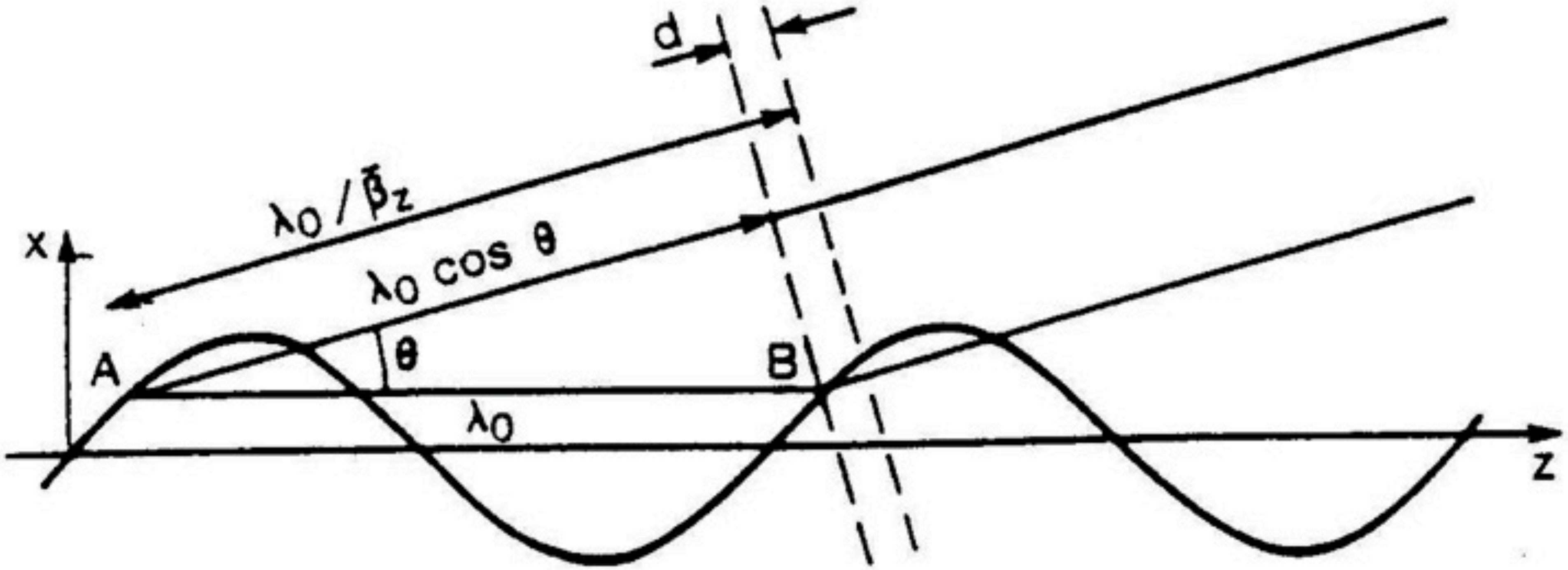
Free Electron Laser Radiation

Undulator radiation



Interference

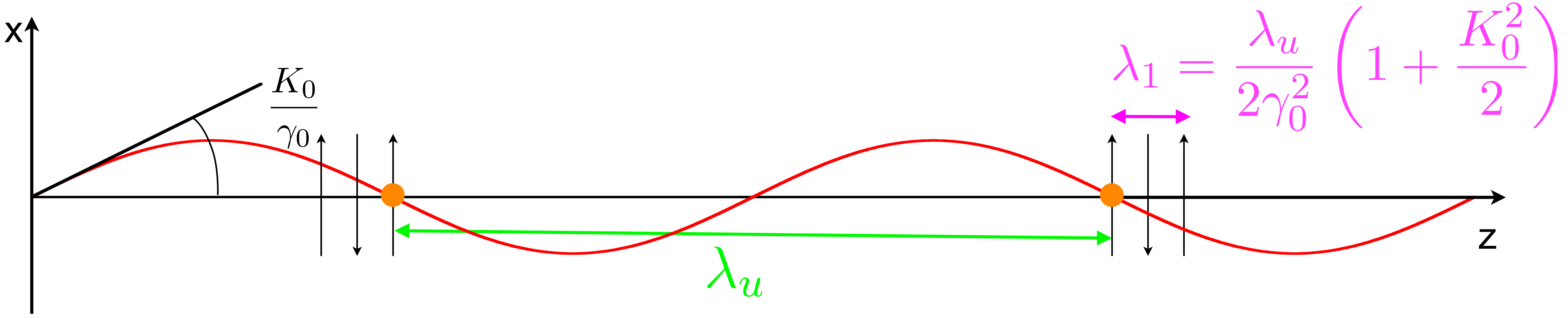
The difference in optical paths between the radiation emitted at A and the radiation emitted at B at an angle θ is

$$d = \lambda_0 \left(\frac{1}{\langle \beta \rangle} - \cos\theta \right)$$

and we get constructive interference if d=nλ

$$\lambda = \frac{\lambda_0}{2n\gamma^2} \left(1 + \frac{K^2}{2} + \gamma^2\theta^2 \right)$$

The FEL basic phenomenon

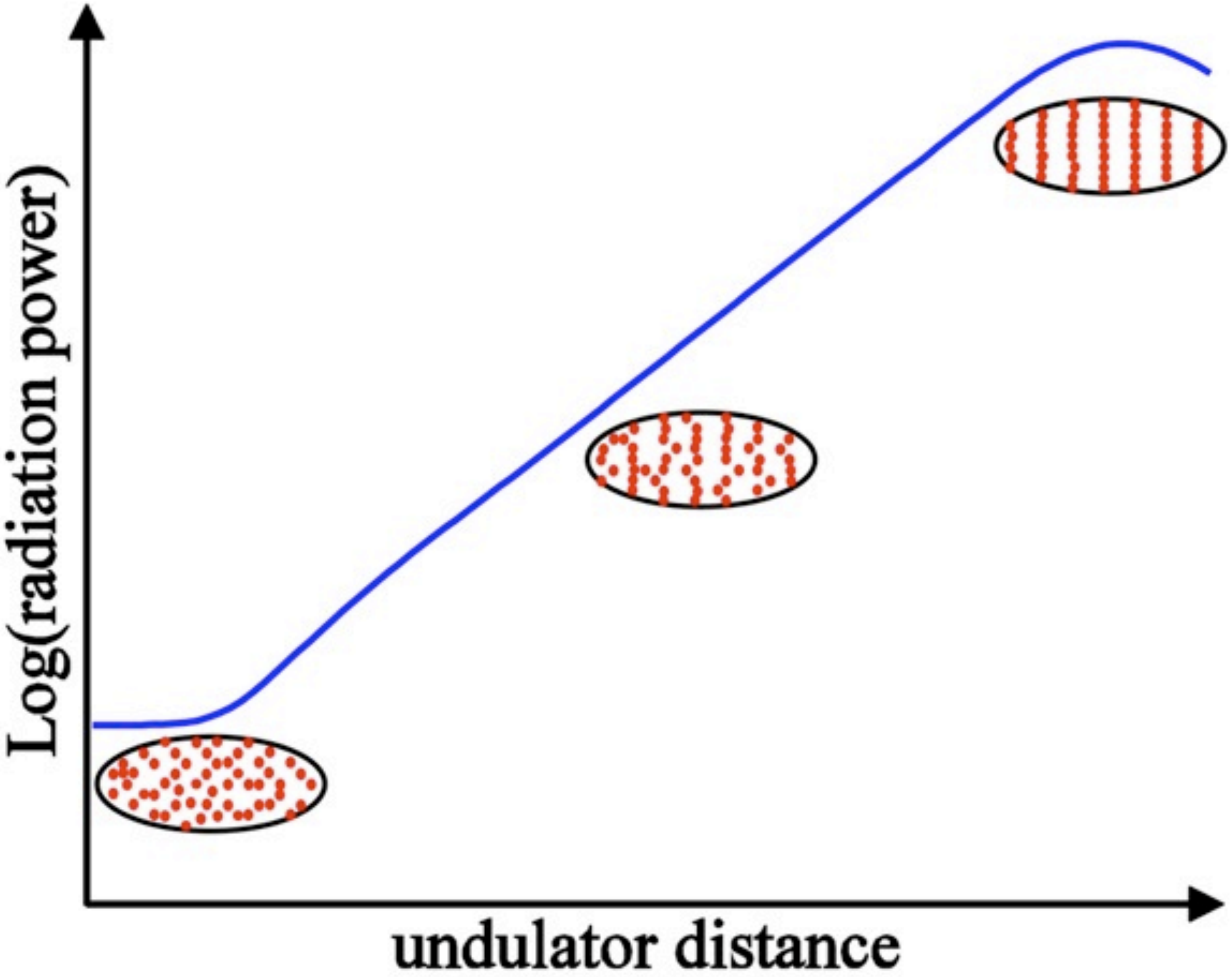


$$\lambda_1 = \frac{\lambda_u}{2\gamma_0^2}\left(1 + \frac{K_0^2}{2}\right)$$

After an electron travels one undulator period λ_u of the sinusoidal trajectory, a plane wave (represented by alternating vertical arrows) overtakes the electron by one resonant wavelength λ_1. Thus, the undulator radiation carrying this resonant wavelength can *exchange energy* with the electron over many undulator periods.

Depending on the phase between the electrons and the plane wave, some electrons **gain** energy from the radiation, while other **lose** energy to the radiation. Slower electrons are accelerated while faster ones are slowed down leading to **“microbunching”**

FEL microbunching



Growth of the radiation power and the electron beam microbunching as a function of the undulator distance for a high-gain FEL.

FEL microbunching

The Pierce scaling parameter is defined as

$$\rho = \left[\frac{K_0^2 \left[JJ\right]^2}{32} \frac{k_p^2}{k_u^2} \right]^{1/3} = \left[\frac{1}{16} \frac{I_e}{I_A} \frac{K_0^2 \left[JJ\right]^2}{\gamma_0^3 \sigma_x^2 k_u^2} \right]^{1/3}$$

$$[JJ] = J_0(\xi) - J_1(\xi)$$

☚Bessel functions

$$\xi = \frac{K_0^2}{4 + 2K_0^2}$$

$$k_p = \sqrt{\frac{2I_e}{\gamma_0^3 I_A \sigma_x^2}}$$

☚longitudinal plasma oscillation wavenumber

$$I_A = \frac{ec}{r_e} \approx 17 \text{ kA}$$

☚Alfvén current

$$r_e \approx 2.8 \times 10^{-15} \text{m}$$

☚classical radius of the electron

$$\sigma_x$$

☚rms transverse size of the beam

FEL microbunching

In terms of the Pierce scaling parameter, the gain power gain length of a monoenergetic beam is

$$L_{G0} = \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$

The relative FEL bandwidth at saturation is close to ρ, and the saturation power is about ρ times the electron beam power.

Electron motion in the presence of undulator radiation

The undulator magnetic fields gives:

$$v_x = \frac{eB_0}{\gamma m k_u} \cos\left(k_u z\right) = \frac{K_0 c}{\gamma} \cos\left(k_u z\right)$$

$$v_z = c\sqrt{1 - \frac{1}{\gamma^2} - \frac{v_x^2}{c^2}}$$

$$\simeq \underbrace{c\left(1 - \frac{1 + \frac{K_0^2}{2}}{2\gamma^2}\right)}_{a \equiv \bar{v}_z} - \frac{K_0^2 c}{4\gamma^2} \cos 2k_u z$$

Electron motion in the presence of undulator radiation

The change in the electron energy in presence of an electric field of the form $\mathrm{E}_x = E_0 \cos\left(k_1 z - \omega_1 t + \psi_0\right)$ is:

$$\begin{aligned} mc^2 \frac{d\gamma}{dt} &= e v_x E_x \\ &= \frac{eE_0 K_0 c}{2\gamma} \left\{ \cos\left[\left(k_1 + k_u\right) z - \omega_1 t + \psi_0\right] \right. \\ &\left. + \cos\left[\left(k_1 - k_u\right) z - \omega_1 t + \psi_0\right] \right\} \end{aligned}$$

We define

$$\theta = \left(k_1 + k_u\right) z - \omega_1 \bar{t}$$

where $\bar{t}$ is the electron arrival time averaged over the undulator period

Electron motion in the presence of undulator radiation

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$$\theta = \left(k_1 + k_u\right) z - \omega_1 \bar{t}$$

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Electron motion in the presence of undulator radiation

the phase variation along the undulator is therefore

$$\frac{d\theta}{dz} = k_1 + k_u - \frac{\omega_1}{\bar{v}_z} = k_u - k_1 \frac{1 + \frac{K_0^2}{2}}{2\gamma^2}$$

if we introduce the interference condition:

$$k_1 = \frac{2\pi}{\lambda_1} = 2\gamma_0^2 k_u \frac{1}{\left(1 + \frac{K_0^2}{2}\right)}$$

$$\frac{d\theta}{dz} = 2k_u \frac{\gamma - \gamma_0}{\gamma_0} = 2k_u \eta$$

we see that the variation of θ at the interference condition is estremely small as it is proportional to the relative variation in energy.

