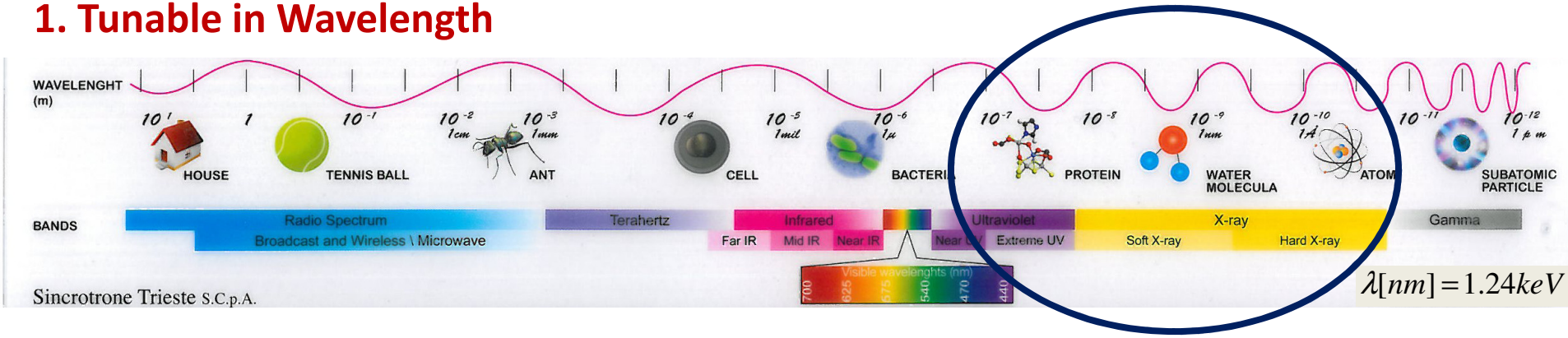
Introduction to single-pass FELs for UV X-ray production

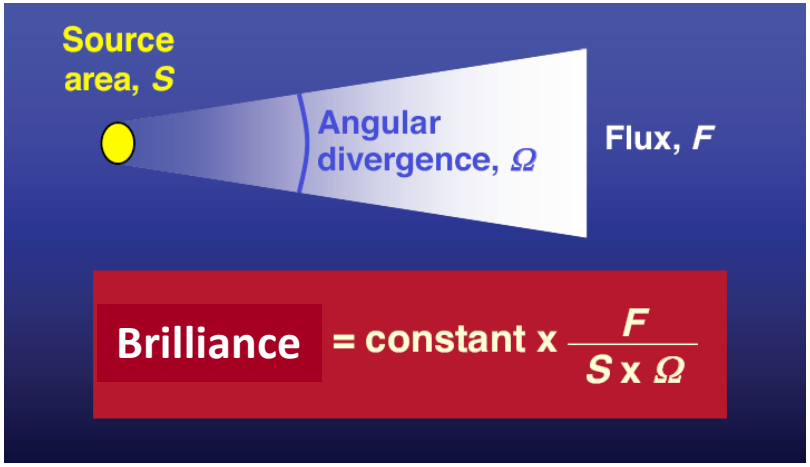
S. Di Mitri (45min.)

An ideal light source should be…

1. Tunable in Wavelength



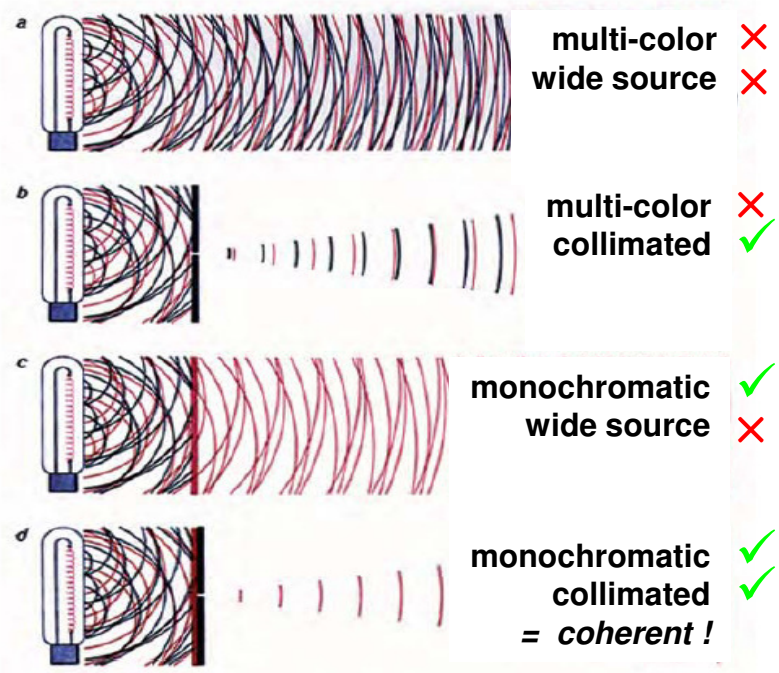
2. Highly Brilliant



Not to be confused with charged beams' *brightness*:

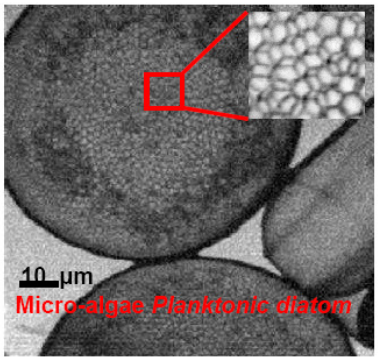
$$B_e \propto \frac{I[A]}{\sigma_x \sigma_{x'}[m\ rad]}$$

3. Fully Coherent



Courtesy of A. Schawlow, Stanford.

An ideal light source should provide…

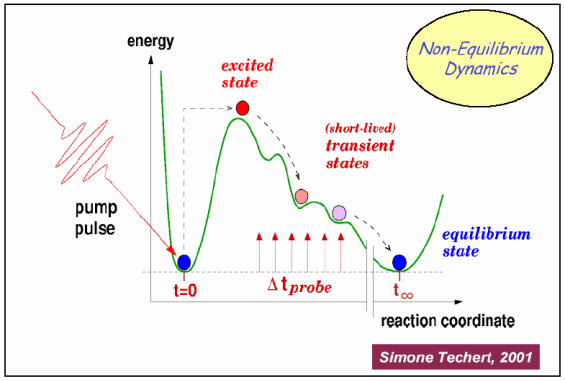


High resolution at small spatial scales

↳ *short wavelength*

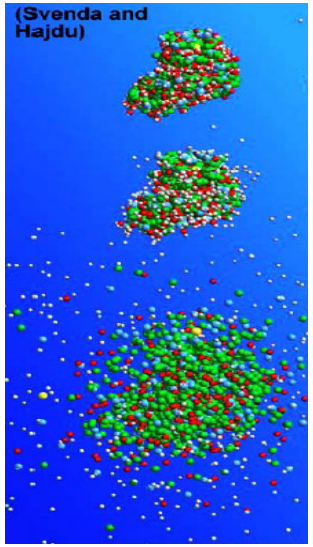
Most of the photons at the same wavelength

↳ *narrow bandwidth*



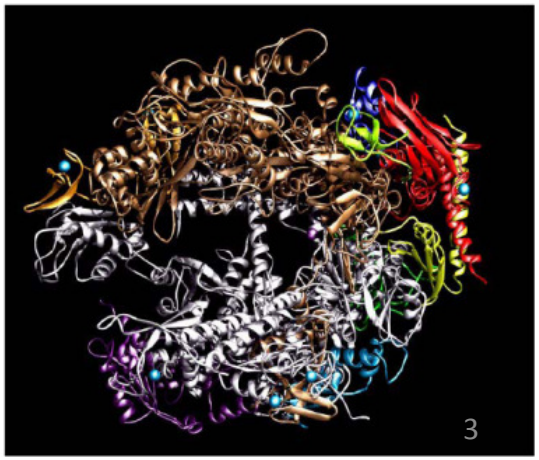
Stroboscopic picture of chimical processes

↳ *short pulse*



Large statistics in single-shot

↳ *large number of photons per pulse*



Large statistics in multi-shot

↳ *high repetition rate*

Advantages of a *linac*-driven light source

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

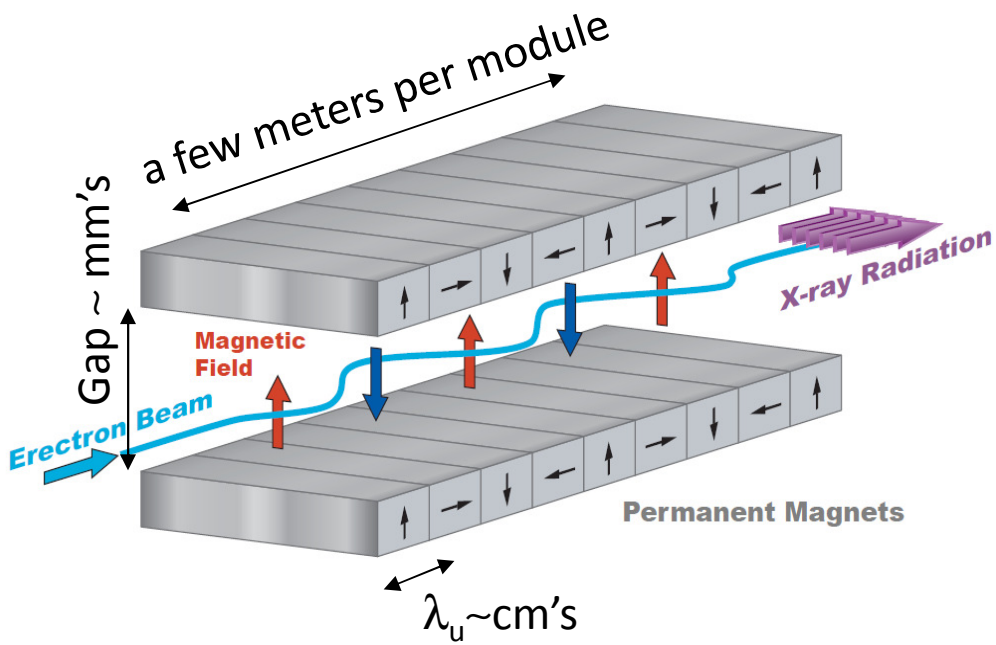
- Leptons (*i.e.*, electrons) radiate more than hadrons (*i.e.*, protons) when subjected to the same force. Circular acceleration is more efficient (and typically cheaper) than linear.

