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FERMI FEL operation in Echo Enabled Harmonic Generation mode

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On behalf of the
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Large collaboration

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DESY.

SOLEIL SYNCHROTRON

MAX IV

…real pleasure to have so many guests in control room for helping, discussing, speculating, … !

Outline

- EEHG introduction and motivation of the experiment
- New design: FEL-2 line was adapted for EEHG scheme
- Experimental achievements
  - EEHG characterization: preliminary analysis (a complete analysis is work in progress)
  - Comparison between HGHG vs EEHG
  - EEHG enabled two-pulse FEL in soft x-ray

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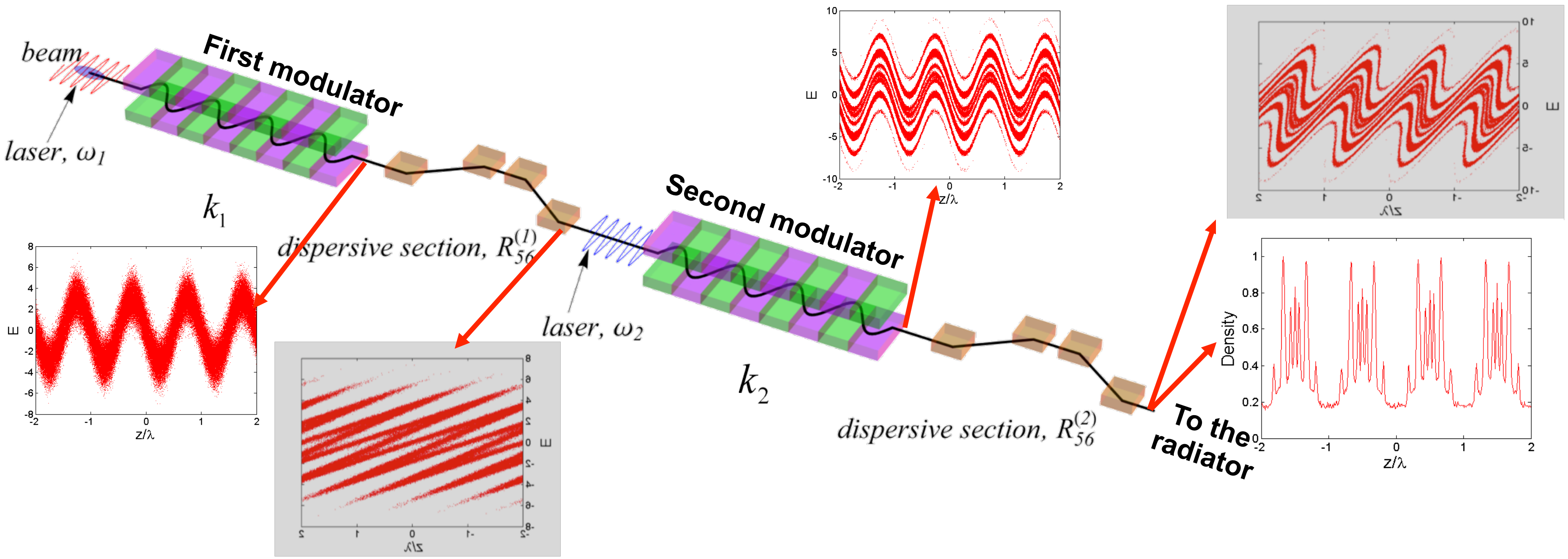
Echo Enabled Harmonic Generation: principle

Courtesy of E. Allaria



$$b_{n,m} = |e^{-(1/2)[nB_1+(Km+n)B_2]^2} J_m[-(Km+n)A_2B_2] \times J_n\{-A_1[nB_1+(Km+n)B_2]\}|.$$

$$A_{1,2} = \Delta E_{1,2} / \sigma_E \qquad B_{1,2} = R_{56}^{1,2} k_{1,2} \sigma_E / E_0 \qquad K = k_2 / k_1$$

$$k_{EEHG} = k_1 n + k_2 m = k_1 \underbrace{(n + Km)}_{\text{harm number } h}$$

- For $k_1=k_2$ (i.e. K=1) one can demonstrate that max bunching is for $n*B_1 \sim h*B_2$ (when perfectly satisfied $J_n=0$, so $\mathbf{b_{n,m}=0}$)
- Highest bunching for $n=-1$ but for high harmonic h this means large first R_{56}

