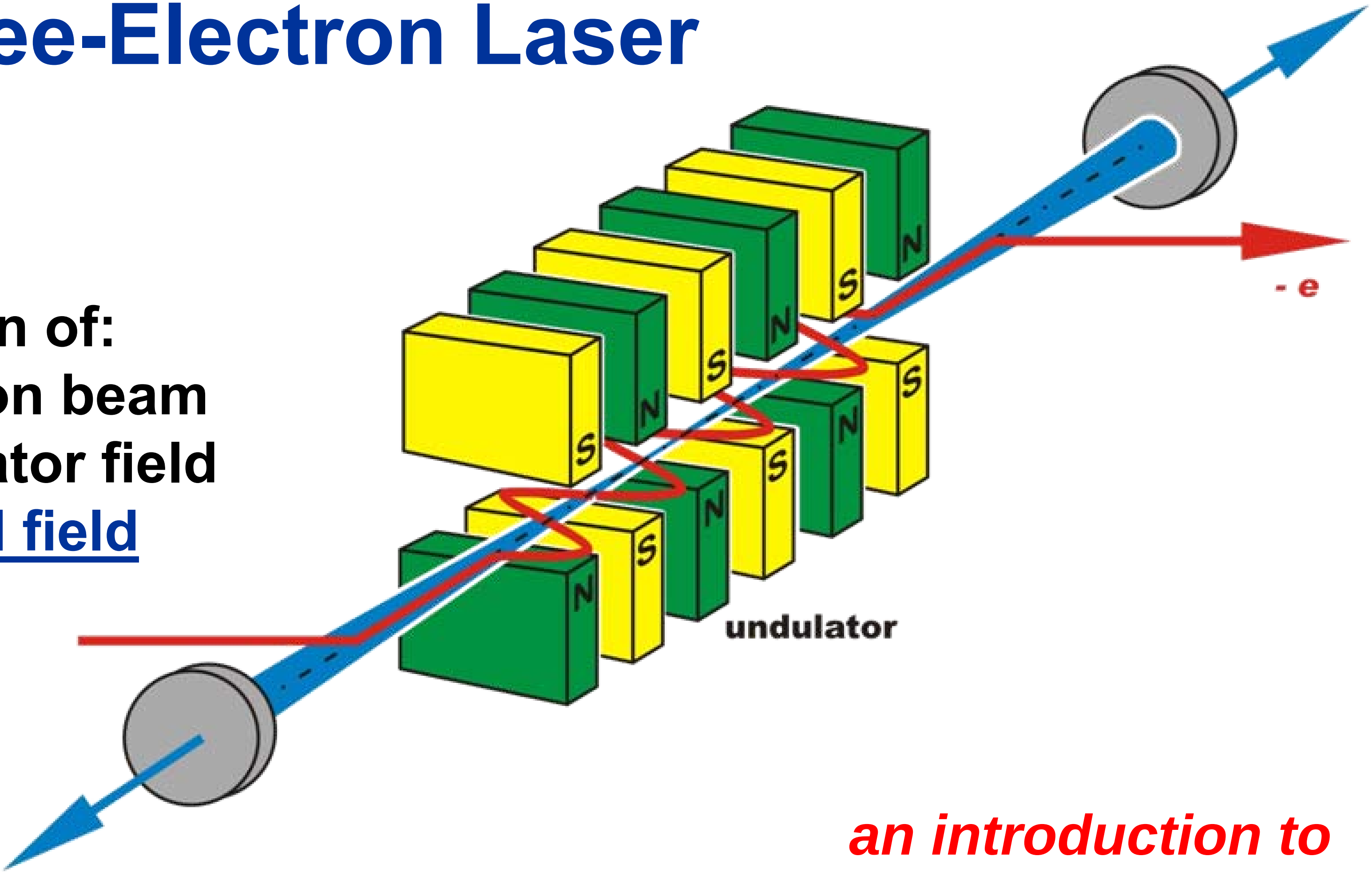
The Free-Electron Laser (FEL)



Interaction of:
- electron beam
- undulator field
- optical field

an introduction to

function and technique

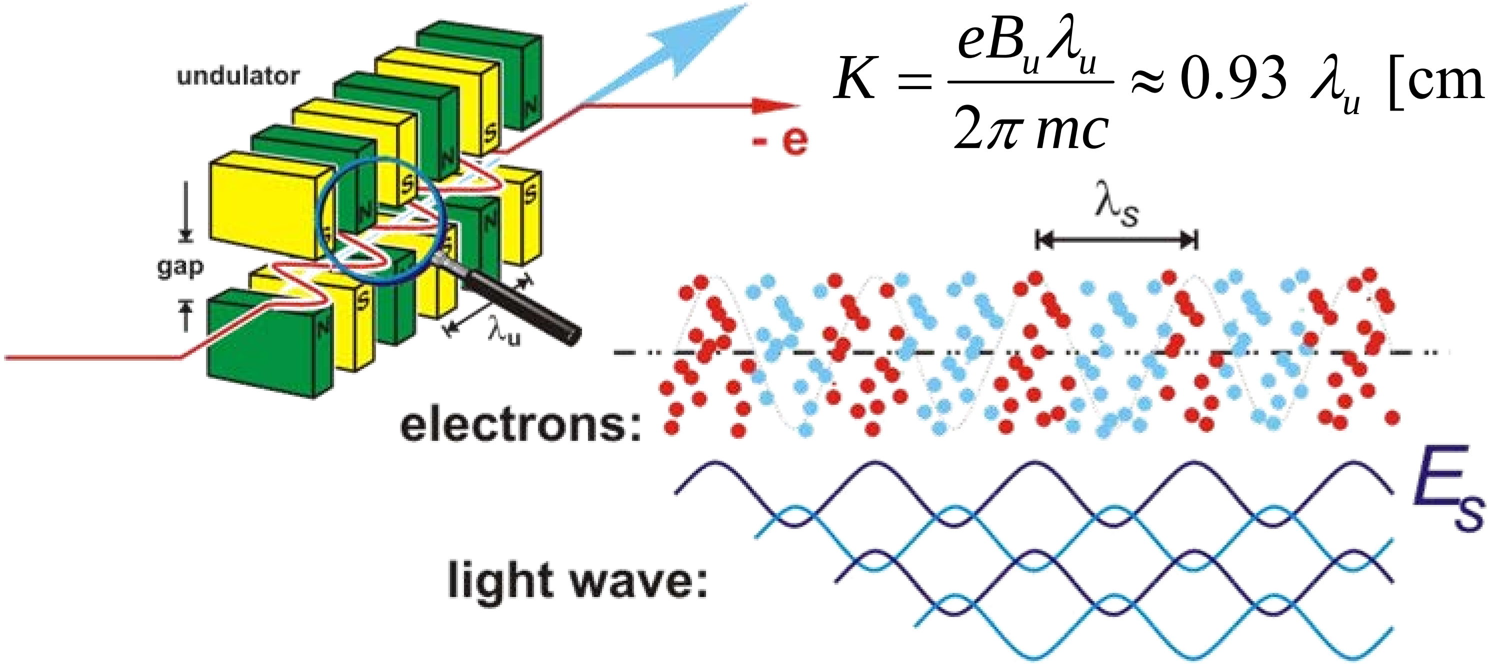
Outline

- Synchrotron radiation, lasers and FELs
- How does it work?
- Examples
- Single-pass FELs and the future

Synchrotron Radiation

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

$$K = \frac{eB_u\lambda_u}{2\pi\, mc} \approx 0.93\ \lambda_u\ [\mathrm{cm}]\ B_u\ [\mathrm{T}]$$



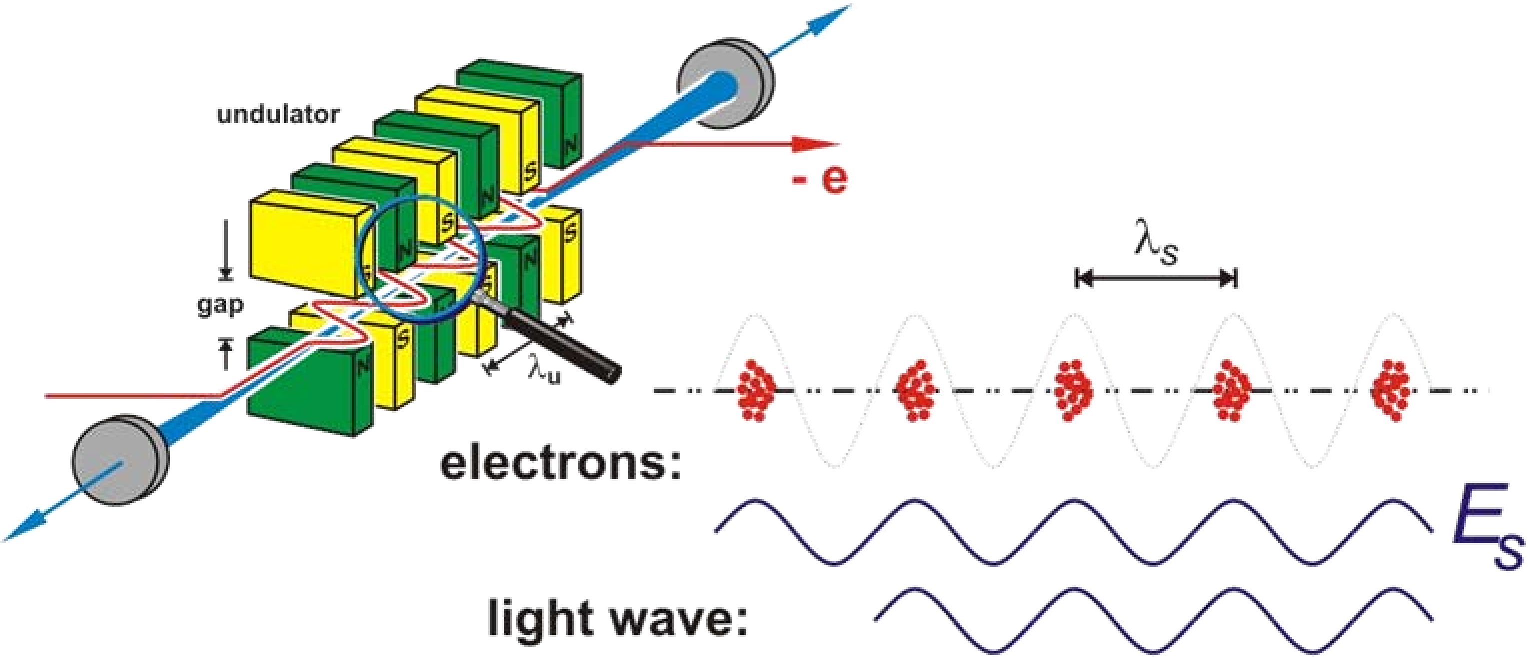
Radiated Power:

$P \propto n_e$ (number of electrons)

destructive interference

⟶ **shotnoise radiation**

FEL interaction



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

⟶ **enhanced emission**

Advantages (synchrotron radiation)

- High power / Brilliance:

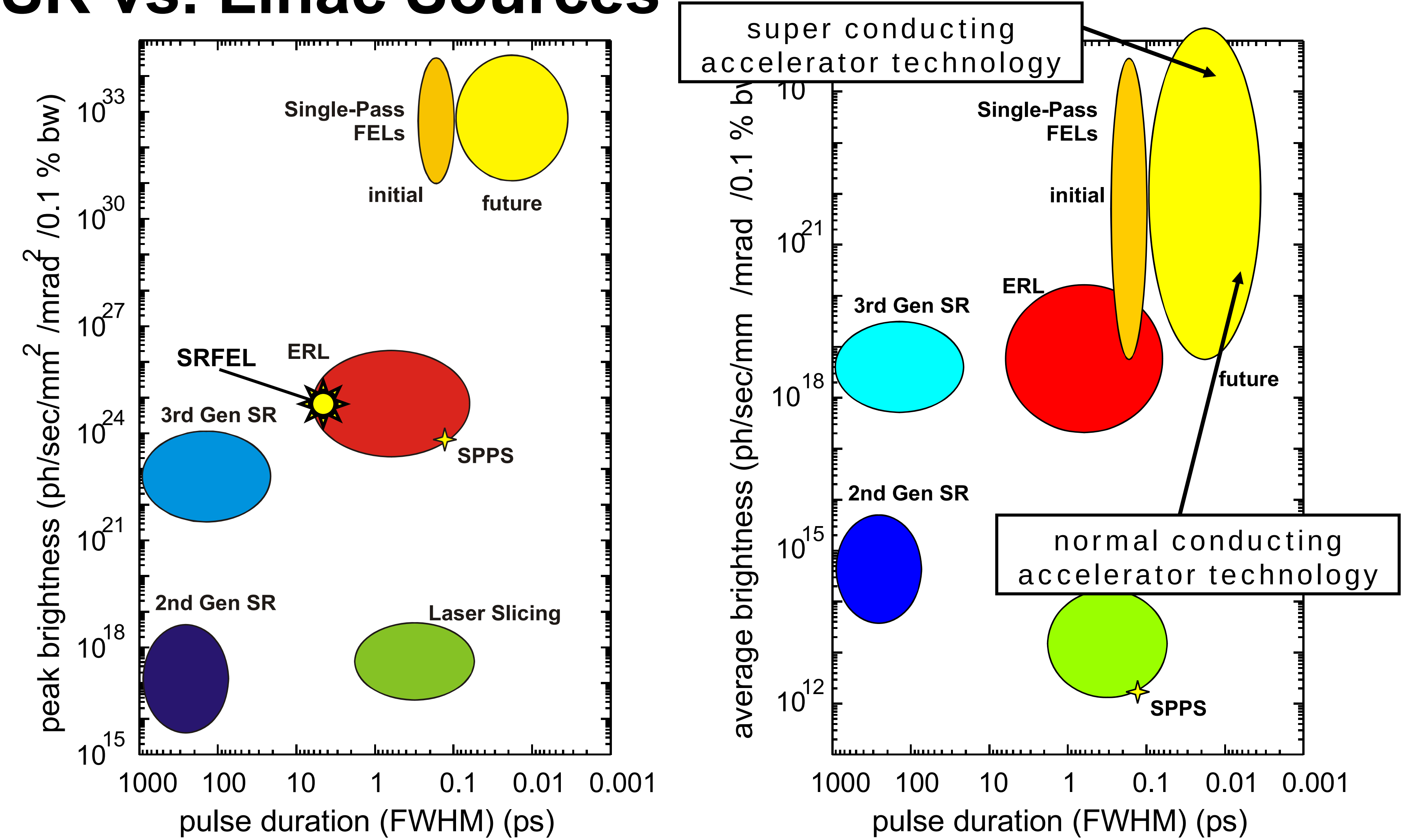
  kW to 100 GW of peak power with short pulses (fs)

  up to 10 kW of time-averaged output power demonstrated

- Full coherent radiation (transverse and longitudinal)

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

SR vs. Linac Sources



super conducting accelerator technology

normal conducting accelerator technology

Advantages (synchrotron radiation)

- High power / Brilliance:

  kW to 100 GW of peak power with short pulses (fs)

  up to 5 kW of time-averaged output power demonstrated

- Full coherent radiation (transverse and longitudinal)

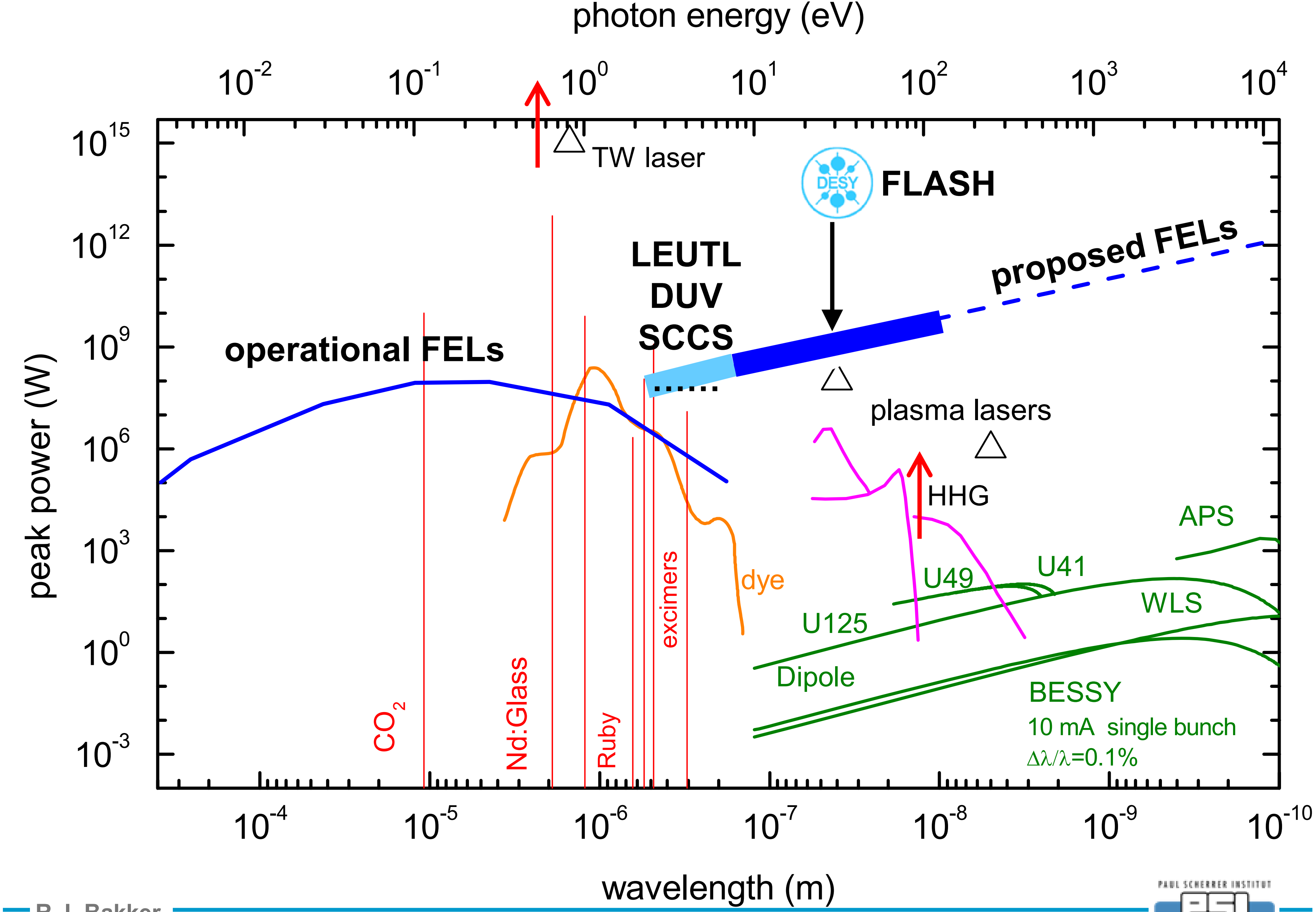
  i.e., $\Delta\lambda/\lambda = 0.1$ (transform limited) → 10^{-8}

Advantages (lasers)

- Works for any wavelength

  mm-waves → 35 nm → 0.85 Å → 0.1 Å → ……?

- Continuously tunable wavelength (fast)
- Flexible output (polarization, pulse-length, …..)


photon energy (eV)
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
peak power (W)
10^{15}
10^{12}
10^{9}
10^{6}
10^{3}
10^{0}
10^{-3}
TW laser
FLASH
LEUTL
DUV
SCCS
proposed FELs
operational FELs
plasma lasers
HHG
APS
U41
U49
WLS
U125
Dipole
BESSY
10 mA single bunch
$\Delta\lambda/\lambda$=0.1%
dye
excimers
Ruby
Nd:Glass
CO_2
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
wavelength (m)

Drawbacks

- Expensive:

    IR: 10 M€ → UV: 40 M€ → XUV: 100 M€ → X-Ray: 650 M€

- Radiation hazard

- Complex technology

    High demands on the electron beam quality

    High demands on the electron beam stability

    Optics

- For X-ray FEL:

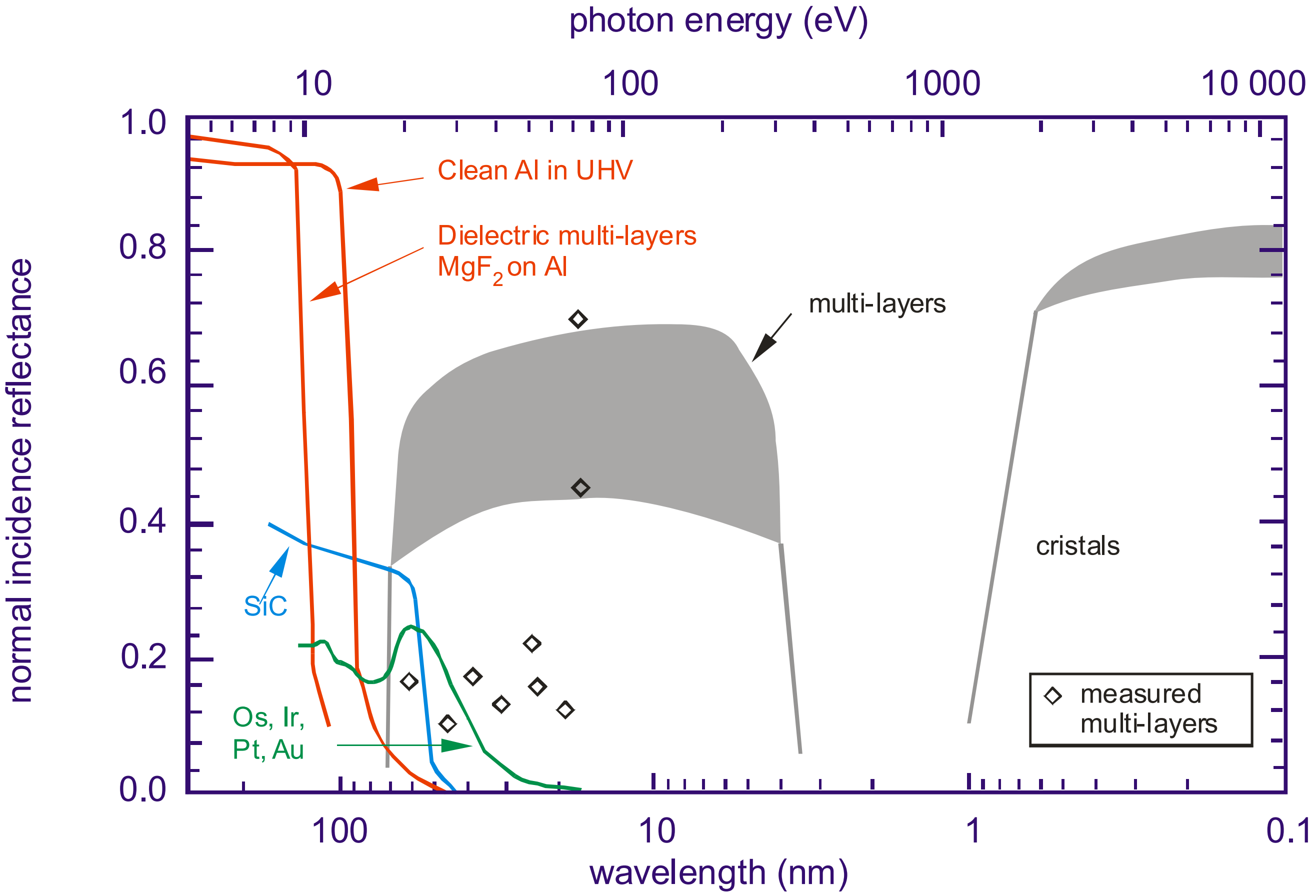
    non-demonstrated (below 35 nm)

N.B. Technological challenges increase towards shorter wavelengths!

Going to the VUV

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

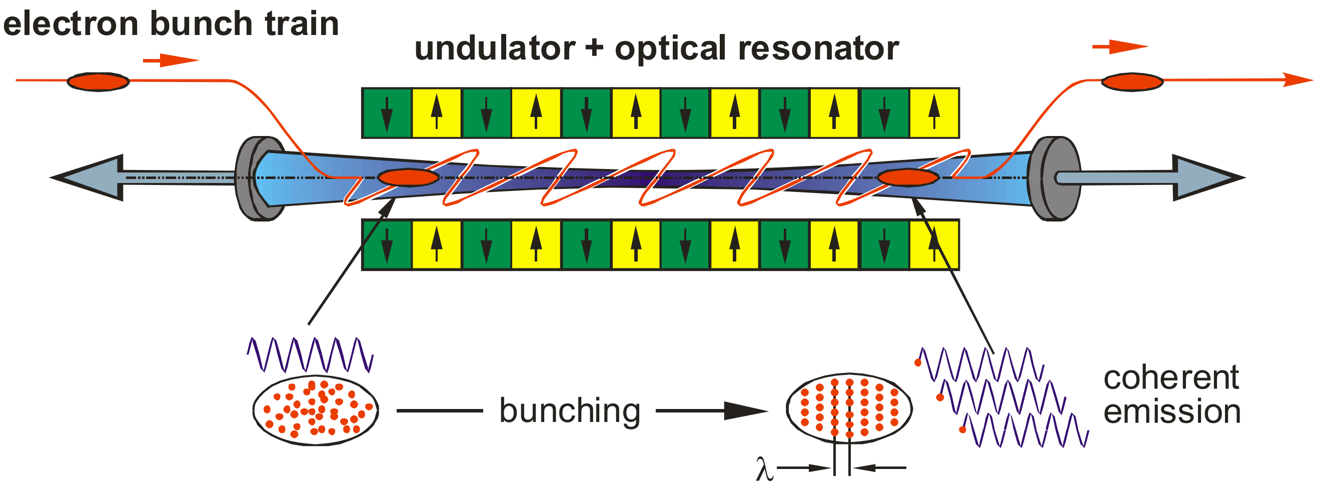
Developing a laser scheme that does not require optical elements.



