



Seeding FELs for Coherent Light

Where We Started and Where We Are Now

Luca Giannessi
Elettra and INFN LNF

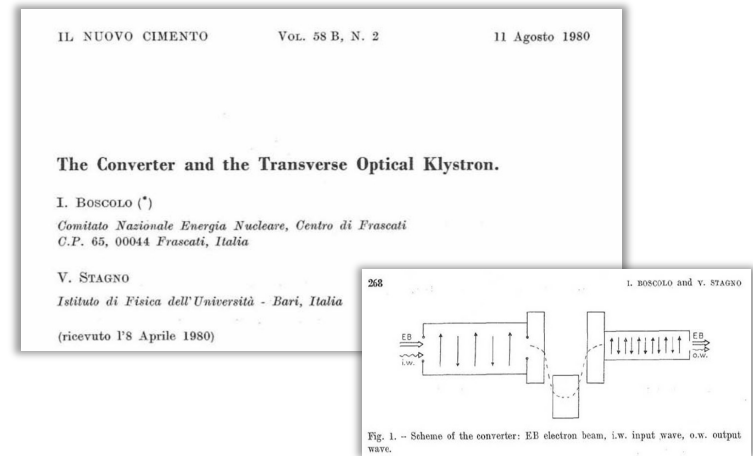
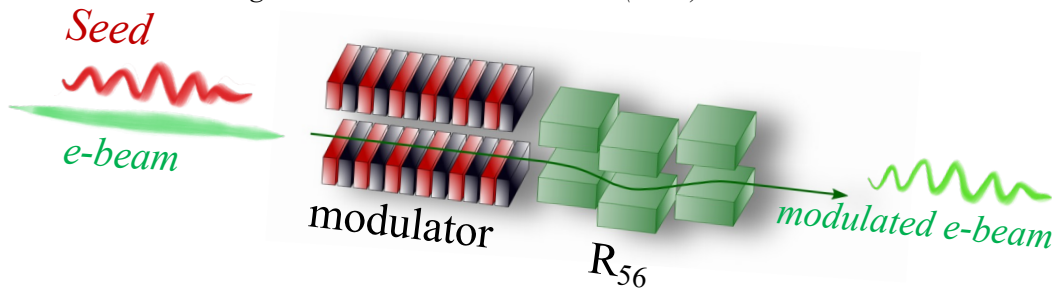


25th Anniversary of the First Lasing at TTF (now FLASH) – International Symposium
17-18 Nov. 2025, Hamburg - DESY Auditorium

Coherence: the «converter» concept

A FEL «modulator» encodes phase and amplitude of a laser field on the phase-space of an electron beam.

The concept of harmonic conversion traces back to the early days of the FEL history
I. Boscolo, V. Stagno, Il Nuovo Cimento 58, 271 (1980)



Seed amplitude and phase

Bunching factor = Fourier transform of the electron density at n-th harmonic.

In HGHG after modulator and dispersive section:

$$b_n(\zeta) = \frac{1}{\lambda_0} \int_{\zeta}^{\zeta + \lambda_0} \rho_e(\zeta') e^{-ink_0 \zeta'} d\zeta' = \exp \left[-\frac{1}{2} \left(nk_0 R_{56} \frac{\sigma_\gamma}{\gamma} \right)^2 \right] J_n \left(nk_0 R_{56} \frac{|a(\zeta)|}{4\pi N} \right) e^{in\Phi(\zeta)}$$

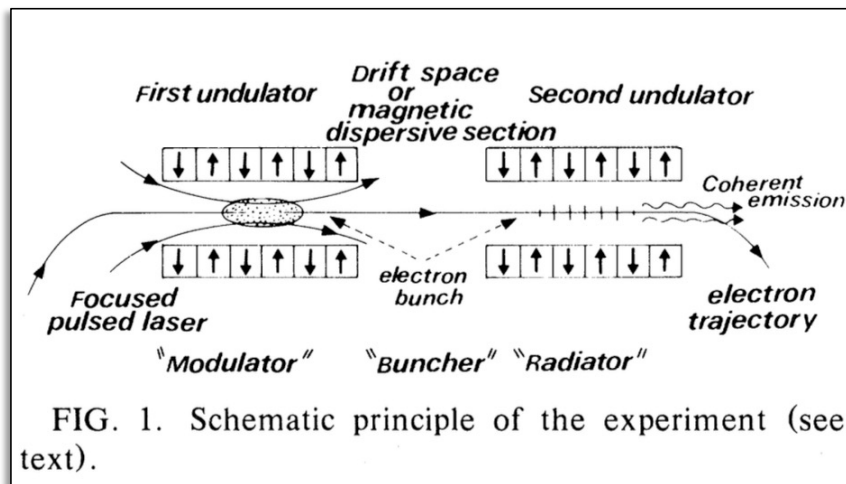
While retaining of the coherence of the original laser, the encoded phase-space can be manipulated in different ways to induce emission of light with different properties, in terms of **wavelength, field amplitude & phase, and polarization**

Selected milestones in the development of externally seeded FELs (not exhaustive)

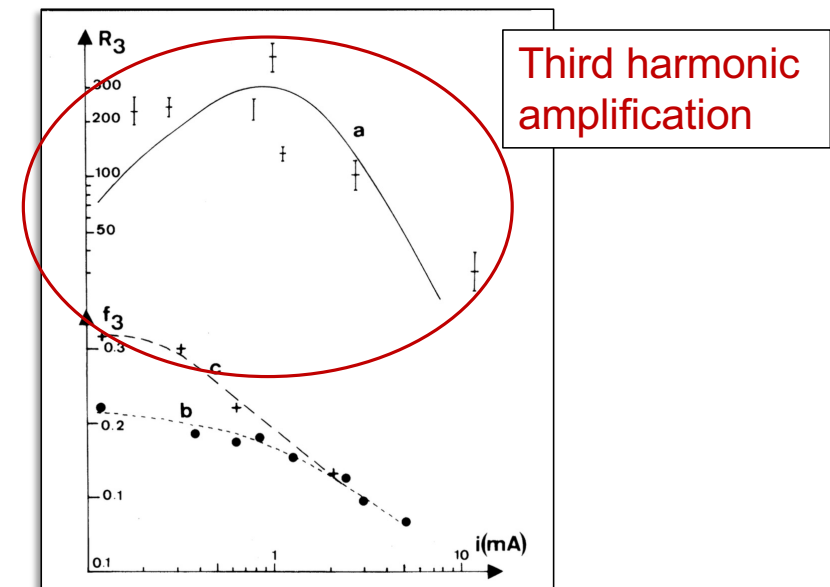
(1980) *The converter concept*: I. Boscolo, V. Stagno, *Il Nuovo Cimento B* 58, 267 (1980)

(1984) *Coherent harmonic generation in Optical Klystron: Proof of the converter concept*. B. Girard, Y. Lapierre, J.M. Ortega, C. Bazin, M. Billardon, P. Elleaume, M. Bergher, M. Velghe, Y. Petroff, *Phys. Rev. Lett.* 53, 2405 (1984).

✓ R. Prazeres, et al., *Nucl. Inst. Meth. Phys. Res. Sect. A: Accelerators. Spectrometers, Detectors and Associated Equip.* 272(1–2), 68 (1988). R. Prazeres, et al. *Europhys. Lett. (EPL)* 4(7), 817 (1987) R. Prazeres et al. *Nucl. Inst. Meth. Phys. Res. Sect. A: Accelerators. Spectrometers, Detectors and Associated Equip.* 304(1–3), 72 (1991).



Hamburg, Germany



Luca Giannessi, 18 November, 2025

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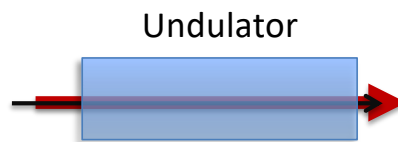
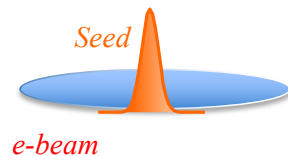
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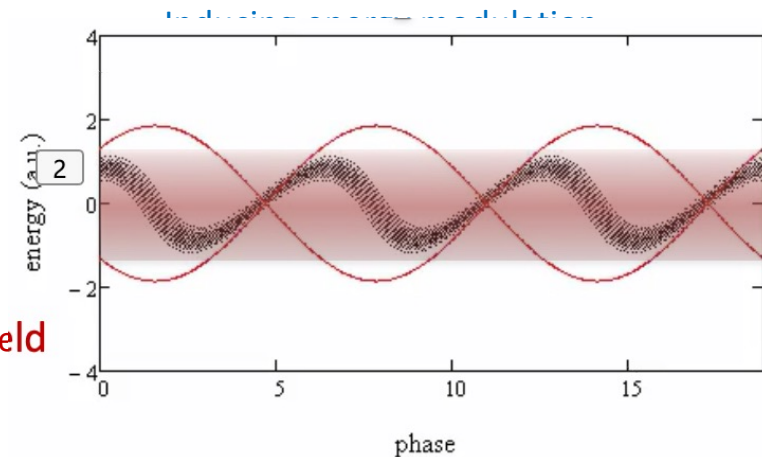
(1991) *High-Gain Harmonic Generation (HGHH) concept* L. H. Yu, *Phys. Rev. A* 44, 5178 (1991).

