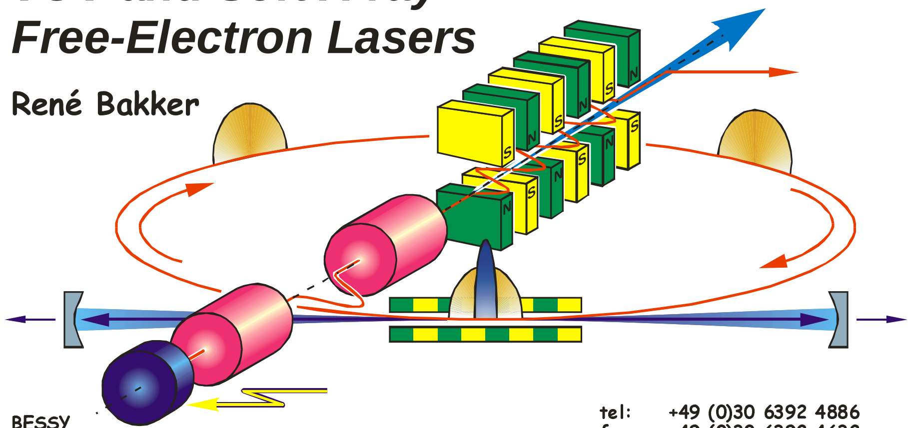
Approaches and Prospects for VUV and Soft X-ray Free-Electron Lasers

René Bakker



BESSY
Albert Einstein Strasse 15
D-12489 Berlin

tel: +49 (0)30 6392 4886
fax: +49 (0)30 6392 4632
email: bakker@mail.bessy.de
inet: http://www.bessy.de/FEL

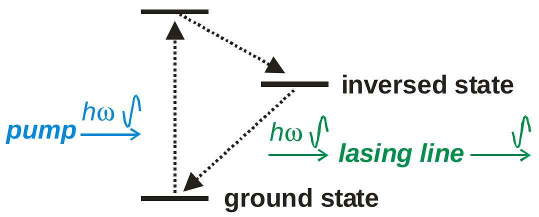
Outline

- Introduction

  (to the **F**ree-**E**lectron **L**aser or FEL)
- from the UV to theVUV: Storage Ring FELs
- from the VUV to X-rays: Linac-based FELs
  - Projects
  - What to expect
  - How to improve
- Summary

Lasers & Free-Electron Lasers

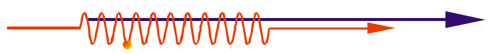
lasers: bounded electrons



the transition-properties and hence, the radiated wavelengths are determined by energy states in the active material and not by the electron properties

free electron lasers: non-bounded electrons

but............
the electrons are forced to radiate, e.g., by producing dipole radiation



radiation-properties are now determined by the electron properties and external forces

Lasers & Free-Electron Lasers

Advantages:

- Works for any wavelength

  mm-waves → 80 nm → 0.85 Å → 0.1 Å → ......?

- Continuously tunable wavelength (fast)
- High power / Brilliance:

  kW to 100 MW to 100 GW of peak power

  up to 2 kW of time-averaged output power demonstrated

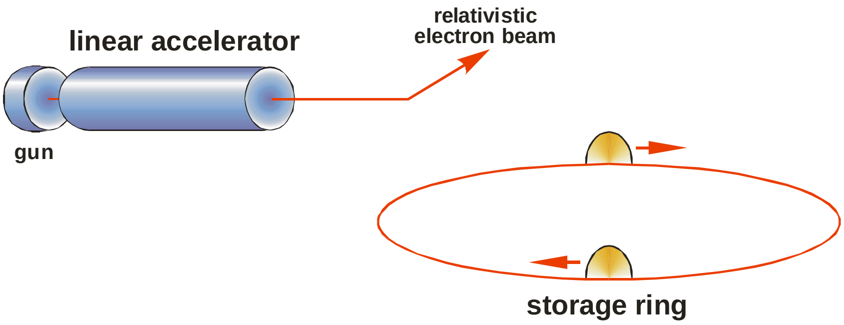
- Full coherent radiation (transverse and longitudinal)

  i.e., $\Delta\lambda/\lambda$ = 0.1 (transform limited) → 10^{-8}

- Flexible output (polarization, pulse-length, ...)

Building your own FEL

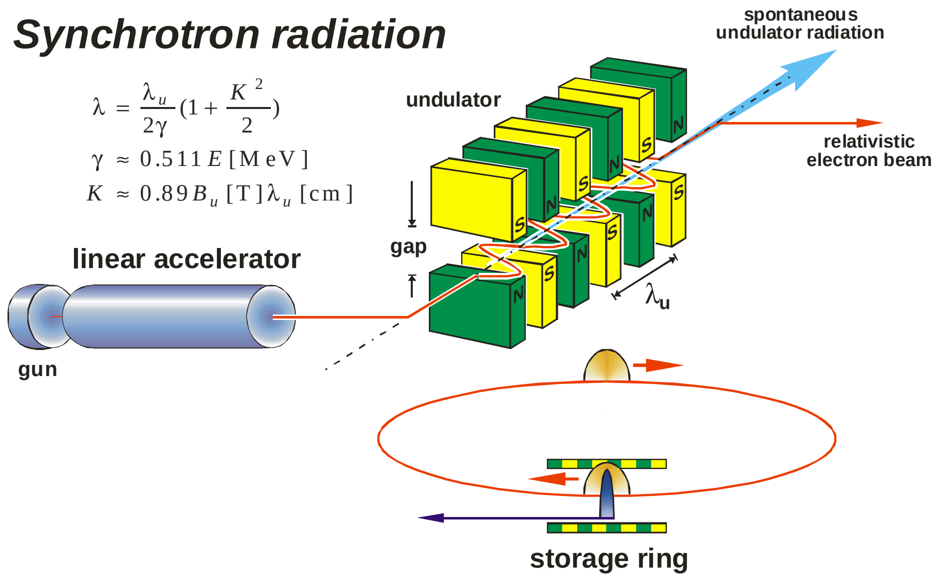
Generating free-electrons



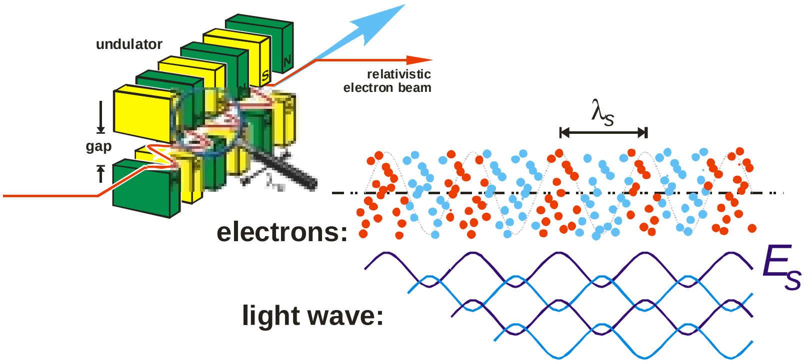
Building your own FEL

Synchrotron radiation

$$\lambda = \frac{\lambda_u}{2\gamma}\left(1 + \frac{K^2}{2}\right)$$
$$\gamma \approx 0.511\, E\,[\mathrm{MeV}]$$
$$K \approx 0.89\, B_u\,[\mathrm{T}]\,\lambda_u\,[\mathrm{cm}]$$



