Elettra
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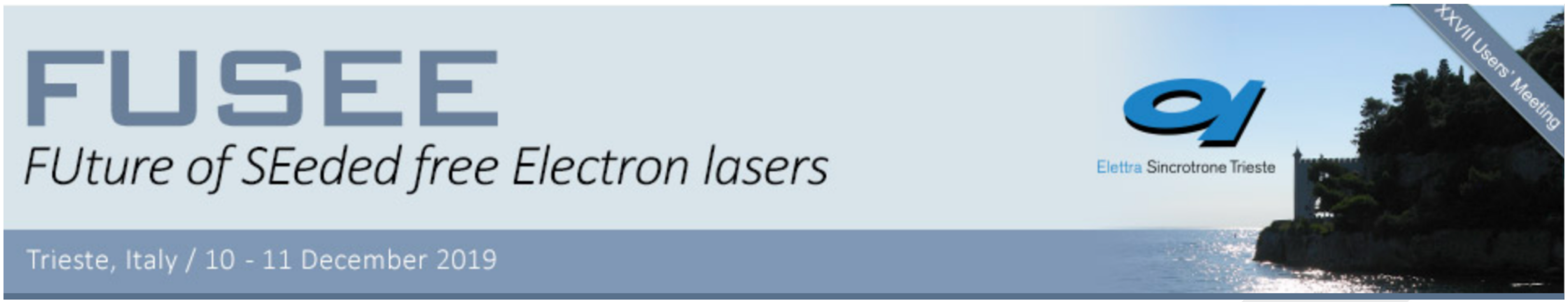
Trieste

# FERMI
# *FERMI Upgrade perspectives*

Luca Giannessi

**ELETTRA** Sincrotrone Trieste and ***INFN LNF***

*Presented on behalf of the FERMI team*



# Outline

Where we are

Where we want to go

Where we we are going

… from the FERMI perspective

# Where we are: **FERMI FEL-1 & FEL-2**

*modulator* *High gain radiator tuned at $n^{th}$ harmonic*

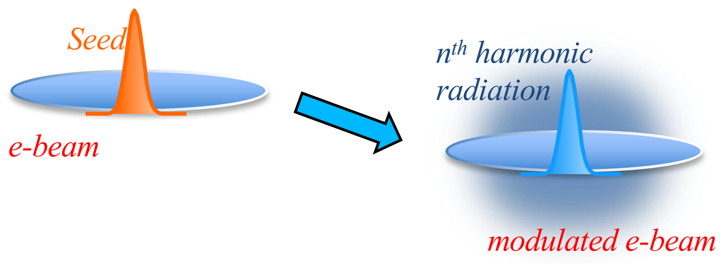
## FERMI FEL-1

*dispersion*

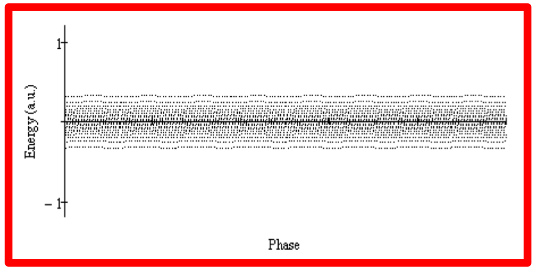
nature photonics | ARTICLES
PUBLISHED ONLINE: 23 SEPTEMBER 2012 | DOI: 10.1038/NPHOTON.2012.233

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

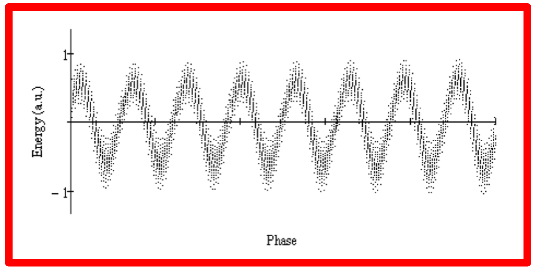
E. Allaria *et al.**



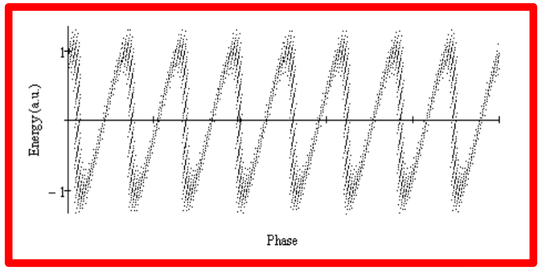

# High Gain Harmonic Generation




Fresh beam



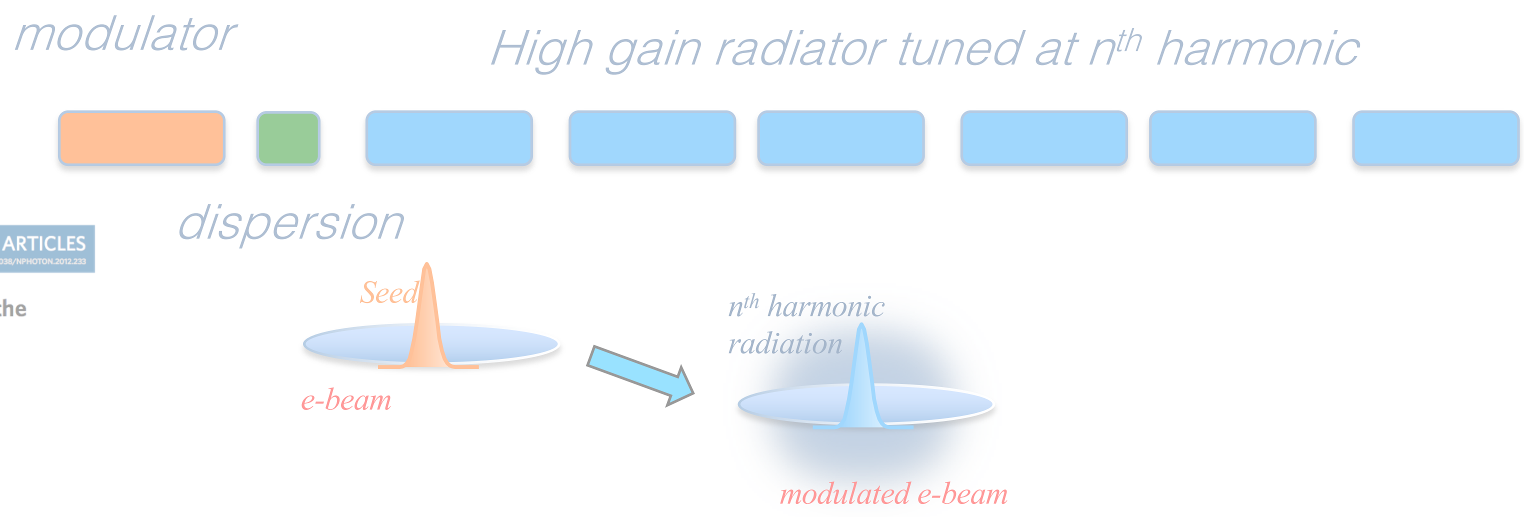

Modulated beam




Bunched beam

# Where we are: **FERMI FEL-1 & FEL-2**

## FERMI FEL-1





nature photonics | ARTICLES
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**Highly coherent and stable pulses from the FERMI seeded free-electron laser in the extreme ultraviolet**


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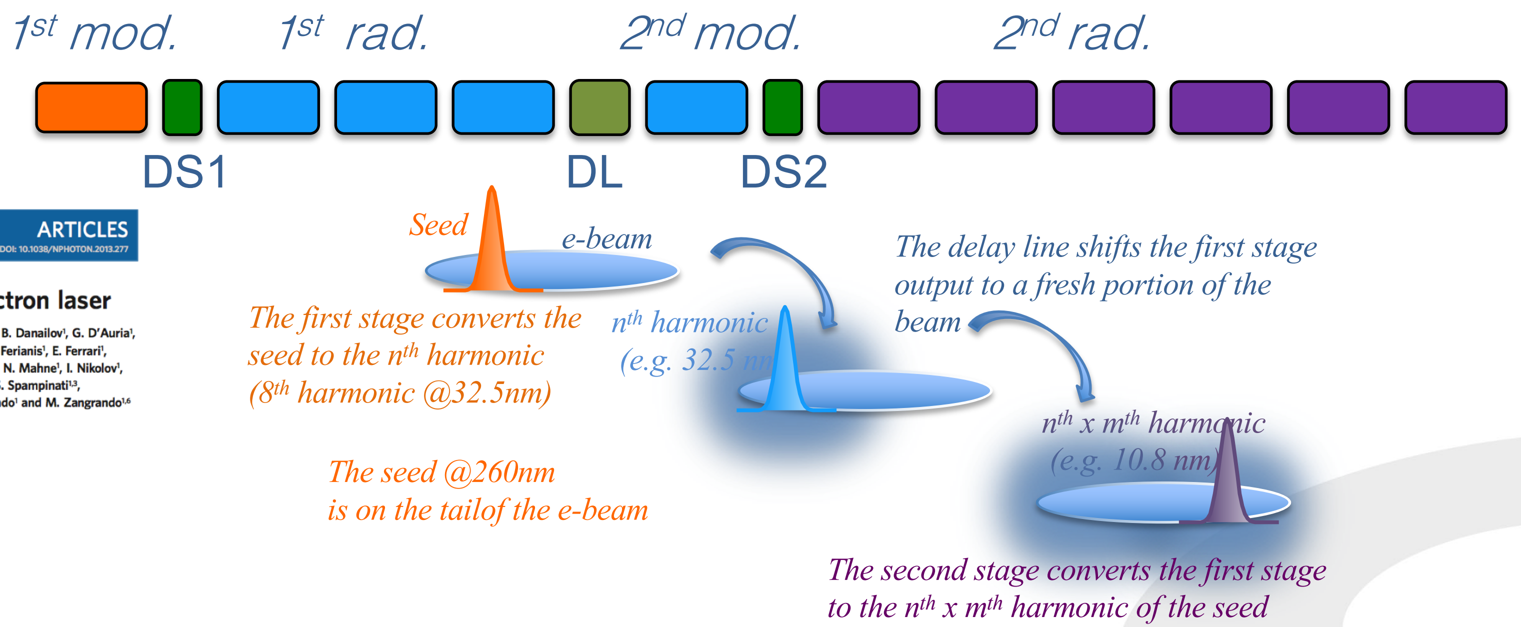
## FERMI FEL-2



