# (Non-invasive) diagnostics on FEL photon beams: general remarks and the case of FERMI@Elettra

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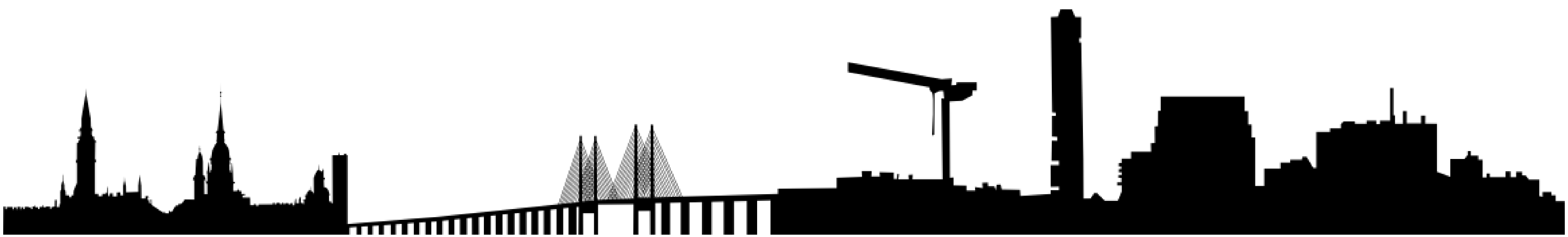


# Outline

- **Introduction**
- **What users want**
- **Layout of the transport system: where can we "diagnose" ?**
- **Diagnostics:** Beam Position Monitors
  Intensity Monitors
  Energy Spectrometer
  TOF-based diagnostics
  Wavefront
  Coherence
  Pulse length
- **Conclusions**

# FEL Radiation Features

Common characteristics: high peak powers, pulsed structure, high coherence...

FERMI@Elettra

| Parameter | FEL 1 | FEL 2 |
|---|---|---|
| Wavelength (nm) | 100 - 20 | 40 - 3 |
| Pulse length FWHM (fs) | 30 - 100 | <100 |
| Bandwidth rms (meV) | ~20 - 40 | ~20 - 40 |
| Polarization | Variable | Variable |
| Peak power (GW) | 1-5 | ~1 |
| Photons per pulse | ~2 $10^{14}$ (100 nm) | ~1 $10^{13}$ (10 nm) |
| Brightness (Ph/s/mm$^2$/mrad$^2$/0.1%BW) | ~6 $10^{32}$ | ~$10^{32}$ |
| Power fluctuation (%) | ~25 | > 50 |
| Central wavelength fluctuation | Within BW | Within BW |
| Pointing fluctuation (μrad) | < 5 | < 5 |
| Source size FWHM (μm) | 290 | 140 |
| Divergence rms (μrad) | 50 (40 nm) | 15 (10 nm) |
| Repetition rate (Hz) | 10 - 50 | 10 - 50 |

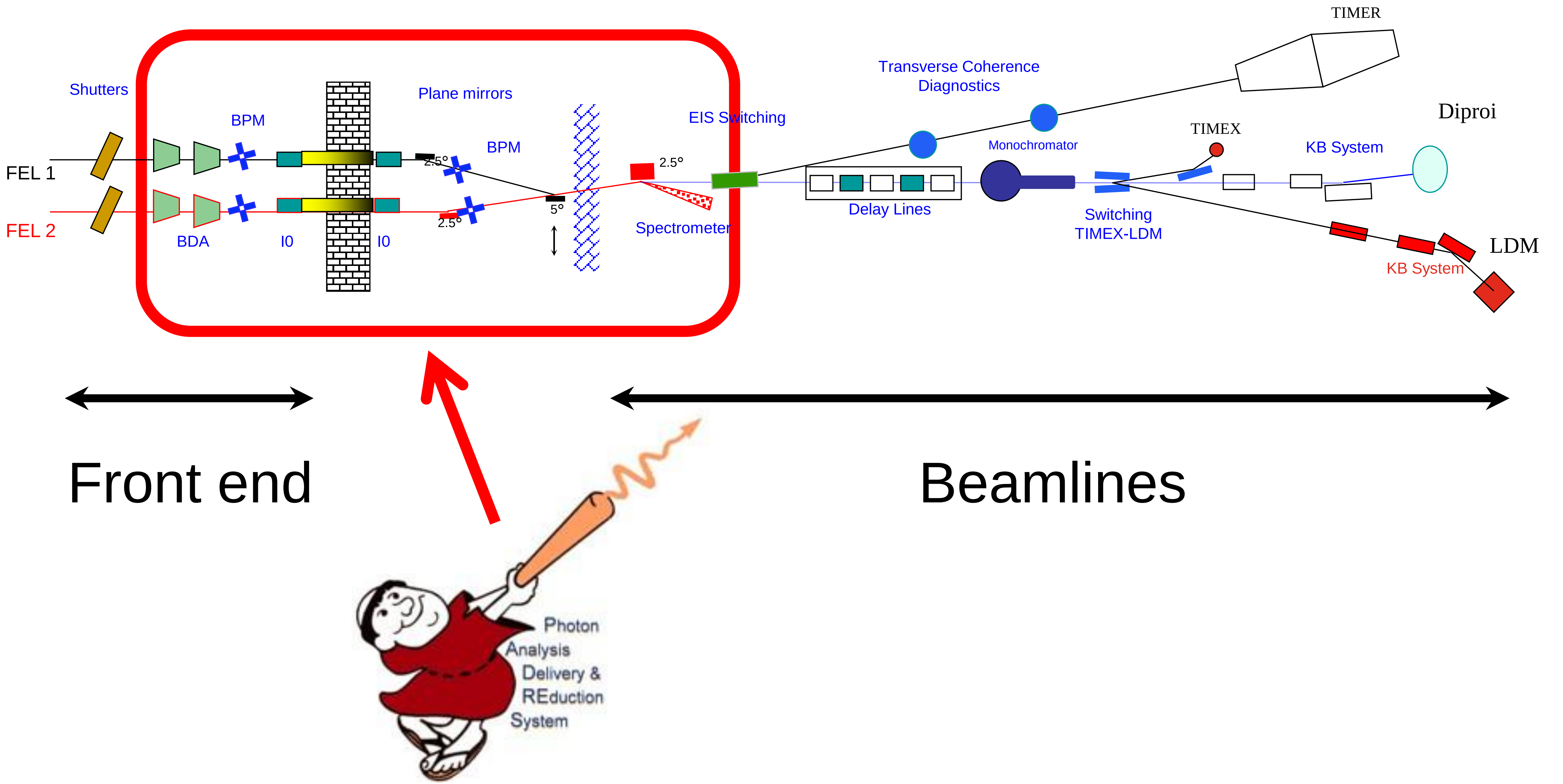
# Users requests

Perfect knowledge of:

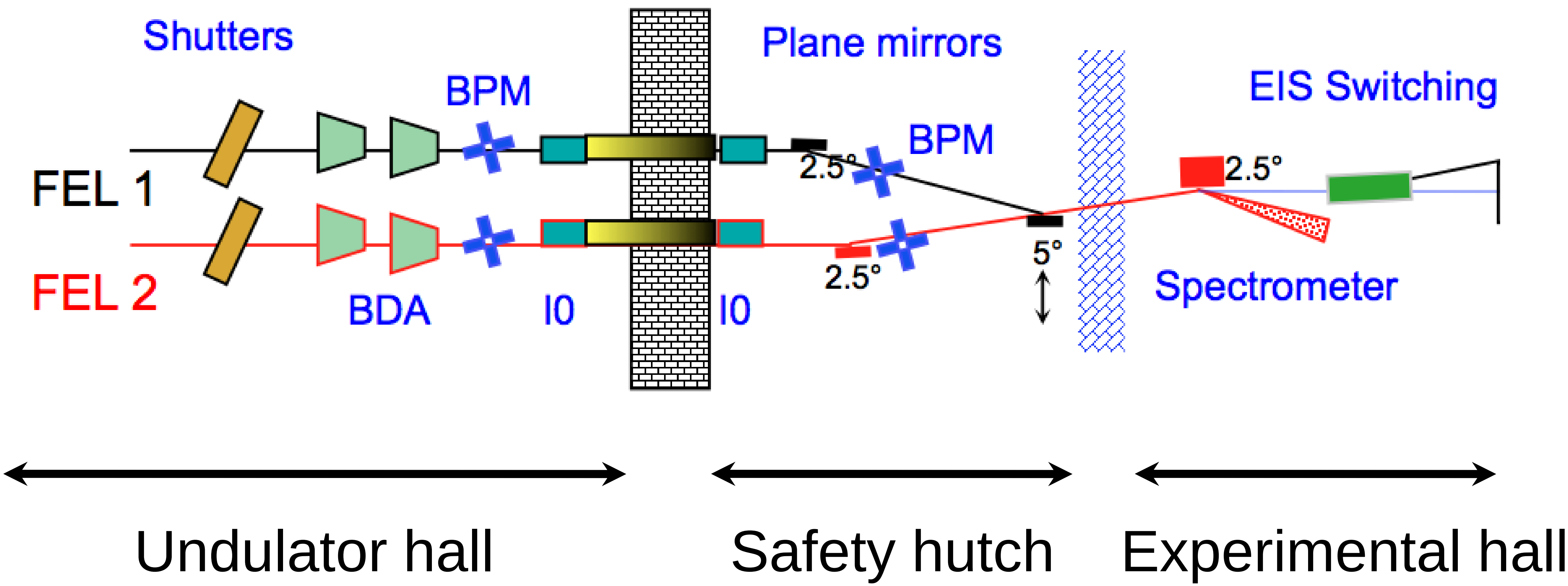
| | |
|---|---|
| **Intensity** | photons/pulse |
| **Photon energy** | eV |
| **Spectral distribution** | meV-resolution |
| **Beam (angular) position** | µrad |
| **Pulse length** | fs |
| **Focus size** | µm-resolution |
| **Wavefront/Coherence** | |
| **…** | |

***...OF EACH PULSE & DURING THE EXPERIMENT !!!***

## Where can we put some diagnostics?

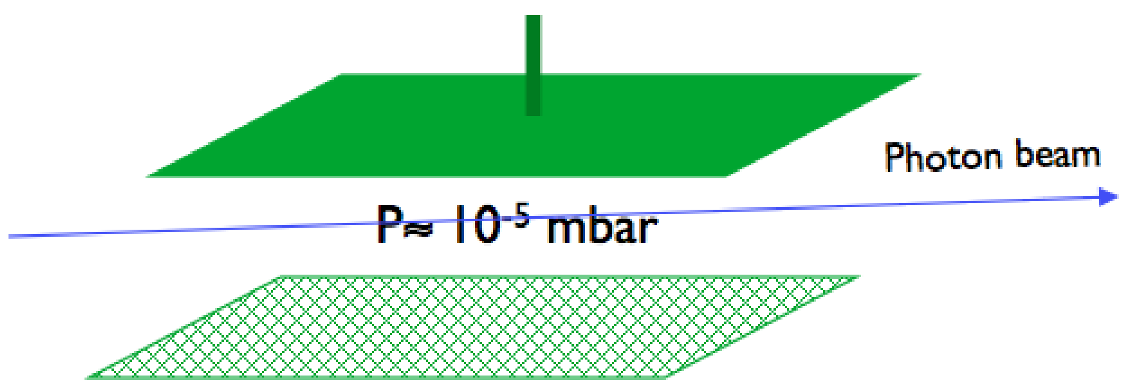


**Target**: collect both FEL paths, diagnose, and redirect to the beamlines



# Intensity monitor

Collected n/pA signal by using an already internally developed fA precision acquisition board (ref. D. Giuressi)




Applied Voltage (Bias)
+ or - depending on tests/noise

Calibrated with High precision IRD photodiodes
(4% absolute calibration, <0.1% repeatability)

The $I_0$ monitor:

- Works online and shot-to-shot
- Is transparent
- Measures the number of photons of each pulse (~3% precision, 1% reproducibility)


MAIN FEATURES

- ULTRA-WIDE INPUT CURRENT RANGE **(from ±140 fA up to ±10 mA)**
- 1, 2, 4-CHANNEL MONITORING
- MULTIRESOLUTION
  - 16-BIT MODE
  - 24-BIT MODE
- LOW NOISE (3 ppm of Full Scale)
- LOW DRIFT (3 ppm/°C)
- MODULAR COMMUNICATION INTERFACE
  - RS-232
  - USB
  - Ethernet TCP/IP
  - Ethernet UDP
  - Wi-Fi (under test)

APPLICATIONS

- 4-QUADRANT BPM (BEAM POSITION MONITOR)
- ION CHAMBERS
- FAST FEEDBACK APPLICATIONS
- GENERIC MULTICHANNEL SIMULTANEOUS CURRENT ACQUISITION