modulator dispersion

High gain radiator tuned at n^{th} harmonic



Increasing the laser field



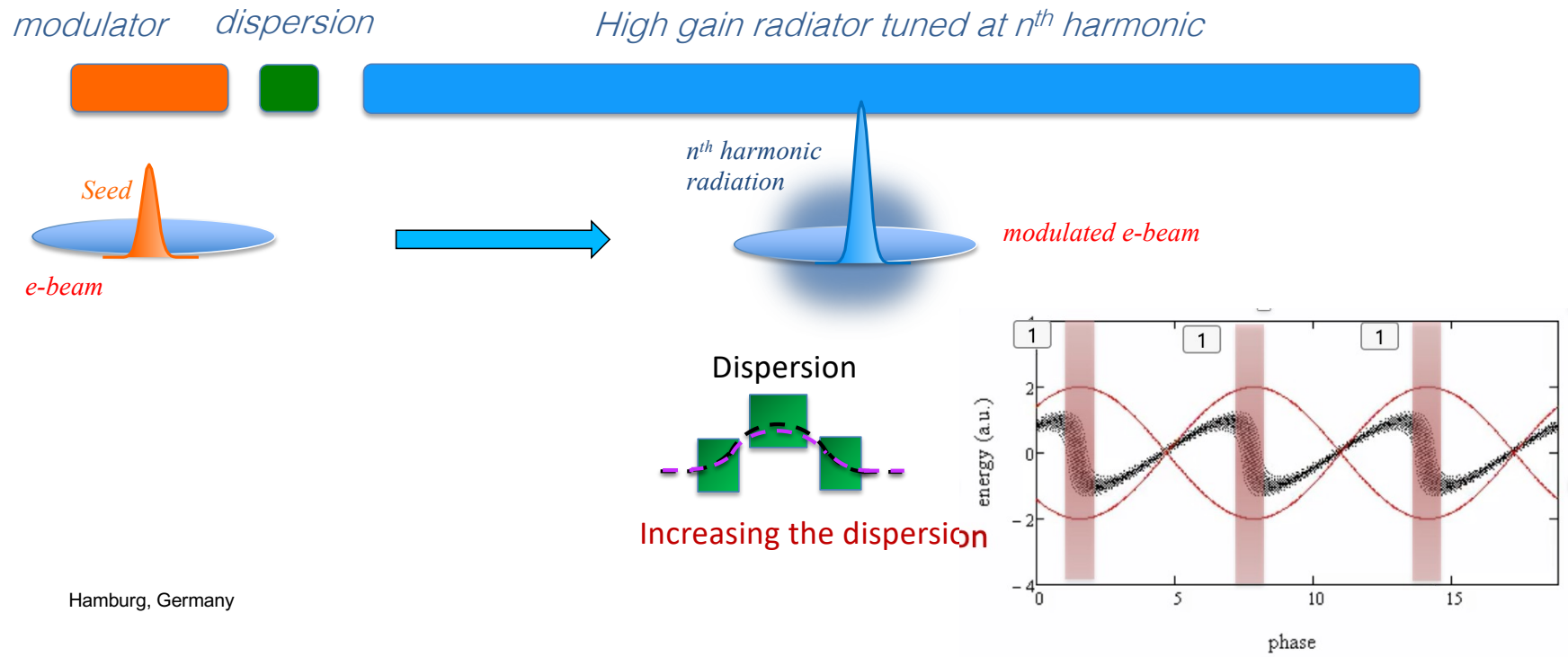
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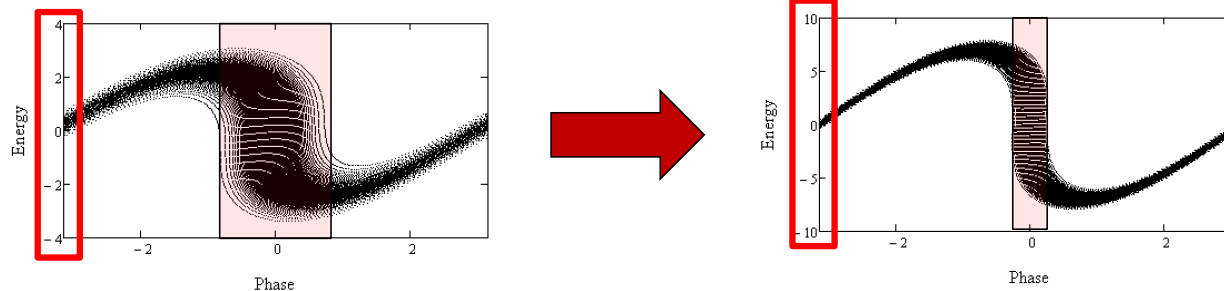
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(1992) **Fresh-Bunch Injection technique concept** I. Ben-Zvi, K.M. Yang, L.H. Yu, Nucl. Inst. Meth. Phys. Res. A 318, 726 (1992)

Virtually any harmonic order can be obtained by increasing the seed power

... at the cost of an increased energy spread



Required energy spread in order to bunch at the n^{th} harmonic (Liouville's theorem) $\left(\frac{\sigma_\gamma}{\gamma}\right)_{\text{induced}} \sim n \left(\frac{\sigma_\gamma}{\gamma}\right)_{\text{initial}}$

Condition to ensure high gain growth in final radiator $n < \frac{\rho_{FEL}}{\left(\frac{\sigma_\gamma}{\gamma}\right)_{\text{initial}}}$

Selected milestones in the development of externally seeded FELs (not exhaustive)

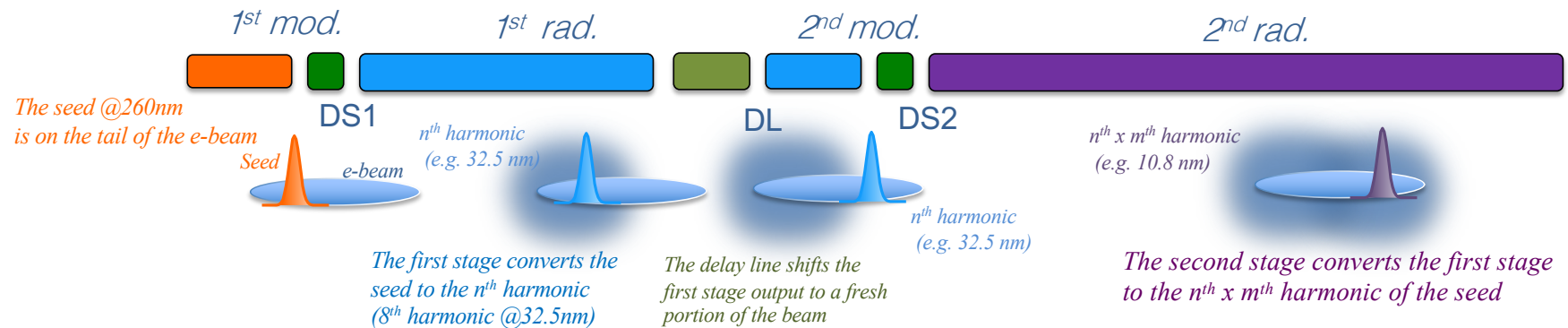
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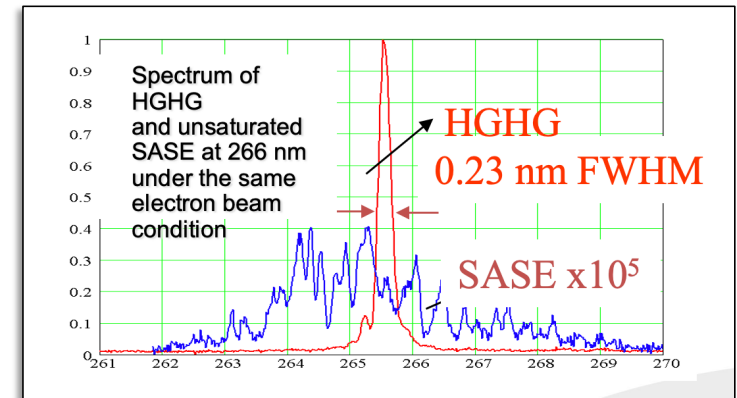
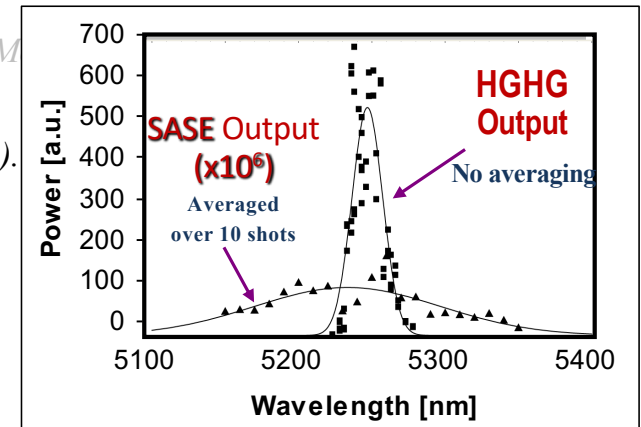
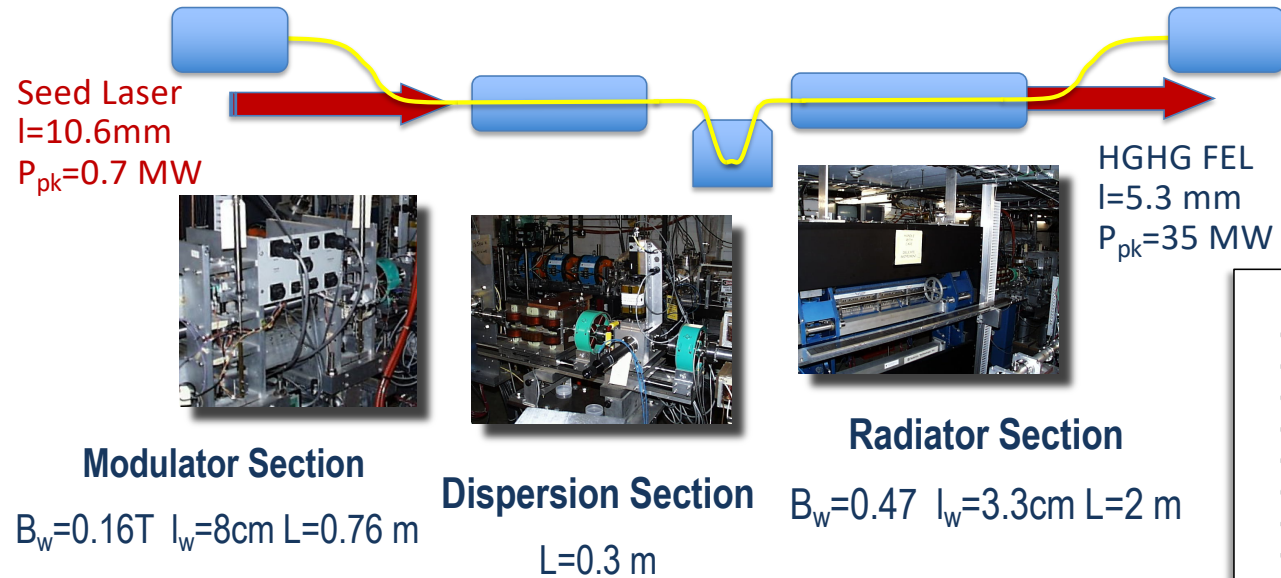


