U.S. Particle Accelerator School

Education in Beam Physics and Accelerator Technology

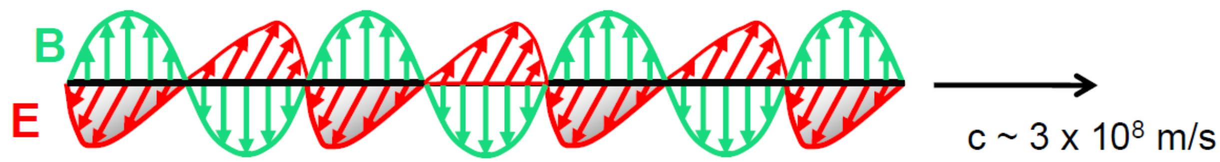
Elettra Sincrotrone Trieste

Introduction to single-pass FELs for UV and X-ray production

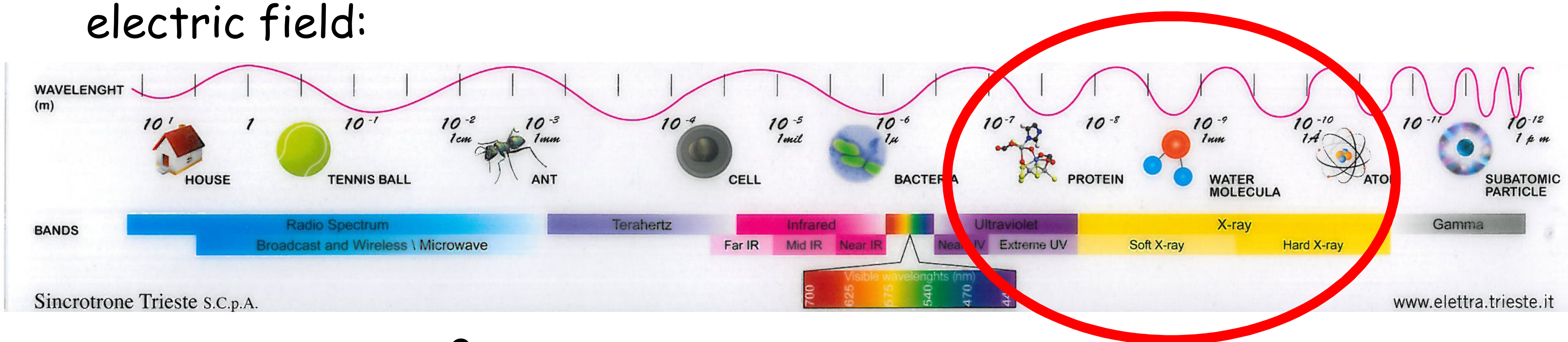
S. Di Mitri (90min.)

Electromagnetic Radiation, Wavelength and Energy

- E.m. radiation consists of individual massless particles called ***photons***.
- Many photons behave collectively as a ***transverse e.m. wave***:



- Photon's ***energy*** scales linearly with ***frequency*** of the associated electric field:

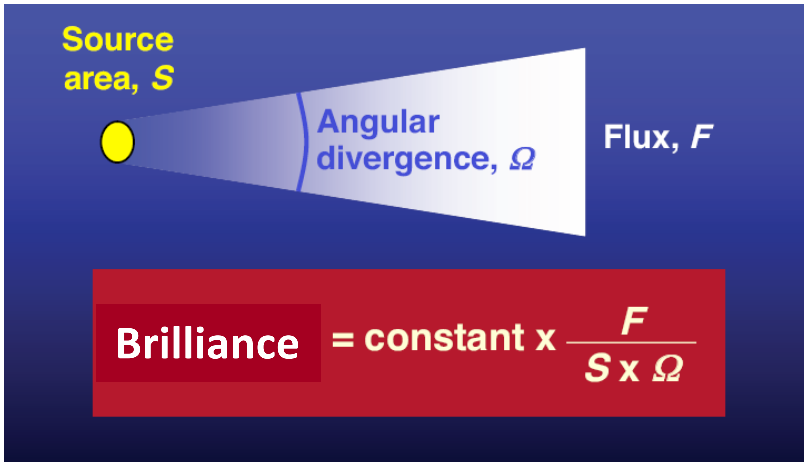


$$\lambda \nu = c \qquad k = \frac{2\pi}{\lambda}$$

$$\omega = 2\pi\nu$$

$$E[eV] = \frac{hc}{\lambda} = \frac{1240}{\lambda[nm]}$$

Peak Brilliance, Total and Spectral

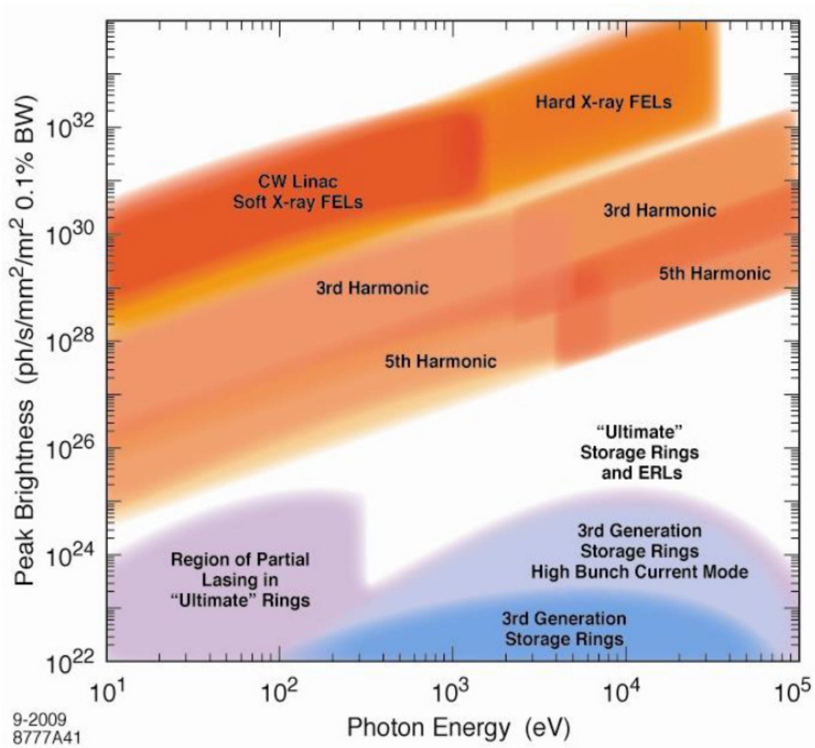


$$B_{pk,tot} = \frac{N_\gamma}{4\pi^2 \sigma_{T,x}\sigma_{T,x'}\sigma_{T,y}\sigma_{T,y'}\Delta t}$$

$$\sigma_{T,x} = \sqrt{\sigma_{x,e}^2 + \sigma_{x,\gamma}^2} \qquad \sigma_{T,x'} = \sqrt{\sigma_{x',e}^2 + \sigma_{x',\gamma}^2}$$

- The **product** of **beam size** and **angular divergence** is called ***emittance***. If they are *not* correlated (e.g., at a beam waist):

$$\varepsilon_x = \sigma_x \sigma_{x'}$$



- An **electron beam** that **overlaps** transversally with a Gaussian **photon pulse** is said to be at the **diffraction limit** when (this has to do with "transverse coherence", see next slides):

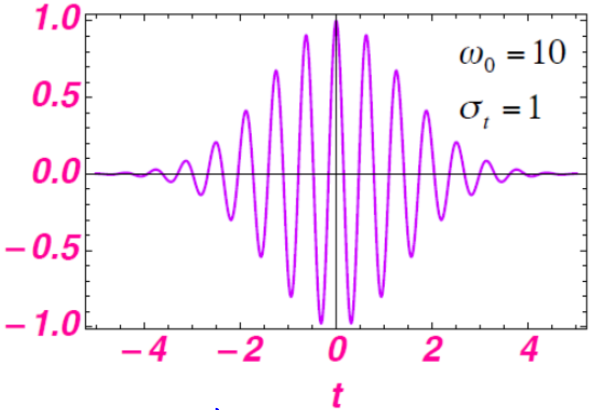
$$\varepsilon_{x,e} = \lambda / 4\pi$$

$$B_{pk}(\omega) = \frac{N_\gamma(\omega)}{4\pi^2 \sigma_{T,x}\sigma_{T,x'}\sigma_{T,y}\sigma_{T,y'}\Delta t(\Delta\omega/\omega)}$$