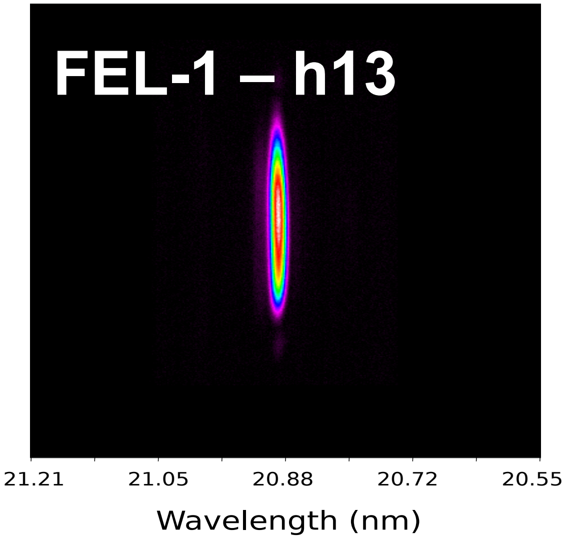


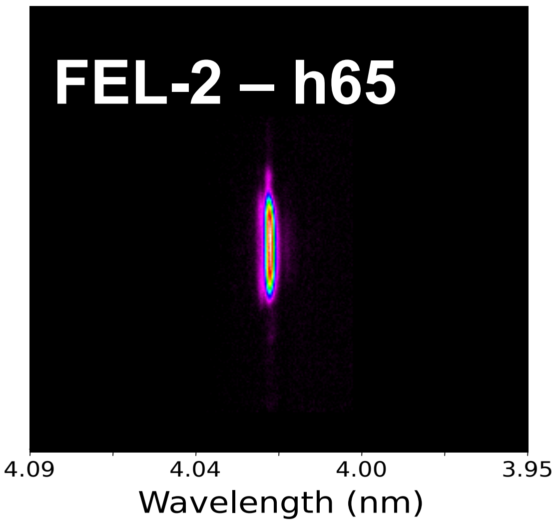
nature photonics | ARTICLES
PUBLISHED ONLINE: 20 OCTOBER 2013 | DOI: 10.1038/NPHOTON.2013.277


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

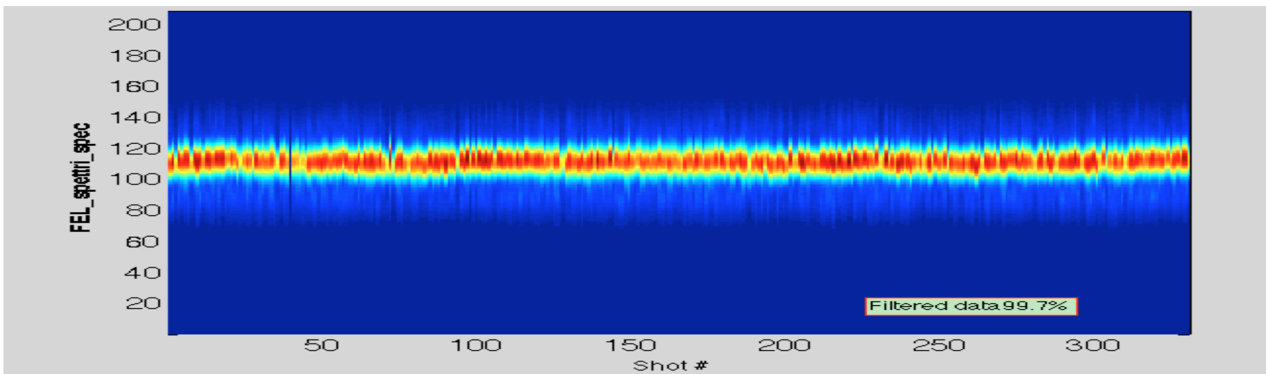

E. Allaria[1], D. Castronovo[1], P. Cinquegrana[1], P. Craievich[1†], M. Dal Forno[1,2], M. B. Danailov[1], G. D'Auria[1], A. Demidovich[1], G. De Ninno[1,3], S. Di Mitri[1], B. Diviacco[1], W. M. Fawley[1*], M. Ferianis[1], E. Ferrari[1], L. Froehlich[1], G. Gaio[1], D. Gauthier[1,3], L. Giannessi[1,4*], 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]

# FERMI FEL-1 & FEL-2

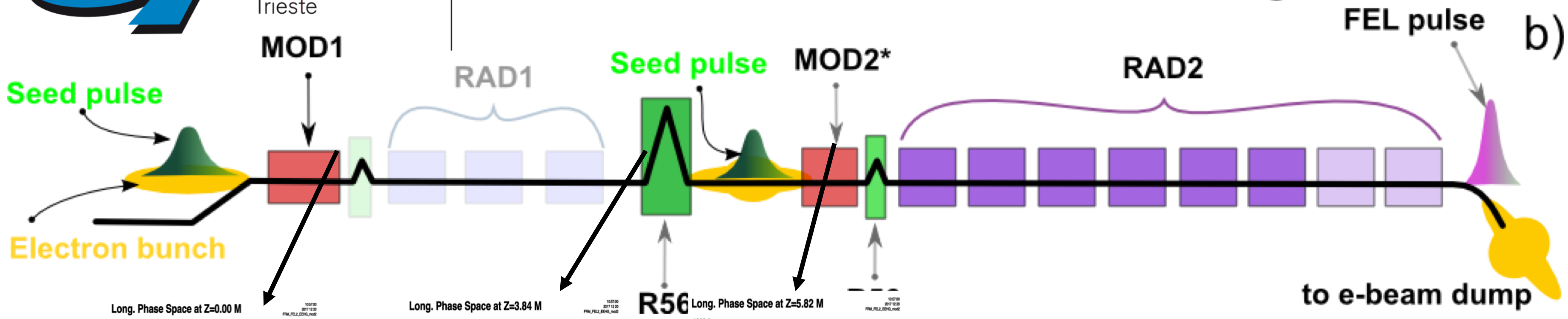


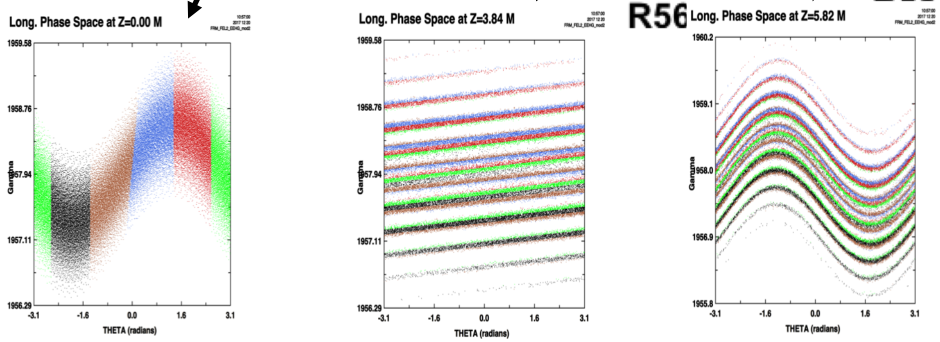




- **FERMI FEL-1 and FEL-2 cover the spectral range from 12 eV to 310 eV with variable polarization, high degree of coherence**
- The spectral properties can be preserved up to **h13-h15 on FEL1** and **h65 on FEL2** (***linewidth down to 2 $10^{-4}$ rms***, *depending on wavelength & seed setting/duration*)
- **Temporal synchronization with external laser 2-6 fs**
- **High stability of central wavelength** set by the seed (**$10^{-5}$ rms**)
- **Energy stability (typical) < 10% on FEL-1 and < 15 % on FEL-2**



# Echo Enabled Harm. Gen. @FERMI




- **Mild dependence of energy spread on harmonic order** (n^1/3)
- **Gain up to H45 demonstrated.**
- **Low sensitivity to uBI** even at intermediate harmonic orders (H30-50)
- **Reasonably «clean» spectra measured up to harmonic 101**

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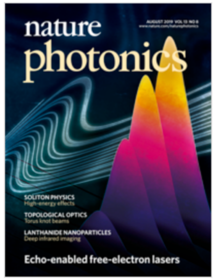


**Echo-enabled free-electron lasers**

Artistic impression of first lasing from a soft X-ray free-electron laser that uses echo-enabled harmonic generation. The development allows the generation of intense, fully coherent, multicolour, laser-like pulses with wavelengths extending into the water window (2–4 nm).

