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PADReS

Soft X-rays Photon Diagnostics: the FERMI experience

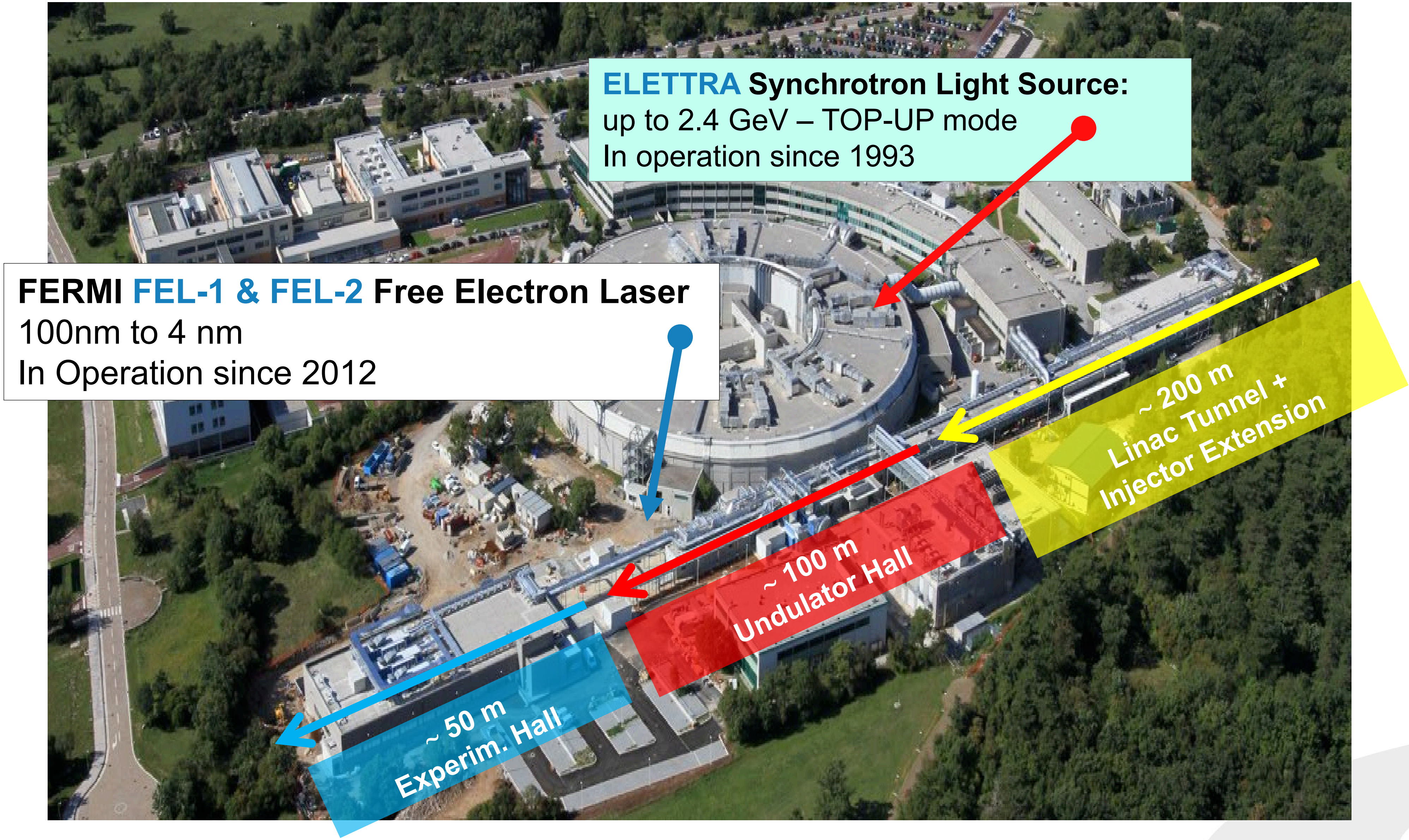
Marco Zangrando

on behalf of the PADReS and FERMI Teams

WP13 EuPRAXIA – Photon Diagnostics

ELETTRA SINCROTRONE TRIESTE

The lightsources

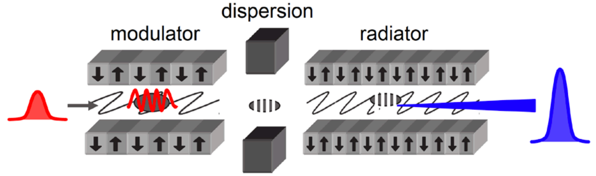


FERMI: HIGH GAIN HARMONIC GENERATION
FEL-1 and FEL-2

nature photonics | ARTICLES
PUBLISHED ONLINE: 23 SEPTEMBER 2012 | DOI: 10.1038/NPHOTON.2012.233

Highly coherent and stable pulses from the FERMI seeded free-electron laser in the extreme ultraviolet

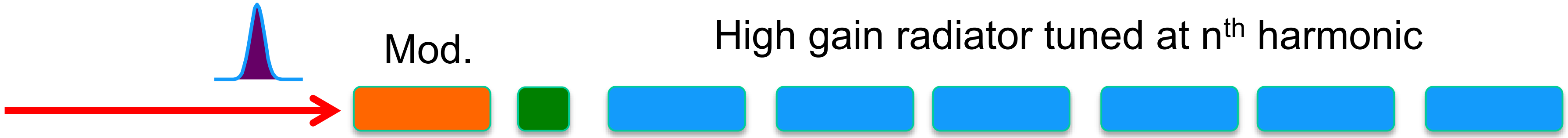
E. Allaria et al.*



* Apple II type helical undulators (variable gap)

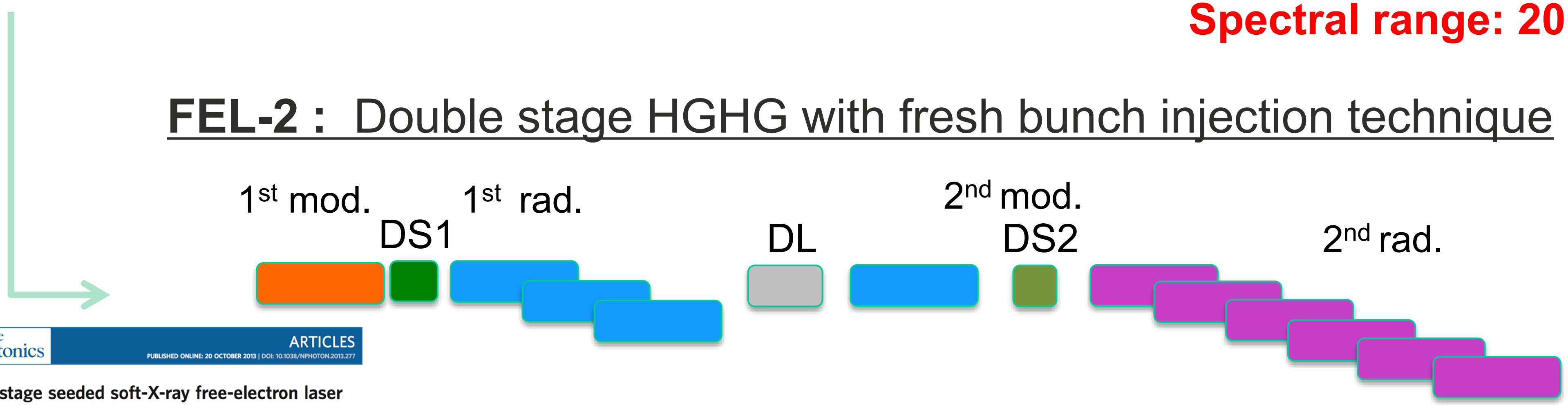
FEL-1 : Single stage HGHG

Seed Laser:
THG (~260nm)
OPA (230-260nm or 296-360nm)



Spectral range: 20 – 100 nm

FEL-2 : Double stage HGHG with fresh bunch injection technique



nature photonics | ARTICLES
PUBLISHED ONLINE: 20 OCTOBER 2013 | DOI: 10.1038/NPHOTON.2013.277

Two-stage seeded soft-X-ray free-electron laser

E. Allaria[1], D. Castronovo[1], P. Cinquegrana[1], P. Craievich[1†], M. Dal Forno[1,2], M. B. Danailov[1], G. D'Auria[1], A. Demidovich[1], G. De Ninno[1,3], S. Di Mitri[1], B. Diviacco[1], W. M. Fawley[1*], M. Ferianis[1], E. Ferrari[1], L. Froehlich[1], G. Gaio[1], D. Gauthier[1,3], L. Giannessi[1,4*], R. Ivanov[1], B. Mahieu[1,5], N. Mahne[1], I. Nikolov[1], F. Parmigiani[1,2], G. Penco[1], L. Raimondi[1], C. Scafuri[1], C. Serpico[1], P. Sigalotti[1], S. Spampinati[1,3], C. Spezzani[1], M. Svandrlik[1], C. Svetina[1,2], M. Trovo[1], M. Veronese[1], D. Zangrando[1] and M. Zangrando[1,6]

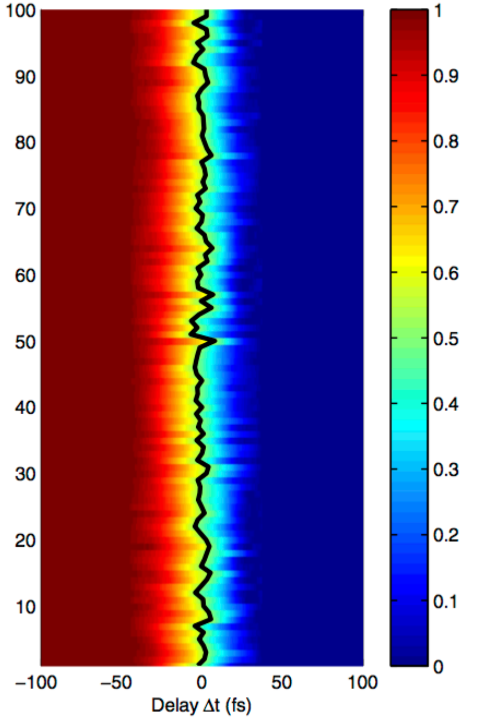
Spectral range: 4 - 20 nm

FERMI: HIGH GAIN HARMONIC GENERATION
Routine performance

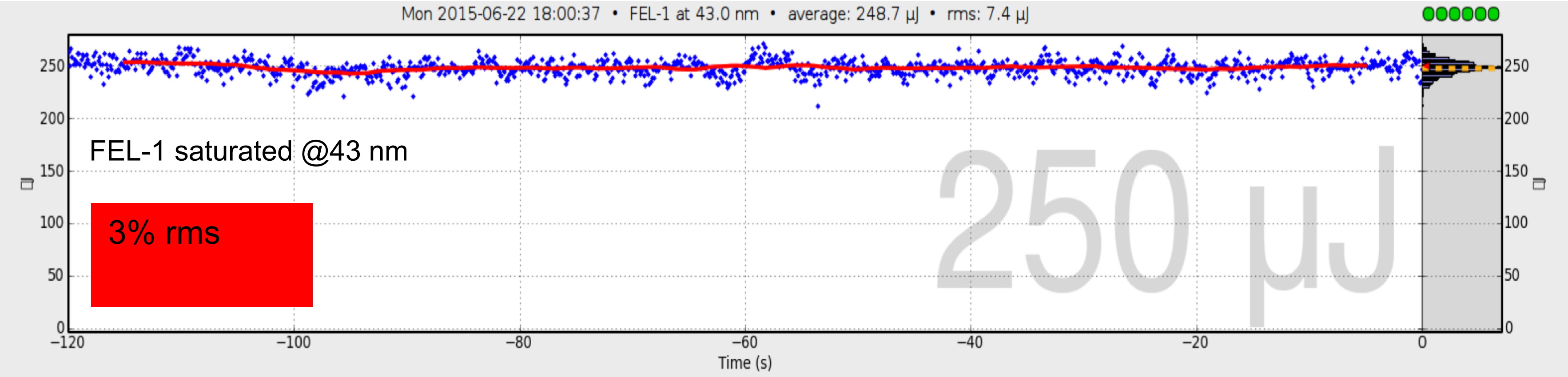
- **High Gain Harmonic Generation** free electron laser
- Covering the **100 – 4 nm range** with two FEL lines (single and double “fresh bunch scheme” cascades)
- Pulse **energy**: 10 – 100s μJ | Pulse **length**: 20 – 100 fs
- Full **polarization** control
- High **coherence** (temporal and spatial)
- Down to $2 \cdot 10^{-4}$ rms **linewidth**
- Central **λ stability** down to 10^{-5} rms

Several unique properties, stability (time, energy, photons):
laser like photon statistics

FEL temporal jitter: (relative to the Seed): 2.2 fs
P. Finetti et al. Phys. Rev. X ***7****, 021043 (2017)*



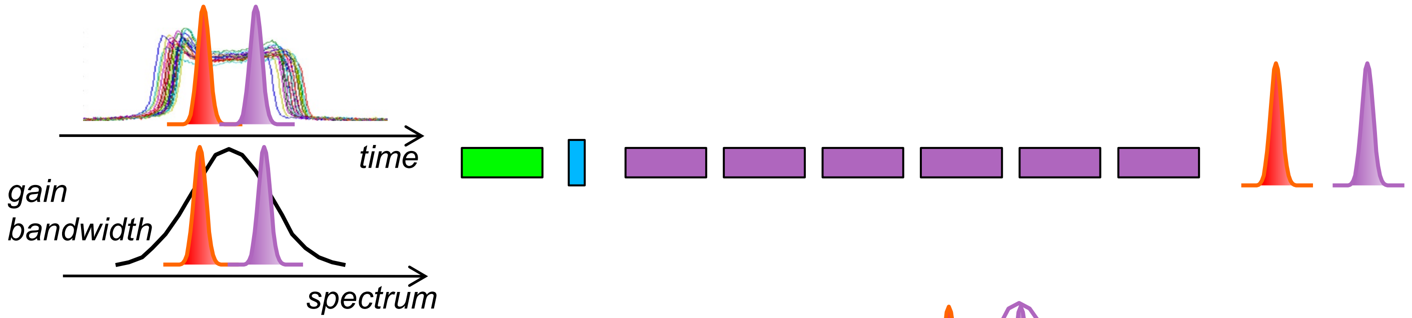
Not standard, Typical 10-15% rms on FEL-1 ~ 2-3 × on FEL-2



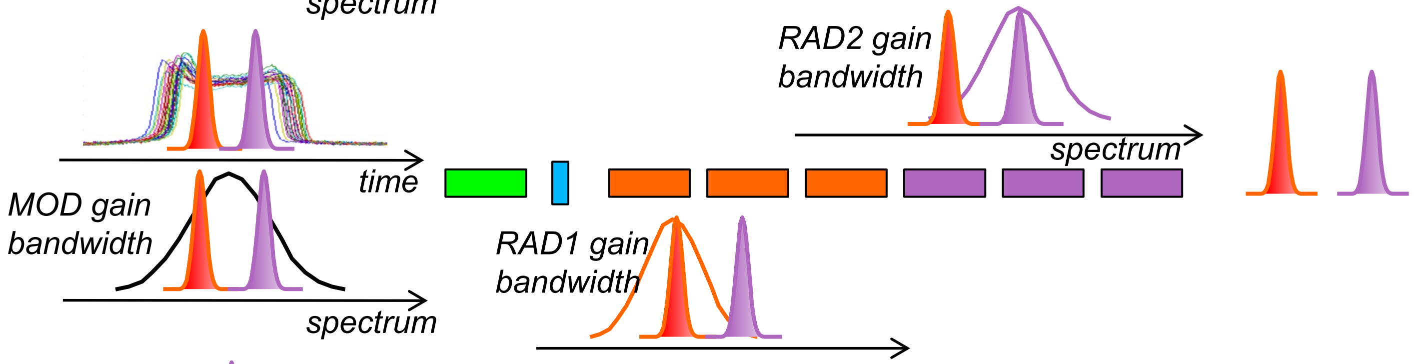
FERMI: HIGH GAIN HARMONIC GENERATION
Versatility → Exotic modes

Multiple pulses can be generated by **double pulse seeding** in different ways, depending on the requirements on the output radiation. Temporal **separation between 25-300 and 700-800 fs**. Shorter separations are accessible via FEL pulse splitting*. Larger separations require the split & delay line.

