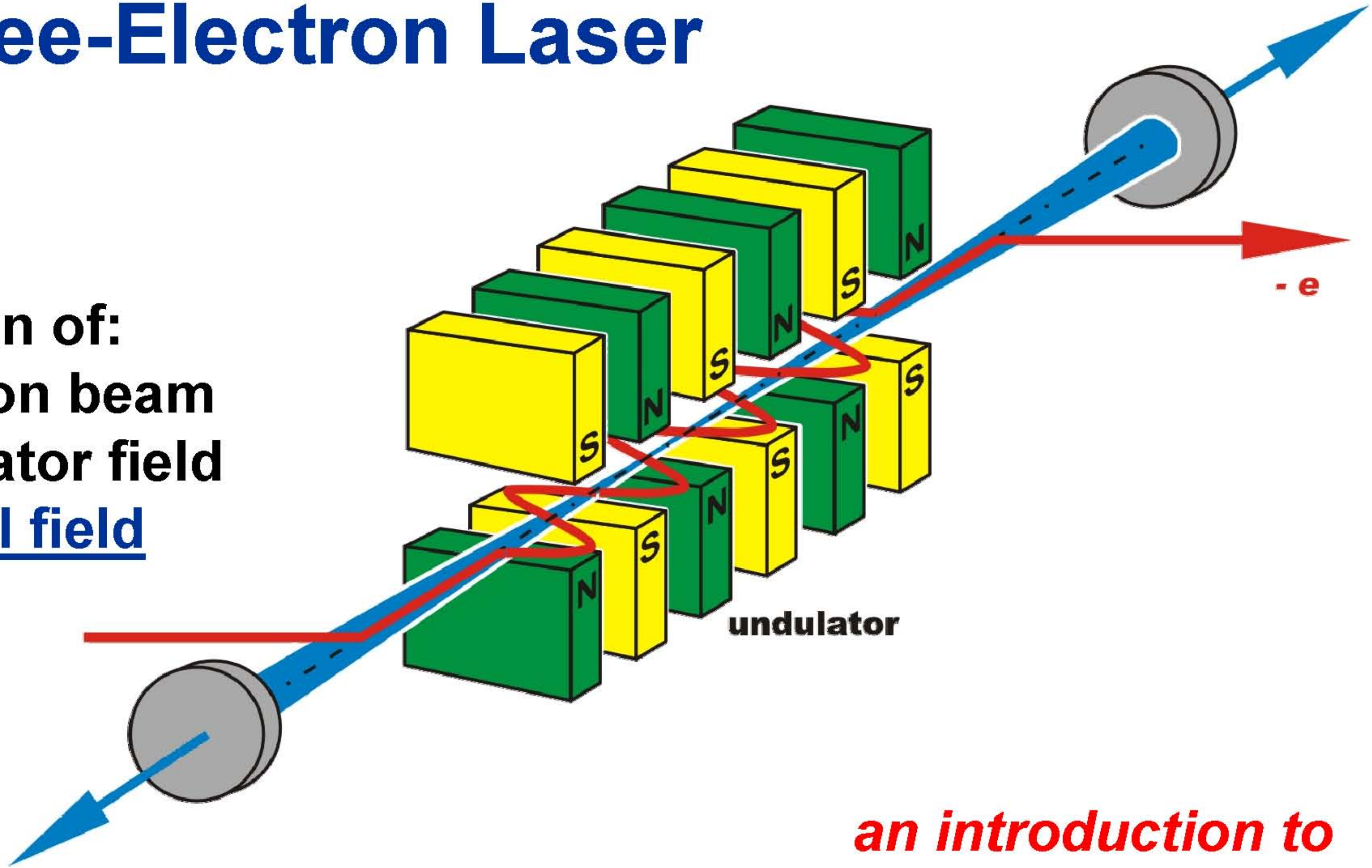
The Free-Electron Laser (FEL)

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



an introduction to

function and technique

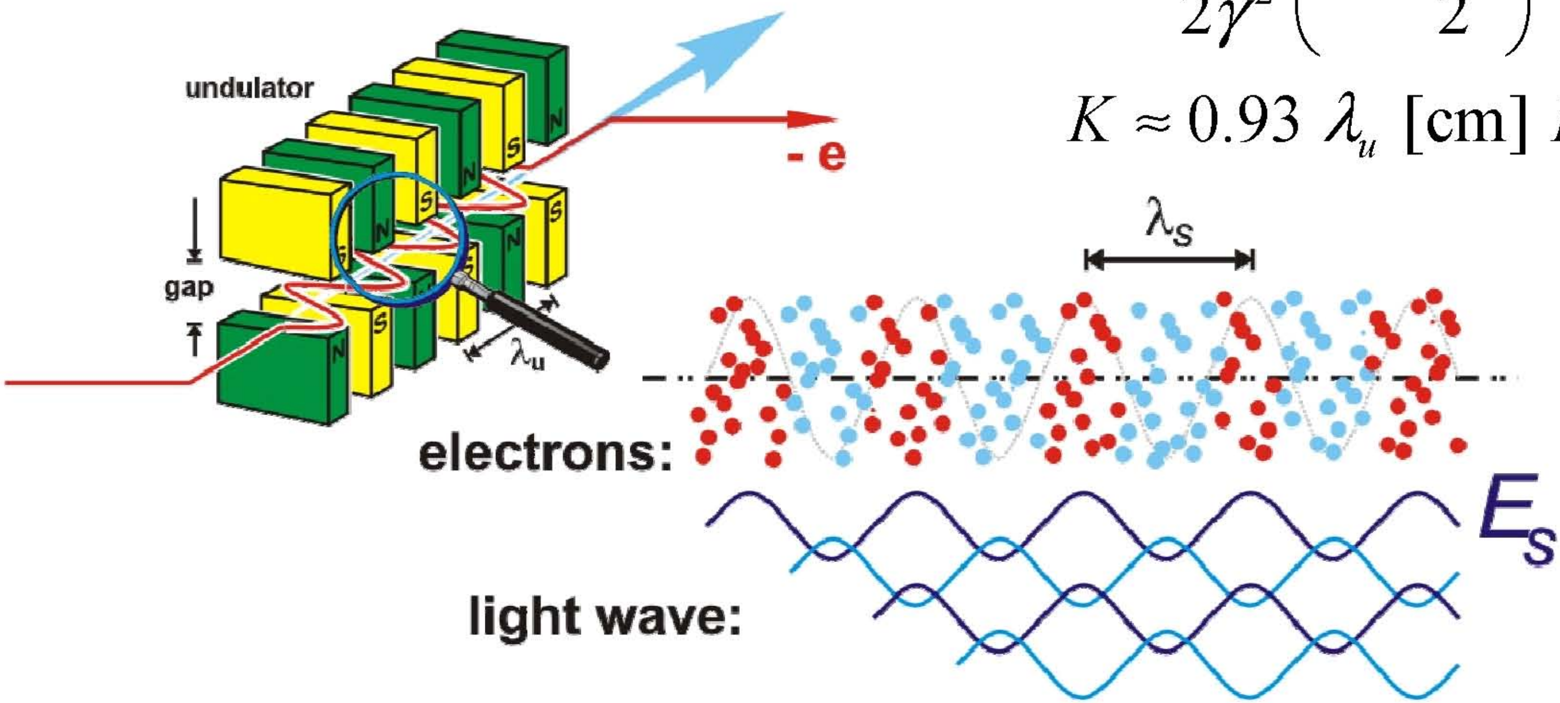
Outline

- Synchrotron radiation, lasers and FELs
- How does it work?
- Examples

Synchrotron Radiation

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

$$K \approx 0.93\ \lambda_u\ [\mathrm{cm}]\ B_u\ [\mathrm{T}]$$



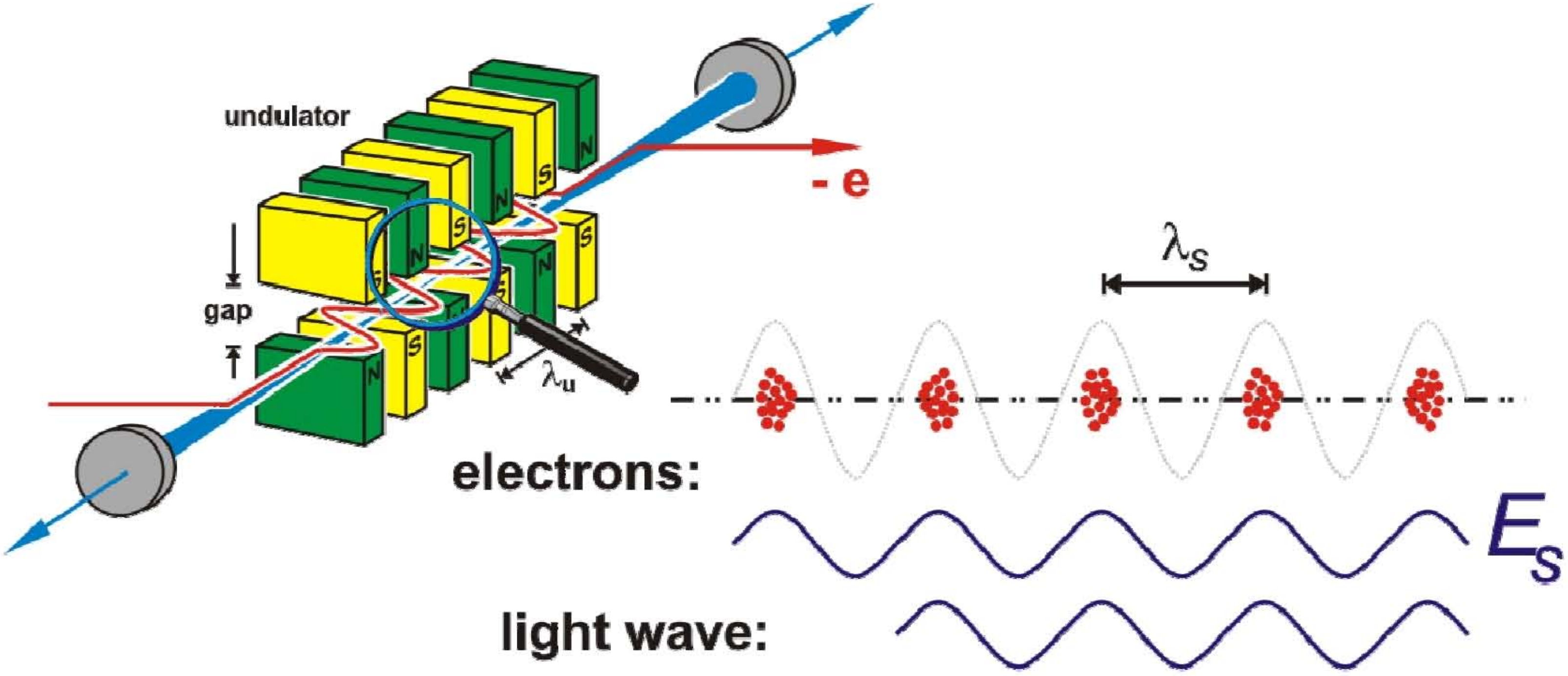
Radiated Power:

$P \propto n_e$ (number of electrons)

destructive interference

⟶ **shotnoise radiation**

FEL interaction



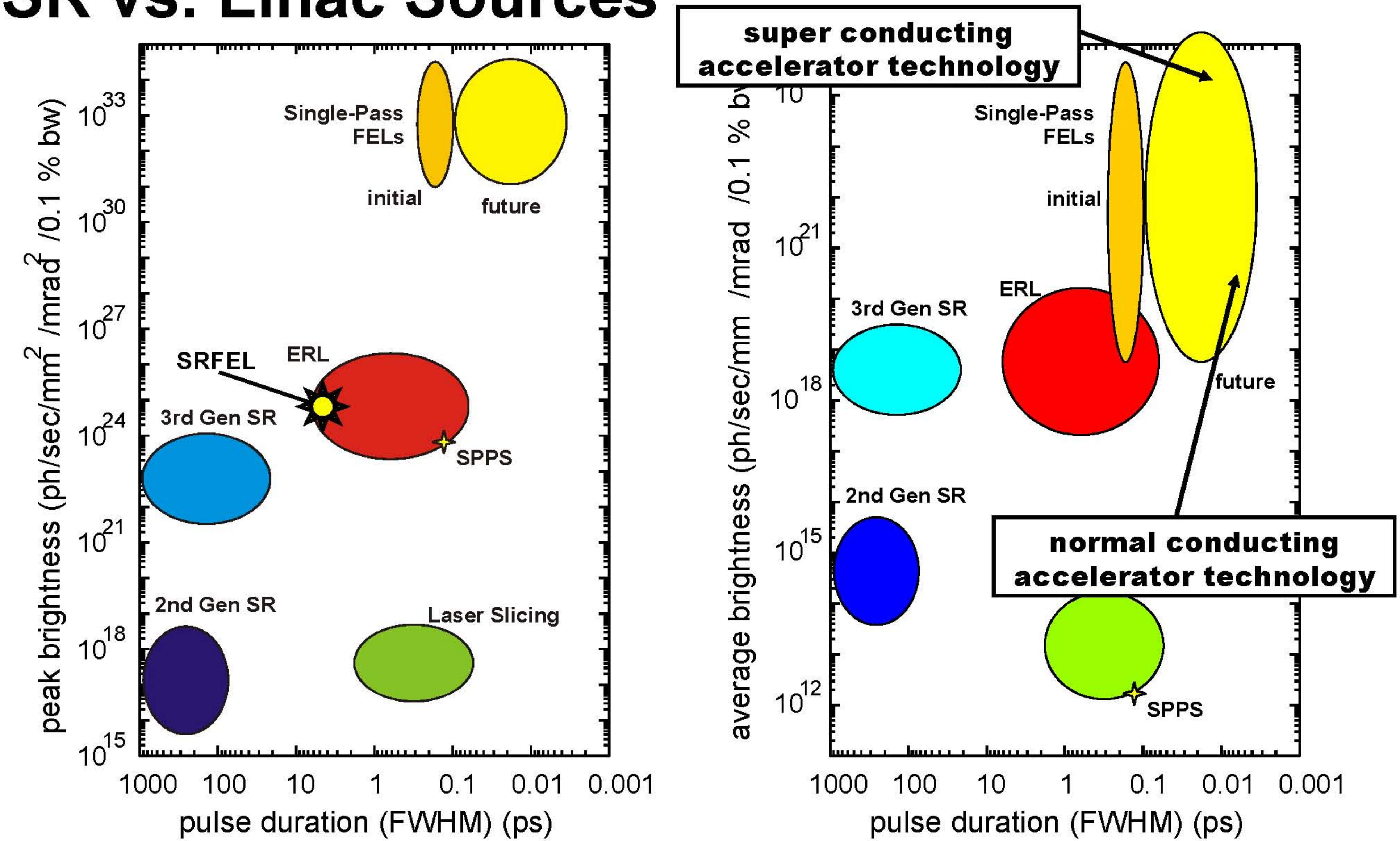
Radiated Power :

$$P \propto n_e^2 \begin{pmatrix} \text{number of electrons} \\ n_e \sim 10^6 - 10^9 \end{pmatrix}$$

constructive interference

⟶ **enhanced emission**

SR vs. Linac Sources

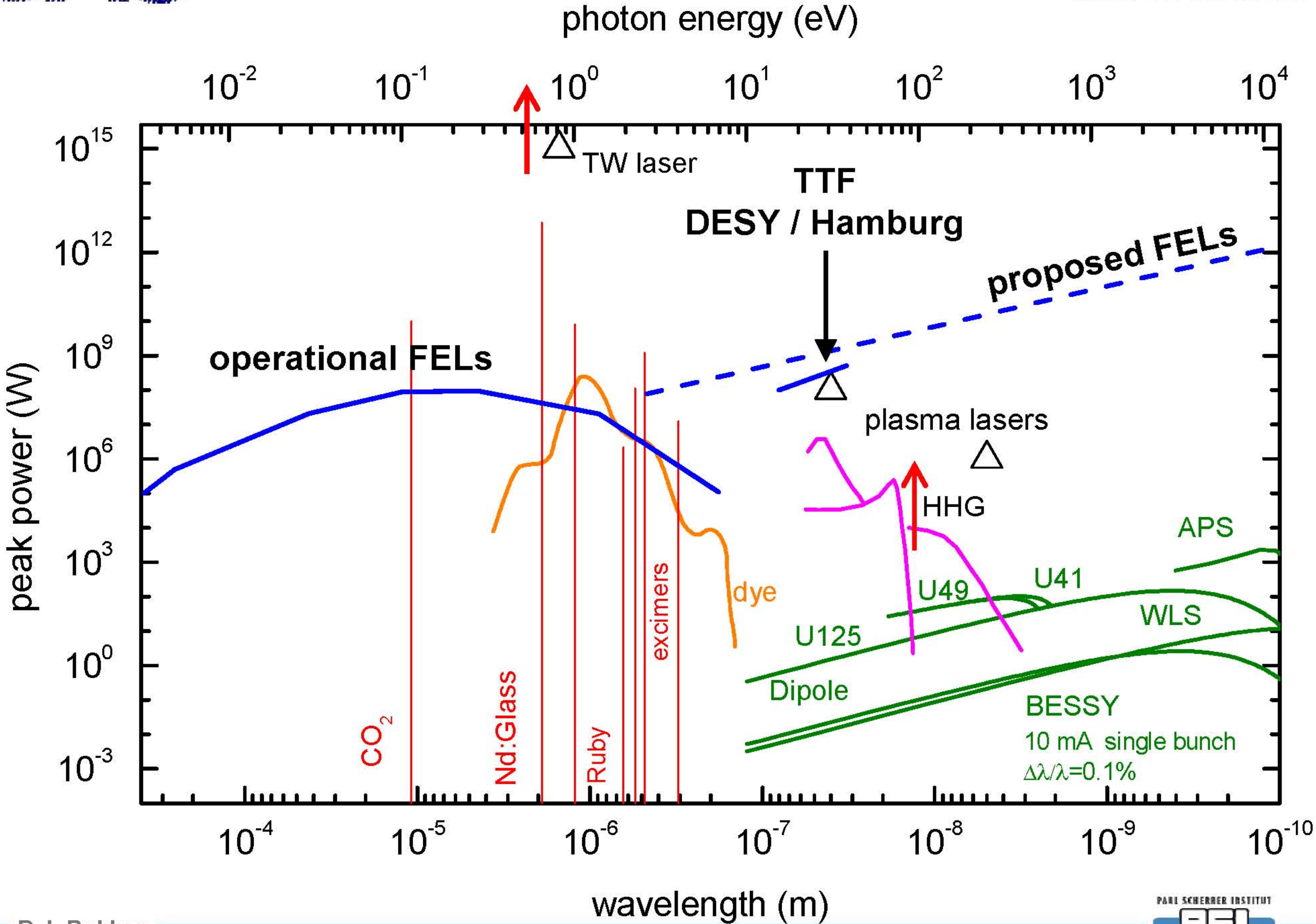


Advantages (synchrotron radiation)

