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

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Outlook

- Motivations
- Radiation emission in undulator
- Self-Amplified Spontaneous Emission (SASE) FEL
- FEL requirements for electron beam
- FEL design from scratch
- Examples
- Summary

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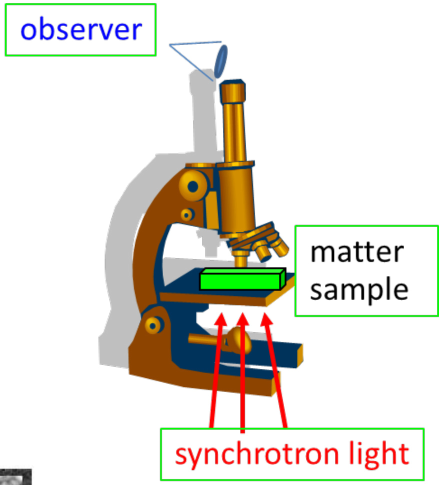
An ideal light source should provide…

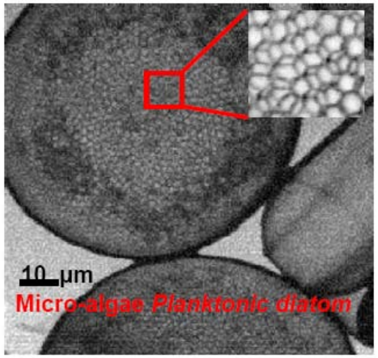


High resolution at small spatial scales

↳ ***short wavelength***

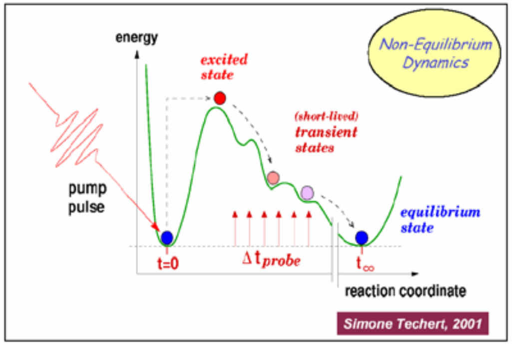
Most of the photons at the same wavelength

↳ ***narrow bandwidth***



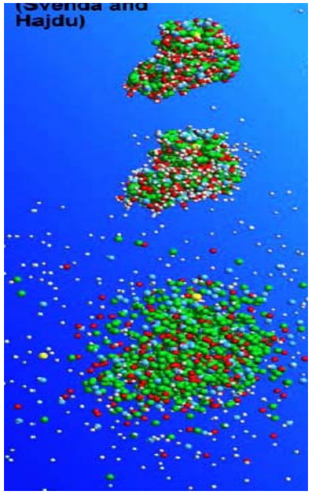
Stroboscopic picture of chimical processes

↳ ***short pulse***



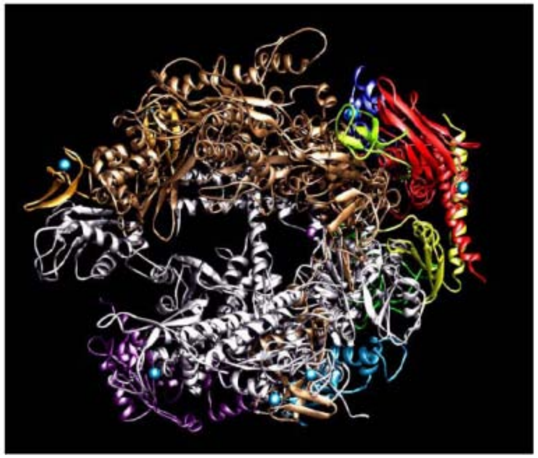
Large statistics in single-shot

↳ ***large number of photons per pulse***



Large statistics in multi-shot

↳ ***high repetition rate***



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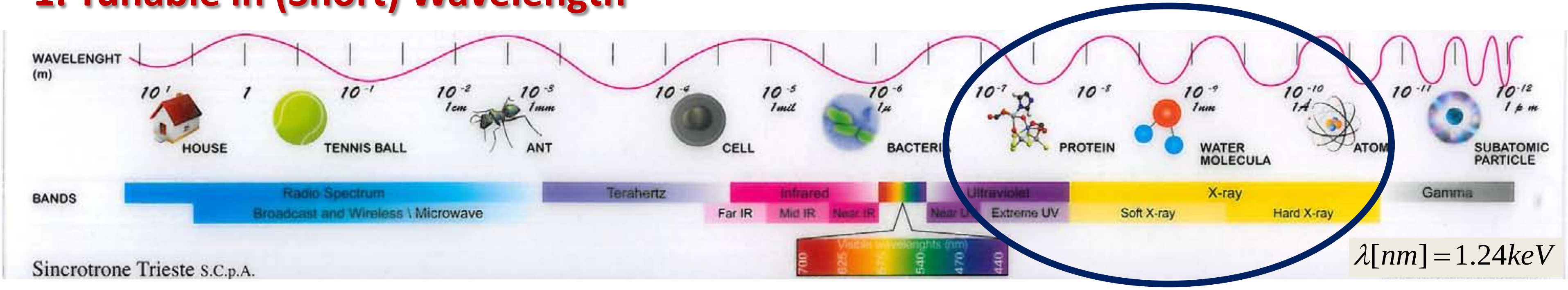
An ideal light source should be…

1. Tunable in (Short) Wavelength

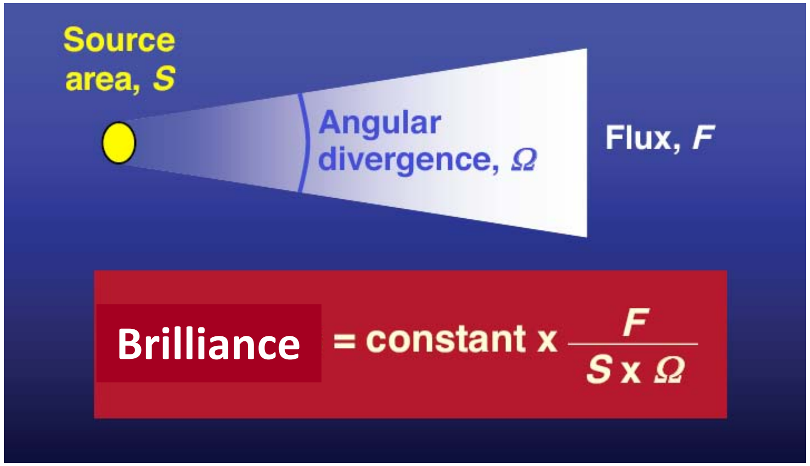
Range of interest here



$$\lambda[nm] = 1.24keV$$

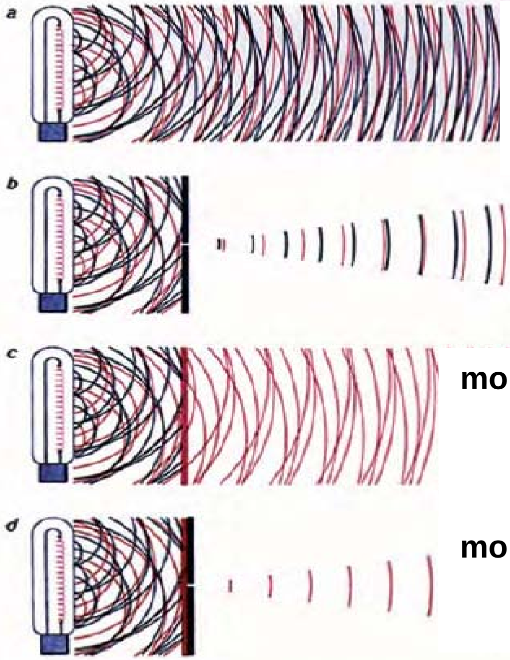
Sincrotrone Trieste S.C.p.A.

2. Highly Brilliant



Brilliance $= \text{constant x } \frac{F}{S \times \Omega}$

3. Fully Coherent



multi-color ✗
wide source ✗

multi-color ✗
collimated ✓

monochromatic ✓
wide source ✗

monochromatic ✓
collimated ✓
= *coherent !*

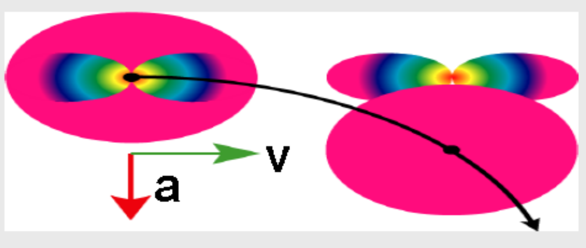
Courtesy of A. Schawlow, Stanford.

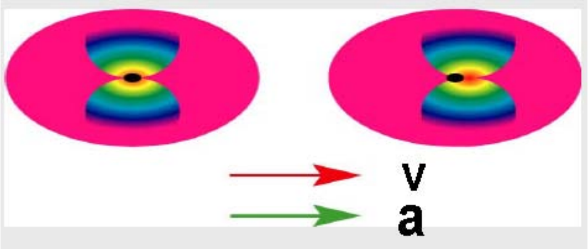
Radiation emission of a charged particle

- ☐ A **charged** particle **radiates** under **acceleration.**
- ☐ **Ligther particles** such as electrons, radiate more than heavier ones such as protons, when subjected to the same force. **Circular acceleration** is more efficient than linear.

$$P_{circ}[kW] = \frac{2}{3}\frac{e^2}{c^3}\frac{\gamma^2}{m_0^2}\left|\frac{d\vec{p}}{dt}\right|^2 = 88.46\frac{E^4[GeV]\cdot I[A]}{R[m]}$$

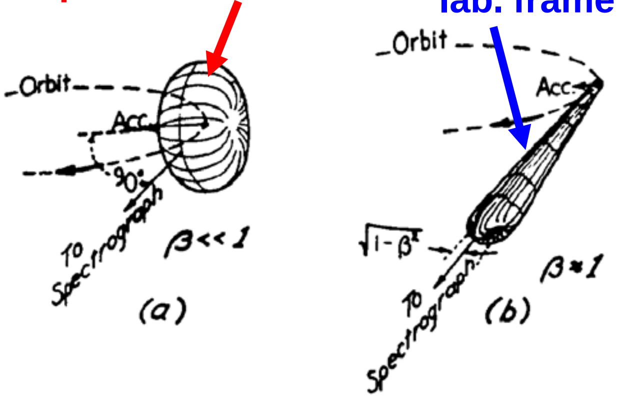
$$P_{lin} = \frac{P_{circ}}{\gamma^2}$$





~ in particle rest frame

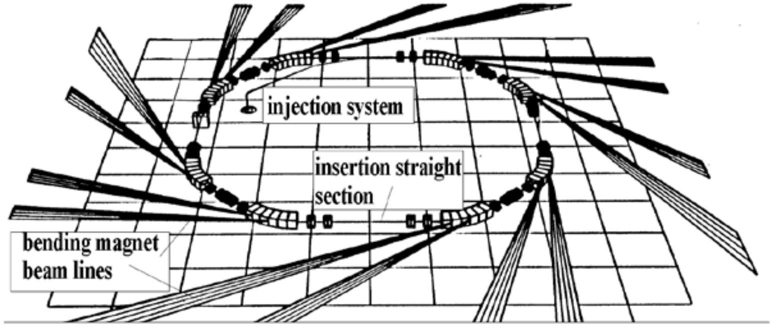
Lorentz-boosted lab. frame



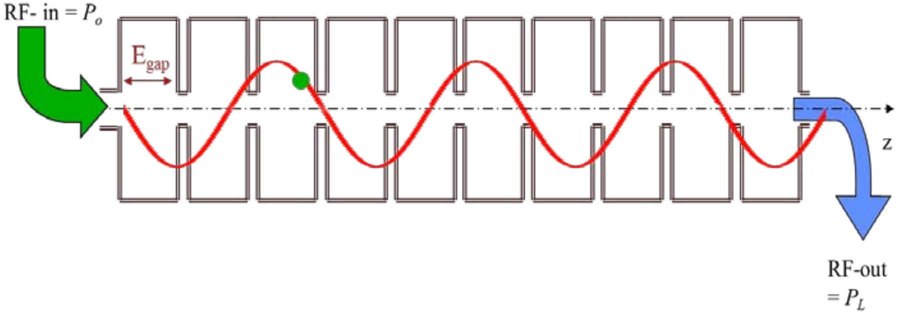
- ***Circular acceleration*** *can be provided by dipole magnetic field:* ***synchrotron light sources.***
- ***Linear acceleration*** *can be provided by longitudinal electric field:* ***RF structures.***

Why a *LINAC*-driven light source

☐ e-beams in **synchrotron light sources** (SLS) reach ***equilibrium* properties** that are typically far from providing short pulses, high intensity, and narrow bandwidth at short wavelengths.



☐ 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…*

Undulator Spontaneous Emission

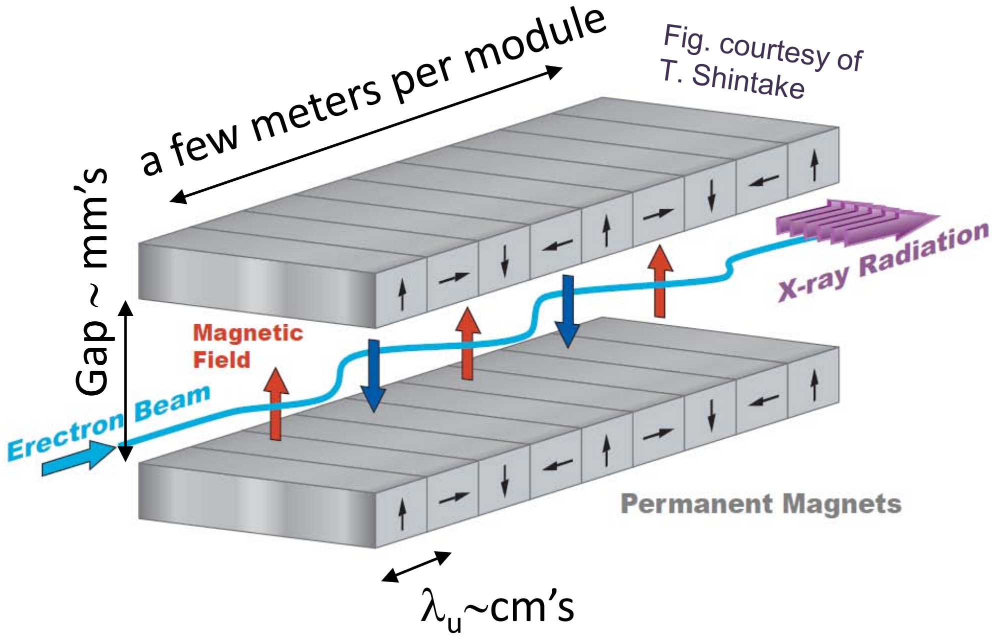
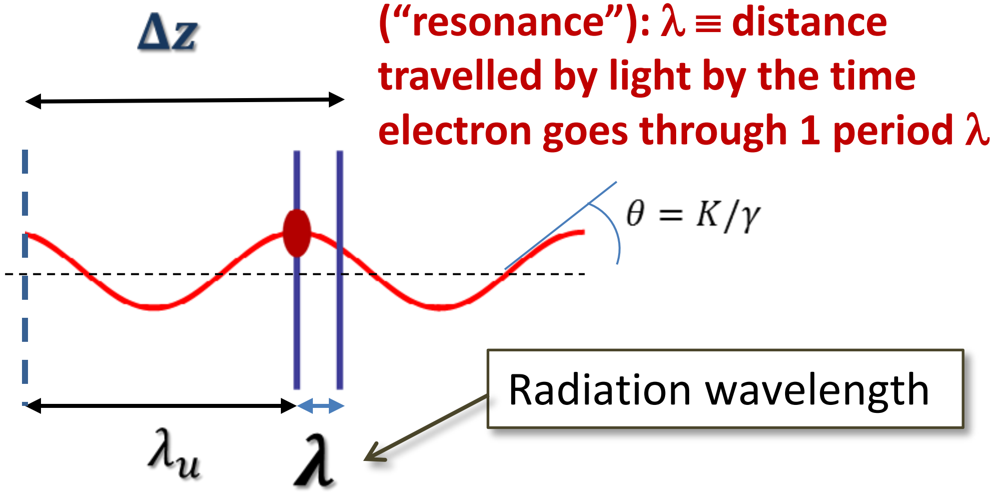