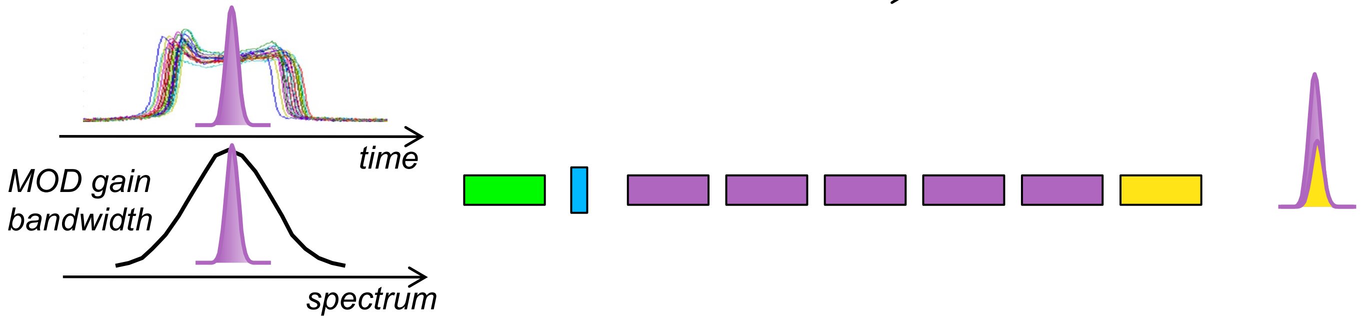
* Pulse Splitting by using a powerful chirped Seed Laser
PRL 110, 064801 (2013)



Spectral separation 0.4-0.7%
Allaria et al., Nat. Comm., 2013

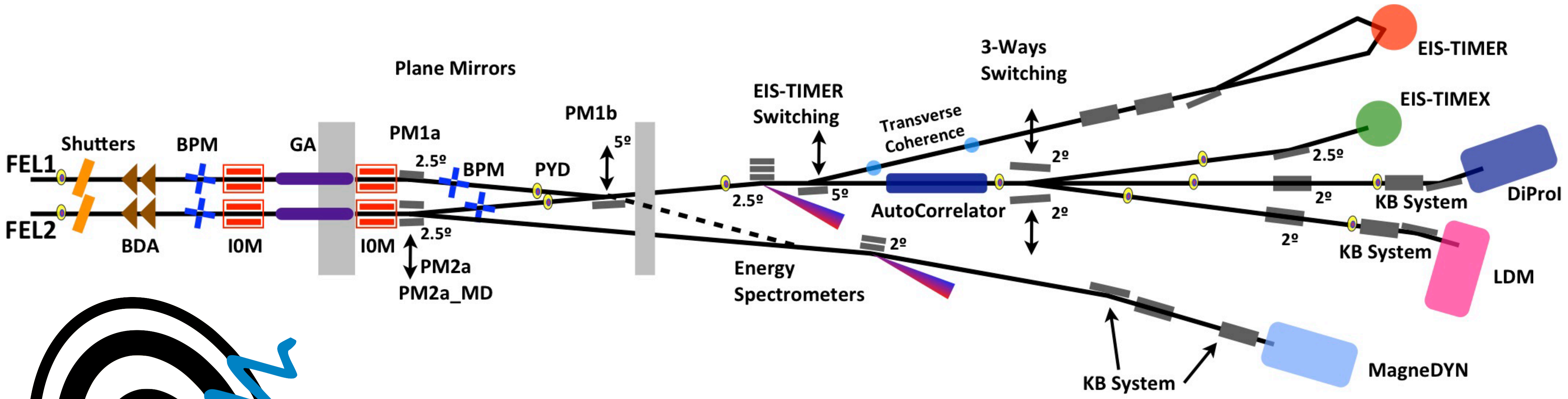


Spectral separation 2-3%
or much larger if the two radiators are tuned at different harmonics
Ferrari et al., Nat. Comm, 2016



Two (almost) temporally superimposed pulses at harmonic wavelengths of the seed. The two pulses are correlated in phase and the phase can be controlled with the phase shifter.
K. Prince et al. Nat. Phot. 10, 176 (2016)

FERMI PHOTON TRANSPORT AND DIAGNOSTICS
Photon Analysis Delivery and REduction System



PADReS

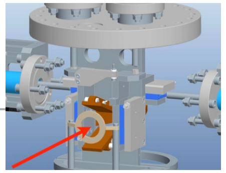
2 Photon diagnostics sections + manipulation capabilities
5 FEL-served endstations

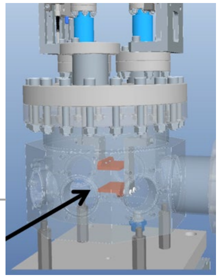
FERMI PHOTON TRANSPORT AND DIAGNOSTICS

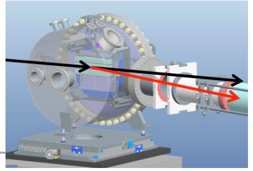
The most peculiar elements

<u>Most</u> of the machine activities devoted to fine tuning and to reach the ultimate performance rely on the photon diagnostics available along PADReS:

- Intensity monitors
- Beam position monitors
- Energy spectrometers (PRESTO/TARDI)



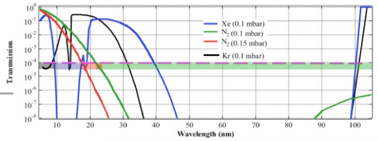


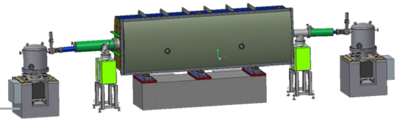


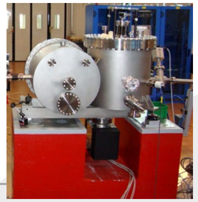
while

<u>All</u> of the experimental activities carried out in the endstations rely, besides the photon diagnostics, on the photon transport/manipulation system

- Gas absorber
- Split and delay line (AC/DC)
- Focusing systems (KAOS and elliptical mirror)

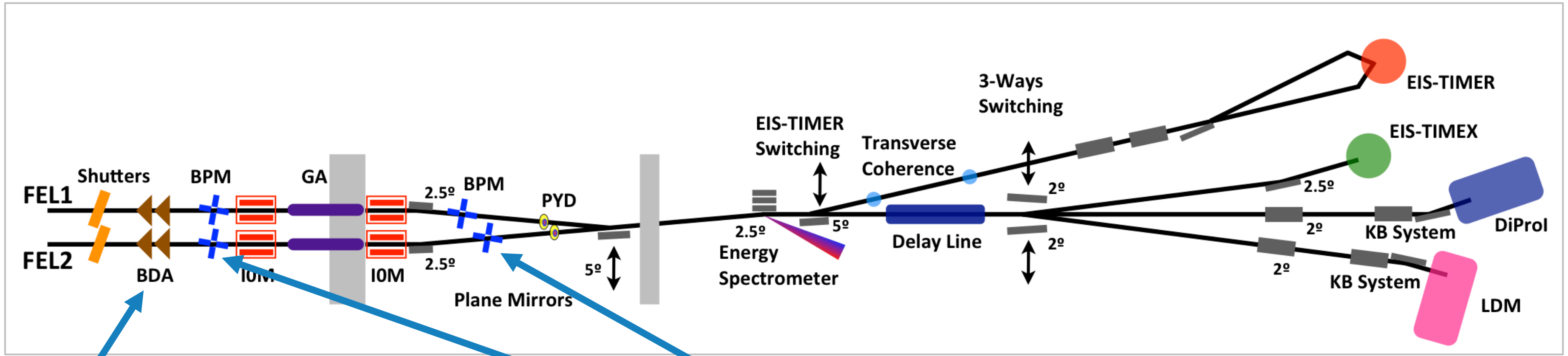




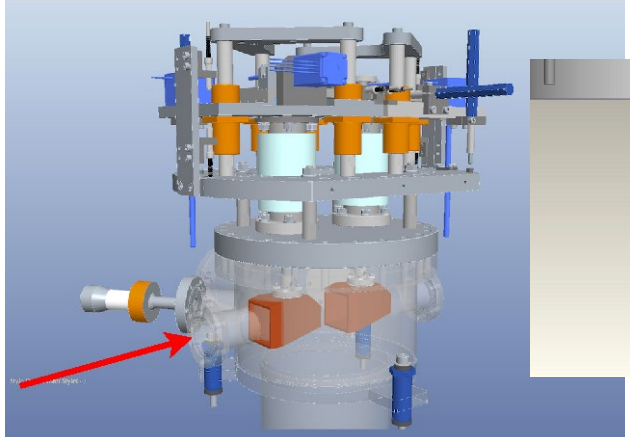


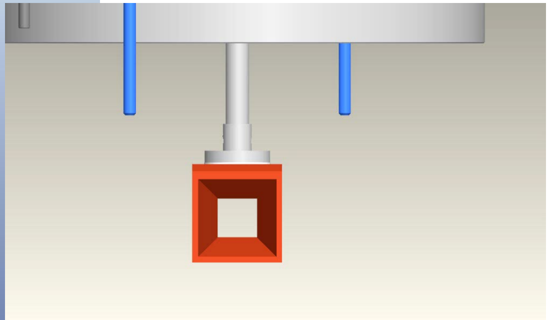
TRANSVERSE DISTRIBUTION

Beam Defining Apertures and Beam Position Monitors

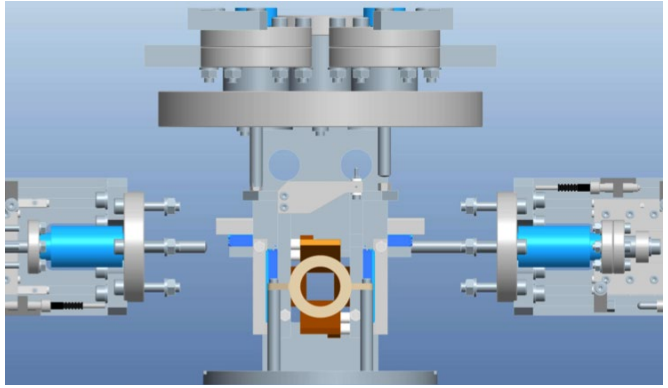


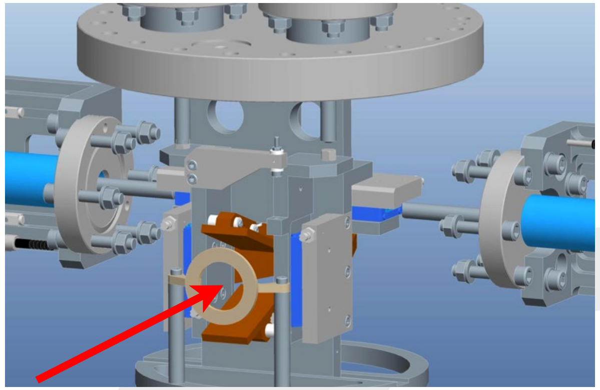
Beam defining apertures:
33 (25) meters from FEL1 (FEL2)
Used to eliminate the non-TEM_{00} modes



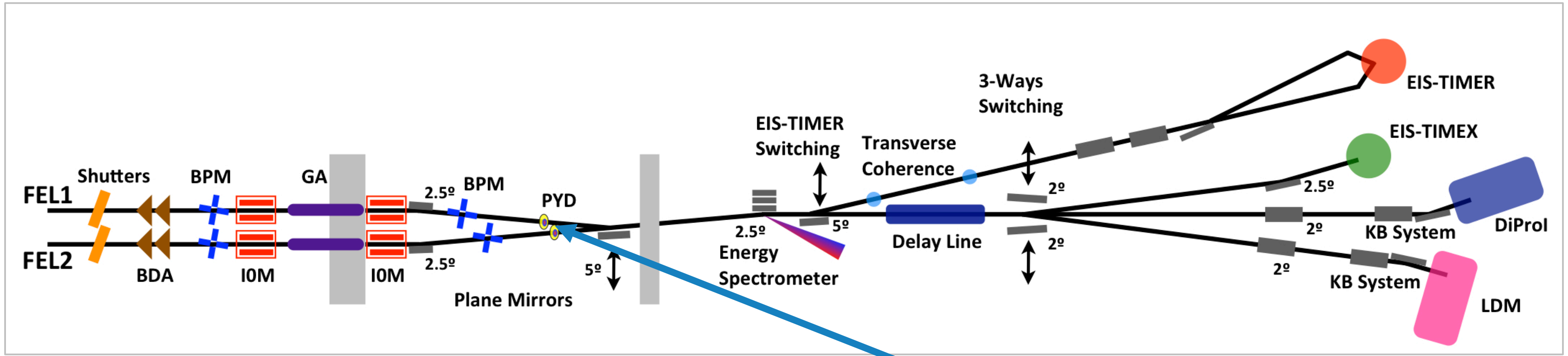


Beam position monitors:
Used to monitor the photon beam angular displacement online and shot-to-shot (knife-edge scans possible)

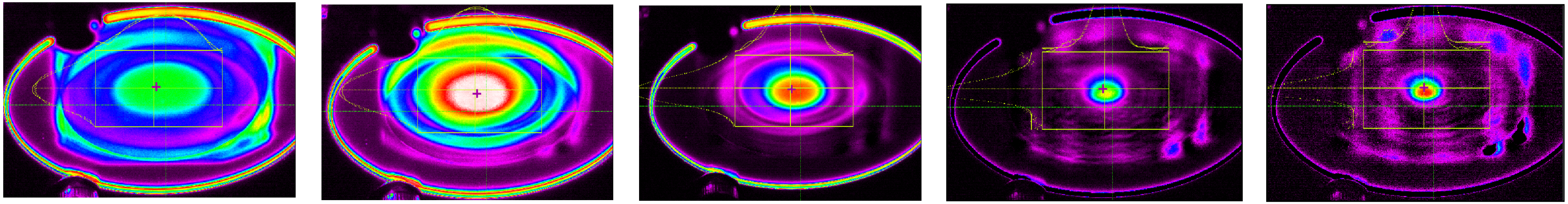




TRANSVERSE DISTRIBUTION
YAG screens



Ce:YAG screens:
Along the whole system (ideally one for each optical element)



FERMI experience:
BDAs and BPMs play an important role in cutting unwanted off-axis emission from undulators and monitoring possible instabilities in the photon beam pointing

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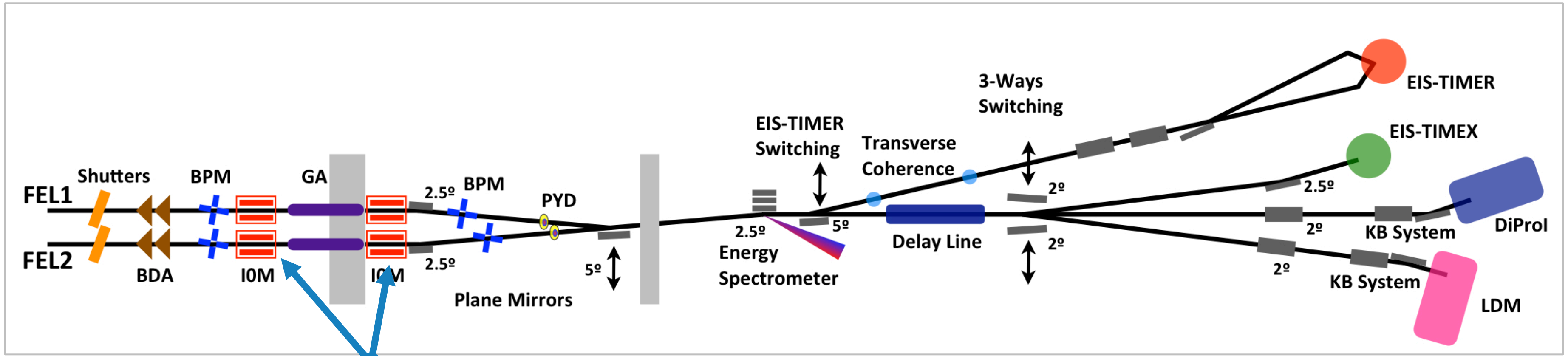
INTENSITY
Gas-based monitors



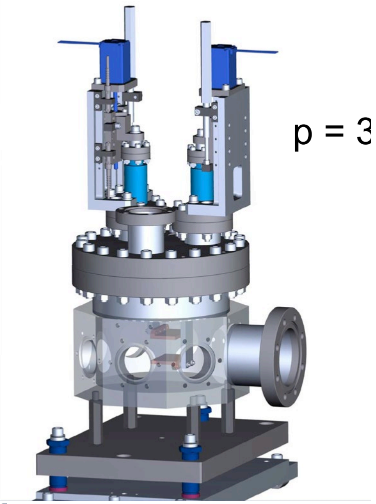
Intensity monitors:

Measures the number of p

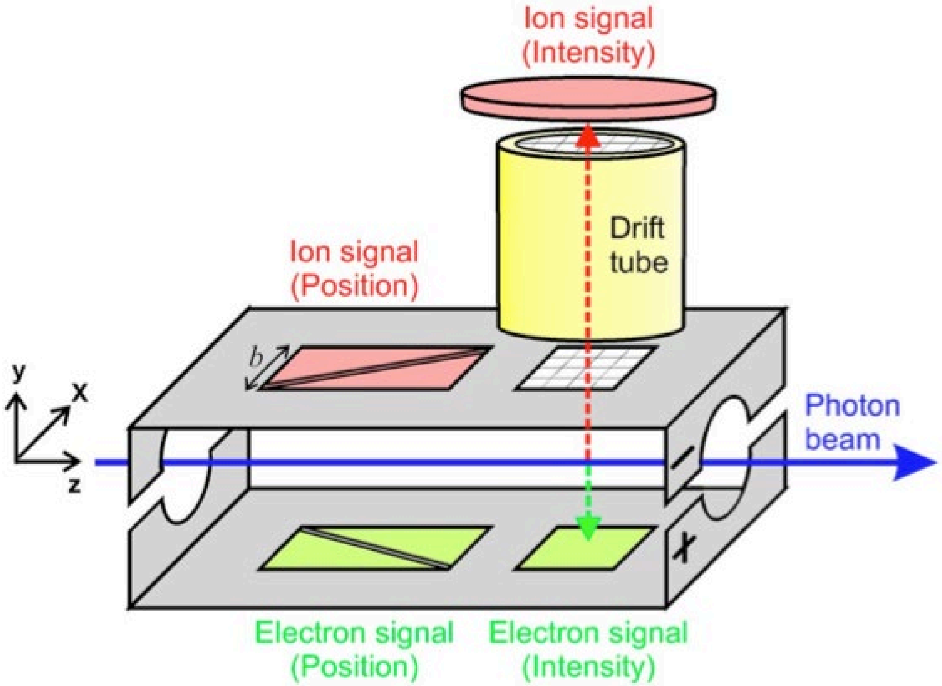
(~3% precision, 1% repro

Online and shot-to-shot

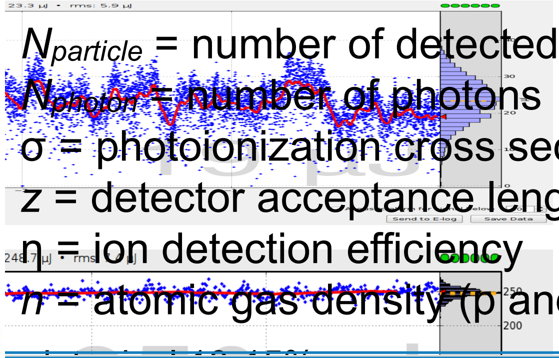
Transparent



p = 3



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



$N_{particle}$ = number of detected particles

N_{photon} = number of photons

σ = photoionization cross section

z = detector acceptance length

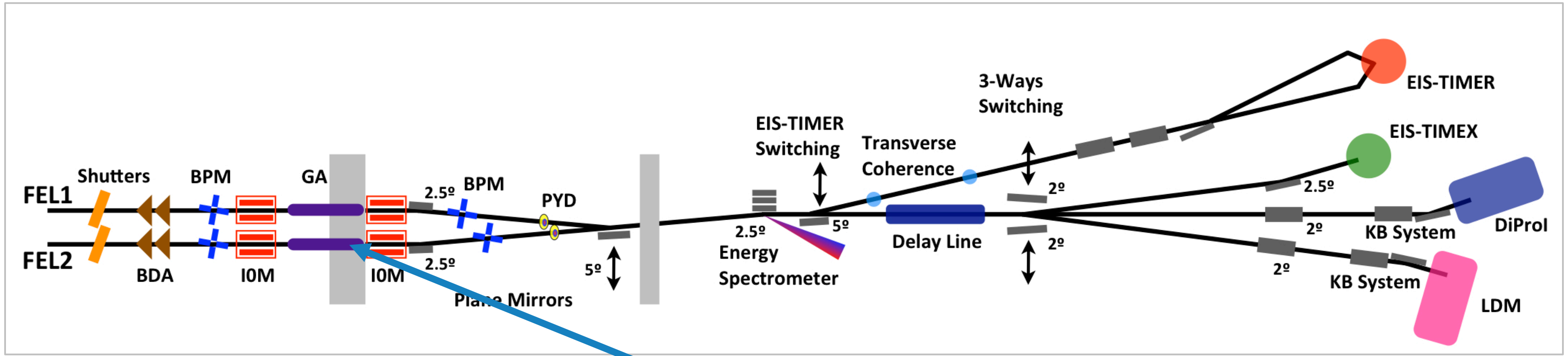
η = ion detection efficiency

n = atomic gas density (p and T required)

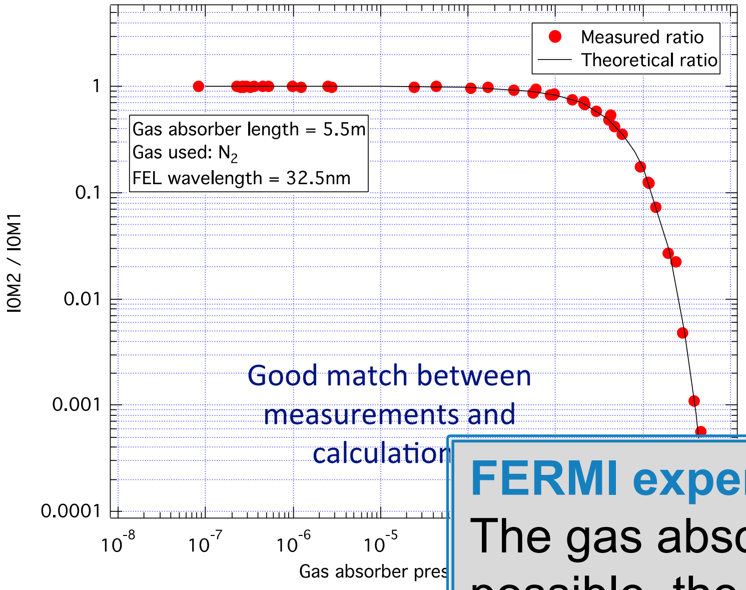
rating-based, mirror photo-current, operating on

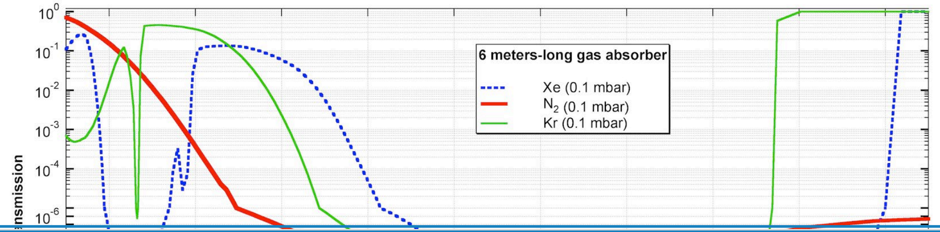
e transport (especially before the endstations)

INTENSITY
Gas-based absorbers



Gas absorber:
Need to align the beam without destroying the sample + intensity-dependent studies
Max attenuation at all λ: 10^{-4}
Preservation of coherence, spectrum, statistics, etc.

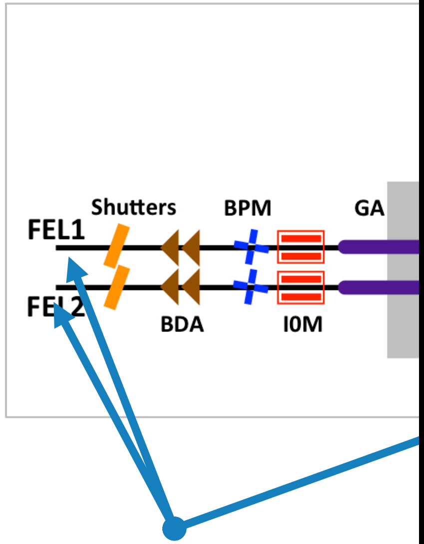


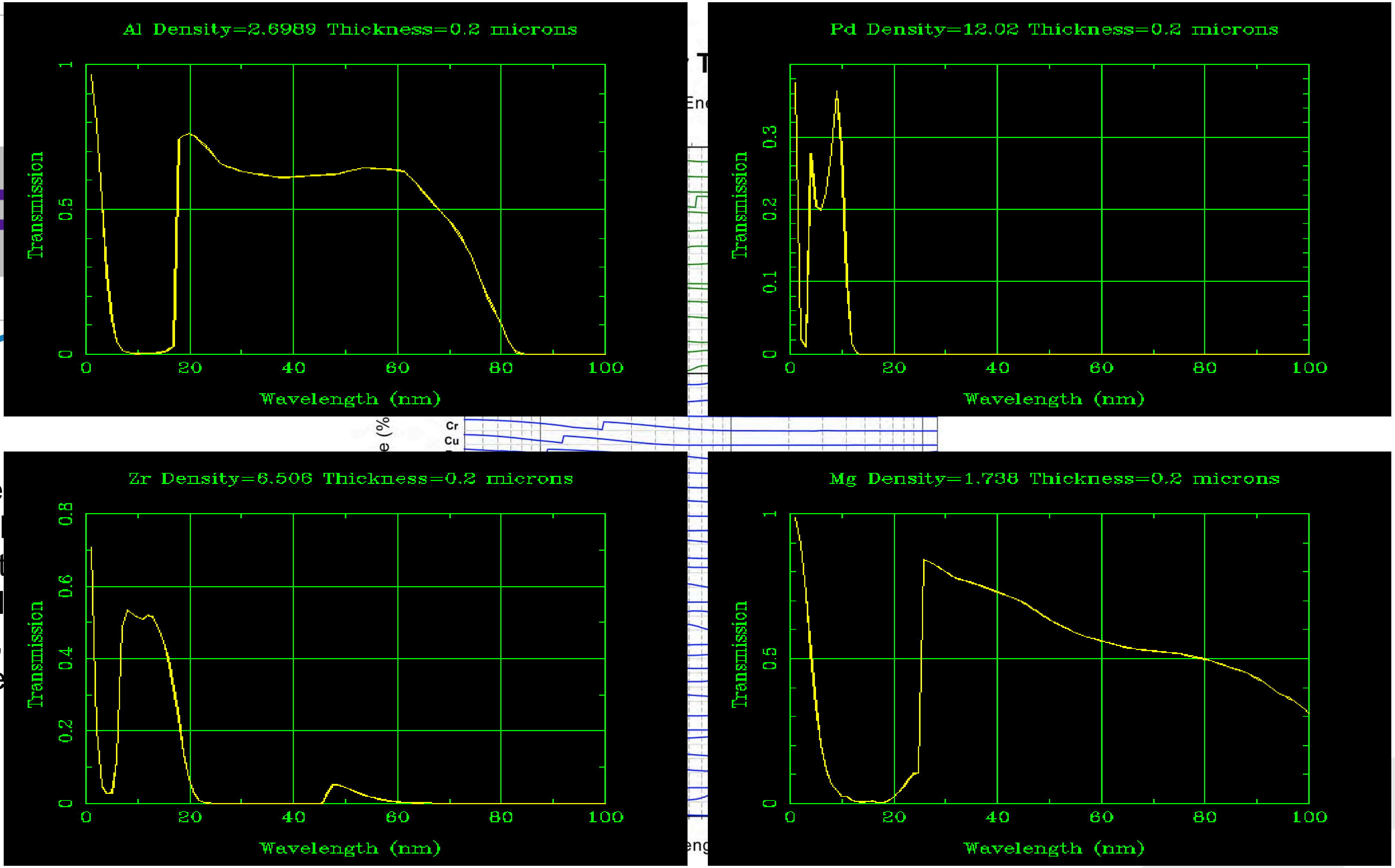


FERMI experience:
The gas absorber should be also able to implement **different gases** in order to meet, if possible, the users' needs (e.g., cutting higher orders and/or multi-cascade FEL photons)

INTENSITY FILTERING

Solid state filters

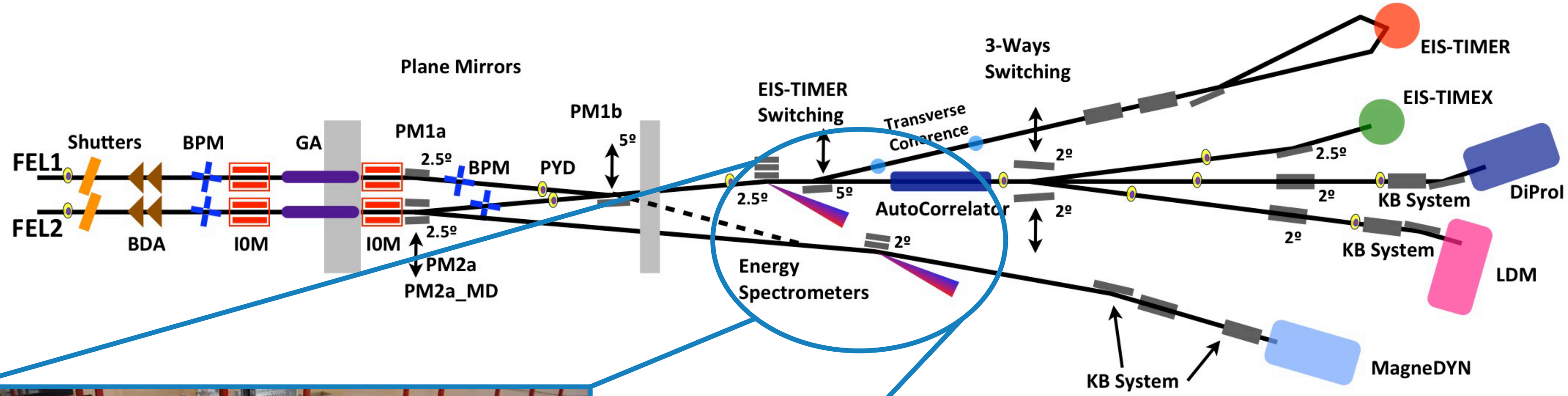


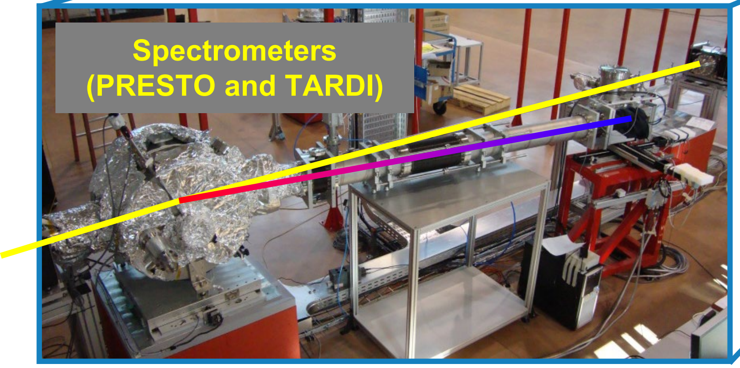


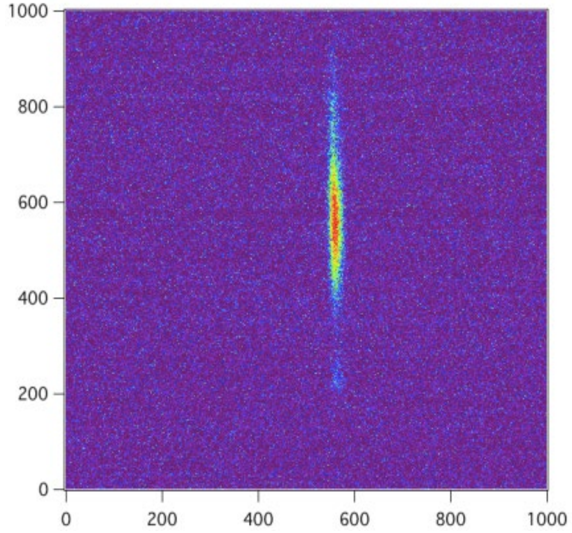
Filtering stations:

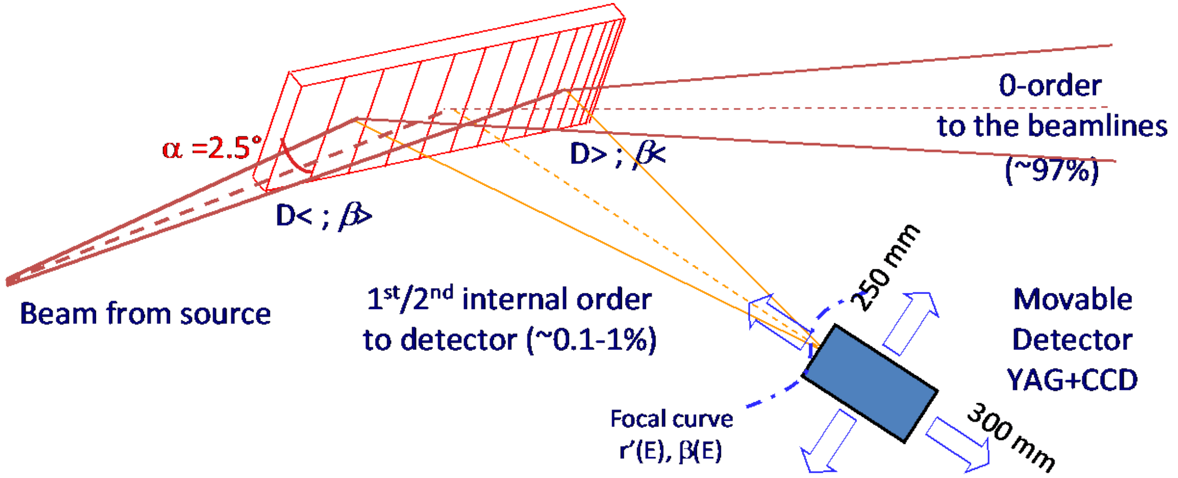
Need to cut unwante
higher harmonics, ot
reduce the overall int
Solid state filters (foi
(50nm → >1000nm),
and variable diamete

