Elettra
Sincrotrone
Trieste

Spectro-Temporal Photon Pulse Shaping at FERMI FEL

S. Di Mitri, ELETTRA SINCROTRONE TRIESTE

on behalf of the FERMI Team

Elettra Sincrotrone Trieste

Outline

- ❑ Facility overview and performance
- ❑ Spectral Shaping
- ❑ Temporal Shaping
- ❑ Multi-Color, Multi-Pulse Operation
- ❑ Upgrade plans

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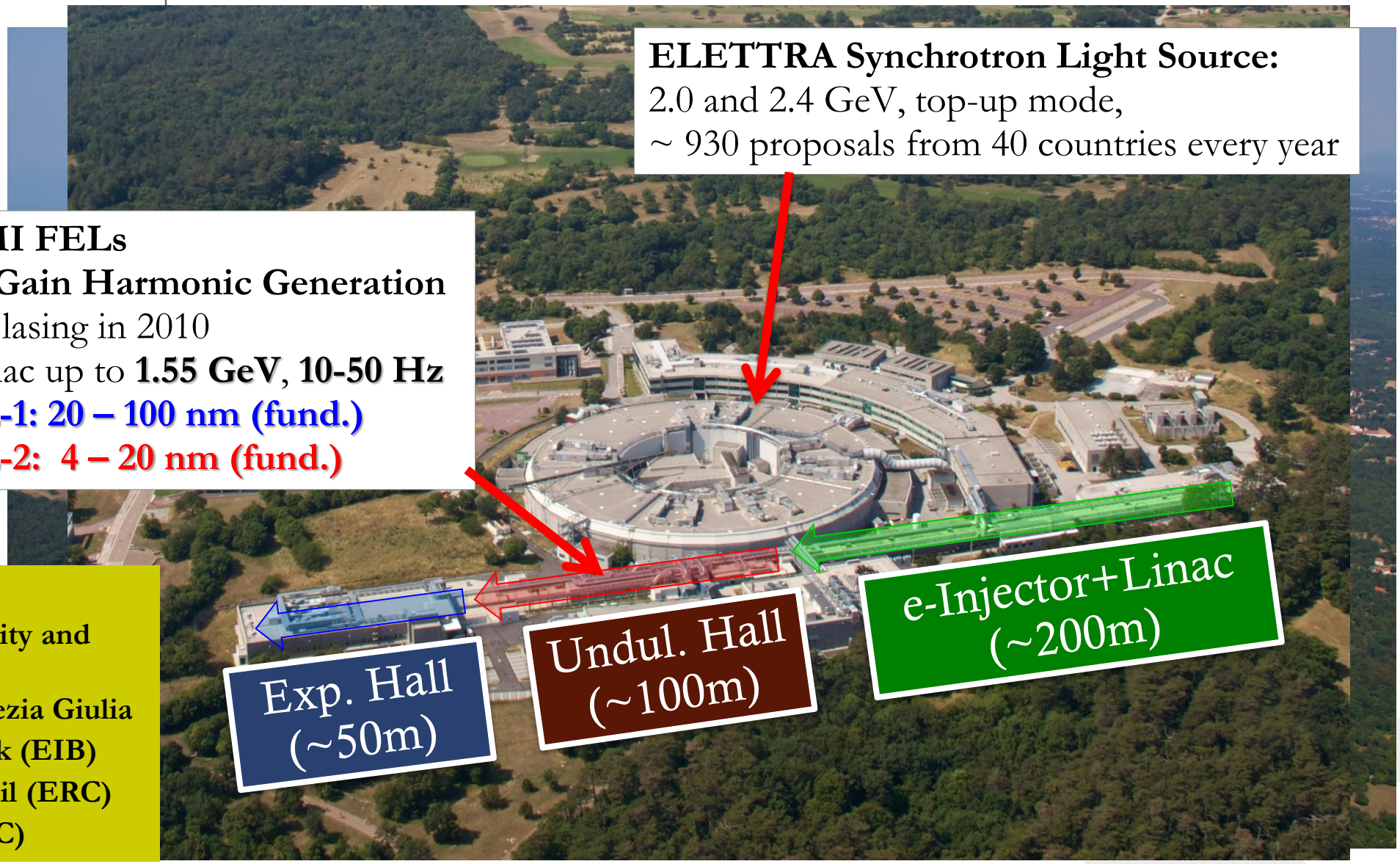
Site



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**, **10-50 Hz**
- **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)

FEL-1 & FEL-2

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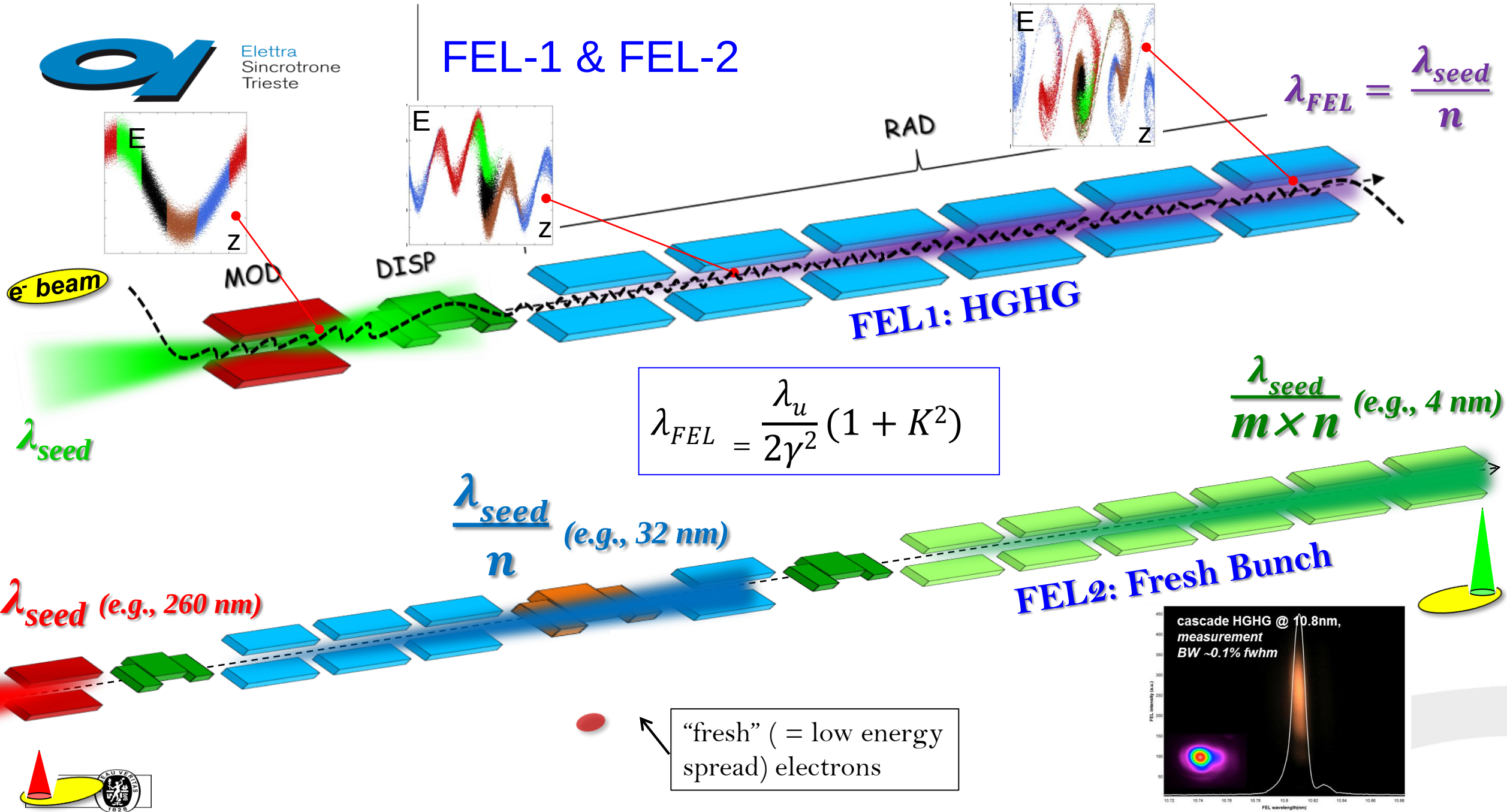

$$\lambda_{FEL} = \frac{\lambda_{seed}}{n}$$

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

λ_{seed}

λ_{seed} (e.g., 260 nm)

$\frac{\lambda_{seed}}{n}$ (e.g., 32 nm)

$\frac{\lambda_{seed}}{m \times n}$ (e.g., 4 nm)

"fresh" (= low energy spread) electrons

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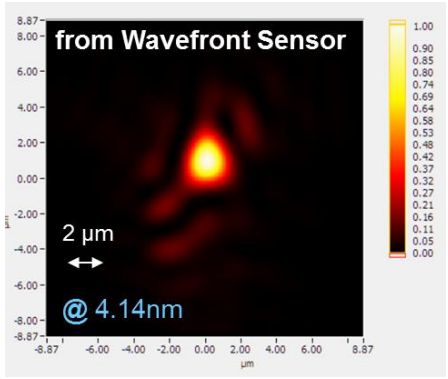
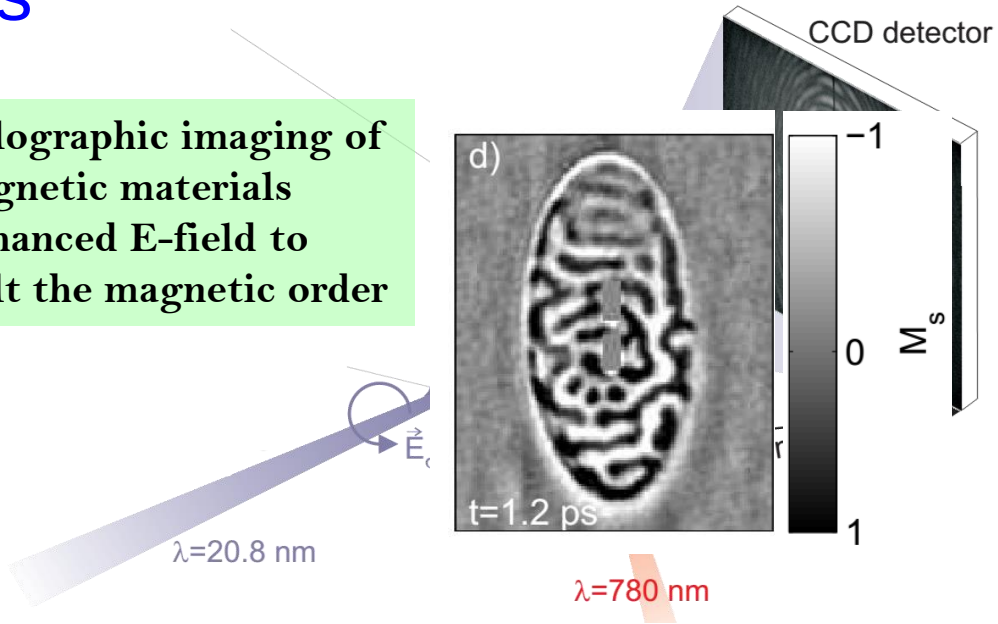
Features

Transverse coherence:



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



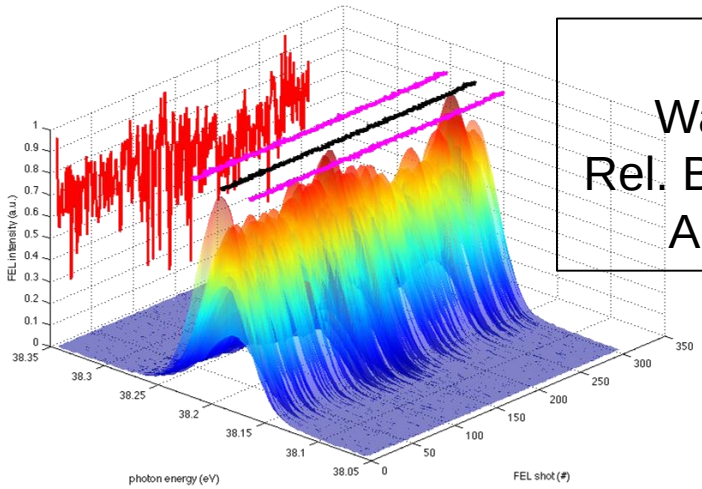
High Flux:

FEL1, *20 – 100 nm:* **~ 20 – 400 µJ**

FEL2, *4 – 20 nm:* **~ 10 – 100 µJ**

depending also on **polarization**,
LH, LV, CR, CL (>95%)