Fig. courtesy of T. Shintake

Constructive interference ("resonance"): λ ≡ distance travelled by light by the time electron goes through 1 period λ_u



Undulator resonance wavelength:

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

short undulator period

High magnetic field

high e-beam energy, small energy spread

small e-beam divergence

Undulator strength parameter:

***K* = 0.934 λ_u[cm] B_{max} [T]** ≈ *1 ÷10*

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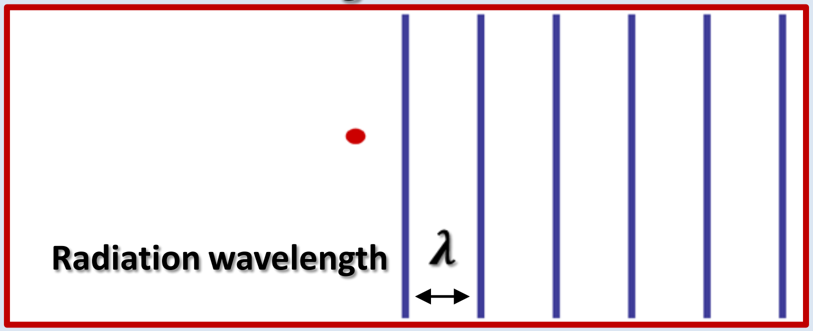
Incoherent vs. Coherent Emission

no. photons emitted by 1 electron through N_u undulator periods in $\sim 1/N_u$ bandwidth and $\sim 1/(\gamma^2 N_u)$ solid angle

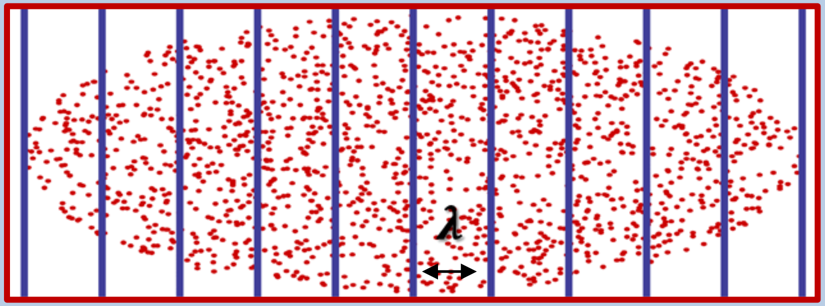
Single electron



$$N_{ph} \sim \pi\alpha \frac{K^2}{1+K^2/2}$$

$\alpha = e^2/\hbar c$ = 1/137 (cgs)

Bunch length ≫ λ

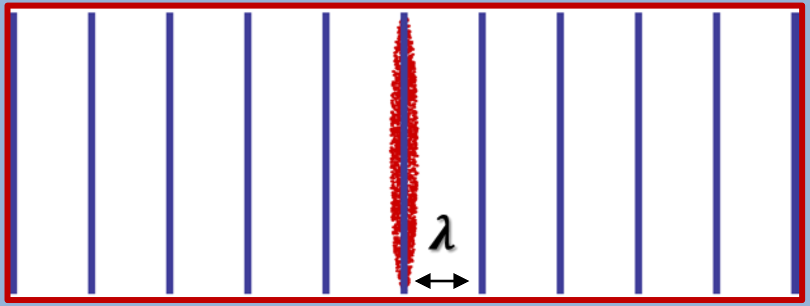


Linear in no. of electrons/bunch

$$N_{ph} \sim N_e \pi\alpha \frac{K^2}{1+K^2/2}$$

Incoherent emission

“Nanobunch” beam length ≤ λ



Quadratic in no. of electrons/bunch

$$N_{ph} \sim N_e^2 \pi\alpha \frac{K^2}{1+K^2/2}$$

Fully coherent emission

Courtesy of M. Venturini

How do micro/nano-bunches form?

1. Electrons initially radiate ‘undulator **spontaneous emission**’. Their longitudinal density distribution is governed by **shot noise**.
2. The electron transverse velocity ***couples*** to the photons’ transverse electric field.
3. 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.

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

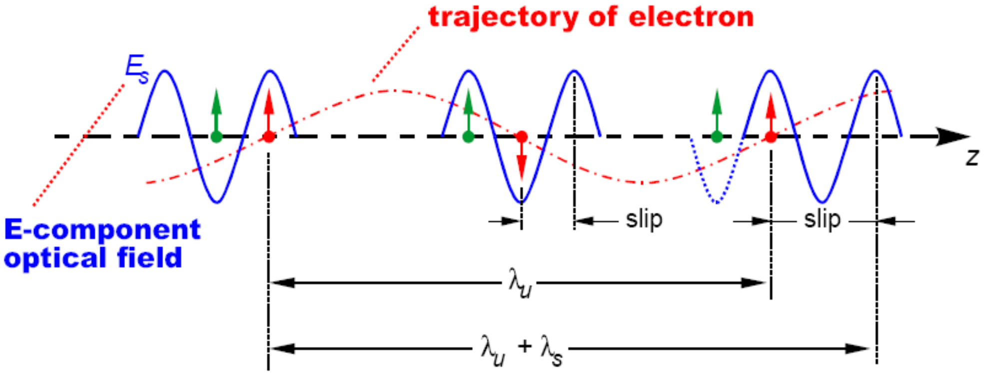


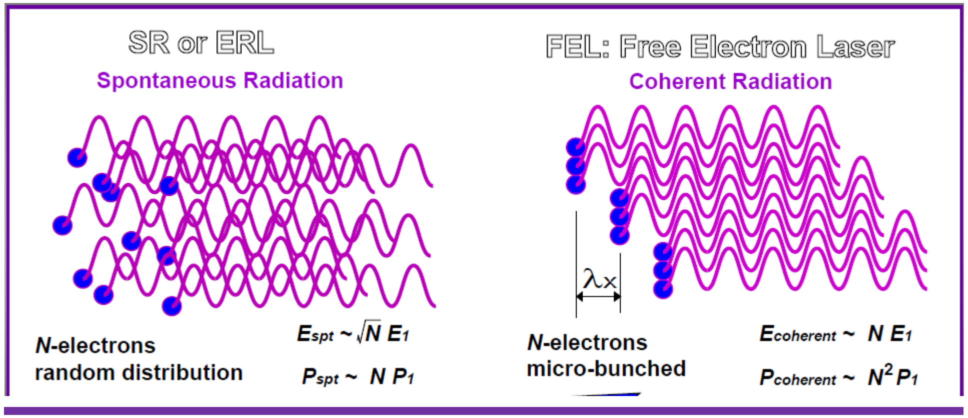
Fig. courtesy of R. Bakker

4. The electrons are modulated in energy at wavelength λ. Their path-length dependence on the energy (intrinsic energy-dispersion in the undulator is $2N_u\lambda_u$) translates the energy modulation into **density modulation** (“bunching”) at the same resonance wavelength.
5. The micro/nano-bunched beam emit coherently → ***Self-Amplified Spontaneous*** **Emission (SASE FEL)**.

FEL resonance condition ≡ undulator radiation constructive interference.
This allows the amplification of the “undulator signal”

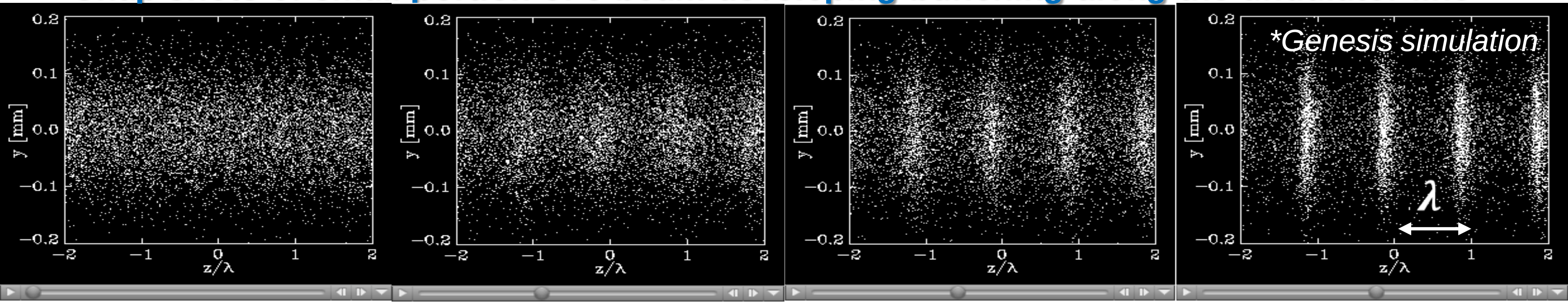
Bunching

Figs. courtesy of
T. Shintake, S. Reiche, S. Milton



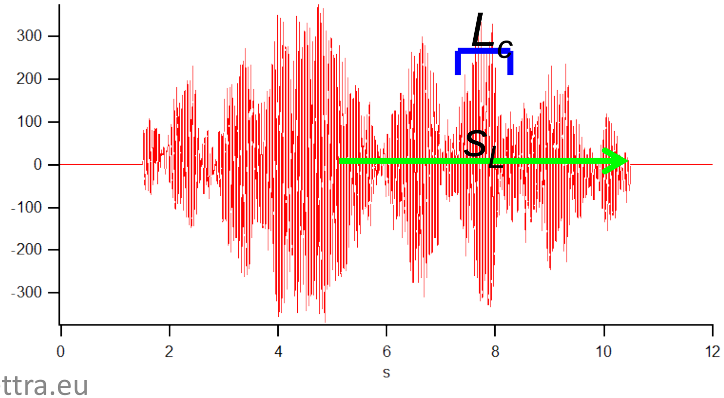
- If the electrons are *independently radiating*, then the phase of their electric field are random with respect to one another, like in *SLS.*
- If the electrons are in lock synch and *radiate coherently*, like in *FELs*, one can get an enormous gain (N) in power emitted.

Snap shots of small portion of e-beam developing bunching along the undulator line*



*Genesis simulation

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



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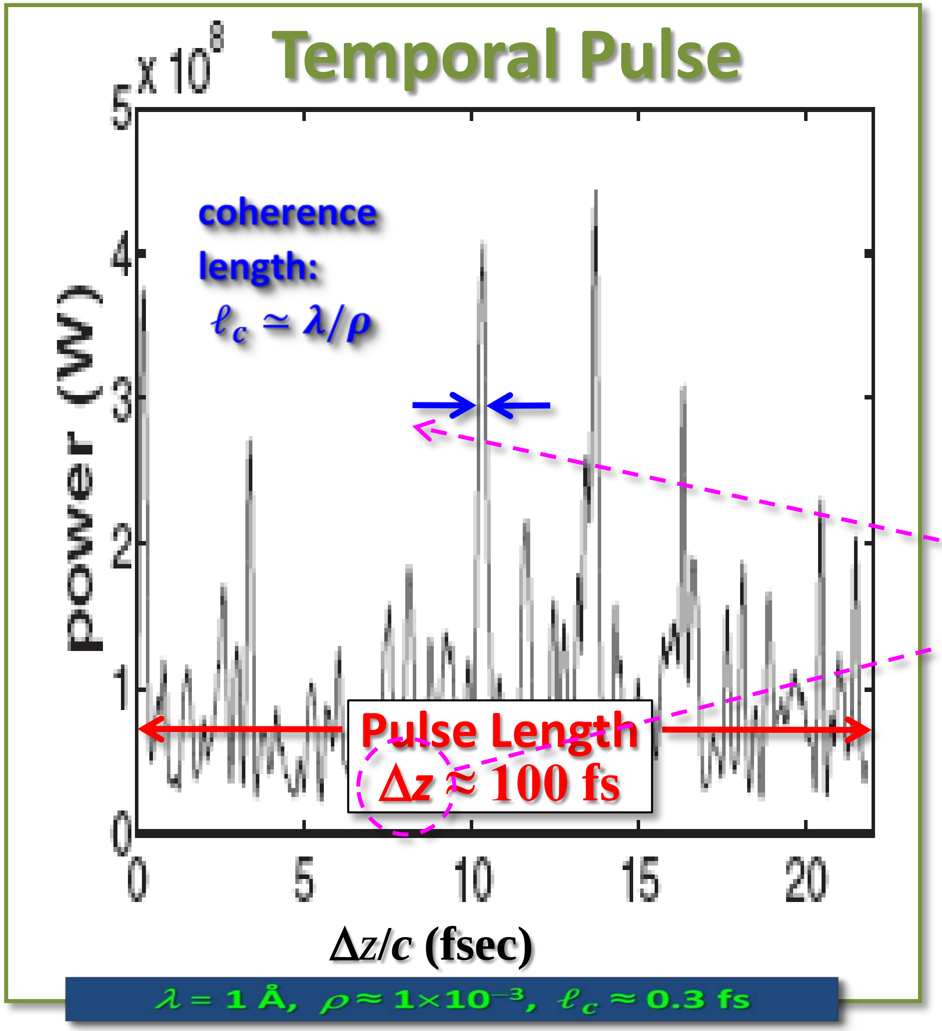
Temporal & spectral radiation pulse structure