Electron motion in the presence of undulator radiation

The second term in the energy variation equation varies quickly (period $2\lambda_u$), not contributing to the energy exchage. Properly taking into account the fact that the electron's longitudinal motion also has an oscillatory part as given, we can write

$$\frac{d\eta}{dz} = \frac{eK_0[JJ]}{2\gamma_0^2 mc^2} E_0 \cos\left(\theta + \psi_0\right)$$

which together with

$$\frac{d\theta}{dz} = 2k_u\eta$$

are known as the "pendulum equations." They describe the motion of electrons under the influenceof the "ponderomotive potential" due to the combined
undulator and radiation fields

Electron motion in the presence of undulator radiation

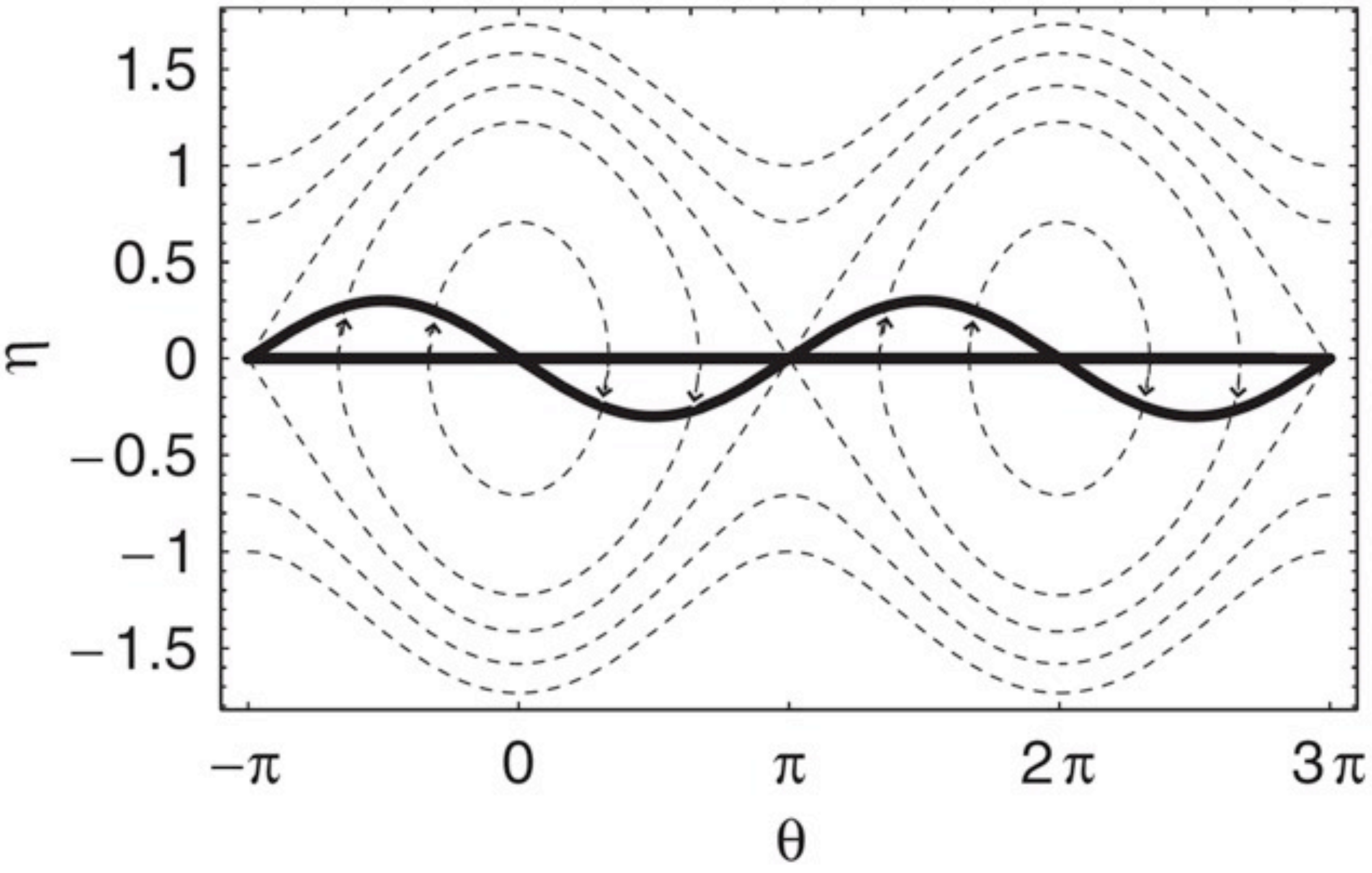


FIG. 4. Electron motion in the longitudinal phase space (θ, η) due to the presence of a resonant EM wave (with an initial phase $\psi_0 = \pi/2$) in the undulator. An initial distribution of the electron beam, shown as a straight line at $\eta = 0$, changes into a distribution on a sinusoidal line, implying that the energy and the density of the electron beam is modulated, i.e., microbunched. The dashed lines are the phase space trajectories.

Undulator Magnets: Resonant Condition

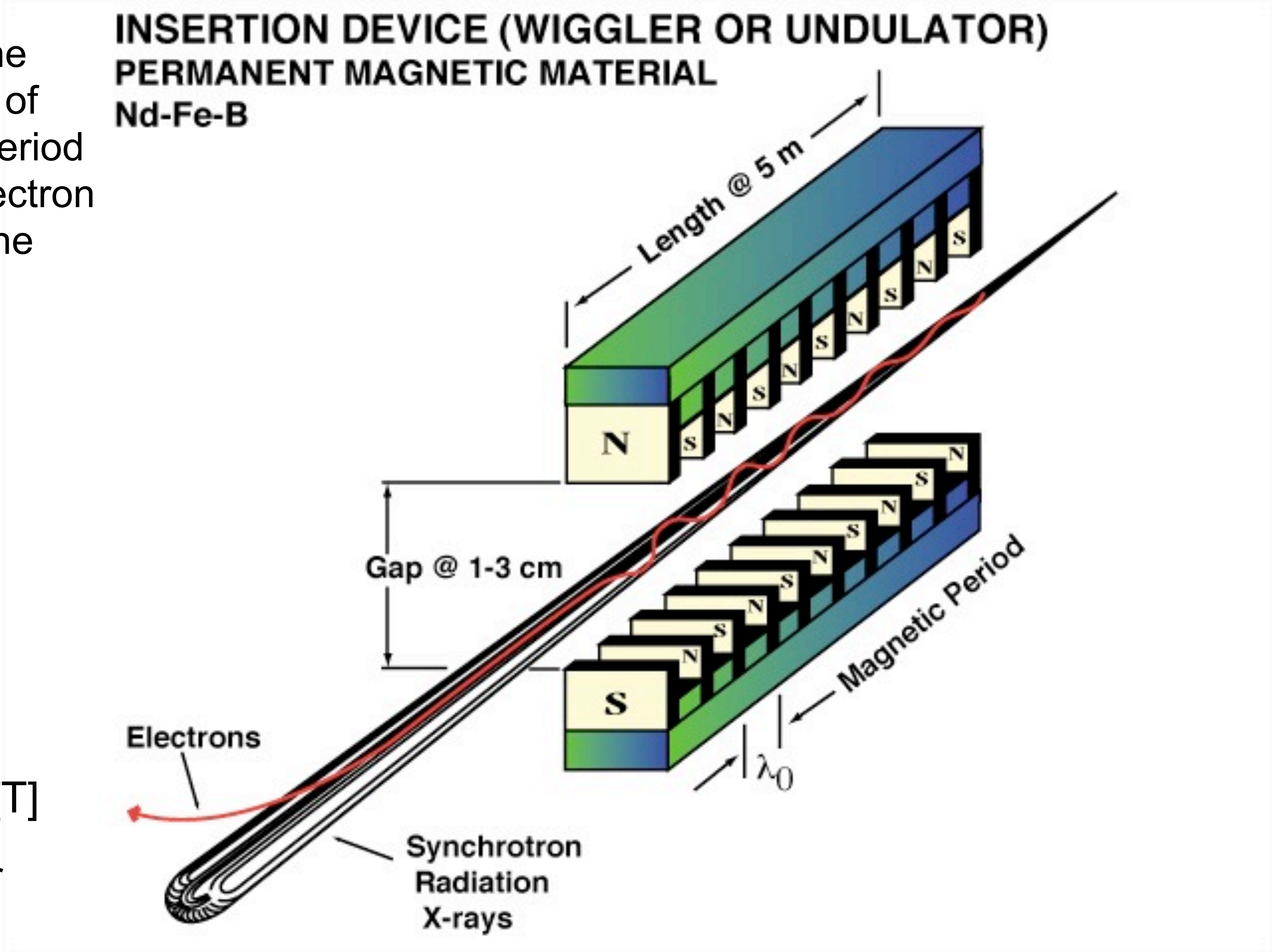
“Resonance” occurs when the light wavefront “slips” ahead of the electron by one optical period in the time that it took the electron to traverse the distance of one undulator period

$$\lambda_{rad} = \frac{\lambda_o}{2\gamma^2}\left(1 + K^2/2\right)$$

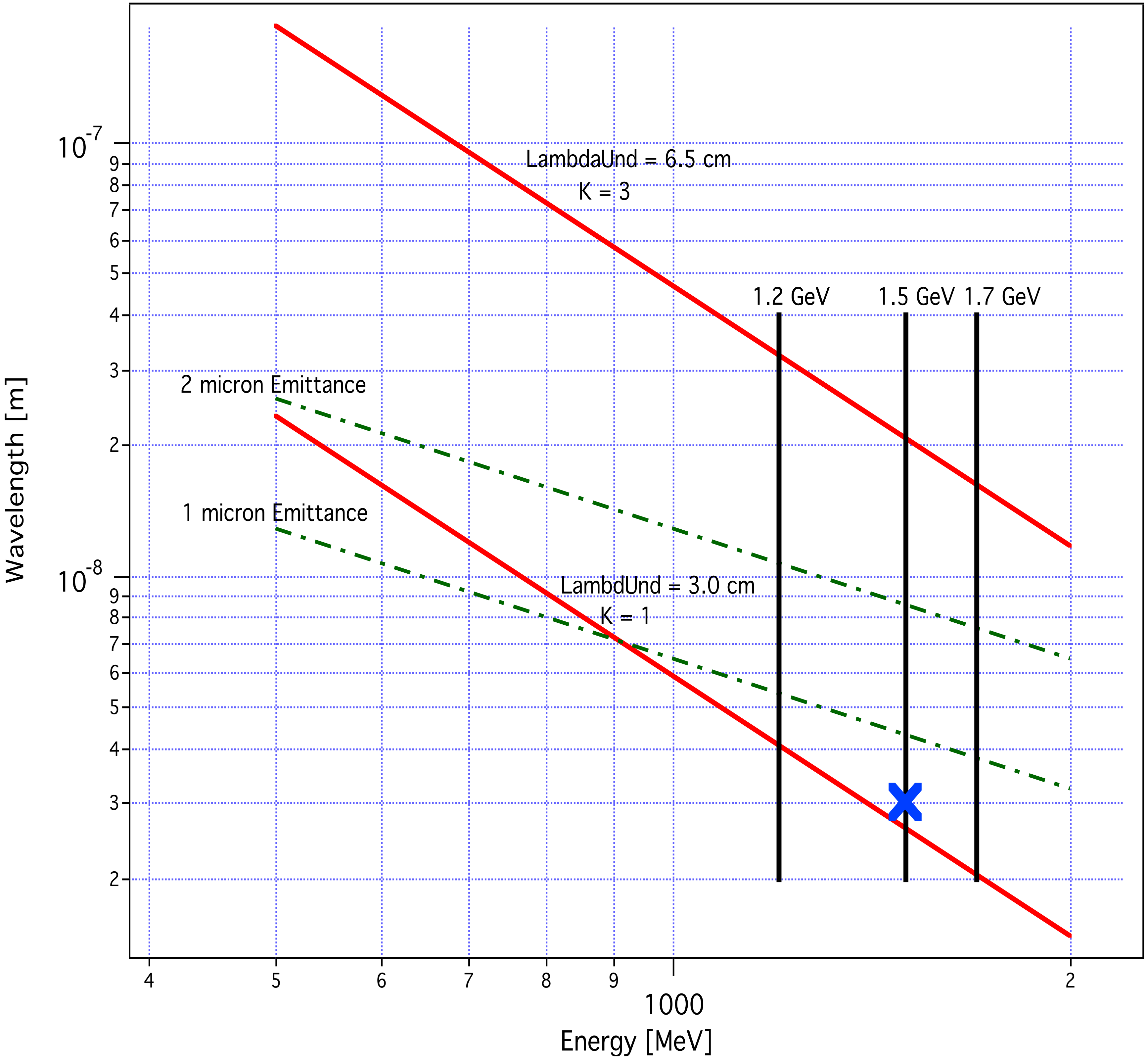
Where γ is the normalized electron beam total energy and

