# FERMI@Elettra

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and many others

# Overview

- FERMI@Elettra
  - Machine layout
  - Parameters
  - Timeline
- FERMI FELs
  - High Gain Harmonics Generation
  - FEL1 – 1-stage HGHG
  - FEL2 – 2-stage HGHG
- Diagnostics + Feedbacks

Map: *Wikimedia Commons*

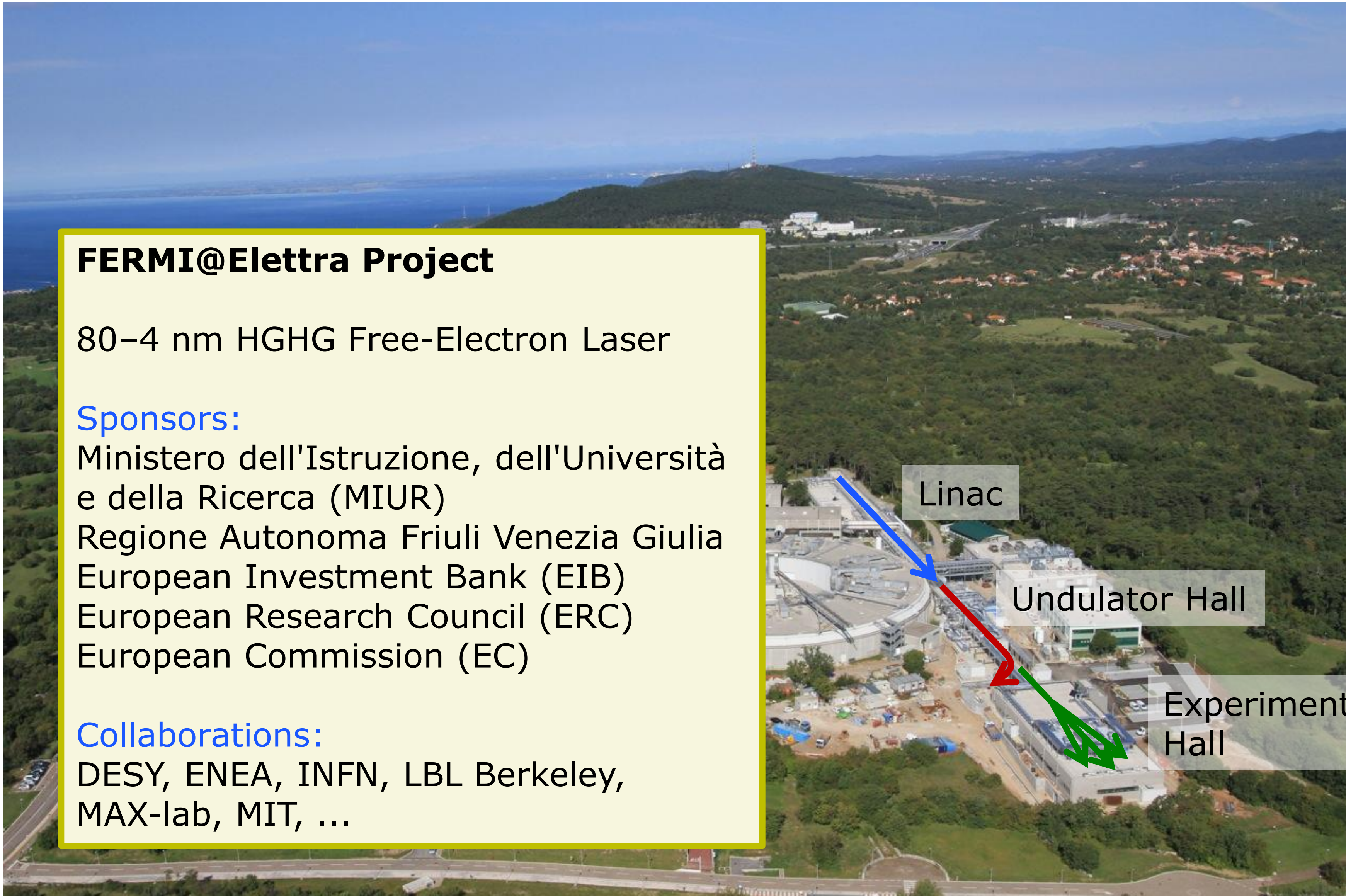
# Elettra & FERMI

**FERMI@Elettra Project**

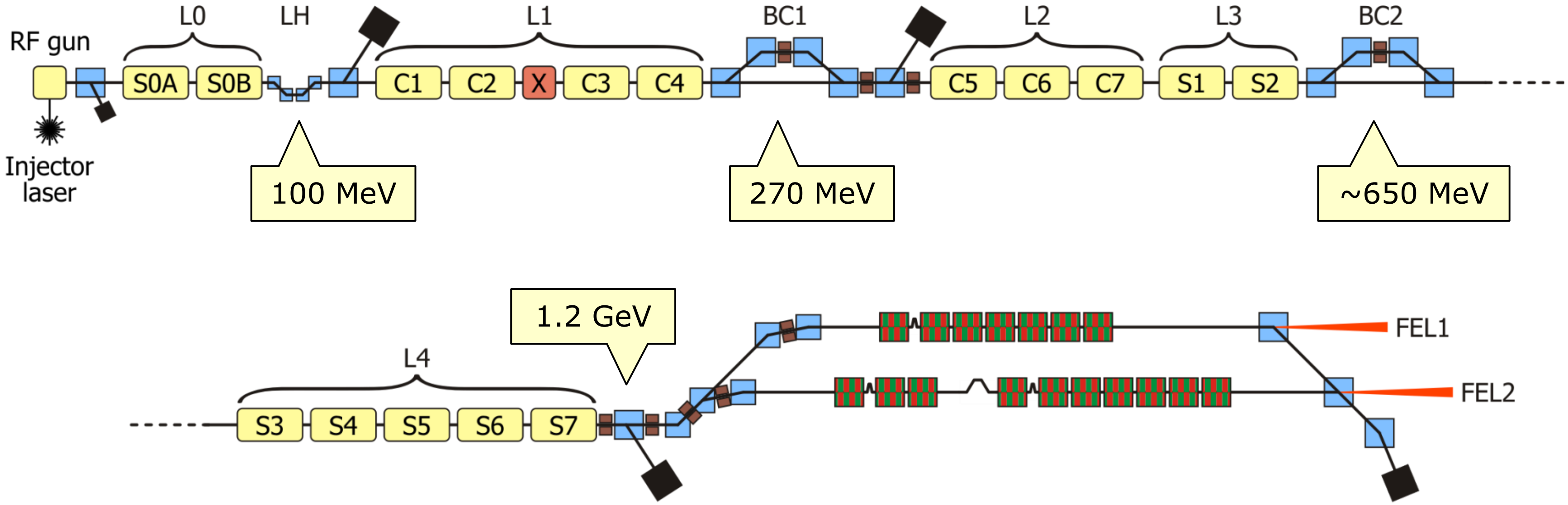
80–4 nm HGHG Free-Electron Laser

Sponsors:
Ministero dell'Istruzione, dell'Università e della Ricerca (MIUR)
Regione Autonoma Friuli Venezia Giulia
European Investment Bank (EIB)
European Research Council (ERC)
European Commission (EC)

Collaborations:
DESY, ENEA, INFN, LBL Berkeley, MAX-lab, MIT, ...

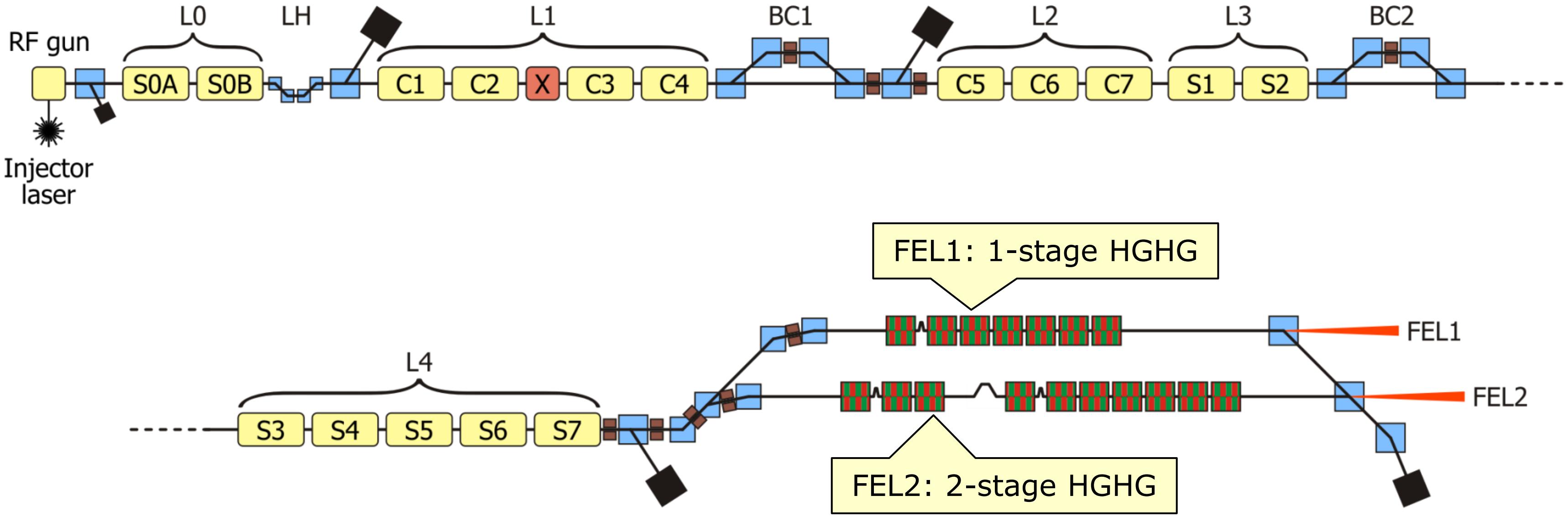


# FERMI@Elettra




| | Energy | Bunch Charge | Repetition Rate | Beam Power |
|---|---|---|---|---|
| Typical | 1.2 GeV | 500 pC | 10 Hz | 6 W |
| Future | 1.5 GeV | <1 nC | 50 Hz | <75 W |