Building your own FEL



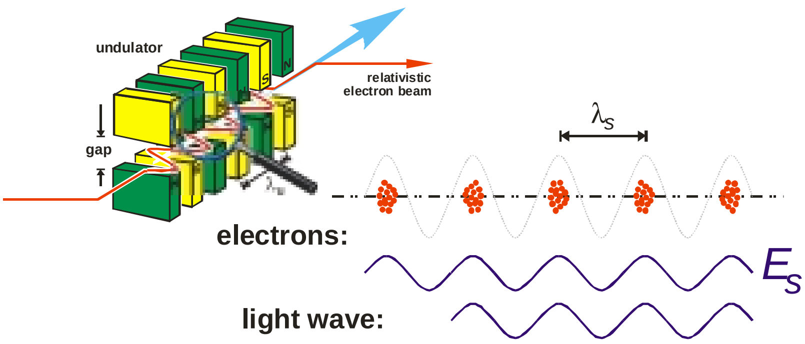
Radiated Power :

$P \propto n_e$ (number of electrons)

destructive interference

$\longrightarrow$ **shotnoise radiation**

Building your own FEL



Radiated Power :

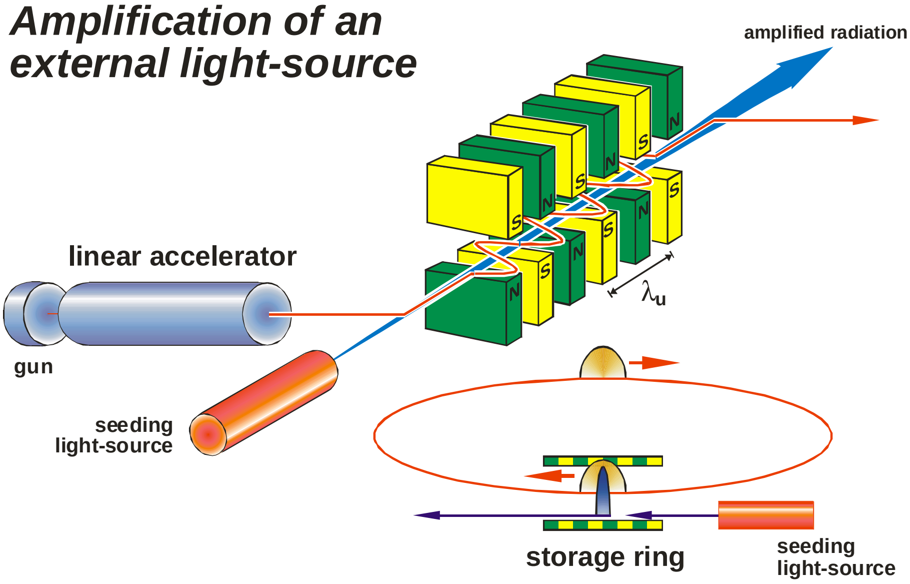
$$P \propto n_e^2 \left(\begin{array}{c} \text{number of electrons} \\ n_e \sim 10^6 - 10^9 \end{array} \right)$$

constructive interference

$\longrightarrow$ **enhanced emission**

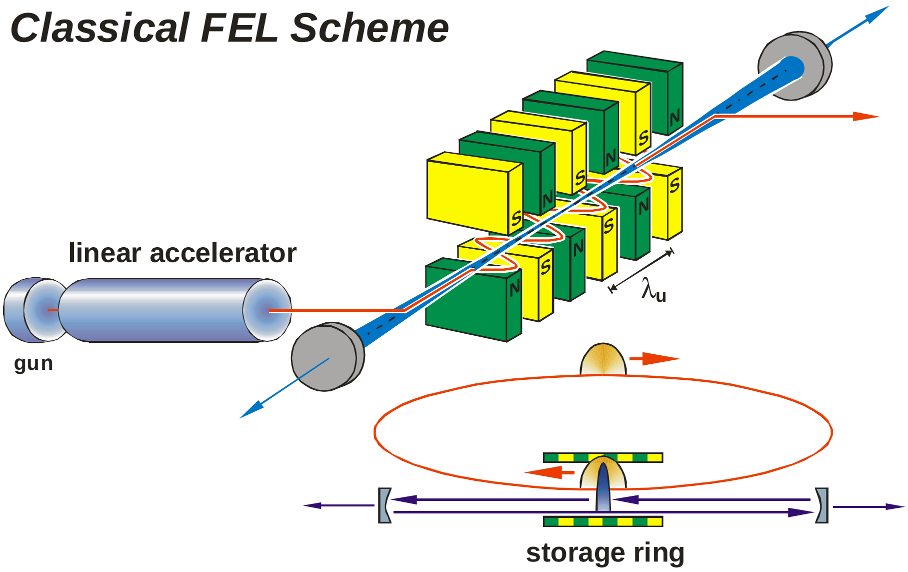
Building your own FEL

Amplification of an external light-source

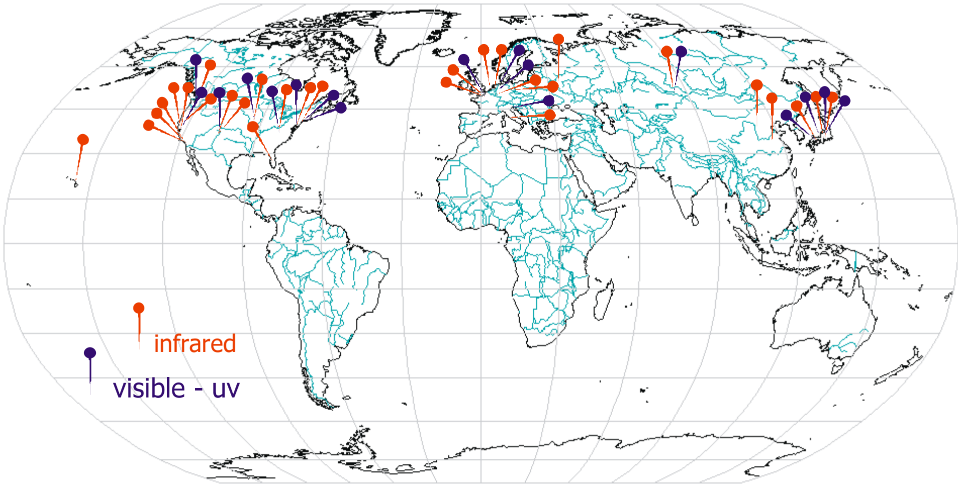


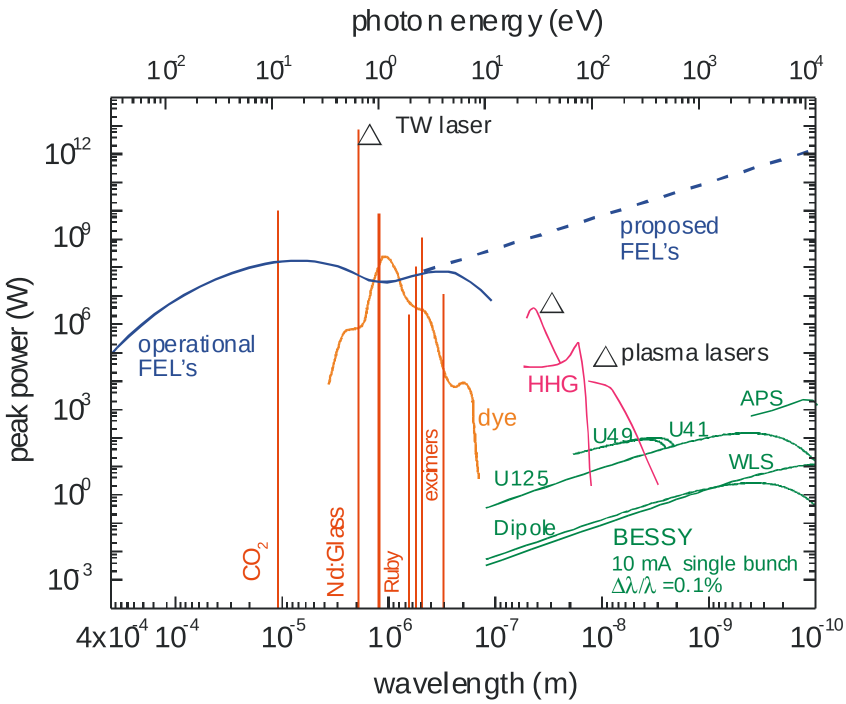
Building your own FEL

Classical FEL Scheme



FEL facilities worldwide

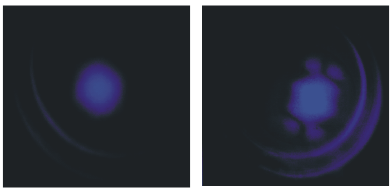




Drawbacks

- **<u>Expensive</u>**
- **<u>Radiation hazard</u>**
- **<u>Complex technology</u>**
  - High demands on the electron beam quality
  - High demands on the electron beam stability
  - Optics
- **<u>For X-ray FEL</u>:**
  - non-demonstrated technology

