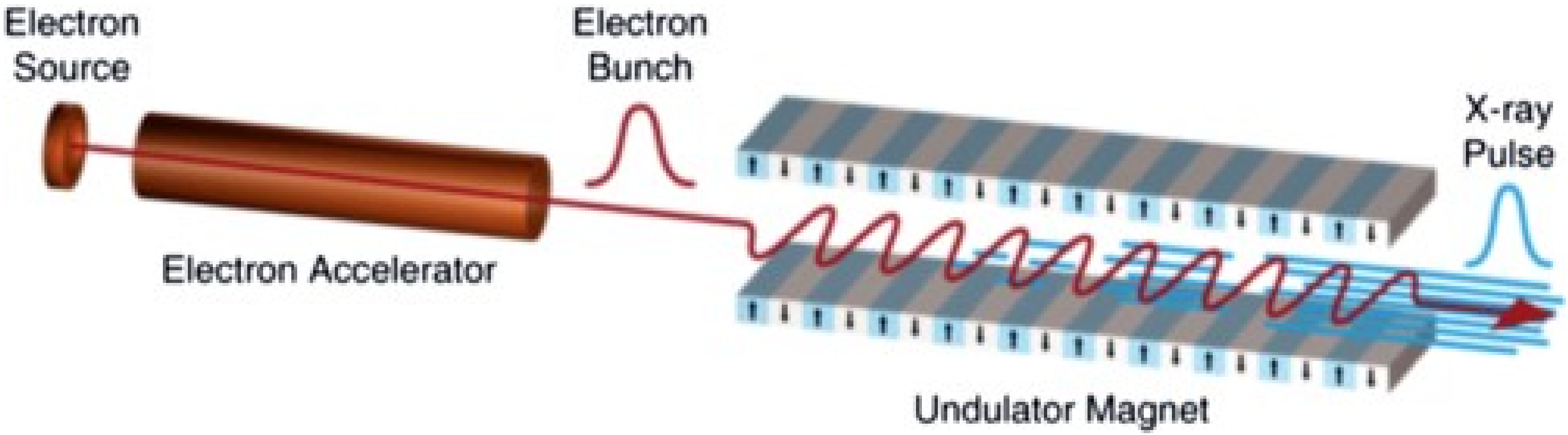
Overview on Laser and Free Electron Laser

Why FEL?

N. S. MIRIAN 10/04/2023

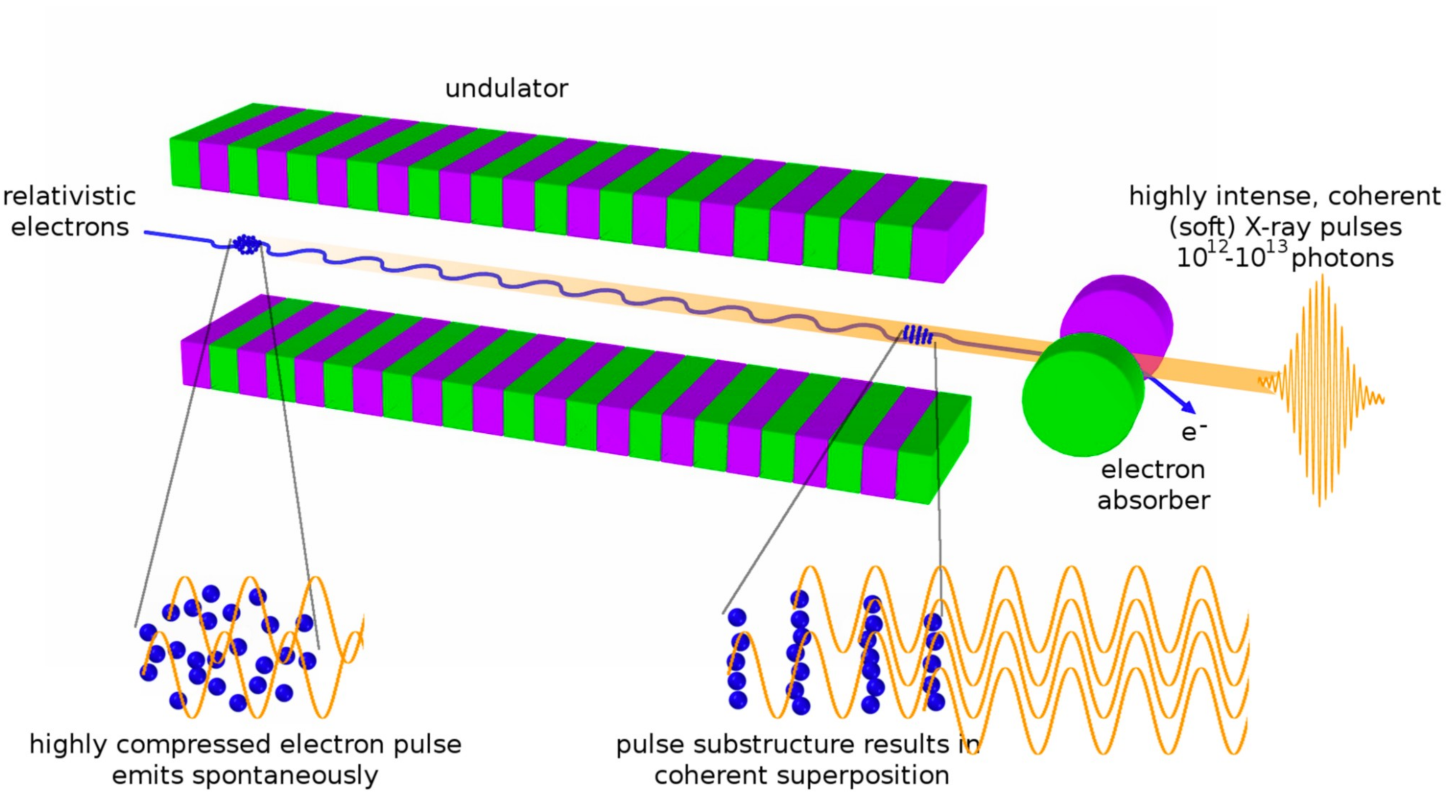
What is FEL ?



- Photo-cathode gun
- RF-accelerator sections
- Compression sections
- Undulator sections

Rev. Mod. Phys. **88**, 015006 – Published 9 March 2016

What is FEL ?

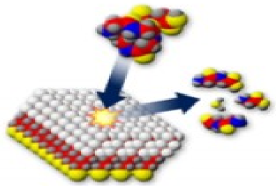

undulator
relativistic
electrons
highly intense, coherent
(soft) X-ray pulses
10¹²-10¹³ photons
e⁻
electron
absorber
highly compressed electron pulse
emits spontaneously
pulse substructure results in
coherent superposition

Why Free electron Laser ?
No, let ask why Laser?

Or why we need Laser?

Time scales in molecules

1 ps = 0.000 000 000 001 s (10^{-12} s)

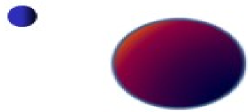


Molecular rotation and dissociation

1 fs = 0.000 000 000 000 001 s (10^{-15} s)

Molecular vibrations

1 as = 0.000 000 000 000 000 001 s (10^{-18} s)

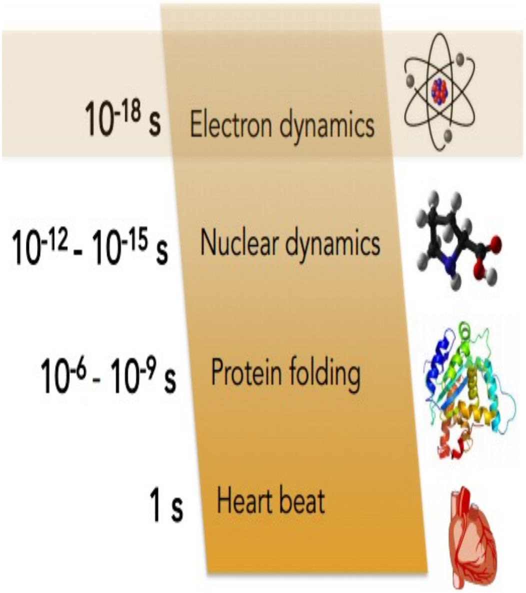


Electron motion in hydrogen atom:

$T=2\pi a_0/v_e \sim 150$ as

Time scale in matter

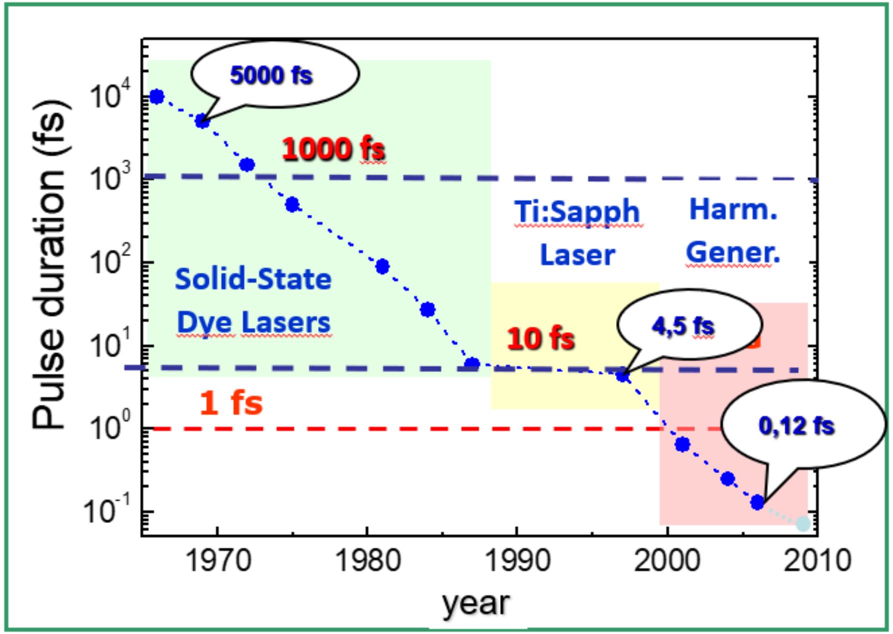
A journey in time...