See Ribič et al.

- This experiment coordinated by **E. Allaria**, with collaborations between Elettra, PSI, SLAC, CNRS, SOLEIL, LBNL, Desy, Max-Lab, STU, **will impact the future of FERMI**.

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# Where we want to go:

Perspectives from **Future of FERMI (FoF)** workshop with joint FERMI MAC & SAC meeting (2016)

⟶ **Reduce pulse duration to the sub-10 fs range** to resolve charge transfer processes, bond dynamics, vibrational dynamics.

✓ *«… **new science opportunities become accessible in the ~10 fs (i.e. 5-15 fs) regime,** and it is highly recommended to develop this capability at FERMI» (FERMI MAC SAC)*

⟶ **Extend photon energy range to N (410 eV), O (543 eV),**

✓ *« …**it is highly recommended that FERMI pursue approaches that would extend the operating range to ~2 nm** in the fundamental which coincides with the O k-edge» (FERMI SAC)*

✓ *« …**pushing the short wavelength limit** of FELs with external seeding **is a scientific achievement by itself** with impact on the international community of FEL builders and users» (FERMI MAC)*

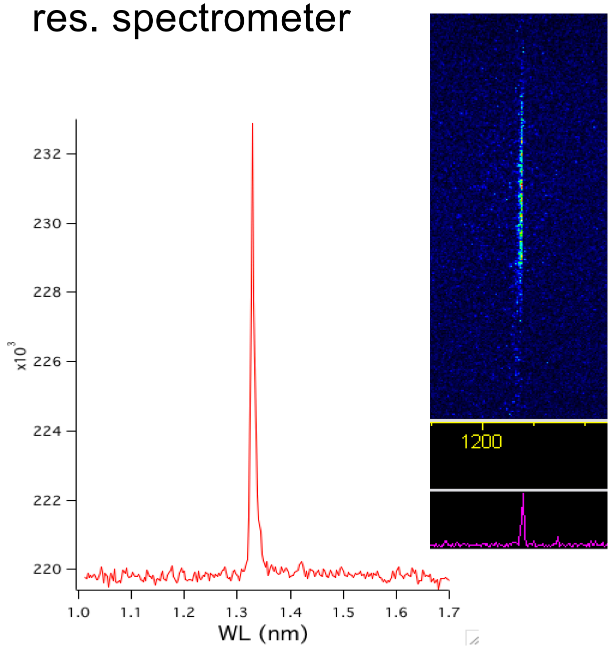
# Questions

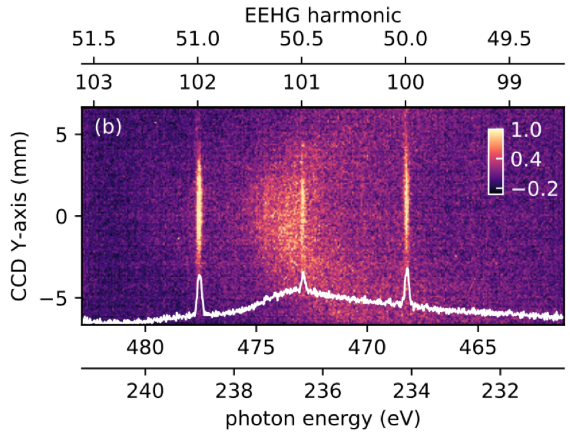
1. What are realistic expectations for future seeded FELs ?
2. Can we make a step further, can we extend the photon energy range to include Fe (707 eV), Cu (933 eV), and Zn (1,022 eV) edges while preserving the features of a seeded FEL?
3. Complementarity between seeding and SASE. Can we accept a loss of peak power to ensure impoved light coherence via seeding ?
4. Not just photon energy ! Seeding improves synchronization, coherence, control of the light properties, as duration and spectral resolution. What is and what will be the situation at other facilities in the next 10 years ?
5. Are there proof of principle experiments we should foresee to solve fundamental issues ?
6. Are there common problems to solve? Can we share part of this scientific effort ?

# High harmonics in EEHG and HGHG

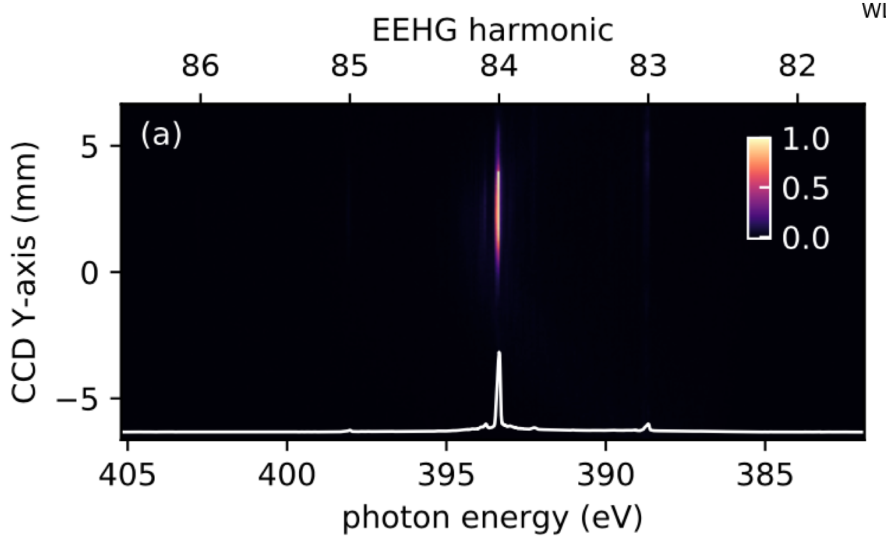
«Extreme» harmonics measured on FEL-2

**FEL-2 3 stages HGHG H192** – Integrated few seconds, low res. spectrometer




**FEL-2 EEHG H101** - Second order of diffraction and few seconds CCD integration time.




**Single shot spectra** with the EUV CCD (Andor) at 3 nm (shortest wavelength for first order of diffraction on PRESTO)

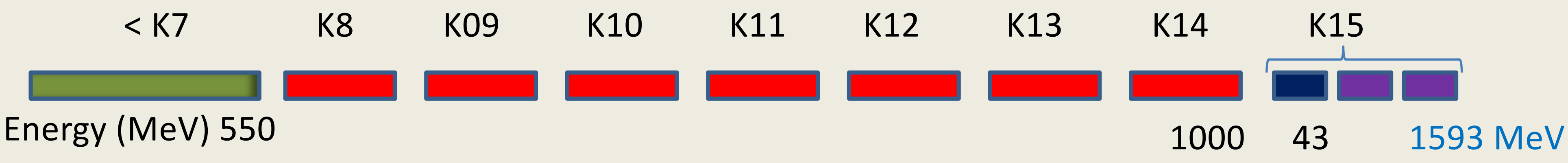
… very low, or negligible FEL gain

We need to increase **beam energy and beam quality**

# Increase beam energy: Linac Upgrade

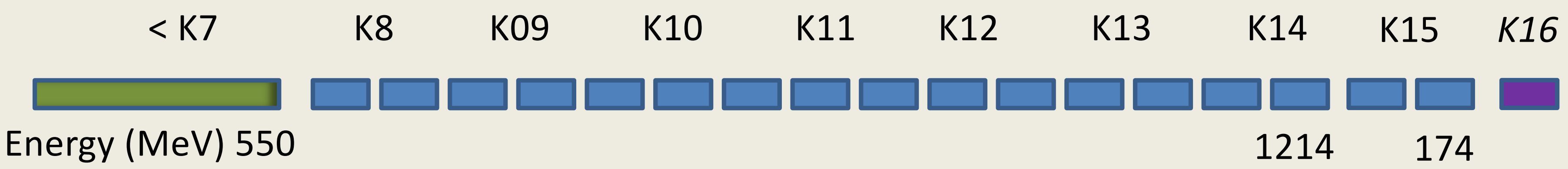
Increase the FEL gain below 4 nm: Beam energy > 1.8 GeV & Increase peak current > 1.0 kA