Time-Bandwidth Product, Gaussian Pulse

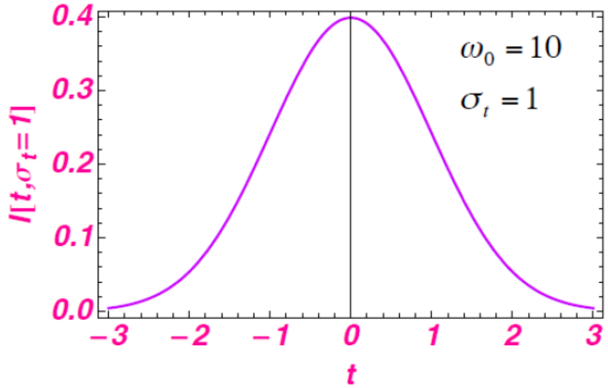
Electric field of a Gaussian wave packet:

$$E(t) = \mathrm{Re}\left[Exp[i\omega_0 t] Exp\left[-\frac{t^2}{4\sigma_t^2} \right] \right]$$

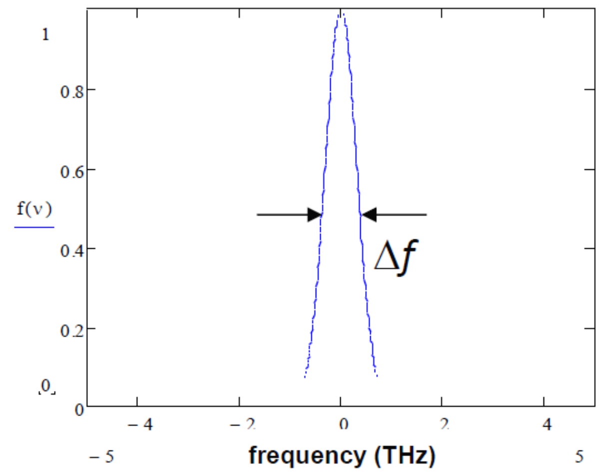


Intensity of a Gaussian wave packet:

$$I(t) = E^*(t)E(t) = Exp\left[-\frac{t^2}{2\sigma_t^2} \right]$$



Spectrum of a Gaussian wave packet:



$$I(t) = \frac{1}{2Z_0}|E(t)|^2$$

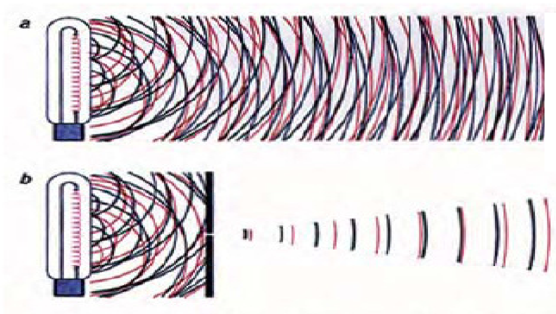
$$Z_0 = 377\Omega$$

$$\sigma_t \sigma_\omega \geq 0.5$$

$$\Delta t_{fwhm} \Delta \omega_{fwhm} \geq 0.44$$

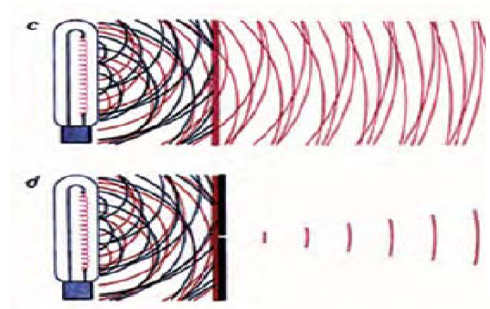
When the **minimum** time-bandwidth product is achieved, then the pulse is said to be **Fourier transform-limited** (from Heisenberg's uncertainty principle). This has to do with "longitudinal coherence", see next slide.

Coherence, Transverse and Longitudinal



multi-color ✗
wide source ✗

multi-color ✗
collimated ✓



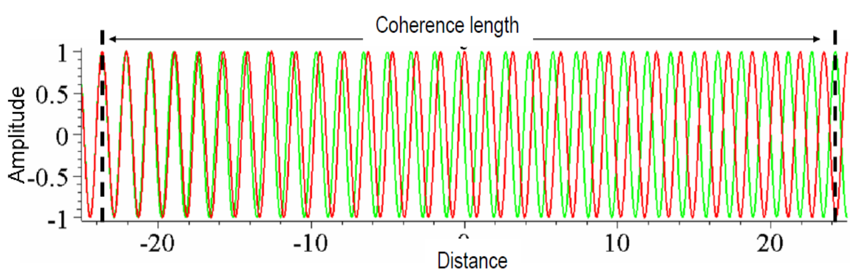
monochromatic ✓
wide source ✗

monochromatic ✓
collimated ✓
= *coherent !*

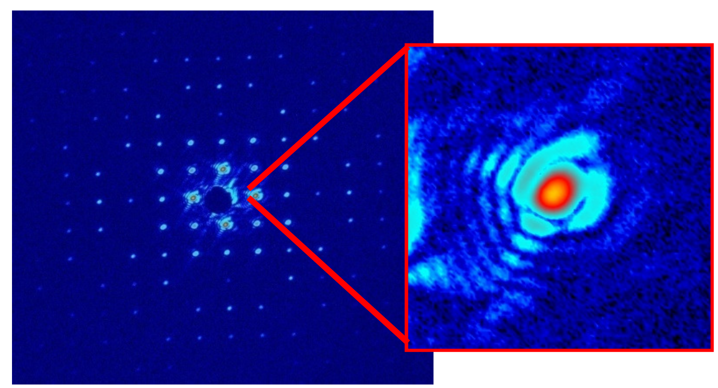
Courtesy of A. Schawlow, Stanford.

Longitudinal coherence length: the distance over which two e.m. waves separated in frequency by $\Delta\omega$ get out of phase by π,

$$L_{c,//} = \frac{c}{\pi \Delta \nu}$$



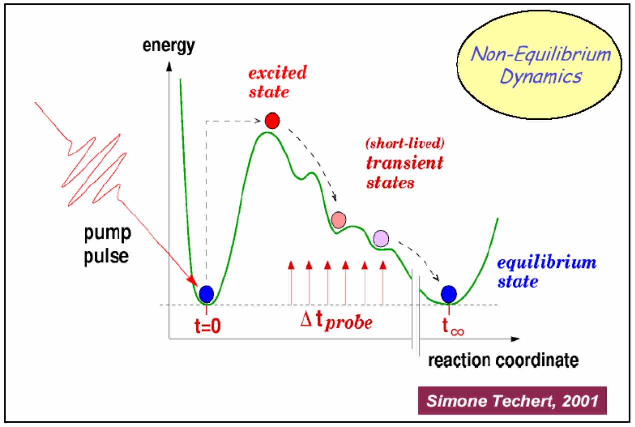
Transverse coherence length: the distance over which the e.m. field can be reconstructed from the knowledge of the field at another point, in the same plane (i.e., the field phase information is preserved). A coherent beam generates interference patterns.



The Ideal Light Source, Wish List

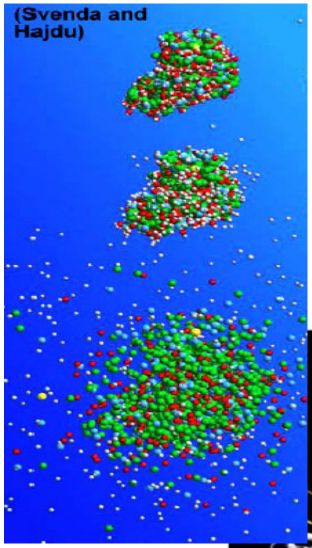
It should include:

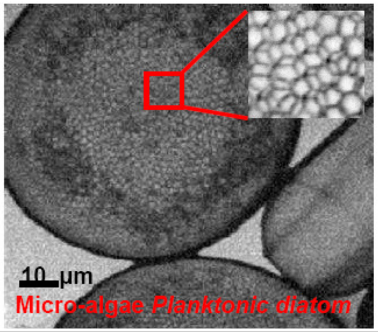
- **wavelength tunability** (e.g., for scanning atomic level resonances);
- high degree of **coherence** (e.g., for coherent diffraction imaging);
- high **brilliance** (e.g., for single-shot scattering experiments).

