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ICFA The 60th ICFA Advanced Beam Dynamics Workshop

SINAP

FLS2018

Mar. 5-9, 2018
Shanghai Institute of Applied Physics

EEHG experiment at FERMI

E. Allaria
on behalf of the FERMI team

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Outline

- **FERMI Free-Electron Laser**
  - Seeded FEL
- **EEHG experiment**
  - New setup
  - Simulations and studies
- **Conclusions**

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FERMI Free Electron Laser

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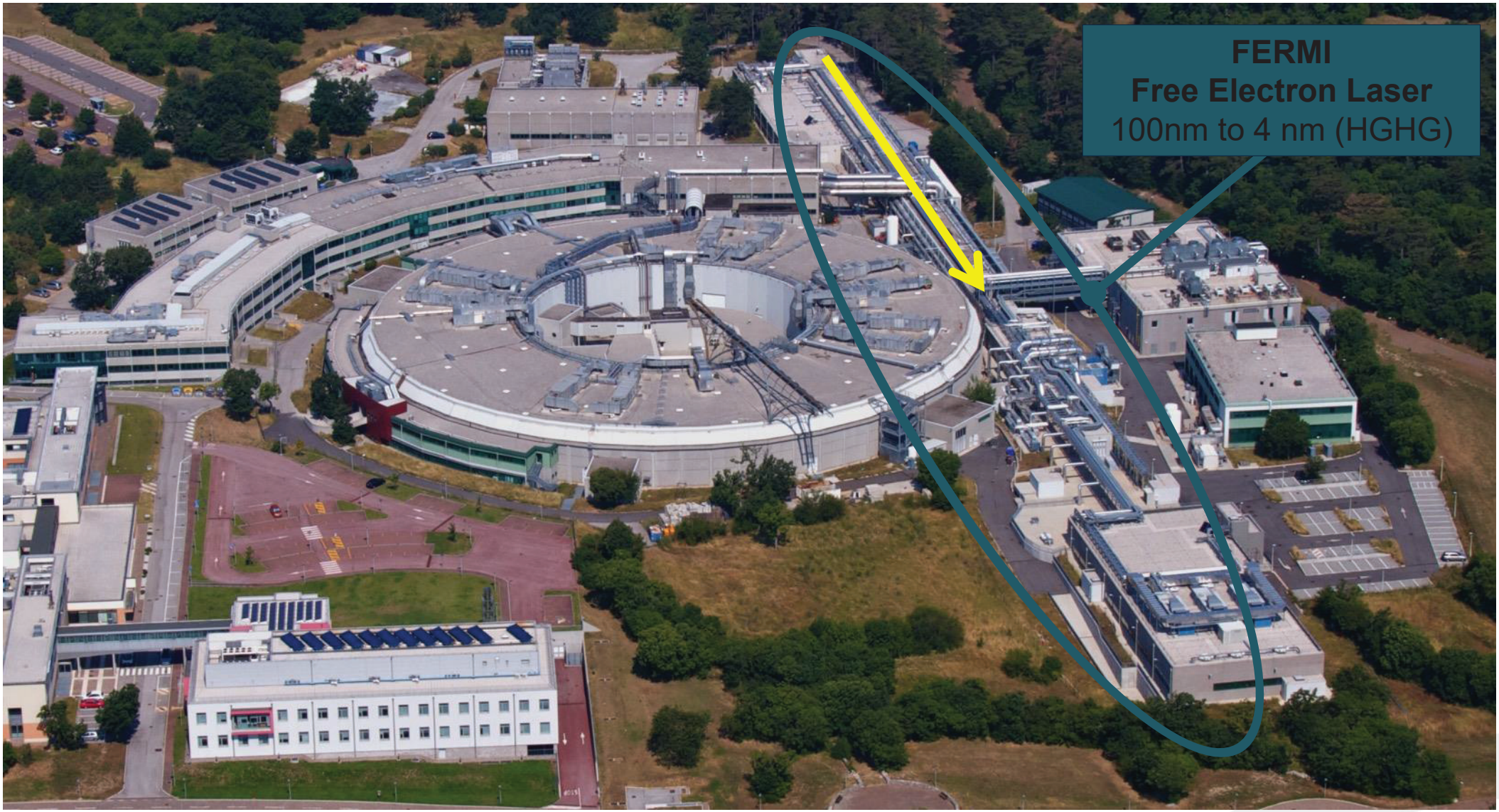
FERMI Free Electron Laser



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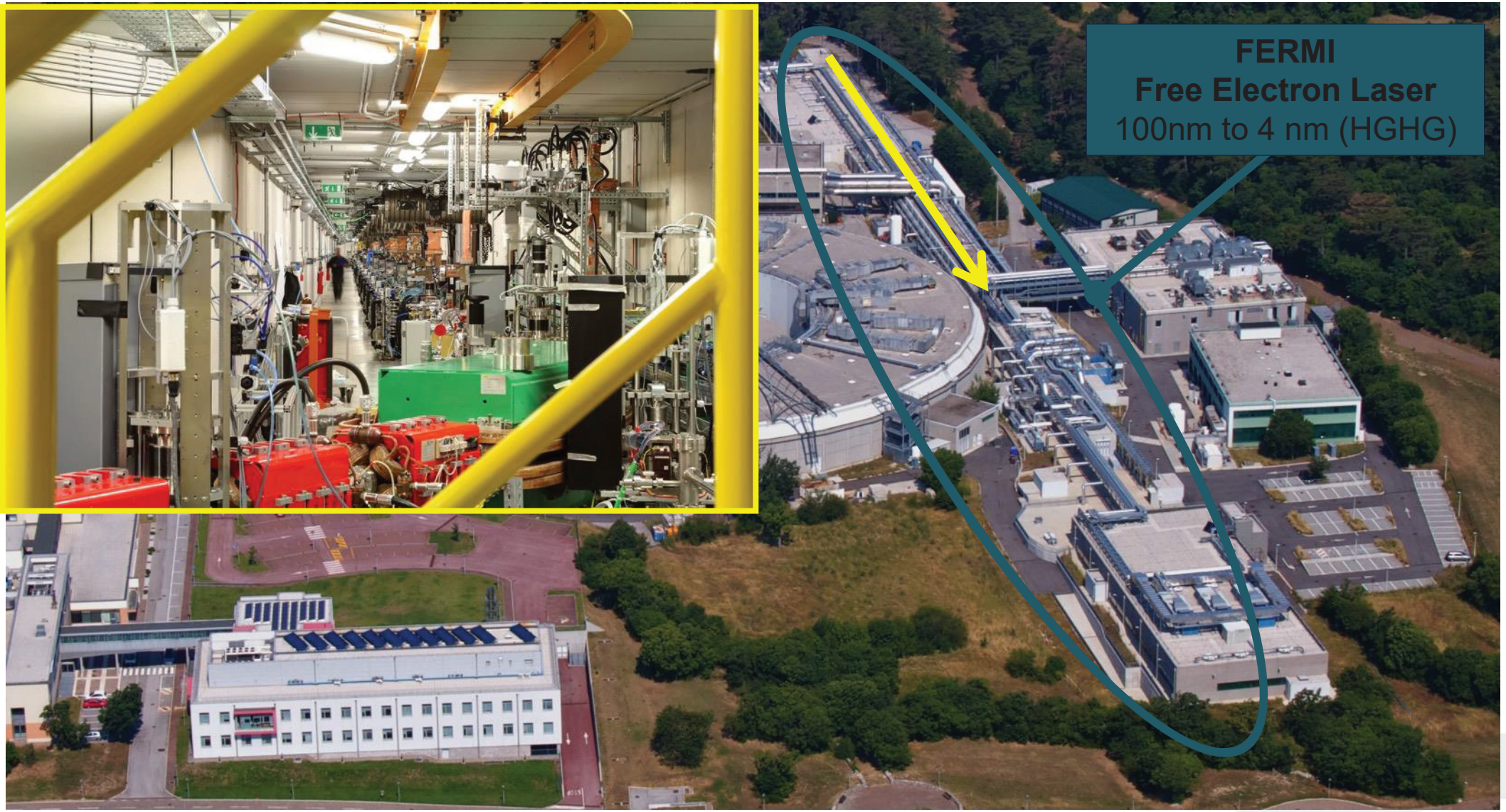
FERMI Free Electron Laser



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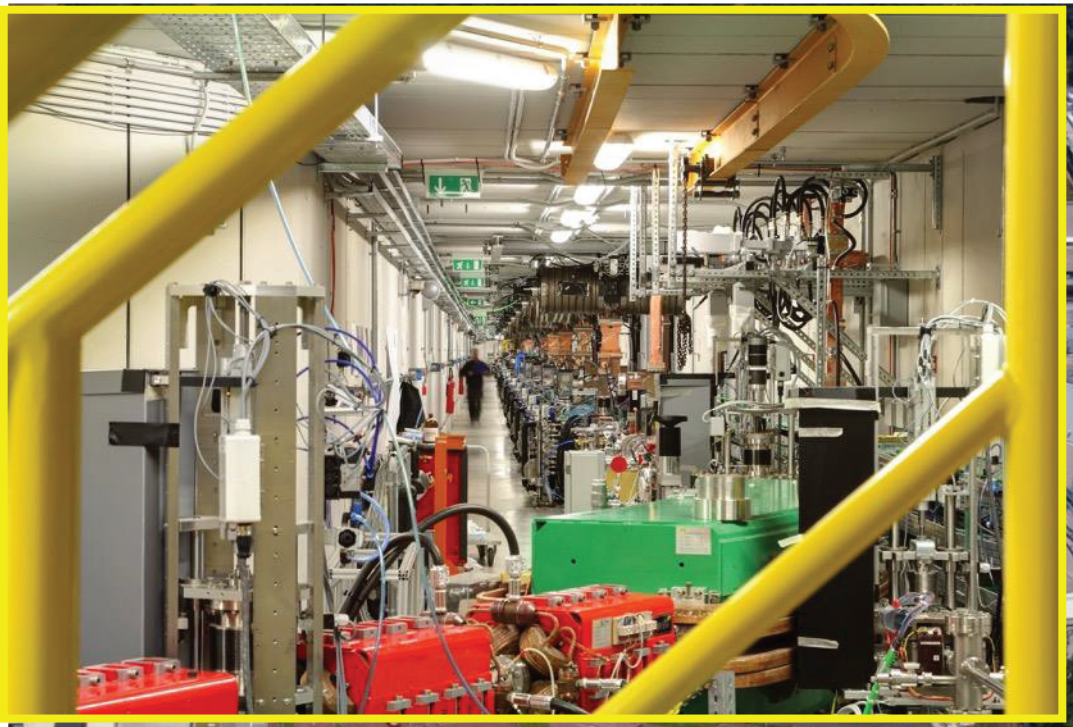

~ 200 m
Linac Tunnel +
Injector Extension

FERMI
Free Electron Laser
100nm to 4 nm (HGHG)

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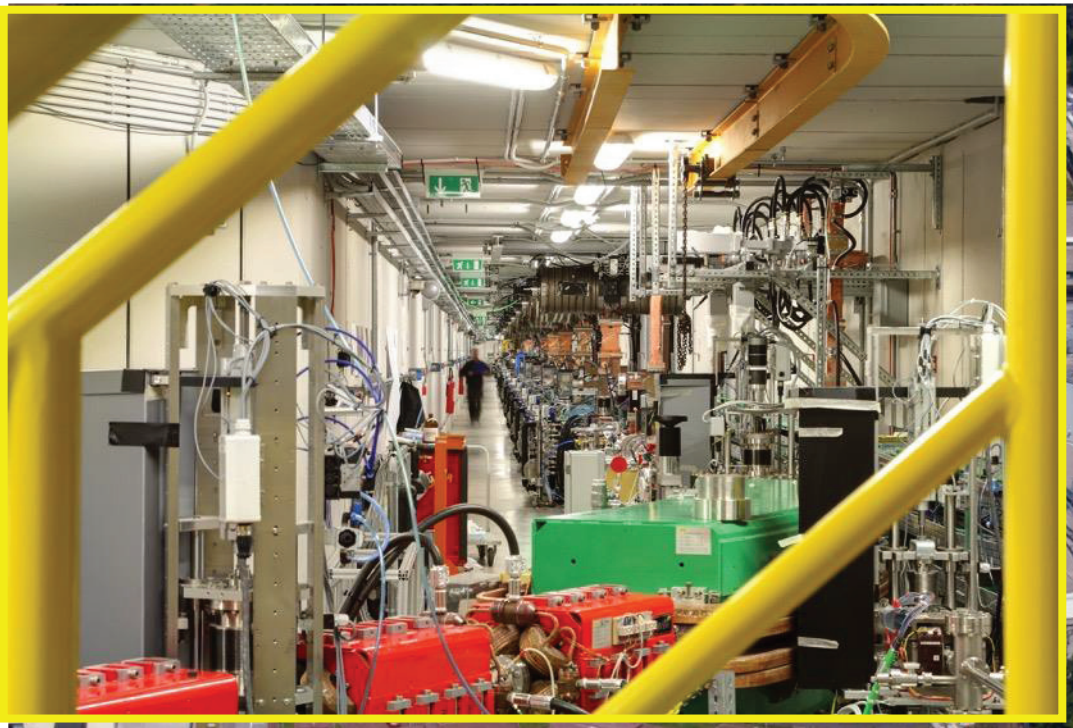
FERMI Free Electron Laser



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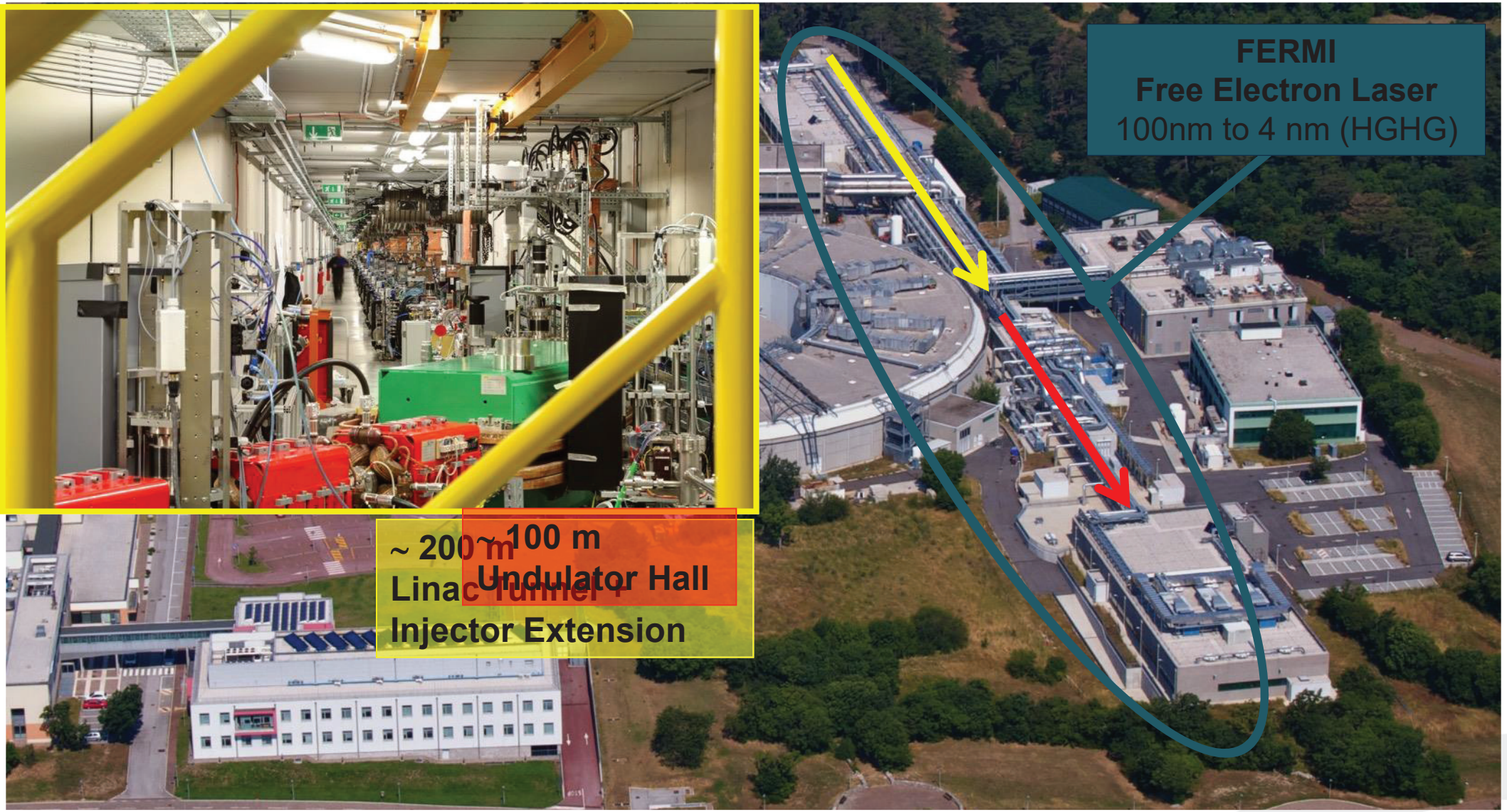