Reference:

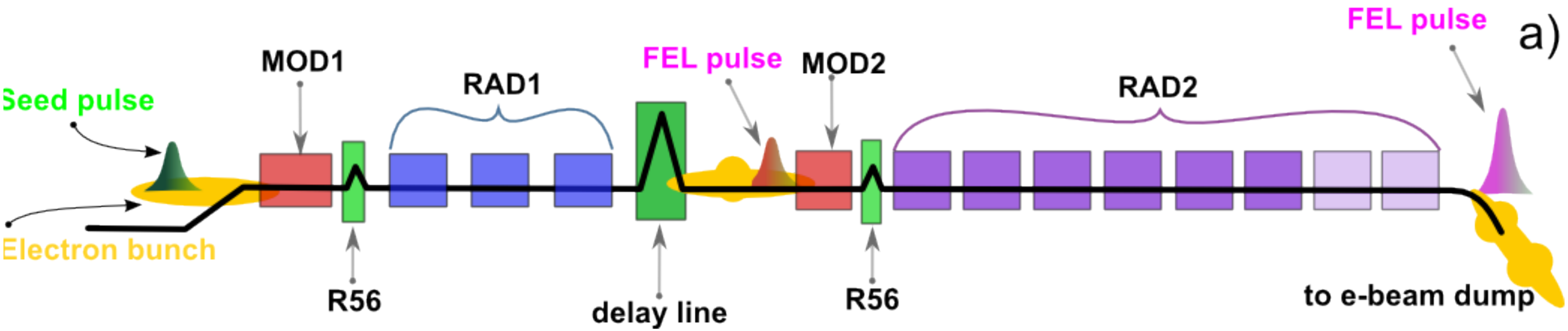
- G. Stupakov, PRL, 2009
- D. Xiang, G. Stupakov, PRST-AB, 2009

Why EEHG at FERMI?

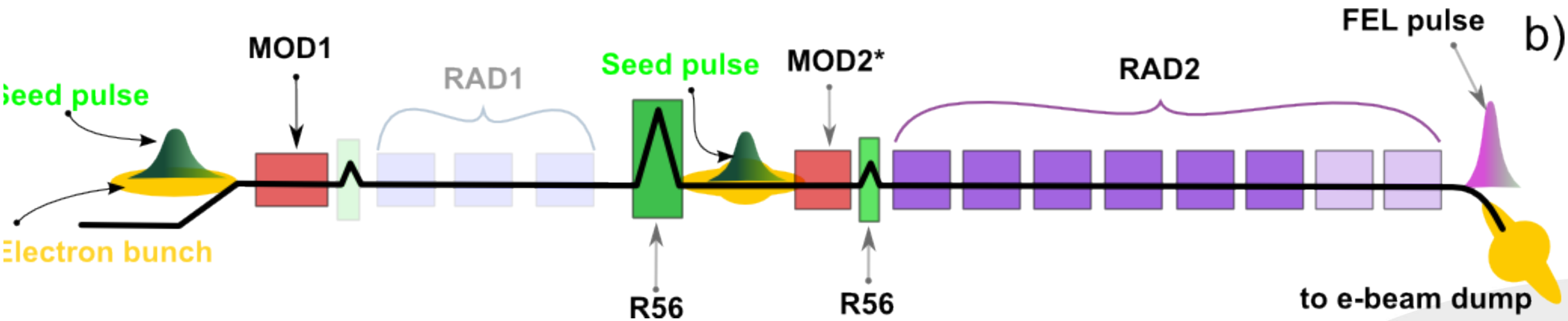
- FERMI FEL-2 layout is very suitable to test this novel scheme in the soft X-ray
- EEHG is less sensitive to the electron longitudinal phase space than HGHG:
  - In HGHG Slice energy spread should be: $\frac{\sigma_\gamma}{\gamma}\sqrt{h^2+1} < \rho_{FEL}$
  - In HGHG electron energy-time curvature increases the FEL output bandwidth and affects the shot-to-shot stability
  - As a consequence microbunching instability must be constrained as much as possible in HGHG
- FERMI FEL-2 is based on a **fresh-bunch** double-cascade scheme: it requires a **"long" portion** of electron bunch to accommodate the two-stage emission, making difficult the implementation of two-color schemes.