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

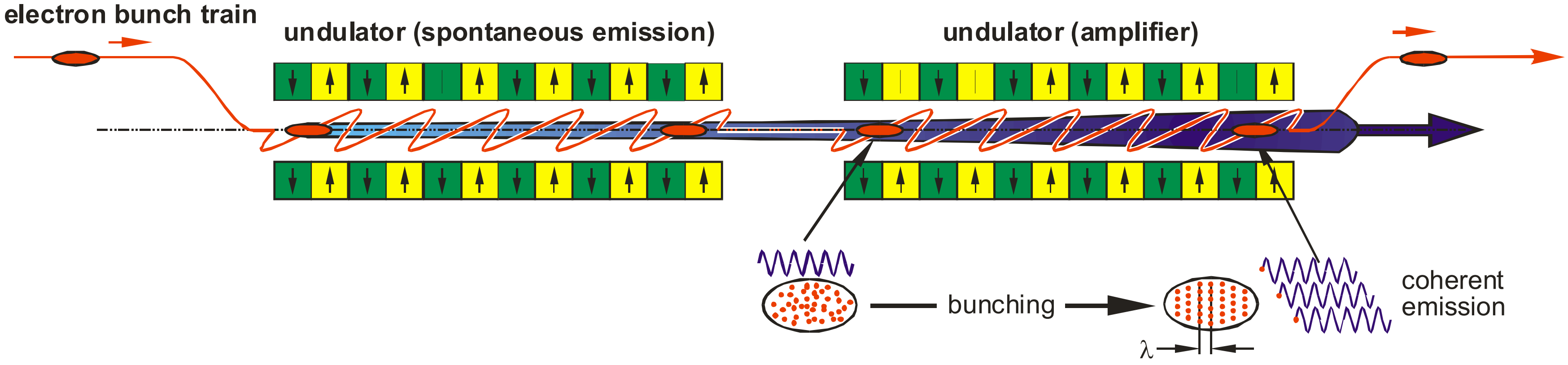
FEL → SASE FEL

Classical FEL Scheme

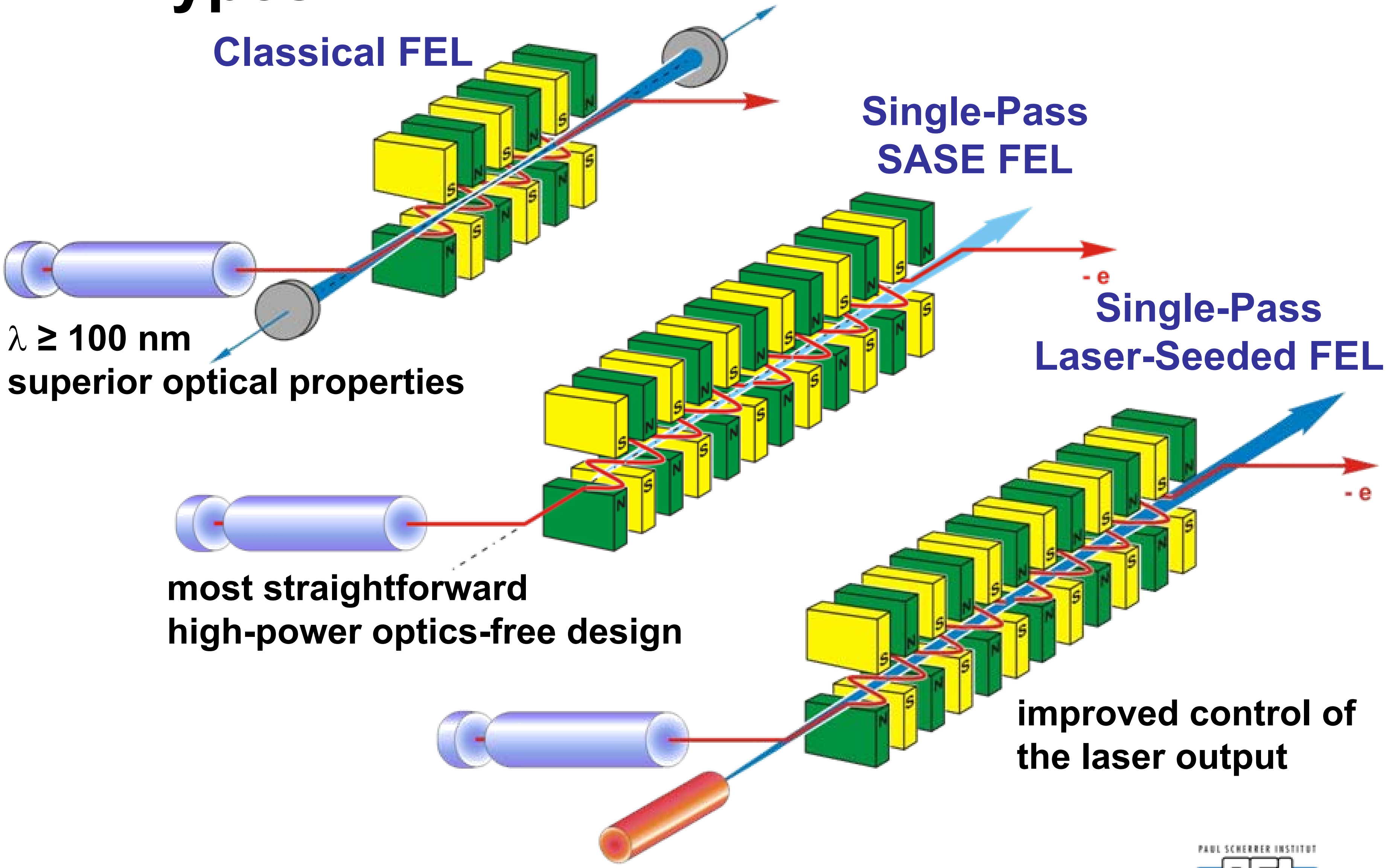


SASE FEL Scheme

(Self Amplified Spontaneous Emission)



FEL Types



Classical FEL

λ ≥ 100 nm
superior optical properties

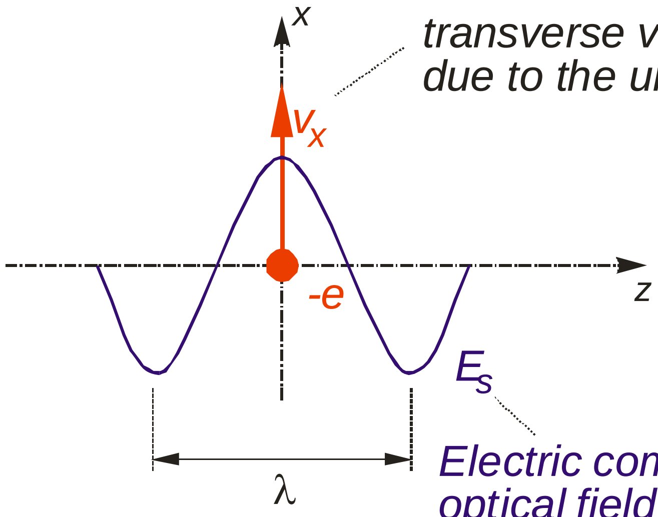
Single-Pass SASE FEL

most straightforward
high-power optics-free design

Single-Pass Laser-Seeded FEL

improved control of
the laser output

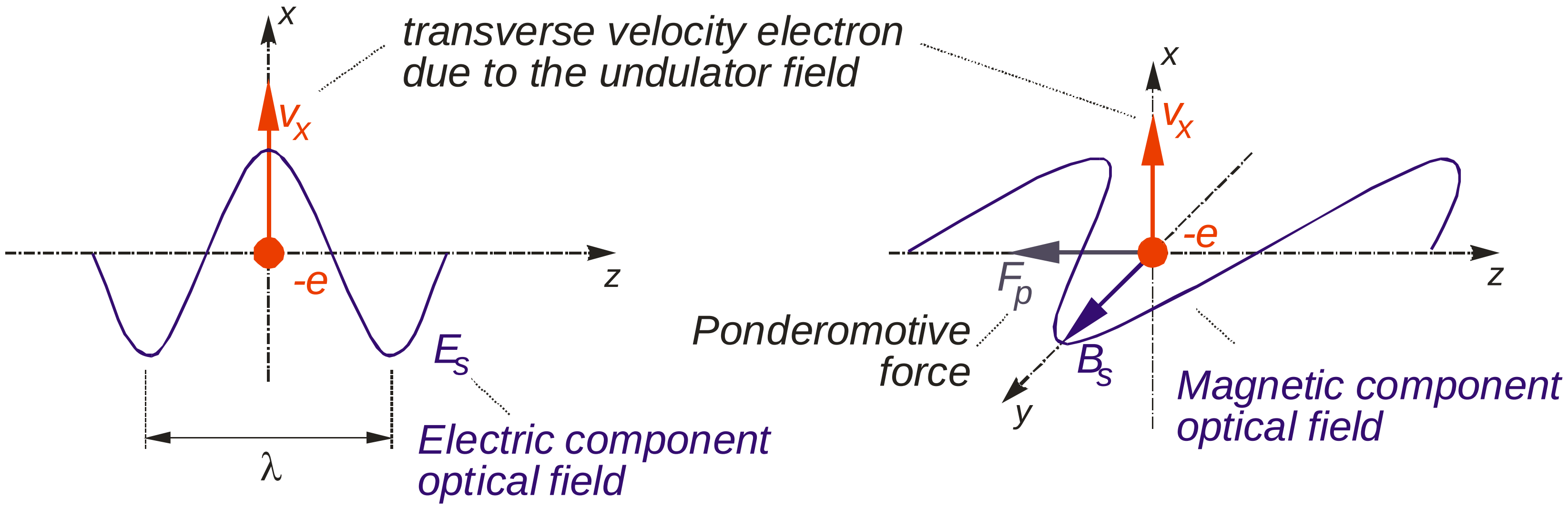
Interaction between an electron and the optical field



transverse velocity electron due to the undulator field

Electric component optical field

Interaction between an electron and the optical field



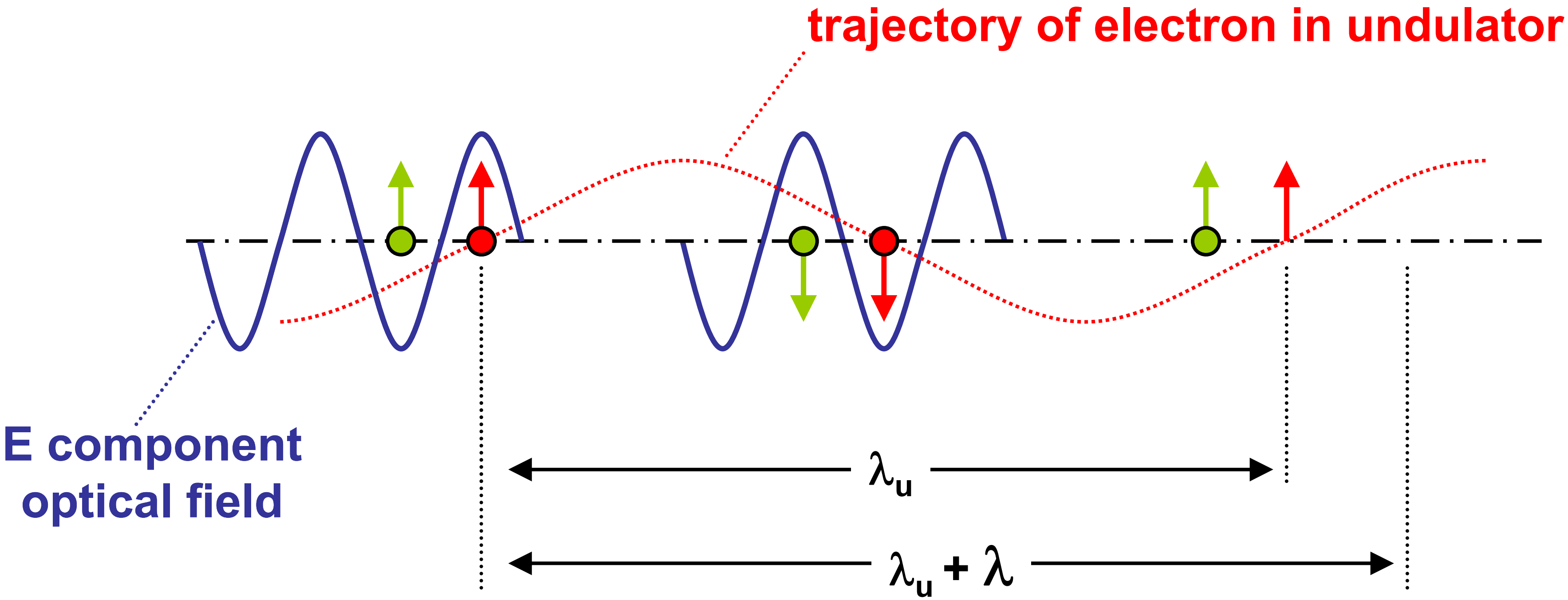
transverse velocity electron
due to the undulator field

Electric component
optical field

Ponderomotive
force

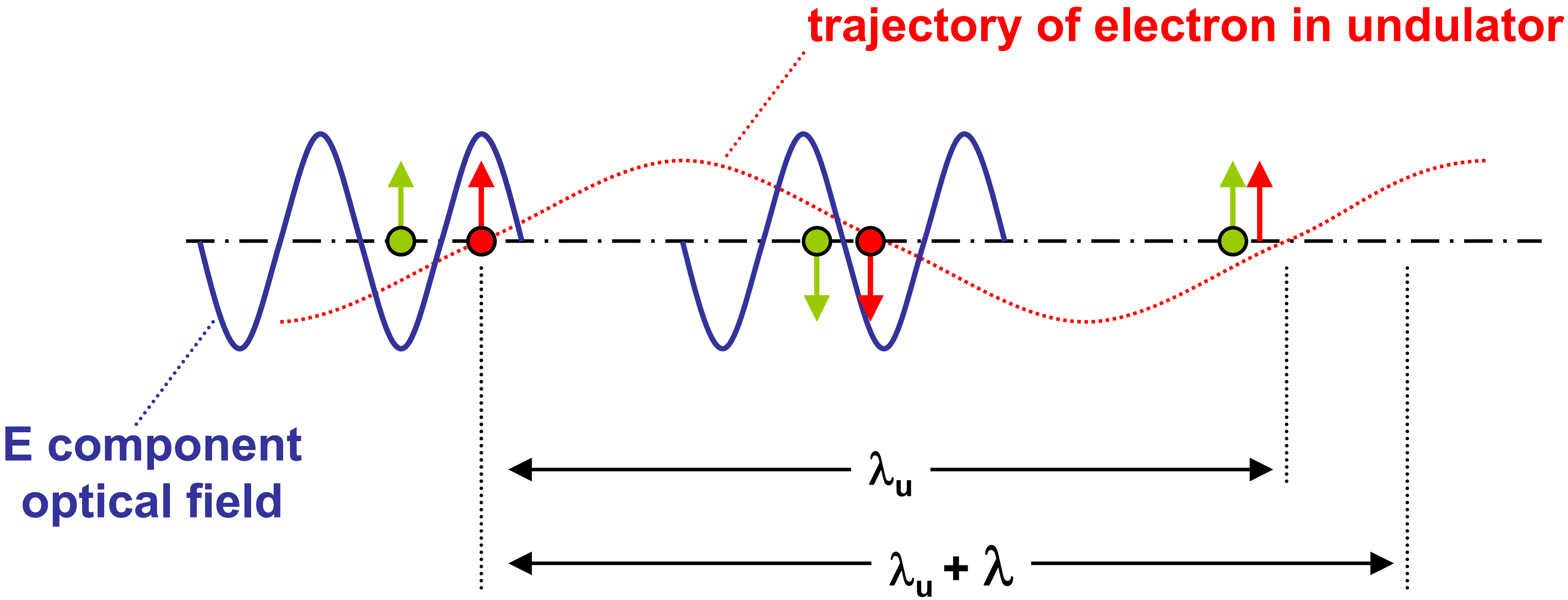
Magnetic component
optical field

Resonance Condition



$$\frac{\lambda_u + \lambda}{c} = \frac{\lambda_u}{v_z} \Longleftrightarrow \lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

Resonance Condition

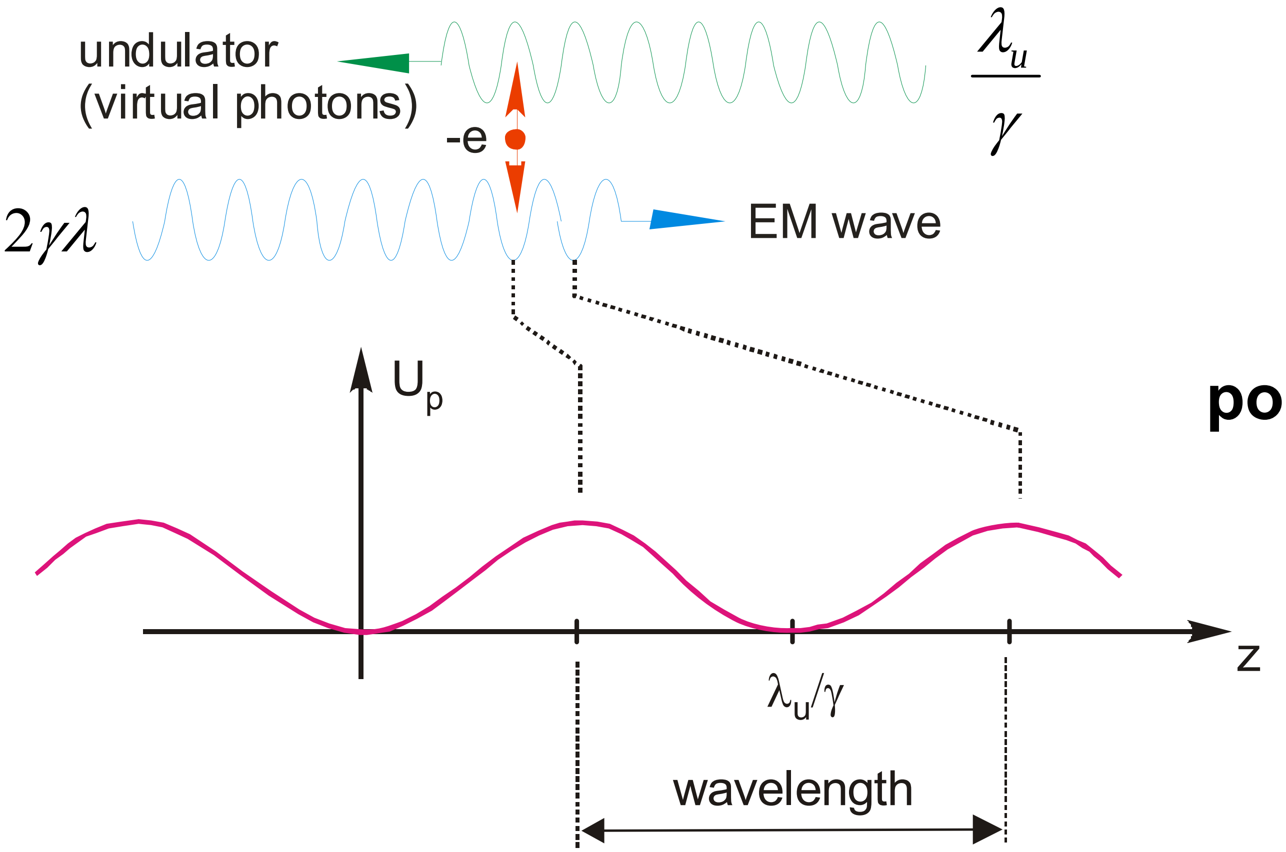


Net effect cancels !
(FEL only works in 2nd order)

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

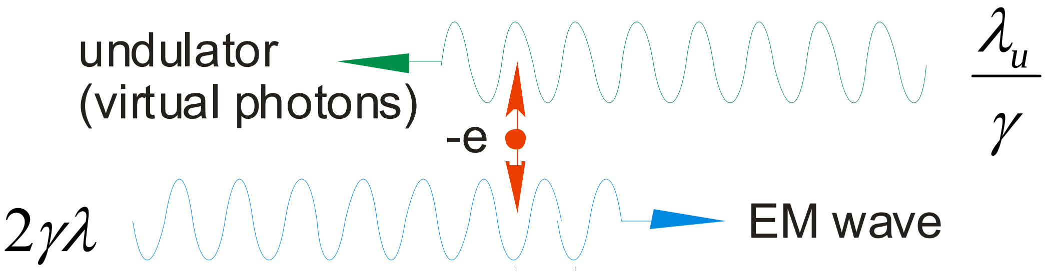
Electron Dynamics

electron rest-frame: $\langle v_z \rangle = 0$



ponderomotive potential

Electron Dynamics

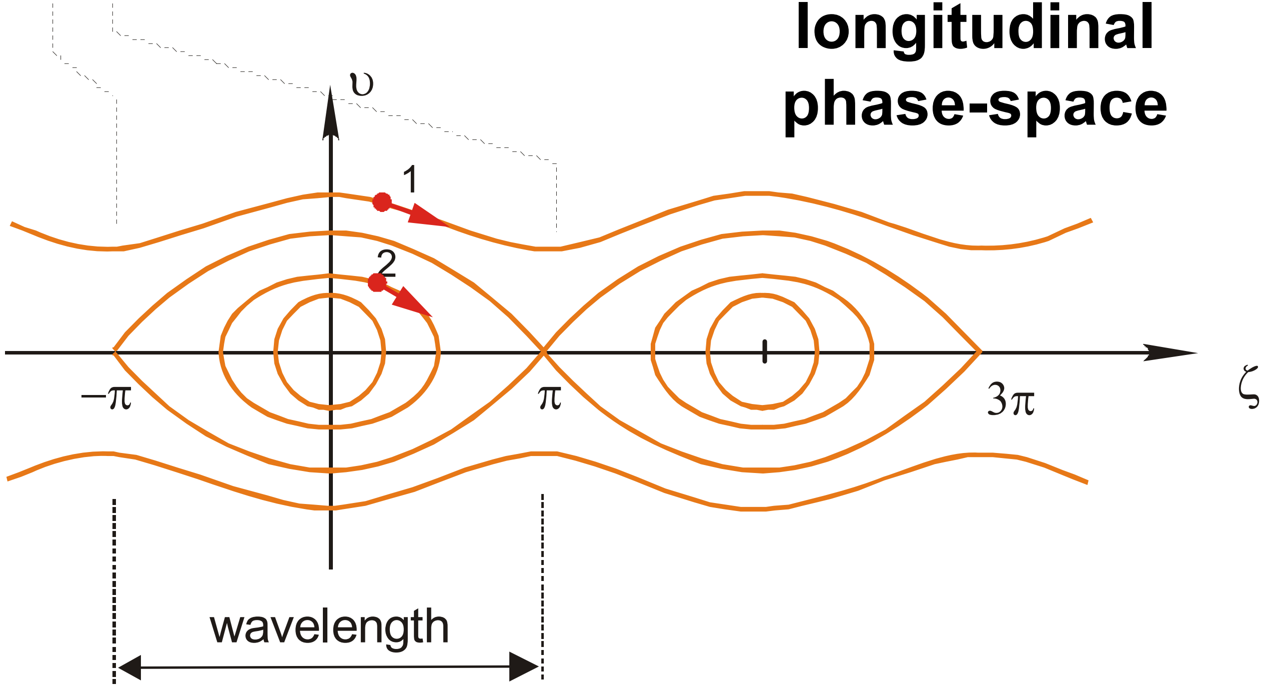


longitudinal phase-space

pendulum equation

$$\frac{\partial^2 \zeta_i}{\partial \tau^2} = |a_z| \cos(\zeta_i + \phi_i)$$

$$\frac{\partial a_z}{\partial \tau} = -j \left\langle e^{-i\zeta_i} \right\rangle_i$$



