CNR IFN
Istituto di Fotonica e Nanotecnologie

Photon handling and diagnostics for free-electron lasers and ultrafast pulses

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Padova

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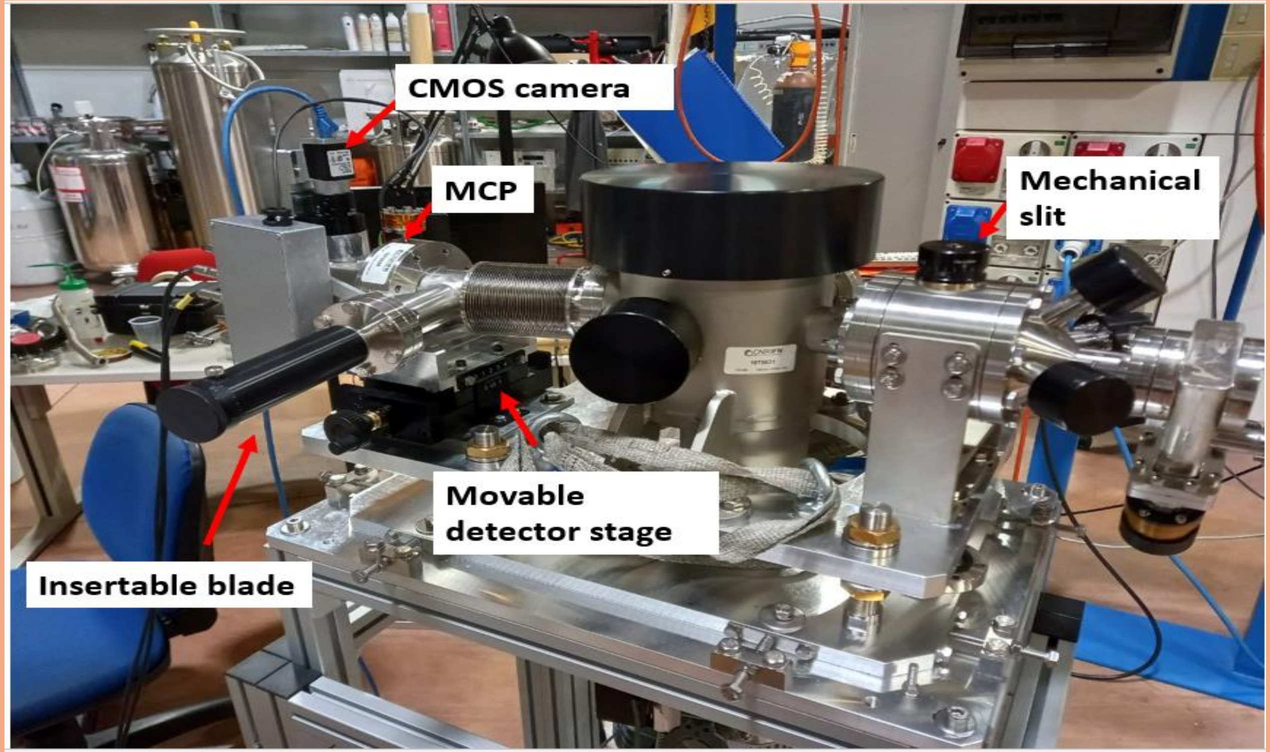
IOM ISTITUTO OFFICINA DEI MATERIALI

COSP: a dedicated compact wide-band spectrometer for free-electron-laser monitoring



At FEL FERMI, generation and control of multiple harmonics

To measure different harmonics or quantify fundamental/harmonics ratio

MEDIUM RESOLUTION GRATING SPECTROMETER

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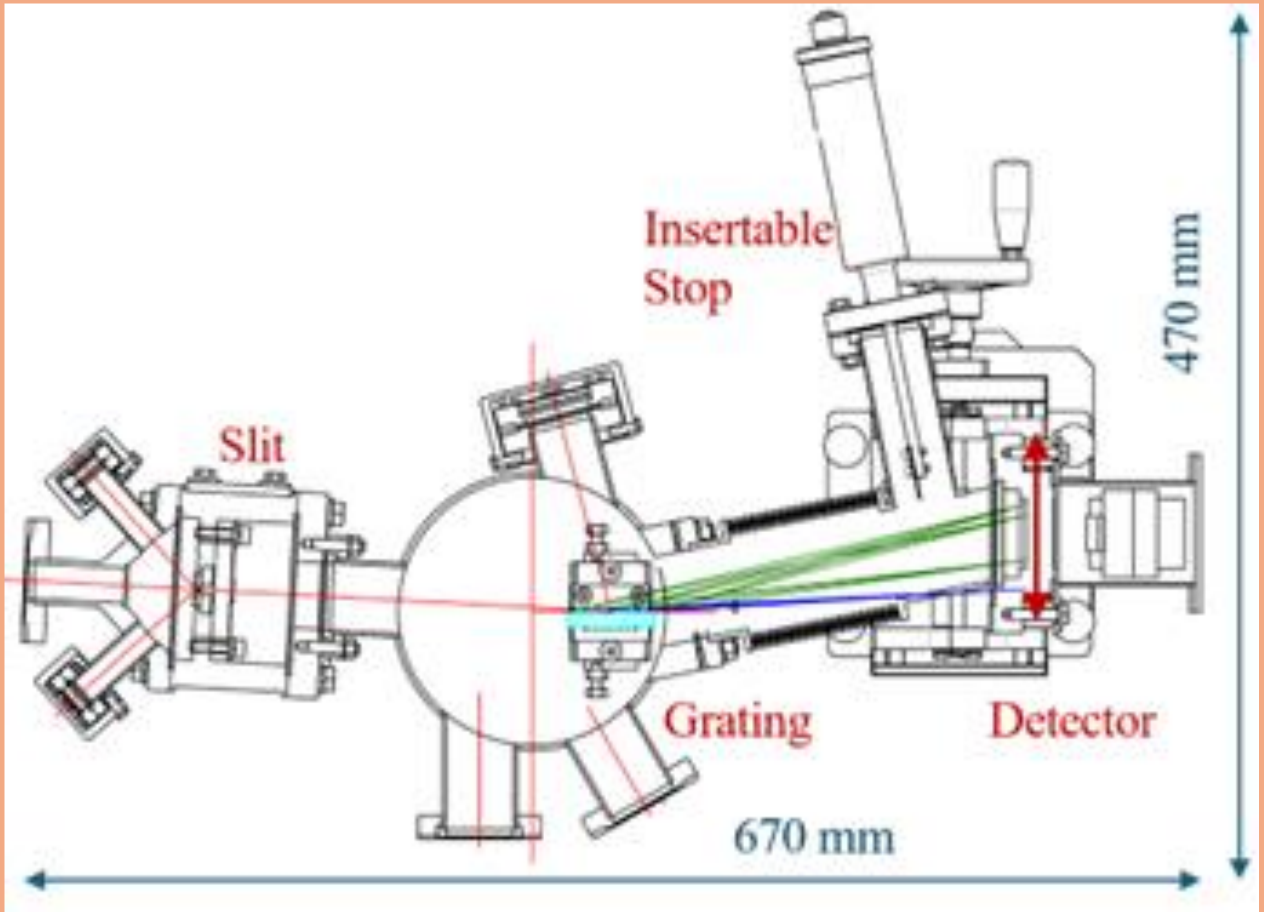


COmpact SPectrometer – COSP

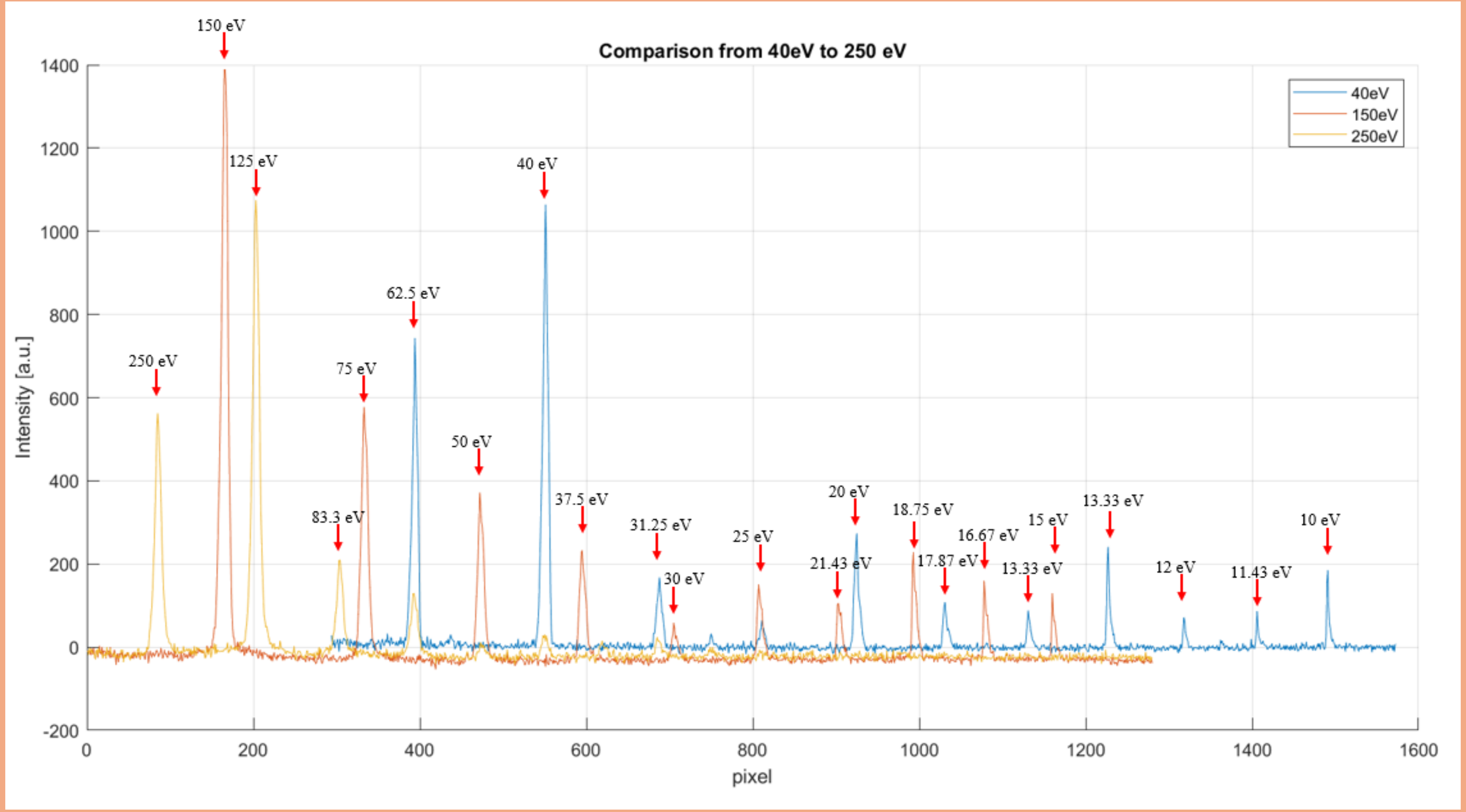
Grating spectrometer for FEL application