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(1992) *Fresh-Bunch Injection technique concept* I. Ben-Zvi, K.M. Yang, L.H. Yu, Nucl. Inst. M.

(2000) *HGFG demonstration in the IR* L.H. Yu, et al. Science 289(5481), 932 (2000).

(2003) *HGFG demonstration in the UV* L.H. Yu, et al., Phys. Rev. Lett. 91(7), 074801 (2003).



Courtesy of I. Ben Zvi

Selected milestones in the development of externally seeded FELs (not exhaustive)

(1991) High-Gain Harmonic Generation (HG) concept L. H. Yu, Phys. Rev. A 44, 5178 (1991).

(1992) Fresh-Bunch Injection technique concept I. Ben-Zvi, K.M. Yang, L.H. Yu, Nucl. Inst. Meth. Phys. Res. A 318, 726 (1992)

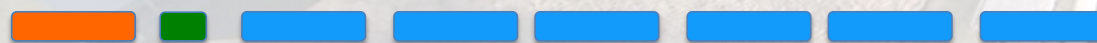
(2012) *HG in the VUV – up to h13 in an operating facility* E. Allaria et al., Nat. Photonics 6, 699 (2012)

(2013) *Demonstration of HG + Fresh-Bunch Injection technique in the soft X-ray – up to h65 in operating facility* E. Allaria et al., Nat. Photonics 7, 913 (2013)

FERMI FEL-1

modulator

High gain radiator tuned at n^{th} harmonic



dispersion

Both seeded by OPA (after frequency up-conversion):

230–260 nm or 296–360 nm



Nominal tuning range 20-100 nm

λ (nm)

FERMI FEL-2

1st mod.

1st rad.

2nd mod.

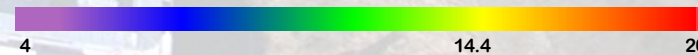
2nd rad.



DS1

DL

DS2



Nominal tuning range 4-20 nm

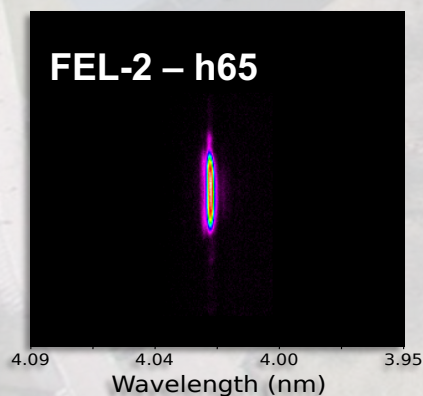
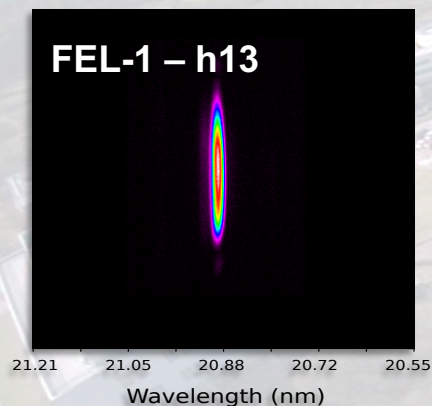
λ (nm)

Hamburg, Germany

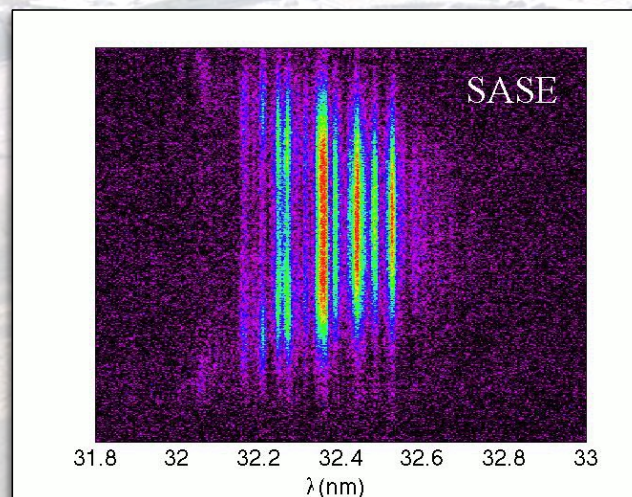
Luca Giannessi, 18 November, 2025

FERMI spectral properties

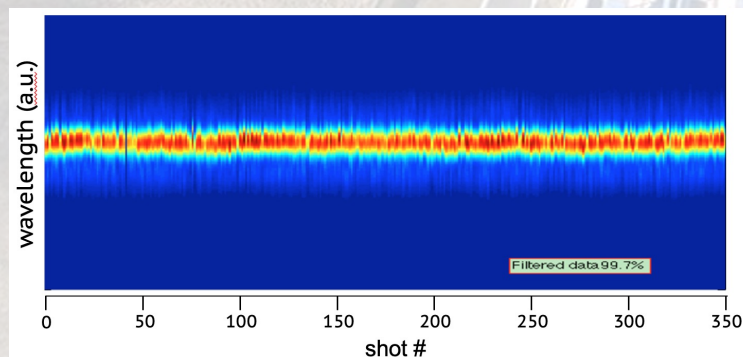
SASE vs. seeded



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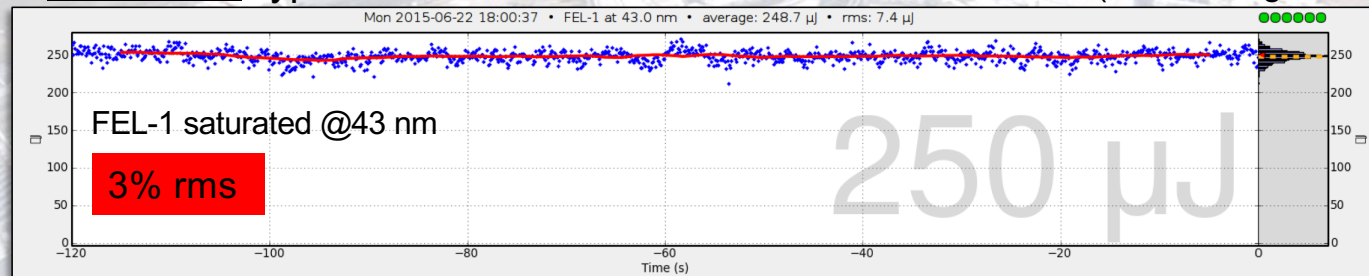
FEL spectrum



- The spectral properties can be preserved up to **h13-h15 on FEL-1** and **h65 on FEL-2** (*linewidth down to $2 \cdot 10^{-4}$ rms*, depending on wavelength & seed setting/duration).
- **laser like photon statistics**
- **High stability of central wavelength** set by the seed (10^{-5} rms)
- **FEL2** with the double stage **similar spectral performances** to the ones of **FEL-1** are possible, even at **h65 = 4 nm**.

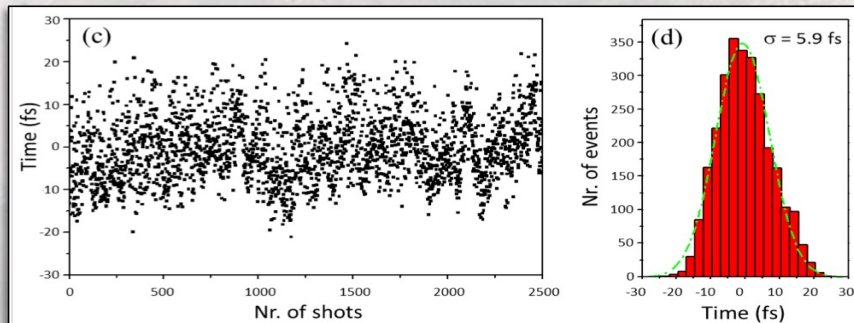
Energy stability and temporal jitter: a deterministic system

Not standard, typical 8-10% RMS on FEL-1 $\sim 1.3 - 1.5 \times$ on FEL-2 (double stage cascade)