$K = 0.934\ \lambda_{rad}\,[\mathrm{cm}]\ B_{max}\ [\mathrm{T}]$

Is the normalized undulator field strength parameter



Wavelength Reach



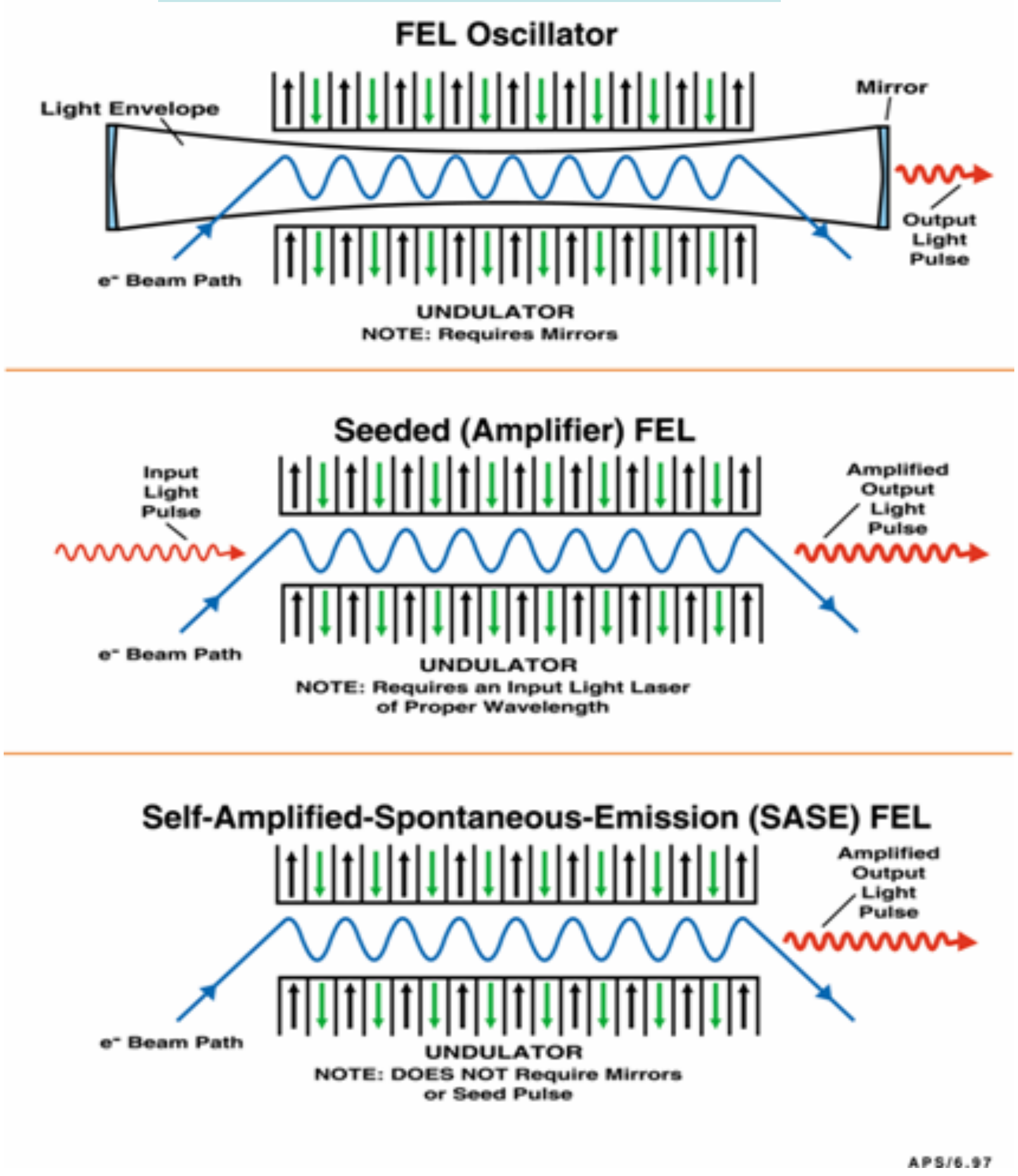
The resonant condition gives a slope of -2 on the log-log graph (red lines).

Geometric emittance decrease inversely with beam energy in a linac.

FELs work best if the geometric emittance is less that the photon beam emittance (TEM_{00} mode) $\lambda/4\pi$ (green lines)

Ones need to realistically assess the capabilities of the linac and electron beam source

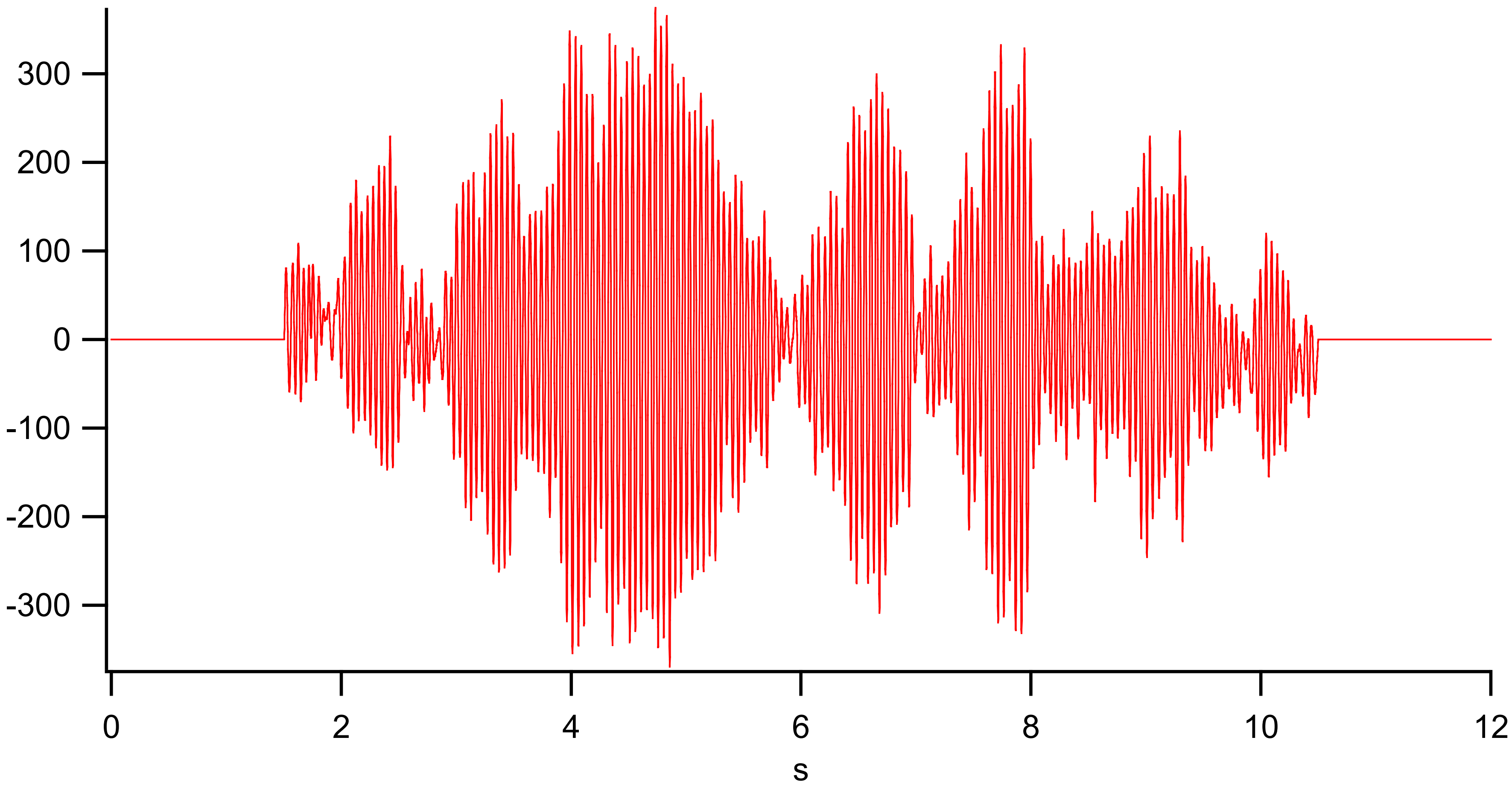
FEL Types: Oscillator, Seeded FEL, SASE



The Start of Microbunching

$$E_{tot}(t) = E_x(t)\sum_{j=1}^{N}\exp(i\phi_j)$$

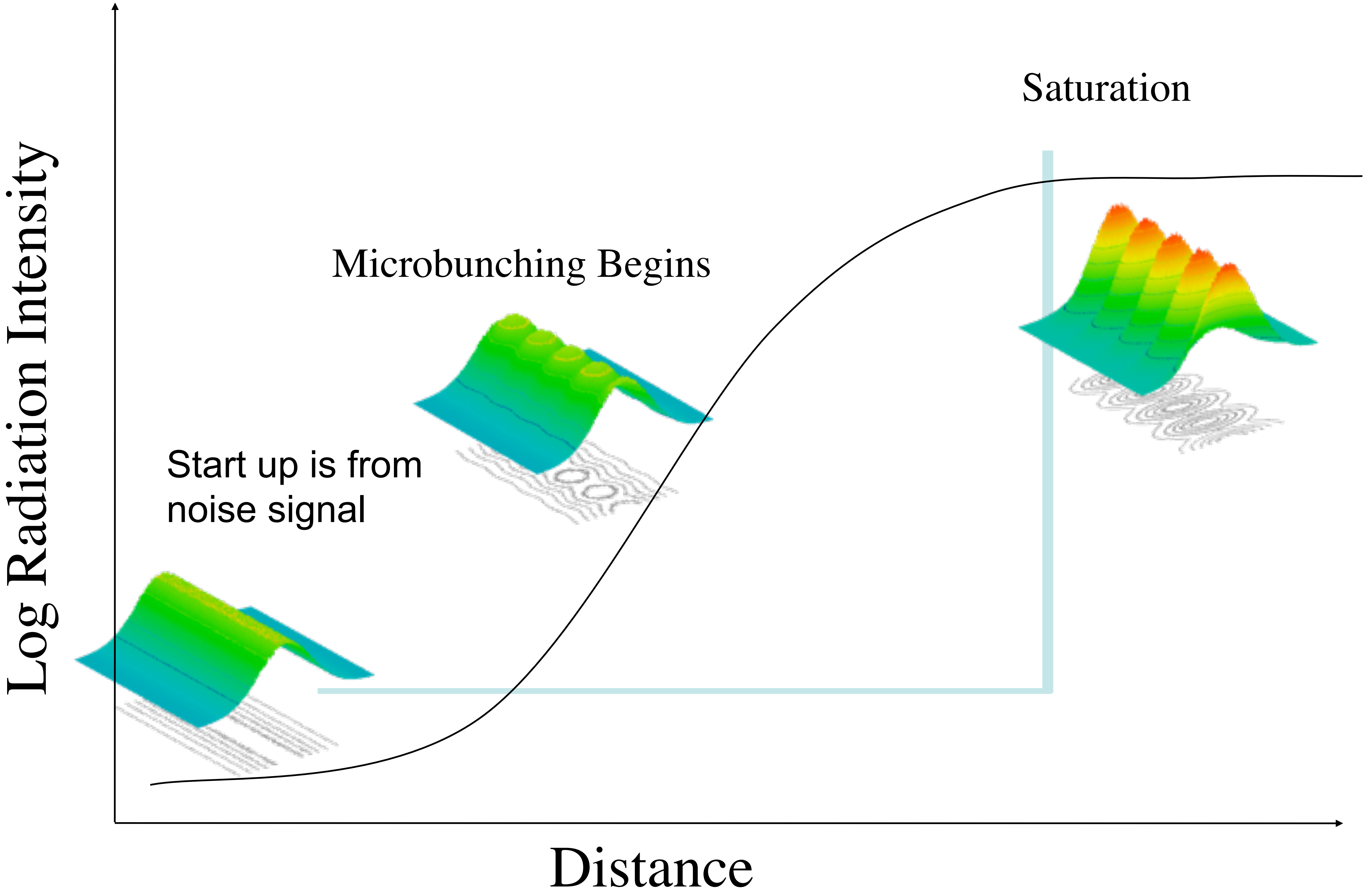
Coherent sum of
radiation from N electrons

