\theta) & \cos(2\theta) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Generation of Linearly Polarized FEL Beams

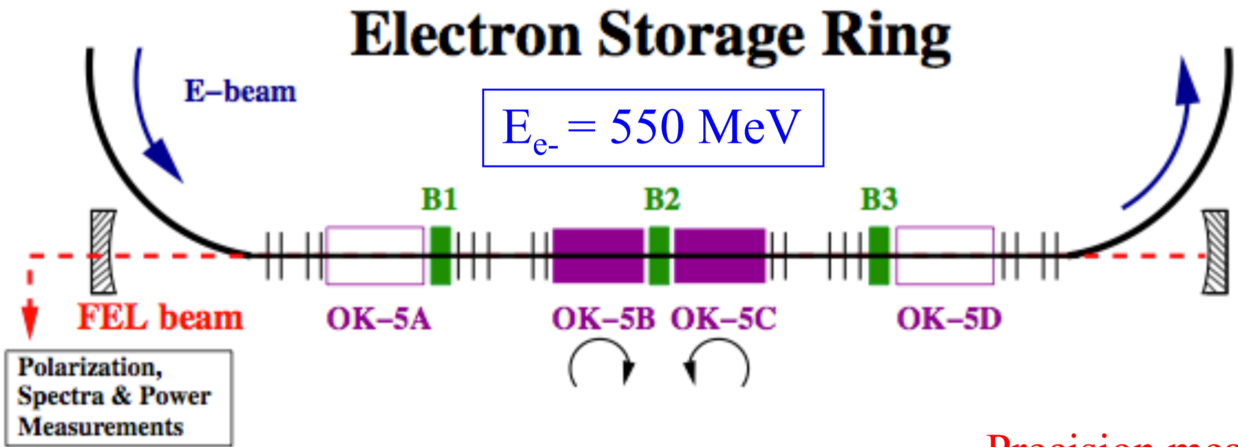


Non-optical

Measured Pol Ellipse

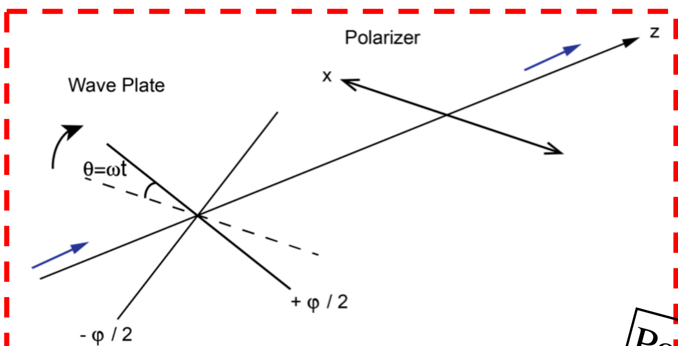


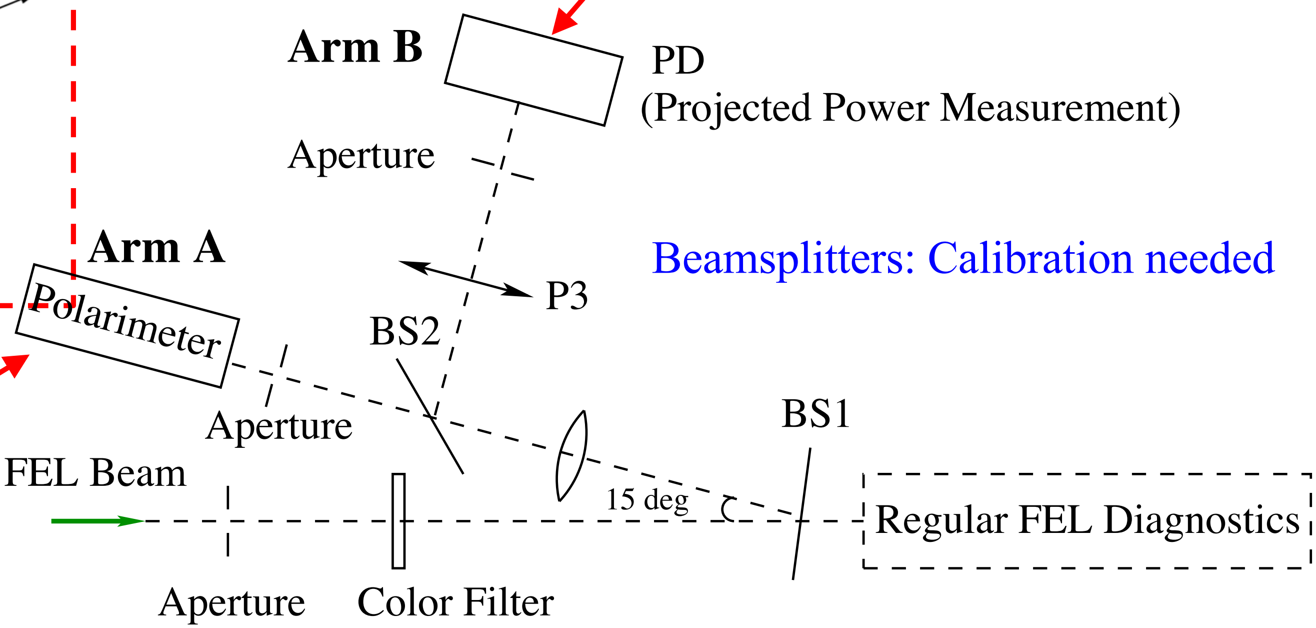
Linear Polarization (Undulator Config. & Pol Meas)