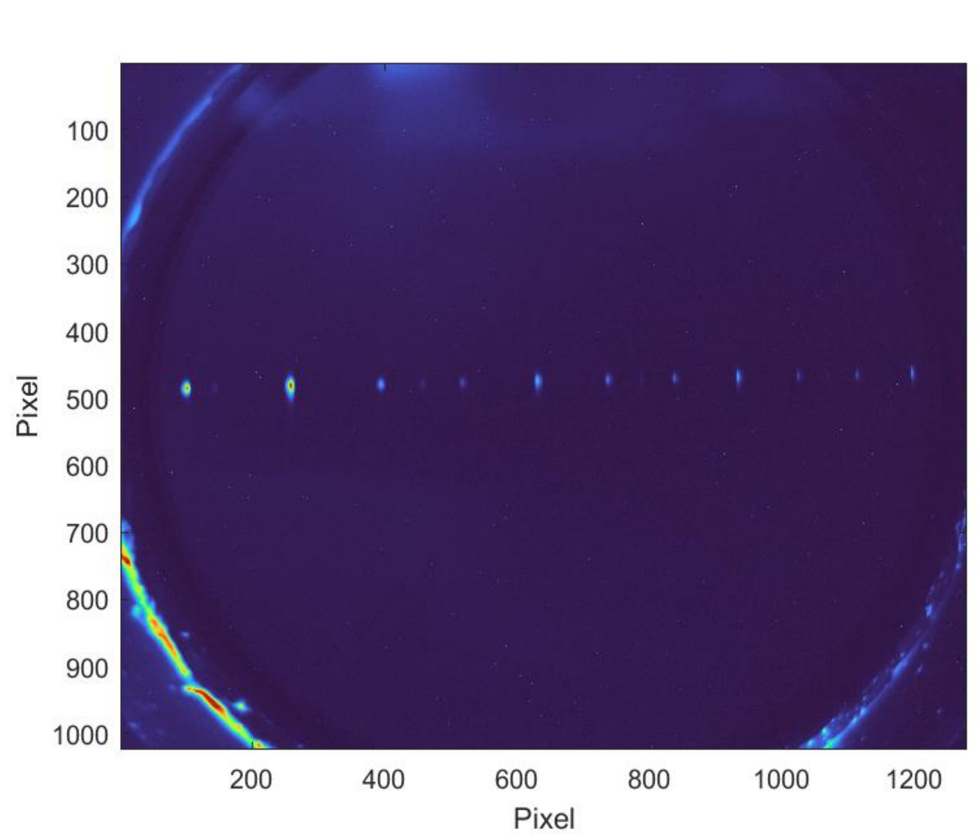
Achieve medium resolution in a wide spectral range

For:

- Optimizing of the machine parameters
- Monitoring of the harmonics stability

Test with CiPo – Circular Polarization beamline
Energies from 40 eV to 250 eV (20 nm to 5 nm)





Identification of spectral energies

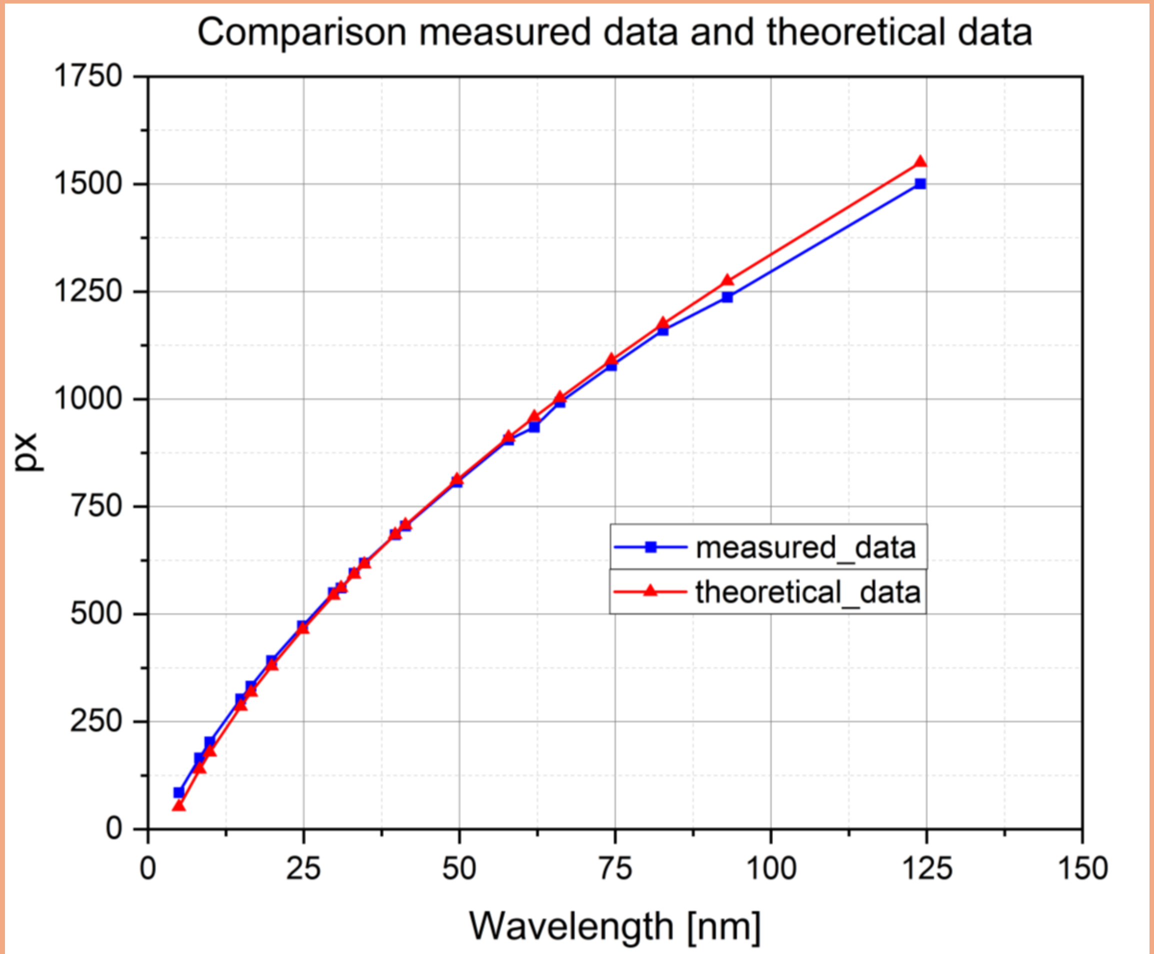
From the position of the signal onto the detector (pixel position)

↓

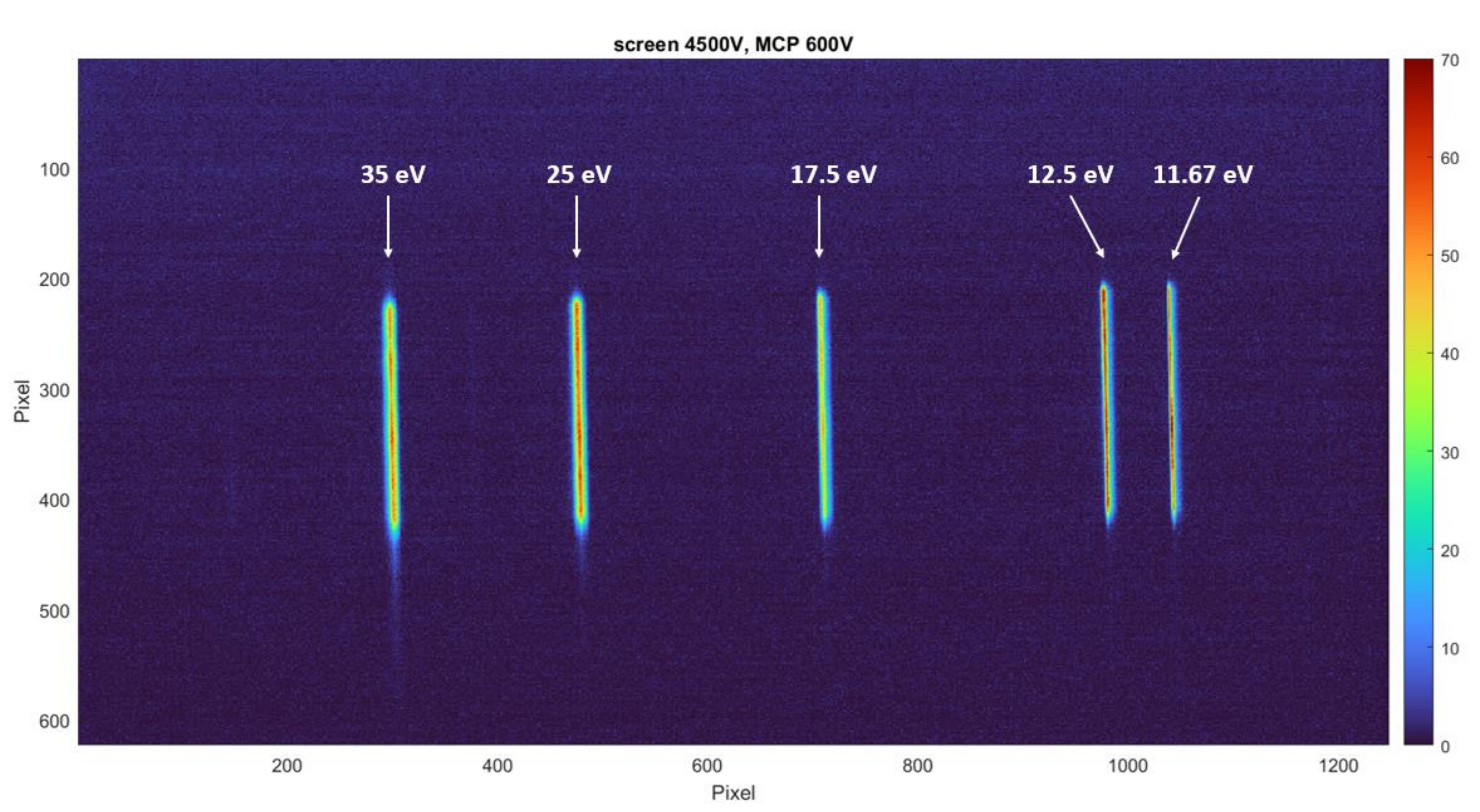
Polynomial fit

$$y = -a + b*\lambda - c*\lambda^2 + d*\lambda^3 - e*\lambda^4 + f*\lambda^5 - offset/0.033$$