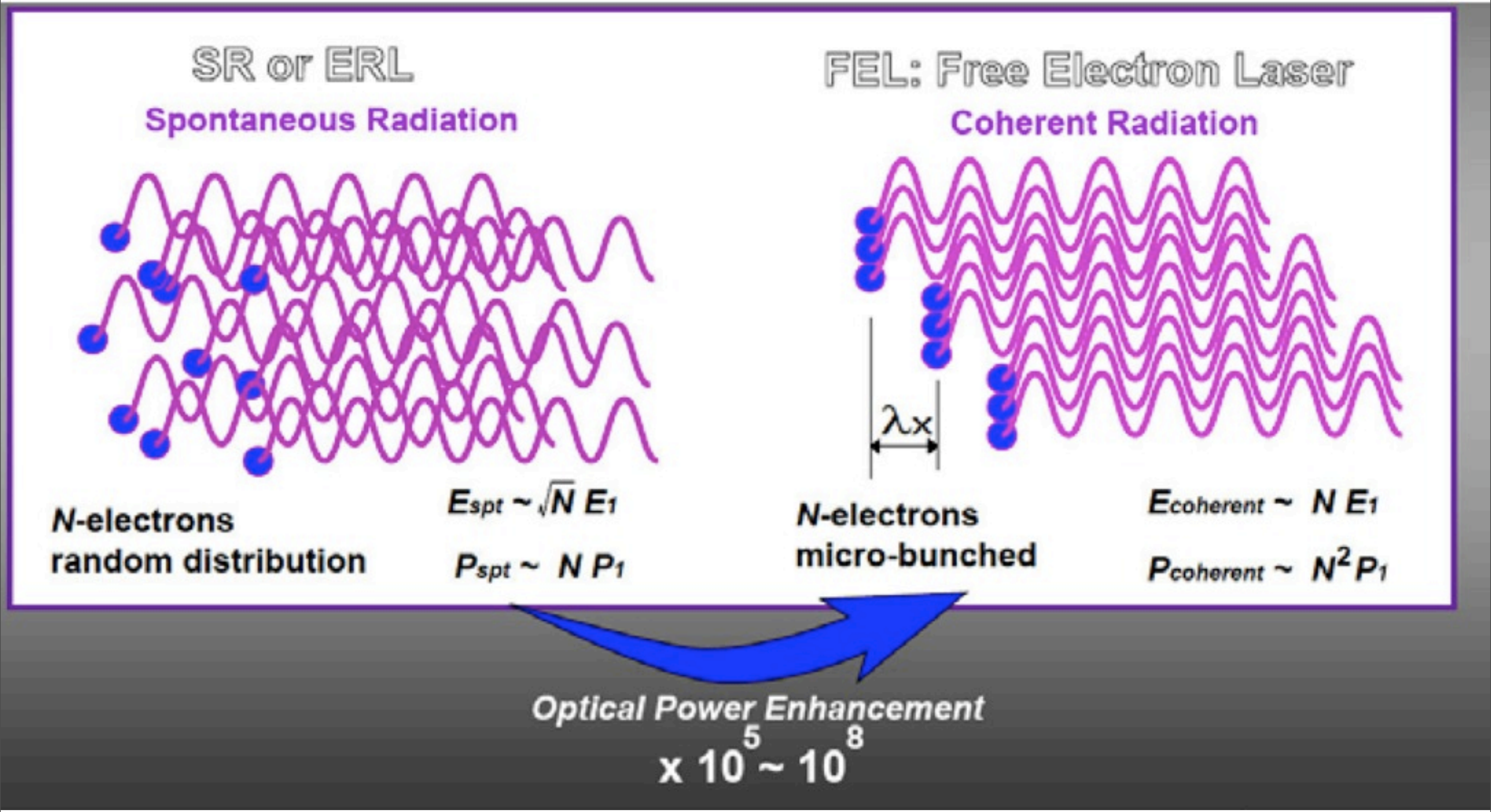


The SASE light consists of several coherent regions, also known as spikes, randomly distributed over the pulse length of the electron beam.

Self-Amplified Spontaneous Emission (SASE)

Exponential Growth





SR or ERL

Spontaneous Radiation

N-electrons random distribution

$E_{spt} \sim \sqrt{N}\, E_1$

$P_{spt} \sim N\, P_1$

FEL: Free Electron Laser

Coherent Radiation

N-electrons micro-bunched

$E_{coherent} \sim N\, E_1$

$P_{coherent} \sim N^2 P_1$

Optical Power Enhancement

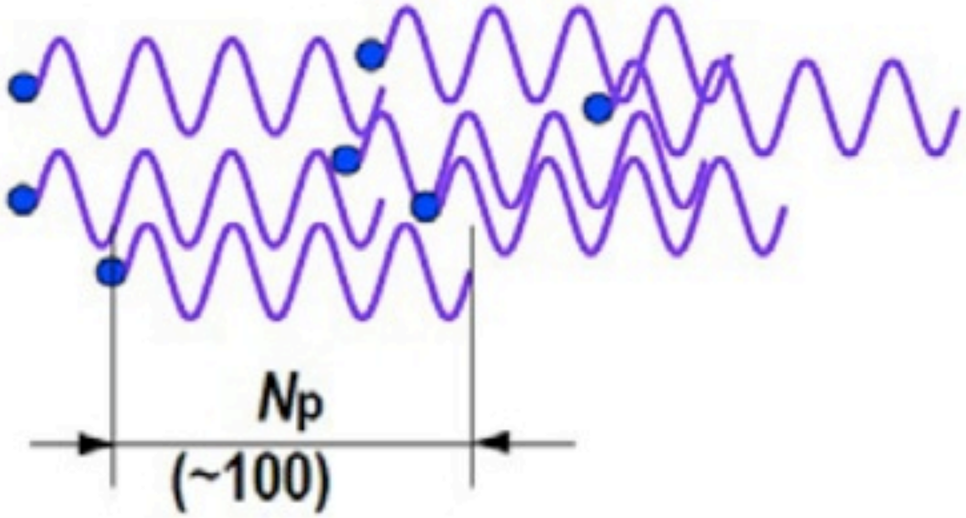
$\times\, 10^5 \sim 10^8$

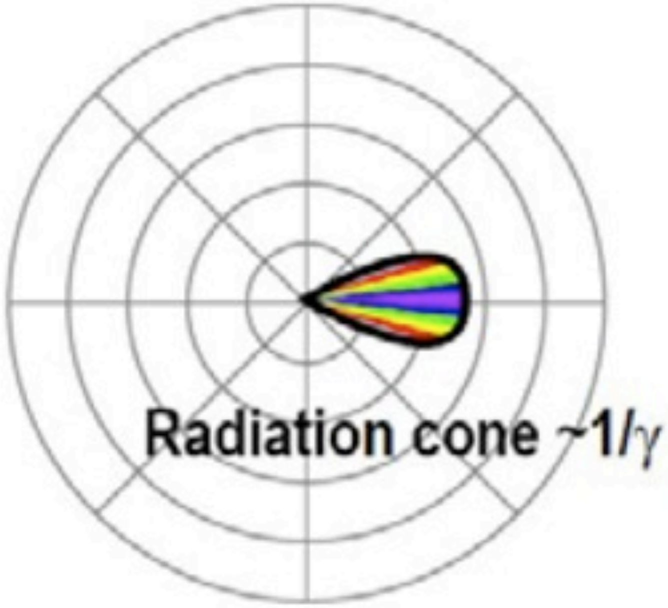
Radiation from Group Electron

T. Shintake, 2006

Spontaneaus Radiation

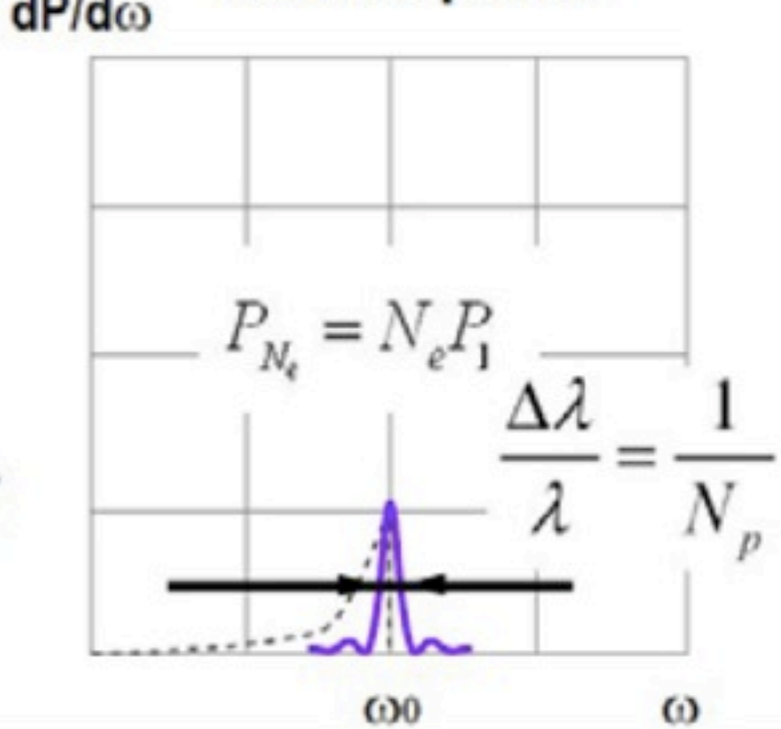
Randomely positioned Ne electrons.