FERMI Free Electron Laser

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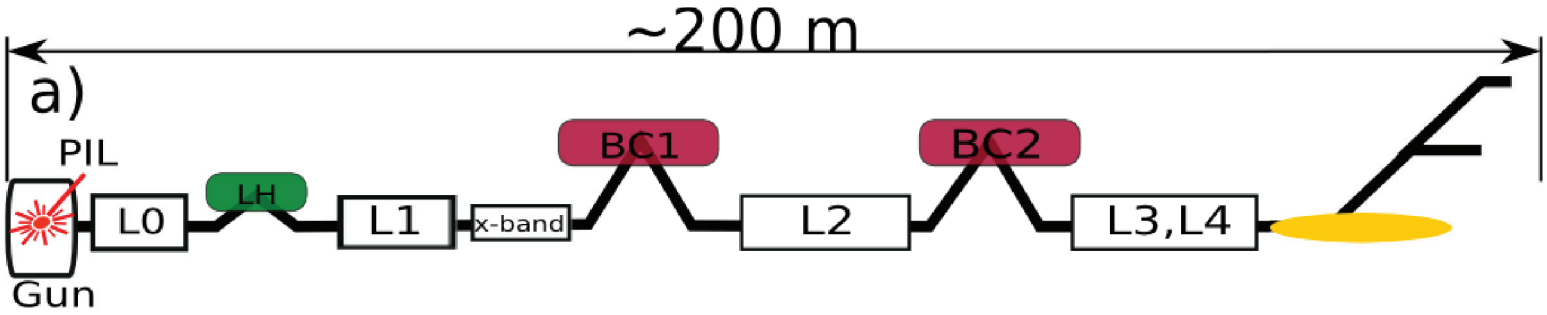
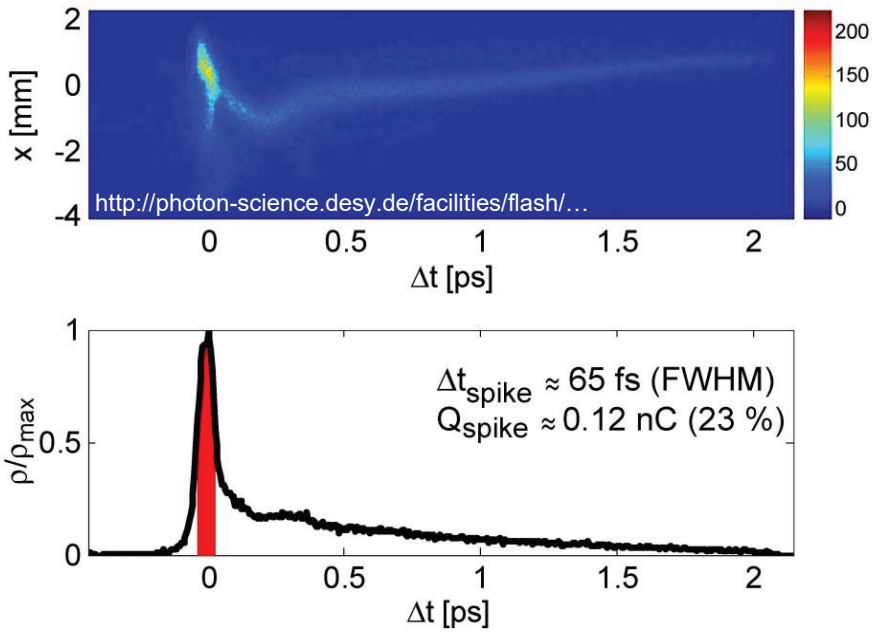
FERMI layout



Linear accelerator:
Rep rate 50Hz
Beam charge 700pC
Beam energy up to 1.5GeV
Peak current ~700A.

Electron beam phase space

E-beam with a current **spike** used for SASE are **not optimal** for seeded FELs.



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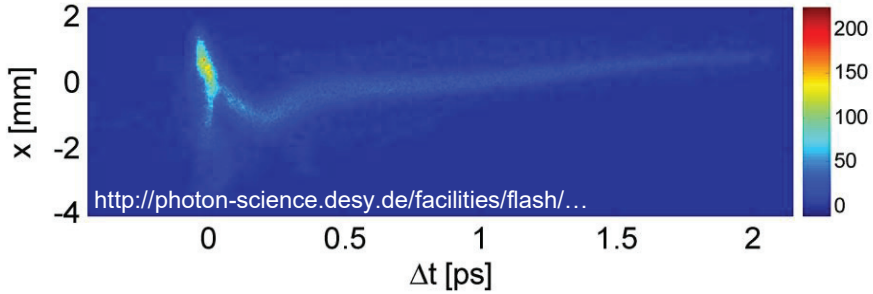

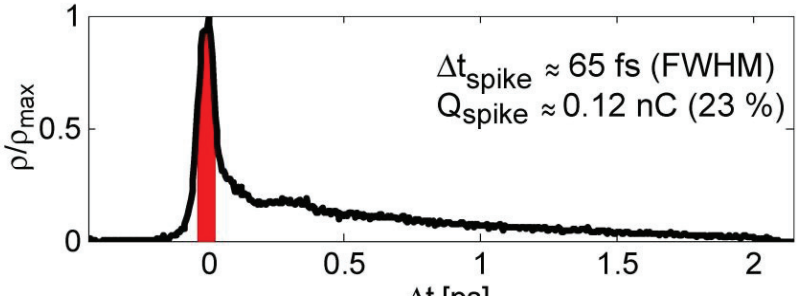

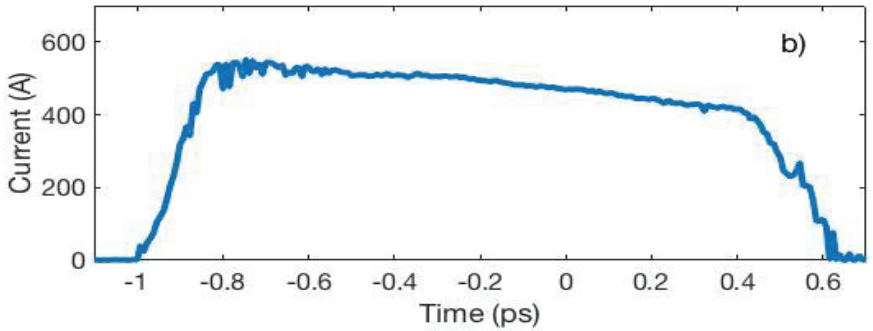

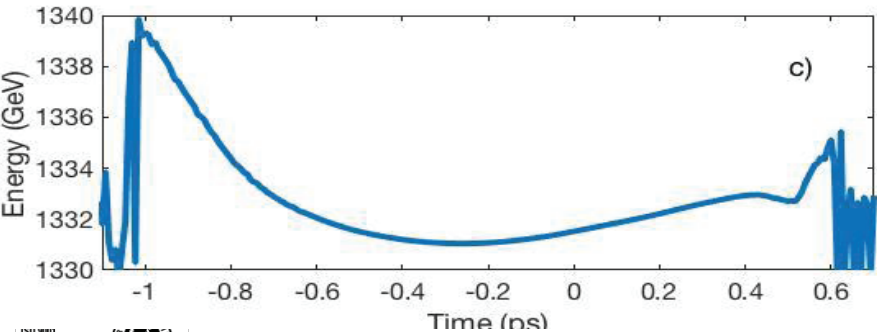

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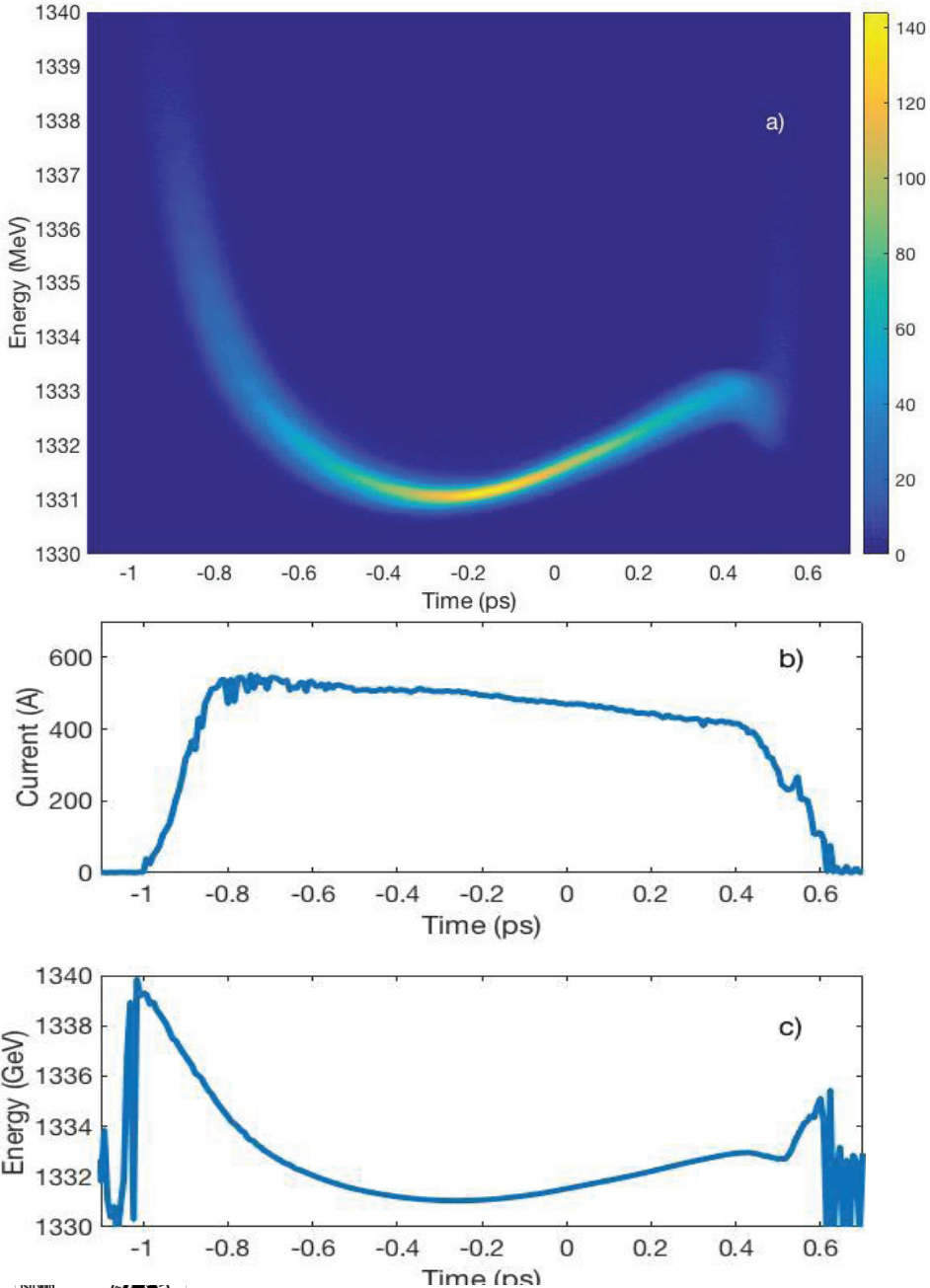

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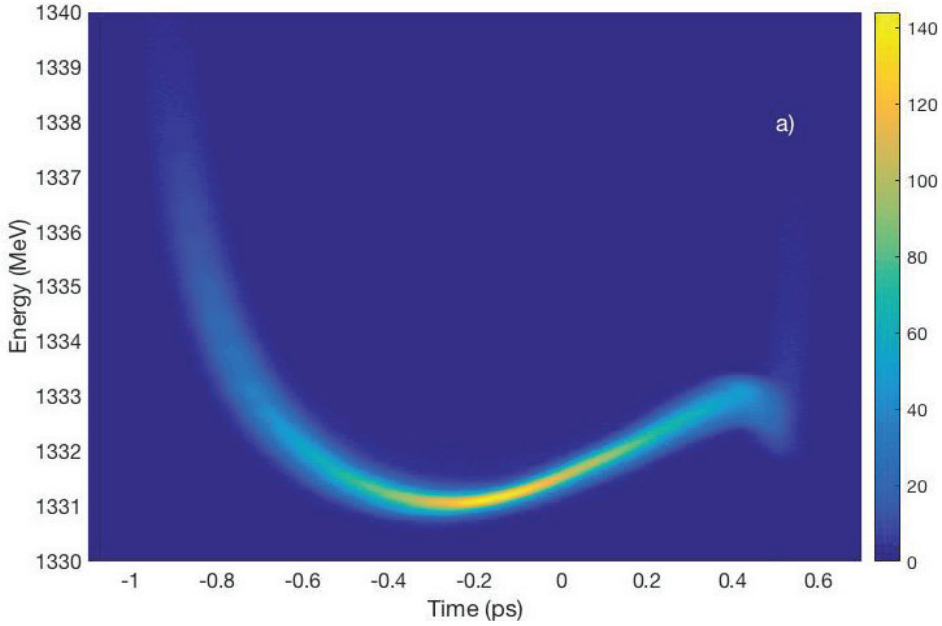