**Present situation**




**Summer of 2021** first two prototypes replace one of the BWT structures – 1720 MeV @ 10 Hz


**Future plan:** new structures for linac energy > 1.8 GeV (@ 50 Hz + beam compression)

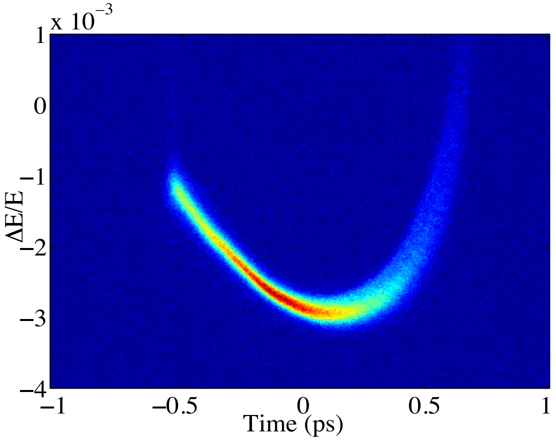



*New sections $@_{avg}$30MV/m

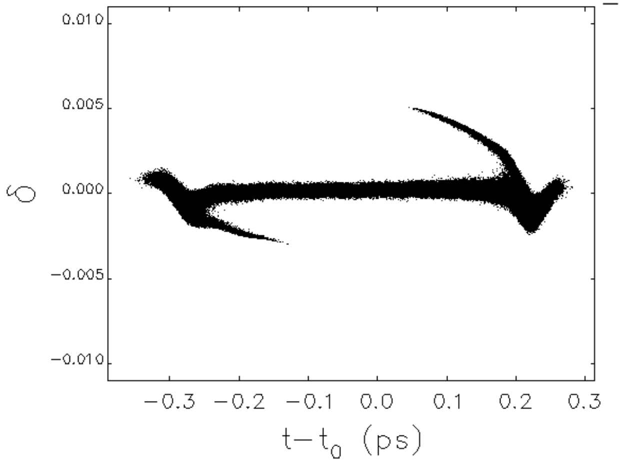
# Increase beam quality …

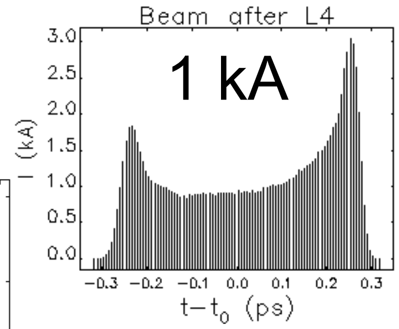
- ✓ The mitigation of wake fields with the new structures should permit a higher peak current while mitigating the phase space higher orders chirp
- ✓ At a bunch charge of 700 pC the lasing region of the longitudinal phase space should still allow accomodating two pulses for two stages of FEL-2

## Present situation

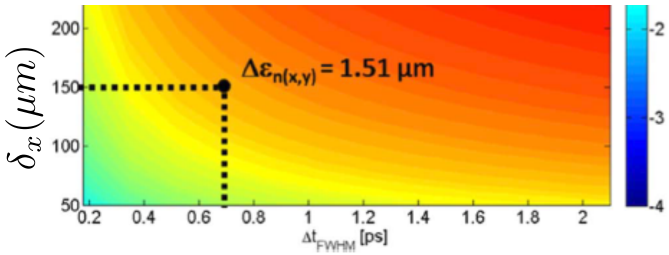


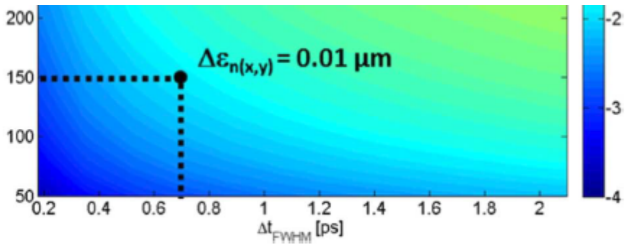

## After the upgrade




Estimated transverse emittance growth from transverse wakefield instability.

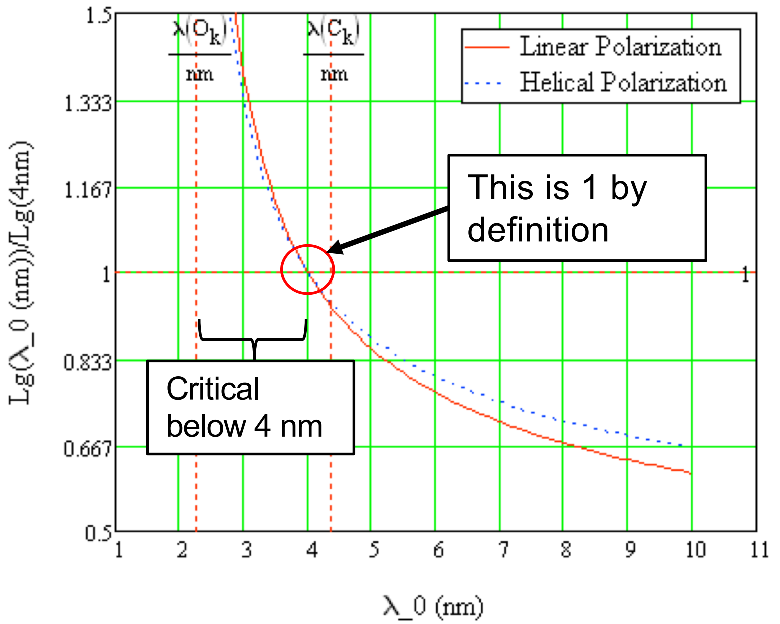


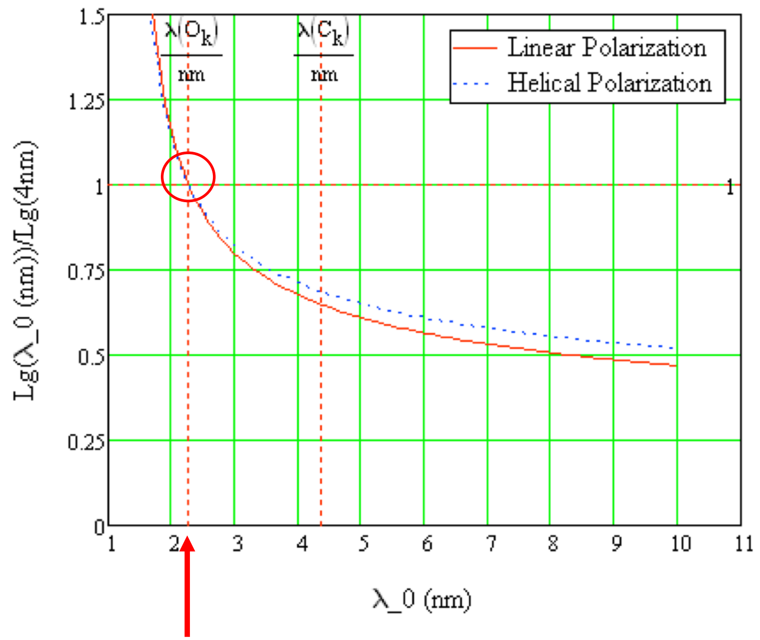
# Ratio of gain length/gain length@4 nm)

## M. Xie scaling relations

Present situation




Linac Upgrade +
**Und. period 3.5 cm ⟶ 3.0 cm**




The linac upgrade together with a reduction of the undulator period from 3.5 cm to 3 cm provides at the Oxigen K-edge **a similar gain length to the one at 4 nm**

An estimate (B. Diviacco) of the K range extension for 30 mm undulator **with Apple-II geometry:**
Min. gap of **8.2 mm K=1.47** (3.8 nm at 1.8 GeV in hel. Pol – tuning range 2.3 nm – 3.8 nm)
Min. gap of **7.2 mm K=1.67** (4.5 nm at 1.8 GeV in hel. Pol – tuning range 2.3 nm – 4.5 nm)

**Apple III Geometry or DELTA geometry have been considered, but these solutions require an entirely new undulator**

# Beam modulation and bunching

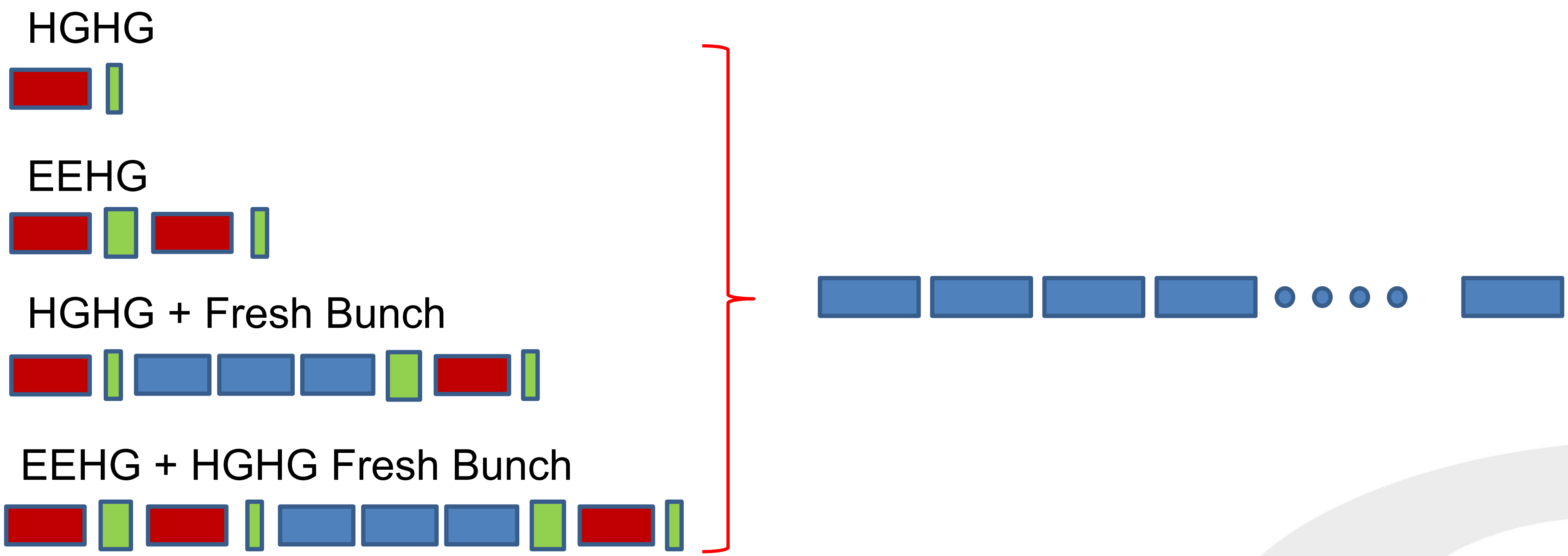
Various schemes aim at providing an efficient and error-free conversion of the seed amplitude and phase into a beam modulation (amplitude and phase) at a higher harmonic