N.B. Technological challenges increase towards shorter wavelengths!



transverse mode profile

The Super ACO FEL

Storage-Ring FEL:

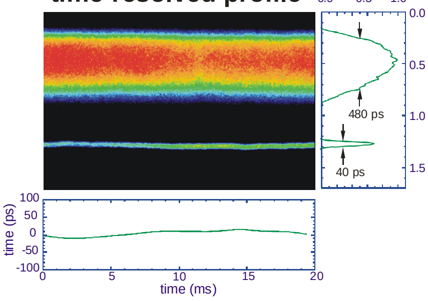
λ 300 - 600 nm

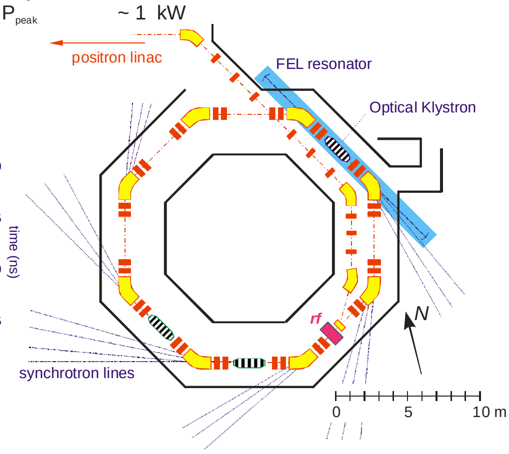
$\Delta\lambda/\lambda$ 0.1 - 0.01 %

P_{avg} ~ 100 mW

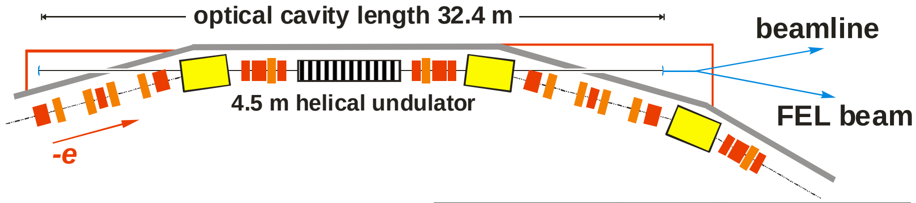
P_{peak} ~ 1 kW

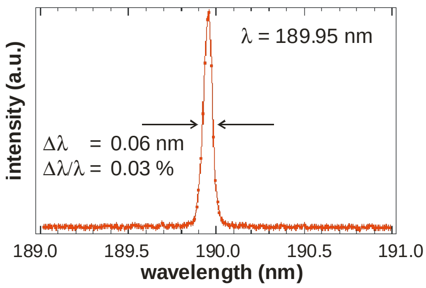
time-resolved profile





The Elettra Storage Ring FEL

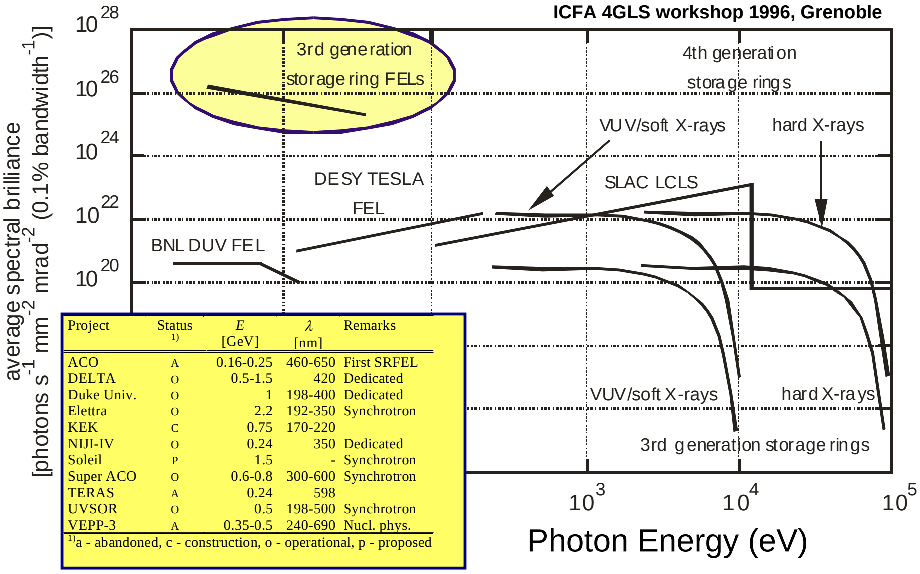




Storage ring operation*	1.0	GeV
Tunability range	350 – 190	nm
	3.5 – 6.5	eV
Average power	≥ 1	W
Pulse length (FWHM)	~ 5	ps
Peak power	≥ 40	kW
Pulse energy	≥ 0.2	mJ
Photon flux**	$\geq 10^{18}$	photons/s
Polarization	circular (linear may also be possible)	
Repetition rate	4.6	MHz
Synchronization with synchrotron radiation	1:1	

*4-bunch operation, **within the laser bandwidth

Prospects of the SR-FEL



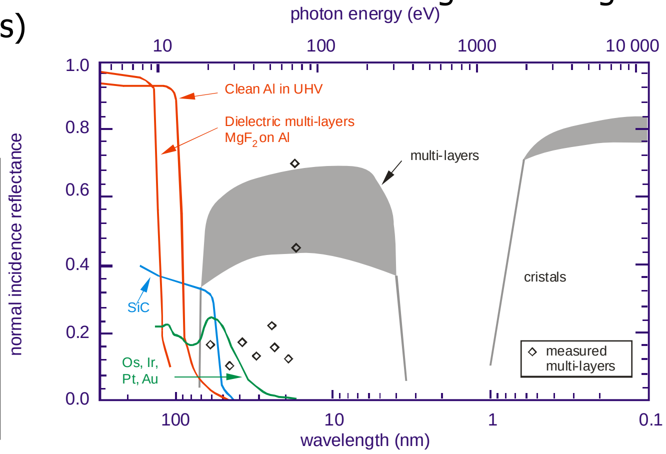
Project	Status [1)]	E [GeV]	λ [nm]	Remarks
ACO	A	0.16-0.25	460-650	First SRFEL
DELTA	O	0.5-1.5	420	Dedicated
Duke Univ.	O	1	198-400	Dedicated
Elettra	O	2.2	192-350	Synchrotron
KEK	C	0.75	170-220	
NIJI-IV	O	0.24	350	Dedicated
Soleil	P	1.5	-	Synchrotron
Super ACO	O	0.6-0.8	300-600	Synchrotron
TERAS	A	0.24	598	
UVSOR	O	0.5	198-500	Synchrotron
VEPP-3	A	0.35-0.5	240-690	Nucl. phys.