And finally … "transforming" FERMI has been a fascinating game and we enjoyed so much!

FEL-2 from HGHG-FB to EEHG



First stage emits coherent harmonic radiation at ~40-20 nm used as a seed for the second stage.



First stage radiator is not used. A second seed laser is injected after the big dispersion.
High harmonic bunching is amplified in the final radiator.

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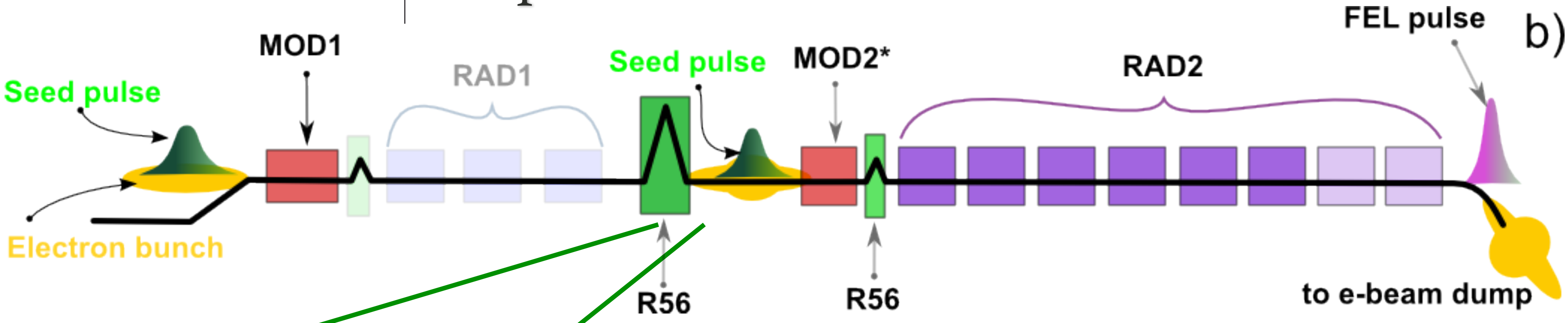
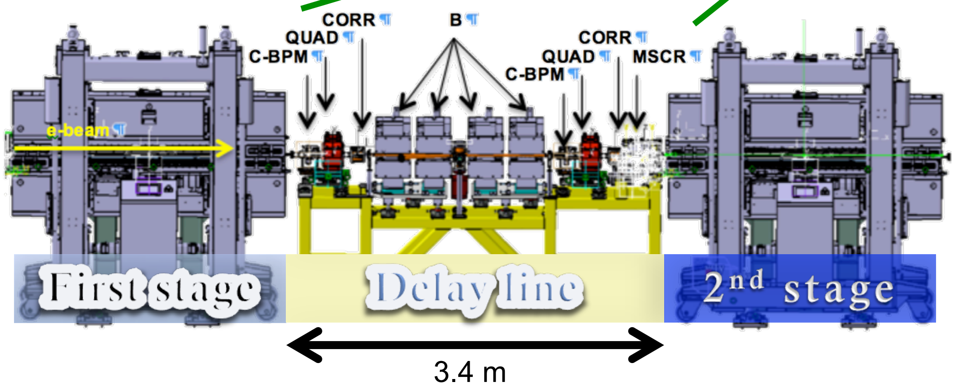
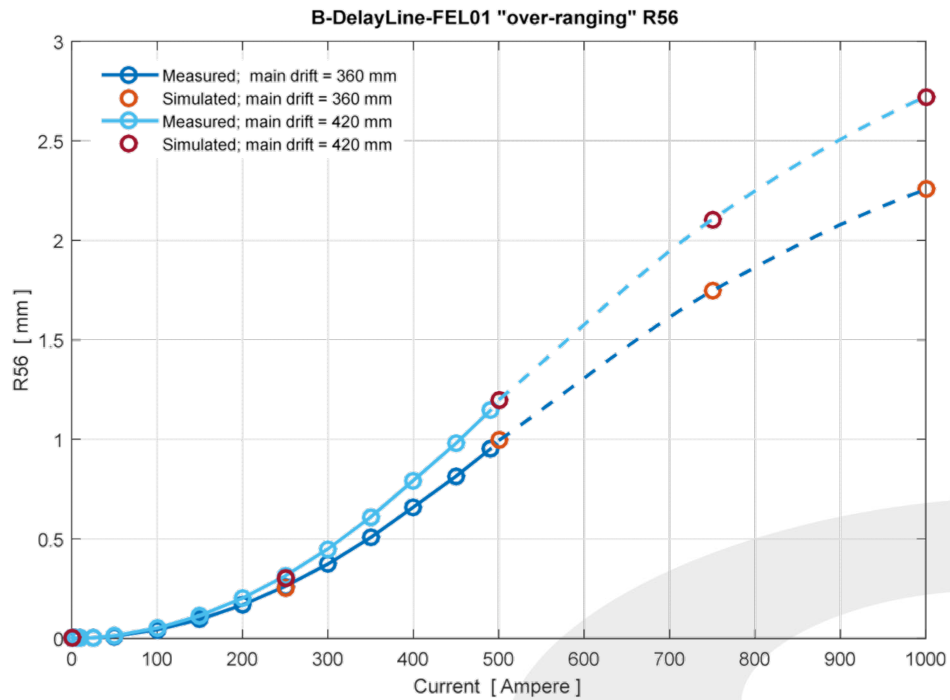
Modification for EEHG at FEL-2: Dispersion