BEAM «PREPARATION»

Bunching factor & energy spread

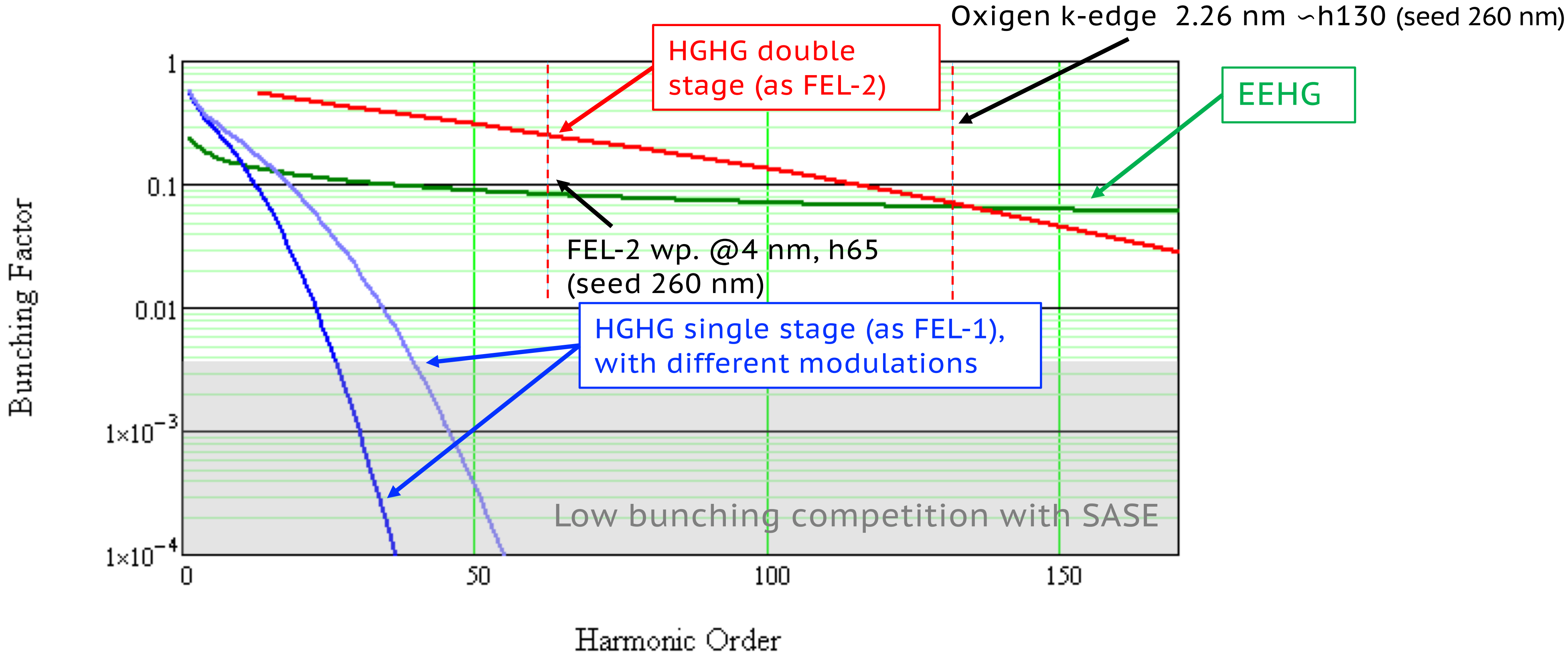
AMPLIFICATION

FEL gain



# Bunching factor vs. harmonic order

We have plotted the maximum bunching factor in HGHG, HGHG+fresh bunch ($1^{st}$stage conv. @h13) & EEHG (for n=-1) vs. the harmonic order




Both EEHG & HGHG 2 stage with fresh bunch are capable of generating bunching at harmonics as high as 130 (2 nm) **but we have to verify the impact of the degraded quality of the bunched beam on the FEL gain**

# Amplification from a pre-modulated beam: «Simplified» FEL integral equation.

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$$\frac{d}{d\tau}a(\tau) = \boxed{-2\pi g_0 b_1 e^{-i\nu_0\tau}} + \boxed{i\pi g_0 \int_0^{\tau} d\xi \xi e^{-i\nu_0\xi} a(\tau-\xi)}$$

$$\rho_{fel} = \frac{(\pi g_0)^{1/3}}{4\pi N}$$

$$\nu_0 = 4\pi N \frac{\omega_0 - \omega}{\omega_0}$$

$$\tau = z/L_u$$

## Bunched beam startup

$$a(\tau) = -2\pi g_0 b_1 \frac{\left(1 - e^{-i\nu_0\tau}\right)}{\nu_0}$$

## Exponential gain

$$a(\tau) = \frac{a_0}{3}\left\{e^{-i(\pi g_0)^{1/3}\tau} + e^{-\frac{i}{2}(\pi g_0)\left(1+i\sqrt{3}\right)\tau} + e^{-\frac{i}{2}(\pi g_0)\left(1-i\sqrt{3}\right)\tau}\right\}$$

Approximated solution by imposing continuity at the threshold* and saturation at $P_F$

$$P(z) = P_{th}\left[\frac{\frac{1}{3}\left(\frac{z}{L_g}\right)^2}{1+\frac{1}{3}\left(\frac{z}{L_g}\right)^2} + \frac{\frac{1}{2}exp\left[\frac{z}{L_g}-\sqrt{3}\right]}{1+\frac{P_{th}}{2P_F^*}\,exp\left[\frac{z}{L_g}-\sqrt{3}\right]}\right] \quad \textbf{(1)}$$

$$P_{th} = \rho_{fel}|b_1|^2 P_{beam}$$

$$P_F = 1.6\rho_{fel} P_{beam}$$

$$\rho_{fel} = \rho_{fel-3D} = f(period, current, energy, energyspread, emittance...)$$

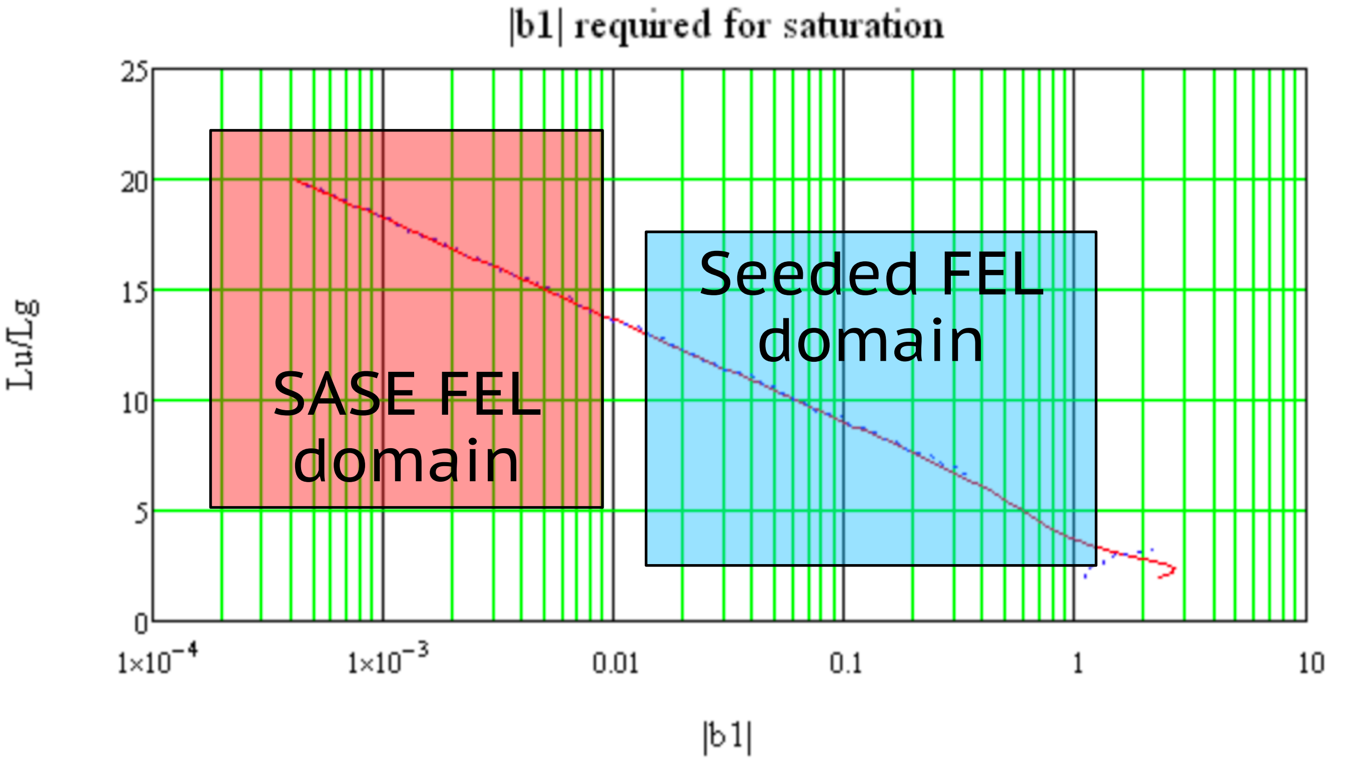
*L. Giannessi, Synchrotron Light Sources and Free- Electron Lasers Accelerators Physics, Instrumentation and Science Applications, edited by E. Jaeschke, S. Khan, J. R. Schneider, and J. B. Hastings (Springer International Publishing, Switzerland, 2015).*