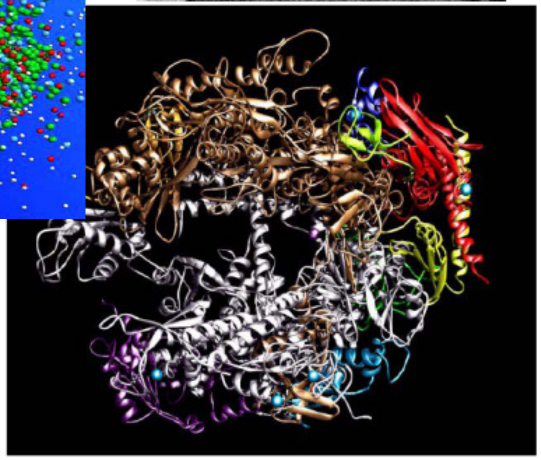


More recent trends are for:

- *short wavelengths* (e.g., for resolution at sub-nm scales);
- *short pulses* (e.g., for stroboscopic pictures of fast chemical processes);
- *high repetition rate* (e.g., for large statistics experiments) .







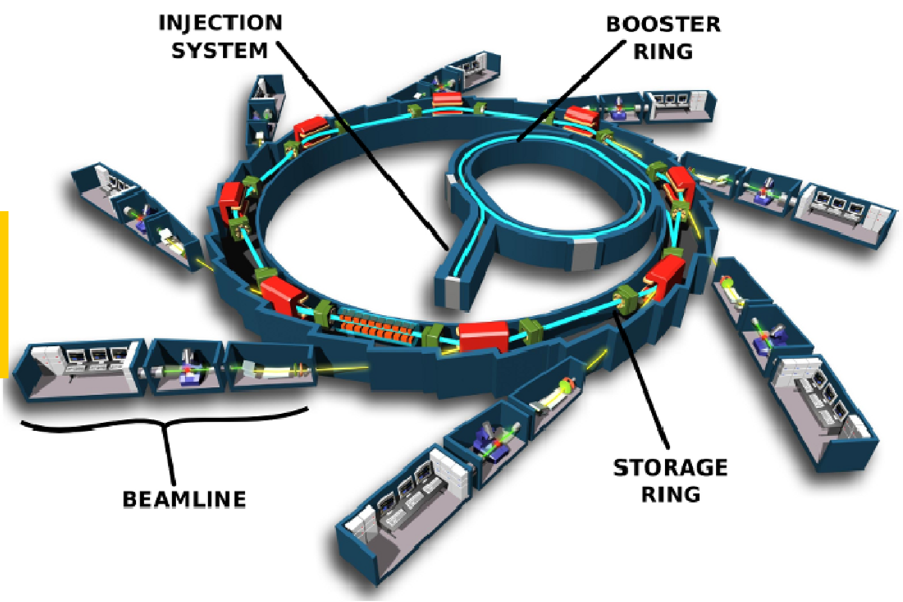
Storage Ring-Based Light Sources: Electron Synchrotrons

Electron synchrotrons are tools of discovery for:

- Life Science (e.g., microcrystal protein structure)
- Chemistry (e.g., chemical species at surfaces)
- Material Science (e.g., phase contrast imaging)
- Condensed Matter Physics (e.g., materials under pressure)

Synchrotron radiation can be generated in:

- dipole magnets,
- wigglers (strong focusing, K >> 1),
- undulators (weak focusing, K~1)



- ❑ Peak brilliance is **10^{22}–10^{25}** (s-mm^2-mrad^2-0.1%bw) for x-ray photons

- ❑ Synchrotrons serve **tens of beamlines** at one time

LINAC-Based Light Sources: Free Electron Lasers

FELs enable new experiments in:

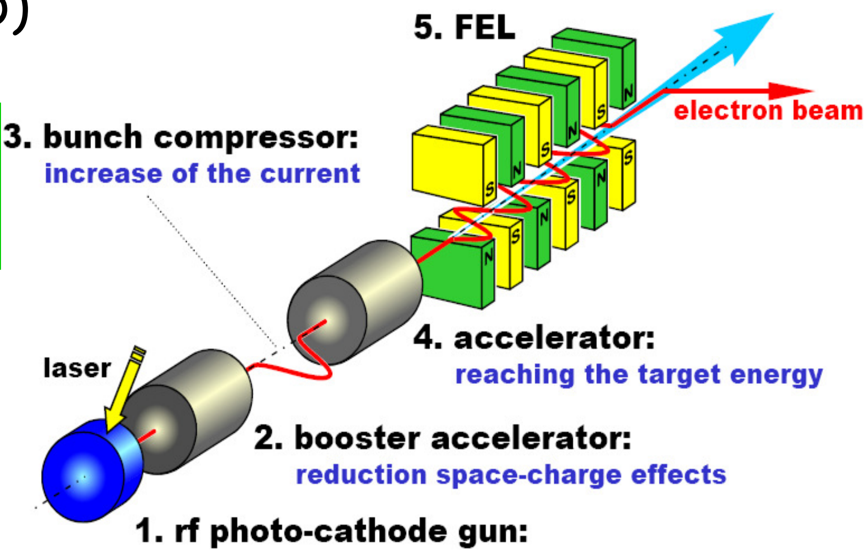
- Life Science (e.g., nanocrystal protein structure)
- Chemistry (e.g., probing ultrafast dynamics of surface reactions)
- Material Science (e.g., 3-D nanomorphology, diffraction imaging)
- Condensed Matter Physics (e.g., materials under extreme conditions)

FEL radiation is generated in:

- undulators (moderate focusing, K~1–5)

❑ Peak brilliance is **10^{30}–10^{33}** /(s-mm^2-mrad^2-0.1%bw) for x-ray photons.

❑ FELs serve one or **few lines** at a time. Multi-beamlines schemes are now under investigation.



Advantages of a LINAC-driven Light Source

- An accelerated charge particle radiates: $P_{circ} = \frac{2}{3}\frac{e^2}{c^3}\frac{\gamma^2}{m_0^{\,2}}\left|\dot{\vec{p}}\right|^2, \; P_{circ} = \gamma^2 P_{lin}$

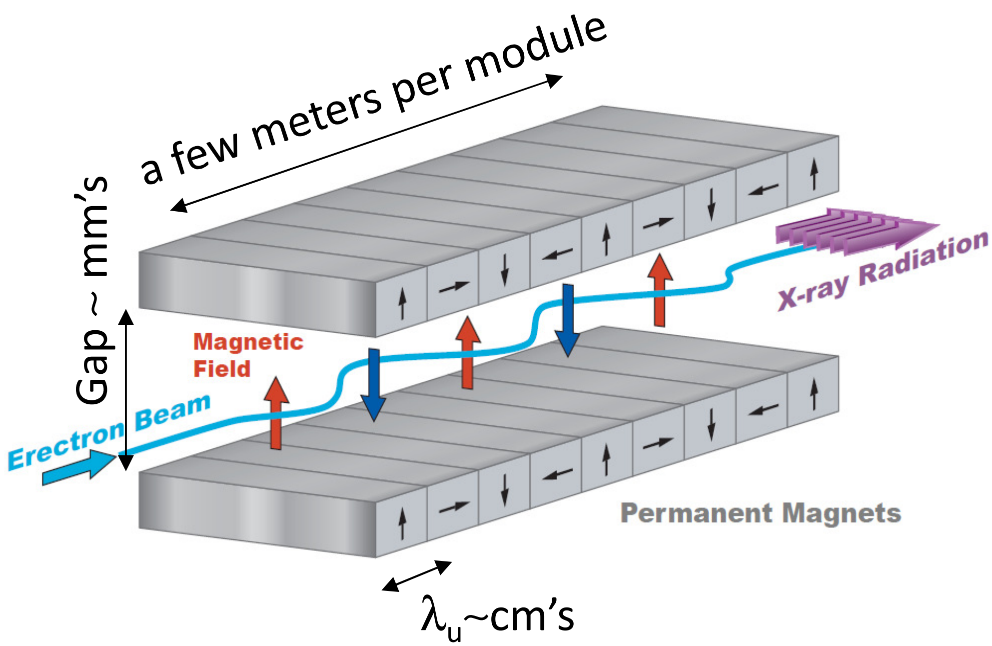
- Leptons (*i.e.*, electrons) radiate more than hadrons (*i.e.*, protons) when subjected to the same force. Circular acceleration is more efficient (and typically cheaper) than linear.