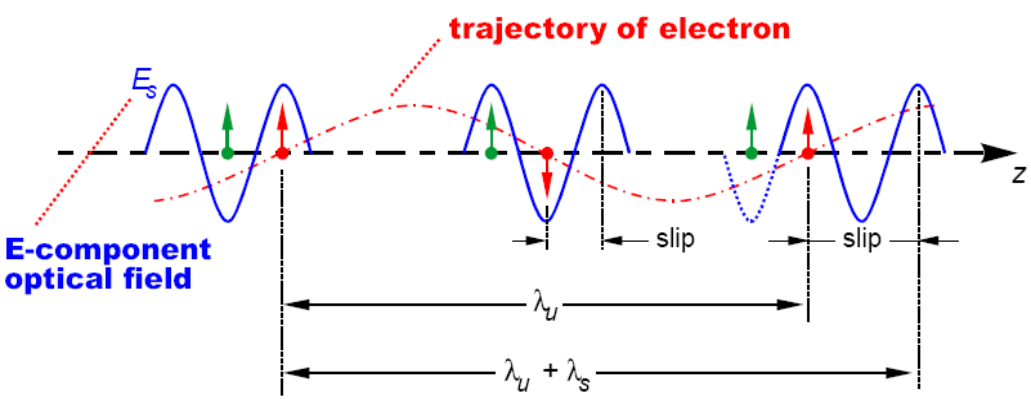
- *But*, e-beams in synchrotron light sources (SLS) reach *equilibrium* properties that are typically far from providing radiation as wished by FEL users (synchrotron radiation damping of particles' velocities is balanced by the quantum excitation due to random emission of photons in time) .

- 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





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

Undulator strength parameter:

$K = 0.934\ \lambda_u[\text{cm}]\ B_{max}\ [\text{T}] \approx 1 \div 10$

Undulator resonance wavelength:

short undulator period

small undulator gap

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

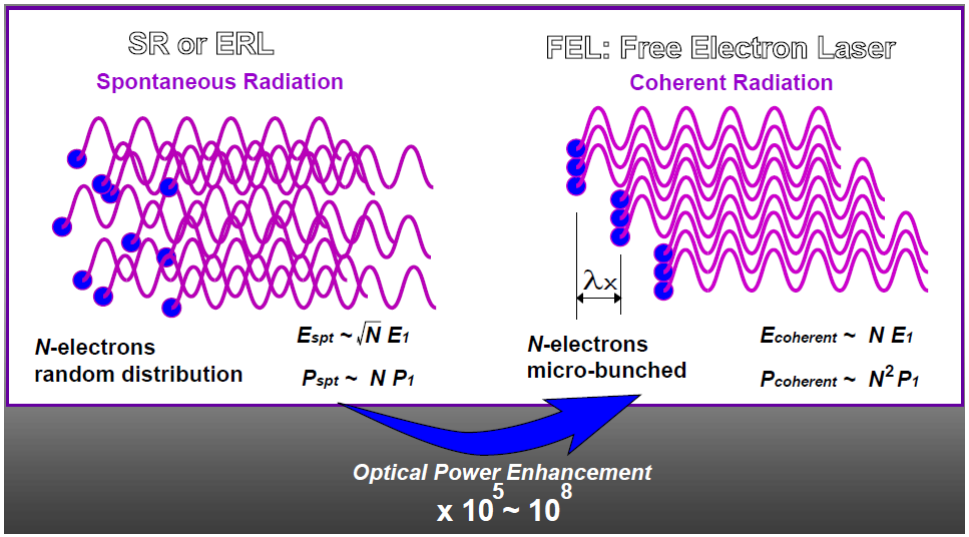
high e-beam energy, small energy spread

small e-beam divergence

- The electron transverse velocity ***couples*** to the photons' 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, S. Milton



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

SLS ~ N

FEL ~ N^2

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:

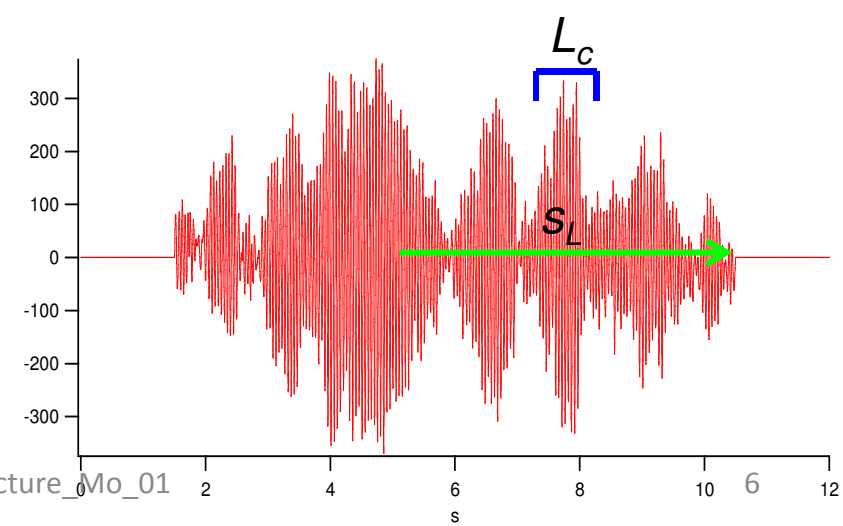
$$\left|\vec{E}\right| \propto \sqrt{N}, \quad P_{\gamma,tot} \propto N$$

If the electrons are in lock synch and ***radiate coherently***, like in ***FELs***, one can get an enormous gain in power emitted:

$$\left|\vec{E}\right| \propto N, \quad P_{\gamma,tot} \propto N^2$$

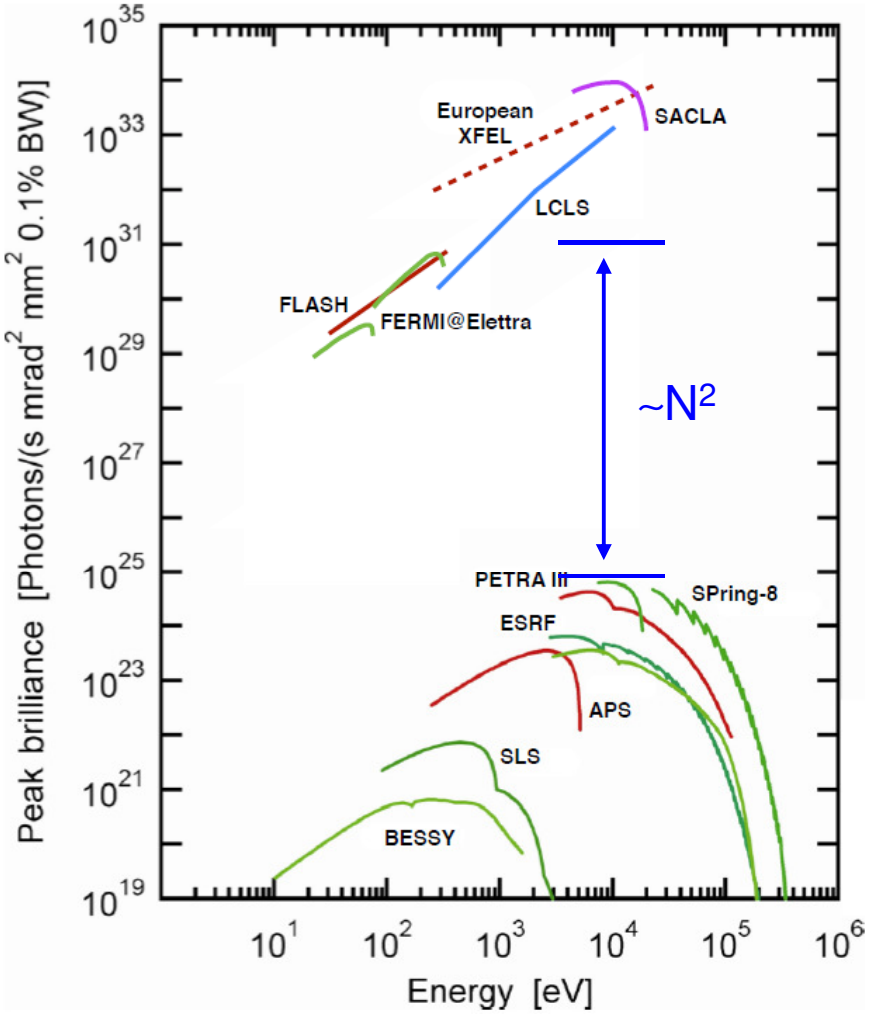
The FEL pulse consists of several coherent regions (*spikes*, L_c) randomly distributed over the e-bunch length. The photons slip over the electrons (*slippage*, s_L) "connecting" multiple spikes.