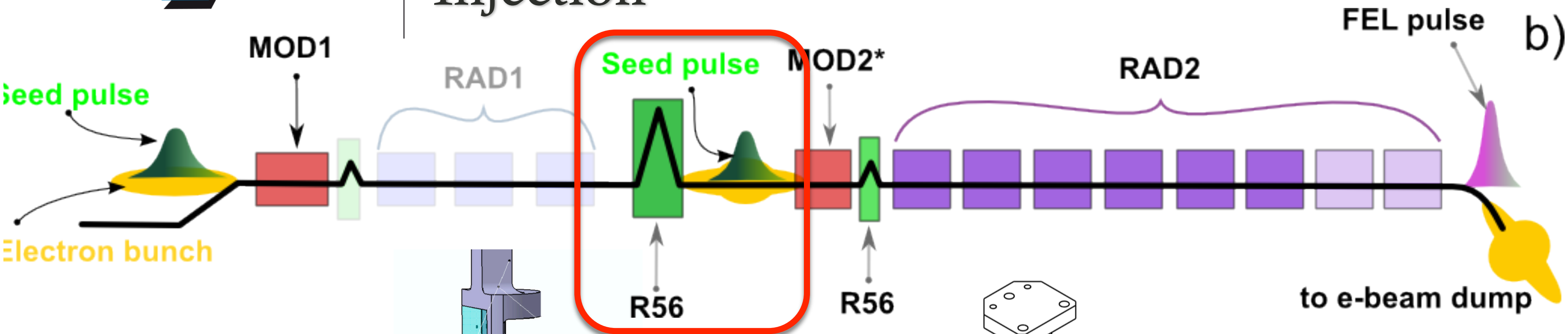


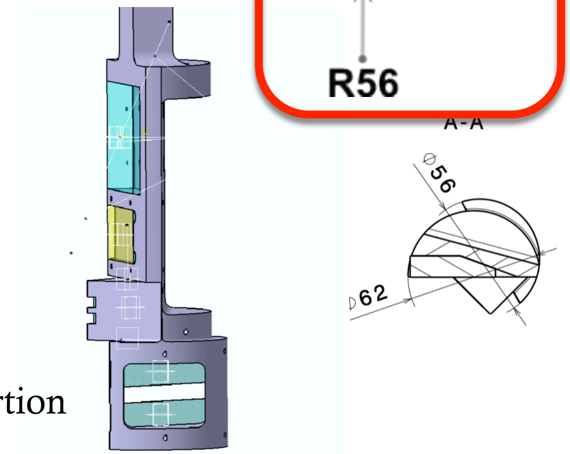
EEHG requires a stronger dispersion in the delay-line chicane.