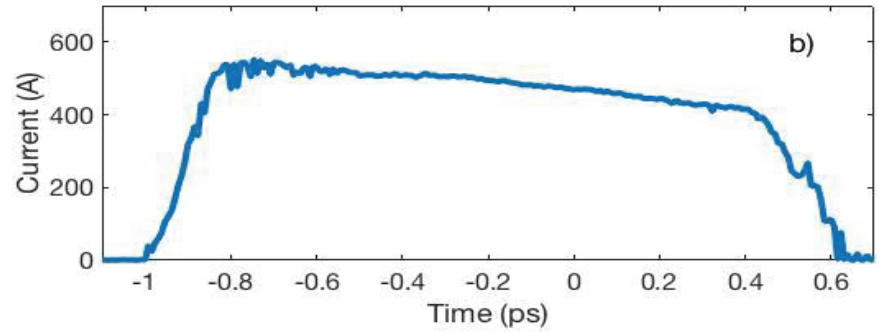

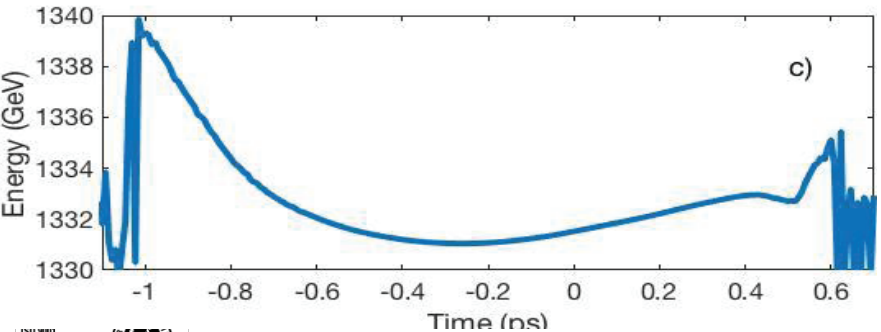

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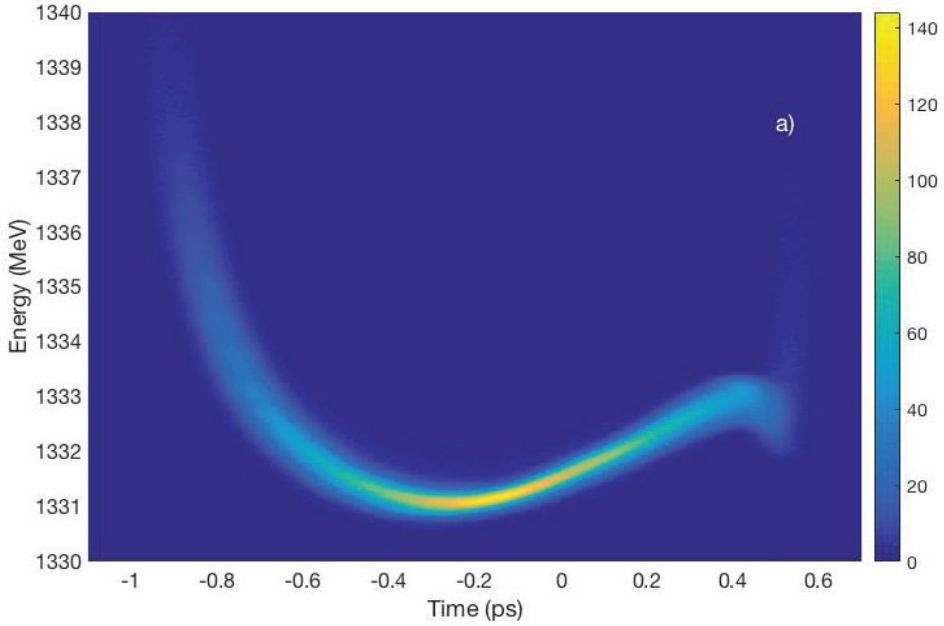
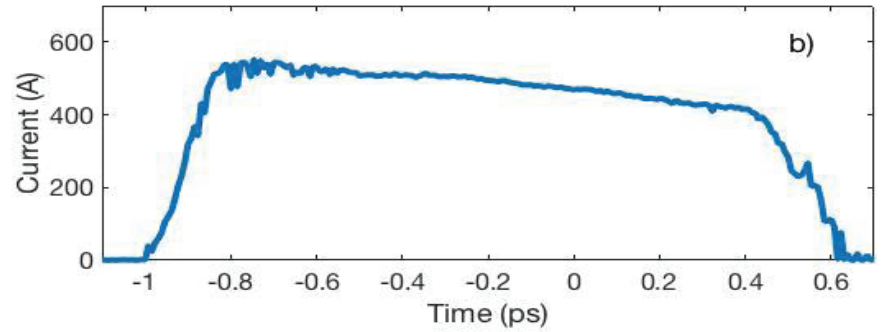
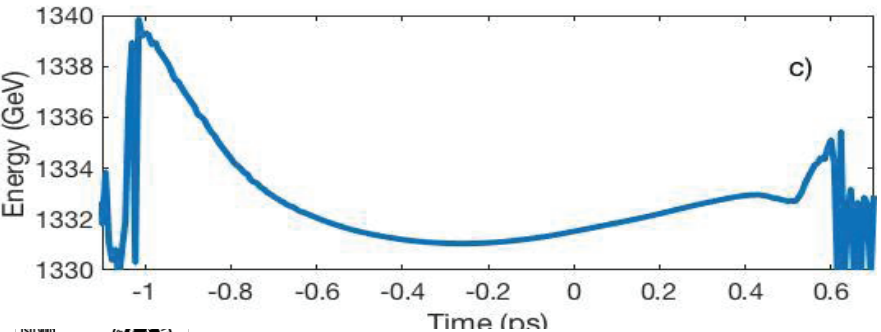
Electron beam **optimization** is **different** than for a **SASE** FEL.

Moderate compression is used.

Electron beam phase space







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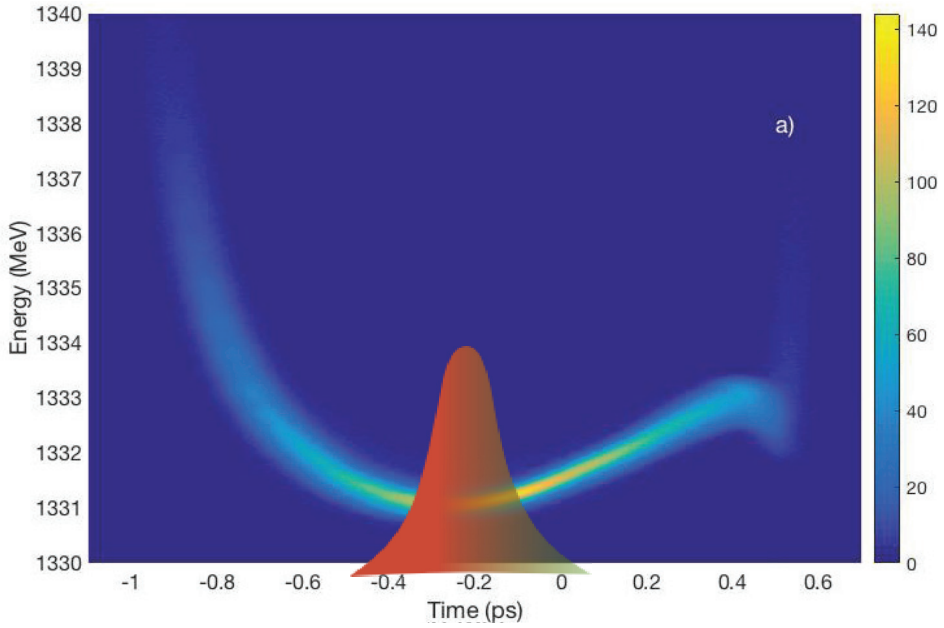

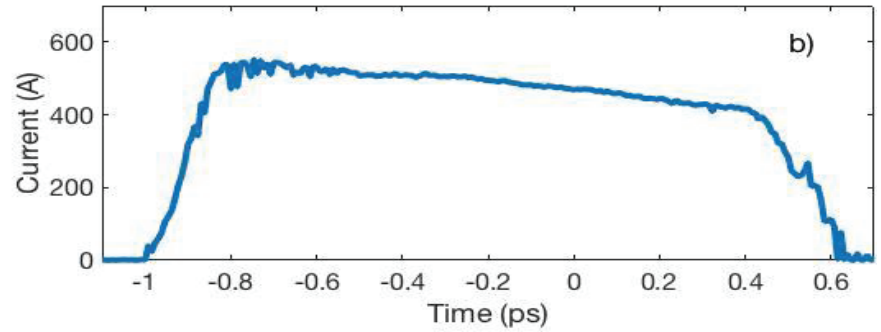

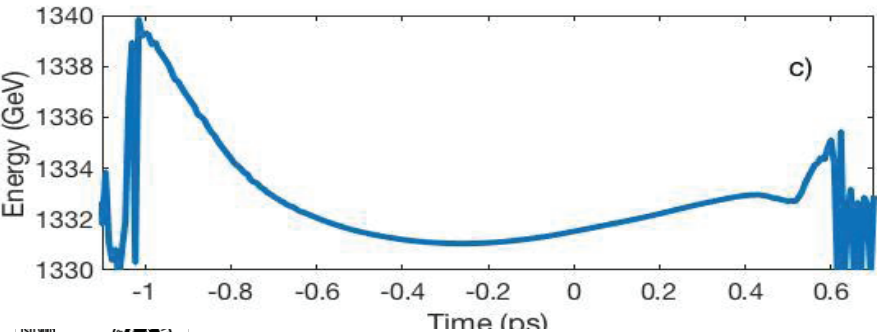

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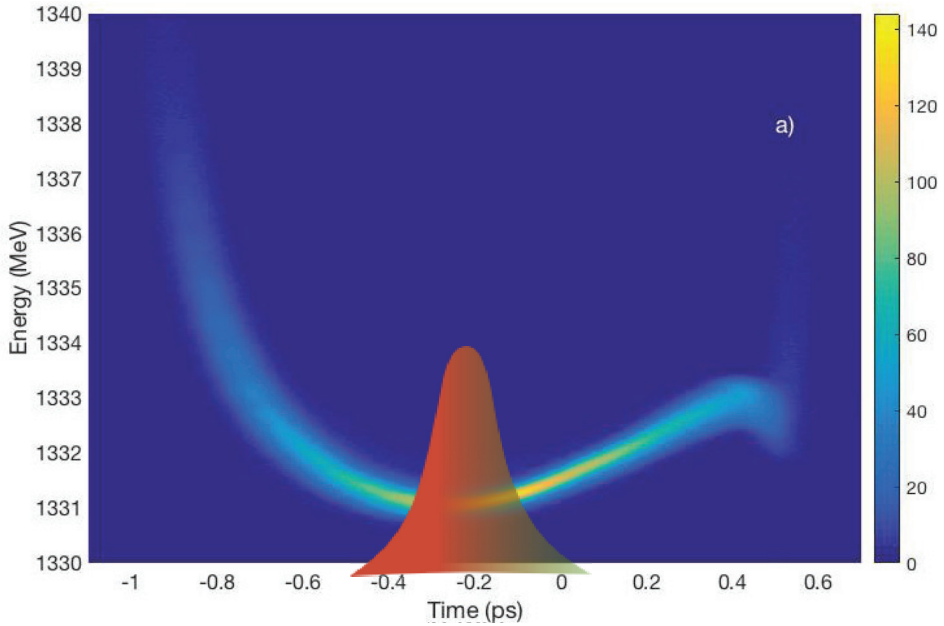

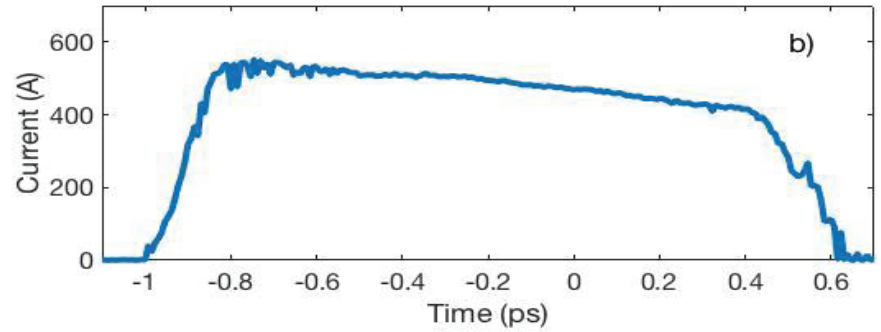

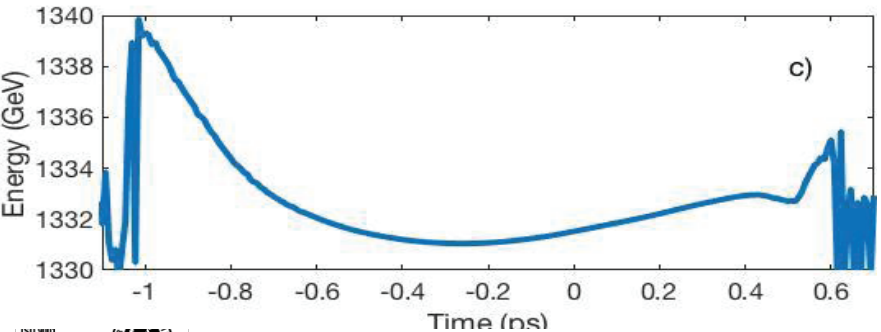

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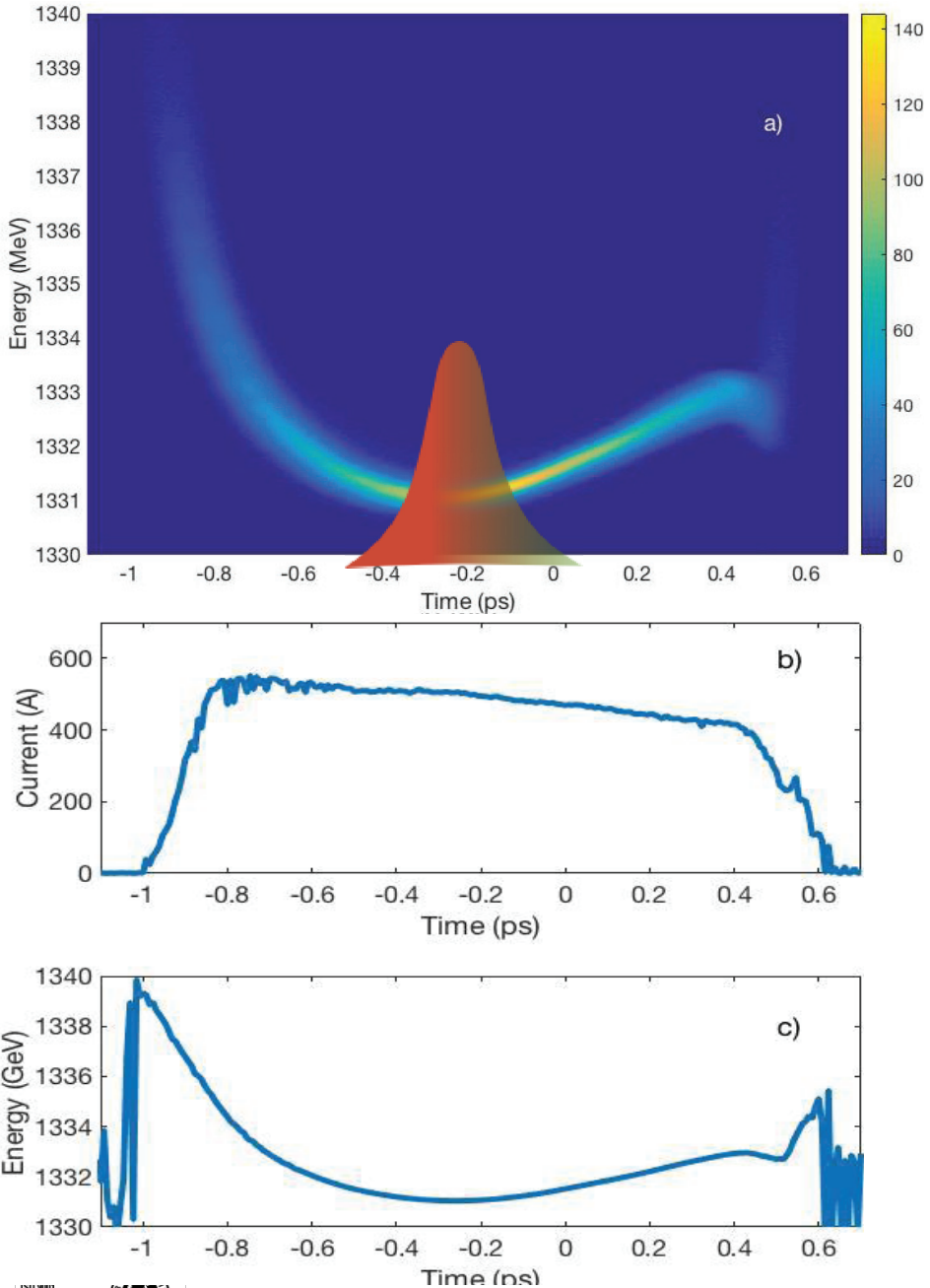
Electron beam parameters

Electron beam phase space



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Electron beam parameters

Charge	700	pC
Peak current	~700	A
Energy	1 – 1.5	GeV
Energy spread	~150	keV
Energy chirp	~3	MeV