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



Recapitulating: SLS vs. linac-driven FEL

Pictures courtesy of
E. Allaria



The breakthrough of FELs' brilliance is allowed by the cohrent emission.

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

	RING	LINAC	*Should be...*
Norm. emitt., $\gamma\varepsilon$ [μm]	(10, 0.1)	0.1 – 1	< diffraction-limited photon emittance: $\gamma\lambda/4\pi \sim 0.1 - 1$
Energy spread, σ_δ [%]	0.1	0.01 – 0.1	< FEL energy bw: $\rho_{FEL} \sim 0.01 - 0.1$
Bunch length, σ_t [ps]	10	0.1 – 1	Tunable in fs-range
Peak current, I [A]	10	1000	As high as possible, $I_{SLS}(\lambda) \propto N$ $I_{FEL}(\lambda) \propto N^2$
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 much as possible

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

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

  ↳ ***Radiofrequency e-linac, normal-conducting (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

  ↳ ***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

  ↳ ***Bunch length compressors, RF or magnetic***
  [e.g., $I \sim$ kA over 10's of fs]

- Beam parameters have to be uniform over many cooperation lengths

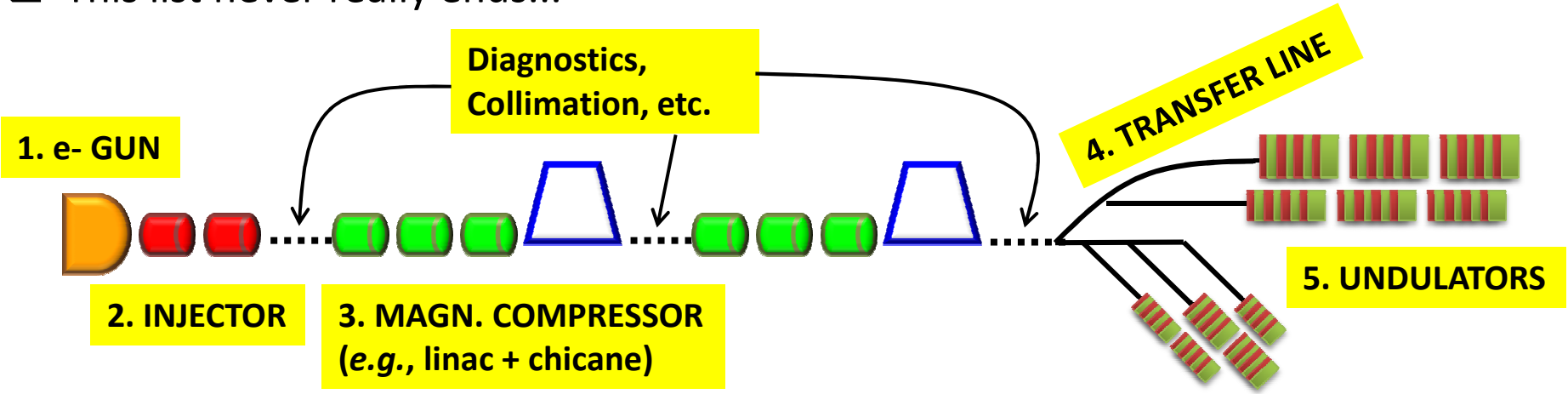
  ↳ ***RF or magnetic manipulation of the longitudinal particle distribution***
  [Collective effects such as wakefields and coherent synchrotron radiation start playing a role here]

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

  ↳ ***Low–gap out-of-vacuum or in-vacuum undulator segments***
  [$\lambda_u \leq 10$cm for EUV soft X-ray, ≤ 3cm for hard X-ray. Total length ~ 30–150 m]

Is that all we really need ?

- Connect different accelerator sections (injector, main linac, undulator, dump)
  - ↳ ***Transfer lines*** *(no acceleration) preserving the e-beam quality*
- Diagnose the e-beam parameters
  - ↳ ***Diagnostic stations*** *for transverse and longitudinal particle distribution*
- Stop the e-beam at intermediate energies and after the undulator
  - ↳ *(Safe) Beam* ***dump*** *lines*
- Clean unwanted halo particles traveling with the beam core
  - ↳ ***Collimation*** *systems*
- This list never really ends...



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.