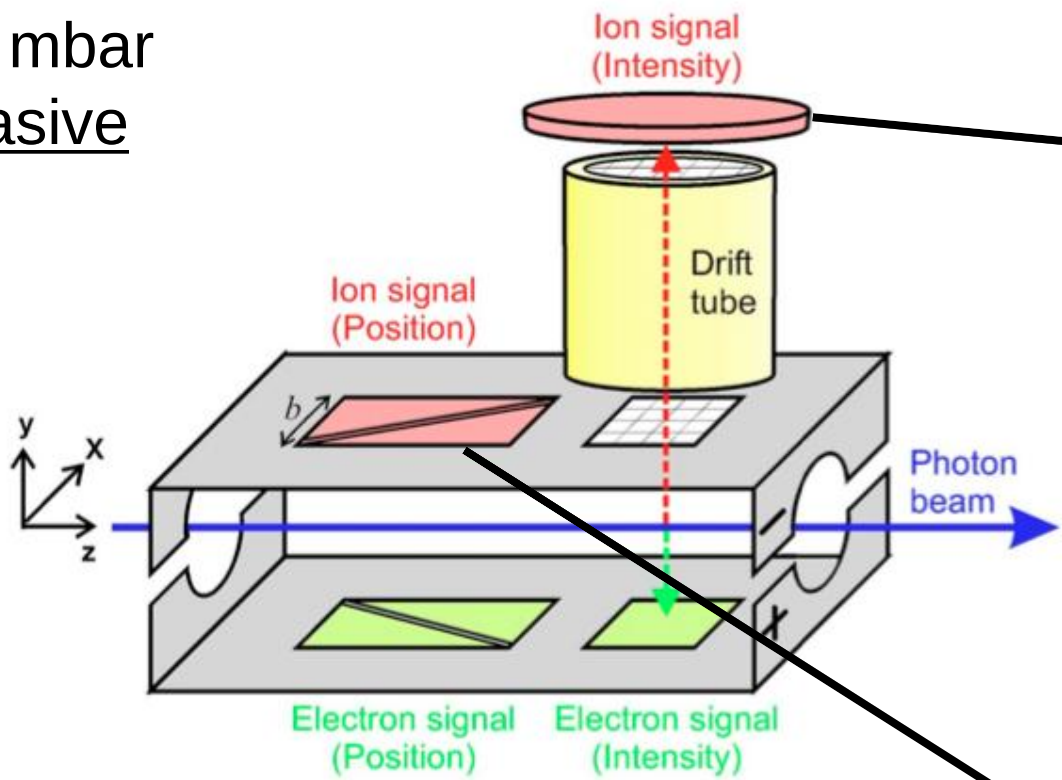
Ref. E. Braidotti (CAENELS-Elettra)

# FLASH Gas Monitor Detector

Tiedtke, et al., J. Appl. Phys. 103 (2008) 094511

$p$ ~ $10^{-5}$ mbar

<u>non invasive</u>




$$N_{particle} = N_{photon} \cdot \sigma(h\nu) \cdot z \cdot \eta \cdot n$$

$N_{particle}$ = number of detected particles

$N_{photon}$ = number of photons

$\sigma$ = photoionization cross section

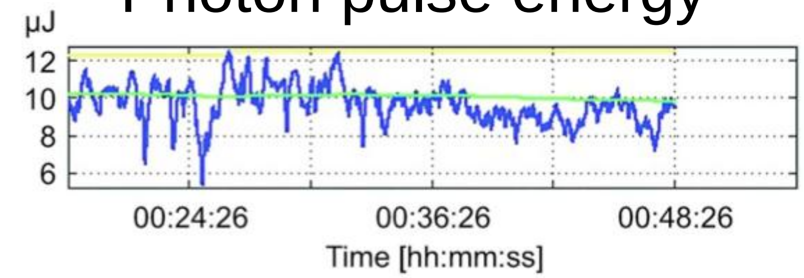
$z$ = detector acceptance length

$\eta$ = ion detection efficiency

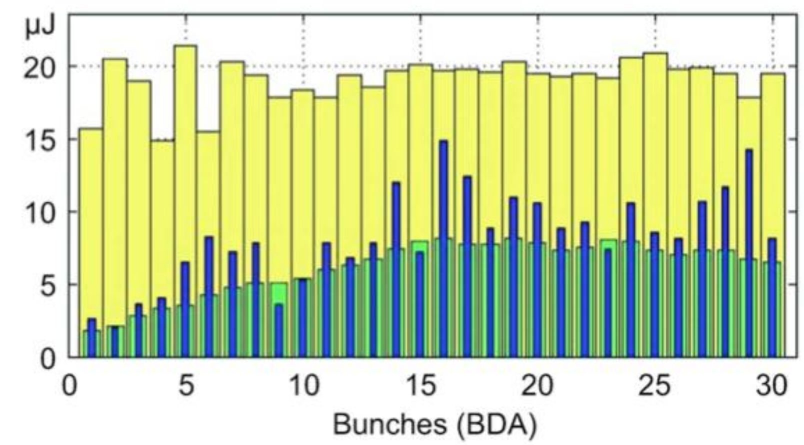
$n$ = atomic gas density (p and T required)

GMD measurements to be done at FERMI@Elettra within the IRUVX-PP European Project (FP7) - WP3

Photon pulse energy



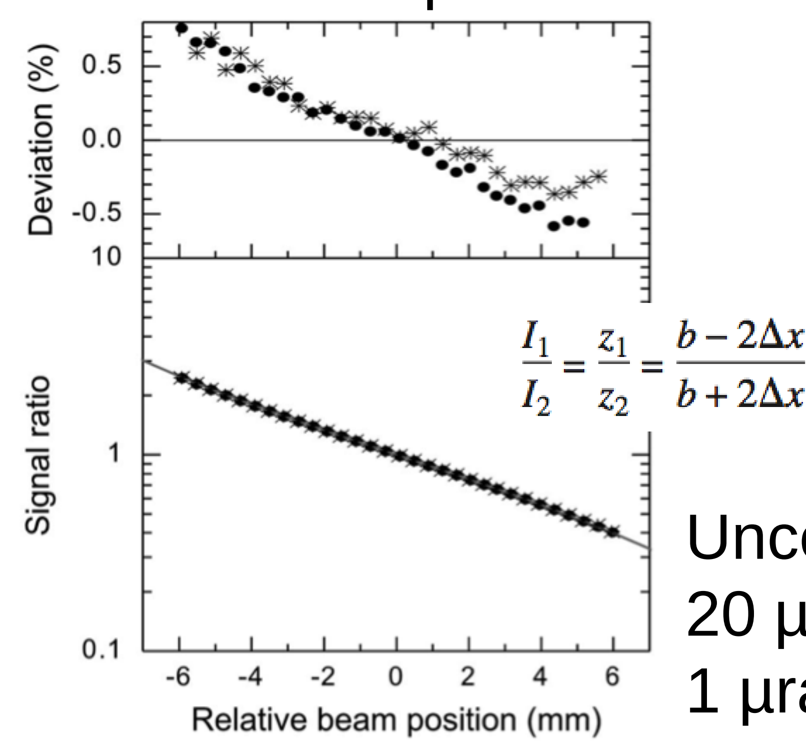

Mean




Individual pulse trains

Uncertainty <7%

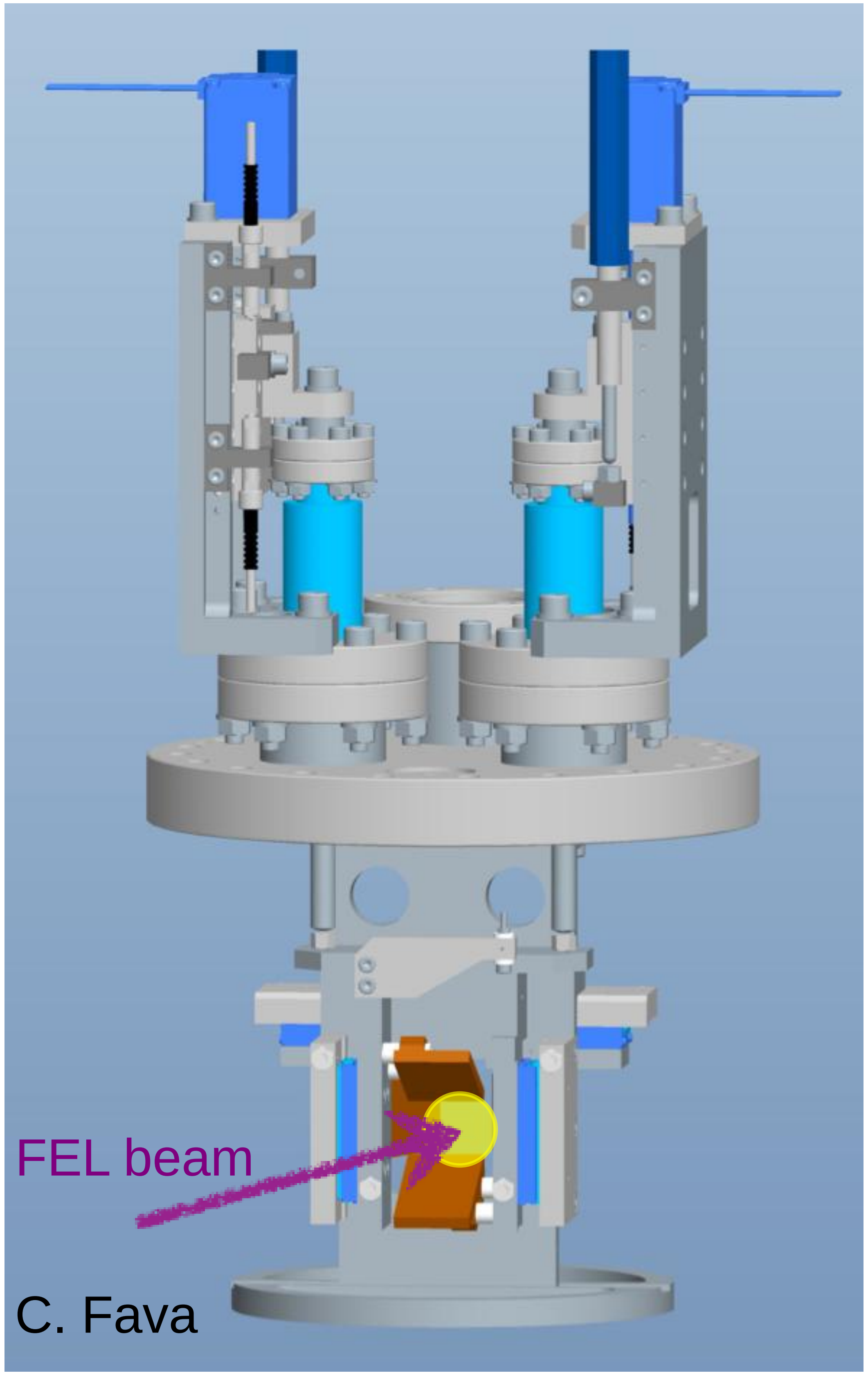
Photon beam position




Uncertainties

20 μm

1 μrad ✓




The BPM:

- Works online and shot-to-shot
- Intercepts 1% of FEL radiation
- Measures the relative position of each pulse (<2 µm rms)
- Determines the angular movement of the beam (<1 µrad)