Pendulum Equation

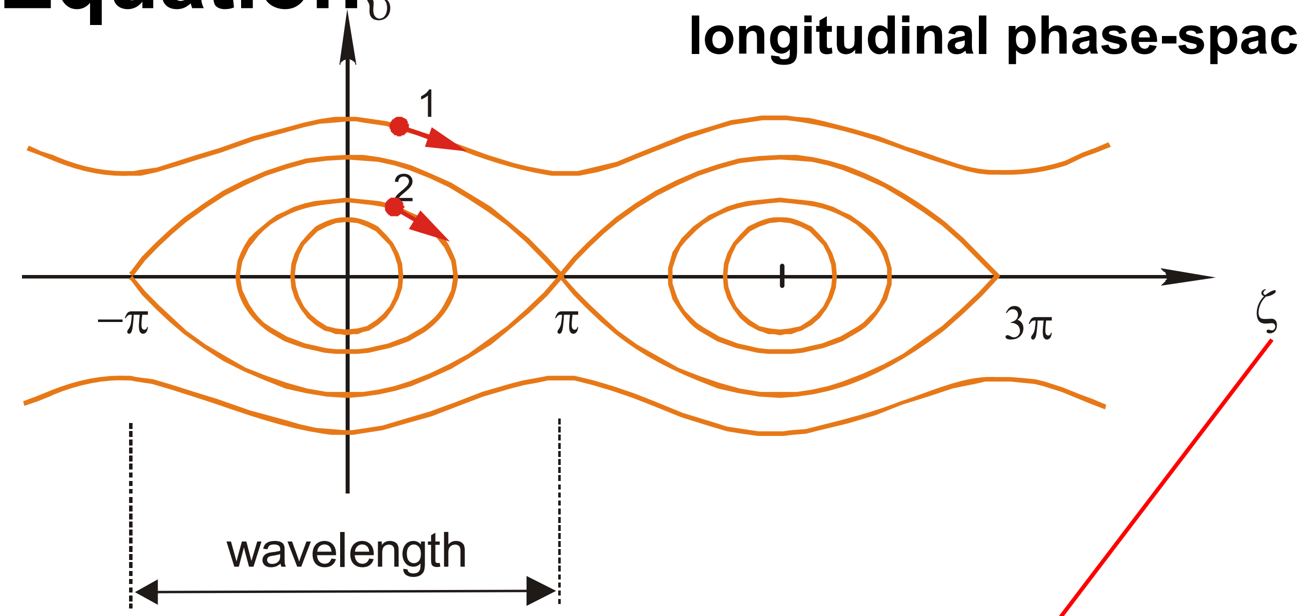
longitudinal phase-space

Pendulum

$$\omega_s = \sqrt{g/L}$$

FEL

$$\omega_s \propto \sqrt{|a|}$$



time

position of electron *i*

initial position of electron *i*

$$\frac{\partial^2 \zeta_i(\tau)}{\partial \tau^2} = |a_z| \cos(\zeta_i(\tau) + \phi_i)$$

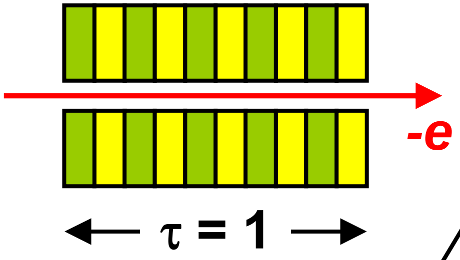
$$\frac{\partial a_z(\tau)}{\partial \tau} = -j \left\langle e^{-i\zeta_i(\tau)} \right\rangle_i$$

average over all electrons

optical field-strength

current-density

Pendulum Equation



$$\tau = \frac{ct}{N\lambda_u}$$

$$|a_z| = \left(4\pi N^2\right)^2 \frac{K}{2+K^2} f(\xi) a_s$$

$$a_s = \frac{eE\lambda}{2\pi mc^2}$$

compare with undulator: $K = \dfrac{eB_u\lambda_u}{2\pi mc}$

$$\xi = \frac{1}{2}\frac{K^2}{2+K^2}$$

(periodic detuning)

$$f(\xi) = \begin{cases} J_0(\xi) - J_1(\xi) & \text{(planar)} \\ 1 & \text{(helical)} \end{cases}$$

$$\frac{\partial^2 \zeta_i(\tau)}{\partial \tau^2} = |a_z| \cos\left(\zeta_i(\tau) + \phi_i\right)$$

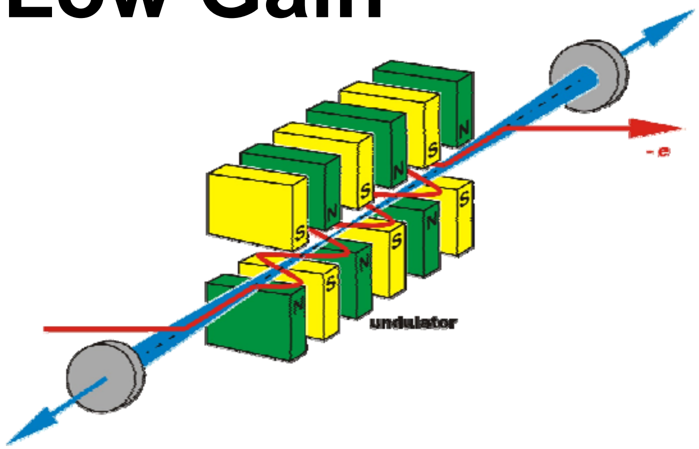
$$\frac{\partial a_z(\tau)}{\partial \tau} = -j \left\langle e^{-i\zeta_i(\tau)} \right\rangle_i$$

current density A/m²

$$j = 4\pi^2 \frac{J}{I_A} K^2 N^3 \frac{\lambda_u^2}{\gamma^3} f^2(\xi)$$

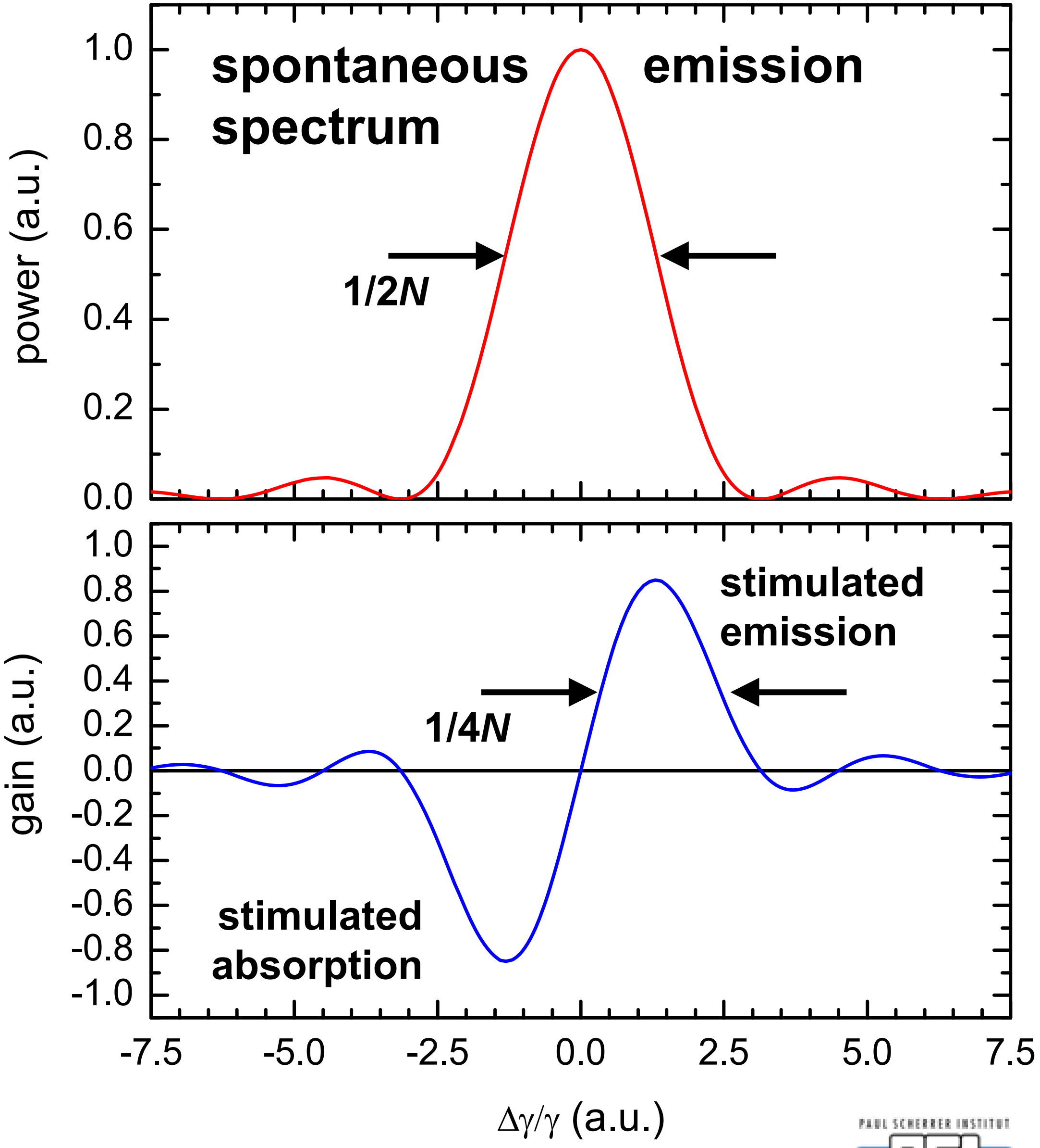
Alfèn current ≈ 17 kA

Low Gain



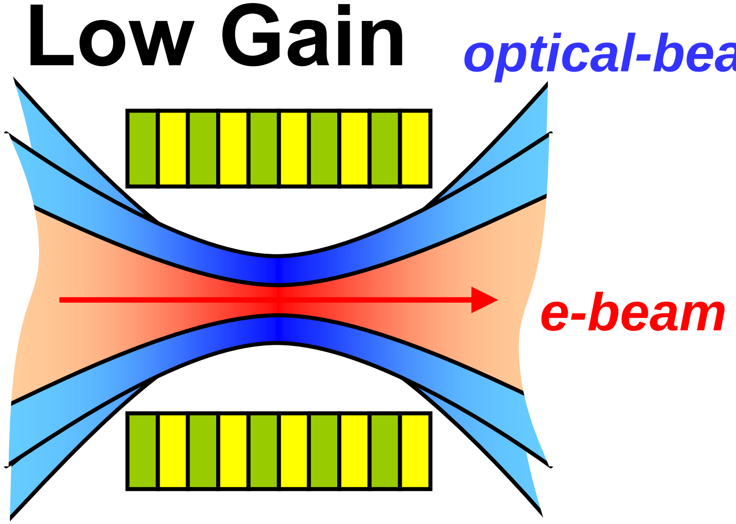
$$G = 0.27\, j$$

$$\approx 6.3 \cdot 10^{-4}\, K^2 N^3 J \frac{\lambda_u^2}{\gamma^3} f^2(\xi)$$



W.B. Colson
Laser Handbook V. 6
Elsevier Science Publishers B.V.
ISBN 0 444 86953 0 (1990)

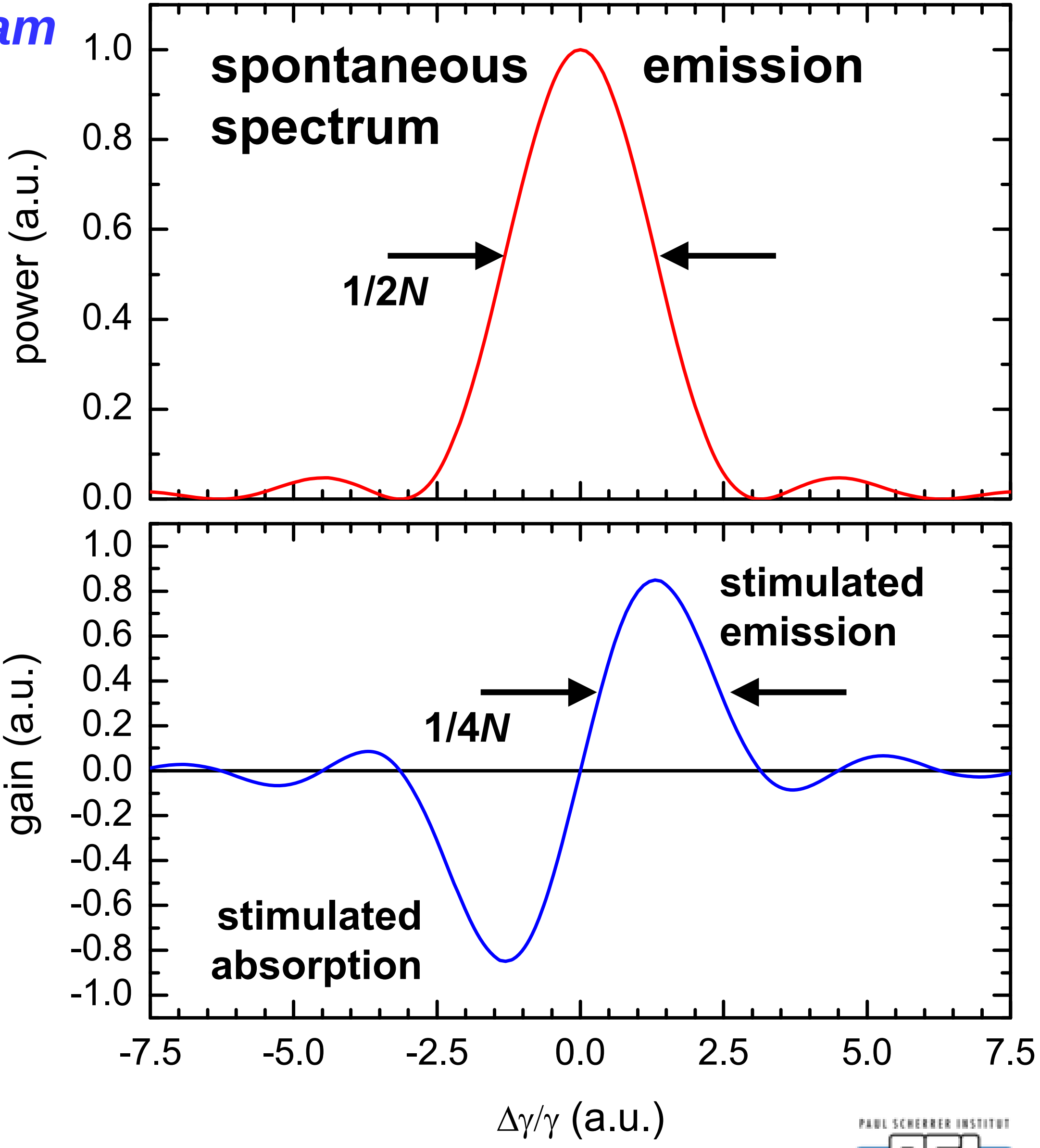
Low Gain



$$G = 0.27\, j$$

$$\approx 6.3 \cdot 10^{-4}\, K^2 N^3 J \frac{\lambda_u^2}{\gamma^3} f^2(\xi)$$

$$\le 9.4 \cdot 10^{-4}\, K^2 N^2 I \frac{1}{\gamma} f^2(\xi)$$



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Requirements

1. **Sufficient beam energy:**

$$\left.\begin{array}{lll} \lambda = 100\,\mu\text{m} \rightarrow & \sim 15 & \text{MeV} \\ \lambda = 10\,\textbf{nm} \rightarrow & \sim 1 & \text{GeV} \\ \lambda = 1\,\textbf{nm} \rightarrow & \sim 3 & \text{GeV} \end{array}\right\} \qquad \lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

2. **Sufficient current:**

50 A (IR) → 5 kA (X-ray)

$$N_{e,\lambda} = \frac{I\lambda}{ec}$$

number of electrons per wavelength

$$N_{e,\lambda} = 1 \rightarrow \begin{cases} 0.5\ \mu\text{A} \ \ (\lambda = 100\,\mu\text{m}) \\ 0.5\ \text{A} \ \ (\lambda = 0.1\,\text{nm}) \end{cases}$$

Requirements

1. Sufficient beam energy:

λ = 100µm → ~ 15 MeV
λ = 10 **nm** → ~ 1 GeV
λ = 1 **nm** → ~ 3 GeV

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

Though for long wavelengths

2. Sufficient current:

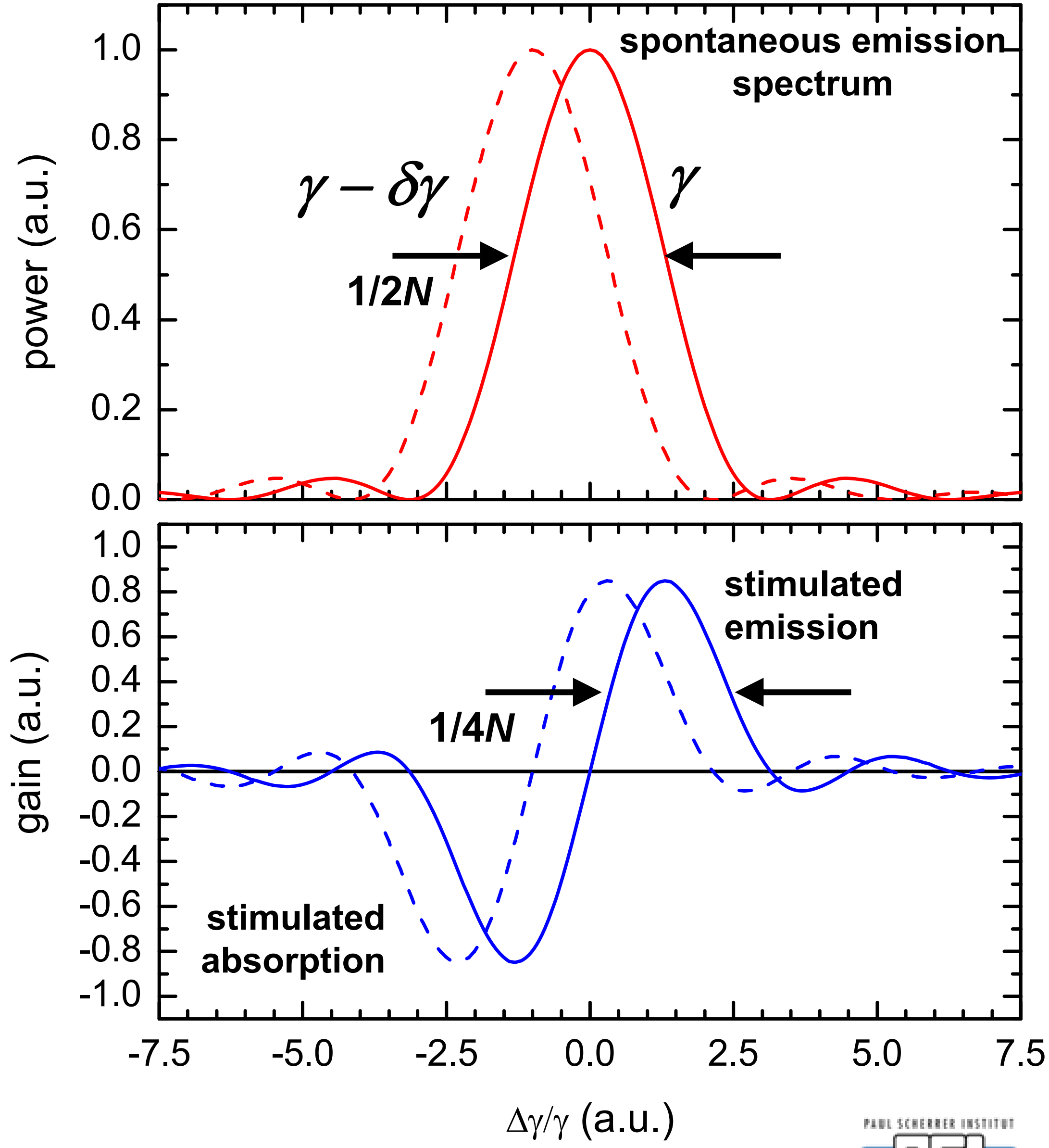
50 A (IR) → 5 kA (X-ray)

3. A good electron beam quality:

Energy spead :

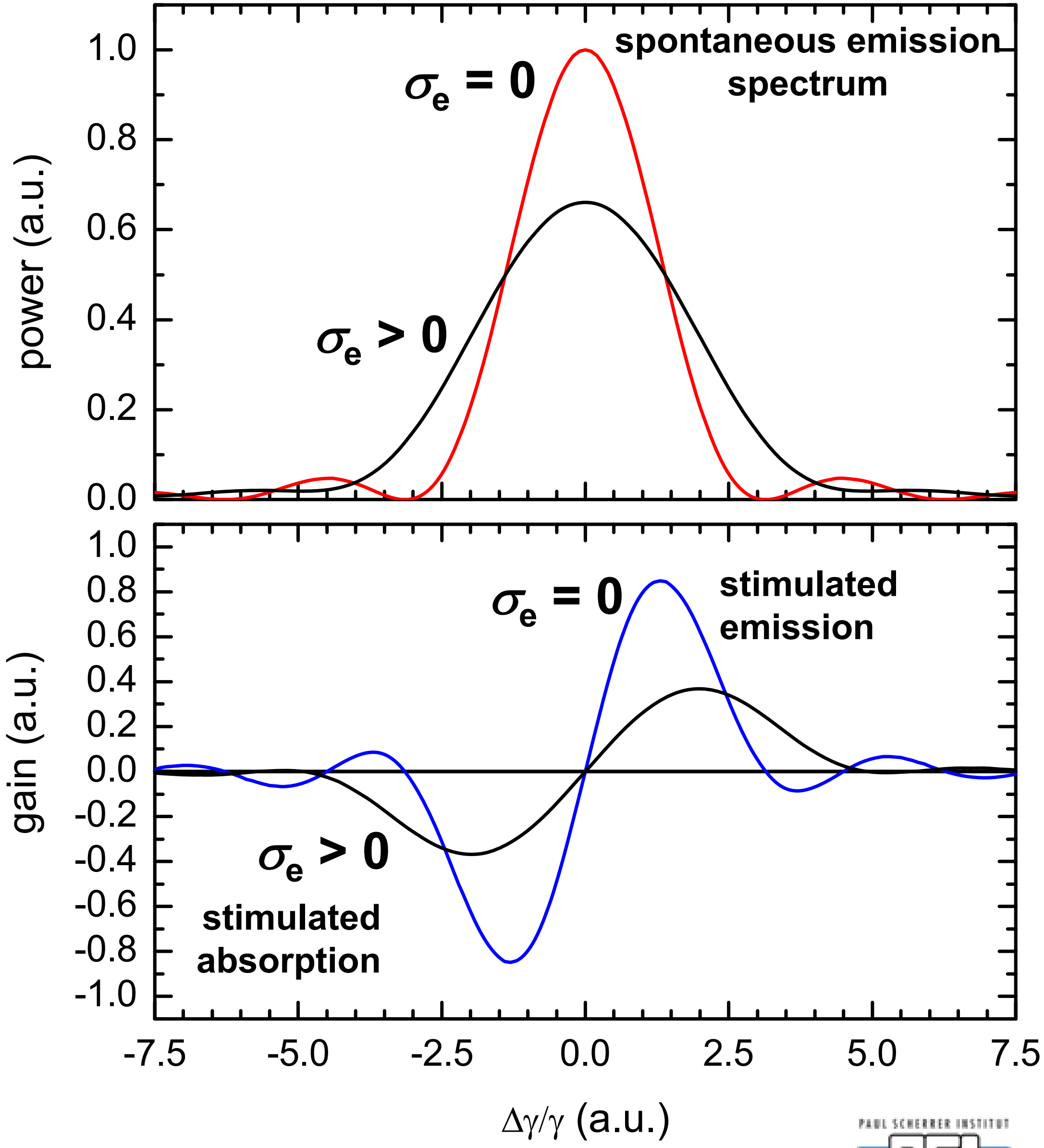
$$\frac{\sigma_E}{E} \leq 10^{-3} \quad \left(\leq \frac{1}{4N}, \leq \rho\right)$$

Energy Spread



Keep electrons within the gain bandwidth

Energy Spread



Keep electrons within the gain bandwidth

Requirements

1. Sufficient beam energy:

$\lambda = 100\mu\text{m} \rightarrow$ ~ 15 MeV

$\lambda = 10\,\text{nm} \rightarrow$ ~ 1 GeV

$\lambda = 1\,\text{nm} \rightarrow$ ~ 3 GeV

$\lambda = 1\,\text{Å} \rightarrow$ ~ 15 GeV

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

Though for short wavelengths

2. Sufficient current:

50 A (IR) → 5 kA (X-ray)

3. A good electron beam quality:

Energy spead :

$$\frac{\sigma_E}{E} \leq 10^{-3} \quad \left(\leq \frac{1}{4N}, \leq \rho\right)$$

Transverse Emittance :

$$\varepsilon \leq \frac{\lambda}{4\pi}, \quad \varepsilon = \varepsilon_n / \gamma$$

Transverse Emittance

1. Relativistic case: transverse momentum is coupled with the longitudinal momentum.

emittance → energy spread

2. Transverse emittance influences the transverse electron beam-size and divergence.

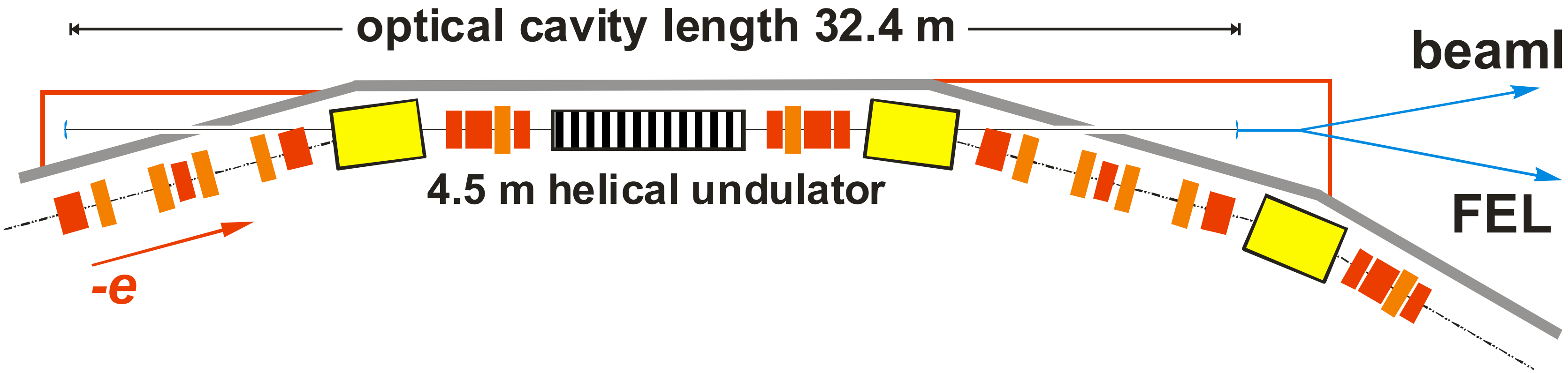
electron beam must diverge less quickly than the optical beam