## Condition for saturation, threshold $P(z, z = L_u) = \Gamma P_F$

$$P(z = L_u) = P_{th}\left[\frac{\frac{1}{3}\left(\frac{L_u}{L_g}\right)^2}{1+\frac{1}{3}\left(\frac{L_u}{L_g}\right)^2} + \frac{\frac{1}{2}exp\left[\frac{L_u}{L_g} - \sqrt{3}\right]}{1+\frac{P_{th}}{2P_F^*}exp\left[\frac{L_u}{L_g} - \sqrt{3}\right]}\right] = \Gamma P_F$$

Depends on the amplitude of the initial bunching factor |b1| and $\rho_{fel}$

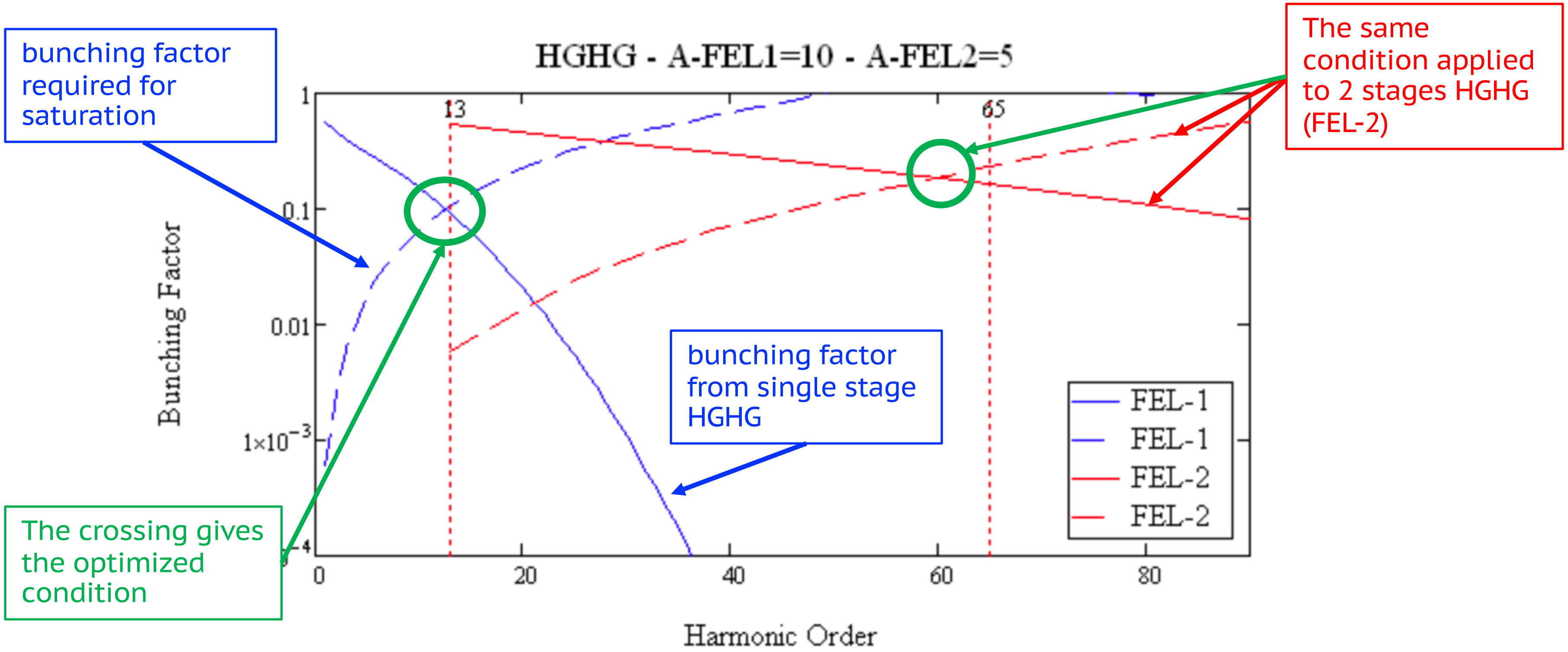
Depend on ratio Undulator length/gain length, and $\rho_{fel}$ i.e. undulator parameters, beam parameters ... including energy spread induced to create bunching |b1|




**Γ**=0.8

# Condition for saturation applied to FEL-1 & FEL-2 (Linear polarization)

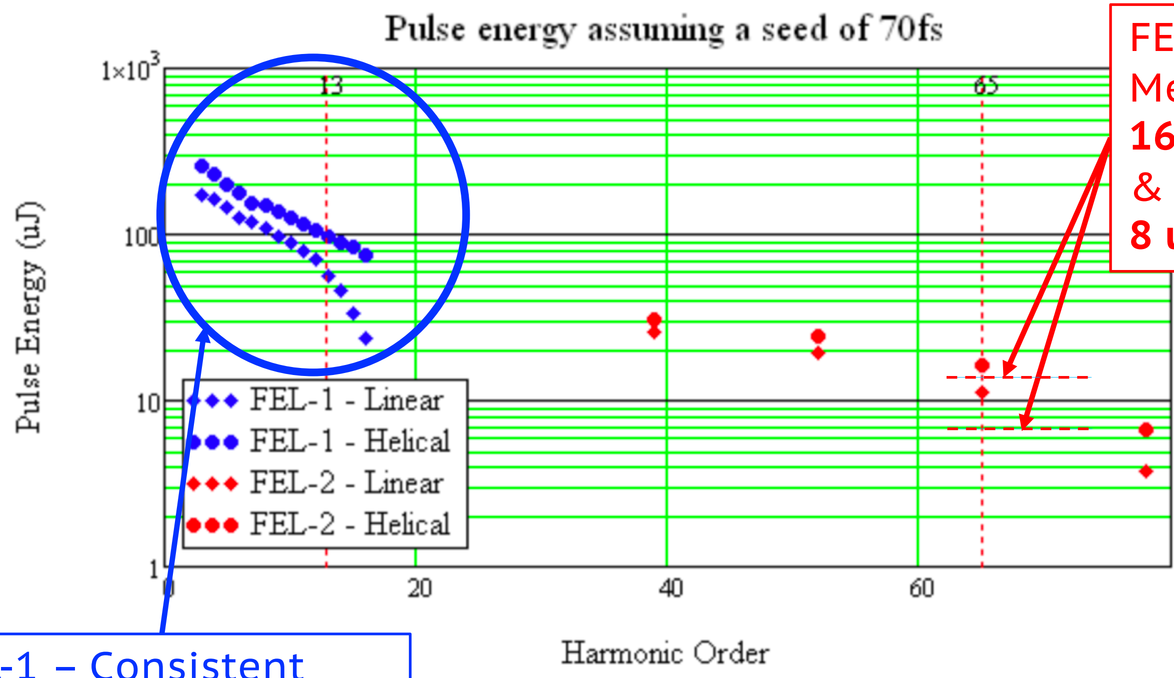
Bunching at radiator FEL-1
Bunching for saturation FEL-1
Bunching at radiator FEL-2
Bunching for saturation FEL-2



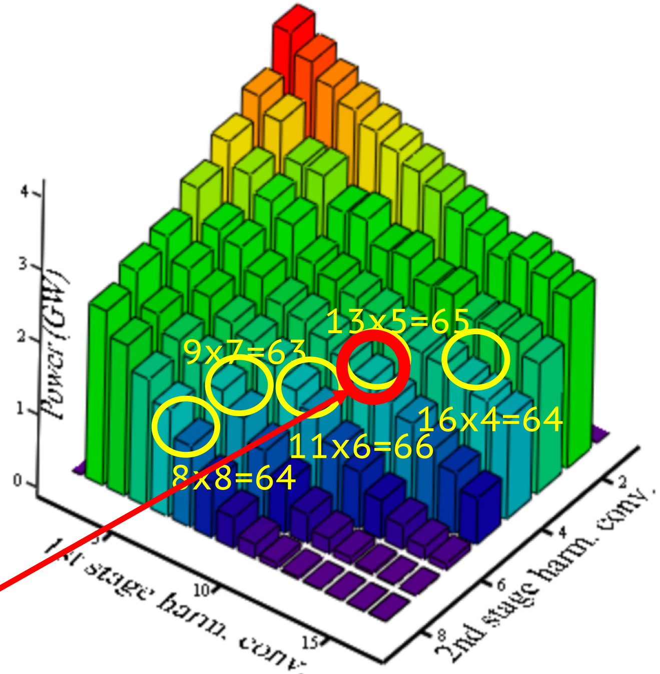

- ✓ The model provides an estimate of the FEL performance, as function of the undulator parameters (period, UM length …), beam parameters (energy, emittance, energy spread … ) and of the scheme used to generate the initial modulation, e.g. EEHG vs HGHG with fresh bunch.
- ✓ It provides the harmonic at which saturation should be reached. The power scaling predicts the output power
- ✓ The power can be converted in pulse energy using *Finetti et al., Pulse duration of seeded free-electron lasers. Phys. Rev. X* ***2017****, 7, 021043* to estimate the expected pulse duration.