- 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) $\rightarrow 10^{-8}$

Advantages (lasers)

- Works for any wavelength
  - mm-waves $\rightarrow$ 35 nm $\rightarrow$ 0.85 Å $\rightarrow$ 0.1 Å $\rightarrow$ ……?
- 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
TTF
DESY / Hamburg
proposed FELs
operational FELs
plasma lasers
HHG
APS
U41
U49
WLS
U125
dye
excimers
Dipole
BESSY
10 mA single bunch
Δλ/λ=0.1%
CO2
Nd:Glass
Ruby
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:

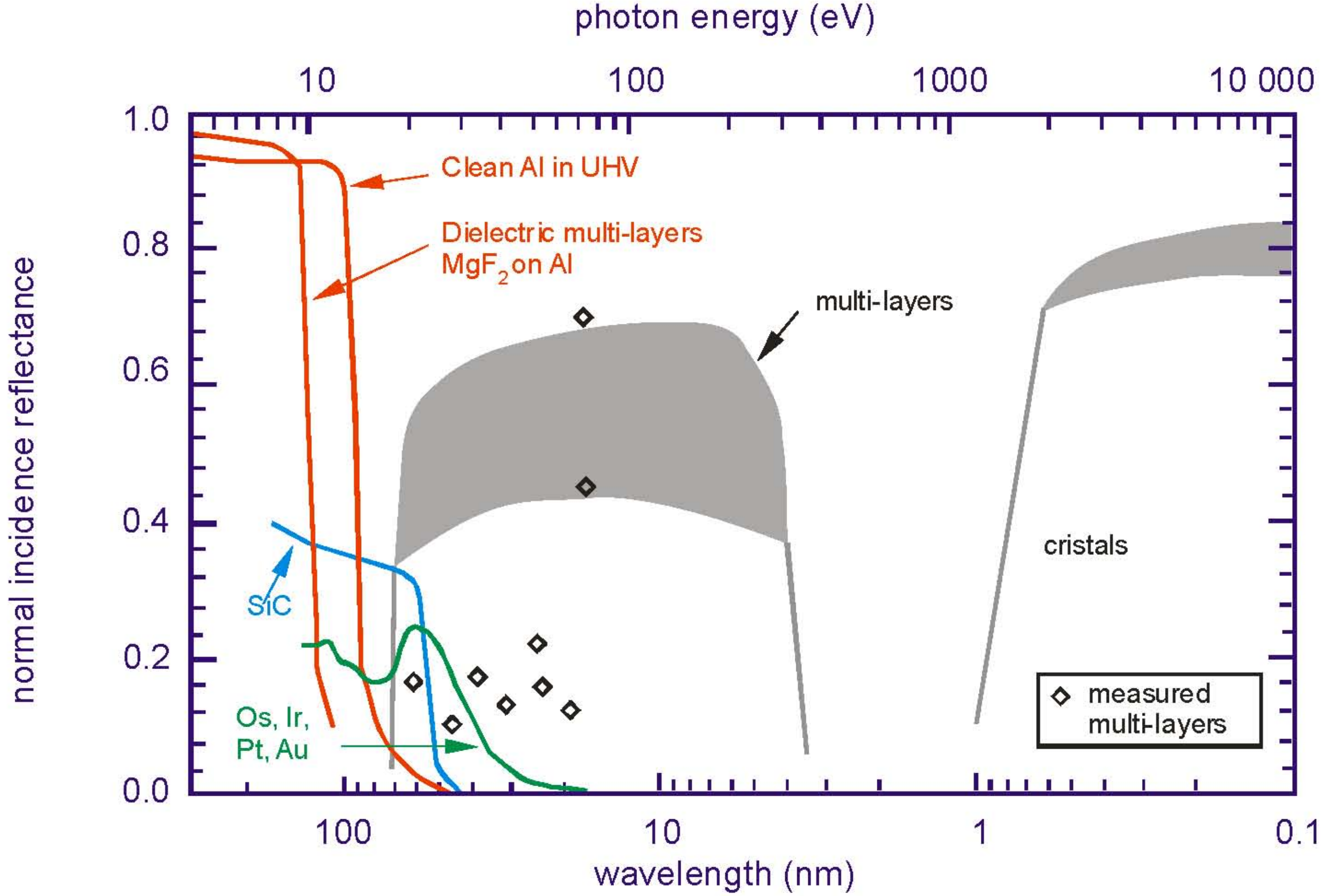
  non-demonstrated (below 35 nm)

N.B. Technological challenges increase towards shorter wavelengths!

Going to the VUV

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

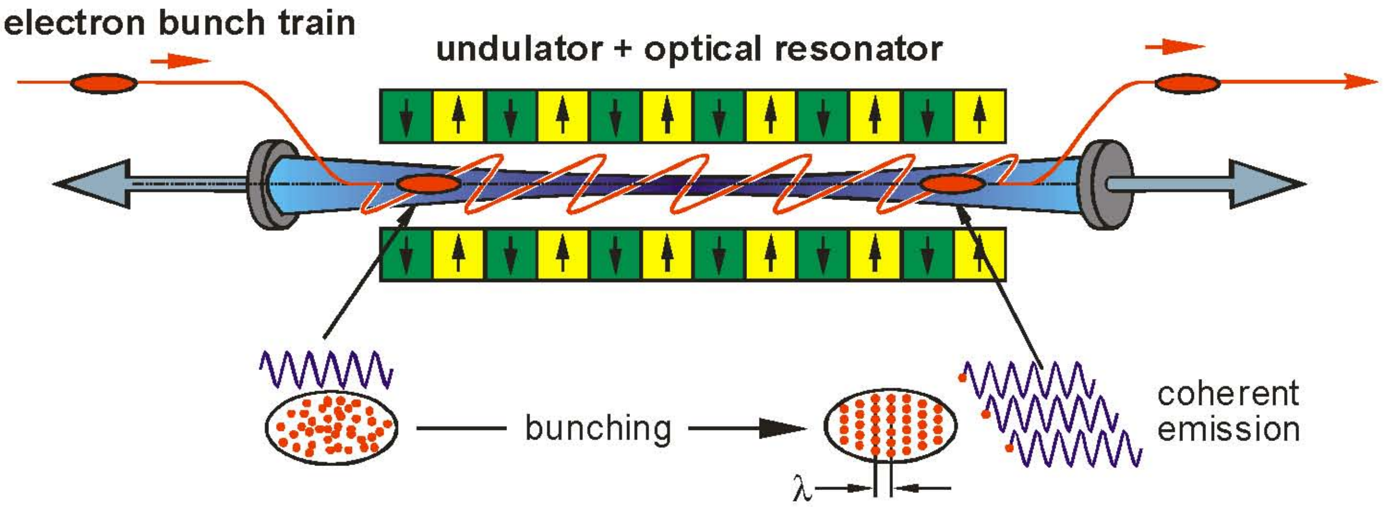
Developing a laser scheme that does not require optical elements.



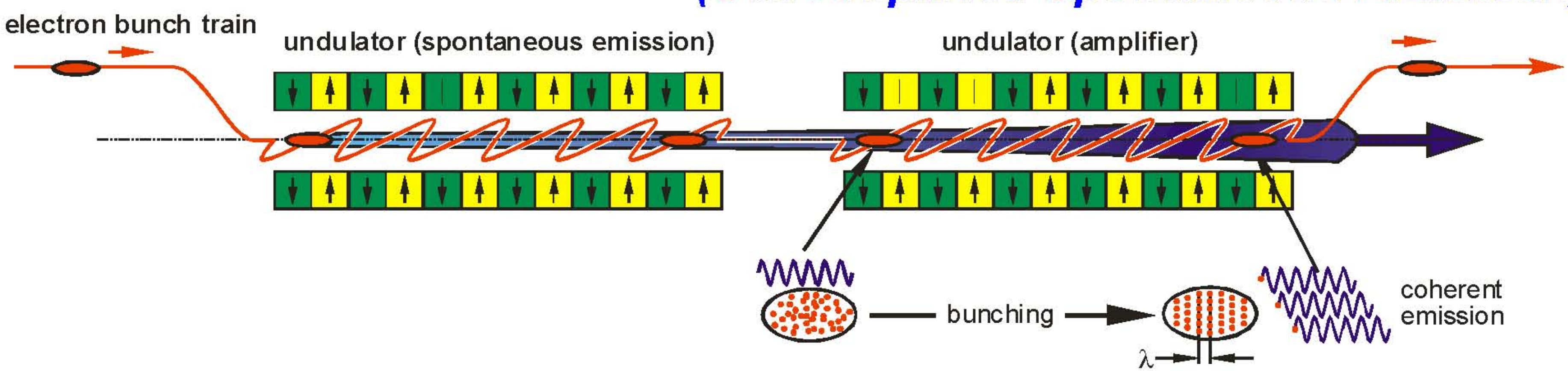
D.T. Attwood et al,
AIP Conf. Proc. 118, eds J.M.J. Madey and C. Pellegrini (AIP, New York, 1983), p. 93

FEL → SASE FEL

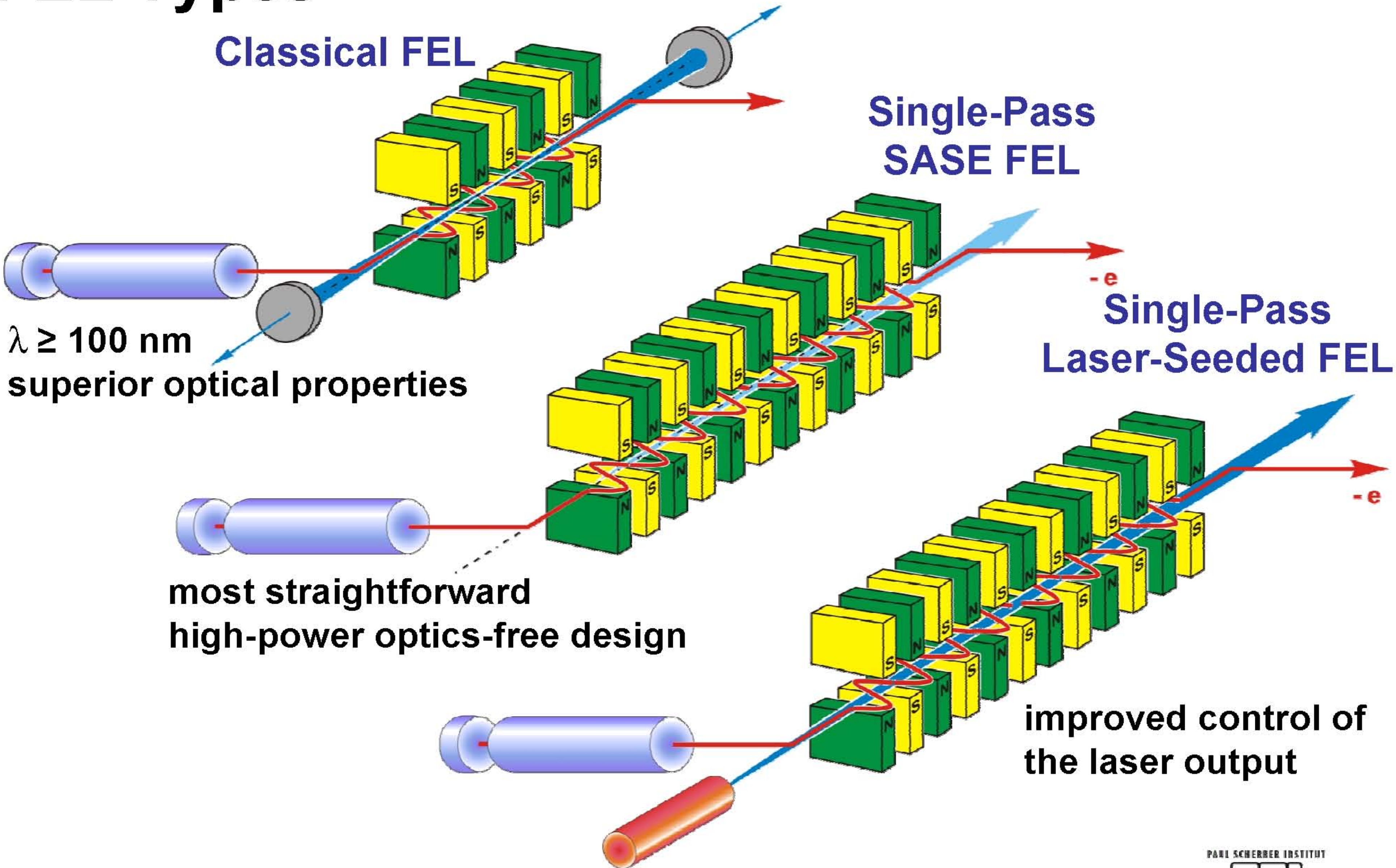
Classical FEL Scheme



SASE FEL Scheme
(Self Amplified Spontaneous Emission)



FEL Types

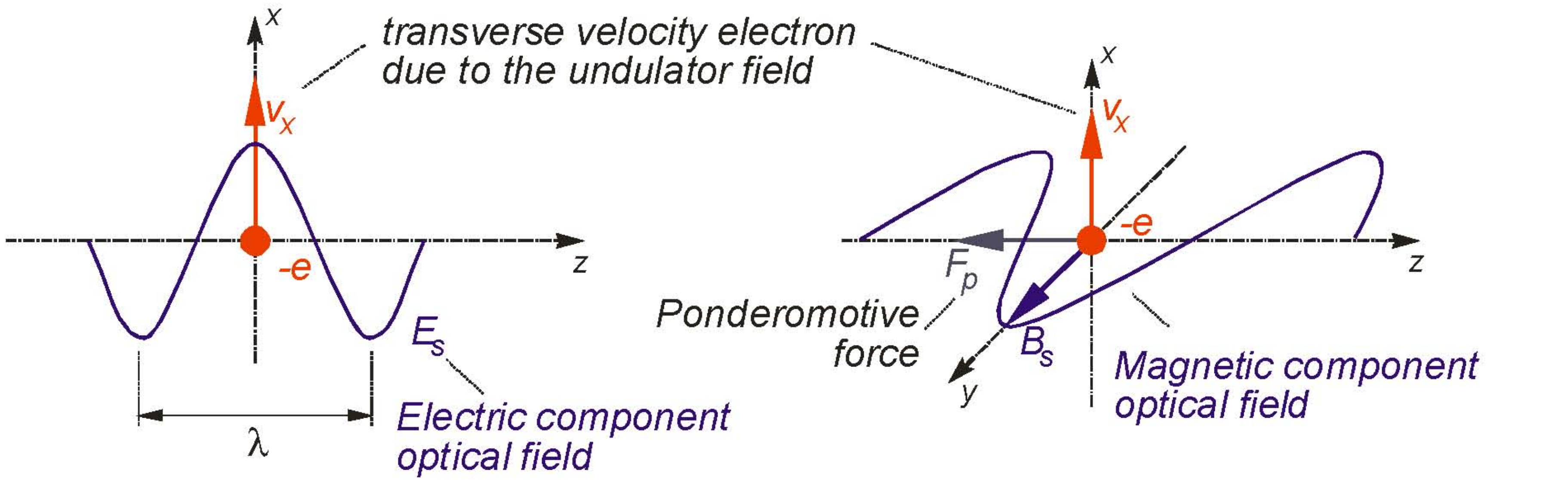


$\lambda \geq 100$ nm
superior optical properties

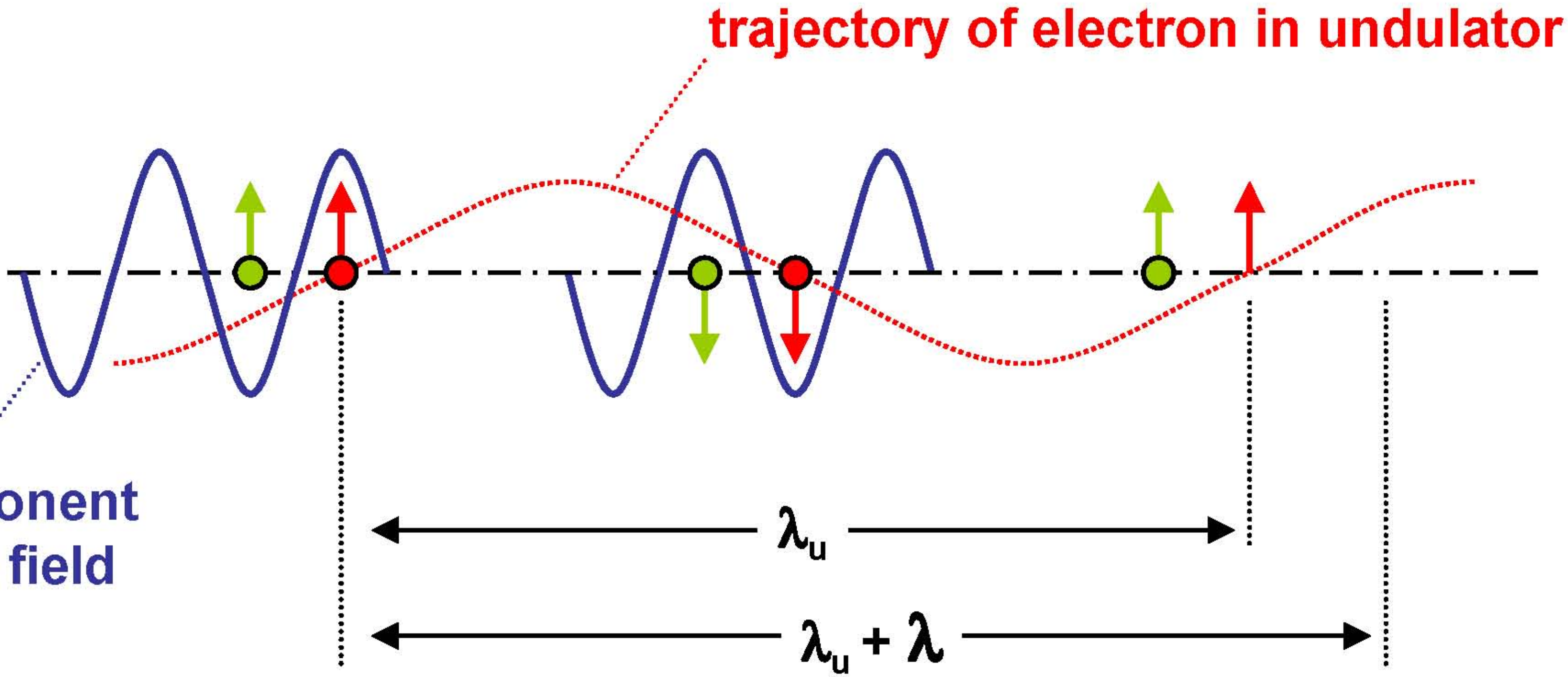
most straightforward
high-power optics-free design