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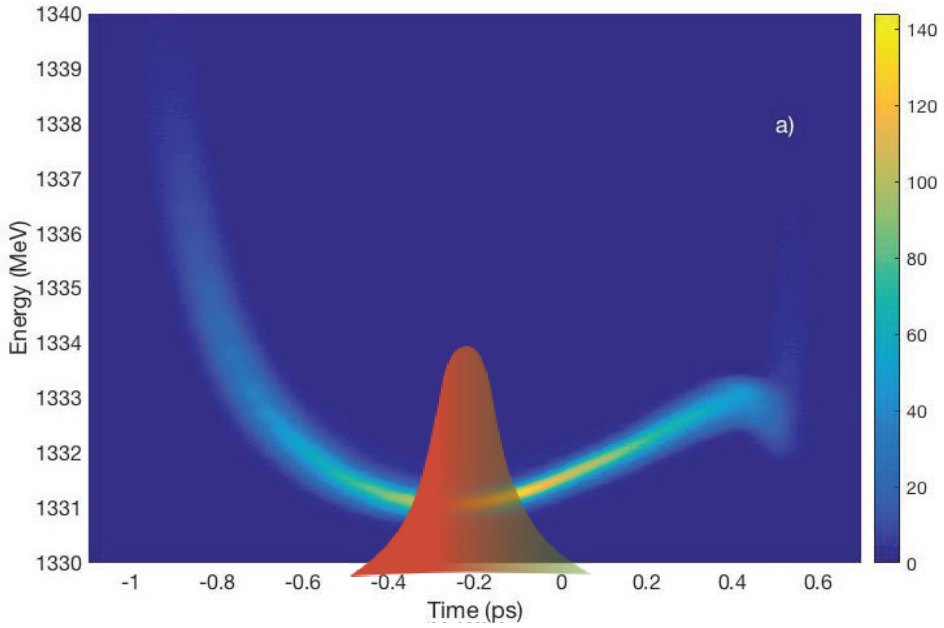
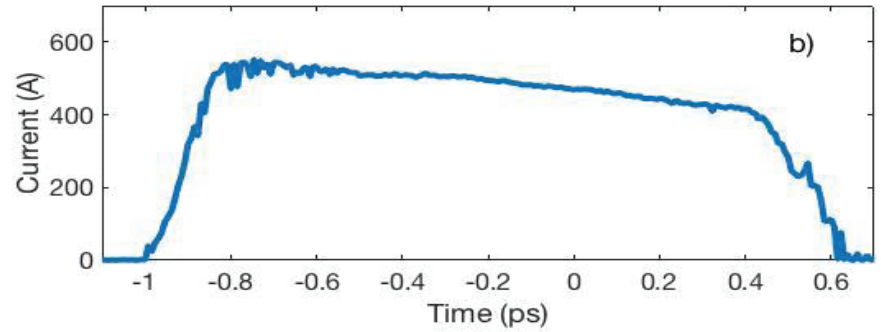
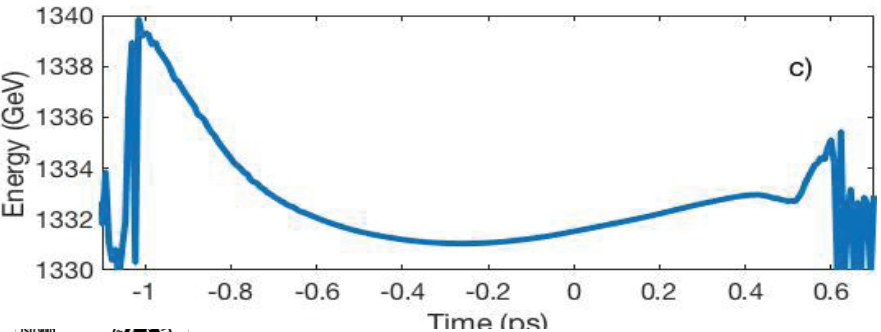
Electron beam phase space







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Peak current	~700	A
Energy	1 – 1.5	GeV
Energy spread	~150	keV
Energy chirp	~3	MeV
Emittance	1	mm mrad
Size (rms)	~100	μm

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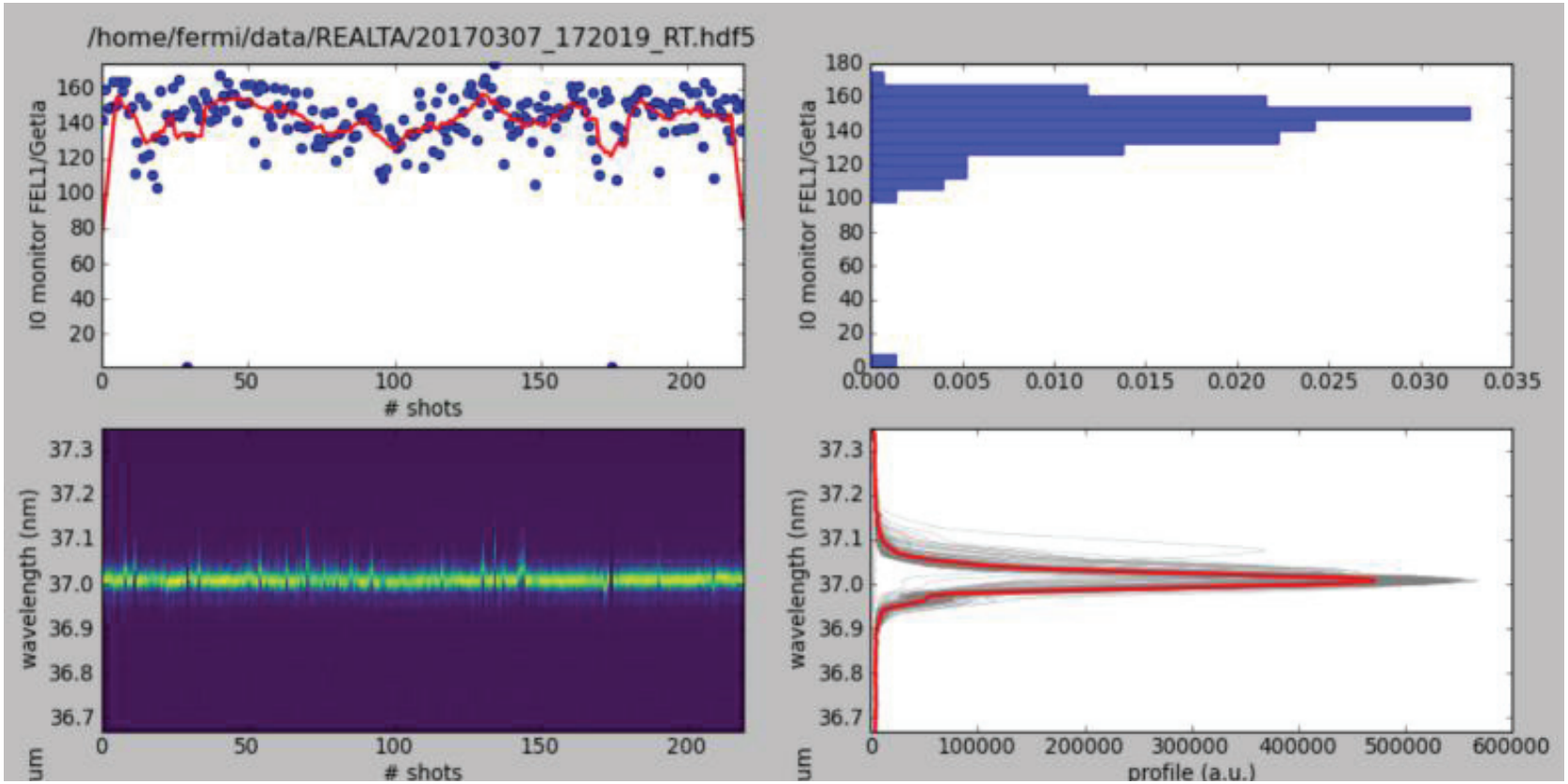
Clean and stable FEL pulses

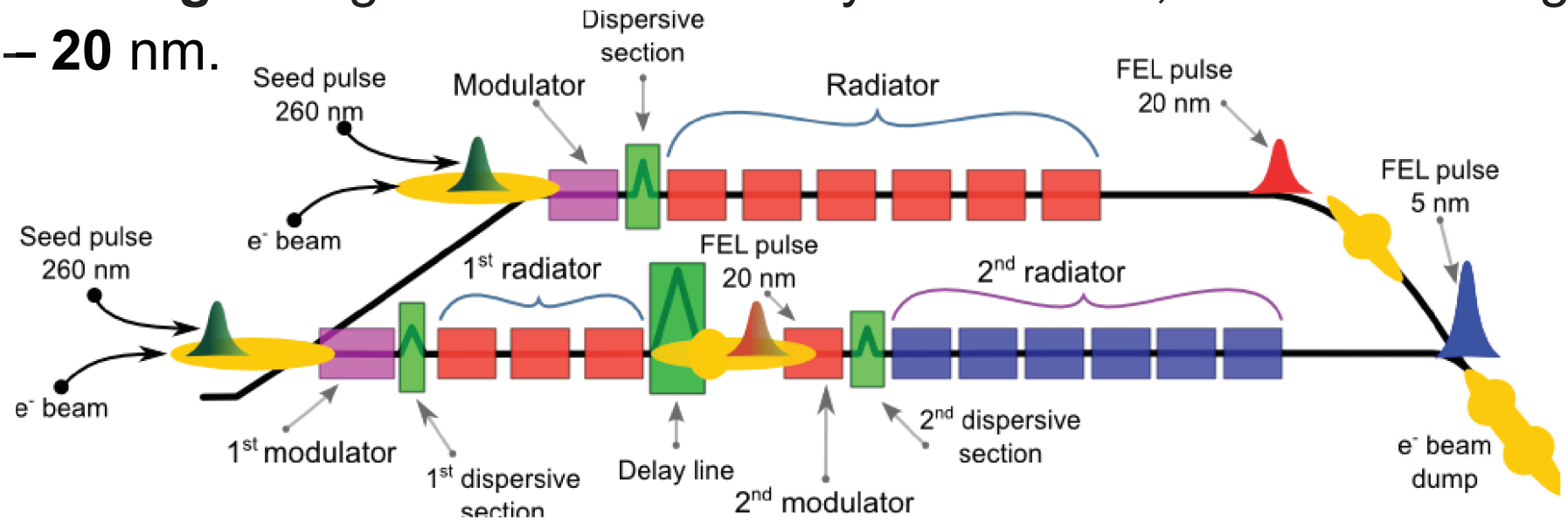
Thanks to the **seeding** and to the **stable** operations of the linac, FEL pulses can be very reproducible in terms of **power** and **spectral** properties.



Fluctuation for the FEL power can be as low as 5% and wavelength fluctuations are a small fraction of the spectral bandwidth.

FERMI FELs: FEL-1 & FEL-2

FEL-1: **single** stage **HGHG** seeded by a **UV laser**, covers the range **100** nm – **20** nm.



FEL-2: **double** cascade HGHG to reach the wavelength **20** nm – **4** nm.

FEL-1 (Nat. Photon. **6**, 699 (2012))	
Tuning range	100-20 nm (12-60eV)
Relative bandwidth	$1x10^{-3}$ (FWHM)
Pulse length	<100 fs
Pulse energy	20-100 μJ

FEL-2 (Nat. Photon. **7**, 913 (2013), JSR 22 (2015))	
Tuning range	20-4 nm (60-300eV)
Relative bandwidth	$1x10^{-3}$ (FWHM)
Pulse length	~50 fs
Pulse energy	10-70μJ

Both FELs have APPLE-II undulators in the final radiator allowing **polarization control**.

EEHG experiment at FERMI

With the **EEHG experiment** we are interested in:

- Detailed **studies** of EEHG at short wavelength;
- **Comparison** of EEHG and HGHG;
- Exploiting **new possibilities** related to EEHG.

The prepared EEHG setup is **not intended** for:

- User's FEL-2 operations;
- Extending FEL-2 wavelength range to shorter wavelengths.

Discussion on **upgrades** of FEL-1 or FEL-2 will be **based on EEHG results**.

G. Stupakov, PRL, 2009

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

Echo Enabled Harmonic Generation

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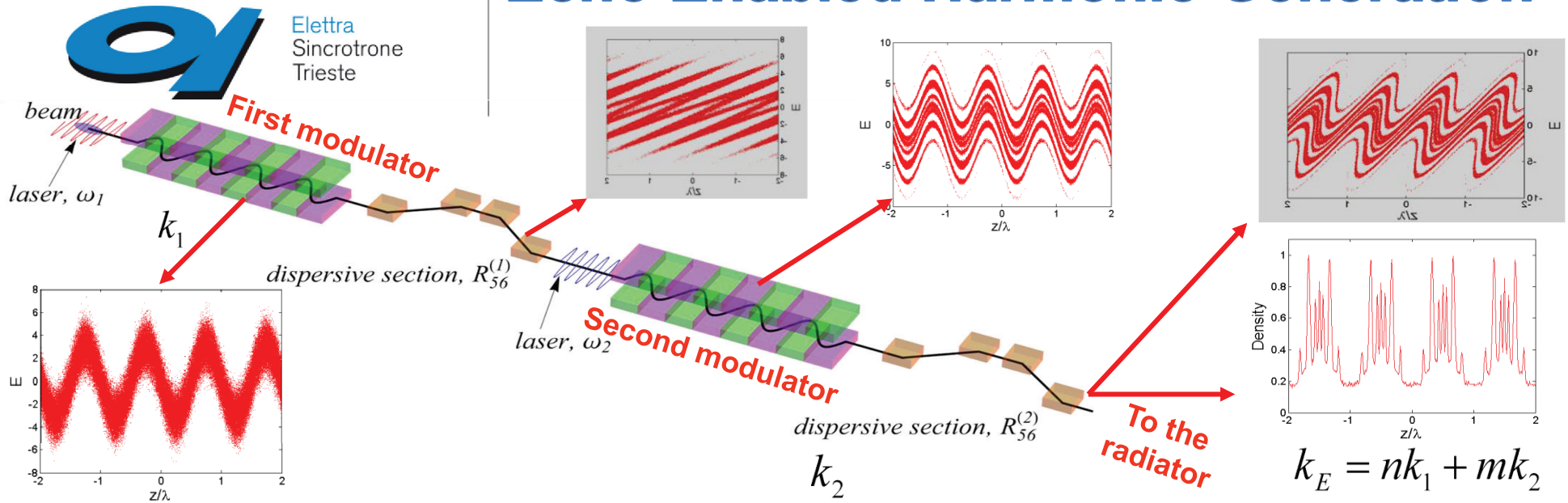

- A first laser generates **energy modulation** in electron beam.
- A strong chicane creates **stripes** in the longitudinal phase space.
- A **second** laser imprints **energy modulation**.
- The second chicane converts energy modulation into harmonic **density modulation**.

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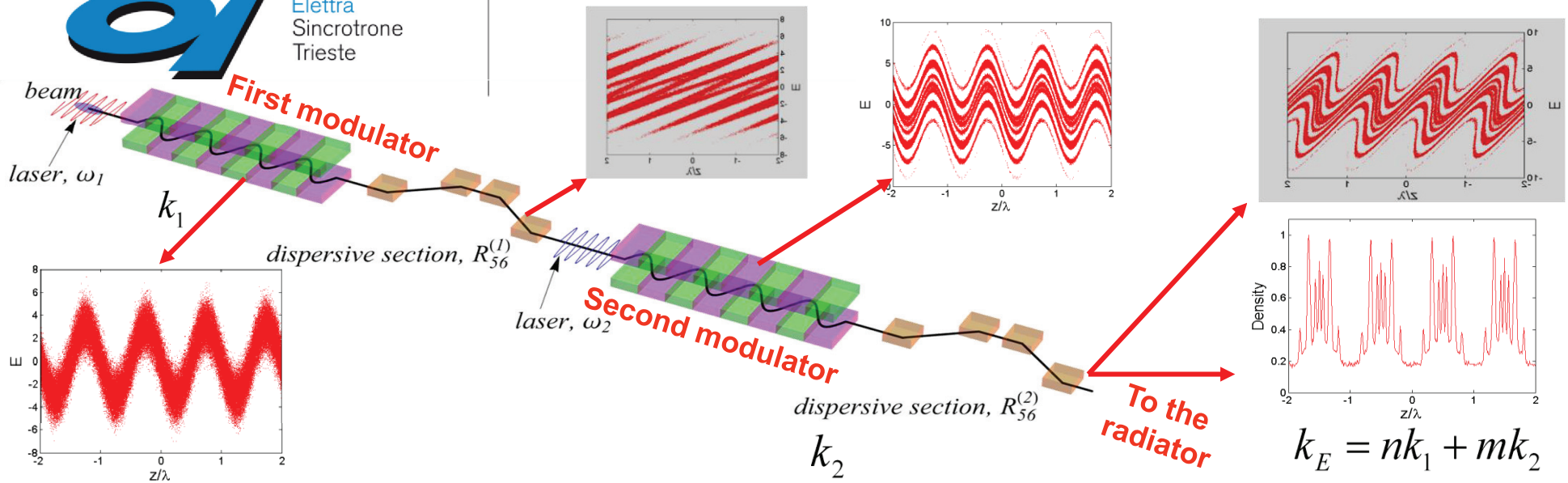
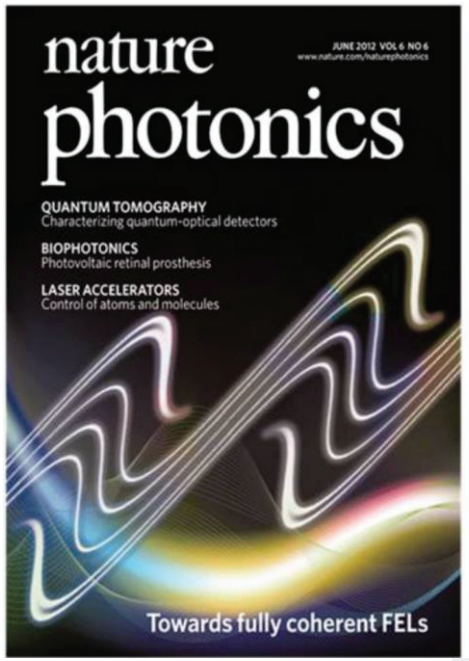
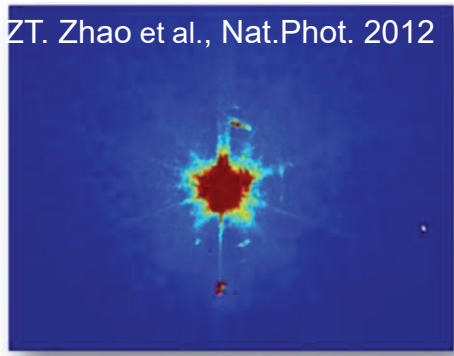
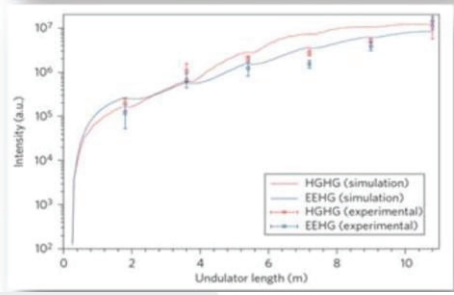


$$k_E = nk_1 + mk_2$$

- A first laser generates **energy modulation** in electron beam.
- A strong chicane creates **stripes** in the longitudinal phase space.
- A **second** laser imprints **energy modulation**.
- The second chicane converts energy modulation into harmonic **density modulation**.
- **FEL amplification** of EEHG bunching has been demonstrated at SINAP at the 3rd harmonic.







