Elettra Sincrotrone Trieste

FERMI FEL, the machine

S. Di Mitri, ELETTRA SINCROTRONE TRIESTE

on behalf of the FERMI Team

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Outline

- ❑ Facility overview, FEL architecture
- ❑ FEL performance
- ❑ Operating modes (incl. two-pulses, multi-color, THz source)
- ❑ Upgrade plans

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Why X/UV FELs

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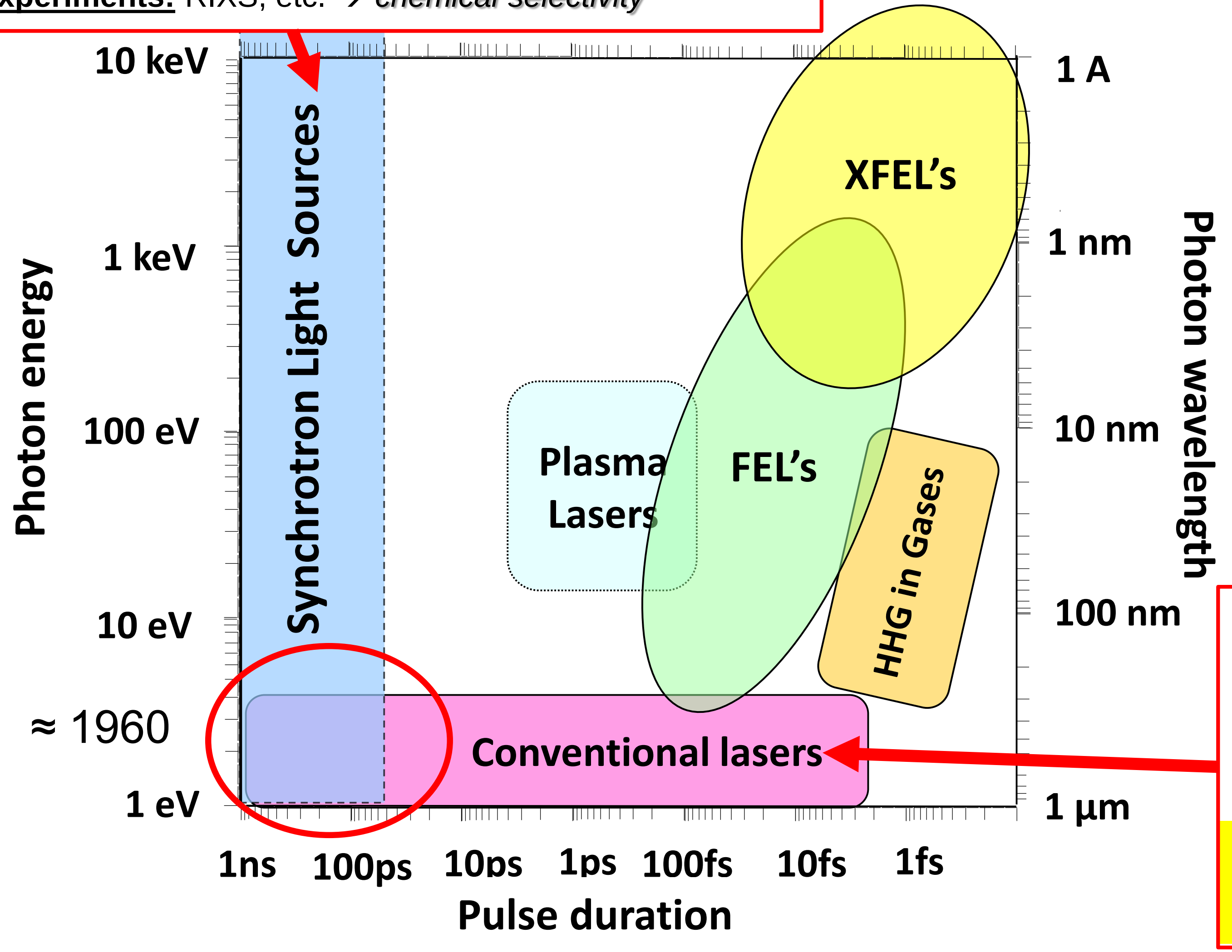
<u>Spatial Resolution (~Å)</u>: imaging, diffraction, etc. → *atomic structure*

<u>Resonant Experiments:</u> RIXS, etc. → *chemical selectivity*



FEL's can combine all these concepts! And take advantage of the achievements of the two scientific communities.

<u>Temporal Resolution (~fs)</u>: "serial" single shot imaging and diffraction → *atomic dynamics in "real time"*

<u>Peak Power (~TW)</u>: high field physics → *warm-dense matter, extreme conditions, etc.*

<u>Coherence</u>: nonlinear optics, coherent control → *photons "work together"* **FERMI's target**

Courtesy C. Masciovecchio & F. Bencivenga

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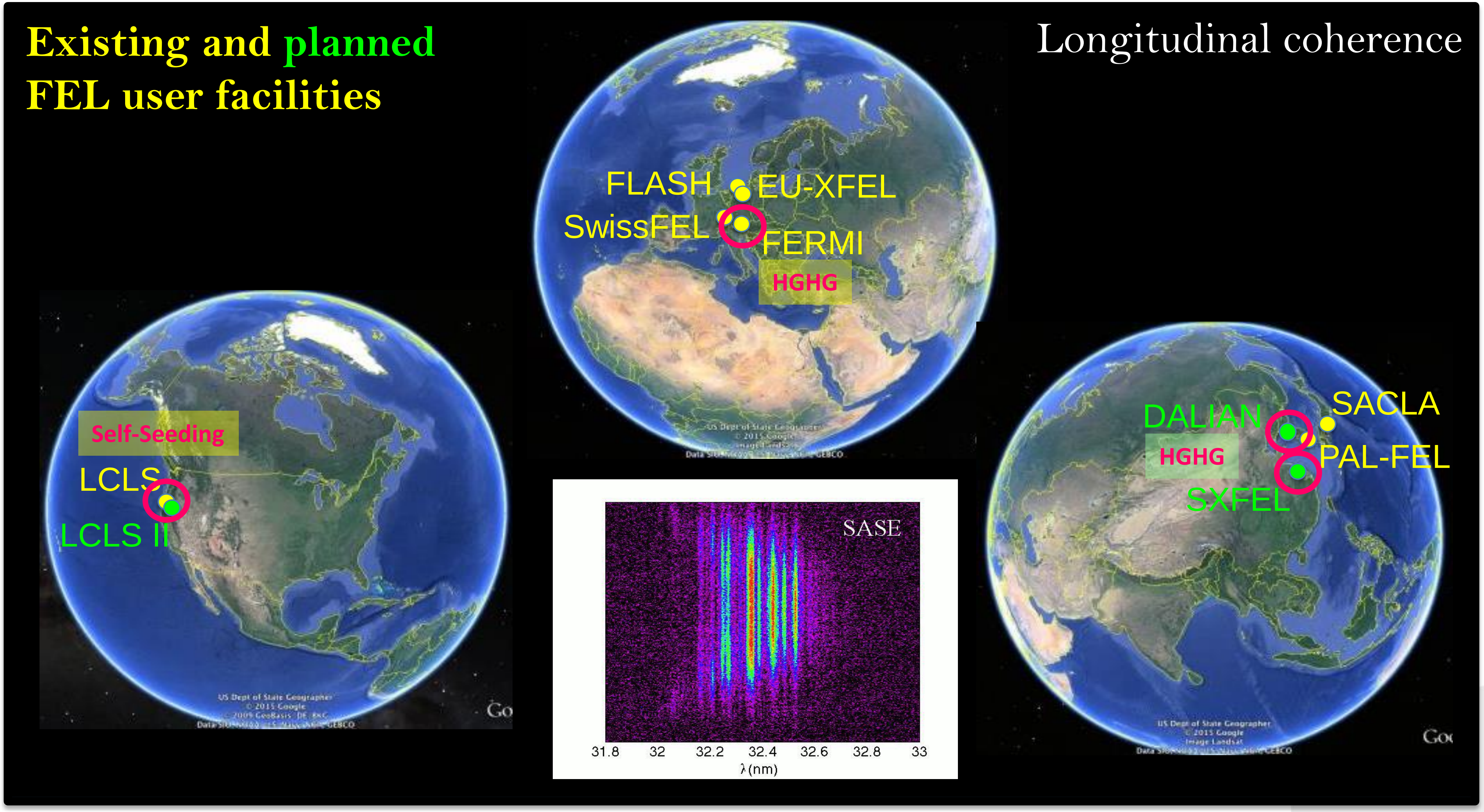
Unique Features



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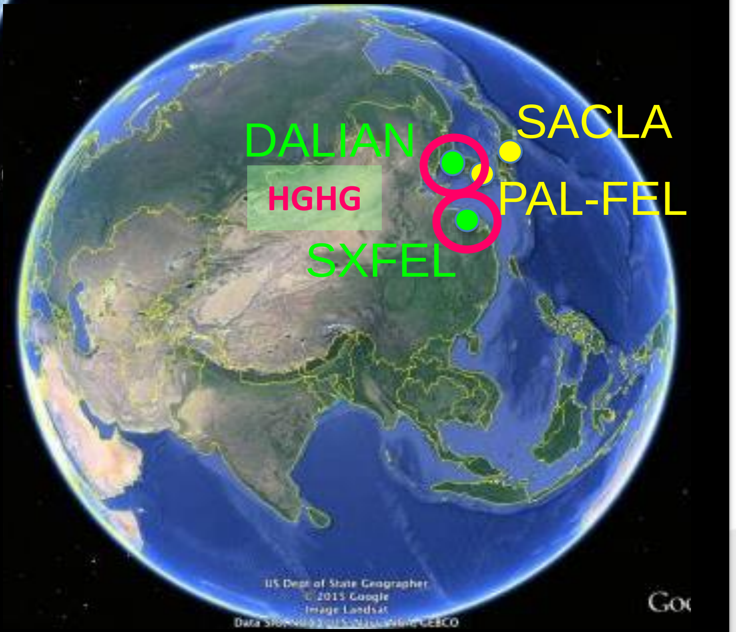
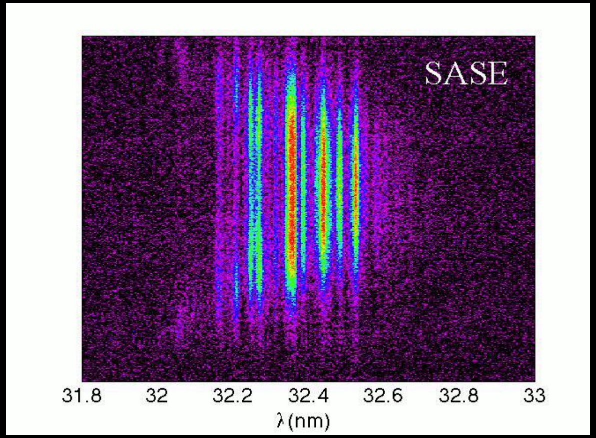
Unique Features

Existing and planned FEL user facilities

Longitudinal coherence
Water window
Few % - Stability
Now running



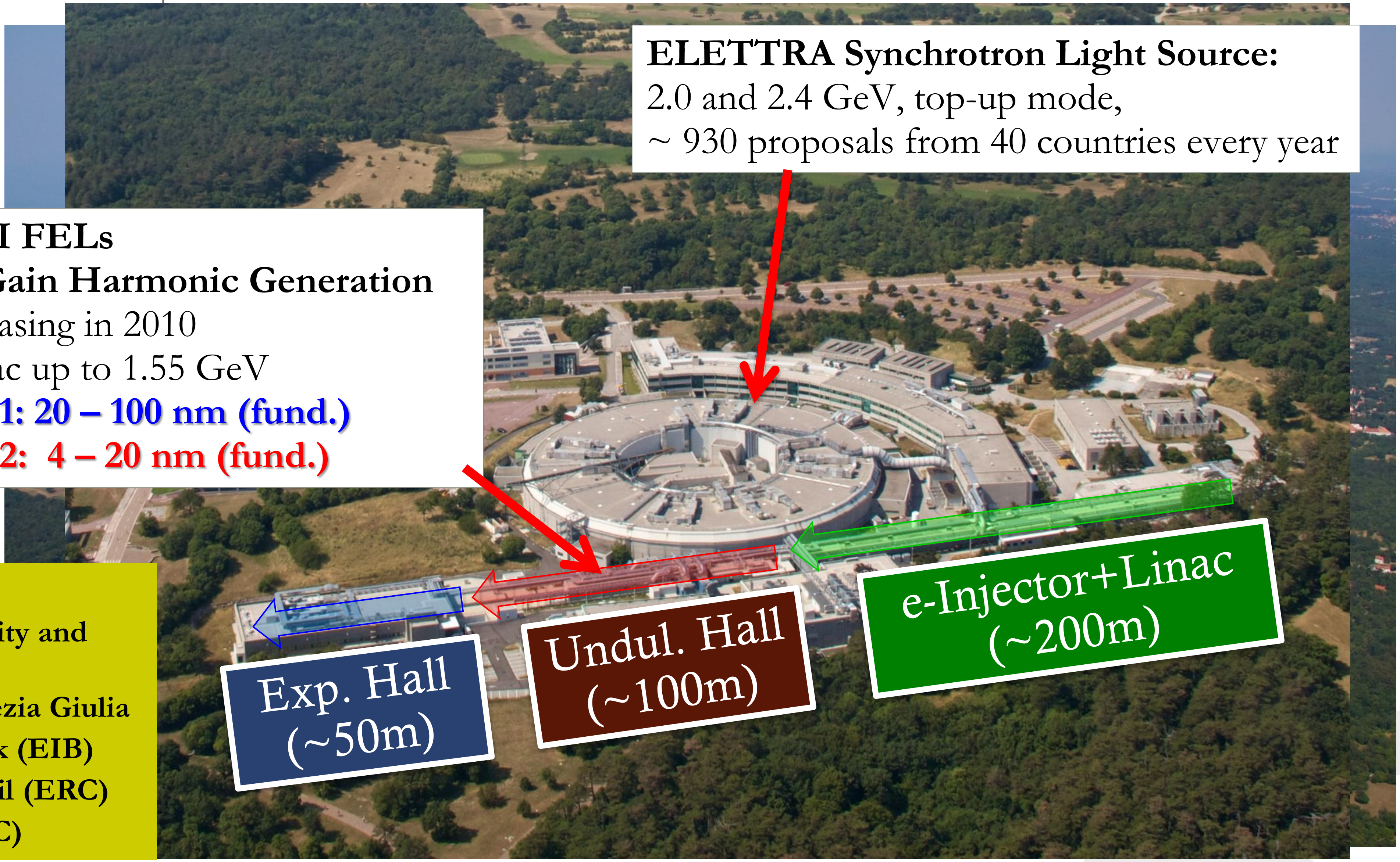


Site

ELETTRA Synchrotron Light Source:
2.0 and 2.4 GeV, top-up mode,
~ 930 proposals from 40 countries every year

FERMI FELs
High Gain Harmonic Generation

- First lasing in 2010
- e-Linac up to 1.55 GeV
- **FEL-1: 20 – 100 nm (fund.)**
- **FEL-2: 4 – 20 nm (fund.)**



Sponsored by:
Italian Minister of University and Research (MIUR)
Regione Auton. Friuli Venezia Giulia
European Investment Bank (EIB)
European Research Council (ERC)
European Commission (EC)

Overview

Project started in 2004
CDR: +3 years
Construction & Installations: +2 years **(2009)**
Commissioning: +9 months
First Lasing: +5 months (2010)
First Users FEL-1: + 3 months **(2011)**
Upgrades, First Users FEL-2: + 9 months **(2012)**

- ❑ High peak power **0.1 - 1 GW** range
- ❑ Short pulse duration **100's to 10 fs** (fwhm)
- ❑ Tuneable wavelength **4-100 nm**
- ❑ Variable polarization **LH, LV, C**

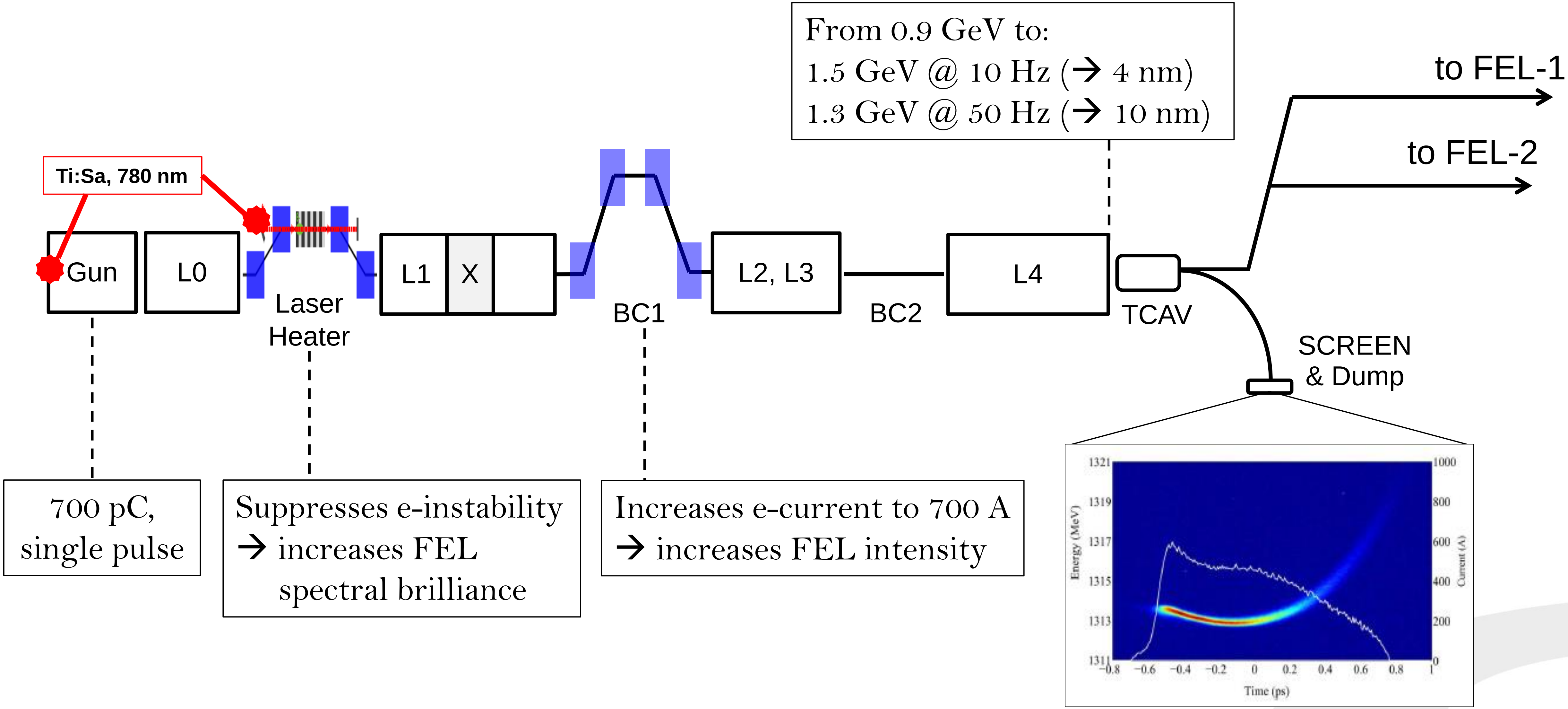
APPLE-II undulators

- ❖ Brilliance $10^{30} – 10^{31}$ ph/sec/mm²/mrad²/0.1%bw
- ❖ Flux $10^{12} – 10^{14}$ ph/pulse
- ❖ Bandwidth ~ Fourier Transf. Limit, **0.02% – 0.1% rms**