Radiation cone ~1/γ

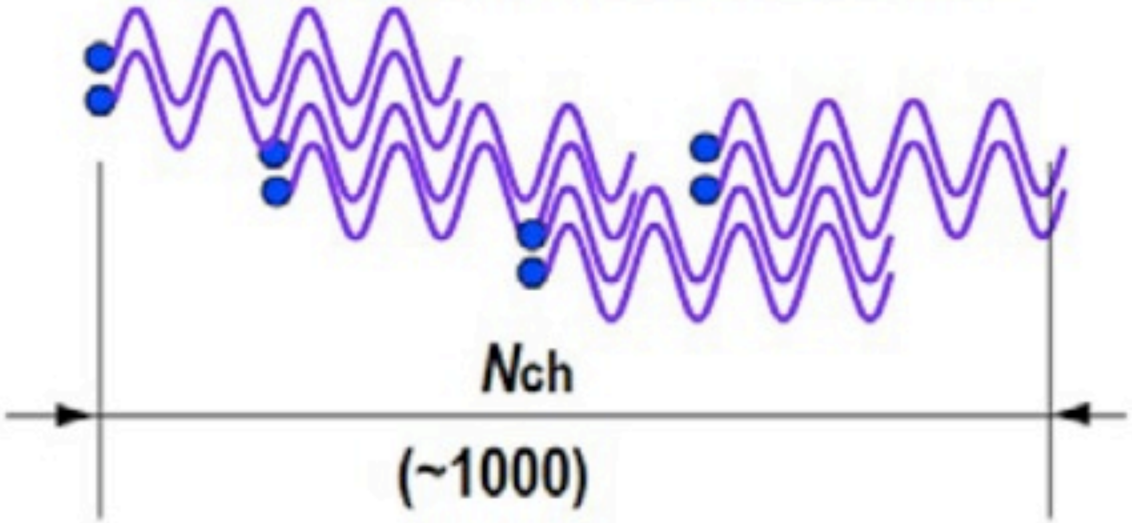
On-axis power



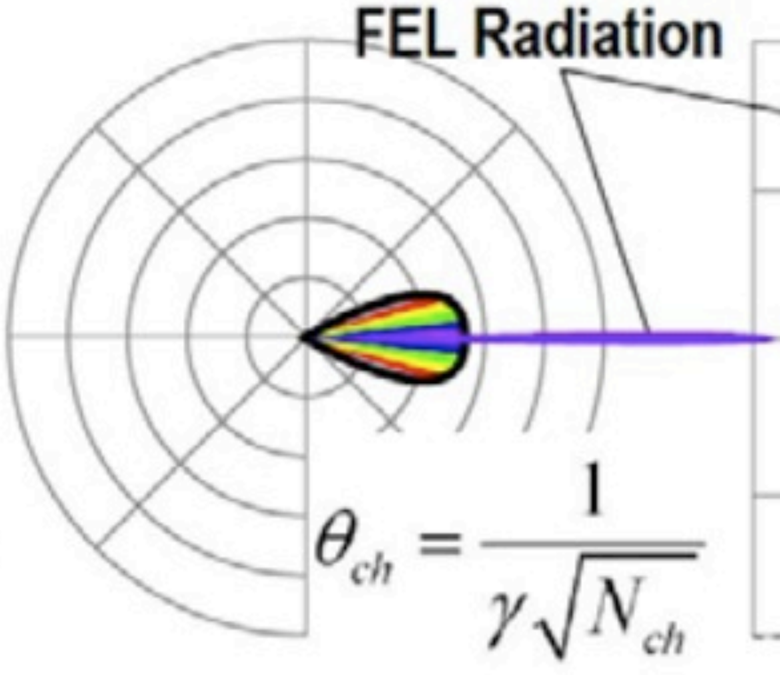
$$P_{N_e} = N_e P_1$$

$$\frac{\Delta\lambda}{\lambda} = \frac{1}{N_p}$$

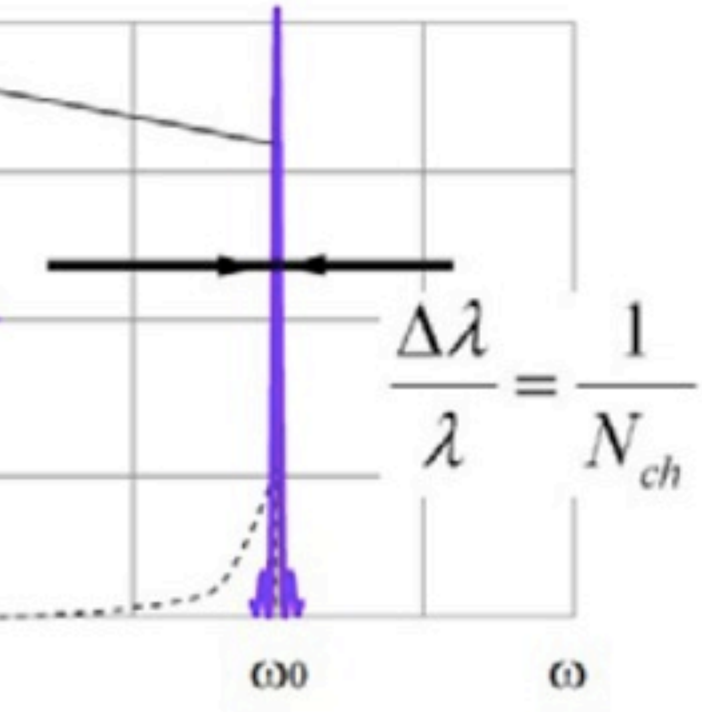
Regulary positioned Ne electrons.



FEL Radiation



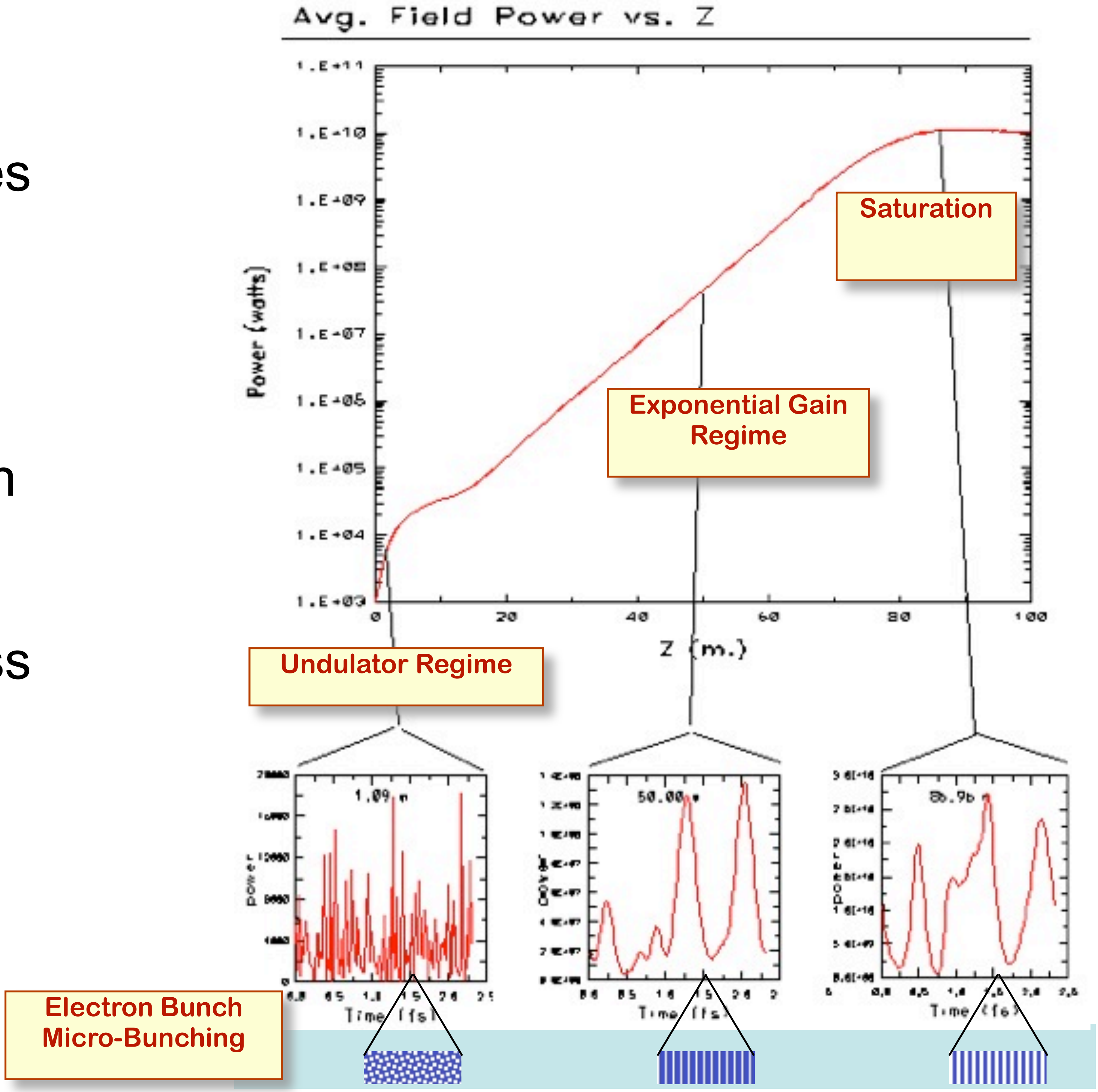
$$\theta_{ch} = \frac{1}{\gamma\sqrt{N_{ch}}}$$



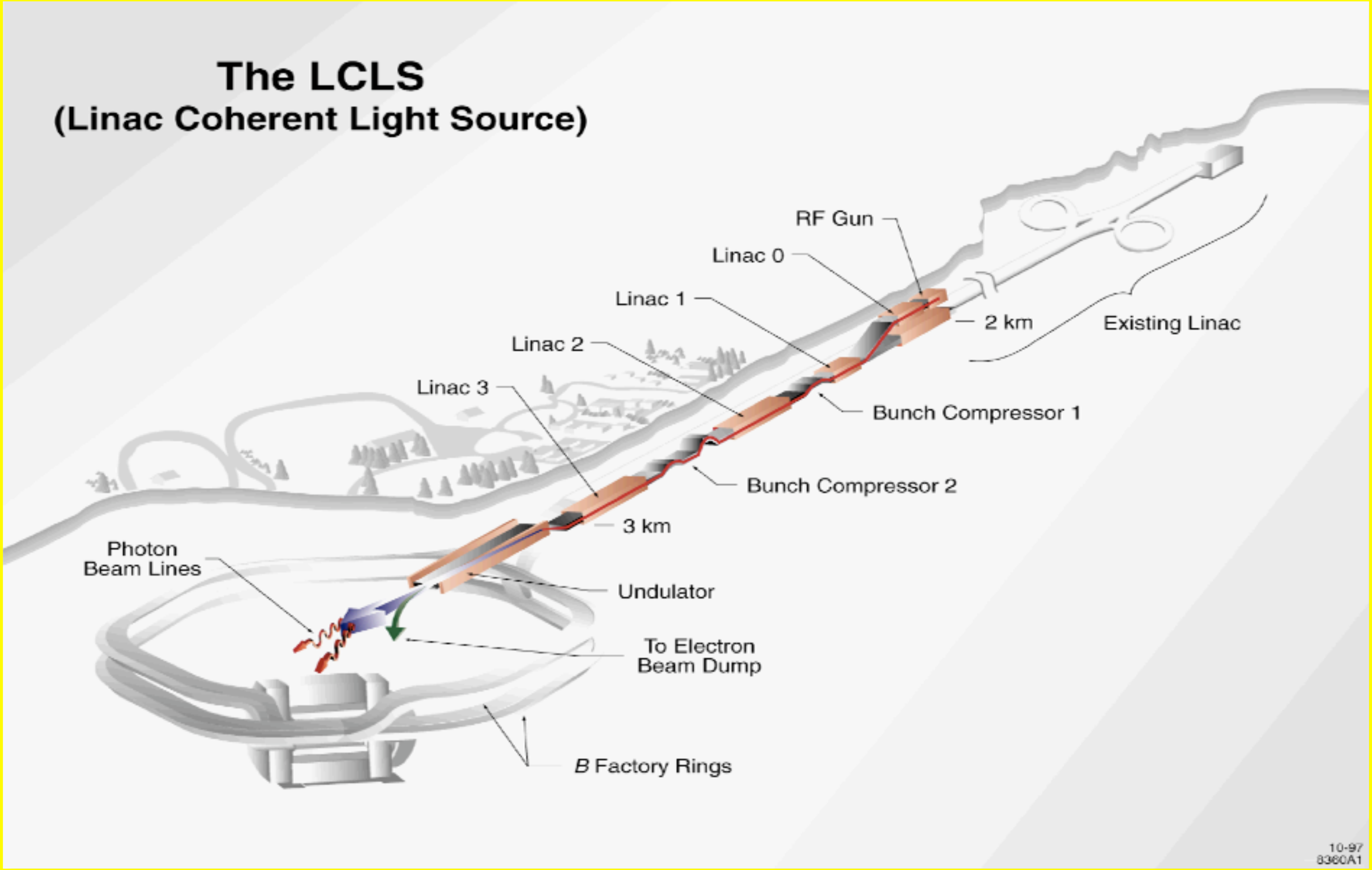
$$\frac{\Delta\lambda}{\lambda} = \frac{1}{N_{ch}}$$

SASE FELs

Since they are regularly spaced, the micro-bunches produce radiation with enhanced temporal coherence. This results in a “smoothing out” of the instantaneous synchrotron radiation power (shown in the three plots) to the right) as the SASE process develops.