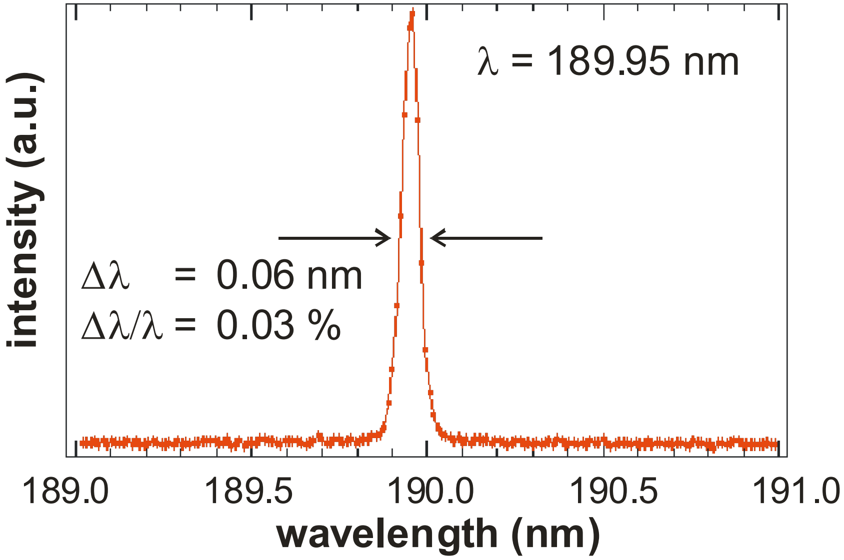
Transverse Emittance:

$$\varepsilon \leq \frac{\lambda}{4\pi}, \quad \varepsilon = \varepsilon_n / \gamma$$

The Elettra Storage Ring FEL

low gain FEL (funding finished in 2005)

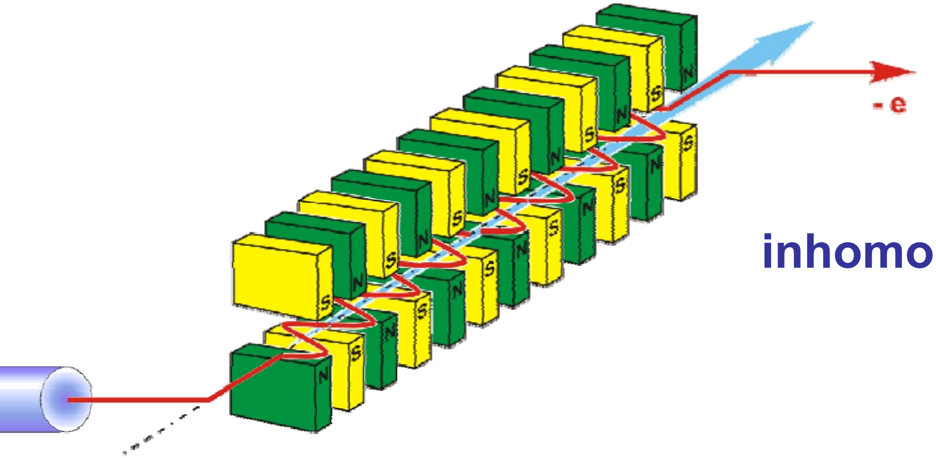




Storage ring operation*	1.0	GeV
Tunability range	350 – 190	nm
	3.5 – 6.5	eV
Average power	≥ 1	W
Pulse length (FWHM)	~ 5	ps
Peak power	≥ 40	kW
Pulse energy	≥ 0.2	mJ
Photon flux**	$\geq 10^{18}$	photons/s
Polarization	circular (linear may also be possible)	
Repetition rate	4.6	MHz
Synchronization with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

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

High Gain



Pierce parameter:

$$\rho = \frac{1}{\gamma}\sqrt[3]{\frac{I}{I_A}\left(\frac{K\lambda_u f(\xi)}{8\sqrt{2}\pi\sigma_{xy}}\right)^2}$$

$$\sigma_{x,y} = \sqrt{\varepsilon\beta_{x,y}}$$

$$f(\xi) = J_0(\xi) - J_1(\xi)$$

$$\xi = \frac{1}{2}\frac{K^2}{2+K^2}$$

Gain length:

$$L_g = \frac{\lambda_u}{4\pi\rho\sqrt{3}}\left(1+\Lambda_T^2\right)$$

inhomogeneous effects: $\Lambda_T = \frac{1}{\rho}\sqrt{\left(\frac{\sigma_\gamma}{\gamma}\right)^2 + \left(\frac{\varepsilon\lambda_u}{4\lambda\beta_{x,y}}\right)^2} < 1$!!

Saturation:

$$L_{sat} = L_g \ln\left(\frac{9+6\Lambda_T^2}{1+6\Lambda_T^2}\frac{P_{sat}}{P_{in}}\right)$$

$$P_{sat} = 1.37\rho P_b\, e^{-0.82\Lambda_T^2}$$

$$P_{in} = 3\rho^2\sqrt{4\pi}\frac{P_b}{N_\lambda \ln\left(\frac{N_\lambda}{\rho}\right)}$$

$$P_b = I \cdot E\ (\mathrm{eV}) = \frac{mc^2}{e_0}\gamma I$$

$$N_\lambda = \frac{I\lambda_s}{ec}$$

The Physics of Free-electron Lasers
E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov
Springer, Berlin-Heidelberg (2000)

High Gain

peak-power of the electron beam

Gain length:

$$L_g = \frac{\lambda_u}{4\pi\rho\sqrt{3}}\left(1+\Lambda_T^2\right)$$

inhomogeneous effects: $\Lambda_T = \frac{1}{\rho}\sqrt{\left(\frac{\sigma_\gamma}{\gamma}\right)^2 + \left(\frac{\varepsilon\lambda_u}{4\lambda\beta_{x,y}}\right)^2} < 1$!!

spontaneous power within the gain-acceptance bandwidth of the FEL

Saturation:

$$L_{sat} = L_g \ln\left(\frac{9+6\Lambda_T^2}{1+6\Lambda_T^2}\,\frac{P_{sat}}{P_{in}}\right)$$

$$P_{sat} = 1.37\,\rho P_b\, e^{-0.82\Lambda_T^2}$$

Pierce parameter:

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$$P_{in} = 3\rho^2\sqrt{4\pi}\,\frac{P_b}{N_\lambda \ln\left(\frac{N_\lambda}{\rho}\right)}$$

$$P_b = I\cdot E\ (\text{eV}) = \frac{mc^2}{e_0}\gamma I$$

$$N_\lambda = \frac{I\lambda_s}{ec}$$

$$\sigma_{x,y} = \sqrt{\varepsilon\beta_{x,y}}$$

$$f(\xi) = J_0(\xi) - J_1(\xi)$$

$$\xi = \frac{1}{2}\,\frac{K^2}{2+K^2}$$

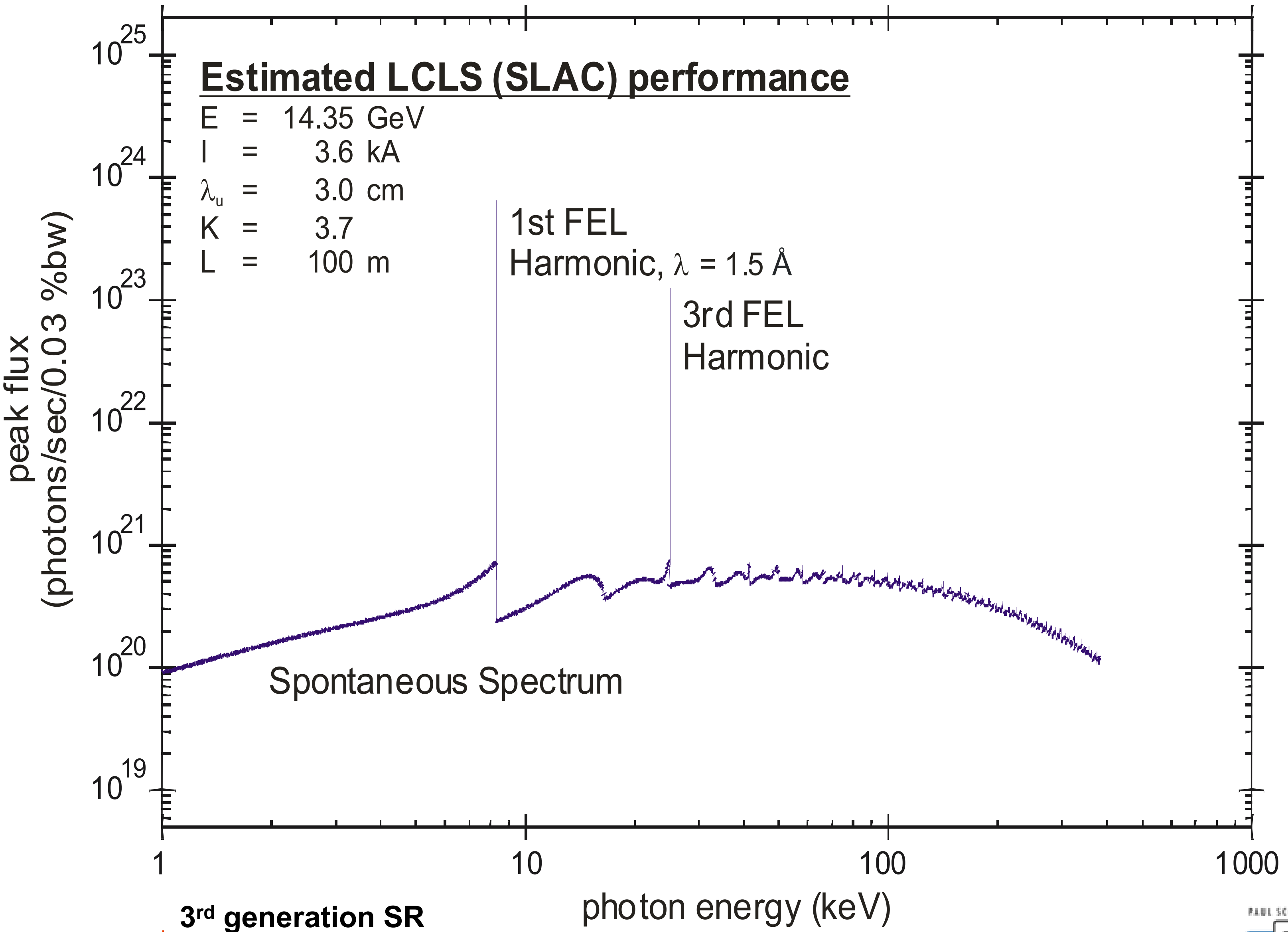
electrons per wavelength

The Physics of Free-electron Lasers
E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov
Springer, Berlin-Heidelberg (2000)

B. Faatz, DESY, Hamburg, DE
http://adweb.desy.de/~faatz/parms.html

(high gain FEL)

SLAC-R-521, p 3-4 (1998)



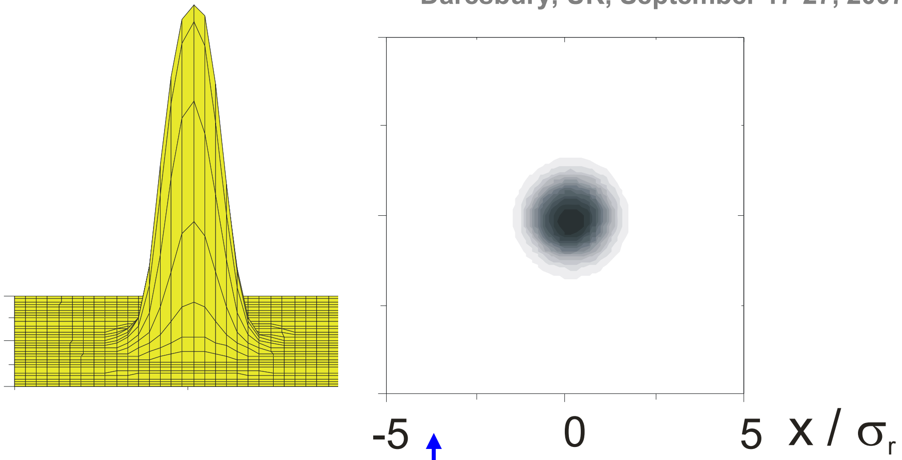
Estimated LCLS (SLAC) performance

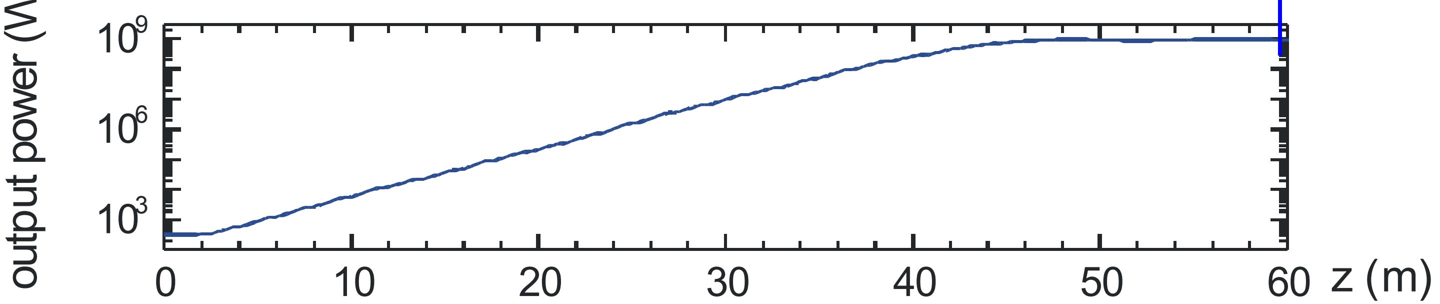
E = 14.35 GeV
I = 3.6 kA
λ_u = 3.0 cm
K = 3.7
L = 100 m

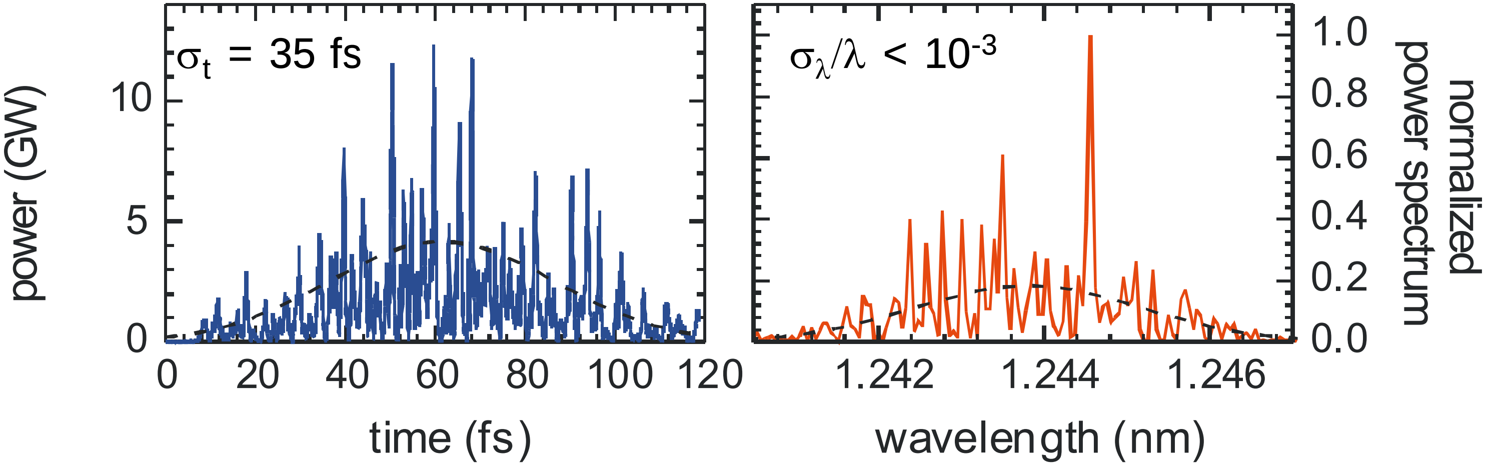
Output properties

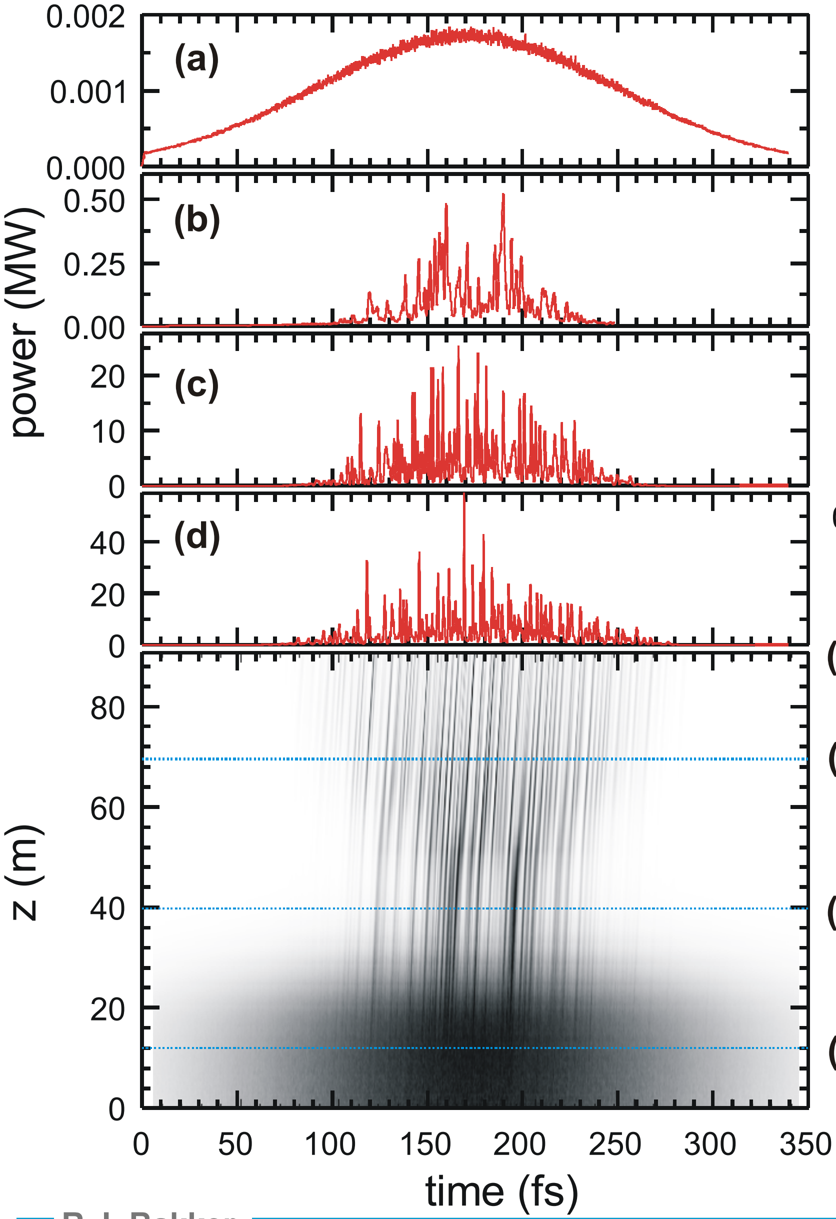
(high gain FEL)

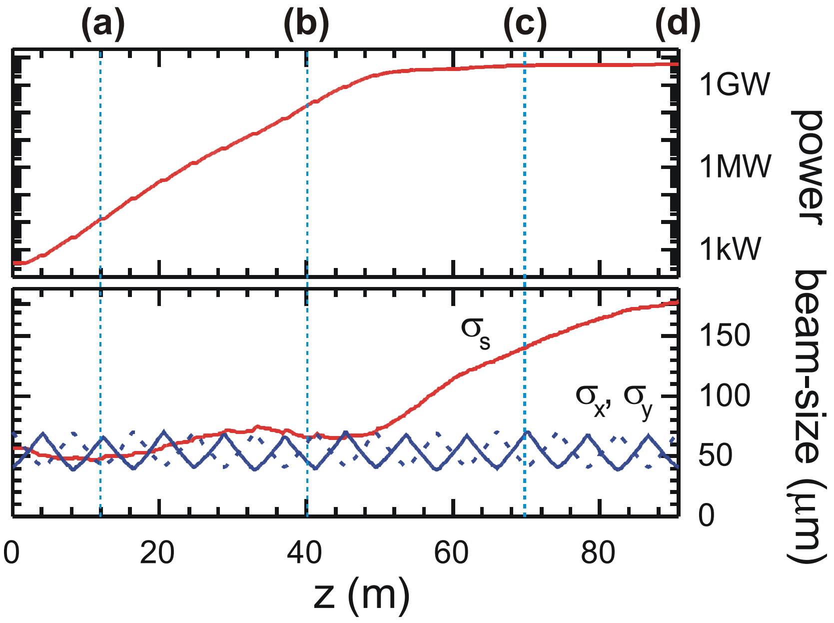
transverse:
diffraction limited TEM_{00} mode











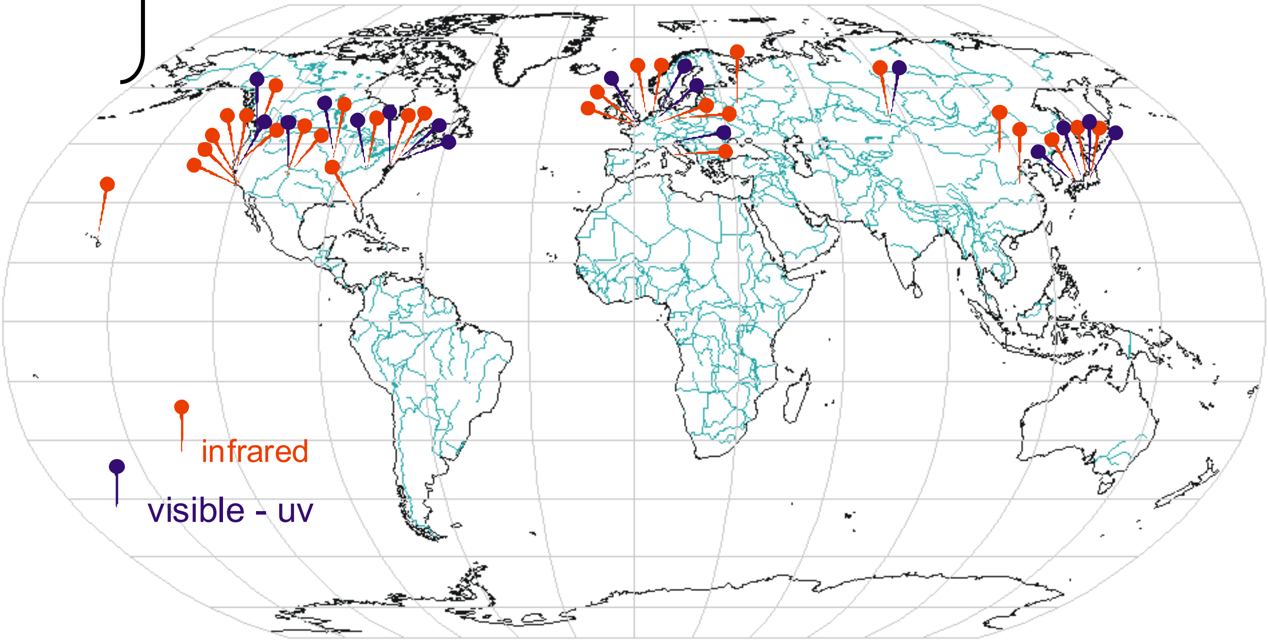
- Each spike is transform limited
- Spikes originate from
  a) noise (SASE)
  b) FEL process (high power instability)
- Position of spikes is random (changes from shot-to-shot)
- The distance between spikes is fixed ($\sim\lambda/\rho$)

Examples

- FEM → UV FEL
- High Average Power
- Single-Pass

Personal Choice !