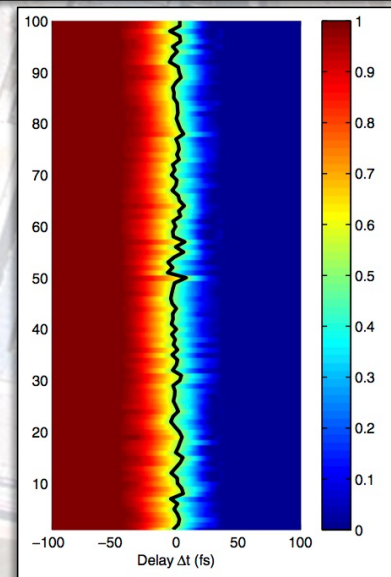


Temporal jitter < 6 fs

M. Danailov et al. Optics Express, Vol. 22, Issue 11, 12869 (2014)



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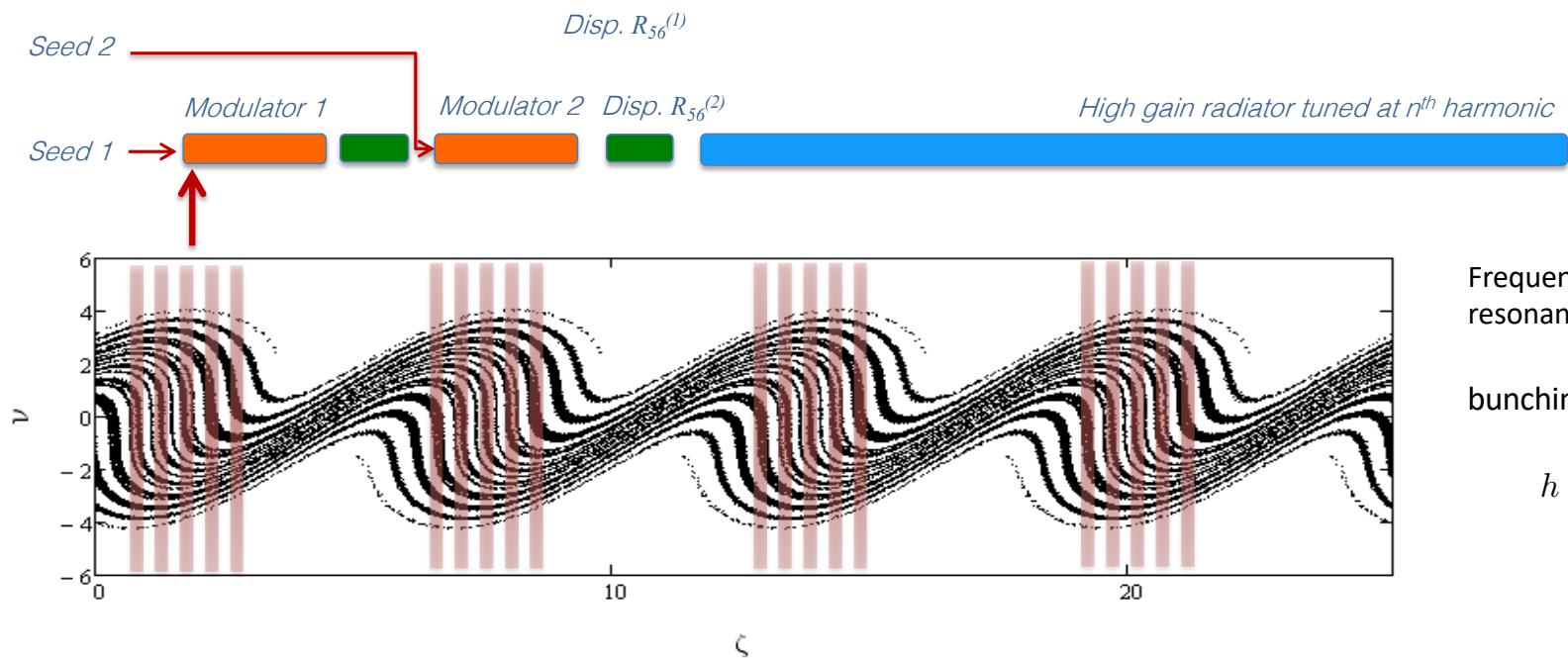
**Temporal jitter
2.2 fs**

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

annessi, 18 November, 2025

Back to ... the selected milestones in the development of externally seeded FELs (not exhaustive)

(2009) *Echo-Enabled Harmonic Generation (EEHG) concept* G. Stupakov, Phys. Rev. Lett. 102, 074801 (2009)



Frequency mixing,
resonance at $k_r = nk_1 + mk_2$

bunching maximized at harmonic

$$h \simeq \frac{\lambda_2}{\lambda_1} \frac{nR_{56}^{(1)}}{R_{56}^{(2)}}$$

Selected milestones in the development of externally seeded FELs (not exhaustive)

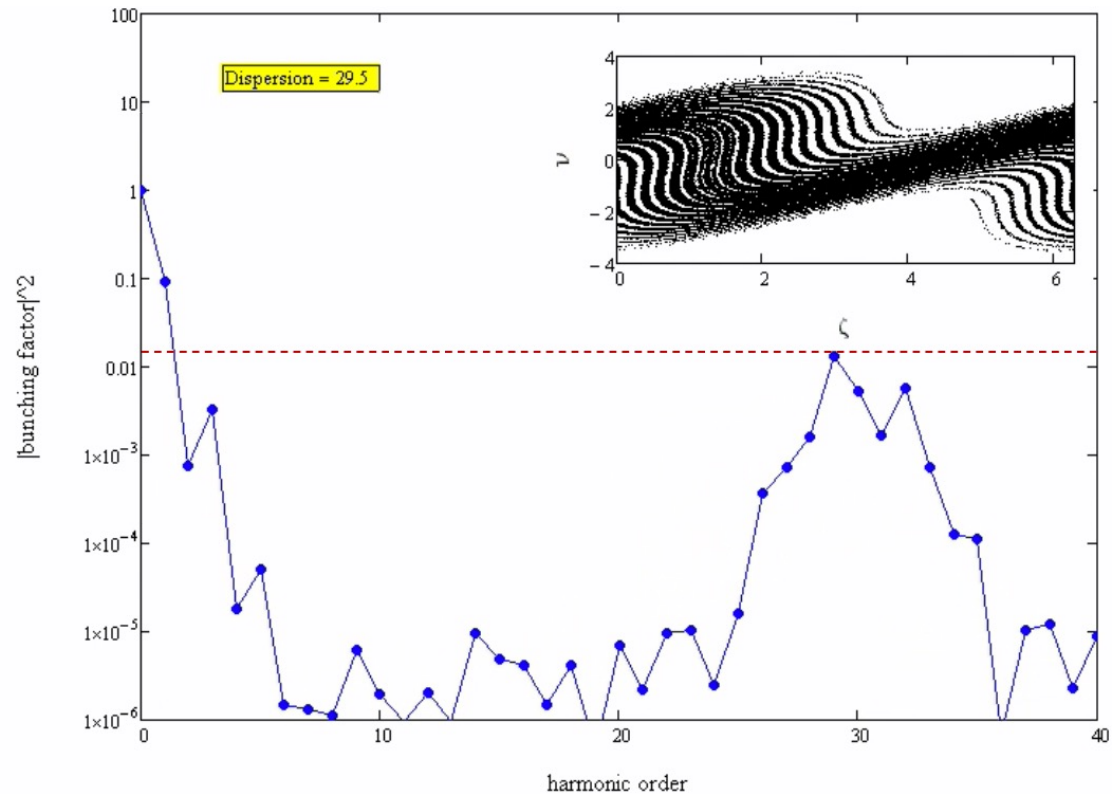
(2009) *Echo-Enabled Harmonic Generation (EEHG) concept* G. Stupakov, *Phys. Rev. Lett.* 102, 074801 (2009)

In EEHG configuration we have **4 parameters to tune the bunching**:

- **seed 1** and **seed 2** intensities and
- **dispersion 1** and **dispersion 2** strengths.

In first approximation **only the seed induces an energy spread growth**

The movie shows the bunching factor vs. harmonic order while increasing **dispersion 1**: i.e. at **constant induced energy spread**

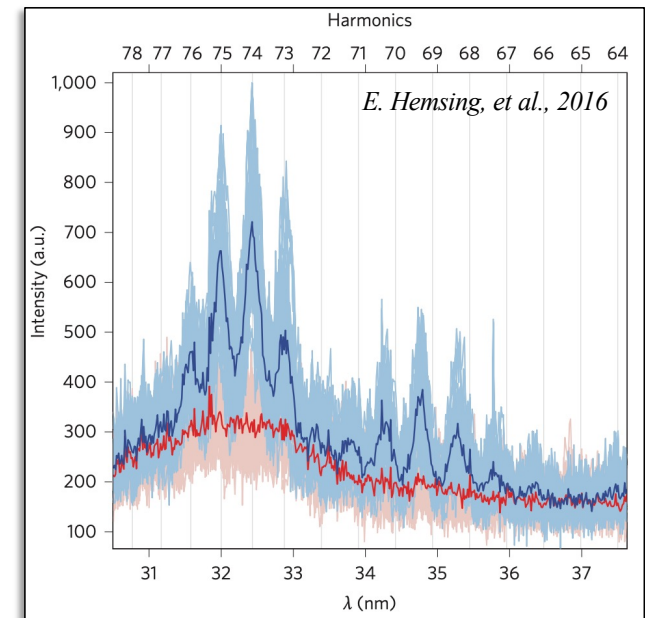
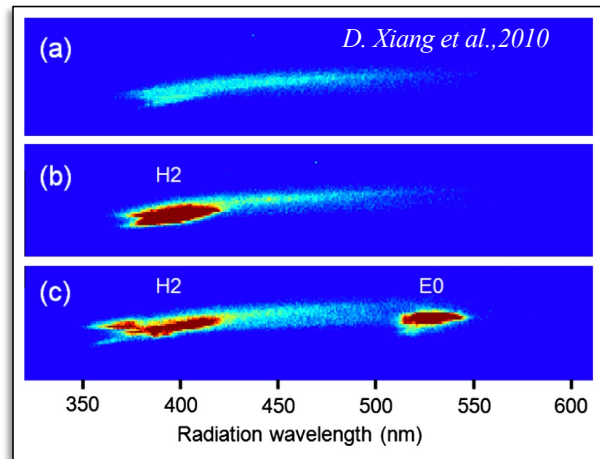
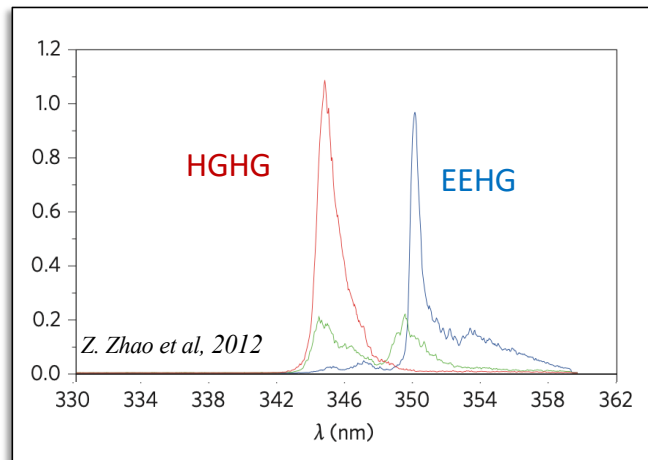