Courtesy of
P. Emma, M. Venturini

spikes appear in temporal pulse

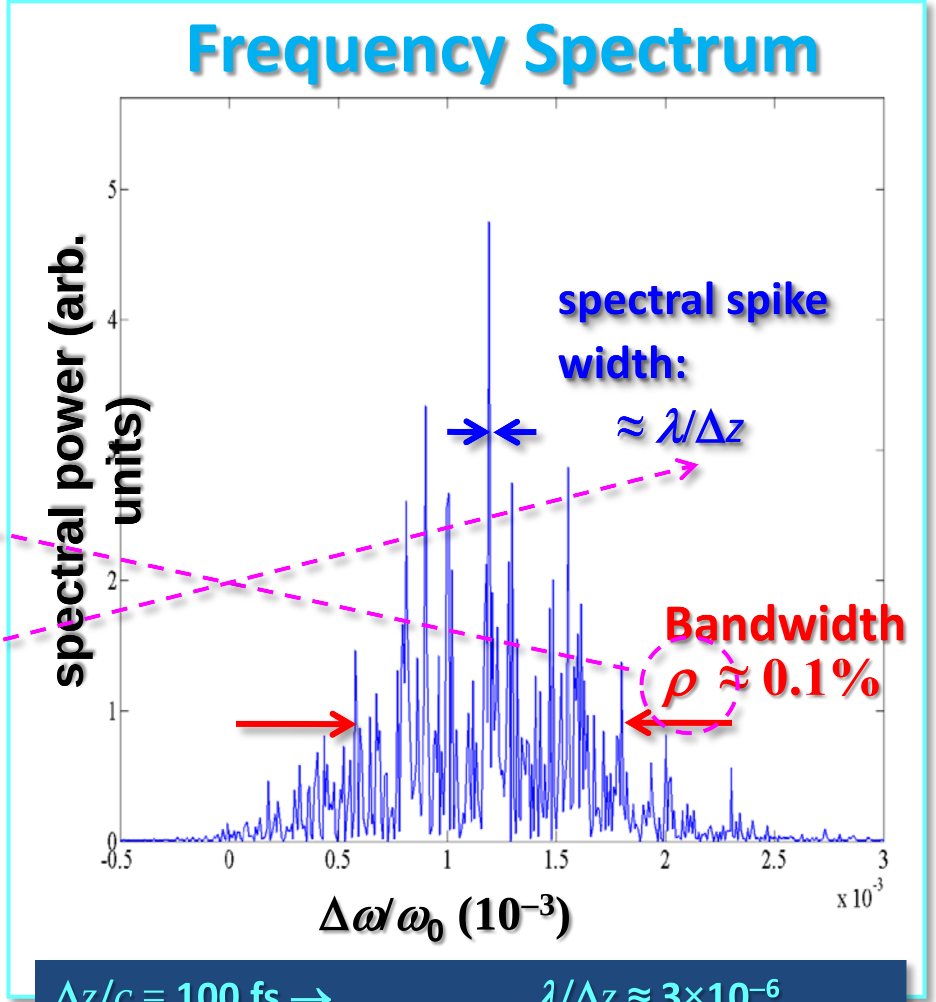
spikes also in spectrum



coherence length: $\ell_c \simeq \lambda/\rho$

Pulse Length $\Delta z \approx 100$ fs

$\lambda = 1$ Å, $\rho \approx 1\times10^{-3}$, $\ell_c \approx 0.3$ fs



spectral spike width: $\approx \lambda/\Delta z$

Bandwidth $\rho \approx 0.1\%$

$\Delta z/c = 100$ fs → $\lambda/\Delta z \approx 3\times10^{-6}$

- Longitudinally radiation is fully coherent over ℓ_c, typically shorter than bunch length
- What is ρ?

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1-D Model for SASE FEL

- 'Cold beam' approx.: zero-emittance, zero-energy spread. Infinitely wide beam with uniform transverse density (no radiation diffraction effects).

e-beam peak current

Undulator parameter

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

Alfven curren

$\boldsymbol{I_A \simeq 17kA}$

Transverse e-beam rms beam size

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

$$\boxed{\ell_c = \frac{1}{4\pi}\,\frac{\lambda}{\rho}}$$

- **Cooperation length.** The length over which electrons within bunch can "communicate" with each other (i.e. how far ahead the radiation emitted by an electron goes by the time it travels through L_g.)

$$\boxed{L_g = \frac{1}{4\pi\sqrt{3}}\,\frac{\lambda_u}{\rho}}$$

- **The FEL power gain length** is inversely proportional to ρ. The smaller the more efficient the FEL process, the sooner we achieve saturation, the shortest the undulator, the less $$$ we need to spend.

$$\boxed{P = P_0 e^{s/L_g}}$$

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

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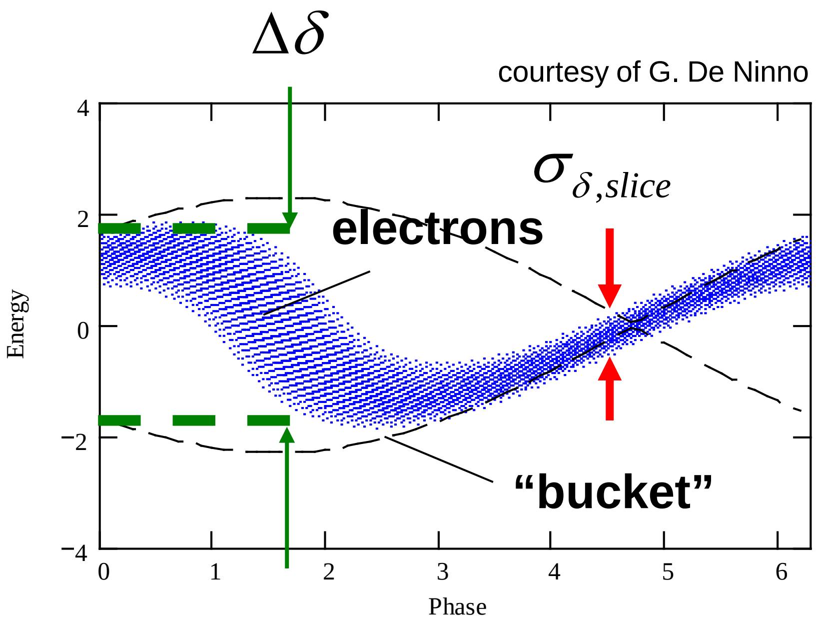
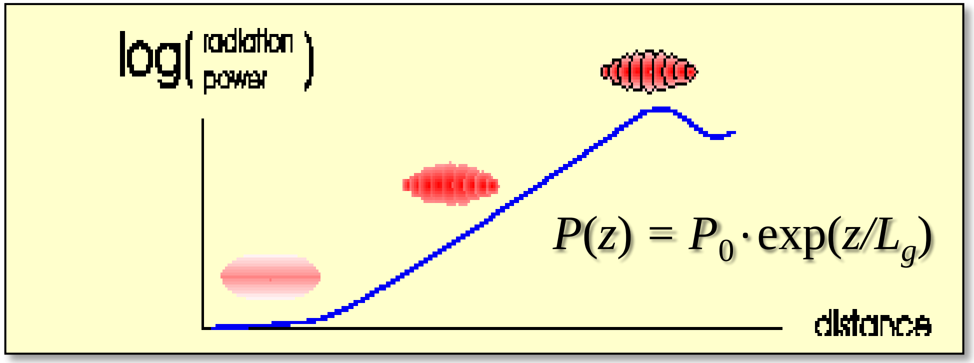
SASE FEL Power at Saturation



At saturation, the beam energy spread reaches its maximum:

→ the longitudinal phase space becomes folded;

→ electrons gain energy from radiation.



$$\boxed{P_s \sim \rho\, P_b}$$

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

$$\boxed{\frac{\sigma_{E,sat}}{E} \sim \rho}$$

- **Beam energy spread** increases along the undulator because of interaction with radiation. When it becomes too large, electrons start falling off resonance, saturation follows.

$$\boxed{L_s \sim \frac{\lambda_u}{\rho}}$$

- **FEL power saturation length**. About $\sim 4\pi\sqrt{3}L_g \sim 20\ L_g$ gain length. This sets the scale for the undulator length

e-Beam Requirements for Lasing

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

1-D model → FEL performance benefits from large ρ → beam high current, small transverse emittance.

$$\boxed{\frac{Q}{c\Delta t} > 0.1\ kA}$$

- **e-beam peak current** should be high (typically from 100s A to kA level) that is a high charge and/or short bunches.

$$\boxed{\varepsilon_\perp \lesssim \frac{\lambda}{4\pi}}$$

- **e-beam transverse emittance** should be on the order of, or smaller than, the radiation emittance (diffraction limit) $\varepsilon_r = \frac{\lambda}{4\pi}$.

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

FEL wavelength → resonance condition for on-energy electrons.

$$\boxed{\frac{\sigma_{E,und}}{E} < \rho}$$

- **Relative energy spread** at the undulator entrance should be small. Electrons with energy too different from nominal slip off the FEL energy-resonance and do not contribute to lasing.

Introduction to beam 2-D emittance

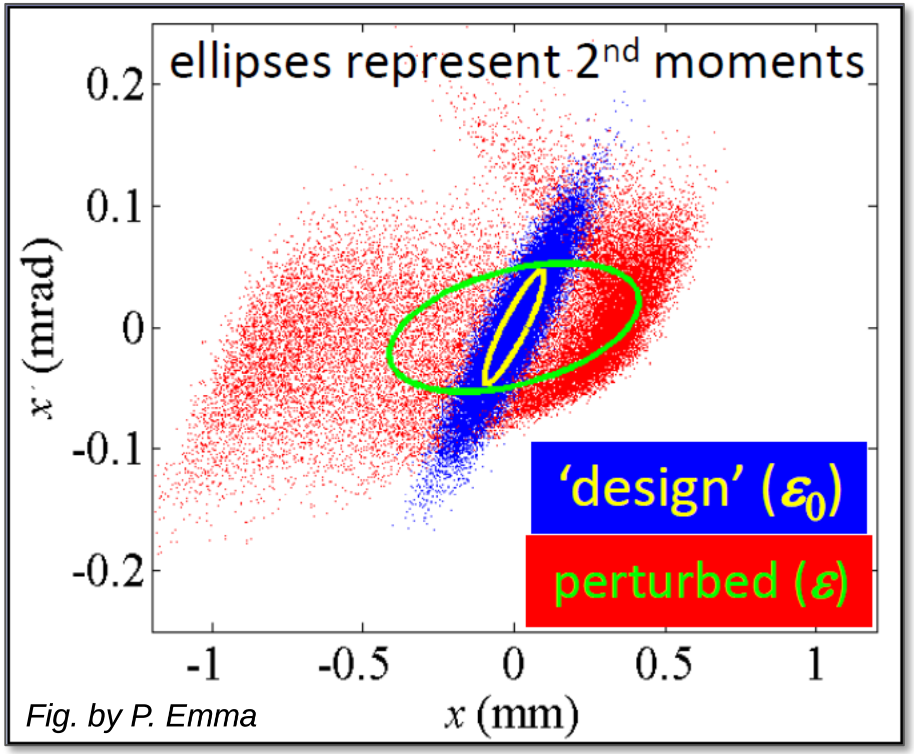


Fig. by P. Emma

$$\langle x^2 \rangle \equiv \int x^2 f(x,x')dxdx'$$

f = beam density distribution function normalized to unity

The beam rms ellipse is defined by the 2D curve in the (x,x') plane:

$$\varepsilon_x = \gamma_x^* x^2 + 2\alpha_x^* x\, x' + \beta_x^* x'^2$$

~ ellipse size in x'

~ ellipse orientation, x/x'

~ ellipse size in x

- ***Geometrical*** meaning of rms emittance: **area $A = \pi\varepsilon_x$ of the beam rms ellipse**
- ***Physical*** *meaning of rms emittance:* ***spread of the particles*** *in the phase space (x, x')*

- **Brightness is best expressed in terms of "normalized" emittances. These are linearly invariant in the presence of acceleration:** $\varepsilon_{nx,y} = \gamma\beta\varepsilon_{x,y} \simeq \gamma\varepsilon_{x,y}$ $\quad \varepsilon_{nz} = \sigma_z\sigma_{E,uncor}$

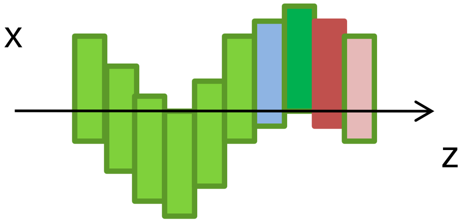
Slice vs. projected emittance

- To function effectively, FELs need beams meeting minimum brightness requirements.
- A concept of 4D or 5D brightness can be also useful:

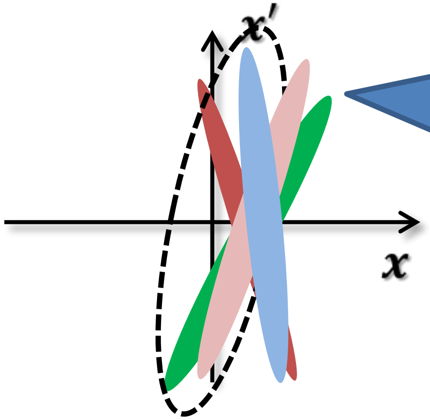
$$B_4 = \frac{Q}{\varepsilon_{nx}\varepsilon_{ny}} \quad \text{or} \quad B_5 = \frac{I}{\varepsilon_{nx}\varepsilon_{ny}}$$

Beam peak current

- **Slice vs. projected transverse emittance:**
  - For lasing, what counts primarily is the rms emittance of the particles within a longitudinal beam *slice* on the order of the **cooperation length** (where the electrons 'talk' to each other) or the **slippage length**.
  - However we should not let the projected emittance grow too much or else individual slices will not be all properly matched to the intended e-beam optics in the undulator.



Snapshot of beam in x/z plane
(various slices highlighted)



*Individual slices may have the same (**slice**) emittance but if the slice rms ellipses are not concentric, the emittance of the whole beam is larger (**projected emittance**)*

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e-Beam 3-D effects (M. Xie's model)

We come up with a figure of merit that captures all the desirable e-beam properties at once – high peak current, small transverse emittance, small energy spread: **e-beam 6-D brightness (energy-normalized)**.

$$B_{6D} = \frac{N}{\varepsilon_{nx}\varepsilon_{ny}\varepsilon_{nz}}$$

No. particles/bunch

Normalized rms emittances in x,y and z

M. Xie (mid ~90s) gave a **parametrization of L_g** based on numerical solutions of 3-D theory: very handy, used extensively for FEL design optimization.

$$L_g = L_{g0}[1 + \Lambda(X_\delta,\ X_d,\ X_\varepsilon)]$$

3D-theory gain length (generally longer than L_{g0})

1D-theory gain length

M.Xie found polynomial approximation to this function

$$X_\delta = \frac{4\pi\sigma_\delta}{\lambda_u} L_{g0}$$

Scaled energy spread

$$X_d = \frac{\lambda}{4\pi\sigma_r^{\ 2}} L_{g0}$$

Scaled transverse size

$$X_\varepsilon = \frac{4\pi\varepsilon_\perp}{\beta_{twiss}\lambda} L_{g0}$$

Scaled transverse emittance

- ✓ 1D limit recovered when X_δ, X_d,$X_\varepsilon \to 0$ while keeping the beam charge density constant
- ✓ Lot of physics goes into L_g. For accurate determination do numerical simulations.

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First estimate of parameters for FEL design

- Science case generally drives the specifications for the FEL output:
  - Shortest wavelength of interest, say $\boldsymbol{\lambda \equiv 1\mathrm{nm}}$.
  - Wavelength tunability, say $\boldsymbol{\lambda < 5\mathrm{nm}}$.
  - No. photons per pulse, say **>10^{12}** in the full λ-range.
  - Possibly, high repetition rate and/or **multiple, independent** beamlines working **simultaneously**.