- *But*, e-beams in **synchrotron** light sources (SLS) reach ***equilibrium* sizes** that are typically far from providing radiation as wished by FEL users (synchrotron radiation damping of particles' velocities is balanced by the quantum excitation due to random emission of photons in time) .

- An electron radiofrequency linear accelerator (***RF e-LINAC***) can be used to overcome the SLS equilibrium dynamics and to **"shape" the e-beam** as desired. However, a more efficient radiating process is still needed to surpass the SLS's brilliance level…

Coherent Radiation from an Undulator

Pictures courtesy of
T. Shintake, R. Bakker



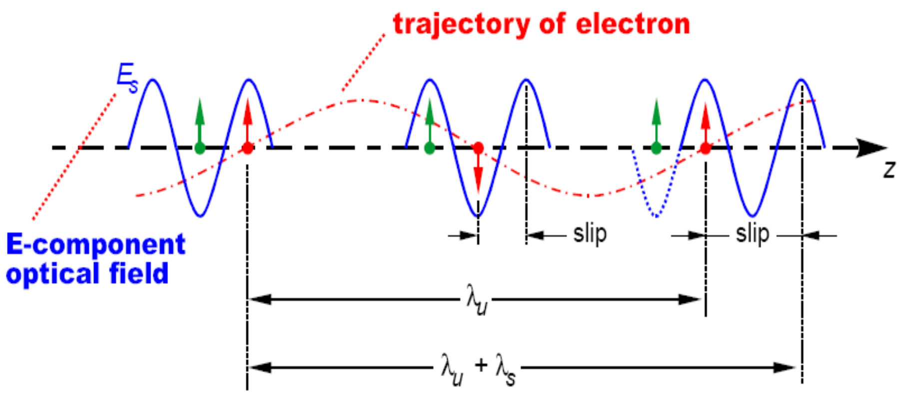
Undulator strength parameter:
***K* = 0.934 λ_u[cm] B_{max} [T]**

Undulator resonance wavelength:

short undulator period — *small undulator gap*

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

high e-beam energy, small energy spread — *small e-beam divergence*

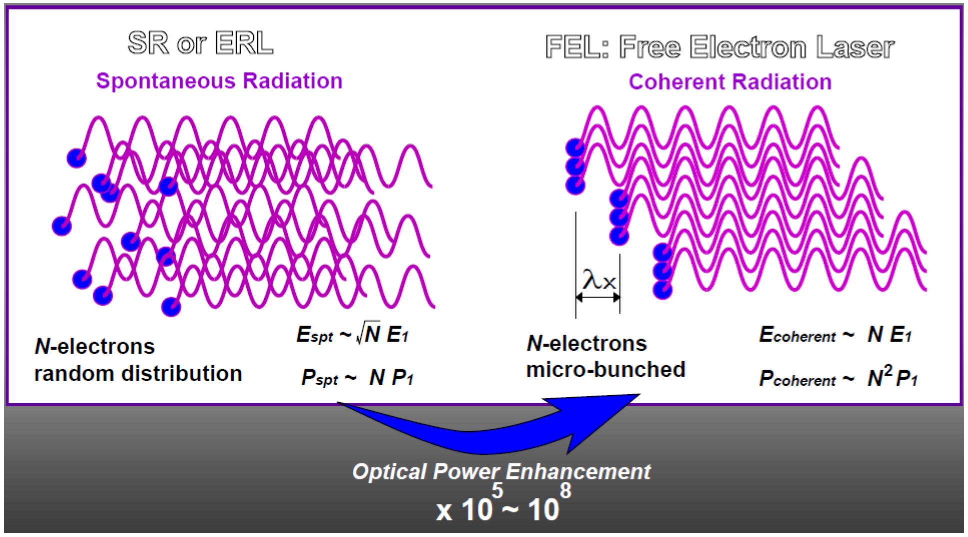


$$\frac{\lambda_u + \lambda_s}{c} = \frac{\lambda_u}{v_z} \iff \lambda_s = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

- Electrons' transverse velocity ***couples*** to the transverse electric field.
- To amplify in intensity, the light should ***overlap*** with the electrons and out race them by one optical wavelength (2π in phase) after they have traveled one full cycle, *i.e.* λ_u.

Microbunching and FEL instability

Pictures courtesy of
T. Shintake



If the electrons are ***independently radiating***, then the phase of their electric field are random with respect to one another, like in ***SLS***, and we have: $\left|\vec{E}\right| \propto \sqrt{N_e},\ P_{\gamma,tot} \propto N_e$

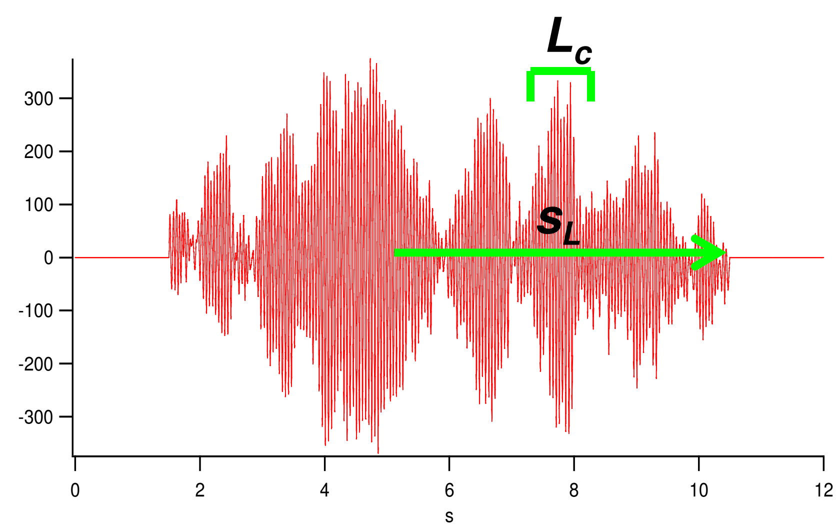
If the electrons are in lock-synch and ***radiate coherently***, like in ***FELs***, one can get an enormous gain in power emitted: $\left|\vec{E}\right| \propto N_e,\ P_{\gamma,tot} \propto N_e^2$

TOTAL EMISSION:

$$\frac{dN_{\gamma,tot}(\lambda)}{dt} = \frac{dN_{\gamma,e}(\lambda)}{dt}\left[N_e + N_e(N_e - 1)f(\lambda)\right]$$

The FEL pulse consists of several coherent regions (L_c) randomly distributed over the e-bunch. Photons slip over the electrons (s_L) "connecting" multiple spikes.