MAIN FEATURES

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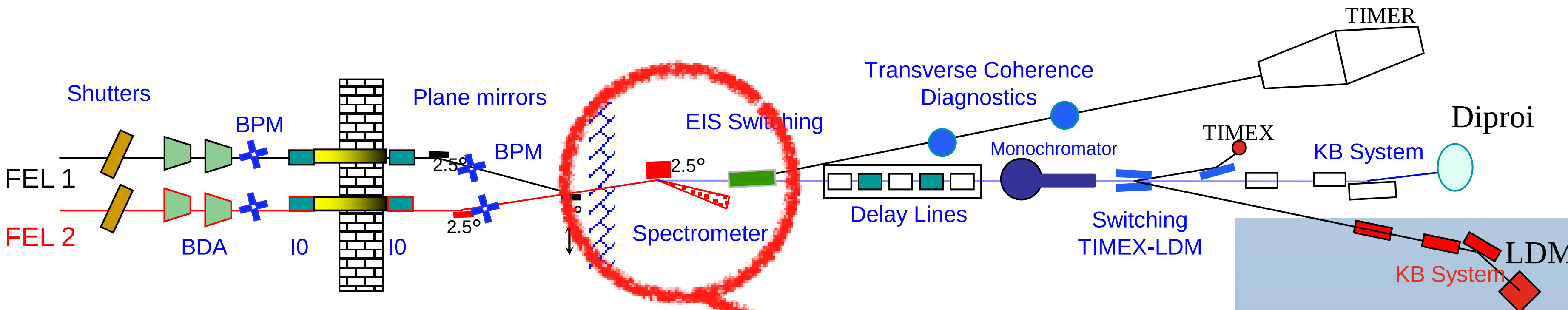
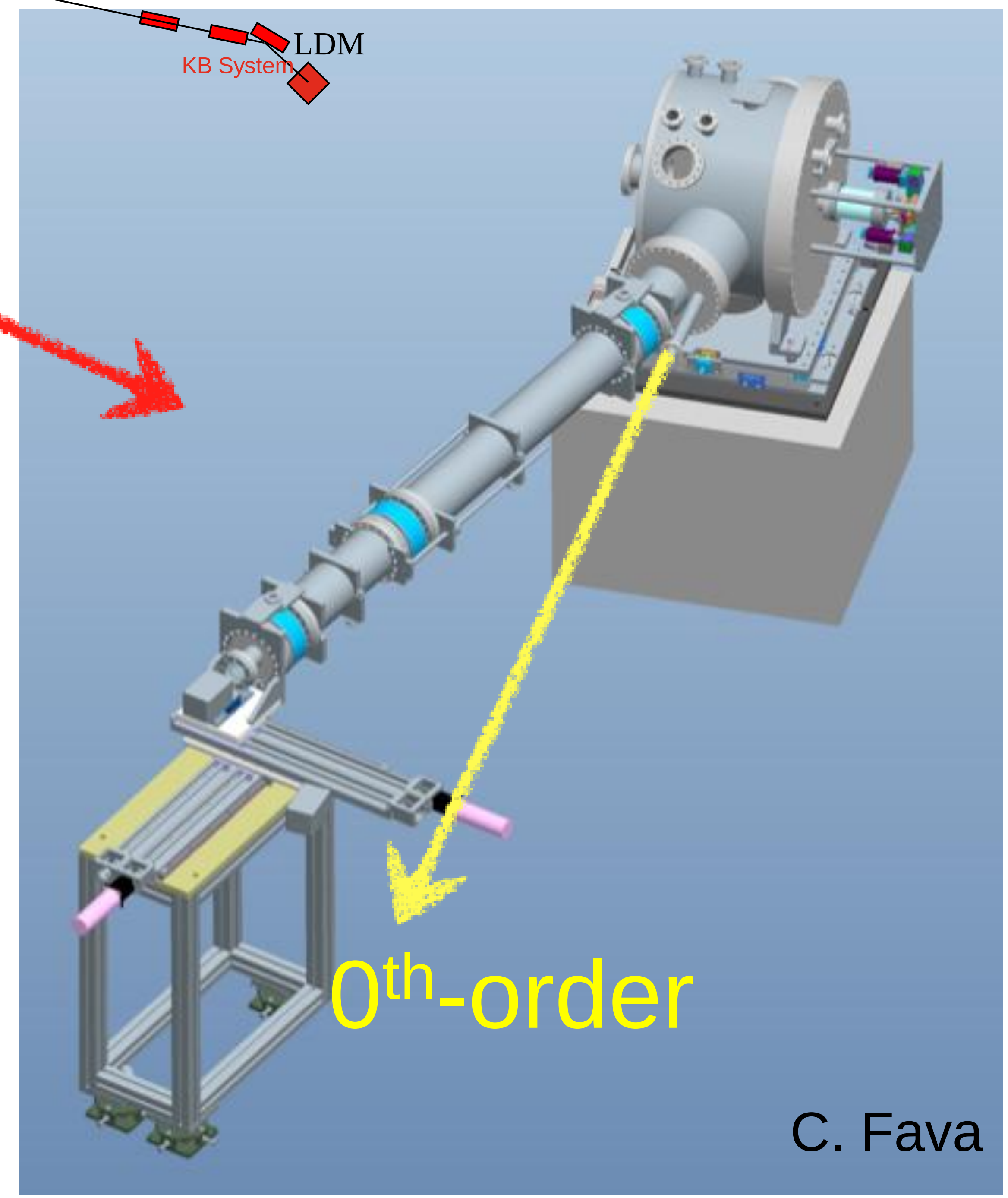


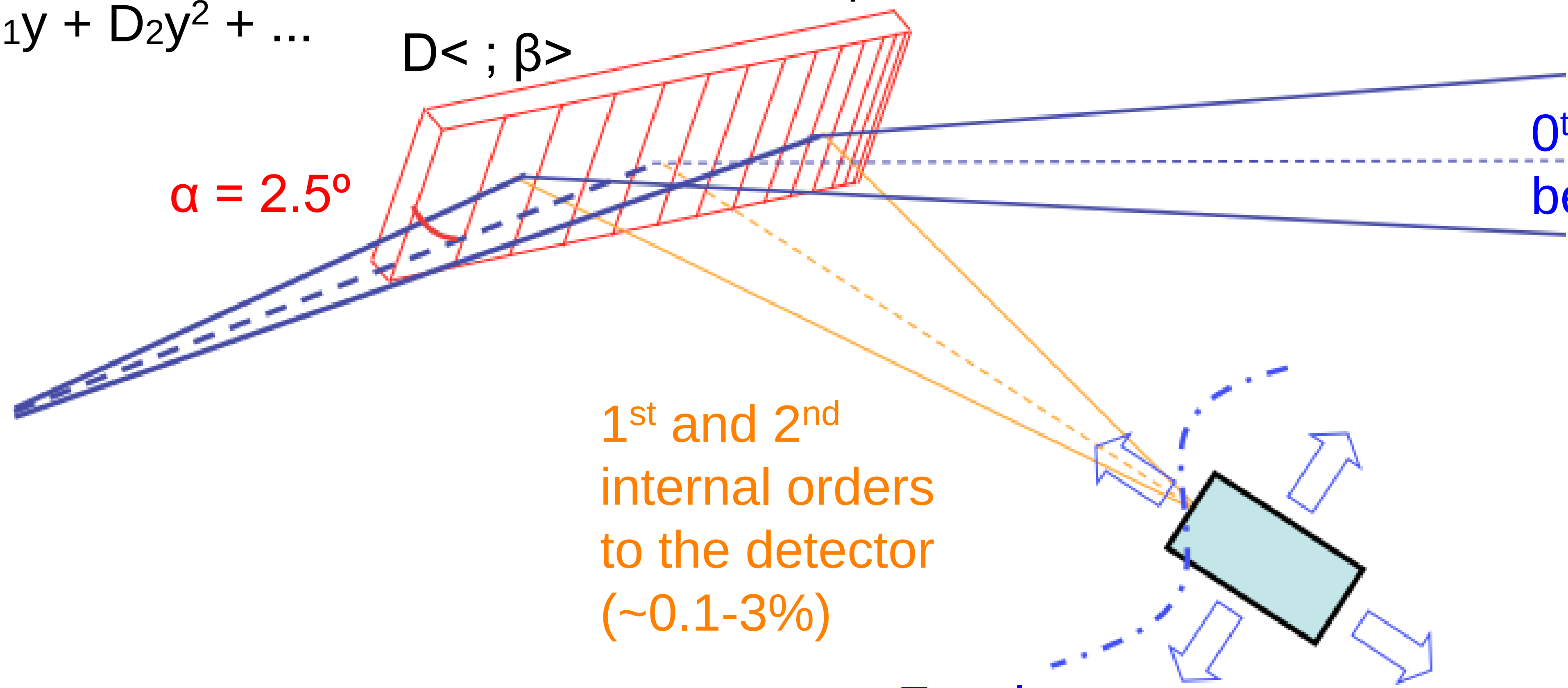

The ES:

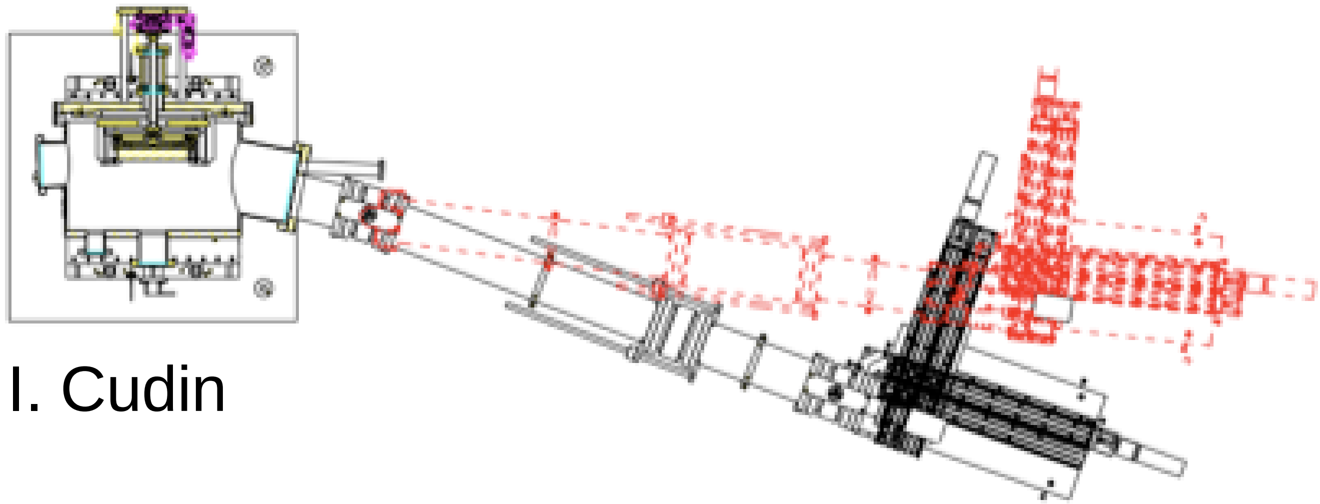
- Works online and shot-to-shot
- Uses~3% of FEL radiation
- Measures the photon energy

(ΔE: sub-meV to few meV)

# VLS gratings

Groove density expanded in Taylor series:
$D(y) = D_0 + D_1 y + D_2 y^2 + \ldots$

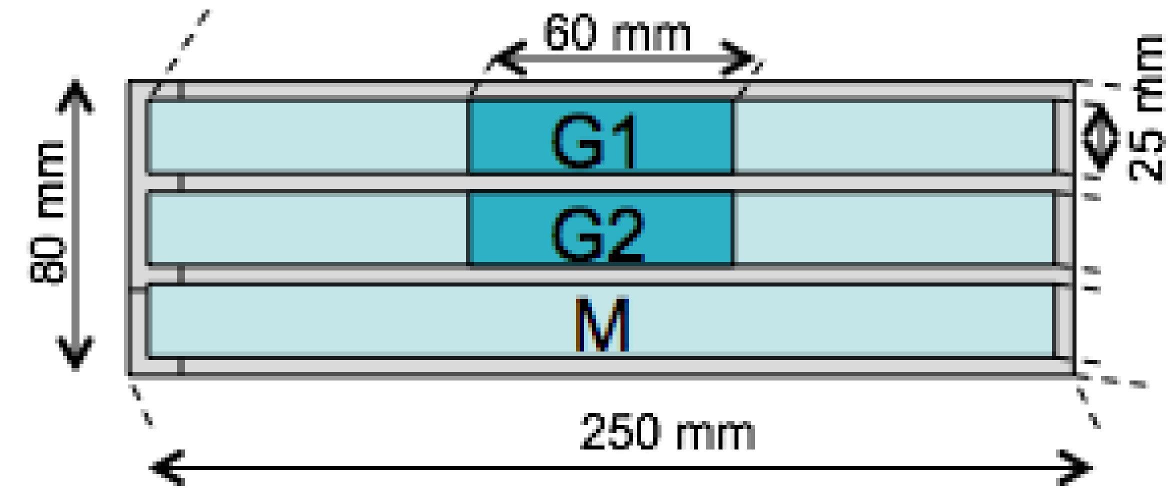


I. Cudin

# Gratings parameters

| Parameter | G1 | G2 |
|---|---|---|
| Energy range m=1 (eV) | 12-30 | 30-120 |
| Energy range m=2 (eV) | 36-90 | 90-360 |
| Energy Resolution (meV) | 0.2-2.9 | 0.3-9.5 |
| $D_0$ (l/mm) | 500 | 1800 |
| $D_1$ (l/mm$^2$) | 0.35 | 1.26 |
| $D_2$ (l/mm$^3$) | $1.7 \times 10^{-4}$ | $6.3 \times 10^{-4}$ |
| Groove profile | Laminar | Laminar |
| Groove height (nm) | 12 | 4 |
| Groove ration (w/d) | 0.60 | 0.65 |
| Coating Material / Thickness | Graphite / 50 nm | Gold / 50 nm |

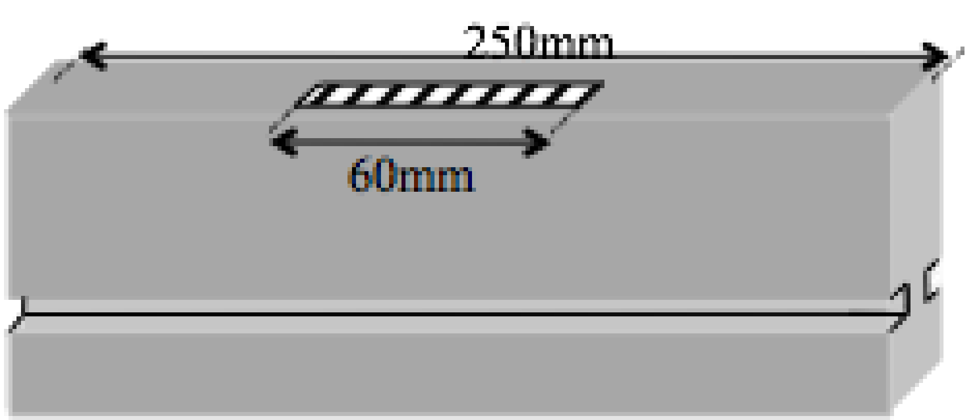



G1 1st order

| E (eV) | β (deg) | r' (mm) | ΔE sim (meV) | Spot (μm) |
|---|---|---|---|---|
| 12 | 20,4372 | 2813 | 0,2 | 3,71 |
| 16 | 17,7203 | 2851 | 0,3 | 4,24 |
| 20 | 15,8767 | 2880 | 0,5 | 4,40 |
| 24 | 14,5219 | 2904 | 0,6 | 4,92 |
| 28 | 13,4730 | 2926 | 0,8 | 4,93 |
| 30 | 13,0303 | 2937 | 0,9 | 4,96 |