# FERMI FEL-1 & FEL-2 (first stage @h13) through the model

Output energy calculated scaling the seed pulse duration at harmonic h with 7/6 h^-1/3 for FEL-1 and 7/6 h1^-1/2 x h2^-1/3 for FEL-2




FEL-2 13x5
Measured:
**16 uJ** in circular pol.
&
**8 uJ** in linear pol.

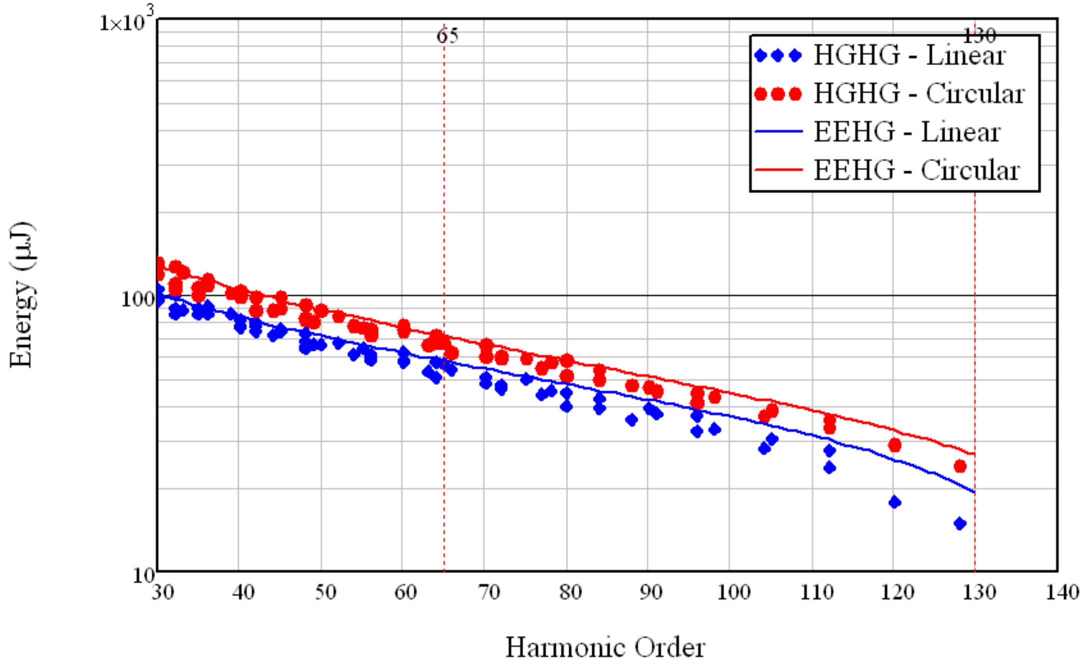



FEL-1 – Consistent with optimized FEL-1 operation

Best working point on FEL-2 is 13 x 5 = 65 (limit on 1st stage power)

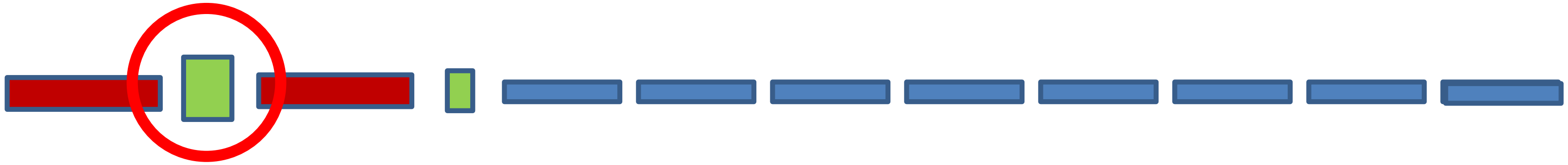
# Upgraded linac, 1 kA, 1.8 GeV
## Undulator period 2.8 cm

The model predicts that a combined upgrade of the linac and the undulator line, may extend the operating range up to h ~130 in circular polarization (2 nm) and h ~120 in linear polarization (2.2 nm).




Both configurations, HGHG with fresh-bunch and EEHG provide similar performances, with a modest advantage of the latter.

# The first chicane in EEHG



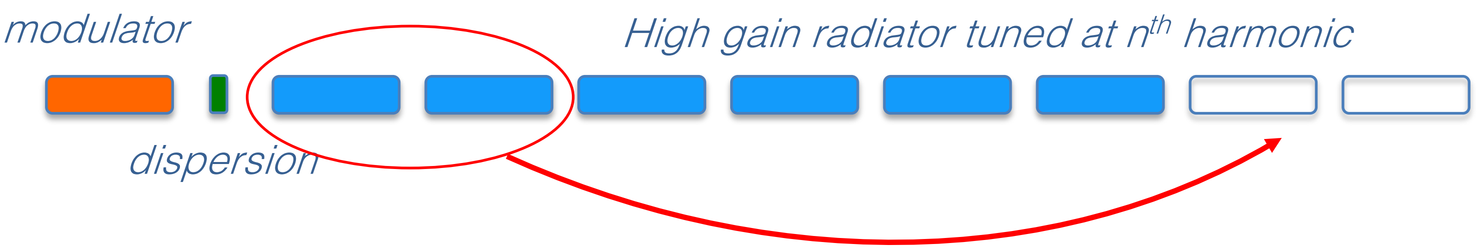
- The first chicane plays the key role of keeping low the induced energy spread during the bunching process. **A large chicane (dispersion of 10-15 mm) is required for h130**.

- At the same time **the chicane itself may degrade the beam properties** and suppress lasing (this is not yet included in the model, and presents some uncertainties)

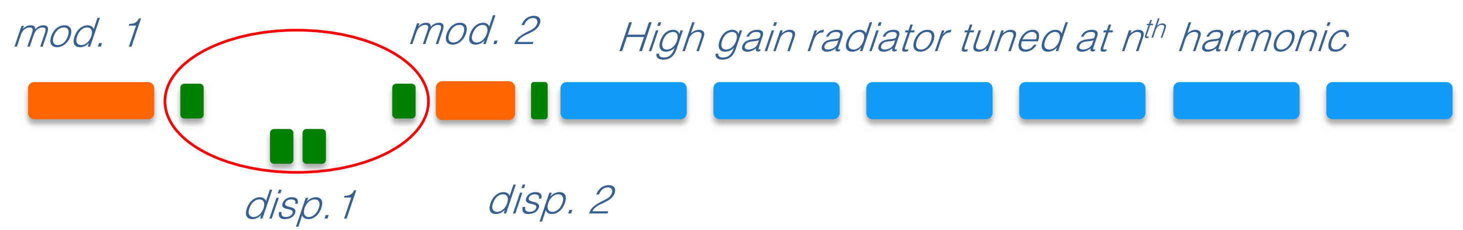
- In **alternative, a lower dispersion would be required in a EEHG + HGHG Fresh bunch configuration**, where a first stage EEHG at harmonic ∽30 seeds in fresh bunch a second stage in HGHG at harmonics 4-5.