The LCLS: An X-ray Laser (1.5 Å)



Capabilities

Spectral coverage: 0.15-1.5 nm

To 0.5 nm in 3rd harmonic

Peak Brightness: 10^{33}

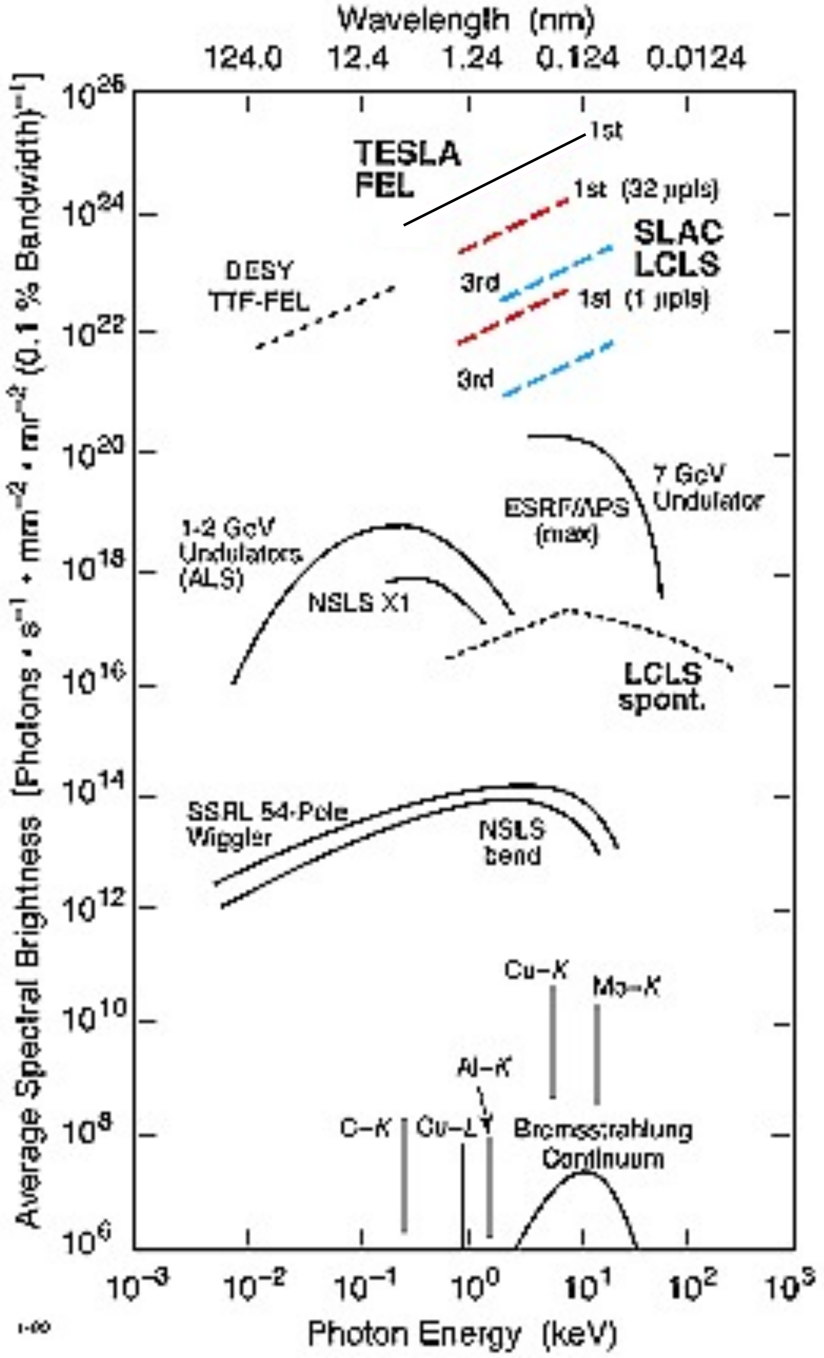
Photons/pulse: 10^{12}

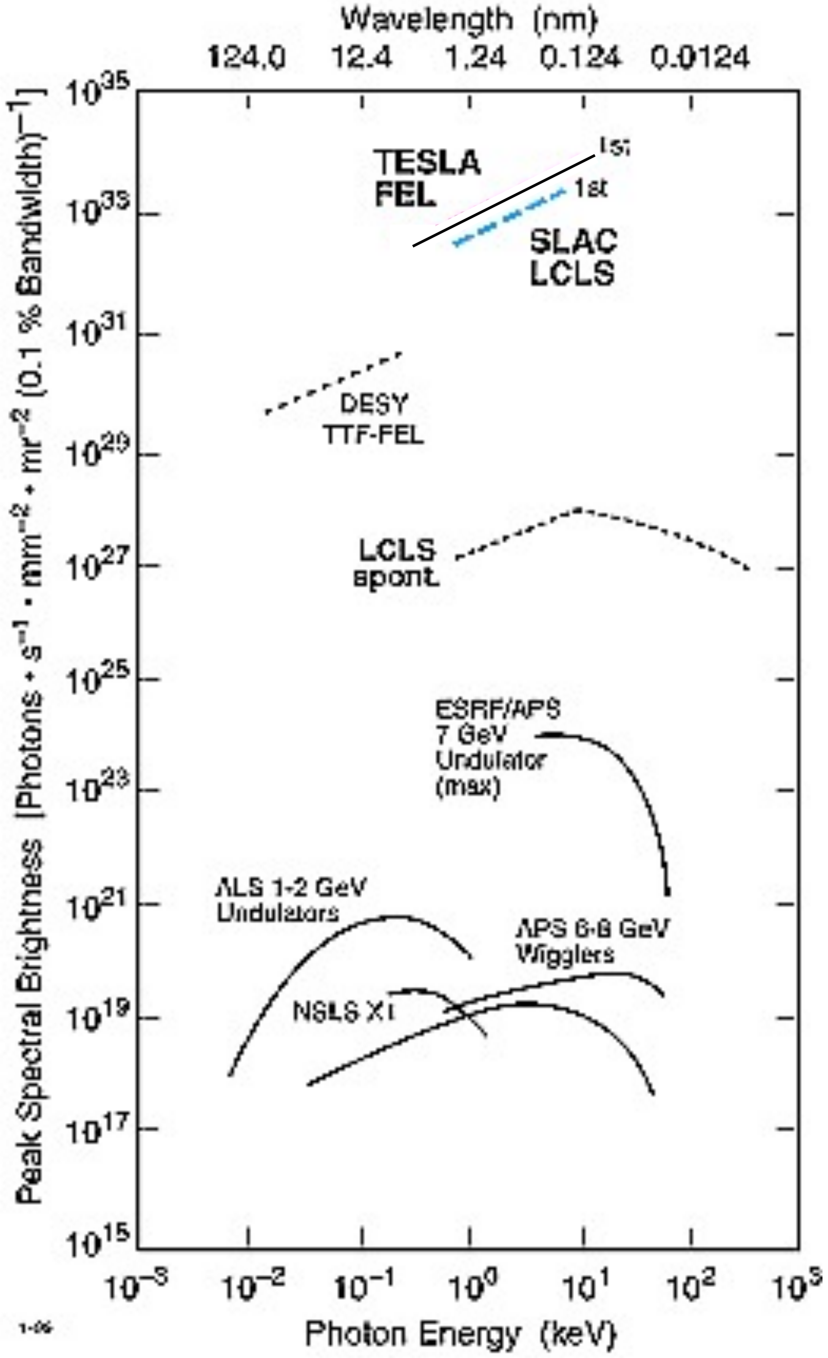
Average Brightness: 3×10^{22}

Pulse duration: <230 fs

Pulse repetition rate: 120 Hz

Upgrade – more bunches/pulse



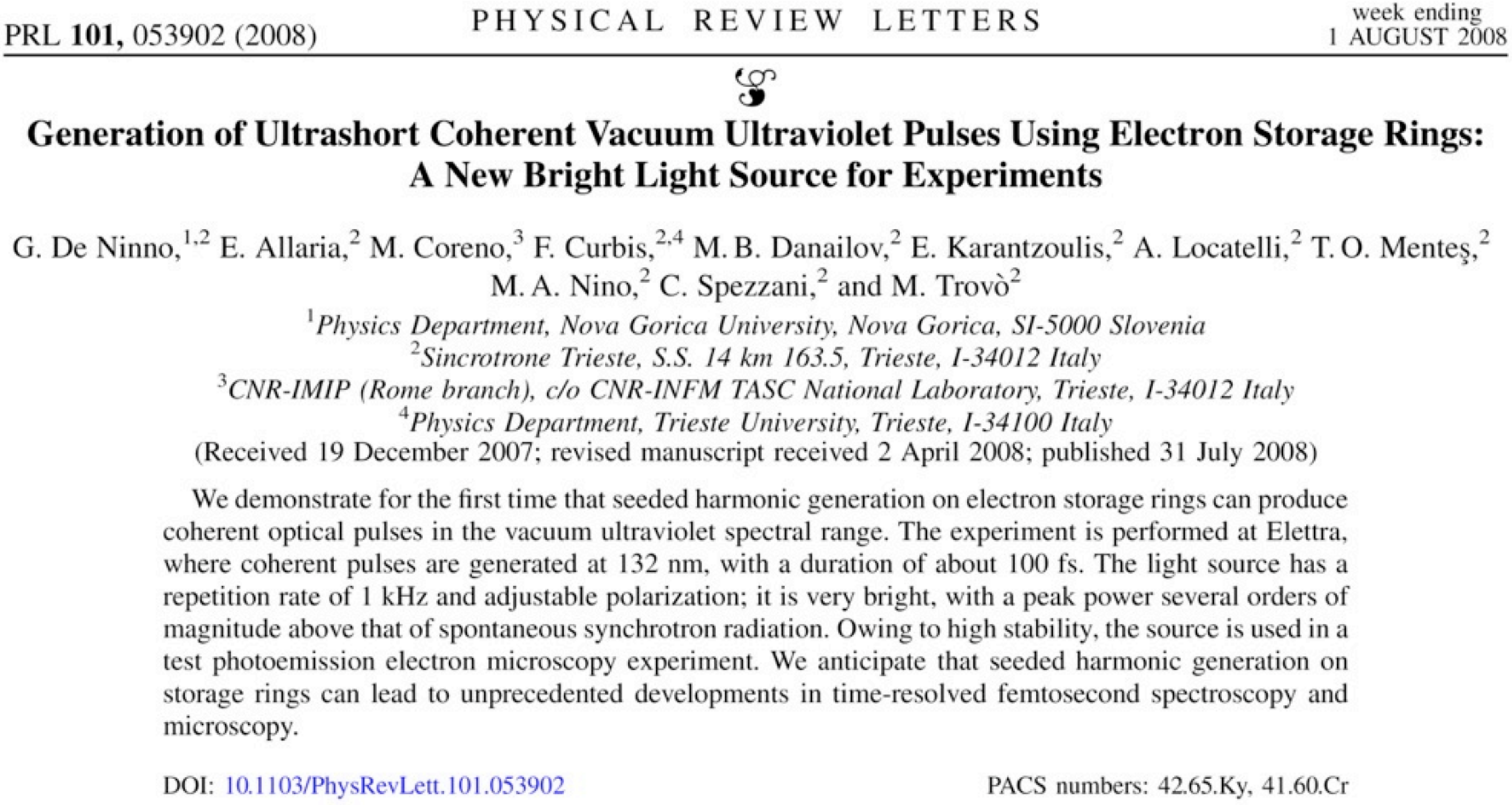


Benefits of a Seeded FEL

- A “seed” laser controls the distribution of electrons within a bunch:
  - Very high peak flux and brightness (comparable to SASE FELs)
  - Temporal coherence of the FEL output pulse
  - Control of the time duration and bandwidth of the coherent FEL pulse
  - Close to transform-limit pulse provides excellent resolving power without monochromators
  - Complete synchronization of the FEL pulse to the seed laser
  - Tunability of the FEL output wavelength, via the seed laser wavelength or a harmonic thereof
  - Reduction in undulator length needed to achieve saturation.