ENERGY SPECTROMETERS
PRESTO and TARDI

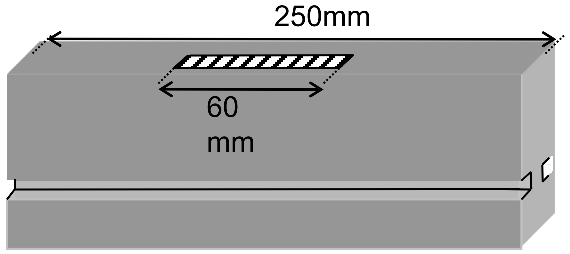








- Online (non invasive)
- Shot-to-Shot
- ~97% of FEL → beamlines
- 1% of FEL → YAG + triggered CCD
- Resolving Power ~15000 @32.5nm (2.5meV)
- Available information: λ, BW, spectral content

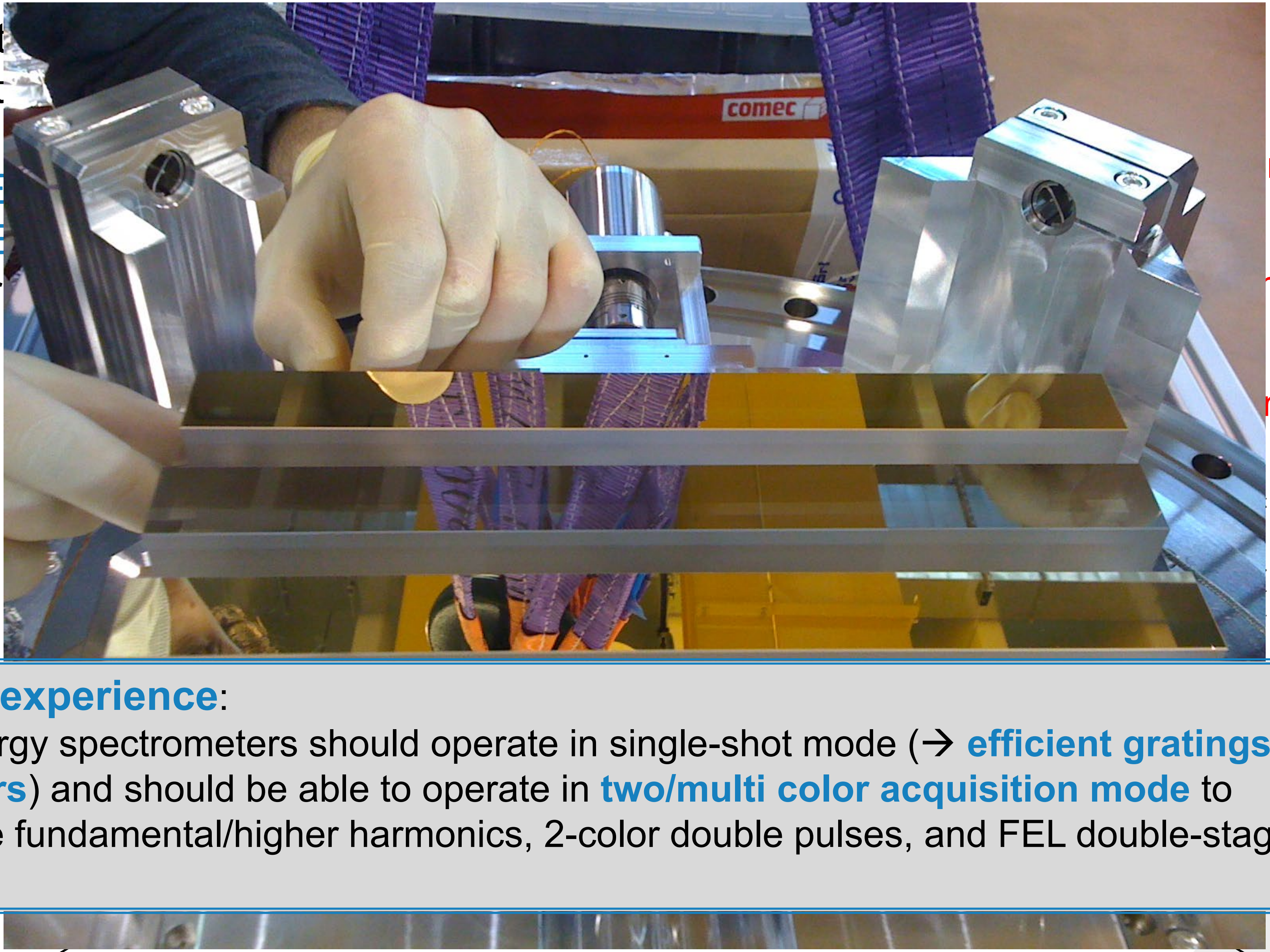


PRESTO:Pulse Resolved Energy Spectrometer, Transparent and Online

Diffraction gratings

The target
wavelengt
3 gratings
Low E
High E
Super

m
m
m



25mm

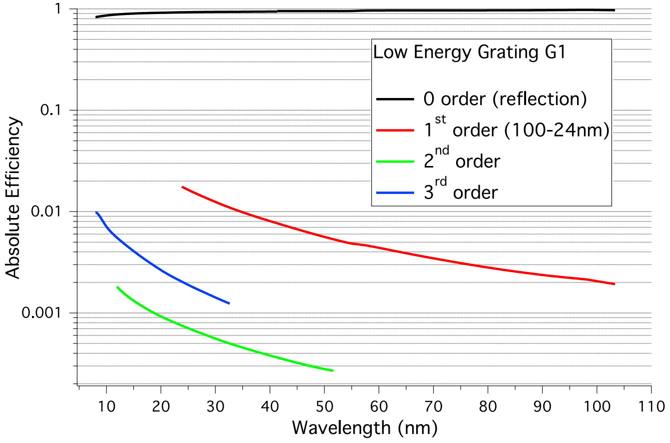
mm

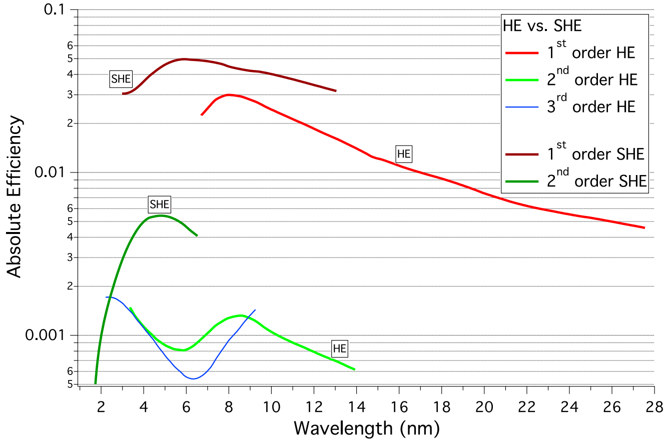
FERMI experience:
The energy spectrometers should operate in single-shot mode (→ **efficient gratings and detectors**) and should be able to operate in **two/multi color acquisition mode** to measure fundamental/higher harmonics, 2-color double pulses, and FEL double-stage photons

PRESTO/TARDI spectrometers

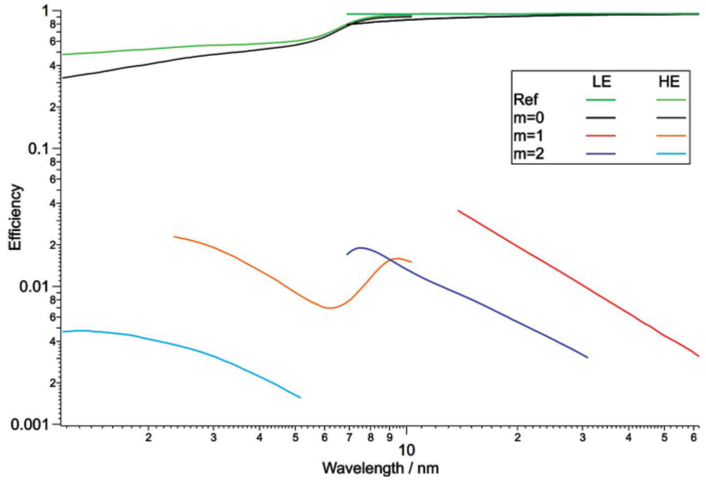
Parameters and Efficiencies

	LE	HE	SHE
λ (nm) – m=1	100-24.8	27.6-6.7	12.7-3.1
D_0 (l mm^{-1})	500	1800	3750
D_1 (l mm^{-2})	0.35	1.26	2.68
D_2 (l mm^{-3})	1.7×10^{-4}	6.3×10^{-4}	1.4×10^{-3}
Groove profile	Laminar	Laminar	Laminar
Groove height (nm)	12	4	9
Groove ratio (w/d)	0.6	0.6	0.65
Coating	Carbon	Gold	Nickel



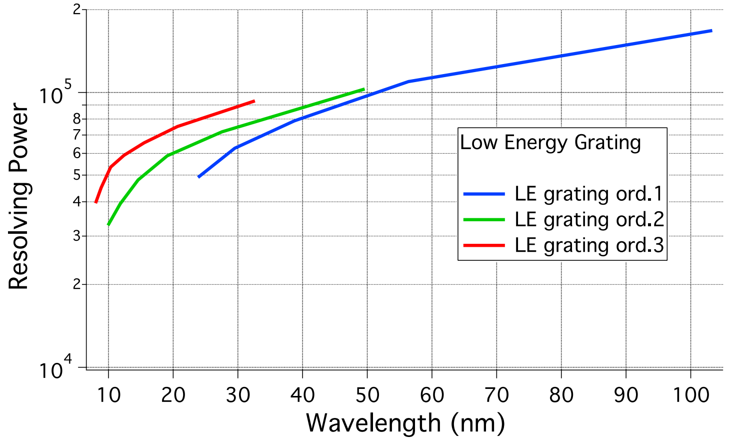


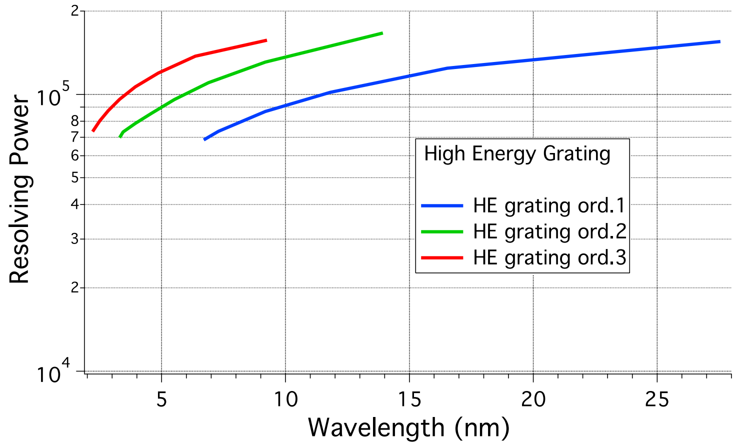
	LE	HE
λ (nm) – m=1	13.5-60.5	2.1-9.6
D_0 (l mm^{-1})	600	3750
D_1 (l mm^{-2})	4.2×10^{-1}	2.6
D_2 (l mm^{-3})	2.10×10^{-4}	1.30×10^{-3}
Groove profile	Laminar	Laminar
Groove height (nm)	10	4.8
Groove ratio (w/d)	0.7	0.64
Coating	Carbon	Gold

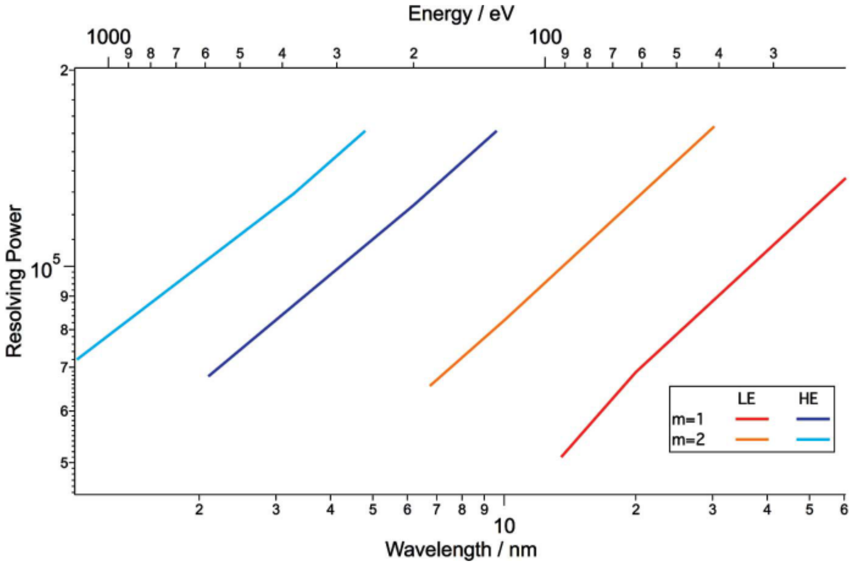


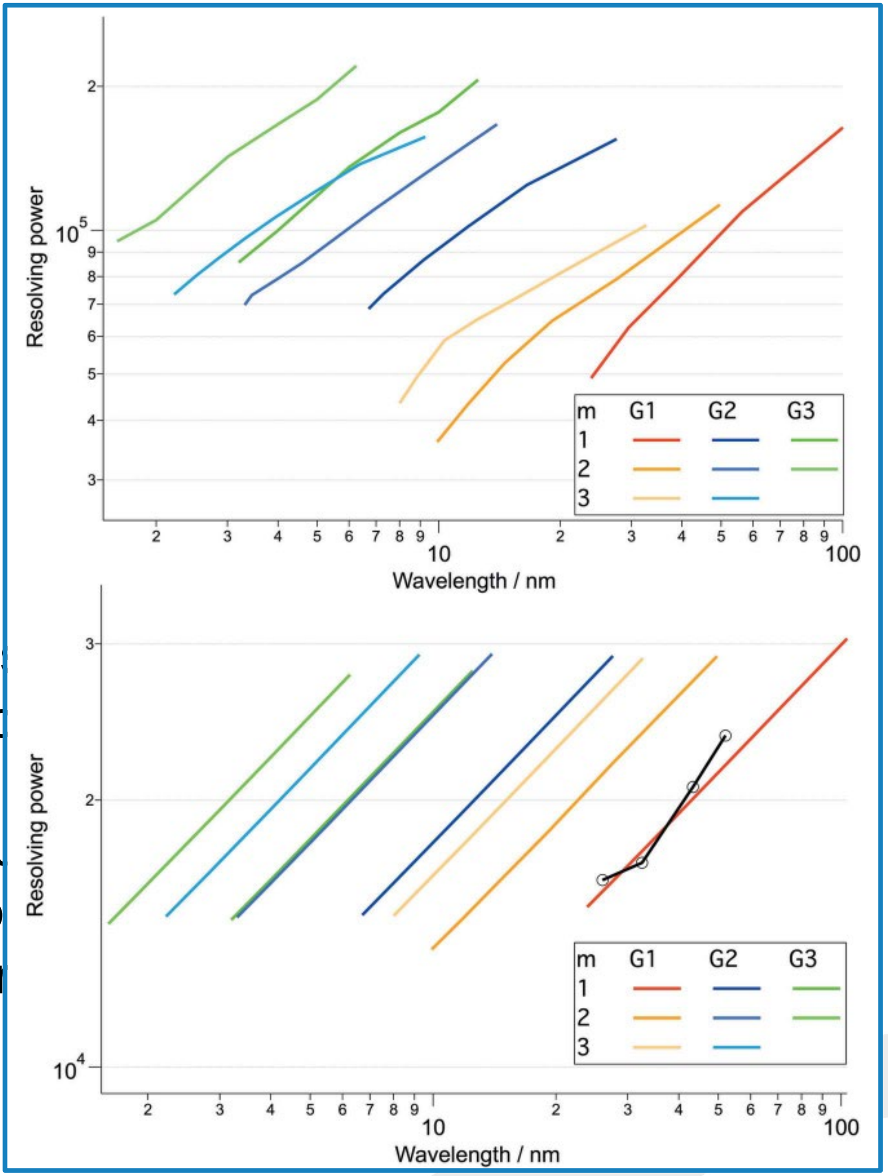
The target was to cover the entire FERMI range in first order of diffraction

PRESTO/TARDI spectrometers
Resolving Powers









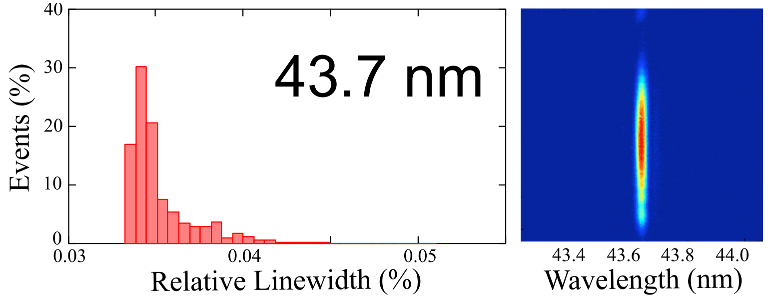
Resolving power to be s
depending on the detec