Courtesy of SLAC ECHO team

NLCTA : EEHG experiments

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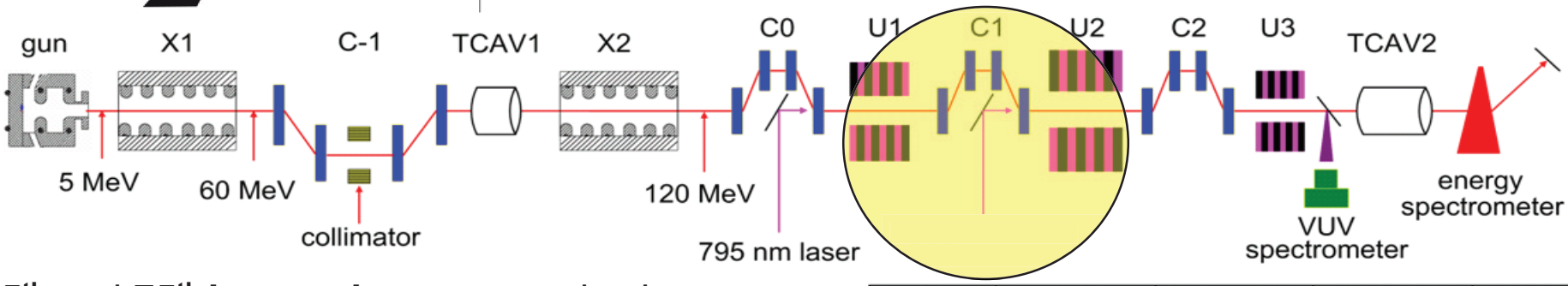
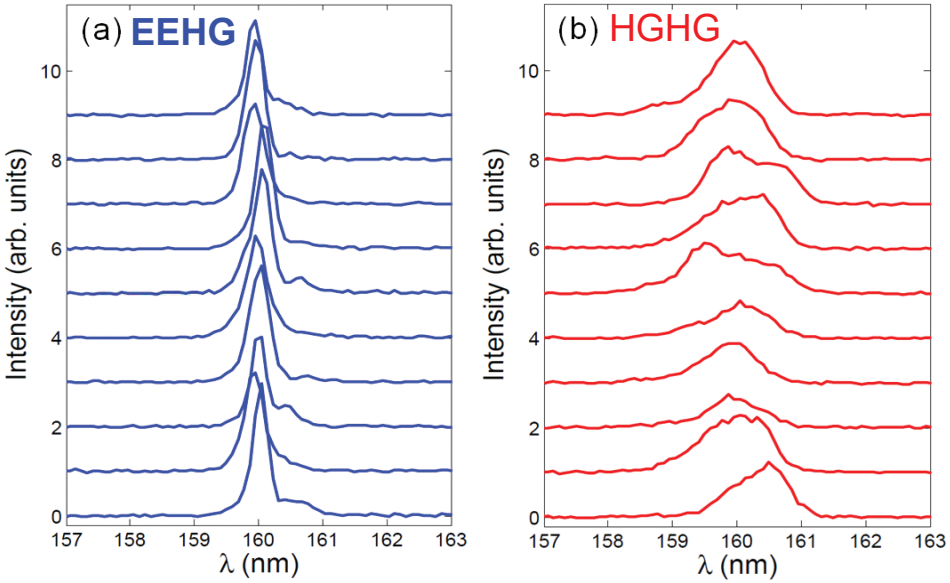
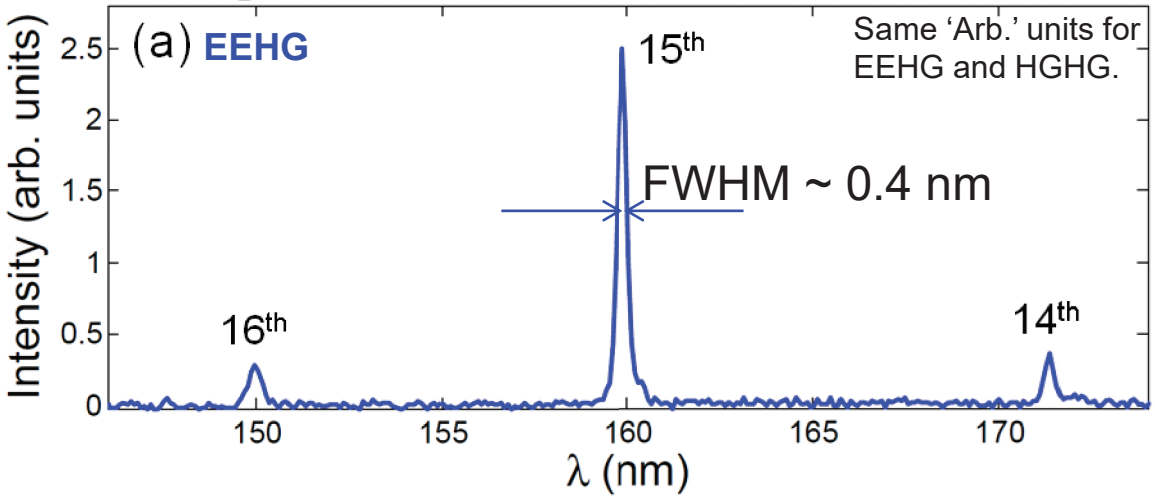
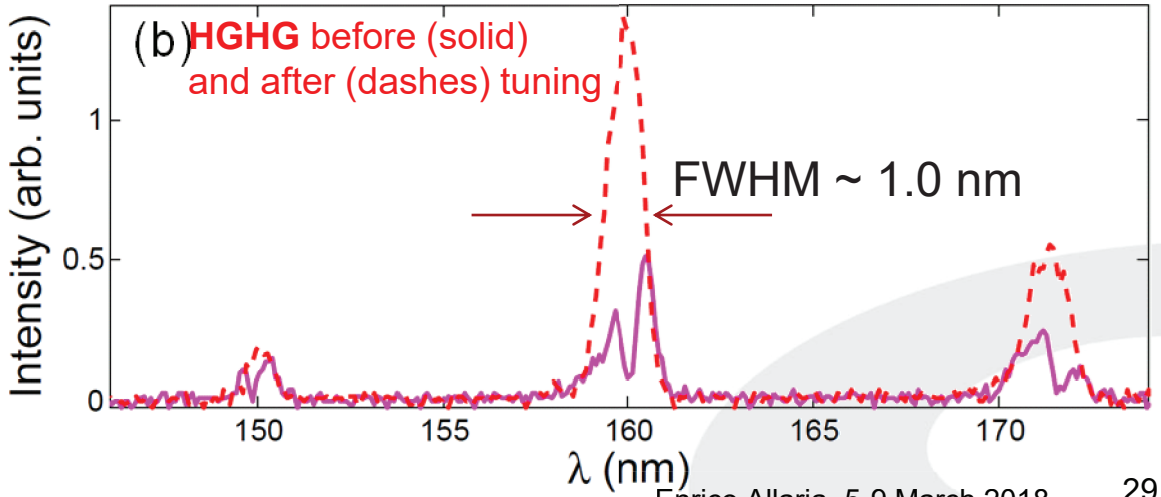


15th and **75th harmonics** measured using a longer wavelength seed.







Experiment shows **better spectral properties with EEHG**.

E. Hemsing, et al PRST-AB **17**, 070702 (2014)
E. Hemsing, et al Nat. Photon. **10**, 512–515 (2016)

Courtesy of SLAC ECHO team

NLCTA : EEHG experiments

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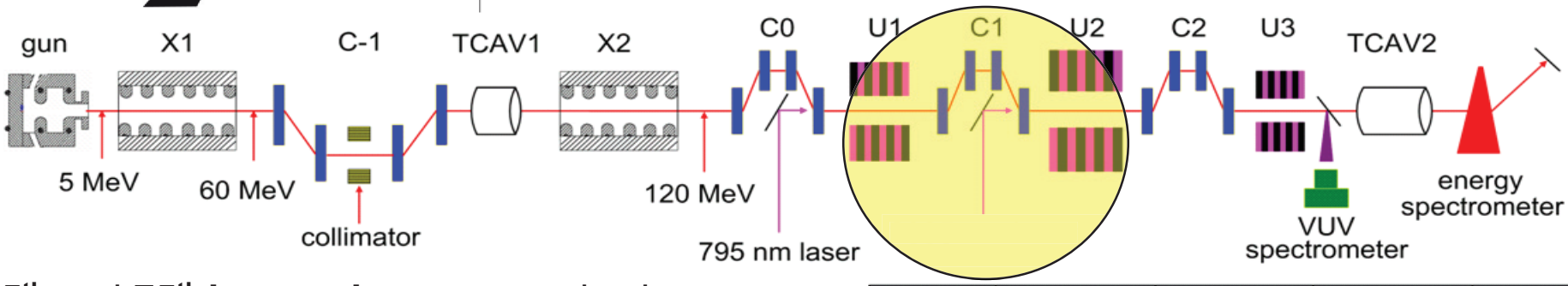

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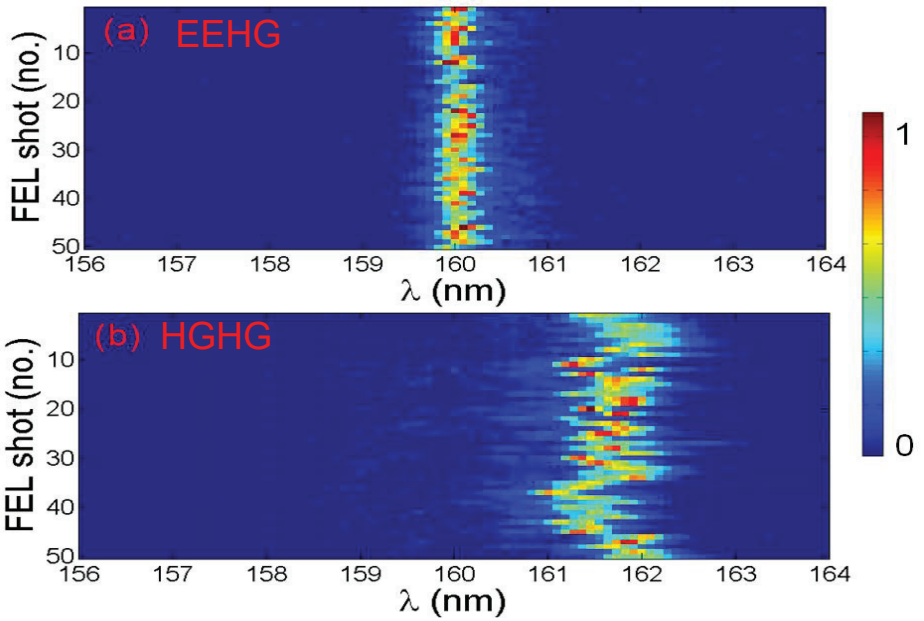