# FERMI@Elettra




| | Seed Wavelength | Modulators | Radiators | Output Wavelength |
|---|---|---|---|---|
| FEL1 | 210–280 nm | 1 (planar) | 6 (APPLE-II) | 80–20 nm |
| FEL2 | 210–280 nm | 2 (planar) | 2 + 6 (APPLE-II) | 20–4 nm |

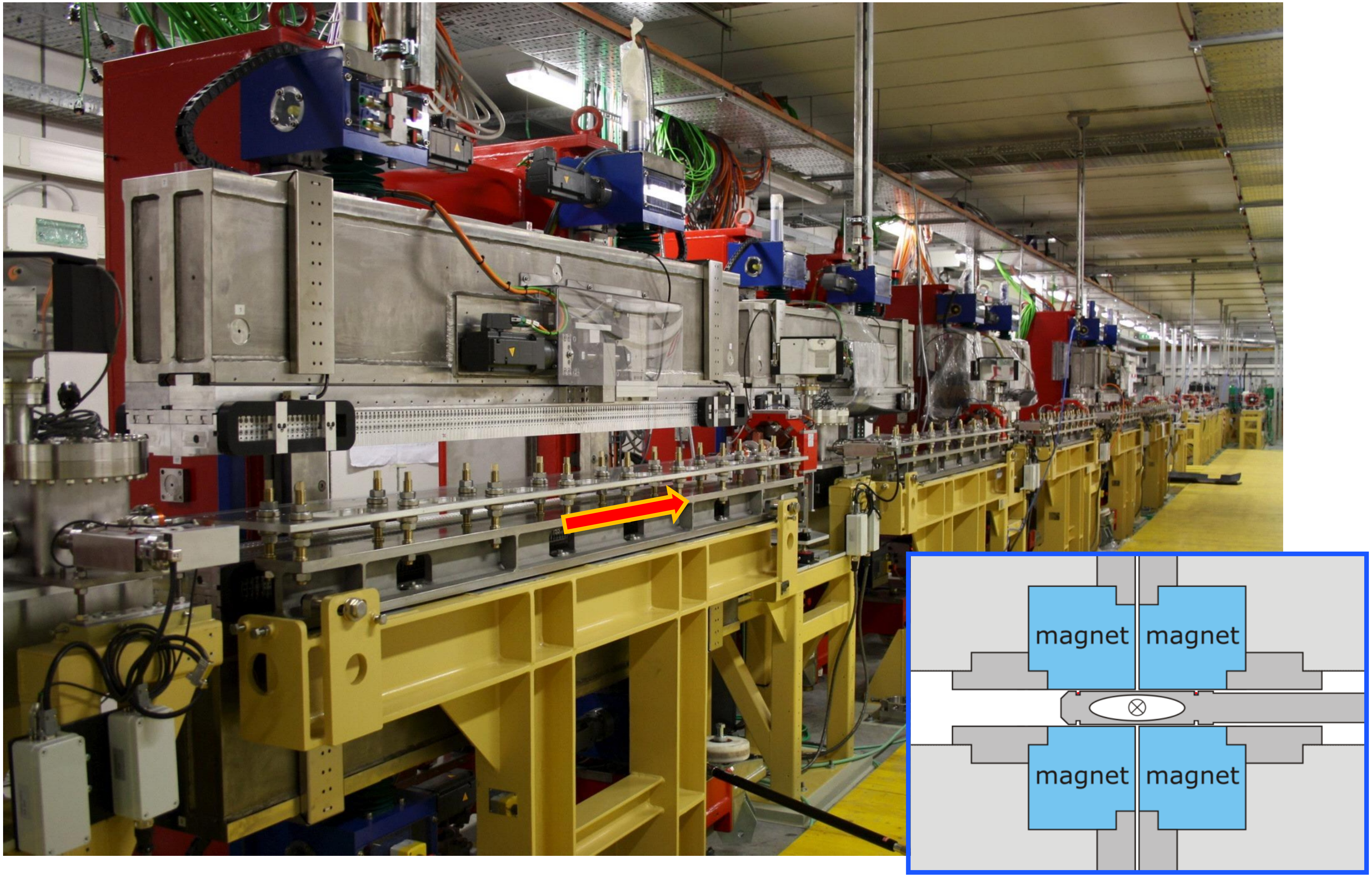
# Injector

# CERN Structures

# SLED Structures

# Spreader

# FEL-1 Radiators



# Dump Line

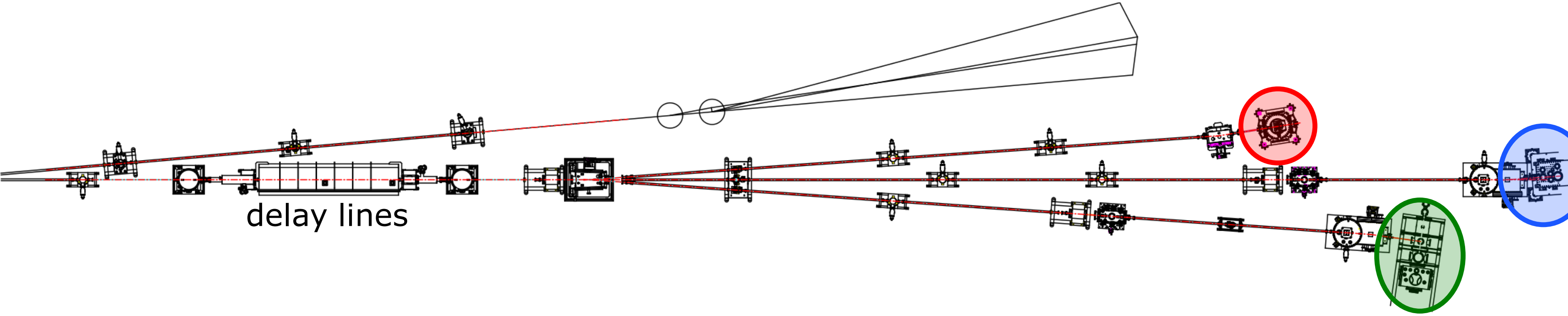
# Experimental Hall

# Beamlines & Scientific Programs

**TIMEX – Elastic and inelastic scattering**
Transient grating spectroscopy
(transform-limited bandwidth)
Pump & probe spectroscopy, ultra-fast magnetization dynamics
(brightness, wavelength tunability)

**DIPROI – (Coherent) diffraction and projection imaging**
- Single shot (bio and solid state structures)
- Resonant (chemical and magnetic imaging)
- Time-resolved (morphology and internal structure at the nm scale)

(brightness, wavelength tunability, circular polarization)




**LDM – Low density matter**
Structure of nano-clusters (brightness)
High resolution spectroscopy (narrow bandwidth, wavelength tunability)
Ionization dynamics (circular polarization)
Catalysis in nano-materials (fs pulse and stability)

# Timeline

**2009**

05 – Linac building ready

08 – Start of photoinjector commissioning

**2010**

06 – Undulator hall ready

07 – BC1 commissioning

09 – Full beam energy reached

10 – FEL1 undulators installed

Experimental hall ready

12 – First coherent emission from FEL1 (43 nm)

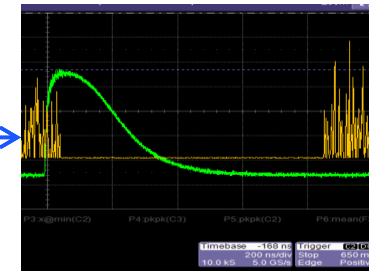
**2011**

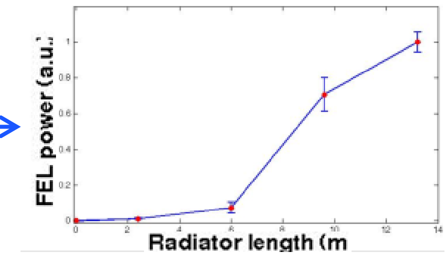
02 – First evidence of FEL gain

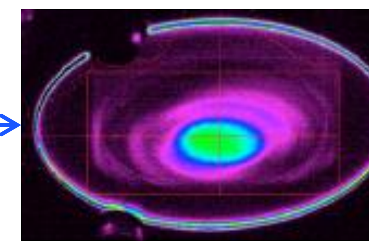
04 – First light to beamlines, initial photon experiments

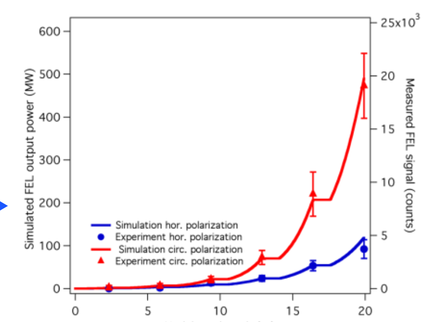
07 – First observation of "Gaussian" spot