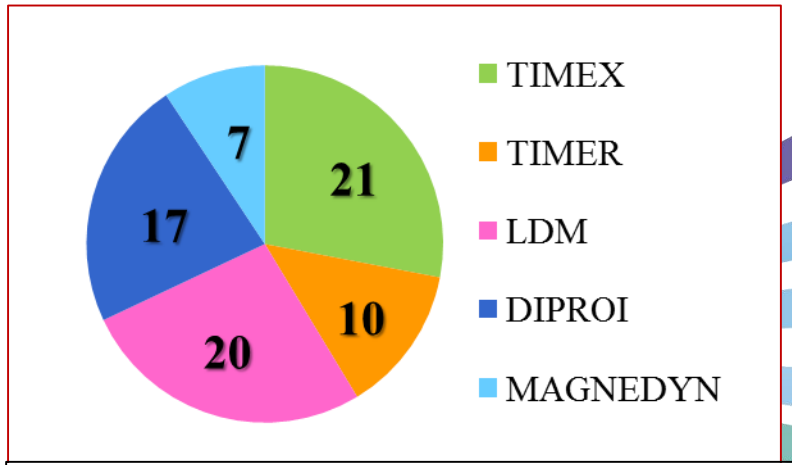
Stability (RMS):

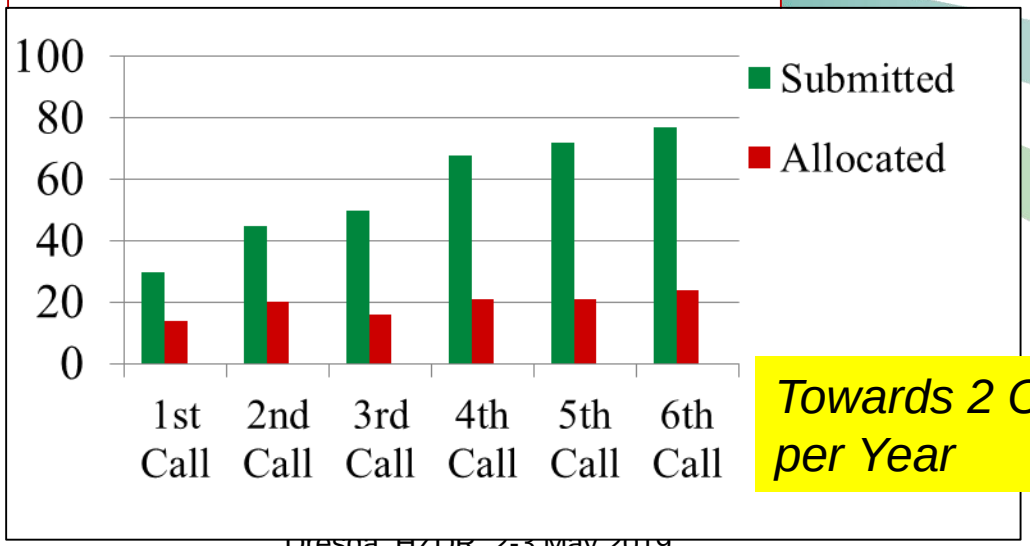


Intensity,	**3% – 15%**
Wavelength,	**0.01% – 0.1%**
Rel. Bandwidth,	**1% – 3%**
Arrival time,	**2 – 6 fs**

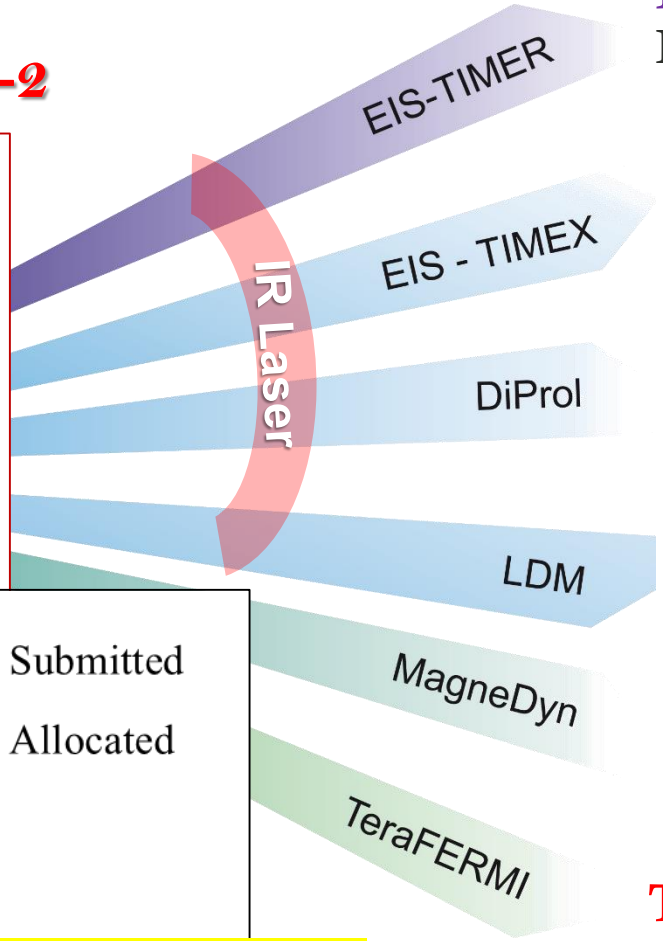
Photon Beamlines

- **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.**

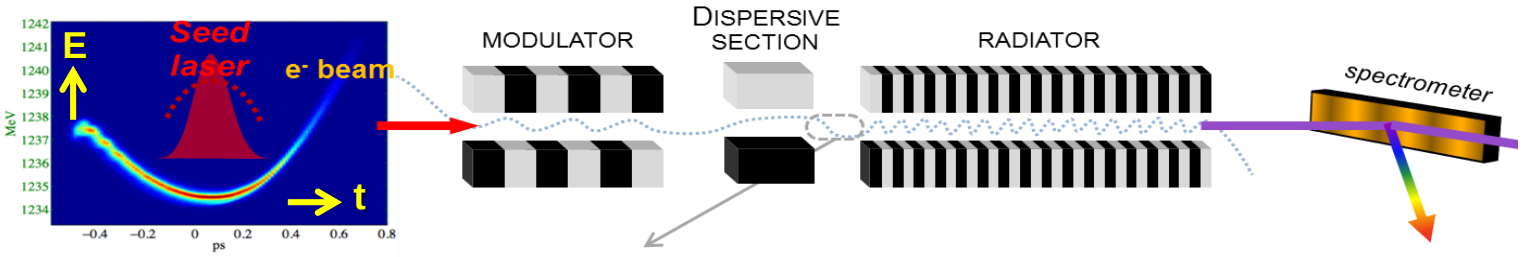
Magnedyn, led by *F. Parmigiani & M. Malvestuto:* **ultrafast magnetization dynamics** and phase transitions in complex materials. *Only FEL-2.*

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

Outline

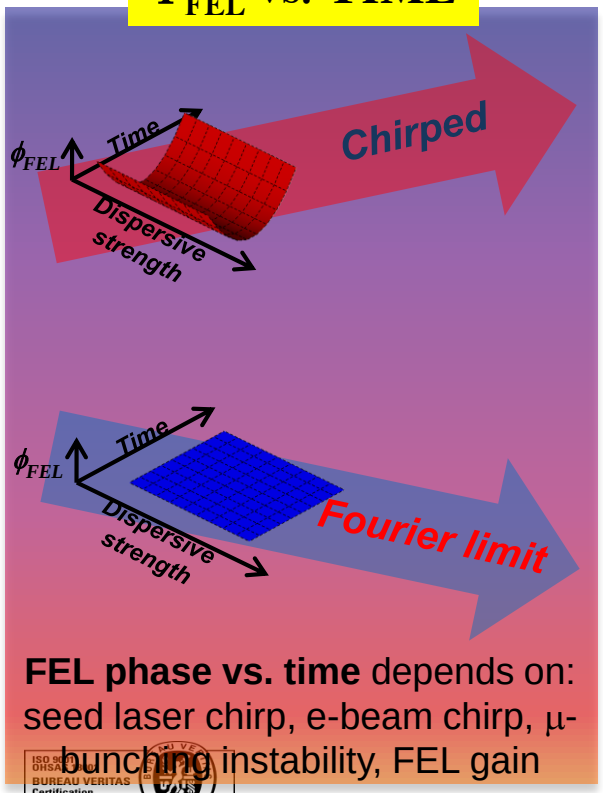
- Facility overview and performance
- Spectral Shaping
  - Fourier Limit
  - Wavelength scan
  - Sidebands
- Temporal Shaping
- Multi-Color, Multi-Pulse Operation
- Upgrade plans

Longitudinal Coherence



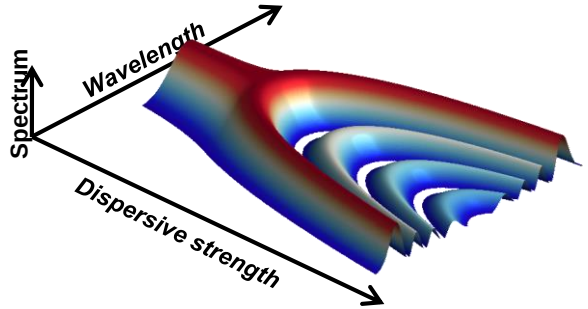
Possibility to **compensate energy-time correlations** in **e-beam** distribution with and seed laser to generate **Fourier transform limited** pulses.

Φ_{FEL} vs. TIME

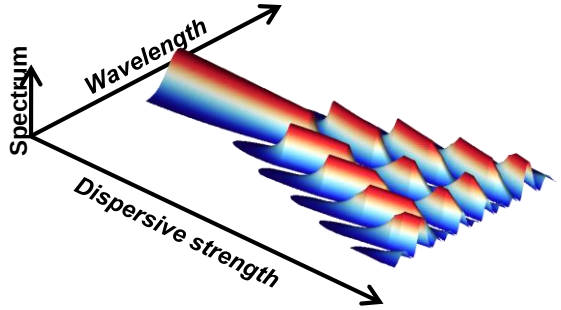


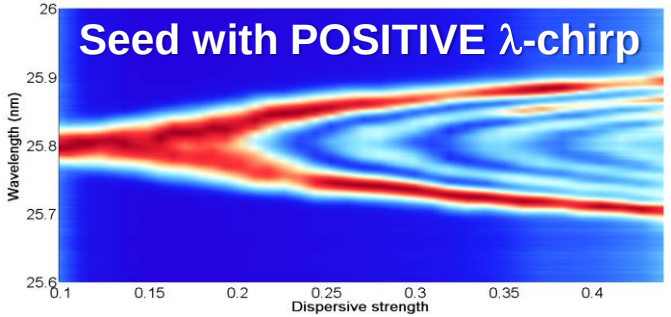
FEL phase vs. time depends on: seed laser chirp, e-beam chirp, μ-bunching instability, FEL gain

SECTRUM vs. DISPERSIVE STRENGTH



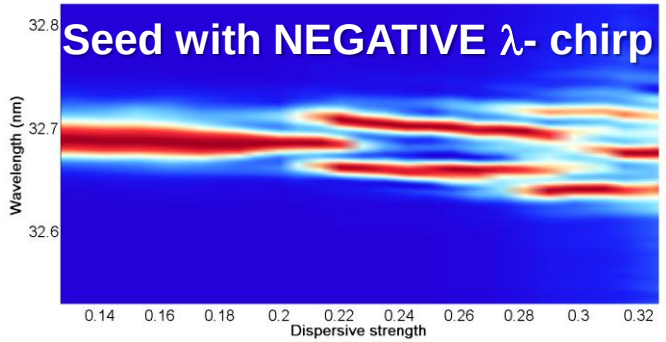
Theory





Measurement

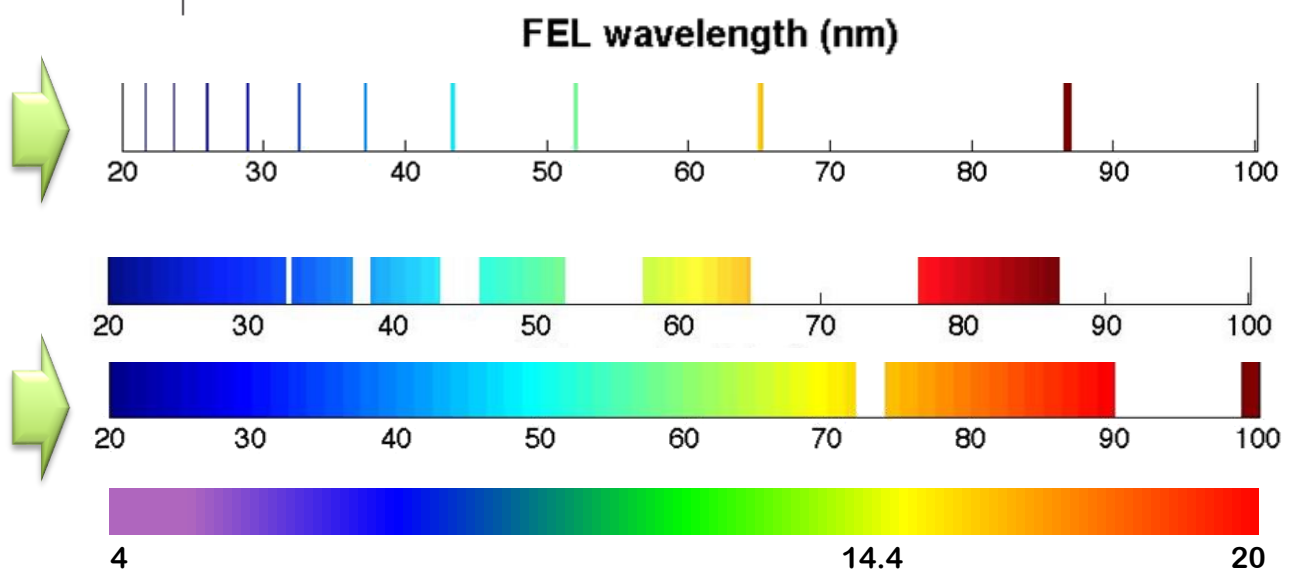
Spectral intensity (a. u.)