Non-optical

Precision measurement





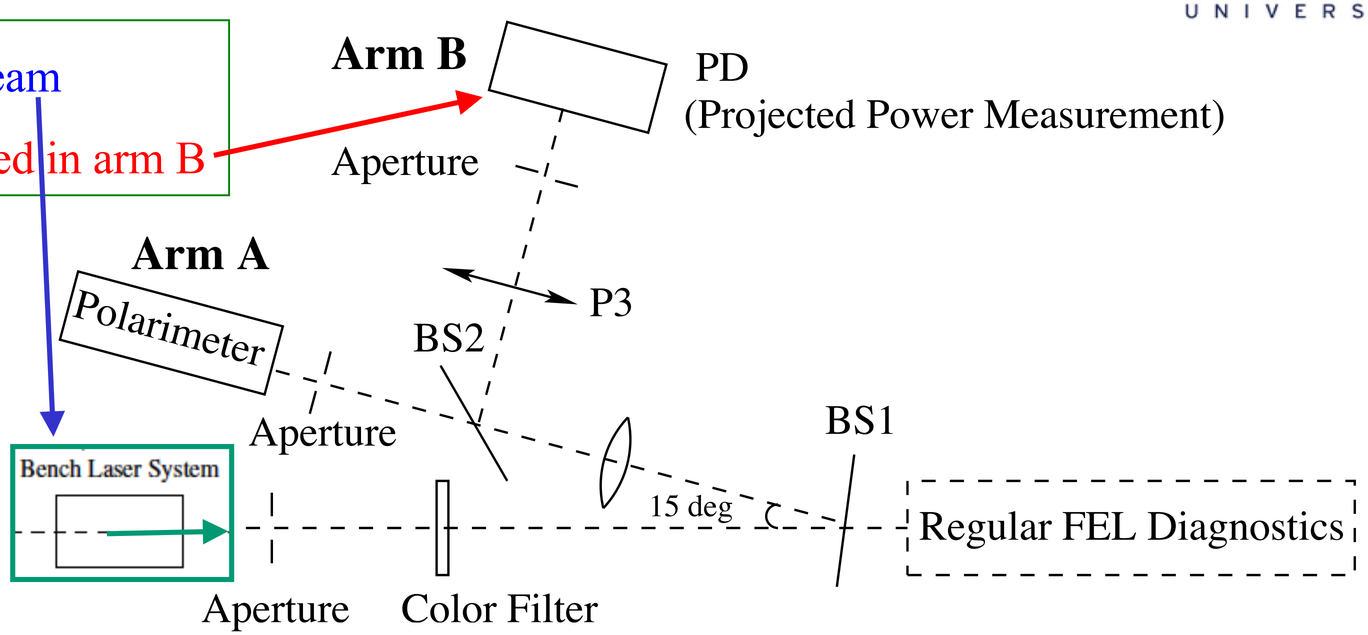
Beamsplitters: Calibration needed

Rotating quarter-wave plate

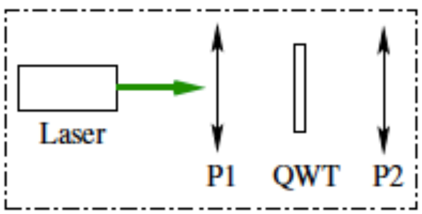
Calibration of Measured Polarization Direction