Measured exponential gain curve







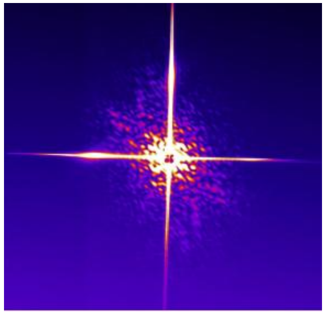
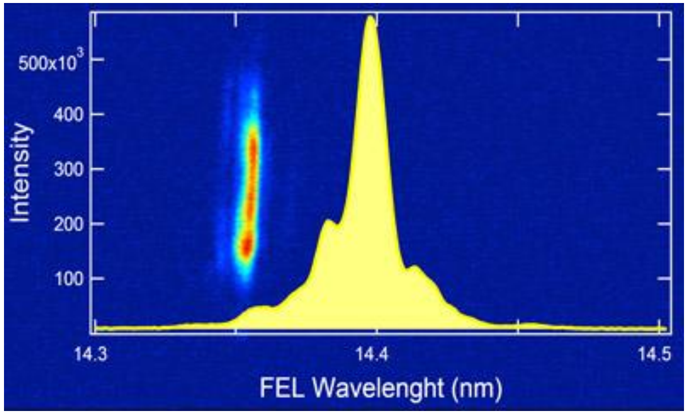
# Timeline

**2012**

02 – First electrons through FEL2 line
03 – First single shot diffraction image →
04 – FEL2 undulators installed
05 – Laser heater commissioned
X-band cavity commissioned
First photons from first stage of FEL2
10 – First lasing of full FEL2 setup →
12 – Dual-color operation with two seed pulses

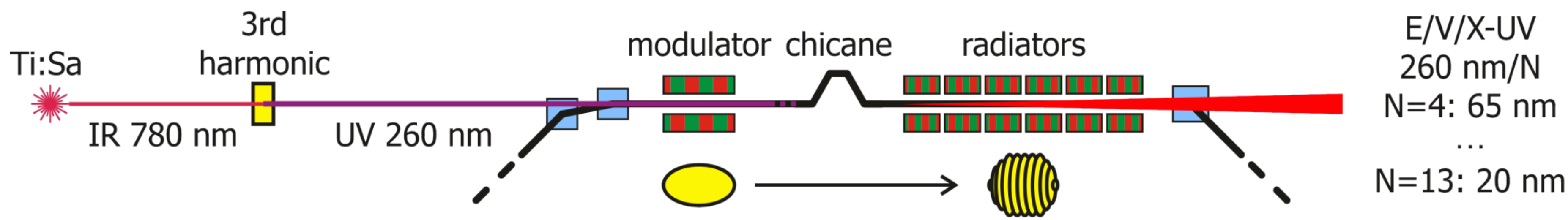
**2013**

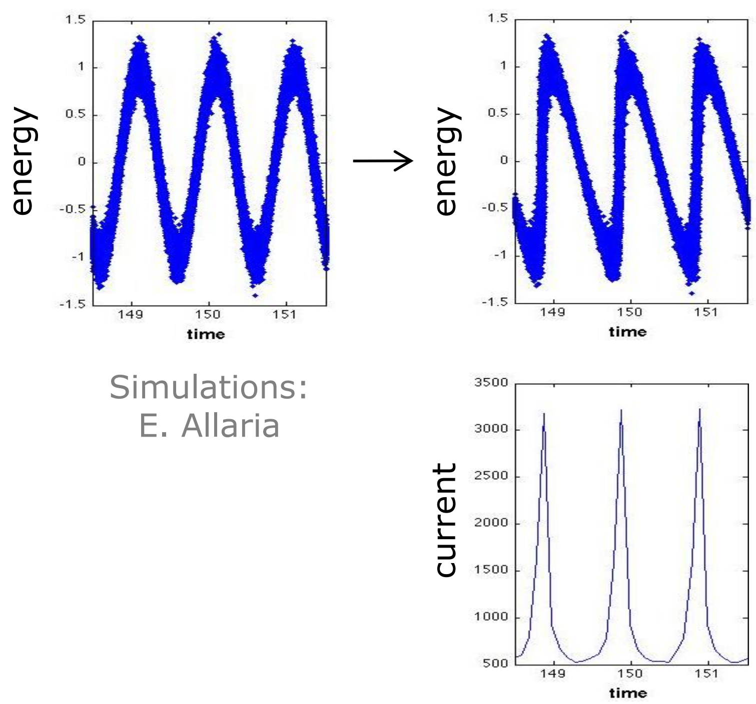
02 – First pump-probe experiments with IR laser
03 – FEL2 commissioning

# FEL1

# FEL1: Single-stage HGHG



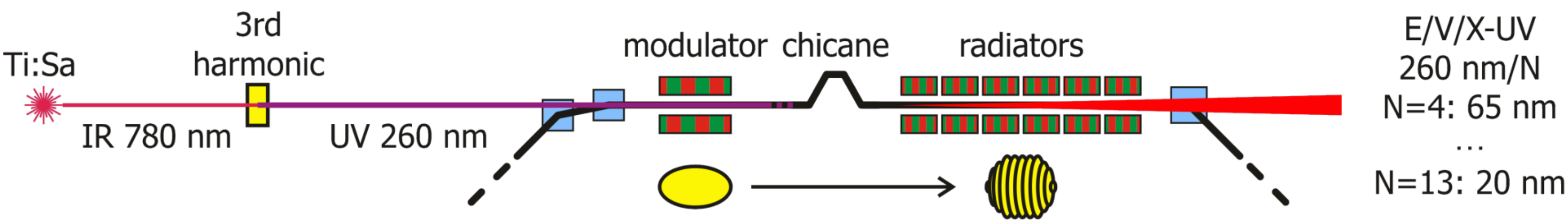




Simulations:
E. Allaria

non-sinusoidal density modulation
→
harmonic content

# FEL1: Single-stage HGHG






**Differences to SASE:**

Hard to reach short photon wavelengths

Added complication of spatial/temporal overlap

Temporal coherence (no single spikes)

More control over lasing process
(e.g. pulse length, energy chirp)

Clean spectrum (small bandwidth)

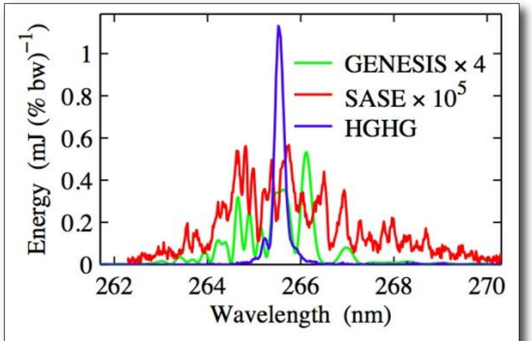
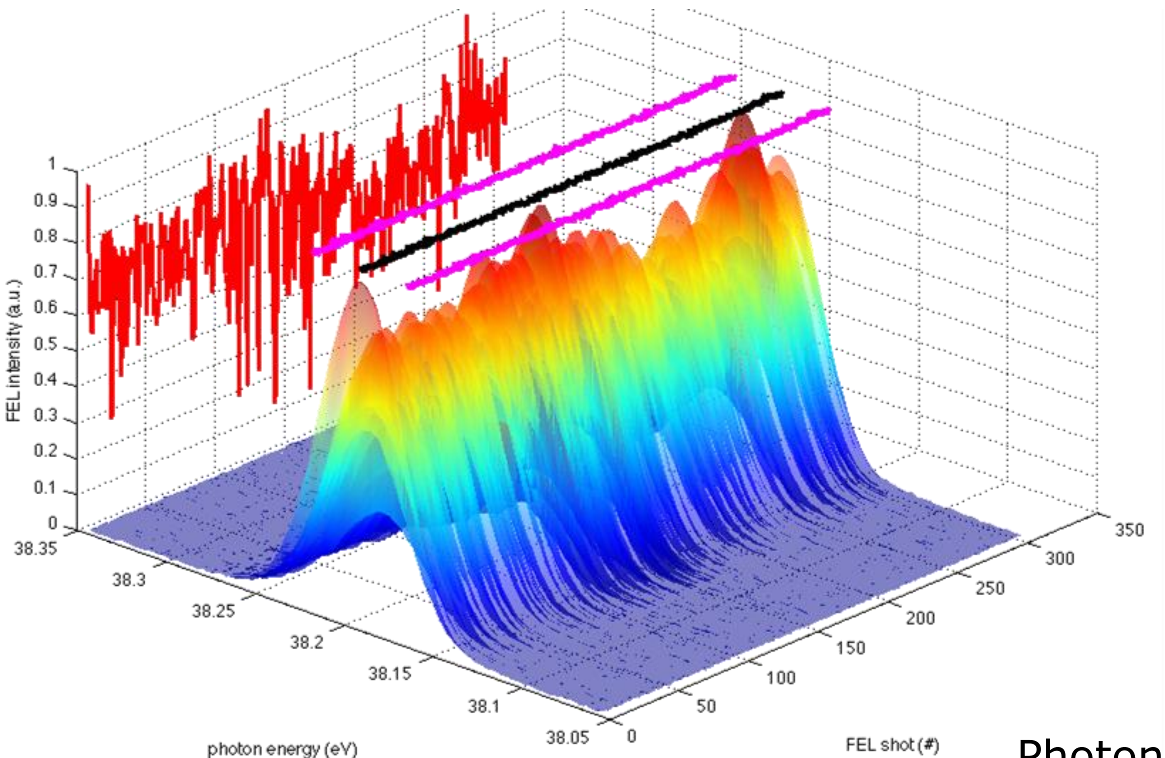



FIG. 4: Single shot HGHG spectrum for 30 MW seed (blue), single shot SASE spectrum measured by blocking the seed laser (red) and simulation the SASE spectrum after 20 m of NISUS structure (green). The average spacing between spikes in the SASE spectrum is used to estimate the pulse length.