Enables new science in…

- **Ultra-fast coherent diffractive imaging.**
- **Time-resolved scattering** processes in chemical and biological systems.
- **Extreme conditions** of matter, phase transitions, population inversion.
- **Low density systems**, i.e. unperturbed atoms, molecules, and clusters.
- **Non-linear processes.**
- **Four wave mixing** with **elemental selectivity.**

Accelerator



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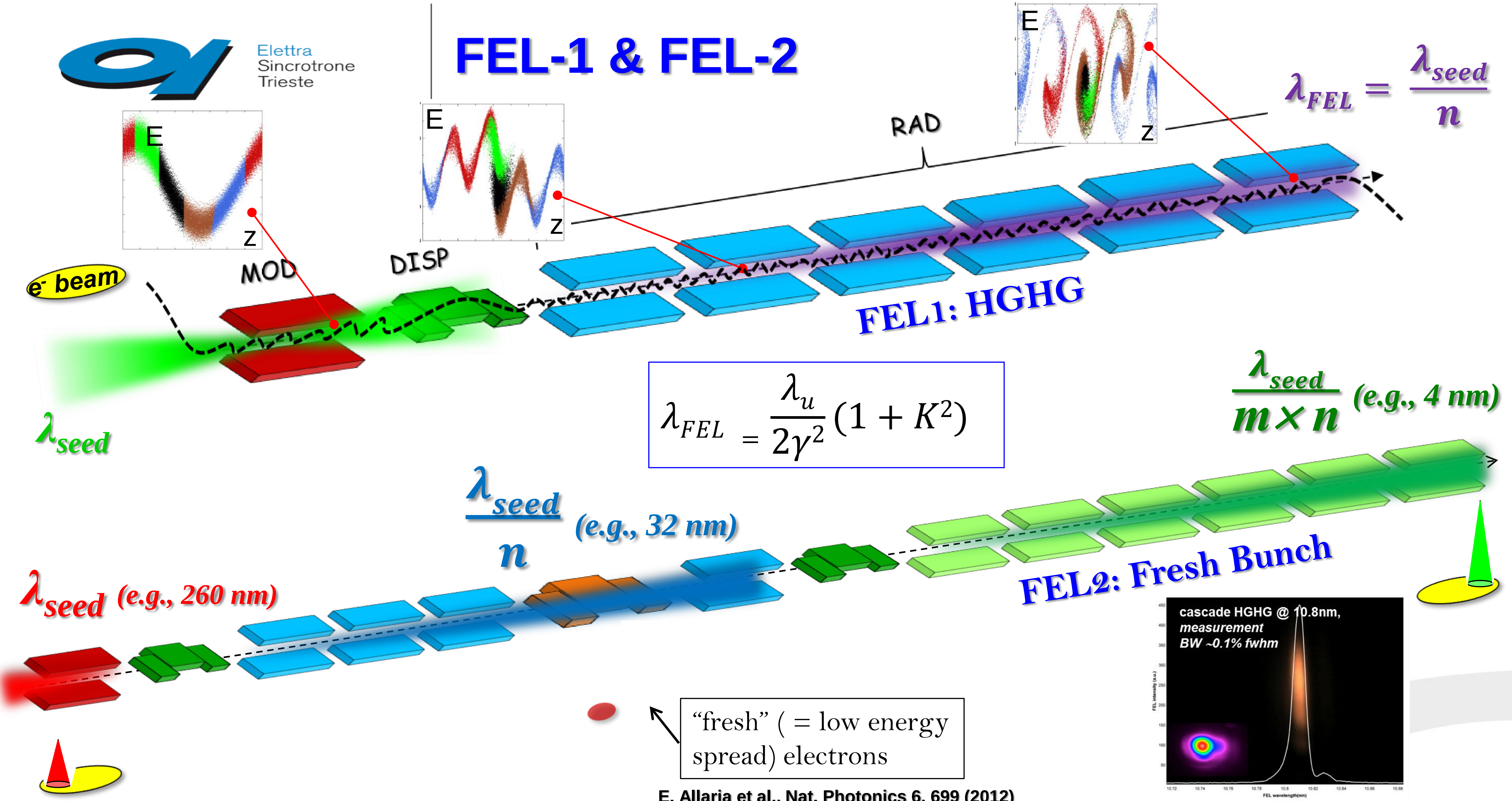
FEL-1 & FEL-2



$$\lambda_{FEL} = \frac{\lambda_u}{2\gamma^2}(1 + K^2)$$

"fresh" (= low energy spread) electrons

E. Allaria et al., Nat. Photonics 6, 699 (2012)
E. Allaria et al., Nat. Photonics 4, 2476 (2013)

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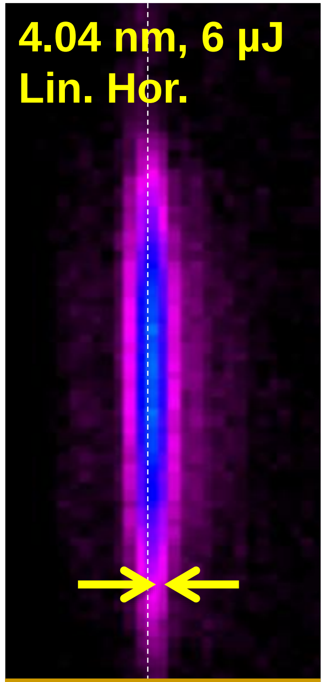
Ultimate Performance

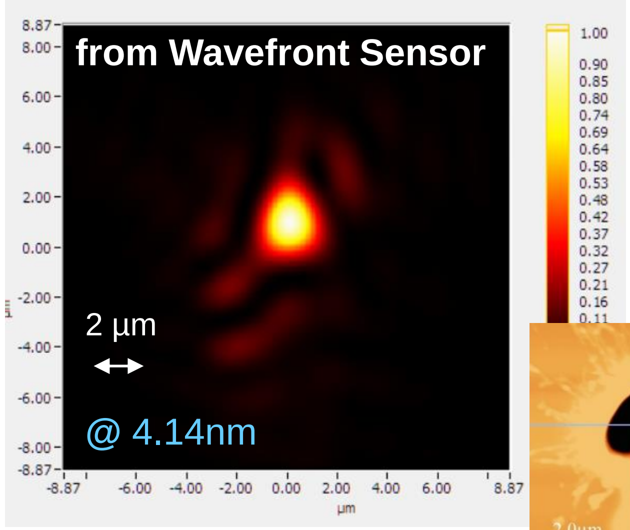
@ TIMEX

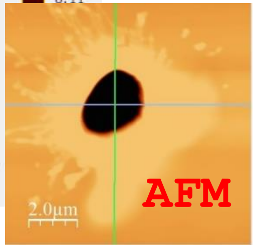
→ 4 nm, FTL



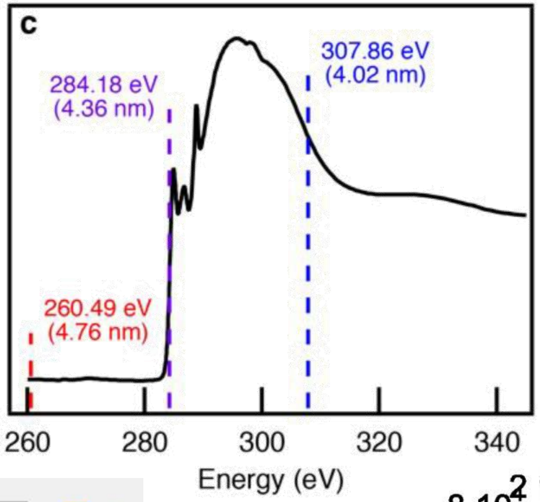
1 pixel = 2.5x10^{-4} nm

Transverse Coherence

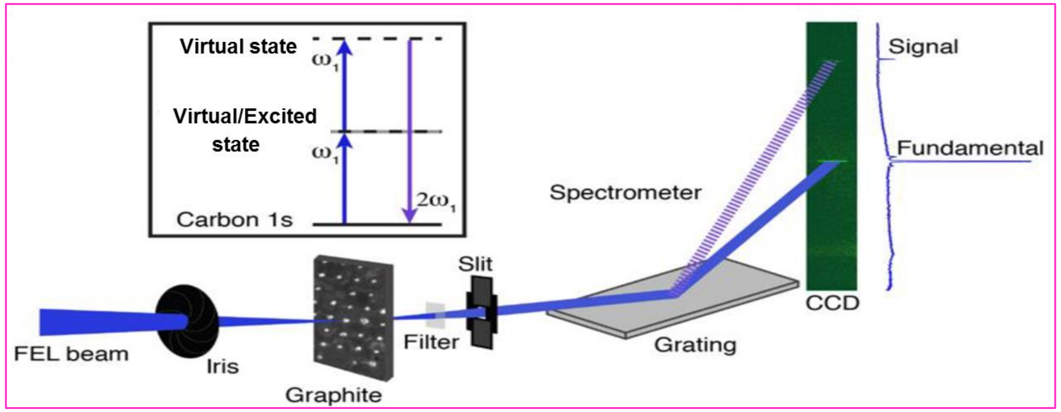




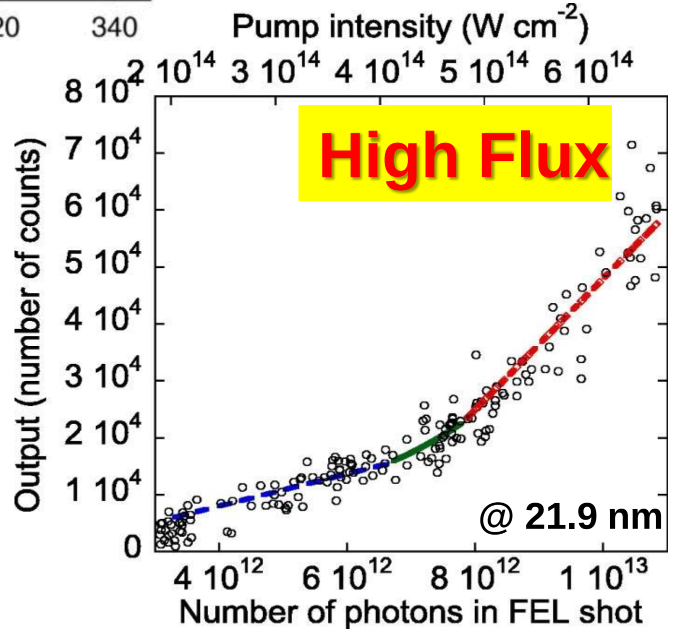
Tuneability



2nd harmonic generation form graphene



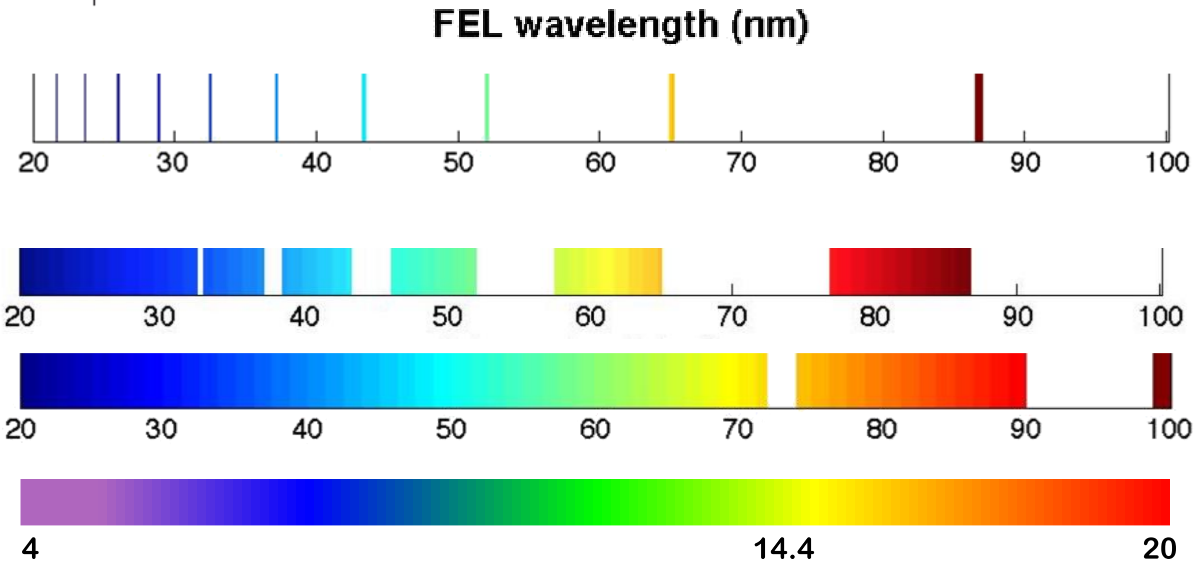
High Flux



R. K. Lam et al., PRL 120, 023901 (2018)
M. Zangrando et al., Proc. FEL 2017
P. Jonnard et al. Str. Dyn. 4, 054306 (2017)
L. Raimondi et al., NIM A, 710, 131 (2013)

Wavelengths (12 – 300 eV)

THG, ~261 nm
or ~265 nm



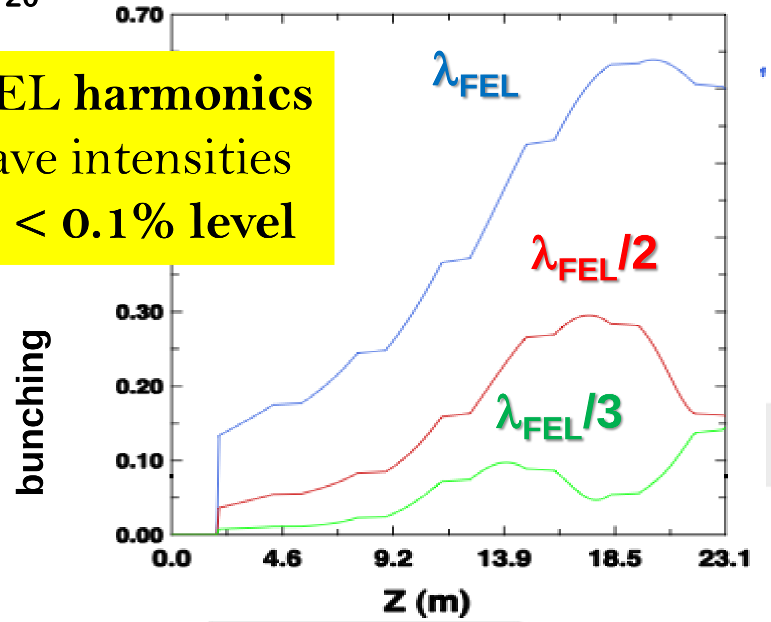
OPA, 230–260 nm
or 296–360 nm

☺ ***peak power***

☺ ***λ-scan***

- **THG** ⇒ ±0.2% λ-tuneability
- **OPA** ⇒ *@FEL-1*, fast λ-scans in selected ranges
  (20 – 65 nm, 30 – 100 nm, etc.)
  ⇒ *@FEL-2*, ±10–20% λ-tuneability
  (depending on the polarization)

FEL **harmonics** have intensities at **< 0.1% level**



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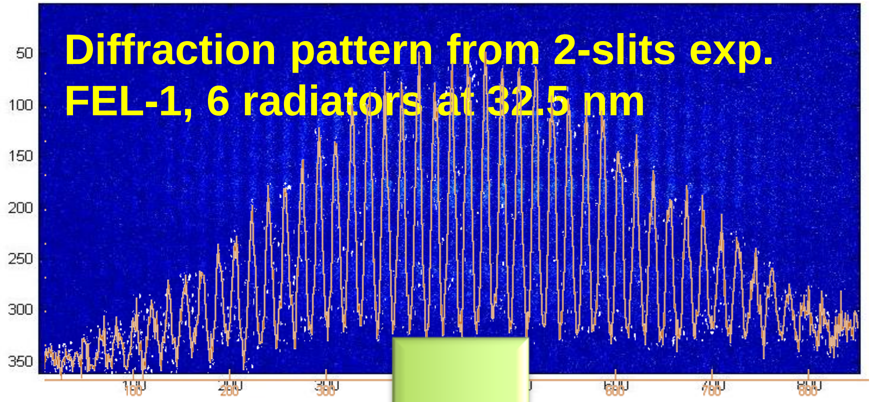
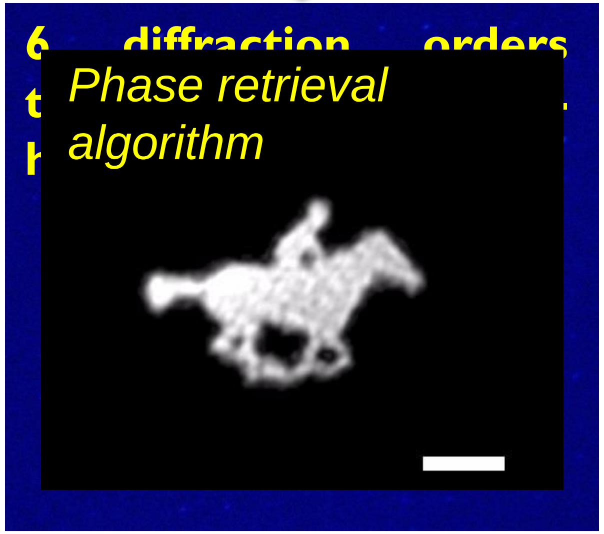
Transverse Coherence

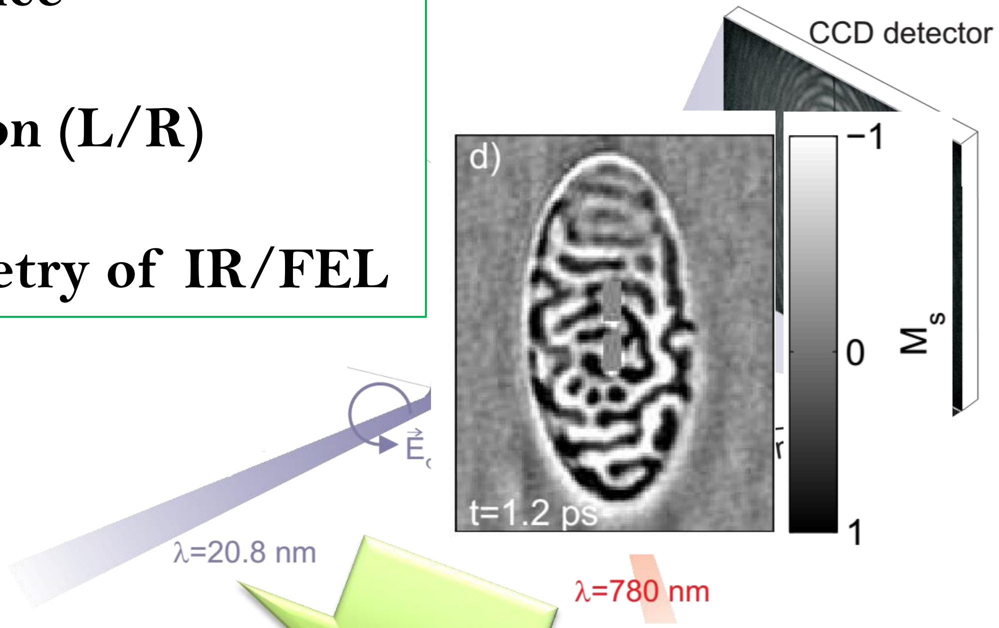
@ DiProI

Young's 2-slits experiment @ DIPROI





Transverse coherence
+
Circular polarization (L/R)
+
No-collinear geometry of IR/FEL