θ_1: Main beam

θ_2: Measured in arm B



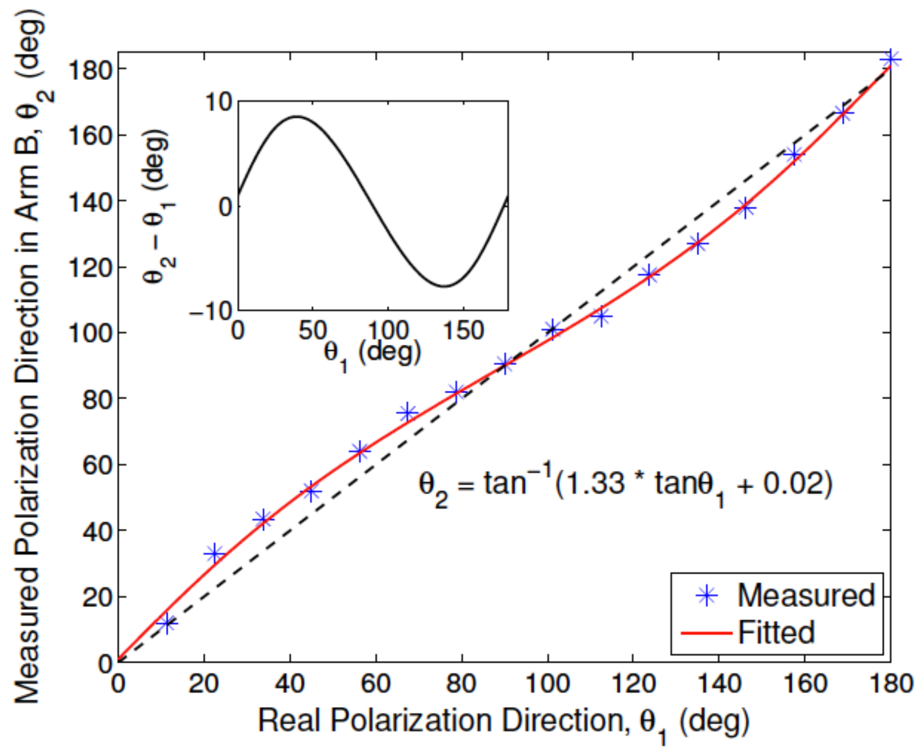
Bench Laser System



$$E_{2x} = p_x E_{1x},$$

$$E_{2y} = p_y E_{1y},$$

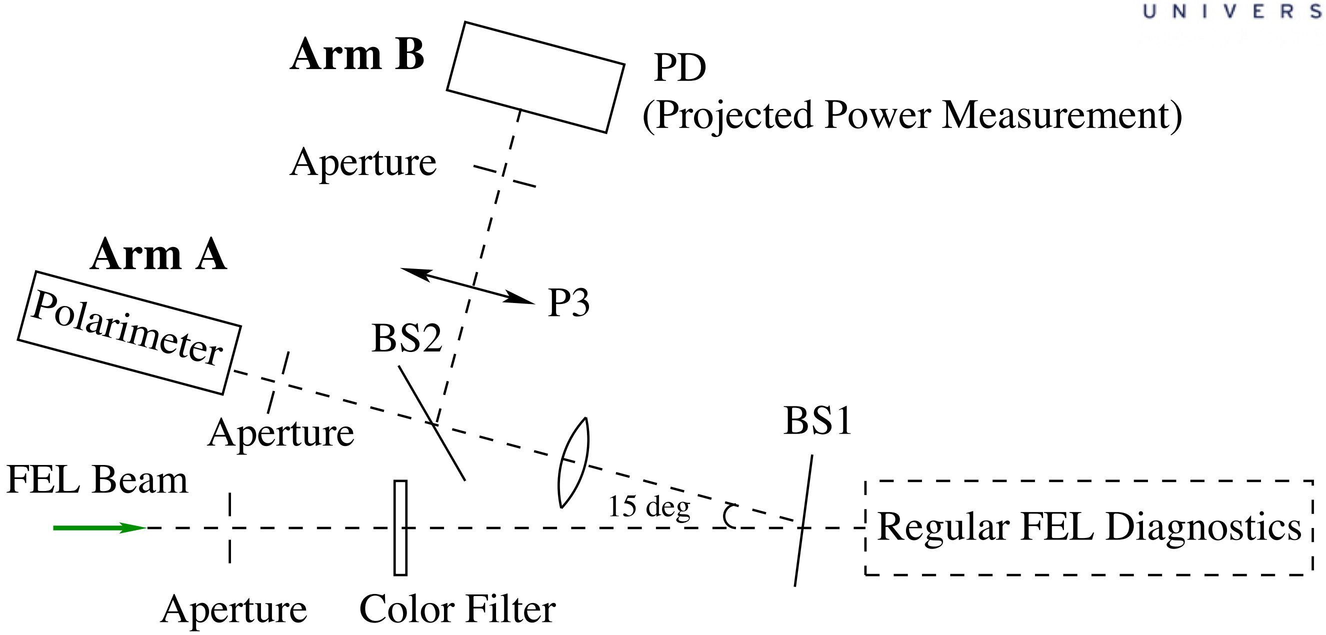
$$\tan\theta_2 = \frac{p_y}{p_x}\tan\theta_1 .$$