L.H. Yu et al., PRL 91, 074801 (2003).

# FEL1: Wavelength Stability




In addition to a very narrow spectrum FERMI delivers excellent spectral stability.

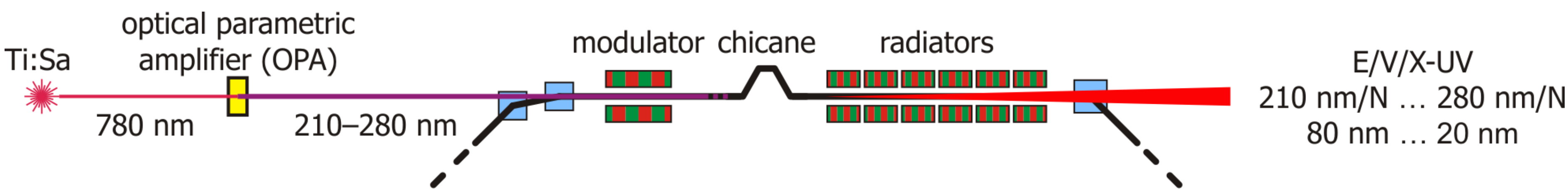
Short and long term measurements show that the spectral peak jitters by less than 1 part in $10^4$.

| | |
|---|---|
| Photon energy | 38.19 eV |
| Abs. fluctuation (rms) | 1.1 meV |
| Rel. fluctuation (rms) | $3\cdot10^{-5}$ |
| Abs. rms bandwidth | 22.5 meV |
| Rel. rms bandwidth | $6\cdot10^{-4}$ |

Electron bunch: 350 pC, 1.24 GeV, CF~3
Resonant wavelength: 32.5 nm

E. Allaria

# Optical Parametric Amplifier



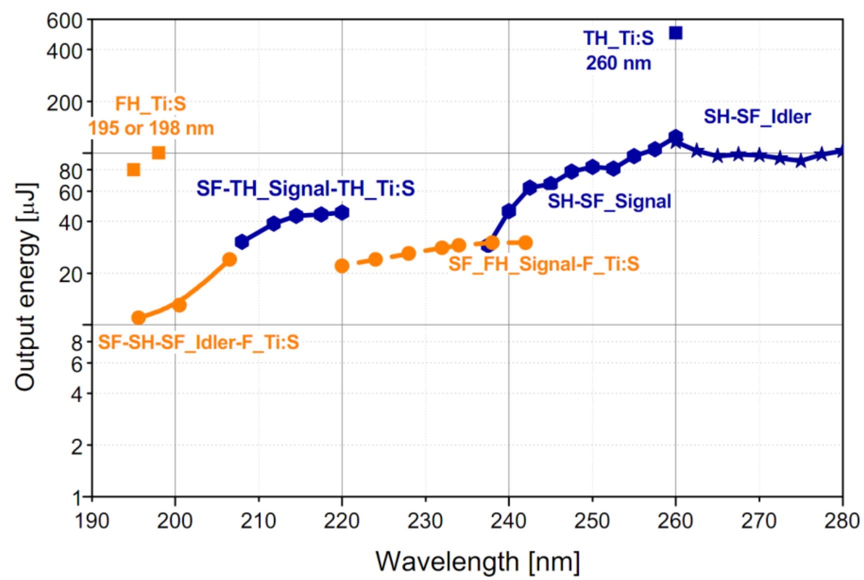

**Operation with OPA**

Tunable seed → tunable FEL wavelength

Drawbacks:

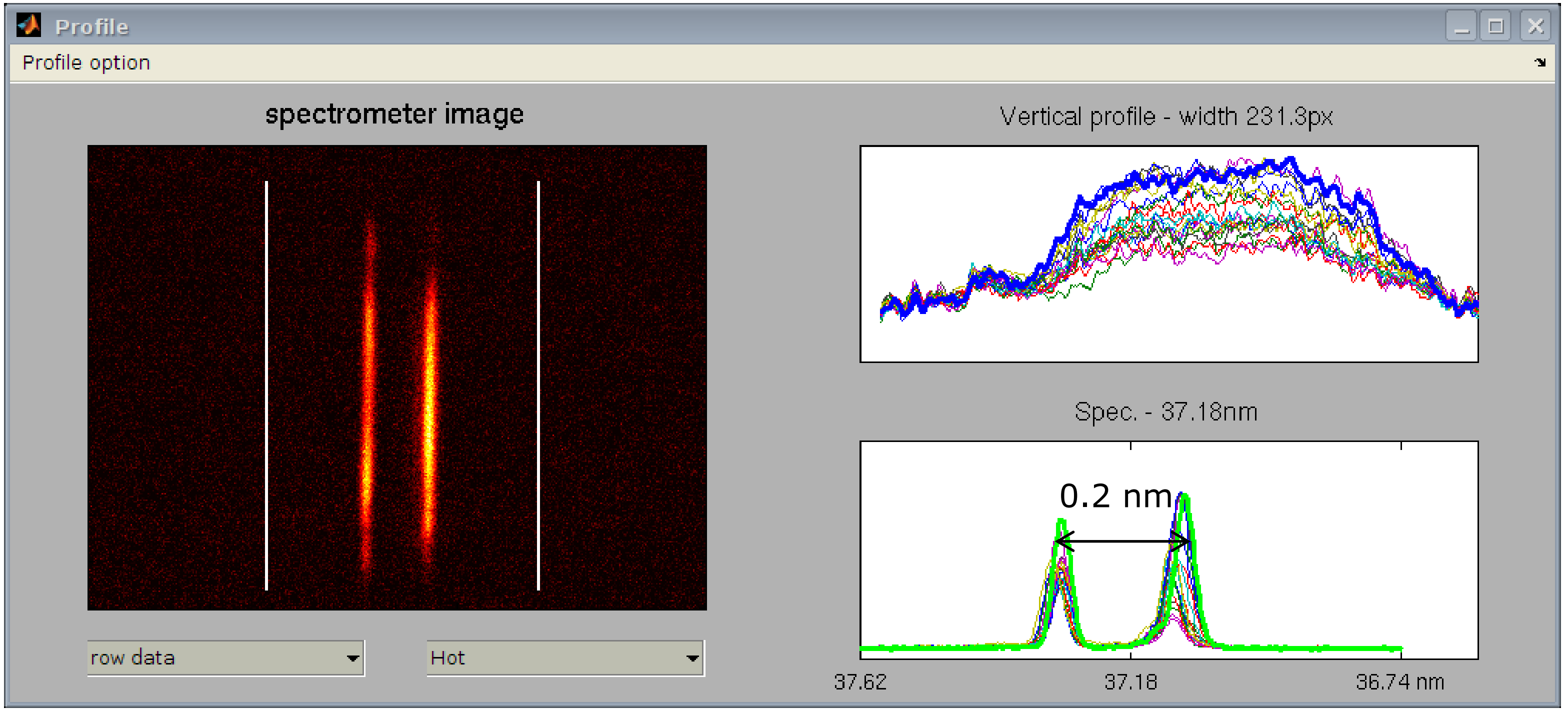
Minor pulse energy

Lower transverse beam quality




M. Danailov et al., Proc. FEL2011, pp. 183–186.

# FEL1: Two Colors

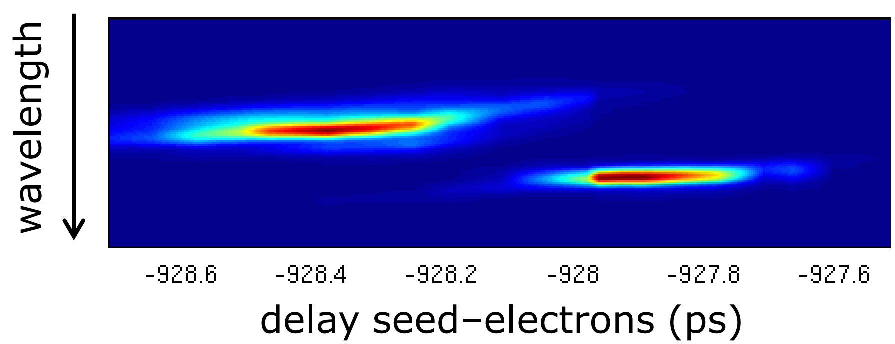



Images: E. Allaria, W. Fawley

**Operation with two seed pulses**

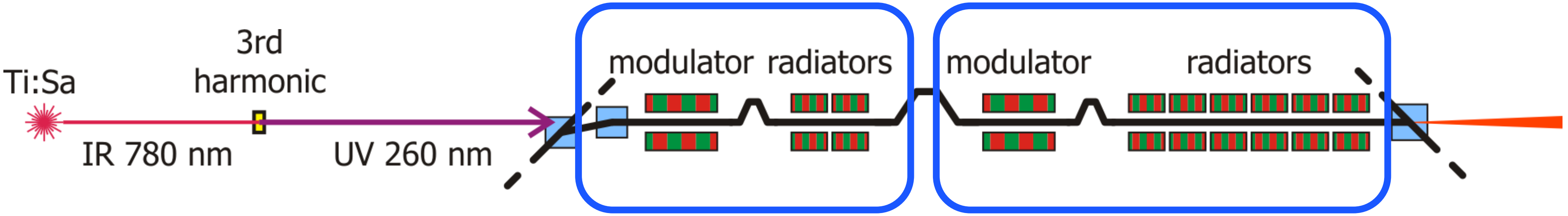
DIPROI pump–probe experiment (December 2012)