☐ Generally the challenge is to reach **short radiation wavelength λ**:

- **Shorter undulator period λ_u** (min. value set by available technology and FEL performance)
- **Larger e-beam energy γ** (max. value set by

Remind:

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

❖ **Step 1**: first rough assessment of needed e-beam energy (we will go back to it). Take $\lambda_u = 2cm$ and $K\sim 1 \Rightarrow mc^2\gamma = mc^2\sqrt{\frac{\lambda_u}{2\lambda}(1+\frac{K^2}{2})}\sim 2GeV$ (energy could get higher if we go with higher K to increase radiation ouput).

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Choice of undulator gap

☐ **λ-tuning range** (i.e. range of radiation spectrum that can be generated once the undulator is installed and λ_u is fixed):

- **Vary beam energy** (can pose operational nuisances; not practical if same linac feeds multiple FELs, operating at the same time and targeting different radiation wavelengths)
- **Vary undulator parameter K** (i.e. magnetic field). Tuning range depends on undulator technology and requirements on the minimum undulator aperture (or 'gap')

❖ **Step 2**: independent beamline tunability → we cannot vary energy to vary λ
→ we have to adjust the undulator gap.

Remind:

$$K = \frac{eB_0\lambda_u}{2\pi mc}$$

- Go with mainstream, well tested "Hybrid PM undulators"
- Ask the magnet designer for magnetic field model:

$$B_0[g,\lambda_u] = 4.22[T]\exp(-5.08\times\left(\frac{g}{\lambda_u}\right)+1.54\times\left(\frac{g}{\lambda_u}\right)^2)$$

- Choose aggressive low-gap, out-of-vacuum undulator gap: g_{min} = 6 mm
- g_{min} gives K_{max} for any fixed λ_u

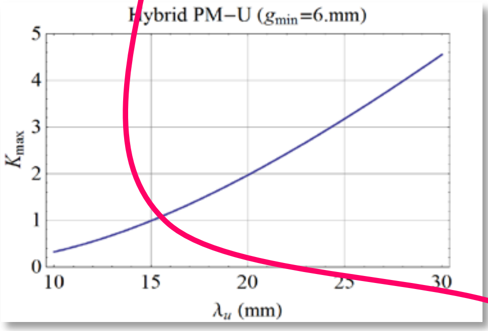
Choice of undulator parameter and beam energy

Courtesy of
M.Venturini

- **Step 3 (a,b,c):**

a) Fix g_{min} = 6mm and compute $K_{max}(\lambda_u)$:

$$K_{max}(\lambda_u) = \frac{eB_0[g_{min},\lambda_u]\lambda_u}{2\pi mc}$$

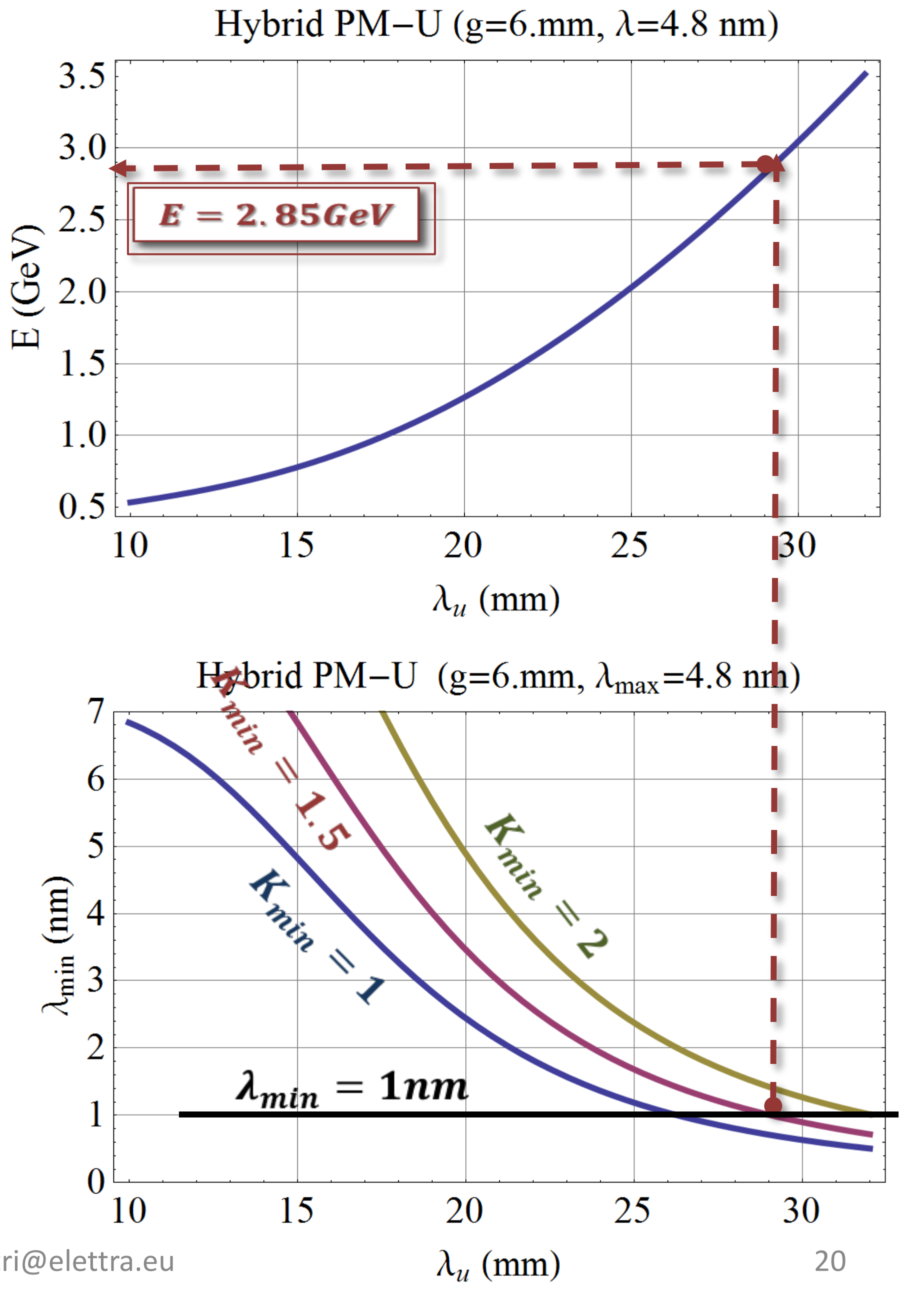


b) Fix λ_{max} = 4.8nm and compute $\gamma(\lambda_u)$:

$$mc^2\gamma = mc^2\sqrt{\frac{\lambda_u}{2\lambda_{max}}\left(1+\frac{K(\lambda_u)^2_{max}}{2}\right)}$$

c) Fix K_{min} >1 and and compute $\lambda_{min}(\lambda_u)$:

$$\lambda_{min} = \frac{\lambda_u}{2\gamma(\lambda_u)^2}\left(1+\frac{K_{min}^2}{2}\right)$$



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Choice of beam charge and emittance

- Match e-beam emittance to radiation emittance at λ=1nm (most demanding wavelength) and E=2.85 GeV:

$$\varepsilon \leq \frac{\lambda}{4\pi}$$

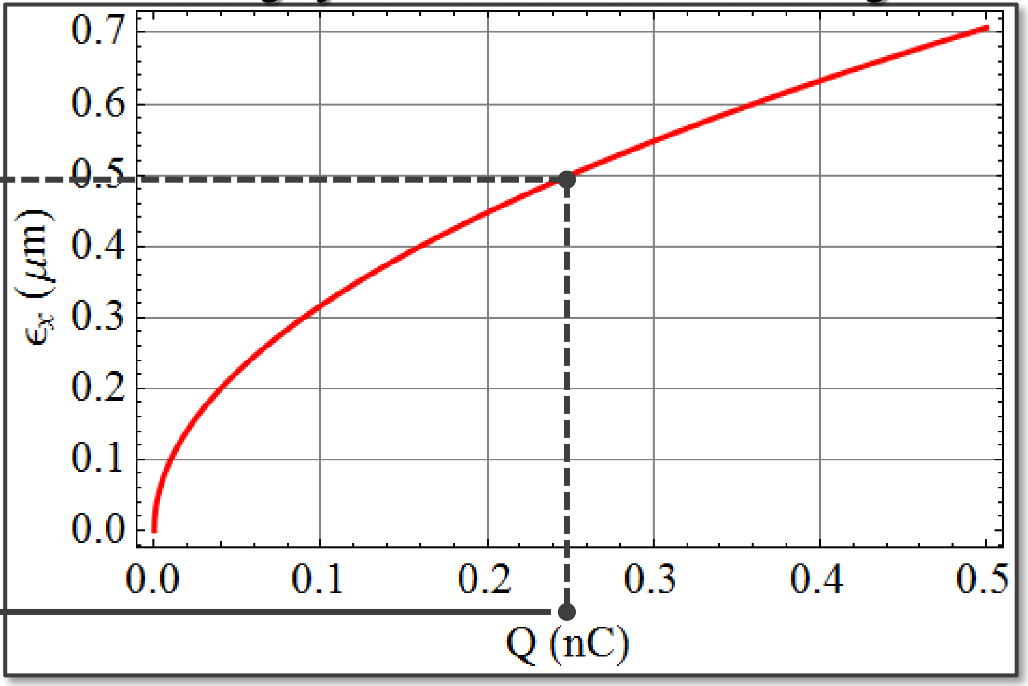
Normalized rms emittance

$$\varepsilon_{nx} = \gamma\frac{\lambda}{4\pi} = 5560 \times \frac{10^{-9}m}{4\pi} = 0.45\mu m$$

Call it $\varepsilon_{nx} = 0.5\mu m$ (slightly larger emittance is OK).

- The minimum emittance is set buy Gun . Use ~$\sqrt{Q}$ scaling law for emittance. (roughly fitting measurements of SLAC Gun):

Scaling of normalized vs. bunch charge



$$\varepsilon_{nx} = 0.5\mu m$$

Bunch charge

$$Q \sim 250pC$$

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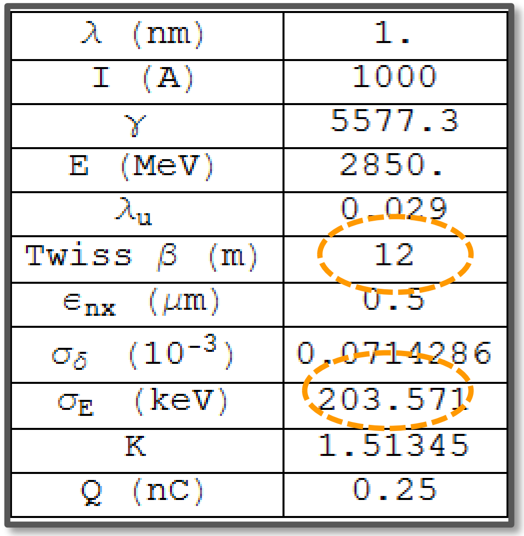
Estimate of FEL performance (1-D vs. 3-D model)

Courtesy of
M.Venturini

Beam/Machine Parameters



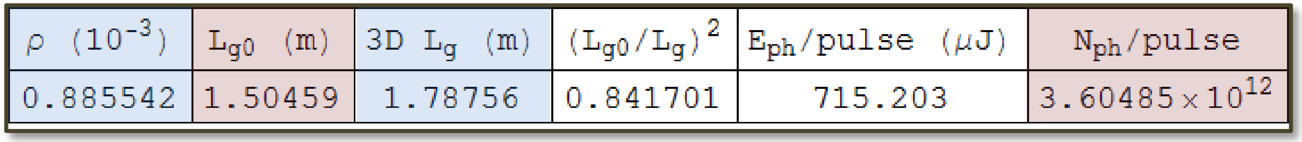
λ (nm)	1.
I (A)	1000
γ	5577.3
E (MeV)	2850.
λ_u	0.029
Twiss β (m)	12
ϵ_{nx} (μm)	0.5
σ_δ (10^{-3})	0.0714286
σ_E (keV)	203.571
K	1.51345
Q (nC)	0.25

** Not optimized*

Can tolerate up to $\Delta E \sim 0.5 \times \rho E_b \sim 1\text{MeV}$ energy spread

20% degradation in gain length because of 3-D effects

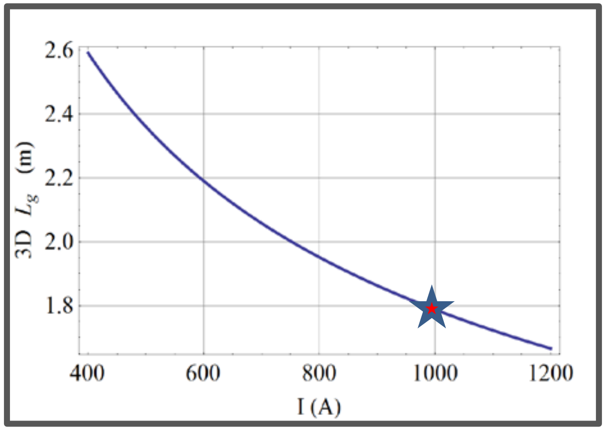
No. photons per pulse at 1 nm



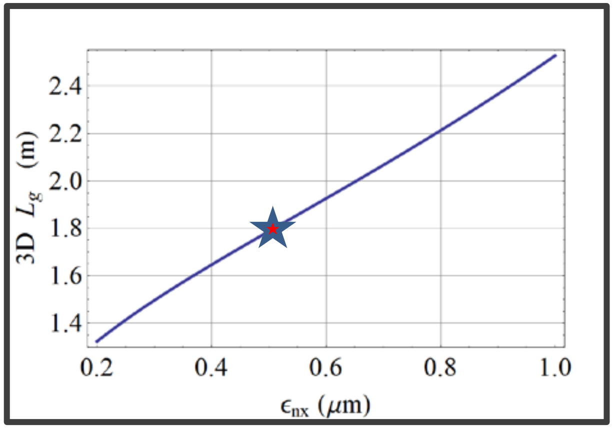
ρ (10^{-3})	L_{g0} (m)	3D L_g (m)	$(L_{g0}/L_g)^2$	E_{ph}/pulse (μJ)	N_{ph}/pulse
0.885542	1.50459	1.78756	0.841701	715.203	3.60485×10^{12}

- Sensitivity study to independent variation of peak current, transverse emittance and energy spread:

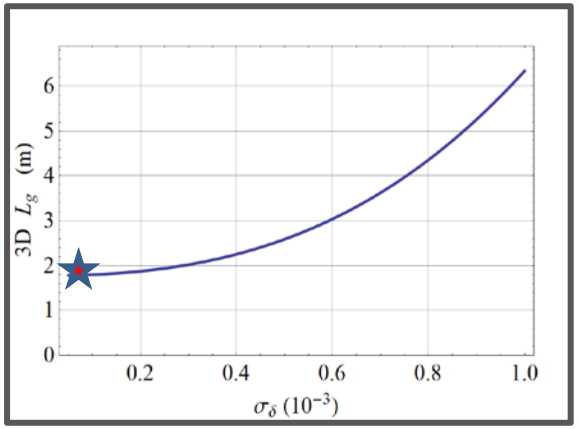
$3D\ L_g$ vs. curr



$3D\ L_g$ vs. rms emitt



$3D\ L_g$ vs. relative rms energy spread



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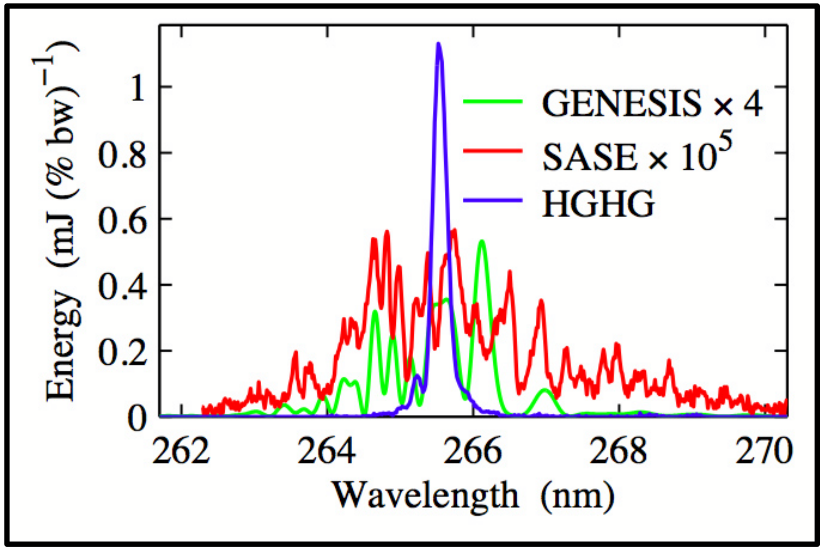
Beyond SASE: (externally) seeded FELs

- Mainly to overcome the poor longitudinal coherence (relatively large spectral bandwidth) from SASE FEL, **external seeding** uses a fully (longitudinally) coherent radiation pulse to initiate the FEL process.
- Several schemes currently in use:
  - High Gain Harmonic Generation (HGHG)
  - Harmonic Cascades (two-stage HGHG, harmonic bunching)
  - Self-seeding
- Each FEL scheme has its own strong and weak points (e.g., limitation in wavelengths, intensity fluctuations, complexity, etc.). Chosen on the basis of specific requirements by users and/or complementarity to existing infrascture.

- Seeding poses **additional demands on beam quality**:
  - longitudinal coherence of radiation asks for a beam that has a long core with uniform profile;
  - uncorrelated energy spread should be low to reach high harmonics of the external laser (i.e., short wavelengths).

Courtesy of L.-H- Yu



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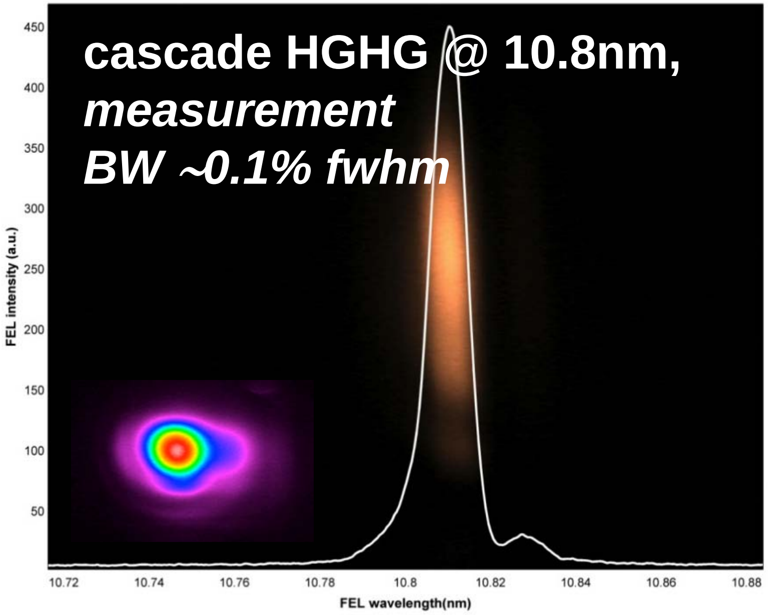
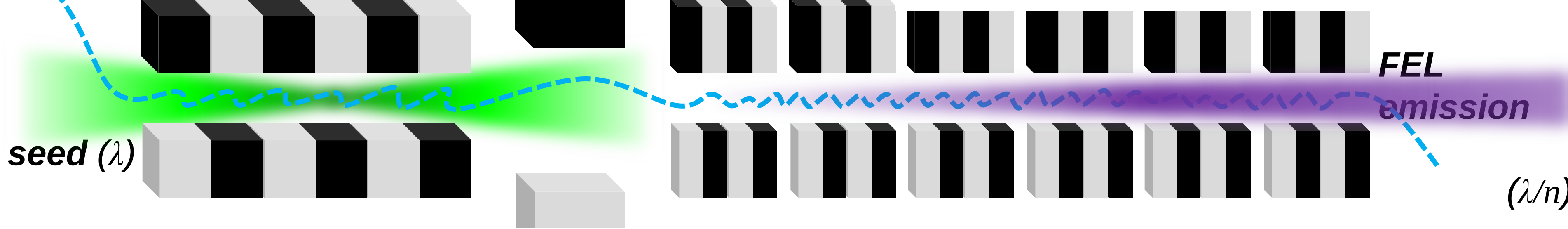
FERMI – HGHG FEL

Figs. courtesy of
G. De Ninno, E. Allaria

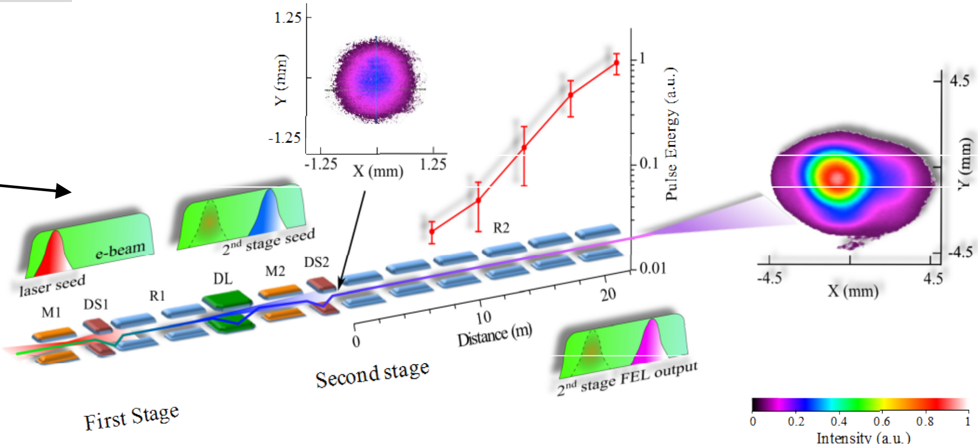
☐ **high peak power** 0.3 to GW's range
☐ **short temporal structure** sub-ps to 10 fs time scale
☐ **tunable wavelength** APPLE II-type undulators
☐ **variable polarization** horizontal/circular/vertical

peak brilliance **10^{30} – 10^{31}** ph/sec/mm^2/mrad^2/0.1%bw
flux **10^{12} – 10^{14}** ph/pulse
bandwidth **~ Fourier Transform Limit**


cascade HGHG @ 10.8nm,
measurement
BW ~0.1% fwhm



Do it twice, in sequence: two-stage HGHG to reach shorter wavelengths (4 nm)



Recapitulating: what do we need for a UV – X-ray FEL

☐ **High energy, monochromatic e-beam, possibly with high bunch rate**

$\hookrightarrow$ ***Radiofrequency e-linac, normal- (NC) or super-conducting (SC)***

~ 1 GeV for EUV, soft X-ray, ~ 10 GeV for Hard X-ray. Energy spread < 0.1%

☐ **Small size, small angular divergence e-beam**

$\hookrightarrow$ ***High brightness e-sources, e.g. photo-injectors***

$\gamma\varepsilon_x \equiv \gamma\sigma_x\sigma_{x'} \leq 10\mu m$ for EUV soft X-ray, $\leq 1\mu m$ for hard X-ray

☐ **Large number of particles in a short duration**

$\hookrightarrow$ ***Bunch length compressors, RF or magnetic***

I ~ kA over tens of femtoseconds

☐ **Beam parameters have to be uniform over many cooperation lengths**

$\hookrightarrow$ ***RF or magnetic manipulation of the longitudinal particle distribution***

Collective effects such as wakefields and coherent synchrotron radiation start playing a role here

☐ **A low–gap, long enough undulator, with short magnetic period**

$\hookrightarrow$ ***Low–gap out-of-vacuum or in-vacuum undulator segments***

$\lambda_u \leq 10cm$ for EUV soft X-ray, $\leq 3cm$ for hard X-ray. Total length ~ 30–150 m

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Typical layout components

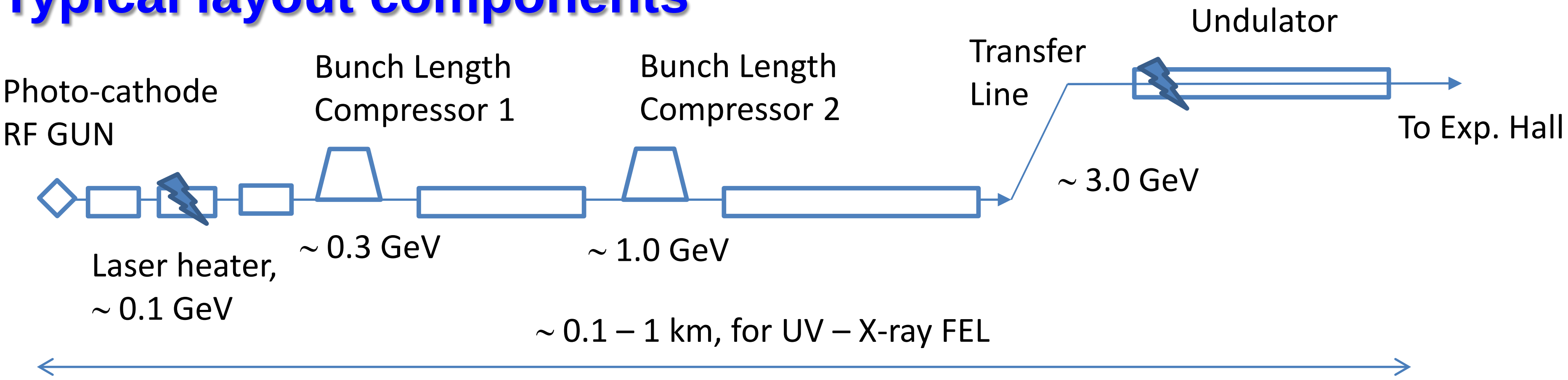


Photo-cathode RF GUN

Bunch Length Compressor 1

Bunch Length Compressor 2

Transfer Line

Undulator

To Exp. Hall

Laser heater, ~ 0.1 GeV

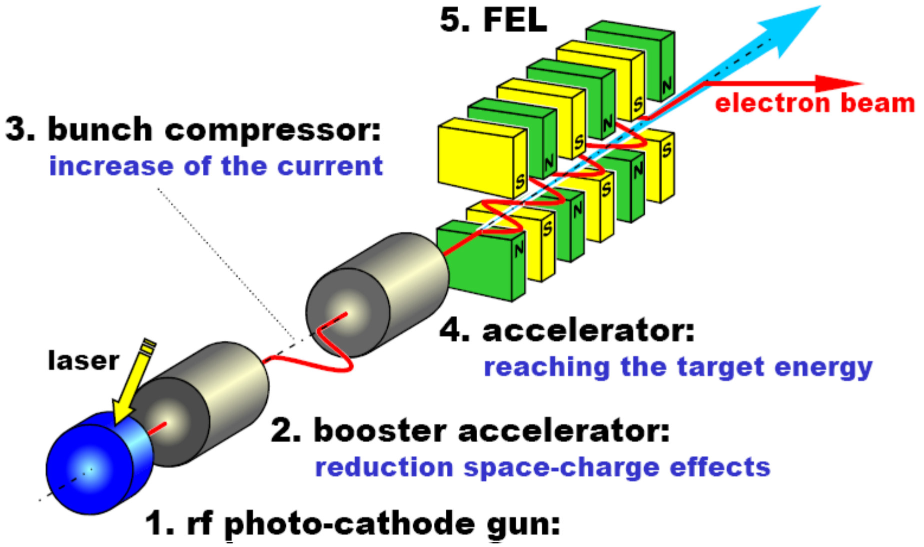
~ 0.3 GeV

~ 1.0 GeV

~ 3.0 GeV

~ 0.1 – 1 km, for UV – X-ray FEL

- **PC RF Gun:** ensures low transverse emittance beams
- **Laser Heater:** enlarges beam incoherent energy spread to damp instabilities
- **Magnetic Compressors:** increase the peak current
- **RF linac:** ensure the beam final energy and energy spread
- **Transfer Line:** switches the beam to different beamlines
- **Magnetic focusing** (not shown): ensures beam transport at reasonable transv. sizes
- **Undulator:** generates lasing till the desired output power



LCLS (SLAC, California): *1.5 – 0.15nm, 14 GeV*

X-FEL based on 1-km of existing NC linac (3GHz, ~20MV/m).
First lasing at 0.1nm in 2009. Now running for users operation.