Calibration of Measured Degree of Linear Polarization

$S^{(1)}$: Main beam

$S^{(2)}$: Measured in arm B



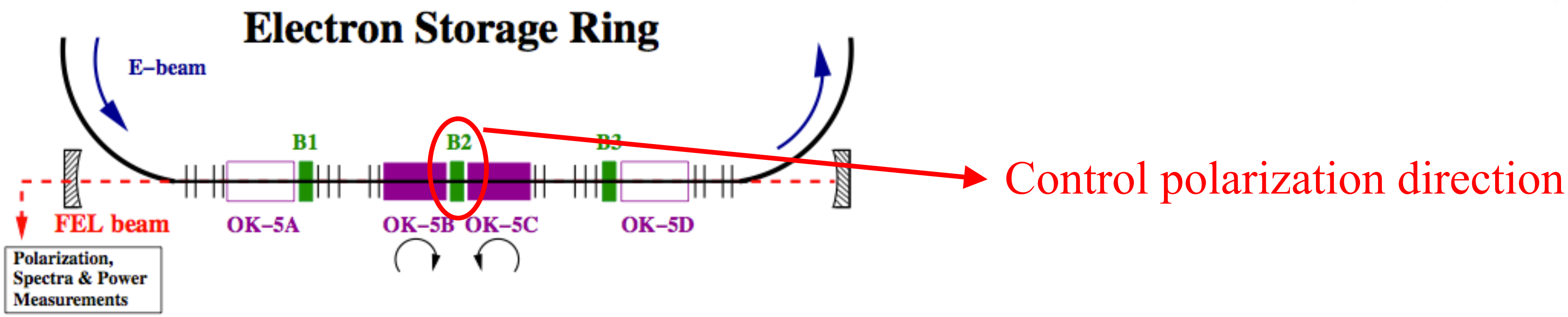
$$\begin{aligned} S_0^{(2)} &= 1, \\ S_1^{(2)} &= \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}, \\ S_2^{(2)} &= 0, \\ S_3^{(2)} &= \text{unknown} \end{aligned}$$