Pulse separation: ~0.6 ps



# FEL2

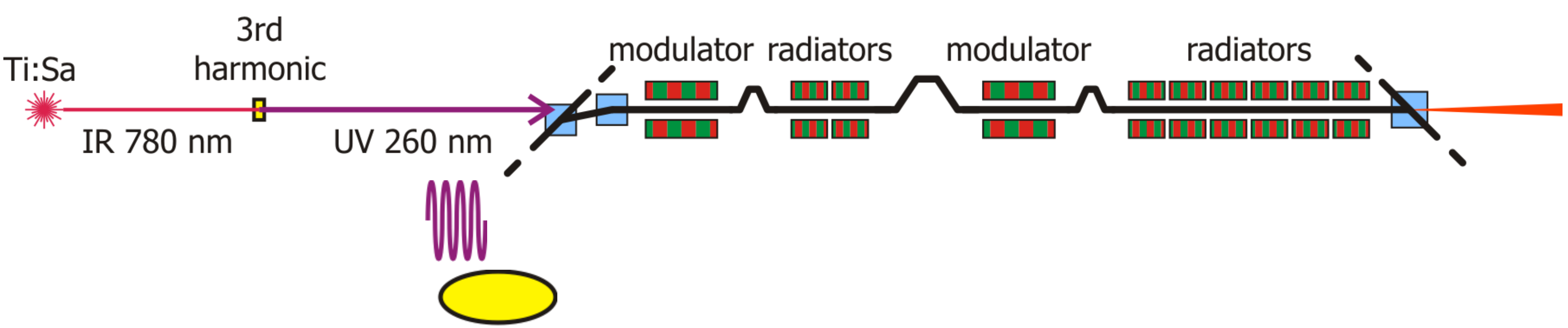
# FEL2: Two-stage HGHG



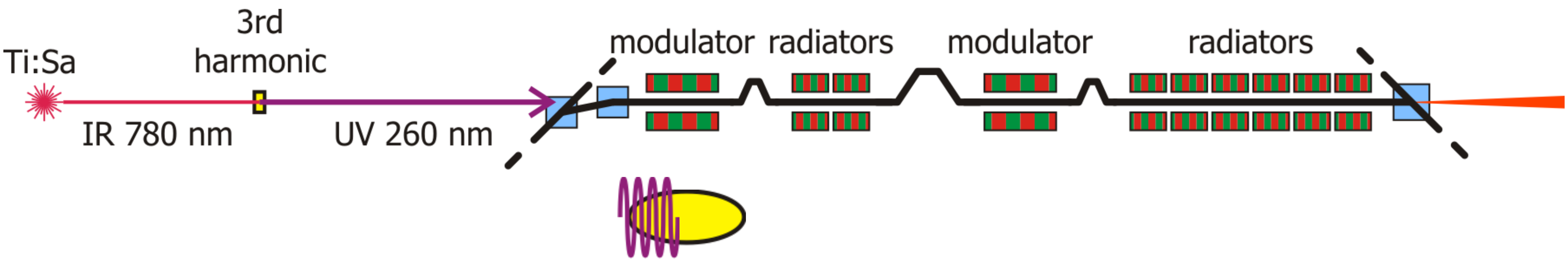

260 nm seed
→
43.3 nm radiation
(6th harmonic)

43.3 nm seed
→
14.4 nm radiation
(3rd harmonic)