[1)] a - abandoned, c - construction, o - operational, p - proposed

Going to the VUV and (soft) X-ray spectral region

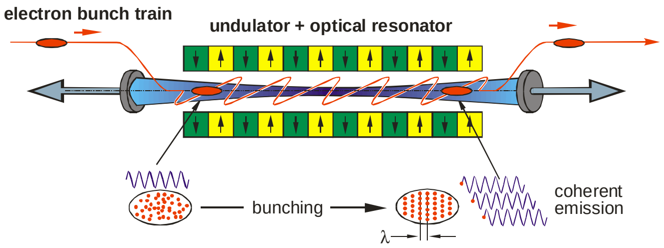
Wavelength limitations due to the need of high-reflecting optics (mirrors)

Developing a laser scheme that does not require optical elements.

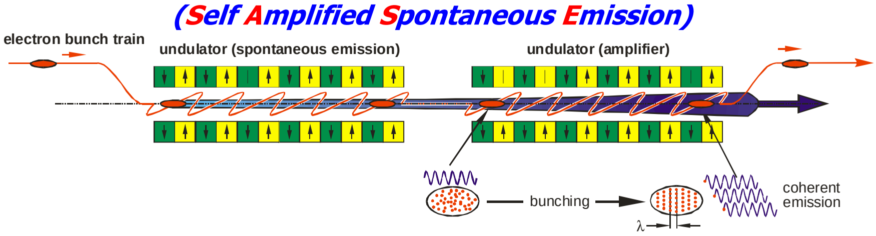


D.T. Attwood et al, AIP Conf. Proc. 118, eds J.M.J. Madey and C. Pellegrini (AIP, New York, 1983), p. 93

Classical FEL Scheme

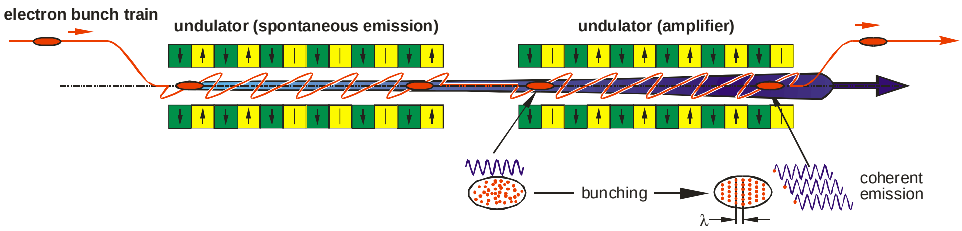


SASE FEL Scheme
(Self Amplified Spontaneous Emission)



SASE FEL scheme

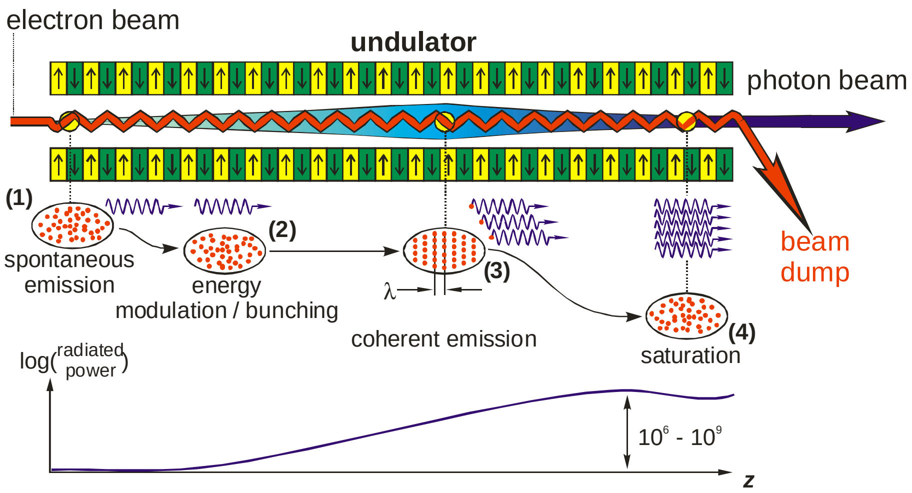
(Self Amplified Spontaneous Emission)



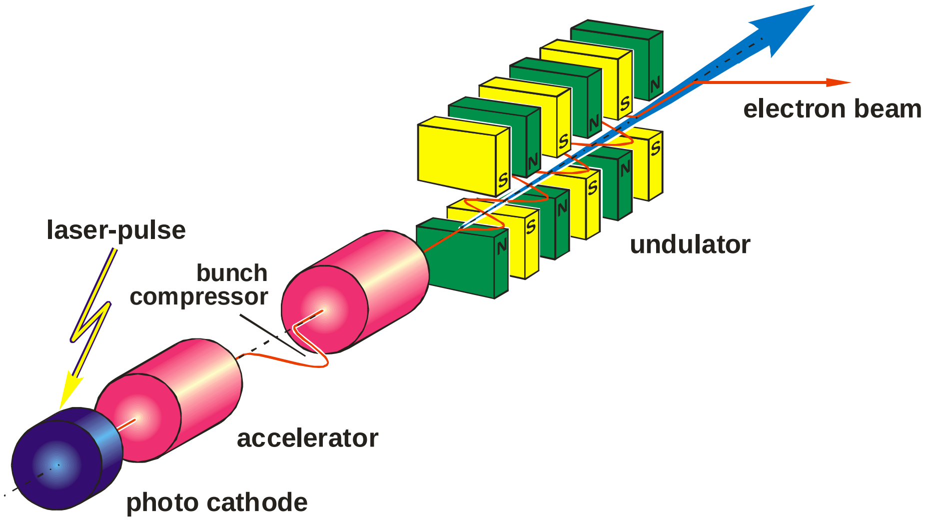
Advantage:
- No wavelength limitations due to optics
- Higher output power

Drawbacks:
- Extreme demands on the Electron beam
  - ❖Beam current
  - ❖Emittance
  - ❖Energy spread
- Long undulators
- Stability
- Some loss of optical quality

The SASE FEL Scheme



SASE-FEL Setup



History of SASE

1980	First proposal
1996	First experimental observation
	UCLA: λ = 16 μm
Dec. 1999	APS: lasing at λ = 523 nm
Feb. 2000	DESY: lasing at λ = 80 nm
Sep. 2000	APS: saturation at λ = 523 nm
Feb. 2001	VISA/BNL: saturation at λ = 800 nm
Apr. 2001	APS: saturation at λ = 385 and λ = 265 nm
Sep. 2001	DESY: saturation at λ = 100 nm
Oct. 2001	First user experiments @ DESY-TTF