improved control of
the laser output

Interaction between an electron and the optical field

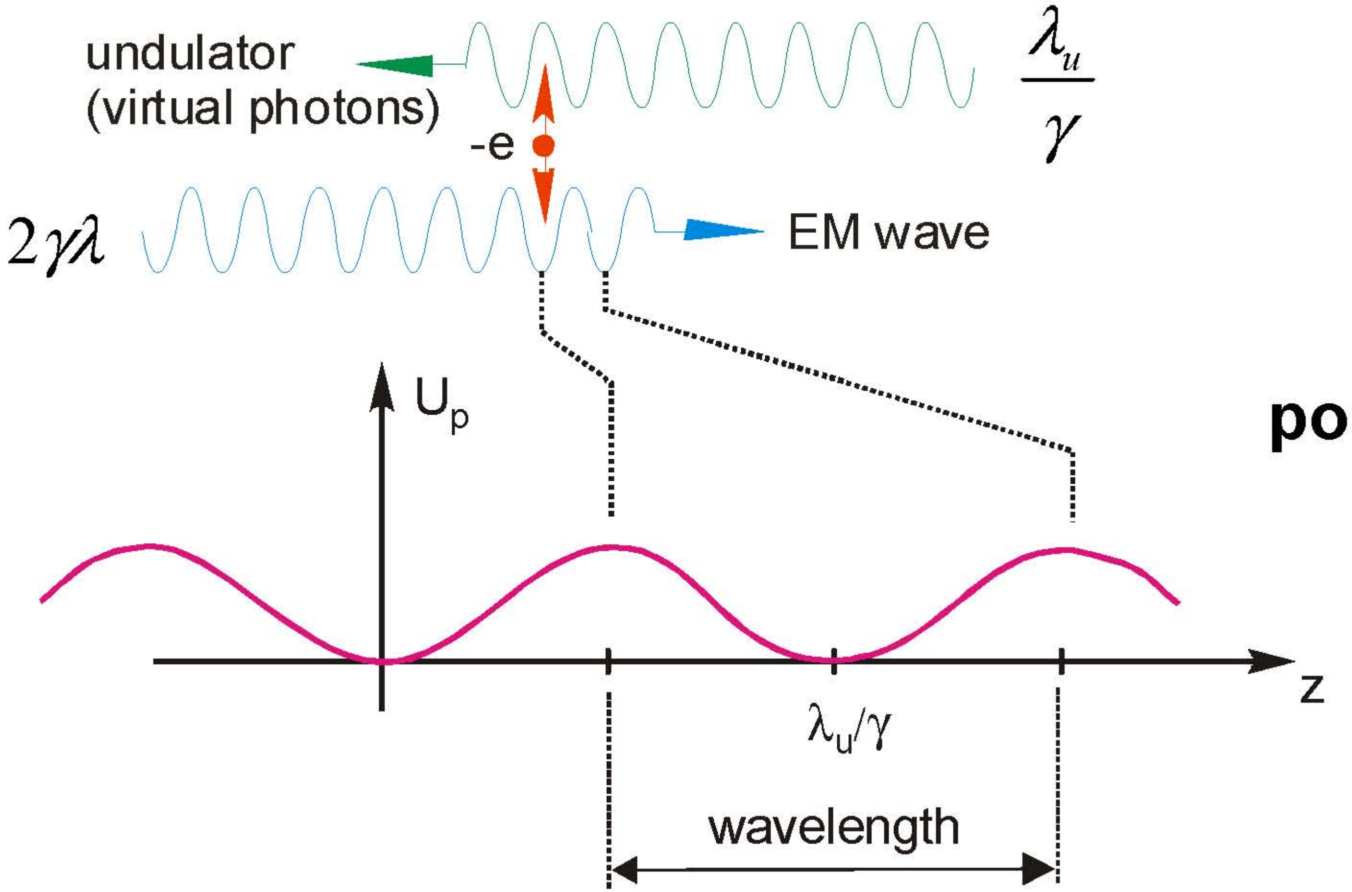


Resonance Condition



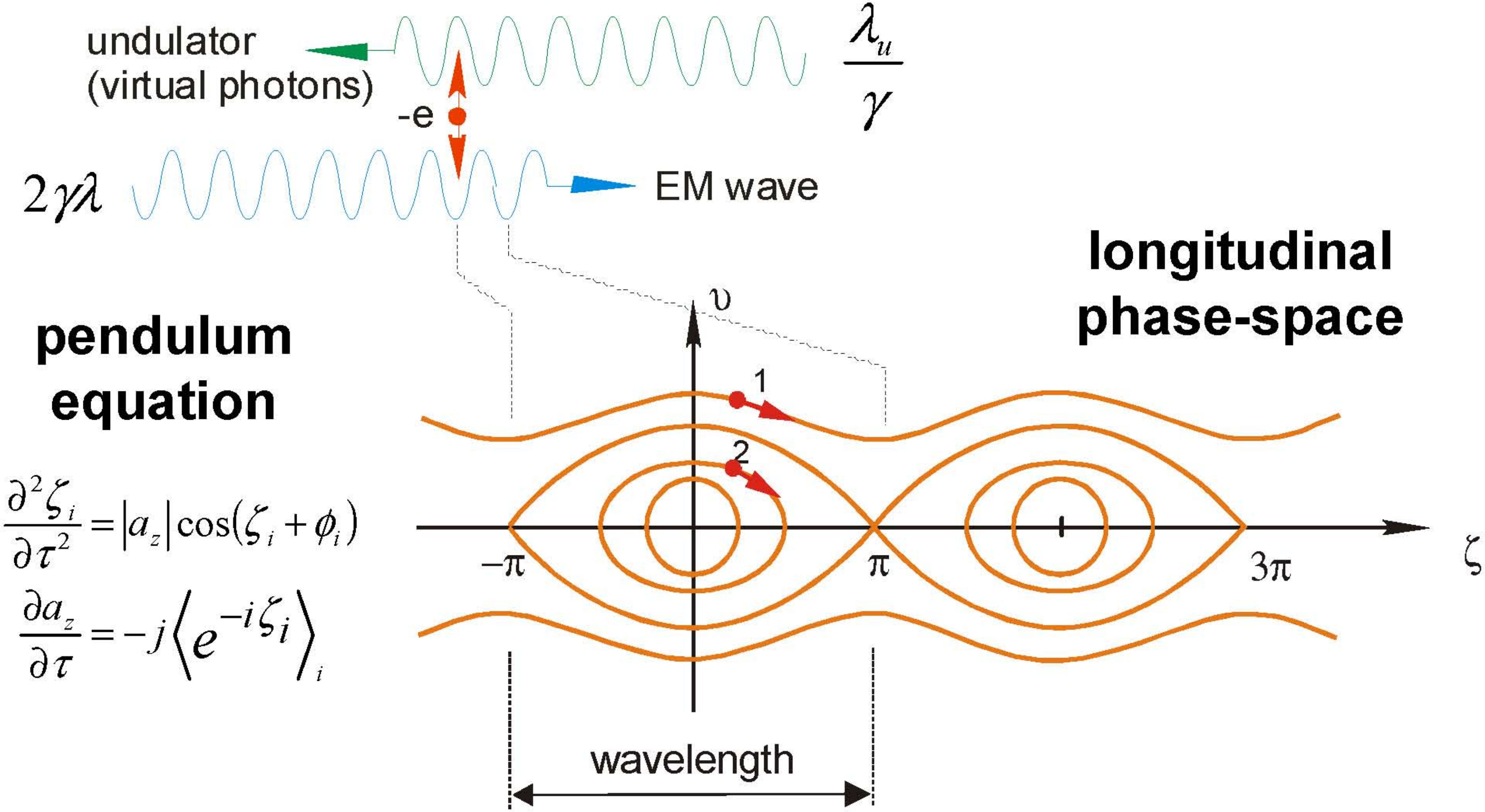
$$\frac{\lambda_u + \lambda}{c} = \frac{\lambda_u}{v_z} \quad \Leftrightarrow \quad \lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

Electron Dynamics



ponderomotive potential

Electron Dynamics



longitudinal phase-space

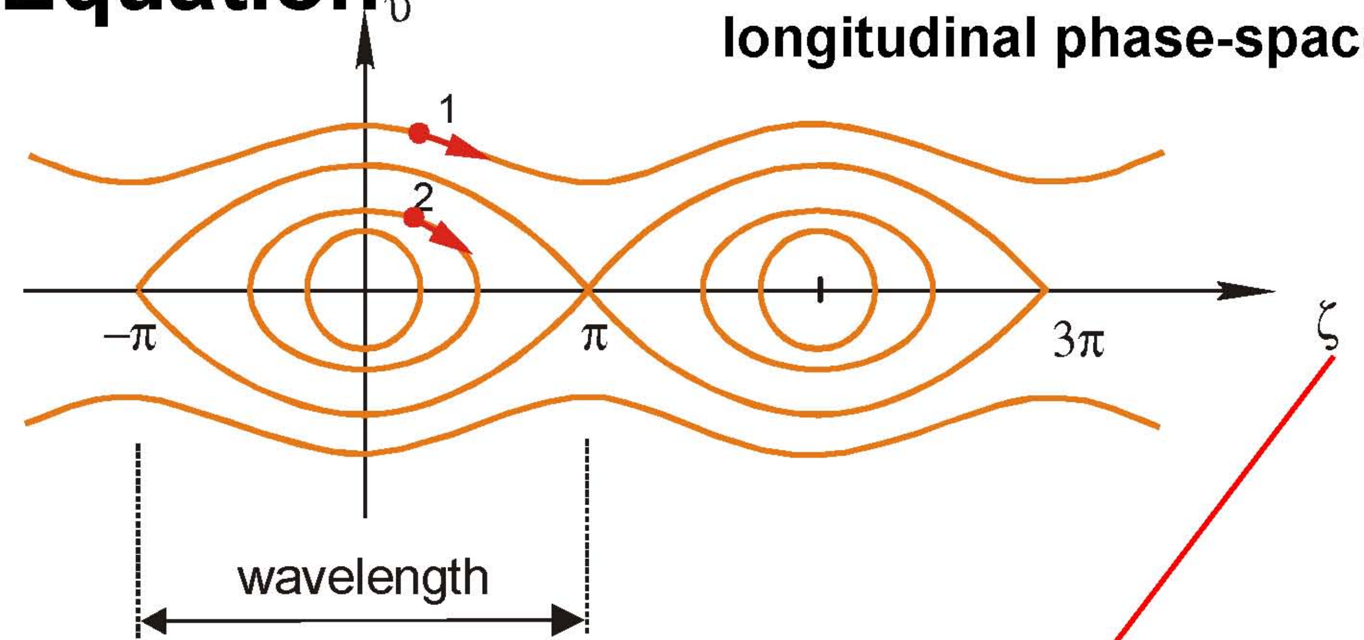
pendulum equation

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

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

Pendulum Equation

longitudinal phase-space



Pendulum

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

FEL

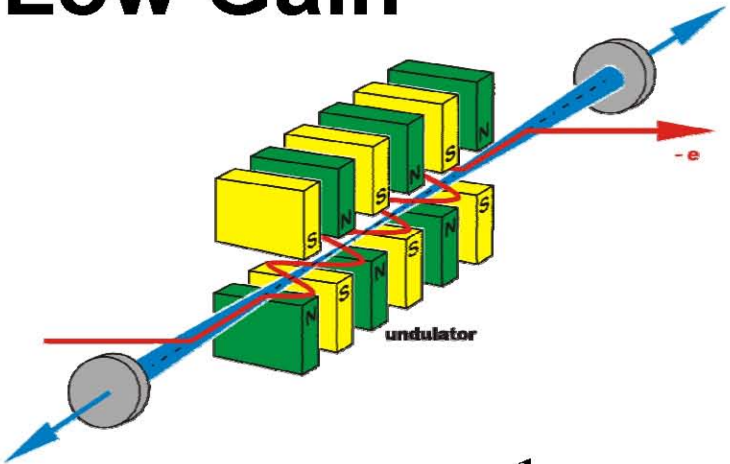
$$\omega_s \propto \sqrt{|a|}$$

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

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

- time: τ
- position of electron *i*: ζ_i
- initial position of electron *i*: ϕ_i
- optical field-strength: a_z
- current-density: j
- average over all electrons: $\langle \ \rangle_i$

Low Gain



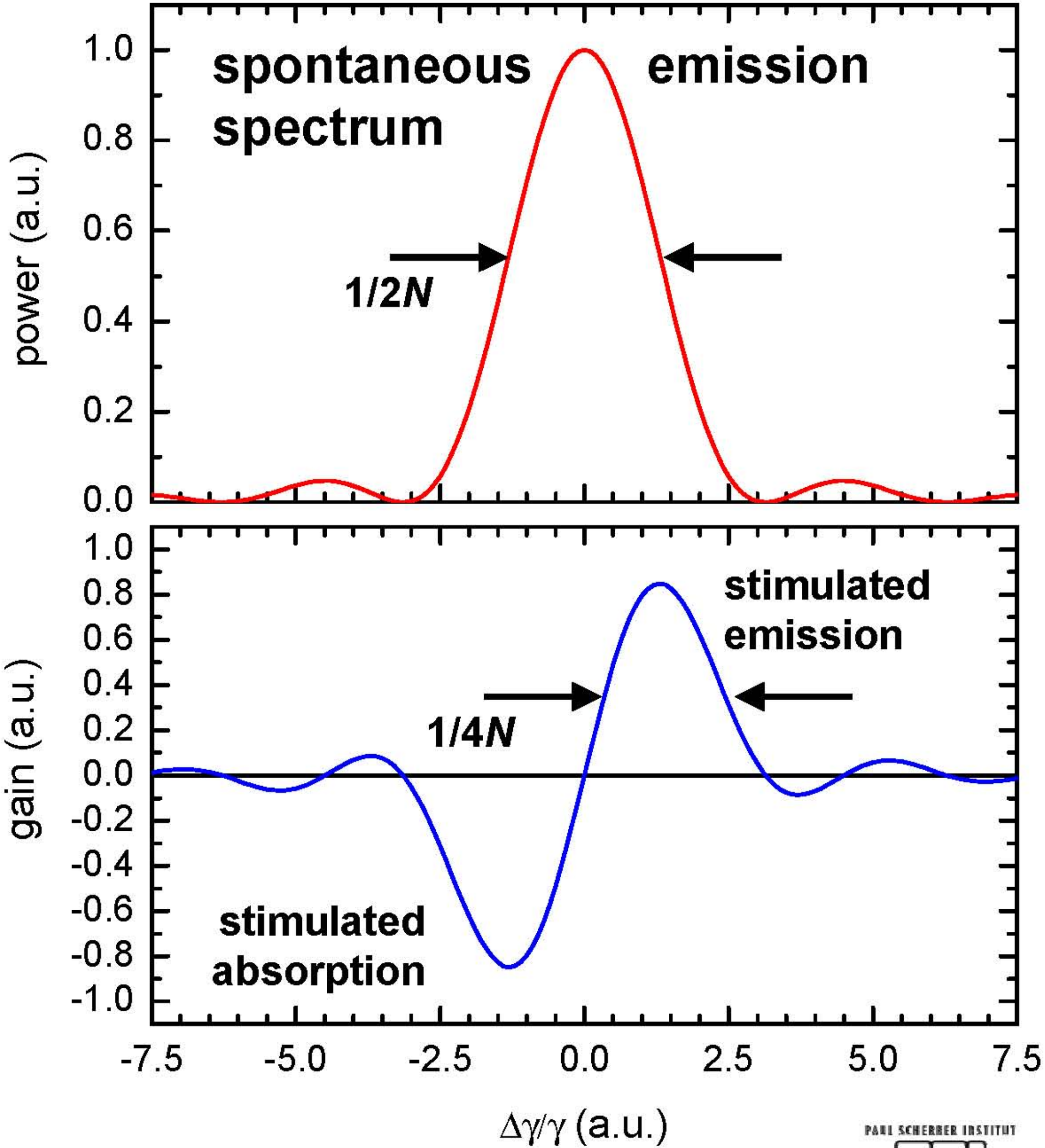
$$G \propto N^2 I \frac{1}{\gamma}$$

$$G \approx 4.4 \cdot 10^{-3}\, N^2 I \frac{\xi}{\gamma} f(\xi)$$

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

planar undulator !