Atomic unit of time:
24 attoseconds

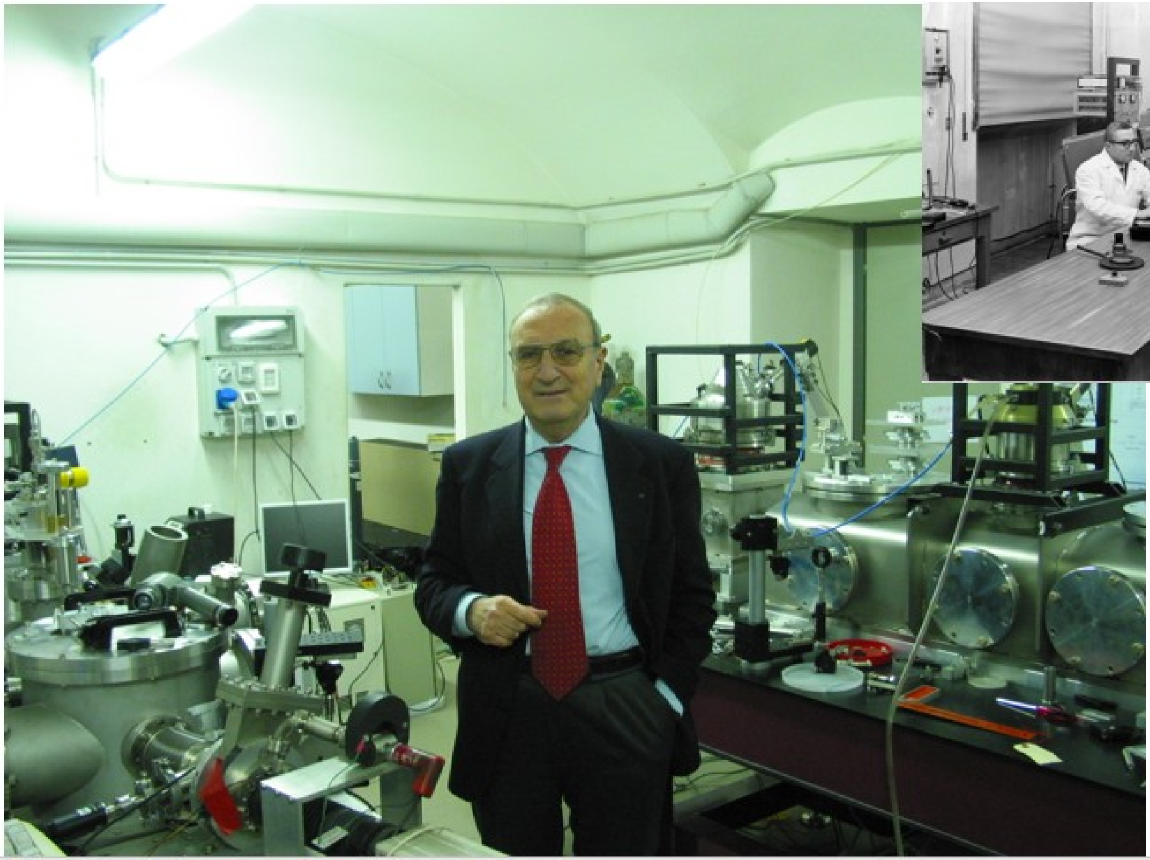
Electron orbit time around the nucleus:
150 attoseconds

Attosecond Science
for following and controlling electron dynamics in matter!

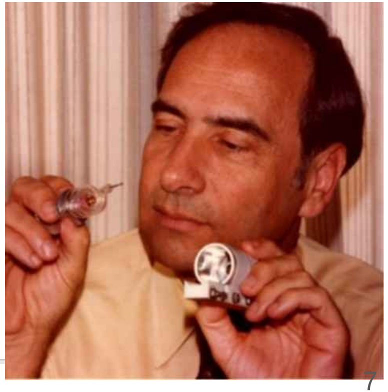


Politecnico di Milano: Attosecond Laser Lab

Orazio Svelto



Th.H. Maiman Holding
the first Laser



- The Laser during first 10 years:

  A bright solution looking for a problem

- The Laser, 50 years afterwards:

  The bright solution for many problems in science and technology

One of the most important invention of last century

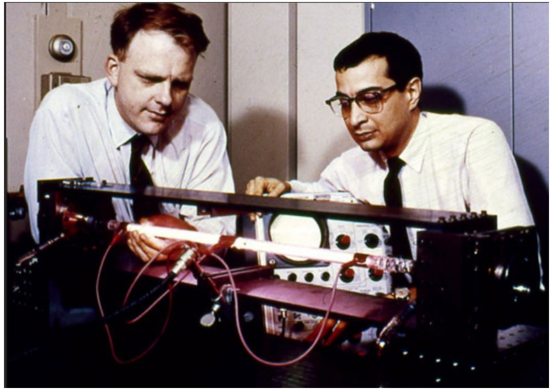
(~ 30 scientists being awarded by the Nobel prize)

It is going to play an even more important role in this century

(The century of the Photon)

End of the Race: December 1960

- May 16 1960:
  First laser demonstration by Maiman (Ruby, Cr^{3+}:Al_2O_3)
- A few months later:
  P.P. Sorokin *et al*. U^{3+}:CaF_2 (2,5 μm) Sm^{2+}:CaF_2 (~700 nm) [4 level lasers, first rare-earth laser, cryogenic temperature]
- October 1960:
  R.J. Collins *et al*. "Coherence, Directionality, and Relaxation Oscillations in the Light Emission from Ruby" *Phys. Rev. Letters* ***5****, pp. 303-305 (1 October 1960)*
- December 1960:
  A. Javan *et al*. He-Ne laser (1.15 μm); the first cw laser; the first gas laser; the first electrically excited
- By the end of 1960:
  quite different types of lasers were operated ⇒ door opened to all successive developments



Orazio Svelto

Period Number 1 (1964-1981)

- 1964, Physics
  C. H. Townes (1/2) and N.G. Basov and A. M. Prokhorov (1/2)
  for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle
- 1971, Physics
  Denis Gabor
  for his invention and development of the holographic method
- 1981, Physics
  Nicolas Bloembergen an Arthur L. Schawlow
  for their contributions to the development of laser spectroscopy

Period Number 3 (2000-2012)

- 2005, Physics
  Roy Glauber (1/2),
  for his contribution to the quantum theory of optical coherence
  John L. Hall and Theodore W. Hänsch (1/2)
  for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique
- 2009, Physics
  Charles K. Kao (1/2)
  for ground-breaking achievements concerning the transmission of light in fibers for optical communications
- 2012, Physics
  Serge Haroche and David Wineland
  for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems

Period Number 2 (1997-2000)

- 1997, Physics
  Steven Chu, Claude Cohen-Tannoudji and William D. Philips
  for development of methods to cool and trap atoms with laser light
- 1999, Chemistry
  Ahmed H. Zewail
  for his studies of the transition states of chemical reactions using femtosecond spectroscopy
- 2000, Physics
  Zhores I. Alferov and Herbert Kroemer
  for developing semiconductot hetrostructures used in high-speed-electronics and -optoelectronics
- 2001, Physics
  Eric A. Cornell, Wolfgang Ketterle, and Carl E. Wieman
  for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates

Period Number 4 (2014 -)

- 2014, Physics
  Isamu Akasaki, Hiroshi Amano, Shuji Nakamura
  for the invention of efficient blue light-emitting diodes (LEDs) which has enabled bright and energy saving white light sources
- 2014, Chemistry
  Eric Betzing, Stephan W. Hell, Wiliam E. Moerner
  for super-resolution fluorescence microscopy
- 2017, Physics
  Rainer Weiss, Barry C. Barish, Kip S. Thorne
  for decisive contributions to the LIGO detector and the observation of gravitational waves