If the energy is unknown, the position on the detector gives the signal energy

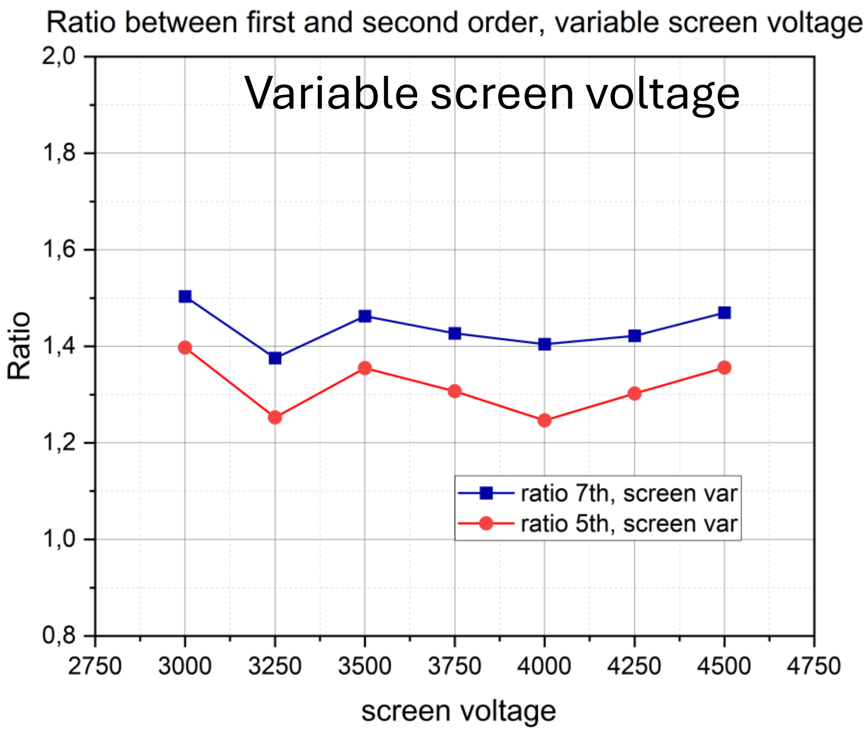


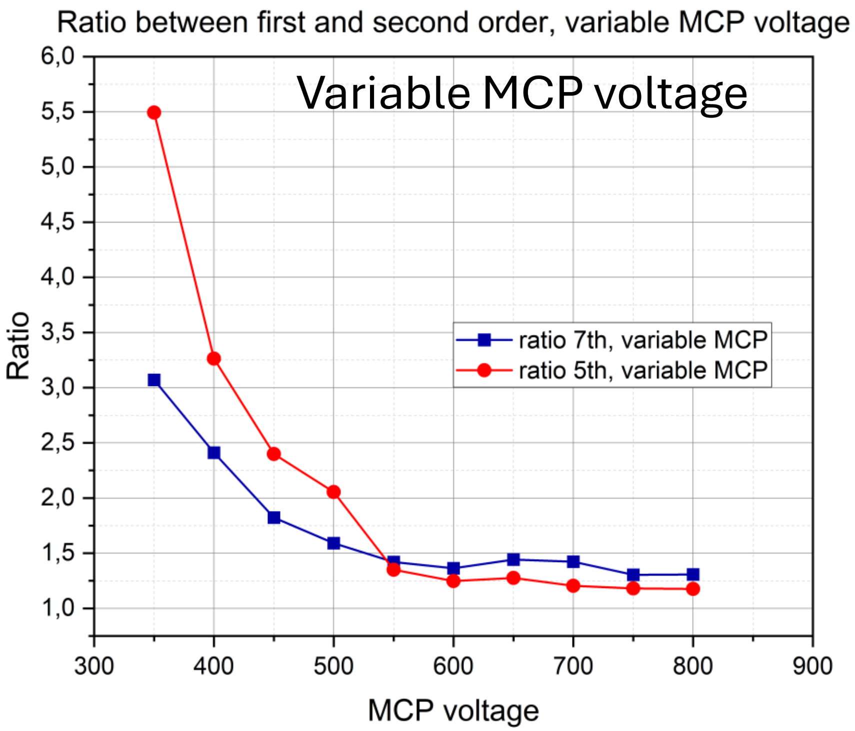
Test at FERMI LDM – Low Density Matter beamline of the free electron laser
Two harmonics, 7th and 5th (35 and 25 eV) and their second order
Variable MCP and screen voltage to test the linearity of the system



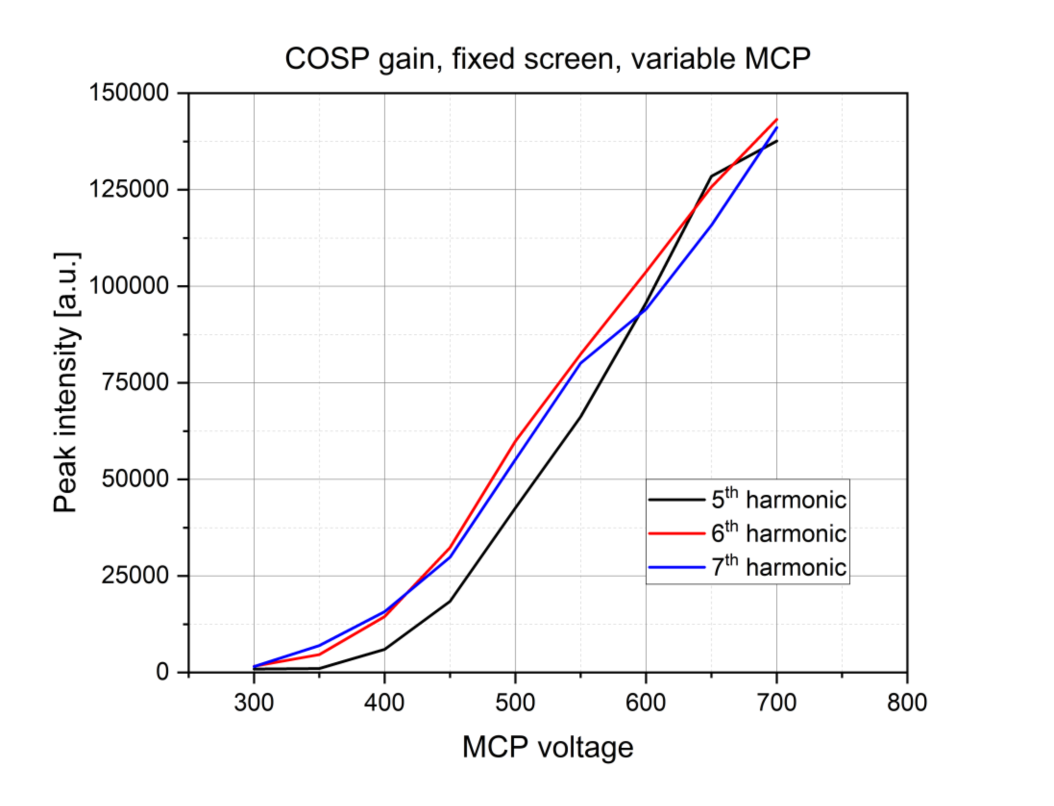
Ratio between first and second order at different MCP and screen voltage

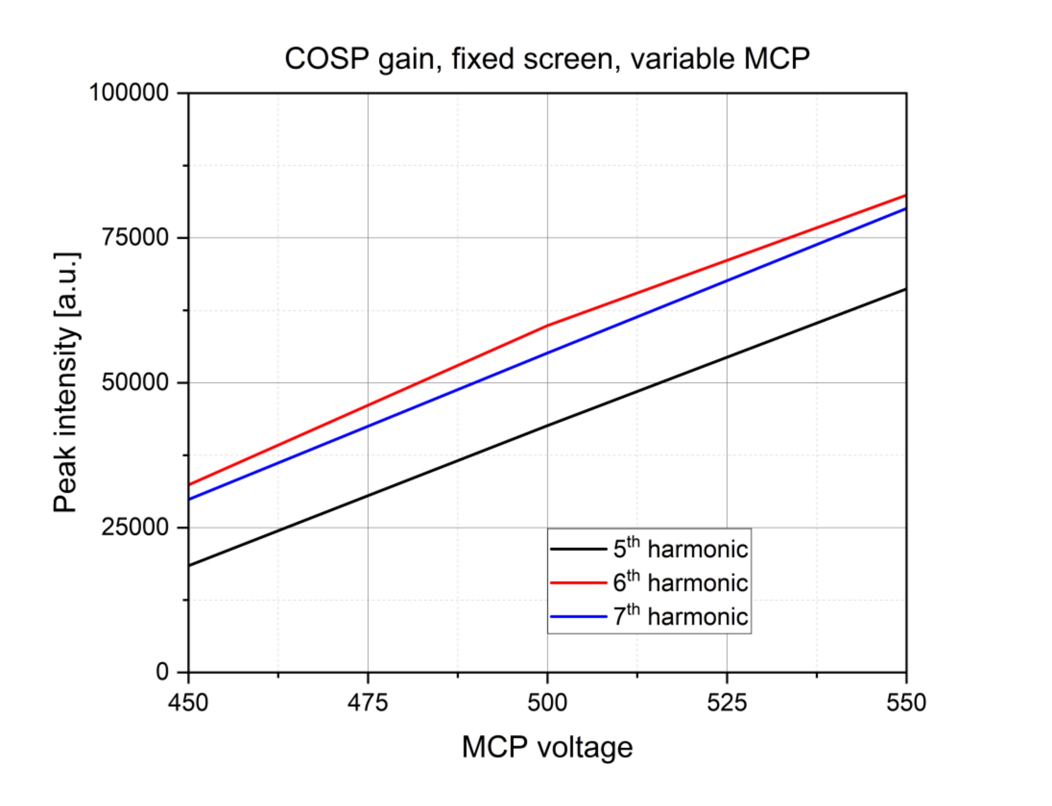
- Screen voltage: no effect on linearity
- MCP voltage: high level of non-linearity





Three harmonics (7th, 6th and 5th) with fixed screen and variable MCP voltage
Region of linear gain: 450-550 V for the MCP





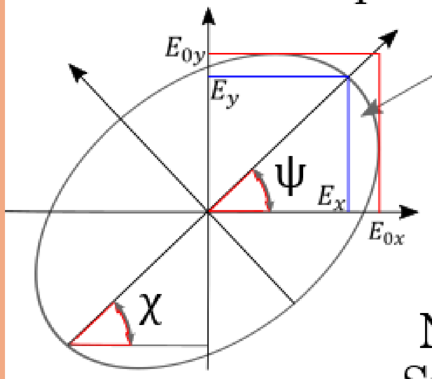
- COSP extends the diagnostic capabilities of FERMI beyond the original design to address new modes of operation with multiple harmonics
- COSP is a secondary intensity monitor, to supplement the calibrated gas intensity monitor. It is particularly useful at long photon energies, below the ionization energy of the intensity monitor working gas (N_2; 15.5812 eV), or at very short wavelengths where the ionization cross section of nitrogen becomes small
- As compared to a photodiode, or a fluorescent screen+camera combination, it has the advantage of spectral selectivity, in particular being insensitive to residual seed laser photons (wavelength range ~260 nm)

- COSP becomes indispensable for machine preparation in a multi-harmonic configuration
- In two-color coherent control ‘ω-2ω” experiments, to monitor the interference between a single-photon path (2ω) and a two-photon path at half the photon energy (ω), the energy per pulse of the two colors is strongly unbalanced, to compensate for the unbalanced cross section of the two paths. COSP will be useful as an intensity monitor of the weak 2ω component, as well as to assess the balance ω/2ω.
- The spectral intensity information provided by COSP will be useful in terms of data validation and post-processing statistical analysis.