# FEL2: Two-stage HGHG

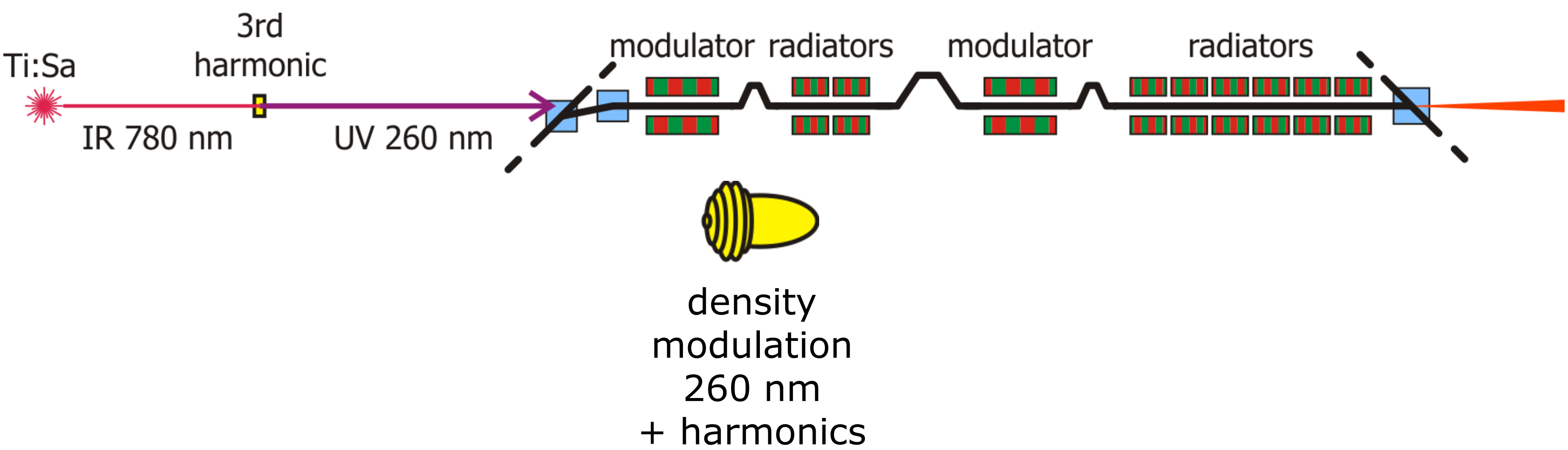


# FEL2: Two-stage HGHG

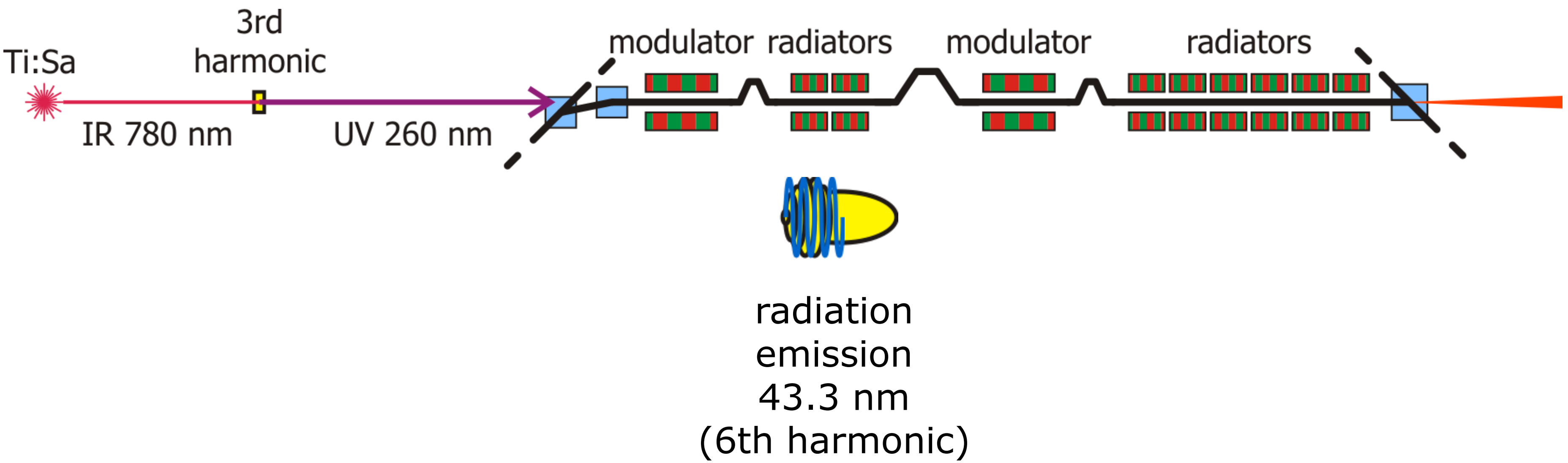



energy
modulation
260 nm

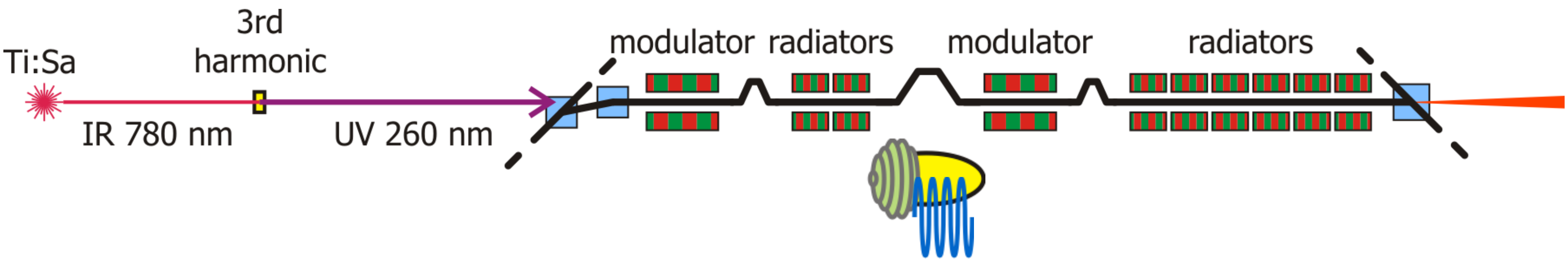
# FEL2: Two-stage HGHG



# FEL2: Two-stage HGHG

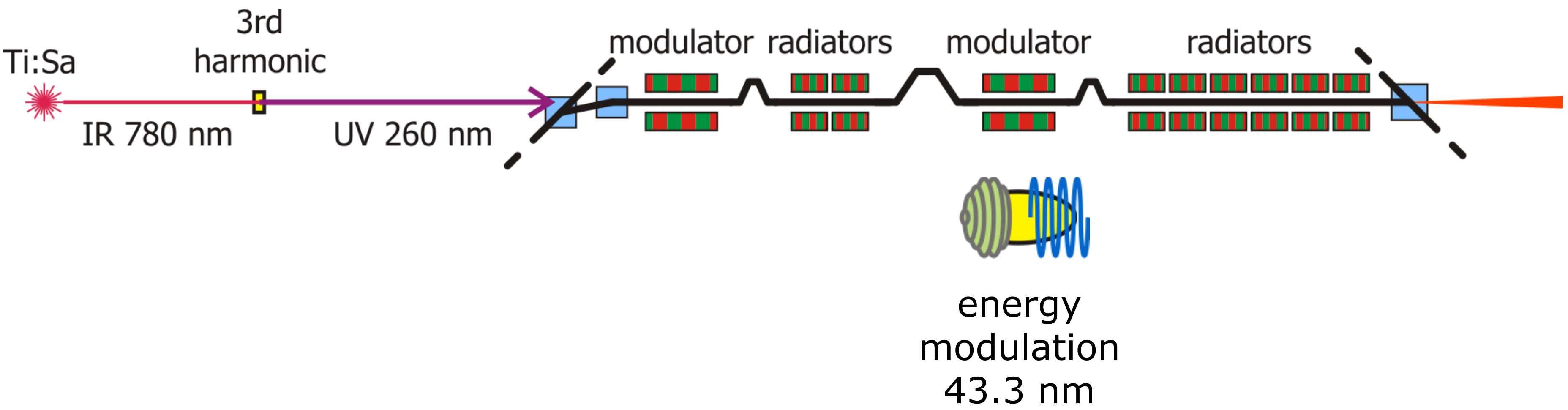


# FEL2: Two-stage HGHG

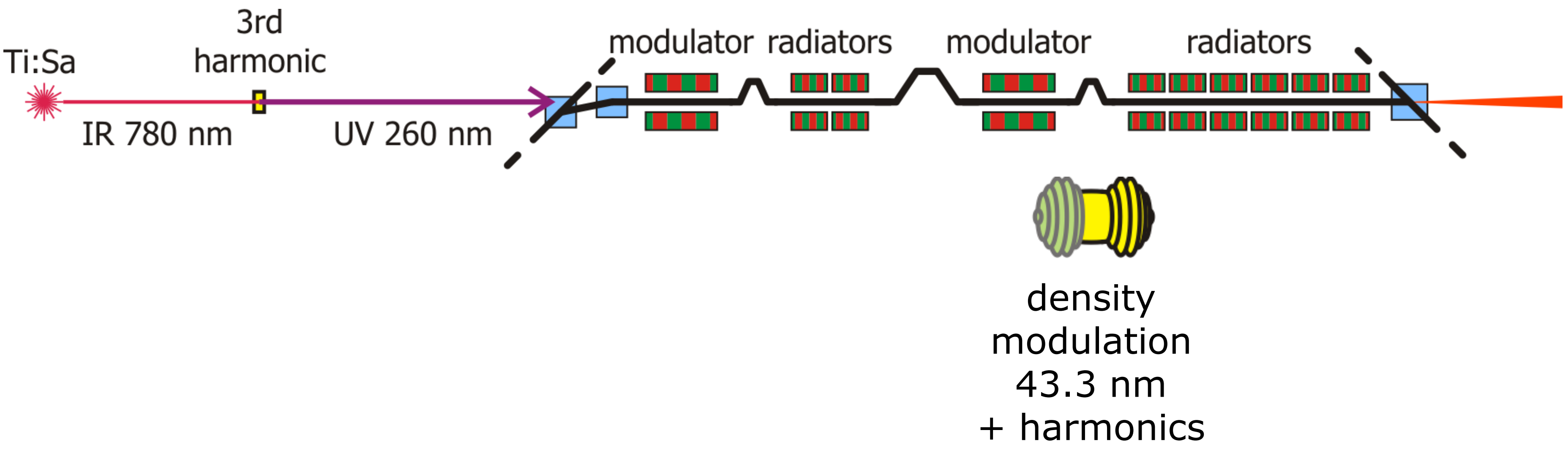



**“Fresh bunch injection”**
Delay electron bunch so that the photon pulse overlaps with a fresh part.

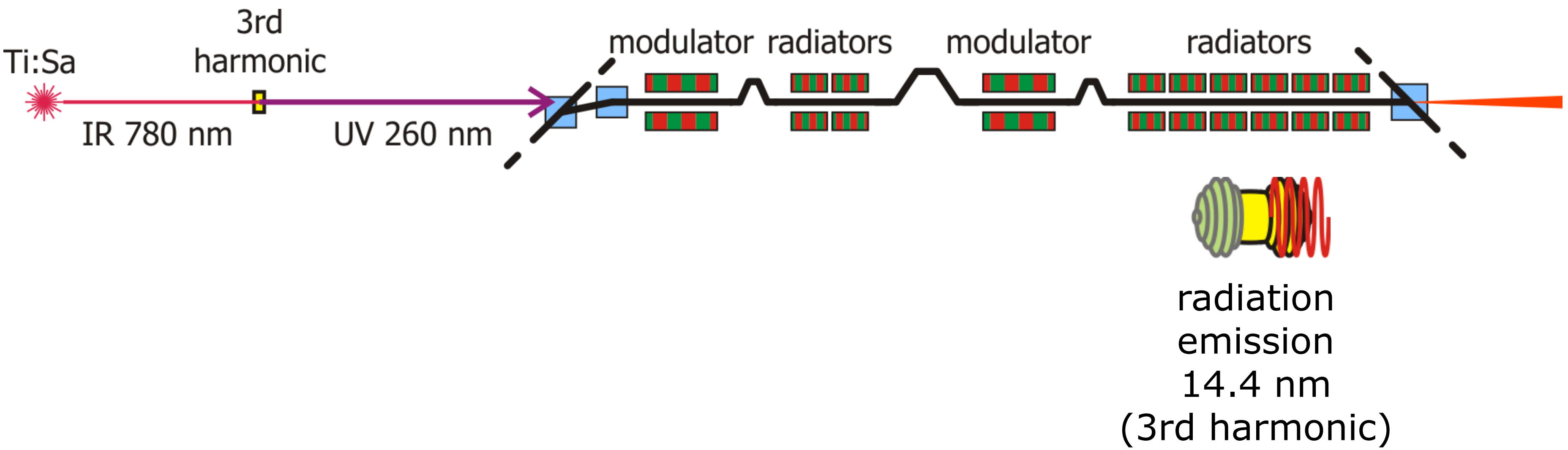
# FEL2: Two-stage HGHG



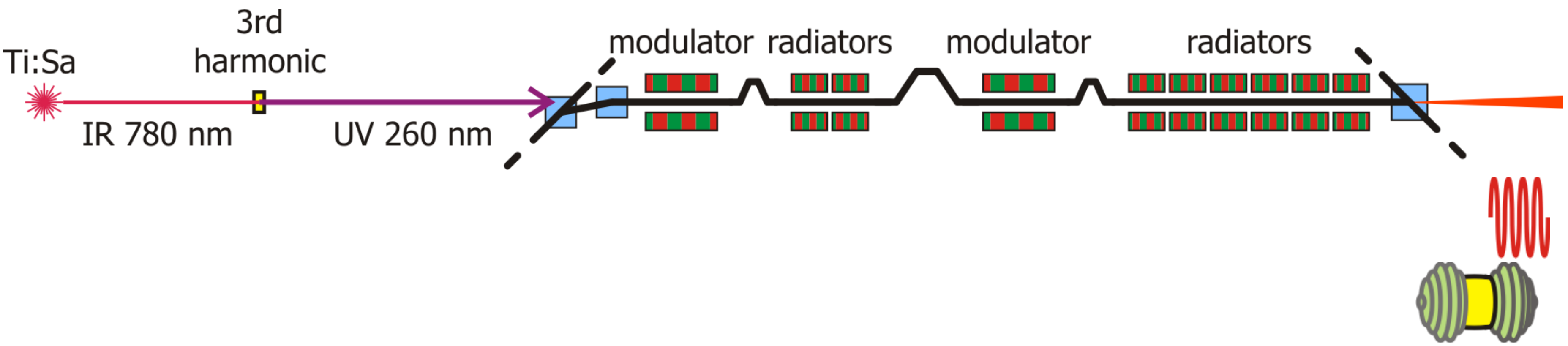
# FEL2: Two-stage HGHG



# FEL2: Two-stage HGHG



# FEL2: Two-stage HGHG

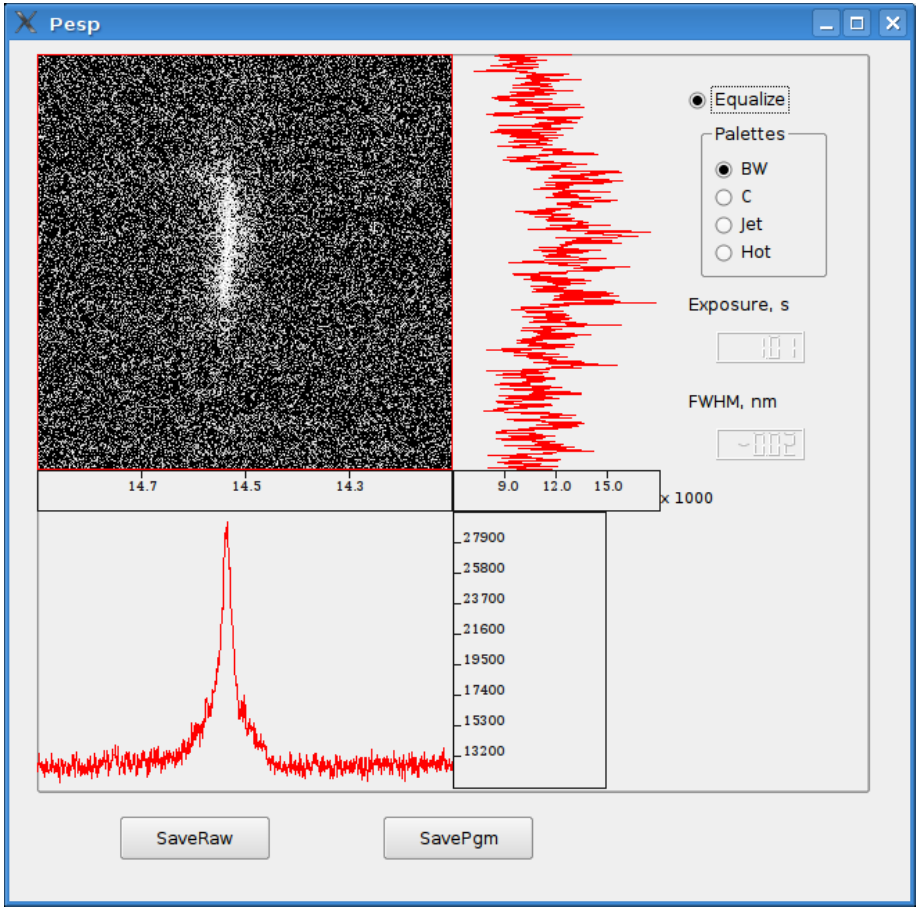


# 14.4 nm without Fresh Bunch

11.10.2012 Morning

Allaria/Giannessi

The FEL was turned on in the morning almost in the same conditions as it was left yesterday, with about 20 uJ at 43nm.
During optimization we found an unexpected behavior of the FEL intensity vs the phase shifter between the two radiators of the first stage. A software problem related to the e-beam energy was fixed by B. Diviacco. Now the phase shifters operate as expected.
**A signal at 14.4 was obtained with the modulator of the second stage tuned at 14.4nm as all the following radiators.**
This signal was used to optimize the emission at this wavelength.
The Zr filter is doing what expected, with a negligible transmission at 43nm and few percent transmission at 14.3 nm. With the filter in it is possible to observe the spot at the short wavelength on the yag screen.



# 14.4 nm with Fresh Bunch

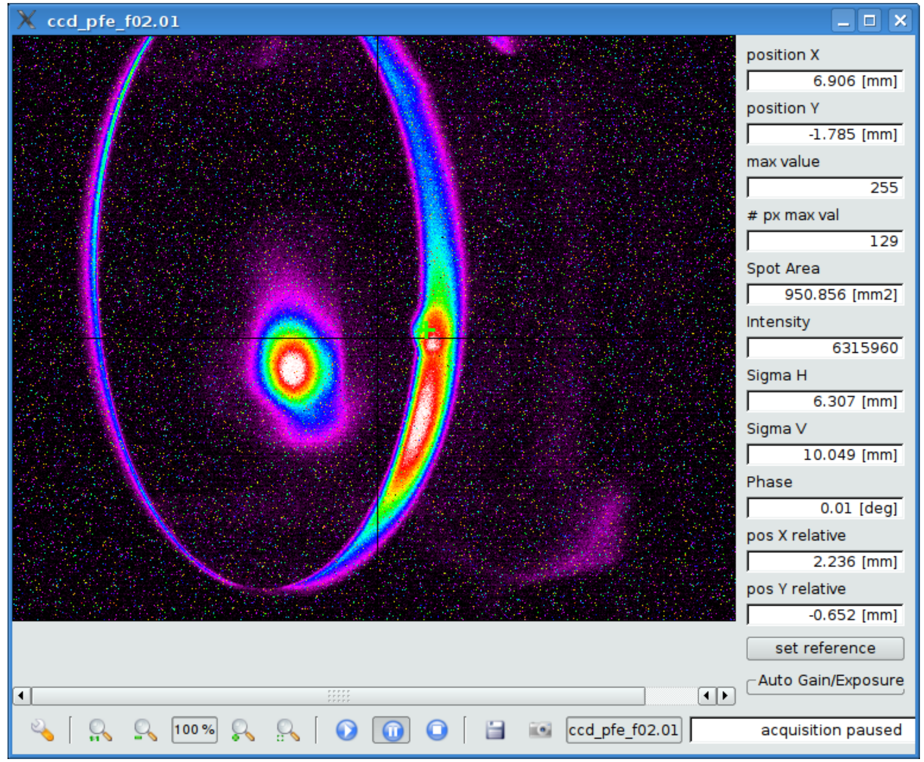
11.10.2012 Afternoon

Diviacco/Fawley