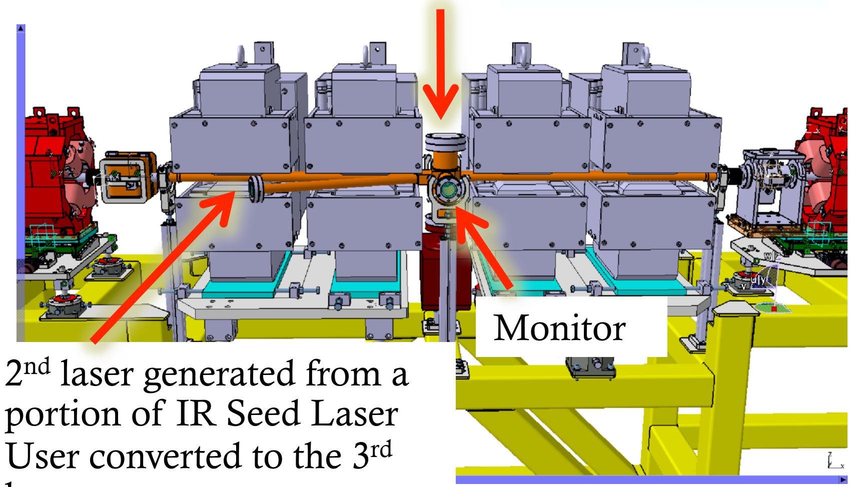
- **New supports** for magnets have been **installed** to increase the magnet separation to > 400 mm.
- Two **power supplies** used in parallel to reach the required 750 A.