$$\xi = \frac{1}{4} \frac{K^2}{1 + \frac{K^2}{2}}$$



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

Requirements

1. Sufficient beam energy:

$\lambda = 100\mu m \rightarrow$ ~ 15 MeV
$\lambda = 10\,nm \rightarrow$ ~ 1 GeV
$\lambda = 1\,nm \rightarrow$ ~ 3 GeV
$\lambda = 1\,\text{Å} \rightarrow$ ~ 15 GeV

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

2. Sufficient current:

50 A (IR) → 5 kA (X-ray)

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

number of electrons per wavelength

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

3. A good electron beam quality:

Energy spead:

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

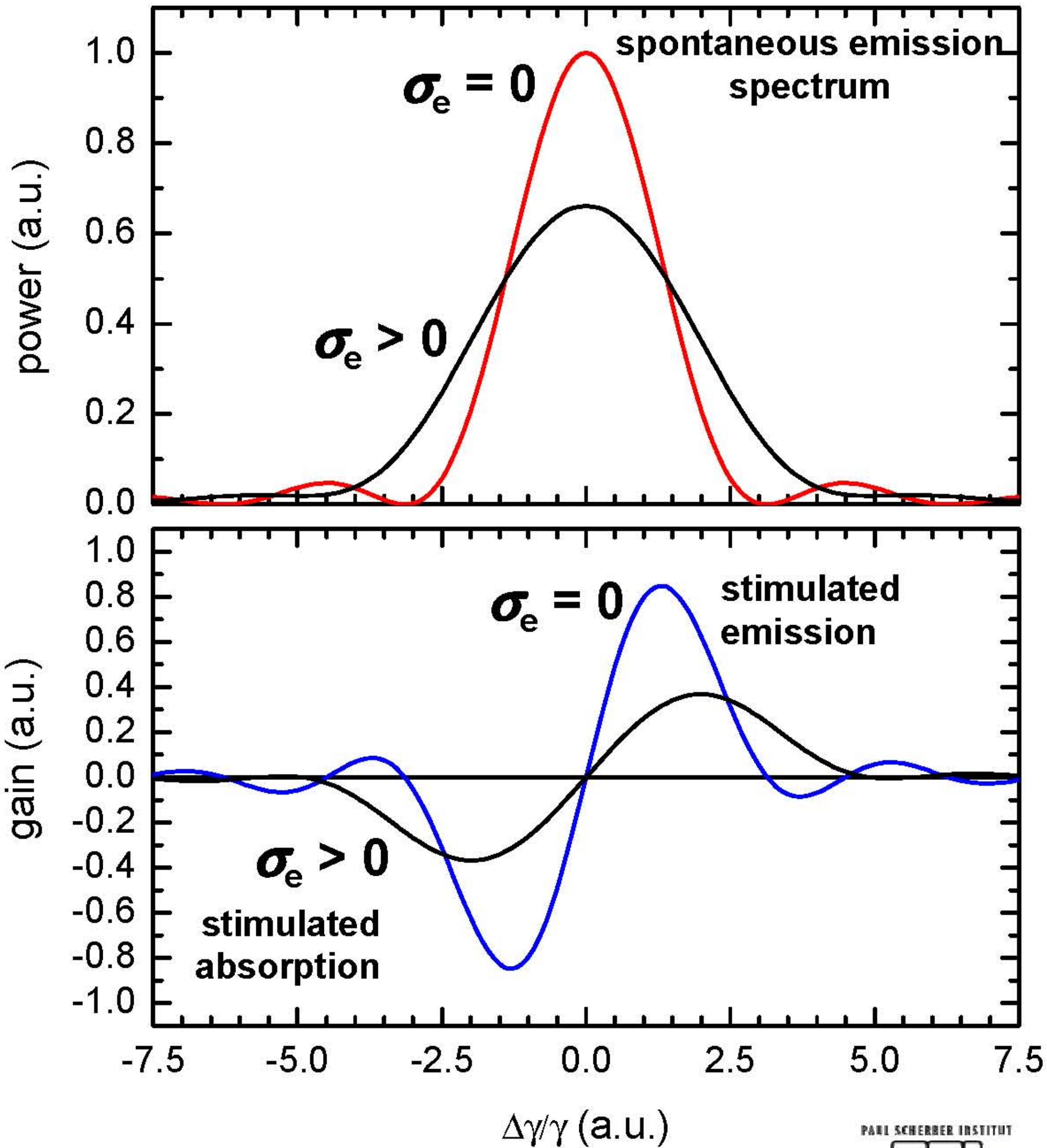
Though for long wavelengths

Transverse Emittance:

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

Though for short wavelengths

Energy Spread



Keep electrons within the gain bandwidth

Transverse Emittance

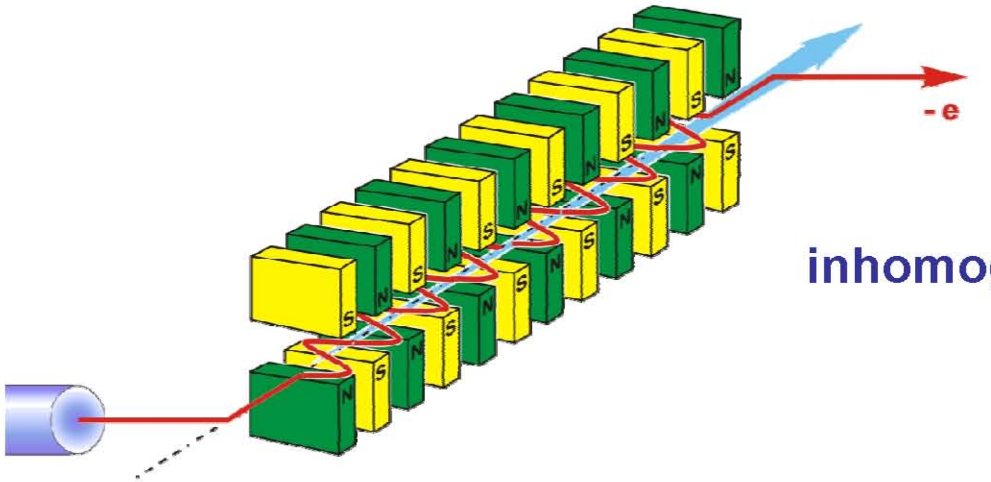
1. Relativistic case: transverse momentum is coupled with the longitudinal momentum.

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

Transverse Emittance :

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

High Gain



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:

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

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

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

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

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

Pierce parameter:

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

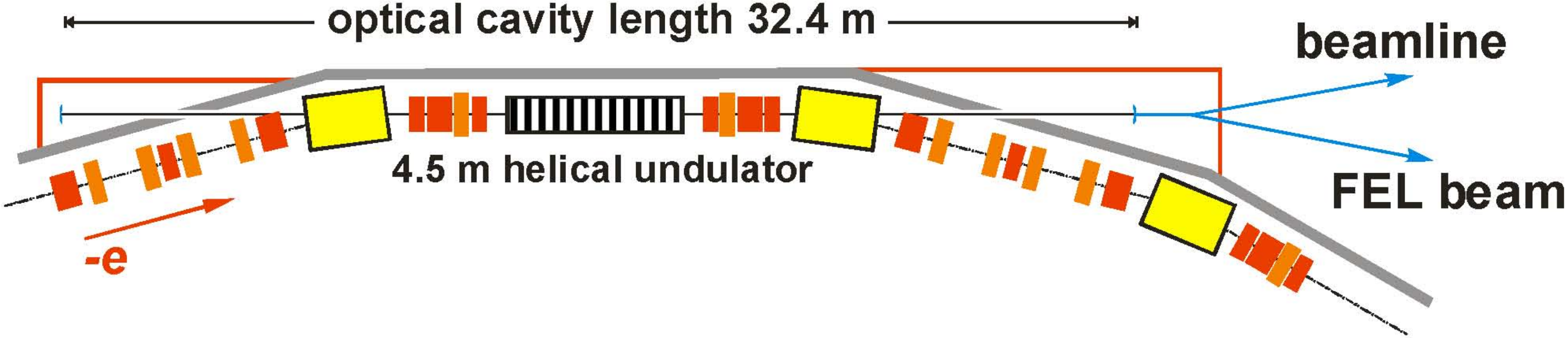
$$f(\xi) = J_0(\xi) - J_1(\xi)$$

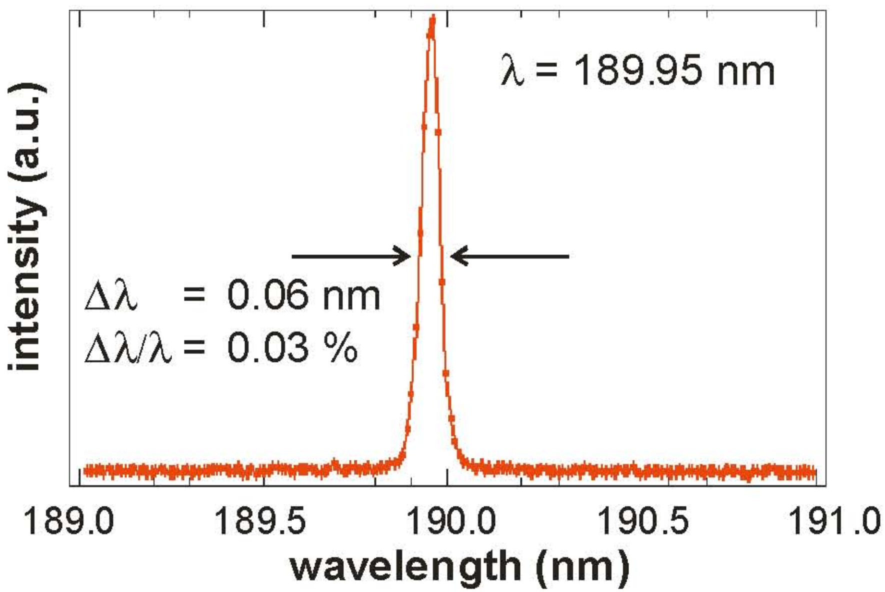
$$\sigma_{x,y} = \sqrt{\varepsilon\beta_{x,y}}$$

$$\xi = \frac{1}{4}\frac{K^2}{1+\frac{K^2}{2}}$$

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

The Elettra Storage Ring FEL

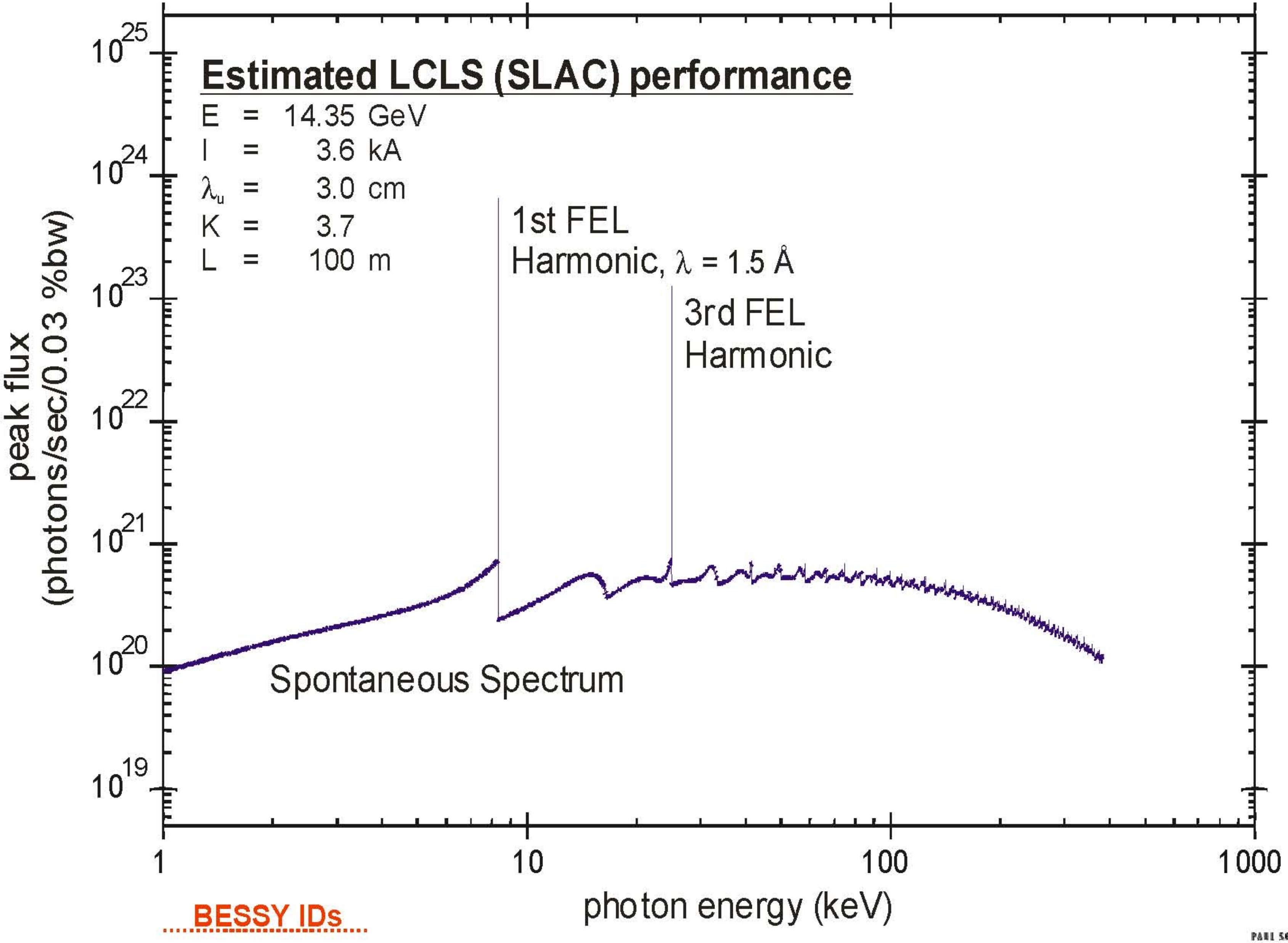




Storage ring operation*	1.0	GeV
Tunability range	350 – 190	nm
	3.5 – 6.5	eV
Average power	≥ 1	W
Pulse length (FWHM)	~ 5	ps
Peak power	≥ 40	kW
Pulse energy	≥ 0.2	mJ
Photon flux**	$\geq 10^{18}$	photons/s
Polarization	circular (linear may also be possible)	
Repetition rate	4.6	MHz
Synchronization with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

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

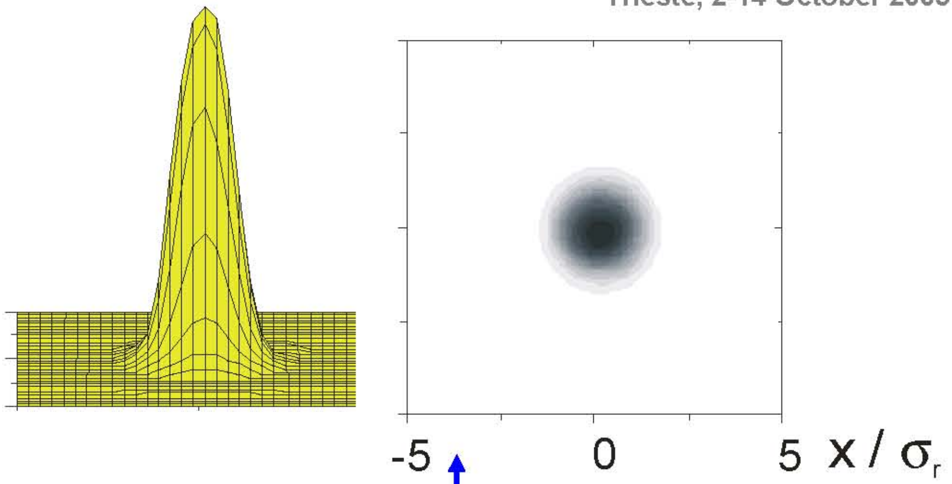
SLAC-R-521, p 3-4 (1998)