- ➢ Holographic imaging of magnetic materials
- ➢ Enhanced E-field to melt the magnetic order

R. A. Kirian et al., Opt. Expr. 18, 6 (2010)
F. Capotondi et al., Rev. Sci. Instr. 84, 051301 (2013)
C. von Korff Schmising et al., PRL 112, 217203 (2014)

Longitudinal Coherence

@ LDM, TIMEX

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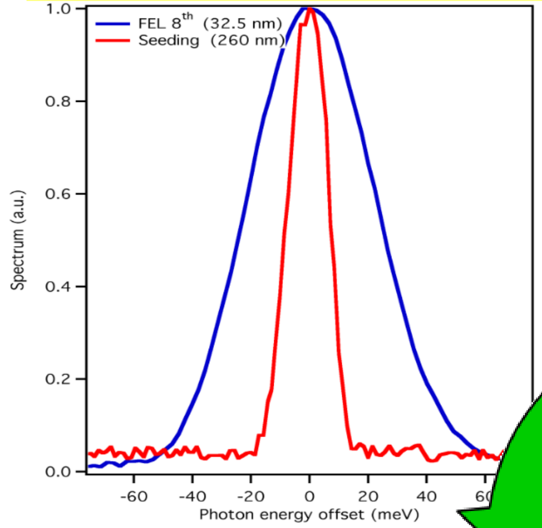
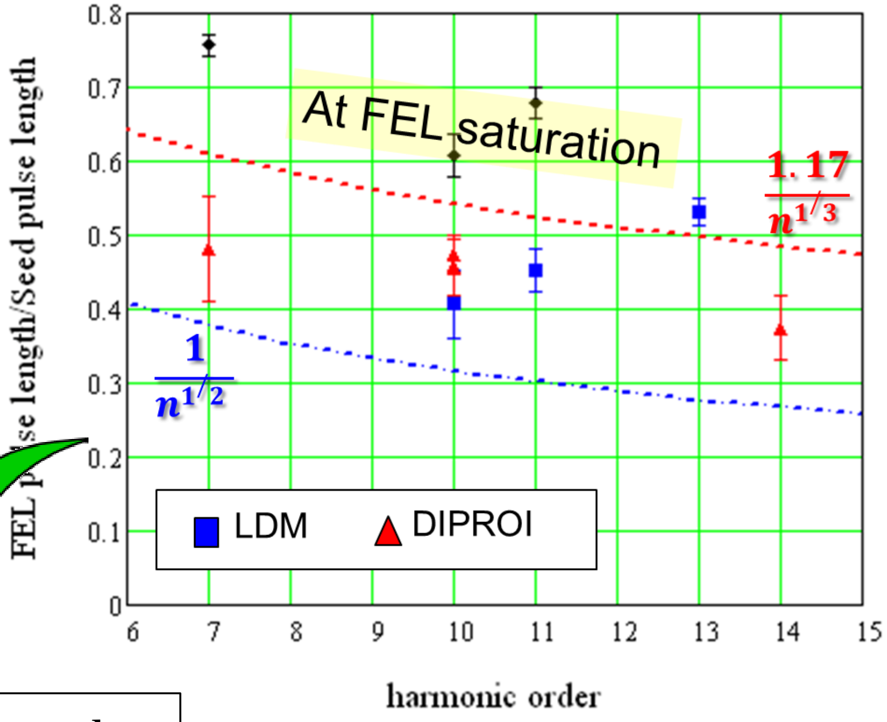
FEL pulse is broader than the seed because is shorter



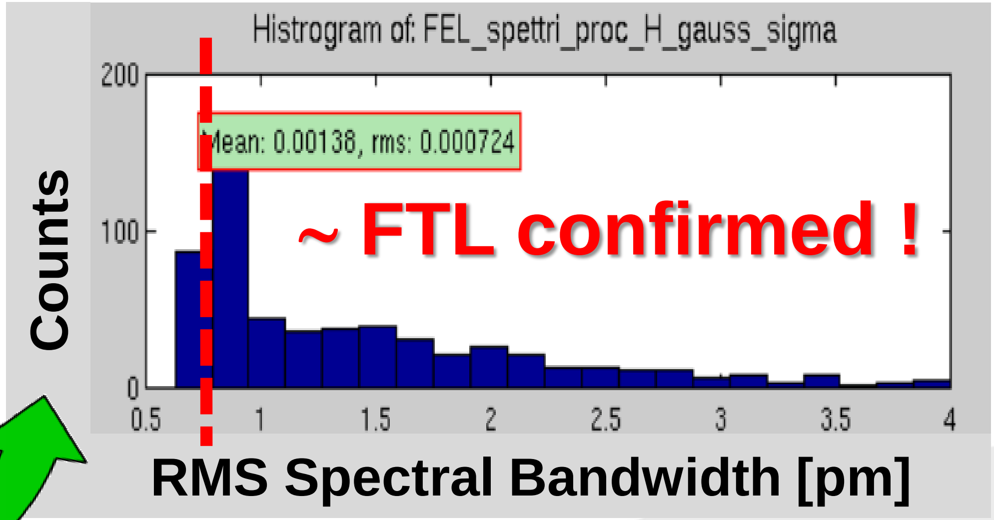


PULSE LENGTH

BANDIWDTH

Δt_{FEL} scaled from seed duration **≈ 20 fs fwhm**

σ_λ @ Fourier Tr. Lim. = **0.8 pm or 0.02%**



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

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Polarization

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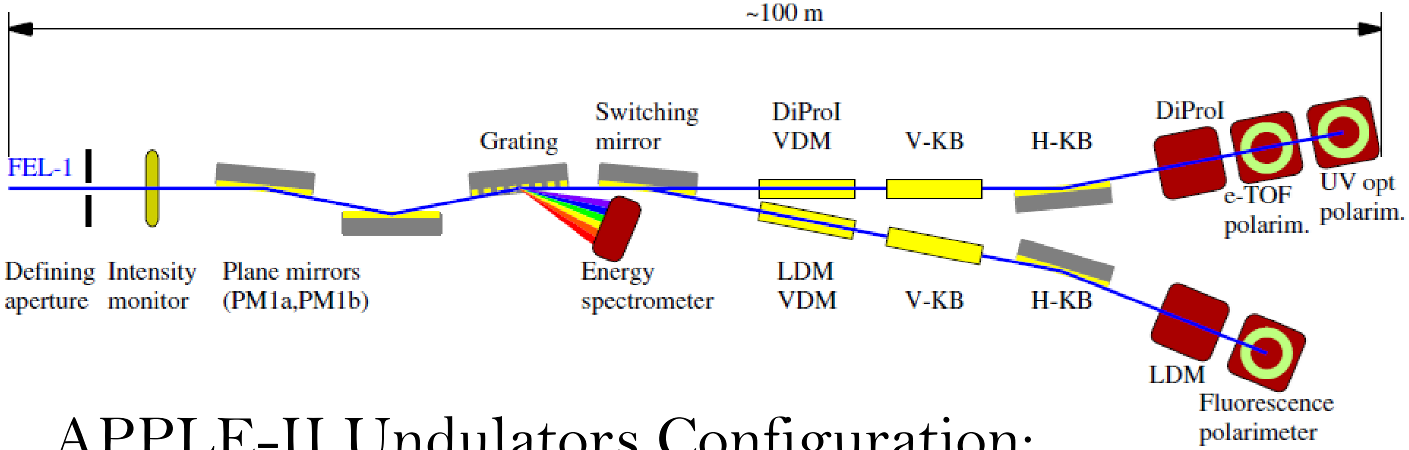
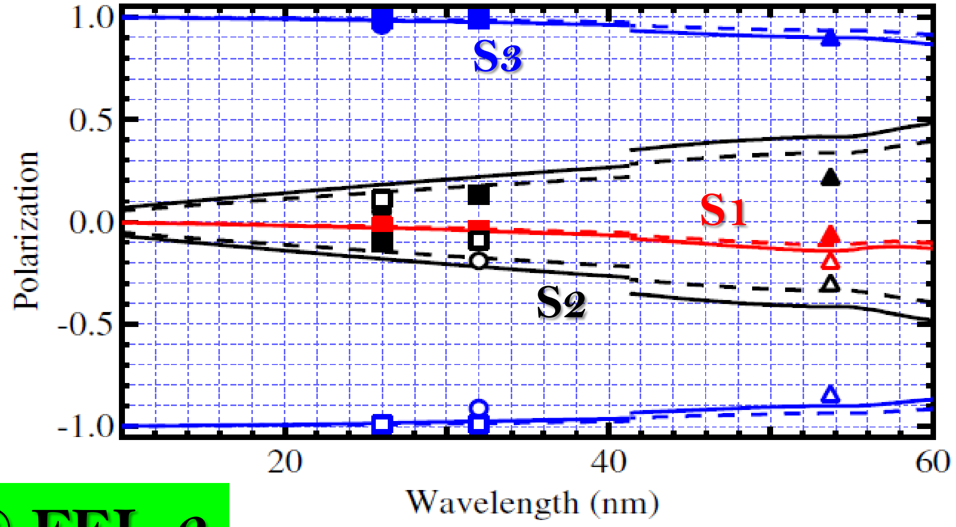


@ DiProI, LDM

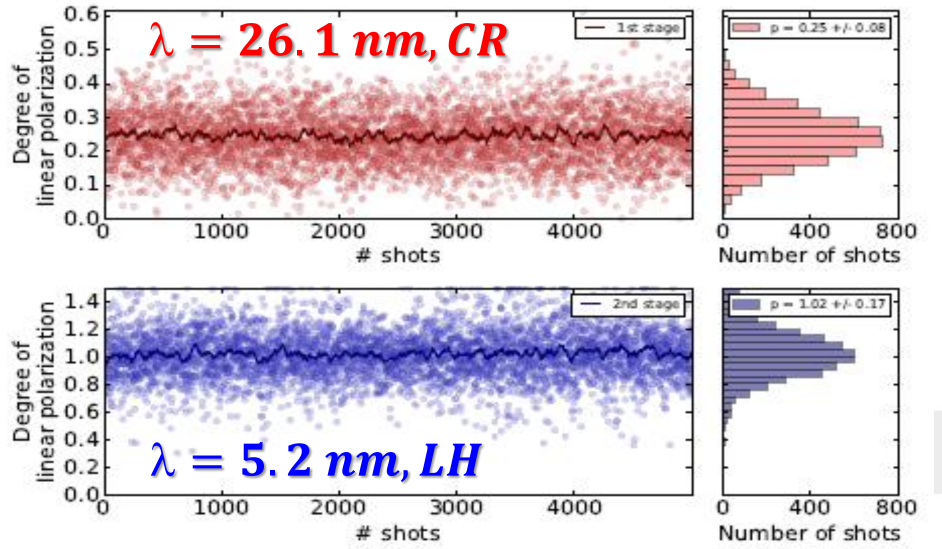
@ FEL-1



APPLE-II Undulators Configuration:

- Phase shift (*standard*)
- Cross-polarized undulators

@ FEL-2



Typical Degree of Polarization at Sample > 95%

Circular → maximum flux

Linear Horizontal → widest wavelength tuneability

E. Allaria et al. Phys. Rev. X 4, 041040 (2014)
E. Ferrari et al., Sci. Reports 5, 13531 (2015)
E. Roussel et al., Photonics 4, 29 (2017)

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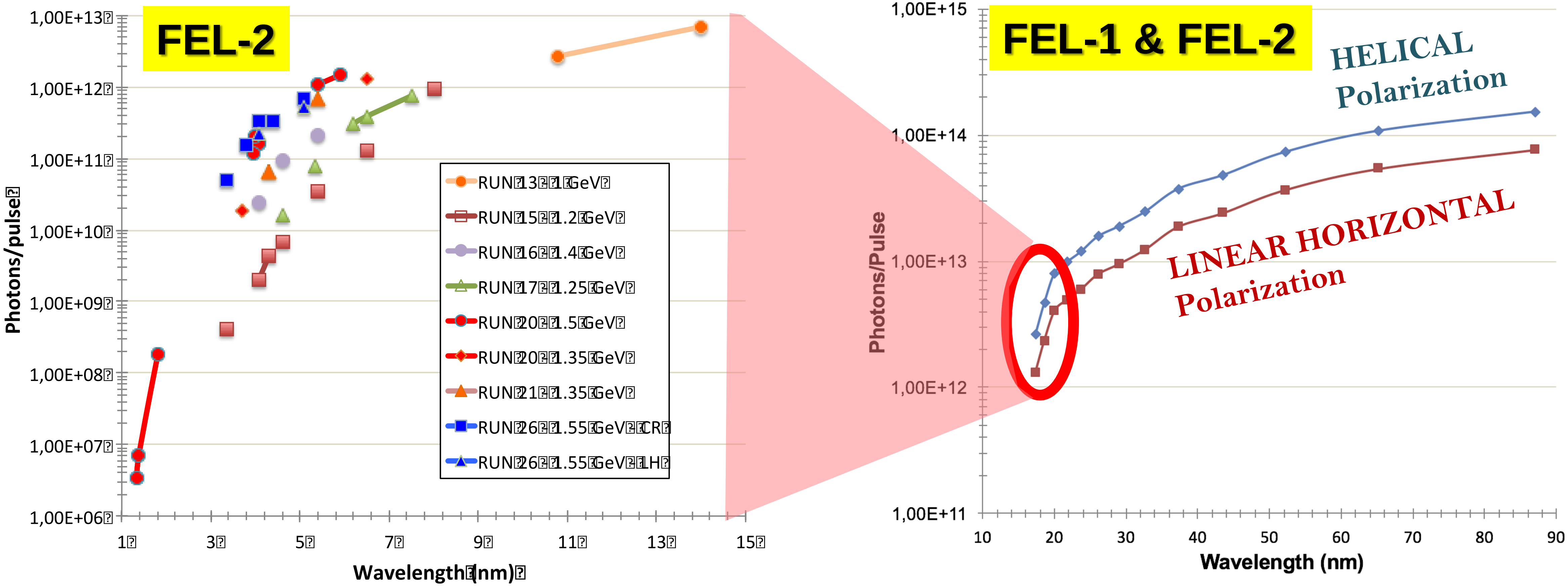
Flux



Energy per pulse ***at the source*** **:**

FEL1, *20 – 100 nm:*	~ **20 – 400 μJ**
FEL2, *4 – 20 nm:*	~ **10 – 100 μJ**

Stability

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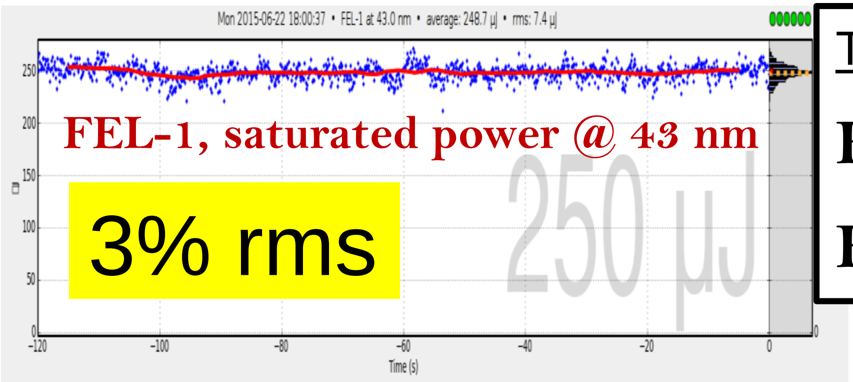
ENERGY / PULSE

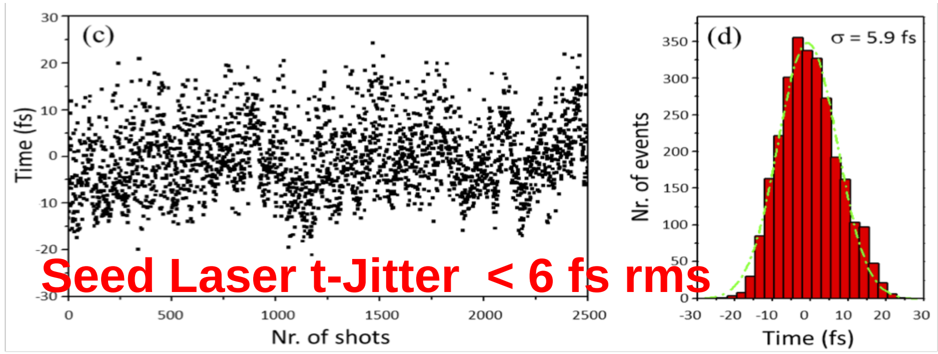


Typical RMS values:

FEL-1, < 15%

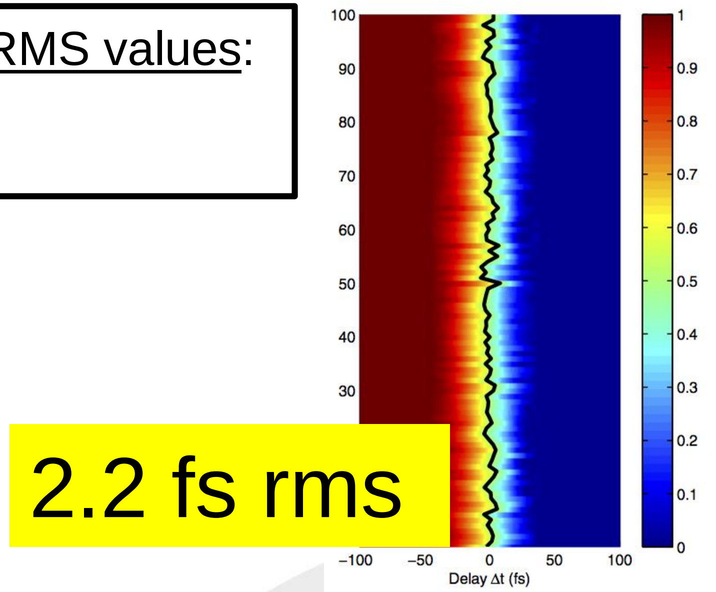
FEL-2, < 30%

ARRIVAL TIME

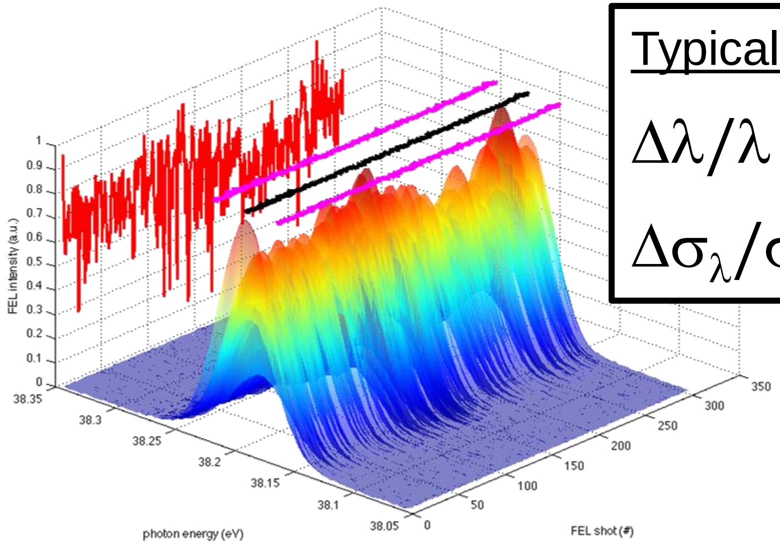


Typical RMS values:

< 6 fs



CENTRAL WAVELENGTH & BANDWIDTH



Typical RMS values:

$\Delta\lambda/\lambda \approx 10^{-5} - 10^{-4}$

$\Delta\sigma_\lambda/\sigma_\lambda < 3\%$

M. Danailov et al. Opt. Expr., Vol. 22, 11 (2014)
P. Finetti et al. Phys. Rev. X 7, 021043 (2017)

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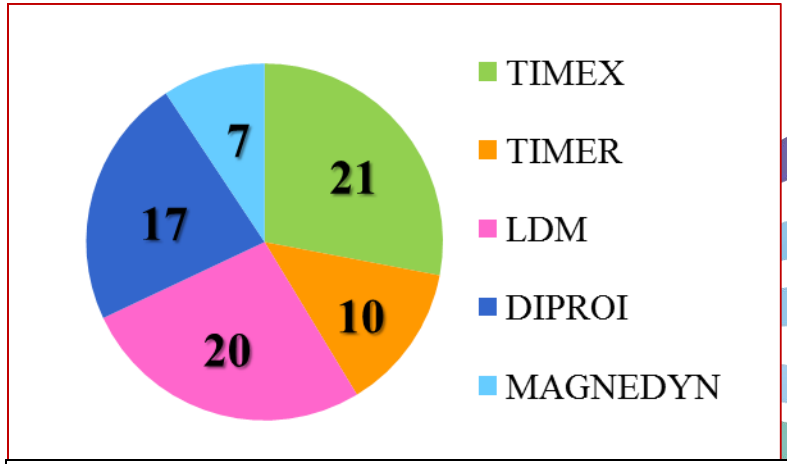
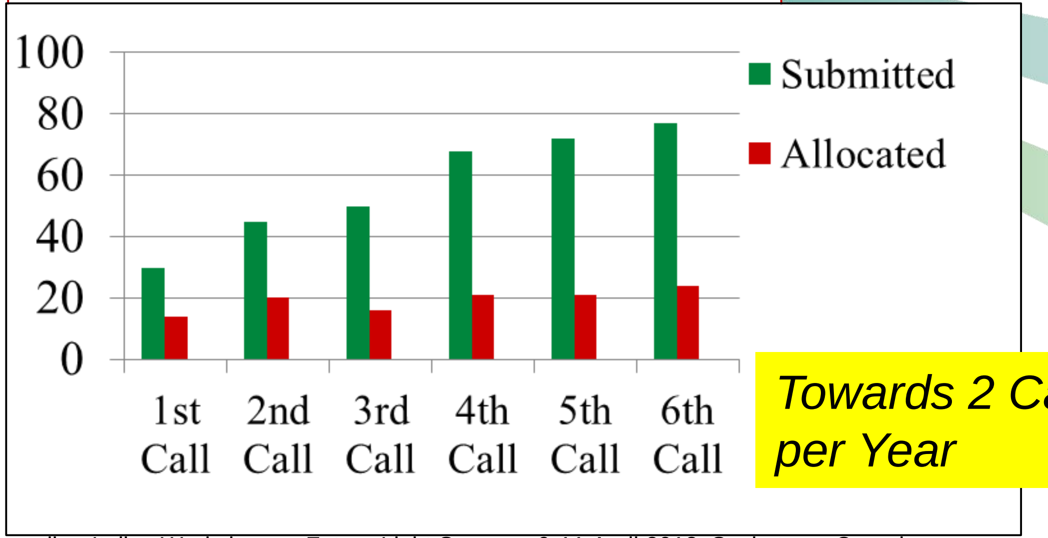
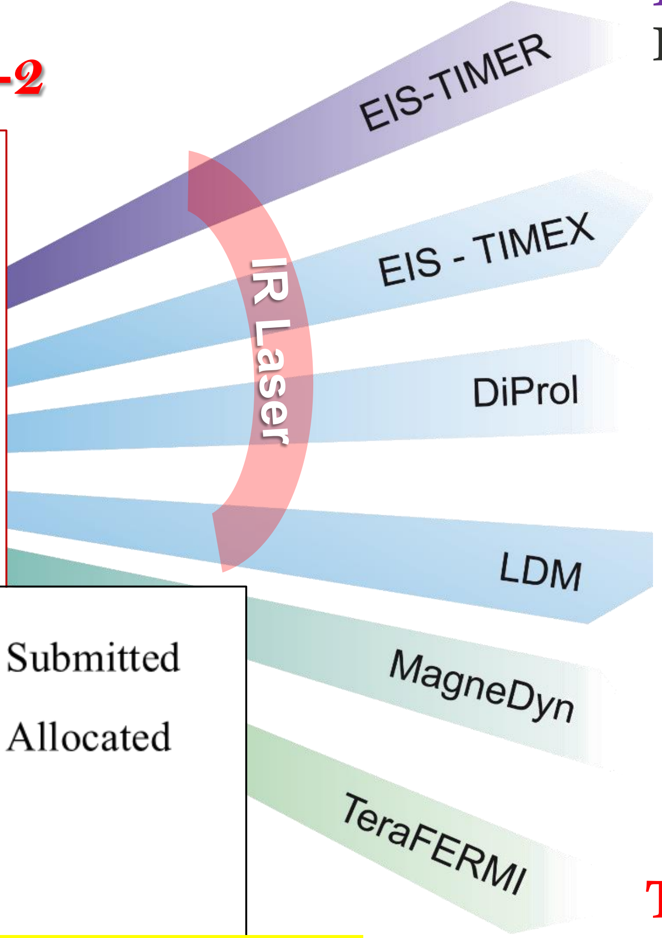
Photon Beamlines

- **1 experiment at a time**
- **Access to FEL-1 or FEL-2**





Towards 2 Calls per Year



EIS-TIMER, led by *F. Bencivenga & C. Masciovecchio*: **FEL-based Four-Wave-Mixing** instrument.

EIS-TIMEX, led by *E. Principi* : **time-resolved pump-probe** experiments on solid-state samples in extreme and metastable conditions.

DIPROI, led by *F. Capotondi:* **coherent** and **resonant diffraction imaging**.

LDM, led by *C. Callegari:* in-vacuum **supersonic jet** of atoms, molecules, and clusters in an **unperturbed environment.**

Magnedyn, led by *F. Parmigiani & M. Malvestuto:* **ultrafast magnetization dynamics** and phase transitions in complex materials. *Only FEL-2.*

TeraFERMI, led by *A. Perucchi,* **coherent THz source,** heatless excitations of low-energy, collective states by MV/cm field. Beamline *parasitic* to FEL.

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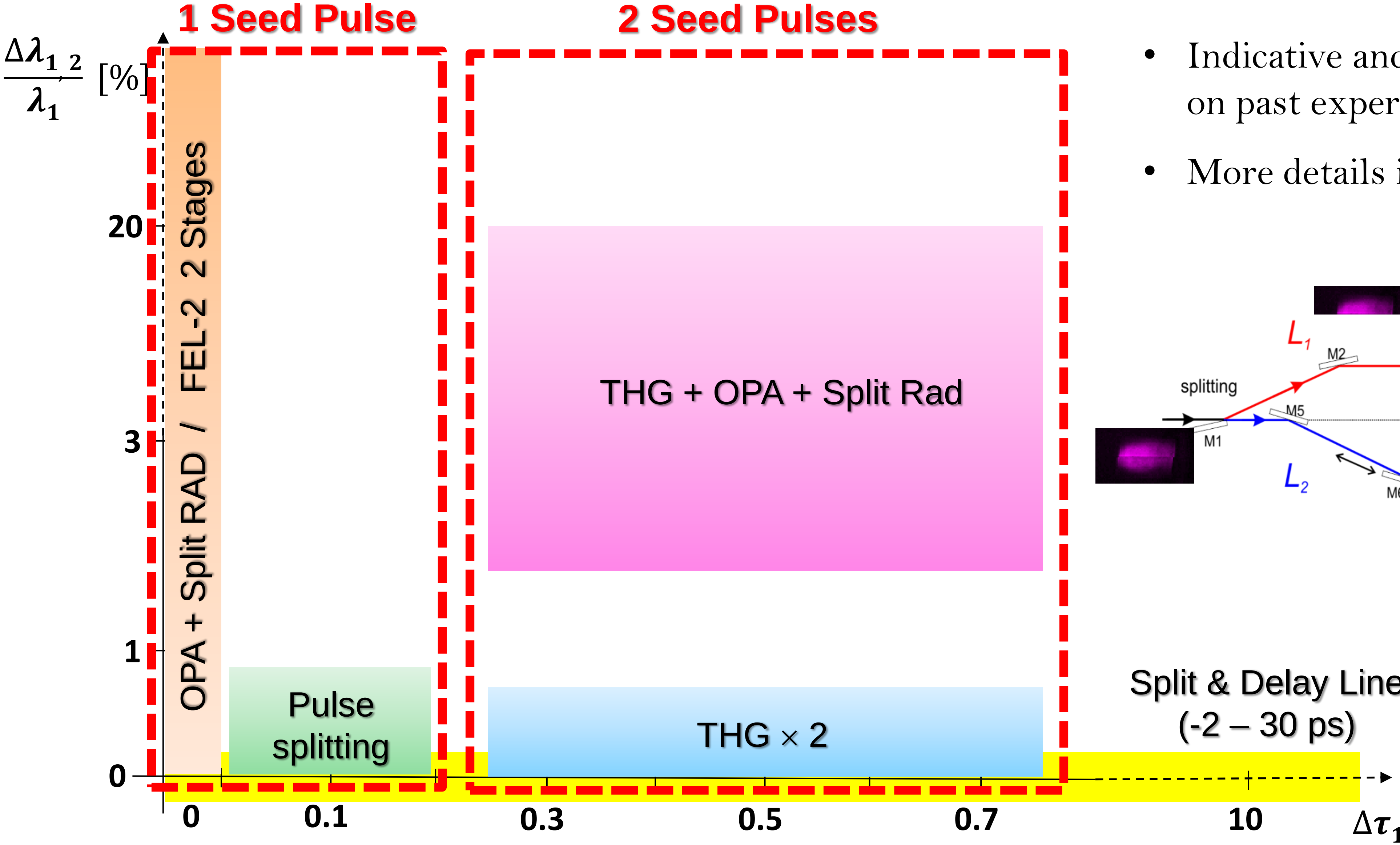
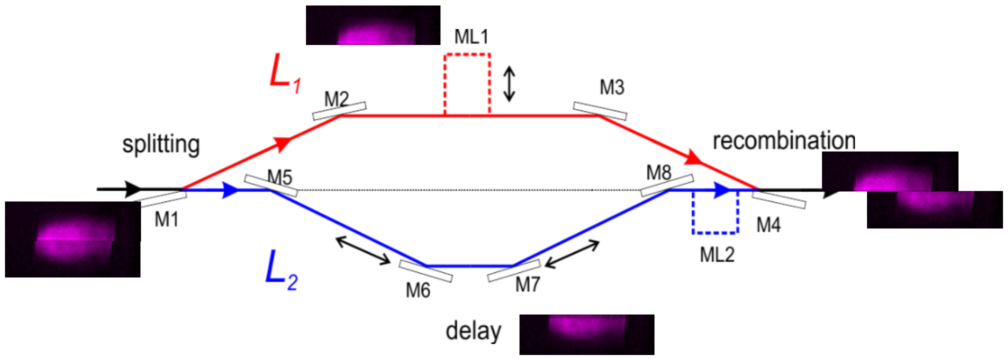
Multi-Pulse, Multi-Colour



- Indicative and not exhaustive; based on past experiments.
- More details in the following slides.



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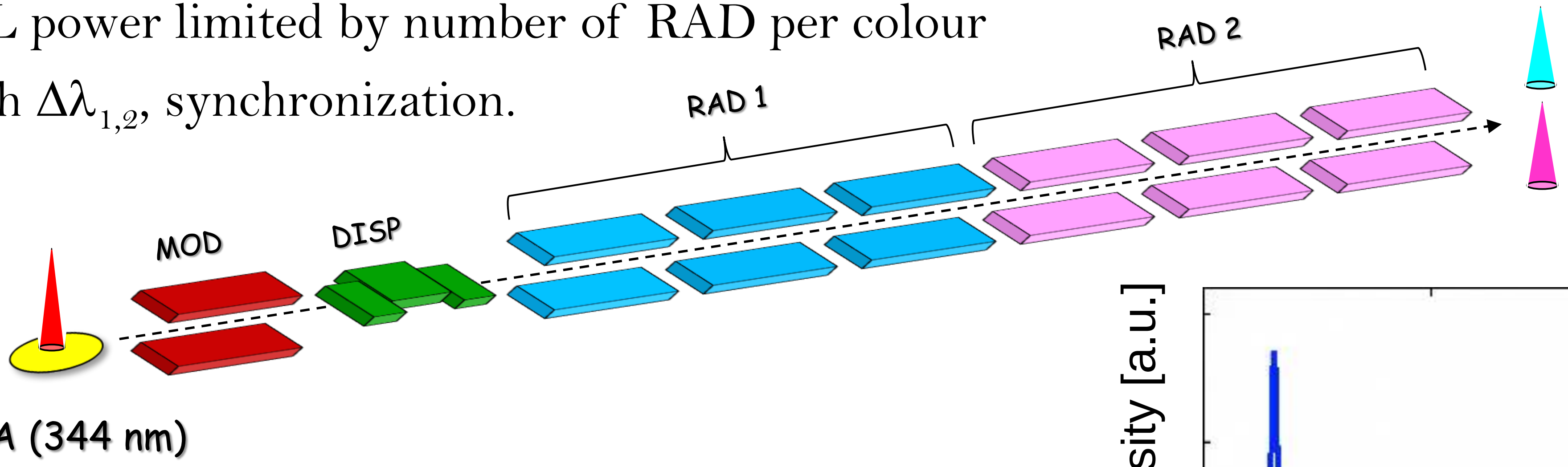
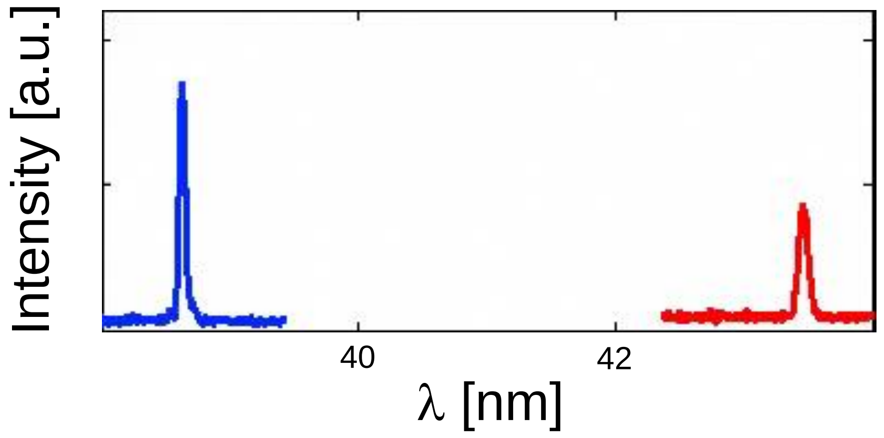
OPA + Split RAD / FEL-2 Two Stages

☹ FEL power limited by number of RAD per colour

☺ High $\Delta\lambda_{1,2}$, synchronization.

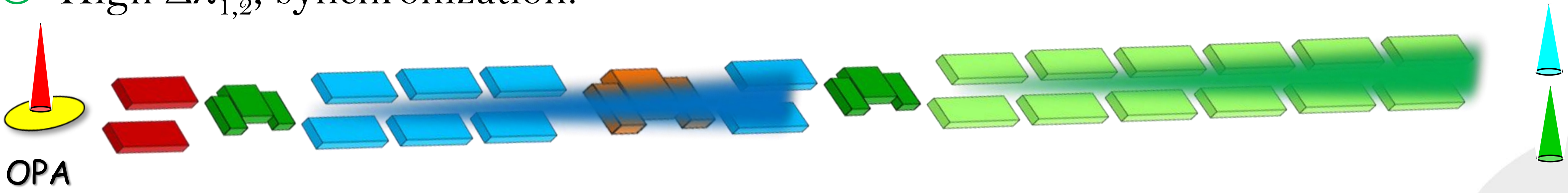


38 & 43 nm
$\Delta t_{1,2} = 0$



☹ First stage angular divergence is larger

☺ High $\Delta\lambda_{1,2}$, synchronization.

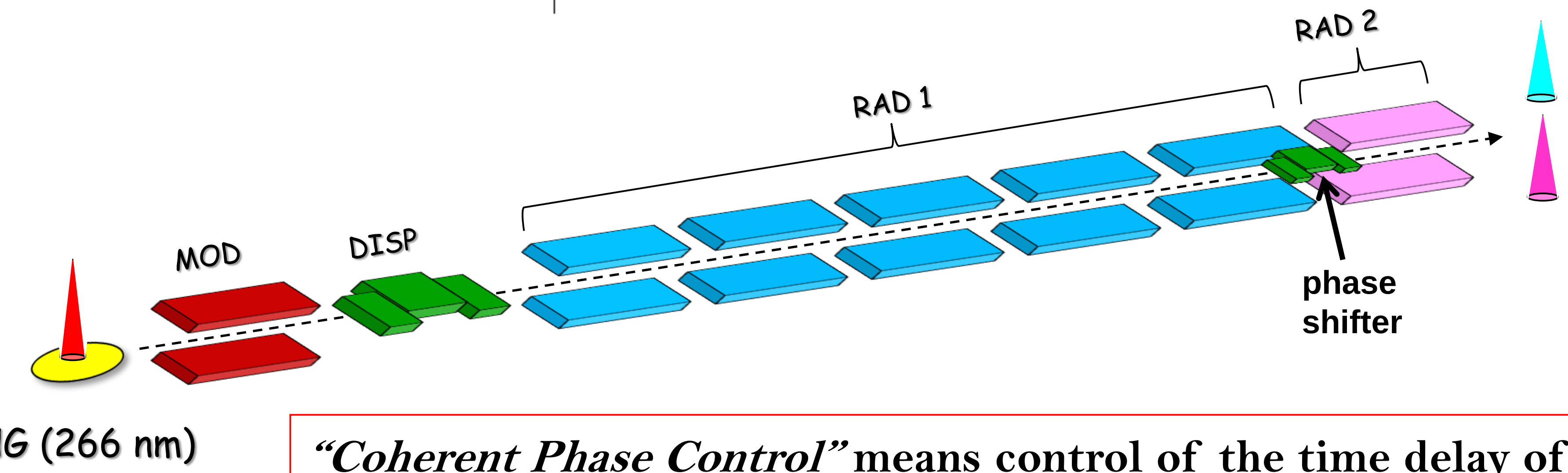


39.9 & 13.3 nm
$\Delta t_{1,2} = 0$

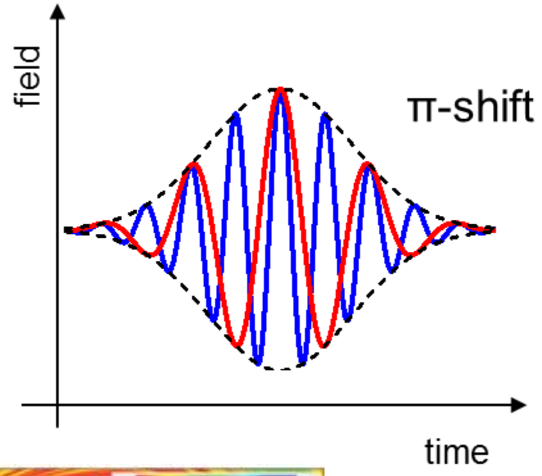
E. Ferrari et al., Synch. Rad. News 29:3, 4 (2016)
E. Allaria et al., Nat. Photonics 4, 2476 (2013)

Coherent Control….