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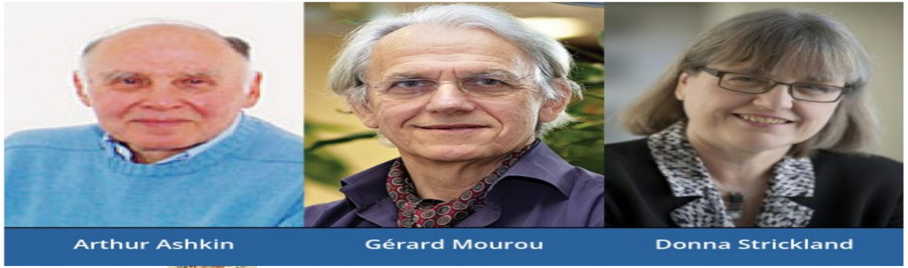
Laser science won 3 scientists 2018 Nobel Physics Prize

By Ikenna Emewu - October 4, 2018 421 0



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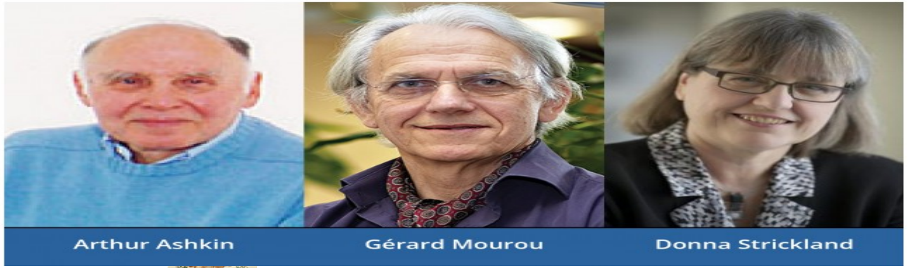

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Where are Iranaian scientists?
(outliers , M.Gladwell)
Now we are backing

Orazio Svelto

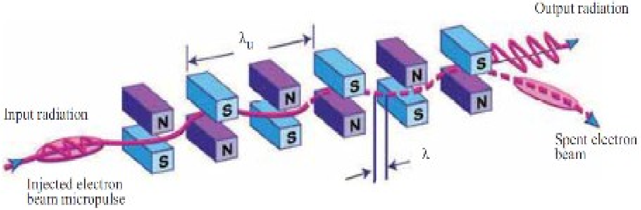
Why FEL ?

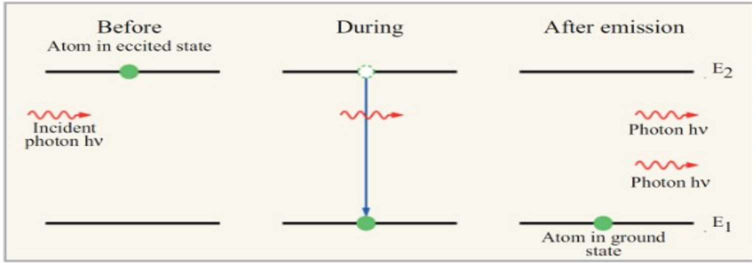
Let‘s first ask what is FEL?

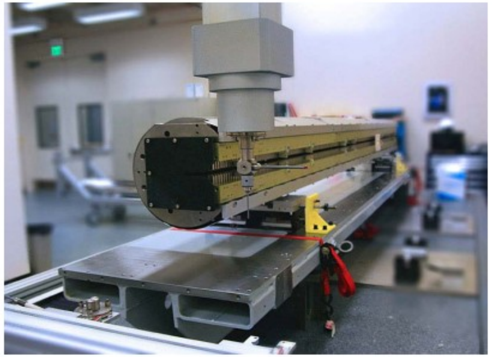
1985 Iran had two FEL scientists
Amirkabir U
Tarbiat Moallem U

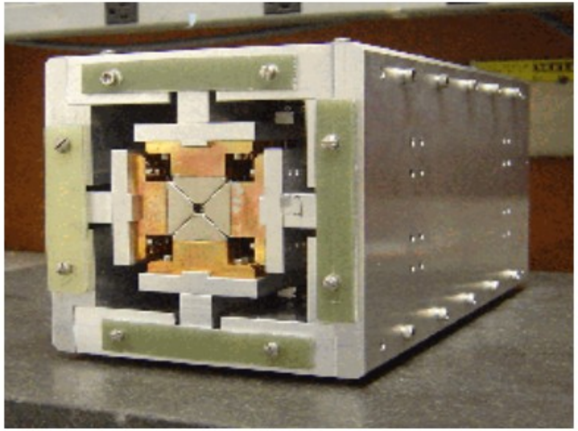
All subjects are so old for 1970s
Until
M.H.Rouhani (2008)
N.S.Mirian (2013)
E. Salehi (2014)

$$\frac{d\vec{p}}{dt} = -\frac{e}{c}\vec{v} \times \vec{B}. \quad (29)$$

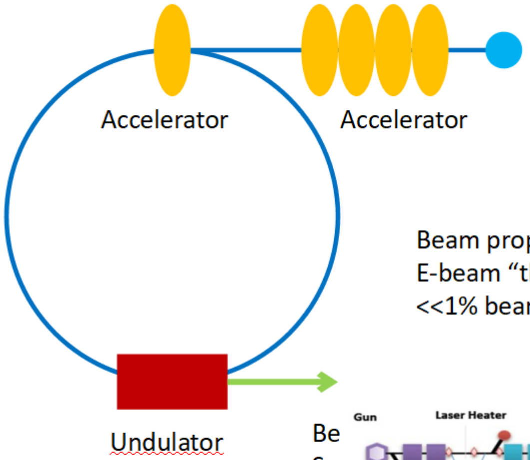


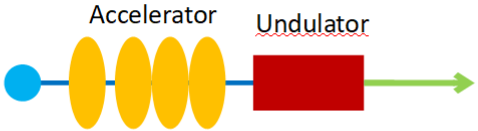






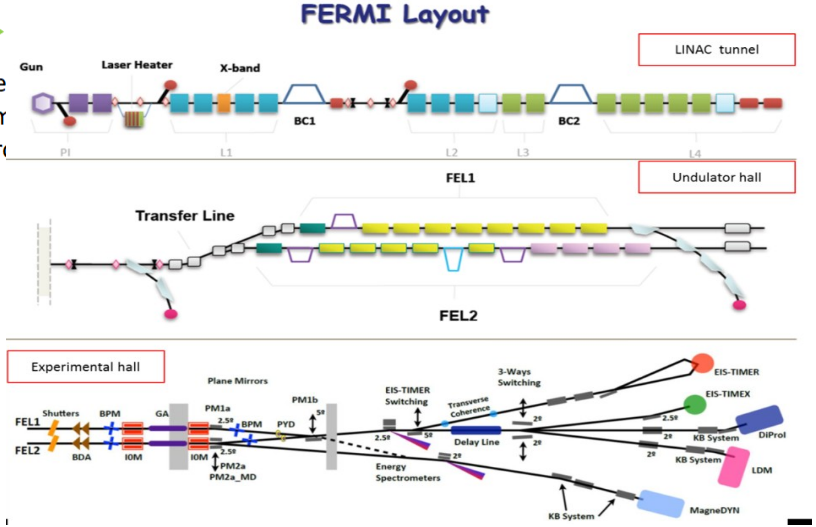
What is different between FEL an SR?

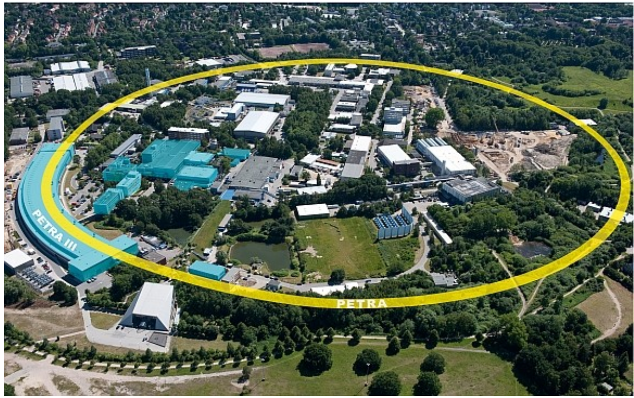


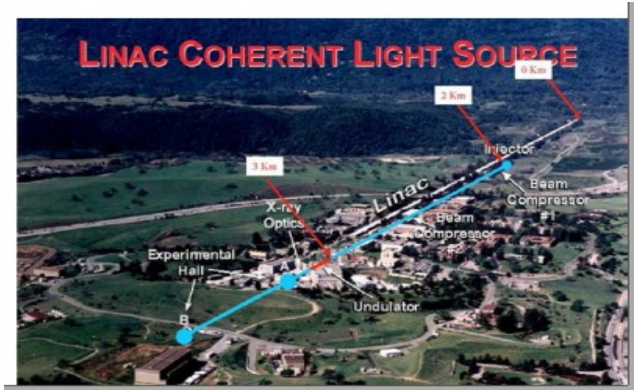


Beam properties mostly determined by the injector.
E-beam “thrown away” after undulator
<<1% beam energy used

Be
Sm
pr







Let’s watch LCLS in youtube
[X-ray Laser Animated Fly-through - YouTube]

Now, WHY FEL?