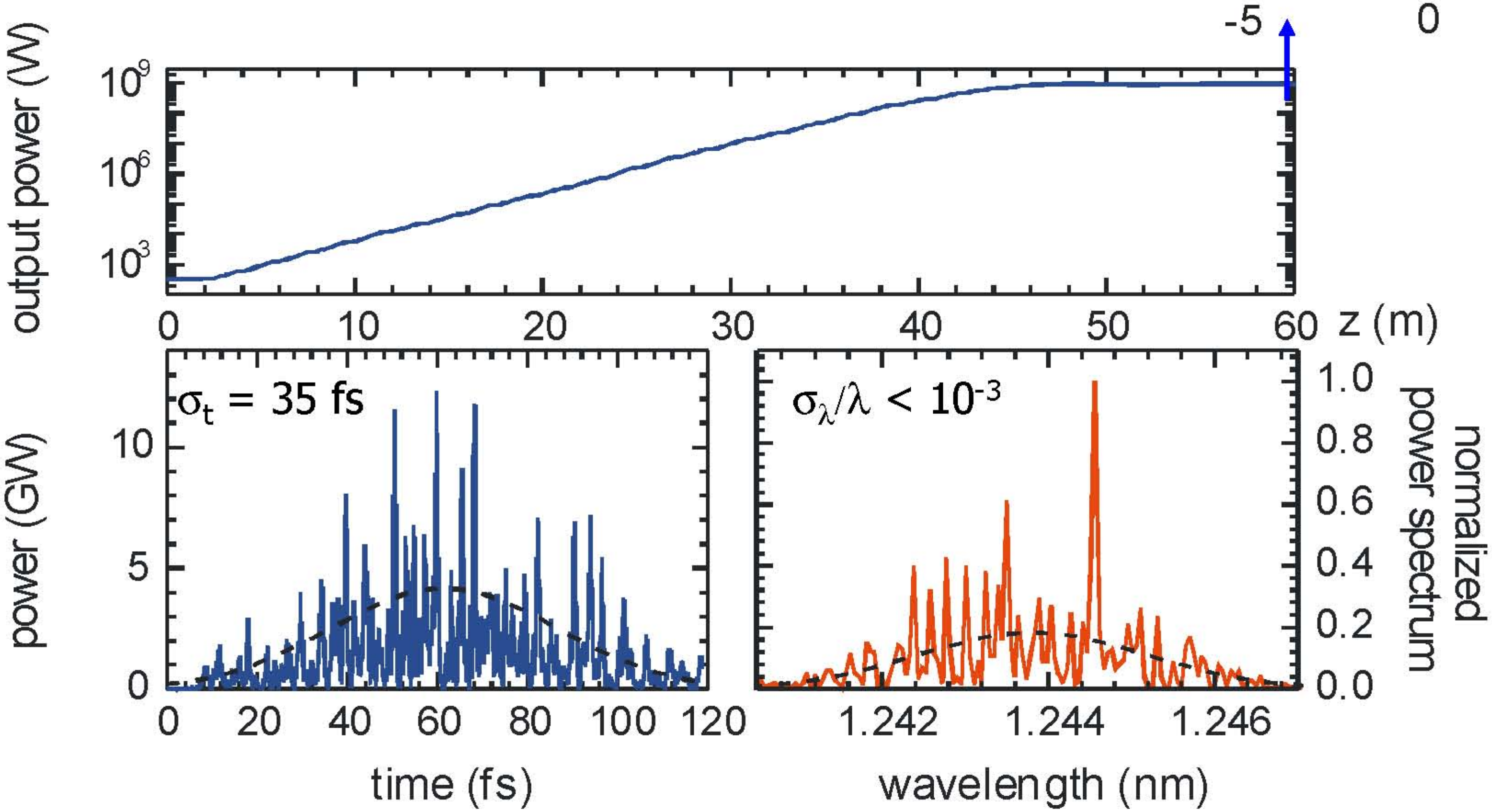


BESSY IDs

Output properties

transverse:
diffraction limited TEM_{00} mode

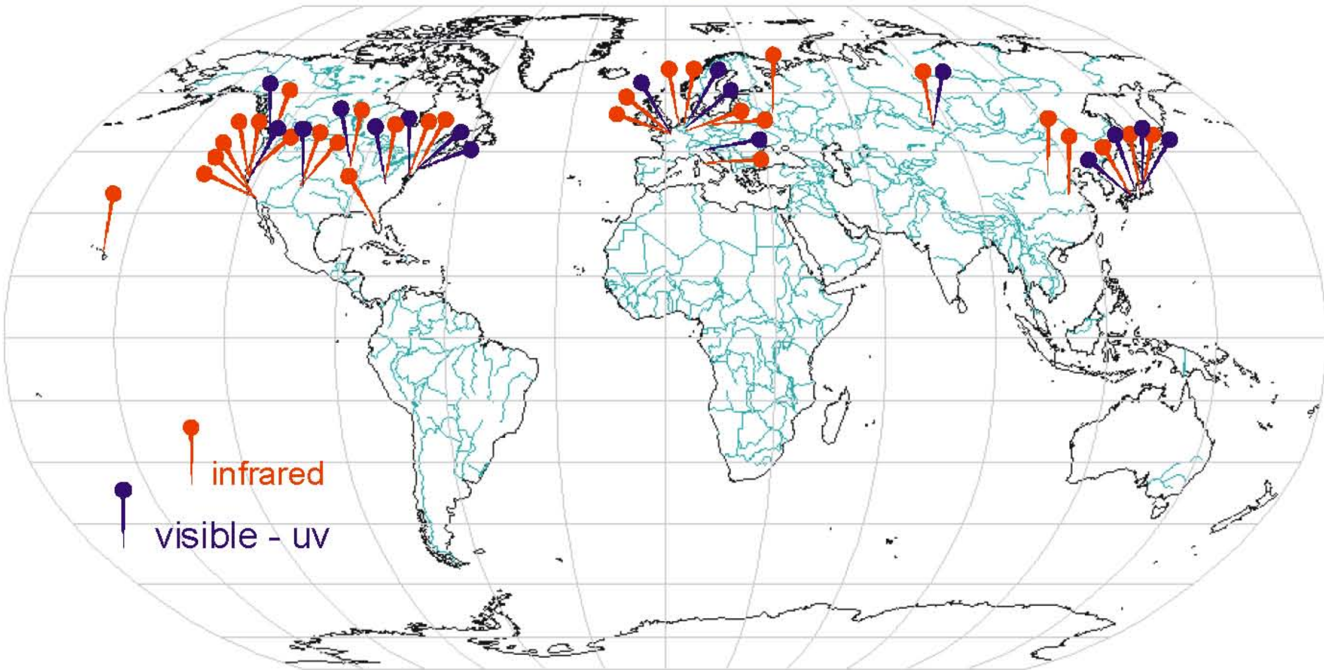




Examples

- High Average Power
- Single-Pass

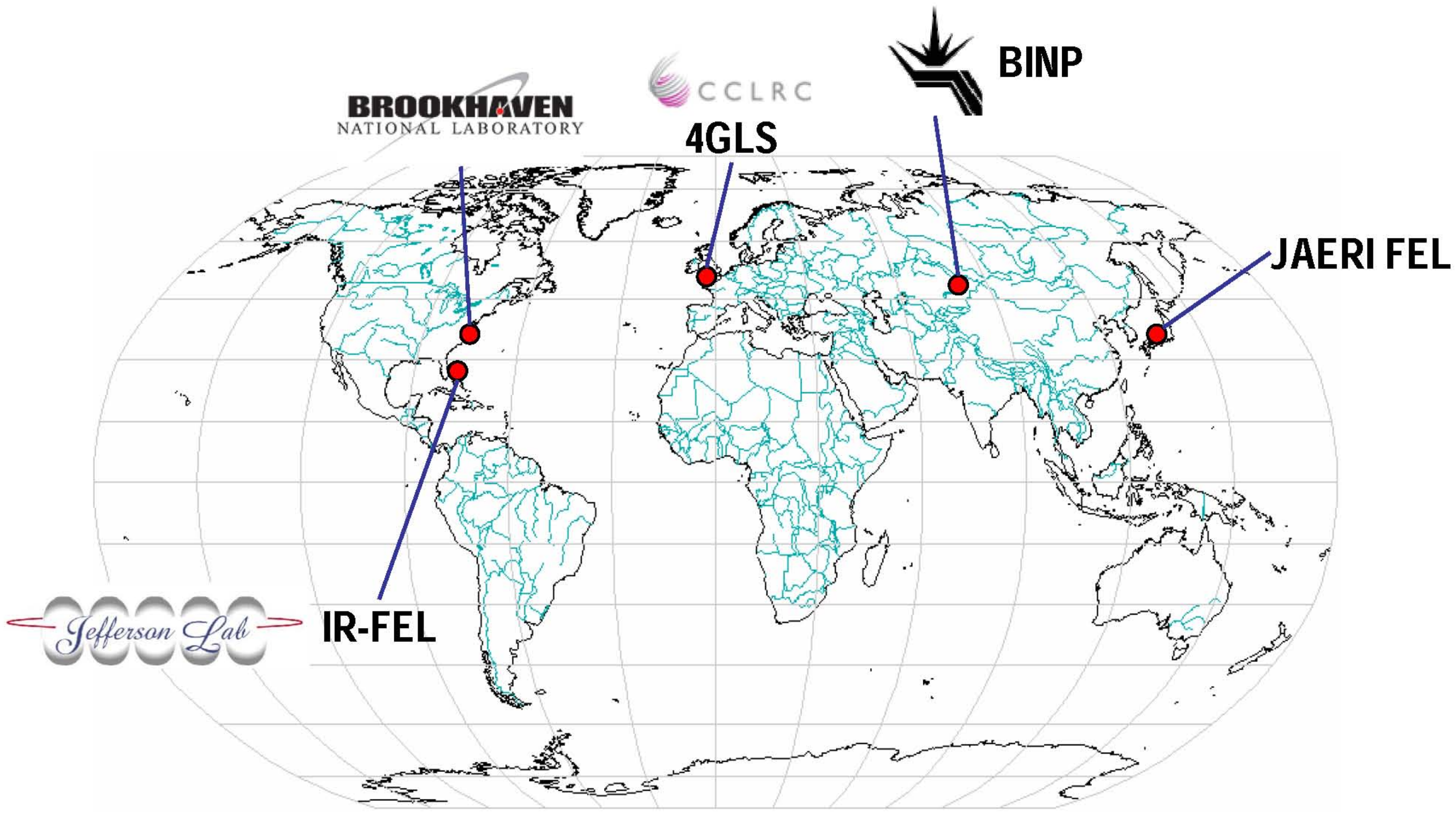
FEL facilities



W.B. Colson p. 706, Proceedings FEL2004 (JACoW)
http://sbfel3.ucsb.edu/www/vl_fel.html

Personal Choice !

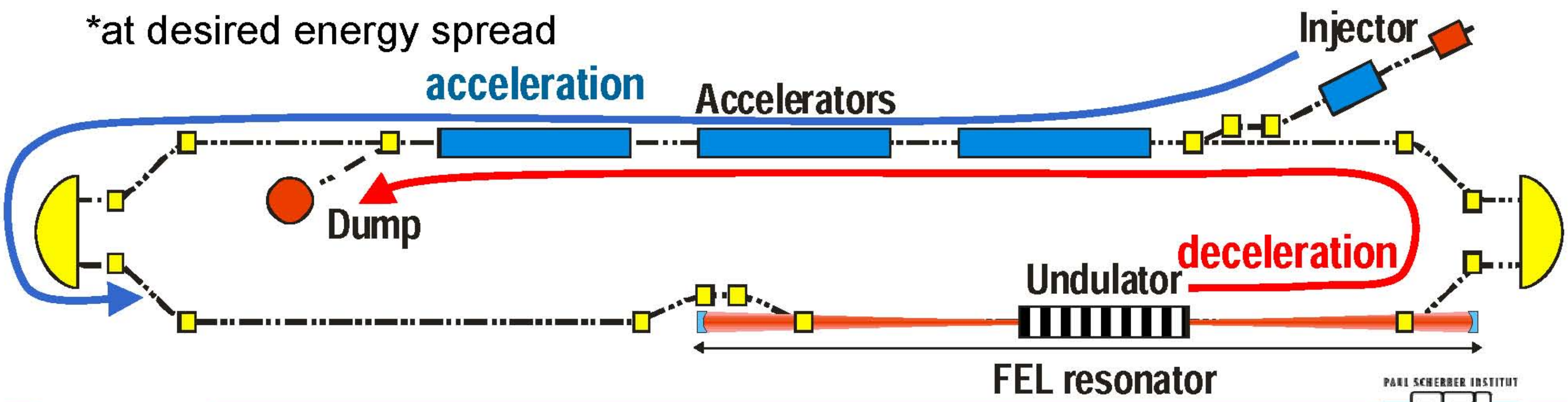
High Average Power FELs



JLAB recirculating FEL

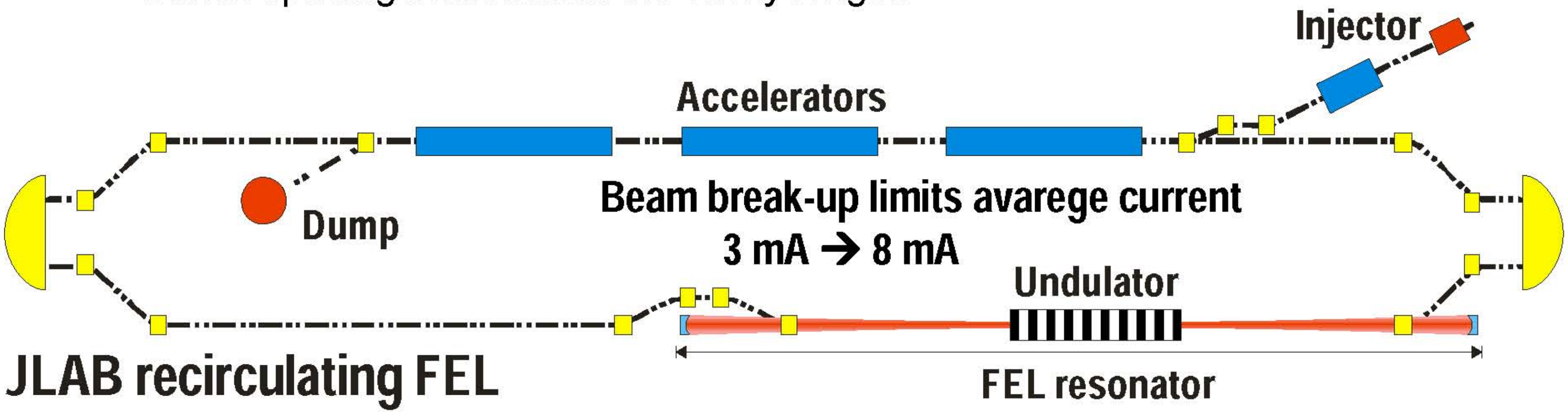
Driver Accelerator	Design Spec.	Achieved (as of Jul. 21 2004)
Linac Energy	145 MeV	160
Linac Ave. Current	10 mA	9.1
Charge	135 pC	150
Transverse Emittance	30 mm-mrad	<15
Energy Spread	0.3%	0.3
Bunch length *	0.5ps	0.35
FEL System		
Ave. Power (cw)	10 kW	8.5
Lasing efficiency	1 kW/mA	2.6
Stored Optical Power (@6μm)		132 kW

*at desired energy spread



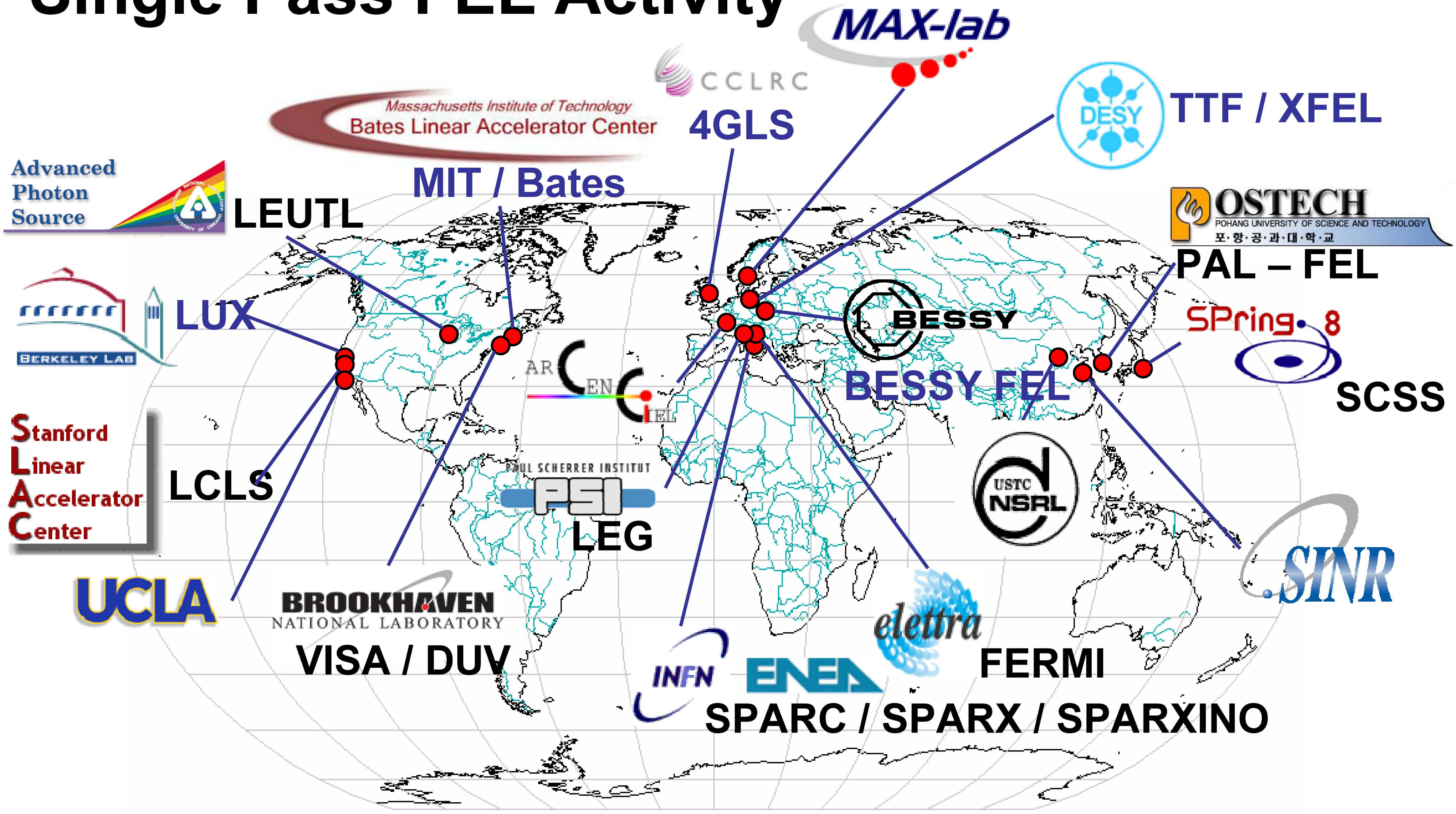
High average-power lasers: JLAB

- 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.



FEL2004 (JACoW): Benson et al.