G1 2nd order

| E (eV) | β (deg) | r' (mm) | ΔE sim (meV) | Spot (μm) |
|---|---|---|---|---|
| 36 | 16,7205 | 2866 | 0,4 | 4,46 |
| 48 | 14,5219 | 2904 | 0,8 | 4,95 |
| 60 | 13,0303 | 2937 | 1,1 | 4,78 |
| 72 | 11,9347 | 2966 | 1,4 | 5,33 |
| 84 | 11,0871 | 2994 | 2,2 | 5,84 |
| 90 | 10,7296 | 3008 | 2,4 | 6,30 |




G2 1st order

| E (eV) | β (deg) | r' (mm) | ΔE sim (meV) | Spot (μm) |
|---|---|---|---|---|
| 40 | 19,3944 | 2827 | 0,3 | 3,28 |
| 50 | 17,3668 | 2856 | 0,5 | 3,62 |
| 60 | 15,8767 | 2880 | 0,7 | 3,65 |
| 80 | 13,7959 | 2919 | 1,1 | 3,83 |
| 100 | 12,3844 | 2953 | 1,9 | 4,18 |
| 120 | 11,3479 | 2985 | 2,0 | 4,67 |

G2 2nd order

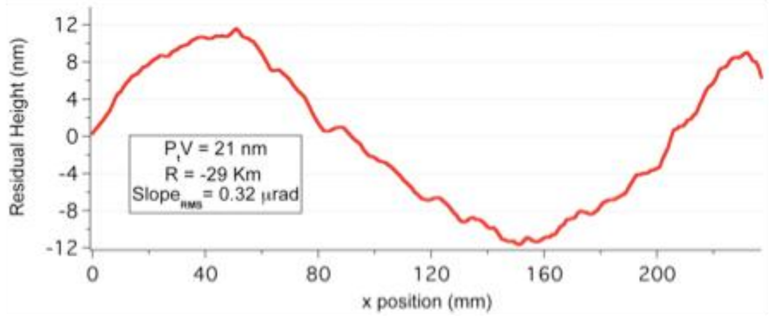
| E (eV) | β (deg) | r' (mm) | ΔE sim (meV) | Spot (μm) |
|---|---|---|---|---|
| 90 | 18,2948 | 2842 | 0,5 | 3,34 |
| 120 | 15,8767 | 2880 | 0,9 | 3,31 |
| 150 | 14,2358 | 2910 | 1,6 | 3,50 |
| 240 | 11,3479 | 2985 | 4,5 | 4,68 |
| 300 | 10,2083 | 3030 | 7,2 | 5,18 |
| 360 | 9,3728 | 3073 | 10,6 | 5,55 |