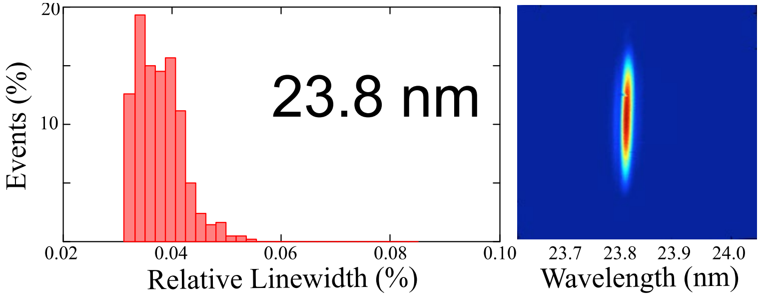
PRESTO and TARDI cu
Ce:YAGs in vacuum co
visible light CCD camer
Res.Power ~ 20.000

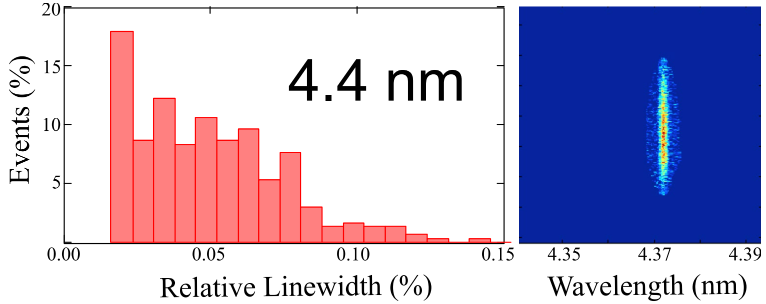
ENERGY SPECTROMETERS

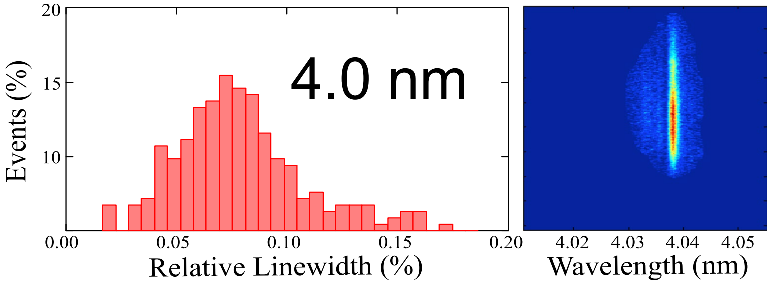
Typical spectra

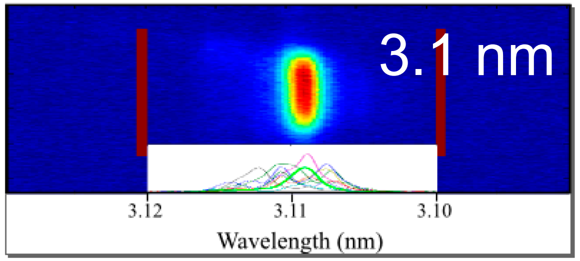
Single shot **spectra** measured down to **4 nm** (3.1nm with PRESTO and 2.1nm with TARDI)



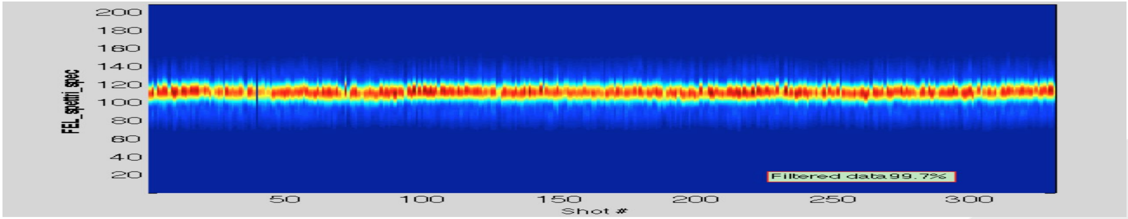






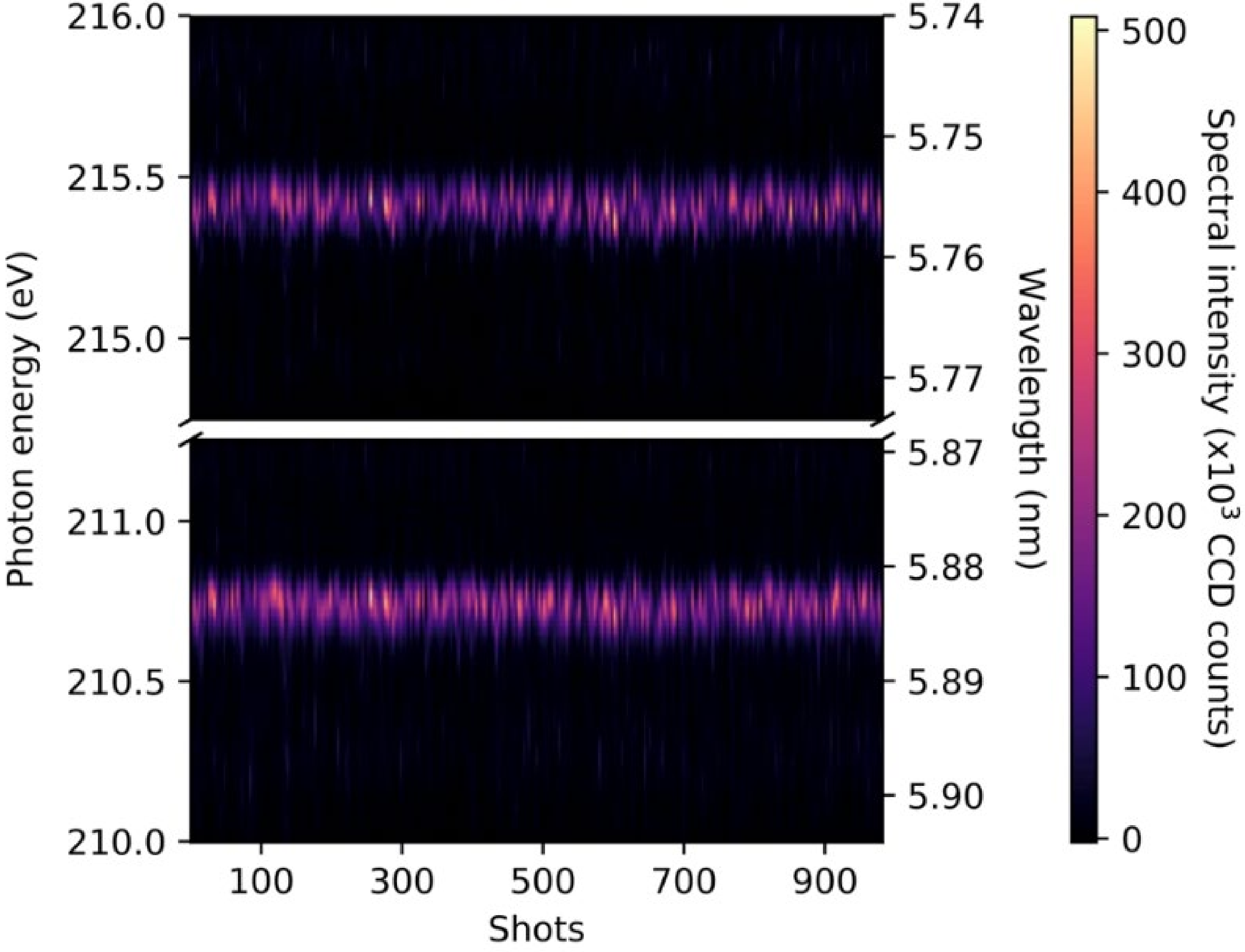


- **Gaussian with both wavelength and bandwidth stability.**



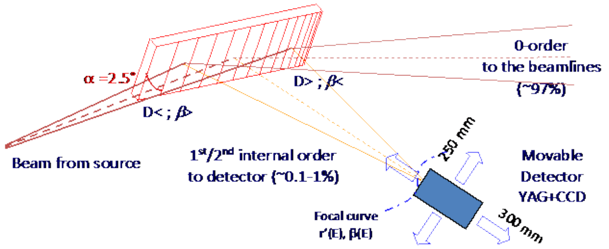
FERMI: EEHG TESTS

Two color mode



Courtesy E. Allaria – P. Rebernik

FEL UNDULATOR LINE ALIGNMENT
Spontaneous emission on PRESTO CCD



- Electron trajectory should be straight;
- Resonance condition to the FEL wavelength should be met in each undulator
- Undulator need to be aligned to the electron beam axis

In case of seeded FEL such as FERMI it is also required that:
- the seed laser is aligned to the same electron beam axis.

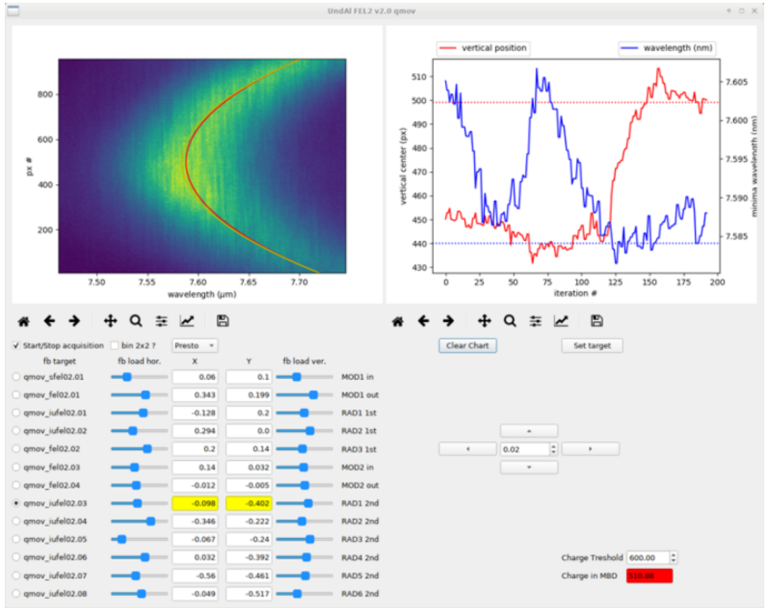
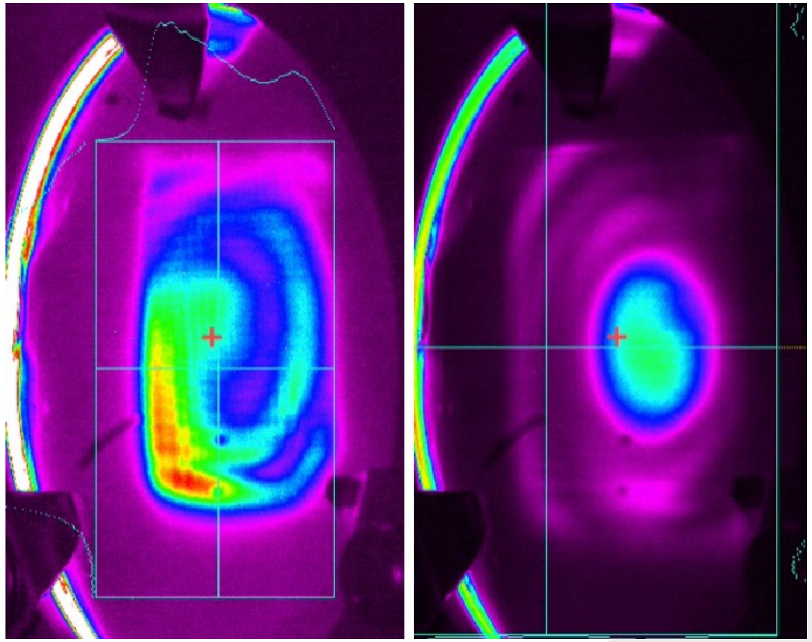


Figure 2: GUI used to monitor the evolution of the spontaneous emission mode while changing the trajectory in the resonant undulator.

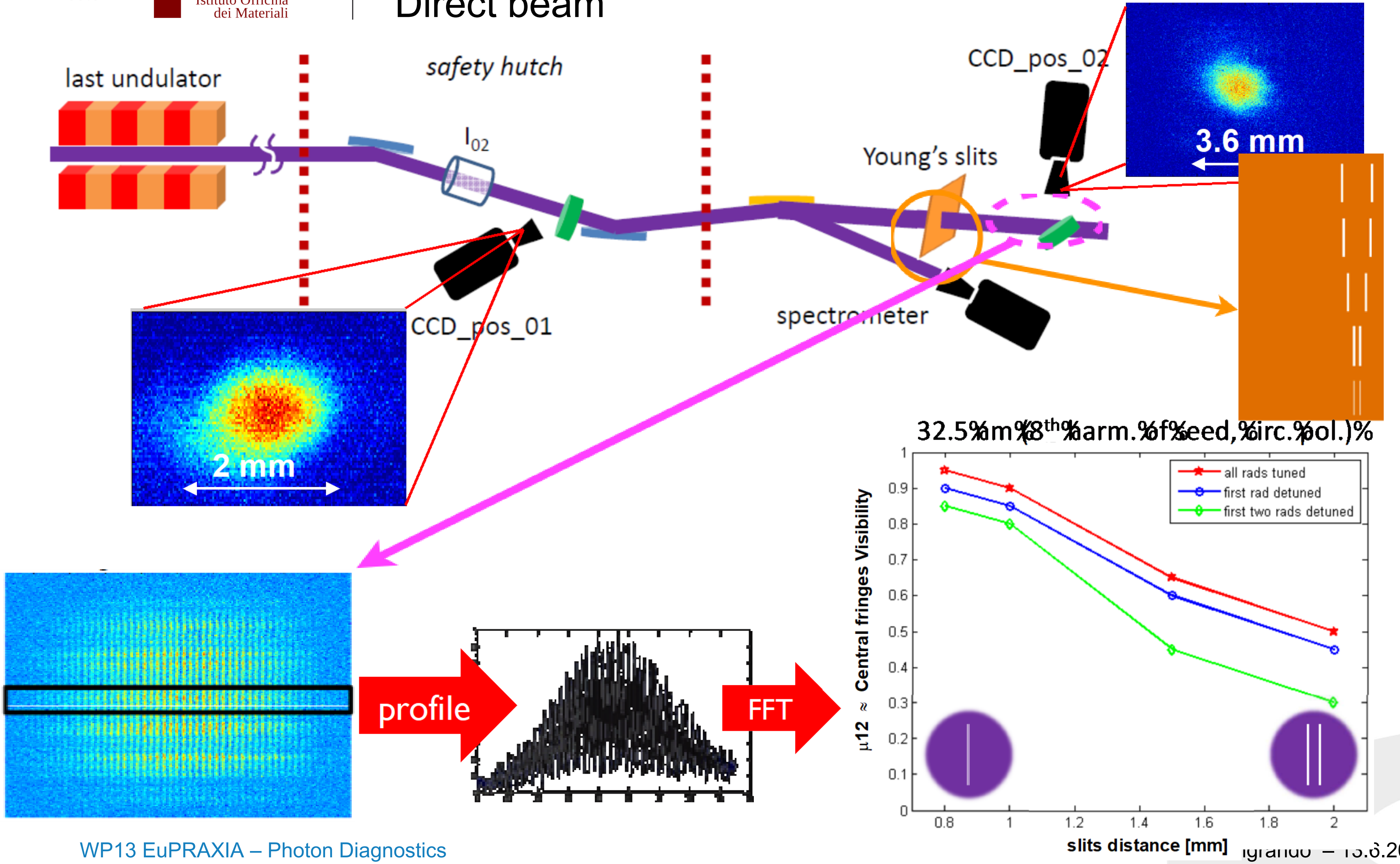
The spontaneous emission appears in a typical C-shape (as show in Fig. 2) corresponding to a vertical cut of the undulator emission cone integrated over the beam defining aperture (BDA). This shape reflects the quadratic relationship between wavelength and angle of deviation from the axis contained in the resonant condition equation for the emission from an undulator. The minimum of the parabola identifies the emission axis. In order to improve the accuracy, we set the BDA to a very small horizontal opening.