Single Pass FEL Activity



SC technology / NC technology

Present status

- 3 projects target X-rays:

  $\lambda \leq 0.1$ nm / $\hbar\omega \geq 12.4$ keV

  - **User facilities**
  - **Increased beam energy to lower the emittance** ⟶ $\frac{\varepsilon_n}{\gamma} < \frac{\lambda}{4\pi}$
  - **Initially SASE only**
  - **Possible seeding as an extended option**

- many projects in the VUV / soft X-ray range

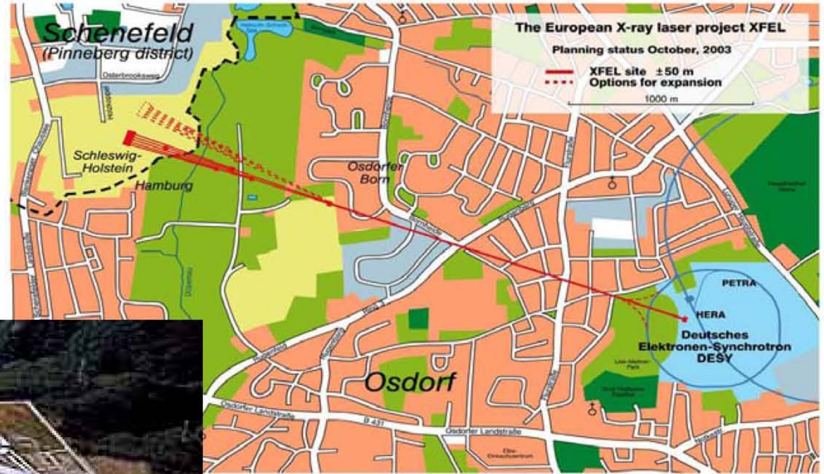
  $\lambda \geq 0.3$ nm / $\hbar\omega \leq 4.1$ keV

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

    - SASE & various seeding options

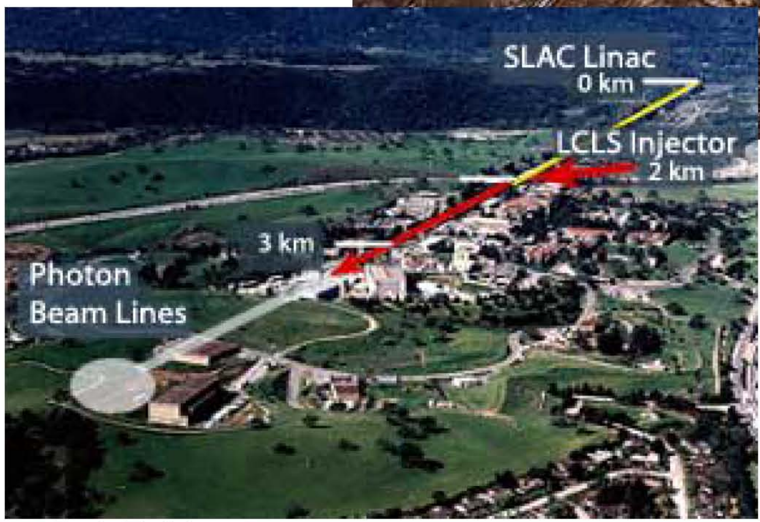
    - FELs in combination with energy recovery linacs (ERL)

X-FEL facilities



Europe
X-FEL – DESY 2012

Japan
SCSS – SPring8 2010



USA
LCLS - SLAC 2009

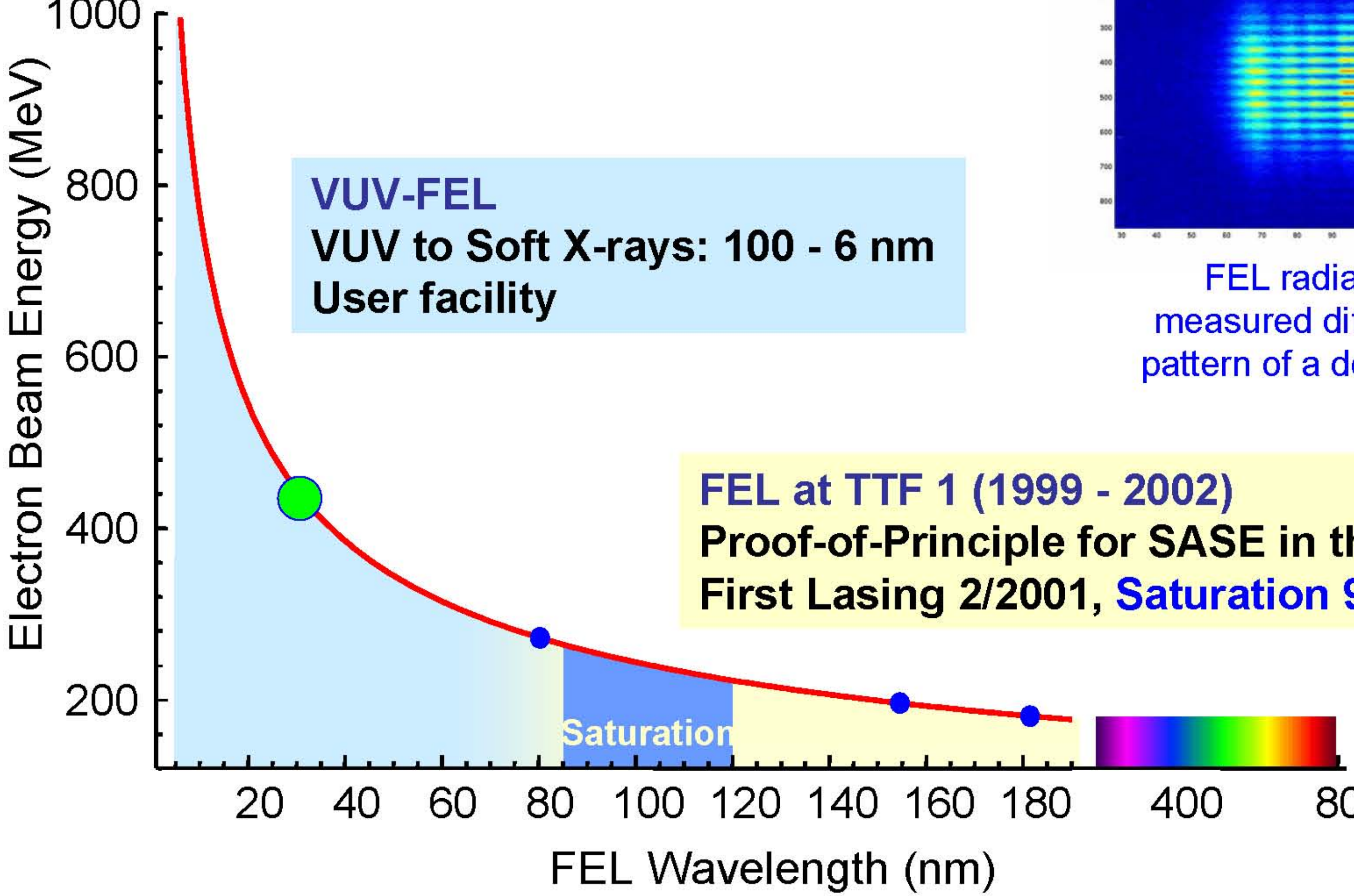
TESLA Test Facility Injector + acceleration + bunch compression

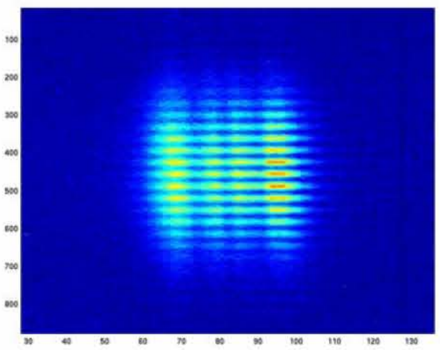
TTF/VUV-FEL tunnel acceleration + undulators

experimental hall

First lasing at 32 nm in January 2005

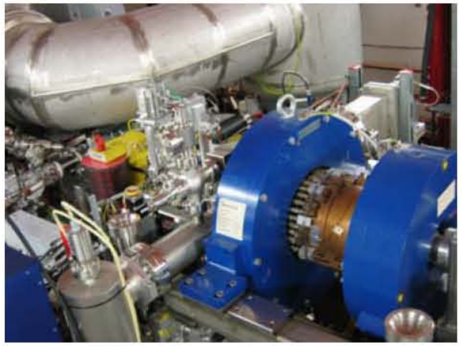
Beam Energy and Wavelength

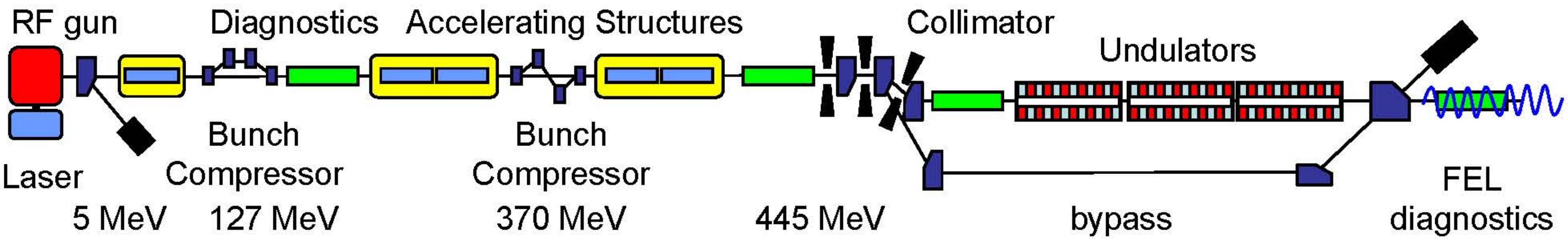




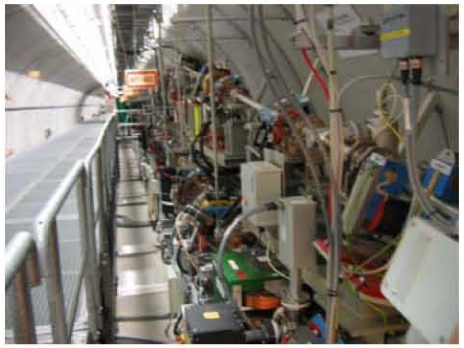
FEL radiation: measured diffraction pattern of a double slit

Present Layout of the VUV-FEL








250 m

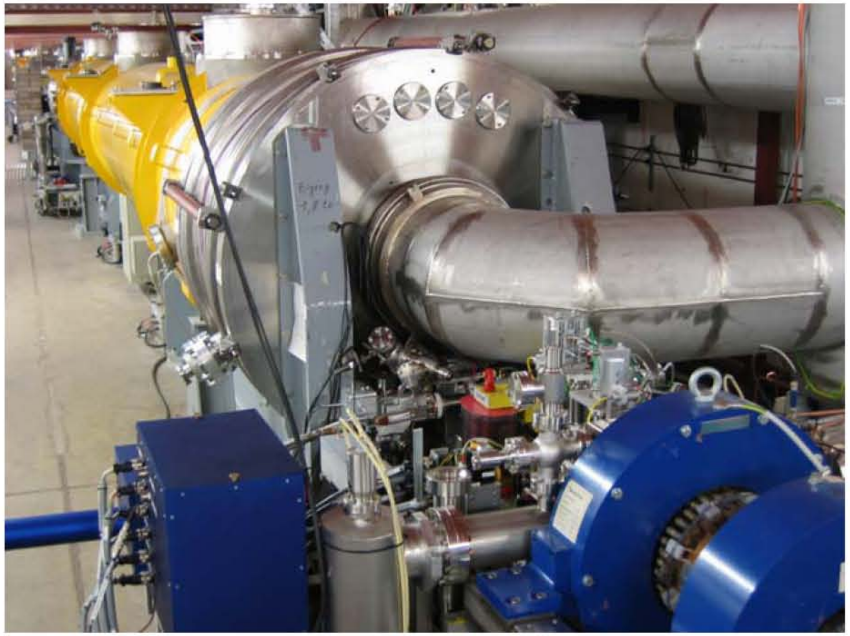
RF Gun

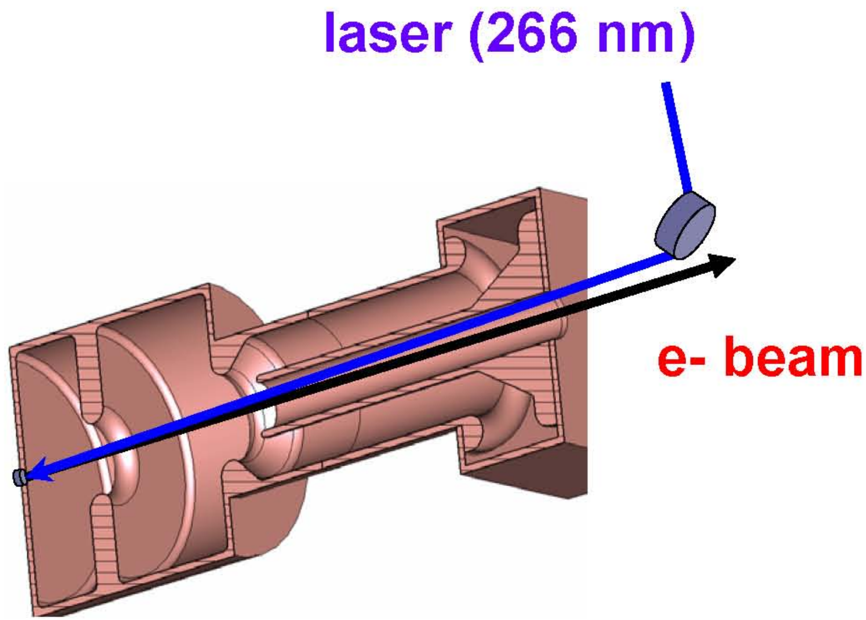
1 1/2 cell L-band 1.3 GHz

Longitudinal RF coupler

Up to 3.5 MW possible with given 5 MW klystron

Extensively tested at PITZ (DESY Zeuthen)



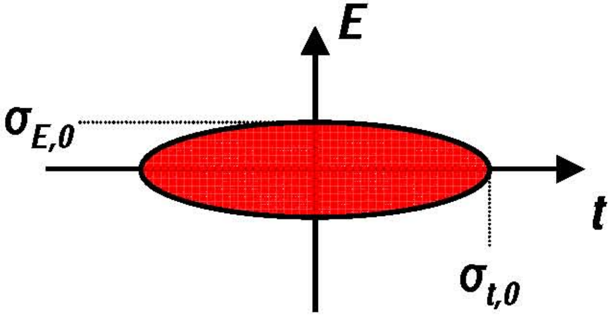


Distance gun to first acc. cavity determined by beam dynamcis

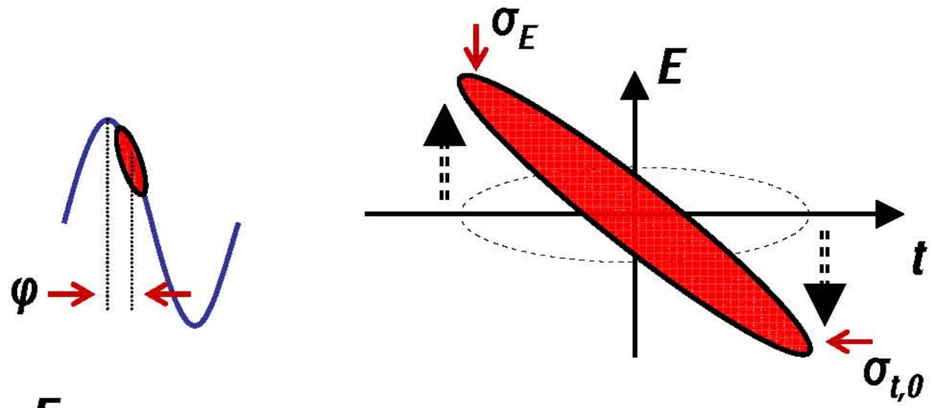
Very difficult to fit diagnostics between gun and module (spectrometer, toroid, BPMs, screens, steerers, laser input…)