C. Svetina

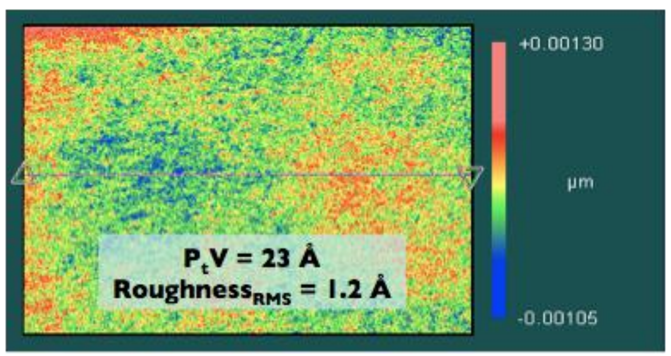
# Grating inspection & performances

## G1

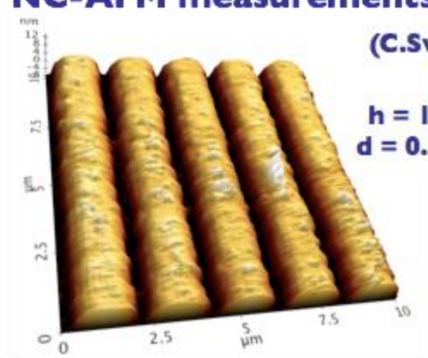
**LTP**
**(G.Sostero)**




**White Light Interferometer (G.Sostero)**



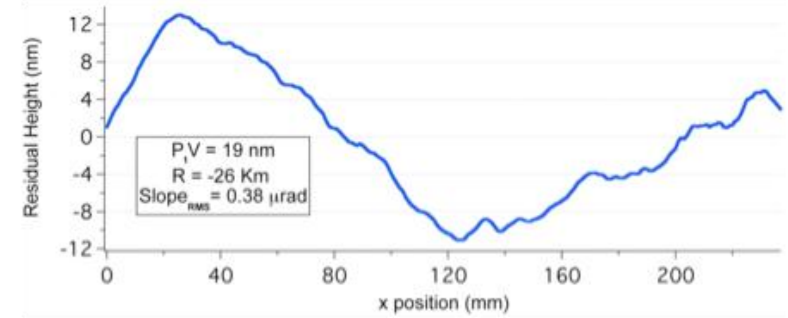

**NC-AFM measurements**
**(C.Svetina)**



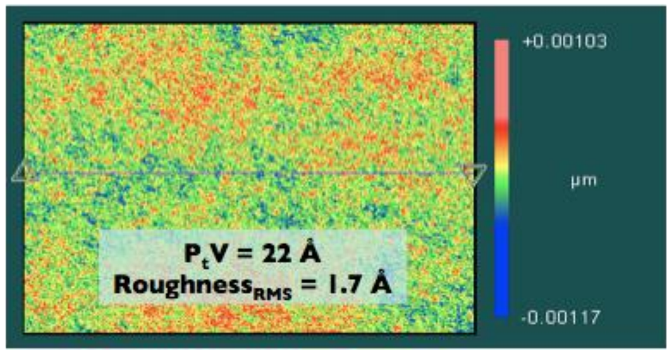
**h = 11.2 nm**
**d = 0.5 gr/µm**

## G2

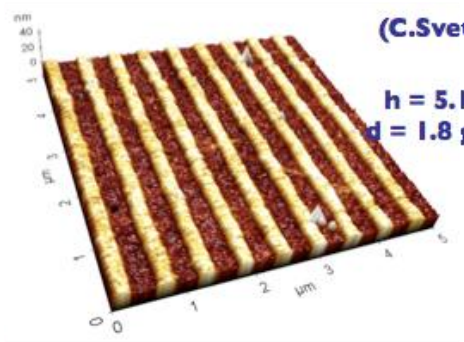
**LTP**
**(G.Sostero)**




**White Light Interferometer (G.Sostero)**

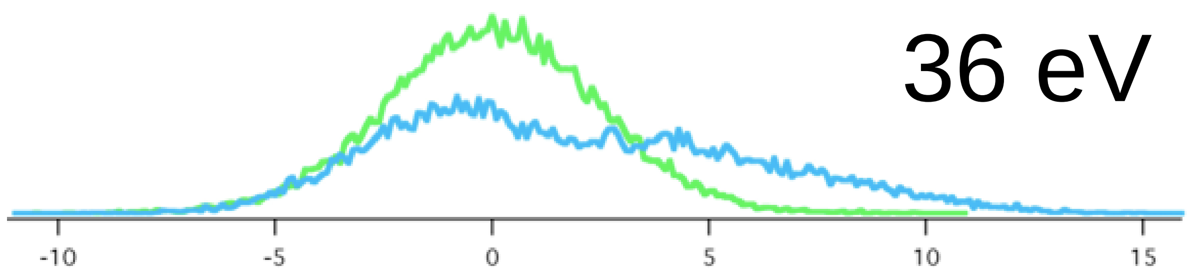


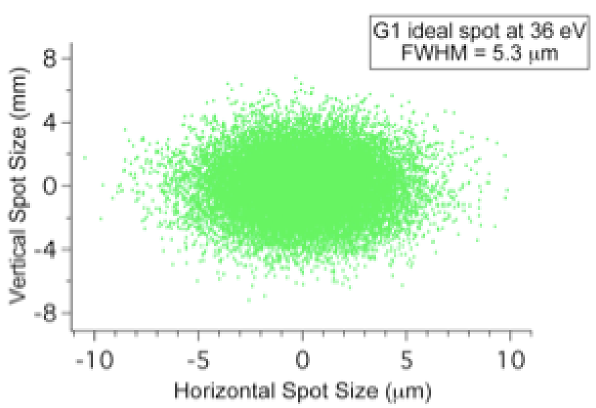

**NC-AFM measurements**
**(C.Svetina)**

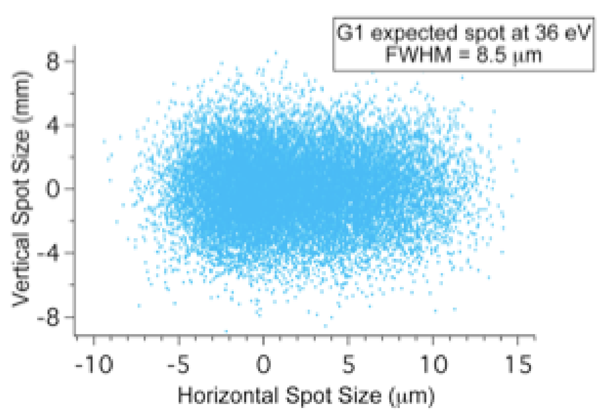


**h = 5.1 nm**
**d = 1.8 gr/µm**

36 eV

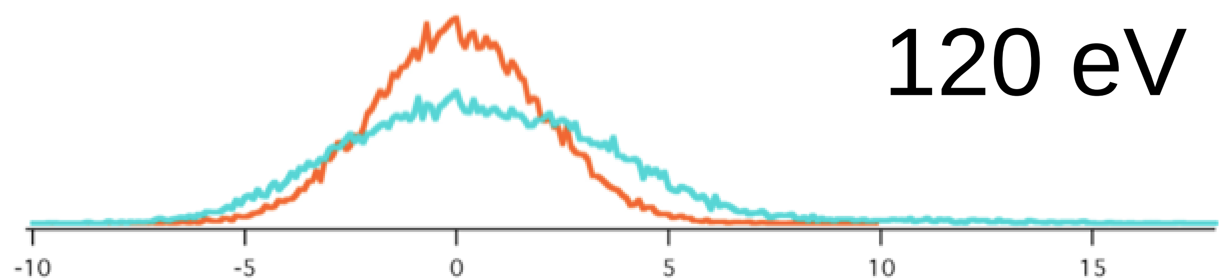


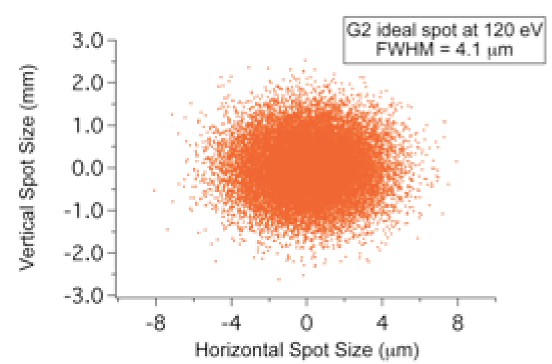


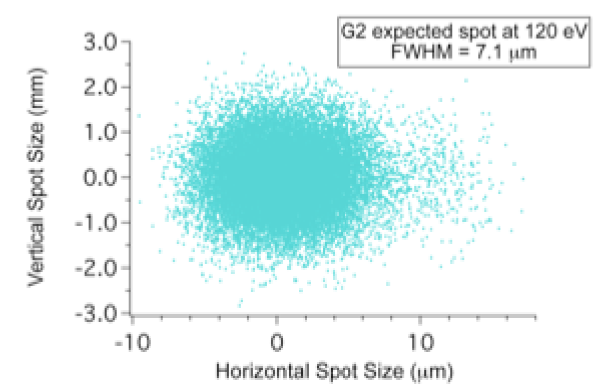




**ΔE=0.6meV → ΔE=1.0meV**

120 eV



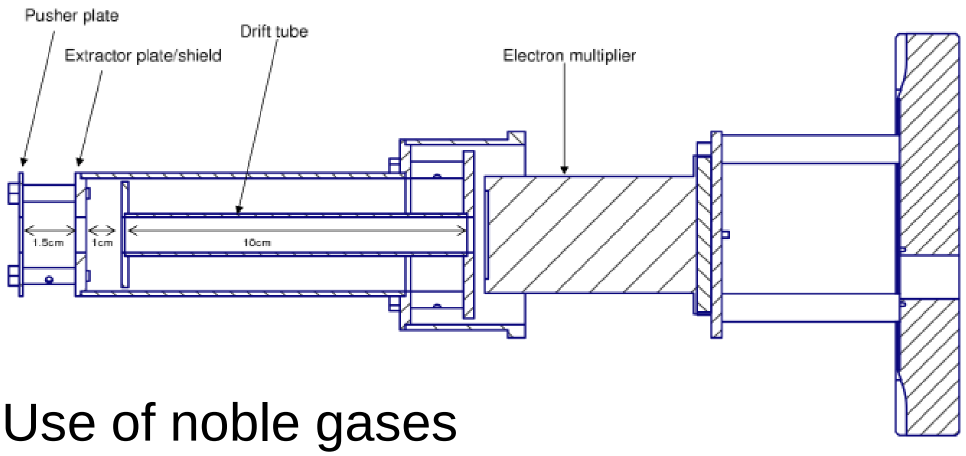


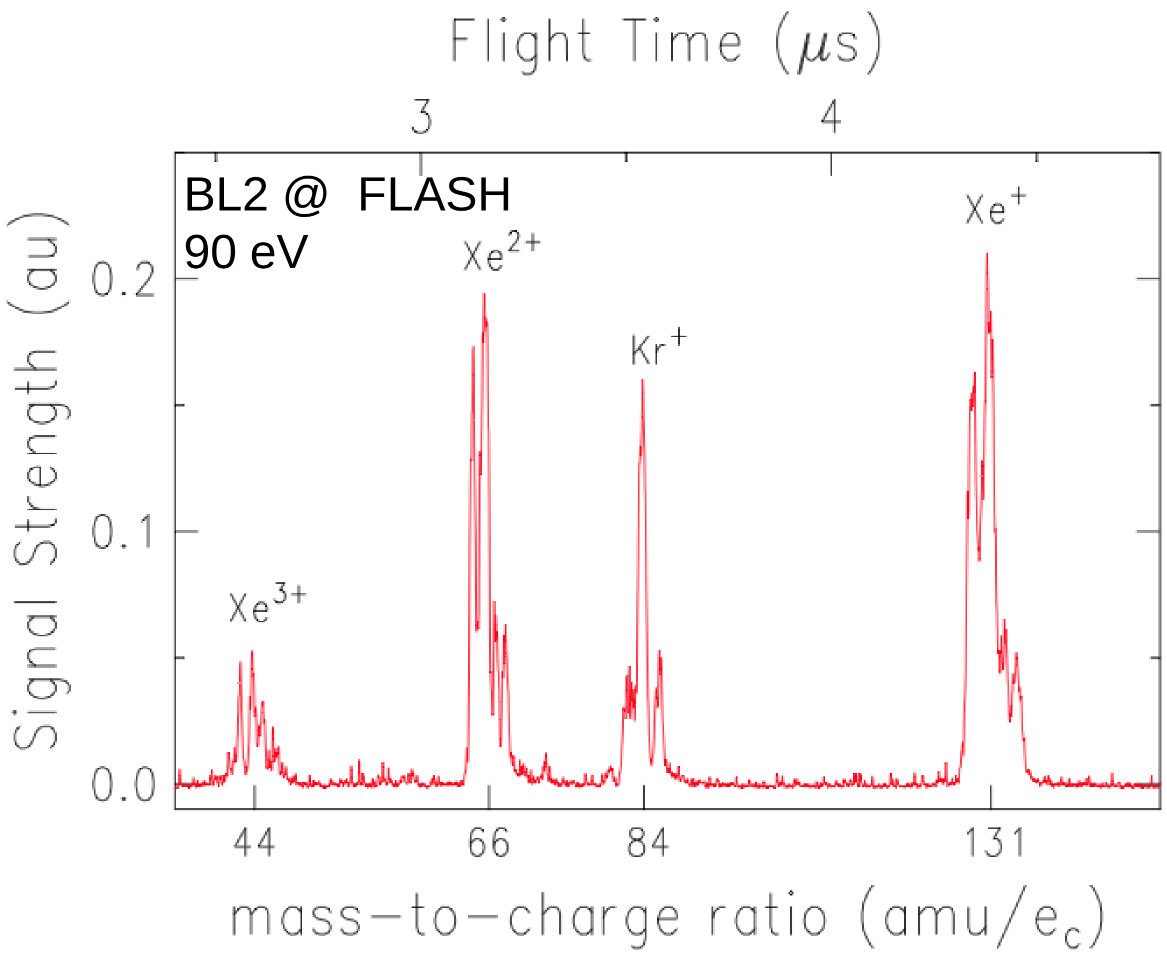




**ΔE=2.2meV → ΔE=2.7meV**

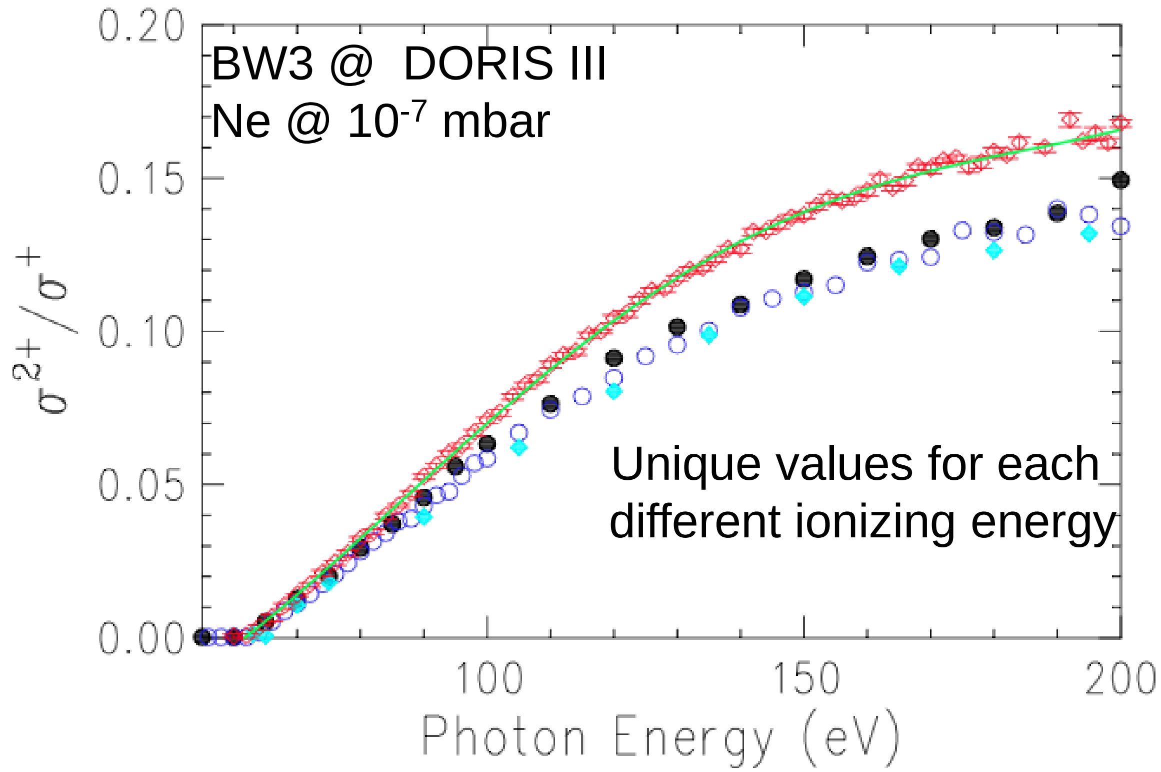
# i-TOF

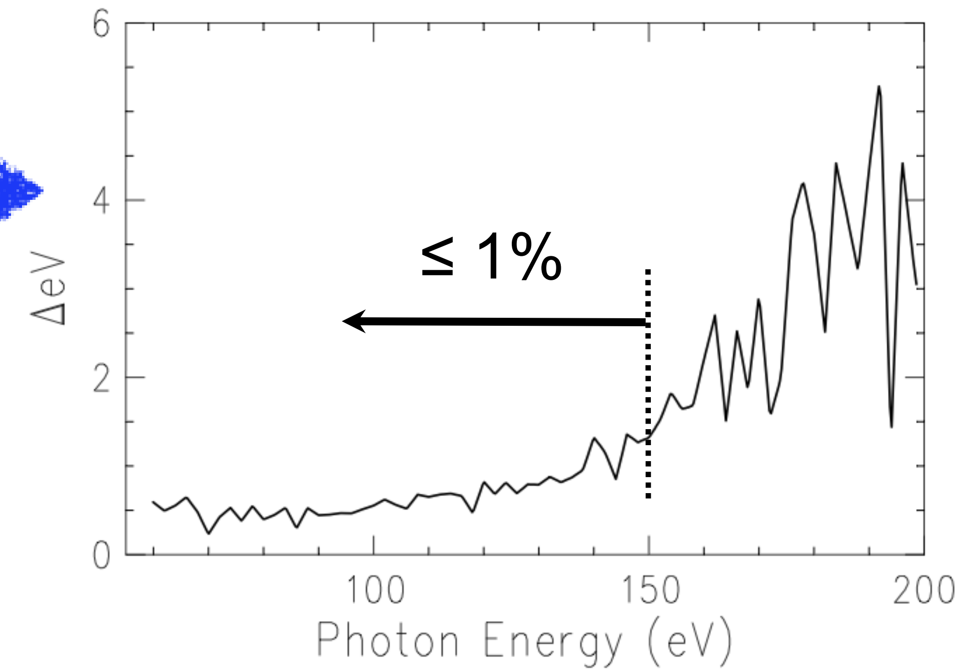
P.N. Juranić, et al., J. Inst. 4 (2009) 09011




Use of noble gases
Detect the partial cross sections
Low flux to work in single-photon photoionization
Upgradable to higher energies



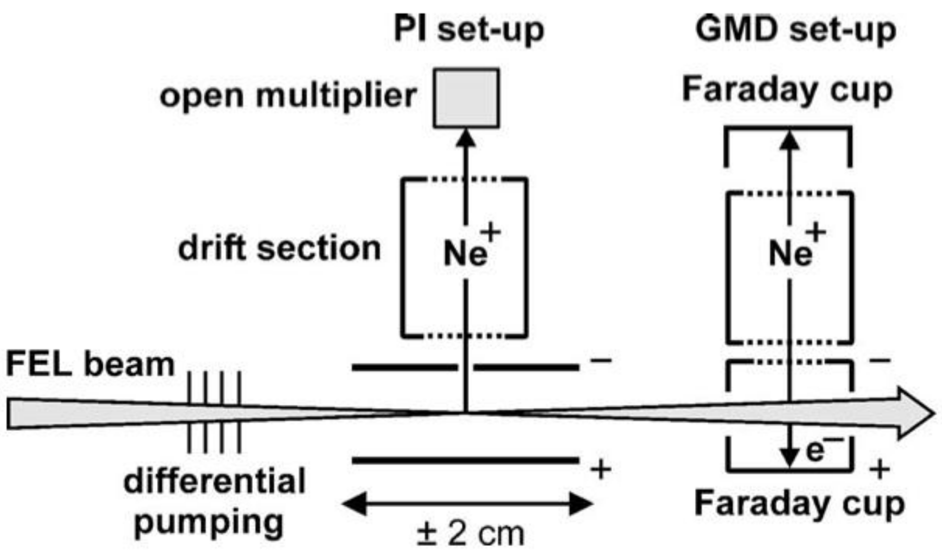



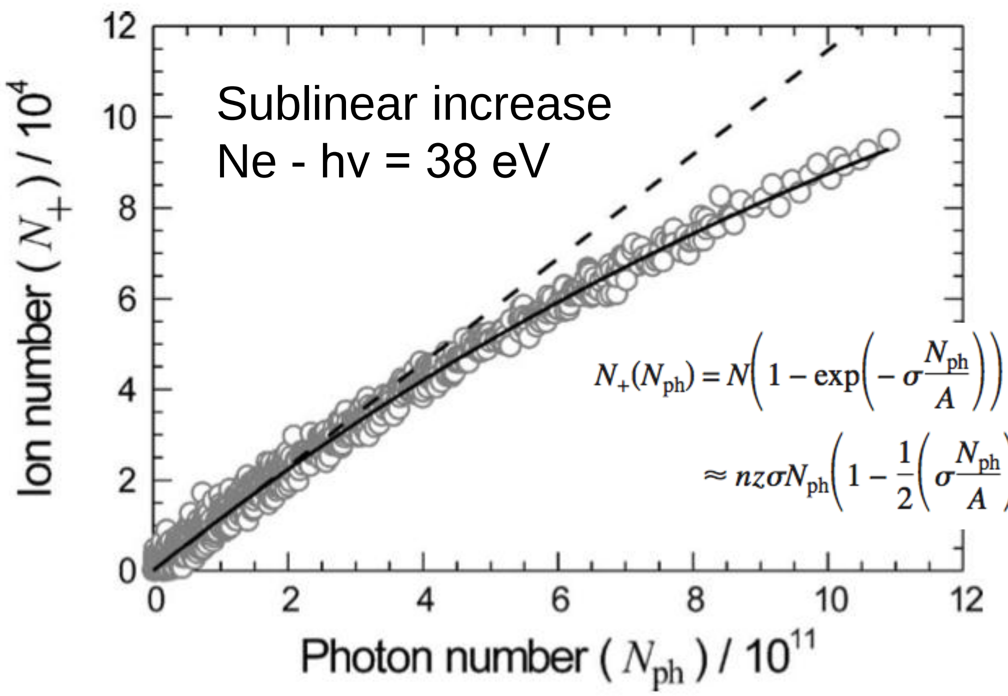
# Focus size

## Approach using a TOF- setup (FLASH)

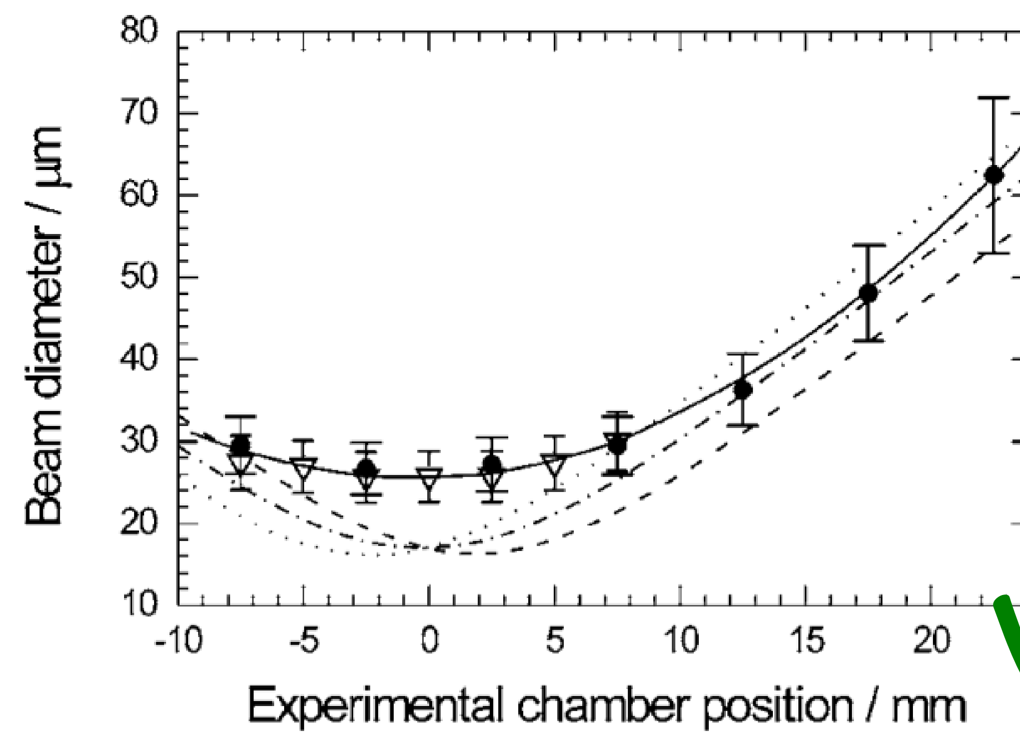
A.A. Sorokin, et al., Appl. Phys. Lett. 89 (2006) 221114