Development steps towards VUV and X-ray FELs

SASE FEL User Facilities

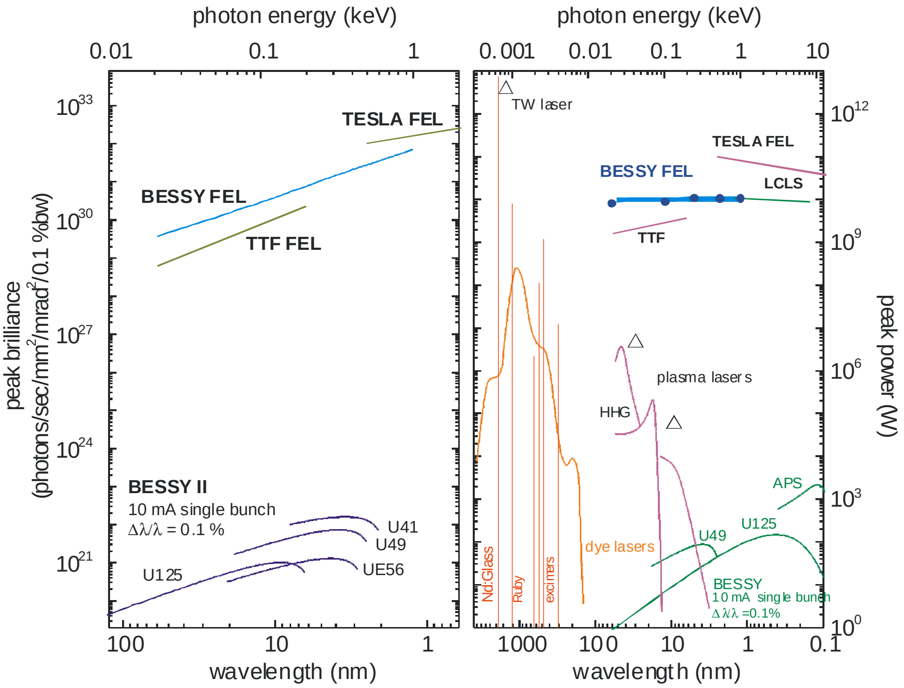
Under construction and/or operational

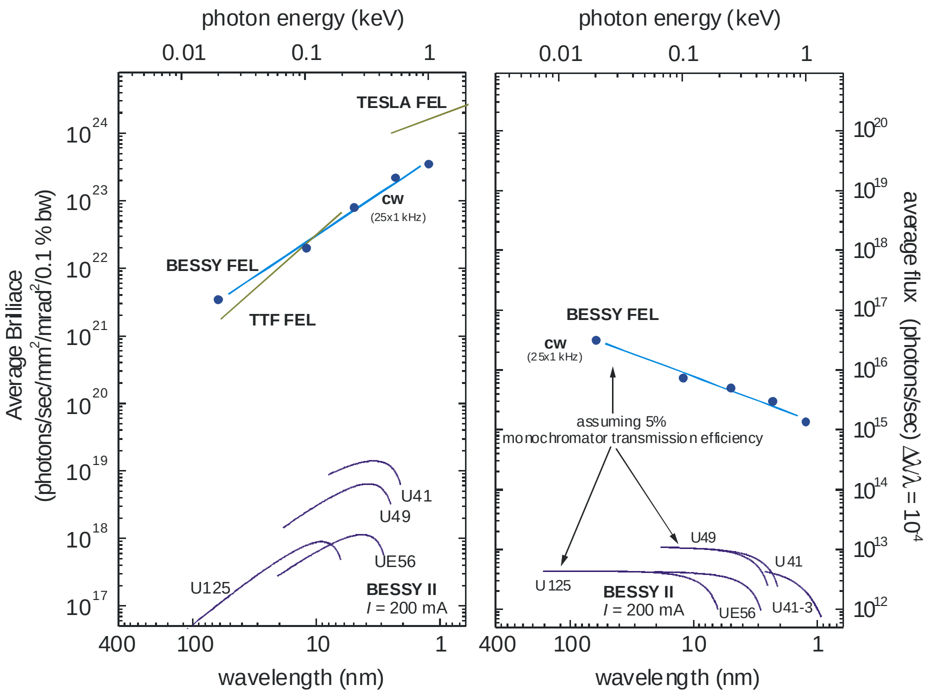
- TTF / DESY* $\lambda > 6$ nm (80 nm)
- LEUTL / APS* $\lambda > 120$ nm (265 nm)

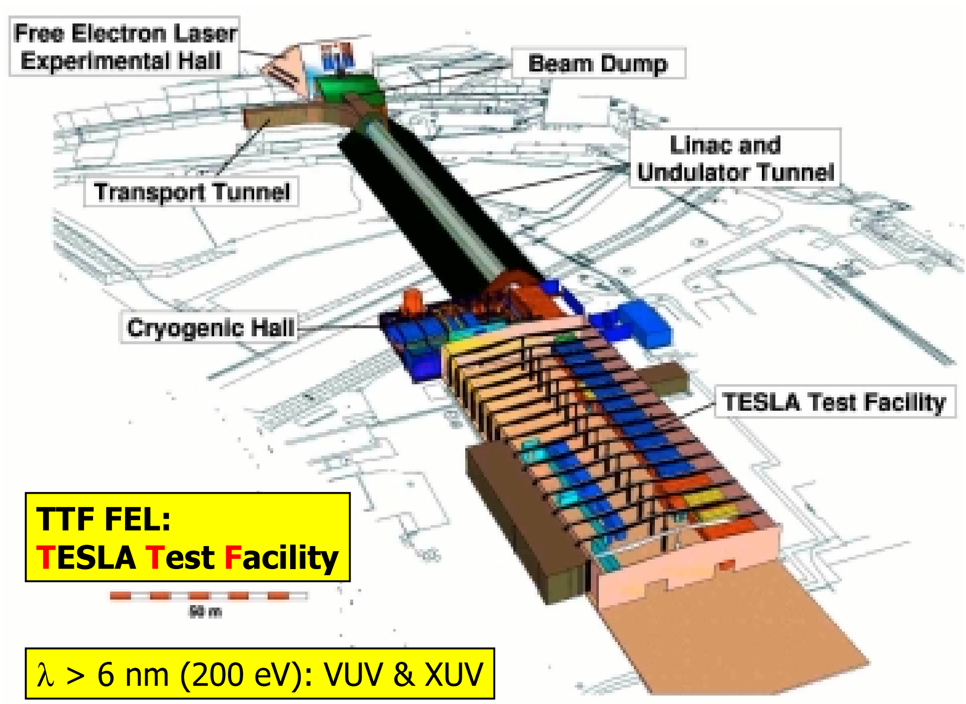
Proposed

- BESSY $\lambda \geq 1.2$ nm (1 keV)
- SLAC $\lambda \geq 1.5$ Å (8 keV)
- SPring8 $\lambda \geq 15$ nm $\rightarrow$ 3.6 nm $\rightarrow$ 0.1 nm
- TESLA $\lambda \geq 0.85$ Å (14 keV)
- ELETTRA, ENEA, Daresbury ……

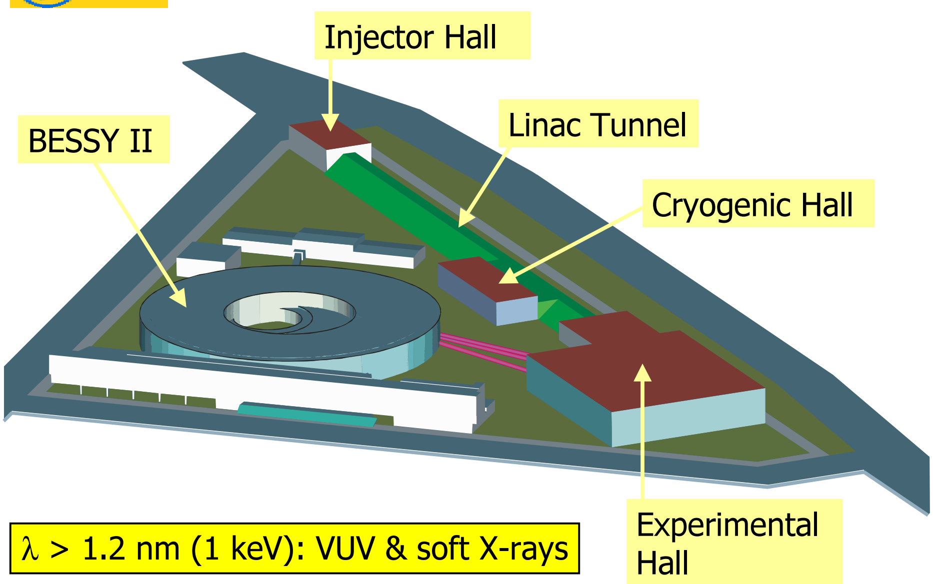
* Hybrid between FEL development & user facility




photon energy (keV)
0.01
0.1
1
TESLA FEL
cw
(25x1 kHz)
BESSY FEL
TTF FEL
Average Brilliace
(photons/sec/mm²/mrad²/0.1 % bw)
U41
U49
UE56
U125
BESSY II
I = 200 mA
400
100
10
wavelength (nm)
assuming 5%
monochromator transmission efficiency
U41-3
average flux (photons/sec) Δλ/λ = 10⁻⁴