Polarimetric analysis of ultrafast pulses

Stokes' formalism: fully polarized light

Nonstandard Polarization ellipse



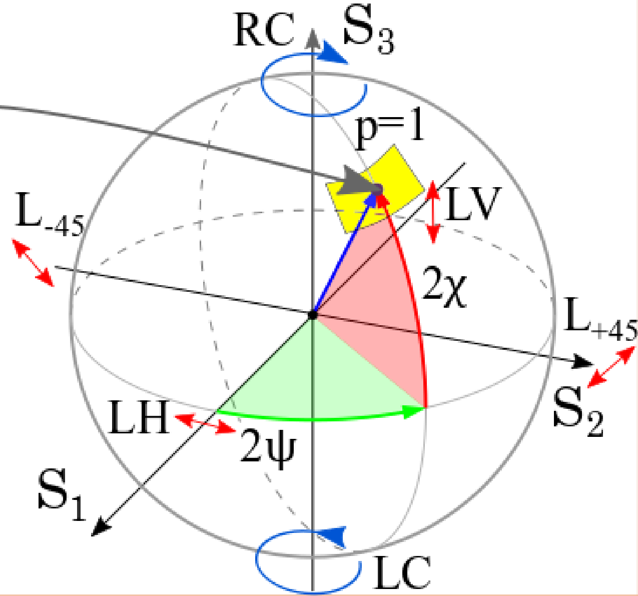
$$E_x(z,t) = E_{0x}\cos(\omega t - kz + \delta_x)$$
$$E_y(z,t) = E_{0y}\cos(\omega t - kz + \delta_y)$$

$$\tan 2\psi = \frac{2E_{0x}E_{0y}}{E_{0x}^2 - E_{0y}^2}\cos\delta \qquad \sin 2\chi = \frac{2E_{0x}E_{0y}}{E_{0x}^2 + E_{0y}^2}\sin\delta$$

Normalized Stokes vector

$$S = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} \qquad S = \begin{pmatrix} 1 \\ S_1/S_0 \\ S_2/S_0 \\ S_3/S_0 \end{pmatrix} = \begin{pmatrix} 1 \\ \cos 2\chi \cos 2\psi \\ \cos 2\chi \sin 2\psi \\ \sin 2\chi \end{pmatrix}$$

Poincarè sphere



Degree of polarization

Linear	Circular
$PL = \frac{\sqrt{S_1^2 + S_2^2}}{S_0}$	$PC = \frac{S_3}{S_0}$

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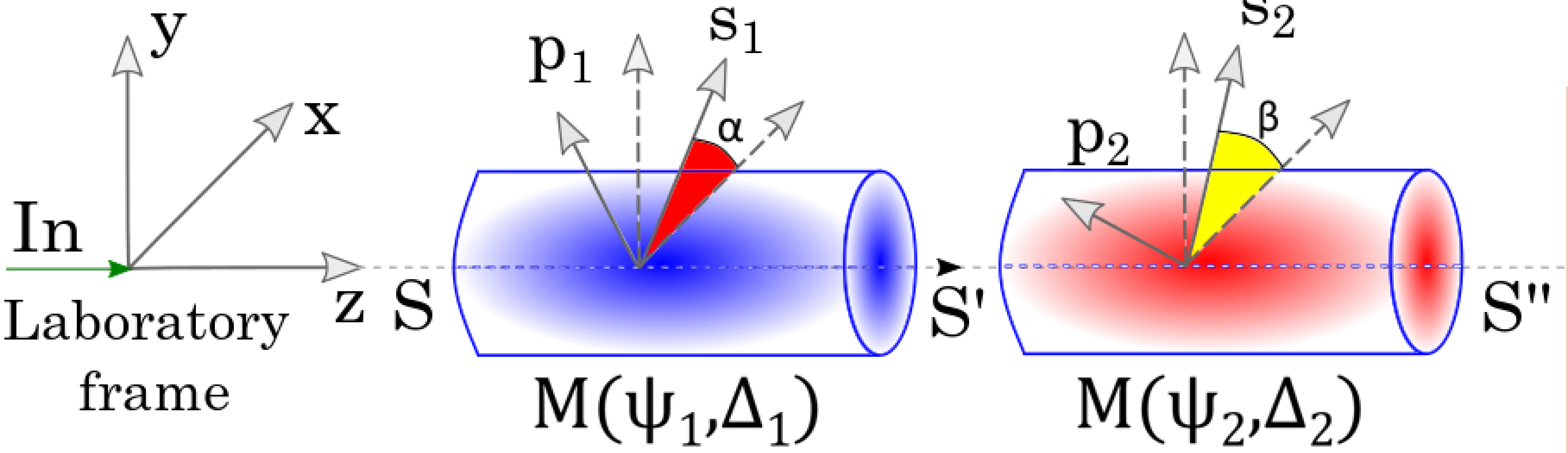
Double stage reflection polarimeter



Mueller rotation matrix

$$R(\alpha) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\alpha & \sin 2\alpha & 0 \\ 0 & -\sin 2\alpha & \cos 2\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\left.\begin{aligned} \tilde{r}_s &= r_s e^{i\delta_s} \\ \tilde{r}_p &= r_p e^{i\delta_p} \end{aligned}\right\}$$

$$\Delta = \delta_p - \delta_s$$

$$\tan\psi = \frac{r_p}{r_s}$$

Mueller reflection matrix

$$M(\psi,\Delta) = \frac{1}{2}(r_s^2 + r_p^2) \begin{bmatrix} 1 & \cos 2\psi & 0 & 0 \\ \cos 2\psi & 1 & 0 & 0 \\ 0 & 0 & \sin 2\psi \cos\Delta & -\sin 2\psi \sin\Delta \\ 0 & 0 & \sin 2\psi \sin\Delta & \sin 2\psi \cos\Delta \end{bmatrix}$$

Non coplanar reflection model

- Single stage equation: only S_1 and S_2 can be obtained from the detected light intensity S_{int}

$$S_{int} = K\left(A + \frac{S_1}{S_0}B + \frac{S_2}{S_0}C\right) = f(K, \psi_1, S_1, S_2)$$

$$\begin{cases} K = \frac{1}{2}(r_p^2 + r_s^2) \\ A = 1 \\ B = \cos 2\alpha \cos 2\psi_1 \\ C = \sin 2\alpha \cos 2\psi_1 \end{cases}$$

- Double stage equation: S_1, S_2 and S_3 can be obtained from the detected light intensity S_{out}

$$S_{out} = K\left(A + \frac{S_1}{S_0}B + \frac{S_2}{S_0}C + \frac{S_3}{S_0}D\right) = f(K, \psi_1, \psi_2, \Delta_1, S_1, S_2, S_3)$$

$$K = \frac{1}{4}(r_{p1}^2 + r_{s1}^2)(r_{p2}^2 + r_{s2}^2)$$

$$A = 1 + \cos 2\psi_1 \cos 2\psi_2 \cos 2(\alpha - \beta)$$

$$B = \cos 2\psi_1 \cos 2\alpha + \frac{1}{2}\cos 2\psi_2 \cos 2\beta\,(1 + \sin 2\psi_1 \cos \Delta_1) + \frac{1}{2}\cos 2\psi_2 \cos(4\alpha - 2\beta)\,(1 - \sin 2\psi_1 \cos \Delta_1)$$

$$D = \sin 2\psi_1 \cos 2\psi_2 \sin \Delta_1 \sin(2\alpha - 2\beta)$$

$$C = \cos 2\psi_1 \sin 2\alpha + \frac{1}{2}\cos 2\psi_2 \sin 2\beta\,(1 + \sin 2\psi_1 \cos \Delta_1) + \frac{1}{2}\cos 2\psi_2 \sin(4\alpha - 2\beta)\,(1 - \sin 2\psi_1 \cos \Delta_1)$$