Modification for EEHG at FEL-2: Injection

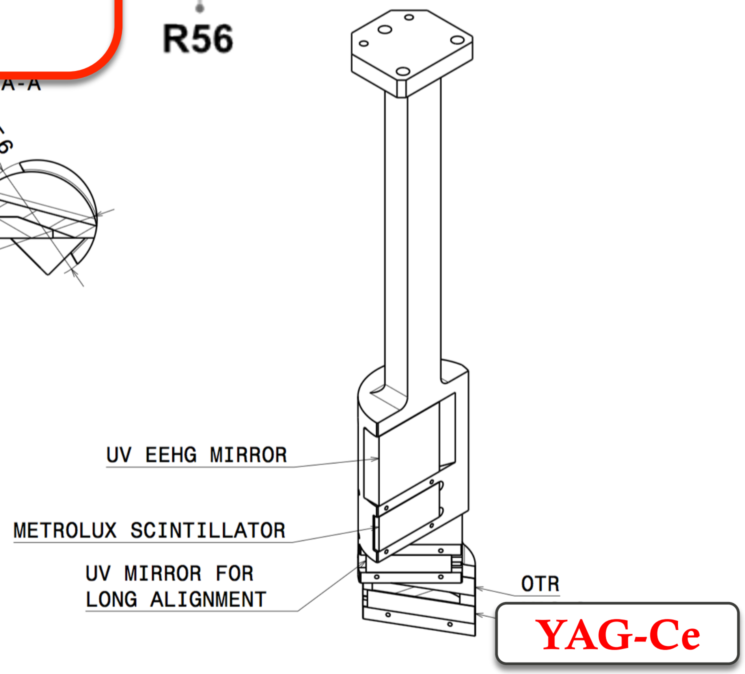




Actuator insertion

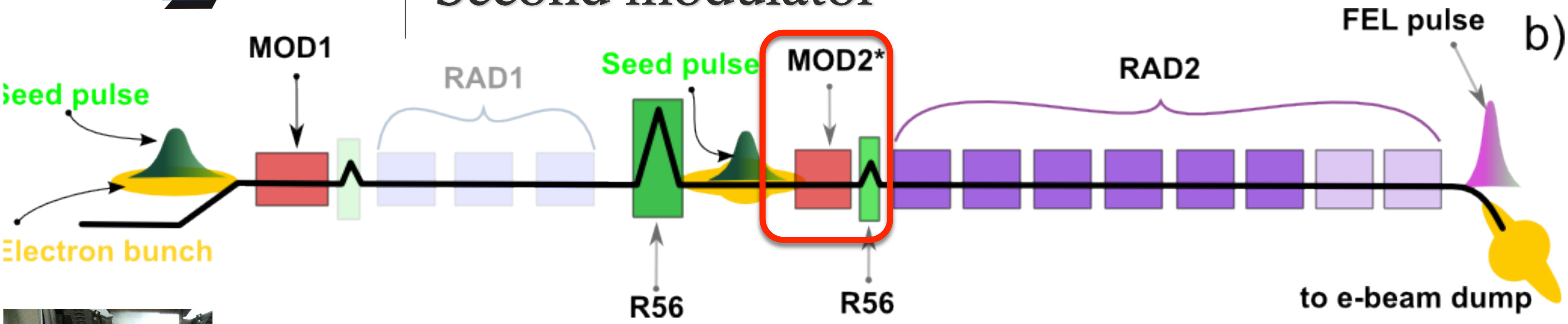


2nd laser generated from a portion of IR Seed Laser User converted to the 3rd harm.

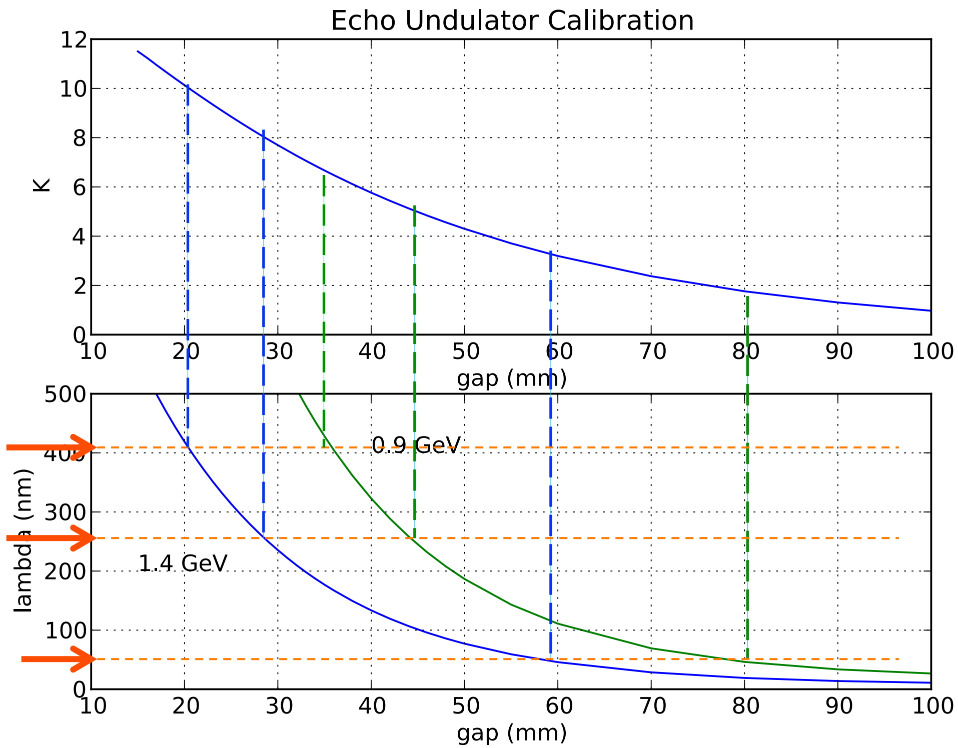


- Transv. Align e-beam/seed
- Delay-Line calibration
- C-OTR measurement

Modification for EEHG at FEL-2: Second modulator



Second modulators is based on a existing Elettra undulator:
Length: ~1.5 m
Period length:11.3 cm
Minimum gap: 10 mm