Wavelength Tuneability (12 – 300 eV)

THG, ~261 nm
or ~265 nm

OPA, 230–260 nm
or 296–360 nm



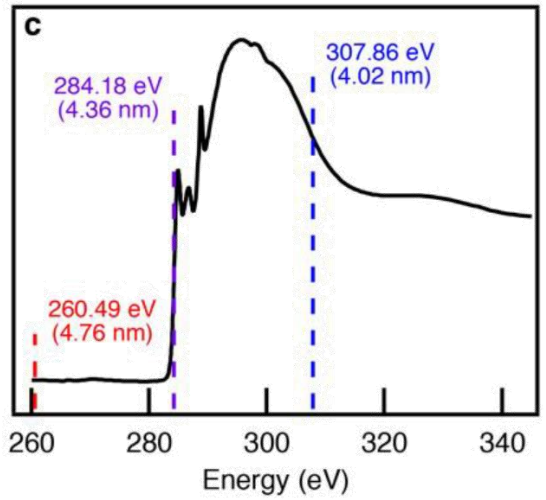
☺ ***peak power***

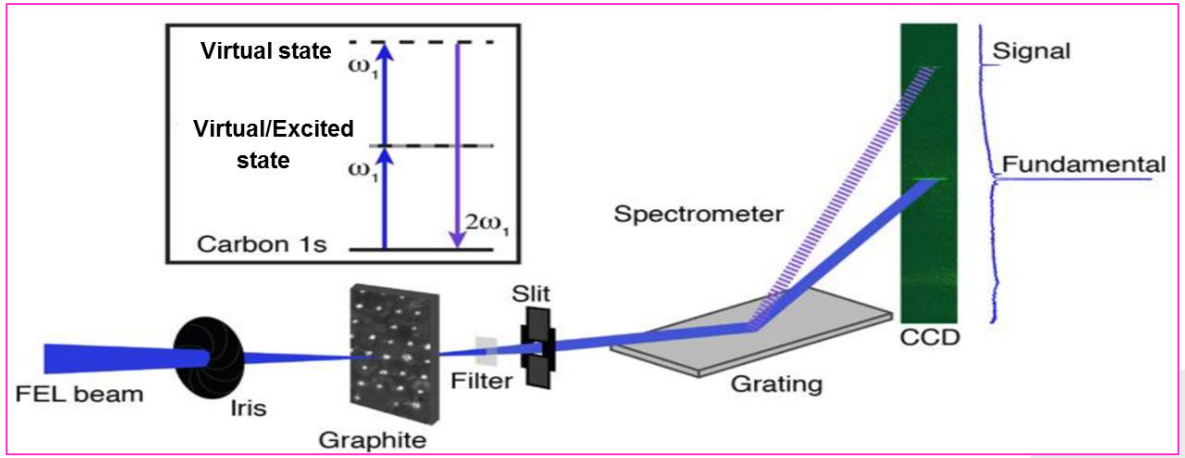
±0.2% tuneable

☺ ***λ-scan***

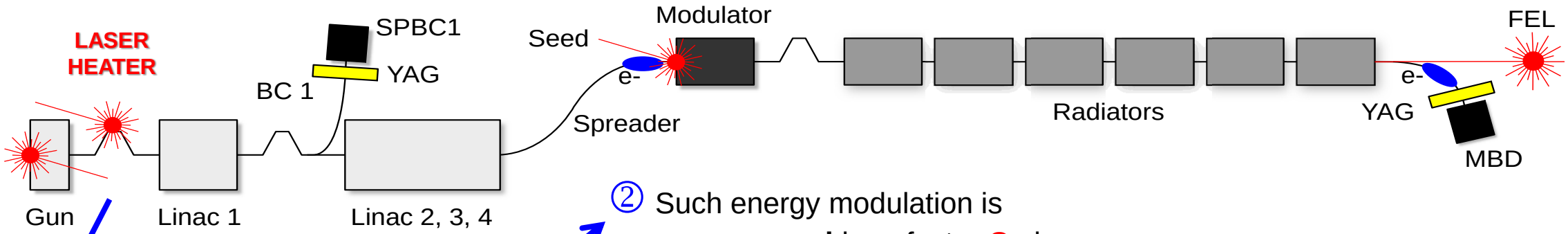
- *FEL-1*, fast scans in selected ranges
- *FEL-2*, ±10–20% tuneable

2nd harmonic generation form graphene





Filling Wavelength Gaps

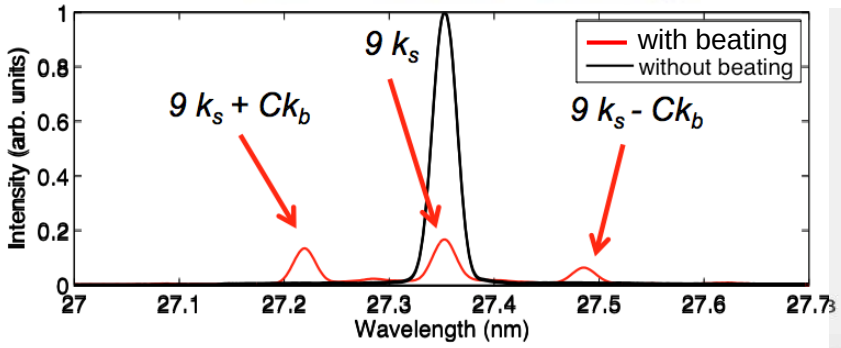


① Modified in order to **modulate** beam **energy spread** at λ_B **> 32 μm.**

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:

$$k = nCk_B + mk_S$$



Outline

- Facility overview and performance
- Spectral Shaping
- Temporal Shaping
  - Shorter seed laser
  - Superradiance
  - CPA
  - e-Beam slicing
- Multi-Color, Multi-Pulse Operation
- Upgrade plans

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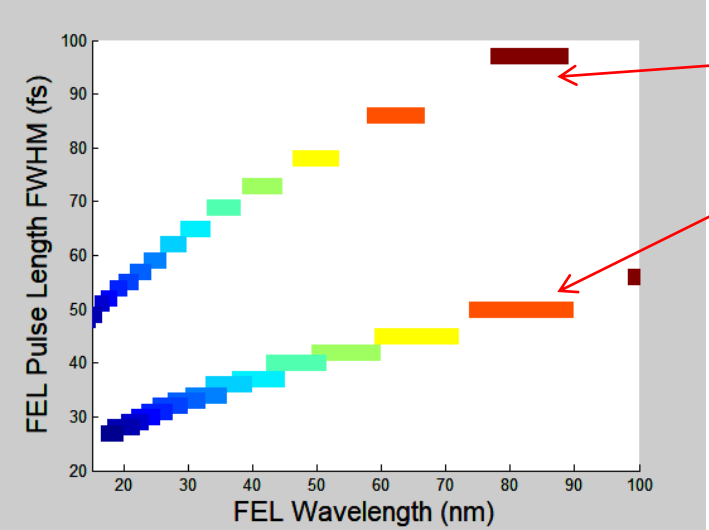
Seed Laser Pulse Duration

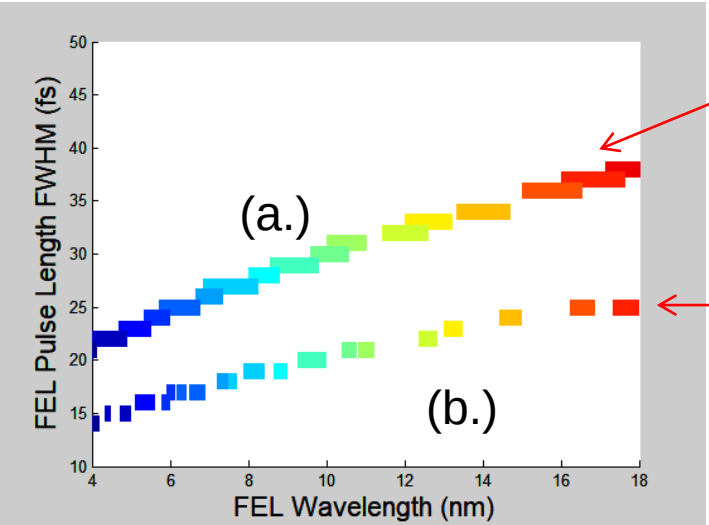


Present OPA: 231 – 267 nm, Δt_{seed} = **130 fs**

Upgraded OPA, *in progress:* 295 – 360 nm, Δt_{seed} = **75 fs**
(in-house modification of a commercial system)

Upgraded OPA, *near future:* 295 – 360 nm, Δt_{seed} **< 50 fs**

FEL-1



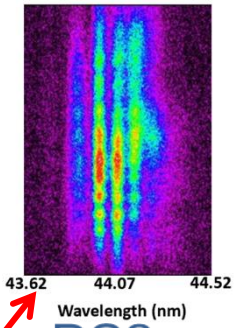
Present OPA: 231 – 267 nm, Δt_{seed} = **95 fs**
Present THG: 263 – 267 nm, Δt_{seed} > 100 fs

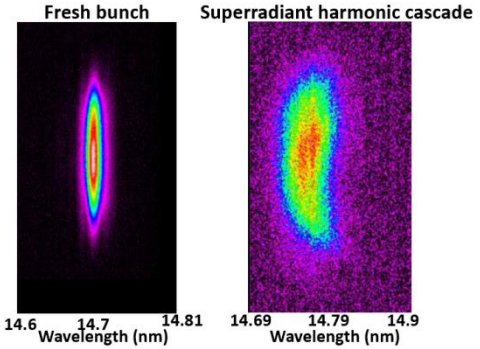
Upgraded THG, *near future:* ~260 – 270 nm, Δt_{seed} = **65 fs**
(dedicated ML oscillator for 2nd amplifier)

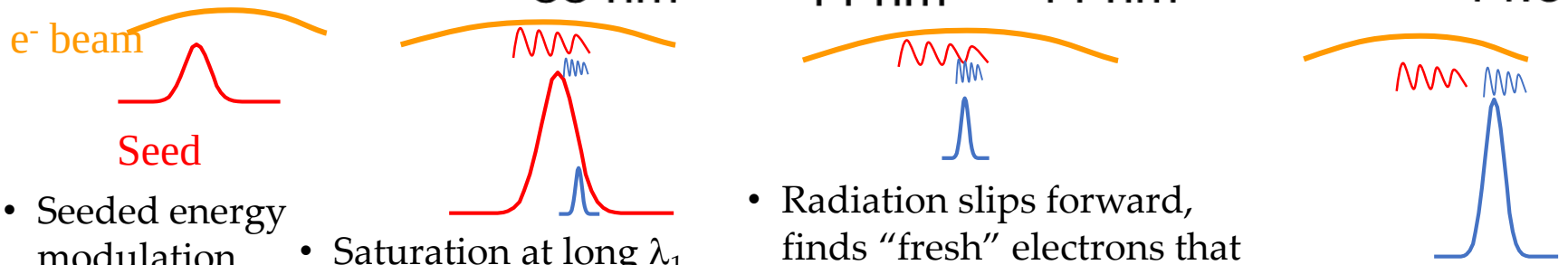
FEL2 needs ~FT, higher peak power at shorter λ seed laser, and smaller seed λ -tuning.