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

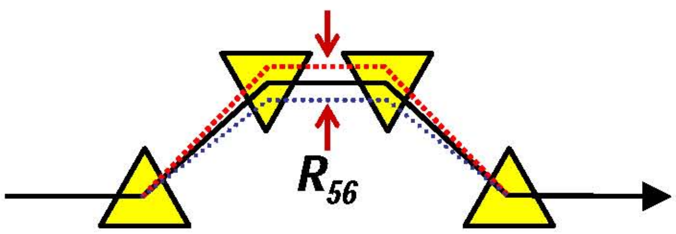
1. Initial condition

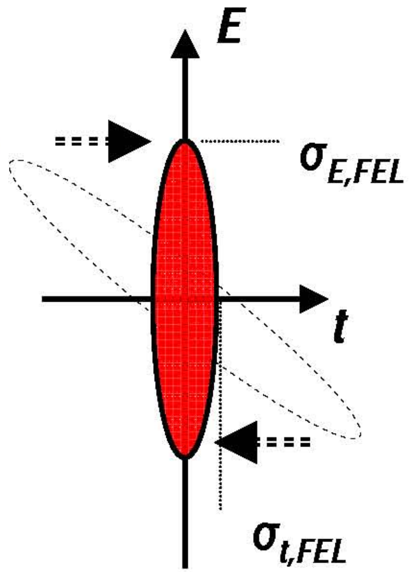


2. Offcrest RF acceleration

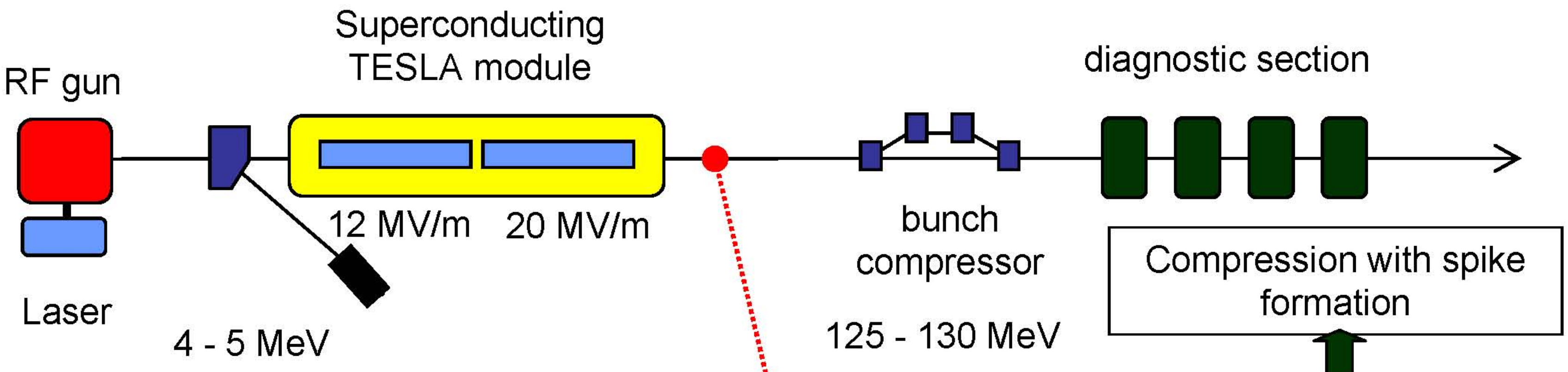


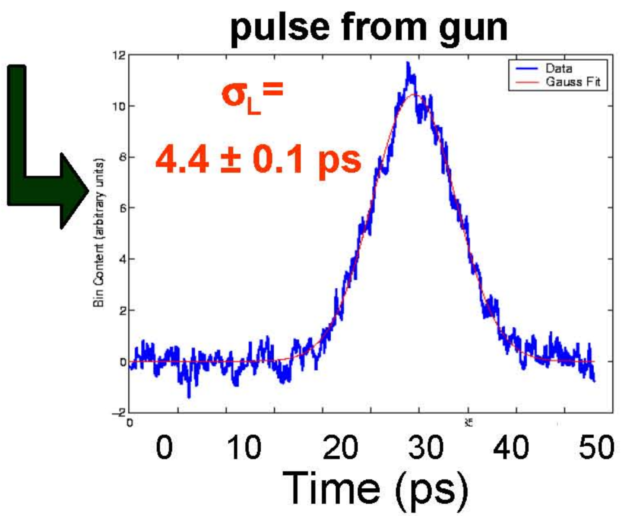
3. Compressor (dipoles): E_c

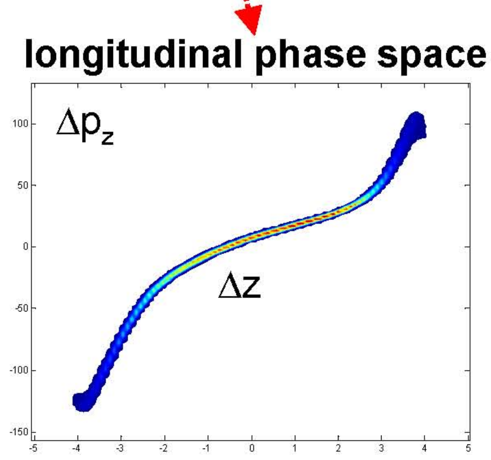


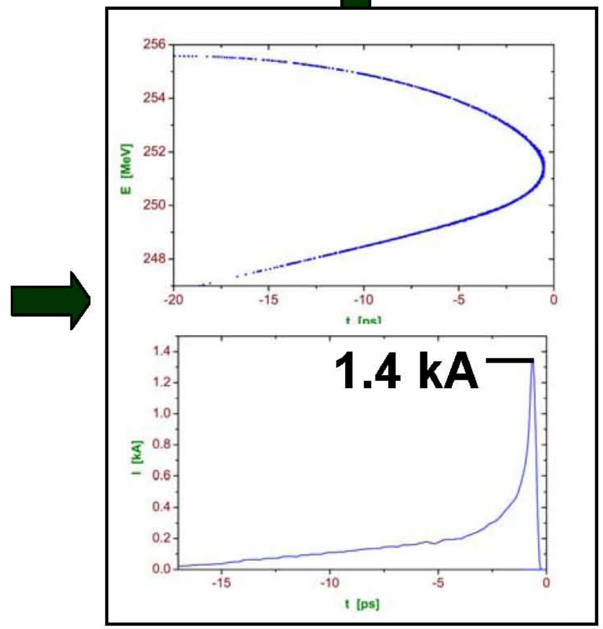


TTF-2 Injector Layout



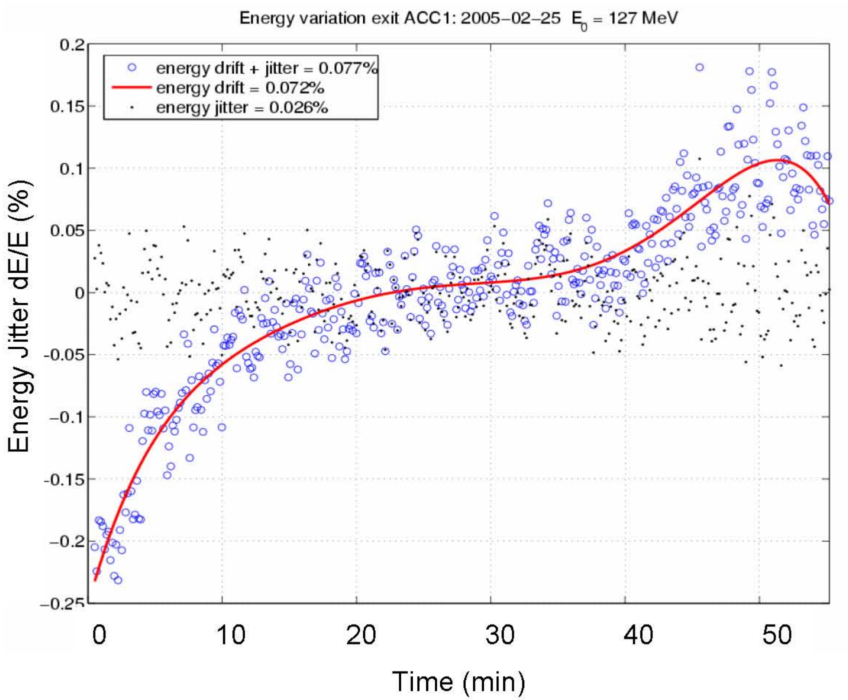


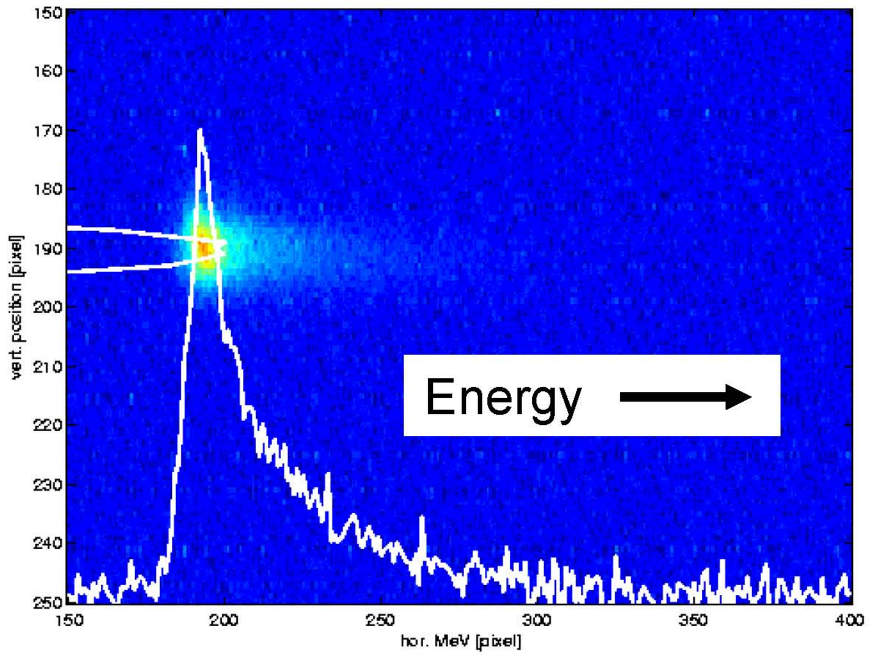




Solenoid field → Match envelope to booster adjust booster gradient → Emittance damping

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 = $2.6 \cdot 10^{-4}$ at 127 MeV

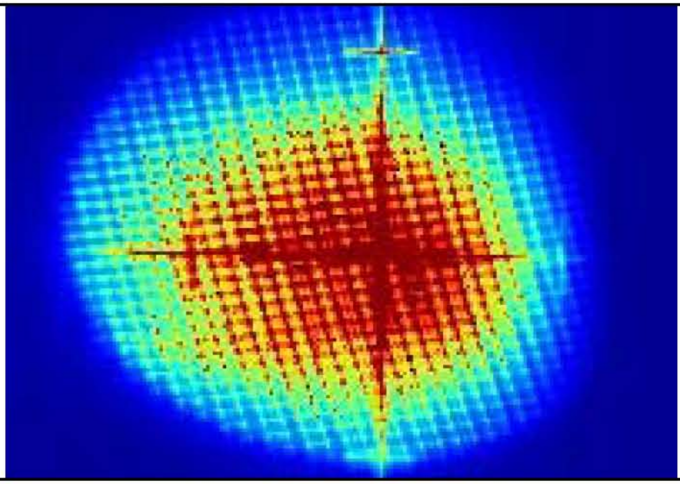
Including the drift yields $7 \cdot 10^{-4}$

Uncorrelated energy spread < 25 keV (resolution limited)

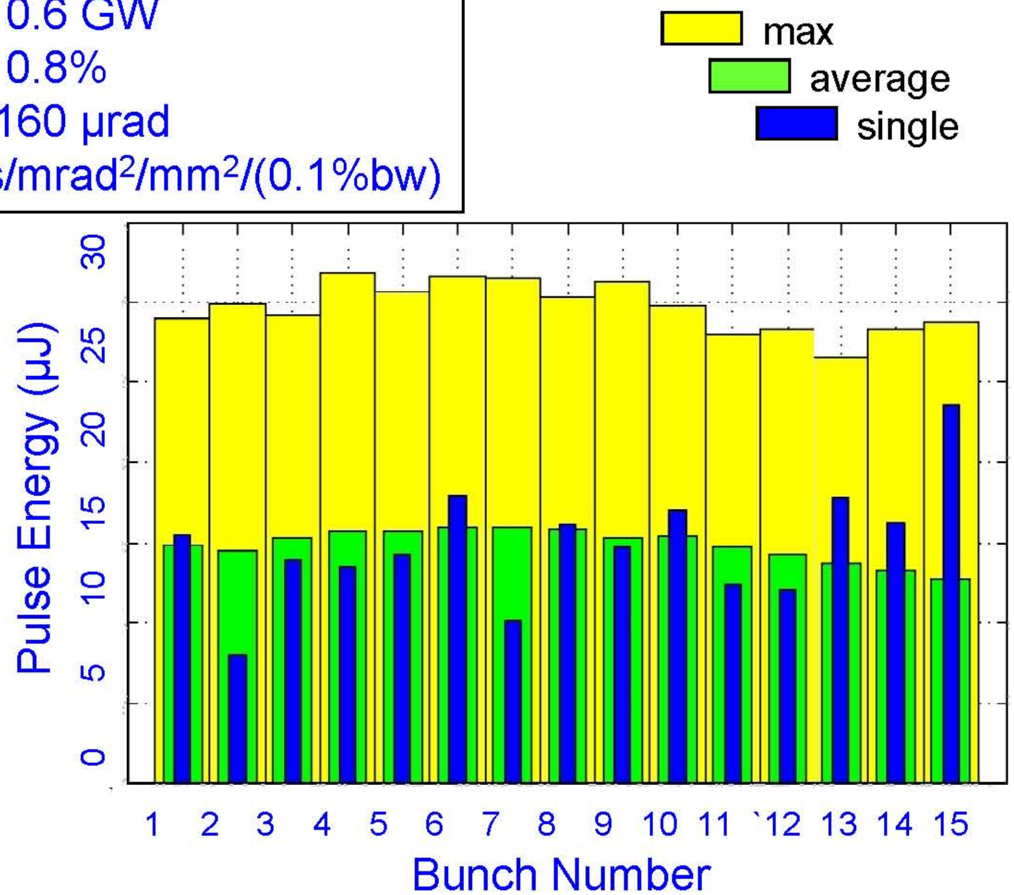
Basic Properties of the Radiation

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)

Multibunch SASE signal (µJ) recorded with MCP Detector

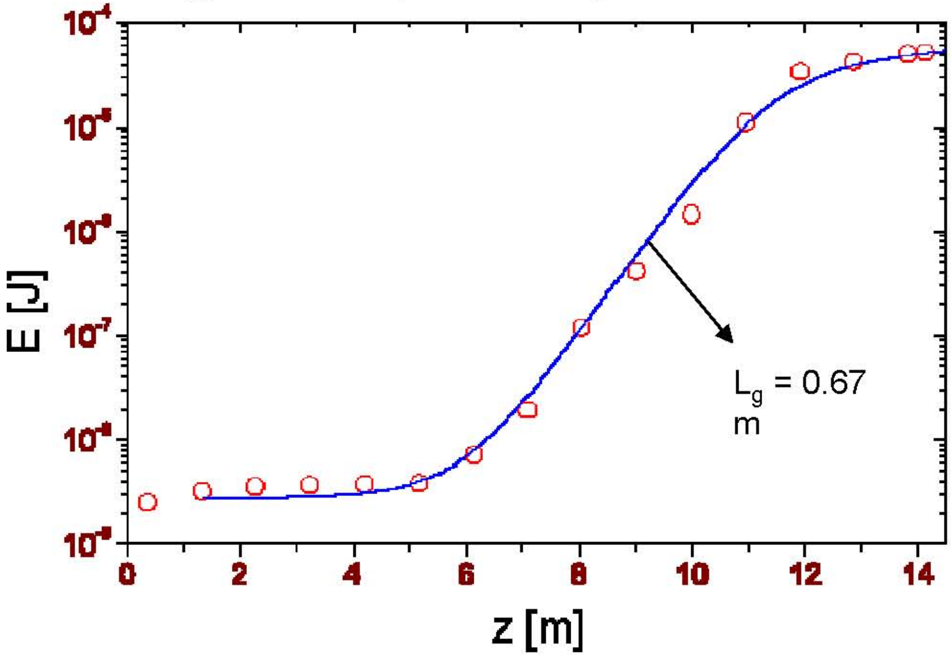


3 mm spot size (FWHM) @ 18.5 m distance
angular divergence 160 µrad
→ high degree of coherence
A gold mesh (0.25 mm pitch) in front of the Ce:YAG screen is used as intensity monitor.



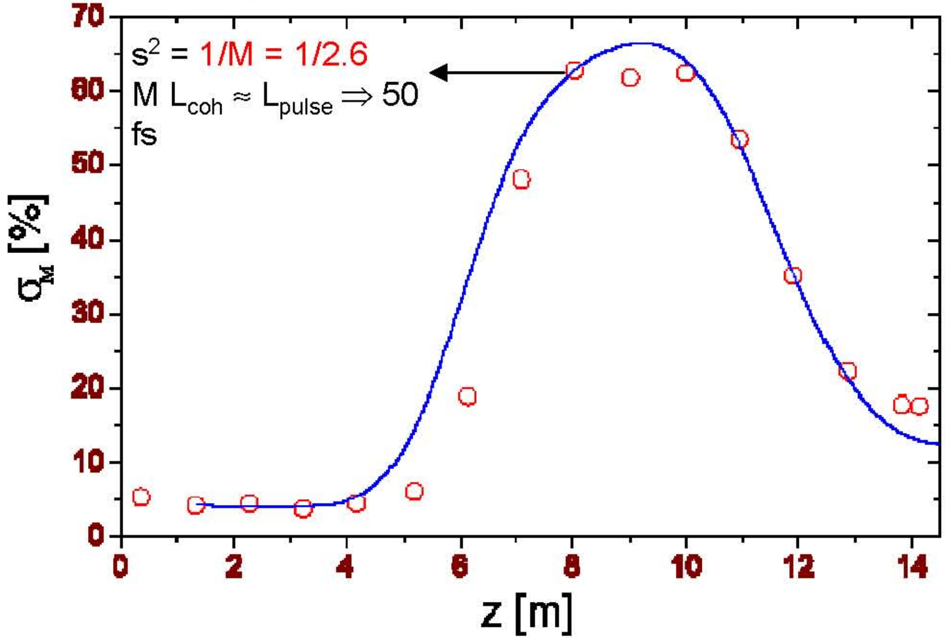
TTF1: Observed Results (λ = 96.5 nm)