Selected milestones in the development of externally seeded FELs (not exhaustive)

(2010) *EEHG demonstration (bunching @h3)* D. Xiang et al., PRL 105, 114801 (2010)

(2012) *Demonstration of EEHG gain at h3* - Z. Zhao et al., Nature Photonics 6, 360–363 (2012).

(2016) *Demonstration of EEHG (bunching at h75)* E. Hemsing, et al., Nature Photonics 10, 512–515 (2016)



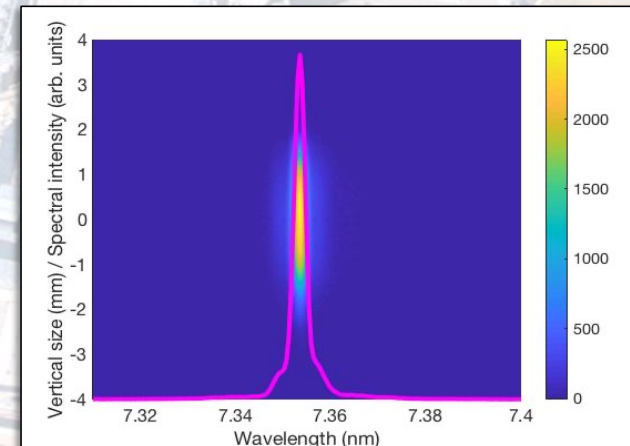
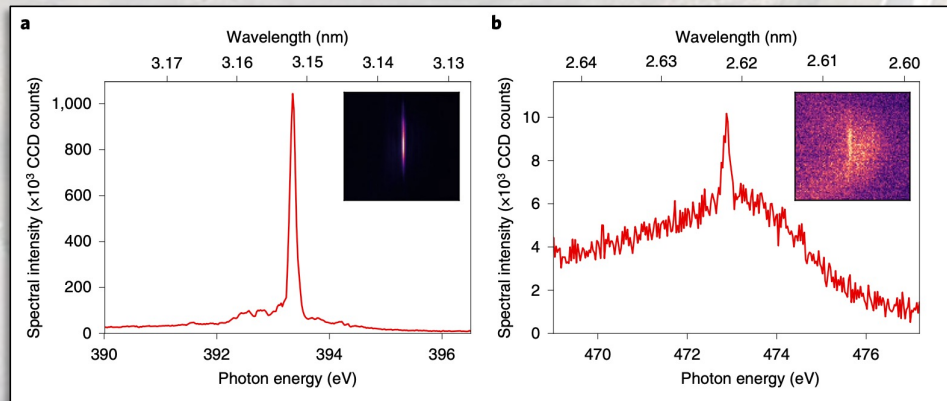
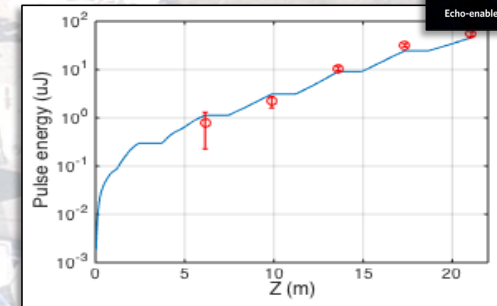
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(2016) *Demonstration of EEHG (bunching at h75)* E. Hemsing, et al., *Nature Photonics* 10, 512–515 (2016)

(2019) *Demonstration of EEHG gain @ h45 & bunching up to h101 at FERMI*, Rebernik Ribič, et al. *Nat. Photonics* 13, 555–561 (2019).

In 2018 we temporary modified FERMI FEL-2 layout to test EEHG & compare to HGHG

- ✓ FEL pulses were measured with $\sim 10 \mu\text{J}$ down to 5 nm with very narrow bandwidth spectra
- ✓ For the first time **amplification** of EEHG modulated beam has been measured and characterized down to $\sim 5\text{nm}$.
- ✓ **Low sensitivity to uBI** even at intermediate harmonic orders (H30-50)
- ✓ **Mild dependence of energy spread on harmonic order**
- ✓ CHG spectra measured up to **harmonic 101**



FERMI: EEHG vs. HGHG

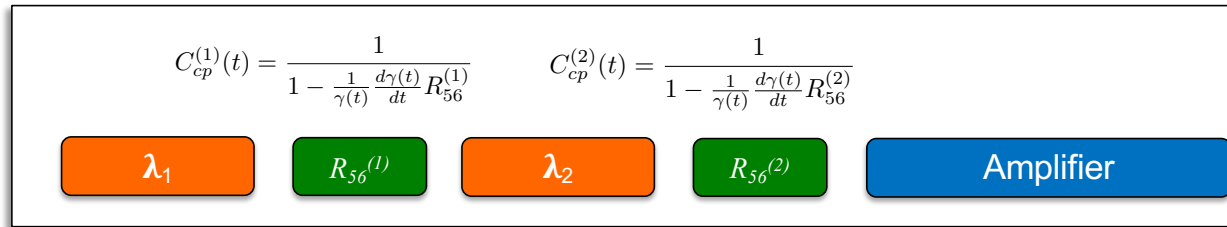
in presence of beam energy modulations

The EEHG scheme present two important advantages over HGHG:

- ✓ It allows reaching higher order harmonics in a single stage conversion
- ✓ **It has a low sensitivity to e-beam modulations:**

Frequency mixing, resonance at $k_{EEHG} = nk_1 + mk_2 = \frac{2\pi n}{\lambda_1} + \frac{2\pi m}{\lambda_2}$

In presence of a phase space distortion

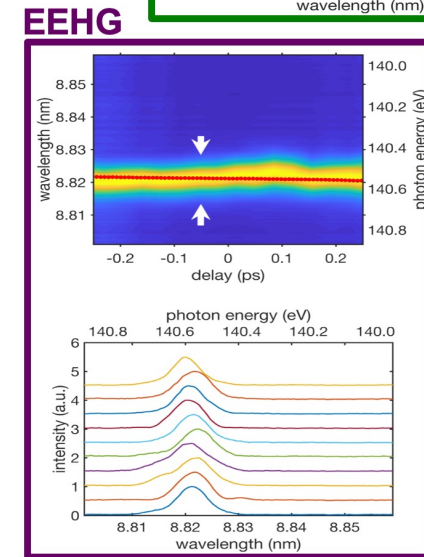
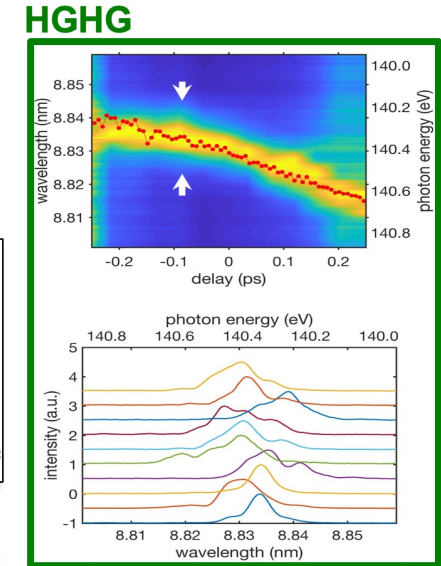
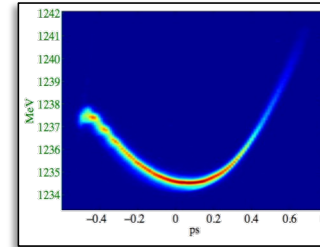


k_{EEHG} -vector detuning due to energy modulation $\delta k_{EEHG} = \frac{1}{\gamma(t)} \frac{d\gamma(t)}{dt} [nk_1 R_{56_1} + mk_2 R_{56_2}]$

bunching maximized at harmonic $h \simeq \frac{\lambda_2}{\lambda_1} \frac{n R_{56}^{(1)}}{R_{56}^{(2)}}$ **by choosing $n = -1$** $\delta k_{EEHG} \simeq 0$

For these reasons, schemes including an EEHG stage perform better than those based on HGHG only.