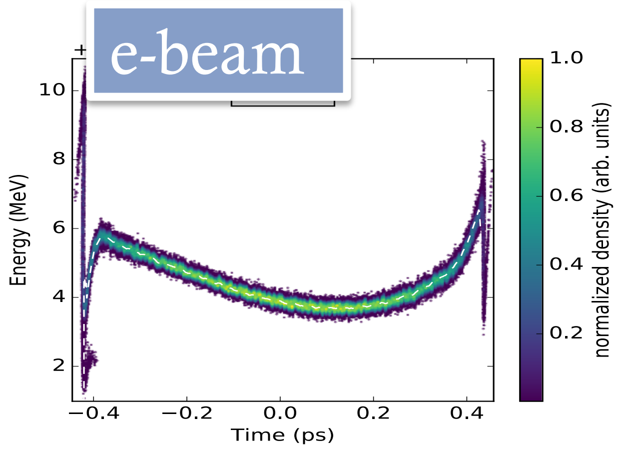


New undulator allows **seeding** with **3rd and 2nd harmonic** of the Ti:Sa laser.
It can also be used for the **standard 2 stages HGHG** with the first stage in the **40-60 nm** spectra range.

Start to end FEL simulations

Table 1. Typical EEHG operating parameters in the nominal (middle column) and advanced (right column) configurations.

Parameter	Nominal Configuration	Advanced Configuration
e-beam peak current I (A)	700	1000
e-beam energy E (GeV)	1.4	1.8
slice energy spread σ_E (keV)	150	250
emittance ε (mm mrad)	1	1
e-beam size (µm)	70	70
1st R56 (mm)	2.1	8
2nd R56 (µm)	74	85
1st seed peak power (MW)	10.7	10.7
1st energy modulation (keV)	450	450
2nd seed peak power (MW)	135	151
2nd energy modulation (keV)	824	868



- Main studies done with standard FERMI e-beam optimized for FEL-1 and FEL-2 operations.
- Long beam is not necessary for EEHG but it allows a direct comparison with HGHG-FB.
- Higher compression or lower charge beams were also studied.
- Both simulations and experiments show that µB can be detrimental for spectral quality.

- The shortest wavelength is around 5nm.
- Simulations and experiments indicate >1GW in HGHG-FB and similar results were expected for EEHG
- Simulations of λ>5nm (as in the experiment)
- Reducing beam energy allows to increase the first R56 to ~5mm

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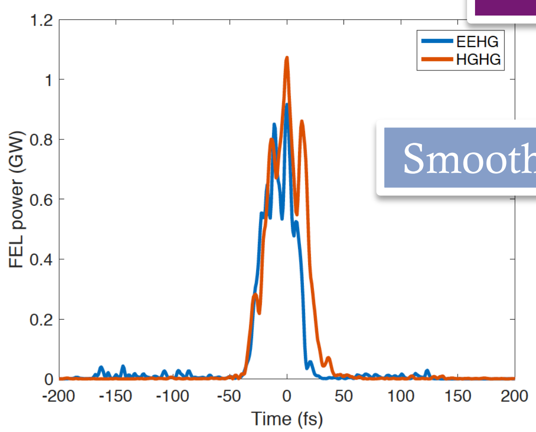
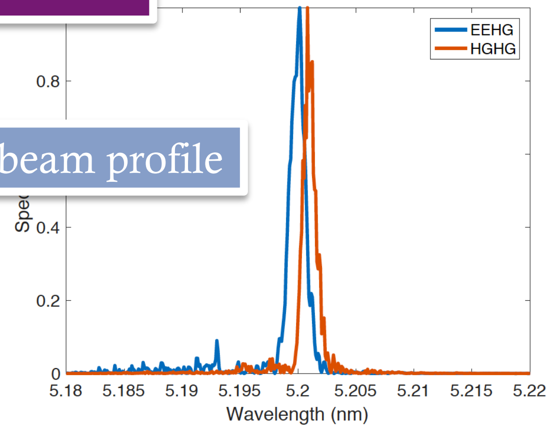
Start to end FEL simulations using a smooth e-beam or a mod. e-beam