@ LDM



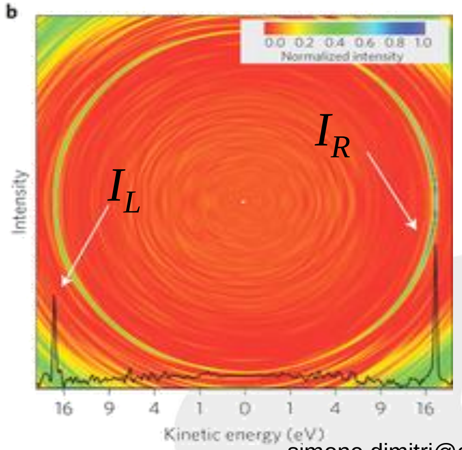
63 nm & 31.5 nm
$\Delta t_{1,2} = 0$



"Coherent Phase Control" **means control of the time delay of two coherent pulses on a level shorter than the optical cycle**

- Ne (gas) has high first ionization potential → FEL-1.
- 2-photons ionization by $n_{FEL}=1$, and 1-photon ionization by $n_{FEL}=2$.
- The two channels have different parity.

Photo-electron distribution is acquired with Velocity Map Imaging, and the ***asymmetry*** recorded ***vs. radiation phase.***

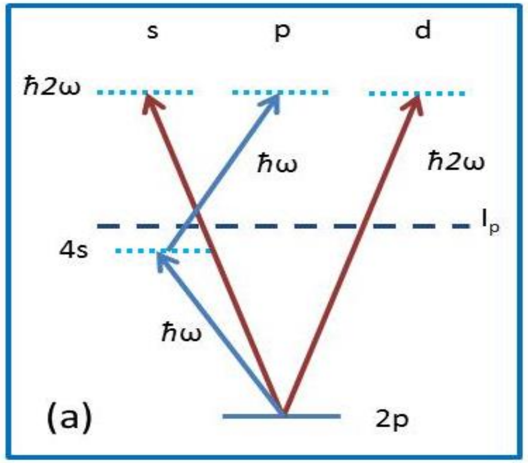


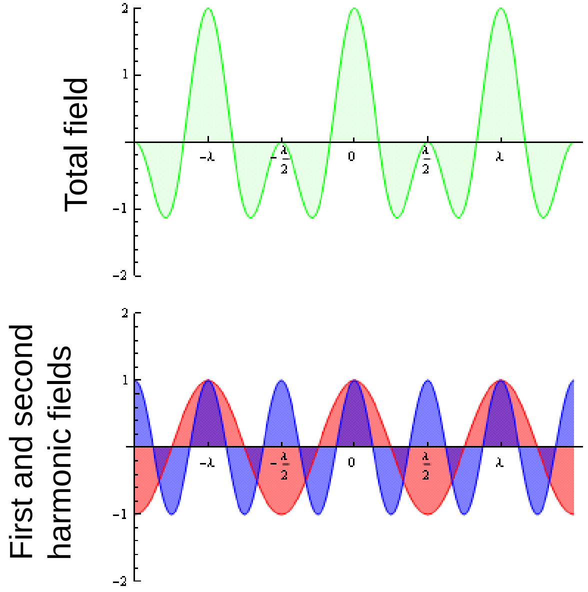
K. Prince et al., Nat. Phot. 10, 176 (2016)

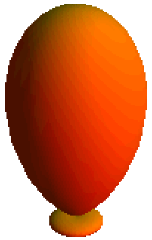
….to ~ as level

@ LDM

- Left-right asymmetry in photoelectron angular distribution is due to the **interference** between p-wave (**2-photon** process from fundamental) and s/d-wave (**1-photon** process from 2nd harmonic).
- Asymmetry depends on the relative **phase** of **t-coherent** radiation pulses.

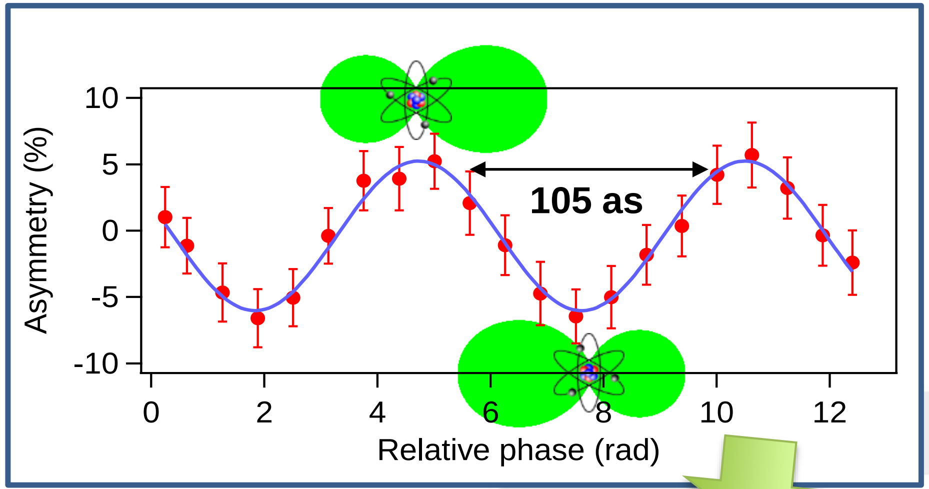






Lobes represent direction and intensity of photo-electron emission from Ne.

Green lobes: schematic polar angle e-distributions.

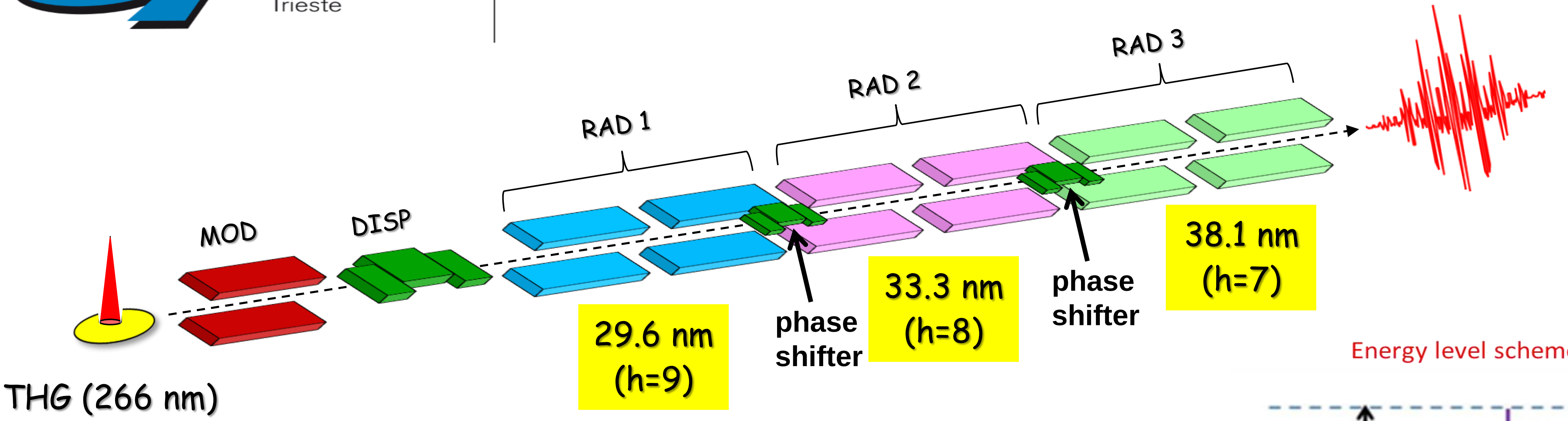


3.1 attosecond resolution

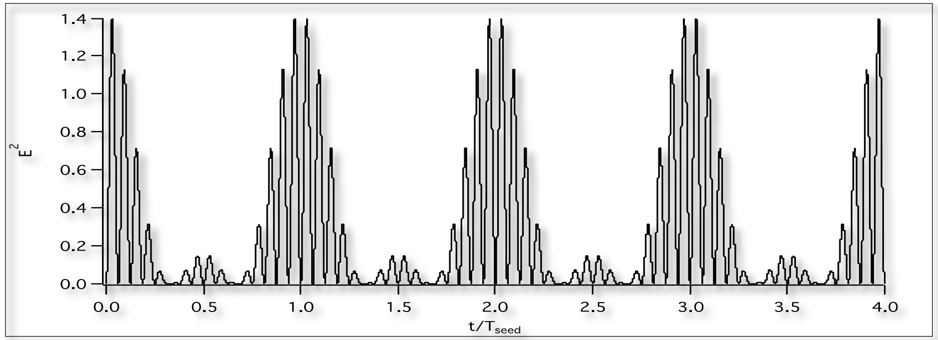
K. Prince et al., Nat. Phot. 10, 176 (2016)

Attosecond Pulse Train

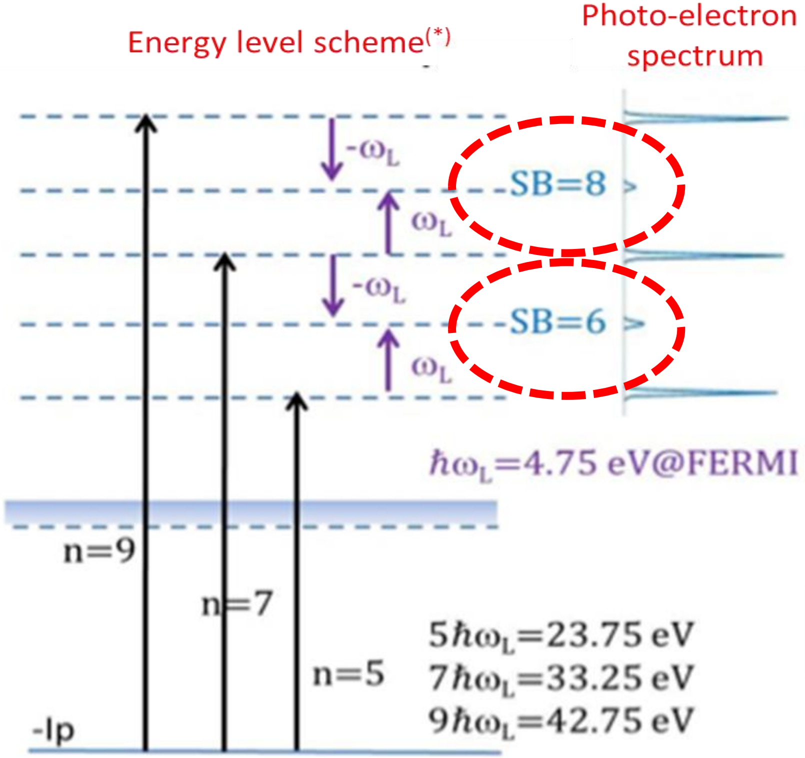
@ LDM



ATTOSECOND PULSE TRAIN



+ IR Laser



The generation of attosecond pulses relies on the "synthesis" of 3 phase-locked harmonics of the FEL ⇒ *attosecond science in EUV*

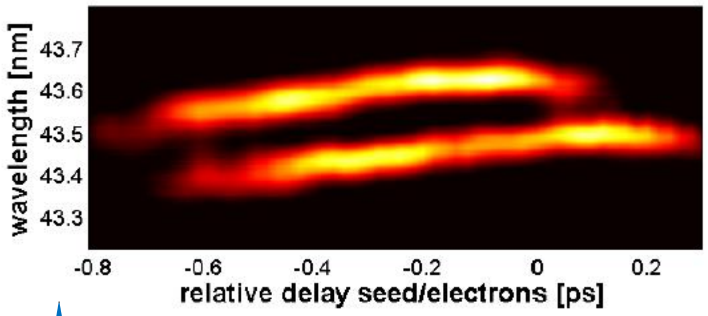
Courtesy of G. Sansone, C. Callegari

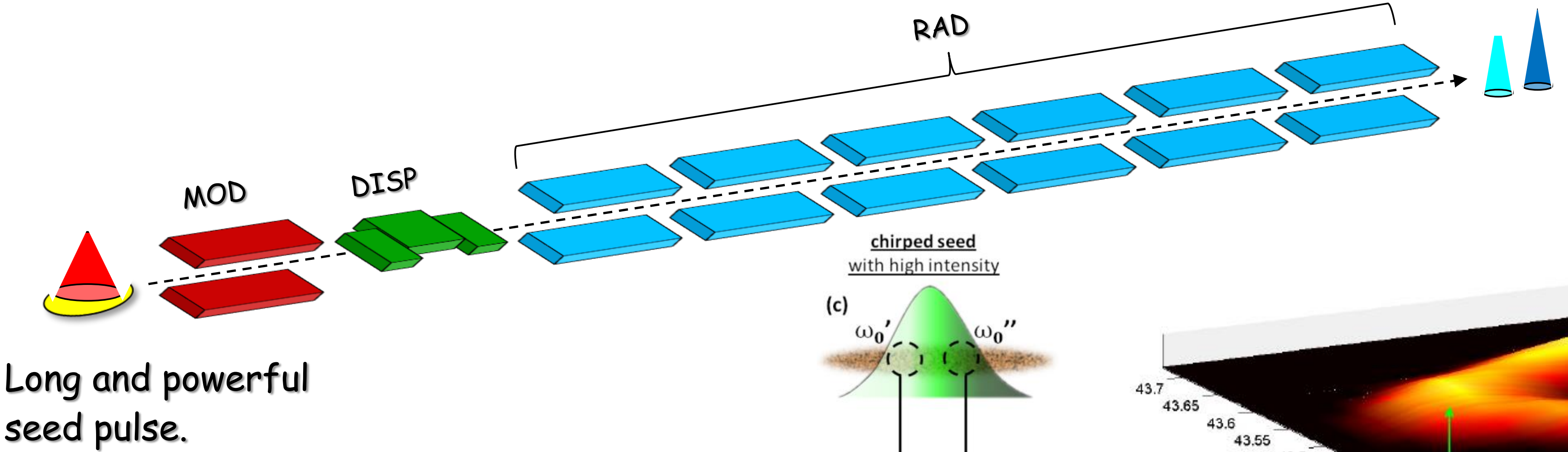
Pulse Splitting

☹ FEL power limited by low e-current at bunch edges.

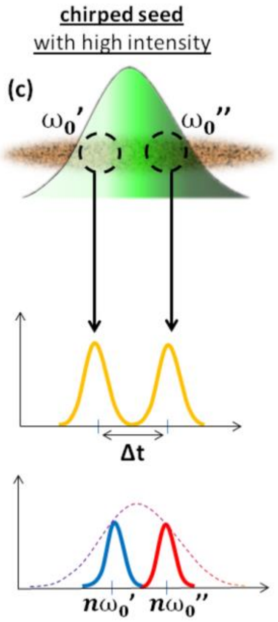
☹ $\Delta\lambda_{1,2}$ and $\Delta t_{1,2}$ limited by e-long. phase space and seed freq.-chirp.

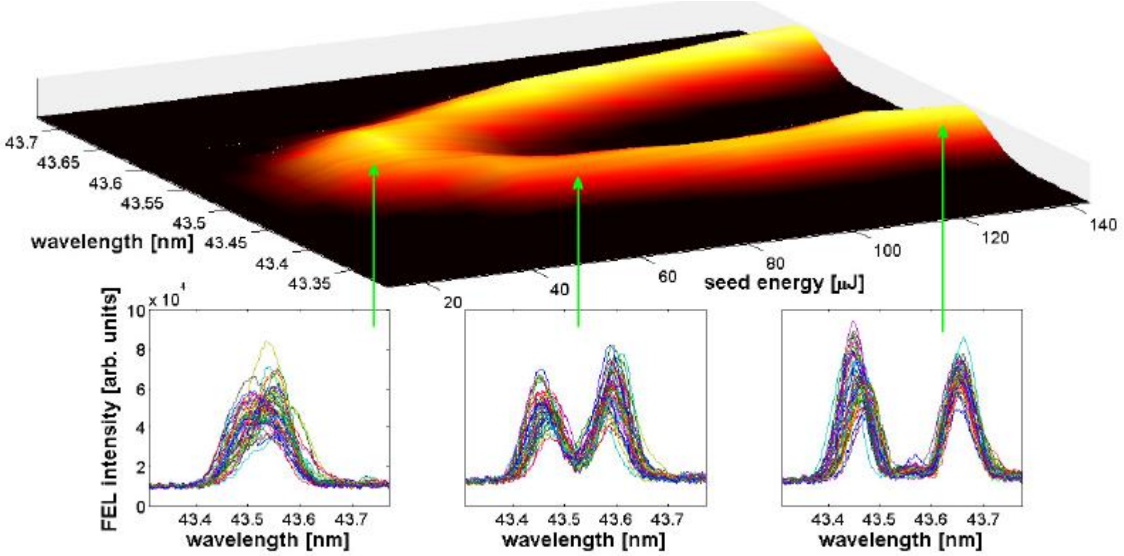
☺ Simple and robust for fixed pulse parameters.