… LG then optimized quad settings to peak emission with all 6 radiators closed and we found a fairly good and tight mode pattern.

Then we turned on the delay section; initially could only get a sporadic signal with about 160 fs of delay in last hour of shift we tried to optimize orbit and timing, often getting a strong signal (>500 pC on the FEL-2 photodiode, comparable to best seen in "whole bunch" operation earlier) but the trajectory feedback in the iUFEL region was unable to keep a steady trajectory as it seems the delay chicane produces a kick which cause the FLE02.02 H corrector to max out in current.

**We are reasonably sure given the delay time that this is true fresh bunch, 2 stage HGHG emission -- if true, more prosecco will be needed by the end of next week (or possibly this weekend).**




Several setups were tried:

14.4 nm (6x3),
10.8 nm (12x2/8x3/6x4/4x6),
8.7 nm (6x5)

# FEL2: Lasing at 10.8 nm

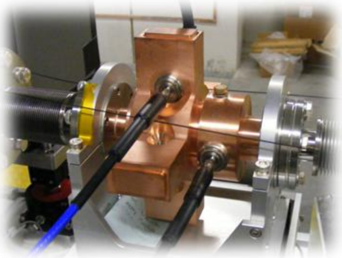
UNPUBLISHED DATA

# Diagnostics + Feedbacks

# Standard Diagnostics

**Beam position monitors**
(S. Bassanese, R. De Monte)

Stripline BPMs + Libera
Undulators: Cavity BPMs (range ±1.5 mm, res. 1.2 μm)

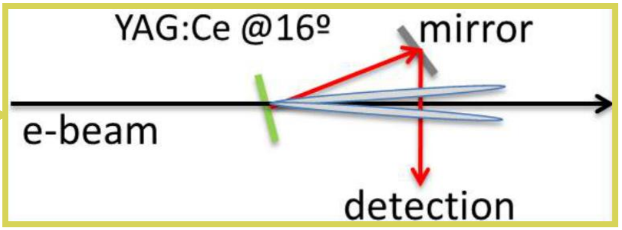


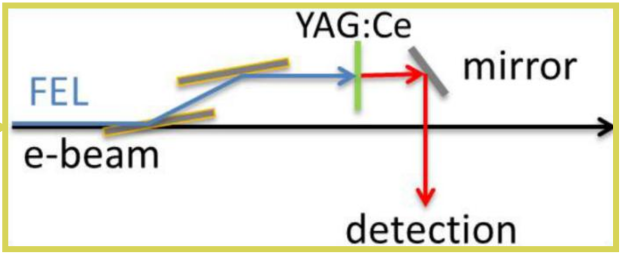
**Charge monitors**
(S. Bassanese)

Bergoz in-flange, ~1% resolution

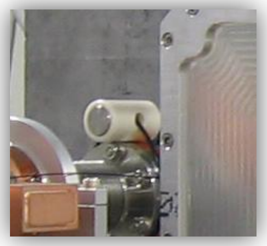
**Screens**
(L. Badano, M. Bossi, M. Veronese)

Standard multiscreens: YAG/OTR at 45°
Undulator screens:
Electron beam — YAG
Photon beam — Mirrors + Al-coated YAG



# Beam Loss Diagnostics

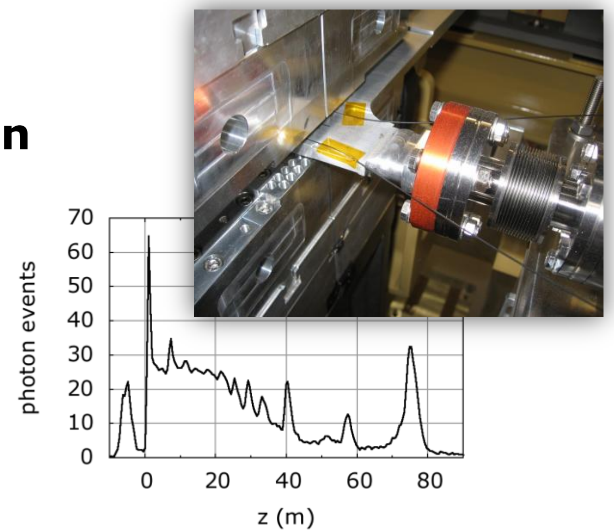


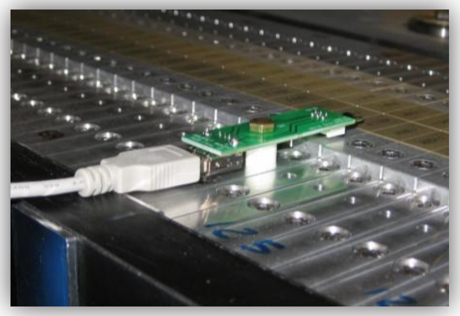
**PIN diodes**
(A. Vascotto)