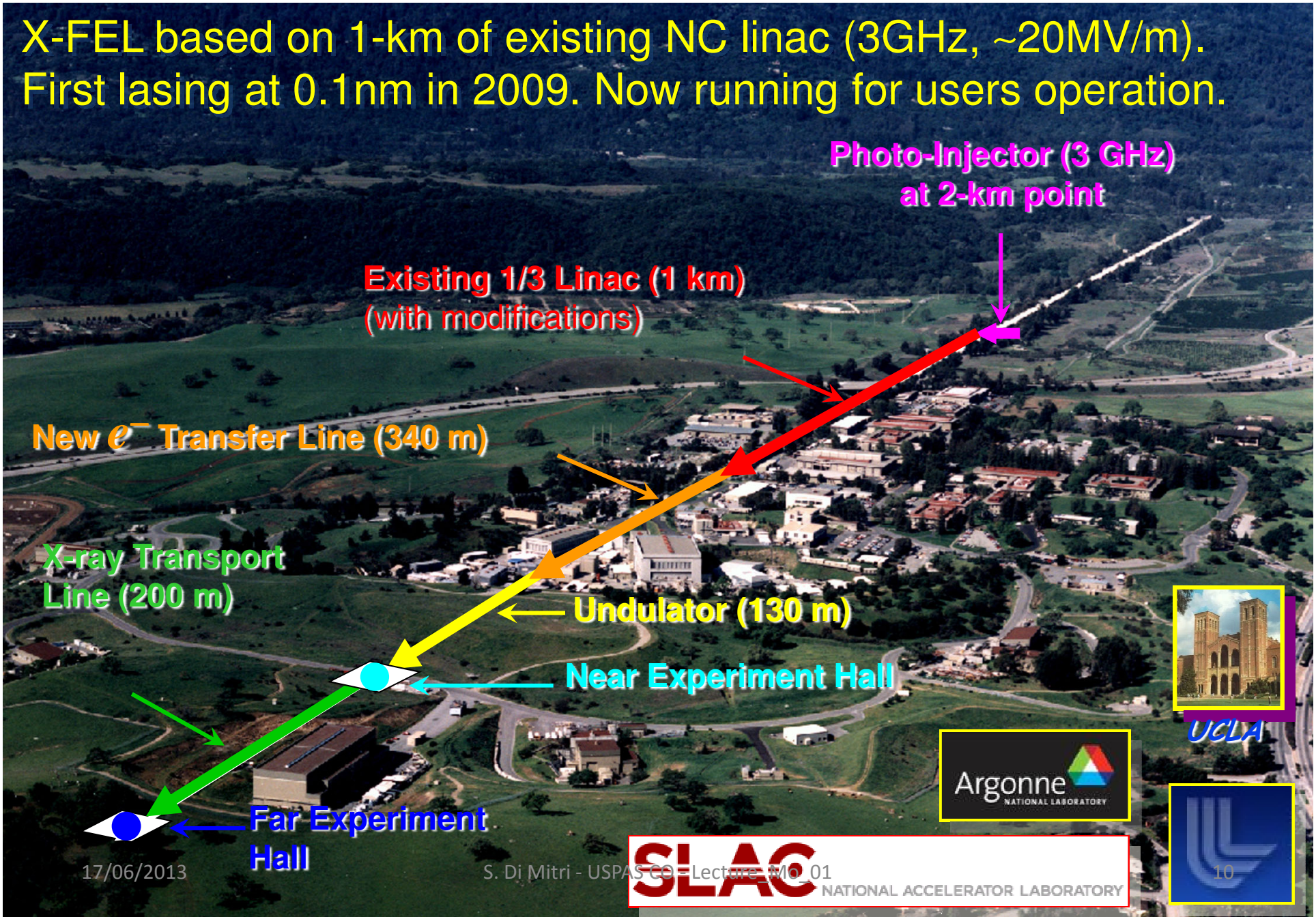
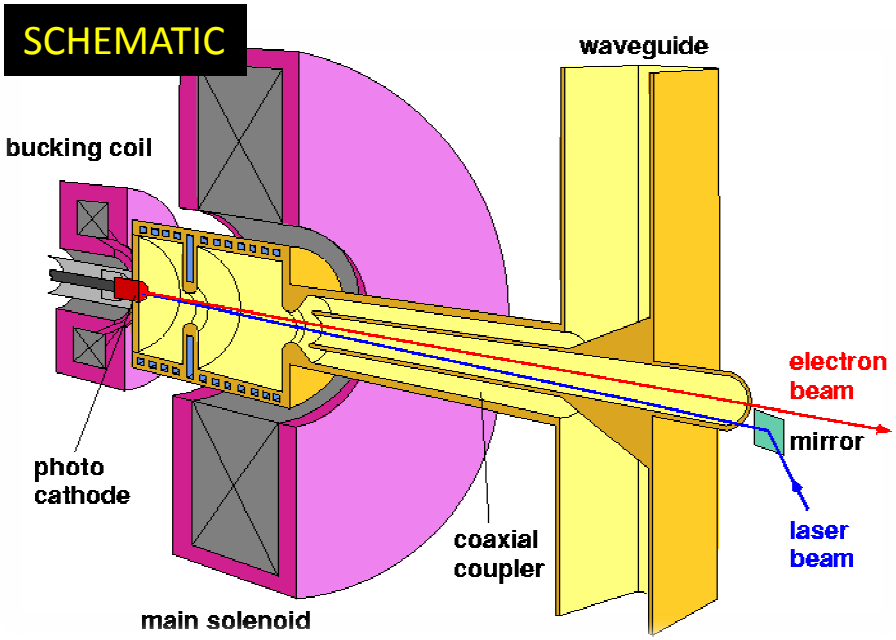
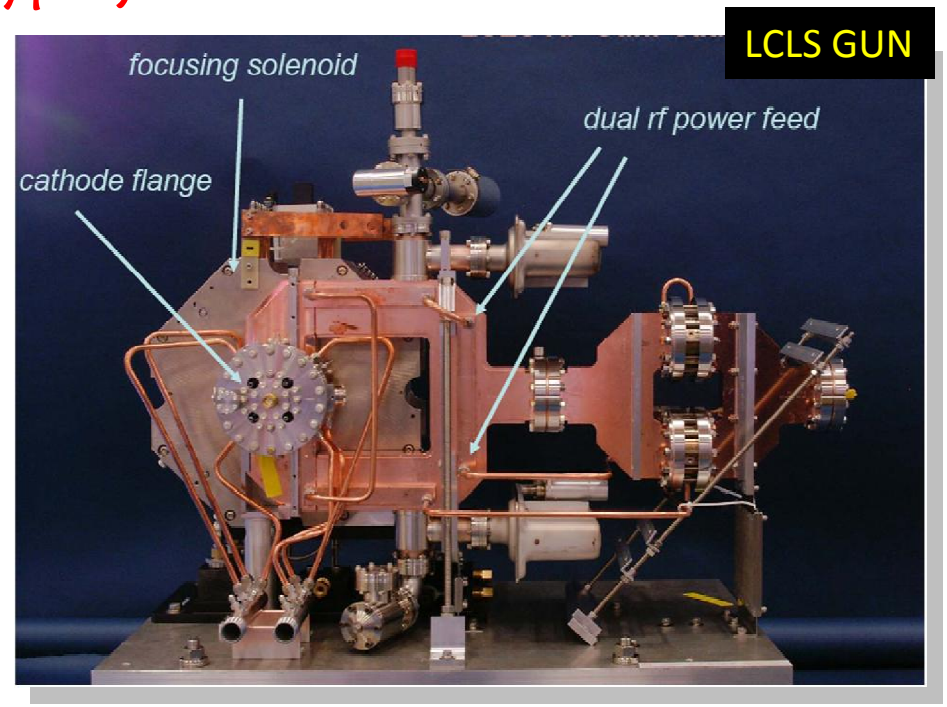
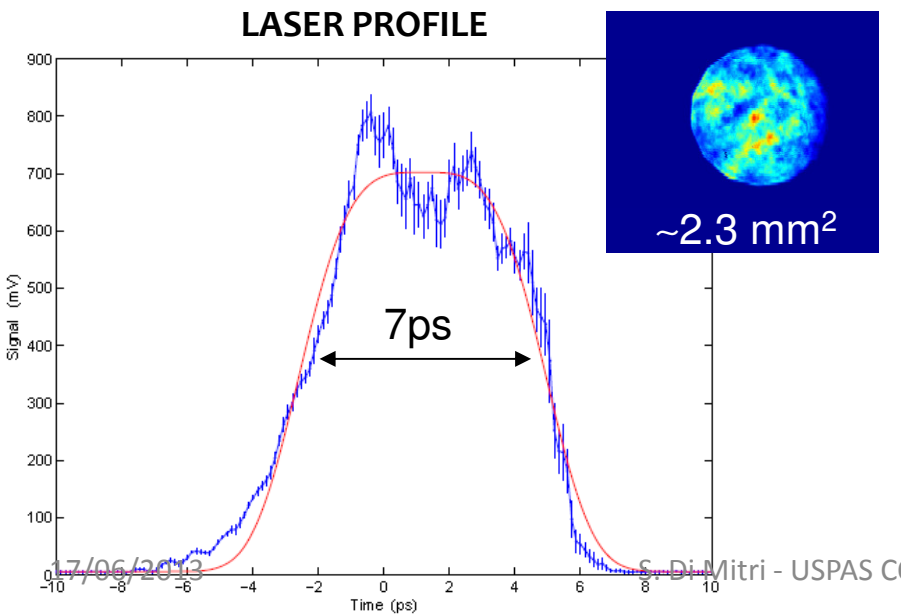


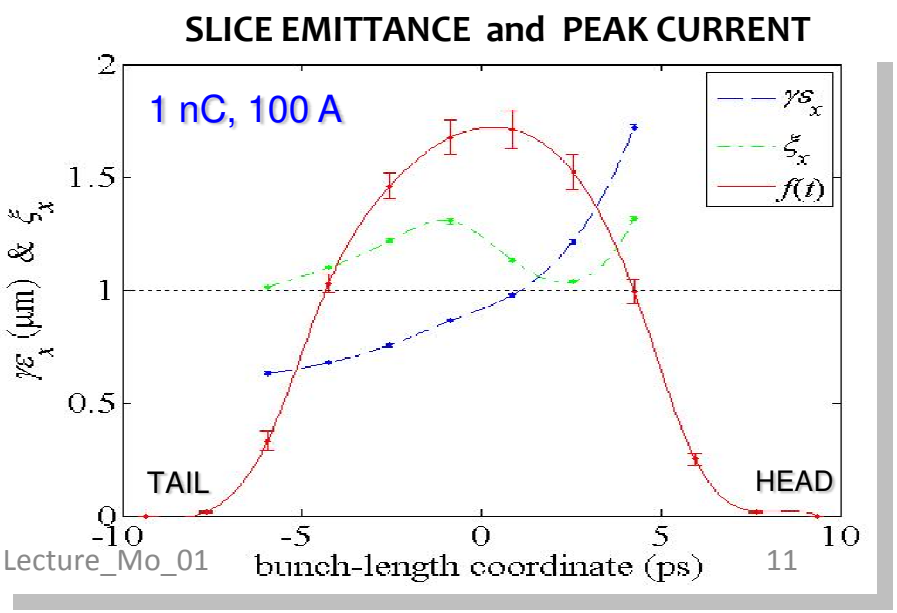
Photo-Injector (UCLA-BNL-SLAC-type)