FEL facilities



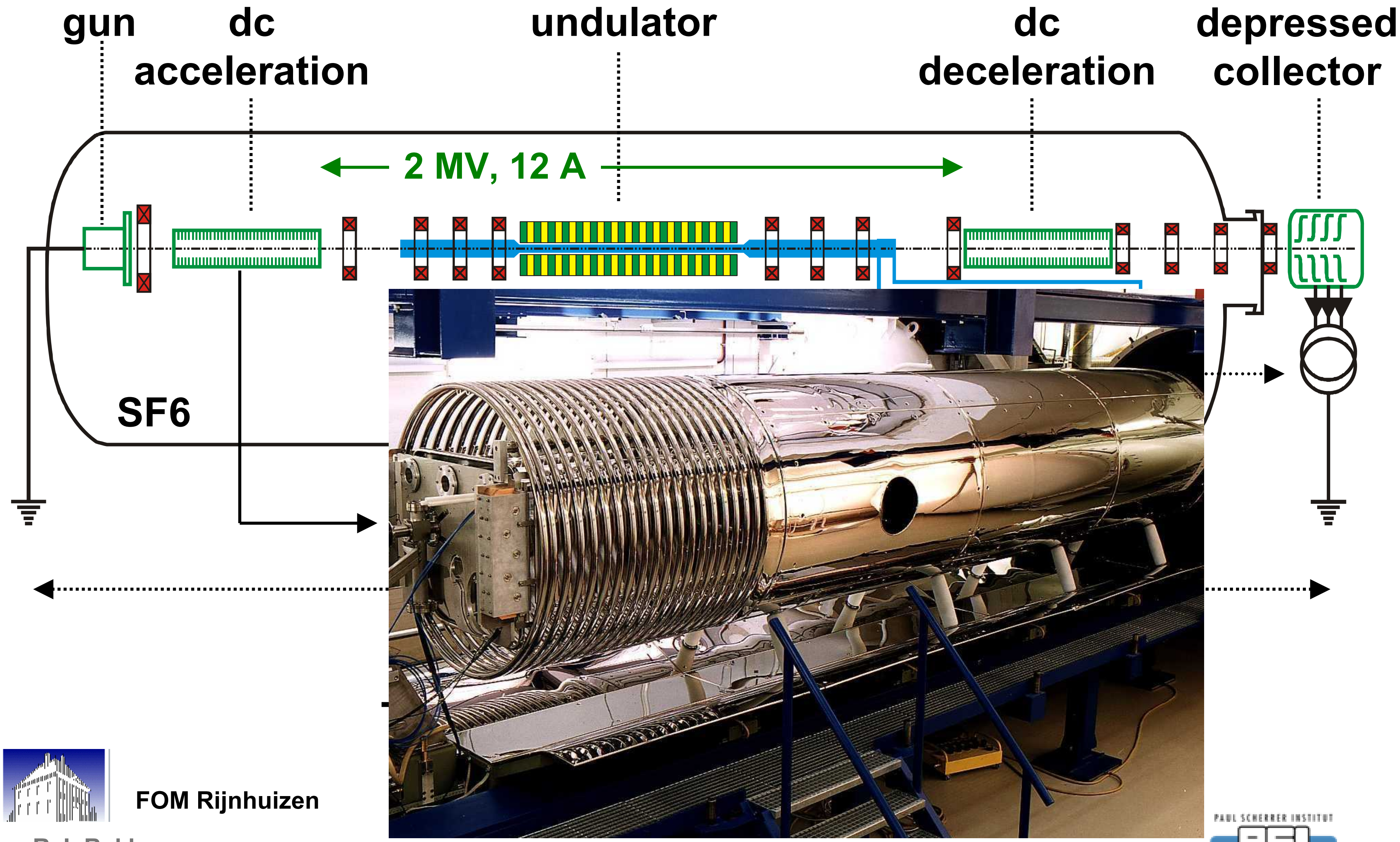
W.B. Colson p. 756, Proceedings FEL2006 (JACoW)

http://sbfel3.ucsb.edu/www/vl_fel.html

http://accelconf.web.cern.ch/AccelConf/f06/PAPERS/THPPH071.PDF

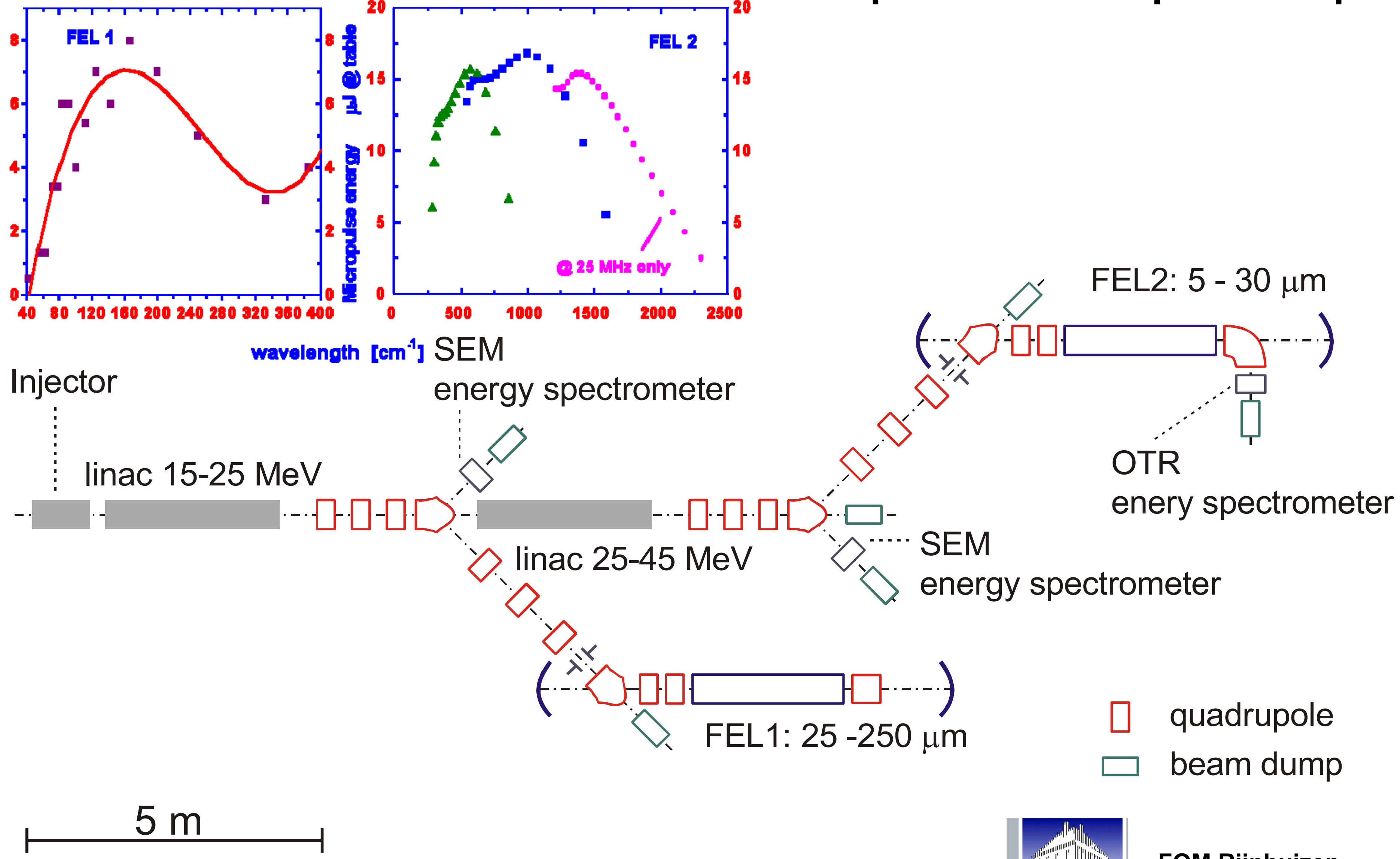
Free Electron Maser: 160 - 260 GHz (λ = 1 - 2 mm)

(decommissioned)

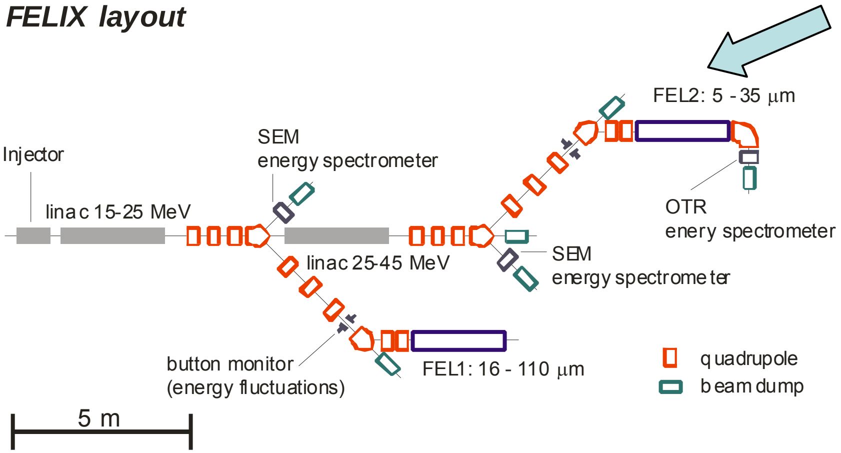


FOM Rijnhuizen

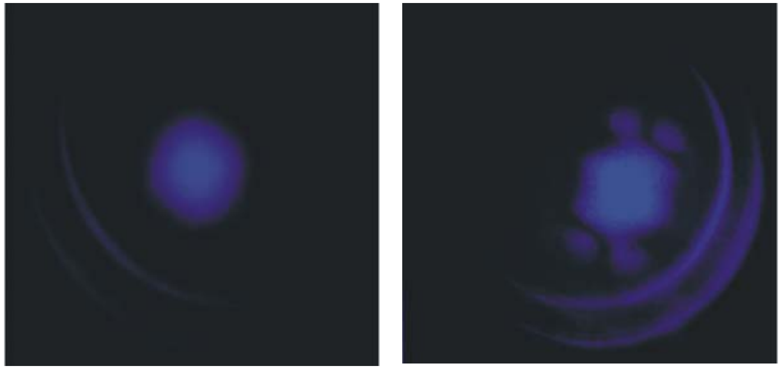
FELIX Free Electron Laser for Infrared eXperiments: 4.5 µm – 250 µm



FELIX layout



The Super ACO FEL



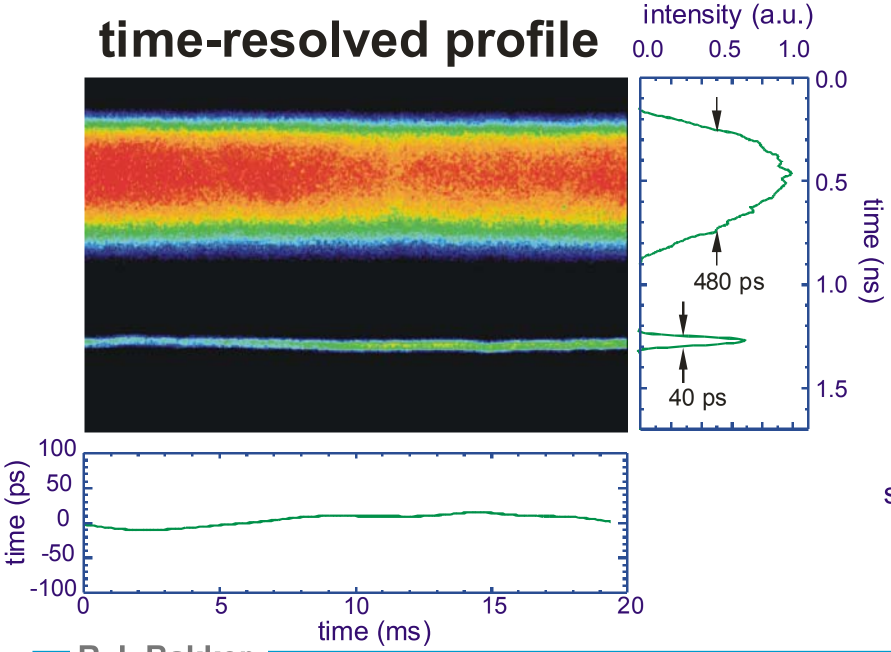
transverse mode profile

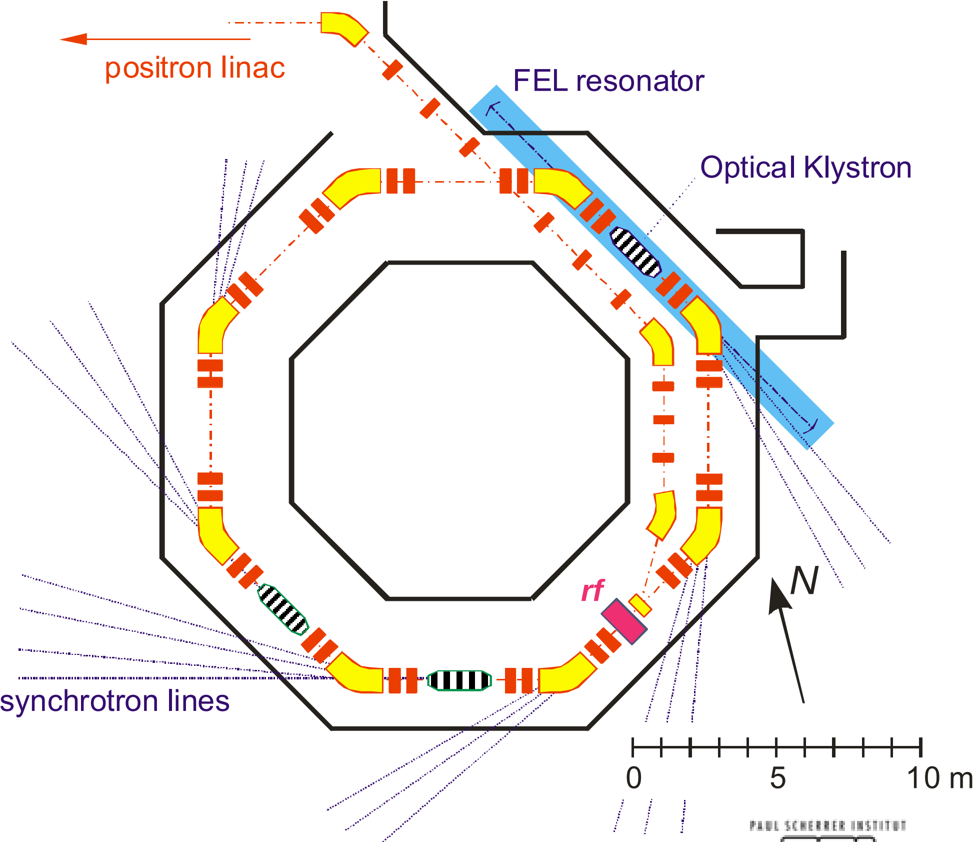
Storage-Ring FEL:

(decommissioned, 2003)

λ	300 - 600	nm
$\Delta\lambda/\lambda$	0.1 - 0.01	%
P_{avg}	~ 100	mW
P_{peak}	~ 1	kW

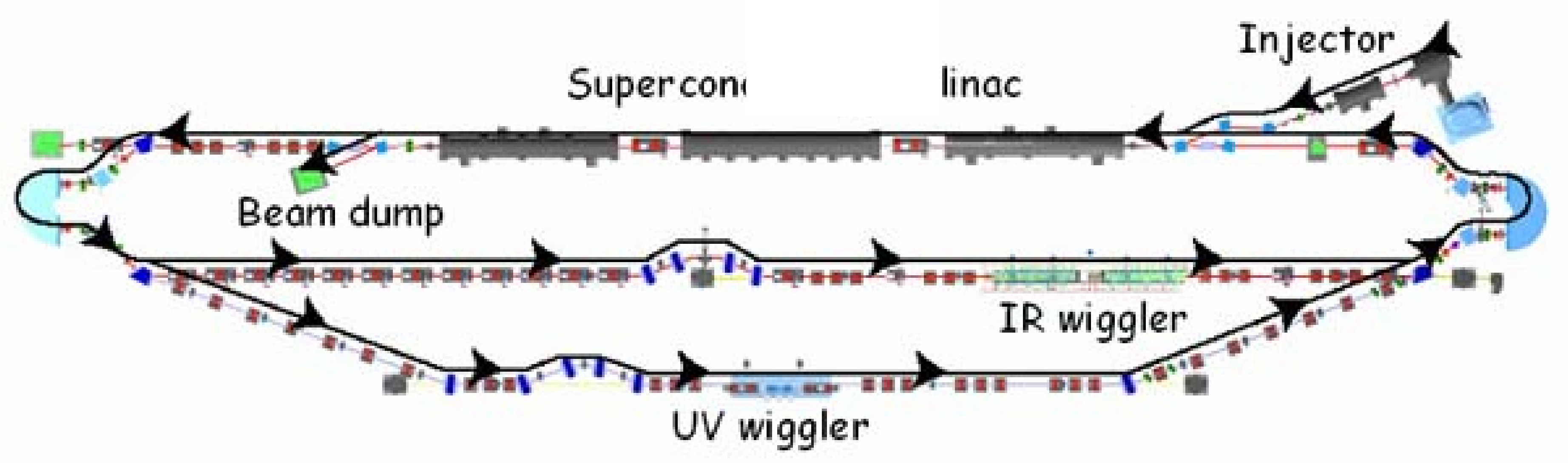
time-resolved profile





JLAB recirculating FEL

Driver Accelerator	**IR**	
Linac Energy	80-200	MeV
Linac Ave. Current	10	mA
Bunch Charge	135	pC
Peak current	270	A
Transverse Emittance	<30	mm mrad (normalized)
Energy Spread	0.3	%
FEL System		
Wavelength	1.5 – 14	μm
Induced Energy Spread	10	%
Pulse Length	0.2 – 2	ps

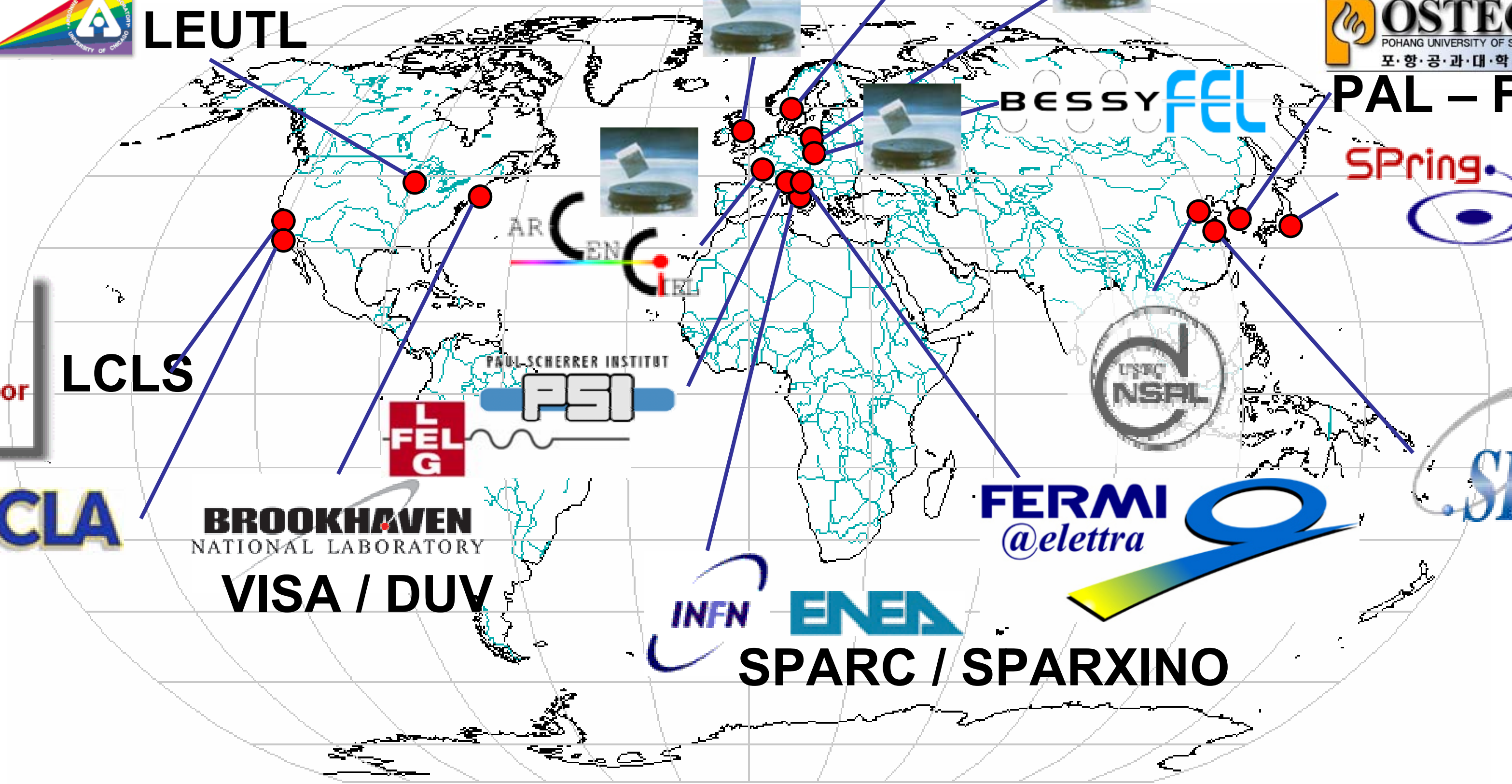


High average-power lasers: JLAB

- FELs need a high peak current.
  - a factor of 4 growth in the longitudinal emittance due to space charge.
  - longer electron bunches in the injector can reduce space charge effects but reduces the machine acceptance.
  - Halo loss initially limited the average current.
- Resonator FELs need a high average current
  - Bunch spacing must match the cavity length.
  - Intra-cavity power load on mirrors
  - Beam break-up limits the average current (JLAB 3 mA → 10 mA)

E.g.: FEL2006 (JACoW):
On the Design Implications of Incorporating an FEL in an ERL, G. R. Neil et. al

Single Pass FEL Activity



MAX-lab

CCLRC

4GLS

DESY **FLASH / XFEL**

Advanced Photon Source **LEUTL**

POSTECH POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY 포·항·공·과·대·학·교

PAL – FEL

BESSY FEL

SPring-8

SCSS

ARC-EN-CIEL

Stanford Linear Accelerator Center **LCLS**

PAUL SCHERRER INSTITUT PSI

L FEL G

USTC NSRL

SINR

UCLA

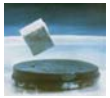
BROOKHAVEN NATIONAL LABORATORY

VISA / DUV

FERMI @elettra

INFN ENEA

SPARC / SPARXINO



Superconducting accelerator technology

Present status

- 4 projects target X-rays:
  $\lambda \leq 0.1$ nm / $\hbar\omega \geq 12.4$ keV
  - **User facilities**
  - **Increased beam energy to lower the emittance** →
  - **Initially SASE only**
  - **Possible seeding as an extended option**

$$\frac{\varepsilon_n}{\gamma} < \frac{\lambda}{4\pi}$$

alternatives

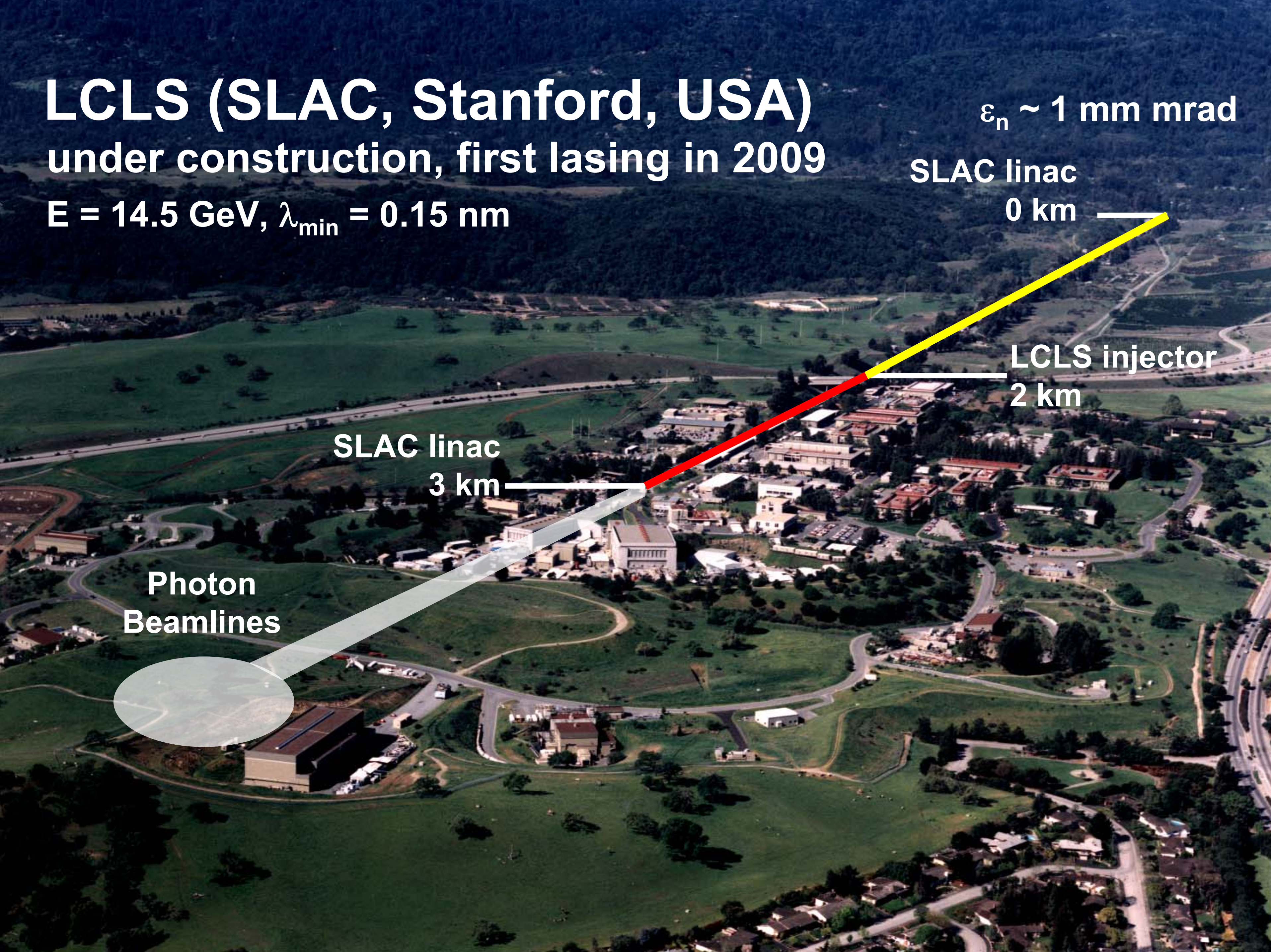
- many projects in the VUV / soft X-ray range
  $\lambda \geq 0.3$ nm / $\hbar\omega \leq 4.1$ keV