Courtesy E. Allaria – C. Spezzani

TRANVERSE COHERENCE

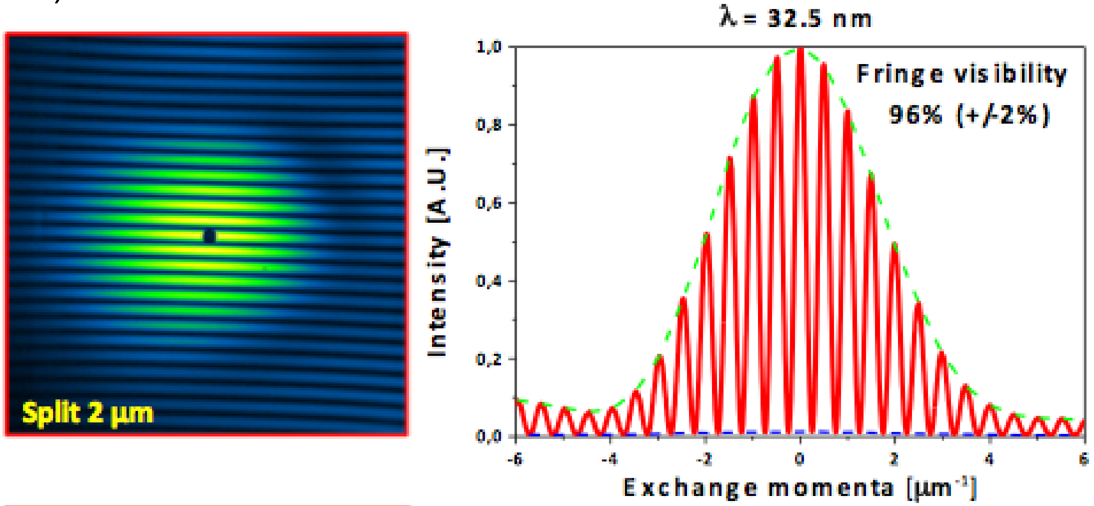
Direct beam

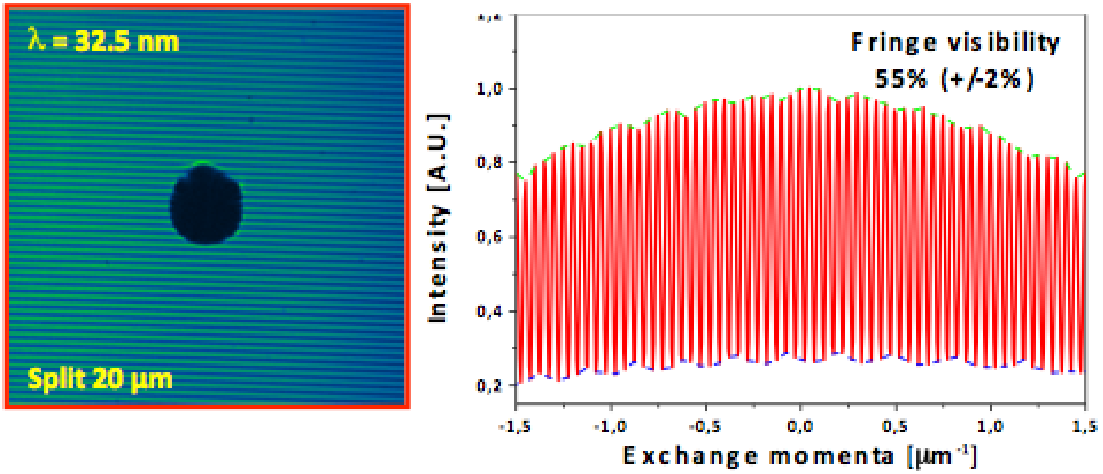


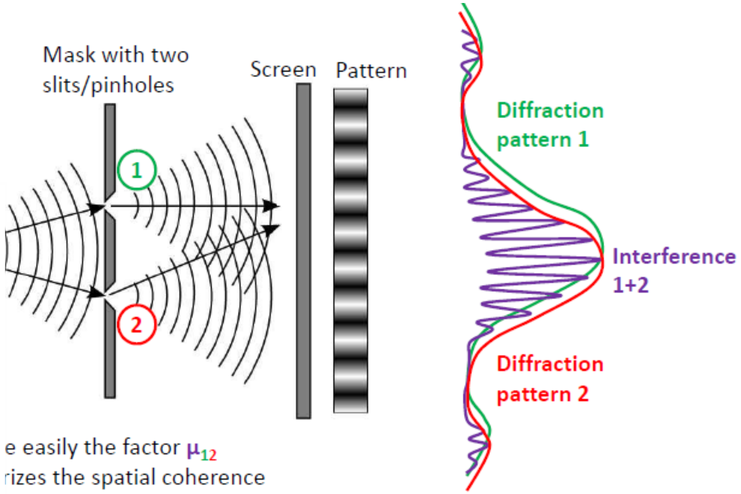
TRANVERSE COHERENCE

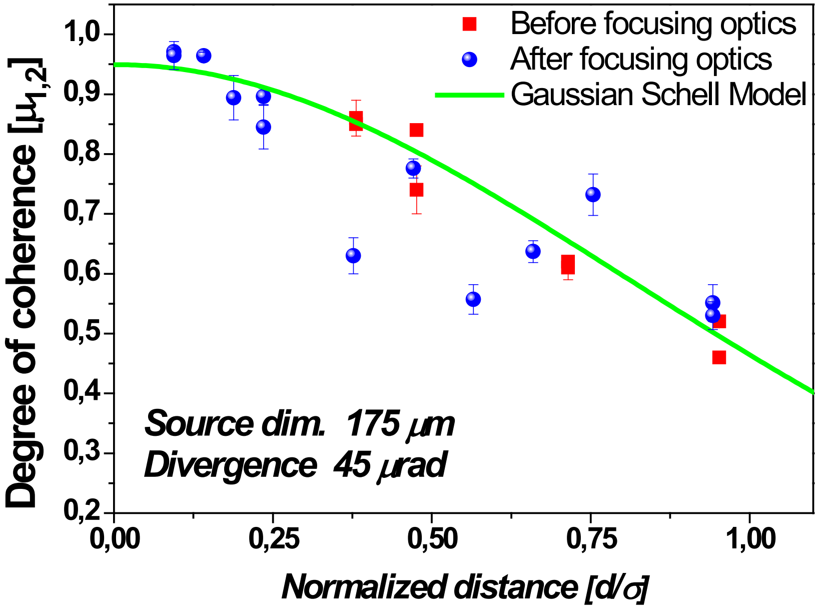
Focused beam

Measurements of the transverse coherence using a mask with pairs of pinholes or slits on it (sample prepared by M. Barthelmess) – beamline DiProI







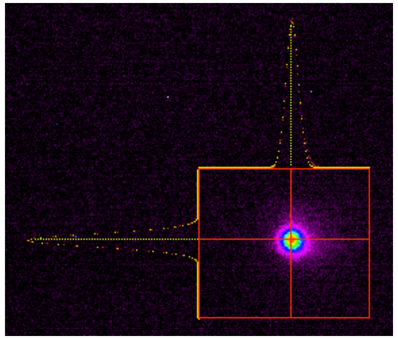


SPOT SIZE DETERMINATION

Different techniques

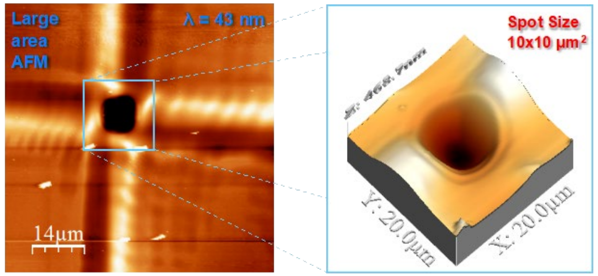
Scintillator-based (e.g. Ce:YAG)

- Invasive
- May suffer from saturation effects
- Scintillator gets damaged in focus
- No single-shot information (generally)
- Quick and cheap



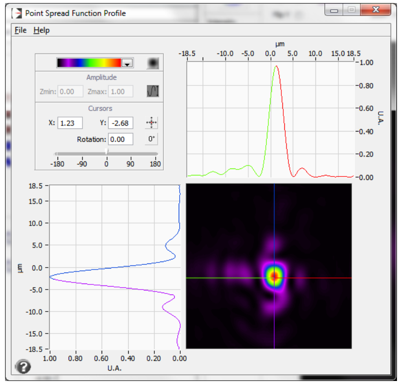
PMMA and Si indentation

- Invasive
- Single shot information
- Deadly time-consuming (not fit for beamtimes)



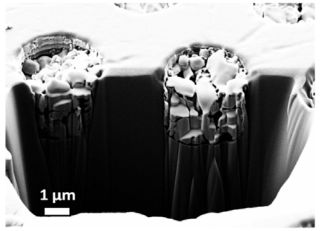
Wavefront sensor

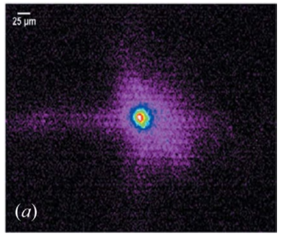
- Almost non invasive (intensity issues)
- Single shot information
- Online
- Quantitative information about focusing

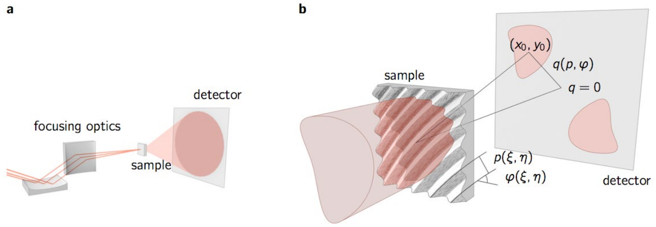


Other techniques

- Pixelated P array
  (ref. A. Matruglio et al., J. Synchrotron Rad. (2016). 23, 29-34)
- VLS grating based spot reconstruction
  (ref. M.Schneider, et al., Nat. Comm. 9 (2018) 214)
- …

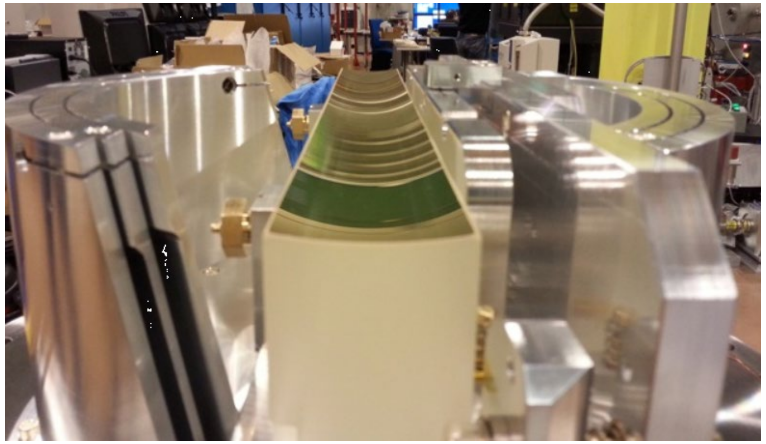


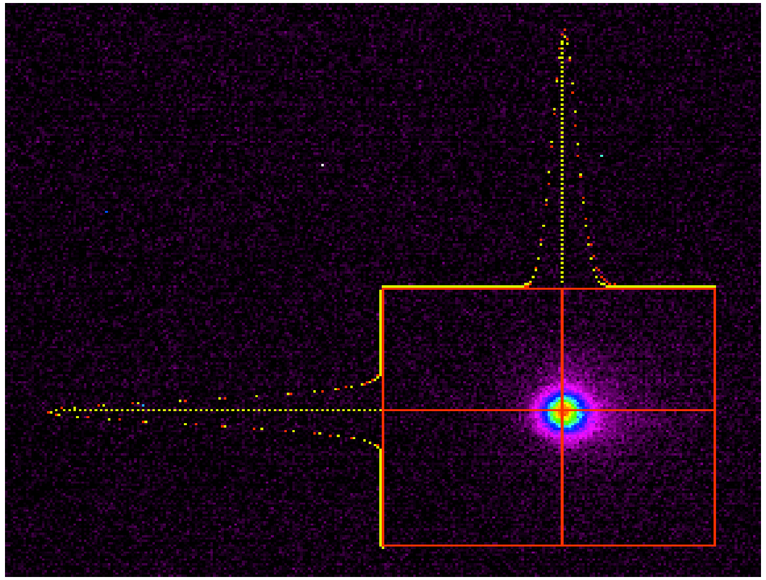




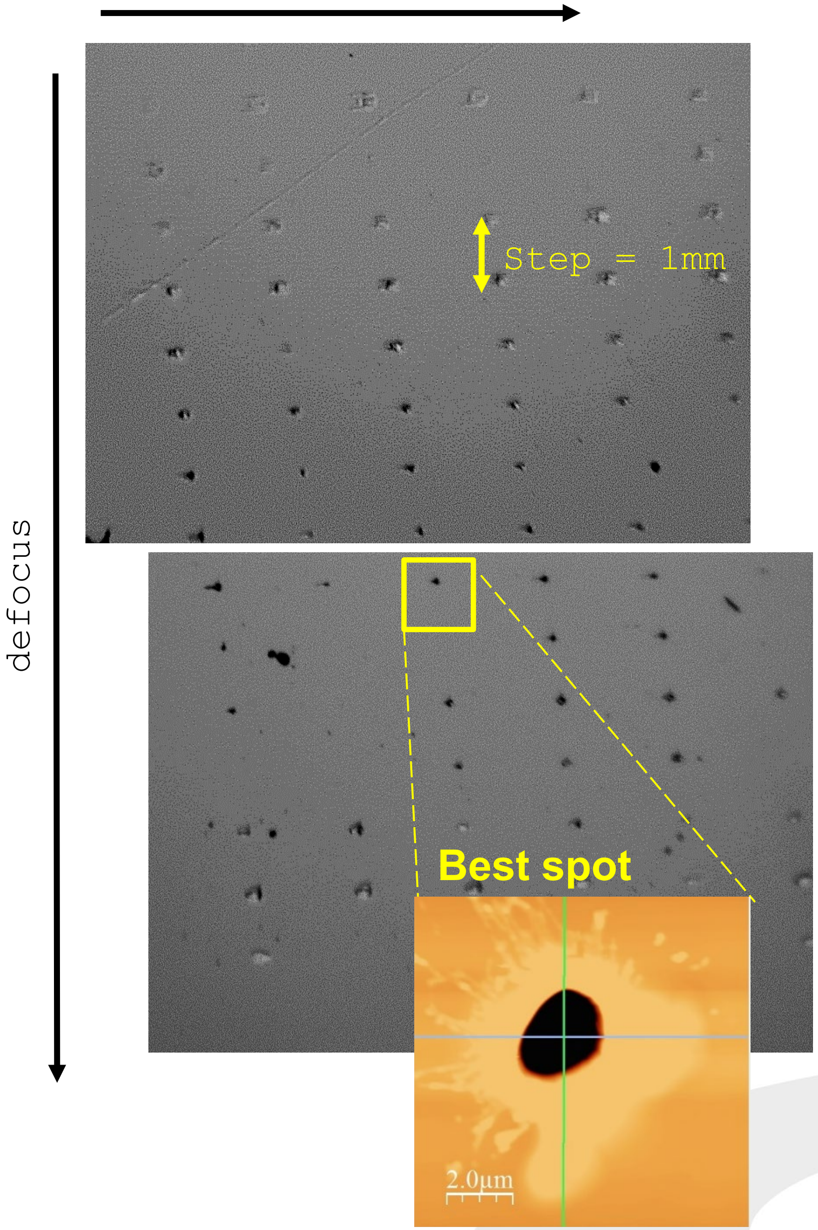
SPOT SIZE DETERMINATION

YAG vs. PMMA indentation

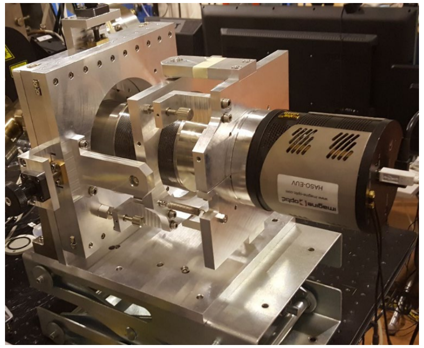


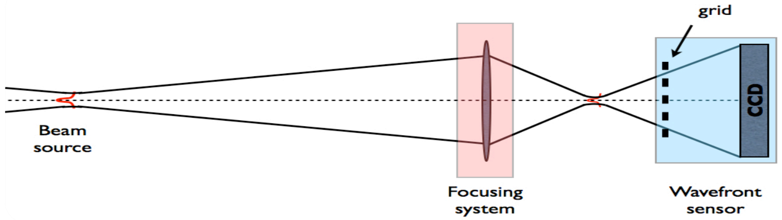


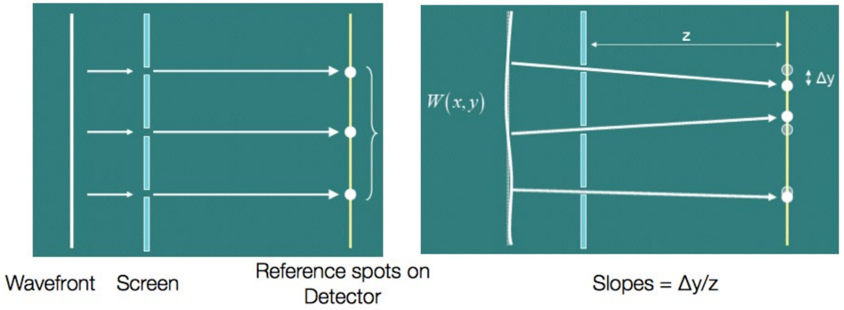
Focal spot of the **ellipsoidal mirror** (10x10μm^2 FWHM)