- Giving:
  - Controlled pulses of 10-100 fs duration for ultrafast experiments in atomic and molecular dynamics
  - Temporally coherent pulses of 500-1000 fs duration for experiments in ultrahigh resolution spectroscopy and imaging.
  - Future possible attosecond capability with pulses of ~100 as duration for ultrafast experiments in electronic dynamics

A seeded storage ring FEL



PRL **101,** 053902 (2008) PHYSICAL REVIEW LETTERS week ending 1 AUGUST 2008

Generation of Ultrashort Coherent Vacuum Ultraviolet Pulses Using Electron Storage Rings: A New Bright Light Source for Experiments

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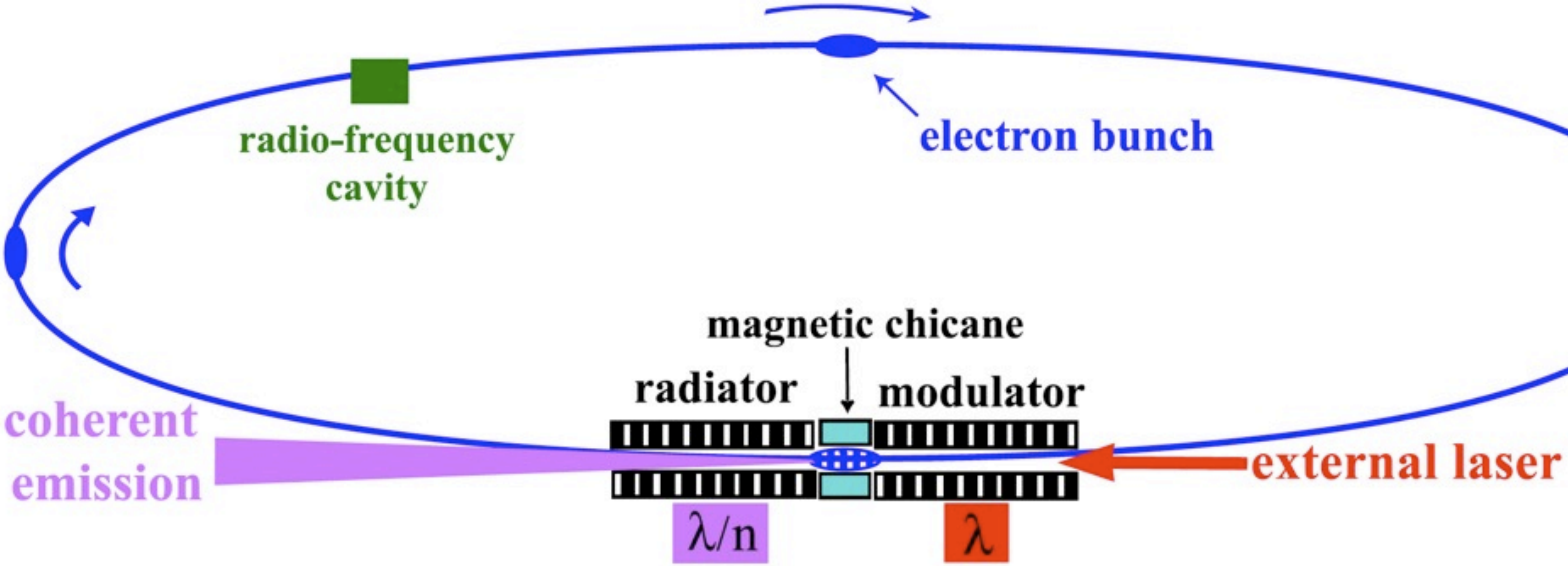
(Received 19 December 2007; revised manuscript received 2 April 2008; published 31 July 2008)

We demonstrate for the first time that seeded harmonic generation on electron storage rings can produce coherent optical pulses in the vacuum ultraviolet spectral range. The experiment is performed at Elettra, where coherent pulses are generated at 132 nm, with a duration of about 100 fs. The light source has a repetition rate of 1 kHz and adjustable polarization; it is very bright, with a peak power several orders of magnitude above that of spontaneous synchrotron radiation. Owing to high stability, the source is used in a test photoemission electron microscopy experiment. We anticipate that seeded harmonic generation on storage rings can lead to unprecedented developments in time-resolved femtosecond spectroscopy and microscopy.

DOI: 10.1103/PhysRevLett.101.053902 PACS numbers: 42.65.Ky, 41.60.Cr

A seeded storage ring FEL



A seeded storage ring FEL

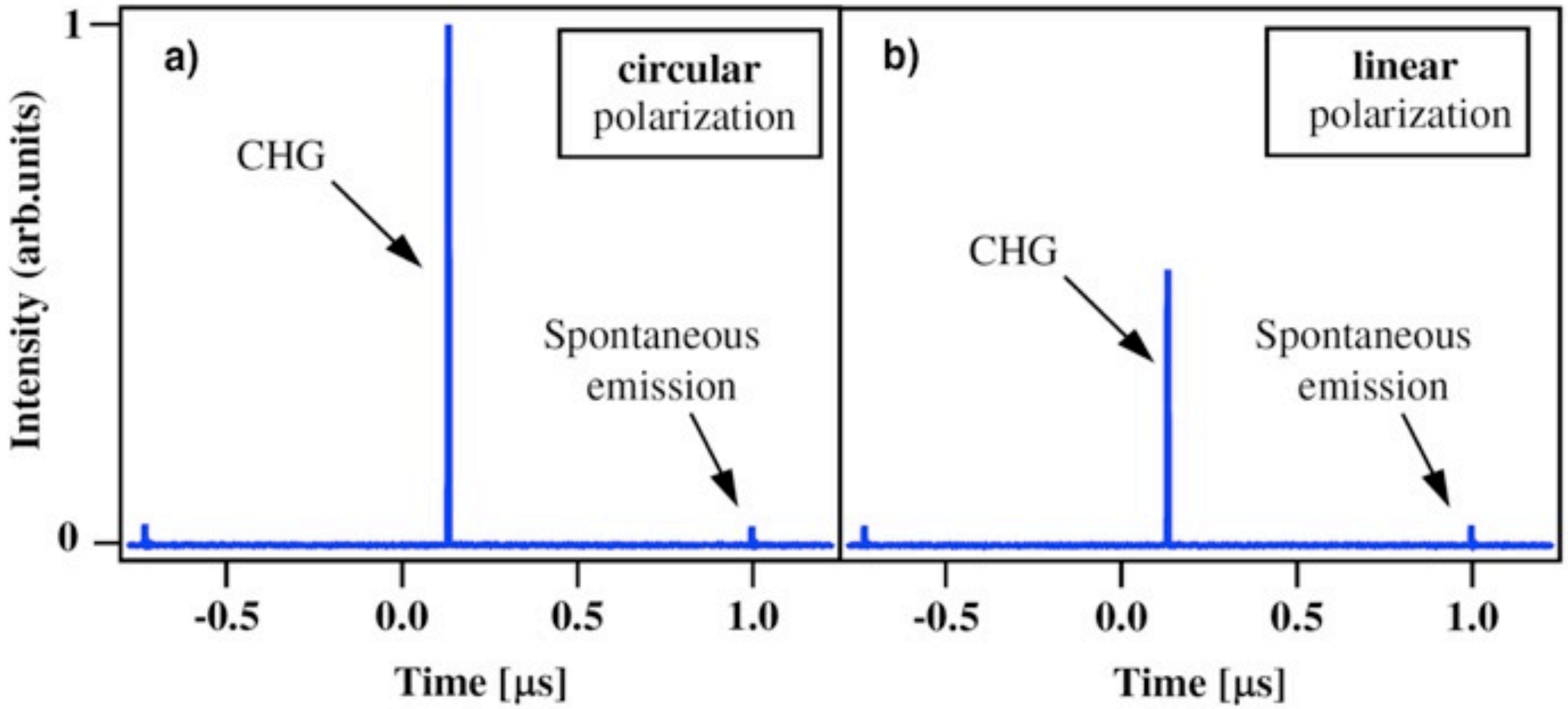


FIG. 2 (color online). Intensity of the UV pulses vs acquisition time. The signal was acquired using a photomultiplier (PMT) placed downstream a monochromator. Note that the PMT does not allow to resolve the sub-ps temporal scale on which the coherent pulse evolves. This, in turn, does not permit direct detection and therefore appreciation of the effective amplitude difference between the seeded and the spontaneous signals, their true ratio being a factor about 10^4 (see text). In (a) the radiator is tuned for circular polarization; in (b) the radiator is tuned for linear polarization.

A seeded storage ring FEL

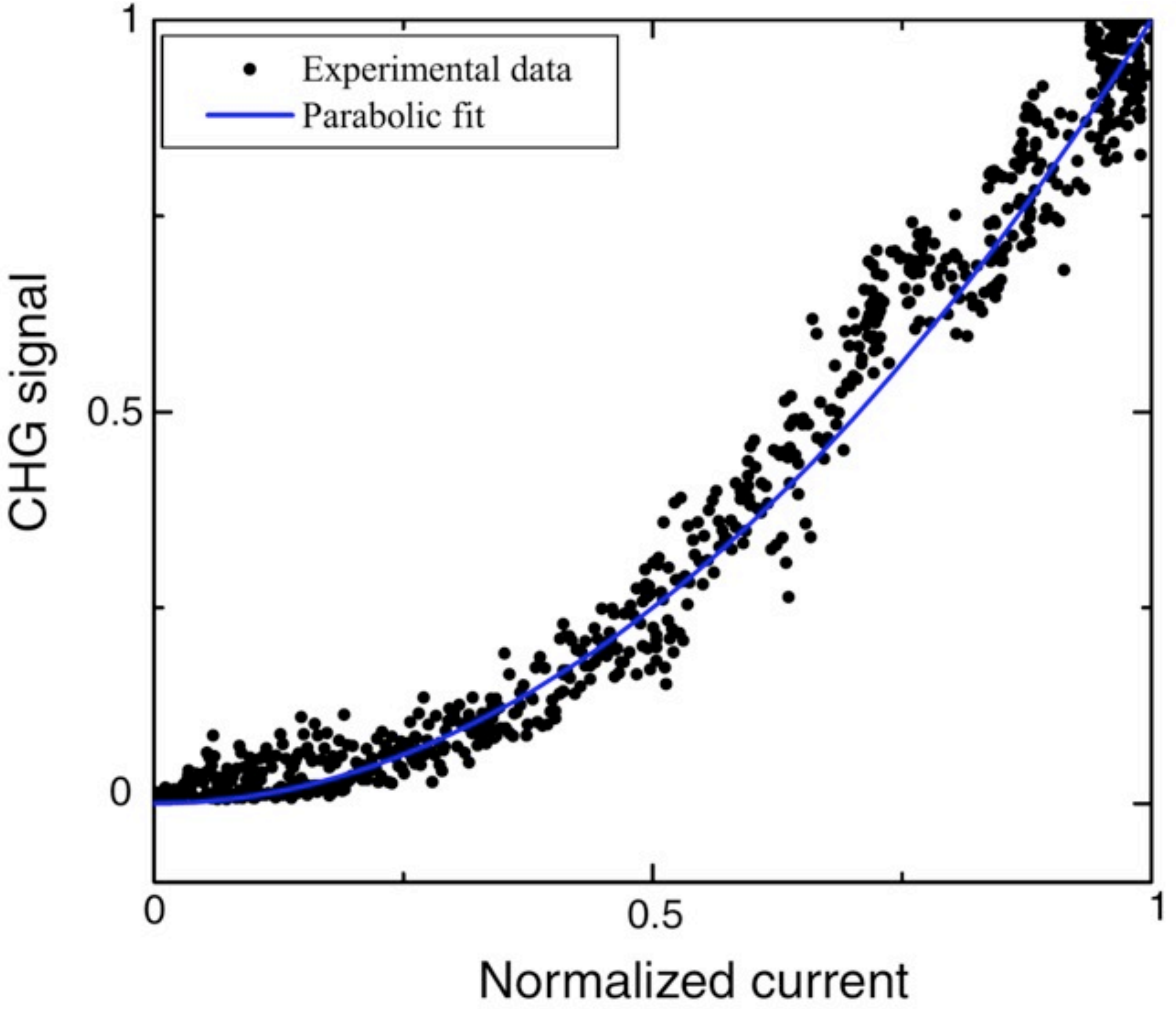
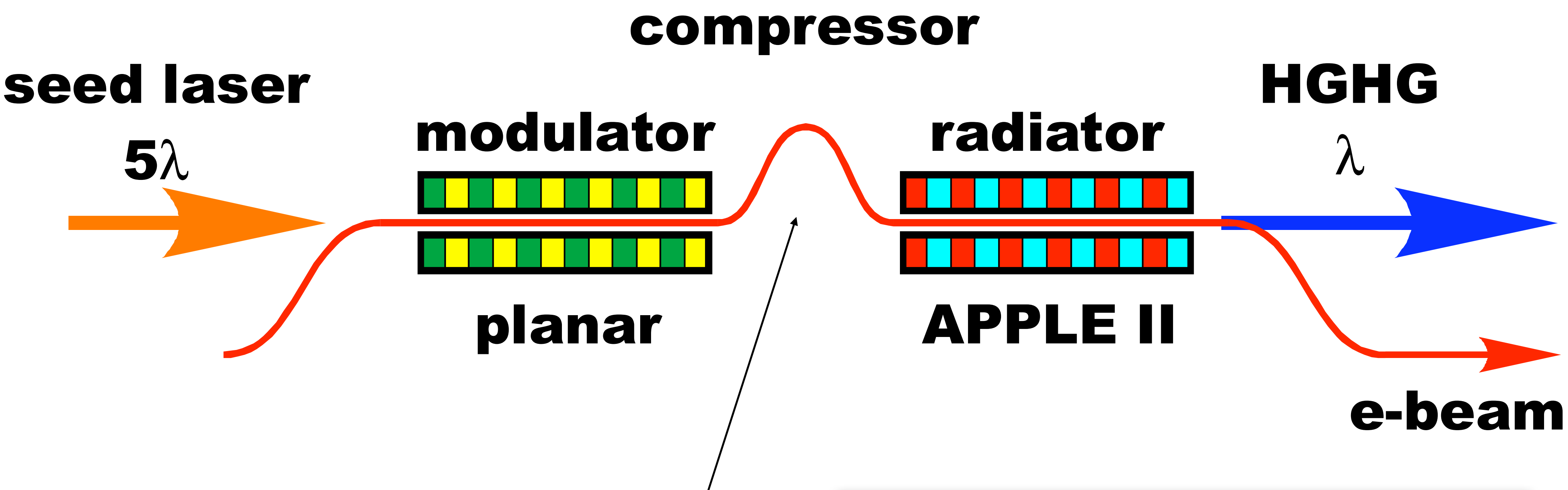


FIG. 3 (color online). Quadratic dependence of the coherent harmonic detected using a PMT vs (normalized) bunch current. Dots represent experimental data; the curve is a fit obtained using a quadratic function.