LCLS (SLAC, Stanford, USA)

under construction, first lasing in 2009

E = 14.5 GeV, λ_{min} = 0.15 nm

ε_n ~ 1 mm mrad

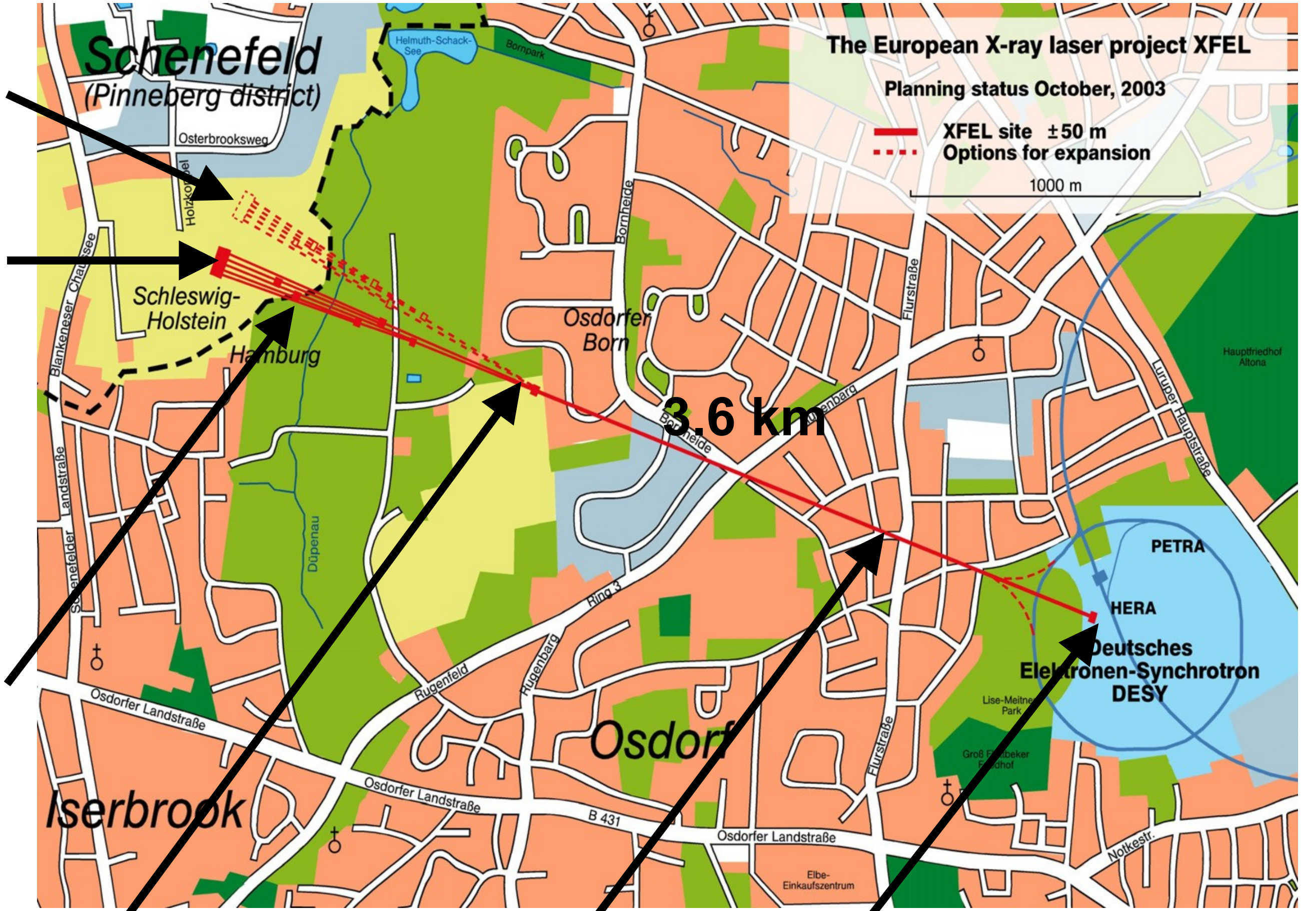


European XFEL Project (2012)

$\varepsilon_n \sim 1$ mm mrad

E = 17.5 GeV, λ_{min} = 0.10 nm

http://xfelinfo.desy.de/_medien/infografik/infoflash.swf



Possible Future Extension

Experimental Hall

undulators & photon beamlines 1.2 km

beam distribution 0.4 km

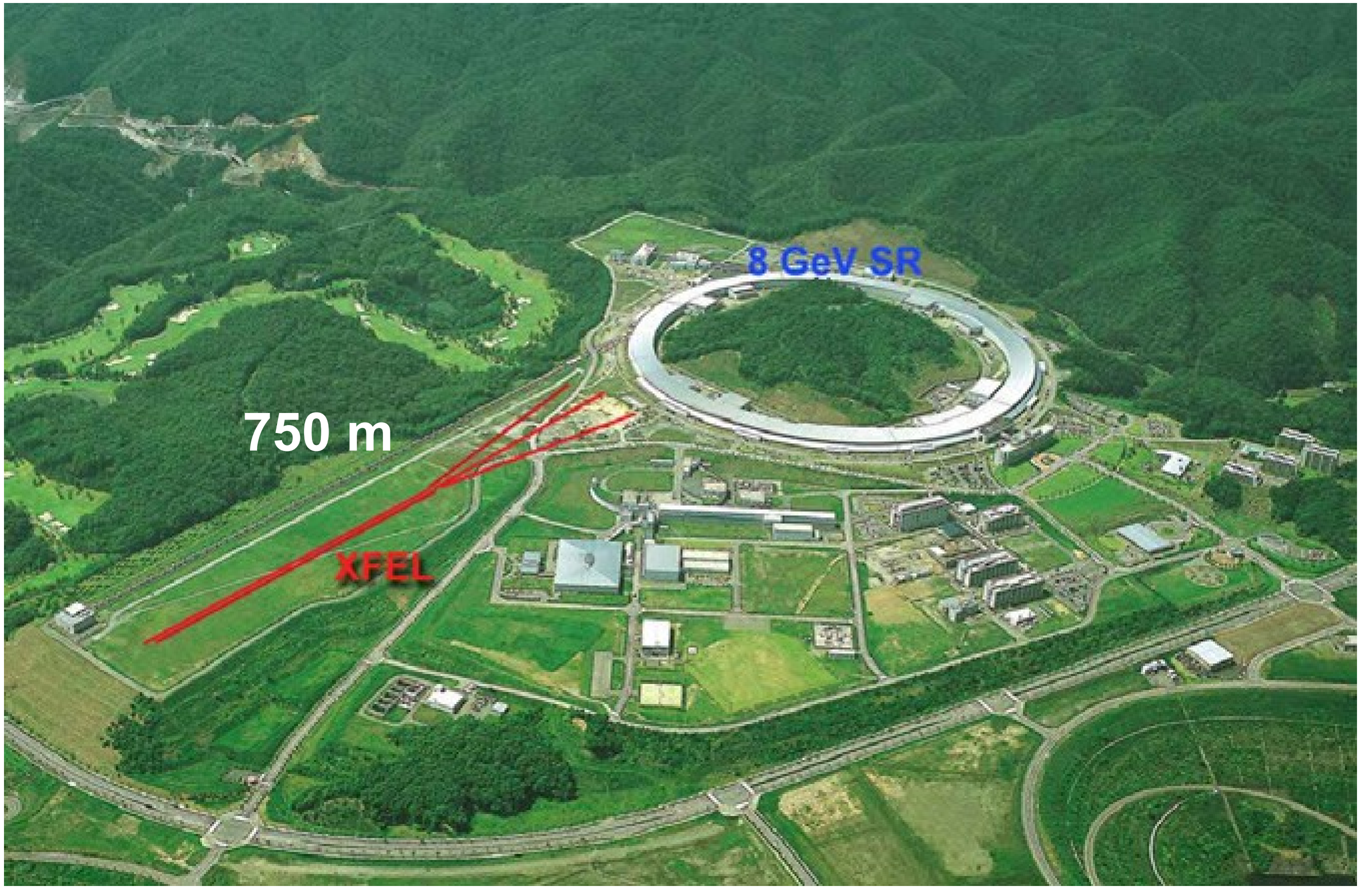
linac tunnel 2 km

Injector

SPRing8, Japan

$E = 8.0$ GeV, $\lambda_{min} = 0.10$ nm

$\varepsilon_n \sim 0.85$ mm mrad



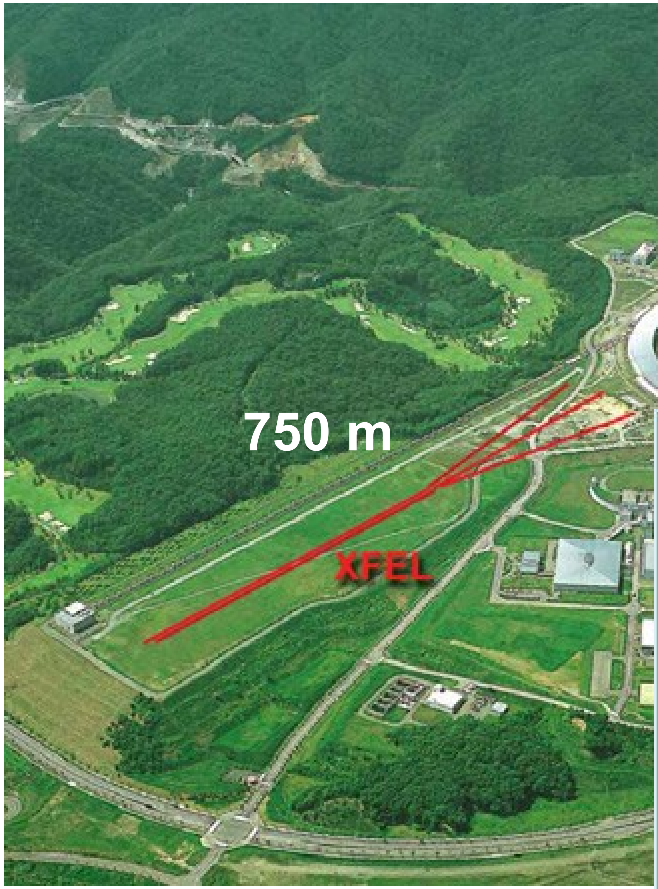
Low emittance electron source

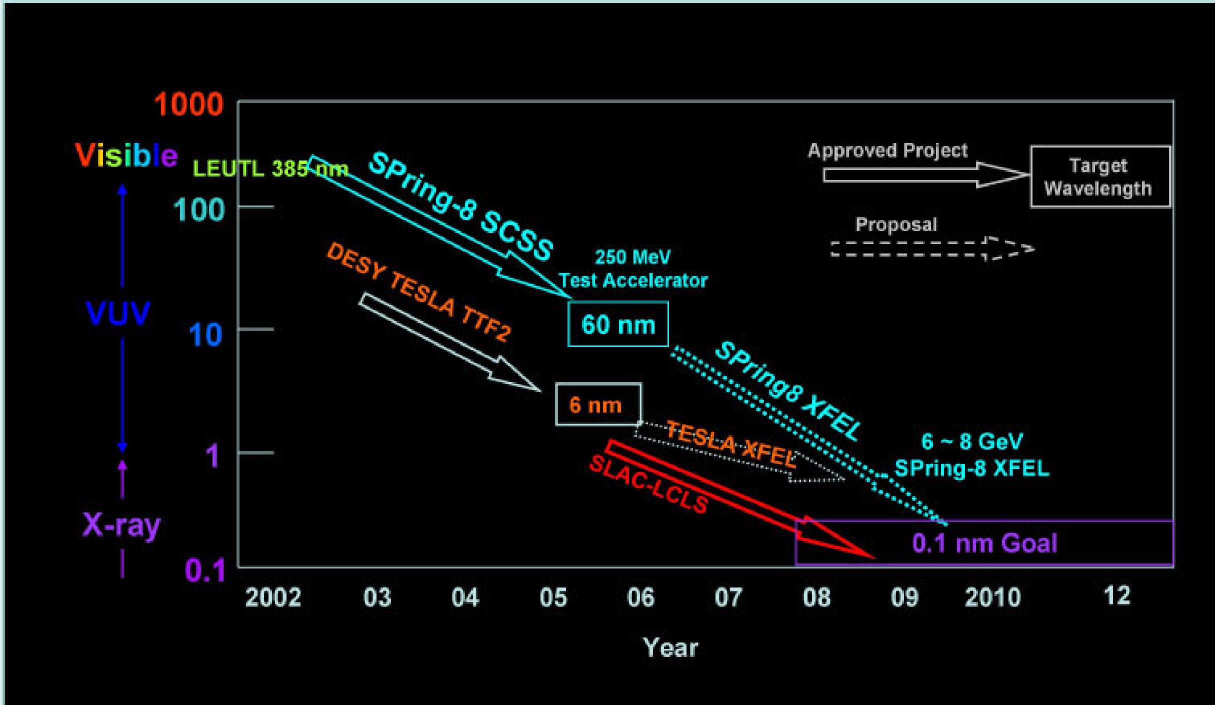
SPRing8, Japan

E = 8.0 GeV, λ_{min} = 0.10 nm

ε_n ~ 0.85 mm mrad

Low emittance electron source





PSI XFEL, Switzerland (> 2016)

$E = 6.0$ GeV, $\lambda_{min} = 0.10$ nm

$\varepsilon_n \sim 0.2$ mm mrad

Present status

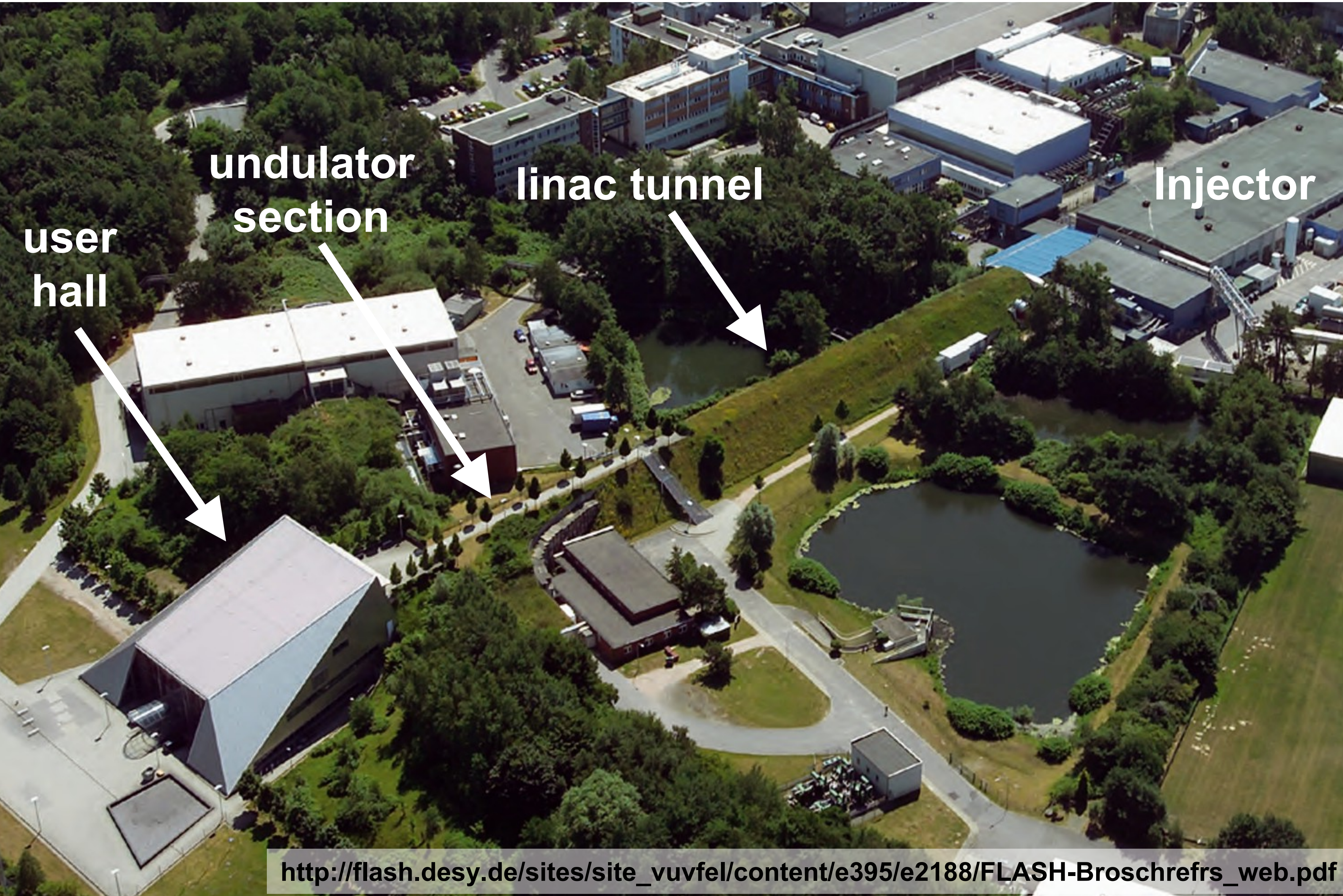
- many projects in the VUV / soft X-ray range
  $\lambda \geq 0.3$ nm / $\hbar\omega \leq 4.1$ keV

  - **FEL R&D & user facilities**
  - **Emittance matched to the undulator technology** → **moderate beam energy**
  - **More diversity**

    - SASE & various seeding options

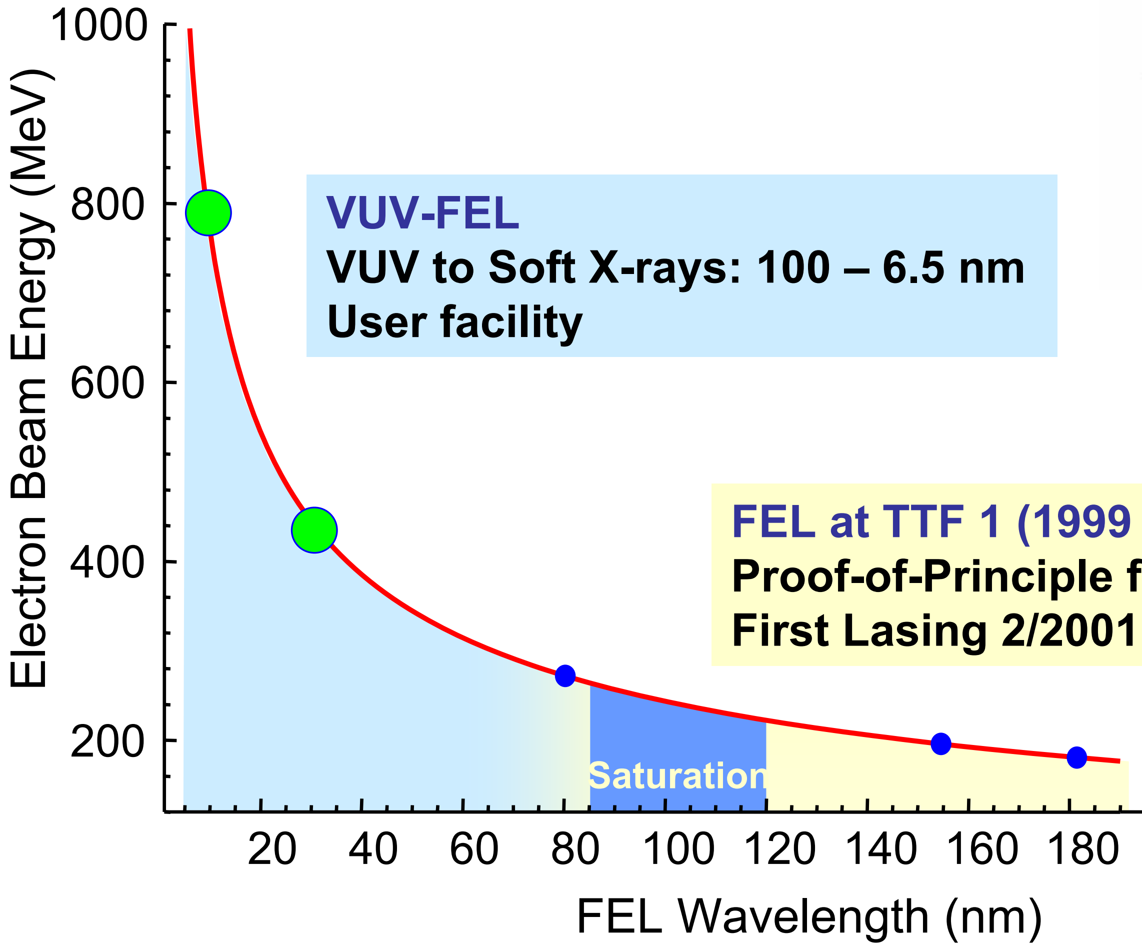
    - FELs in combination with energy recovery linacs (ERL)

FLASH – VUV Single-Pass FEL, Hamburg



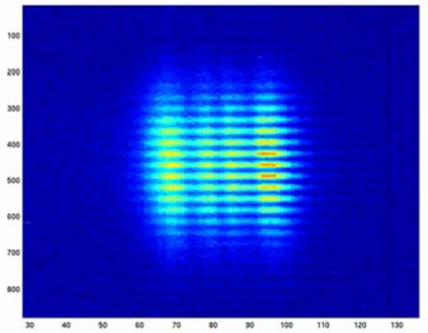
http://flash.desy.de/sites/site_vuvfel/content/e395/e2188/FLASH-Broschrefrs_web.pdf

Beam Energy and Wavelength



VUV-FEL
VUV to Soft X-rays: 100 – 6.5 nm
User facility

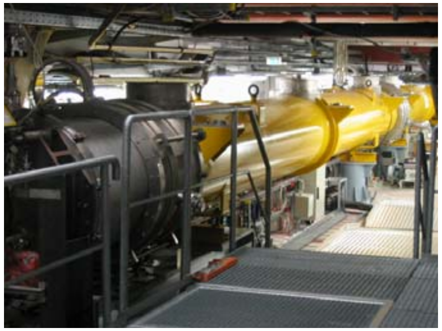
FEL at TTF 1 (1999 - 2002)
Proof-of-Principle for SASE in the VUV
First Lasing 2/2001, Saturation 9/2002

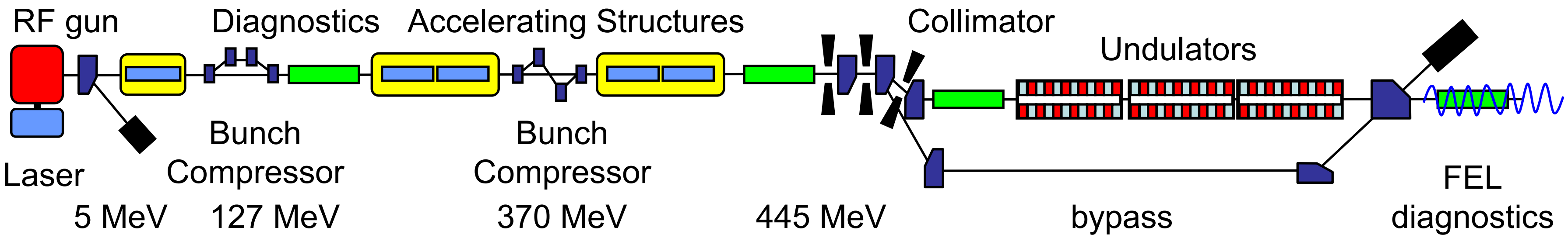


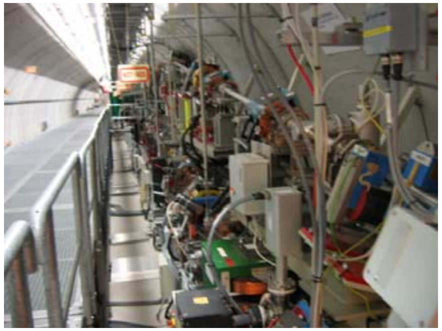
FEL radiation:
measured diffraction
pattern of a double slit

Courtesy Bart Faatz (DESY)

Layout of the VUV-FEL (status 2005)