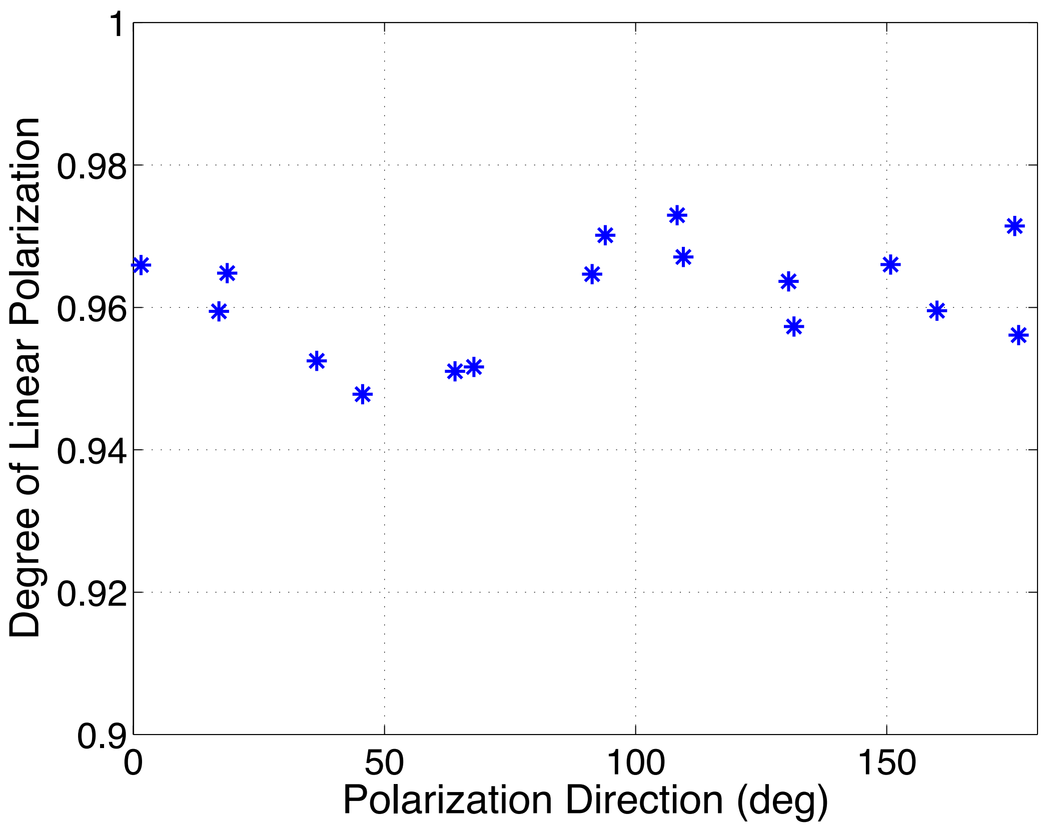
$$M_{\rm BS} = \frac{1}{2}\begin{pmatrix} p_x^2 + p_y^2 & p_x^2 - p_y^2 & 0 & 0 \\ p_x^2 - p_y^2 & p_x^2 + p_y^2 & 0 & 0 \\ 0 & 0 & 2p_xp_y & 0 \\ 0 & 0 & 0 & 2p_xp_y \end{pmatrix},$$

$$M_{\rm R}(\theta) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(2\theta) & \sin(2\theta) & 0 \\ 0 & -\sin(2\theta) & \cos(2\theta) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\vec{S}^{(2)} = M_R(\theta_2) M_{\rm BS} \vec{S}^{(1)} \quad \Rightarrow \quad \vec{S}^{(1)} = \left(M_R(\theta_2) M_{\rm BS}\right)^{-1} \vec{S}^{(2)}$$

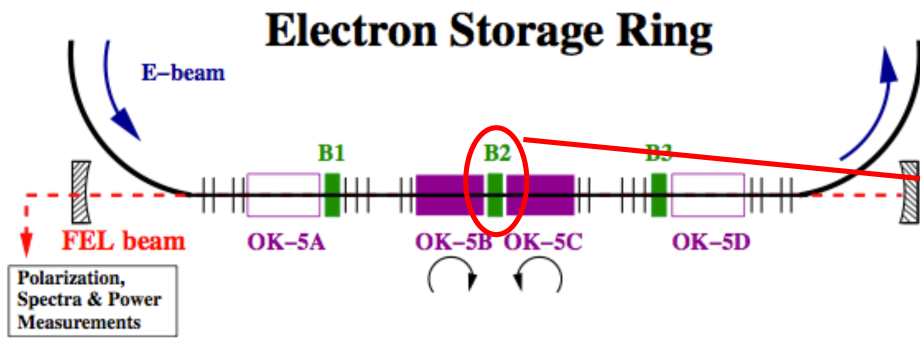
Generation and Rotation of Linear Polarization