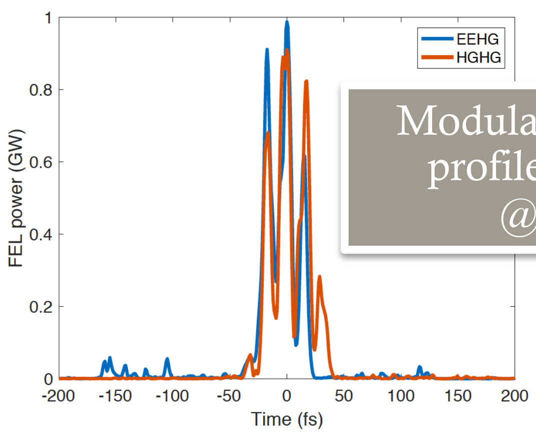
λ=5nm

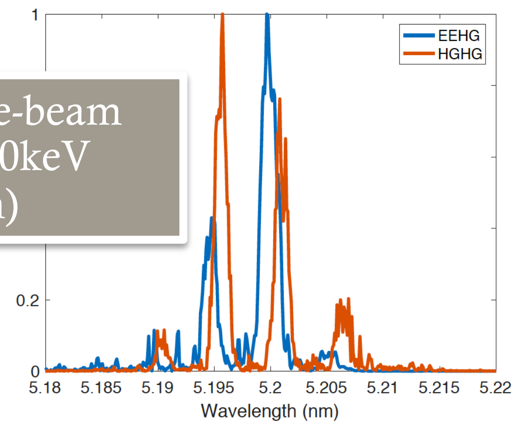
Smooth e-beam profile





Modulated e-beam profile (100keV @5um)





λ=3nm

For having enough bunching : the first R56 should be increased to 8mm

To reach saturation: Ebeam=1.8GeV or more radiator sections

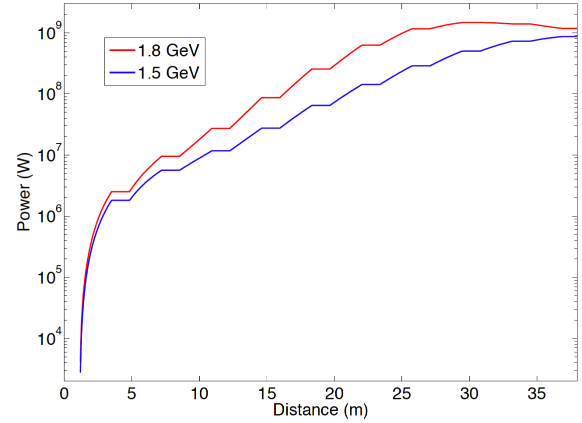


Figure 5. EEHG power at 3 nm as a function of the distance in the radiator. Flat regions (no increase in the power) are due to drift spaces between the radiators to accommodate e-beam focusing optics.

Power modulation are induced by μB instabilities: - HGHG resulted more sensible;

- The strong first R56 transforms initial energy modulation into density modulation

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EEHG at FERMI experiment

7 weeks
e-beam Energy: 0.9-1.1-1.35-1.45 GeV

*** For the slides contact Giuseppe Penco**
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Conclusions

- EEHG spectral quality and especially the central wavelength stability are better compared to HGHG-FB.
- HGHG-FB gives more energy per pulse in the nominal compression (600-700 A); however, EEHG can be operated at increased compression (still a better spectrum compared to FB). No evidence of de-bunching (i.e. far from saturation) thus with more undulators EEHG will grow.
- EEHG tolerates stronger laser heater so μ-bunching can be suppressed more efficiently (strong 1^{st} R_{56} enhances μ-bunching but could be constrained by LH)
- EEHG is less sensitive to e-beam properties (energy chirp).
- Two soft x-ray pulses have been successfully generated in EEHG at the same wavelength. This proof-of-principle opens the way to provide two-color two-pulse FEL for pump-probe experiments.

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Vielen Dank