Hamburg, Germany

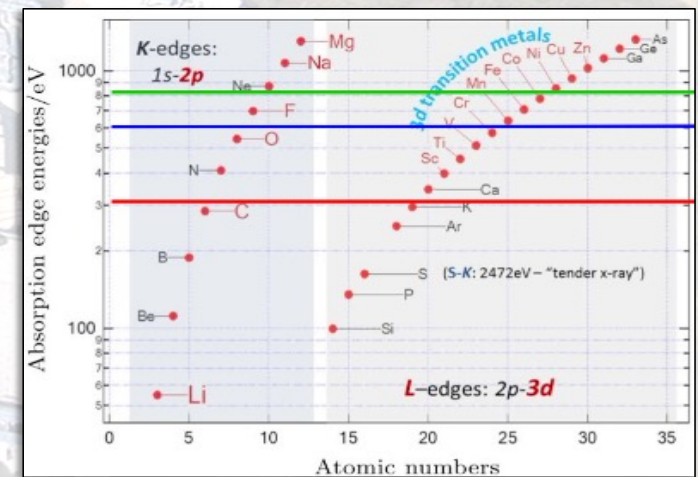


Rebernik et al. Nat.
Phot. 13, 555–561 (2019)

FERMI 2.0: *Where do we want to go...*

Workshops: **Future of FERMI (FoF)** (2016, Trieste) – **FLS** (2018, Shanghai) – **FUSEE** (2019, Trieste), **Advanced FEL techniques** (2020, Stockholm) – Feedback from **ELETTRA MAC SAC**, FERMI beamline scientists, FERMI users

- (1) Extend photon energy range to N (410 eV), O (543 eV) K-edges and possibly beyond (800 eV), while **preserving the features of a seeded FEL: coherence, fs-synchronization, control of the field properties.**
- (2) Reduce FERMI pulse duration below 10 fs (in selected spectral ranges)



Modifications to:

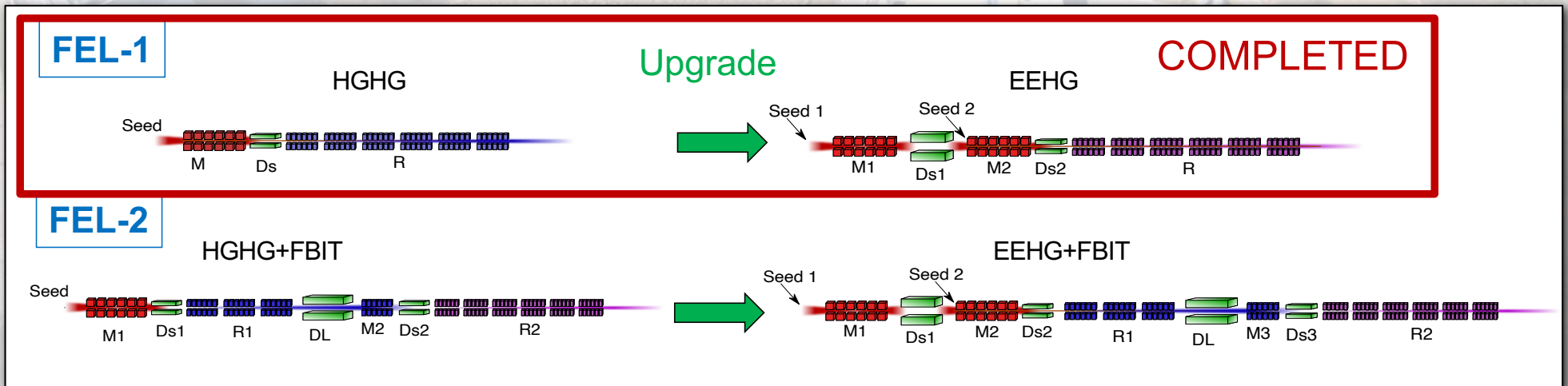
- ✓ **Linac:** increase the beam energy **up to 2 GeV**, reduce wakes improve beam quality
- ✓ **FELs:** FEL-1 & FEL-2 (first stage), to exploit the advantages of **Echo Enabled Harmonic Generation** vs. HGHG
- ✓ Several methods under study/implemented for the **reduction of the pulse duration**

Early/Long term phases separated in time to build experience with EEHG FEL with users & to minimize interferences with ELETTRA 2.0 upgrade

FERMI 2.0: FERMI Upgrade strategy

(see <https://www.elettra.eu/lightsources/fermi.html>)

1. FEL-1 in HGHG (as in the present configuration) **and EEHG with double-seed / double-modulator (100-10nm) (Completed in 2023, now in operation)**
2. **Beam energy increase** from 1.5 up to 2.0 GeV **(2028 – now 1.67 GeV)**
3. **FEL-2 first stage in EEHG second stage (fresh-bunch) in HGHG (10 - 2 nm) (2028)**

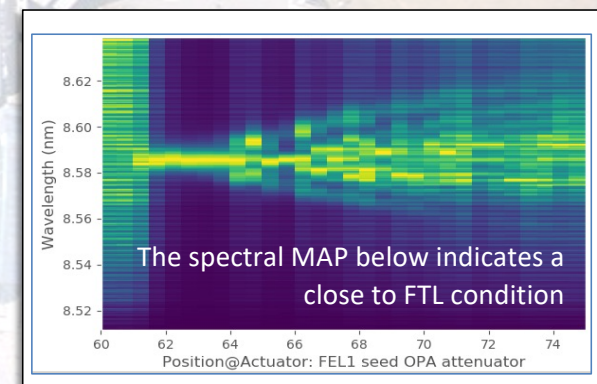
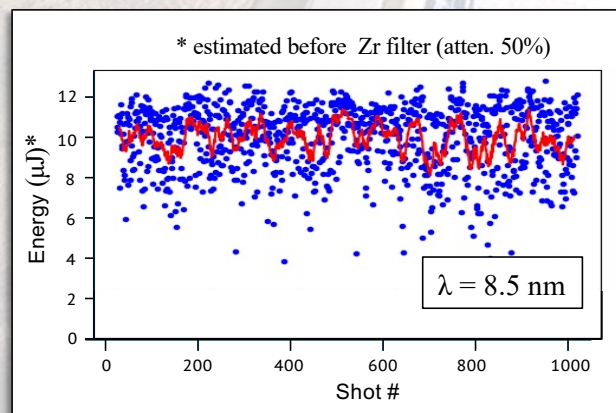
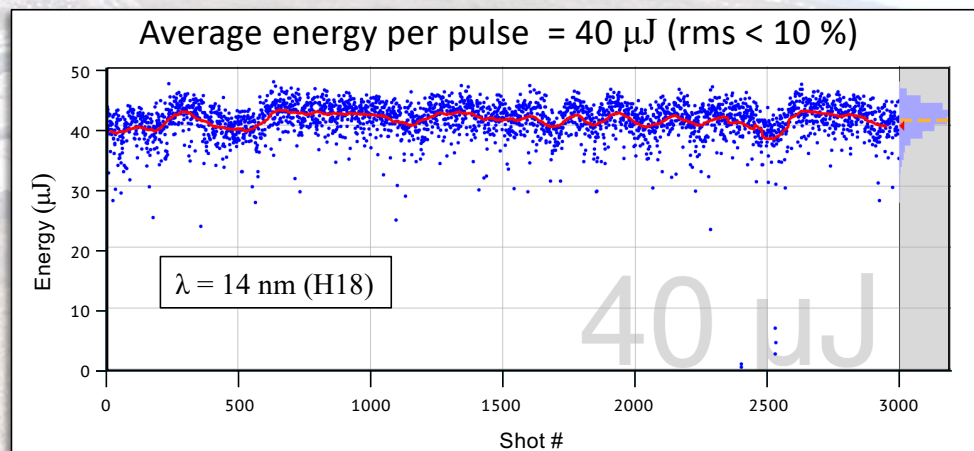
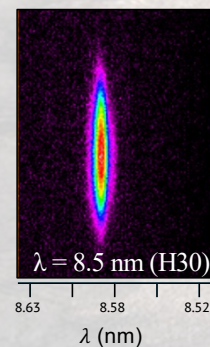
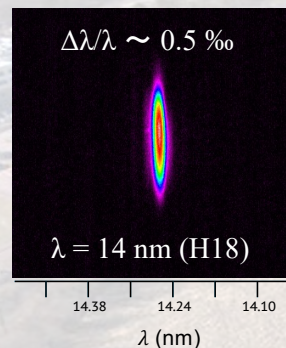


FERMI FEL-1 in Echo-Enabled Harm. Gen.

The FEL was optimised at different output wavelengths.