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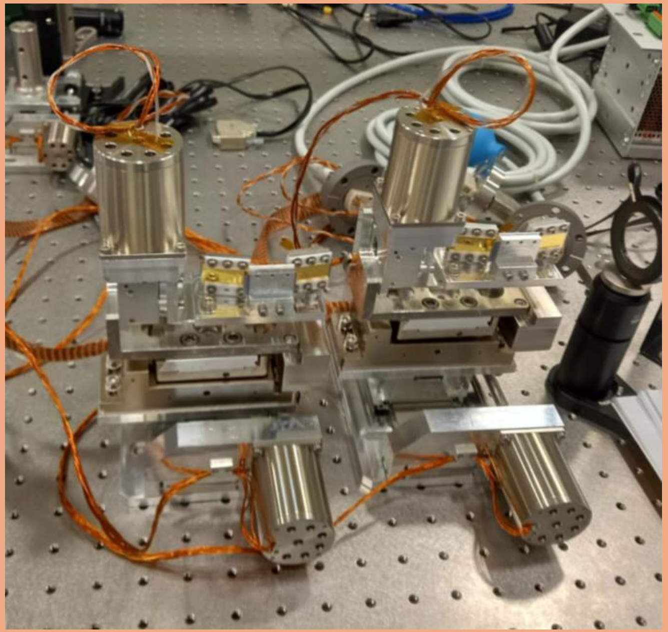
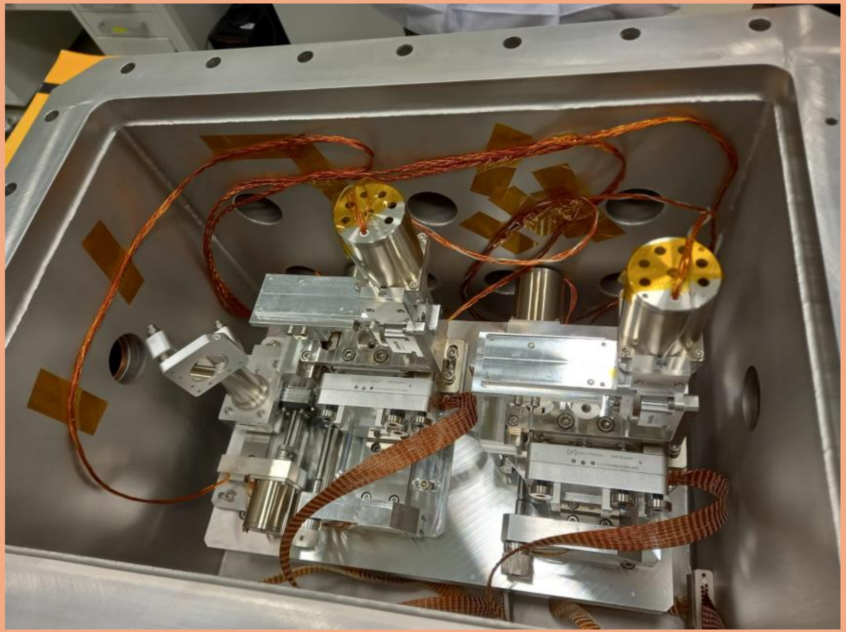
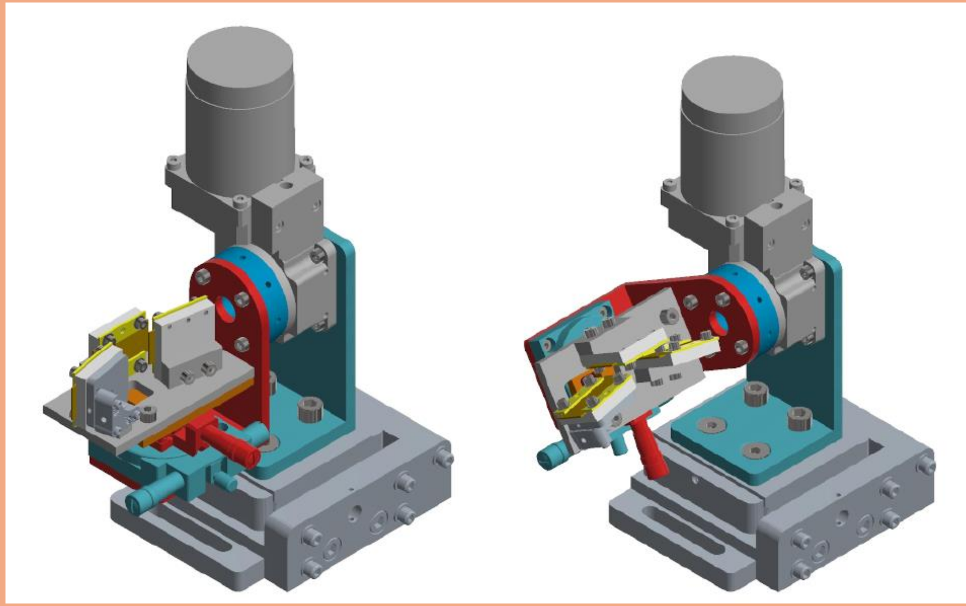
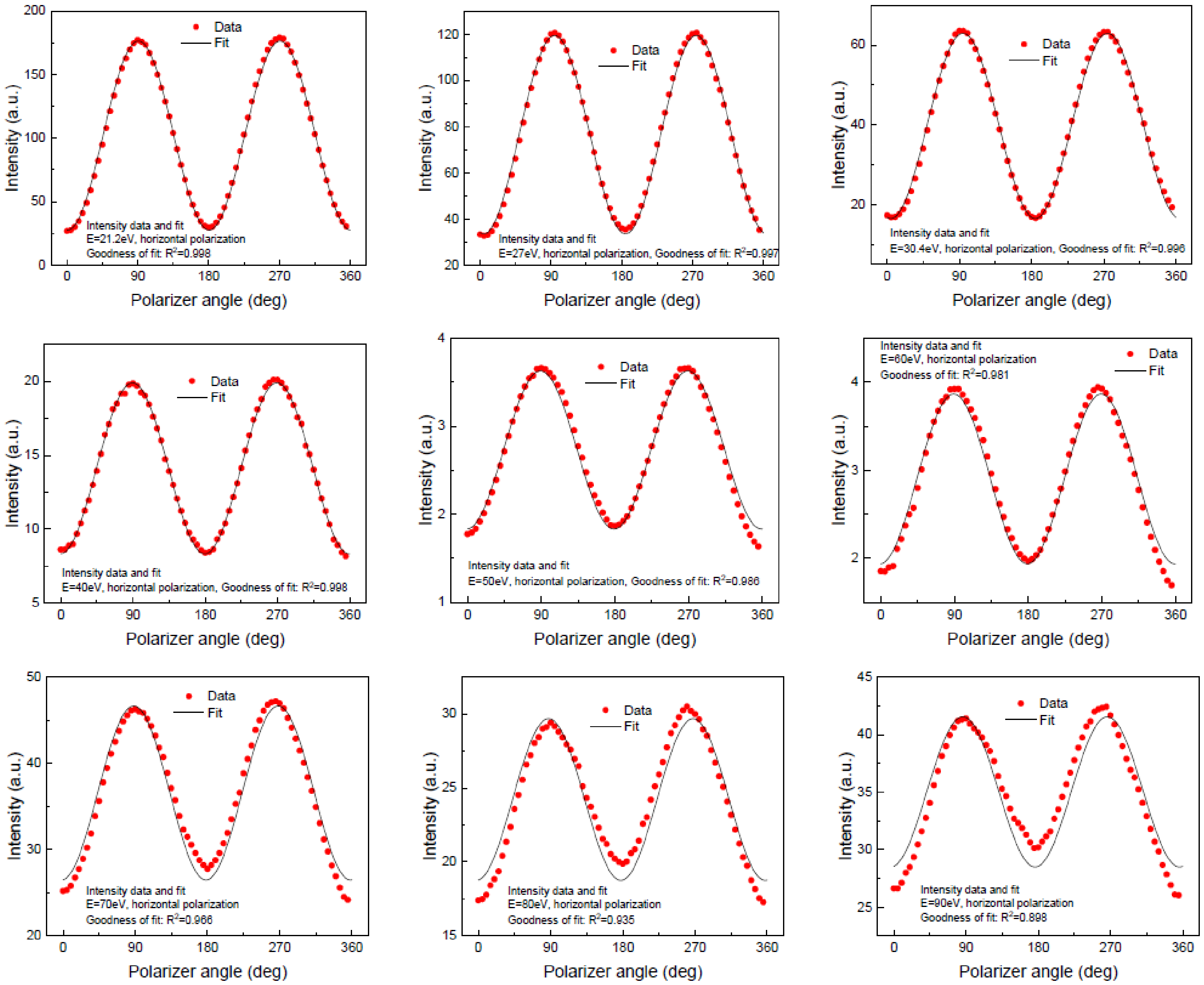
Polarimetry in the XUV range (15-100 eV)





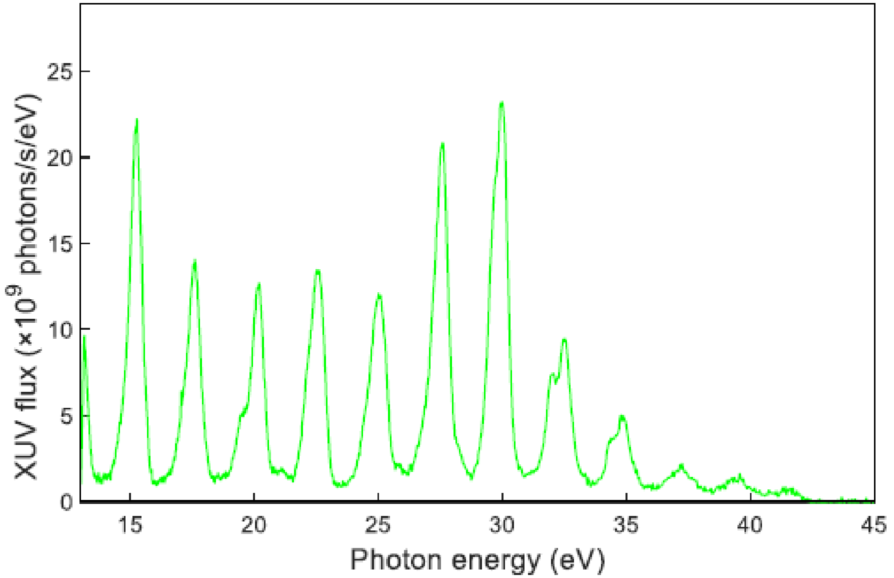


Results obtained at synchrotron beamline CIPO, ELETTRA

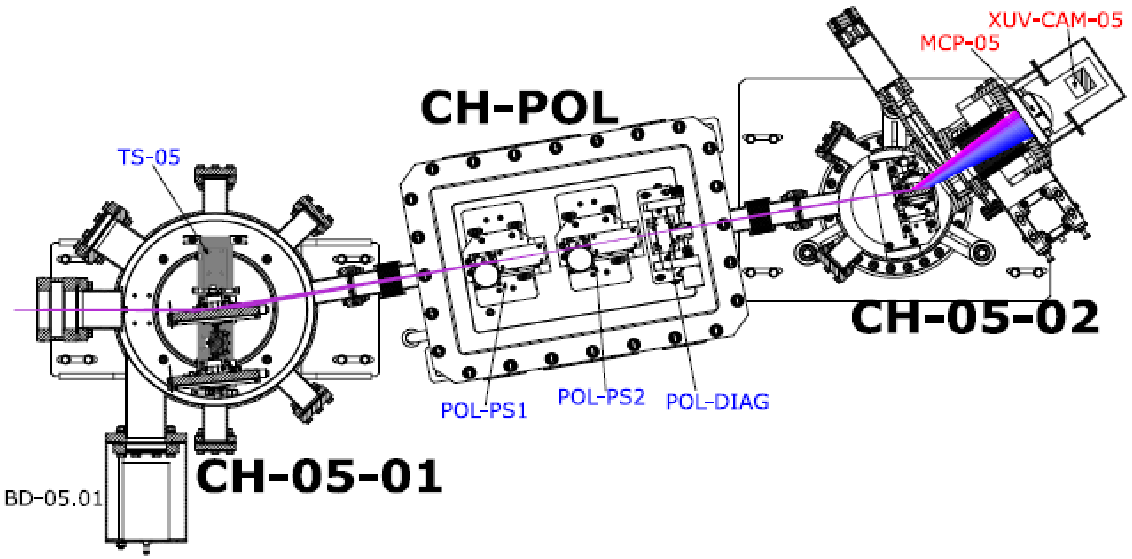


Experimental arrangement

Typical high harmonic spectrum generated using HR Alignment laser
(~1 mJ, sub-7 fs, 10 kHz rep. rate)



Double stage XUV polarimeter installed in subsytem-5 of the HR Gas beamline



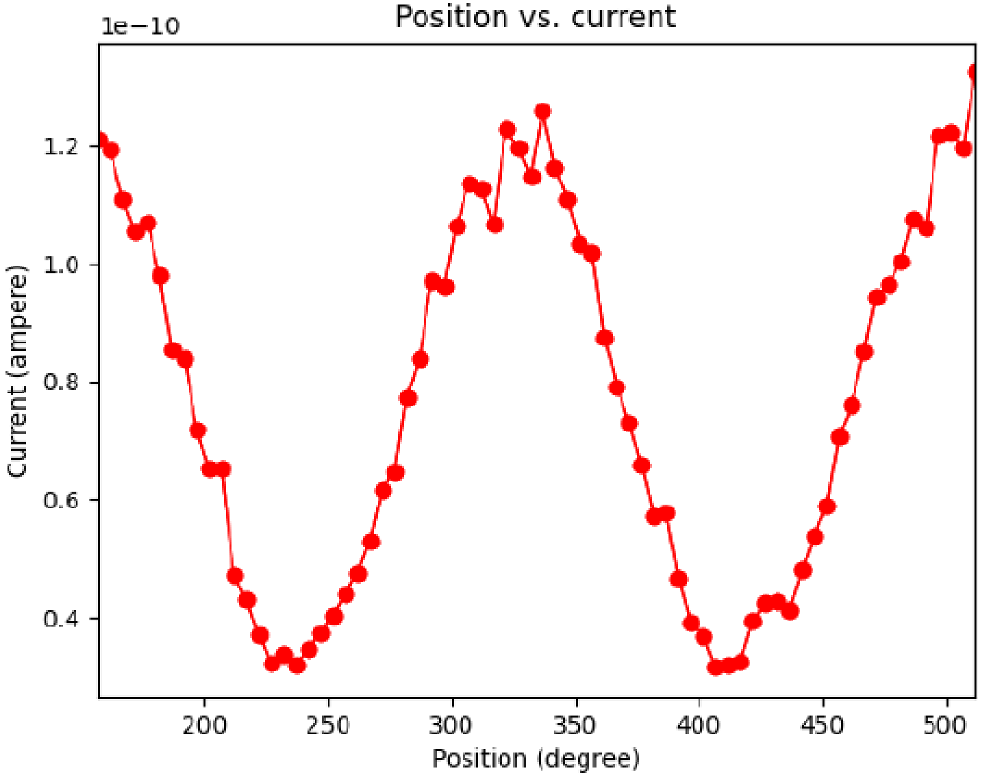
Polarization control (halfwave plate) and diagnostic (analyser and camera) was implemented for the driving laser beam.