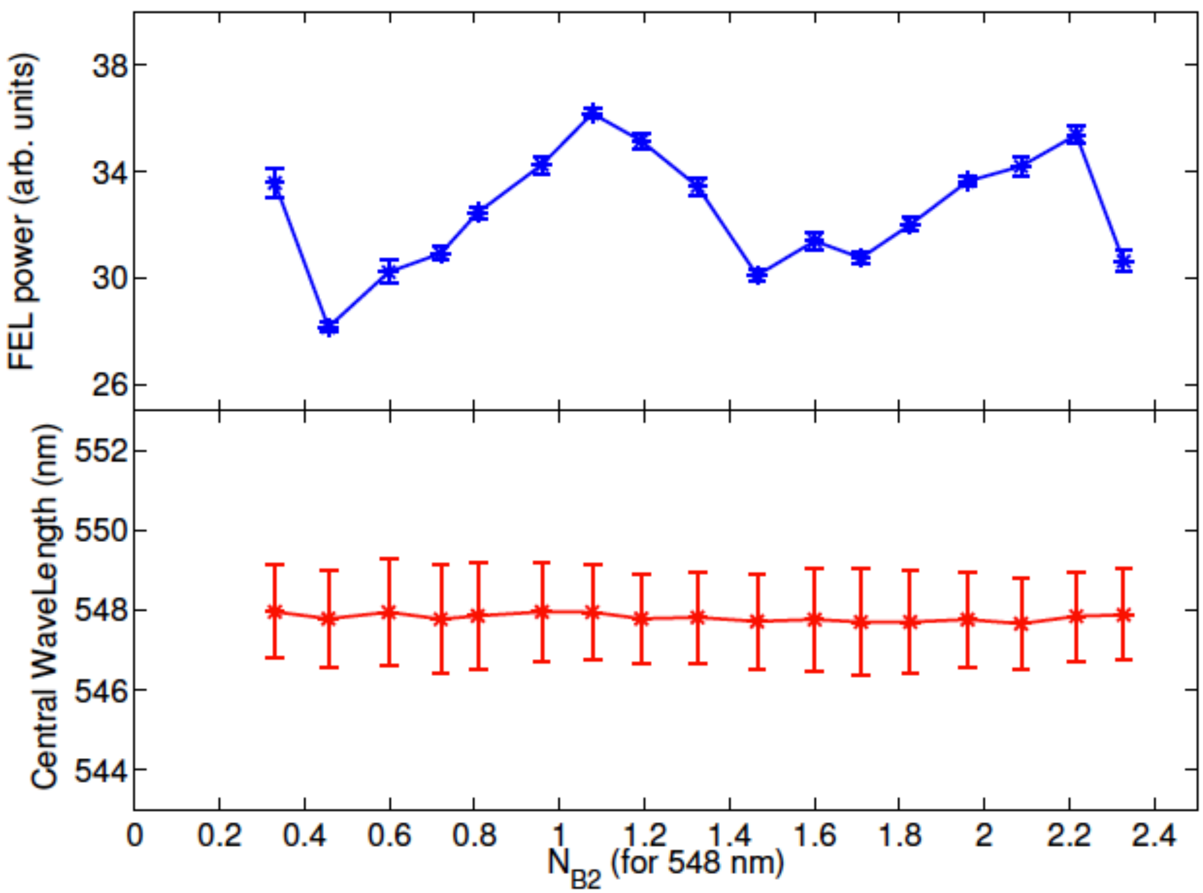


$P_{lin} = 0.94 – 0.98$

FEL Power and Spectra



Control polarization direction



$\sigma_P = 6.8\%$

$\lambda_{FEL} = 547.81 \pm 0.10$ nm

The High Intensity γ-ray Source (HIγS) at Duke

Facility/Project: HIGS

Institution: TUNL and Duke University

Country: US

Energy (MeV): 1 – 100

Accelerator: Storage Ring, 0.24 – 1.2 GeV

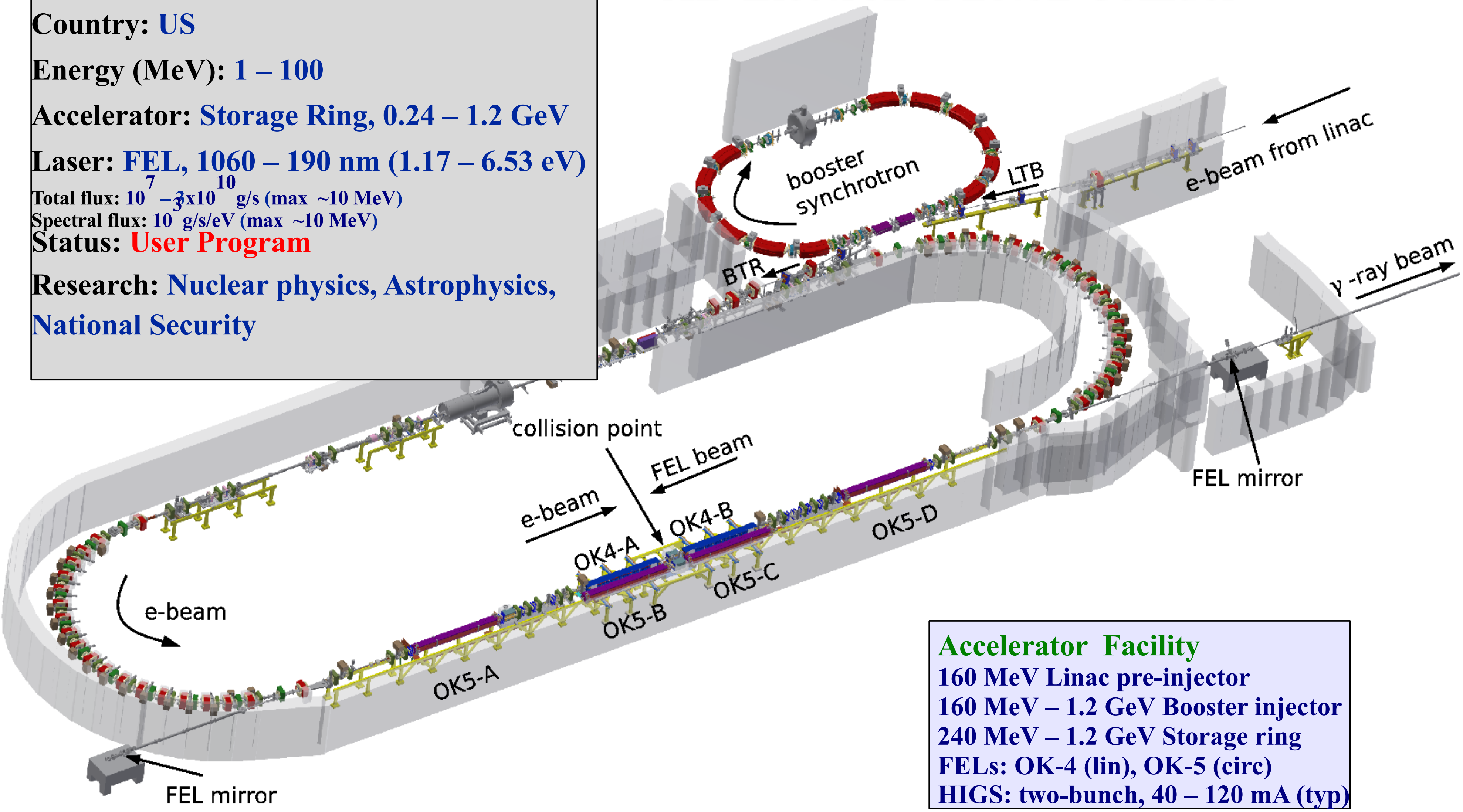
Laser: FEL, 1060 – 190 nm (1.17 – 6.53 eV)

Total flux: $10^7 - 3\times10^{10}$ g/s (max ~10 MeV)
Spectral flux: 10^3 g/s/eV (max ~10 MeV)

Status: User Program

Research: Nuclear physics, Astrophysics, National Security

HIGS
An Electron -Photon Collider



Accelerator Facility
160 MeV Linac pre-injector
160 MeV – 1.2 GeV Booster injector
240 MeV – 1.2 GeV Storage ring
FELs: OK-4 (lin), OK-5 (circ)
HIGS: two-bunch, 40 – 120 mA (typ)

FEL Polarization Manipulation Without Using Optics

- Realized helicity switching of circularly polarized FEL beam
- Produced linearly polarized FEL beam using crossed helical undulators
- Demonstrated full rotation of the linear polarization with high degree of linear polarization
- Developed a precision measurement for linear polarization
- Realized polarization control of Compton γ-ray beam

Thank You!