250 m

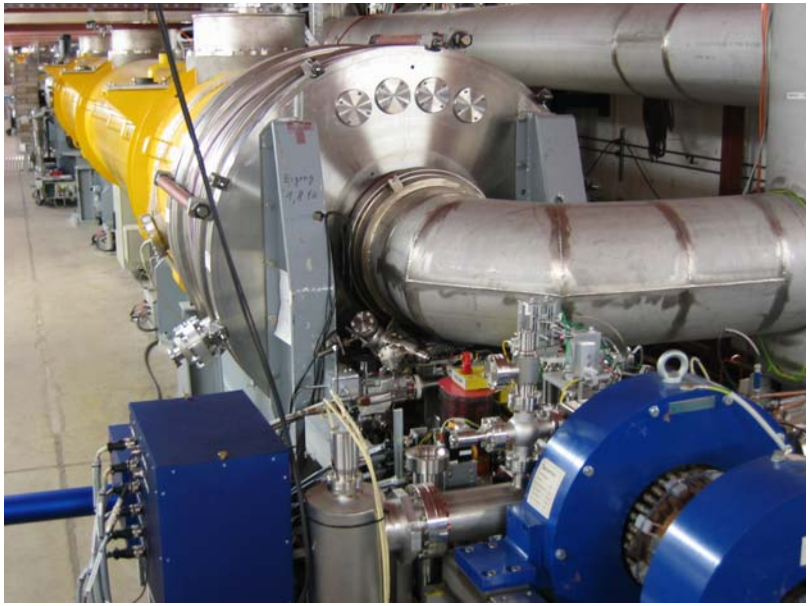
RF Gun

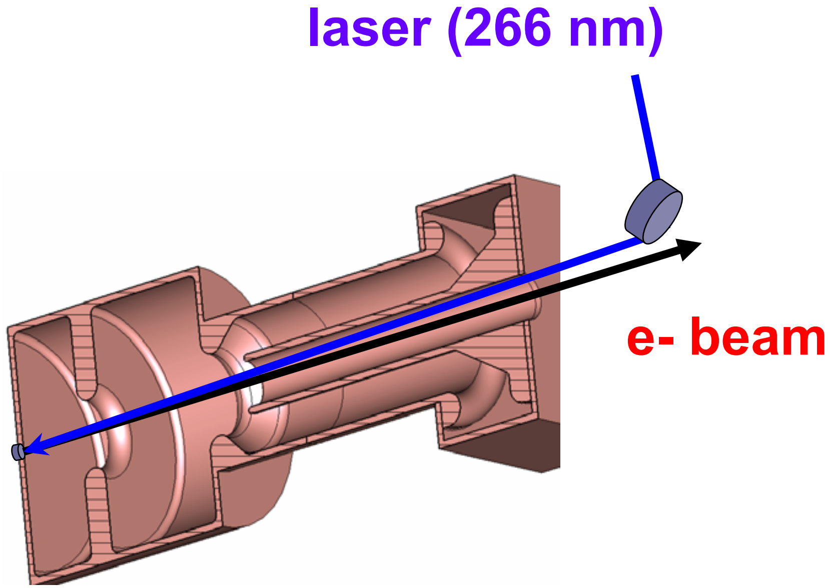
1 1/2 cell L-band 1.3 GHz

Longitudinal RF coupler

Up to 3.5 MW possible with given 5 MW klystron

Extensively tested at PITZ (DESY Zeuthen)



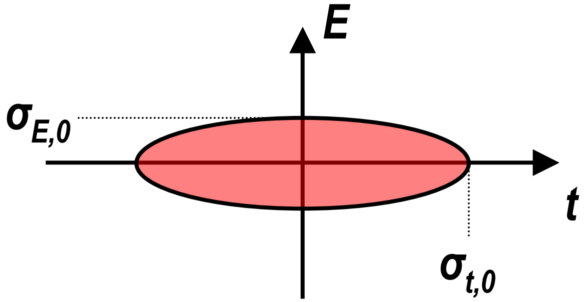


Distance gun to first acc. cavity determined by beam dynamcis

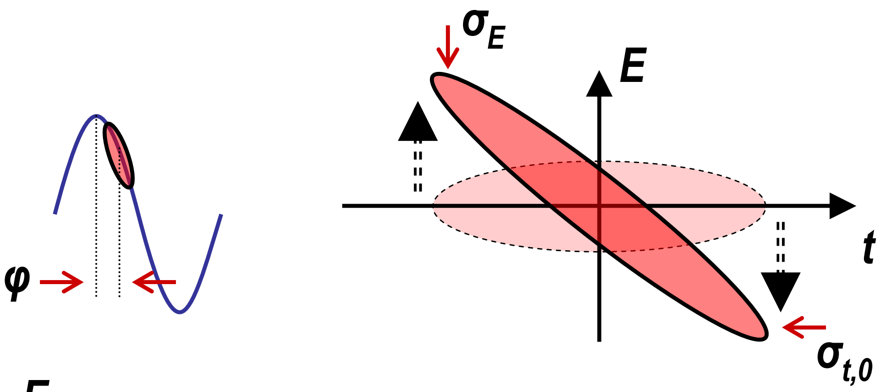
Very difficult to fit diagnostics between gun and module (spectrometer, toroid, BPMs, screens, steerers, laser input…)

Bunch Compression: e-distribution in *t,E* phase-space

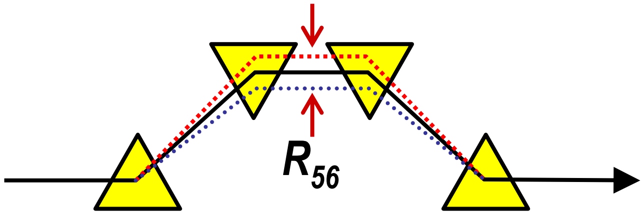
1. Initial condition

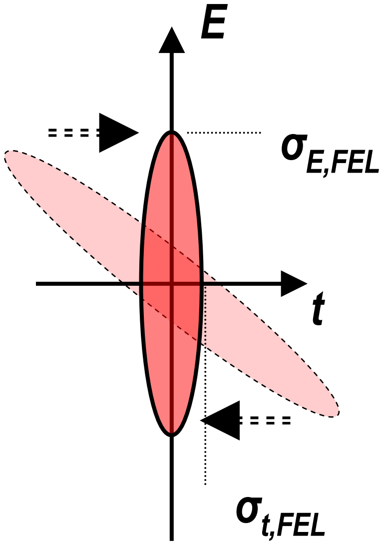


2. Offcrest RF acceleration

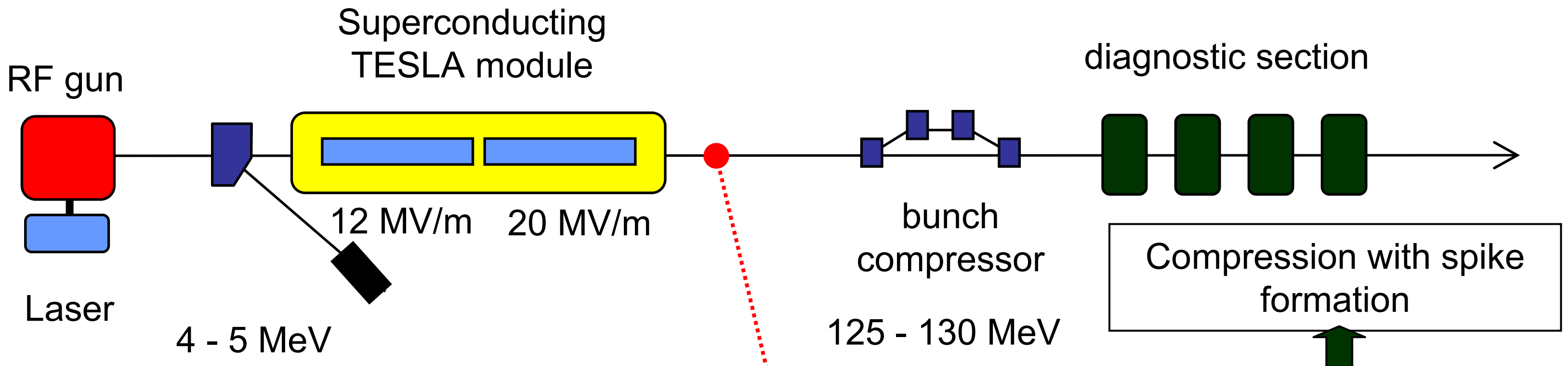


3. Compressor (dipoles): E_c



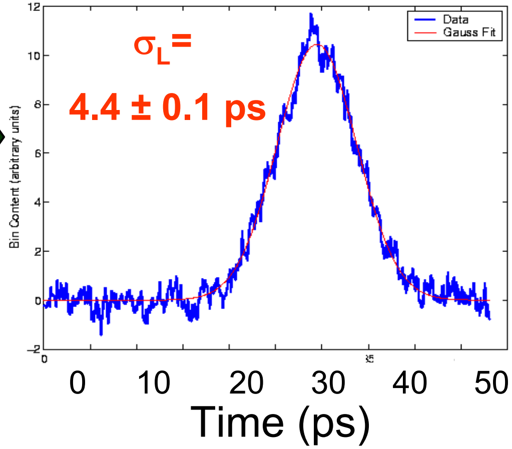


FLASH Injector Layout

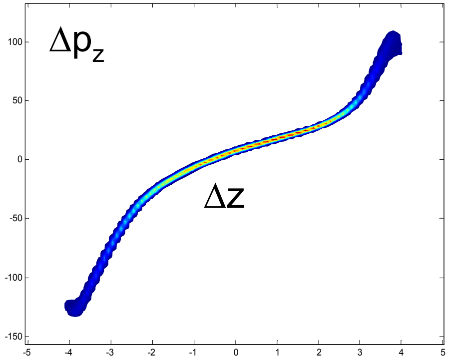


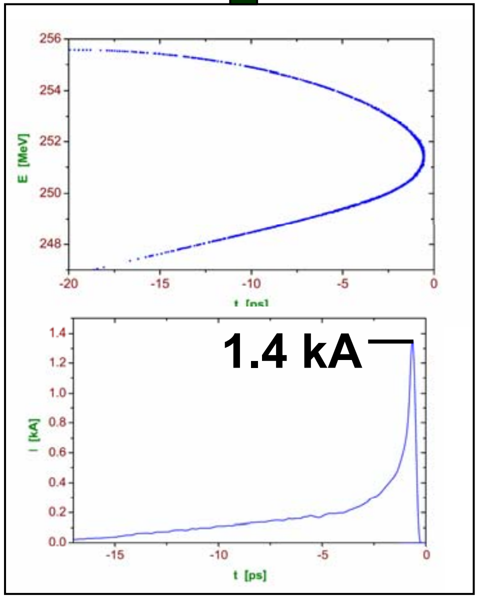
Compression with spike formation

pulse from gun



longitudinal phase space

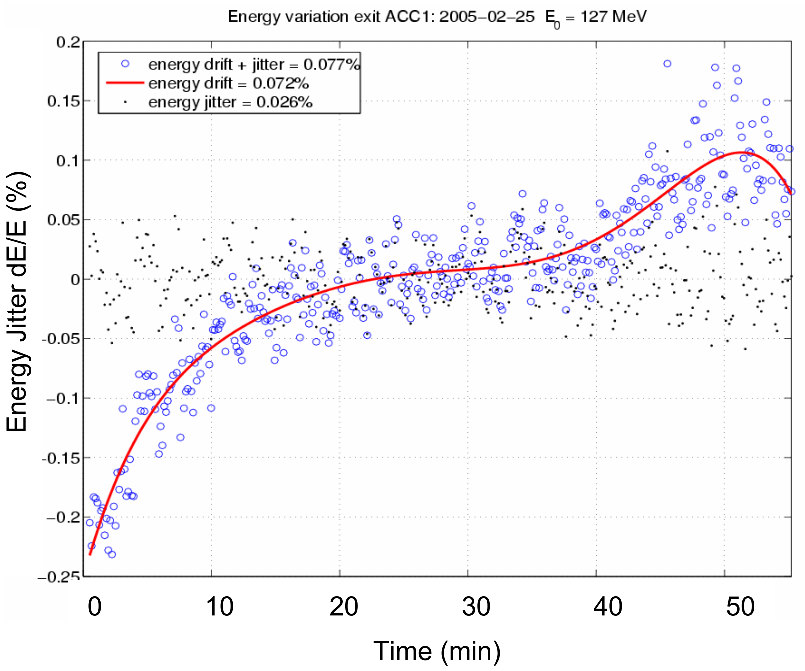


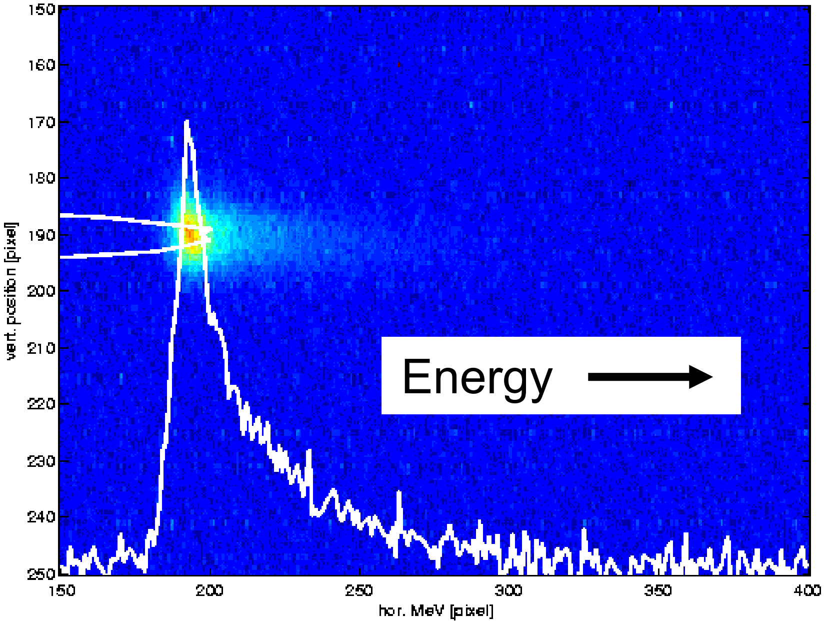


Solenoid field → Match envelope to booster adjust booster gradient → Emittance damping

Courtesy Bart Faatz (DESY)

FLASH: Energy and Energy Spread





Energy measured using the OTR screen in the dispersive section of the first bunch compressor

Energy jitter w/o drift dE/E = 2.6·10^{-4} at 127 MeV

Including the drift yields 7·10^{-4}

Uncorrelated energy spread < 25 keV (resolution limited)

FLASH: Undulator Section

6 permanent magnet undulators with a length of 4.5 m each

Quadrupole doublets for flexible focusing of the electron beam

L_{und} = 27.3 m

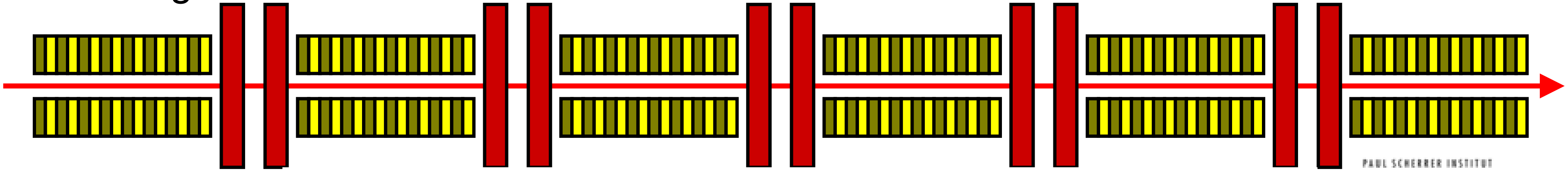
B_{peak}= 0.47 T

Gap = 12 mm

E = up to 1 GeV

K = 1.17

λ_{rad} = 100 ... 6 nm



http://flash.desy.de/sites/site_vuvfel/content/e395/e2188/FLASH-Broschrefrs_web.pdf

Alignment tolerances

6 permanent magnet undulator modules are installed with a length of 4.5 m each

Quadrupole doublets between undulator give flexibility for a wide wavelength range

L_{und} = 27.3 m

B_{peak}= 0.47 T

Gap = 12 mm

E = up to 1 GeV

K = 1.17

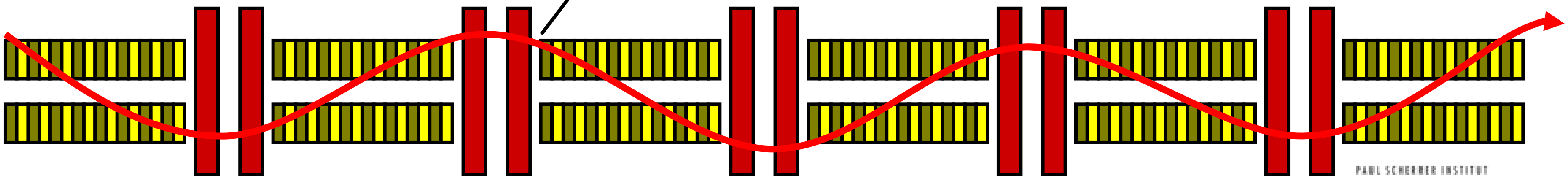
λ_{rad} = 100 ... 6 nm

FEL lases at different wavelengths along the undulator

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\boxed{+\gamma^2\theta^2}\right)$$

misalignment

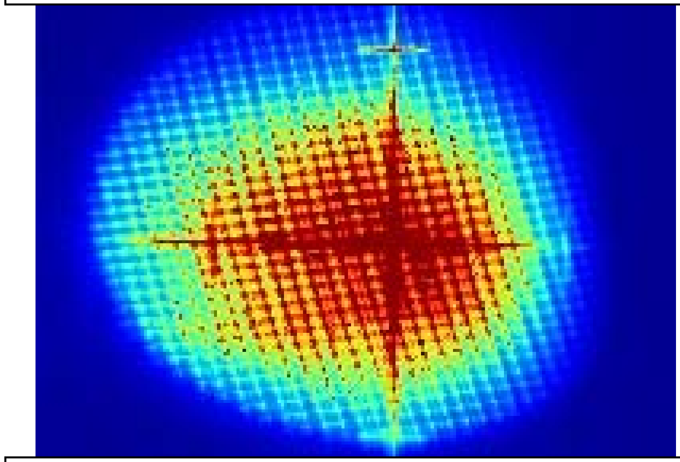
µm tolerance on alignment



Courtesy Bart Faatz (DESY)

FLASH: Basic Properties of the Radiation

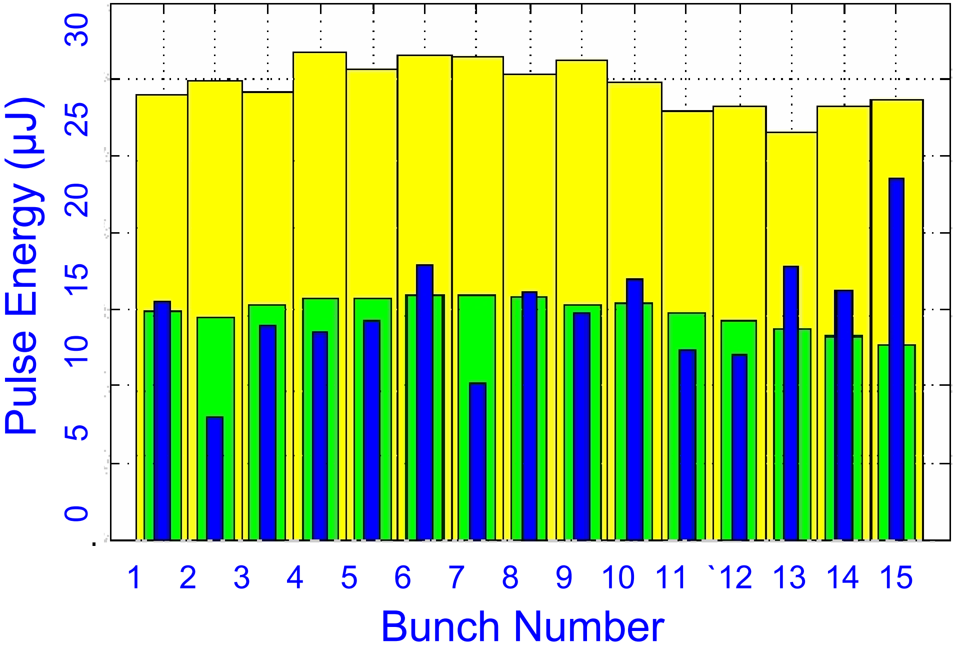
Wavelength	32 nm
Average energy per pulse	16 μJ
Maximum energy per pulse	40 μJ
Radiation pulse duration	25 fs
Peak power (from average)	0.6 GW
Spectral width (FWHM)	0.8%
Angular divergence (FWHM)	160 μrad
Peak Brilliance	~ 10^{28} ph/s/mrad^2/mm^2/(0.1%bw)



3 mm spot size (FWHM) @ 18.5 m distance
angular divergence 160 μrad
→ high degree of coherence
A gold mesh (0.25 mm pitch) in front of the Ce:YAG screen is used as intensity monitor.

Multibunch SASE signal (μJ) recorded with MCP Detector

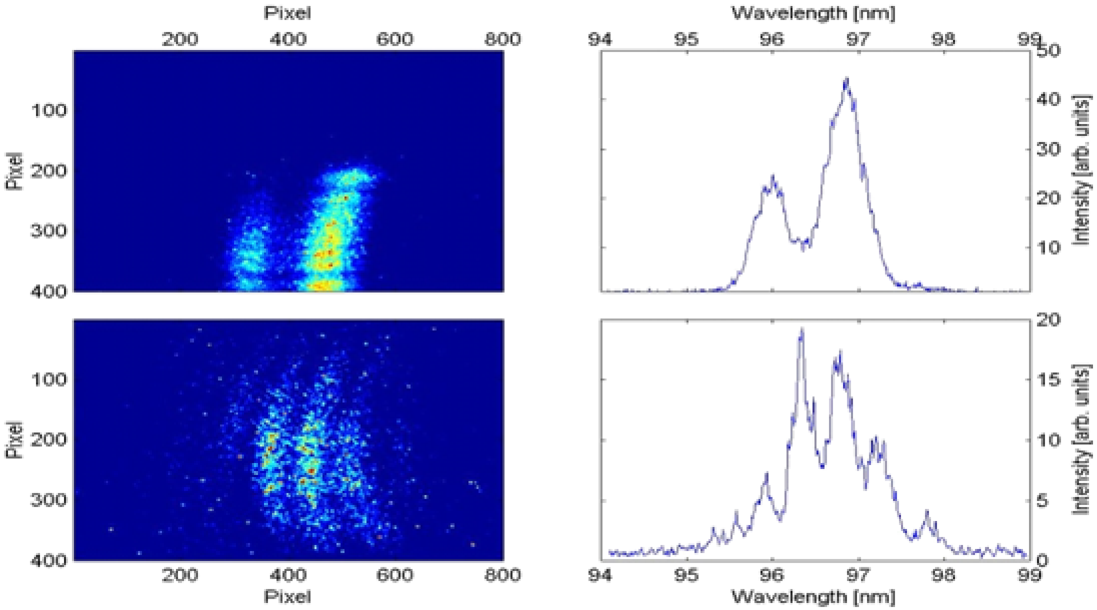
🟨 max
🟩 average
🟦 single

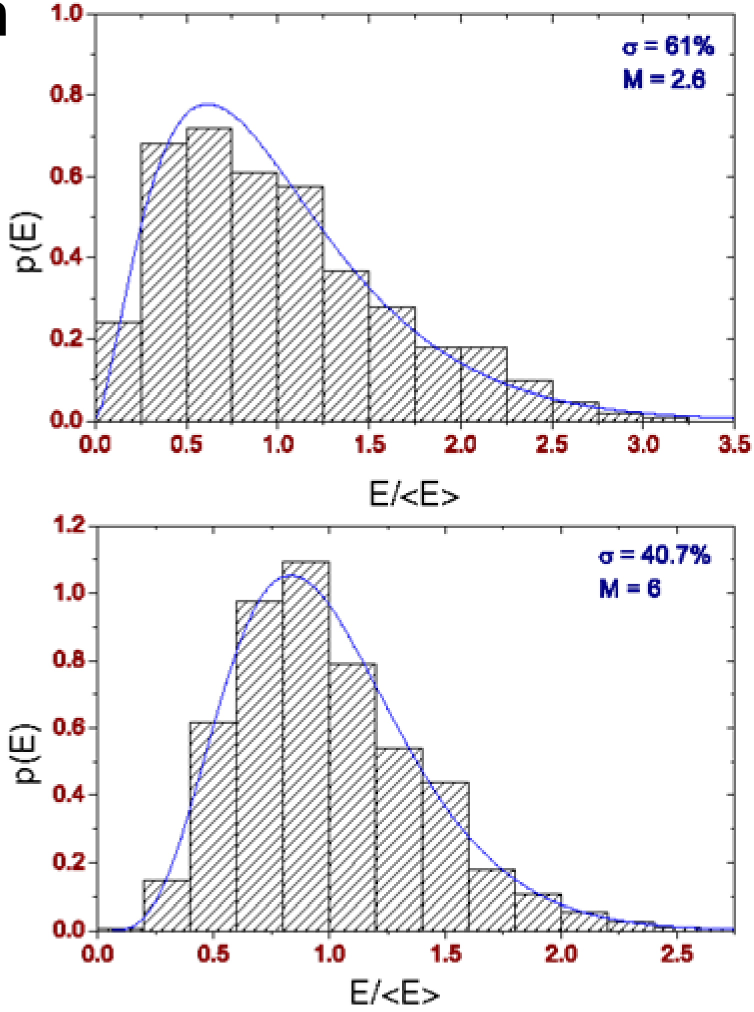


Courtesy Bart Faatz (DESY)

TTF-1: Tuning of the pulse-length

Modes:
M ≅ 2 - 3



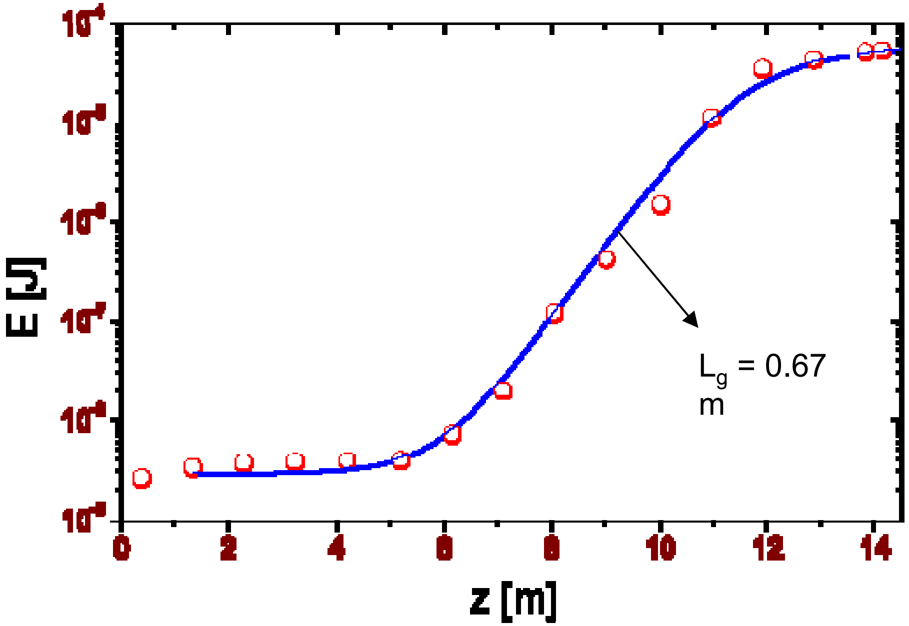


Modes:
M ≅ 7 - 10

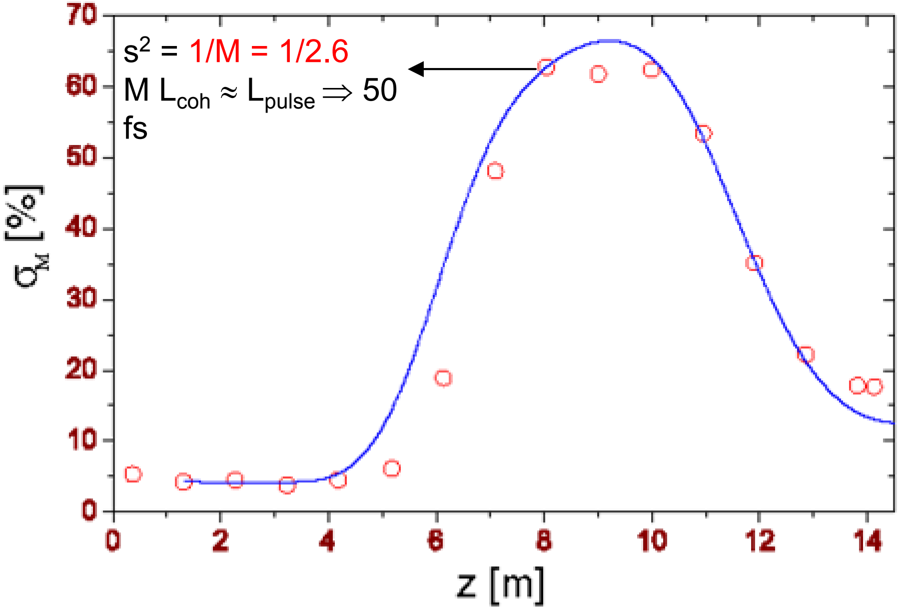
Left figures – spectral measurement. Right figures – probability distributions of the radiation energy in the linear regime. Solid curves represent gamma distribution.