Courtesy from Dr. Tamàs Csizmadia, ELI-ALPS

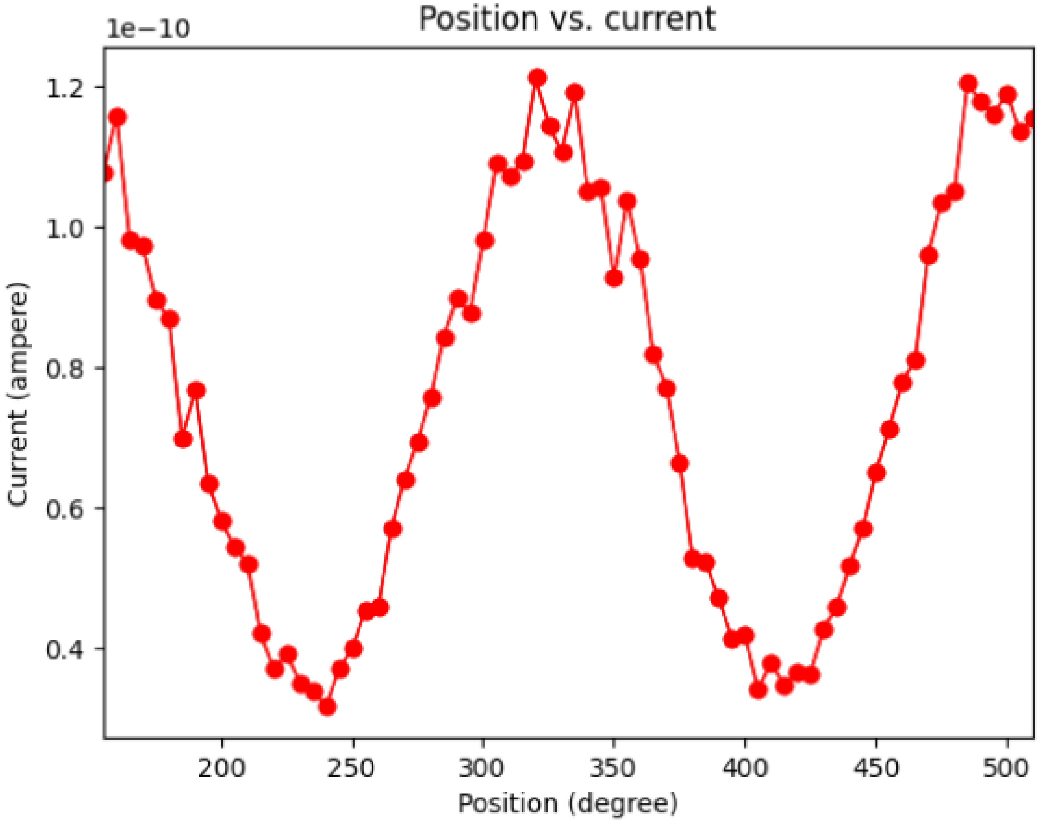
Single stage measurements

Detector: NIST-calibrated Al_2O_3 photodiode

Only POL-PS1



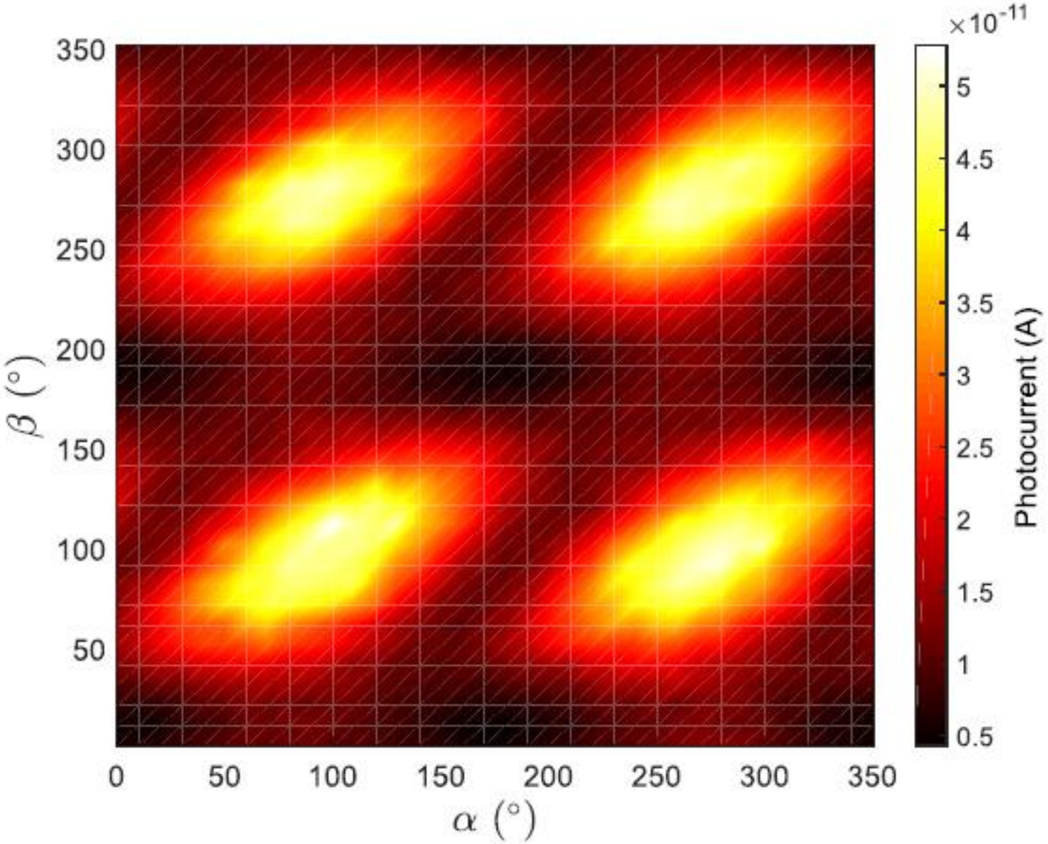
Only POL-PS2



Position in machine units, including offset

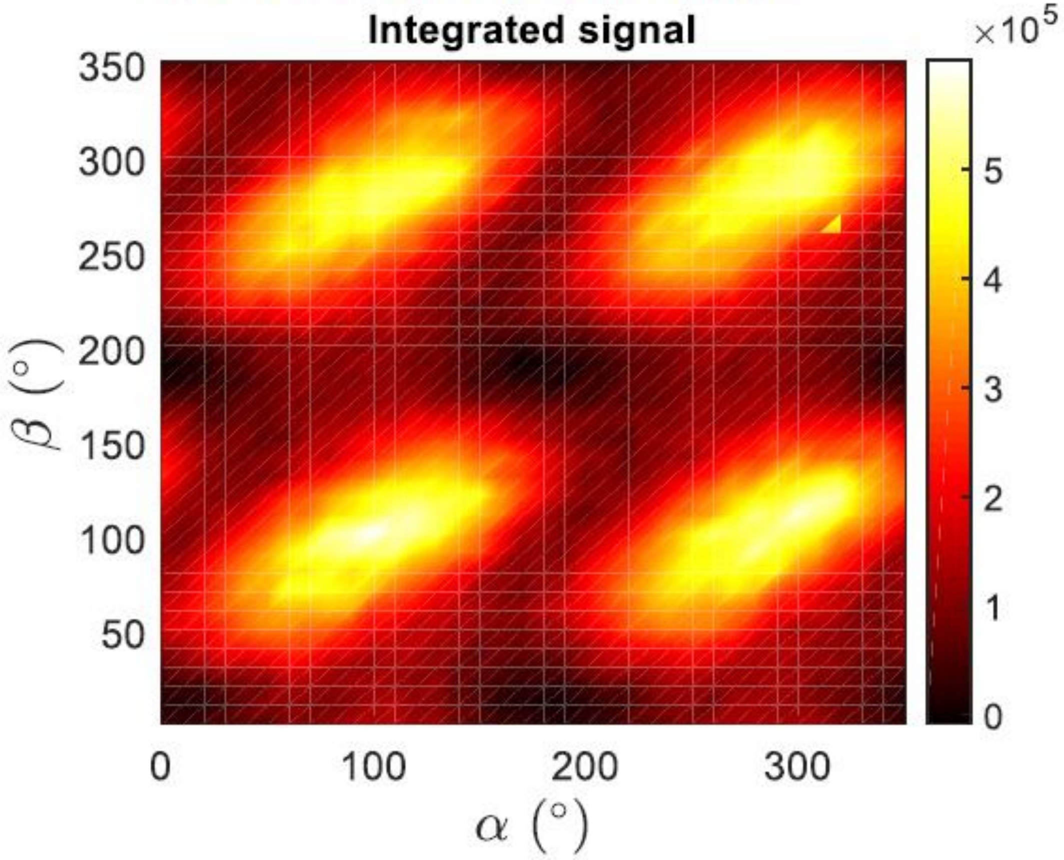
Double stage measurements
p polarization