Moderate compression (500-600 A) and 1.37 GeV beam energy

shorter wavelength and larger $R_{56}^{(2)} = 4$ mm



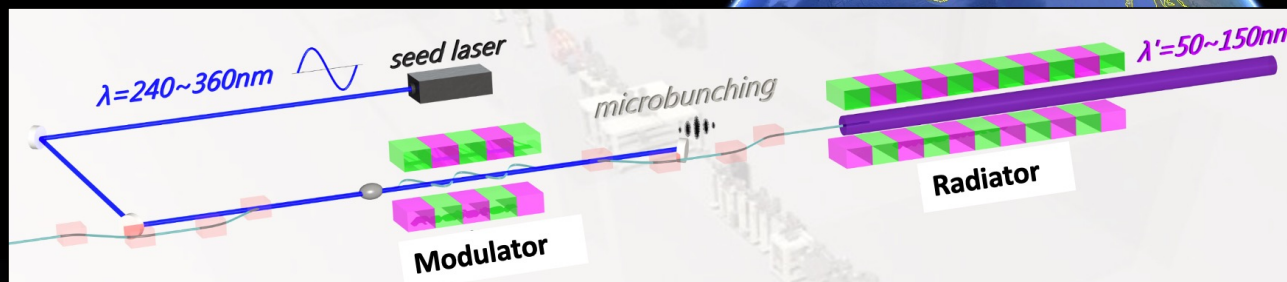
FEL User Facilities

Externally Seeded

In construction

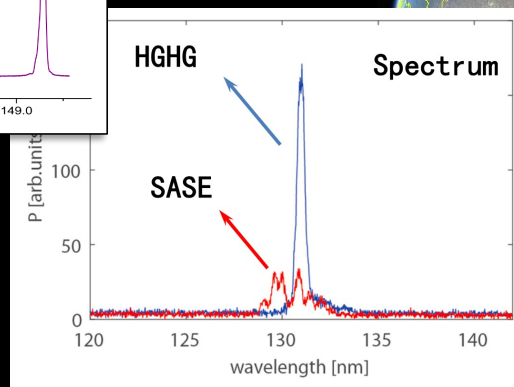
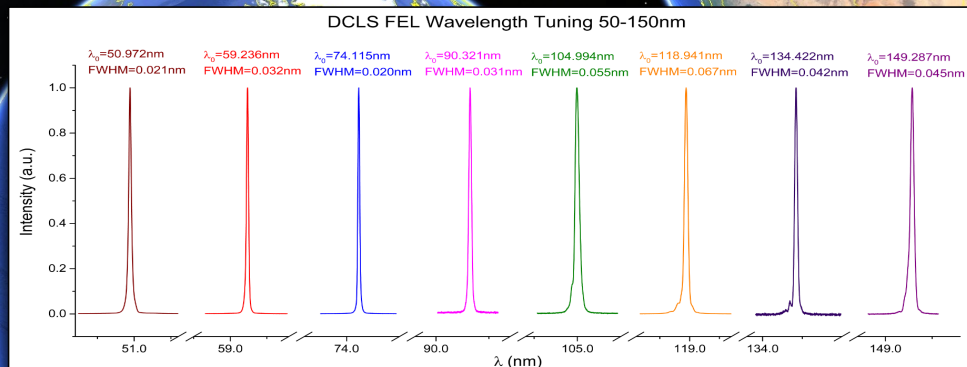


HGHG FEL



- Tunable Wavelength : 50 – 180 nm
- Pulse Energy : >100 uJ (1 mJ)
- Pulse length : 100 fs / 1 ps
- Bandwidth : Fourier transform limit
- Jitter : <30 fs
- Rep Rate : 50 Hz

2016/12 FEL HGHG lasing

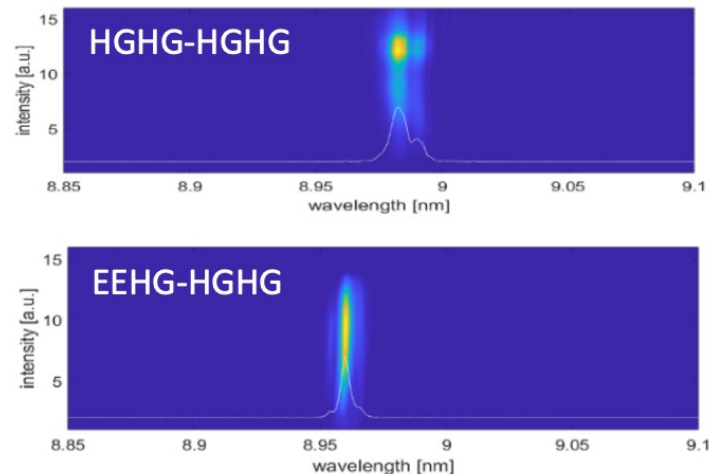
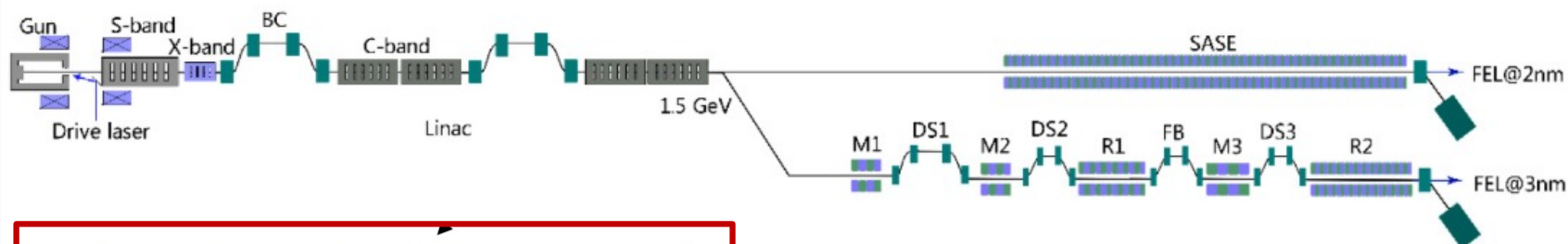


DCLS SACLA
PAL
SXFEL
SHINE

Courtesy of Dr. Weiying Zhang

Two stages with fresh bunch EEHG + HGHG FEL

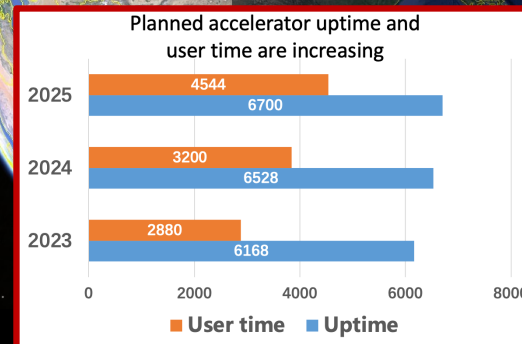
FEL User Facilities
Externally Seeded



C. Feng, Z. Zhao*, et al., *Optica* 9, 2022, 785

	Design	Realized
Wavelength (nm)	3.0	2.96
duration (fs)	~100	~100
Peak power (GW)	≥ 0.1	>0.2

SX FEL

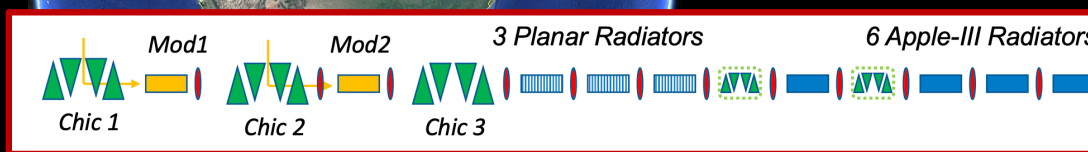
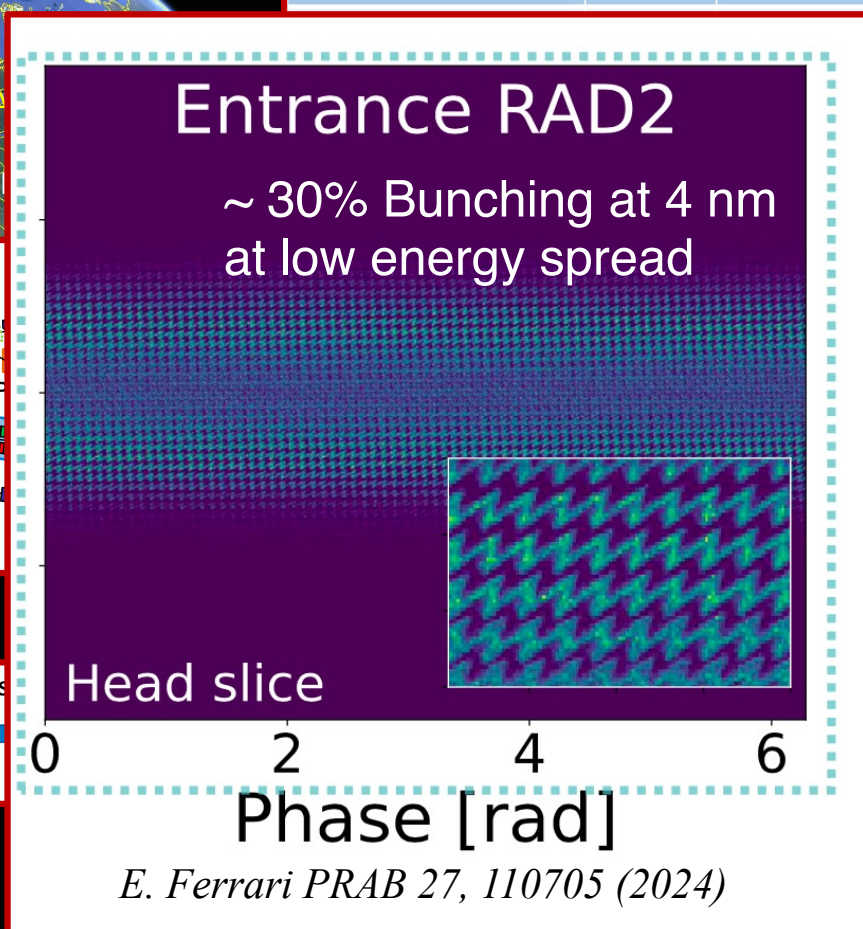
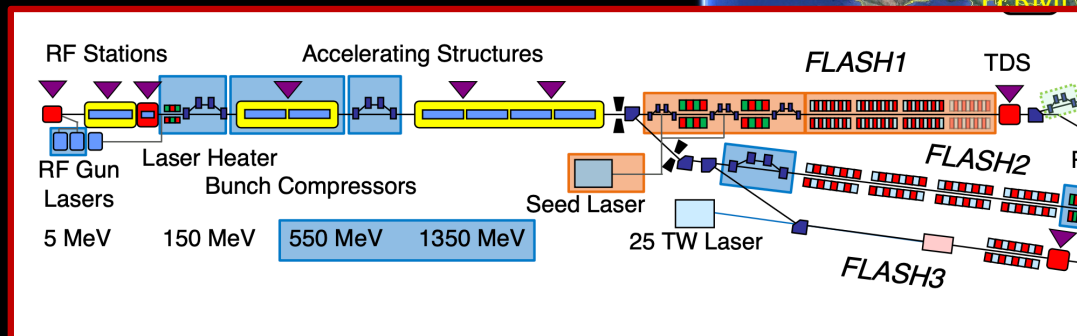