FEL-2

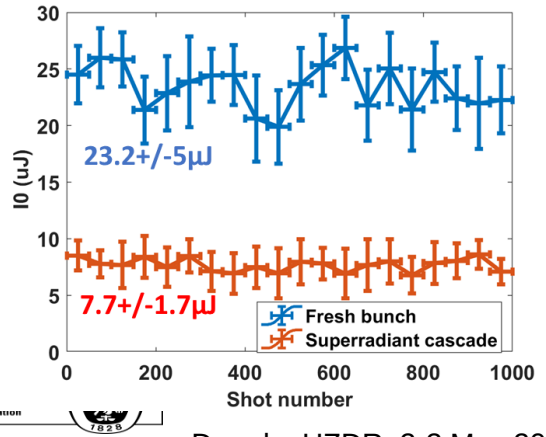
Superradiance

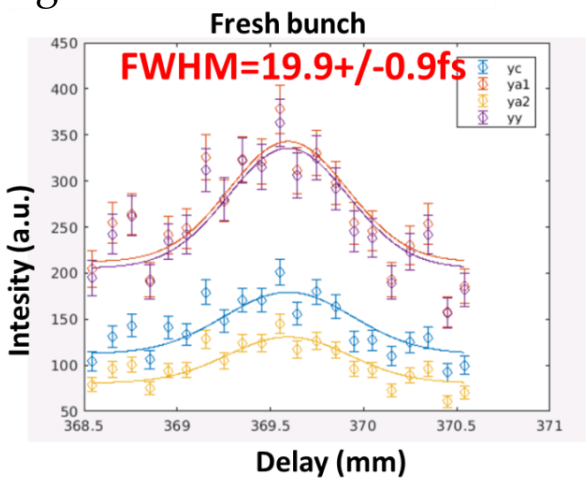


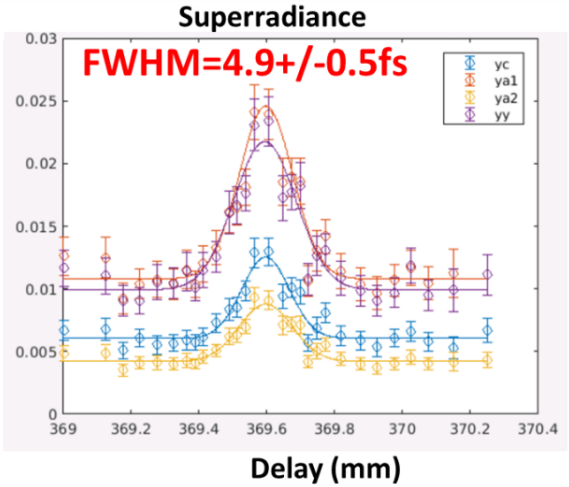




- Seeded energy modulation
- Saturation at long λ_1
- Energy spread is now on too large for lasing
- Radiation slips forward, finds "fresh" electrons that radiates at $\lambda_1/2$ (CHG)
- Radiation pulse shortens, slips forward and is amplified at $\lambda_1/6$



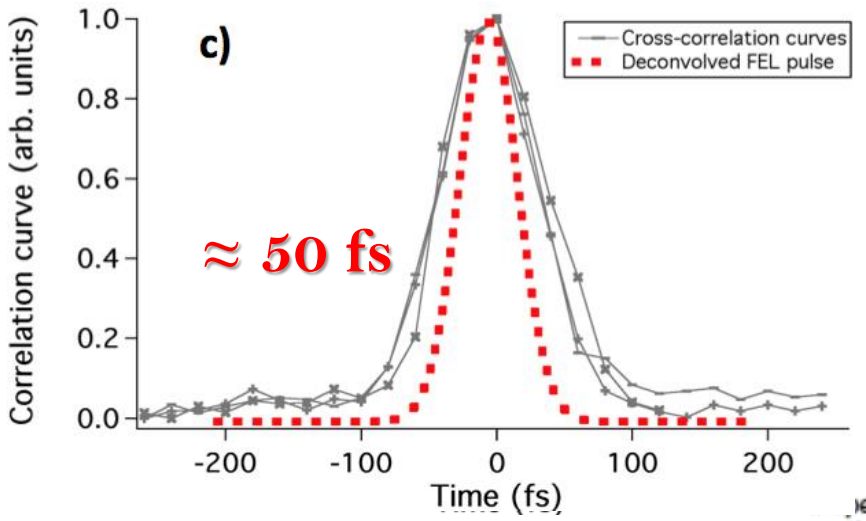




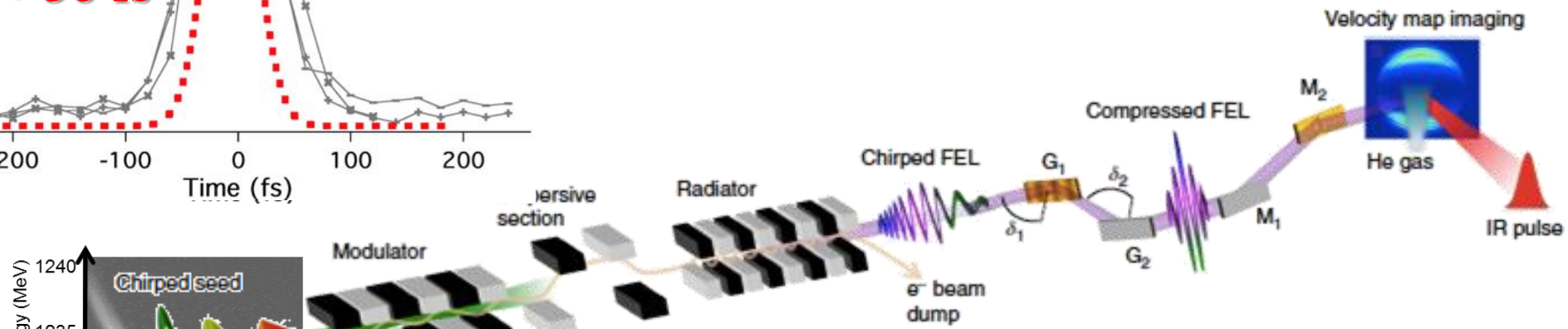
- ❑ Autocorrelation of FEL pulses by 2-photons ionization of Ar
- ❑ **Superradiant pulse is at GW level and at Fourier-limit.**

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.

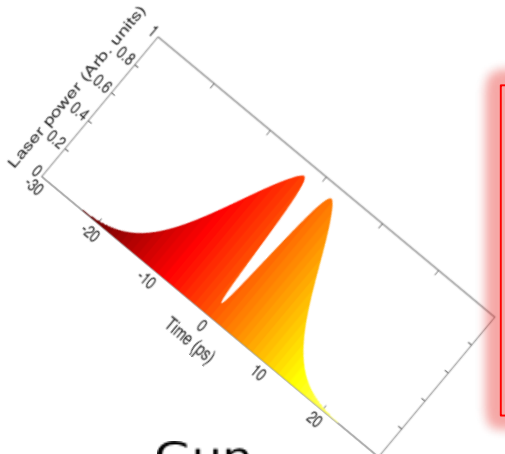


- ❑ FEL pulse compression confirms the high degree of **longitudinal coherence.**
- ❑ It paves the way to **~fs pulse duration.**

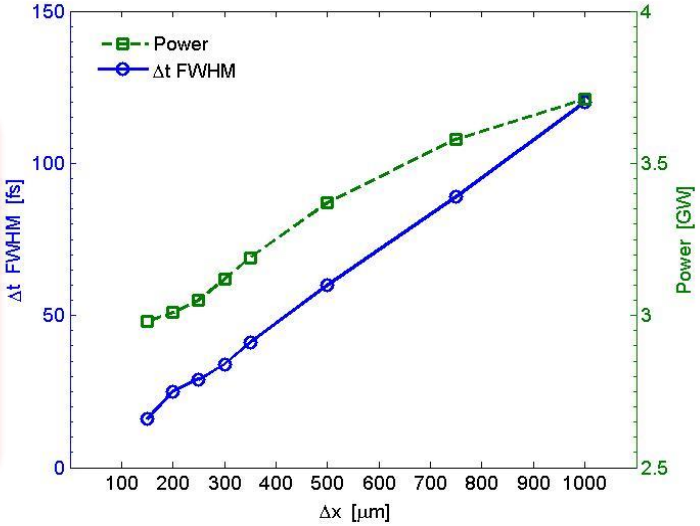


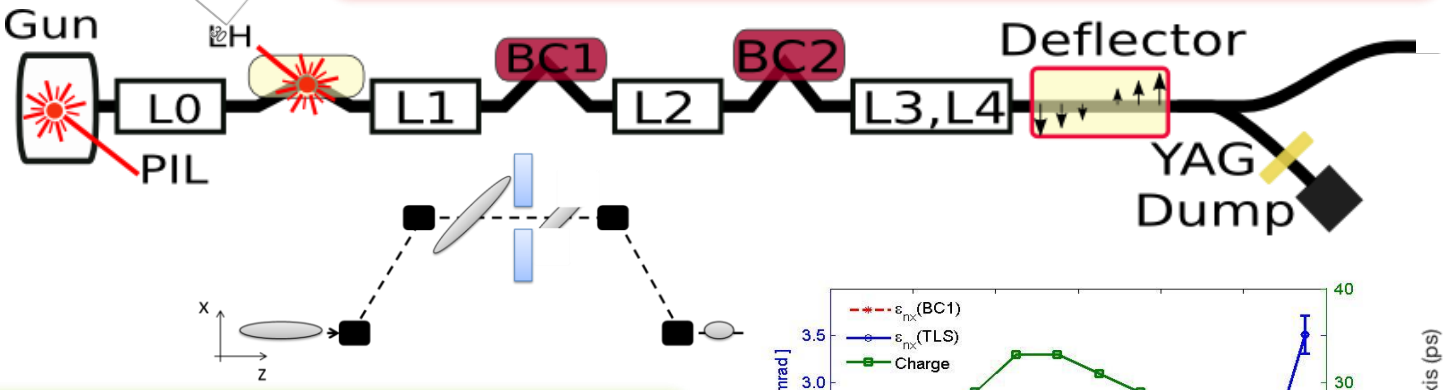
$\Delta t_{seed} \approx 290$ fs
$\Delta \lambda_{seed} \approx 0.9$ nm
$\Rightarrow$ ~ 3 × FTL

e-Beam Slicing

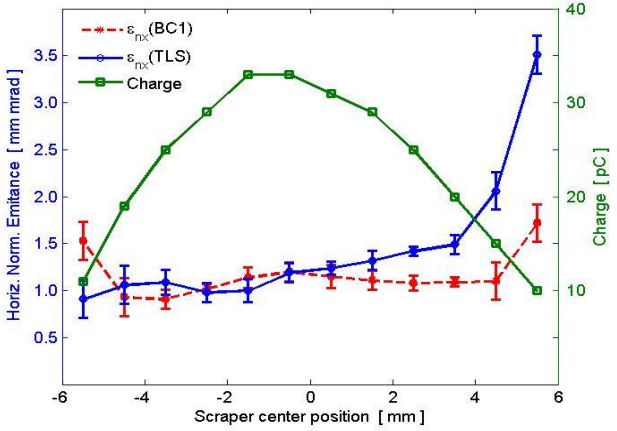


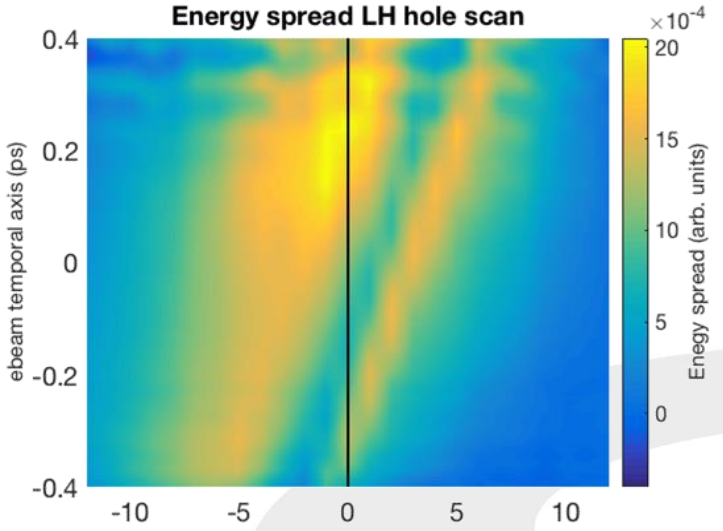
- Intensity modulation of the LH pulse suppresses lasing in regions with large energy spread.
- ~10 fs short lasing region can be selected.





- e-beam is scraped in BC1, brightness is preserved, and can be seeded by a longer laser.