Free Electron Laser
Experimental Hall
Beam Dump
Transport Tunnel
Linac and
Undulator Tunnel
Cryogenic Hall
TESLA Test Facility
TTF FEL:
TESLA Test Facility
50 m
λ > 6 nm (200 eV): VUV & XUV

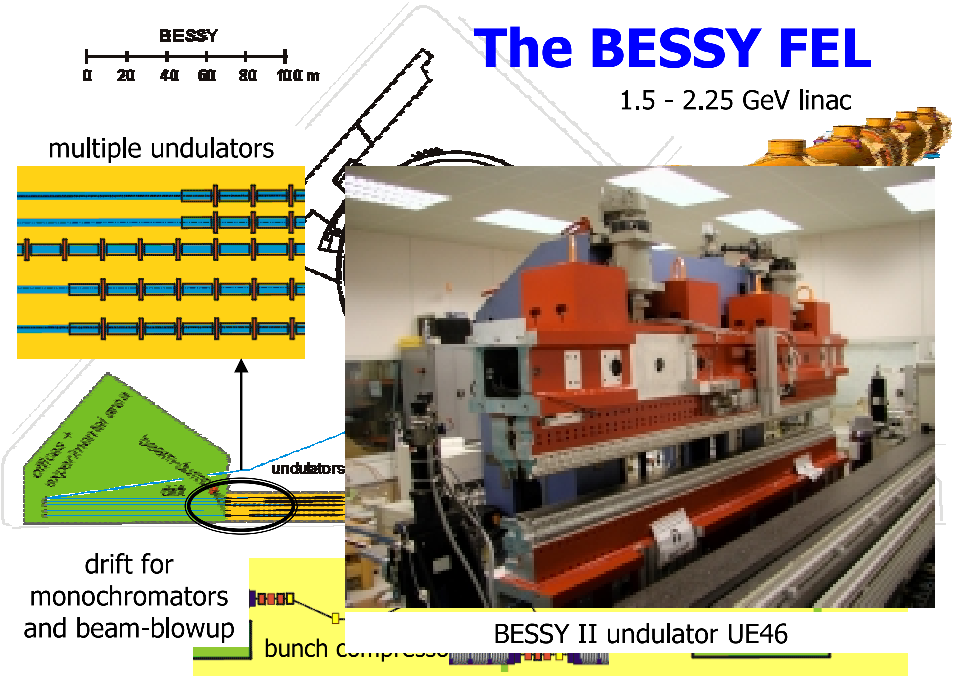
The BESSY FEL



λ > 1.2 nm (1 keV): VUV & soft X-rays

The BESSY FEL

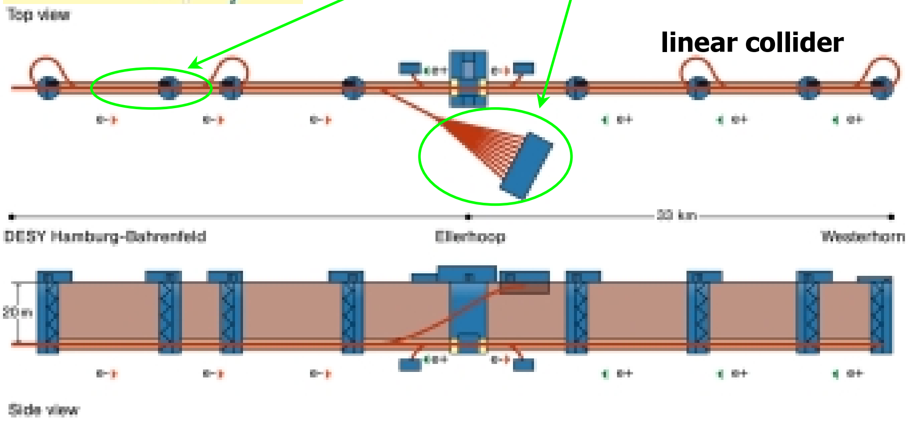
1.5 - 2.25 GeV linac

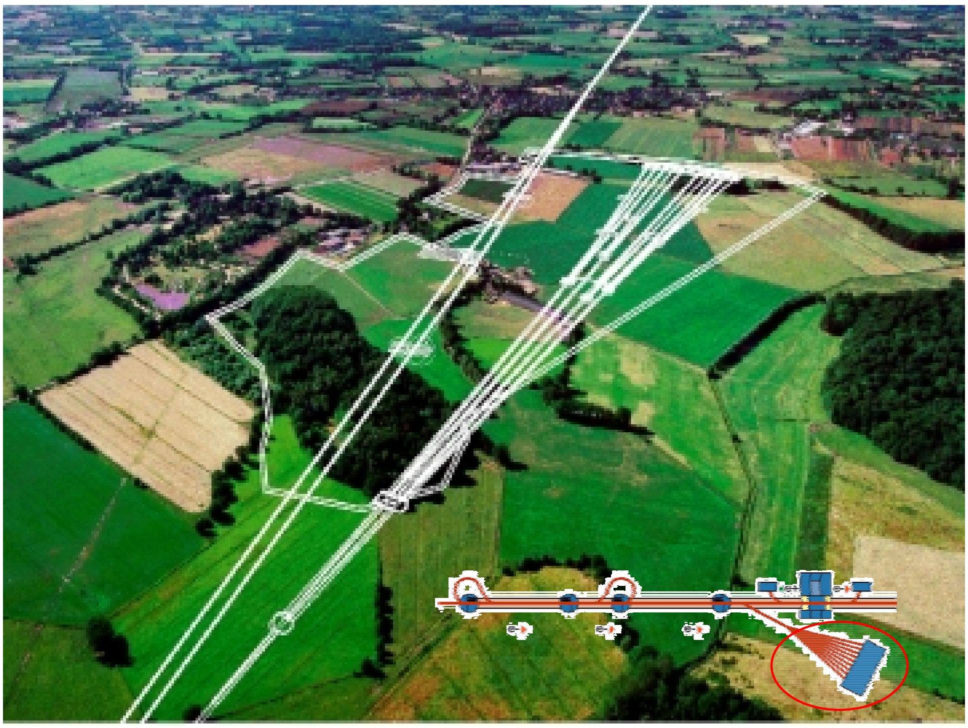


BESSY II undulator UE46

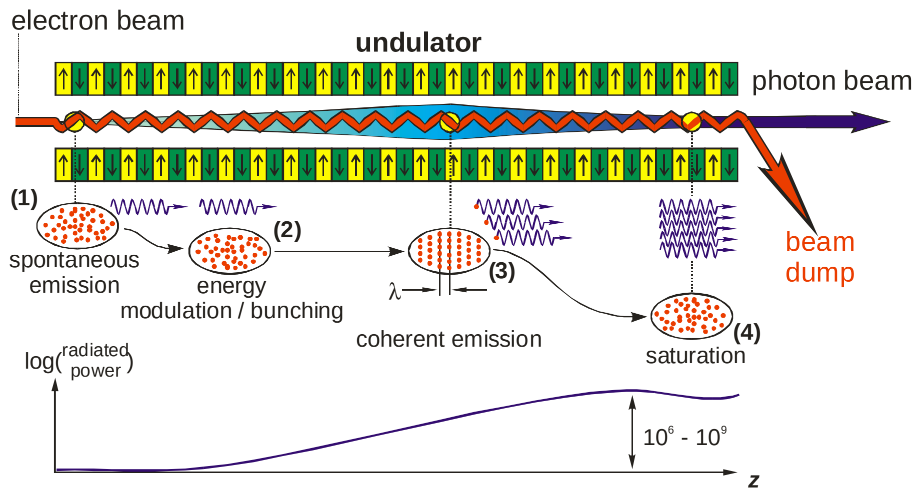
TESLA X-ray FEL

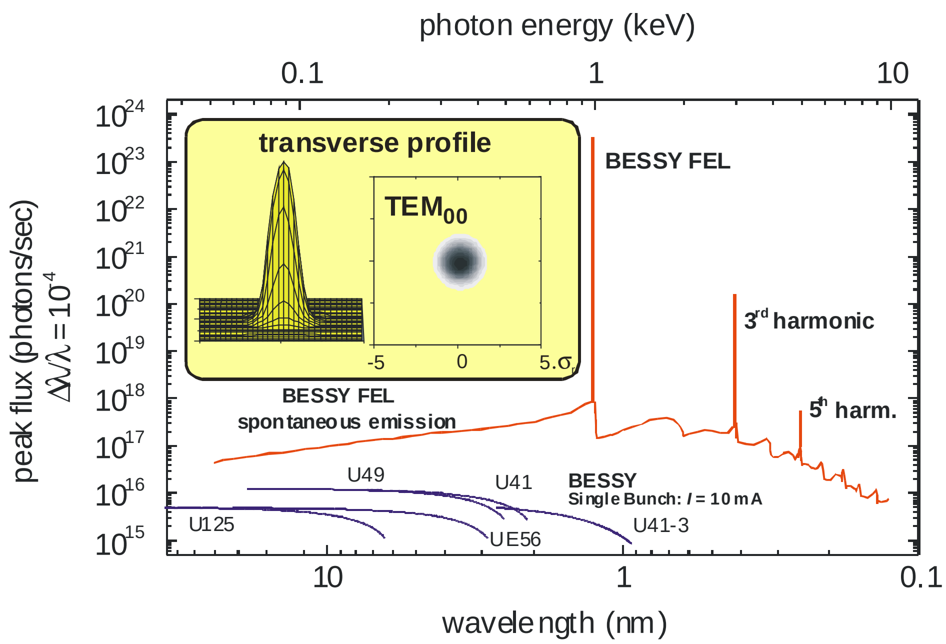