A free-electron laser (FEL) is a source of intense and coherent electromagnetic radiation with tunable wavelength.

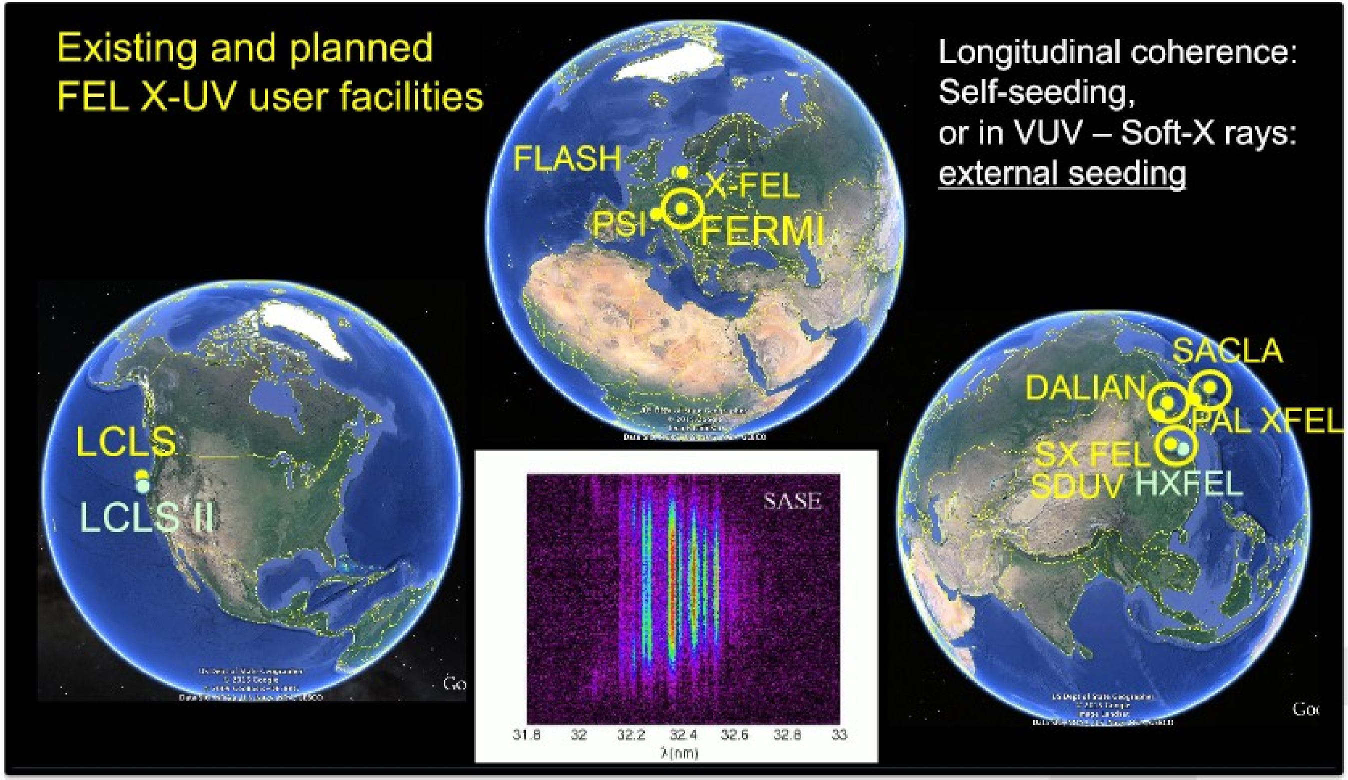
- ✓ Tunable in wavelength ➔ VUV- X-Rays
- ✓ Coherence (Transverse, single TEM 00 mode, **FERMI also temporally coherent**)
- ✓ Narrow spectral bandwidth (10^{-3} – 10^{-4} relative bandwidth)
- ✓ Ultra-short pulses (100 fs – 1fs)
- ✓ High Peak power (Multi GW to TW)

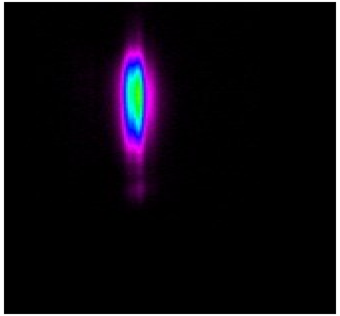
Ultra-fast coherent diffractive imaging and time-resolved scattering processes in chemical and biological systems, non-linear processes in ultra-intense X-ray radiation fields, matter in extreme states, phase transitions, population inversion & X-ray atomic lasers, low density systems, i.e. unperturbed atoms, molecules, and clusters.

Two class of FEL :

SASE (self-seed, optical klystron and ...)

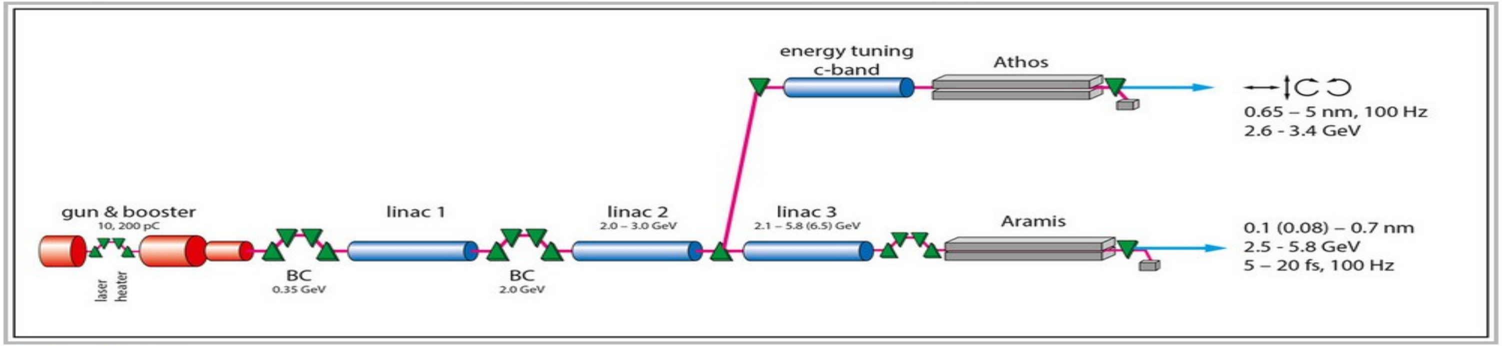
Seeded (HGHG and EEHG)





SwissFEL Accelerator Design

The SwissFEL design (see image below) is based on an electron accelerator, consisting of a high-brightness electron gun, a booster, three sections of linear accelerator (linac) and two bunch compressors (BC).



The SwissFEL design

?

What is the RF-band of Linac?

Electrons are extracted at energies from 2.1 to 5.8 GeV and fed to two undulators, long arrays of alternately-poled permanent magnets, where intense, coherent X-ray pulses are generated for two X-ray beamlines, "Athos" and "Aramis", operating in parallel.

Main parameters	
Wave length	1A -50Å
Photon energy	0.25-12 keV
Pulse duration	1fs - 20fs
e Energy	5.8 GeV
e Bunch charge	10 - 200 pC
Repetition rate	100 Hz

The FELs

Two SASE FEL lines are driven by the linac: a hard X-ray FEL named "Aramis" and a soft X-ray line named "Athos".

SwissFEL	Aramis beamline	Athos beamline
Undulator period	15 mm	38 mm
Undulator parameter	1.2	1.0-3.5
Undulator module length	4.0 m	2.0 m
Undulator section length	4.75	2.8m
Average ß-function	15 m	10 m

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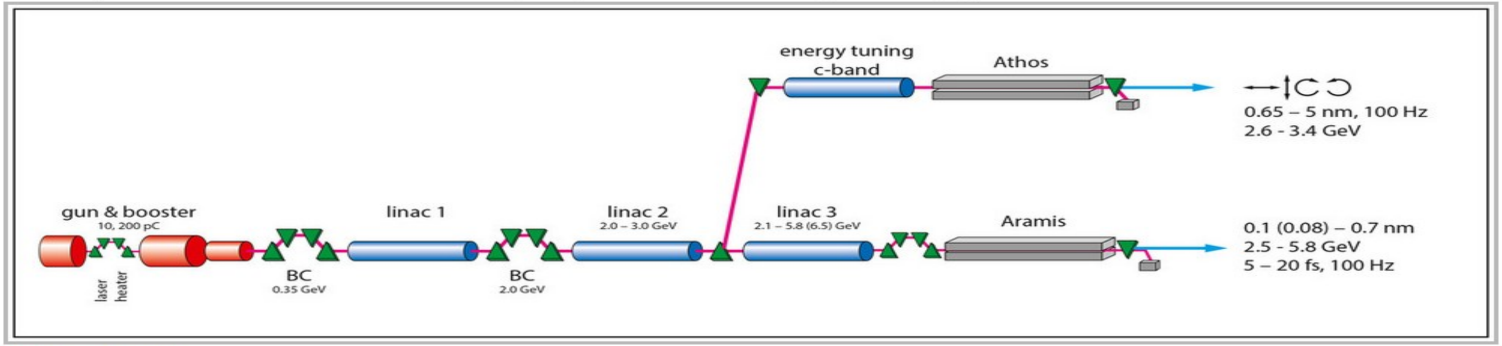