- Use of noble gases
- Used pulse: 38 eV, 25 fs (BL2)
- Not dependent on beam position
- Determination of beam waist and focus size
- Based on saturation effect upon photoionization of rare gases
- Extendable to higher (HXR) energies
- µm-resolution



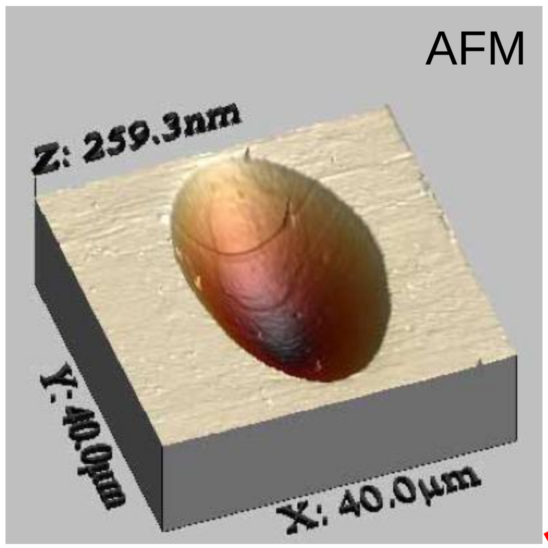

$$N_+(N_{ph}) = N\left(1 - \exp\left(-\sigma\frac{N_{ph}}{A}\right)\right)$$
$$\approx nz\sigma N_{ph}\left(1 - \frac{1}{2}\left(\sigma\frac{N_{ph}}{A}\right) + \frac{1}{6}\left(\sigma\frac{N_{ph}}{A}\right)^2\right)$$



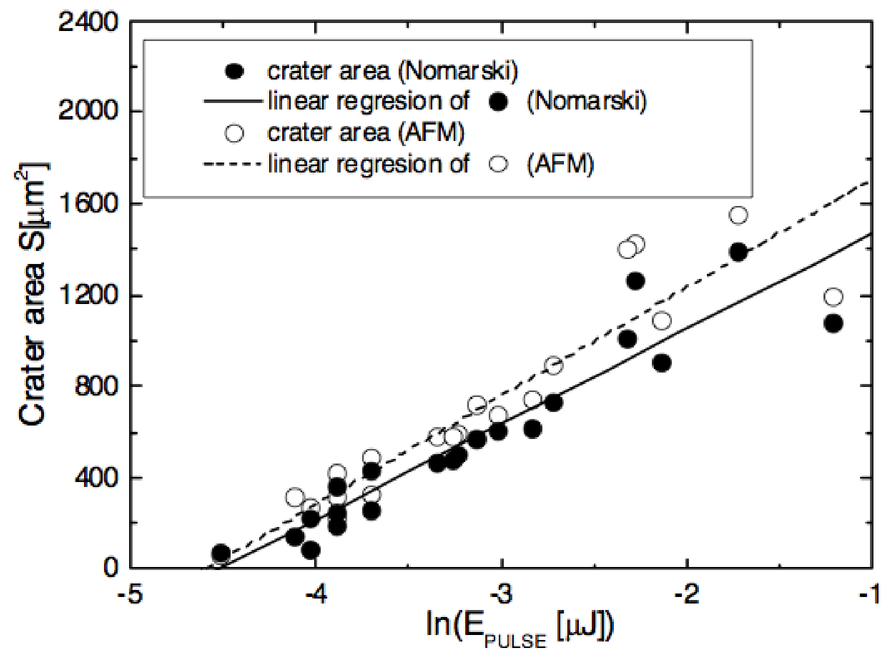
# Focus size /2

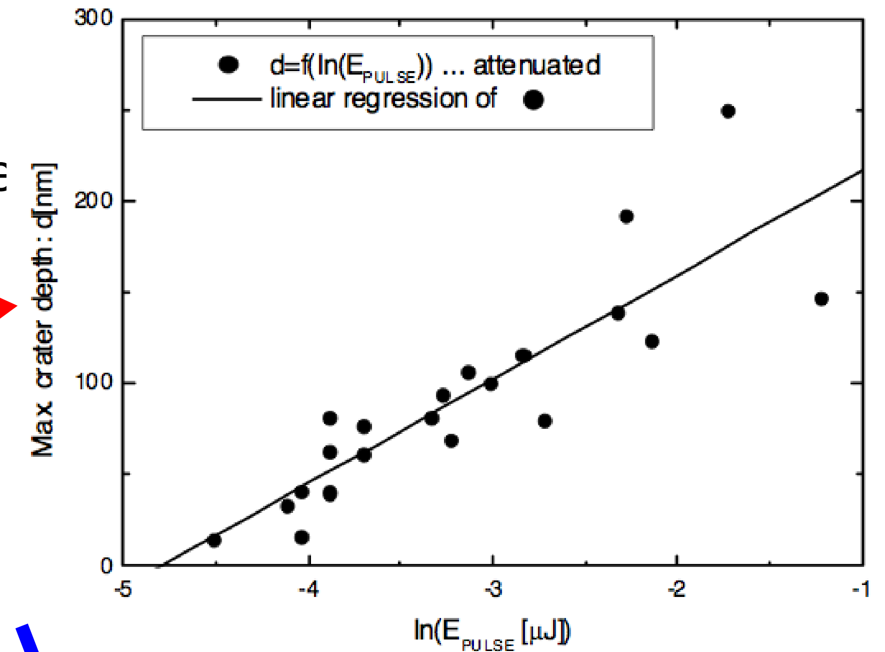
J. Chalupský, et al., Opt. Expr. 15 (2007) 6036

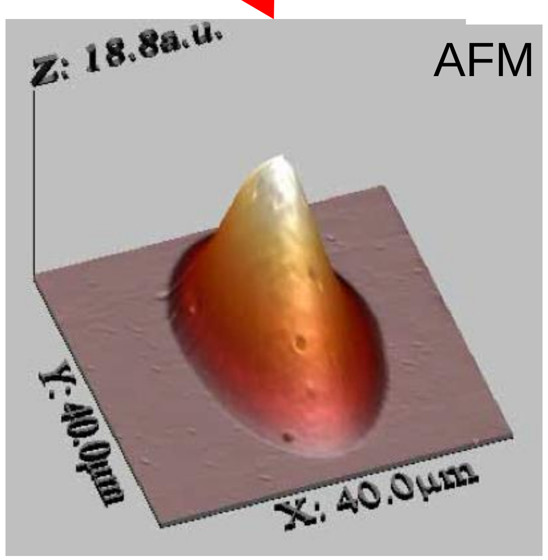
- Craters investigated with Nomarski (DIC) optical microscopy and AFM
- PMMA sample used (material removal governed by non-thermal processe
- Used pulse: 32 and 21.7 nm, 25 fs, 10 µJ (BL2)
- Beam diameter and shape determined (µm-resolution)




No features of thermal damage



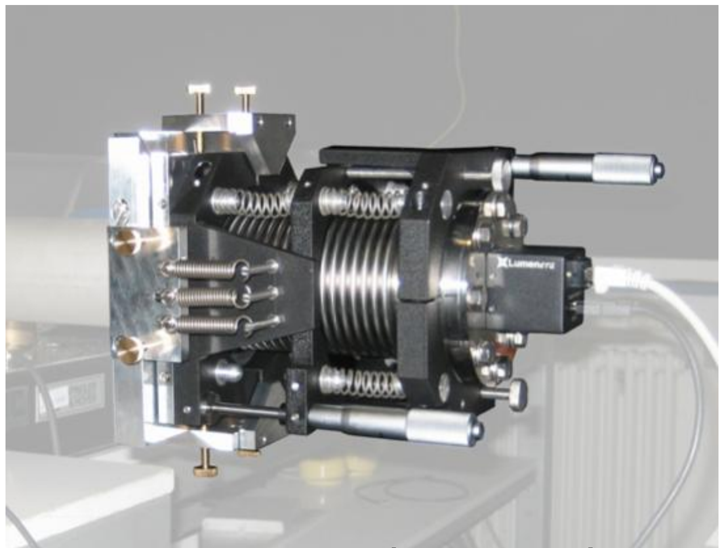




| ablation feature evaluated | type of microscope | ablation threshold $F_{th}$ [mJ/cm$^2$] | attenuation length $l_{at}$ [nm] | focal spot diameter 2ρ [µm] |
|---|---|---|---|---|
| crater area | DIC | (2.6±1.2) | --- | (23.0±0.5) |
| | AFM | (2.1±1.1) | --- | (24.6±0.6) |
| crater depth | AFM | (1.8±1.4) | (56.9±7.5) | --- |