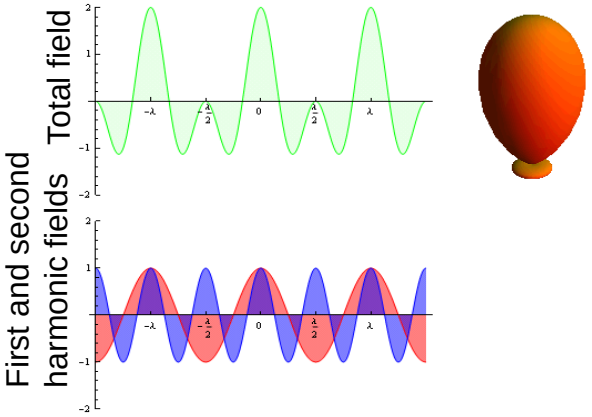
Elettra Sincrotrone Trieste

Outline

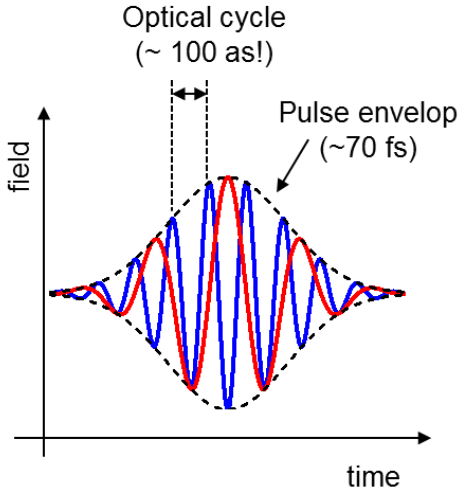
- ❑ Facility overview and performance
- ❑ Spectral Shaping
- ❑ Temporal Shaping
- ❑ Multi-Color, Multi-Pulse Operation
  - 1 seed pulse
  - 2 seed pulses
- ❑ Upgrade plans

Split Radiator & Phase Control

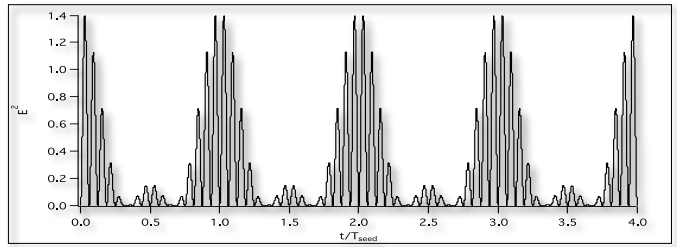
"Coherent Phase Control" = control of the delay of two coherent pulses on a level shorter than the optical cycle.

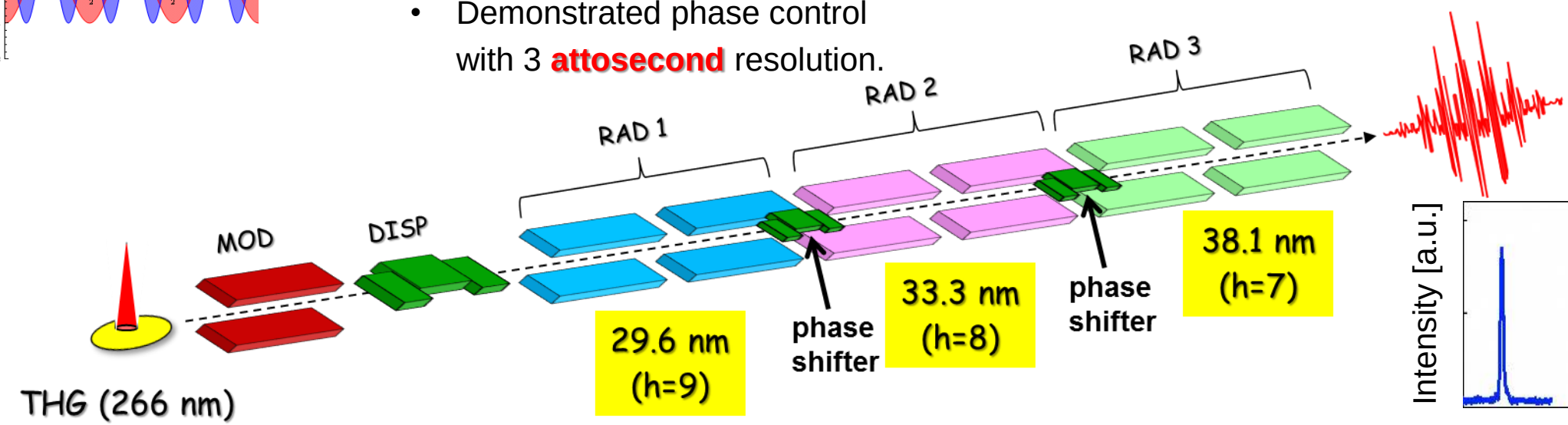


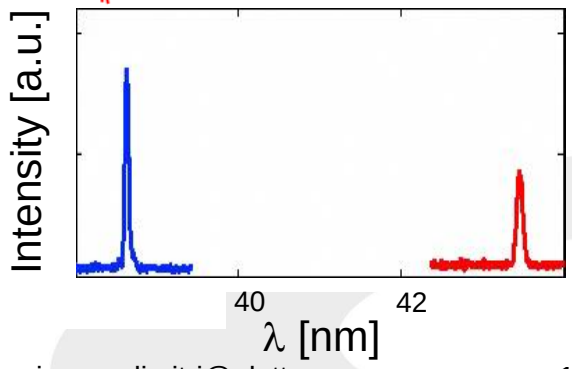
- **Lobes** represent direction and intensity of photo-electron emission from Ne.
- **Asymmetry** (recorded by VMI) depends on the relative phase of t-coherent FEL pulses.
- Demonstrated phase control with 3 **attosecond** resolution.



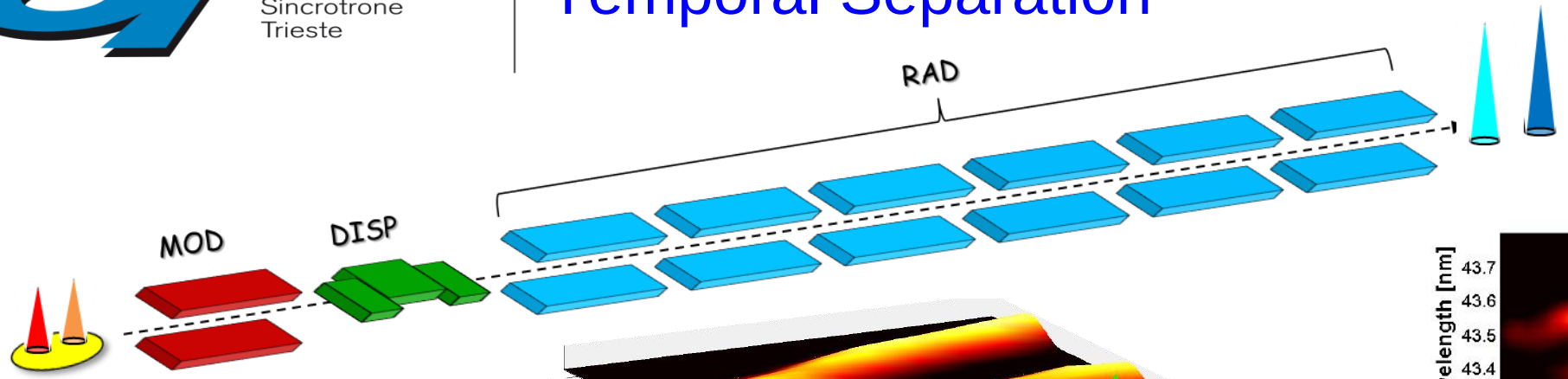
Train of *attosecond pulses* from the "synthesis" of 3 phase-locked FEL harmonics.



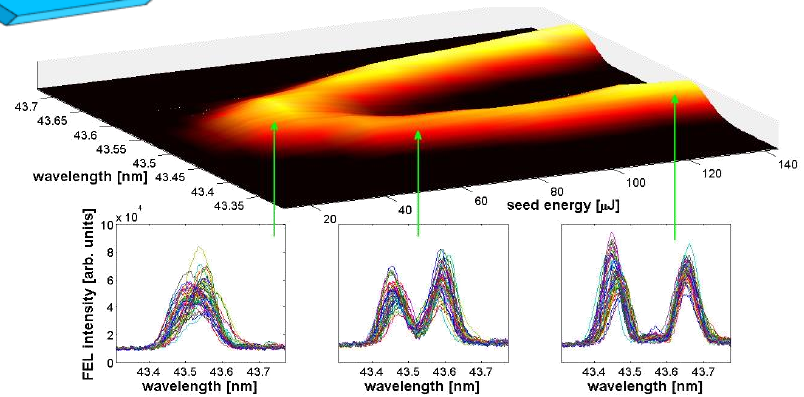


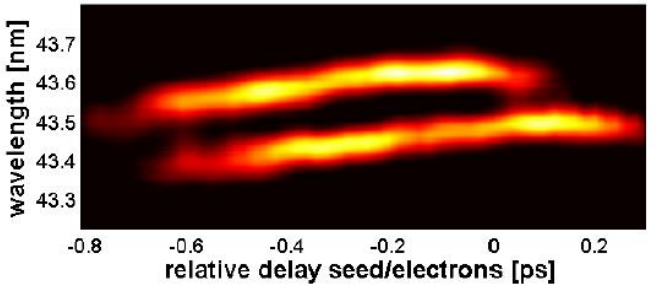


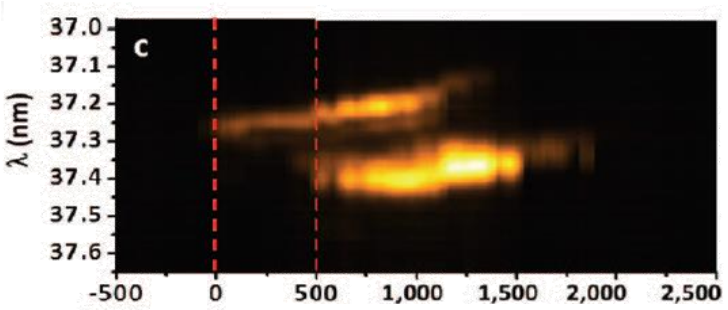
Temporal Separation



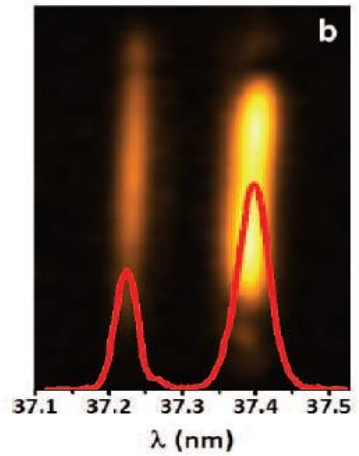
37.2 & 37.4 nm
$\Delta t_{1,2} \approx 500$ fs



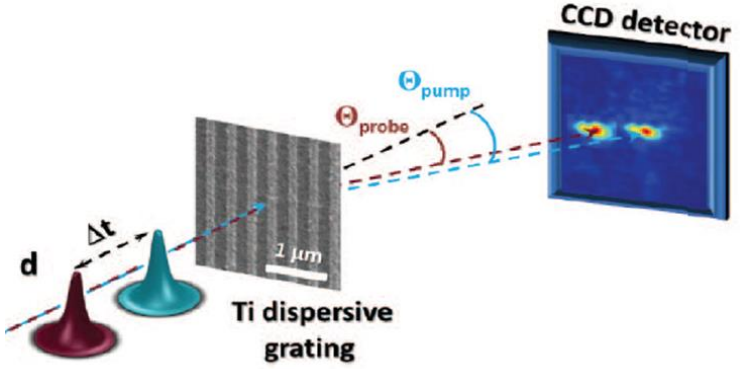




- **A strong seed pulse drives lasing at the bunch edges**
- **Two phase-locked seed pulses generate phase-locked FEL pulses. Relative phase can be scanned.**

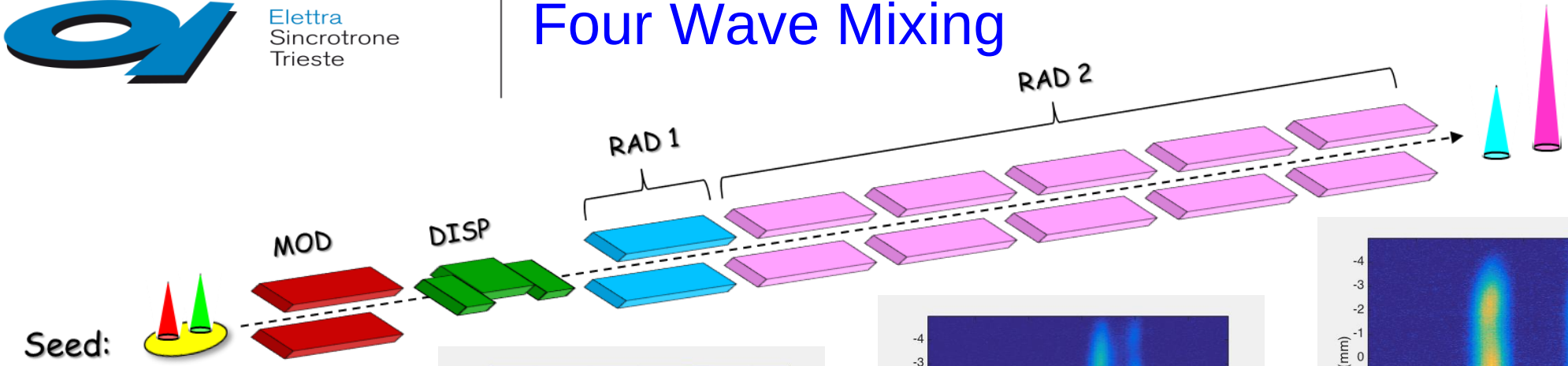


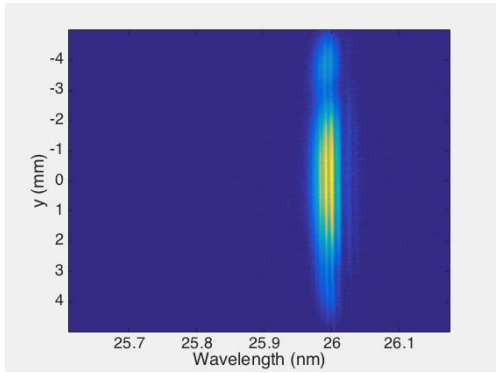
FEL-Pump & FEL-Probe
"across" the Ti M-edge.
Determination of dielectric function in highly photoexcited Ti at given time delays vs FEL flux.