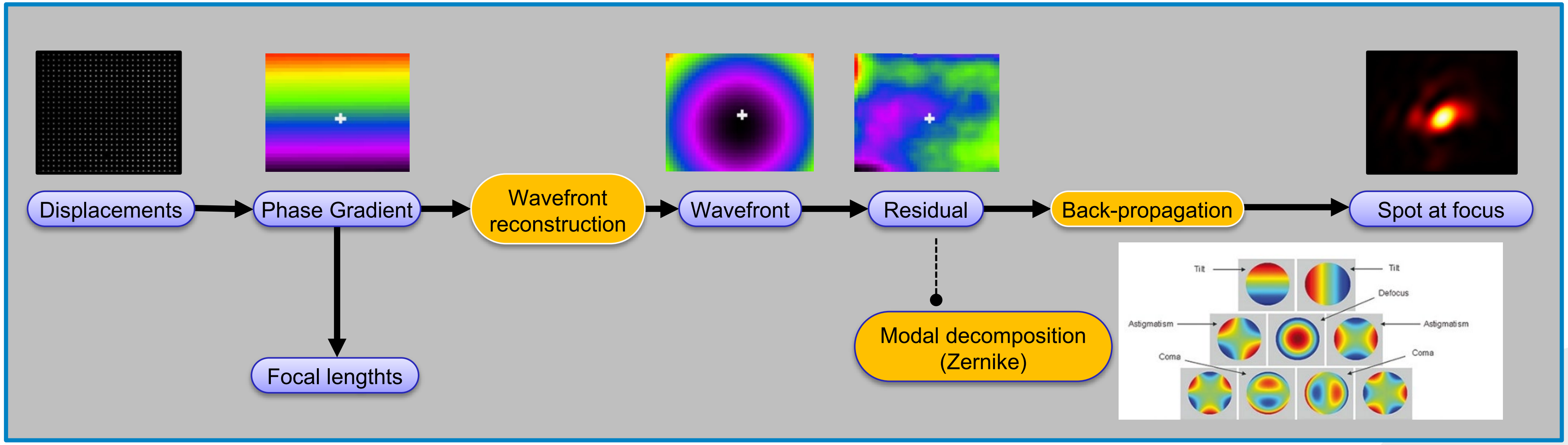
SPOT SIZE DETERMINATION
Wavefront Sensor





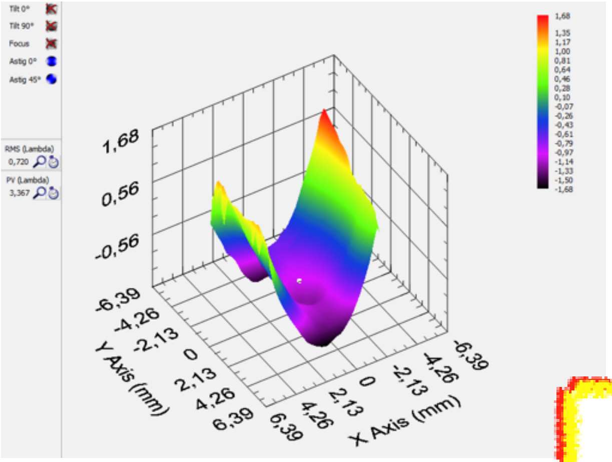


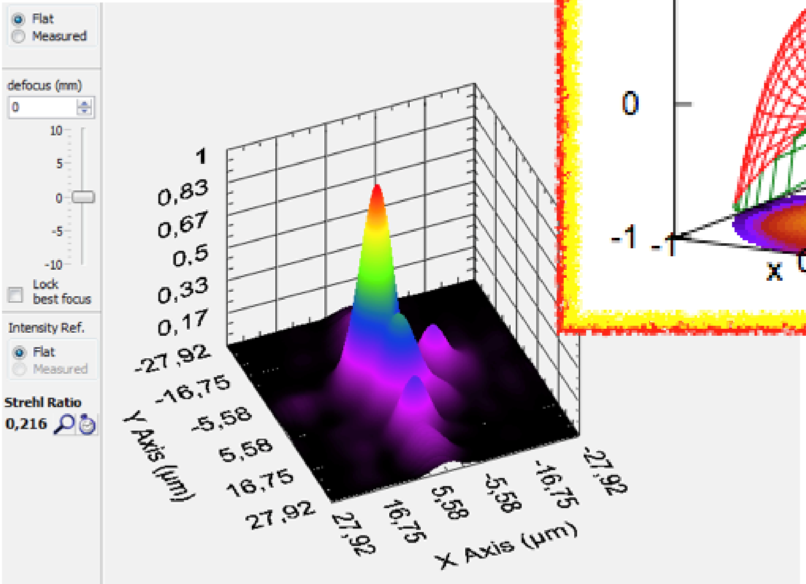
SPECS
- 72 x 72 grid (13 x 13) mm^2
- Pitch=180µm, Pinhole diameter: 60µm
- Wavelength range: 4-40nm
- Accuracy ~λ/10
- Squared pinholes !

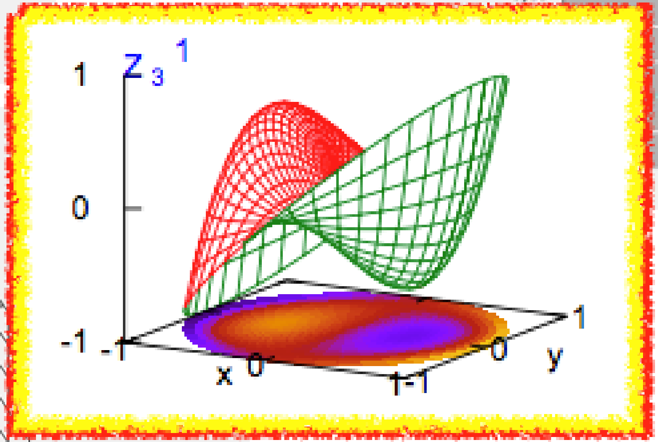


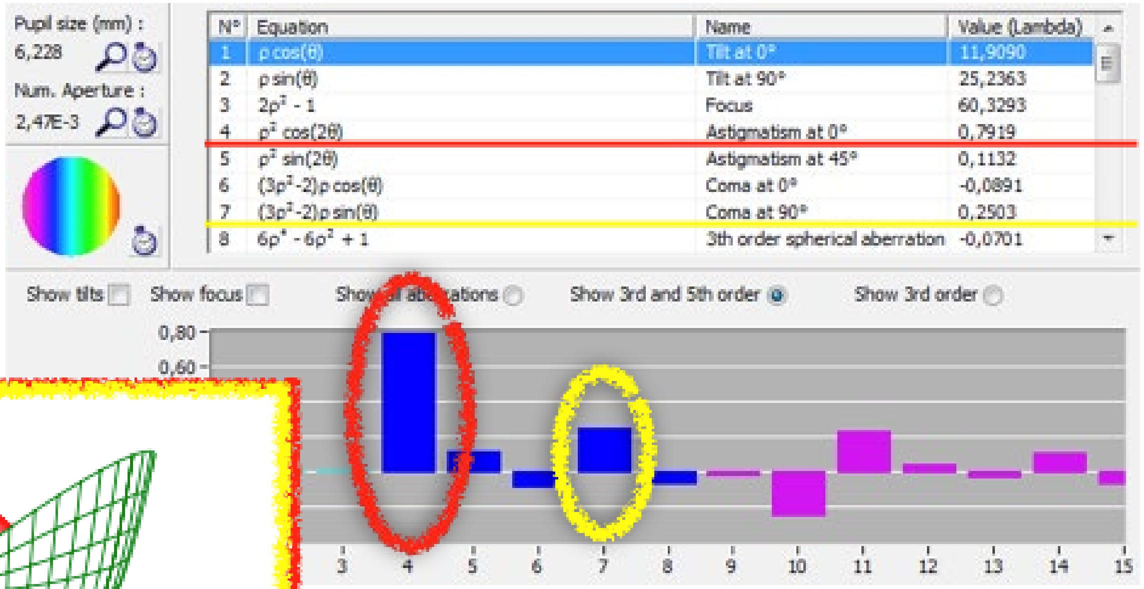
SPOT SIZE DETERMINATION

WFS-based optimization





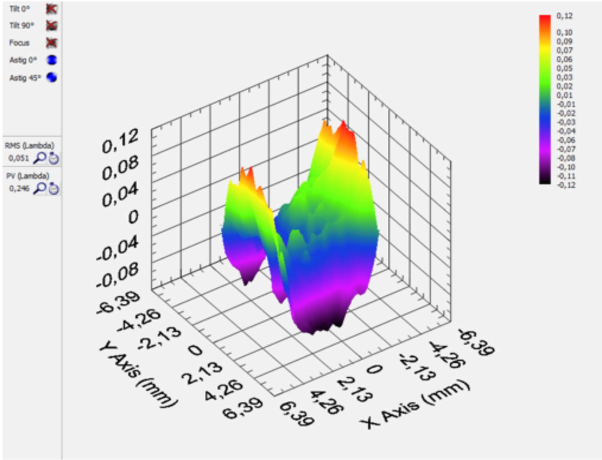


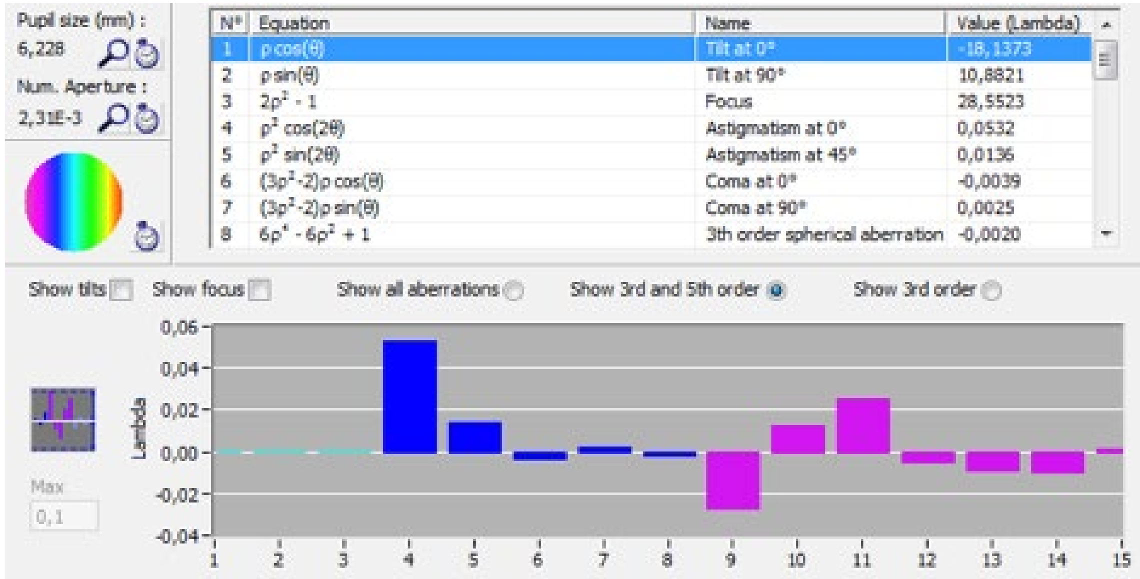


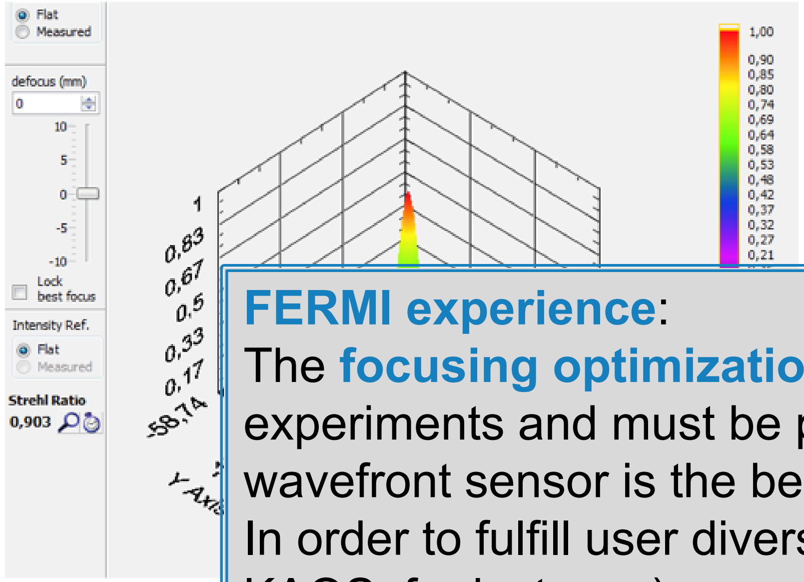
λ = 32 nm
Evidence of:
astigmatism at 0º 0.80 Lambda
coma at 90º 0.25 Lambda
RMS = 0.720 Lambda
Strehl ratio = 0.216

SPOT SIZE DETERMINATION

WFS-based optimization





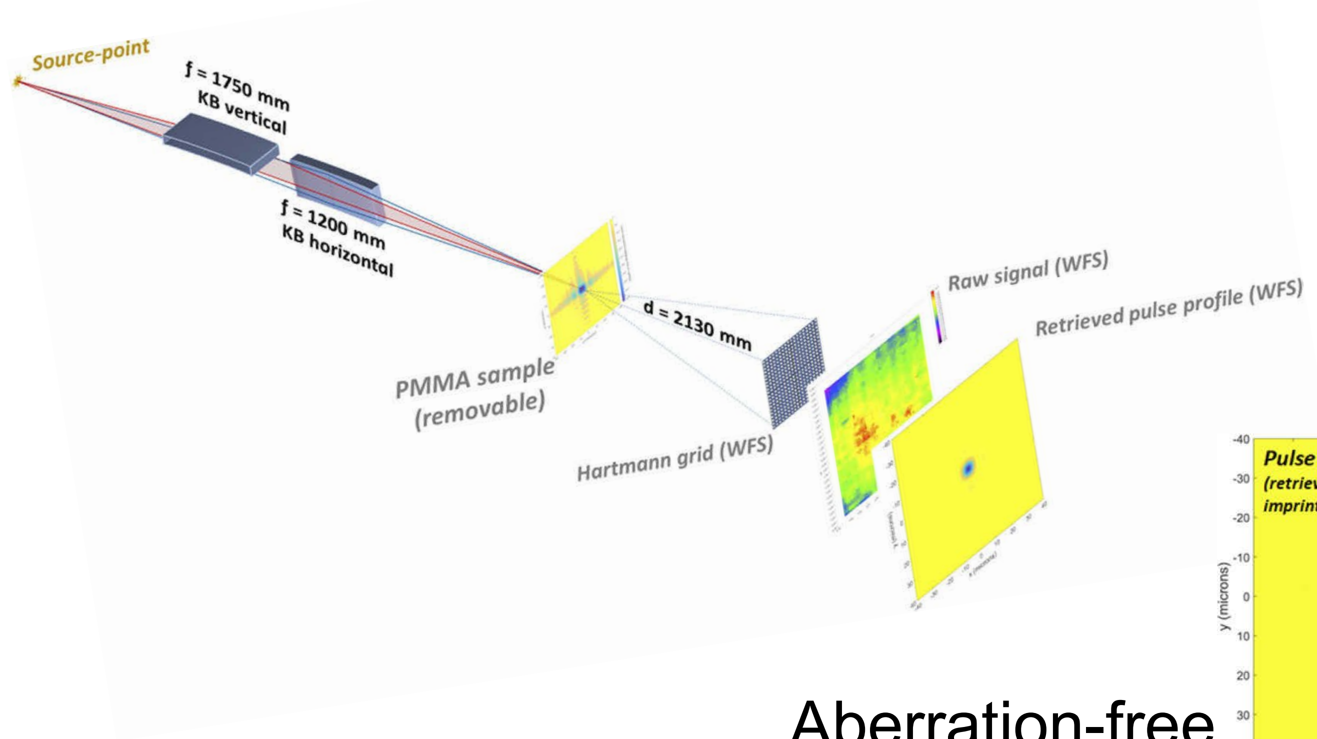


λ = 32 nm

FERMI experience:
The **focusing optimization** and consequent **spot size characterization** is fundamental for experiments and must be pursued by means of non-invasive and online diagnostics → the wavefront sensor is the best, so far.
In order to fulfill user diverse and often exotic requests, the **active optics systems** (like KAOS, for instance) seem to represent the best solution.