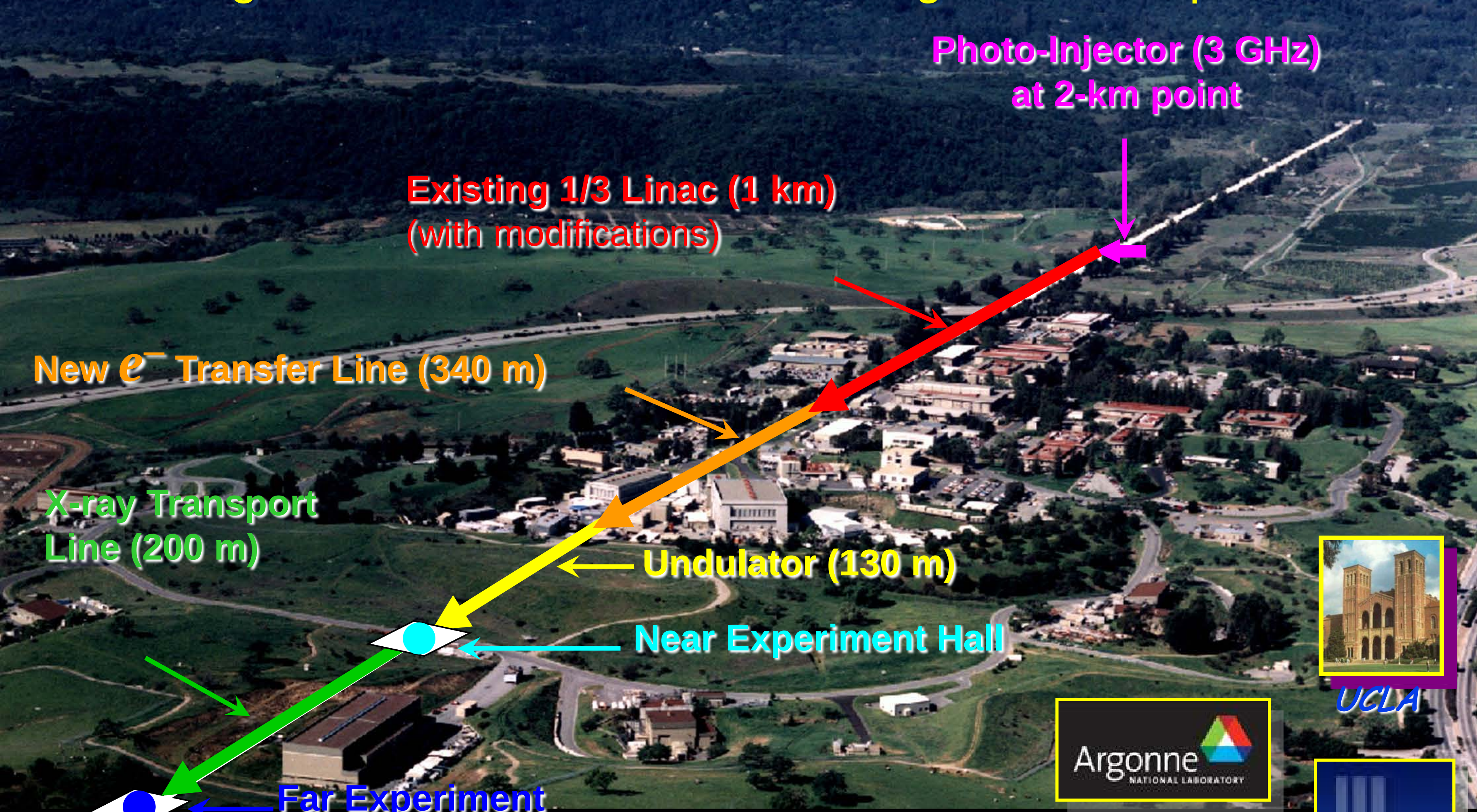


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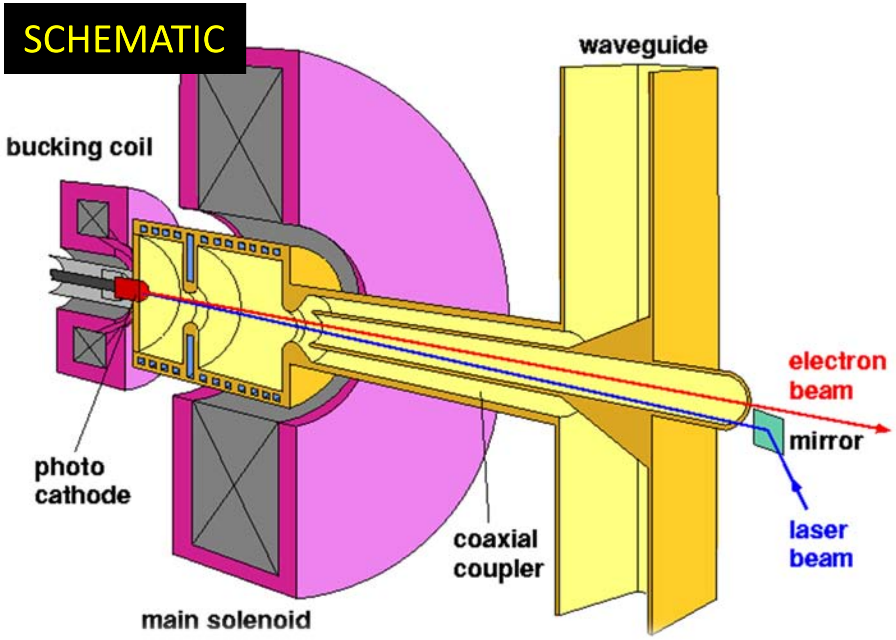
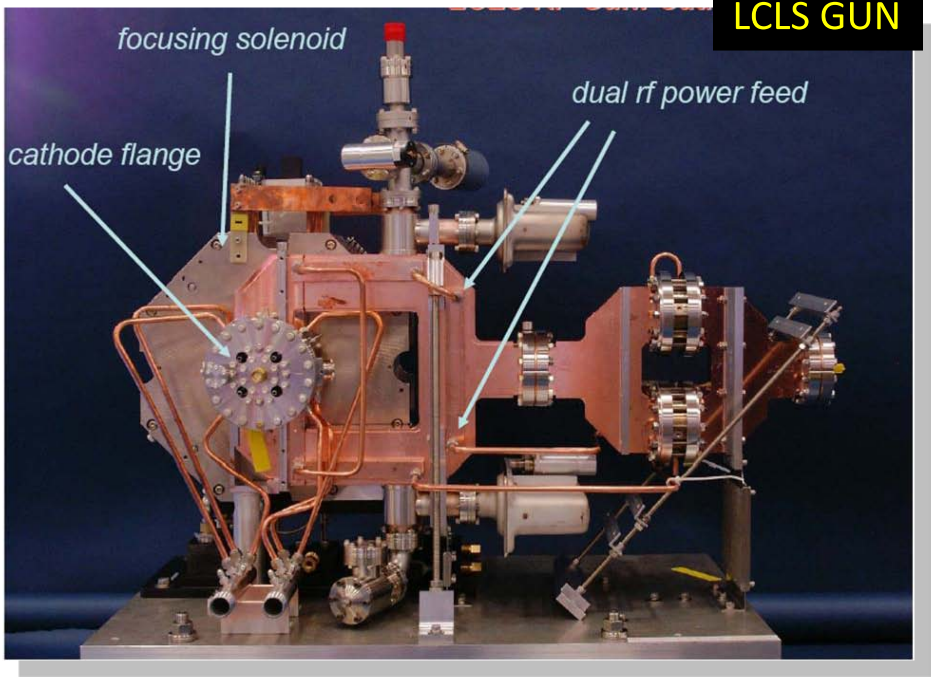
Photo-Cathode Rf Gun (UCLA-BNL-SLAC-type)

Figs. courtesy of
D. Dowell

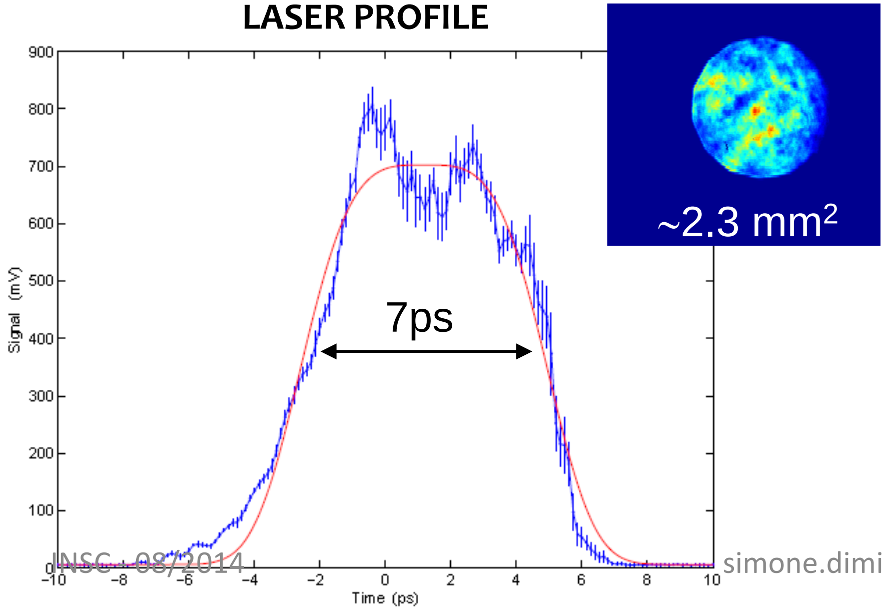
SCHEMATIC



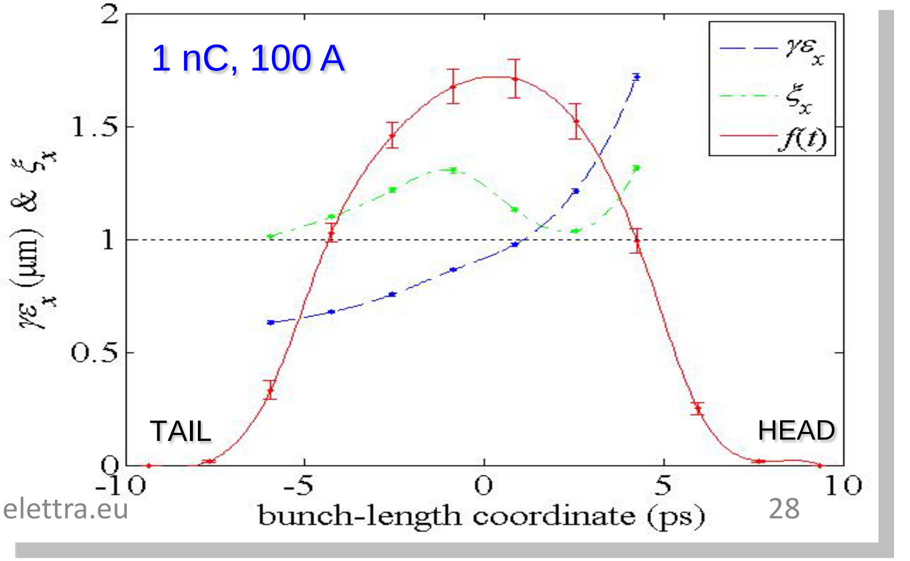
LCLS GUN



LASER PROFILE



SLICE EMITTANCE and PEAK CURRENT



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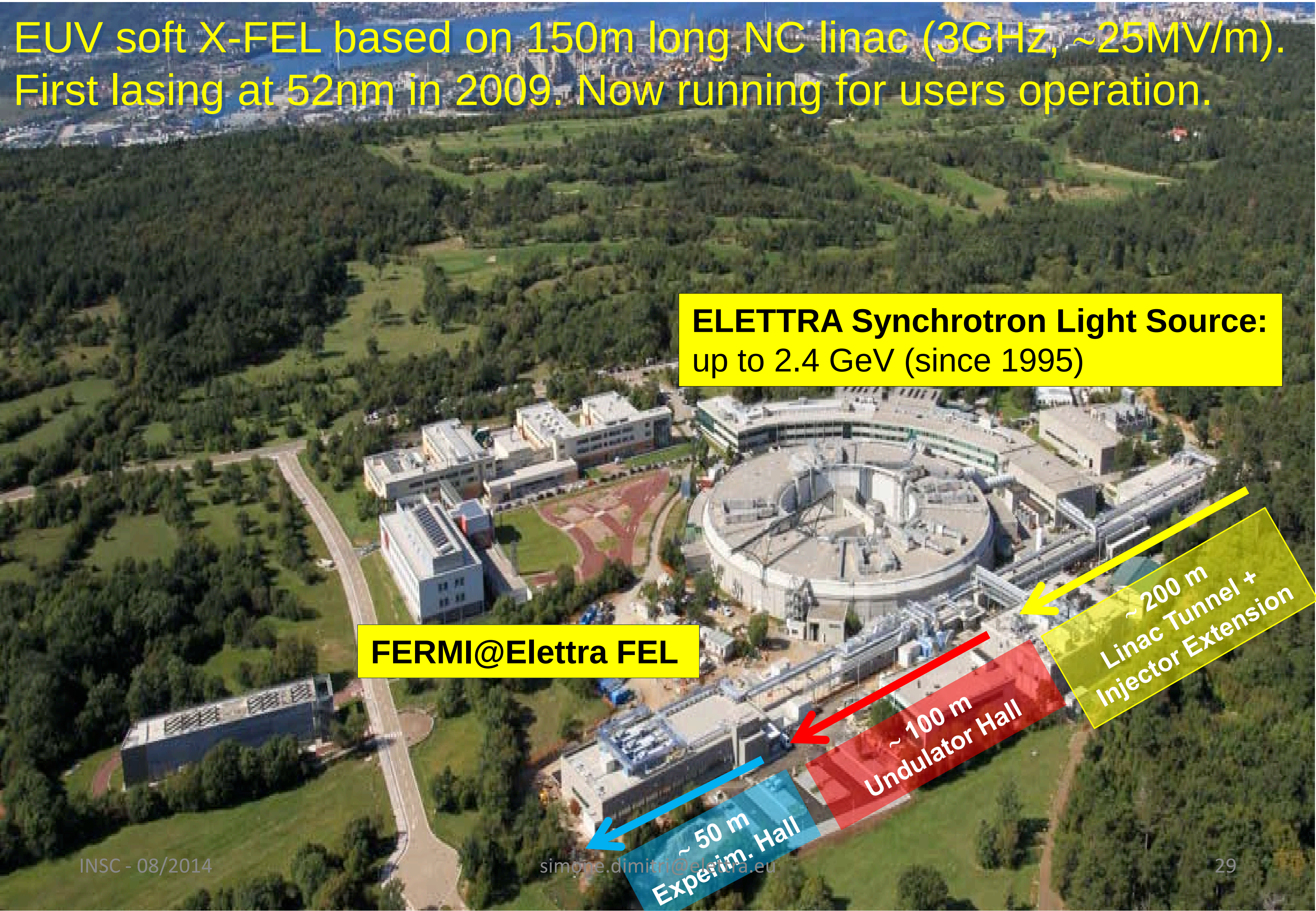
FERMI (Elettra, Italy): *100–4nm, 0.9–1.5 GeV*

EUV soft X-FEL based on 150m long NC linac (3GHz, ~25MV/m). First lasing at 52nm in 2009. Now running for users operation.