The SwissFEL design

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What is the RF-band of Linac?
Please search about it

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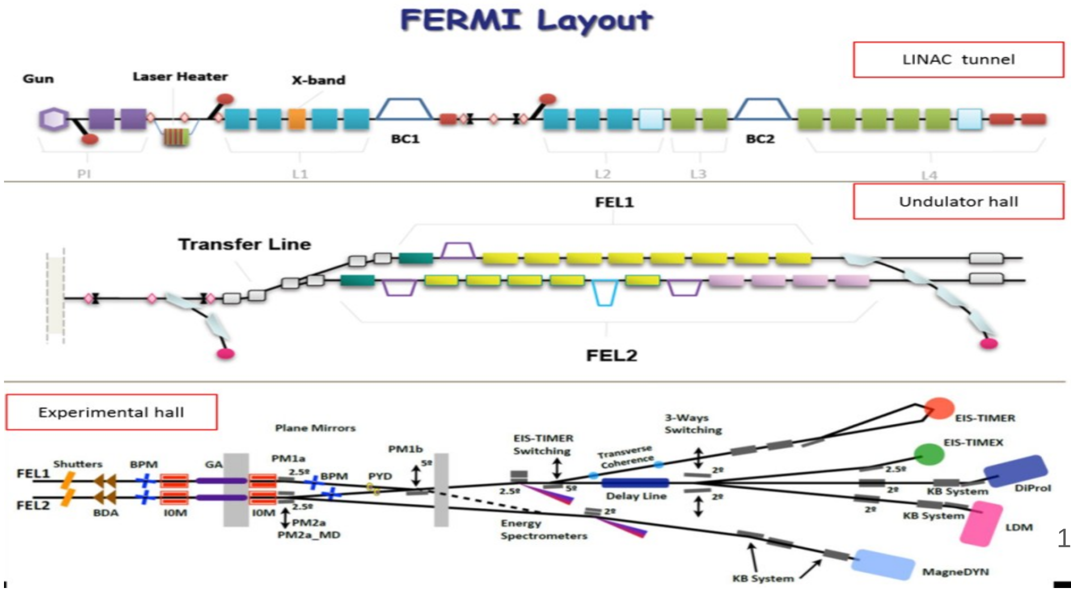
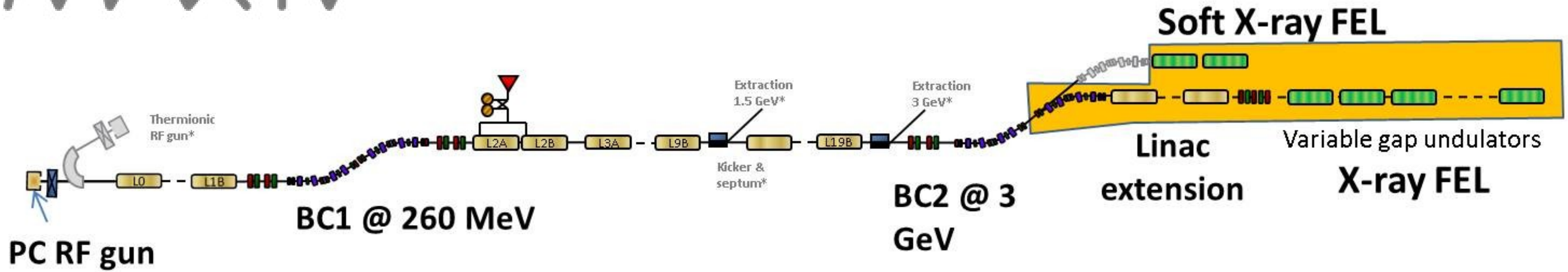
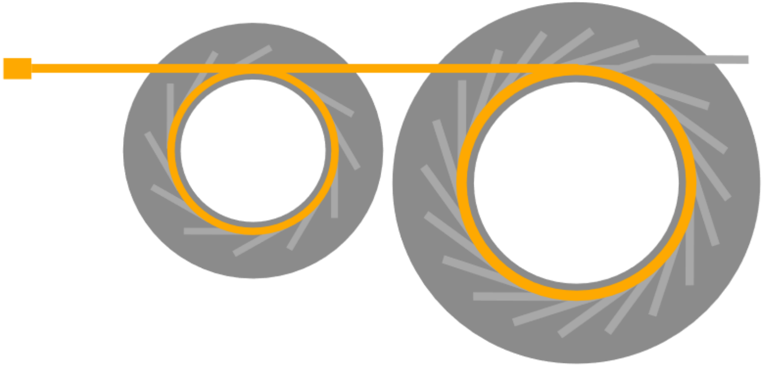
Great and powerful Facility in Italy (2010)
Lianc was from CERN, sections to sections are different.
Undulators are apple II (Modern)
Very good scientists

Photon Beam Parameters	FEL-1 *	FEL-2 *
Photon Energy (eV)	12.4-65	65-310
Average pulse energy [μJ]	200-25 **	100-10 **
Pulse duration [fs] (FWHM)	100-50	60-20
Peak power [GW]	3-0.4	2.5-0.4
Repetition rate [Hz]	10-50	10-50
FEL mode	SEEDED, TEM_00	SEEDED, TEM_00
Photon energy fluctuations [meV][rms]	1-2	4-15
FEL bandwidth ΔE/E [rms]	2.5-5 (x10sup^{-4})	2-7 (x10^{sup-4})
FEL bandwidth fluctuations [%][rms]	3-5	3-40
Polarisation	Linear Horizontal Linear Vertical Circular Left Circular Right	Linear Horizontal Lineal Vertical Circular Left Circular Right





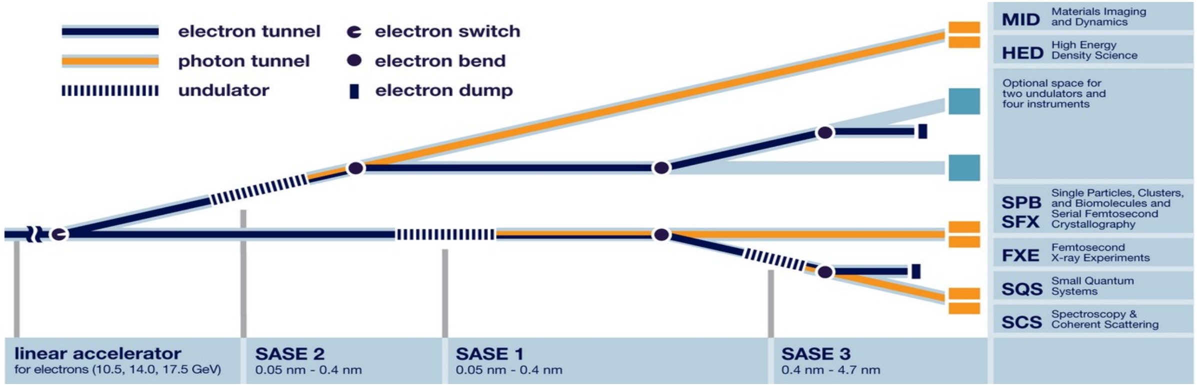


The MAX IV facility consists of a 3 GeV storage ring, a 1.5 GeV storage ring, and a linear accelerator (fed by two guns) that serves as a full-energy injector to the rings, but also as a driver for the Short Pulse Facility. The 3 GeV storage ring with a circumference of 528 m is geared towards hard x-ray users, while the 1.5 GeV storage ring, 96 m circumference, serves soft x-ray and UV users.

https://www.fels-of-europe.eu/

EUROPEAN XFEL

Note :
This is big brother ,
Germans learned a lot from Flash,
let's say Europeans learned a lot by Flash



Beam parameters	Value
Max. Electron Energy [GeV]	17.5
Wavelengthrange [nm]	0.05 - 4.7
Photon/pulse	~10e12
Peak brilliance	5x10e33
Pulses/second	27 000

Undulators of the European XFEL

	SASE1, SASE2	SASE3
Wavelengths	0.4 nm to below 0.05 nm	4.7 nm to 0.4 nm
Photon energy	3 keV to over 25 keV	0.26 keV to 3 keV
Instruments	SPB/SFX, FXE (SASE 1) MID, HED (SASE 2)	SQS, SCS
Magnetic length	175 m	105 m

There are three important concept in FEL

- How to generate high coherent radiation?
- How to generate ultra-short pulse FEL?
- How to control and optimise electron beam and radiation beam ?