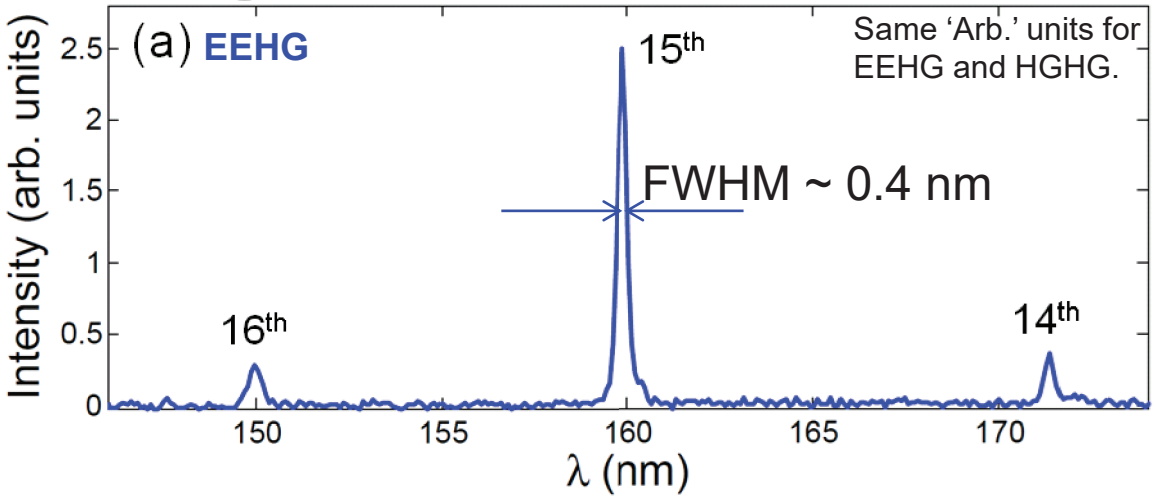

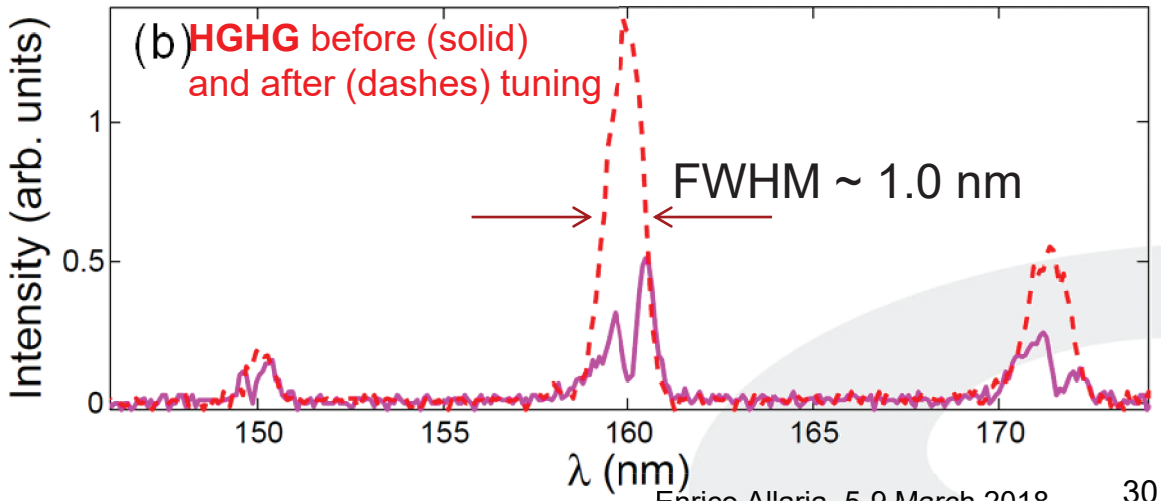

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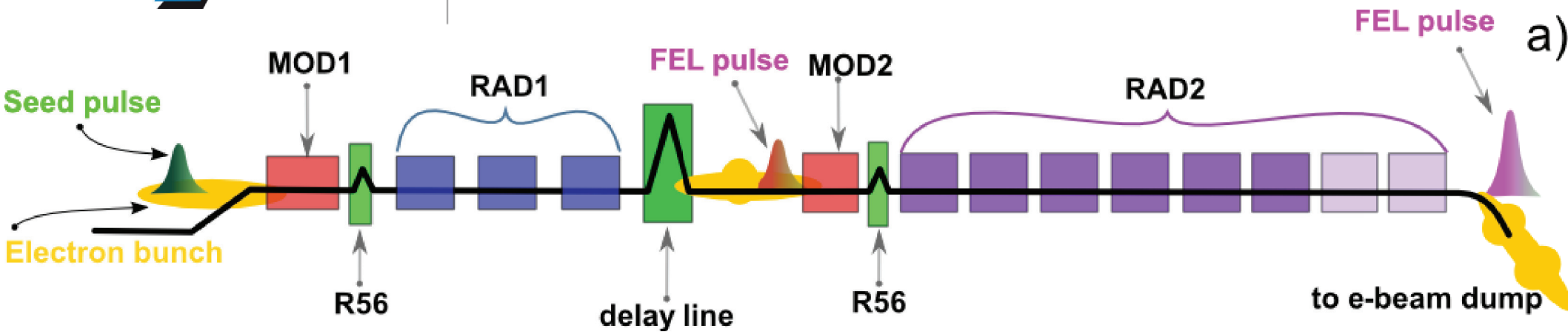
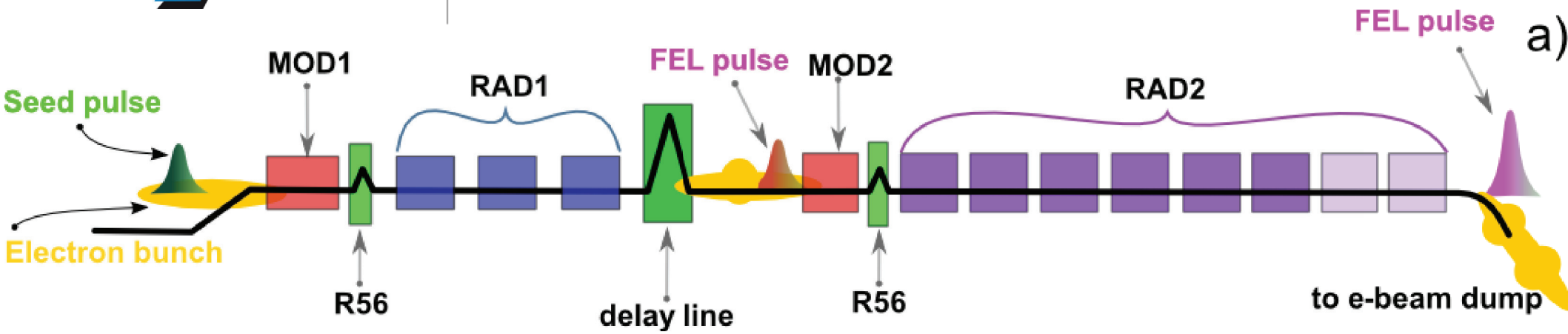
FEL-2 from HGHG-FB to EEHG

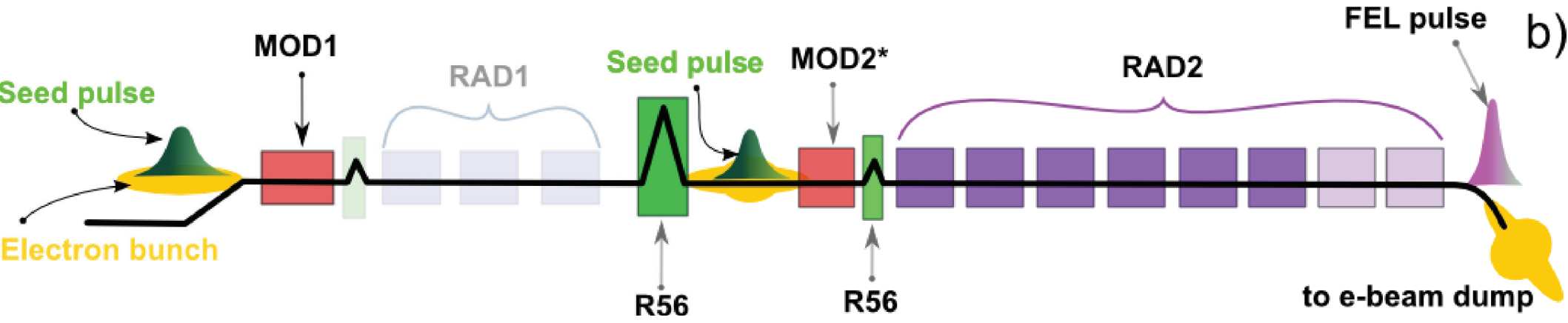


First stage emits coherent harmonic radiation at ~20 nm used as a seed for the second stage.

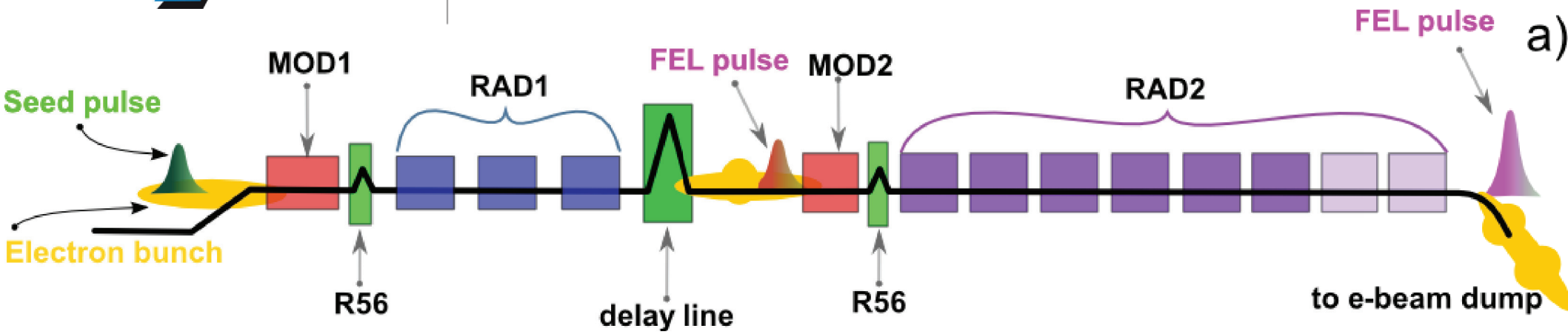
FEL-2 from HGHG-FB to EEHG



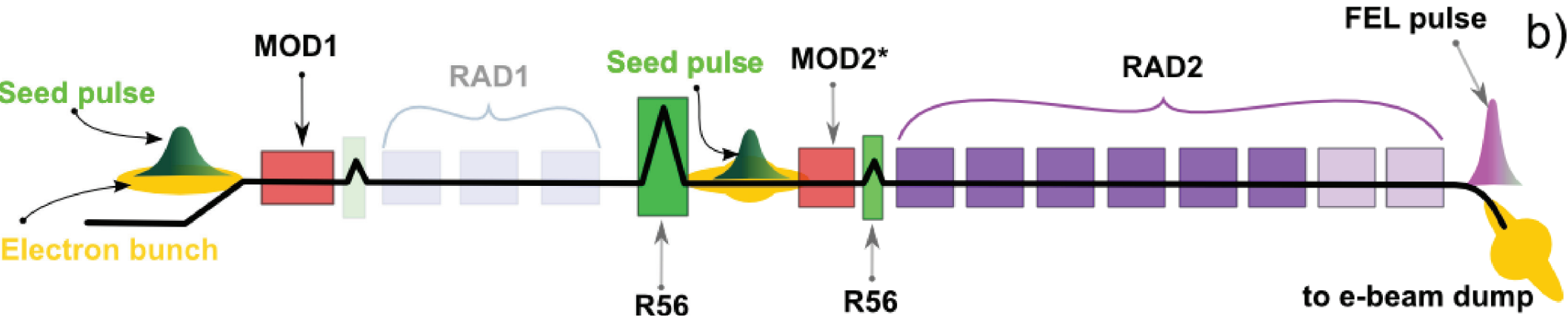
First stage emits coherent harmonic radiation at ~20 nm used as a seed for the second stage.



FEL-2 from HGHG-FB to EEHG



First stage emits coherent harmonic radiation at ~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.

Modifications for EEHG at FEL-2: Dispersion

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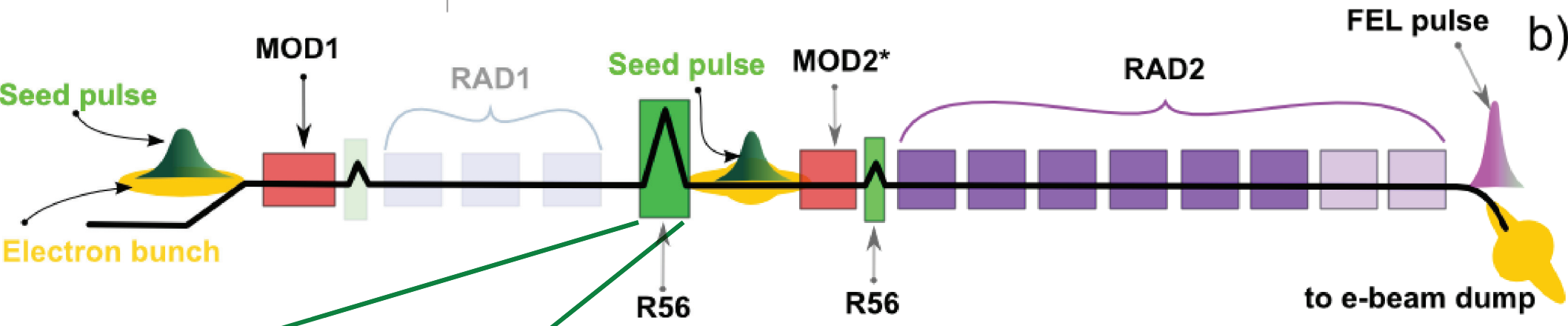
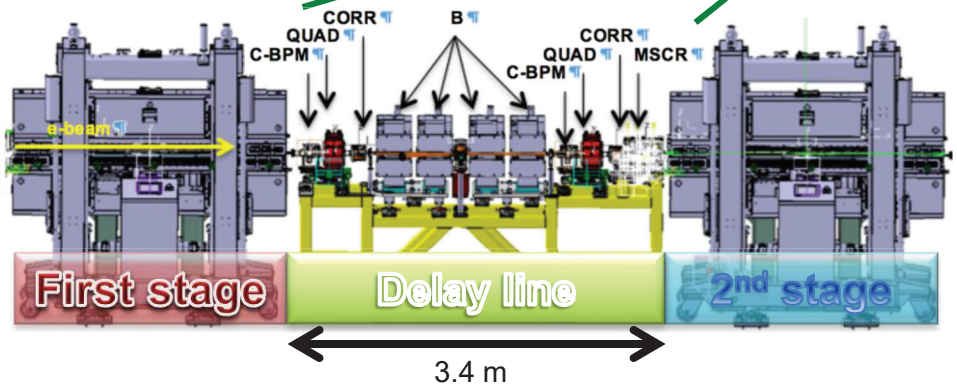
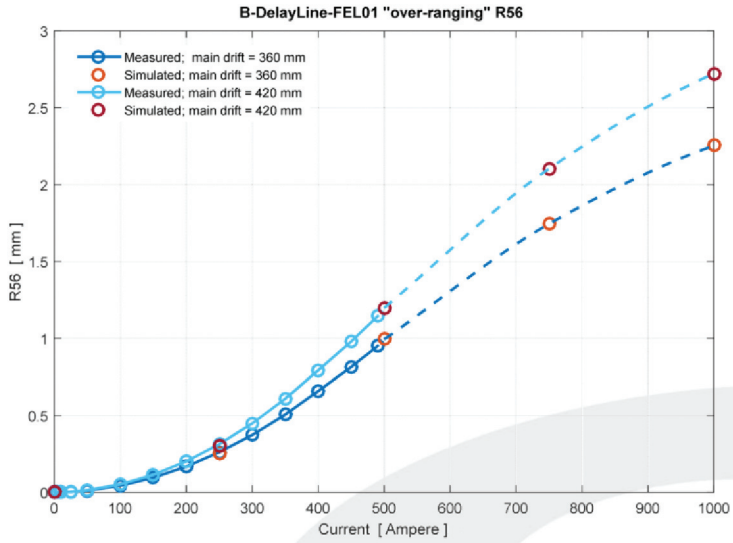




EEHG requires a **stronger dispersion** in the the delay-line chicane.



- **New supports** for magnets have been **installed** to increase the magnet separation to > 400 mm.
- Two available **power supplies** used in parallel have been **tested** and have shown to be suitable for generating the required 750 A.

Modifications for EEHG at FEL-2: Injection

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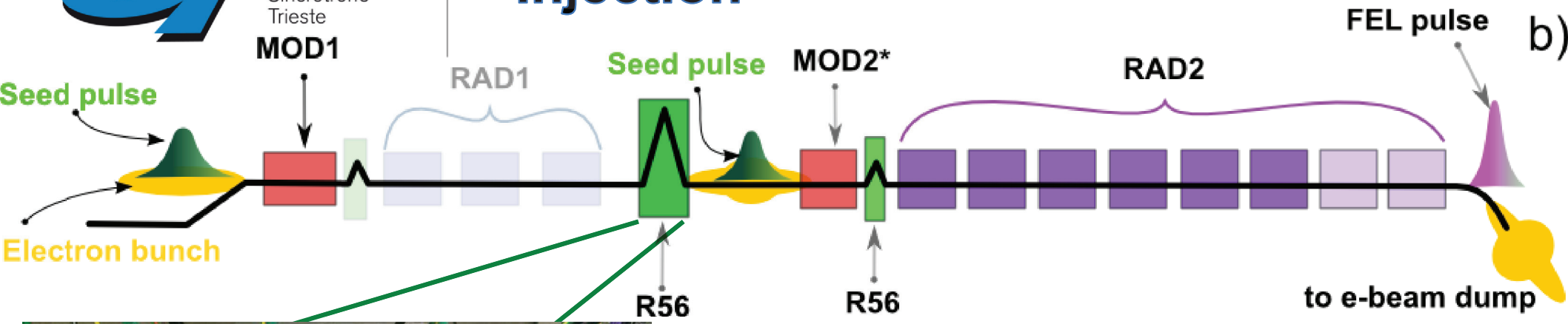
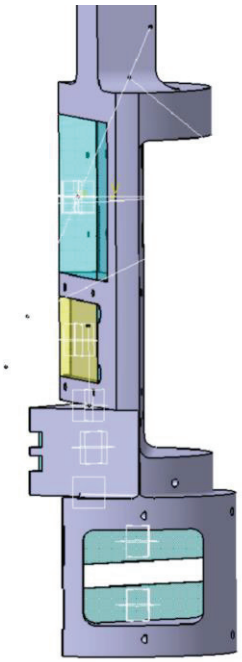
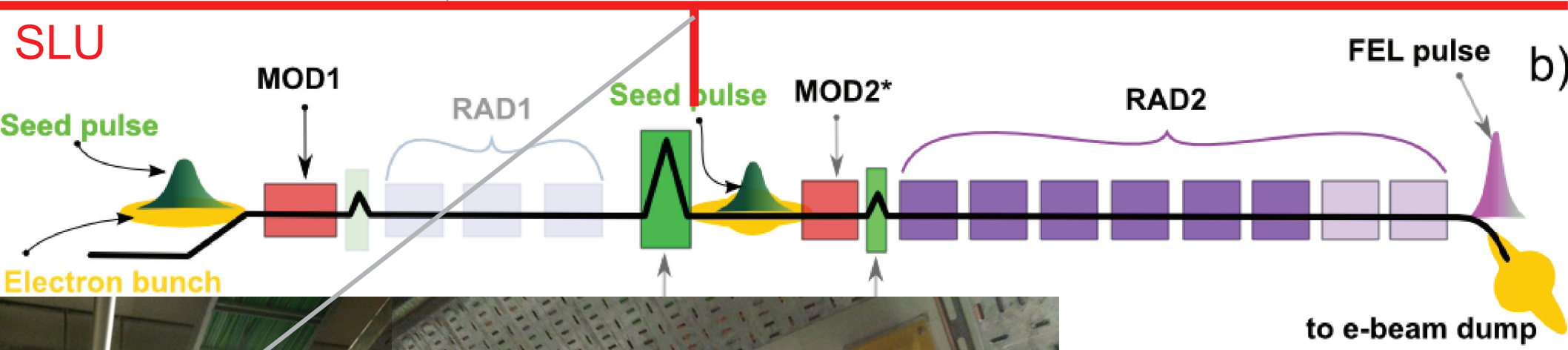