Pictures courtesy of D. Dowell

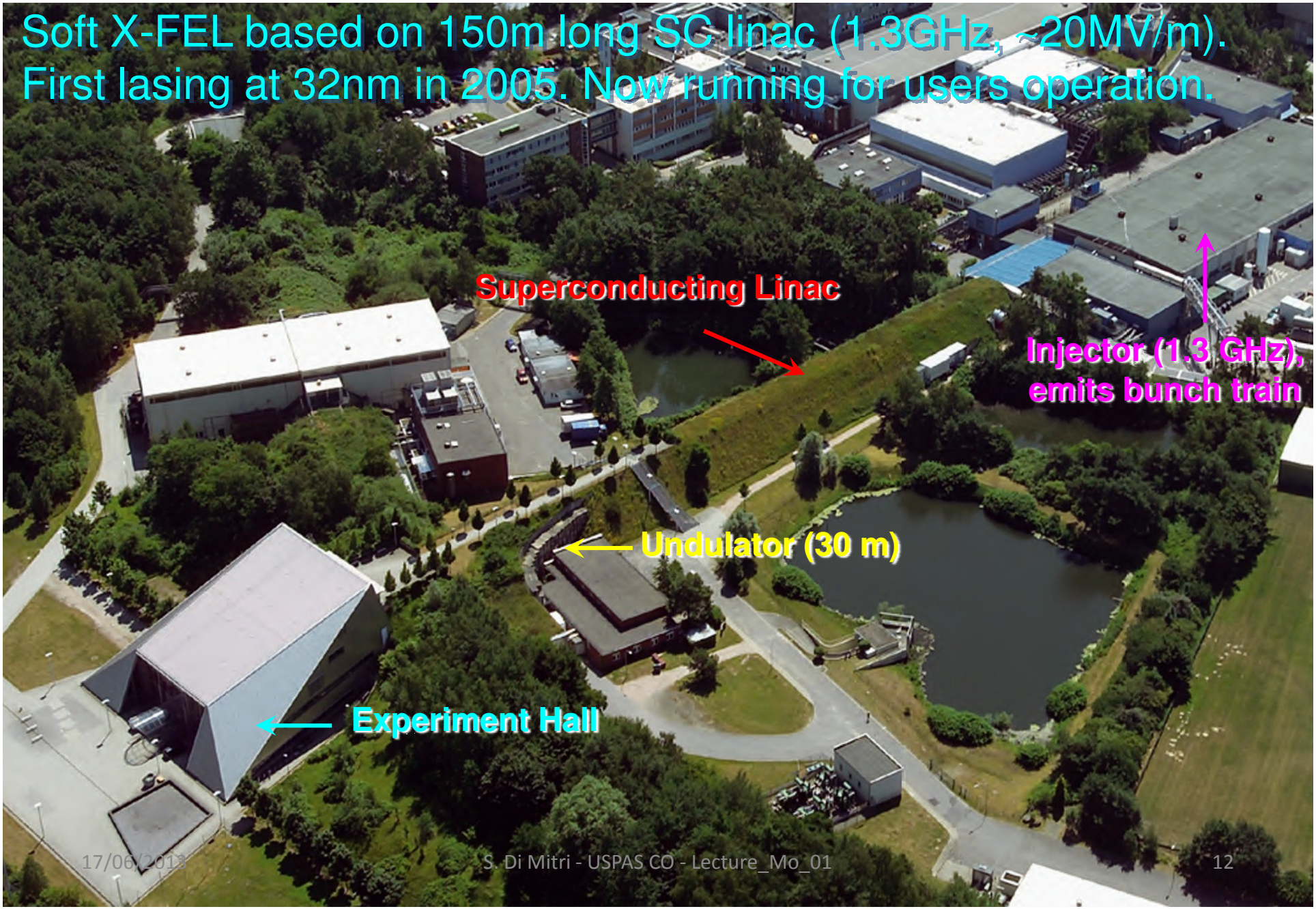






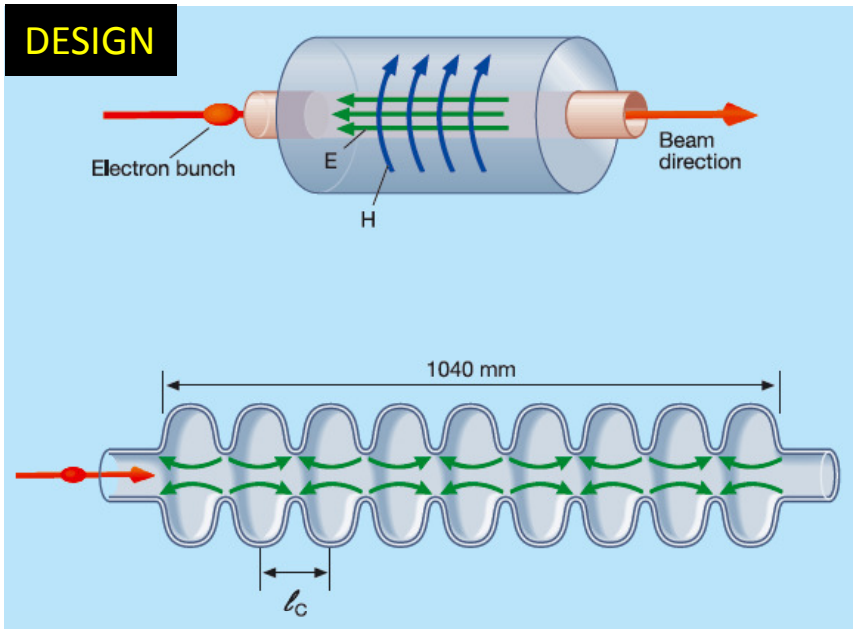


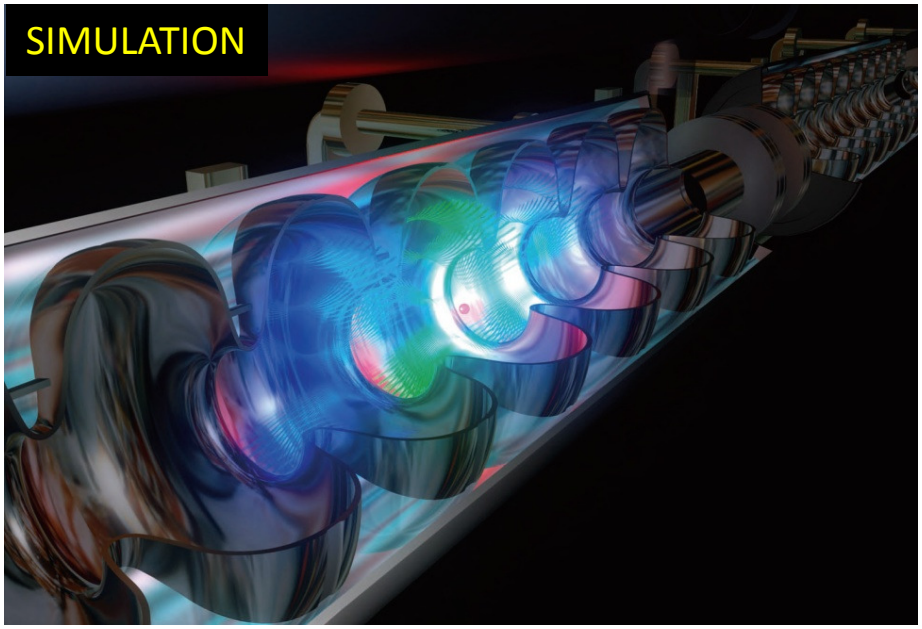
FLASH (DESY, Germany): *45 – 4nm, 1.3 GeV*

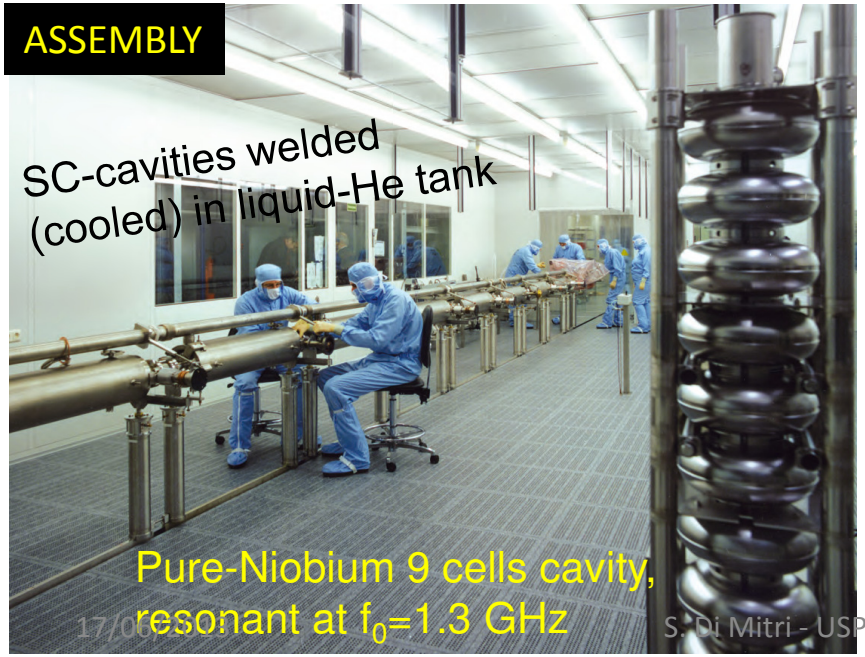


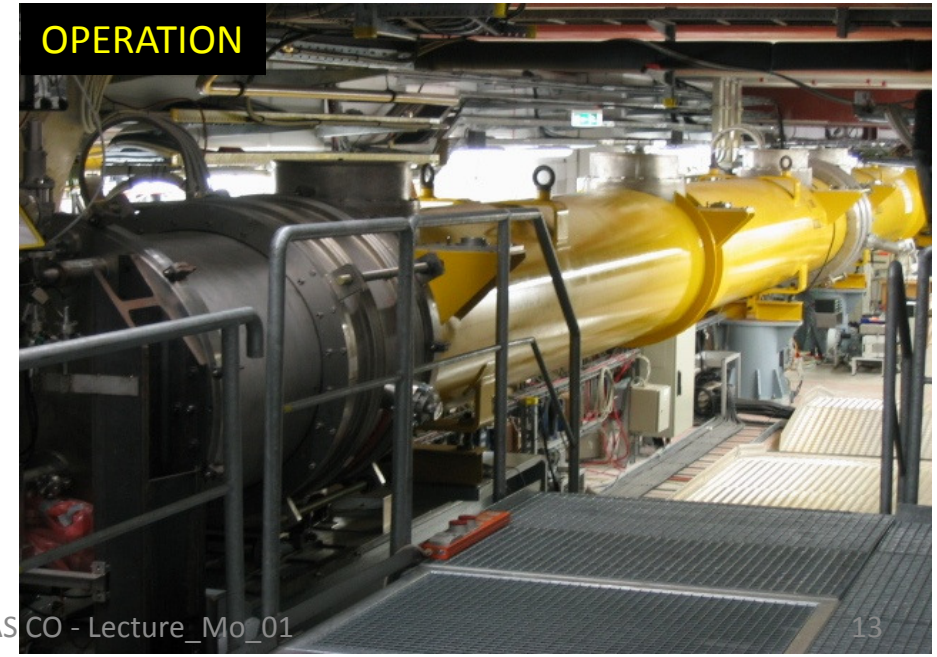
Superconducting linac (TESLA-type)