43.4 & 43.6 nm
$\Delta t_{1,2} \approx 100$ fs

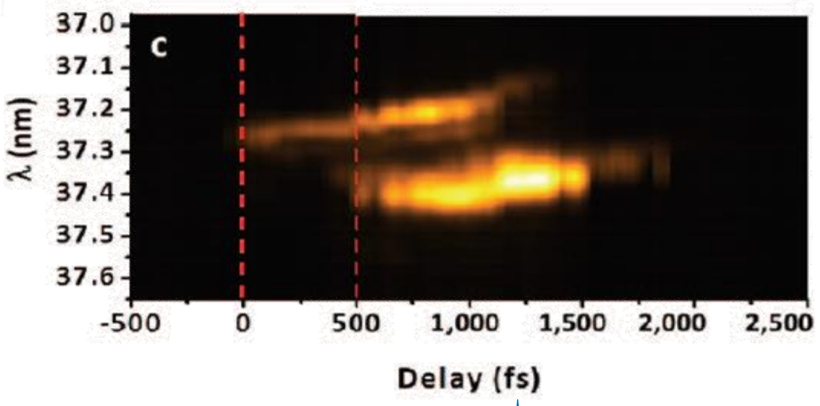


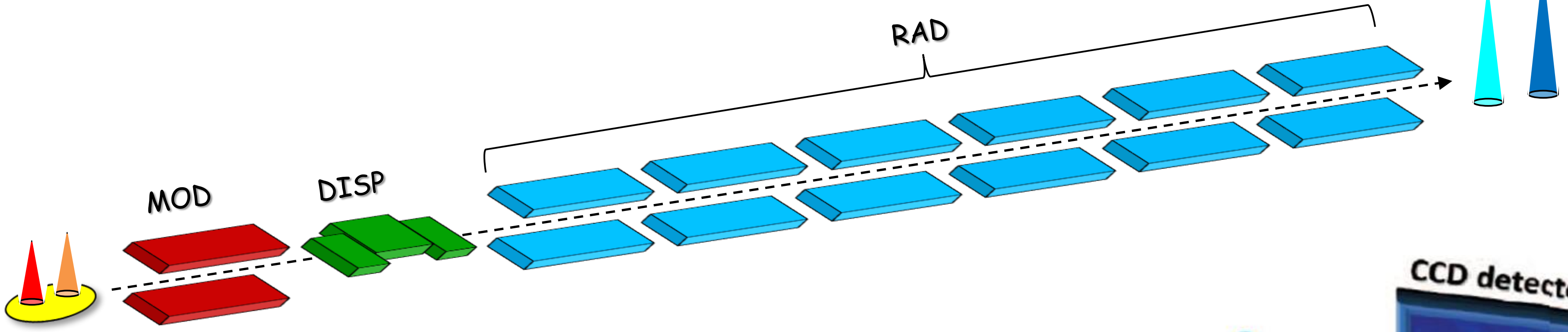


B. Mahieu et al., Opt. Expr. 22730, 21, 19 (2013)

THG × 2

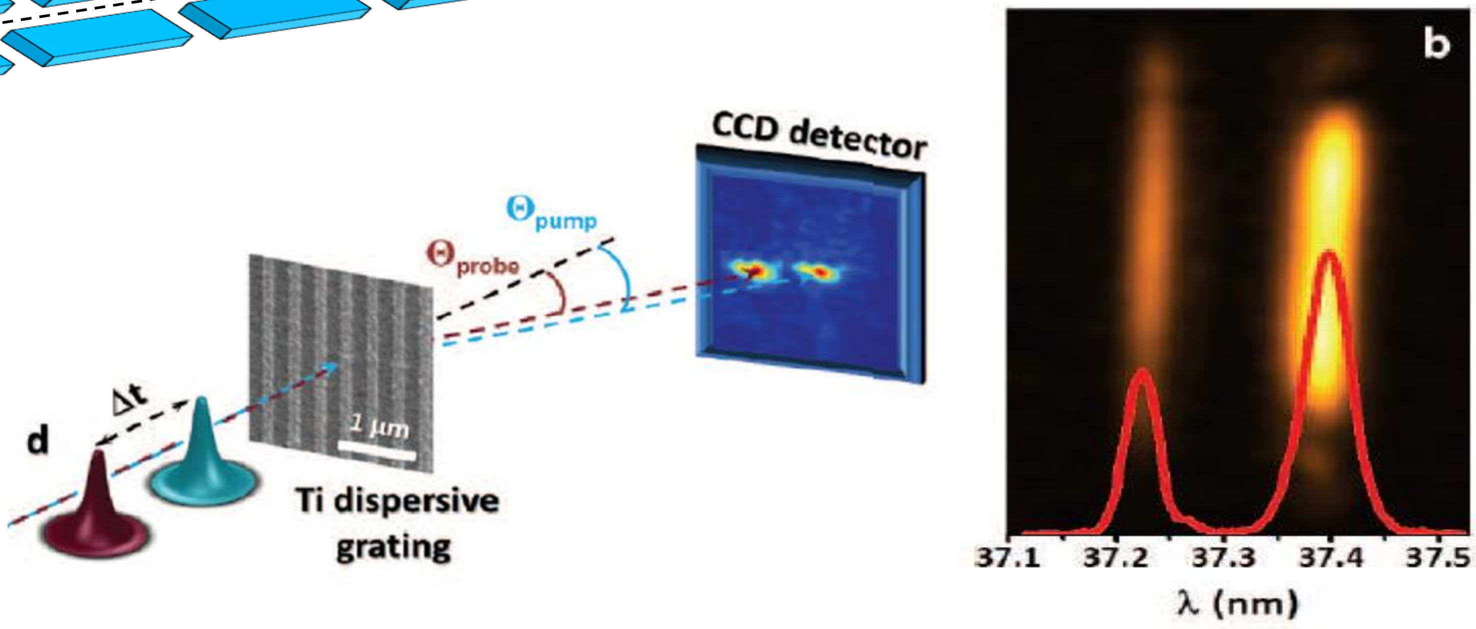
- ☹ $\Delta\lambda_{1,2}$ and λ-tuneability limited by THG seed laser bandwidth (< 1%) and RAD gain bandwidth.
- ☺ Large $\Delta t_{1,2}$.





37.2 & 37.4 nm
$\Delta t_{1,2} \approx 500$ fs

Each seed tuneable within, e.g., 260-262 nm.



FEL-Pump and FEL-Probe "across" the Ti M-edge. *Determination of dielectric function in highly photoexcited Ti at given time delays vs FEL flux.*

E. Allaria et al., Nat. Commun. 4:2476 (2013)

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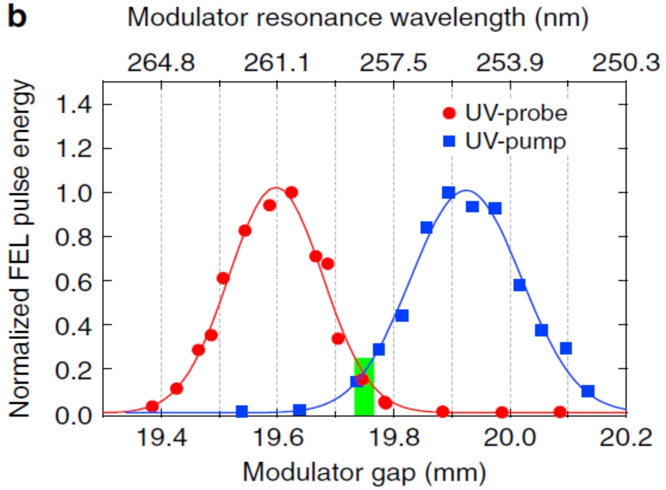
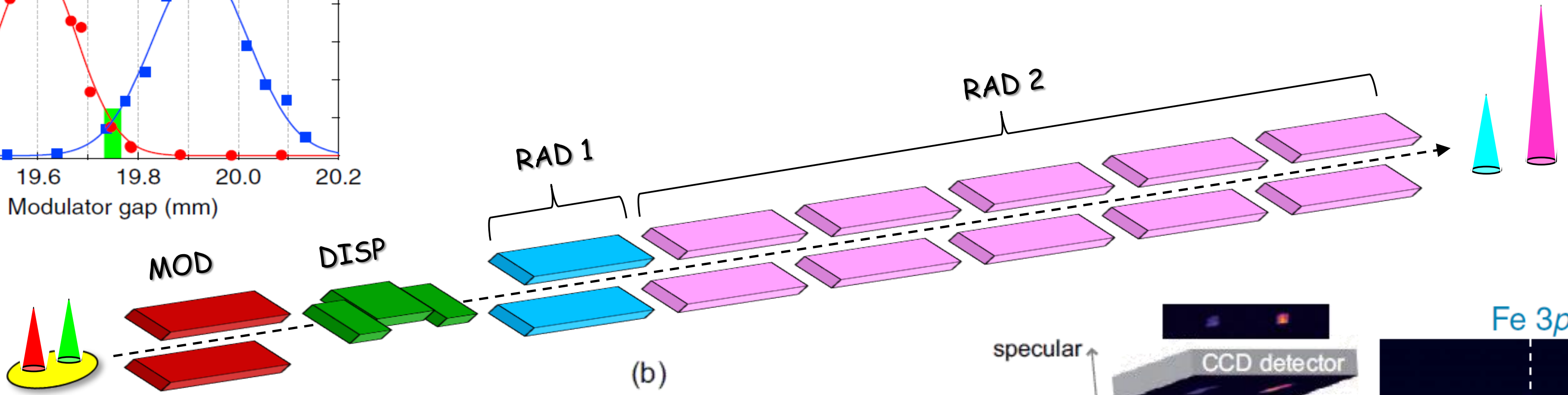
THG + OPA + Split RAD

@ DiProl



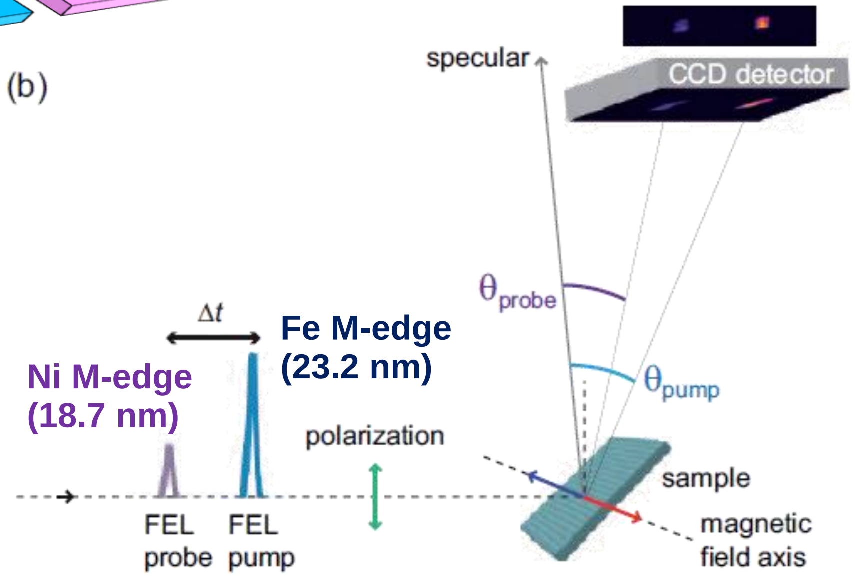
☹ FEL power limited by MOD bandwidth

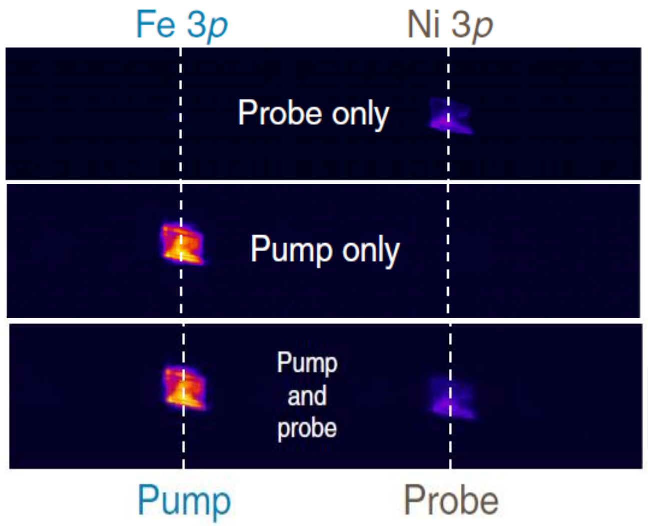
☺ Large $\Delta t_{1,2}$, flexible relative FEL intensity.



18.7 & 23.2 nm
$\Delta t_{1,2} \approx 500$ fs

Seed:
THG (261 nm) +
OPA (255 nm)





Ultrafast magnetic dynamics with pump and probe resonant with two atoms, though in a limited time-delay range.

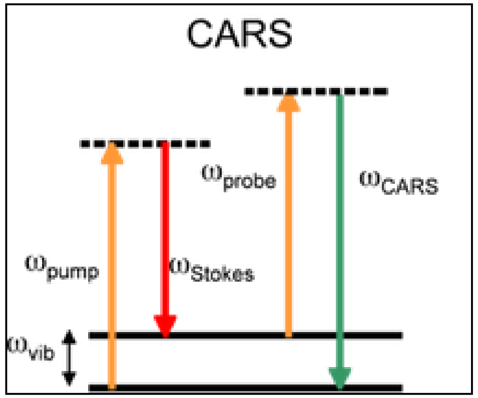
E. Ferrari et al., Nat. Commun. 7:10343 (2015)

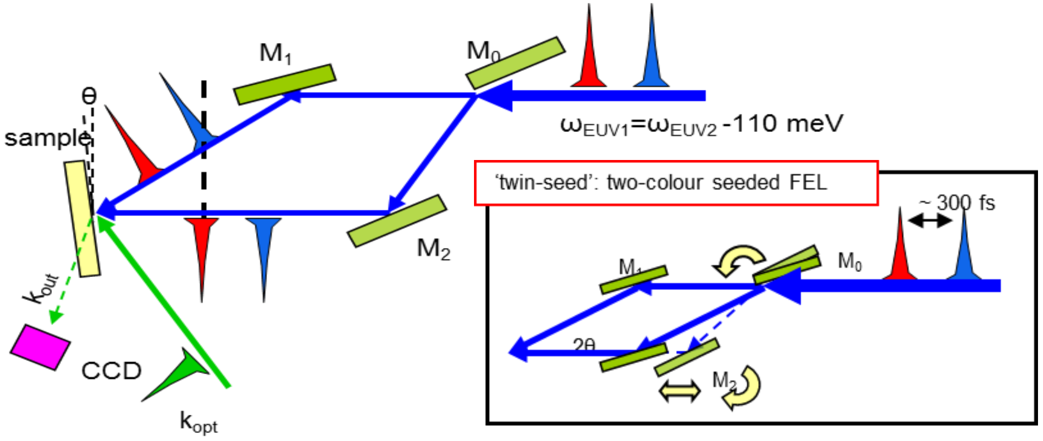
mini-TIMER

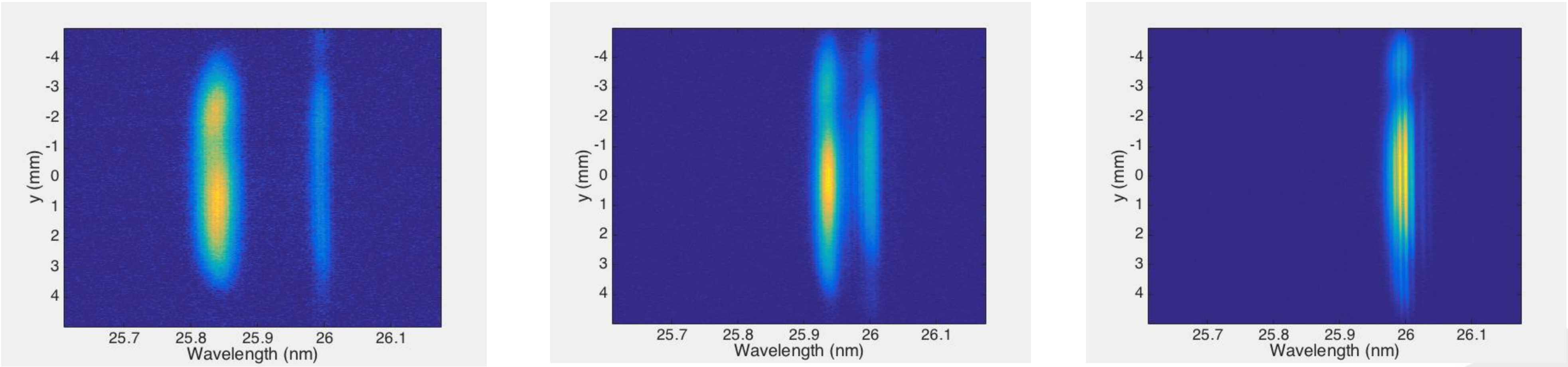
Elettra Sincrotrone Trieste

Four Wave Mixing: *EUV + Optical*

EUV-induced **T**ransient **G**rating & **C**oherent **A**nti-Stokes **R**aman **S**cattering spectroscopy to *investigate* collective *atomic dynamics at the nano-scale* & *control* atomic *levels on demand*.







The **two FEL-1 pulses** are at **285** ± 5 fs **constant** temporal separation; wavelength of first pulse is tuned.

F. Bencivenga, Nature, 502, 205 (2015)
F. Bencivenga, Faraday Discussion (2016)

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Four Wave Mixing: *ALL EUV*

@ TIMER

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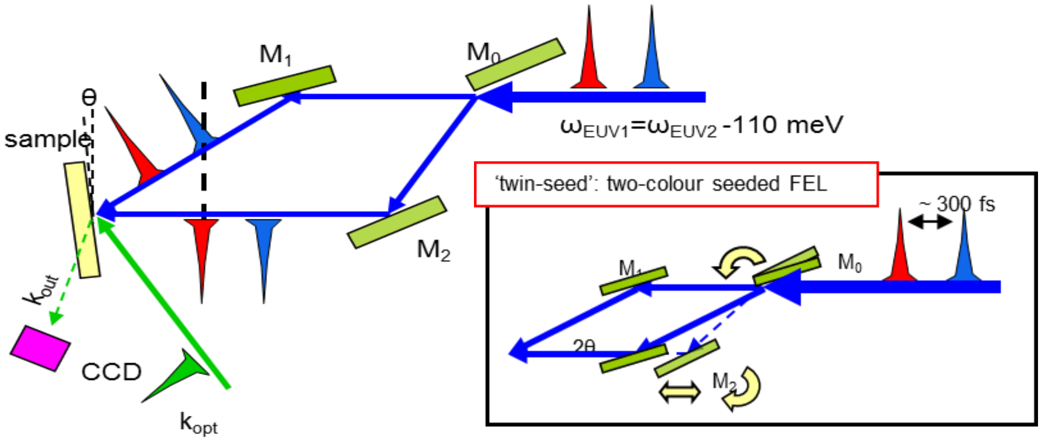
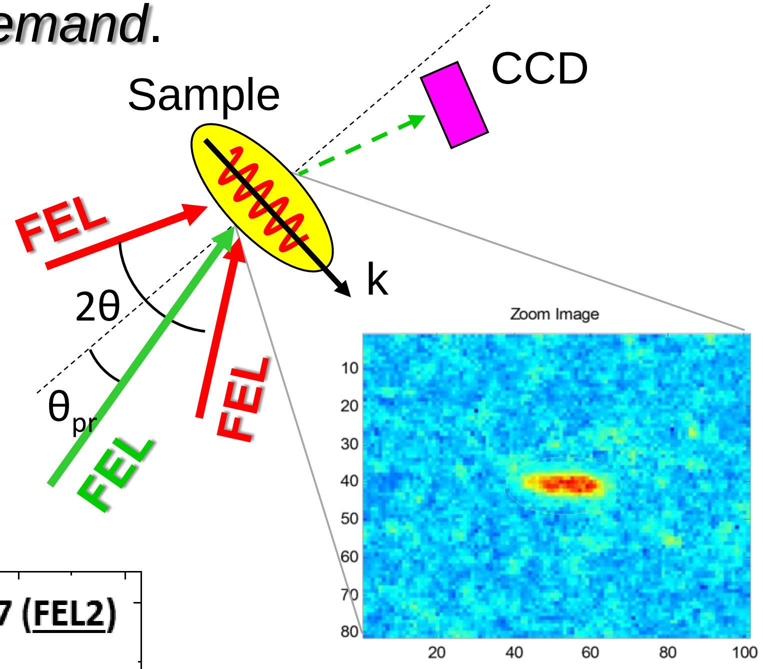
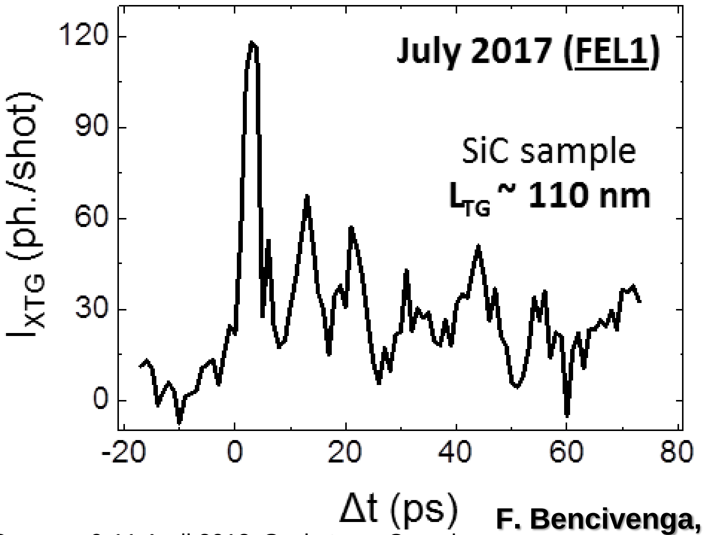
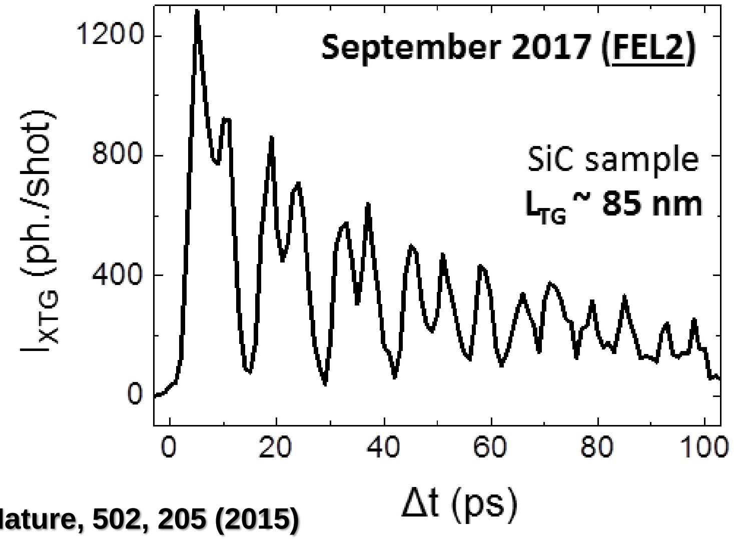
EUV-induced **T**ransient **G**rating & **C**oherent **A**nti-Stokes **R**aman **S**cattering spectroscopy to *investigate* collective *atomic dynamics at the nano-scale* & *control* atomic *levels on demand*.