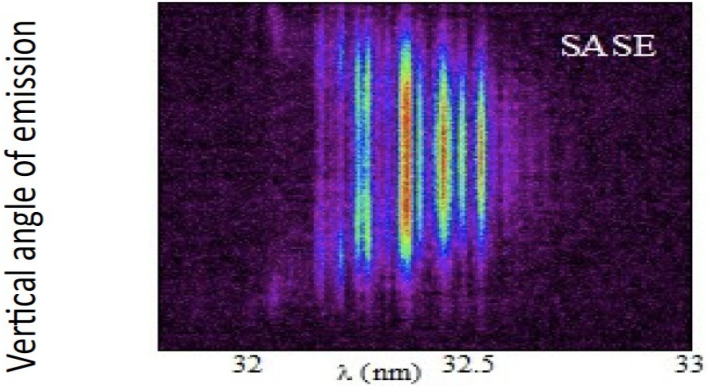
Which kinds of problems and solution we are dealing with FEL :

- How to generate fs and As laser ? (manipulation e-beam or manipulation of radiation)
- How to generate two or multi pulses ? how generate multi color pulses? How change the delay between pulses?
- How to change the radiation properties (like coherence length or polarization and etc
- How reduce the cost of the FEL facility

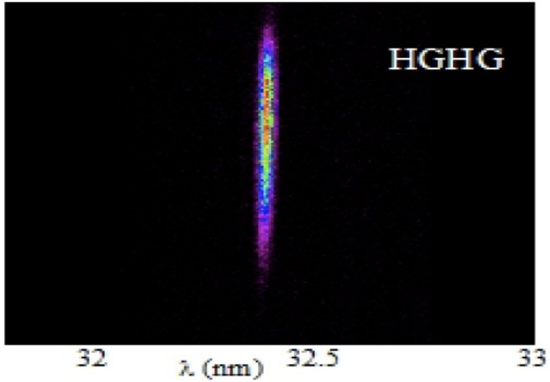
SASE and FERMI Free-Electron Lasers: why seed?

Starting from Noise
In SASE FEL, noises are amplified

Starting from laser !
In seeded FEL, harmonic of the seed are amplified



FERMI operated in SASE mode, single shot.



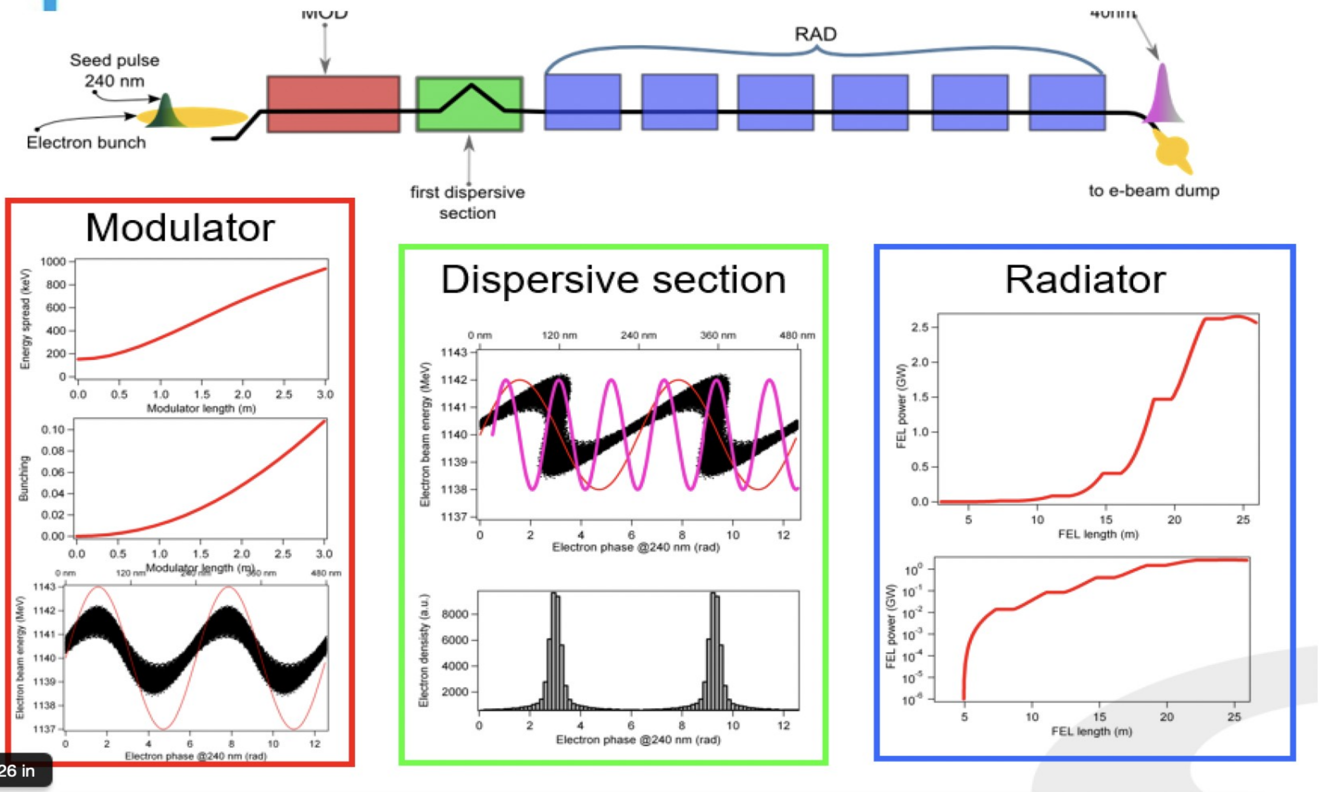
FERMI operated in HGHG mode, single shot.