Courtesy of Dr. Chao Feng

FLASH

Two stages with fresh bunch
EEHG + EEHG/HGHG FEL

Photon parameters	FLASH1 seeded	FLASH2 SASE
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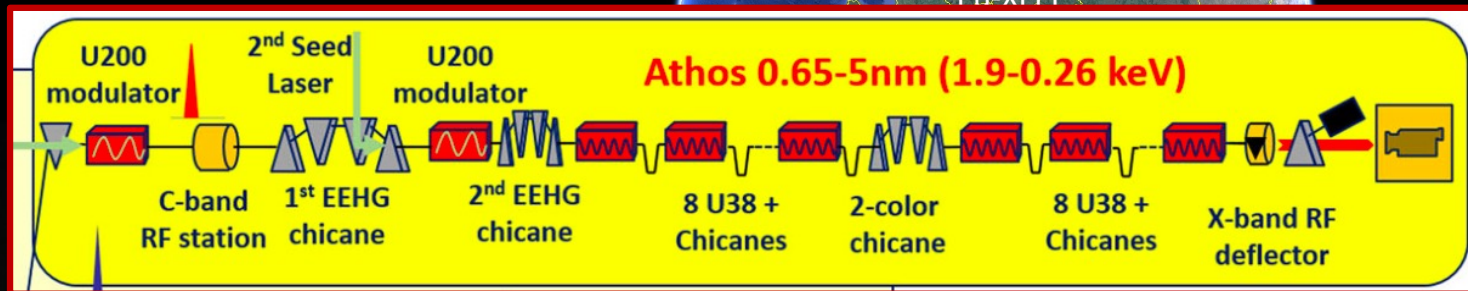
Courtesy of Dr. Lucas Schaper

Seeded Light Expected by the end of 2025

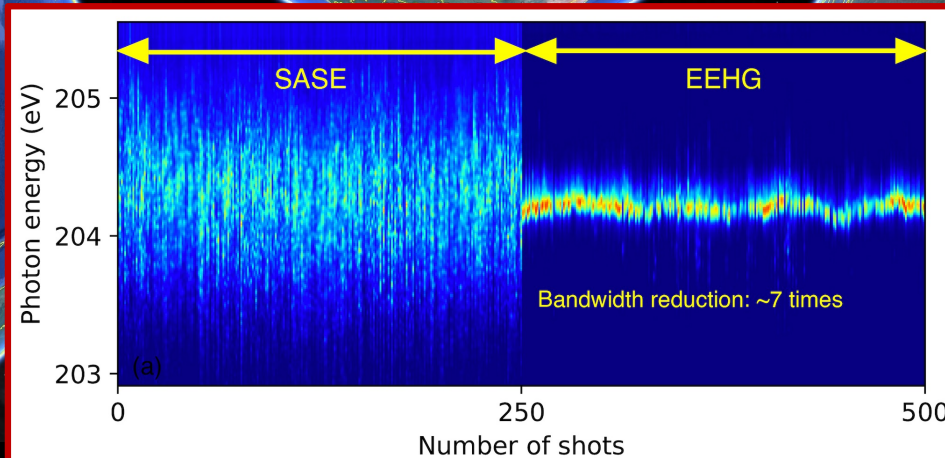
SwissFEL

May operate in SASE – OK SASE - HB SASE
and **EEHG seeded mode**

FEL User Facilities
Externally Seeded
In construction



In operation (SASE)
since 2023
APPLE-X (U38) -
0.65 and 5 nm (1.9
to 0.26 keV)
EEHG up to 1 keV



**Clear bandwidth
narrowing at 200 eV -
coherent signal up to
400 eV.**

US Dept of State Geographer
© 2015 Google
© 2009 GeoBasis-DE/BKG
Data SIO/NOAA, U.S. Navy, NOAA, GEBCO

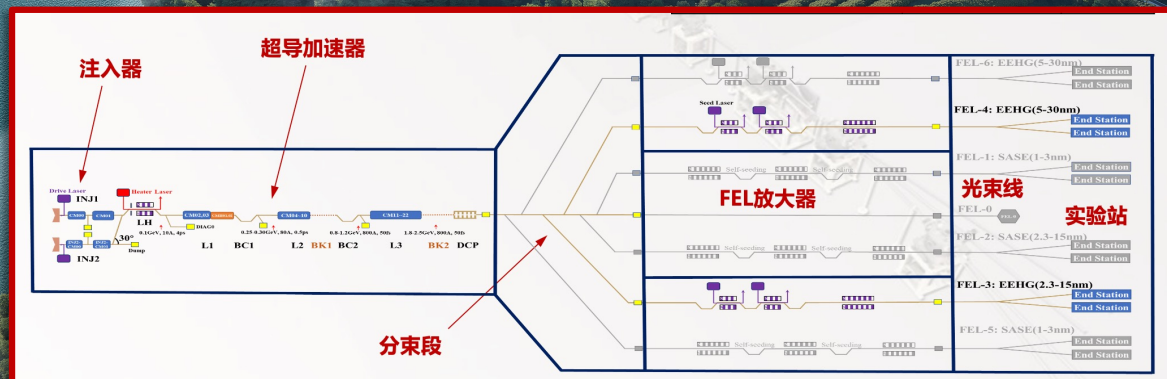
Go

Courtesy of Dr. Sven Reiche

Ariel view of architecture design(S³FEL in Shenzhen)

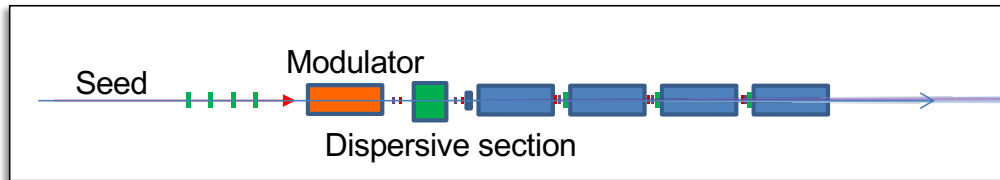
Generating 1MHz soft X-ray
free electron laser

Six FEL lines- 3 EEHG FELs
It has been approved and will
start construction this year.

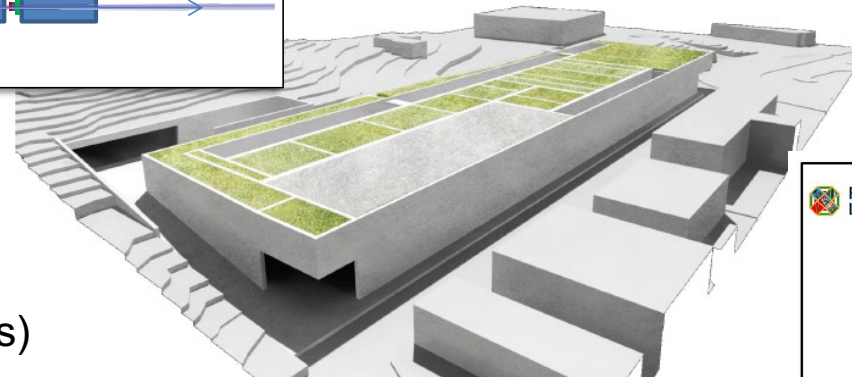


Courtesy of Dr. Weiqing Zhang

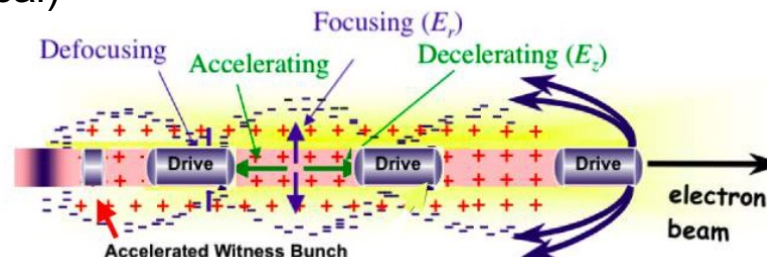
ARIA at EUPRAXIA facility in Frascati



- ✓ **FERMI - FEL-1 / DCLS like**
- ✓ **Wavelength range 50 – 180 nm – continuously tunable**
- ✓ **Long/short pulse mode (10-200 fs)**
- ✓ **Pulse energy: 10-100 μ J**
- ✓ **Variable polarization** (circular left/right, horizontal and vertical)
- ✓ **To be completed by 2029**



EUPRAXIA @ SPARC_lab



Hamburg, Germany

Agreement INFN -
Regione Lazio for the
realization of the
second beamline



a Giannessi, 18 November, 2025

More than just reducing the saturation length.

- ✓ **Stability** of the central wavelength (10^{-5} relative)
- ✓ Typical few- 10^{-4} **linewidth** (relative FWHM): no need for monochromatization
- ✓ fs **synchronization** with an external laser
- ✓ **Coherent** at first and higher orders (close to FTL)
- ✓ Extended spectral range by **coherent harmonic** generation

Light control and
COHERENCE

- ✓ **Superradiance**: FEL saturation to shape the pulse
- ✓ Generation of **multiple pulses** separated in time – photon energy (even with large energy separation with fresh-bunch inj.)
- ✓ **Control of the phase** of individual pulses/colors: **Coherent Control**
- ✓ **Attosecond pulse train generation**
- ✓ **Attosecond synchronization** with an external laser
- ✓ Circular **polarization** available even at higher harmonics
- ✓ **Intra-pulse polarization/color** switching

Light "by design"

Thank you!