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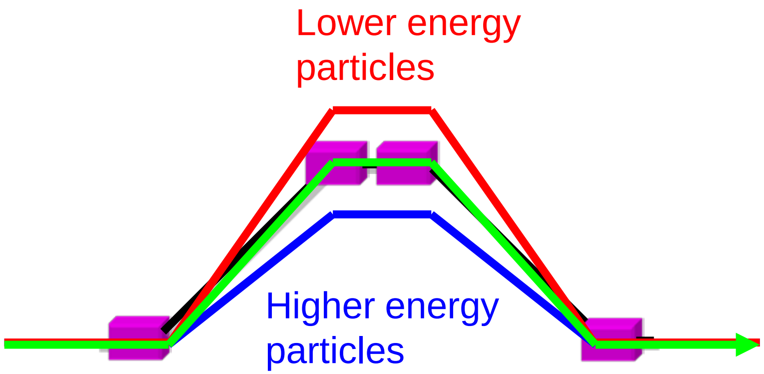
Magnetic bunch length compressor

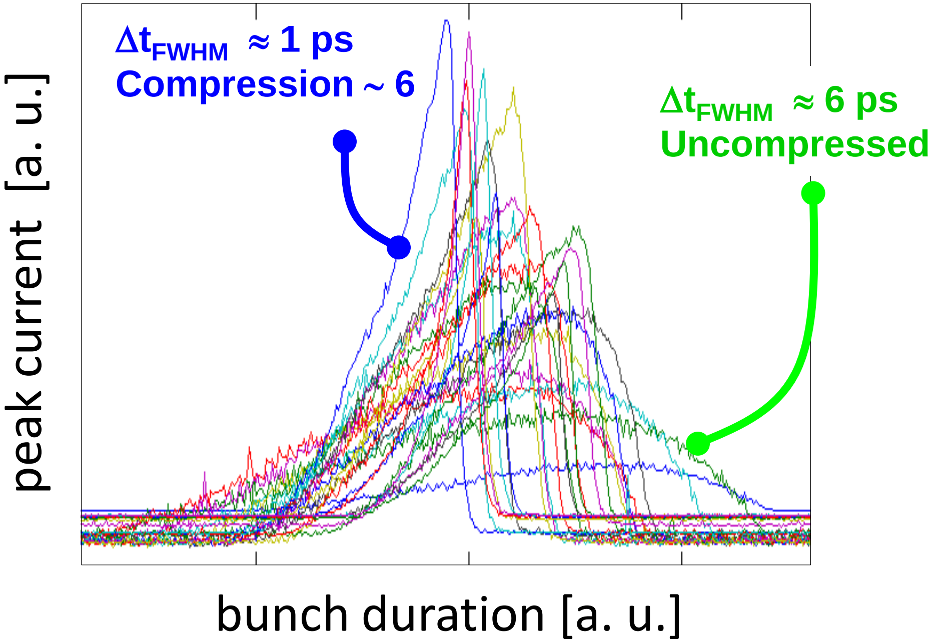


Lower energy particles

Higher energy particles

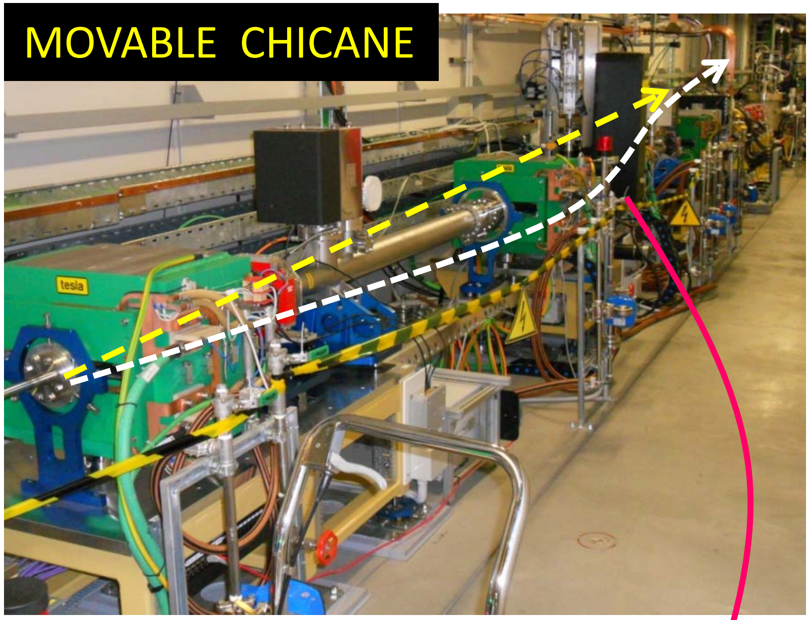
Path length difference (bunch shortening) $\propto$ particles' energy difference

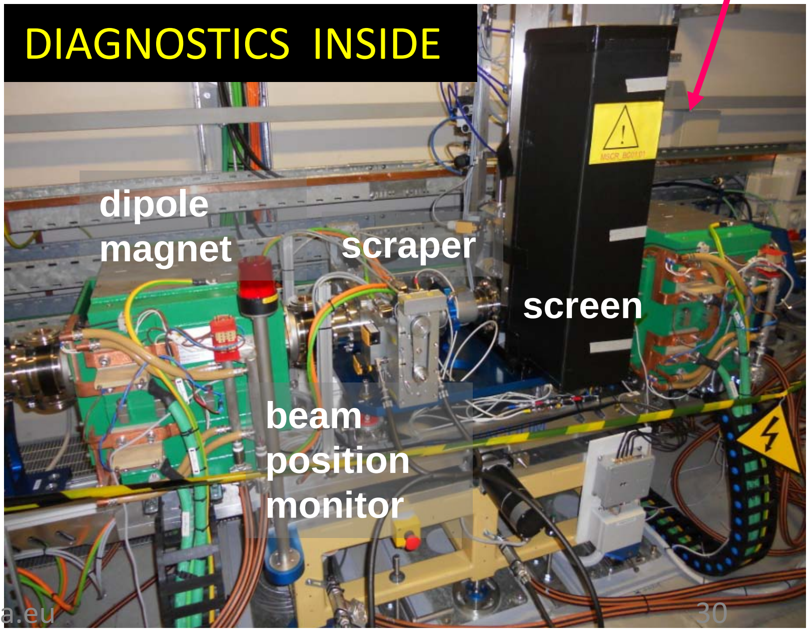
Fig. by G. Penco



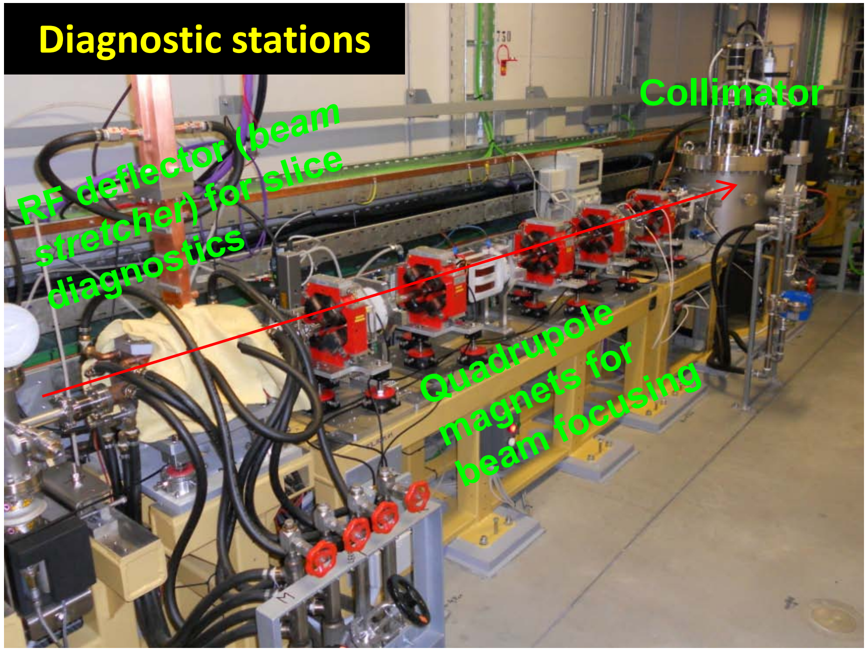
$\Delta t_{FWHM} \approx 1$ ps
Compression ~ 6

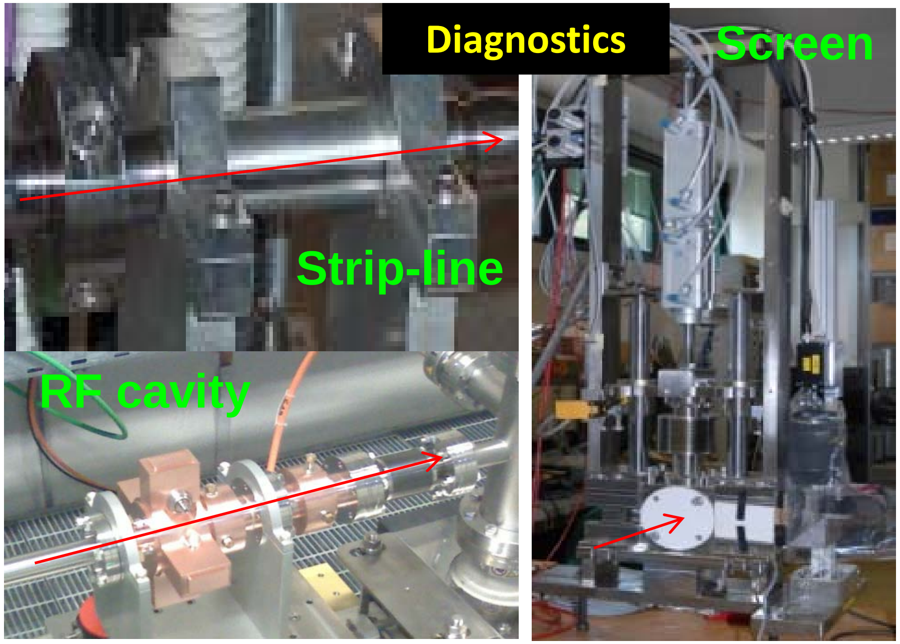
$\Delta t_{FWHM} \approx 6$ ps
Uncompressed

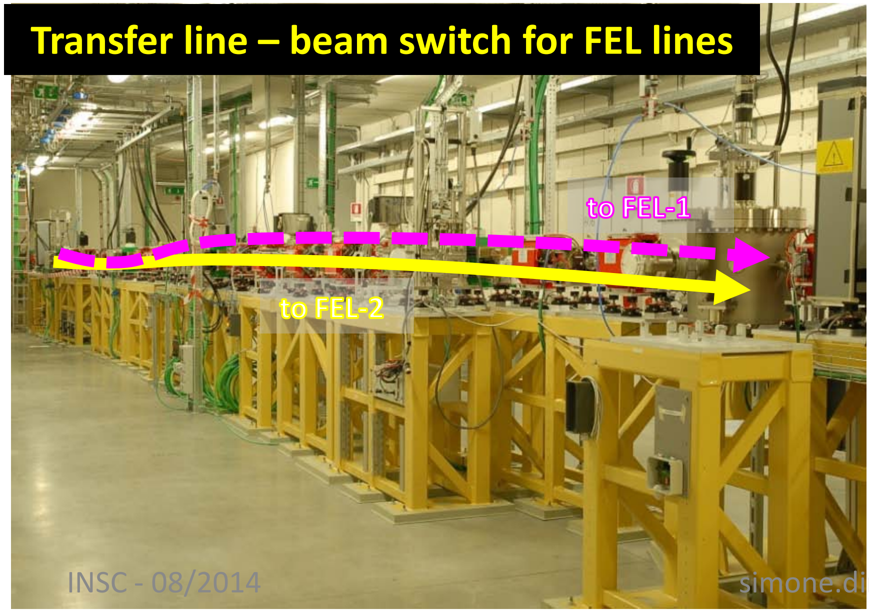


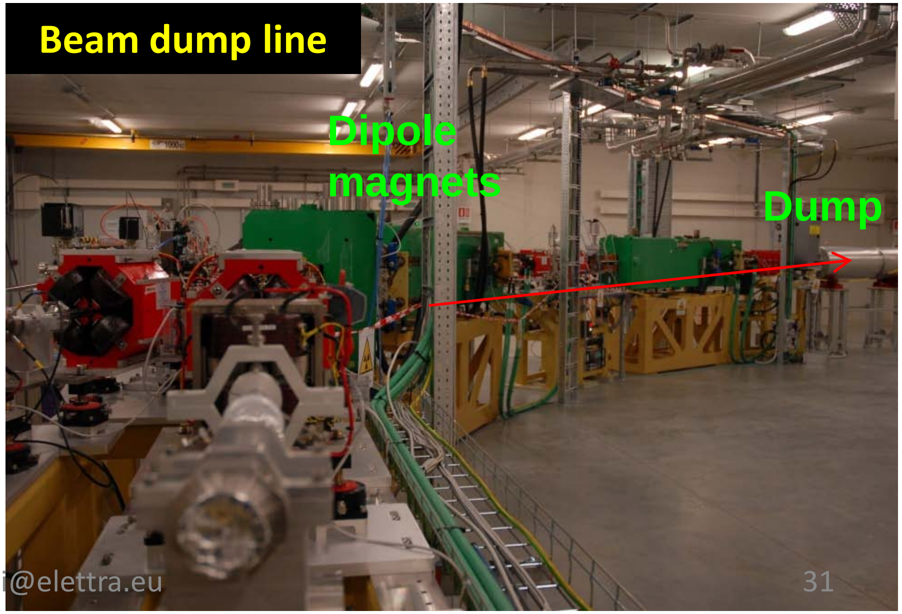


Other accelerator components


Diagnostic stations


Diagnostics


Transfer line – beam switch for FEL lines


Beam dump line

SACLA (Spring-8, Japan): *<0.1nm, 8 GeV*

Hard X-FEL based on 230m long NC linac (5.7GHz, ~35MV/m). First lasing at 0.12nm in 2011. Commissioining is finishing.