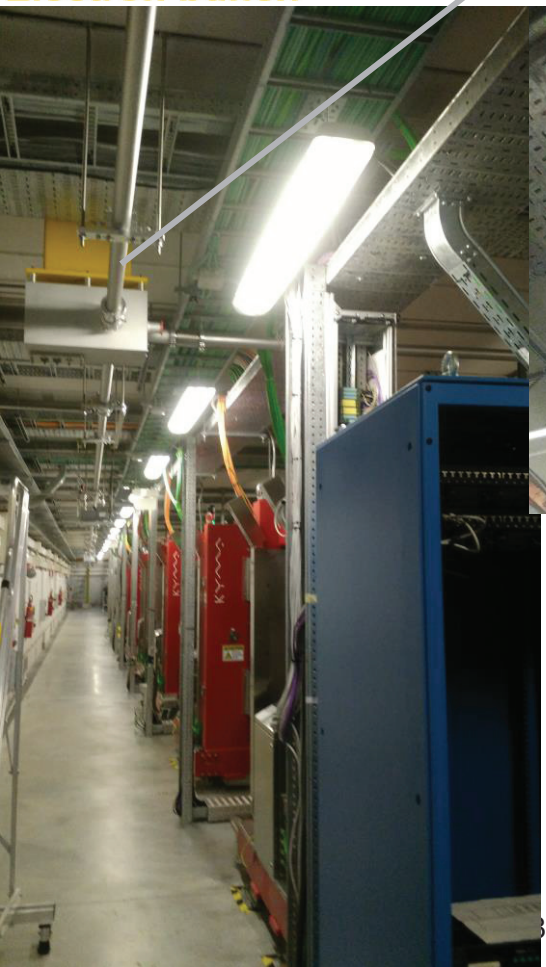
Injection system for second seed in delay-line.



- New **vacuum chamber received**, actuator required some refinement.
- **Tests** started in **metrology lab**.
- Mirrors and diagnostic components received.

Modifications for EEHG at FEL-2: second seed





Second seed pulses generated from a portion of infrared laser converted to the 3rd harmonic in the undulator tunnel.

- The **SLU splitting chamber** has been **installed**.
- **Transport path** to the EEHG seed laser table **ready**.
- **Optical** table, **components** and systems **received**.

Modifications for EEHG at FEL-2: second modulator

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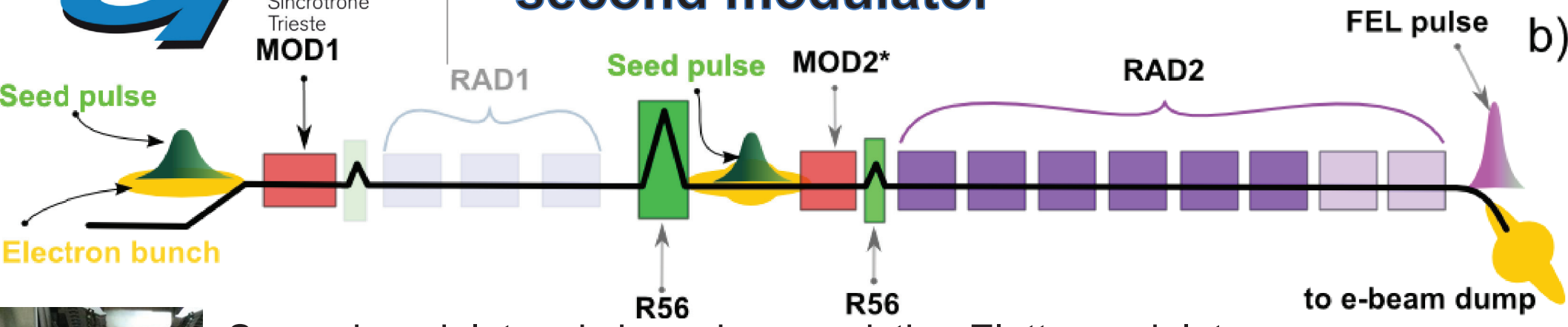
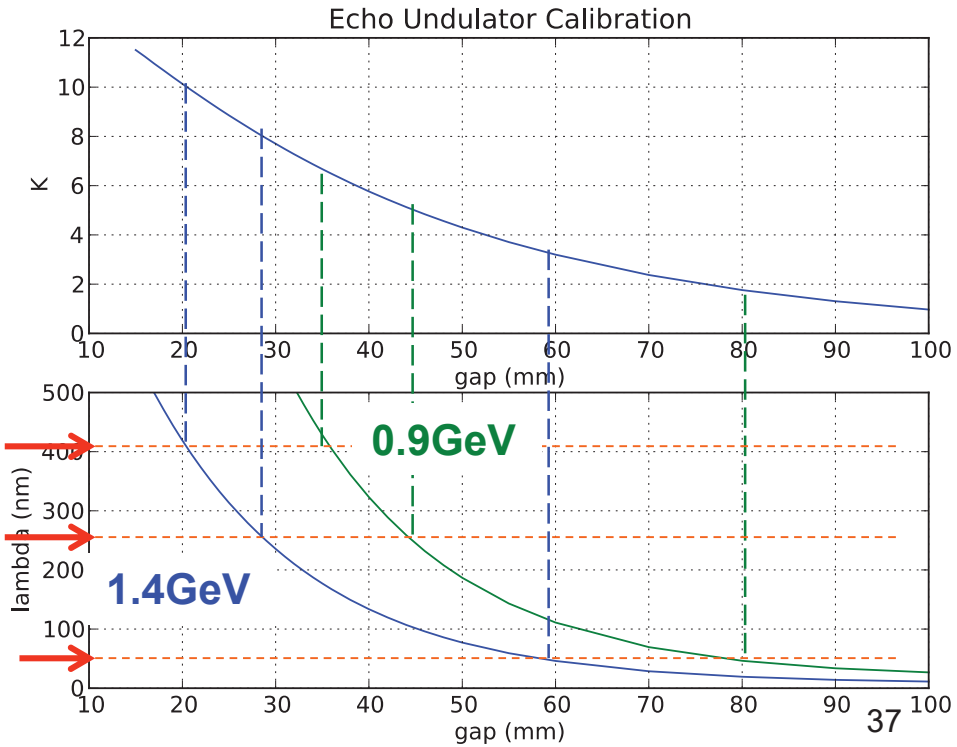


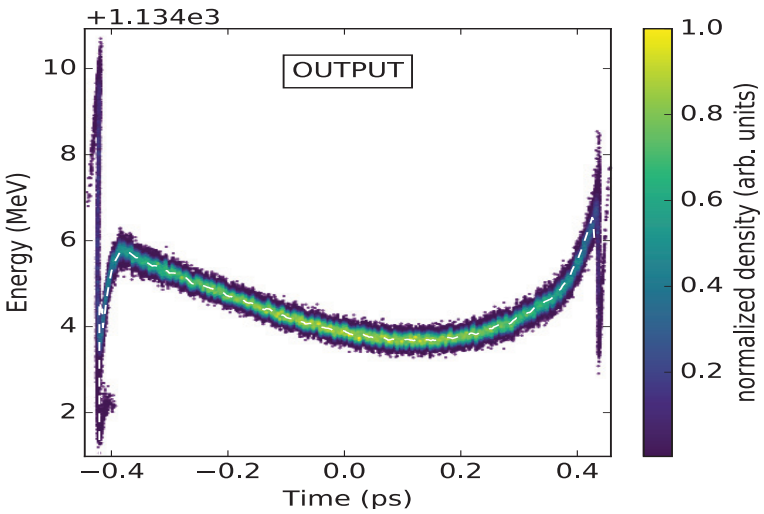
Second modulators is based on a existing Elettra undulator.
Parameters for U113 undulator are:
Length: ~1.5 m
Period length:11.3 cm
Minimum gap: 10 mm

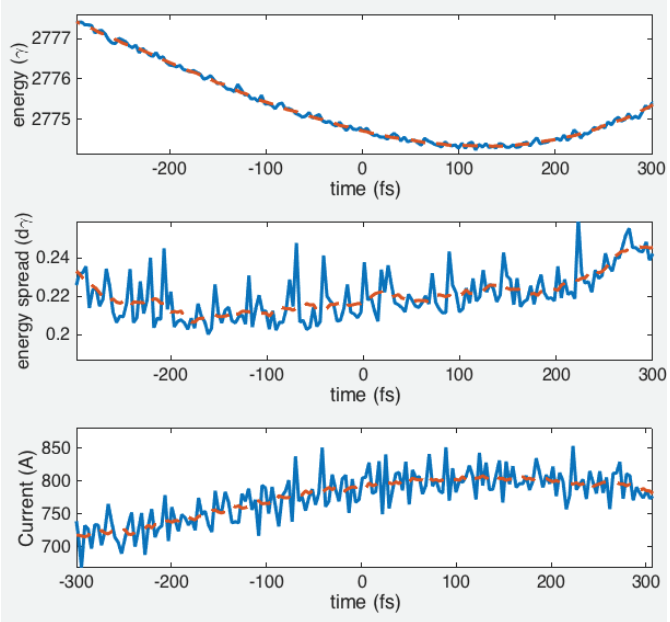
New undulator allows **seeding** with **3rd** and **2nd harmonic** of the Ti:Sa laser.
It can also be used for the **standard 2 stages HGHG** with the first stage in the **40-60 nm** spectra range.



- **Undulator** is **ready** and will be installed in April.

Start to end FEL simulations





Main studies done with **standard** FERMI e-**beam** optimized for FEL-1 and FEL-2 operations.

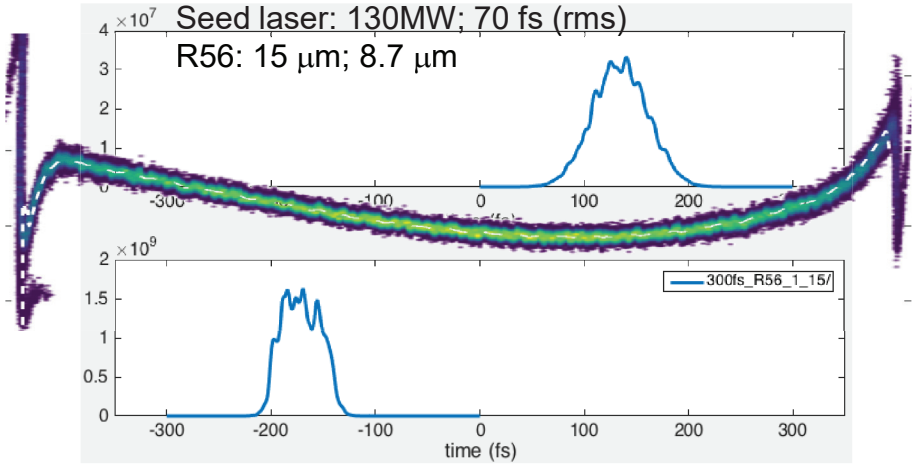
Long beam is **not necessary** for EEHG but it allows a direct comparison with HGHG-FB.

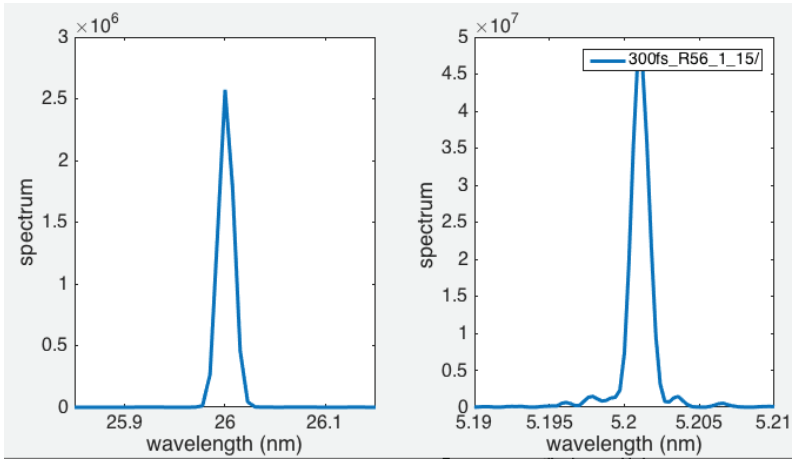
Higher compression or lower charge beams will be also studied.

Both simulations and experiments show that **μB** can be **detrimental** for spectral quality.

FEL simulations 5.2 nm

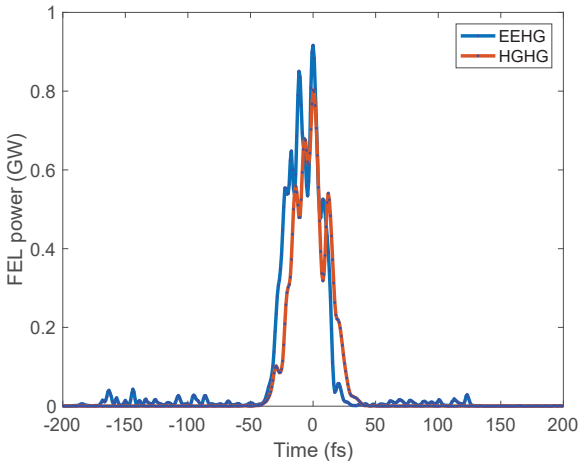
With the given setup, the **shortest wavelength** is around **5 nm**.
Simulations and experiments indicate >1GW in HGHG-FB.

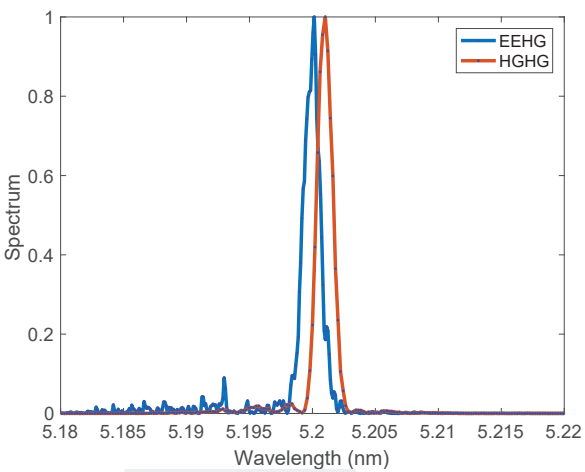




Spectral quality at 5 nm is affected by μB.

Similar results are expected also for EEHG according to start to end simulations.