Coherent e-beam produces coherent light

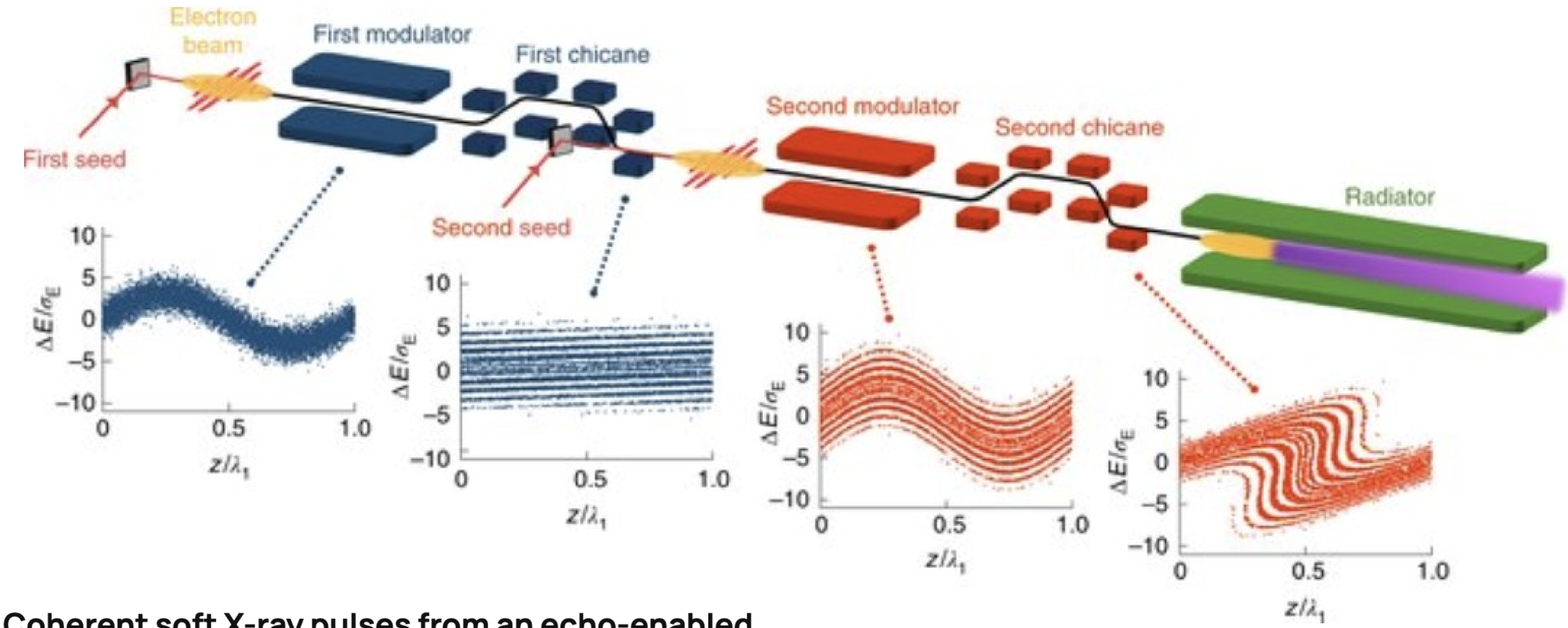
HGHG
EEHG

How to make the coherent e-beam

Concept of FEL -HGHG



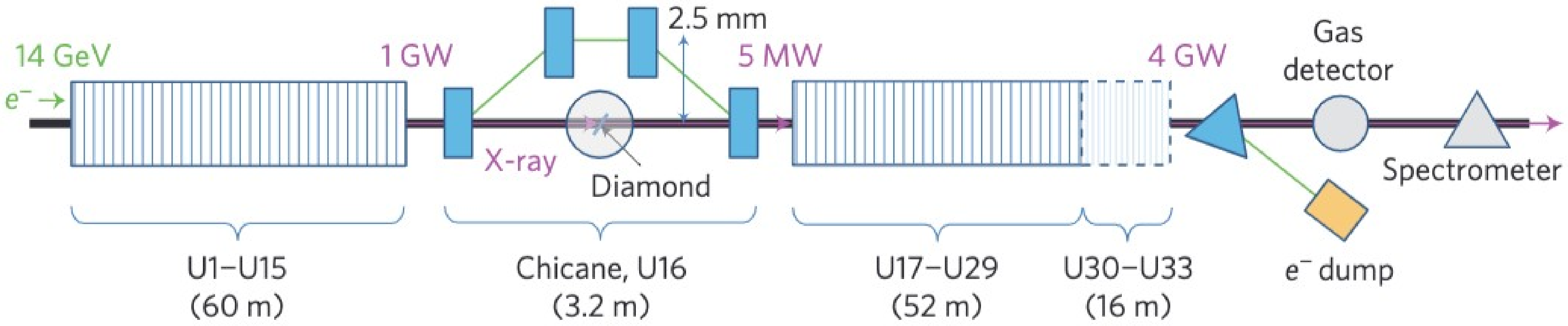
Echo Enable Harmonic generation (EEHG)



Coherent soft X-ray pulses from an echo-enabled harmonic generation free-electron laser

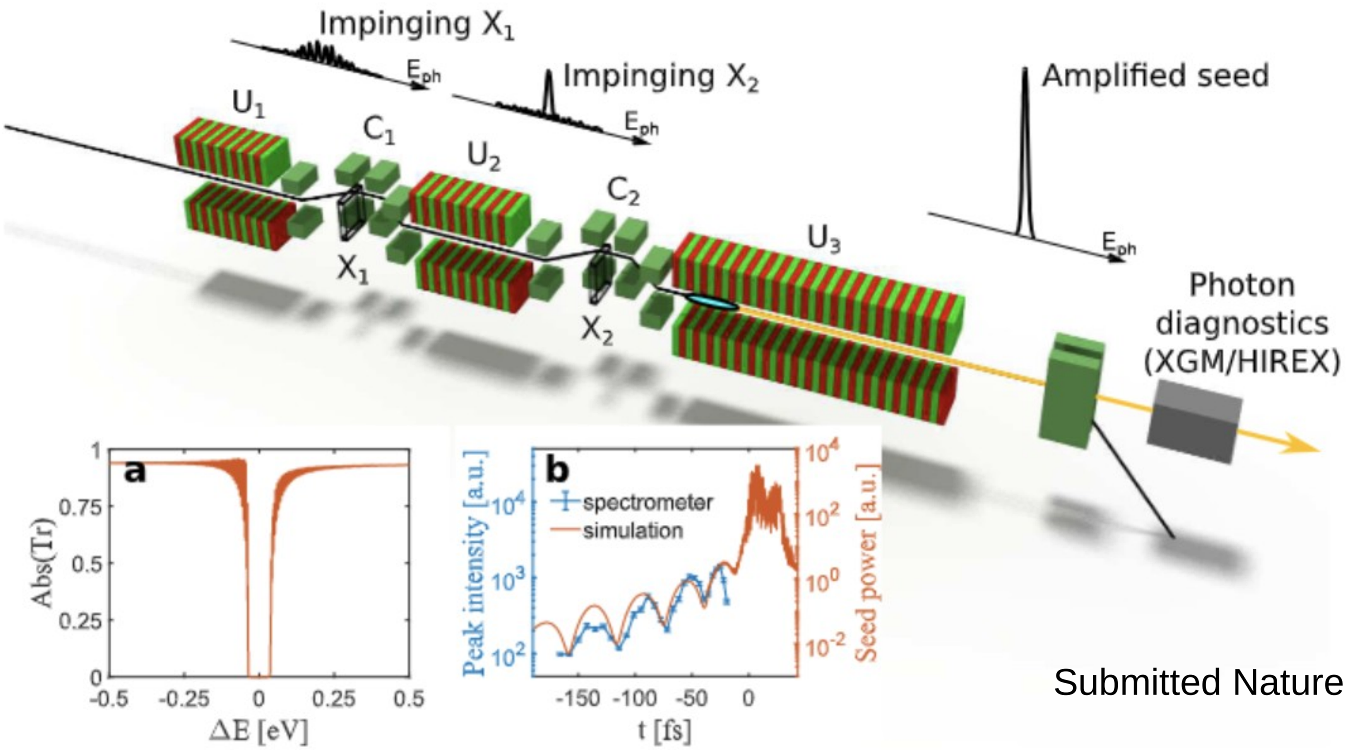
natureresearch
August 2019 · Nature Photonics 13(8):1-7

Self seeding FEL



We monochromize the radiation from first stage and amplify the coherent radiation in second stage.

Self seeding FEL



Submitted Nature photonics, 2023

Generation of short pulse with Modulator before SASE

Or superradiant FEL

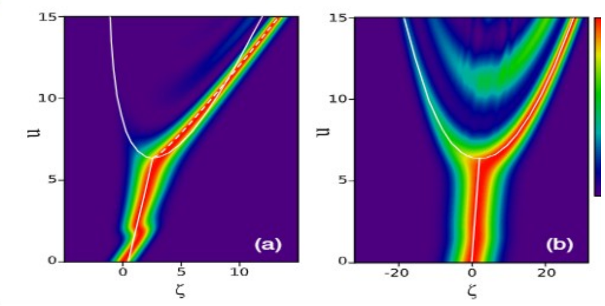
Or shaping beam

Or ...

Free electron laser radiation

Longitudinal manipulation of the e-beam (and radiation)

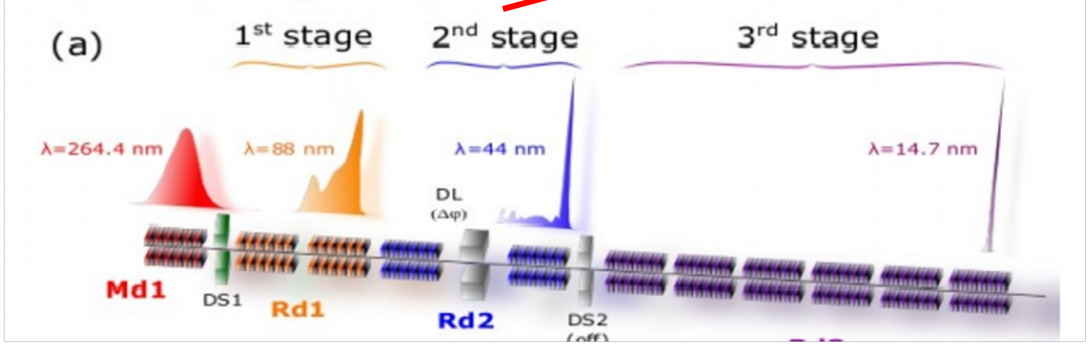
- Postsaturation dynamics and superluminal propagation of a superradiant spike in FEL PhysRevAccelBeams.23.010703 (2020)

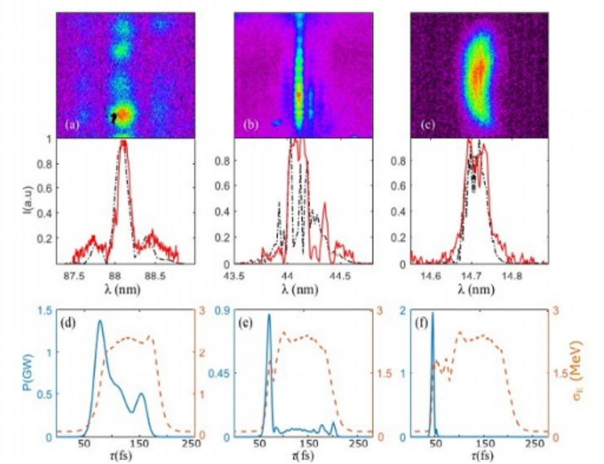


- Generation and measurement of intense few-femtosecond superradiant soft X-ray FEL pulses

published

(In FERMI, I managed this experimet, ~~submitted~~ in nature photonics)





Enhance SASE (modulation electron beam)