SPring-8 SLS
Operating 12 years

50 m
Experimental Hall

200 m
Undulator Hall

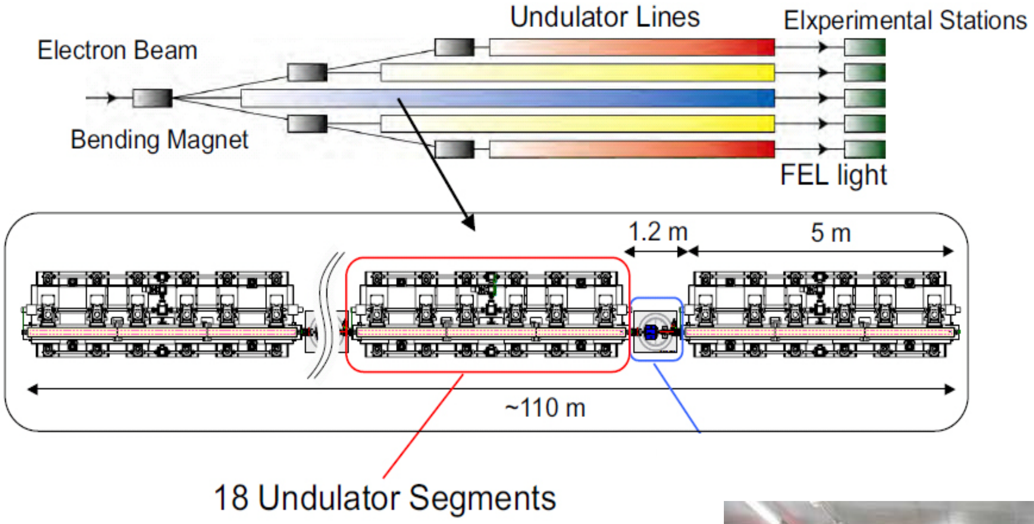
400 m Accelerator Tunnel

SACLA

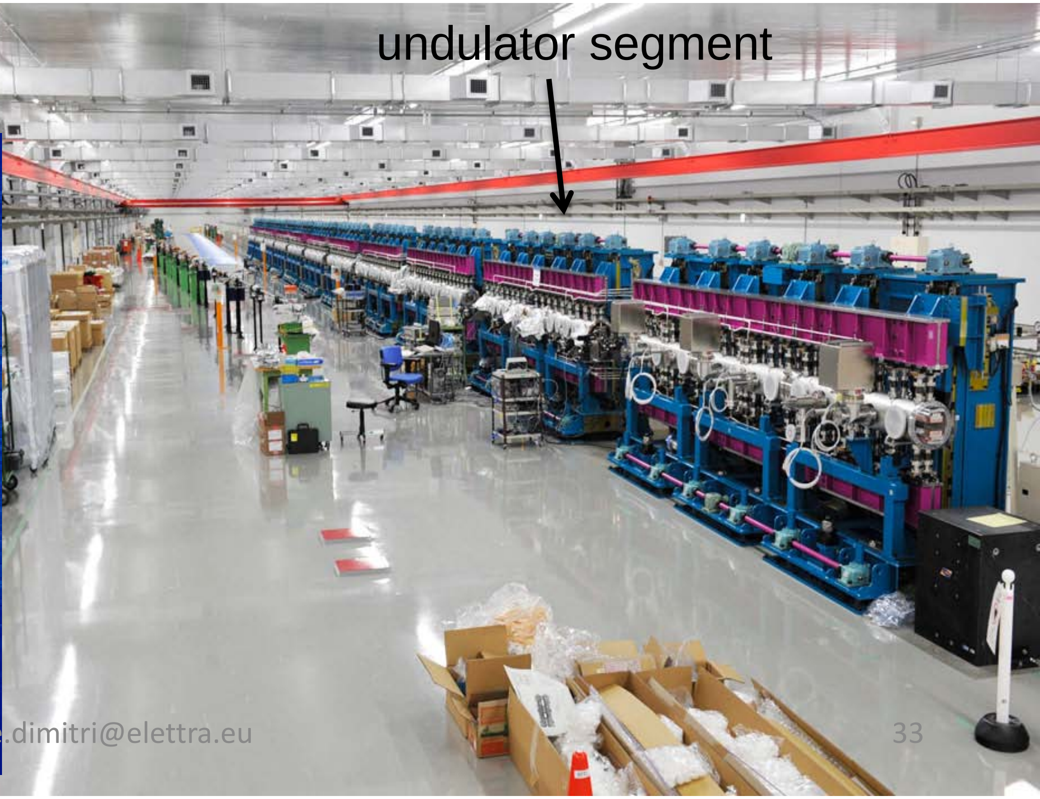
SCSS Test Accelerator
Since 2006, EVU user facility

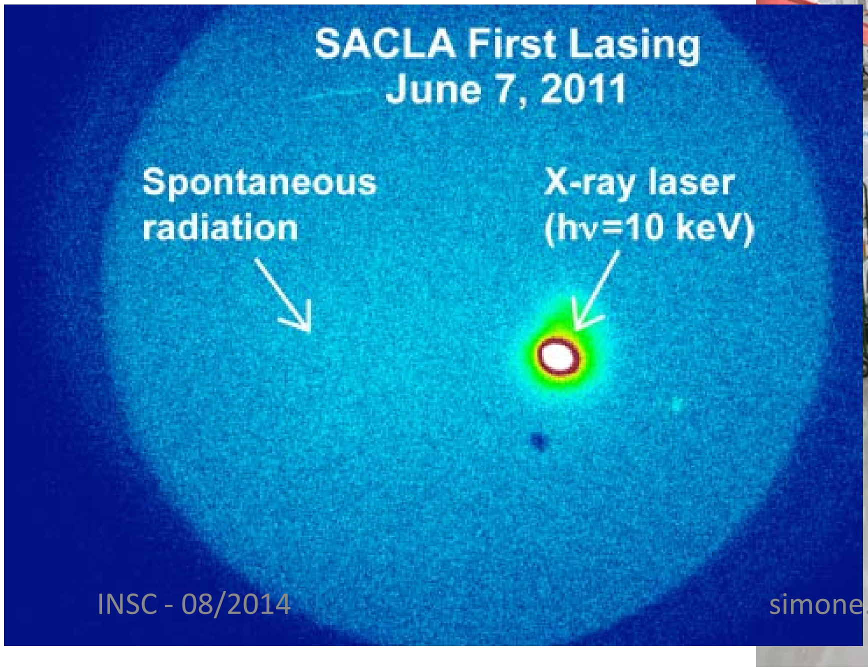
Machine Assembly Hall

In-vacuum undulator



Undulator Type		In-Vacuum Planer Undulator
Active Length		5 m
Undulator Period		18 mm
Magnetic Circuit		Hybrid (NdFeB+Permendur)
Peak Field	Maximum	1.31 T
	Nominal	1.13 T
K	Maximum	2.2
	Nominal	1.9
Gap	Minimum	3.5 mm
	Nominal	4.5 mm
Maximum Attractive Force		~ 6 ton





Summary highlights: *what is an FEL ?*

- ☐ **FELs are 4-th generation light sources:**
  - SLS spectral range is extended to sub-Angstrom level
  - SLS brilliance is overwhelmed by ~9 orders of magnitude
  - Light pulse control: wavelength tunability, variable polarization, two-color pulses, pump-probe experiments

- ☐ **Intense coherent radiation** is emitted by “free” electrons in a tens of meter long undulator chain

- ☐ **Electron beams** are required to have very **high 6-D brightness**:
  - non-equilibrium dynamics in single-pass or recirculating linacs
  - round beams, transverse emittance smaller than ultimate SRs
  - up to 1000 times smaller longitudinal emittance than in SRs

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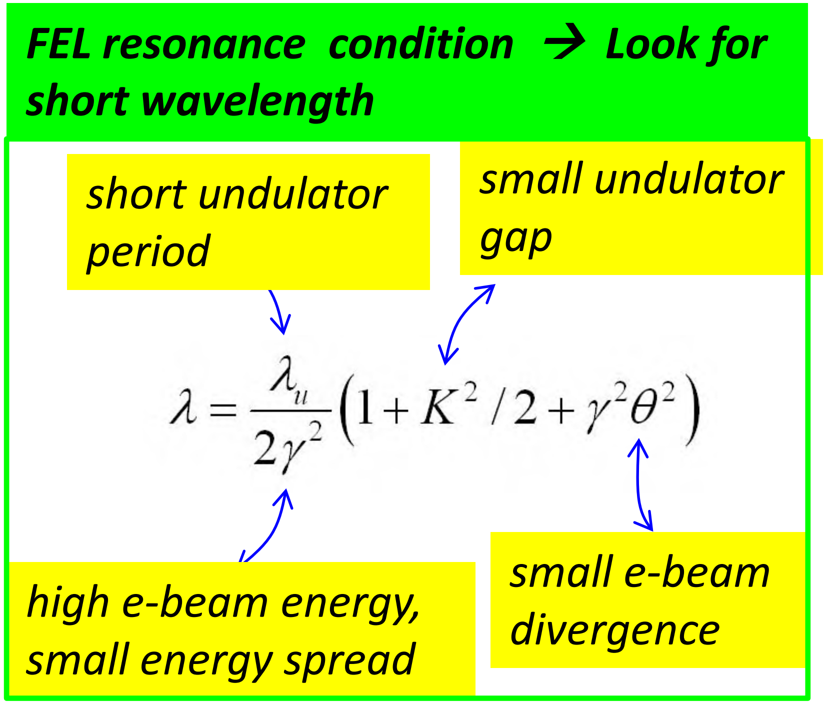
Summary highlights: *requirements on e-beam*



FEL resonance condition → Look for short 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

☐ N large & short pulses $\Rightarrow I \sim kA$

☐ e-/γ transv. overlap $\Rightarrow \gamma\varepsilon \sim 1.0\mu m$

☐ energy resonance $\Rightarrow \sigma_\delta < 0.1\%$

☐ short λ ⇒ E > 1 GeV,

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

$$P_{FEL}(z) \sim e^{z\frac{\rho_{FEL}}{\lambda_u}} \sim e^{z\left(\frac{I}{\sigma_\perp}\right)^{1/3}}$$

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

$$\sigma_\delta < \rho_{FEL}$$

High 6-D e-Beam Brightness

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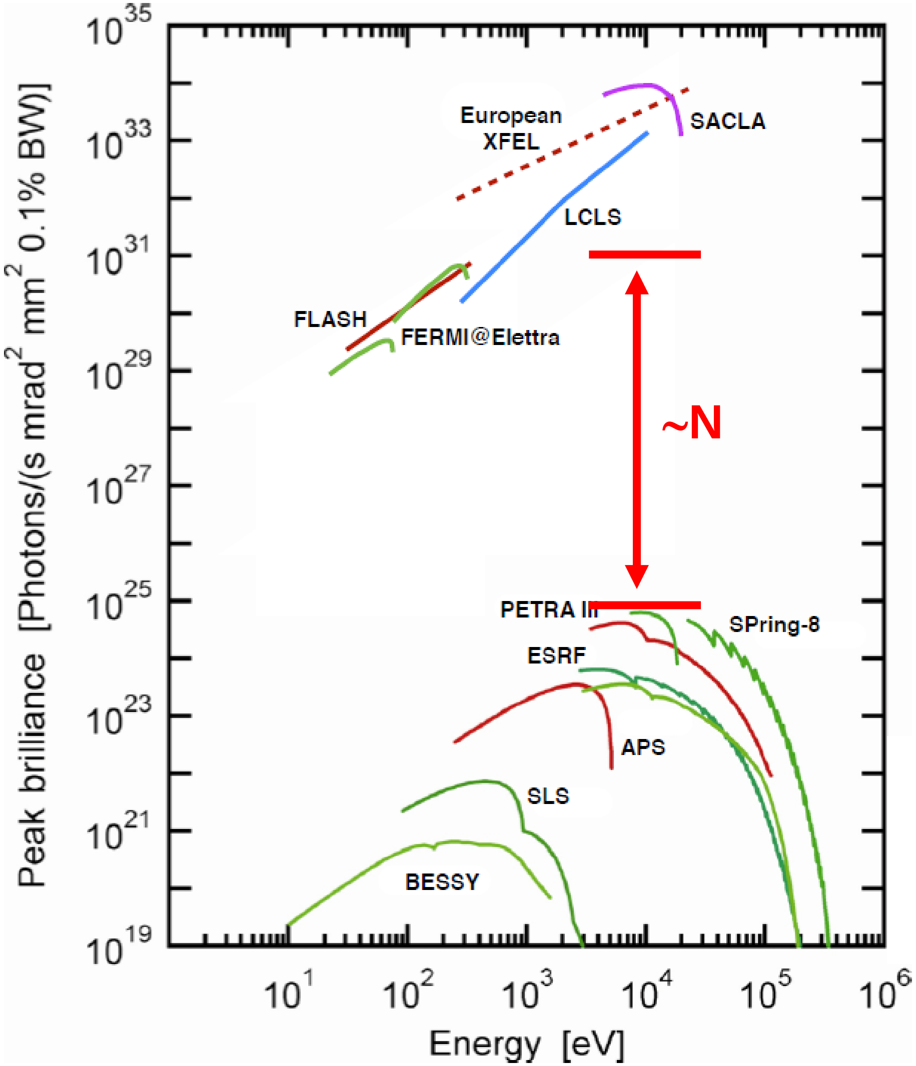
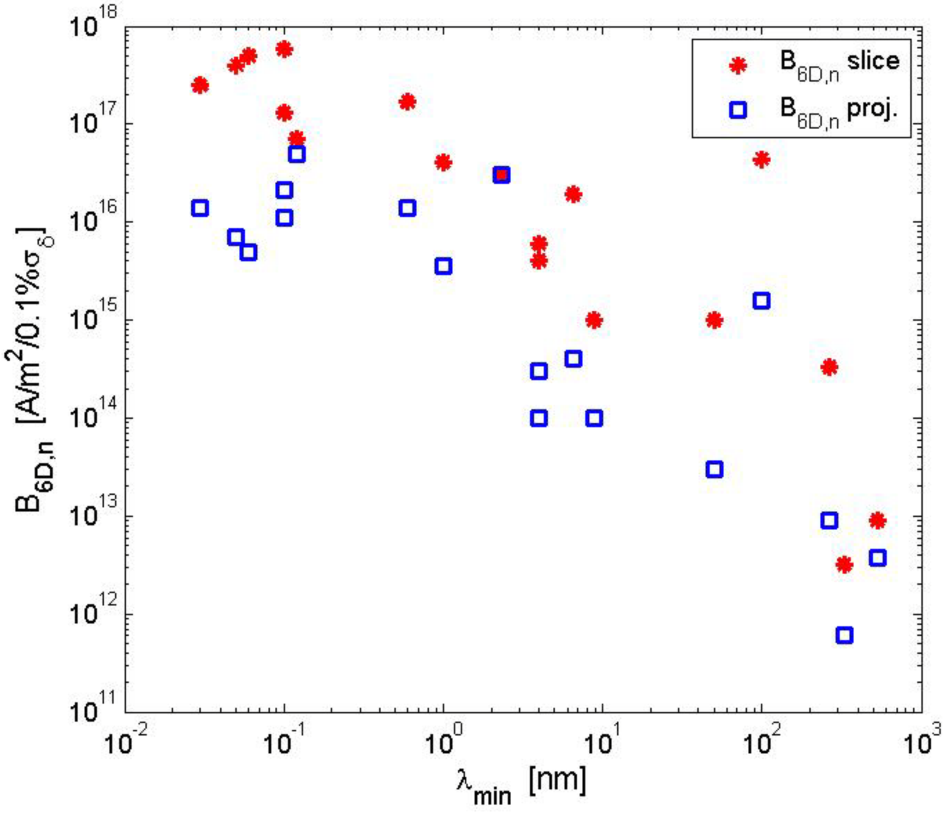
Summary highlights: *FEL brilliance*





The breakthrough of FEL brilliance is allowed by the cohrent emission.

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FELs vs. Synchrotron Light Sources

	SLS	**LINAC-FEL**	***Should be…***
Norm. emitt., $\gamma\varepsilon$ [μm]	**(10, 0.1)**	**0.1 – 1**	$\approx$ diffraction-limit
Energy spread, σ_δ [%]	**0.1**	**0.01 – 0.1**	$< \rho_{FEL}$
Bunch length, σ_t [ps]	**10**	**0.1 – 1**	Tunable in fs – ps range
Peak current, I [A]	**10**	**1000**	As high as possible
Repetition rate [Hz]	**10^8**	**$10^1 – 10^4$**	As high as possible
Energy and intensity stability	**$10^{-5} – 10^{-6}$**	**$10^{-2} – 10^{-3}$**	As high as possible

- Storage rings are **complementary** to FELs as for **λ-tunability**, **multiple-users access**, **stability** and **pulse rate**.

Acknowledgements / References (not exhaustive)

Credits: M. Venturini (and myself), USPAS Course 2013, CO, USA.

http://uspas.fnal.gov/materials/materials-table.shtml

and W. Barletta, H. Widemann, A. Wrulich

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- S. Di Mitri and M. Cornacchia, *“Electron Beam Brightness in Linac Drivers for Free-Electron Lasers”*, Physics Reports **539** (2014) 1–48.
- E. Allaria et al., Nature Photonics **6** (2012) 699.

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Thank You for Your kind attention

Questions and Comments are Welcome !