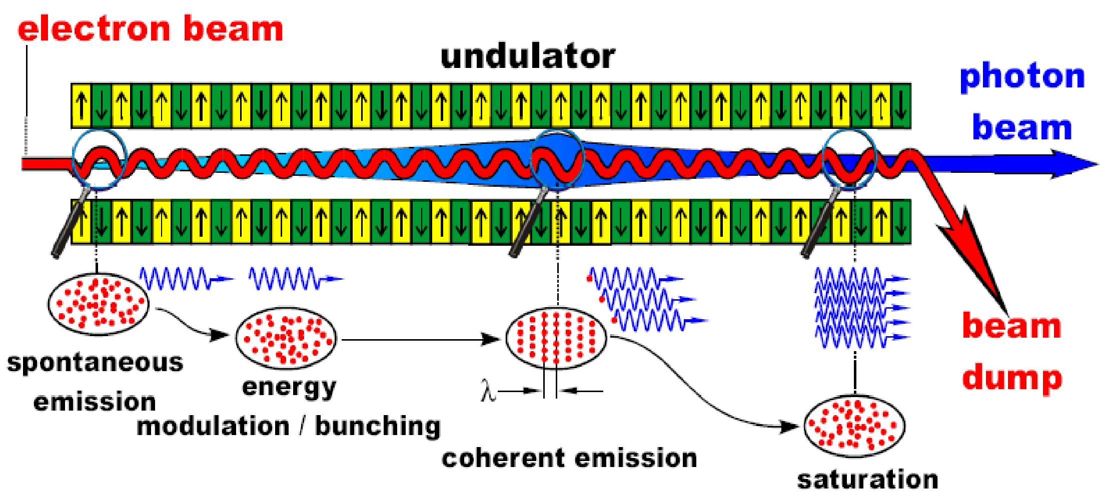
$$L_c \equiv \frac{\lambda}{4\pi\rho_{FEL}} \qquad s_L \equiv N_u\lambda$$

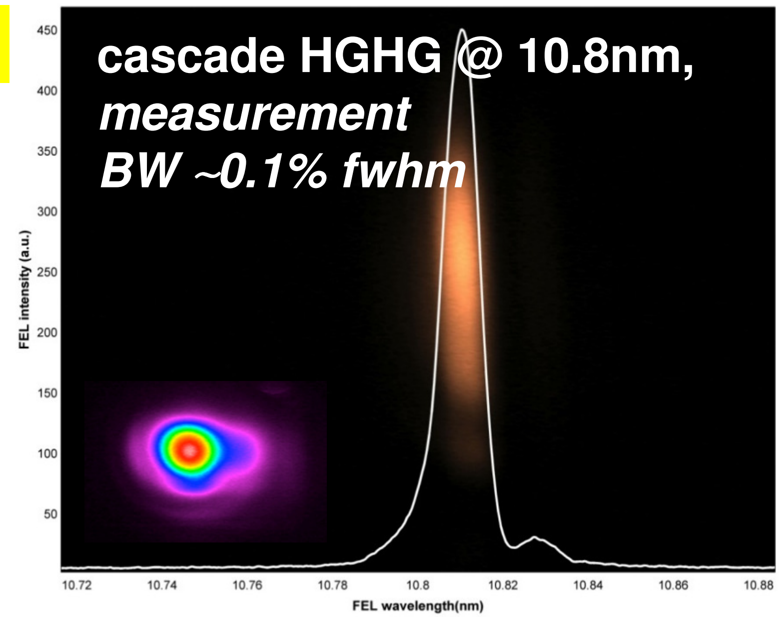


Optical Architectures: SASE vs. Seeded FEL

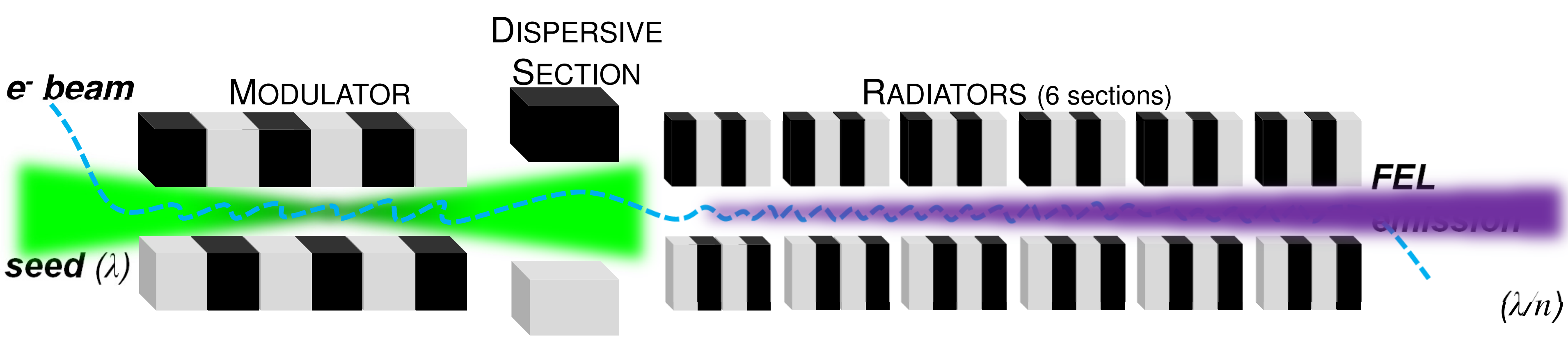
Pictures courtesy of
R. Bakker, E. Allaria,
G. De Ninno

❑ Self-Amplified Spontaneous Emission FEL:





❑ Externally Seeded FEL: High Gain Harmonic Generation



Requirements on Undulator and e-Beam

e-beam peak current — *Undulator parameter*

$$\rho = \frac{1}{4}\left[\frac{1}{\pi^2}\frac{I}{I_A}\frac{\lambda_u^2}{\gamma^3\sigma^2}(K \times JJ[K])^2\right]^{1/3}$$

e-beam energy — *e-beam transverse size*

- **Pierce parameter ρ.** The jack of all trades of 1D FEL theory. Typically $\rho \lesssim 10^{-3}$

$$P(s) = P_0 e^{\frac{4\pi\sqrt{3}}{\lambda_u}\rho s}$$

- **Radiation power** grows exponentially along the undulator (typical behavior for instability-driven processes) until *saturation.*

$$P_{sat} \sim \rho\, P_b$$

- **Radiation power at saturation** is proportional to ρ and e-beam power: $P_b = E_b I/e$.

$$L_{sat} \sim \frac{\lambda_u}{\rho}$$

- **FEL power saturation length**. This sets the scale for the undulator length.

> **To have a large ρ, we need high peak current, small transverse emittance, small energy spread.**
>
> **For any given ρ, we need an undulator as long as ~ λ_u/ρ (standard SASE).**

e-Beam Brightness

- **6-D energy-normalized e-beam brightness** (i.e., emittances do not change with acceleration, and are assumed to be uncoupled):

$$B_{n,0} \equiv \frac{Q}{\varepsilon_{n,x}\varepsilon_{n,y}\varepsilon_{n,z}} = \frac{Q}{\gamma_0^2 \varepsilon_{x,0}\varepsilon_{y,0}\sigma_{z,0}\sigma_{E,0}}$$

  - *Apply both to projected and slice emittances*
  - *(2π) normalization factors skipped here*

- In the presence of **collective effects** (frictional forces due to inter-bunch Coulomb interactions, image charges, etc.), the normalized emittances grow by a factor ζ (in each plane):

$$B_{n,f} \equiv \frac{Q}{\varepsilon_{nx,f}\varepsilon_{ny,f}\varepsilon_{nz,f}} = \frac{Q}{\zeta_x\zeta_y\zeta_z\gamma_0^2 \varepsilon_{x,0}\varepsilon_{y,0}\sigma_{z,0}\sigma_{E,0}} = \frac{B_{n,0}}{\zeta_x\zeta_y\zeta_z}$$

- The contributions from different collective effects to the final emittance growth (ζ) can in principle be balanced, in order to have the minimum impact on $B_{n,0}$.

  Minimize collective effects and/or to balance them, is a major part of Linac Design for FELs.