~120 installed

**Cherenkov fiber beam loss position monitor**

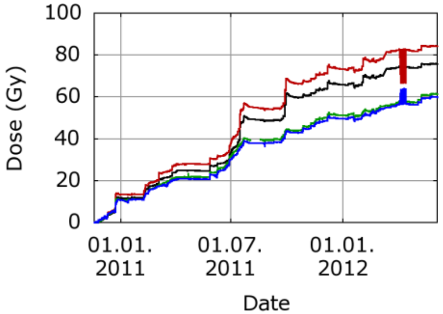
Resolution:
50 cm

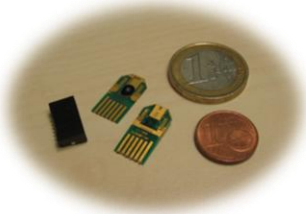


**RADFET online dosimetry**

Integrating dosimeters, readout every minute



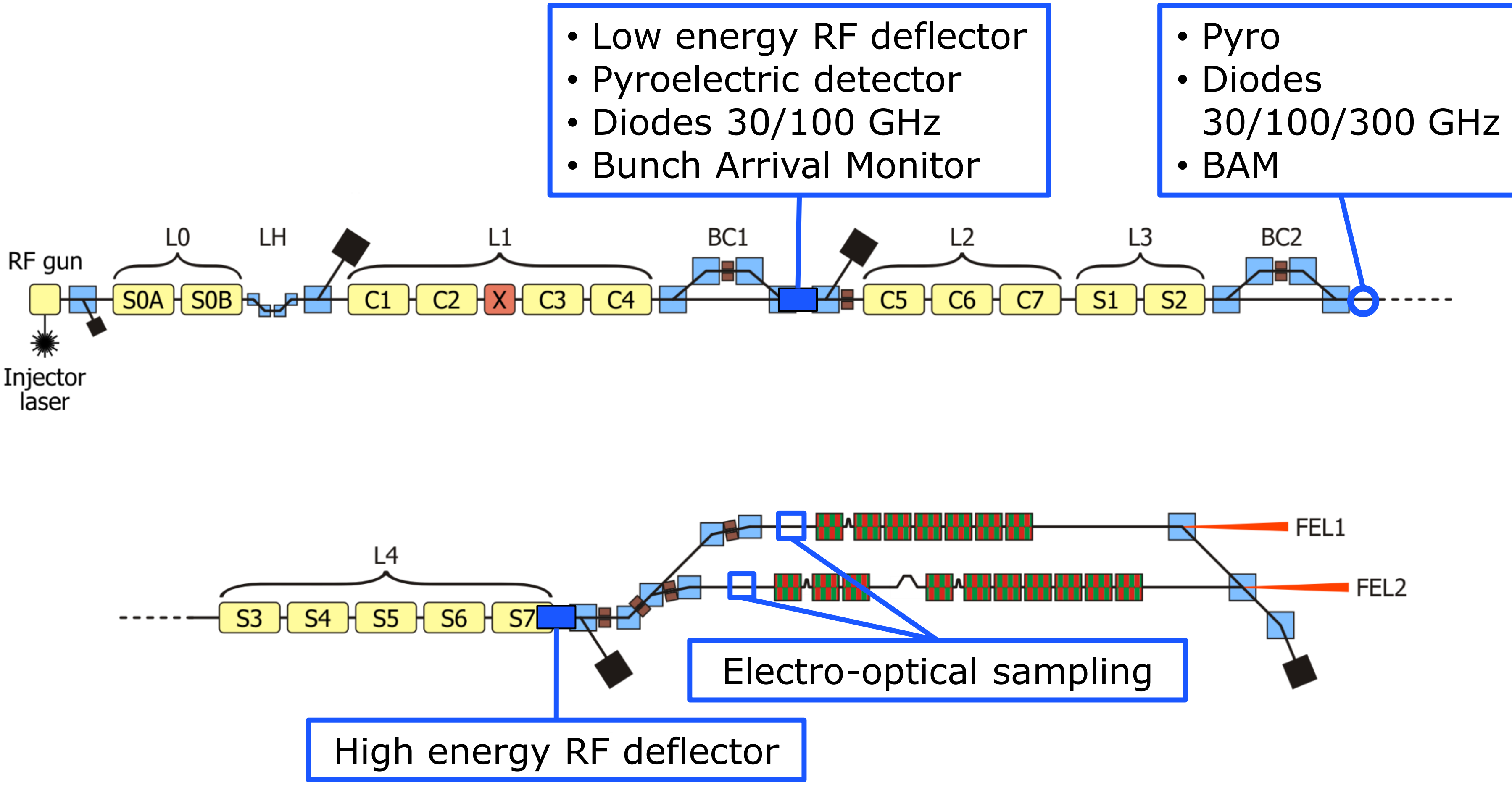



**Ionization chambers**

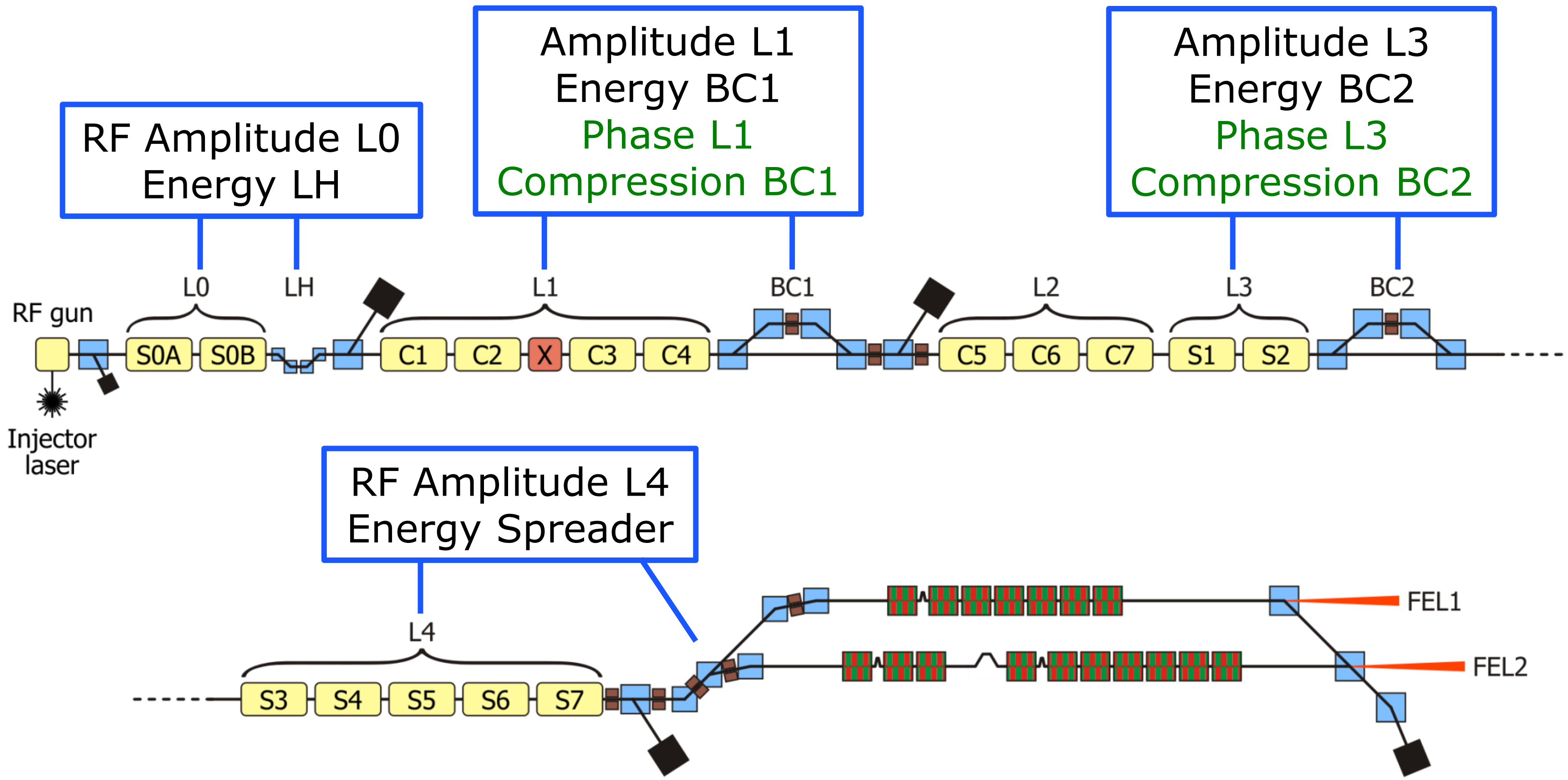
Voltage: 1000 V

Noise: <0.4 µGy/h rms

# Longitudinal Diagnostics



# Beam-based Feedback Loops




Other feedback loops:
- Charge
- Seed laser pointing
- Beam position/LINAC
- Beam position/FEL

And the X-band cavity?

# Thanks for your interest.

Thanks for slides, images+input to:
E. Allaria, B. Diviacco, L. Giannessi, S. Di Mitri, M. Svandrlik