Detector: Al_2O_3 photodiode

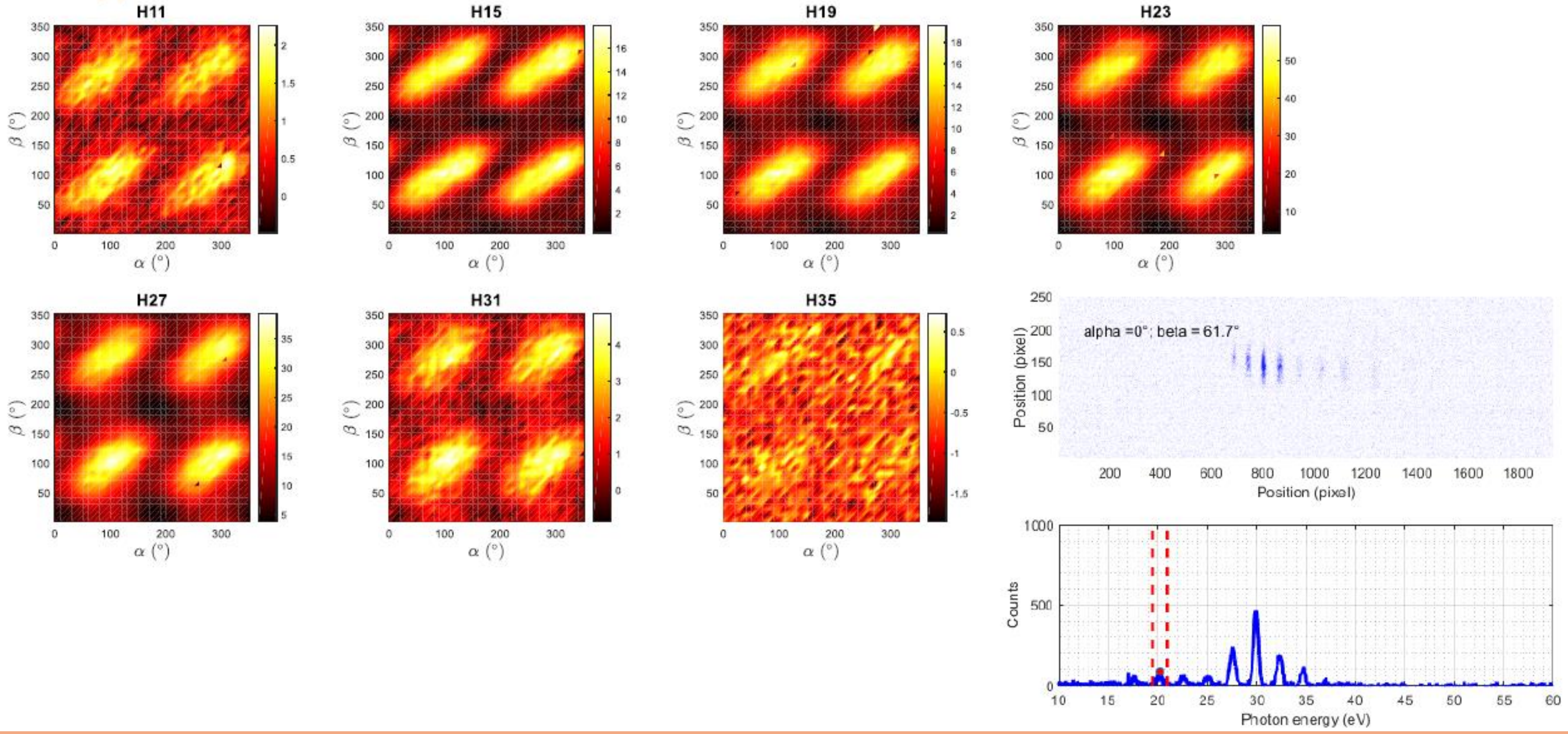


Rotational positions offset corrected

Detector: XUV spectrometer, total signal is evaluated from each camera image



Spectrally resolved measurements
p polarization



- XUV polarimetry of spectrally resolved ultrafast pulses (high-order laser harmonics) by a combination of double-stage polarimeter and spectrometer

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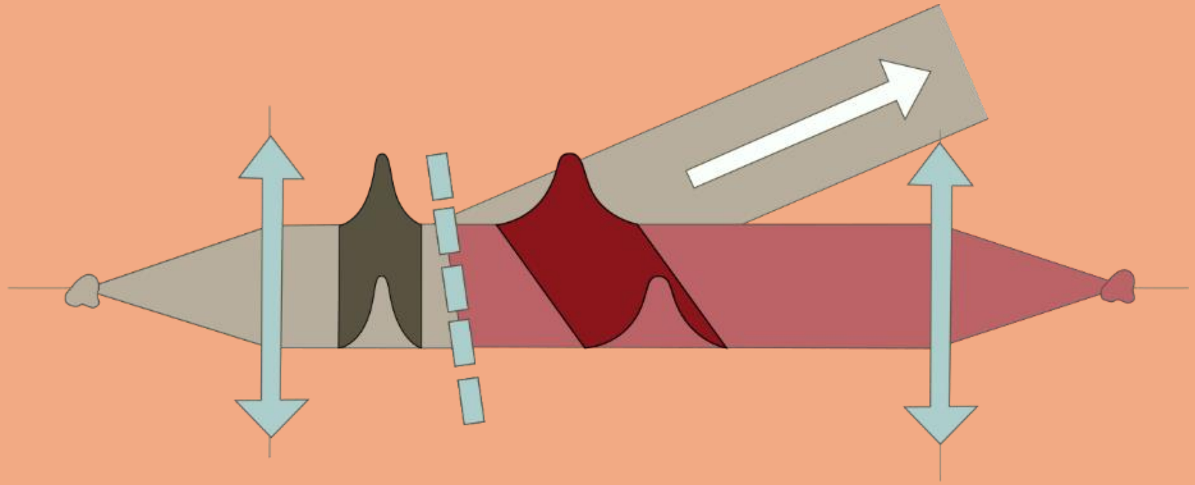
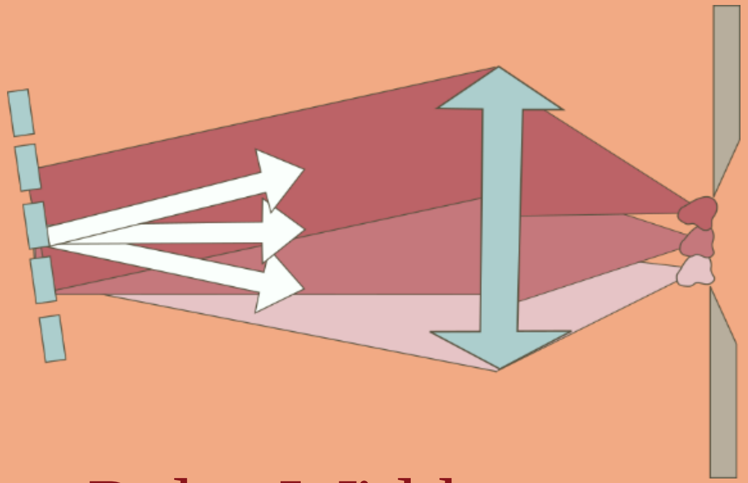
Monochromatization of ultrafast pulses

The monochromator has to preserve the temporal duration of the XUV pulse.



Pulse Front Tilt



Pulse Width

$$\tan(\phi_0) = \frac{m\lambda_0}{\sigma}\frac{1}{\cos(\theta_0)}$$

$$\tan(\phi) = \frac{\tan(\phi_0)}{1+u}$$

$$\tau^2 = \tau_0^2\left[(1+u)\frac{4k^2z^2\beta^4}{1+u}\tau_0^4\right]$$

- O. E. Martinez, Opt. Commun. 59, 229–232, 1986
- O. E. Martinez, “J. Opt. Soc. Am. B 3, 929–934, 1986

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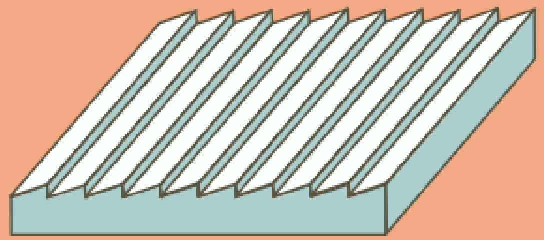
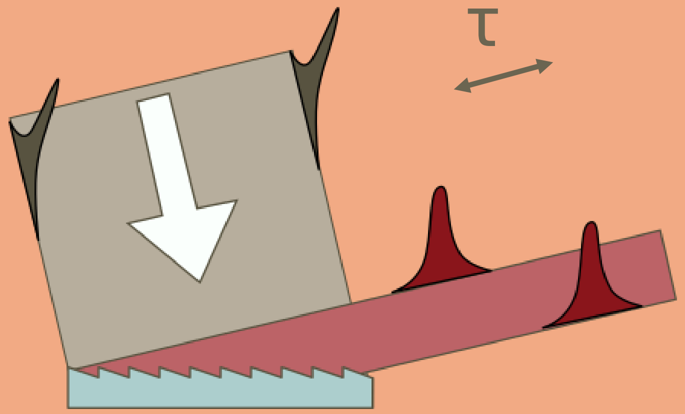
Spectral selection of ultrafast pulses

$$\tau = m\lambda_0 N$$

Reflective Diffraction Grating





Example:

5-mm FWHM beam (5 mrad with 1 m focal length)

λ=30 nm (41 eV), 300 gr/mm grating, normal incidence

⇒ 1500 illuminated grooves

⇒ path-difference ΔOP_{FWHM} = 45 µm, Δt_{FWHM} = 150 fs

Design of single-grating monochromators

Goal of the optical design: to keep the number of illuminated grooves as close as possible to the resolution.

Classical diffraction

Conical diffraction

CLASSICAL DIFFRACTION

The temporal broadening in the XUV is in the range 200-400 fs.

The efficiency is limited by the quality of the grating surface (»10%)

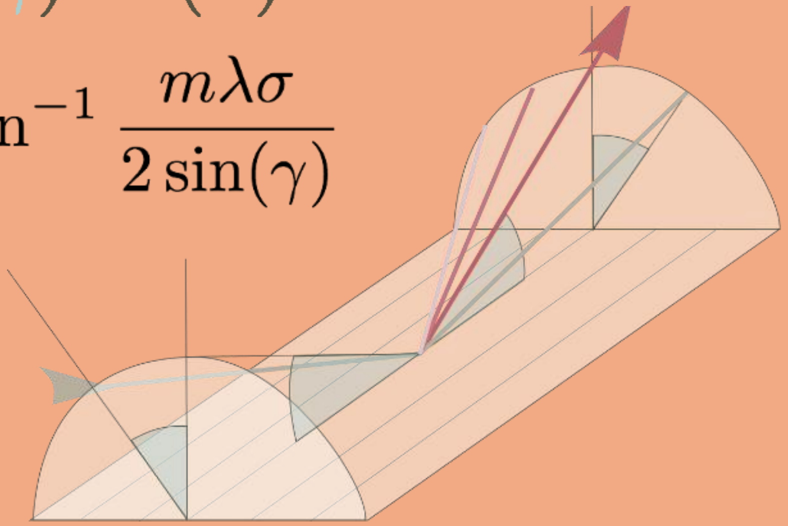
L. Poletto and F. Frassetto, Appl. Opt. 49, 5465 (2010)