TTF-1: Observed Results (λ = 96.5 nm)

Energy of the m-pulse along the undulator

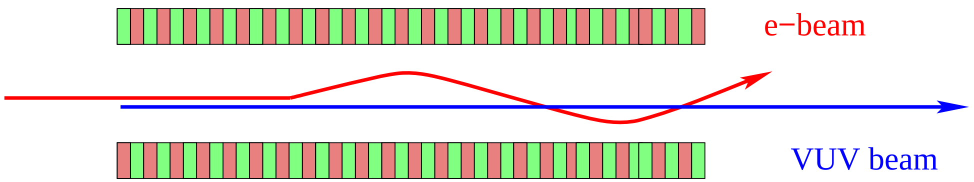


Energy fluctuation along the undulator



Average energy in the radiation pulse versus undulator length

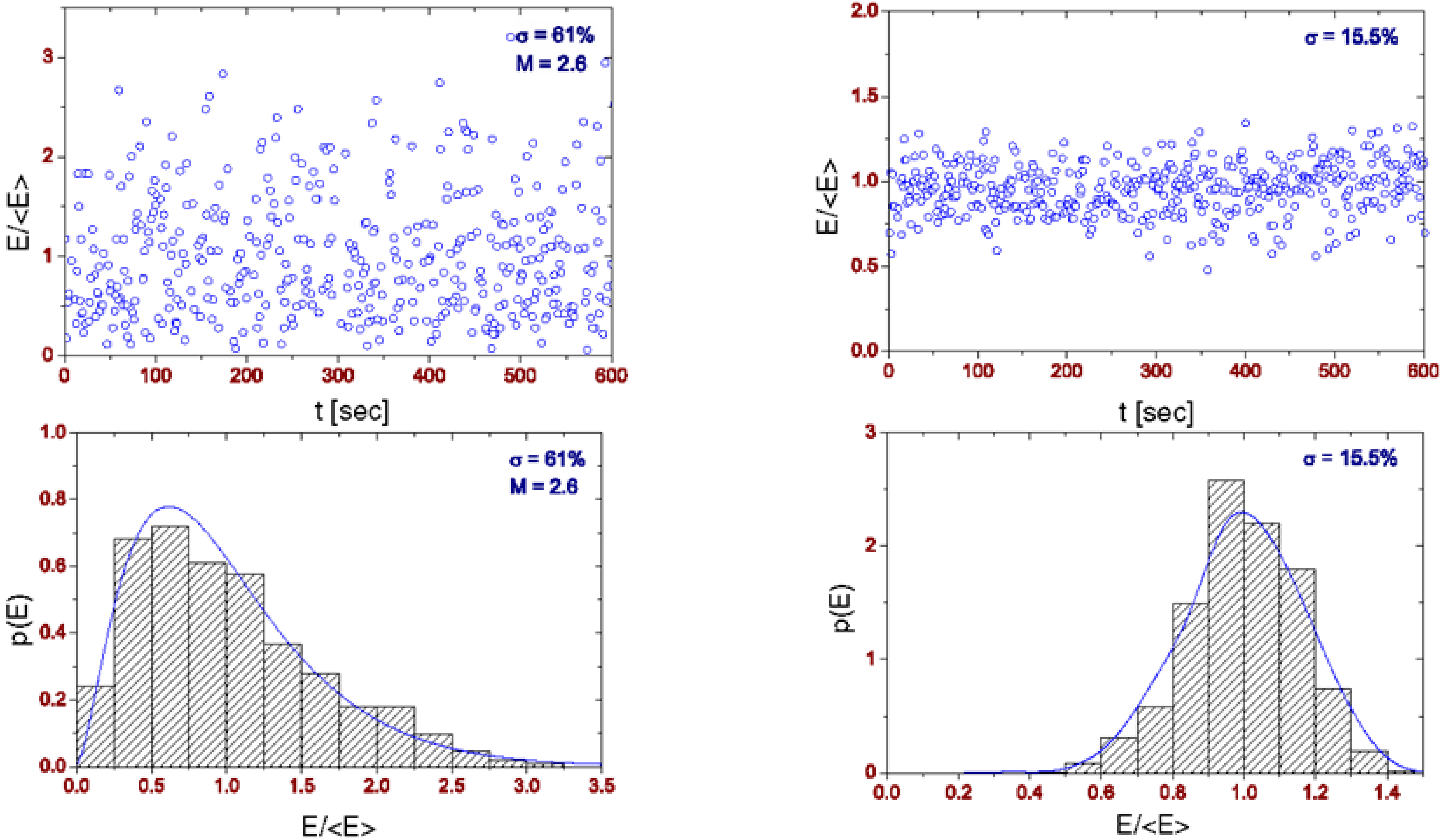
Fluctuations of energy in the radiation pulse versus undulator length



Correctors in the undulator were used to control the length of the interaction between electron beam and radiation

Courtesy Bart Faatz (DESY)

TTF-1: Experiment vs. Simulation

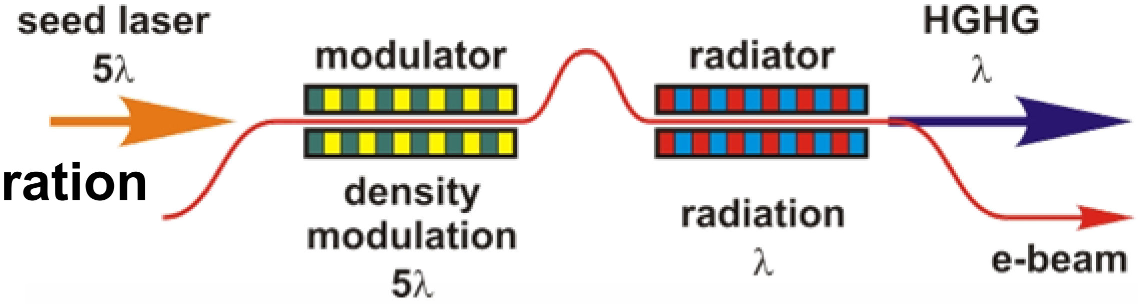


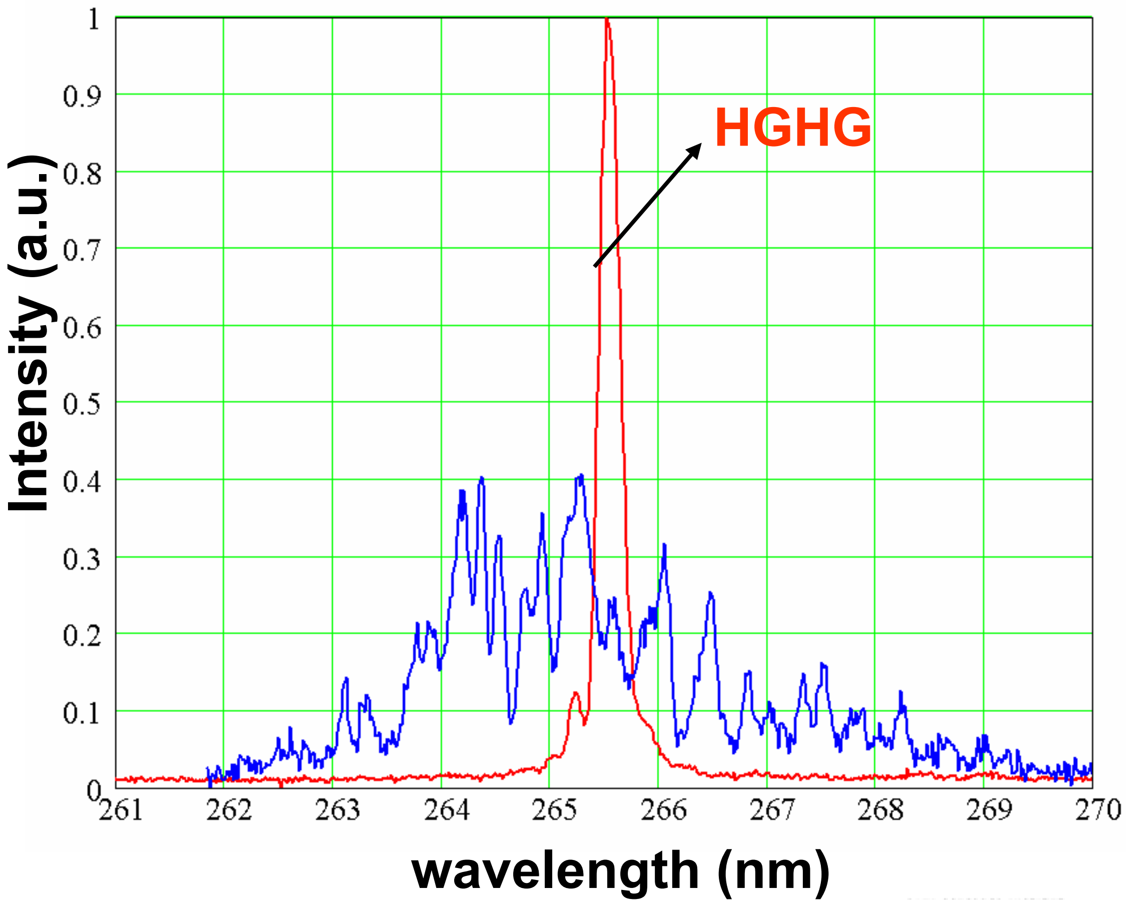
Signal from the radiation detector (top figures) and corresponding probability distributions (bottom figures) for linear (left) and saturation (right) regime. Solid curves represent simulation results with code FAST.

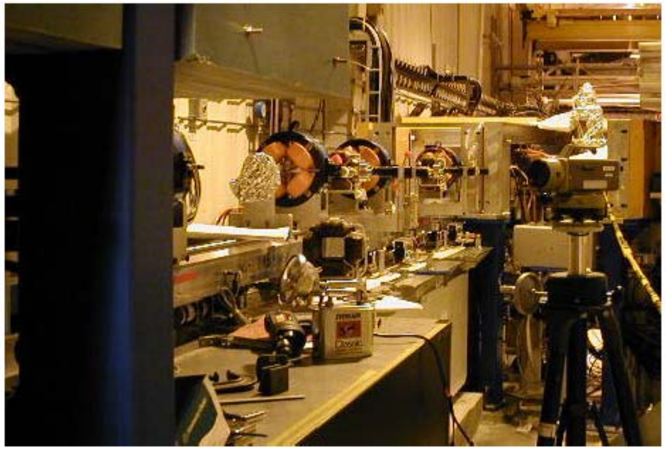
Courtesy Li Hua Yu (BNL)

Seeding: HGHG

High Gain Harmonics Generation



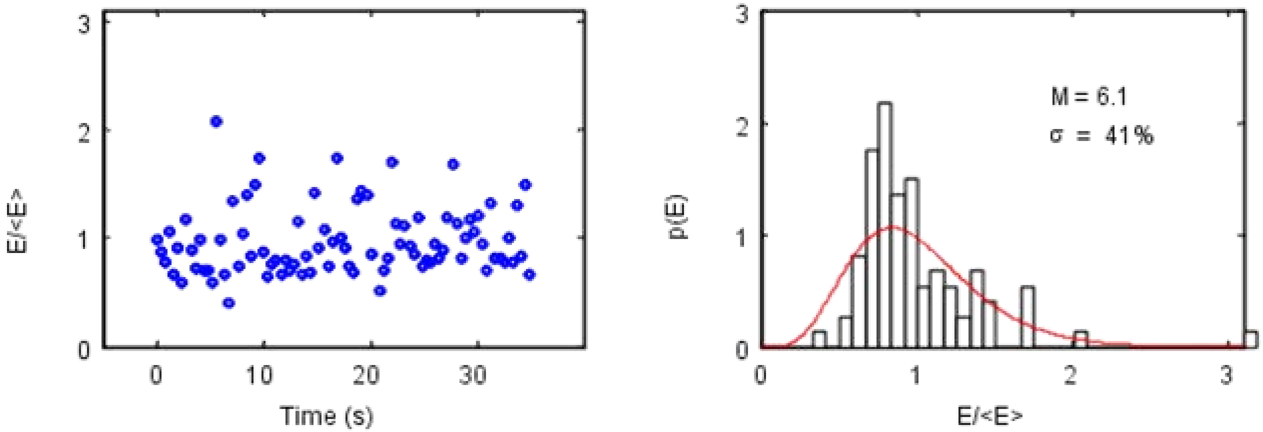




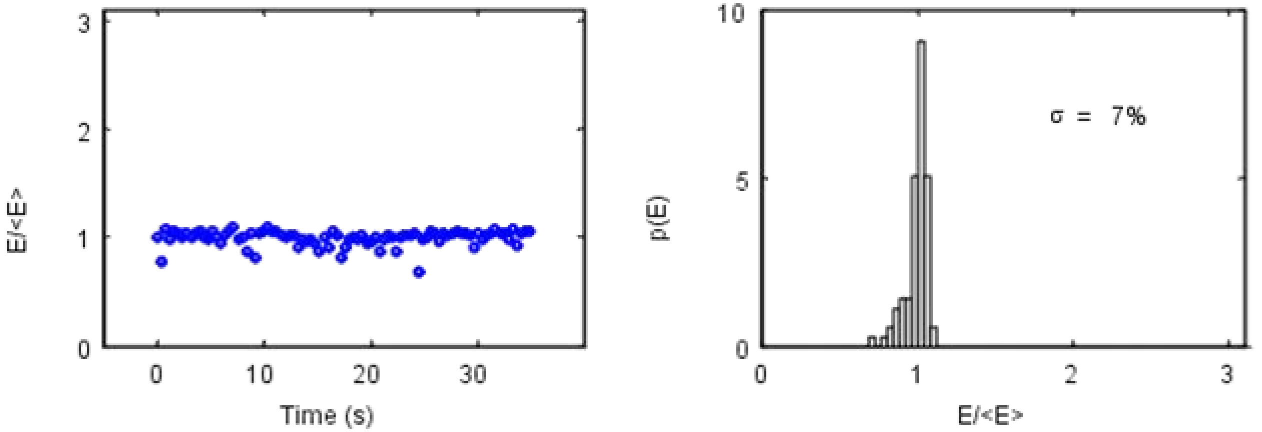
Shot to Shot Intensity Fluctuation

Shows High Stability of HGHG output

SASE



HGHG

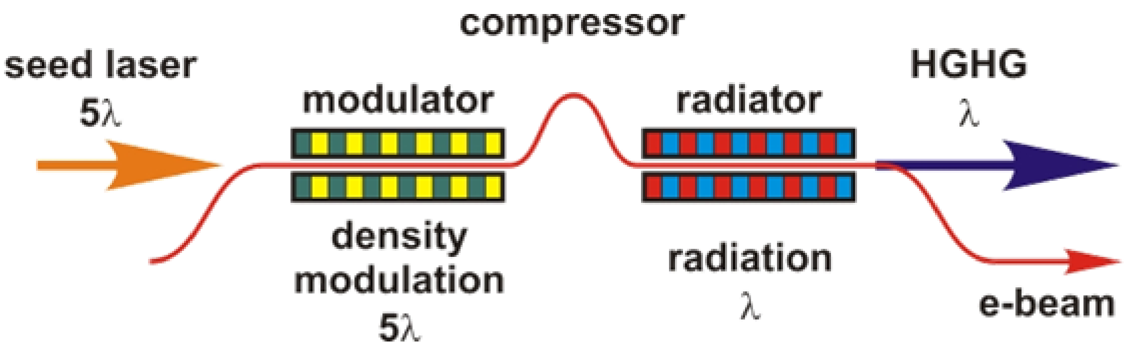


Courtesy Li Hua Yu (BNL)

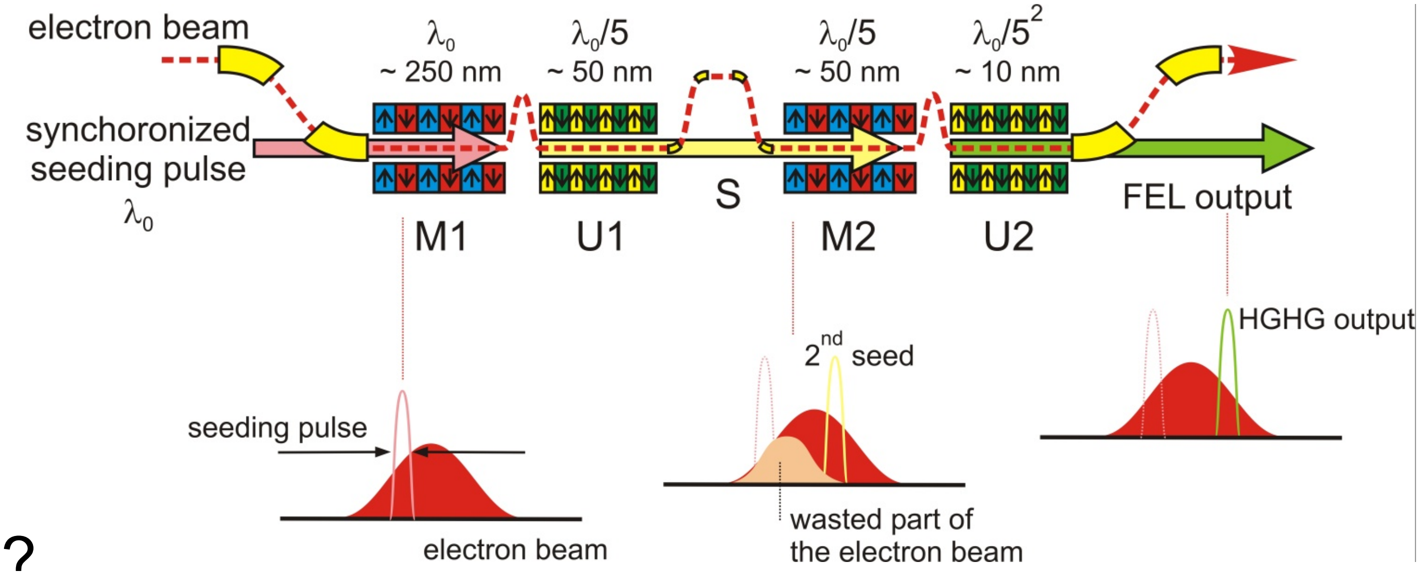
Seeding

High Gain Harmonics Generation
(HGHG)

UV:



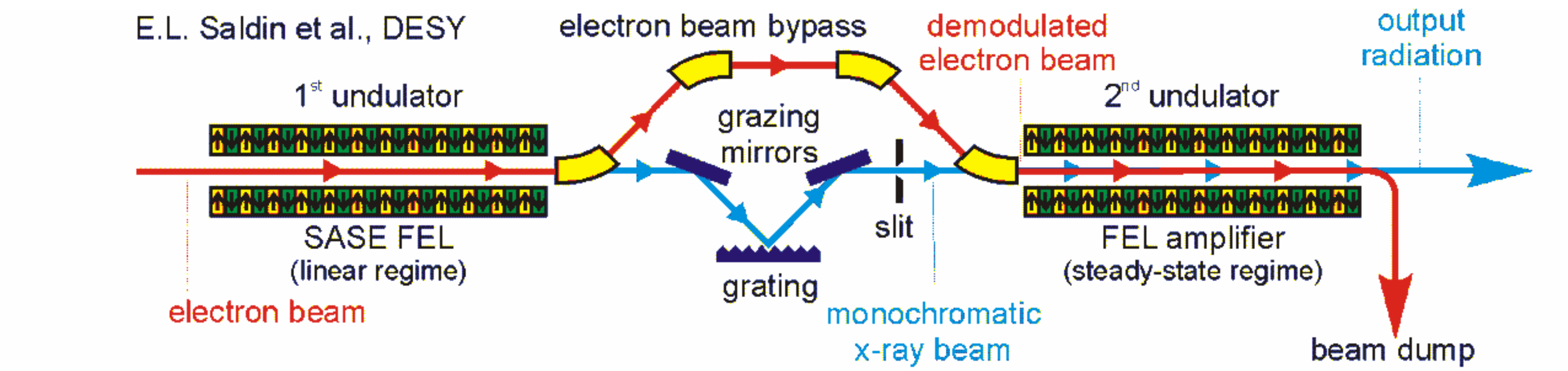
VUV:

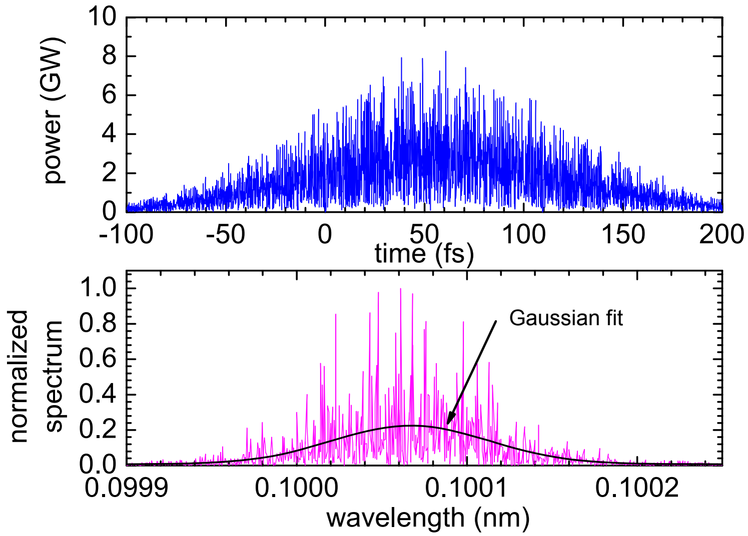


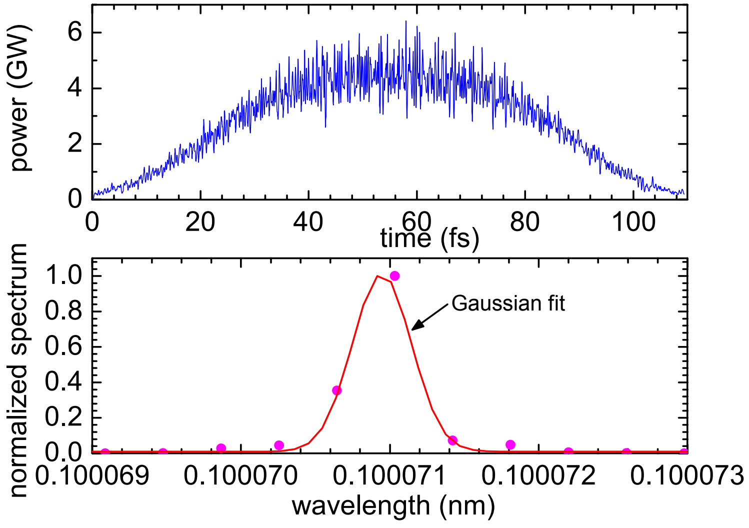
(Soft) X-Ray ?

2-Stage Seeding

(demo for X-FEL)







Single-Pass FELs

- Principle demonstrated in several experiments
  - UCLA
  - BNL
  - APS
  - DESY / TTF
- First user-experiments successful
- Still long way to go for stable synchrotron-alike operation