Pictures from
DESY website

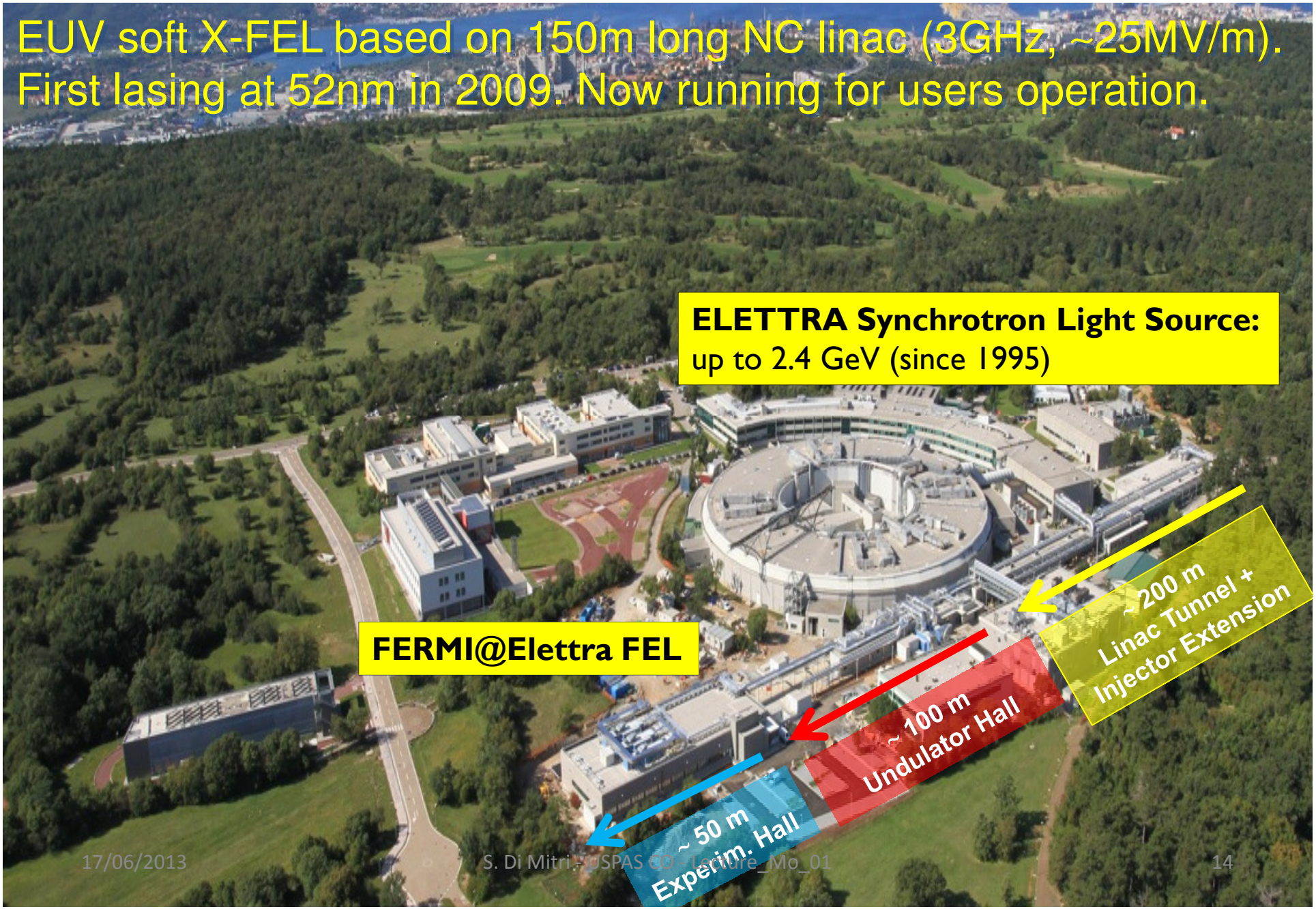






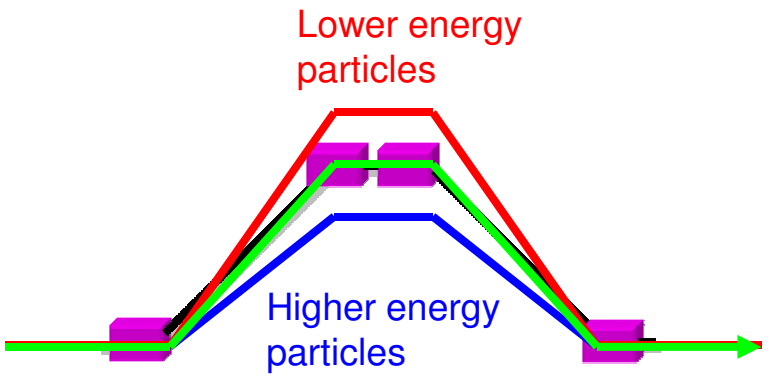


FERMI@Elettra (E-ST, Italy): *80–4nm, 0.9–1.5 GeV*

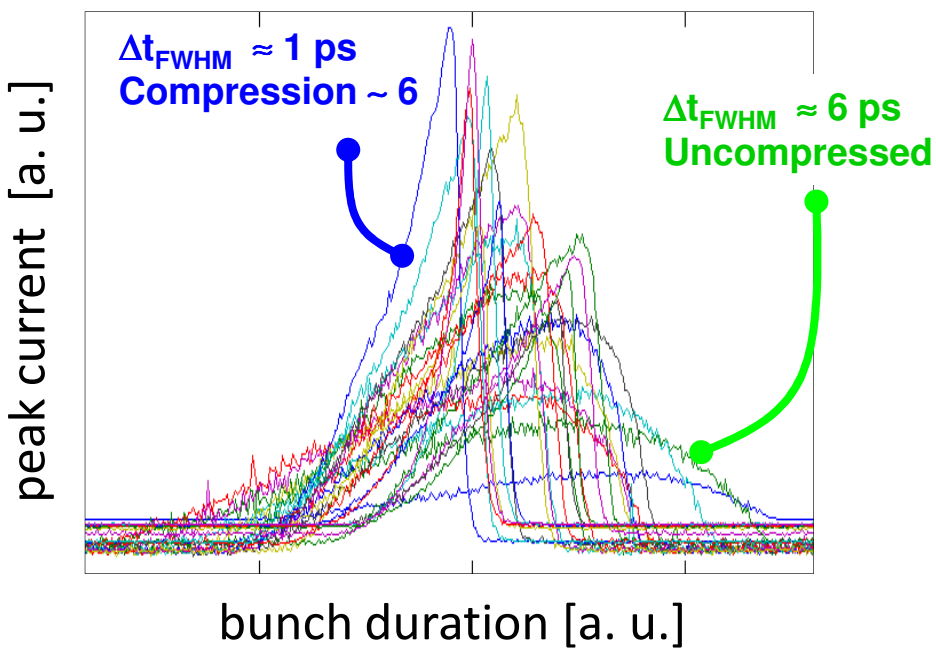


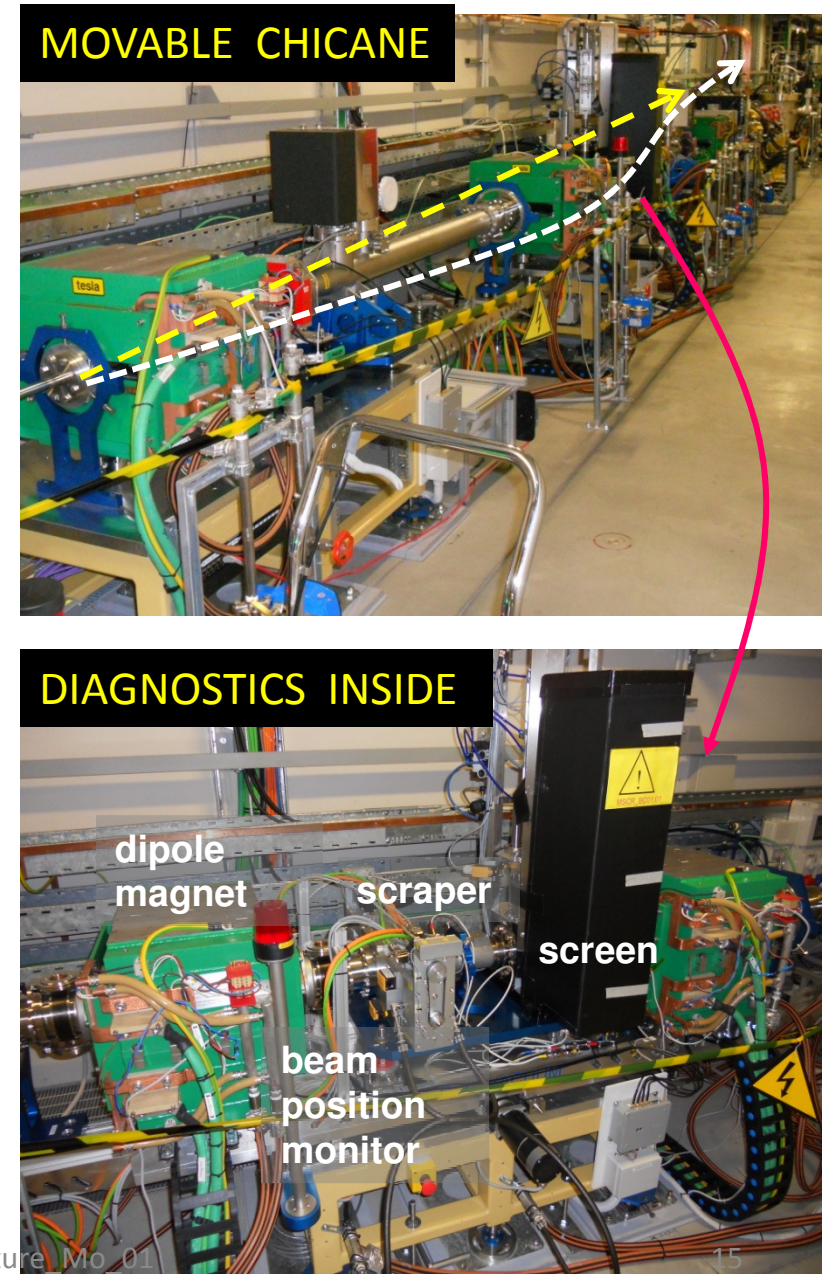
Magnetic bunch length compressor (LEUTL-type)

Pictures courtesy of
G. Penco et al.