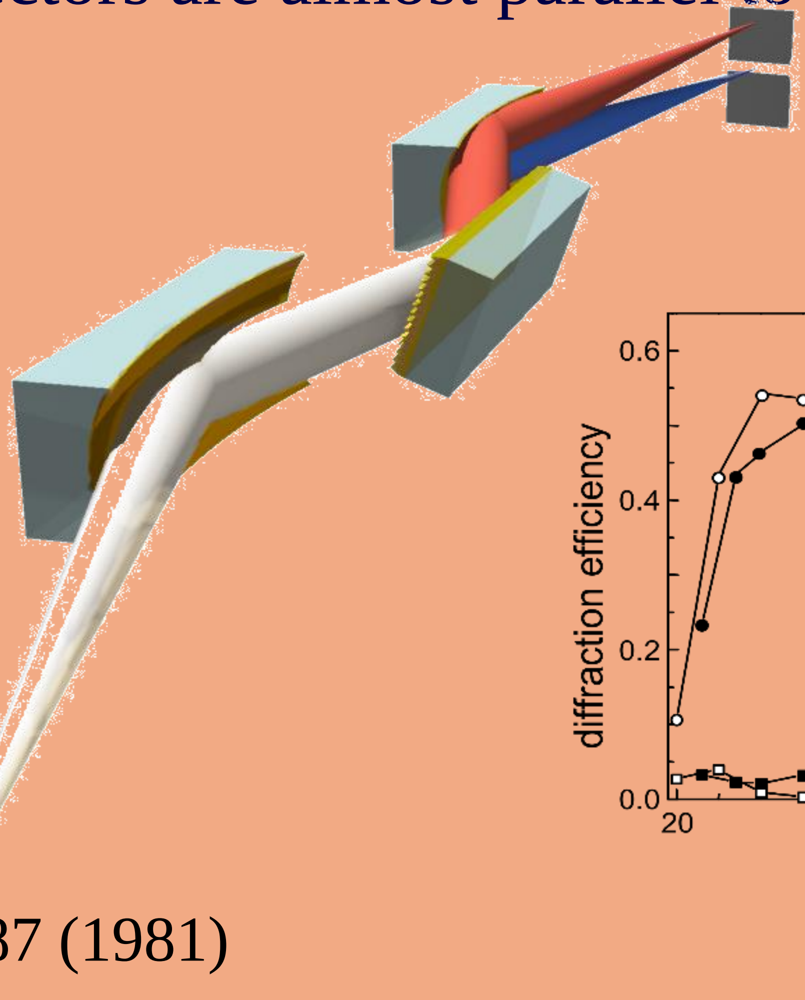
Monochromators: conical diffraction

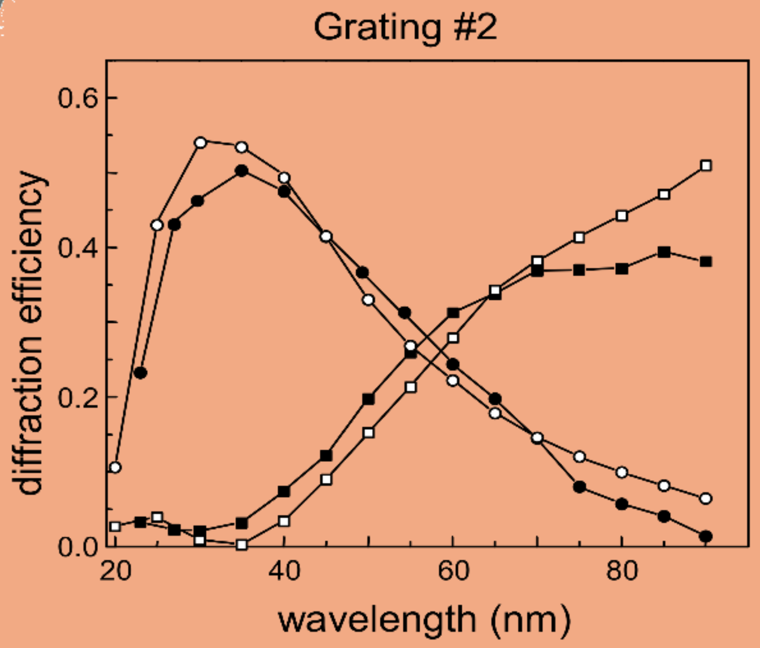
The incident and diffracted wave vectors are almost parallel to the grooves

$$2\sin(\gamma)\sin(\alpha) = m\lambda\sigma$$

$$\alpha = \sin^{-1}\frac{m\lambda\sigma}{2\sin(\gamma)}$$



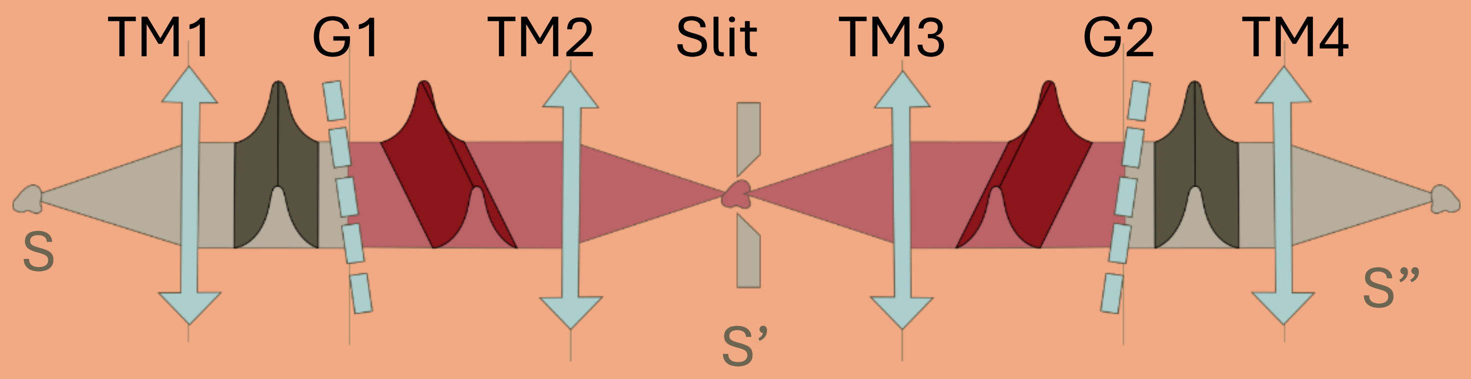




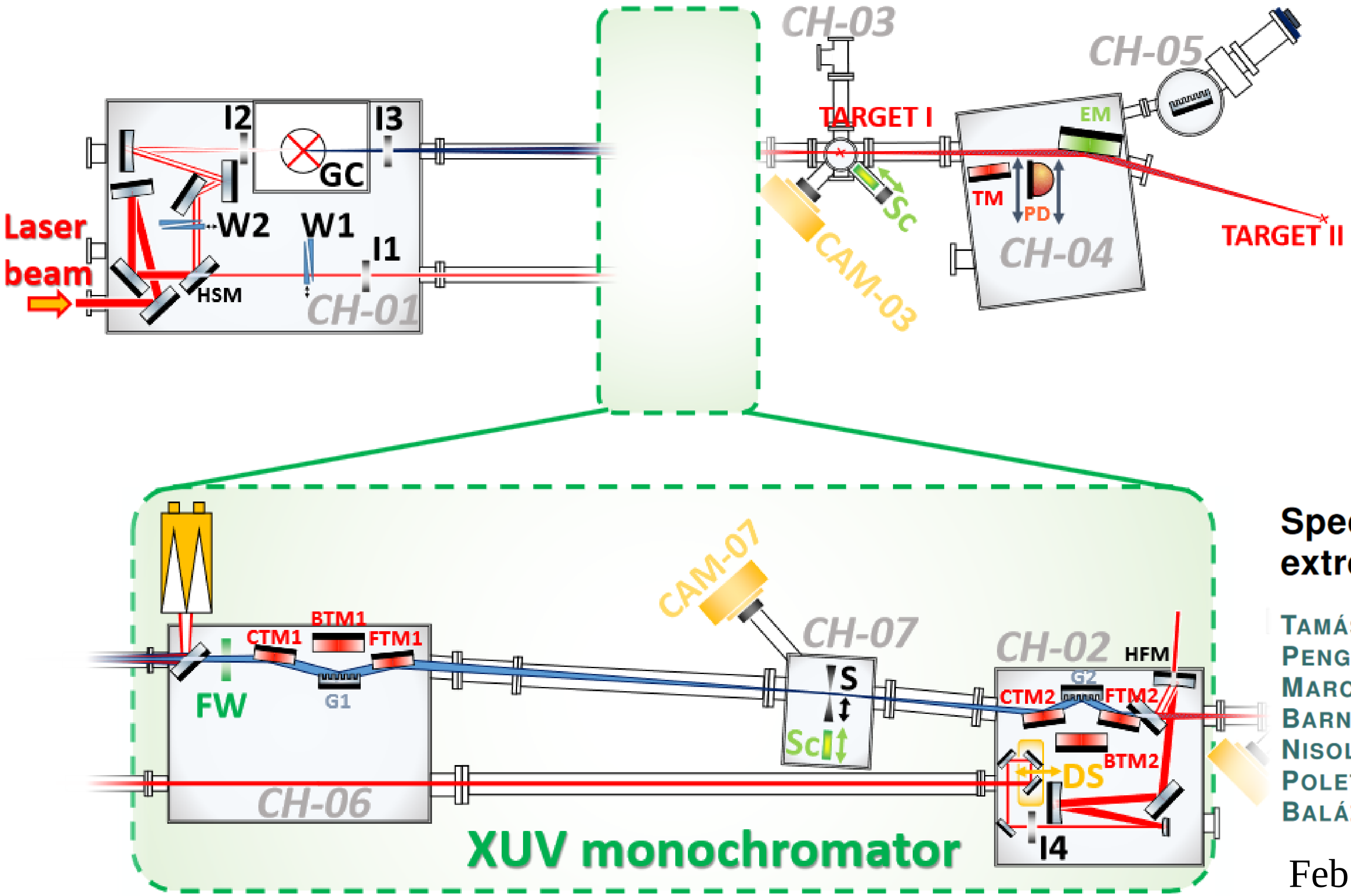
W. Cash, Appl. Opt. 21 710 (1982)

W. Werner and H. Visser, Appl. Opt. 20, 487 (1981)

Monochromators: Double-grating design



Monochromators: Double-grating design



GHHG beamline of the Extreme Light Infrastructure - Attosecond Light Pulse Source ELI ALPS facility.

Spectrally tunable ultrashort monochromatized extreme ultraviolet pulses at 100 kHz

TAMÁS CSIZMADIA[1,*], ZOLTÁN FILUS[1], TÍMEA GRÓSZ[1], PENG YE[1,2], LÉNÁRD GULYÁS OLDAL[1], MASSIMO DE MARCO[1], PÉTER JÓJÁRT[1], IMRE SERES[1], ZSOLT BENGERY[1], BARNABÁS GILICZE[1], MATTEO LUCCHINI[3,4], MAURO NISOLI[3,4], FABIO FRASSETTO[5], FABIO SAMPARISI[5], LUCA POLETTO[5], KATALIN VARJÚ[1,6], SUBHENDU KAHALY[1,7], AND BALÁZS MAJOR [1]

Feb. 2023

Monochromators: Double-grating design

Results:

- High monochromatic XUV flux
  2.8×10^{10} photons/s at 39.7 eV
  selected with 700 meV FWHM bandwidth

- ultrashort pulse duration
  4.0 fs using 12 fs driving pulses

- small spot size at the target area sub-100 μm.

Spectrally tunable ultrashort monochromatized extreme ultraviolet pulses at 100 kHz

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H13 ~ 35 um

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H13 ~ 35 um

- XUV spectral selection of sub-10-fs ultrafast pulses by a time-delay-compensated monochromator

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THANK YOU!