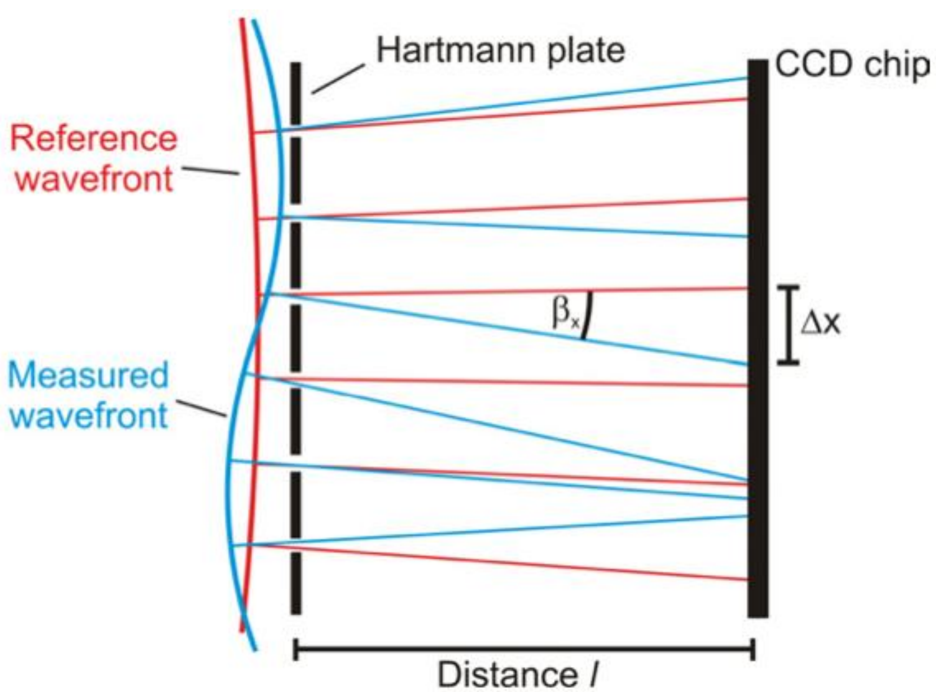
# Wavefront

B. Flöter, et al., New J. of Phys. 12 (2010) 083015

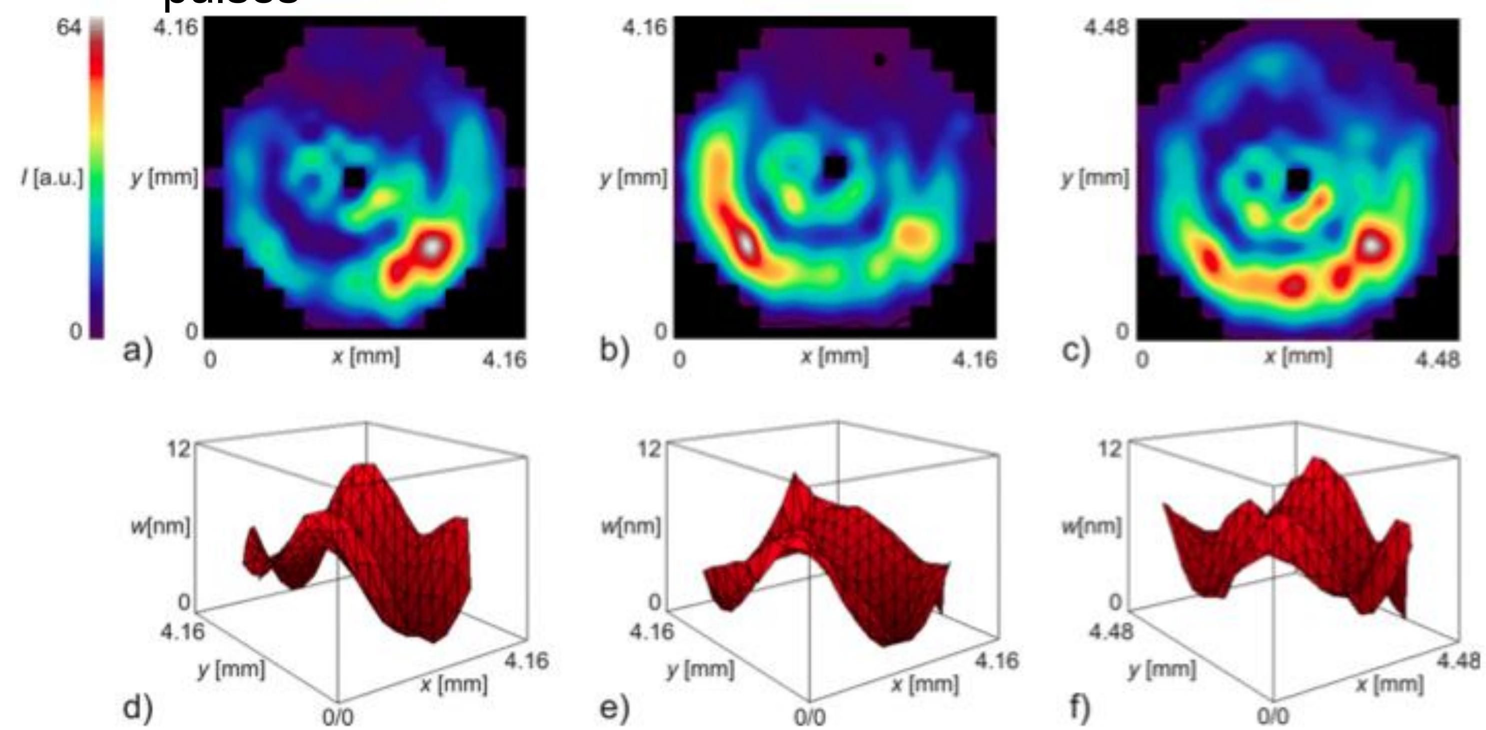


Hartmann sensor (Laser-Lab Göttingen & DESY)

Operates from 6 to 30 nm, pulse-to-pulse (BL2)
Useful also for beamline alignment and monitoring behind endstations
Used pulse: 13.8 and 25.9 nm, either attenuated or higher harmonics (BL2)
Wavefront, beam profile, divergence, waist diameter and position, etc. can be ob
Wavefront PV deformation: $w_{PV}$ ~ 14 nm ($w_{rms}$ = 2 nm)

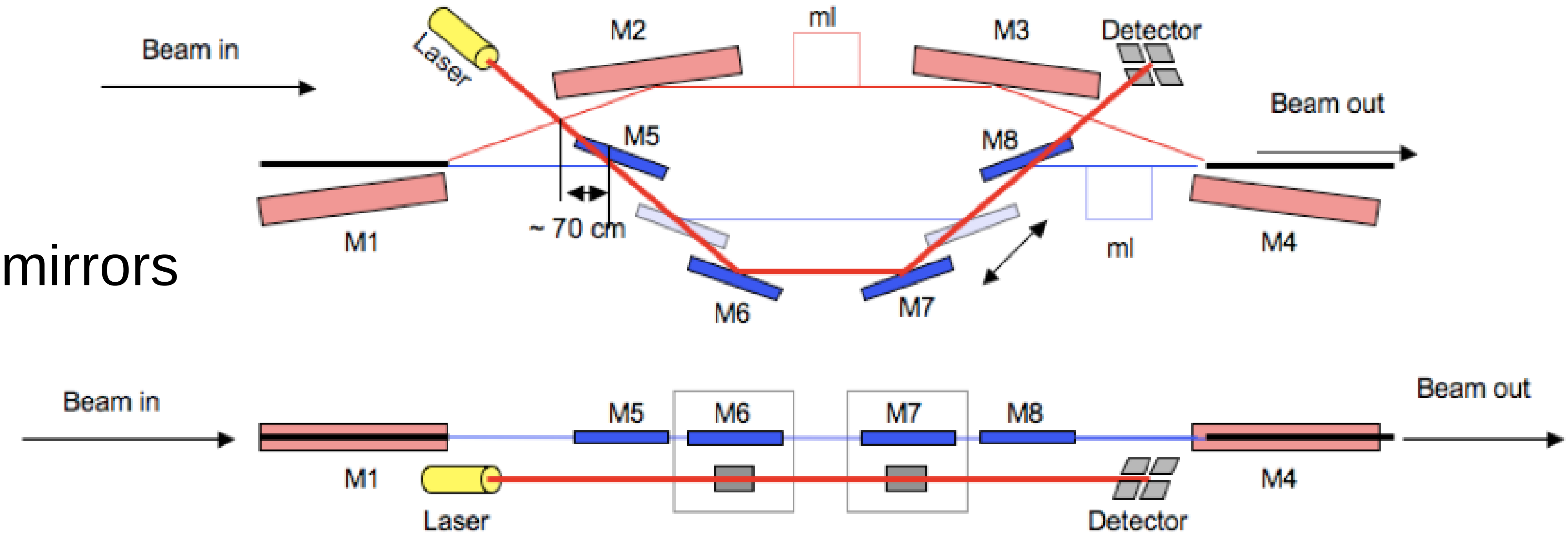



Intensity profiles and corresponding wavefronts for 3 single pulses

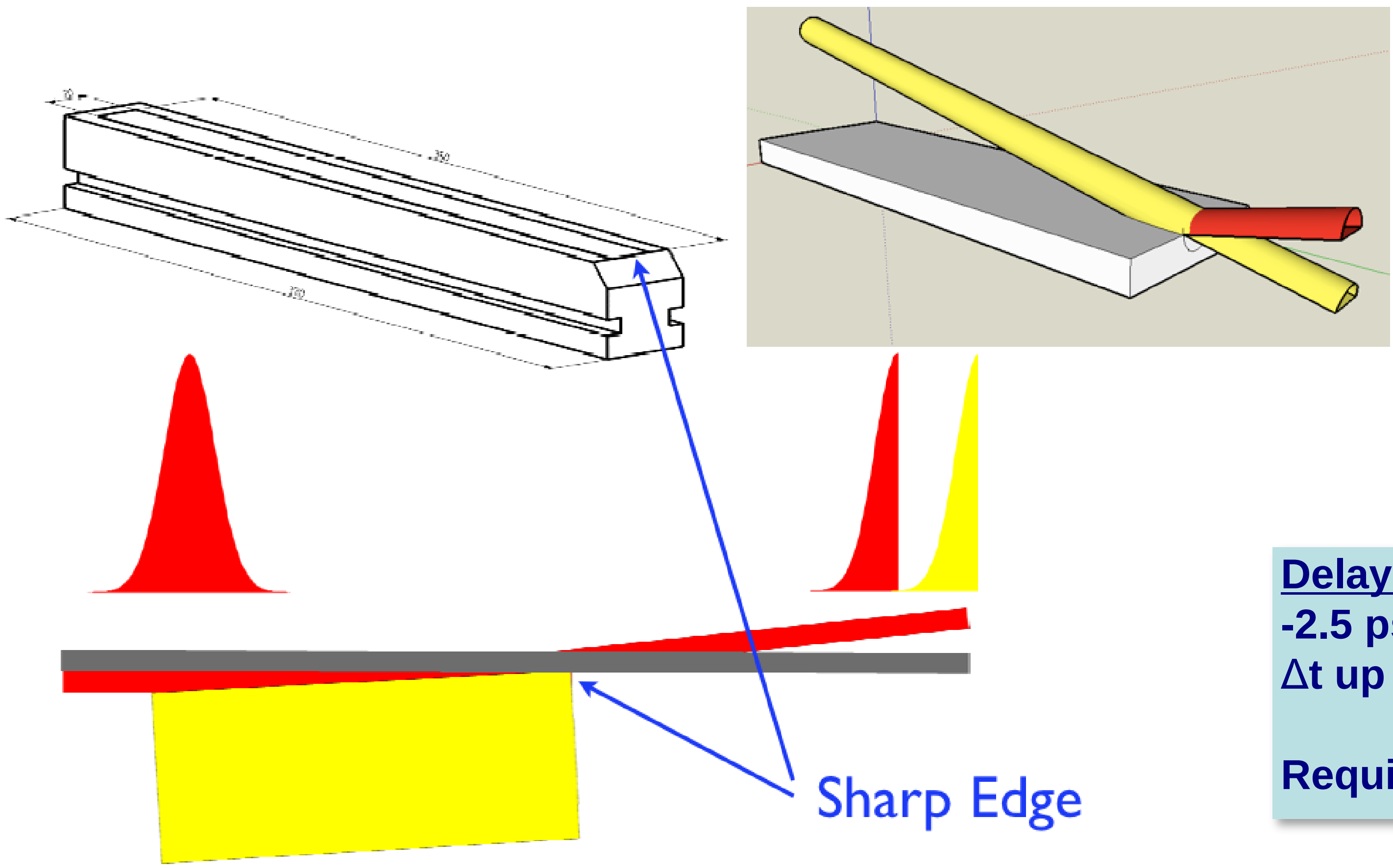



Wavefront measurements to be done at FERMI@Elettra
within the IRUVX-PP European Project (FP7) - WP3

# Beam splitting and delay




Wavefront splitting
Grazing incidence mirrors



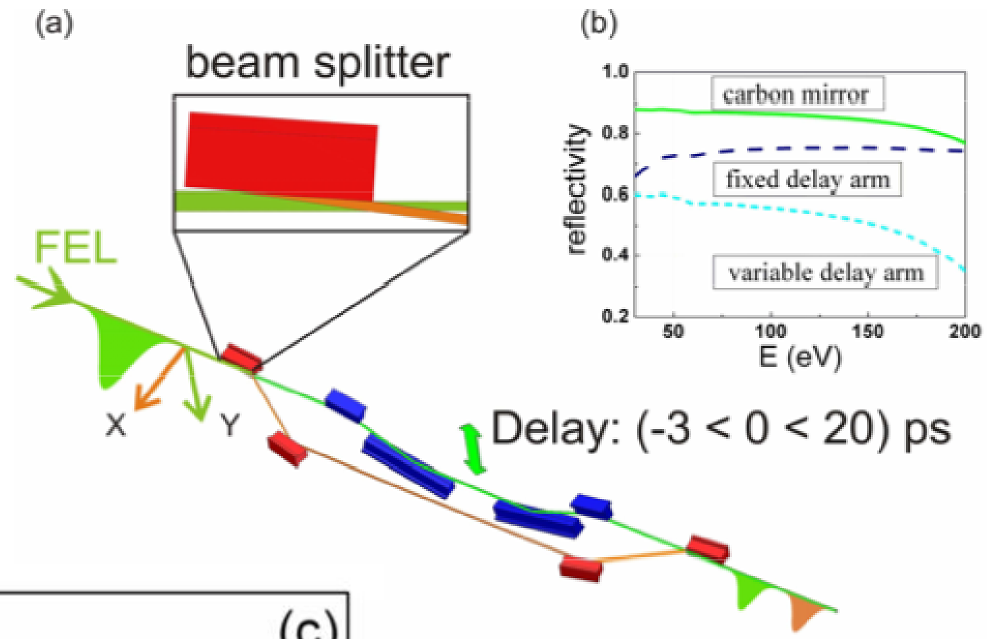

**<u>Delay line</u>**
**-2.5 ps < Δt < 35 ps without multilayers**
**Δt up to 1 ns with ML**

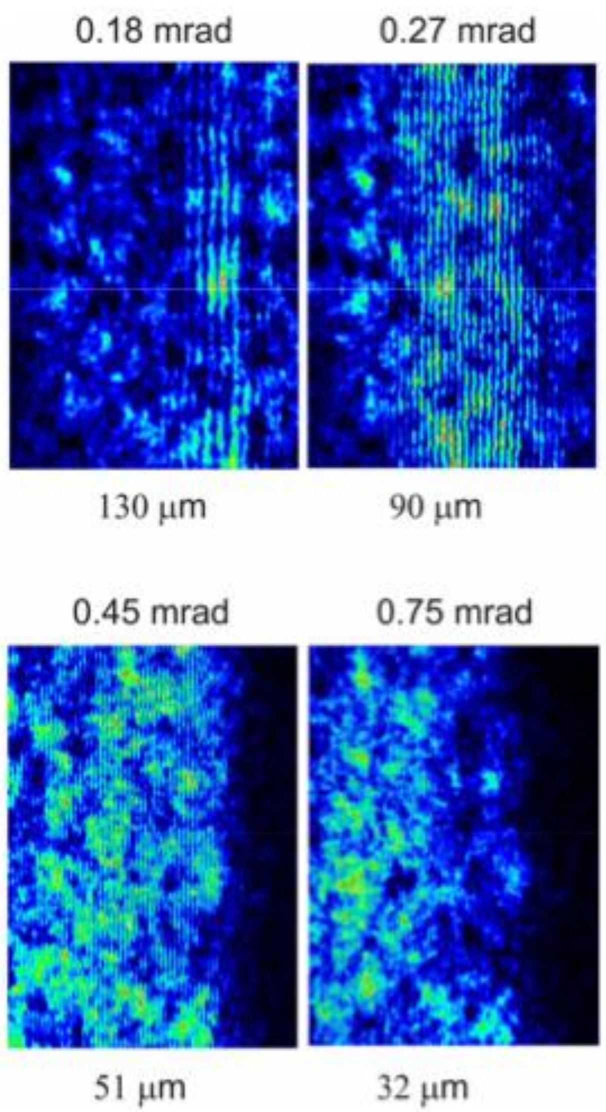
**Required movement travel and step: ~1m and few µm**