FEL-1 Two-Seeds + Split RAD:
54 nm + 18 nm



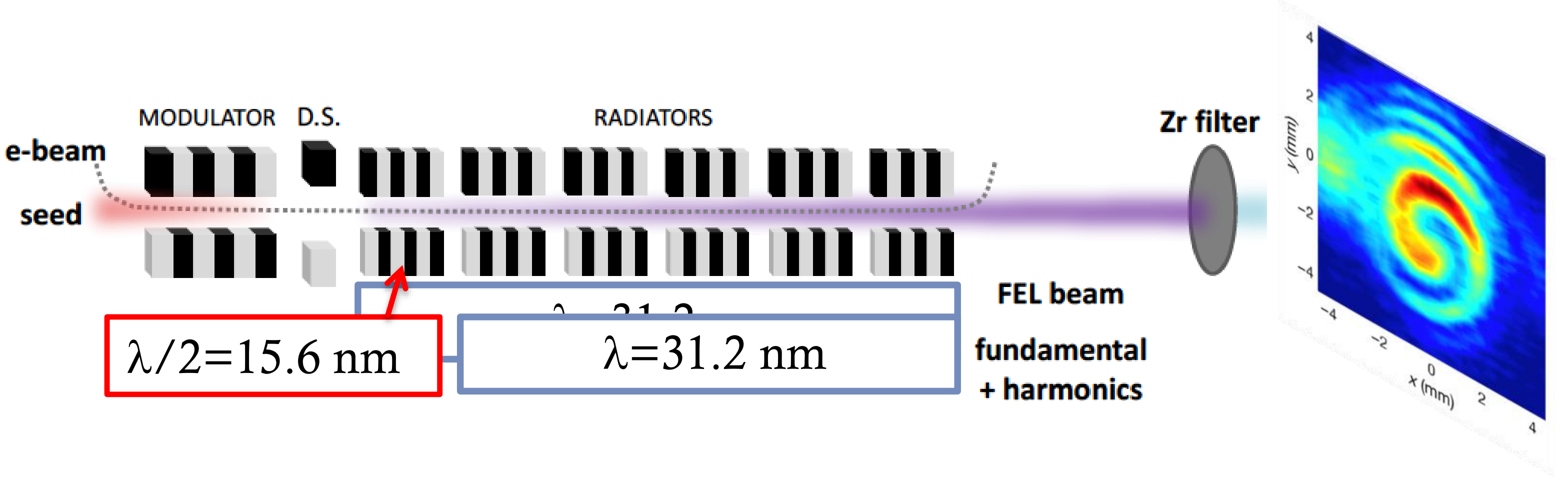


FEL-2 Two-Stages:
39.9 nm + 13.3 nm

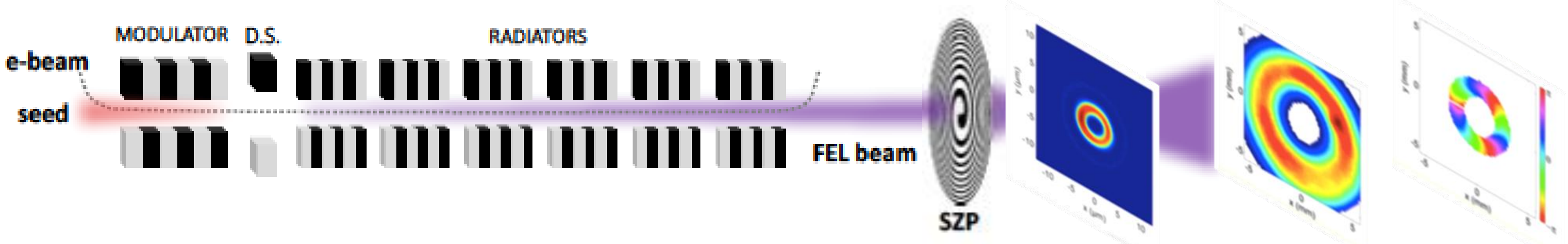
F. Bencivenga, Nature, 502, 205 (2015)
F. Bencivenga, Faraday Discussion (2016)

Orbital Angular Momentum

@ TIMEX



- Zr filter blocks light at $\lambda = 31.2$ nm
- FEL 2^{nd} harmonic emerges from the helical-pol. radiator
- Interference of Gaussian (n=2) and OAM mode (2^{nd} harm. of n=1) shows spiral intensity distribution.



Spiral Zone Plate (Si): ***l*** **= 1, 2, 3**

PMMA imprint at focus → FEL intensity

Wavefront sensor at far field → FEL spot & phase

This exp. paves the way to *much brighter OAM pulses* than from *conventional (short) IDs*

- The SZP imprints a helical phase (l=1,2,3) directly onto the EUV, and suppresses the 0^{th}-diffraction order.

P. Rebernik et al., PRX 7 , 031036 (2017)

THz Source

@ TeraFERMI

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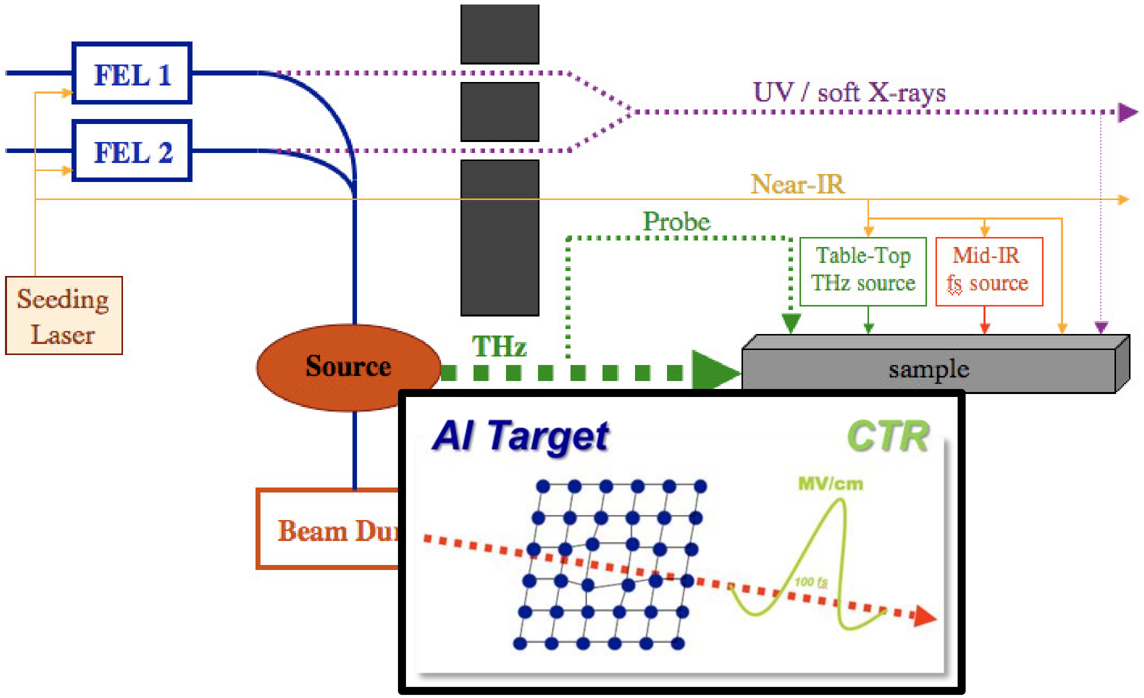
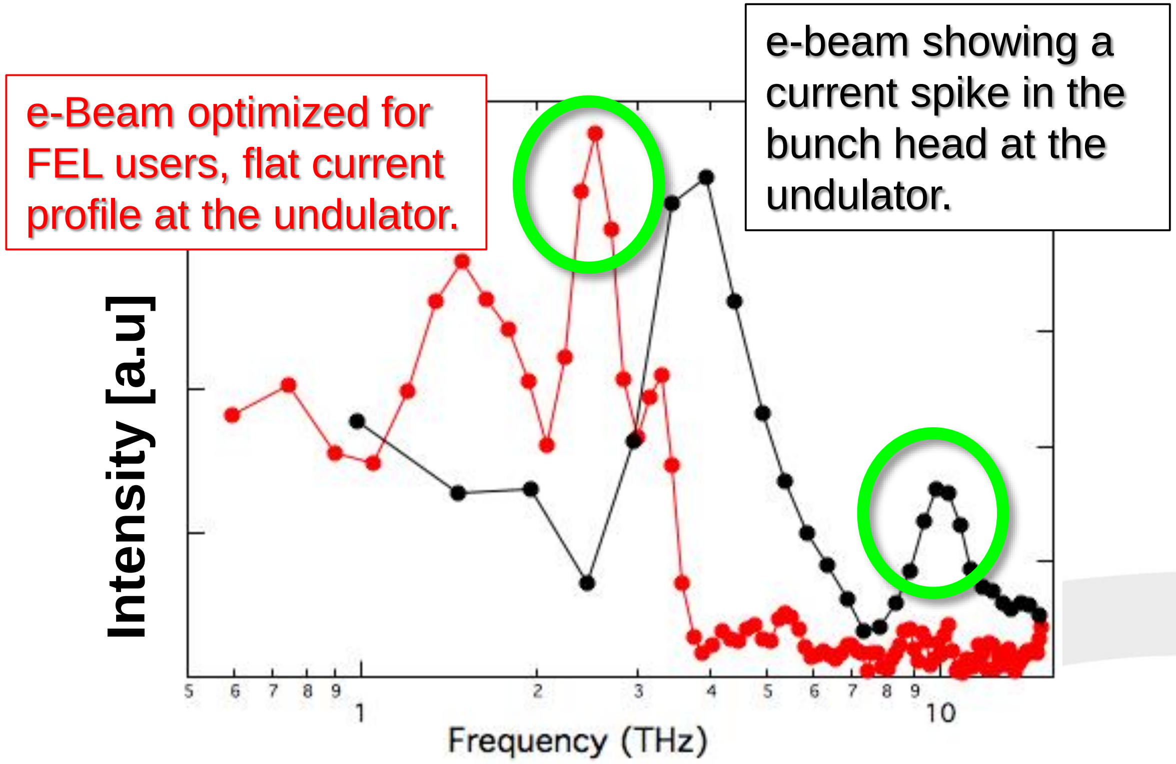


Coherent Transition Radiation occurs when relativistic electrons cross the boundary between two media of different dielectric constant.

- ***High-power, broadband THz pulses*** from ***100s fs-short electron*** bunches.



Operational parameters *at sample* :

Frequency Range	0.1 – 10 THz
Pulse Energy	10 μJ – 50 μJ
Peak Field	Up to 2 MV/cm
FEL Operation	*FEL1, 10 or 50 Hz*

A. Perucchi et al. Rev. Sci. Instrum. 84, 022702 (2013)

Conclusions

- ✓ FERMI FEL-1 and FEL-2 are open to user experiments, providing unprecedented performance in terms of **longitudinal coherence** and **spectral stability** for **pump-probe** and **EUV-FWM** configurations.
- ✓ **New classes** of experiments in EUV and soft X-ray: **coherent control,** 2nd and 3rd order **nonlinear optics,** control of **magnetic domains,** etc.
- ✓ Dedicated **diagnostics** and **data acquisition** systems are available to help machine and experimental physicists carrying out experiments.

- ○ **FEL-2** is **more sensitive** to e-beam and seed laser perturbations, and harder to set up.

- ➢ **Upgrade plans** for the **Linac** (e-beam diagnostics, e-beam optics, new acc. structures, etc.) and the **FEL** (shorter seed pulses, EEHG, etc.) promise **substantial improvements** of the FELs' performance at **shorter wavelengths**, and access to an even **wider range of parameters.**


Thank you for Your attention
Questions are very welcome,
and please come visit us…..
we are open all night !

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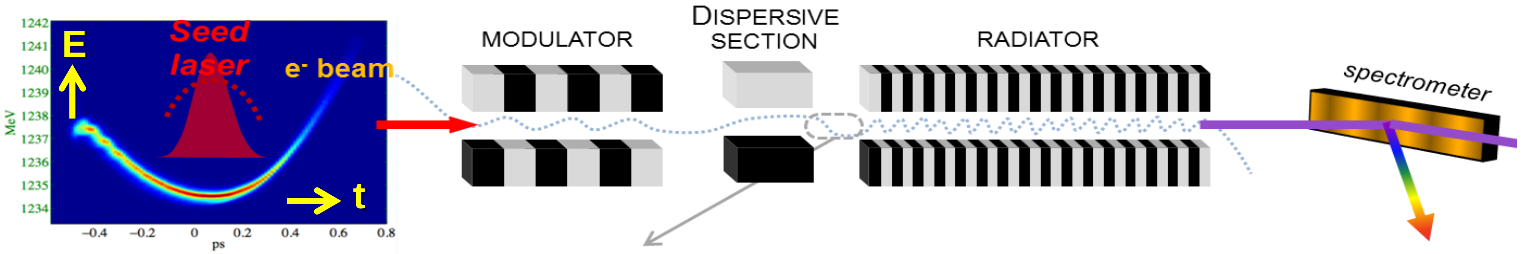
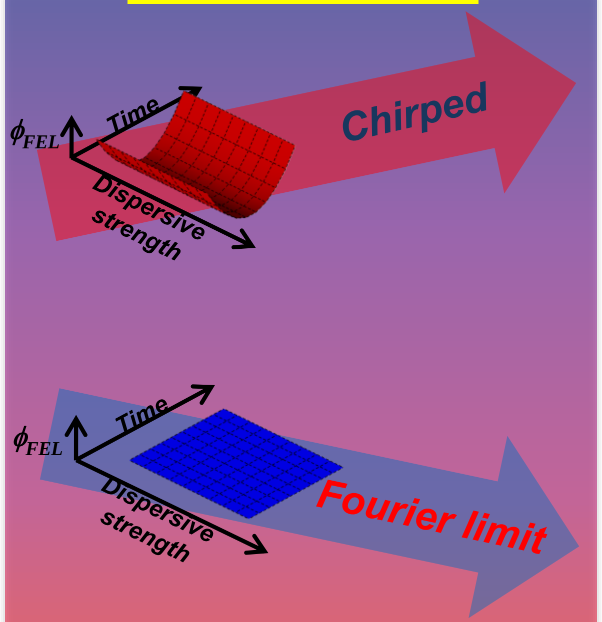
Spectro-Temporal Shaping



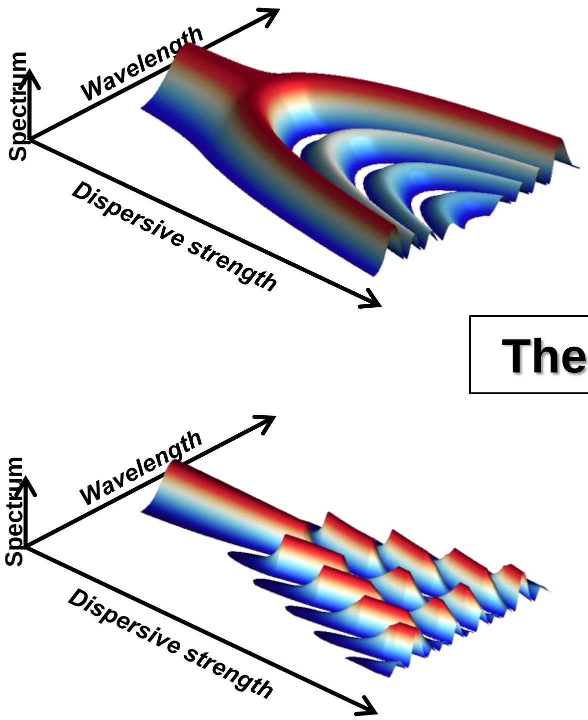
Possibility to **compensate energy-time correlations** in **e-beam** distribution with and seed laser to generate **Fourier transform limited** pulses.