Brightness and FEL Wavelength

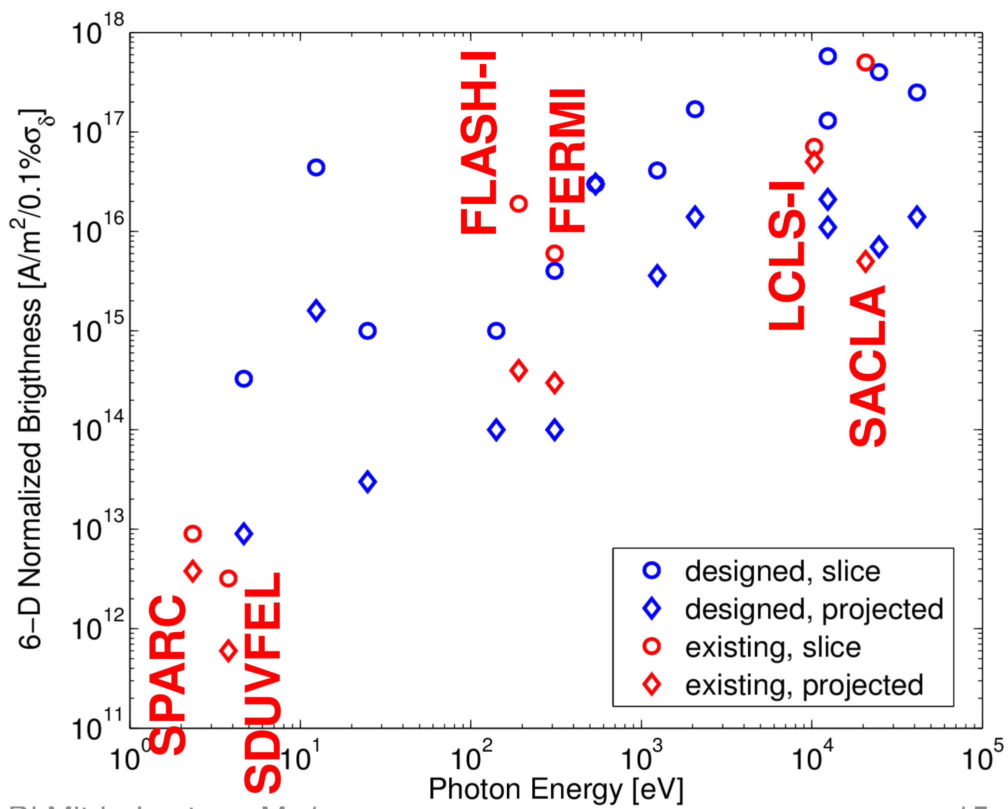
Picture in PR 539 (2014)

- Take $B_{n,0}$ (previous slide) and set the transverse emittances at the diffraction limit, $\varepsilon_{x,y}=\lambda/4\pi$, then substitute λ with the FEL resonance condition. We thereby obtain a dependence of the (required) brightness on the (desired) FEL wavelength:

$$B_{n,0}(\lambda) \equiv \frac{Q}{\varepsilon_{n,x}\varepsilon_{n,y}\varepsilon_{n,z}} = \frac{I}{c\sigma_E\gamma_0^2\varepsilon_0^2} \approx \frac{32\pi^2}{c}\frac{I}{\sigma_E}\frac{1}{\lambda_u\left(1+K^2/2\right)}\frac{1}{\lambda}$$

→ The ***shorter*** the lasing ***wavelength*** we want to reach, the ***higher*** the e-beam ***brightness*** has to be at the undulator.

→ This plot summarizes a series of estimated/measured peak brightness vs. minimum FEL fundamental wavelength, in existing/planned FEL facilities (2013).



Brightness and FEL Parameter

- Take $B_{n,f}(\lambda)$ (see previous slide) and substitute it into the definition of ρ_{FEL}, again with emittances at the diffraction limit. As a practical case, assume K=1. We find:

$$\rho \approx 0.016 \frac{E[GeV]^{4/3} \lambda[nm]}{\beta_u [m]^{1/3}} \sigma_\delta^{1/3} B_{n,f} \left[\frac{A}{\mu m^2} \right]^{1/3},$$

N.B.: for *any given brightness*, the strongest dependence of ρ is on the beam **energy**.

- Equation above can be further manipulated to highlight the dependence of ρ_{FEL} on the e-beam parameters at the undulator:

$$\rho \approx 3.1 \times 10^{-4} \left(\frac{I[A] \varepsilon_{n,x}[\mu m]}{\beta_u [m]} \right)^{1/3}$$

N.B.: at *any given* λ, it is always convenient to **increase** the **peak current**, while there is no practical convenience in **reducing** the **emittance** below the diffraction limit, because this would reduce ρ_{FEL} (with much improvement neither in the FEL output power, nor in the FEL transverse coherence).

Layout and Physics Challenges

Picture courtesy of
D. Nguyen

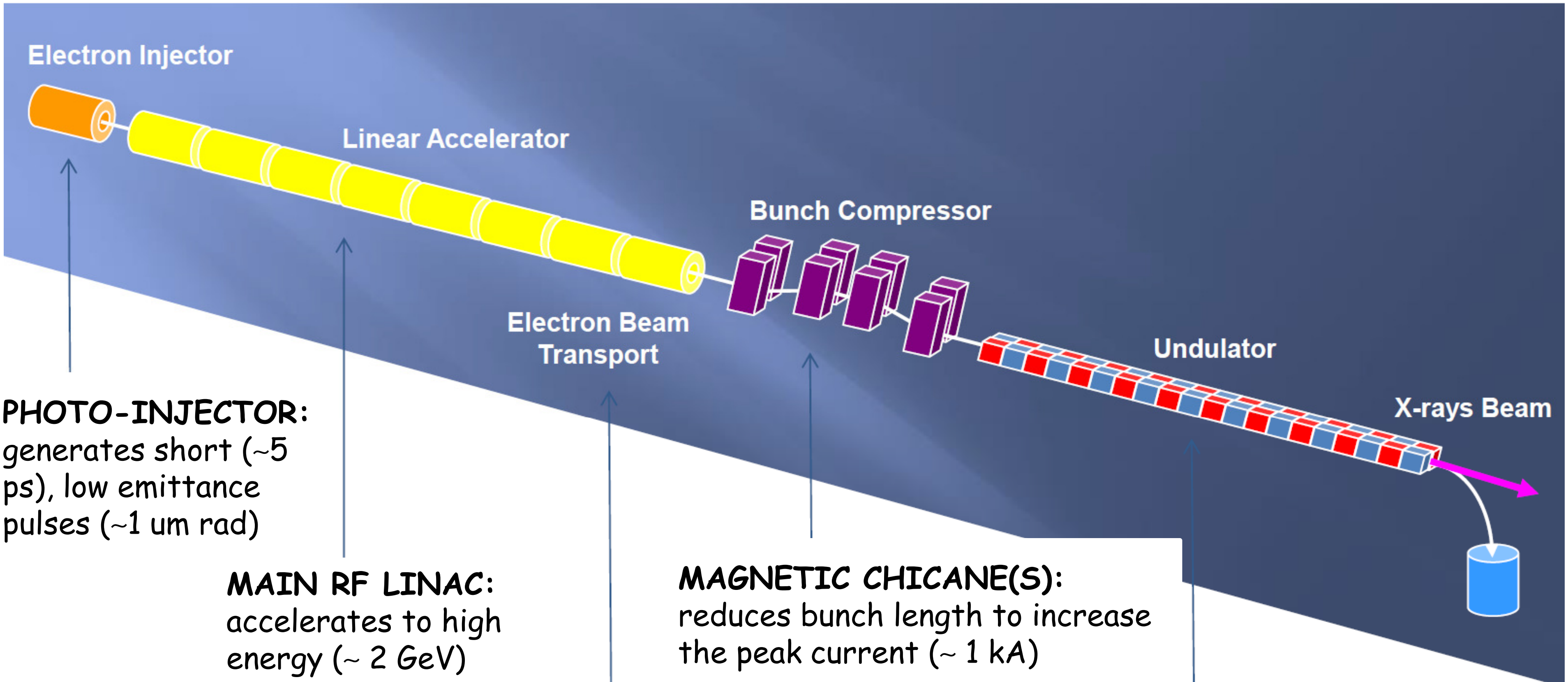


PHOTO-INJECTOR:
generates short (~5 ps), low emittance pulses (~1 um rad)

MAIN RF LINAC:
accelerates to high energy (~ 2 GeV)

MAGNETIC CHICANE(S):
reduces bunch length to increase the peak current (~ 1 kA)

MAGNETS:
direct and focus electrons to ensure full and safe bunch charge transport

UNDULATOR:
for lasing at desired wavelength (~ 1 nm), and output power (~ 1 GW)