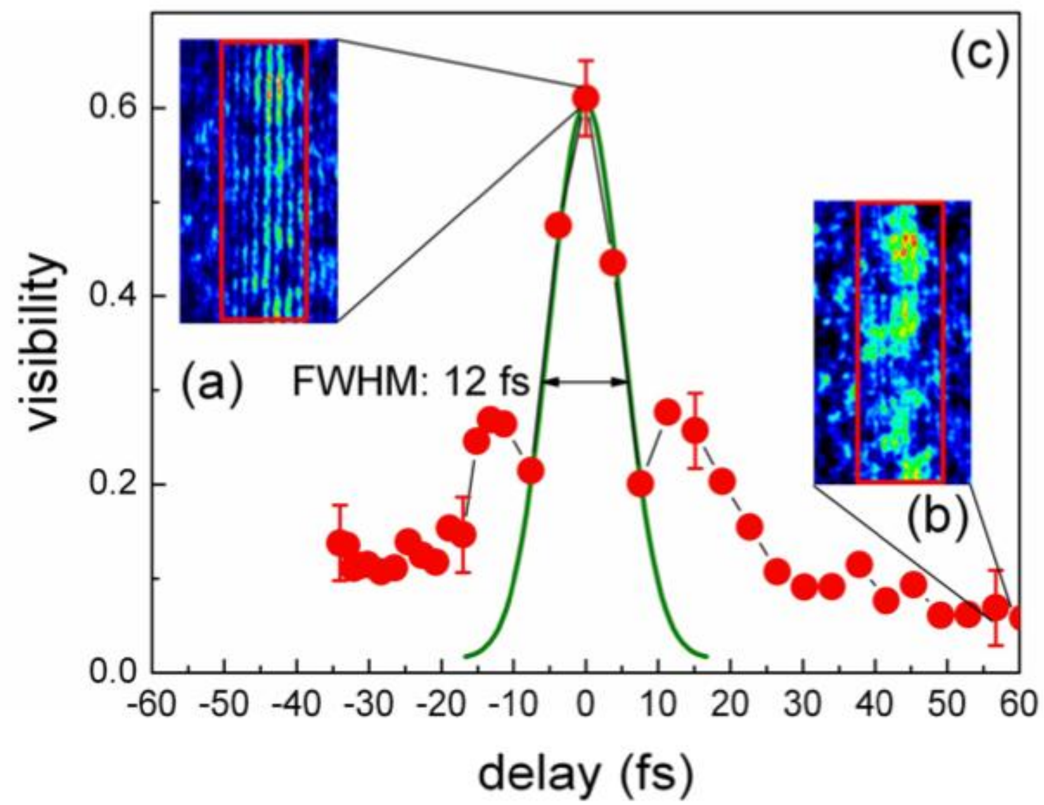
# Coherence

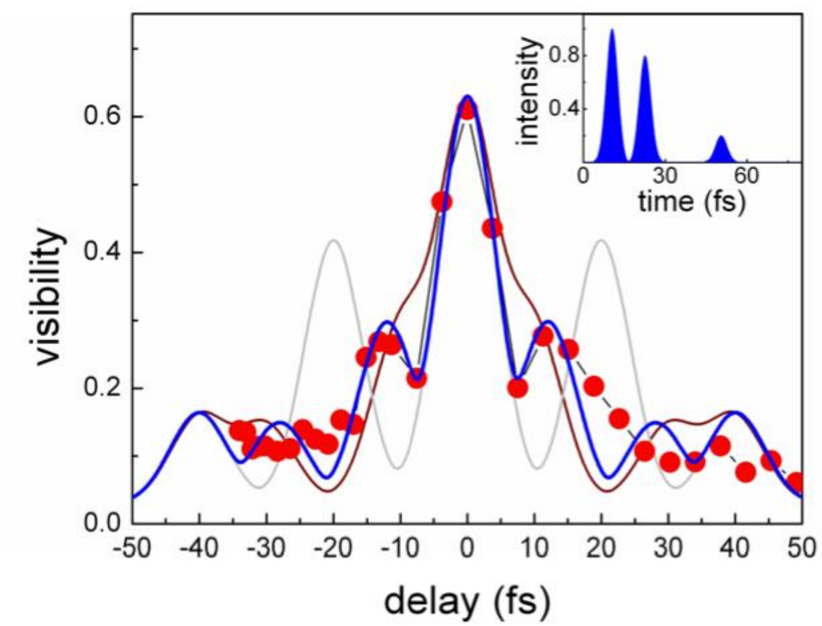
R. Mitzner, et al., Opt. Expr. 24 (2008) 19909

Wavefront splitting
Grazing incidence mirrors
Measurements taken at 23.9 nm
Visibility, temporal and spatial coherence,
and presence of multiple pulse structure determined



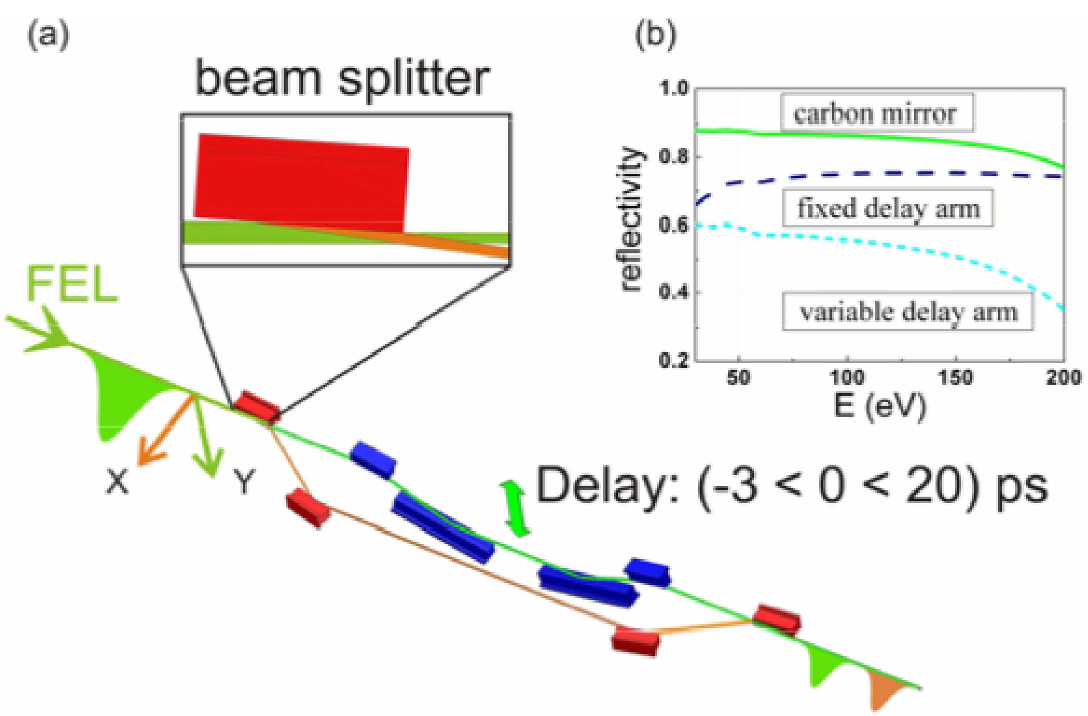



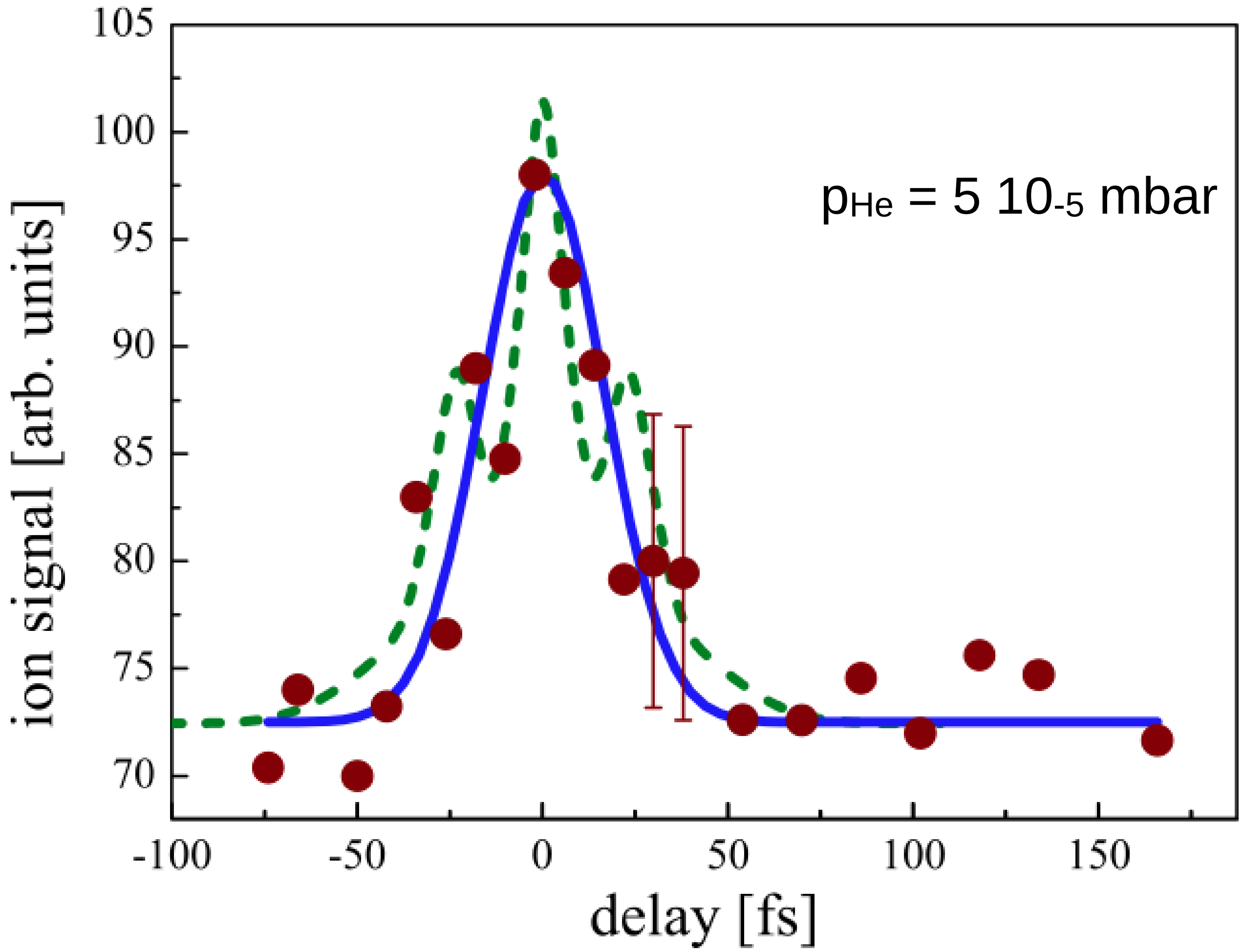



R. Mitzner, et al., Phys. Rev. A 80 (2009) 025402

51.8 eV photon energy
Peak intensities ~ 1.8 $10^{14}$ W/cm$^2$
5 µm-spots




Beam splitting and delay introduced.
The two half-beams are focused in an ionizing region seen by a TOF spectrometer and the $He^{2+}$ is detected.

# Conclusions

• Photon beam diagnostics already tested on some FELs

• Existing and developing expertise worldwide

• Photon beam parameters shot-to-shot and online:

*intensity, photon energy, spectral distribution, position, focus size*

• Photon beam parameters NOT shot-to-shot and online:

*pulse length, coherence, …*

• FERMI@Elettra will benefit from collaborations within the EuroFEL-IRUVX-PP project

# Acknowledgments

- **FERMI@Elettra Photon beam transport group:** Daniele Cocco Cristian Svetina Claudio Fava Simone Gerusina Luca Rumiz

- **ELETTRA Mechanical design group:** Ivan Cudin

- **ELETTRA Detectors & Instrumentation Group** Dario Giuressi Rudi Sergo Enrico Braidotti (CAENELS)

- **FERMI@Elettra Beamlines coordinators:** Carlo Callegari Maya Kiskinova Claudio Masciovecchio

- **FERMI@Elettra people**

- **IRUVX-PP people**

**…AND YOU FOR YOU ATTENTION !**