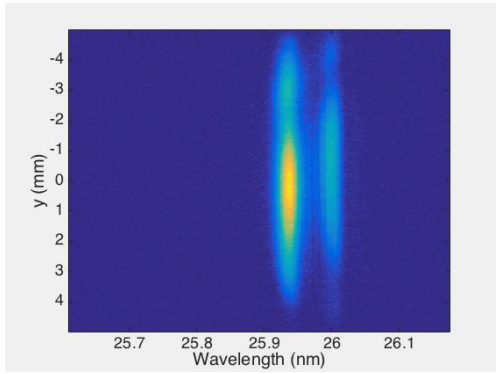


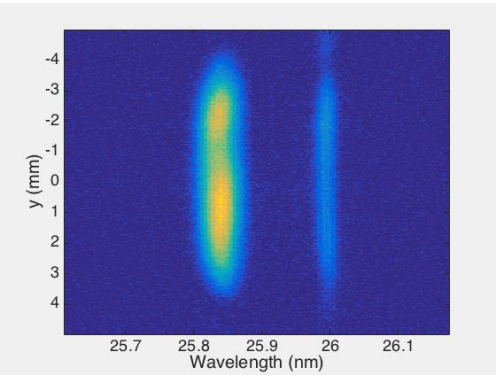
Four Wave Mixing

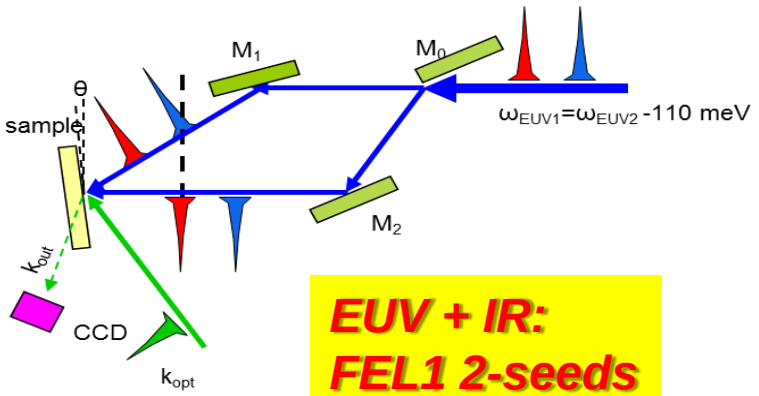
18.7 & 23.2 nm
$\Delta t_{1,2} \approx 500$ fs