λ > 0.85 Å (14 keV): X-rays

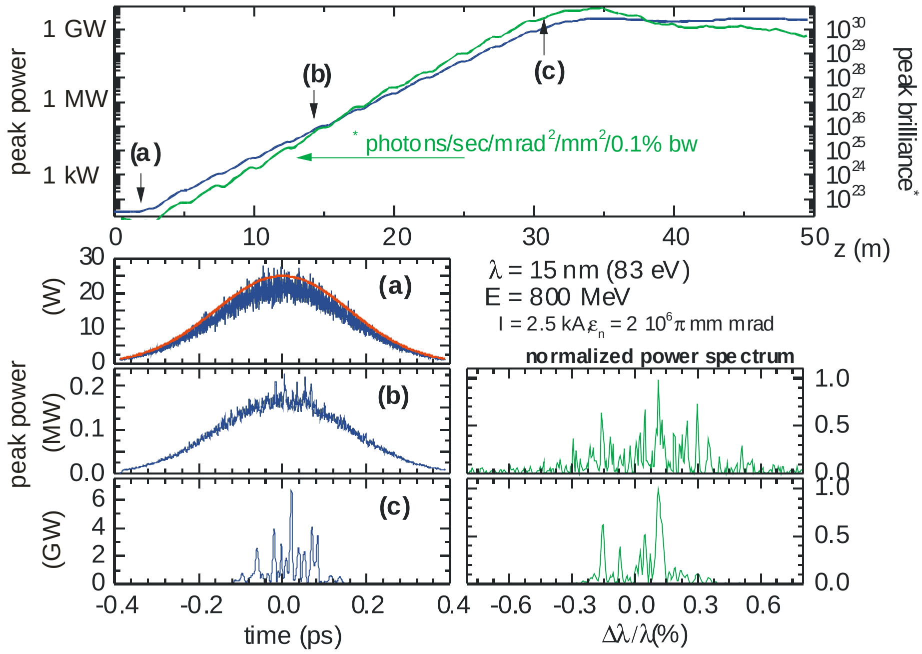




The SASE FEL Scheme





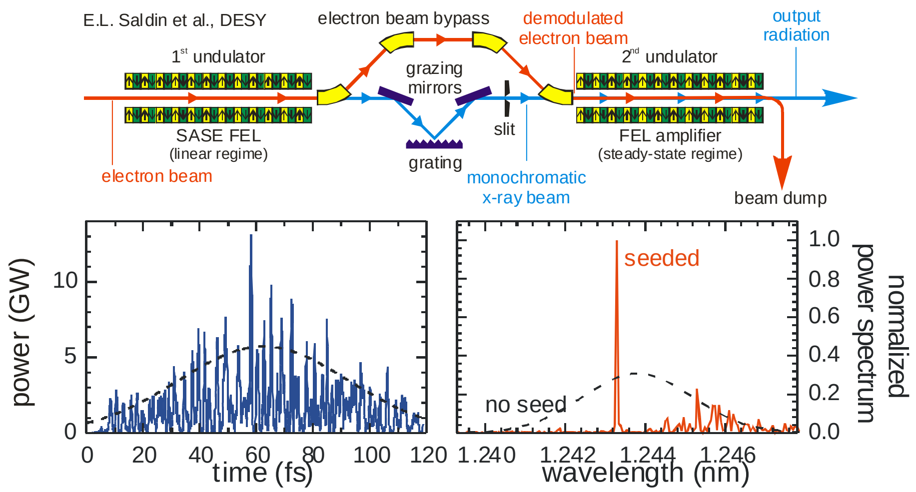


User Feedback

Important issues:

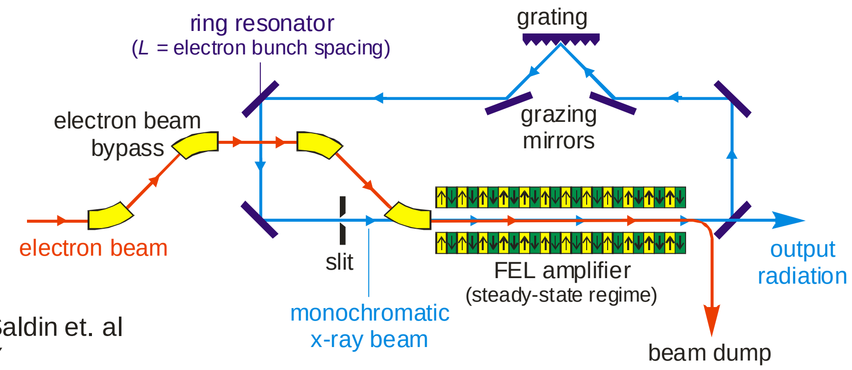
- Wavelength :.. $\lambda \leq 60$ nm
- Narrow spectral width:.......................... $\Delta\lambda/\lambda \leq 10^{-4}$
- Synchronization with fs lasers
- Micro-pulse duration:............................ $\tau \leq 20$ fs
- Preferably no spikes
- As many as possible photons per pulse
- High average brilliance