Φ_{FEL} vs. TIME

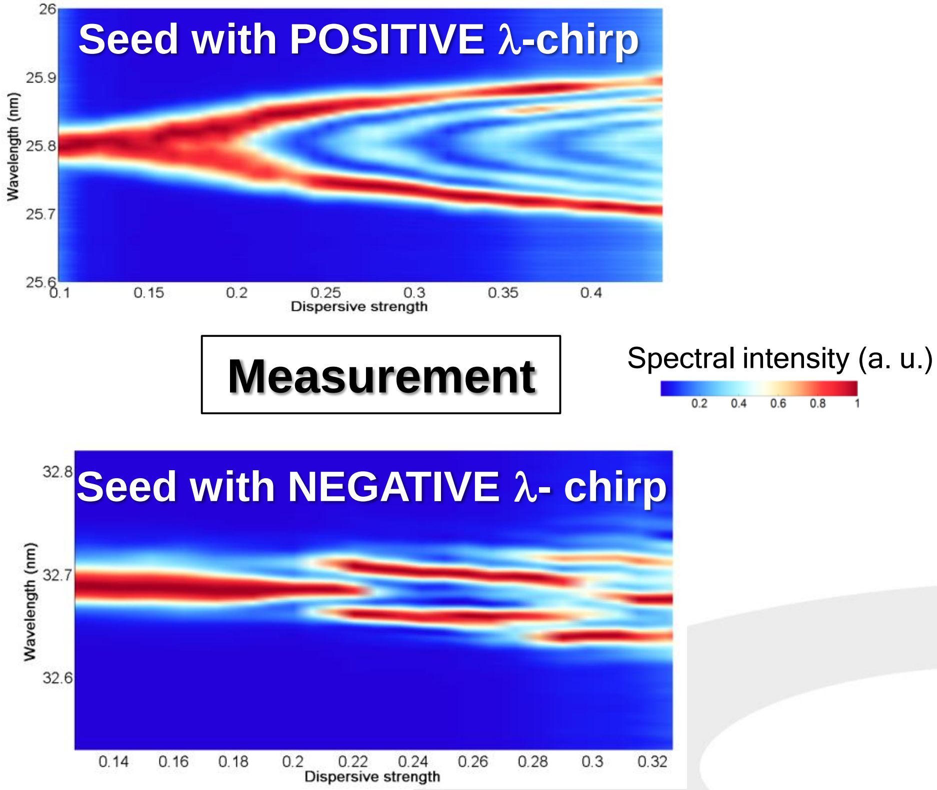


FEL phase vs. time depends on: seed laser chirp, e-beam chirp, μ-bunching instability, FEL gain

SECTRUM vs. DISPERSIVE STRENGTH



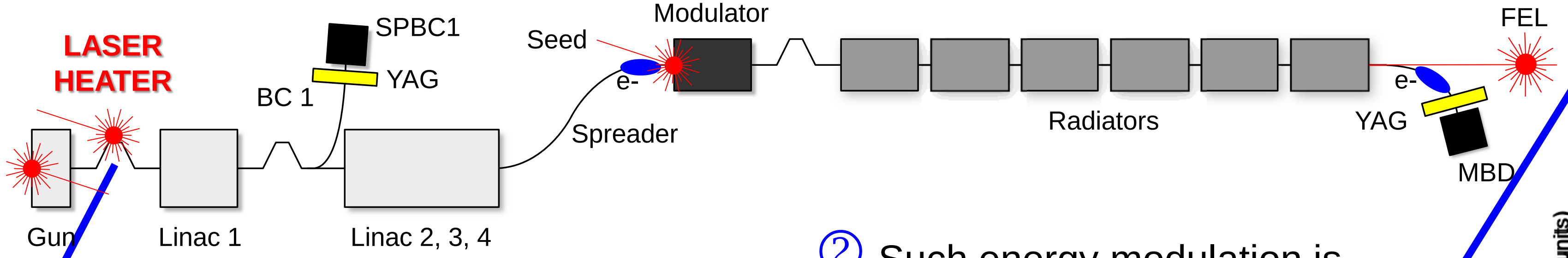
Theory



Measurement

D. Gauthier, PRL 115, 114801 (2015)

Filling λ-Gaps

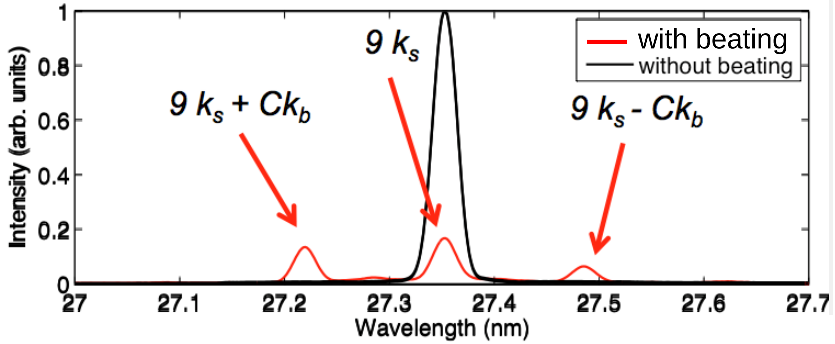


① Modified in order to **modulate** beam **energy spread** at **λ_B > 32 μm.**

② Such energy modulation is **compressed** by a factor **C** along the linac to **> 3 μm**, and eventually translates into **density modulation.**

③ After seeding at λ_S, the beam will have bunching content at:

$$k = nCk_B + mk_S$$



E. Roussel et al., PRL 115, 214801 (2015)

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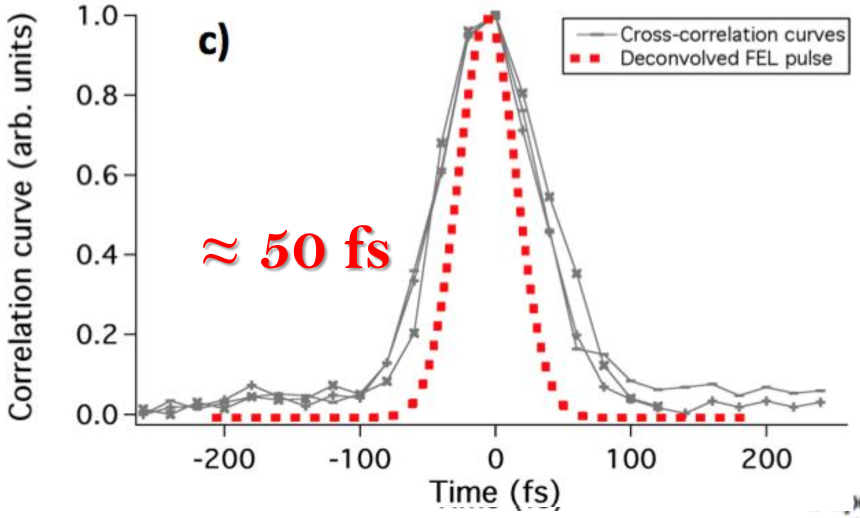
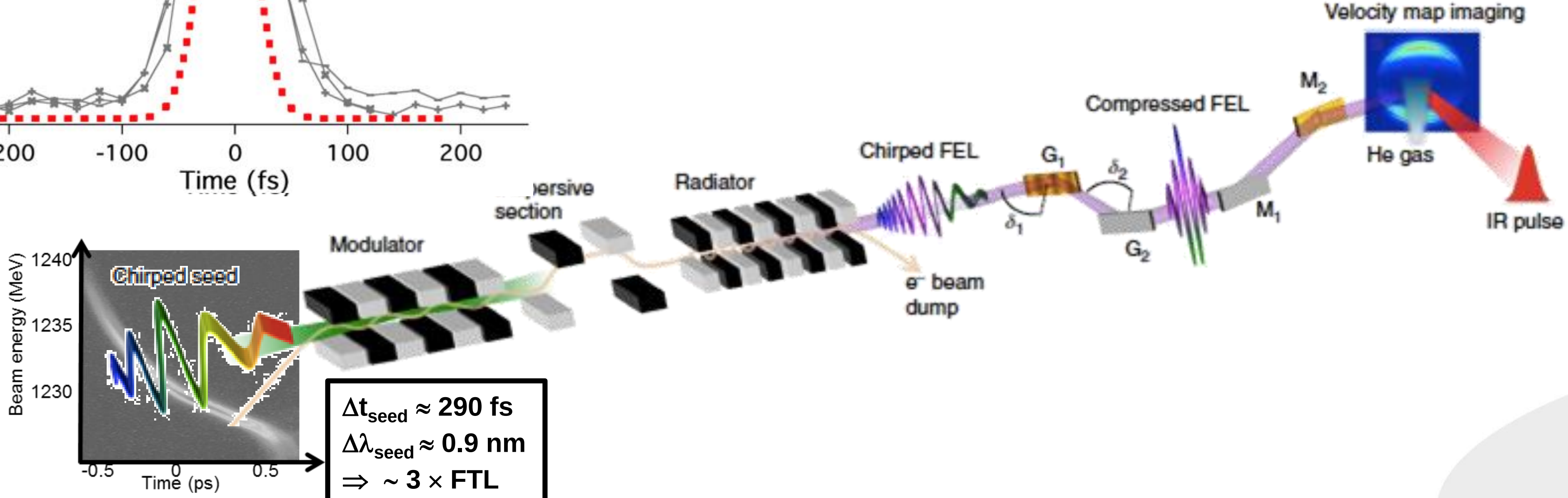
Chirped Pulse Amplification

1. An **E- chirped e-beam** is used in combination with a **λ-chirped seed laser** to create **FEL** pulses with **time-wavelength correlation.**
2. The chirped FEL pulse can be **compressed** with dispersive elements, such as a double grating system.



- FEL pulse compression confirms the high degree of **longitudinal coherence.**
- It paves the way to **~fs pulse duration.**



$\Delta t_{seed} \approx$ 290 fs
$\Delta\lambda_{seed} \approx$ 0.9 nm
$\Rightarrow$ ~ 3 × FTL

D. Gauthier et al. Nat. Commun. 7, Article 13688 (2016)

Echo-Enabled Harmonic Generation

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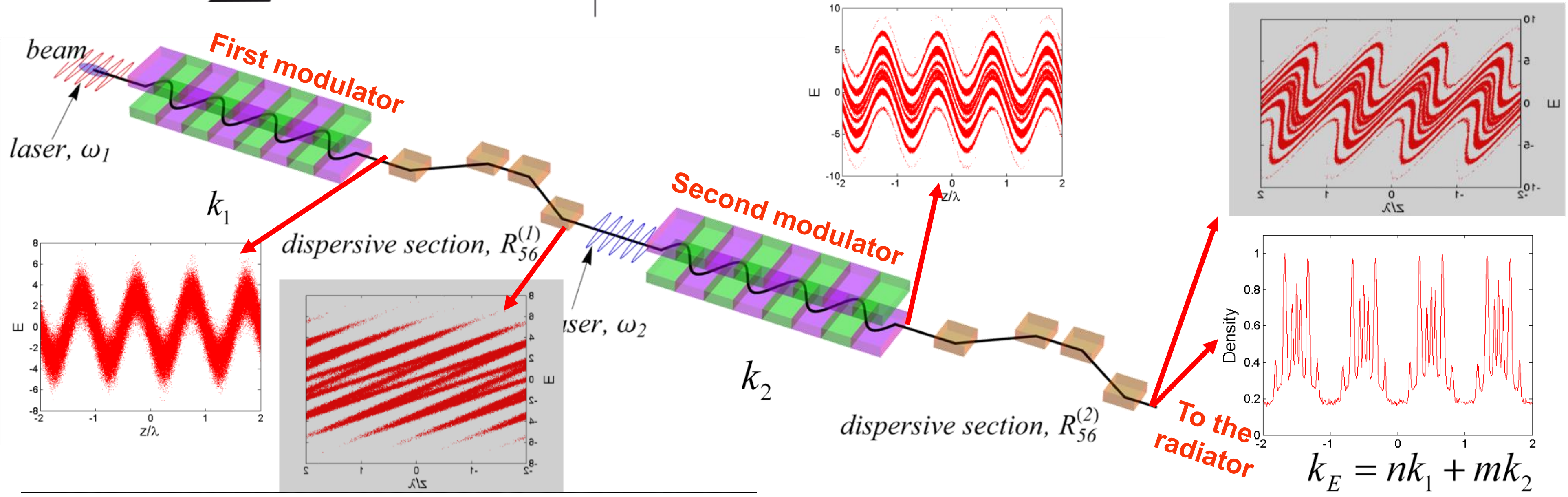

EEHG at FERMI from May 2018 !
266 nm → 5 nm

i. A first laser generates energy modulation in electron beam.
ii. A strong chicane creates “energy” structures in the longitudinal phase space.
iii. A second laser imprints energy modulation.
iv. The second chicane converts energy modulation into harmonic density modulation.

- Echo appears insensitive to e-beam phase space distortions
  $\Rightarrow$ **more stable** central wavelength and **narrower** bandwidth.

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Bird'eye view

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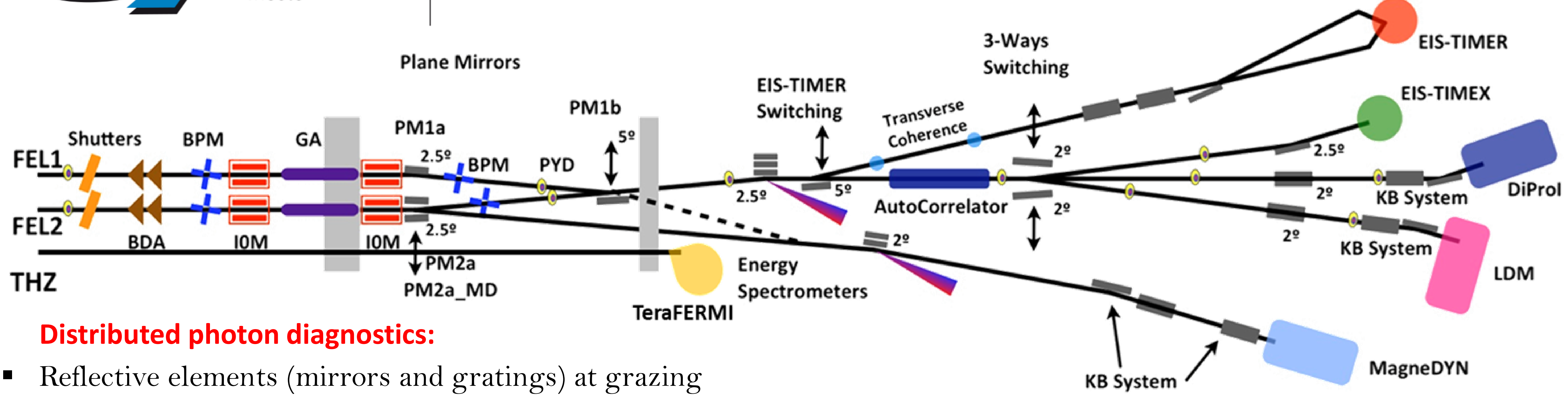
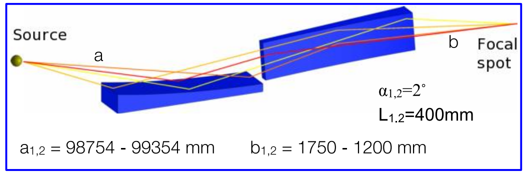
Photon Beamlines



Distributed photon diagnostics:

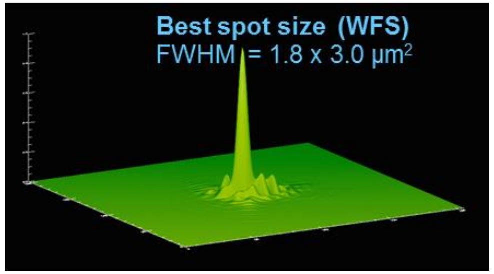
- Reflective elements (mirrors and gratings) at grazing incidence and single-layer optical coating
- **KB** focusing elements and **active optics** systems
- **Filters** on revolver
- **Gas** absorber (attenuator)
- **Intensity** monitor
- **Spectrometer**
- Photon BPM
- YAG screens
- Photodiodes
- **Split & Delay line**



on-line, non-destructive

In synergy with beamlines:

- **Wavefront sensor**
- Measurement of:
  - **polarization,**
  - **pulse duration,**
  - **arrival time,**
  - **transverse coherence**



M. Zangrando et al., Proc. FEL'17
L. Raimondi et al., NIM A, 710, 131 (2013)

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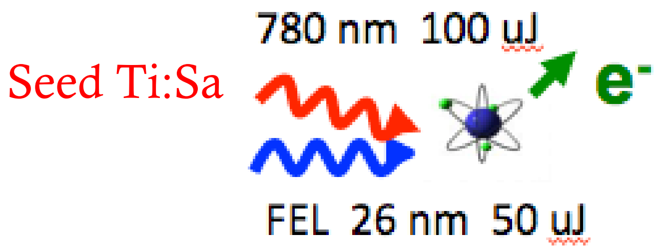
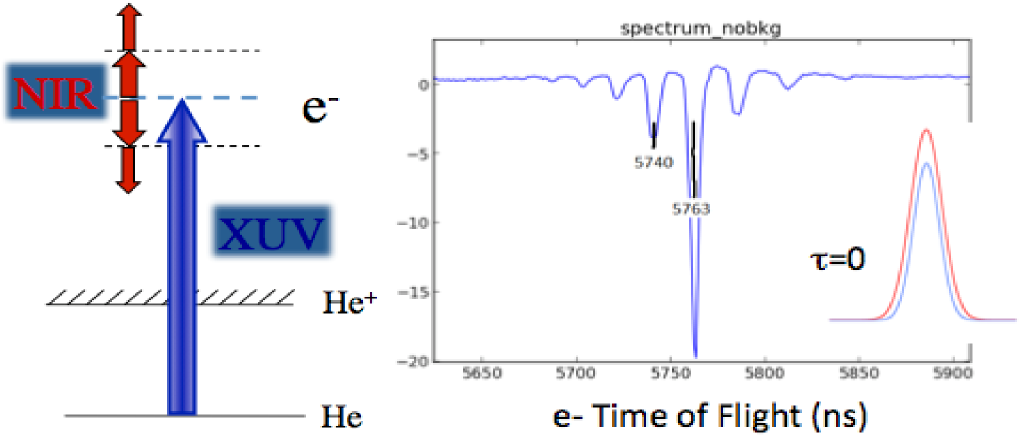
Pulse Length Measurements

"Sideband method" @ LDM

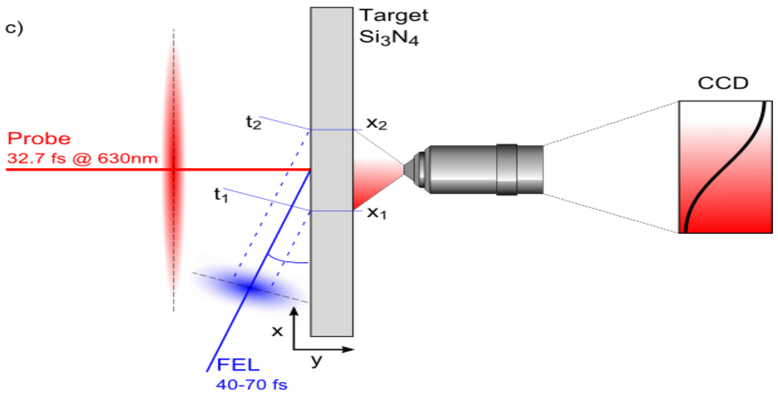


Cross correlation measurement **probing the intensity of the sidebands** in the photoelectron spectrum of He vs ΔT of **FEL(pump)-IR(probe)**



"Single-shot cross-correlation" @ DIPROI

Solid state target EUV cross correlation:
The FEL wavefront is tilted so that its fluency and temporal structure are **encoded spatially and temporally** into the surface of a Si_3N_4 target & **probe it with an ultrashort laser pulse**: the transmitted light is a cross-correlation between FEL and optical pulse.



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