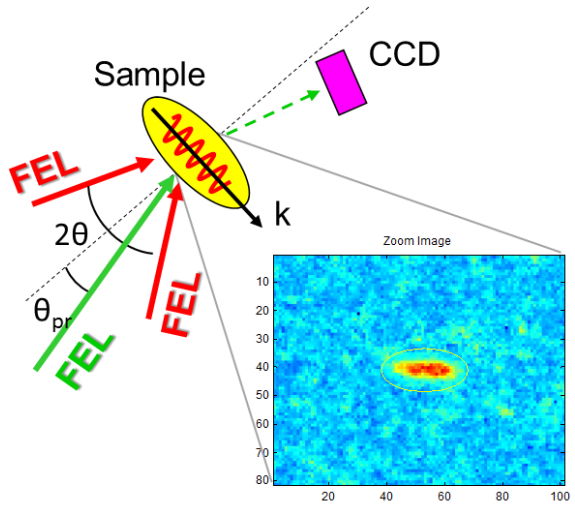


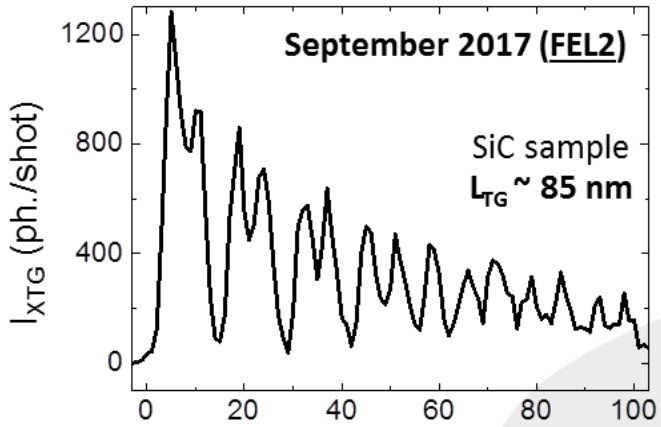






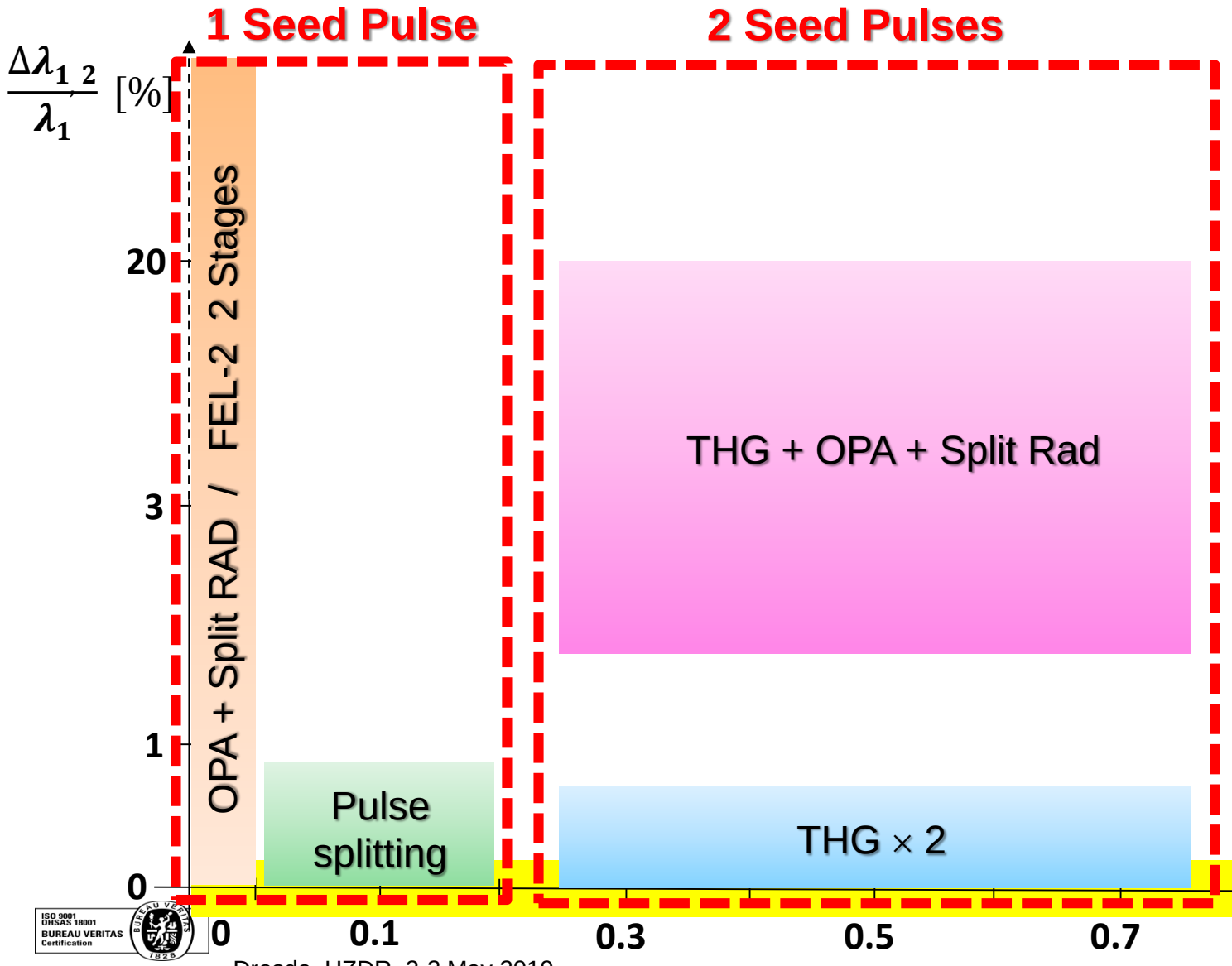
EUV + IR: FEL1 2-seeds



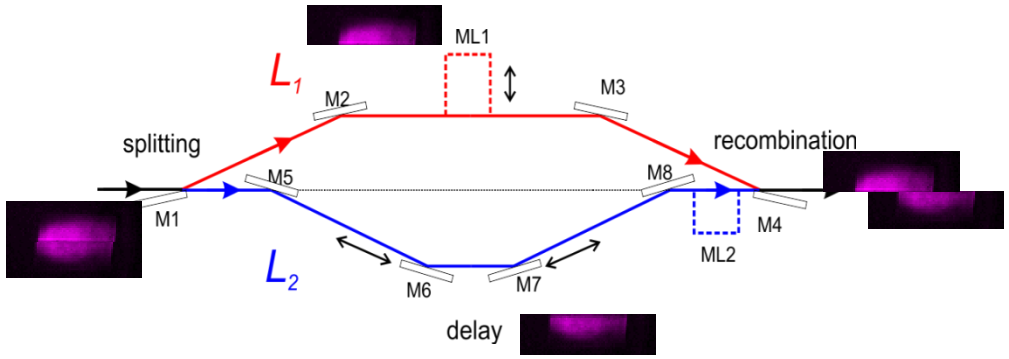


All EUV: FEL2 1st and 2nd stage

Summary of Spectro-Temporal Control



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

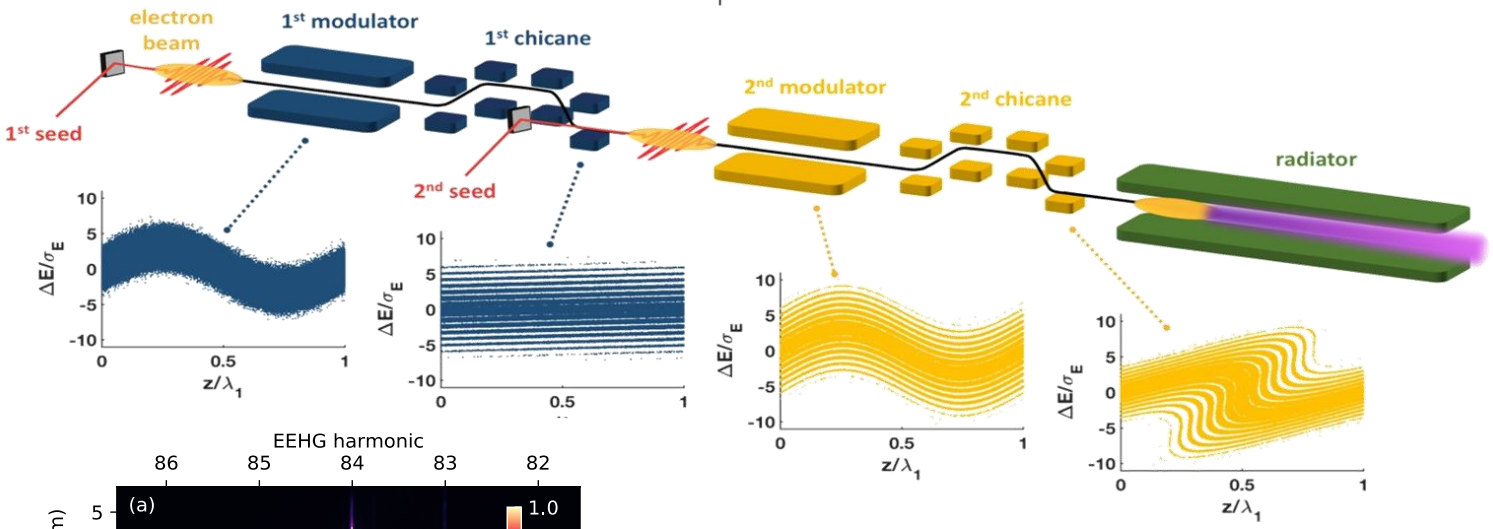


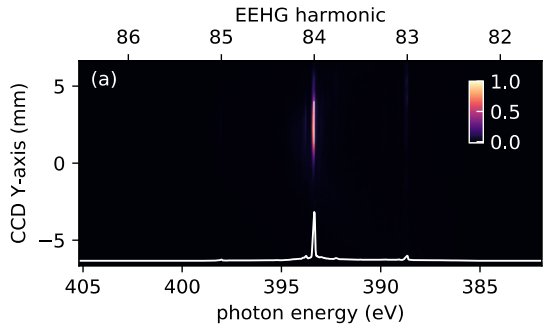
Elettra Sincrotrone Trieste

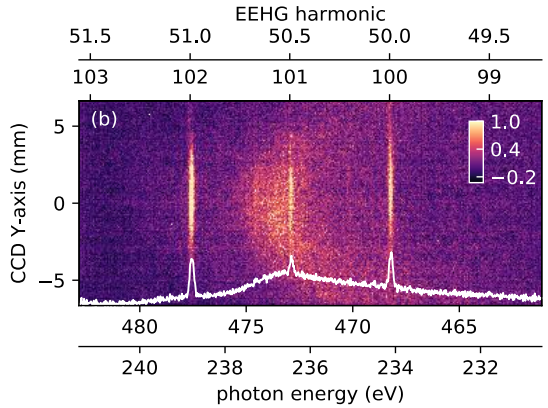
Outline

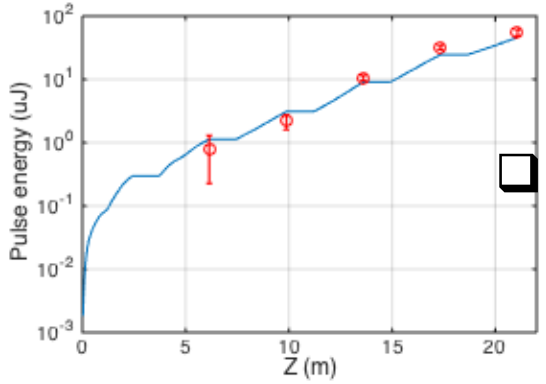
- ❑ Facility overview and performance
- ❑ Spectral Shaping
- ❑ Temporal Shaping
- ❑ Multi-Color, Multi-Pulse Operation
- ❑ Upgrade plans
  - EEHG
  - Linac

Echo-Enabled Harmonic Generation



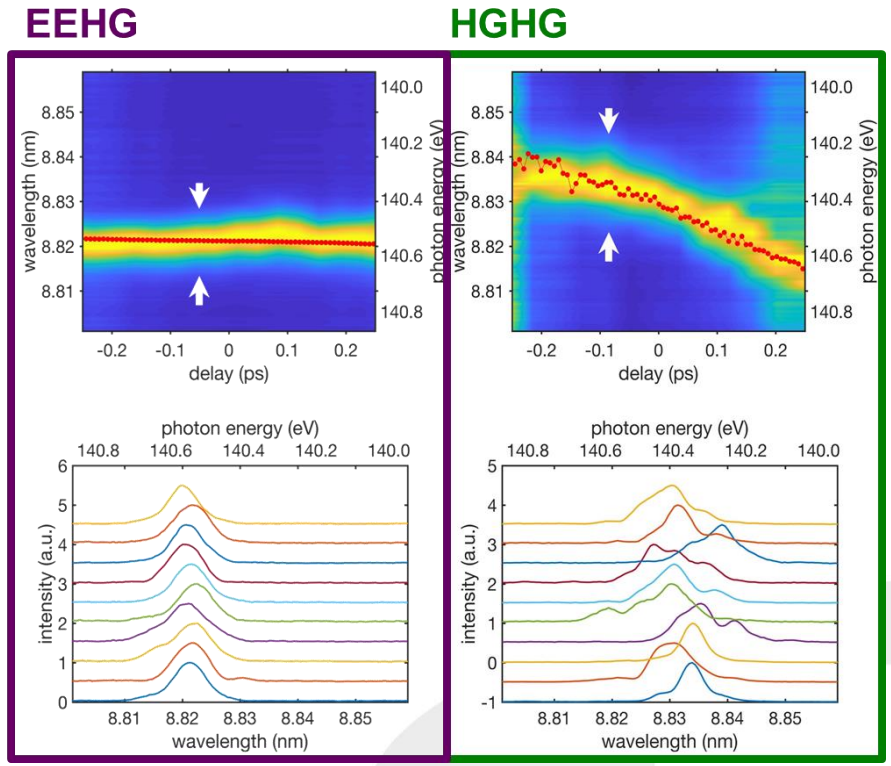






- Measurements match the model

- EEHG spectral brightness is far les sensitive to e-beam E-chirp. Sidebands from microbunching inst. only at very high harmonics.
- EEHG is more "radiator-hungry" than HGHG, but generates higher bunching, thus higher harmonics.



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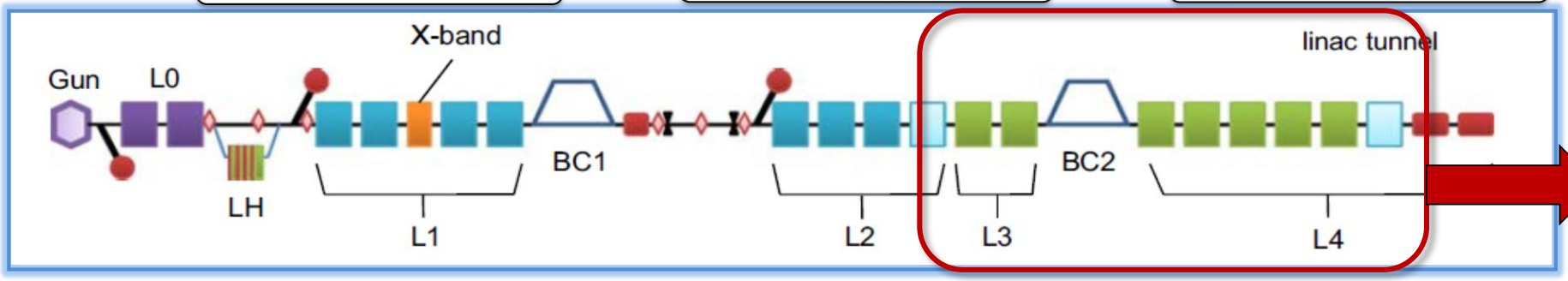
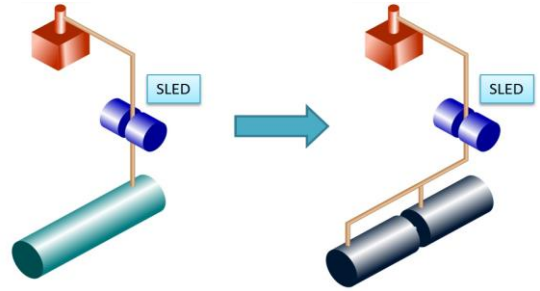
Linac Energy

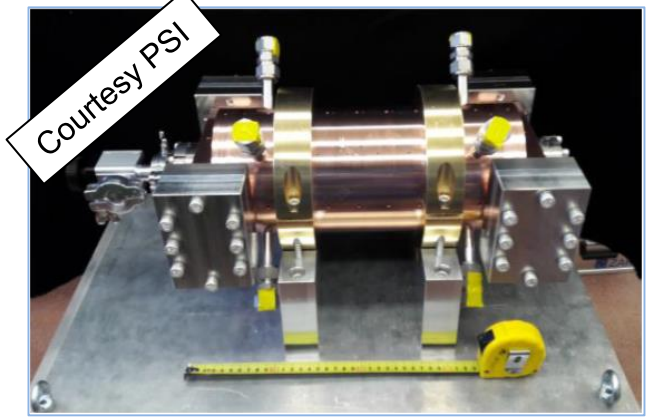
GOAL: TO EXTEND THE FEL RANGE TO SHORTER WAVELENGTH down to 2 nm → **NEEDS** →

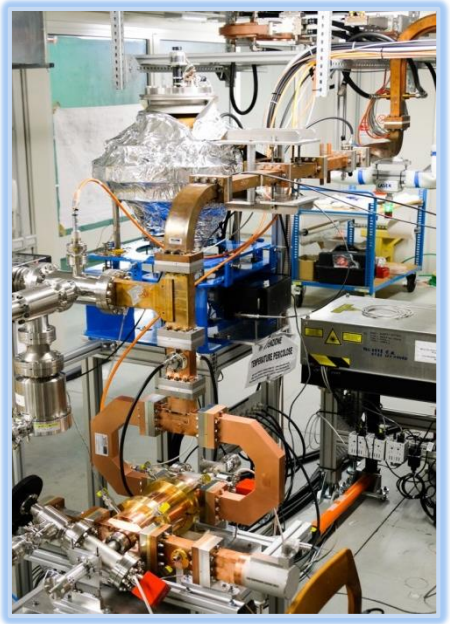
Actual Linac Energy	Target Linac Energy	Solution
1.5 GeV @ 10Hz	**1.8 GeV @ 50Hz**	**High Gradient 30MV/m**



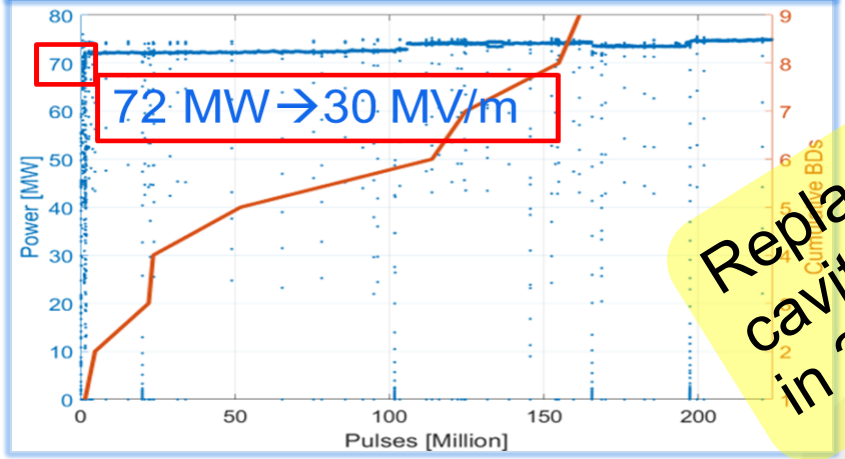
Replace 7 BTW with high gradient accelerating modules







Four breakdowns in the structure
In 50 days of operation at 50Hz at Acc. Gradient of 30MV/m