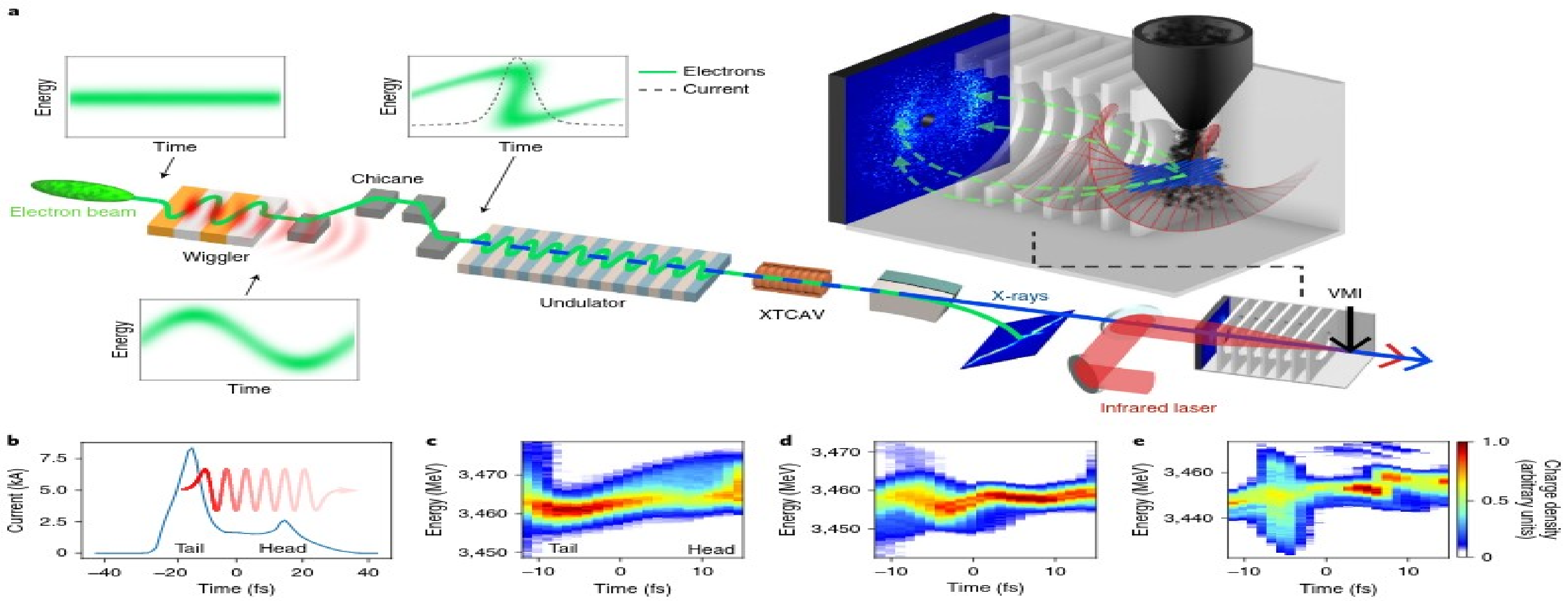


Fig. 1 | Diagram of the XLEAP operation. a, Schematic representation of the experiment. The electron beam travels through a long-period (35 cm) wiggler and develops a single-cycle energy modulation. The energy modulation is turned into a density spike by a magnetic chicane and sent to the LCLS undulator to generate sub-femtosecond X-ray pulses. After the undulator, the relativistic electrons are separated from the X-rays and sent to a transverse cavity (labelled XTCAV) used for longitudinal measurements of the beam. The X-rays are overlapped with a circularly polarized infrared laser and interact with a gas jet to generate photoelectrons. The ejected photoelectrons are streaked by the laser and detected with a velocity map imaging (VMI) spectrometer. The momentum distribution of the electrons is used to reconstruct the pulse profile in the time domain. **b–e**, The measurements of the ESASE modulation process. **b**, The measured current profile of the electron bunch generated by the accelerator. The tail of the bunch has a high-current horn that generates a high-power infrared pulse, represented by the red squiggle, which is used for the ESASE compression. **c–e**, The longitudinal phase space of the core of the electron bunch in three different conditions: with no wiggler and no chicane we measure the electron distribution generated by the accelerator (**c**); after inserting the wiggler we observe a single-cycle energy modulation generated by the interaction between electrons and radiation (**d**); after turning on the chicane the modulation is turned into a high-current spike at $t = -5$ fs (**e**).

Generation High photon energy for high energy physics study

Generation of higher than 30 kev photon energy for QCD and QED

Generation of higher than 2 Mev by inverse competition scarring

New concepts in FEL field

Plasma accelerators

Plasma lens

Plasma undulators

Crystal undulator

Diagnostic devices

Controlling system with new technology and numerical methods.

Useful links:

The European Cluster of Advanced Laser Light Sources (EUCALL):
https://www.eucall.eu/

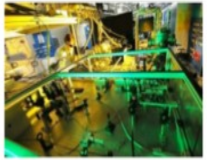
FELS OF EUROPE
https://www.fels-of-europe.eu/

Thanks for your attention

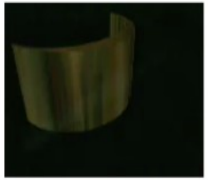
Please think about this field
think about future

And think about our problems

Access to atto- and few-femto second dynamical processes is now a real possibility



Tabletop laser sources (high-order harmonic generation, HHG): XUV atto pulses



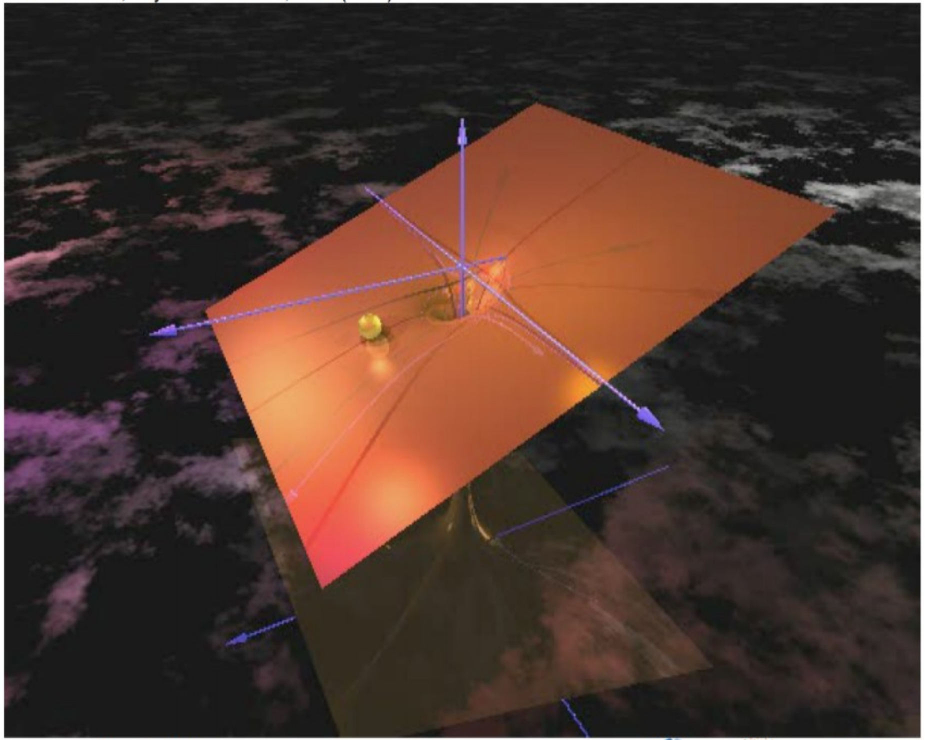
Accelerator-based free-electron lasers (X-ray FEL): few-femto pulses

Do they allow us to image ultrafast electron and nuclear dynamics in molecules, and eventually to control it?

High harmonic generation

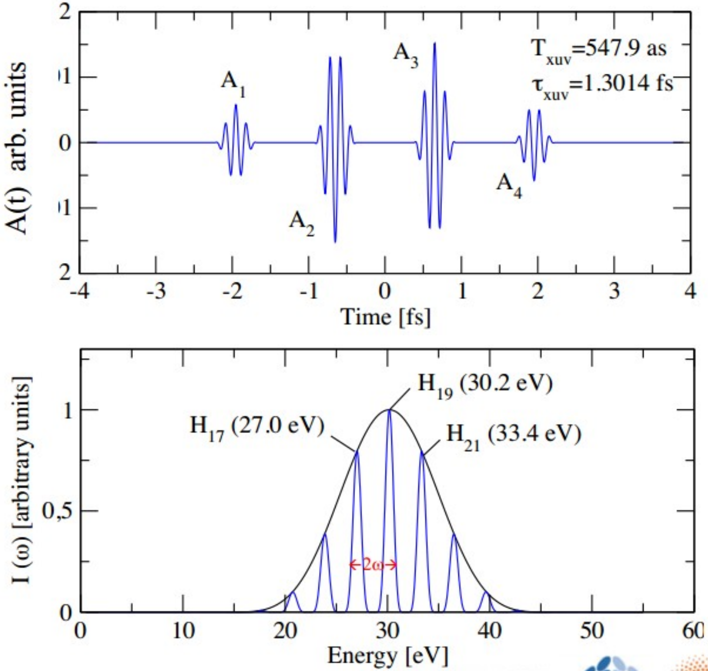
J. L. Krause, K. J. Schafer, and K. C. Kulander, Phys. Rev. Lett. 68, 3535 (1992)

P. B. Corkum, Phys. Rev. Lett. 71, 1994 (1993)



Courtesy Paula Rivière

Attosecond pulse train (APT)



Fourier transform →