Energy of the m-pulse along the undulator

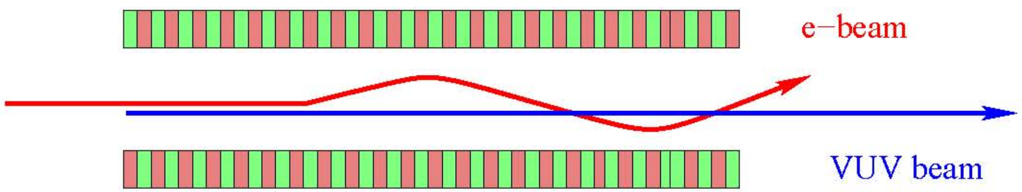


Average energy in the radiation pulse versus undulator length

Energy fluctuation along the undulator

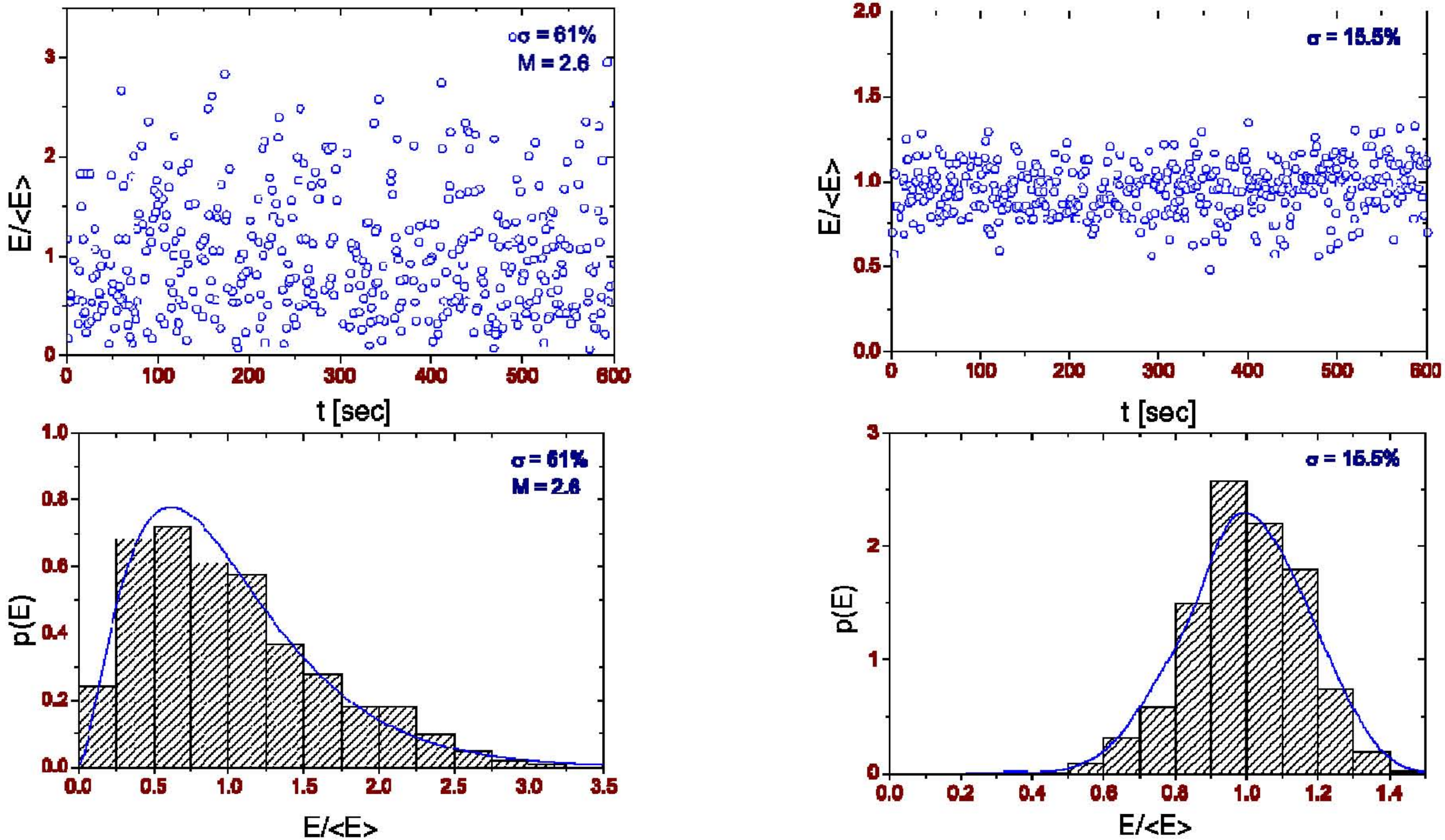


Fluctuations of energy in the radiation pulse versus undulator length



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

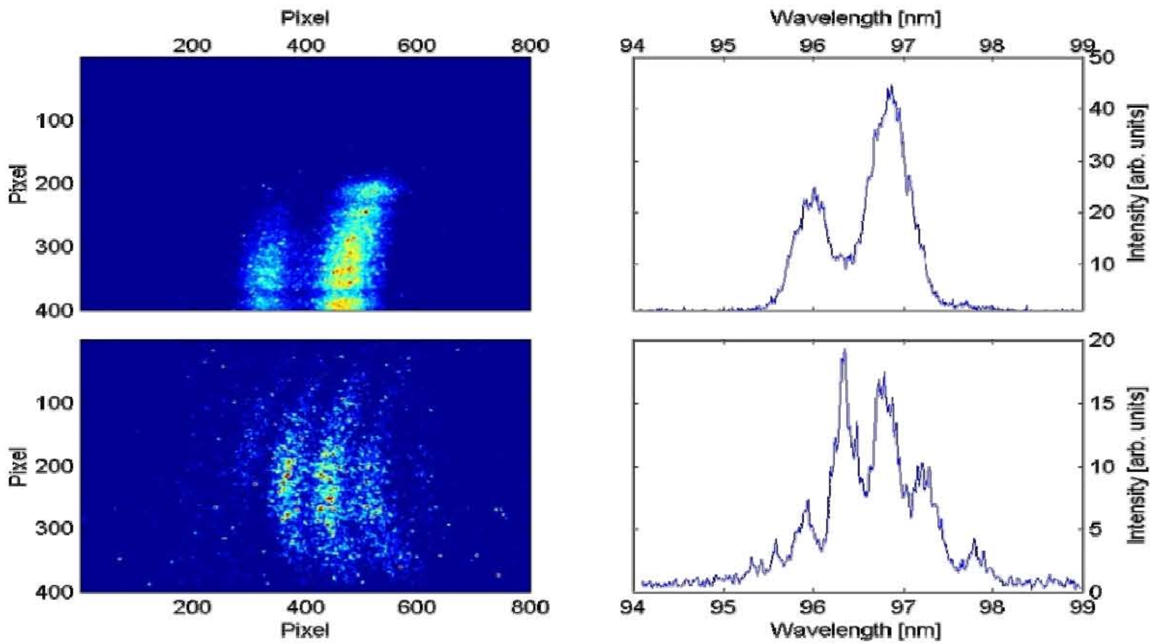
TTF1: Experiment vs. Simulation

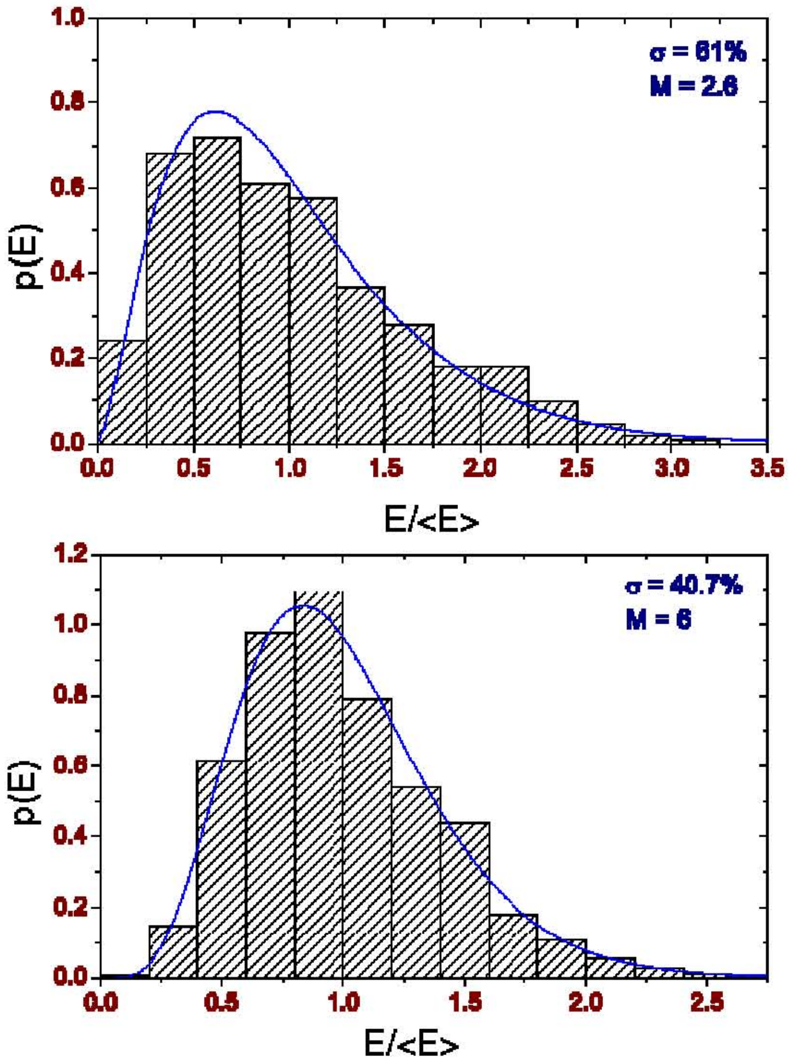


Signal from the radiation detector (top figures) and corresponding probability distributions (bottom figures) for linear (left) and saturation (right) regime. Solid curves represent simulation results with code FAST.

TTF1: Tuning of the pulse-length

Modes:
M ≅ 2 - 3



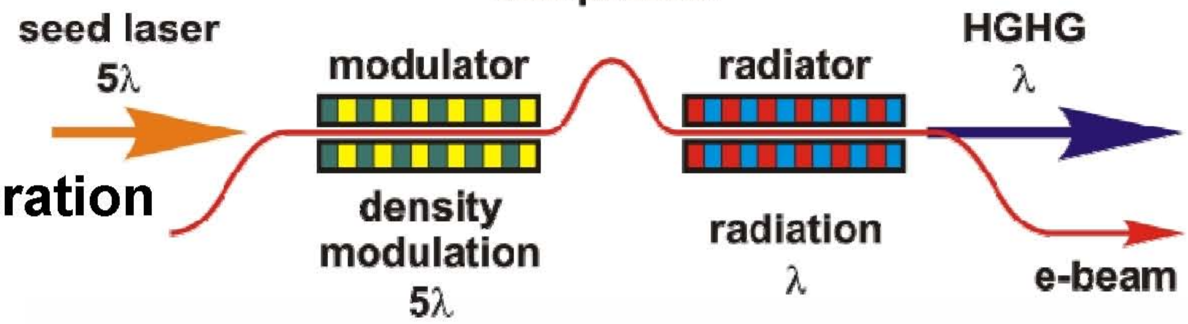


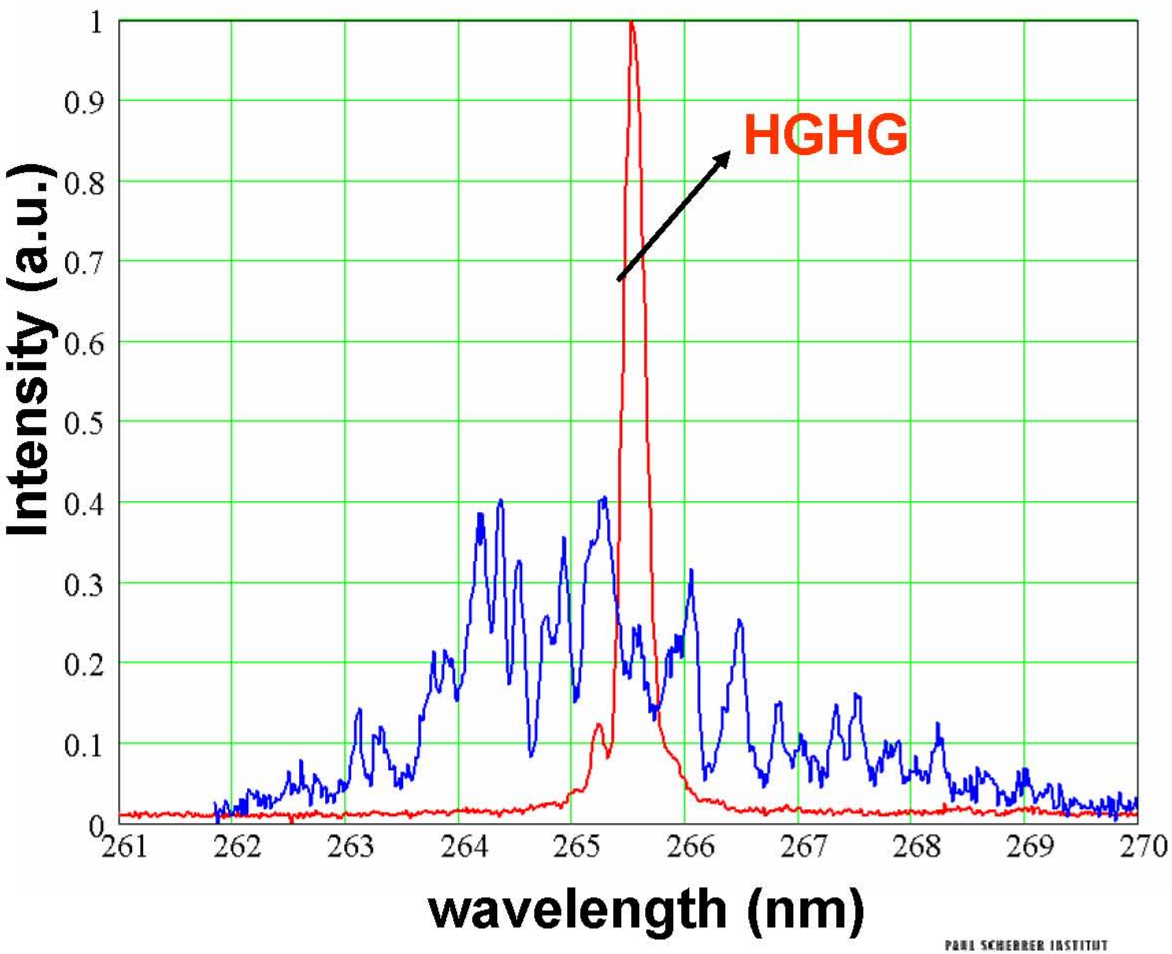
Modes:
M ≅ 7 - 10

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

Seeding: HGHG

High Gain Harmonics Generation



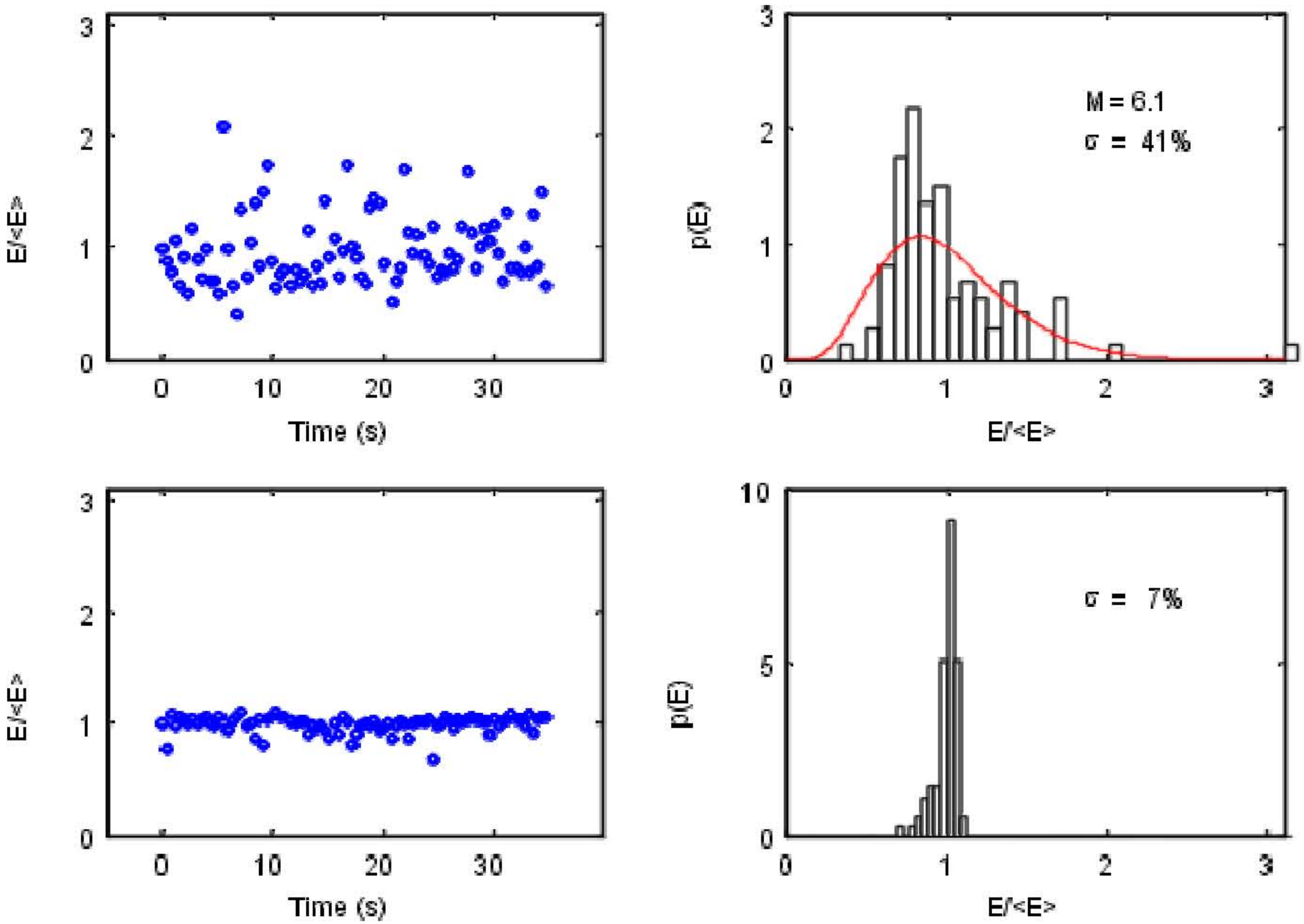


Shot to Shot Intensity Fluctuation

Shows High Stability of HGHG output

SASE

HGHG



Courtesy Li Hua Yu (BNL)

2-Stage Seeding
(demo for X-FEL)