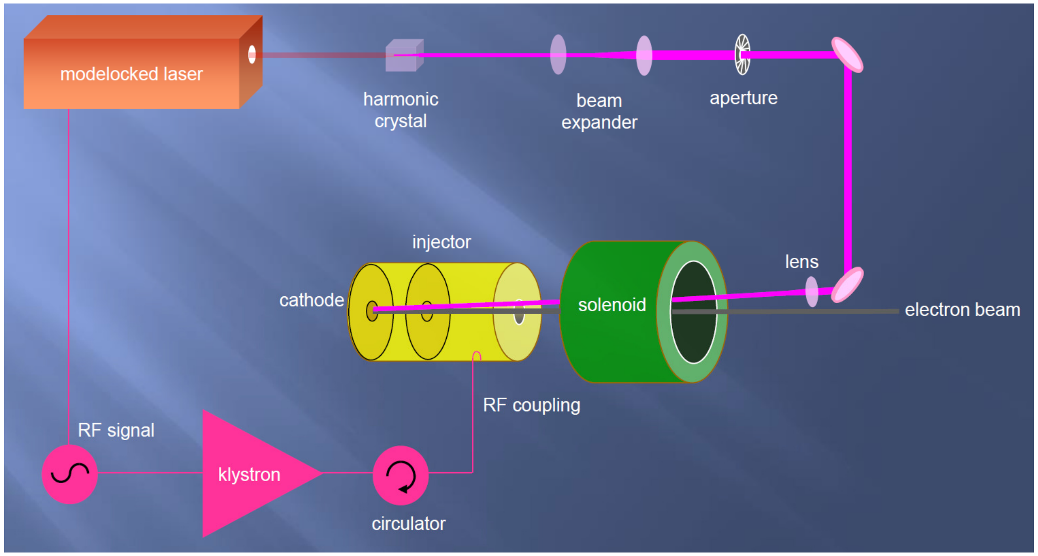
Other Components

Picture courtesy of
D. Nguyen

- ***Transfer lines:*** connect different accelerator sections (injector, main linac, undulator, dump), while preseving the beam quality.
- ***Diagnostic stations:*** include diagnostic elements (also RF) and magnets, to characterize the beam sizes and emittances; both non- and invasive.
- ***Collimation systems:*** scatter/absorb halo particles, traveling at large betatron and energy coordinates, while not interfering with the main beam.
- ***Dump lines:*** stop the beam at intermediate/full energy, often associated with spectrometer lines for diagnostics.

- ***Injector:*** normal conducting, RF photo-injector is the most common to date. Others involve, e.g., superconducting / DC / VHF / thermo-ionic systems.

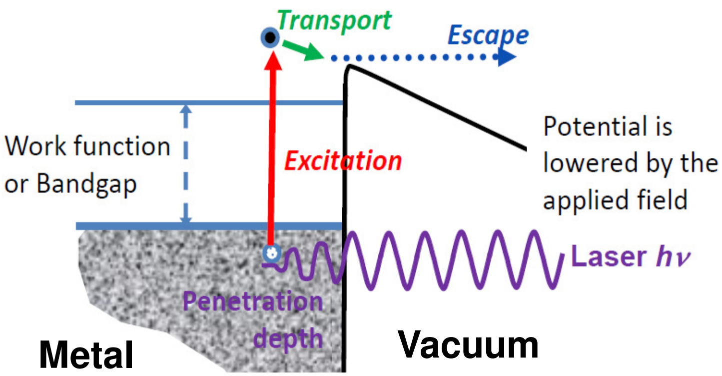
Crucial component!
It defines the ***lowest value*** for the ***normalized beam brightness*** along the entire facility (emittance exchange schemes not considered here).



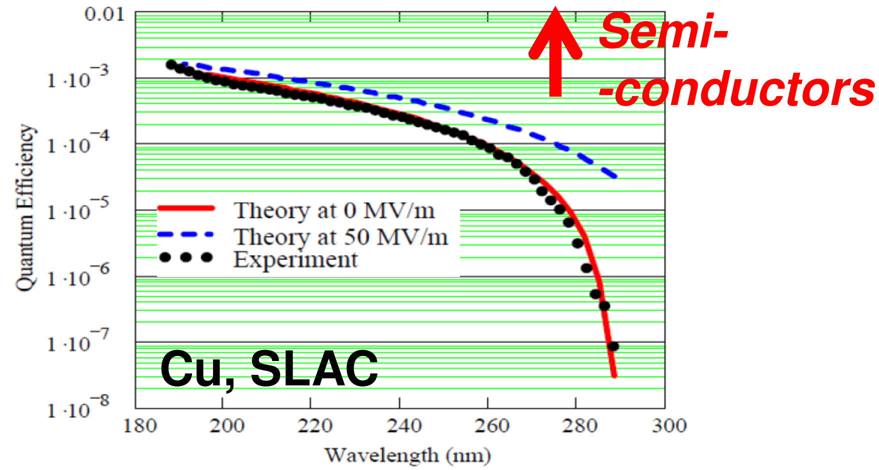
NC-RF Photo-Injector (mention)

Picture courtesy of
D. Nguyen, D. Dowell

❑ **3-Steps Photo-Emission:**

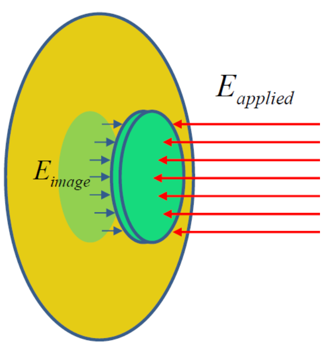


❑ **Quantum Efficiency := Q[C]/(#photons)**



❑ **Thermal Emittance, Radius**

$$\varepsilon_{n,thermal} = \sigma_r \sqrt{\frac{h\nu - \phi_{eff}}{3m_e c^2}} \approx \sigma_r \times (0.3 - 0.5) mrad$$



$$E_{cathode} = E_{applied} - E_{image}$$

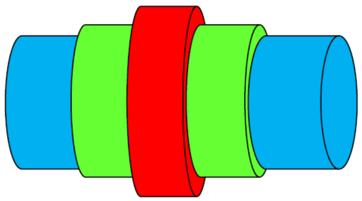
$$E_{image} = \frac{q}{\varepsilon_0 A}$$

❑ **Typical ranges for metal cathode NC-RF PIs are:**

- Gradient ~ 100 MV/m
- QE ~ 10^{-4}
- Rep. Rate ~ 100 Hz
- Cathode lifetime ~ year(s)
- Beam energy ~ 5 MeV
- Total charge ≤ 1 nC

«Emittance Compensation»

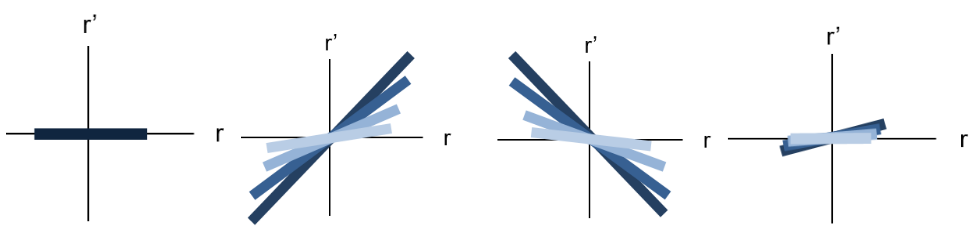
Pictures courtesy of
M. Ferrario, M. Trovò, C. Harris

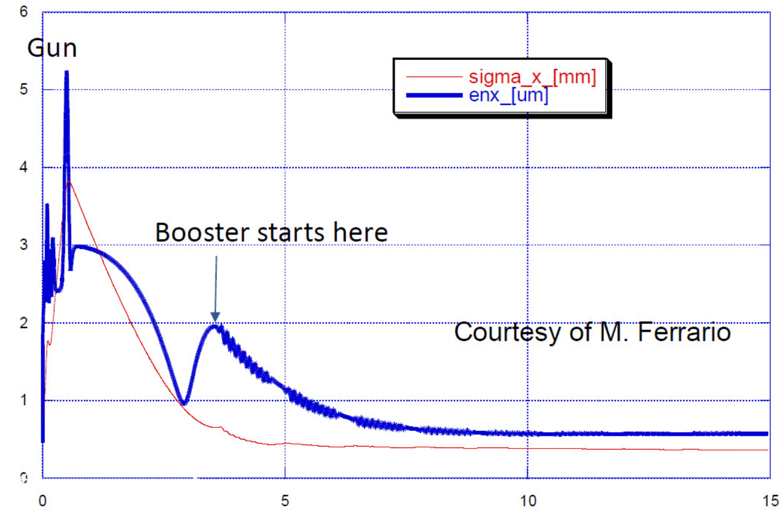


$$r'' = \frac{qI}{2\pi\varepsilon_0 m_e c^3 \beta^3 \gamma^3} \frac{r}{R^2} \rightarrow F(r) \propto \frac{r}{\gamma^2}$$