KAOS – KIRKPATRICK-BAEZ ACTIVE OPTICS SYSTEM

WFS vs. PMMA indentations



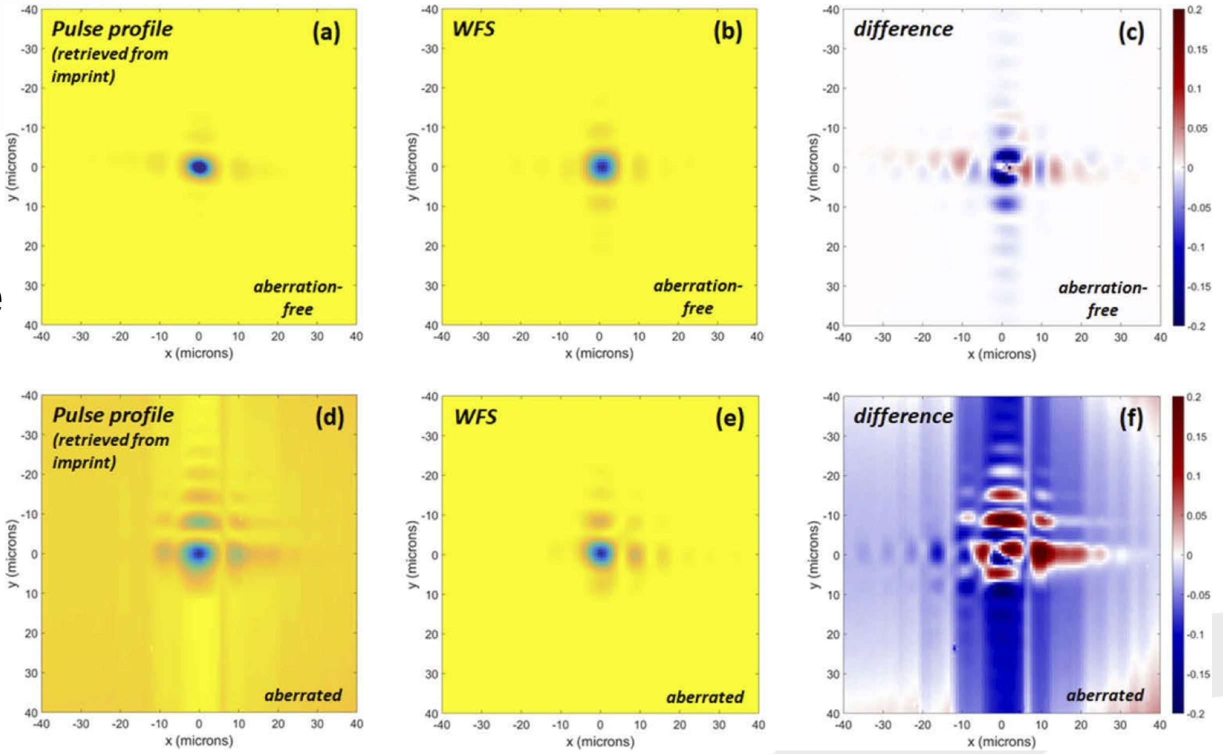
Research Article
Vol. 29, No. 22 / 25 Oct 2021 / Optics Express 36086
Optics EXPRESS

Tomography of a seeded free-electron laser focal spot: qualitative and quantitative comparison of two reconstruction methods for spot size characterization

ALBERTO SIMONCIG,[1,*] MICHELE MANFREDDA,[1] BENEDIKT RÖSNER,[2] NICOLA MAHNE,[1,3] LORENZO RAIMONDI,[1] FLAVIO CAPOTONDI,[1] EMANUELE PEDERSOLI,[1] GIOVANNI DE NINNO,[1,4] PIETRO PARISSE,[3] AND MARCO ZANGRANDO[1,3]

Aberration-free

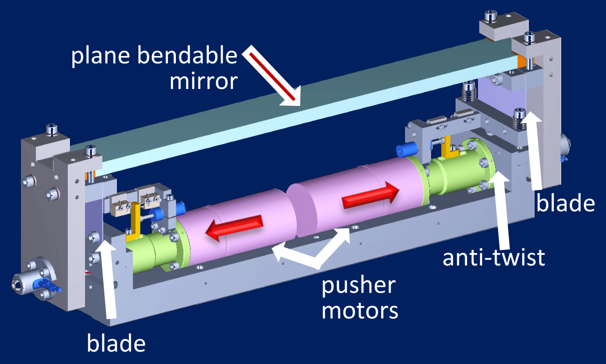
Aberrated (on purpose)



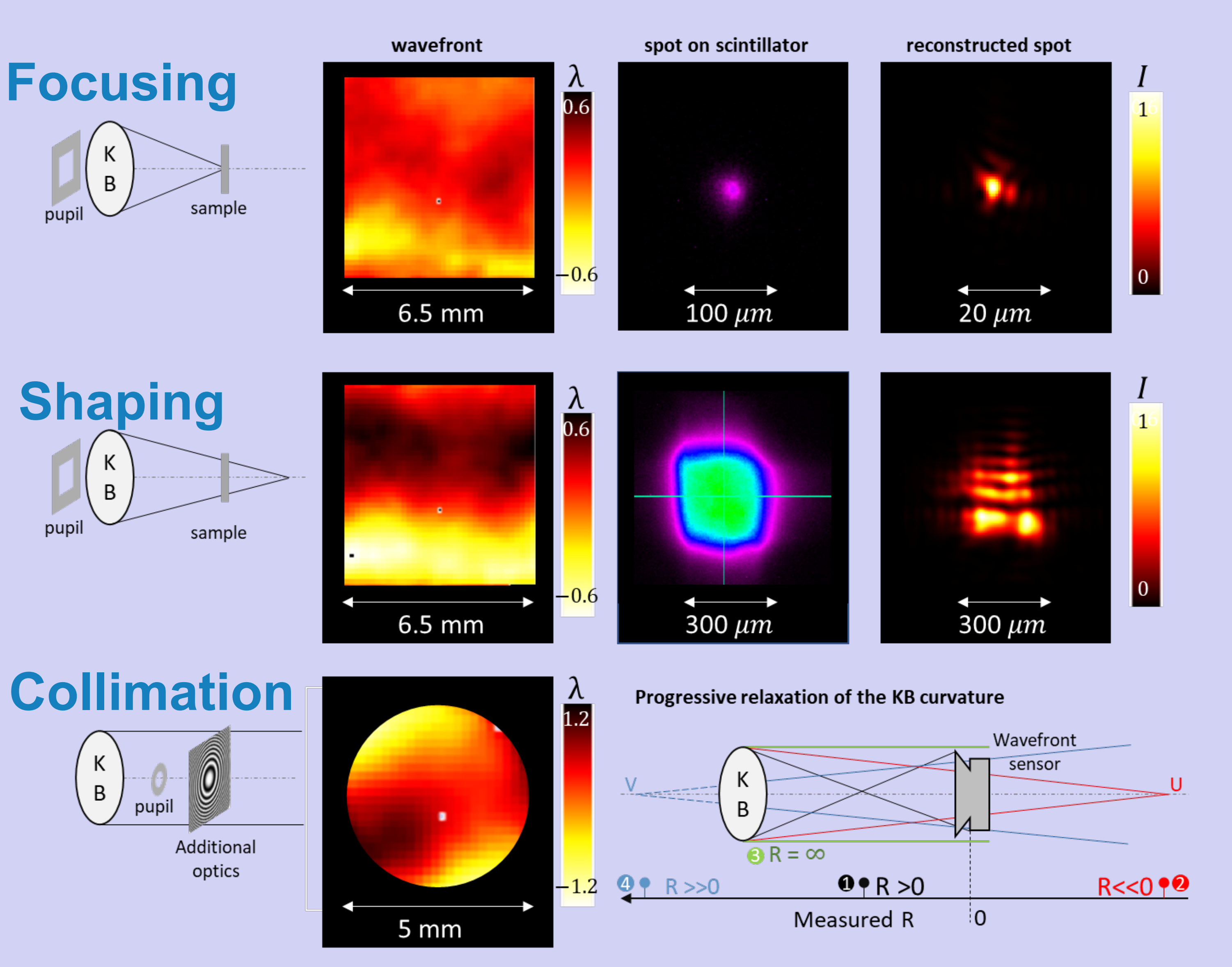
KAOS – KIRKPATRICK-BAEZ ACTIVE OPTICS SYSTEM

Versatility

KAOS
The Kirkpatrick-Baez Active Optical System

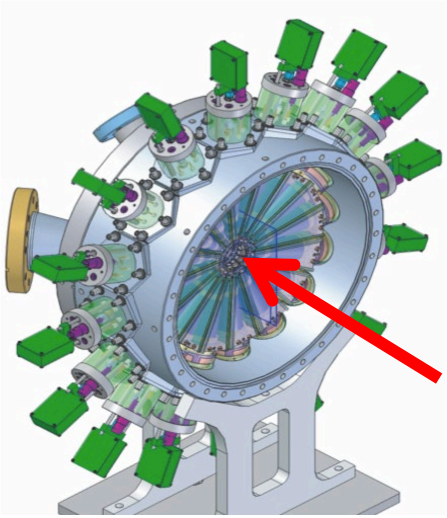


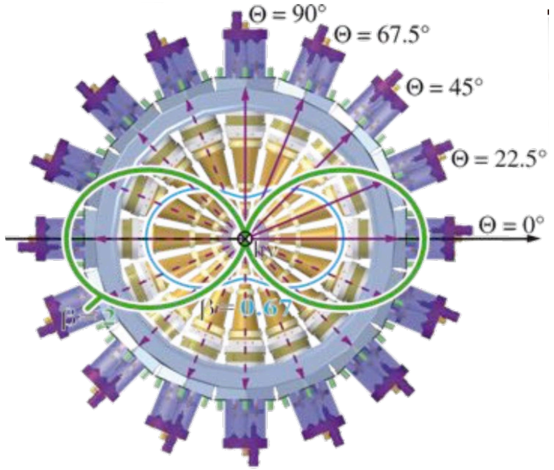
- λ: $1\ nm\ - 100\ nm$
- **Max Power:** $\sim 90\times$
- **Min. R:** $\sim 60\ m$
- **Residual: not *super low*, but a good compromise**



POLARIZATION

A universal diagnostic?





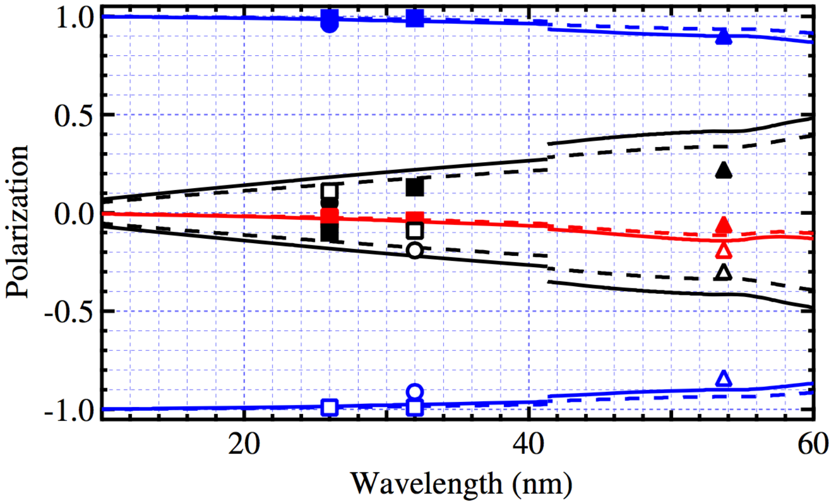
A **single shot polarimeter** based on angle resolving electron spectrometer (J.Viefhaus' group at DESY and then R.Coffee at LCLS)
Theory predicts specific electron distributions over the 16 detectors depending on the used gas and FEL polarization.

Diagnostics

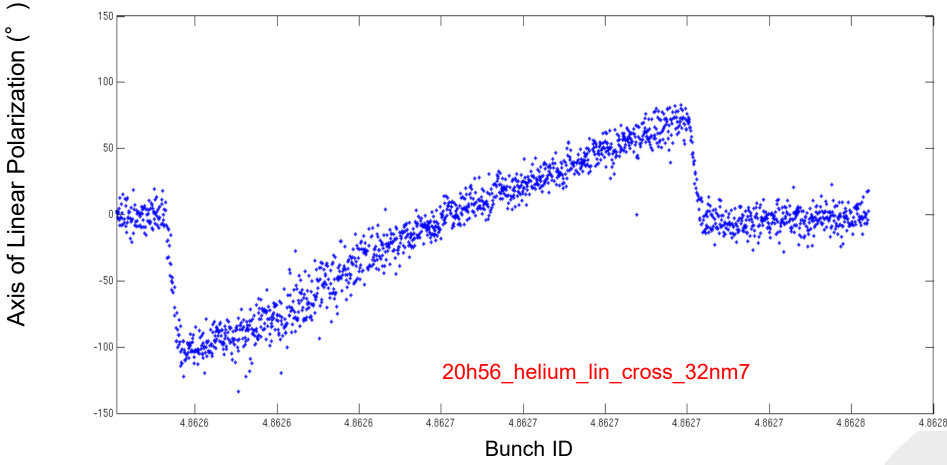
- Versatile online beam diagnostics unit
- Used at PETRA III, FERMI, LCLS, …
- Feasible as a (X)FEL diagnostic
- Polarization characterization on a shot-to-shot

Detection scheme

- Single-shot spectra → High detection efficiency ~4% of 4π
- Energy resolution → Resolution up to 10^{-3}
- Angular resolution → 16 spectrometers 22.5°
- Energy range → 0.02-25 keV (for European XFEL)



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

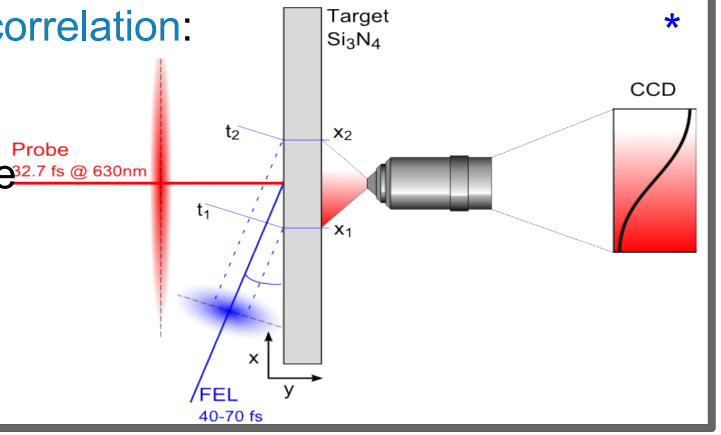


PULSE LENGTH
Cross correlation techniques

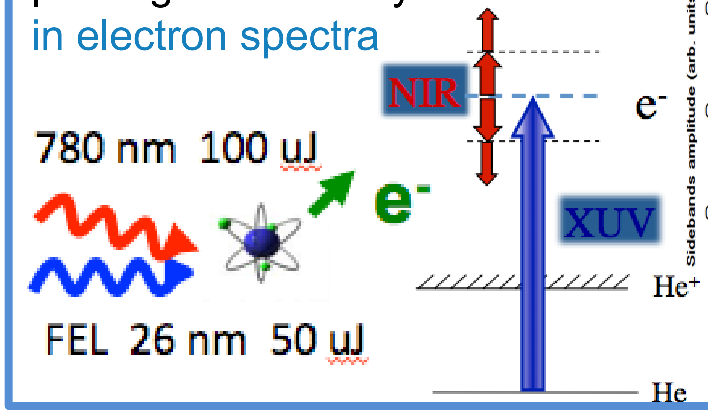
Two cross-correlation methods have been implemented and used for **measuring the FEL pulse length**.

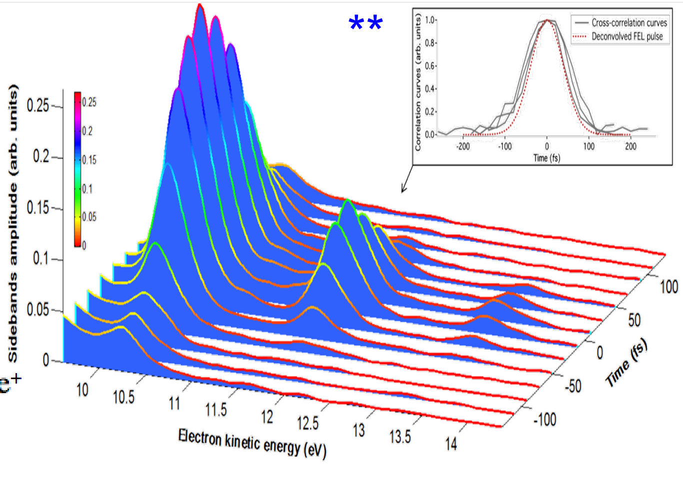
In both cases FEL pulse length has been studied as a function of seed laser parameters and FEL wavelength.

Solid state cross correlation: temporally & spatially encode FEL on the surface of a Si_3N_4 target probed with an ultrashort laser pulse



Cross correlation measurement probing the intensity of sidebands in electron spectra





P. Finetti et al. Phys. Rev. X **7**, 021043 (2017)

* In collaboration with F. Tavella team
** In collaboration with C. Callegari and LDM team

λ_{seed} (nm)	λ_{FEL} (nm)	τ_{seed} (fs)	τ_{FEL} (fs)
257.8	25.78	140	61.5 ± 3
261.1	23.74	140	63 ± 4
261.1	20.08	140	74 ± 3
261.7	37.38	112.5	52 ± 8
261.7	26.17	112.5	53 ± 3
261.7	26.17	157.5	72 ± 6
261.7	18.69	112.5	42 ± 6

Expected FEL pulse shortening at higher harmonics (shorter wavelength) has been confirmed by measurements.

PHOTON ANALYSIS DELIVERY AND REDUCTIONS SYSTEM

Members and collaborations

Current PADReS:

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R. Gobessi, S. Gerusina, C. Fava

Beamlines:
L. Foglia (TIMEX/TIMER)
F. Capotondi, E. Pedersoli, M. Pancaldi (DiProI)

IT:
A. Abrami, & ITC

Machine Physics :
E. Allaria, G. De Ninno, L. Giannessi & FERMI team

Former PADReS:
N. Mahne (CNR-IOM), L. Raimondi (Elettra), C. Svetina (IMDEA),
D. Cocco

PADReS

Imagine Optic – G. Dovillaire

Berkeley Lab – D. Cocco

Paul Scherrer Institut PSI – B. Rösner, et al.

CERIC – A. Hafner

Argonne National Laboratory – L. Rebuffi

DESY – E. Ploenjes, K.Tiedke, et al.

CENILS – G.De Ninno (CENILS)

Thank you!


Elettra
Sincrotrone
Trieste