# Where we are going: **FEL-1 Upgrade**

- **Doubling the photon energy of FERMI requires retargeting the operating ranges of FEL-1 and FEL-2.** An upgrade of **FEL-1 to EEHG will extend the operating range of FEL-1 to sub-10nm wavelengths**




FEL-1 would require a first dispersion of about 5 mm, but **we have room for a dispersion up to 15 mm** which is **of the order of what is required for FEL-2** optimised up to h130. **FEL-1 will be an ideal test bed for EEHG studies with large dispersion in the first chicane.**




- ✓ FEL-1 may operate as **HGHG at low harmonics** and **EEHG at intermediate harmonics (h15-h35. After the beam energy increase to 1.8 GeV, FEL-1 could cover most of the present FEL-2 range**
- ✓ **The advantages of EEHG (stability, spectral quality) and double pulse operation will be available for FEL-1 users**
- ✓ The double seed, double modulator may allow **multicolor operations with totally independent colors, i.e. not constrained by a common seed resonance (not possible in the present configuration)**

# FEL-1 perf. in EEHG configuration

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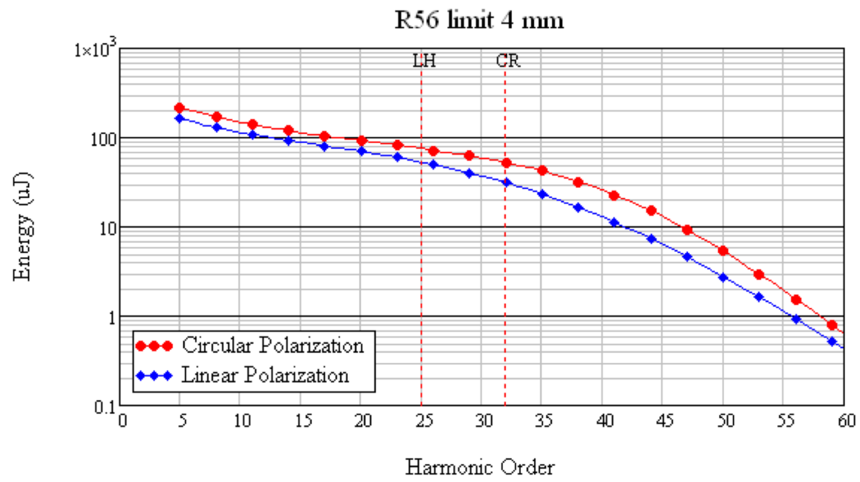
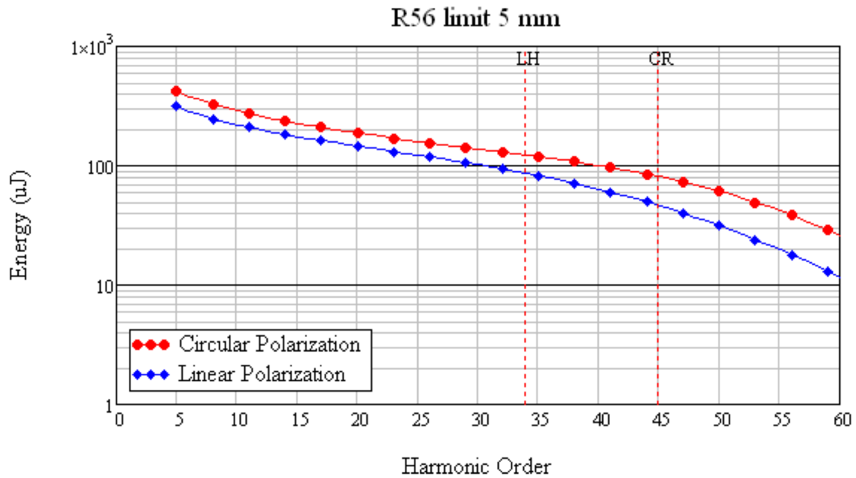
We assume here a dispersive section of **4 mm** for the first disp. of an EEHG configuration with the FEL-1 amplifier (6 UM - 2.2 m long, 5.5 cm of period).

Highest harmonics reaching saturation are h32 (8.1 nm) and h25 (10.4 nm) in circular and linear polarization respectively.

**FEL-1 in HGHG reaches h18 & h13 – the present FEL-1 is limited by the HGHG configuration**




After the linac upgrade, assuming 1.8 GeV, 1 kA and a dispersion of 5 mm, the highest harmonics reaching saturation are 45 (5.5 nm) and 34 (7.2 nm) (circular and linear )




These figures support the fact that FEL-1 is limited by the configuration (HGHG vs. EEHG) and can cover in EEHG the range 100 nm to sub-10 nm wavelengths

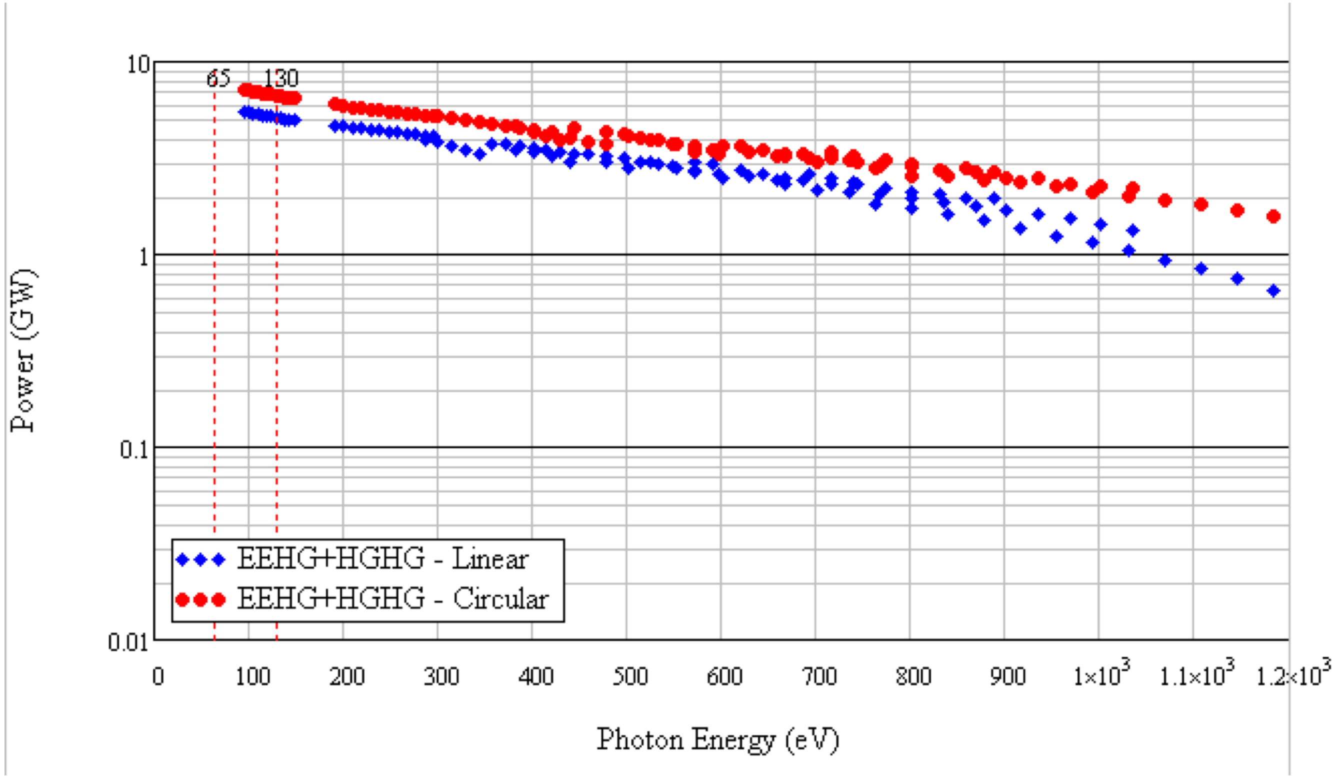
Elettra Sincrotrone Trieste

# Conclusions

- ✓ The **spectral range of FEL-2 can be extended to the oxigen K-edge implementing an EEHG or EEHG+HGHG scheme.** In the first case a dispersive section of about 15 mm is needed, together with an increase of the beam energy and peak current, and a reduction of the undulator period.
- ✓ The **upgrade of FEL-2 to reach power/energy at harmonics of the order of 120-130 requires a shift of FEL-2 spectral range** to higher photon energy.
- ✓ The **photon energy range of FERMI FEL-1** is mainly limited by the **energy spread induced in the bunching formation** process. **FEL-1 could operate down to 10 nm with an EEHG modulation scheme**
- ✓ The shift of the operation range of FEL-2 can be **compensated by an upgrade of FEL-1** that would provide the advantages of EEHG to wavelength down to 10 nm
- ✓ FEL-1 could be an ideal test bed to study the high dispersion chicane needed as first dispersive section by an EEHG FEL operating up to harmonics of the order of 130.

# Higher Energy (2.0 GeV & 2.4 GeV)

# **Toward 1 keV photons**




Energy 2.0 GeV
Peak current **1.0 kA**
Undulator period **2.0 cm**
Energy spread $10^{-4}$
Dispersion 15 mm

# Summary

- ✓ **Seeded FELs are extremely flexible tools** providing an extended control on temporal coherence and on the longitudinal properties of VUV-soft X-ray light. **FERMI FEL-1 and FEL-2 provide unprecedented performances in terms of longitudinal coherence, wavelength stability and spectral purity.**

- ✓ The advent of high intensity, short wavelength sources with femtosecond resolution, is giving us an unprecedented view of the structure and dynamics of matter at the smallest spatial and temporal scales.

- ✓ With the improved control on the machine **we are demonstrating the feasibility of new classes of experiments where coherence plays a major role**, and that were so far accessible only to optical lasers. Experiments with multicolor-multi pulses for pump and probe that could be only dreamed a few years ago, are now reality.

- ✓ New communities of scientists interested in the time domain are growing around these facilities. **The fertilization due to the close interaction with a strong user community is the key for the introduction of these new concepts.**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