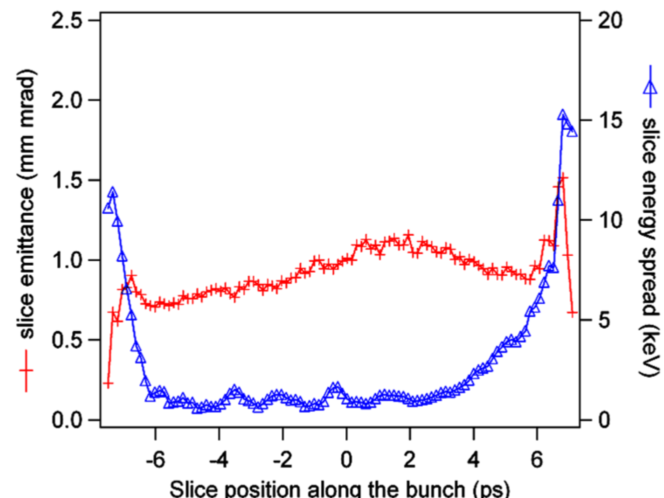
- Because of non-uniform longitudinal charge distribution, slices expand radially at different rates. The force is linear with r.

- External *linear* focusing (e.g., solenoid) realign slices in phase space, reducing the *projected emittance.*



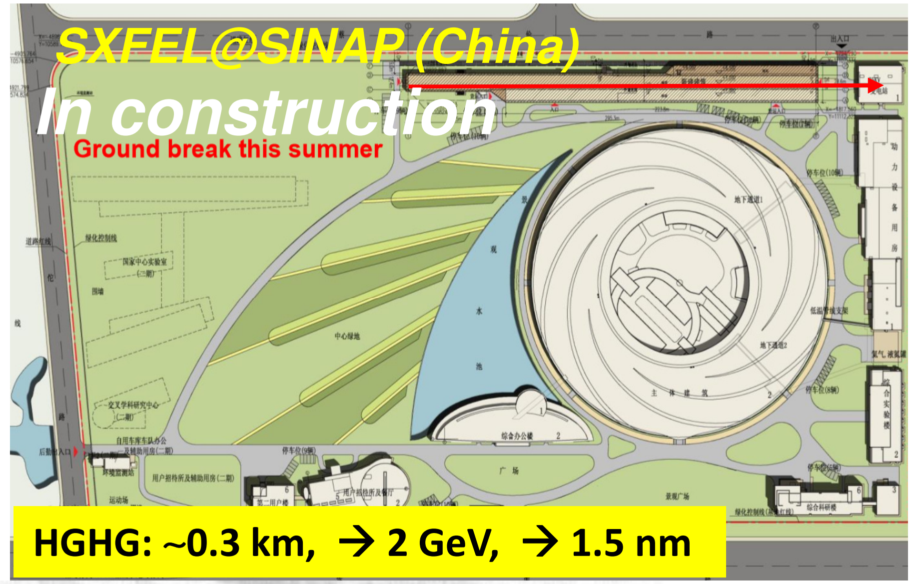


$$\varepsilon_{n,tot}[\mu m] \approx \sqrt{Q[nC]}$$



Worldwide XUV FEL *User Facilities*: now running

Worldwide XUV FEL *User Facilities*: coming soon

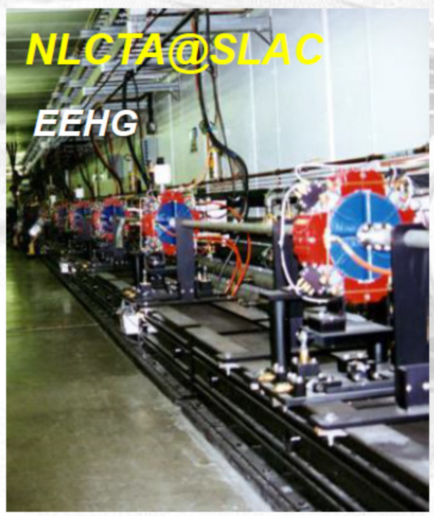


Worldwide FEL *Test Facilities*

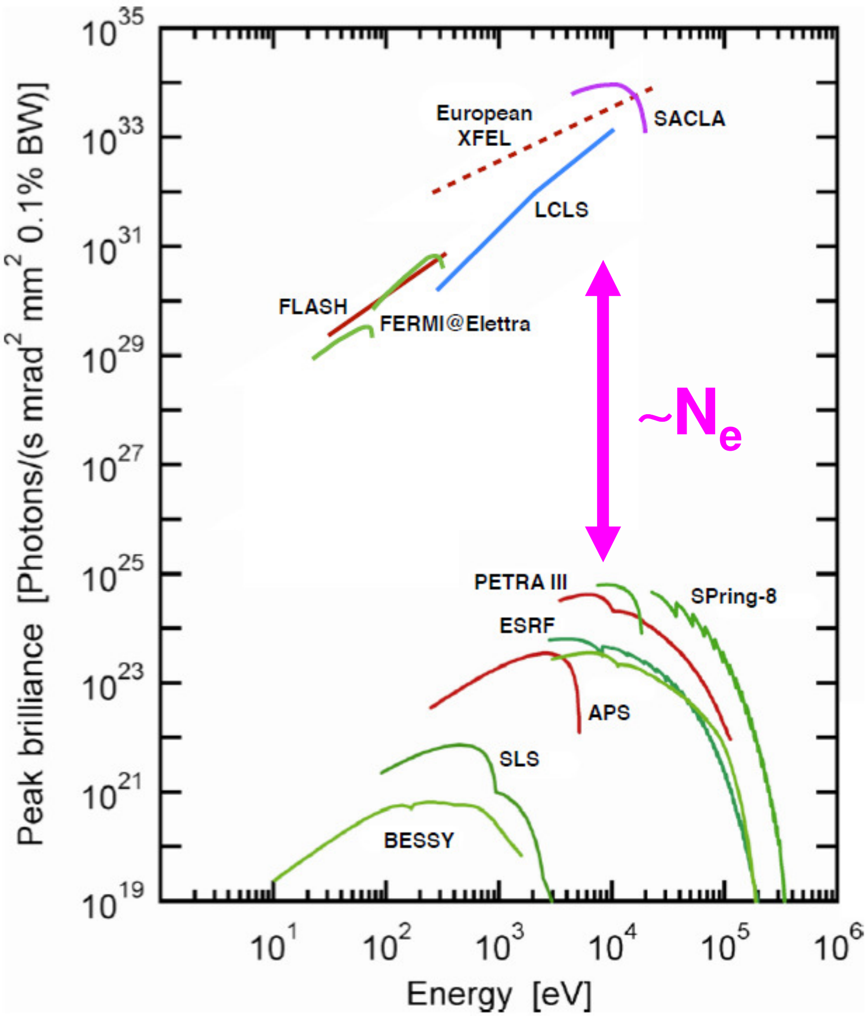
All the present test facilities experimented SASE and Seeded FEL schemes.

Proof-of-principle FEL studies are carried out at lower beam energy – longer wavelength than user facilities.

Research on several seeded schemes are ongoing…



Summary Highlights: FEL vs. SLS



	SLS	FEL
Emittance	10 um	<1 um
Energy spread	0.1%	<0.1%
Bunch length	10 ps	0.1 ps
Peak current	30 A	1000 A
Repetition rate	10^8 Hz	$<10^4$ Hz
Intensity stability	10^{-6}	10^{-4}

Synchrotrons are **complementary** to FELs as for:

- λ-tunability
- Multi-users access
- Stability
- Pulse rate

Summary Highlights: FEL Requirements

- High Intensity & Short Pulses $\Rightarrow$ ***$I \sim kA$***
- Electron/Photon Overlap $\Rightarrow$ ***$\gamma\varepsilon < 1.0\ \mu m$***
- Energy Resonance $\Rightarrow$ ***$\sigma_\delta < 0.1\%$***
- Short Wavelength $\Rightarrow$ ***E > 1 GeV***

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

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