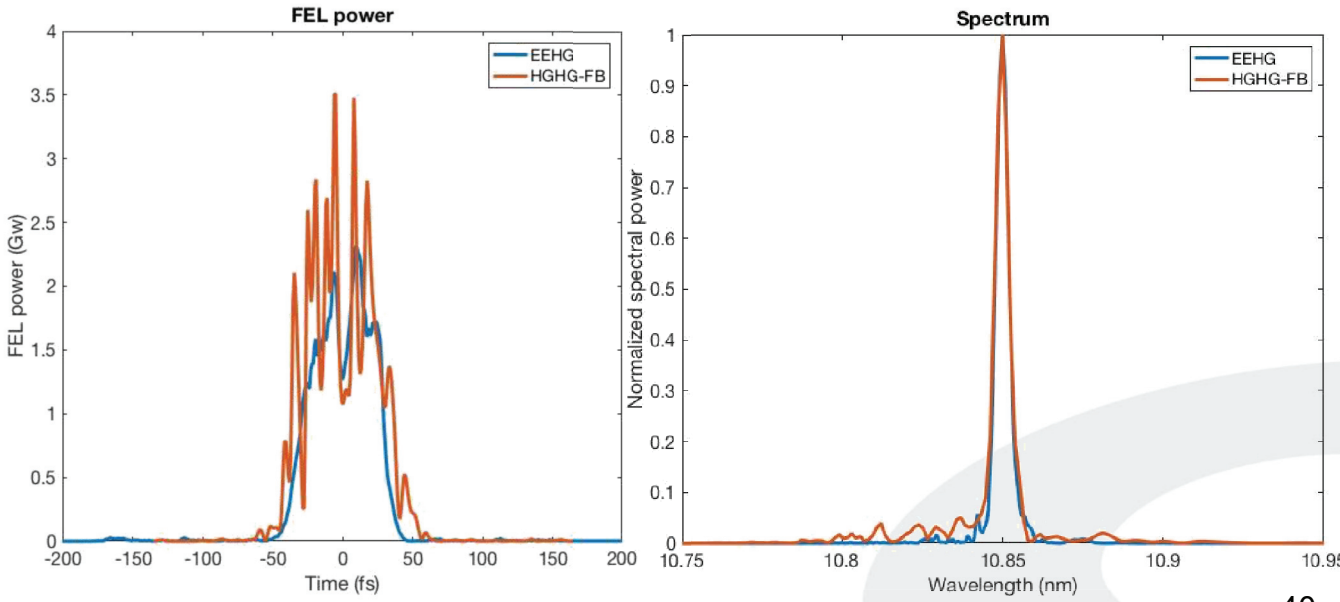


FEL intermediate wavelength

New simulations focused at **longer wavelength** (~10 nm).
Reduced beam energy (**~1GeV**) to increase the dispersion to ~5 mm in the chicane (n=1).
Large R56 is important for studying the sensitivity to μB.
Both **HGHG-FB** and **EEHG** are studied **with** the **new undulator setup** (same e-beam).

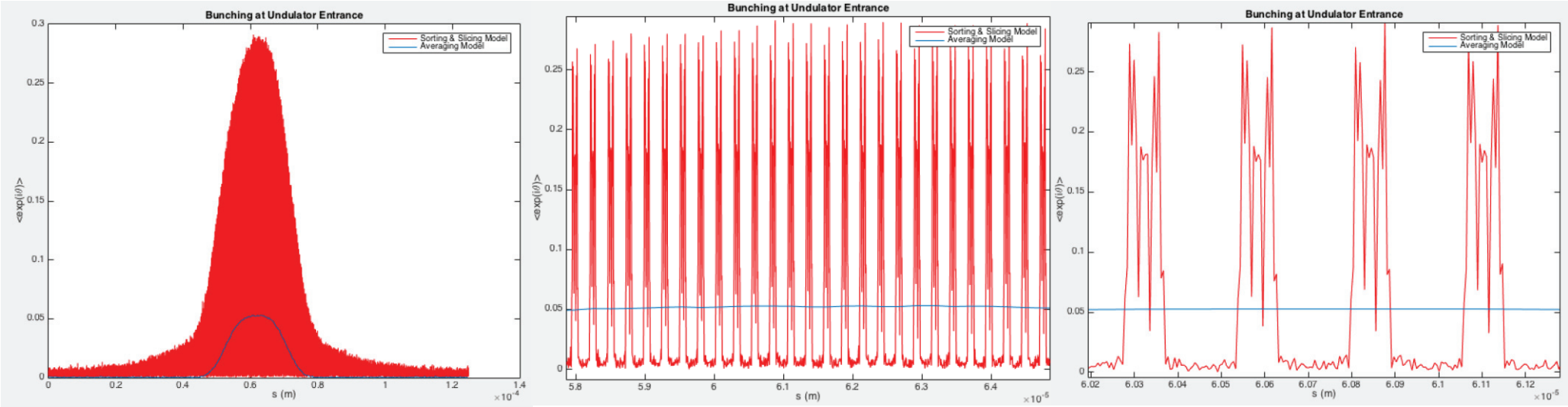
With HGHG >**100 MW** at **~30 nm** sufficient for **bunching** the beam at **10 nm** in the **second stage** even with the short modulator.

μB modulation in the S2E beam are responsible of power modulation and spectral degradation.
Simulations show a larger sensitivity of HGHG to μB.



EEHG studies

Simulations of the FERMI case with the new version of Genesis done by S. Reiche. The new *'sorting & slicing'* gives a more realistic prediction of the electron beam dynamics in EEHG.



As a result of the localized reduced current between high bunching regions, the final FEL power is slightly reduced and require a different optimization.

Plans for studies on laser phase errors and mode quality with the new genesis version.

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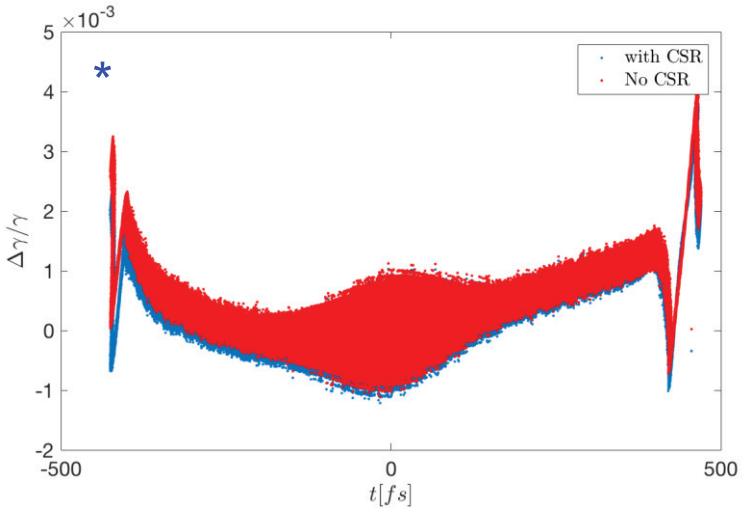
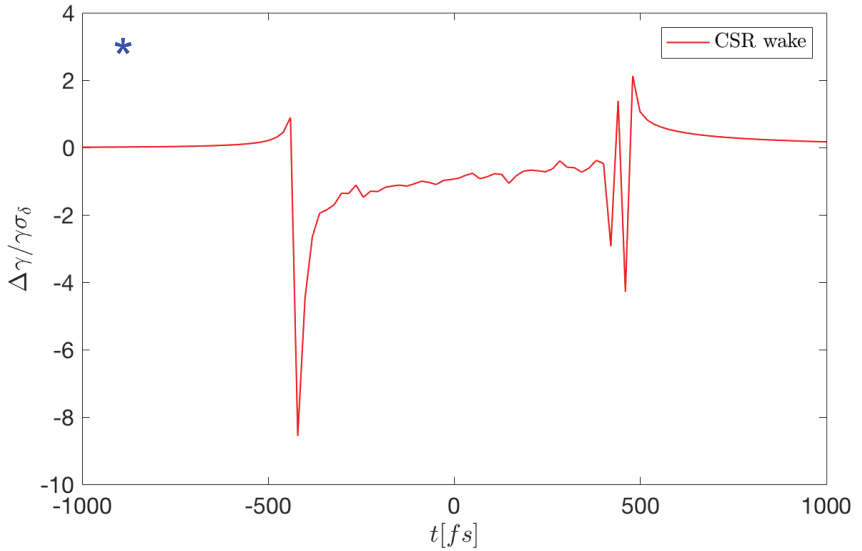
CSR studies

CSR studies by E. Hemsing applied to the FERMI case.

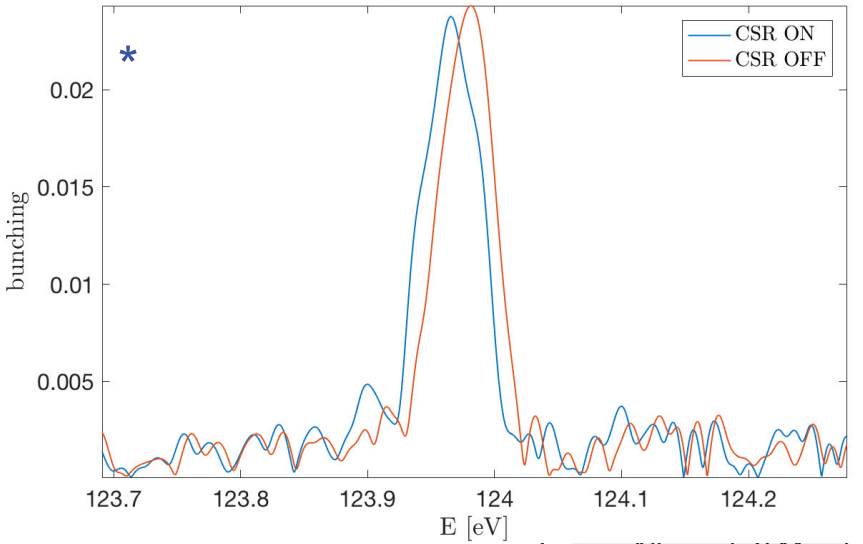
FERMI e-beam analyzed taking into account the short seed laser of FERMI





H = 26, final wavelength 10 nm,
R56_1 = 2.6mm,
R56_2 = 100um.

The CSR wake is dominant on the ends of the beam while the central part is less affected. This limit the impact on the EEHG spectrum



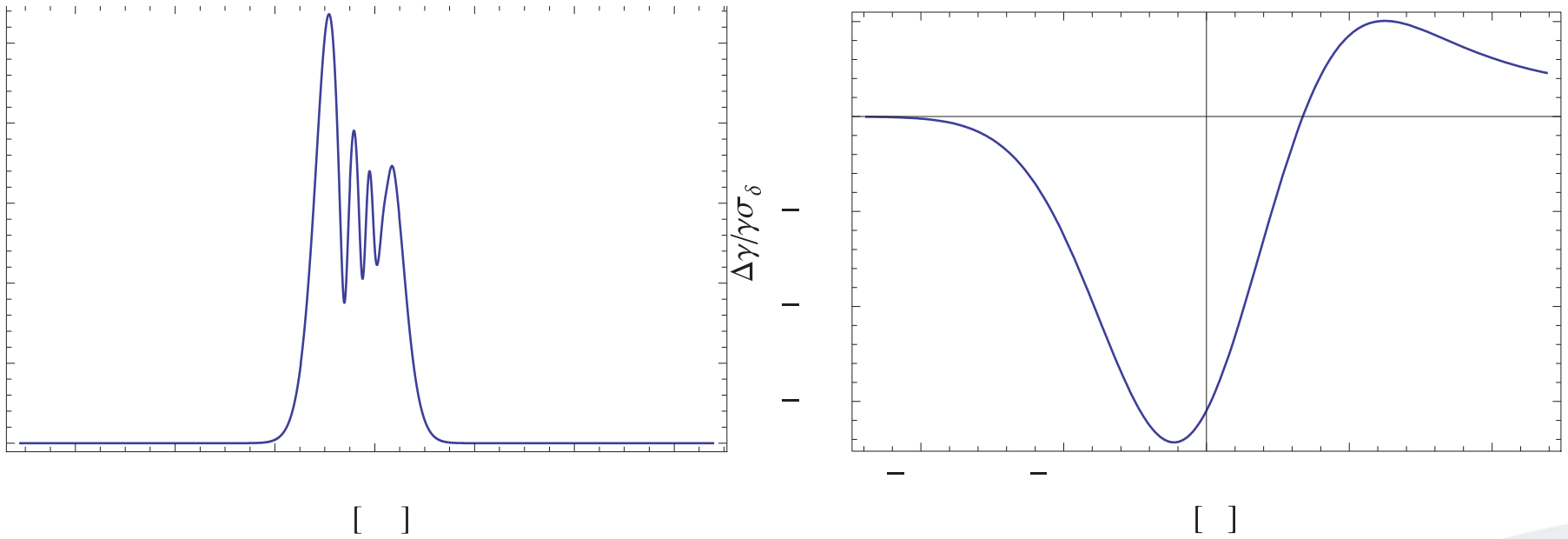
* E. Hemsing (private commun.)

CSR with long seed laser

Long seed covering the whole bunch is also possible

- 140 fs FWHM Gaussian e-beam
  - Lasers completely cover beam
- 1e-4 rel. energy spread, 700 amps
- Steady-state CSR Only
- Non-linear CSR wake significantly impacts bunching spectrum

H = 26, final wavelength 10 nm, R56_1 = 2.6mm, R56_2 = 100um, Ebeam =1.2GeV.



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* E. Hemsing (private commun.)

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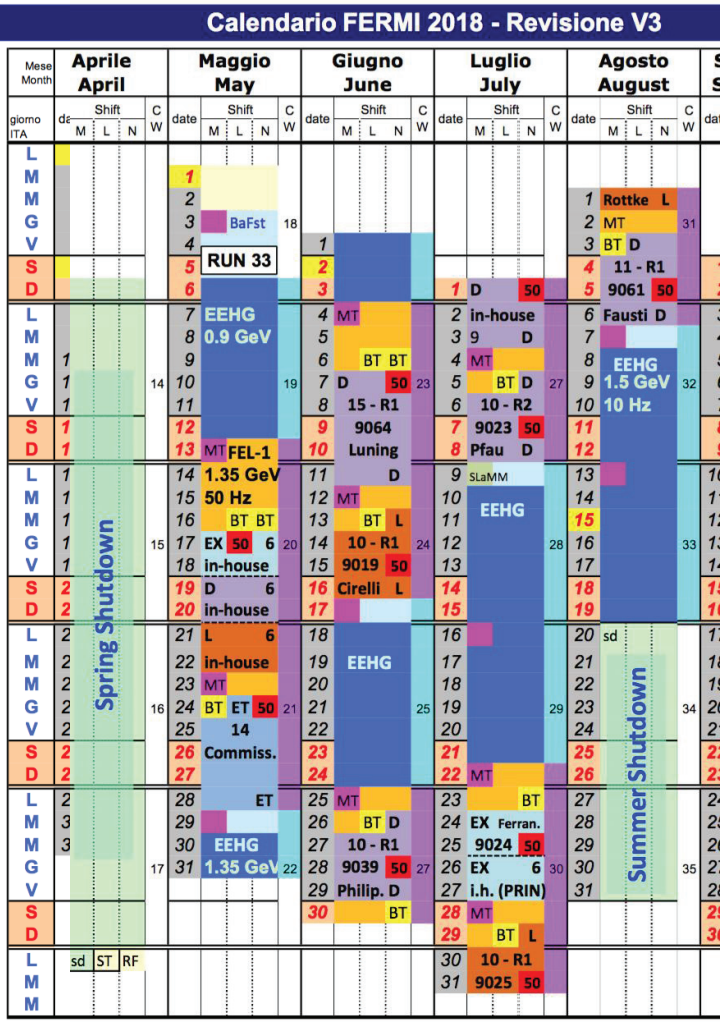
Plan



Period 1: May 6 - May 12:

Systems commissioning

Period 2: May 30 - June 3:

Seed laser alignment
HGHG double stage
EEHG at medium harmonic (~20)
FEL sensitivity studies

Period 3: June 18 - June 24:

Seed laser alignment
EEHG at medium harmonic (with n=-1 and n=-2)
EEHG at high harmonics (h~40)
Optimize the FEL

Period 4: July 10 - July 21:

EEHG at high harmonics (h~40)
Optimize the FEL
Study EEHG vs uB and phase space
Study EEHG with seed laser control (chirp, length, …)
Test two color EEHG: various options

Period 5: August 8 - August 19:

EEHG at high harmonics (h~40) and very high harmonics (h~50)
Optimize the FEL
Experiment with EEHG

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Conclusions

- Routinely operations at 4-5 nm are achieved at FERMI in HGHG fresh bunch mode.
- An experiment of EEHG at similar wavelength is planned.
- Upgrade of FERMI will depend on EEHG results.

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Thank you!

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