Spectral Narrowing: Seeding



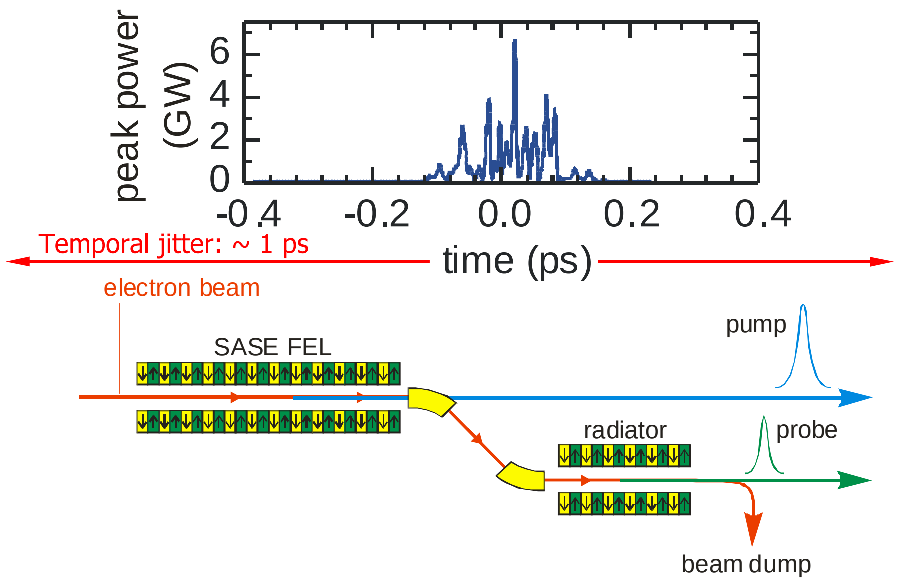
Spectral Narrowing: Seeding

RAFEL:
Regenerative FEL amplifier with monochromator



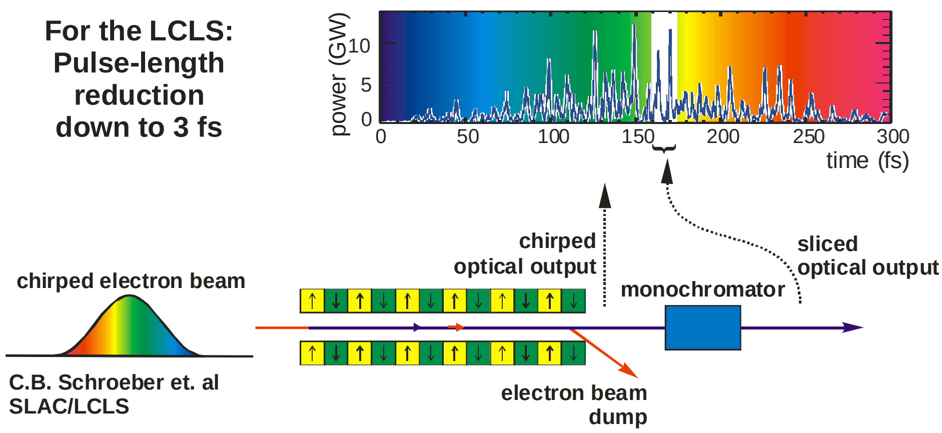
E.L. Saldin et. al
DESY

Synchronization



Pulse Slicing

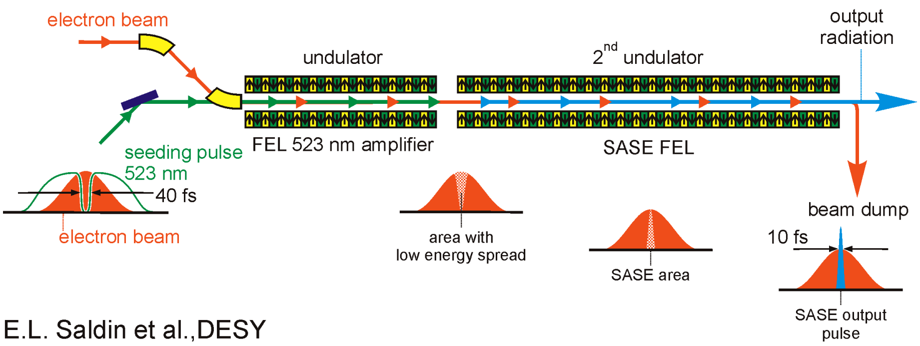
For the LCLS: Pulse-length reduction down to 3 fs



C.B. Schroeber et. al
SLAC/LCLS

Pulse-Length Reduction

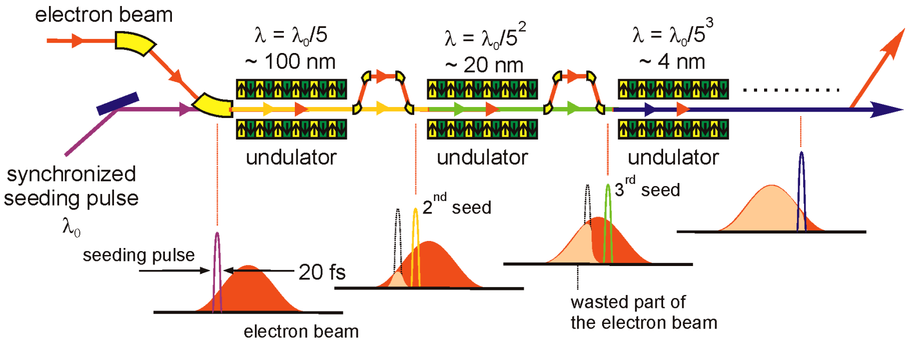
1. Side-band Seeded FEL



E.L. Saldin et al.,DESY

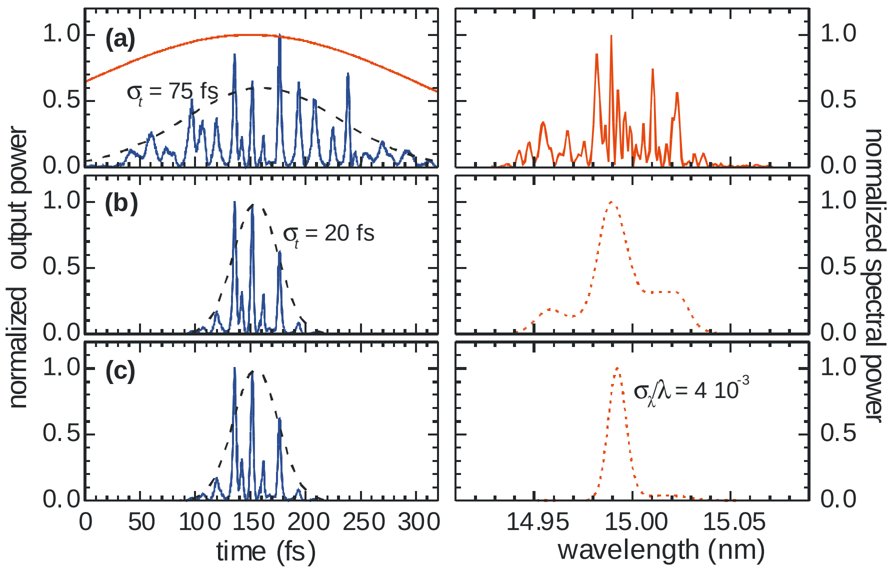
Pulse-Length Reduction

2. Fresh-bunch Higher Harmonics Generation



E.L. Saldin et al.,DESY

Pulse-Length Reduction



The Storage Ring FEL

+ Excellent Optical quality
  - Spectral width
  - Pulse profile (temporal and transverse)
  - Stability
+ High repetition rate and average brilliance
+ Naturally synchronized with the storage ring
+ Existing experience in facilitating user experiments

– Limitations in the operational wavelength range
  - $\lambda \geq 190$ nm (present), ≥ 120 nm …… 50 nm (?) (future)

– Difficulties to go below 1 ps temporal resolution

The SASE FEL

+ Access to a spectral range where there are presently no other (tunable) laser sources available.
  - High power (peak and average)
  - Short pulses
  - Tunable wavelength
  - Good spectral and transverse optical beam properties

– Novel and non-tested technology

– Special user-requests require additional development
  - Synchronization with other fs laser-sources
  - Ultra short pulses
  - Spectral purity