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



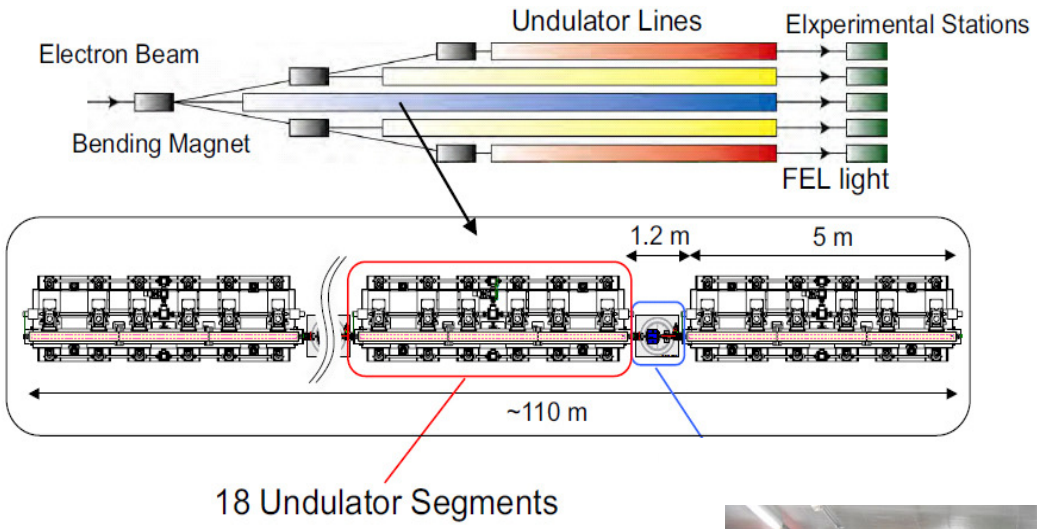


SACLA (Spring-8, Japan): *<0.1nm, 8 GeV*

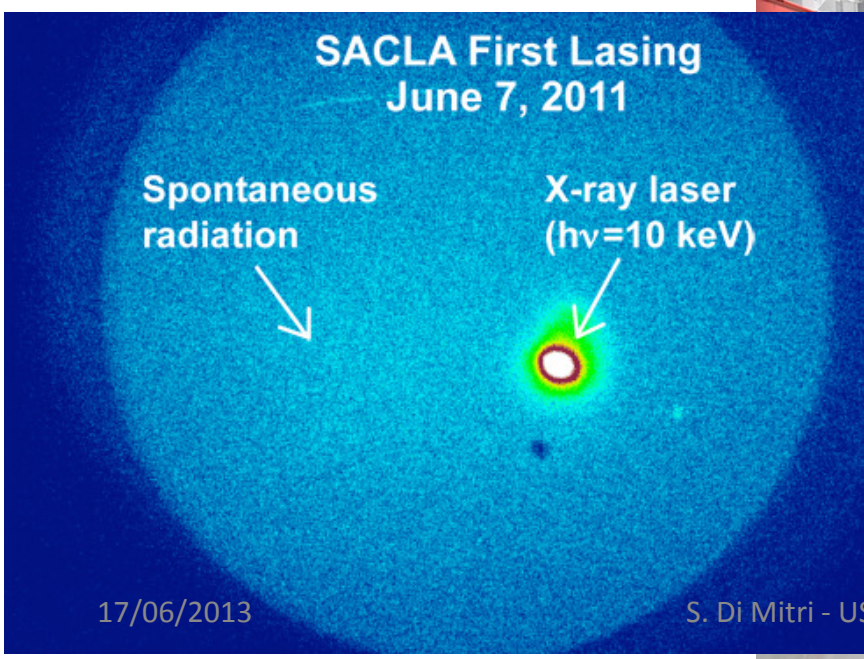
Hard X-FEL based on 230m long NC linac (5.7GHz, ~35MV/m).
First lasing at 0.12nm in 2011. Commissioining is finishing.

Undulator (short-period, in-vacuum)