Replacement of cavities will start in 2020

Thank you for Your attention,

questions are very welcome

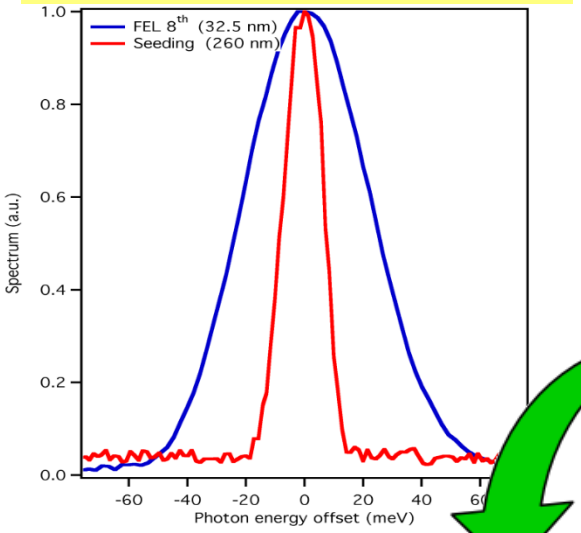
Main References

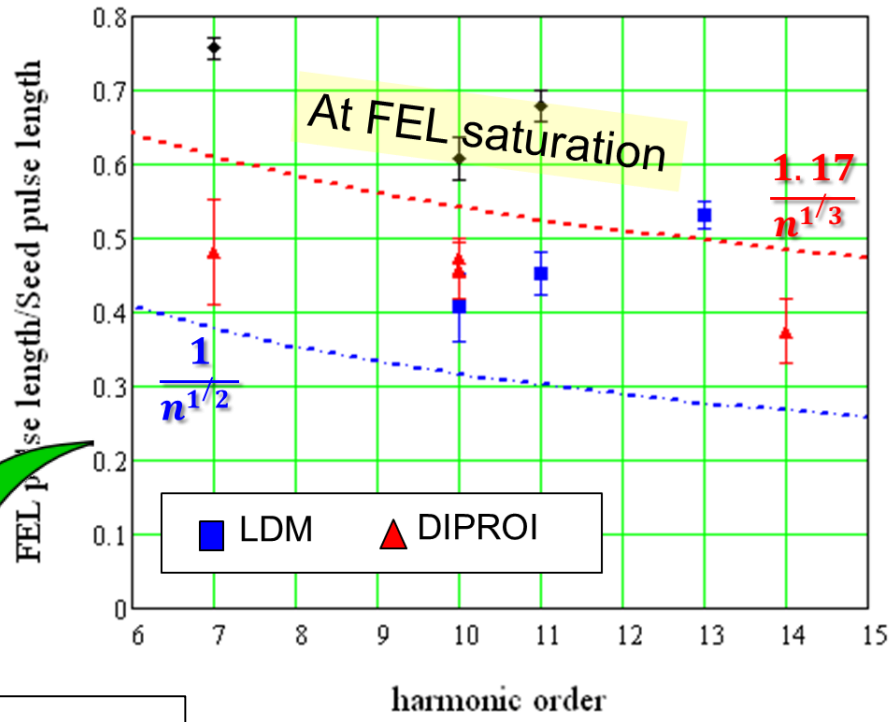
E. Allaria et al., Nat. Photonics 6, 699 (2012) – slide 4
E. Allaria et al., Nat. Photonics 4, 2476 (2013) – slide 4
F. Capotondi et al., Rev. Sci. Instr. 84, 051301 (2013) – slide 5
D. Gauthier, PRL 115, 114801 (2015) – slide 8
M. Danailov et al. Opt. Expr., Vol. 22, 11 (2014) – slide 9
R. K. Lam et al., PRL 120, 023901 (2018) – slide 9
E. Roussel et al., PRL 115, 214801 (2015) – slide 10
S. Spampinati, N. Mirian, L. Giannessi (submitted, 2019) – slide 13
D. Gauthier et al. Nat. Commun. 7, Article 13688 (2016) – slide 14
S. Di Mitri et al., PRSTAB 16, 042801 (2013) – slide 15
K. Prince et al., Nat. Phot. 10, 176 (2016) – slide 17
E. Ferrari et al., Synch. Rad. News 29:3, 4 (2016) – slide 17
B. Mahieu et al., Opt. Expr. 22730, 21, 19 (2013) – slide 18
E. Allaria et al., Nat. Commun. 4:2476 (2013) – slide 18
E. Ferrari et al., Nat. Commun. 7:10343 (2015) – slide 18
F. Bencivenga, Nature, 502, 205 (2015) – slide 19
F. Bencivenga, Faraday Discussion (2016) – slide 19
P. Rebernik et al., Nat. Photonics (accepted, 2019) – slide 22
N. Shafquat et al., NIM A 867 (2017) – slide 23

Fourier Limit Validated

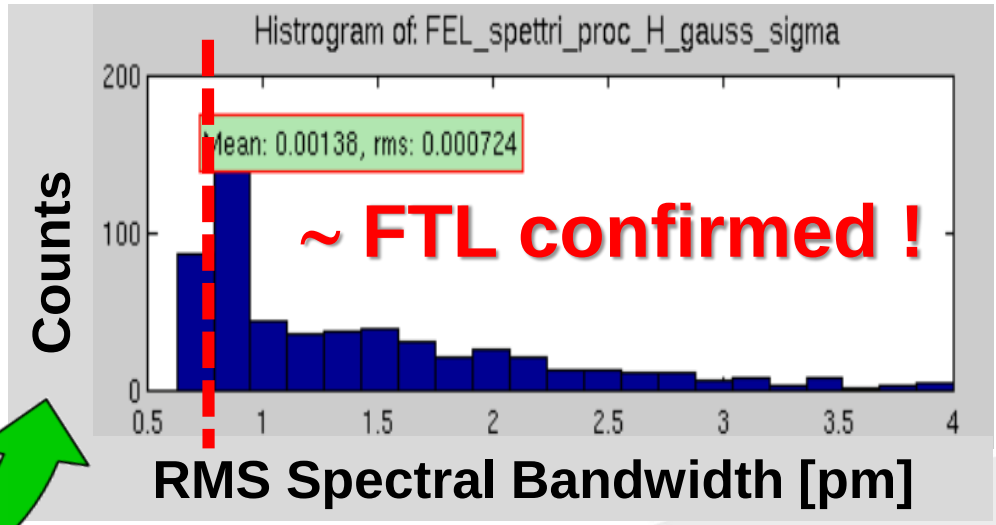
@ LDM & TIMEX

FEL pulse is broader than the seed because is shorter





PULSE LENGTH ⟷ **BANDIWDTH**



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

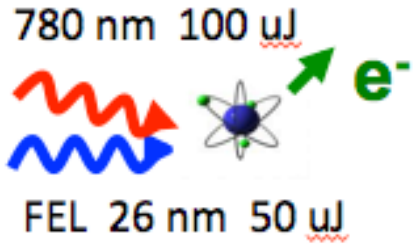
σ_λ @ Fourier Tr. Lim. = **0.8 pm or 0.02%**

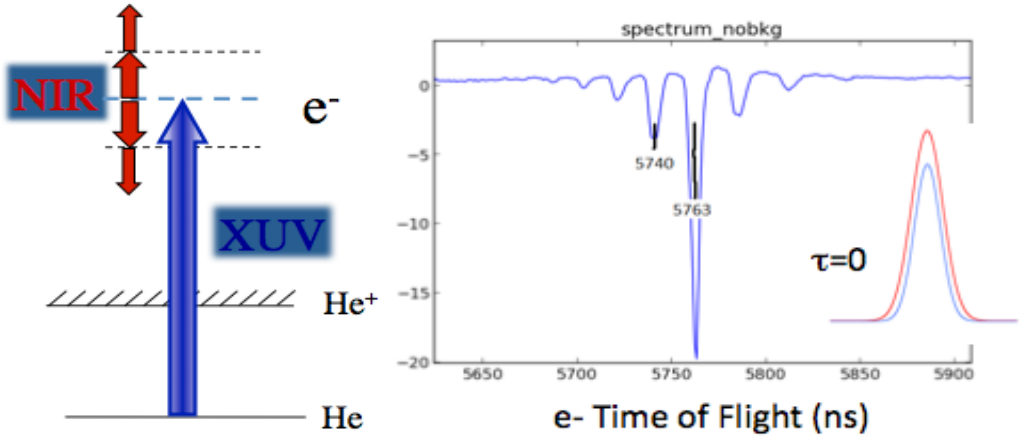
Pulse Length Measurements

@ LDM & DIPROI

"Sideband method" @ LDM

Seed Ti:Sa

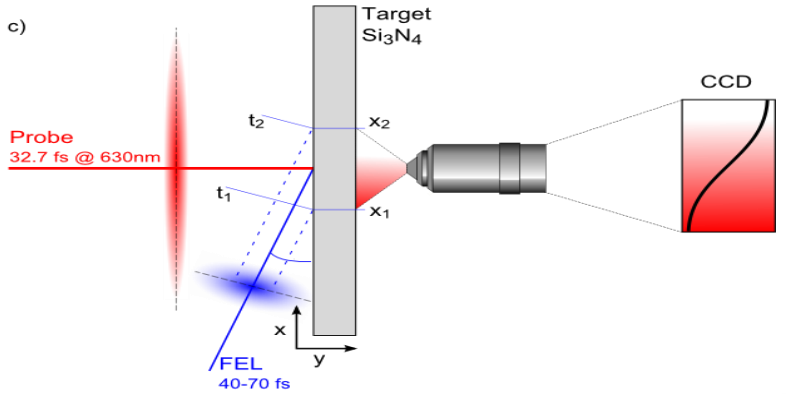




Cross correlation measurement **probing the intensity of the sidebands** in the photoelectron spectrum of He vs ΔT of **FEL(pump)-IR(probe)**

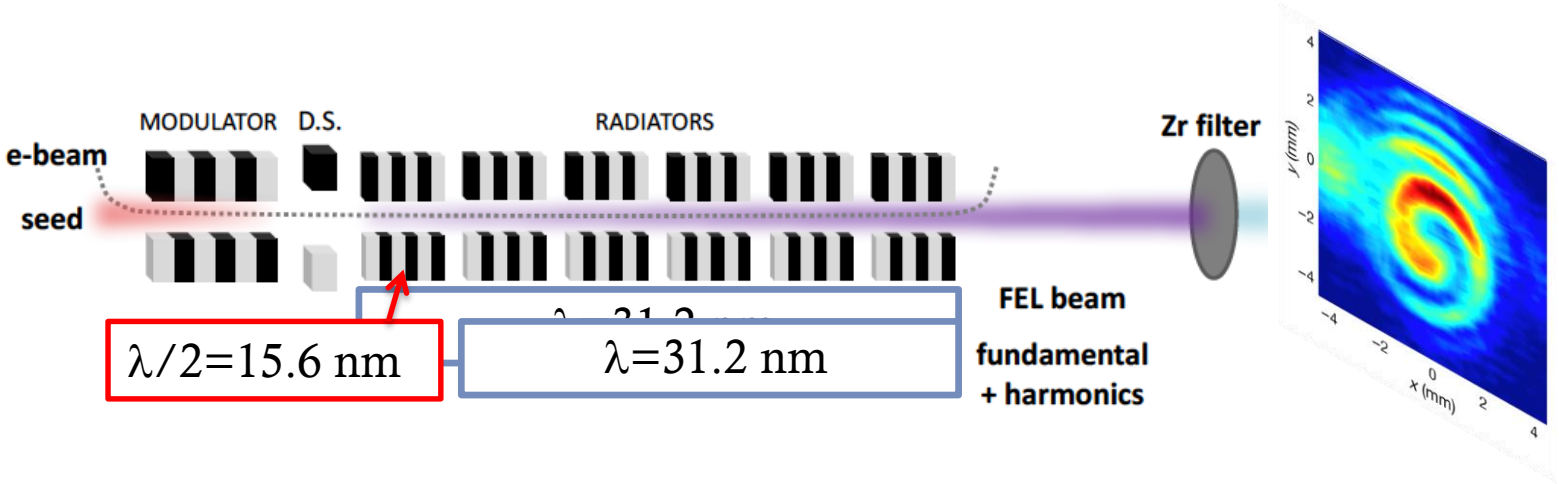
"Single-shot cross-correlation" @ DIPROI

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.

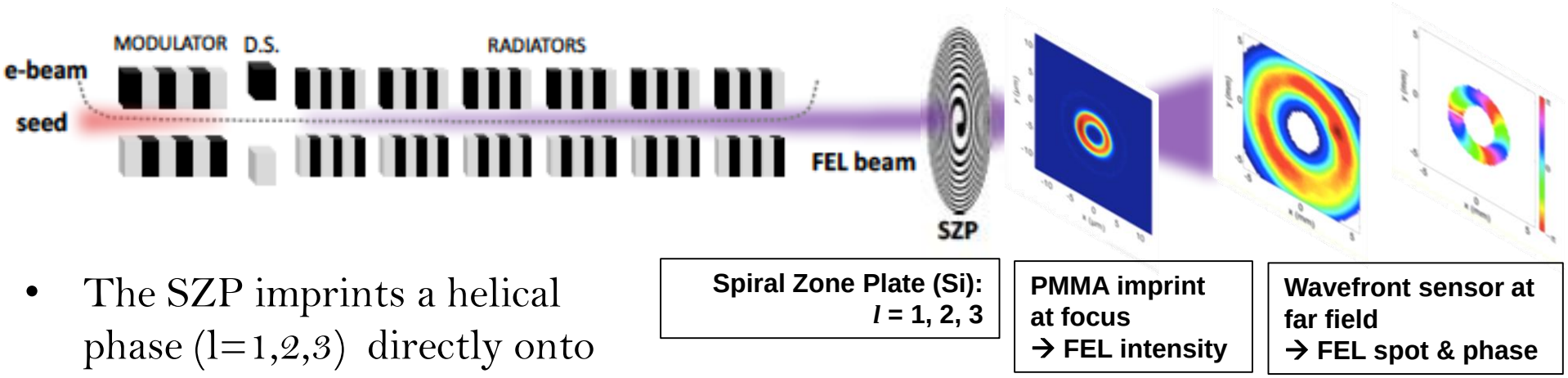


P. Finetti et al. Phys. Rev. X 7, 021043 (2017)

Orbital Angular Momentum



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



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 0th diffraction order.

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

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