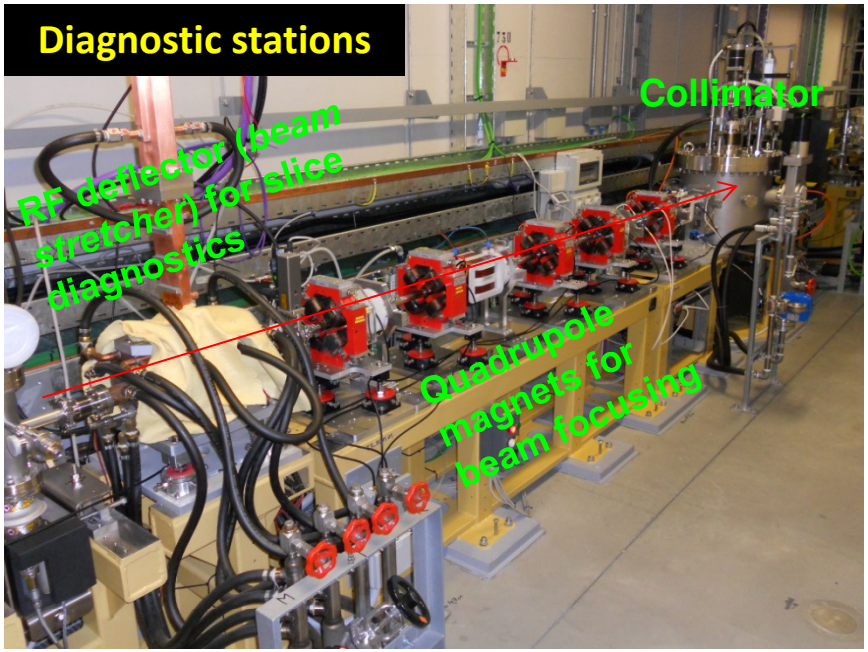
Pictures courtesy of
T. Shintake

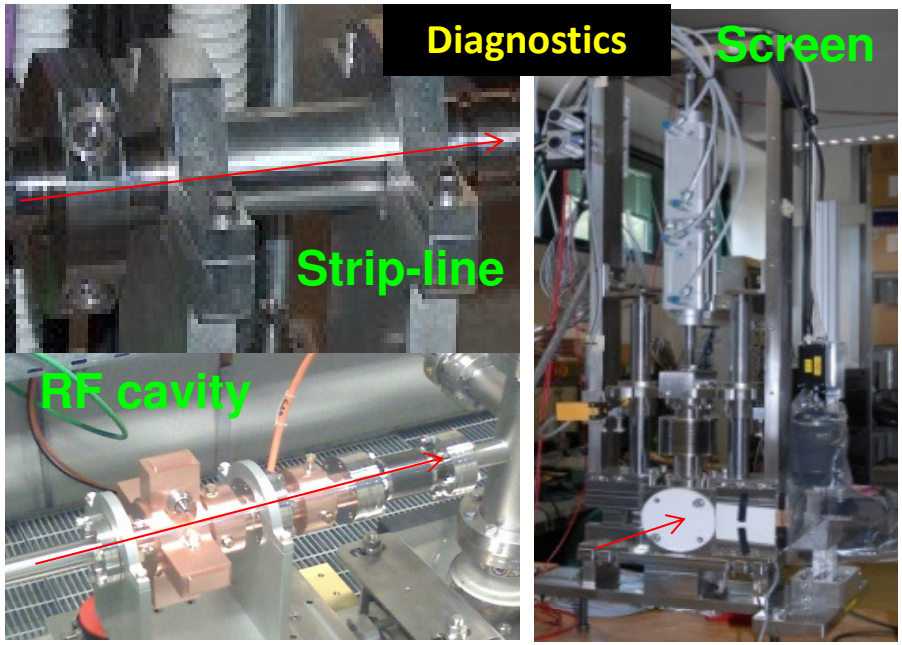


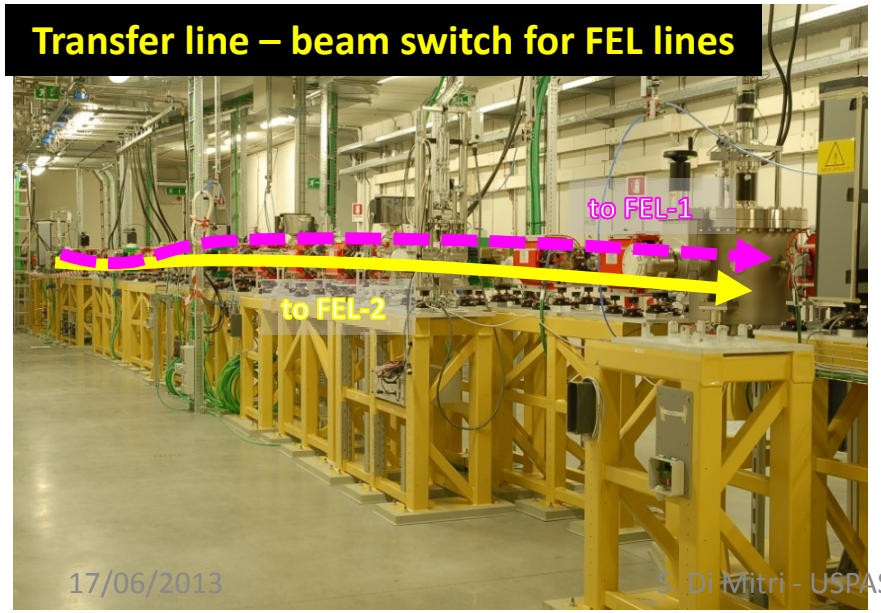
Undulator Type		In-Vacuum Planer Undulator
Active Length		5 m
Undulator Period		18 mm
Magnetic Circuit		Hybrid (NdFeB+Permendur)
Peak Field	Maximum	1.31 T
	Nominal	1.13 T
K	Maximum	2.2
	Nominal	1.9
Gap	Minimum	3.5 mm
	Nominal	4.5 mm
Maximum Attractive Force		~ 6 ton

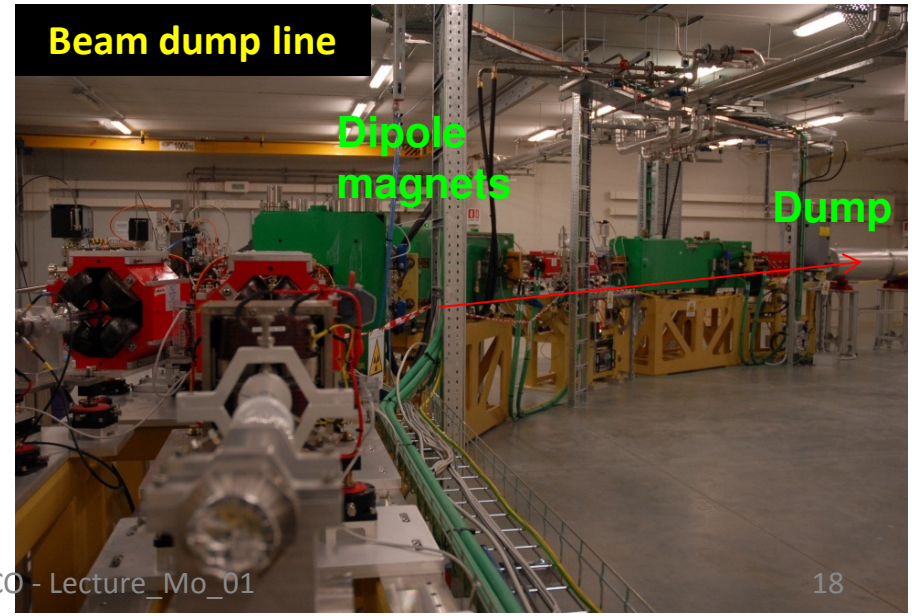


Other accelerator components

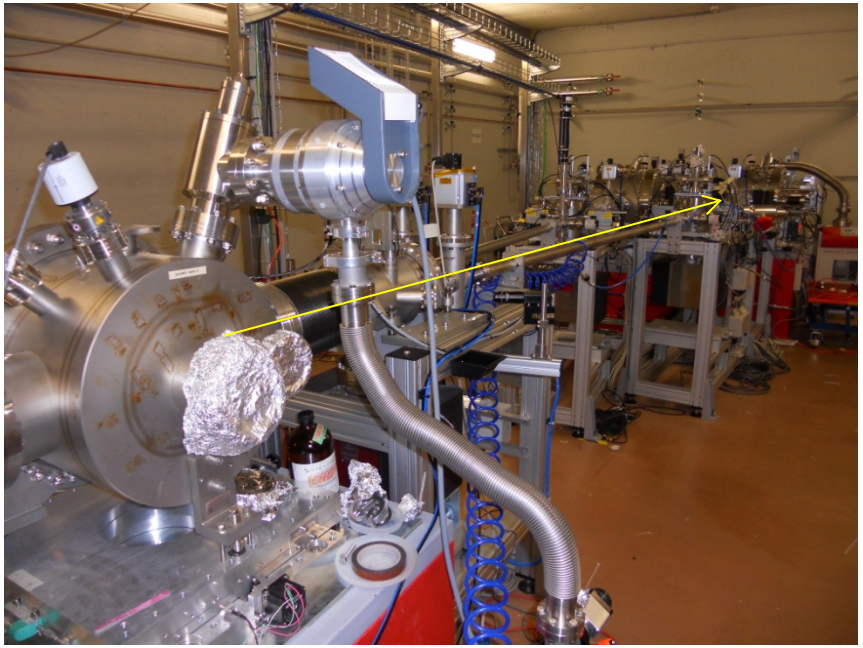






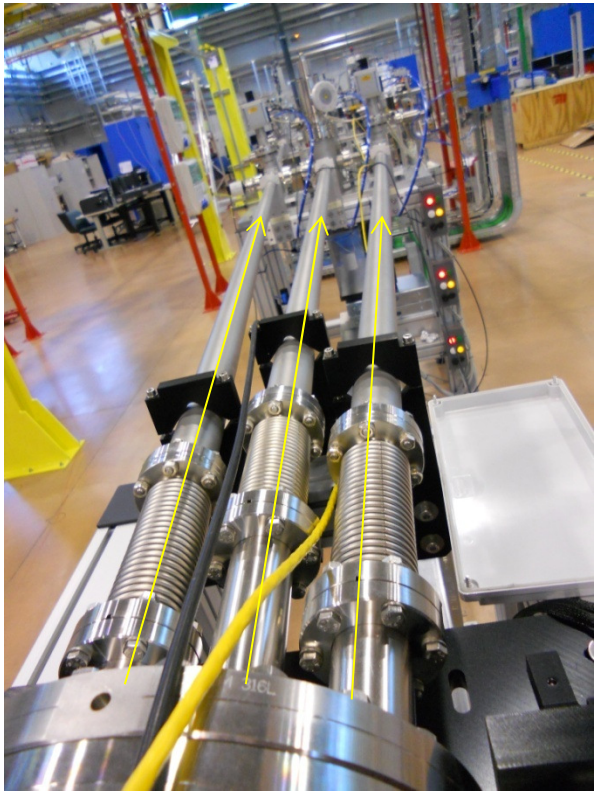


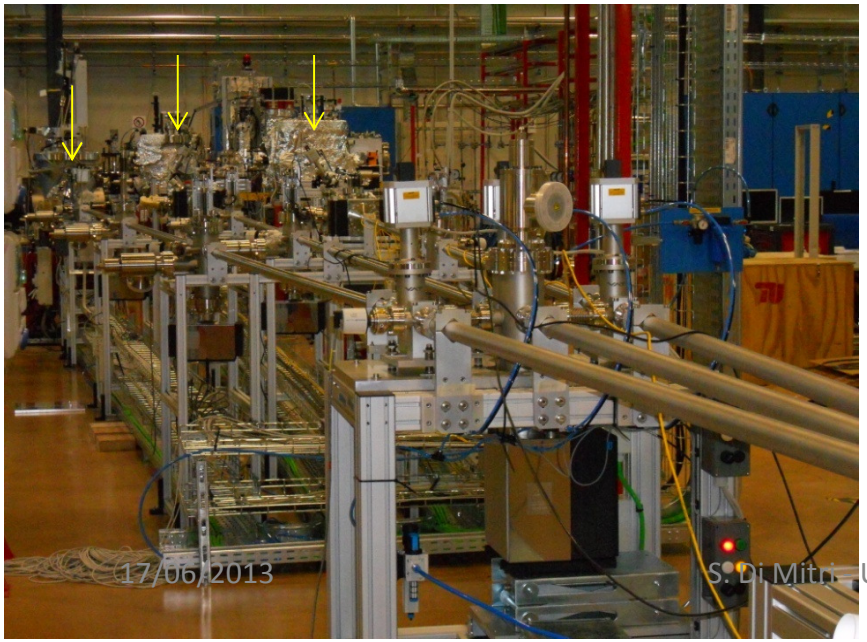
Photon transport



1. FEL photons escaping the undulator are diagnosed before going to the user station (*photon hutch*).

2. The FEL is switched to different users stations with *gratings* and *mirrors*.





3. The FEL finally reaches the *sample*.