High Gain Harmonic Generation - HGHG



Bunching at harmonic λ

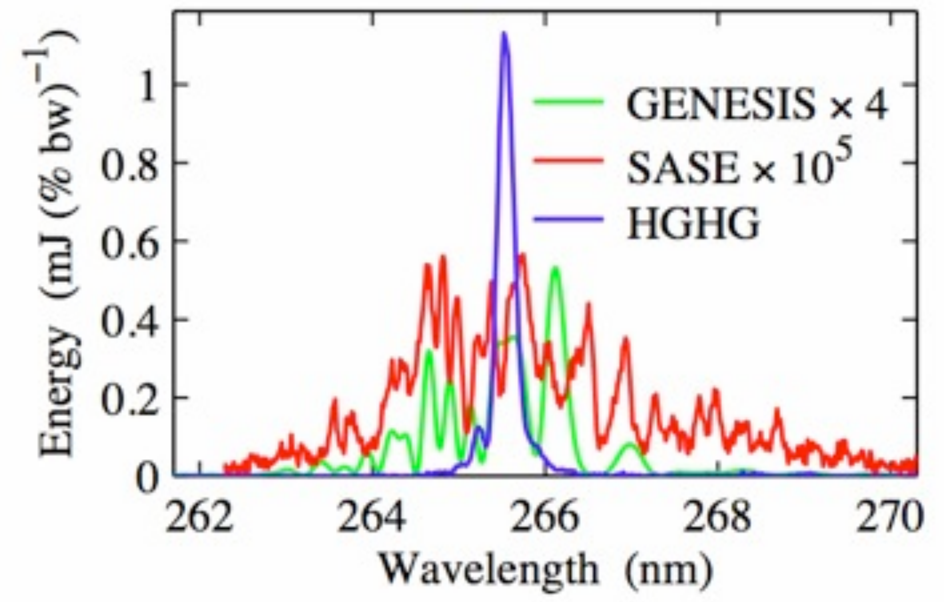
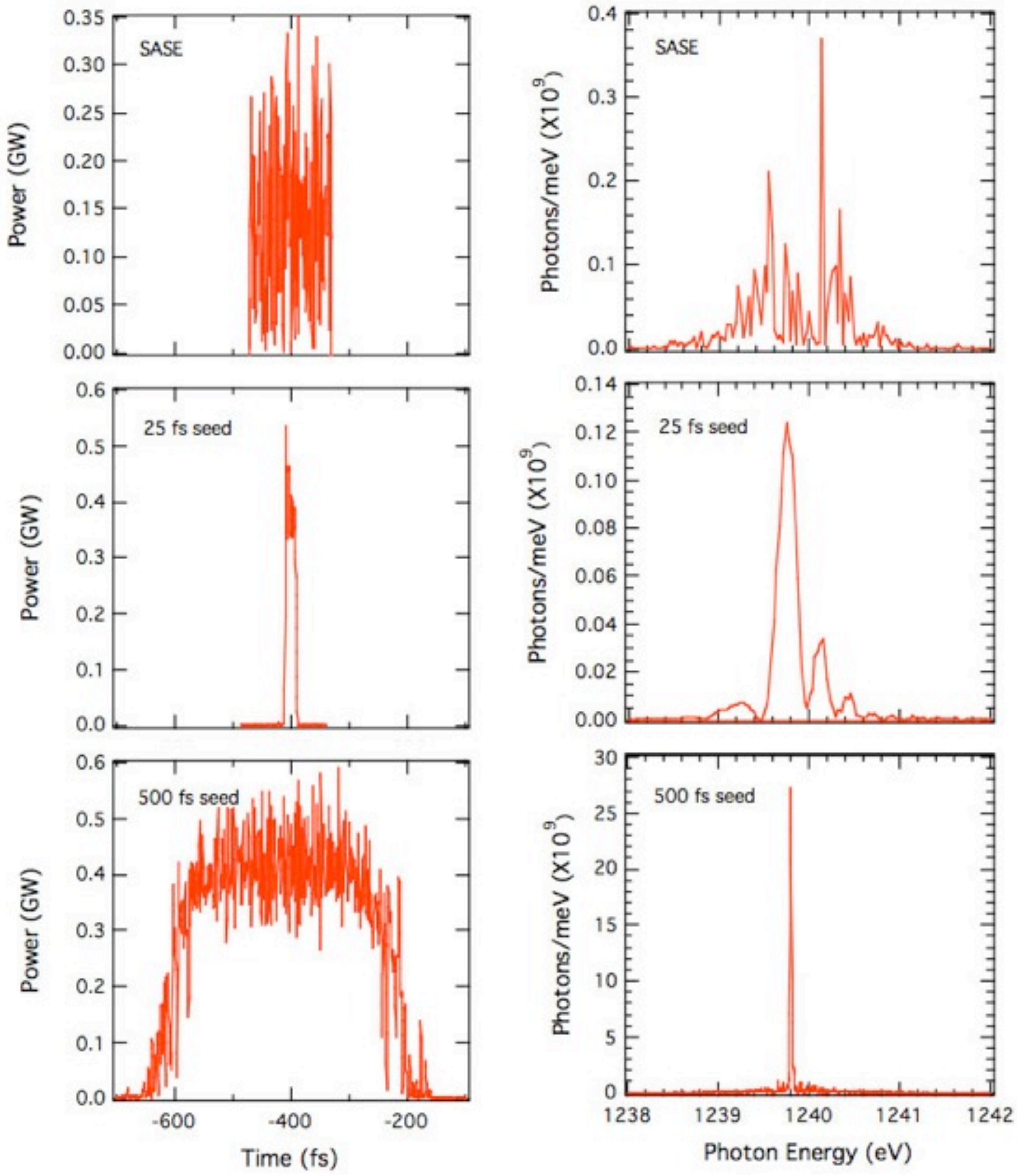


FIG. 4: Single shot HGHG spectrum for 30 MW seed (blue), single shot SASE spectrum measured by blocking the seed laser (red) and simulation the SASE spectrum after 20 m of NISUS structure (green). The average spacing between spikes in the SASE spectrum is used to estimate the pulse length.

More compact and fully temporally coherent source, control of pulse length and control of spectral parameters.

Li-Hua Yu
DUV-FEL

FEL Seeding a Long Bunch



← SASE

← Seeded FEL
Short bunch

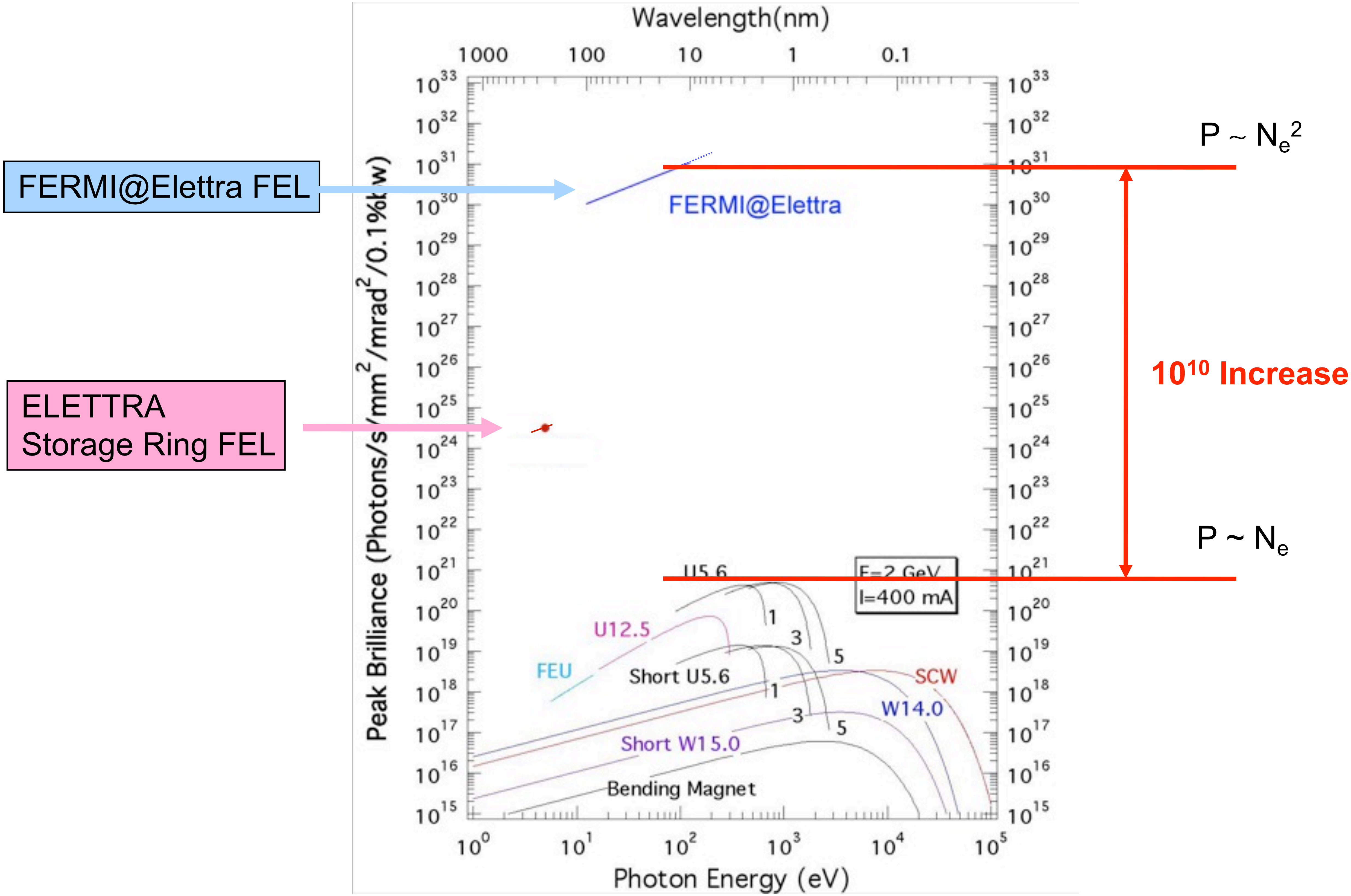
← Seeded FEL
Long bunch

Courtesy of J. Corlett, LBNL

FERMI FEL Output Parameters

Parameter	**FEL-1**	**FEL-2 (in discussion)**
Wavelength range [nm]	100 to 20	40 to 10 (to 3?)
Output pulse length (rms) [fs]	< 100	> 200
Bandwidth (rms) [meV]	17 (at 40 nm)	5 (at 10 nm)
Polarization	Variable	Variable
Repetition rate [Hz]	50	50
Peak power [GW]	1 to >5	0.5 to 1
Harmonic peak power (% of fundamental)	~2	~0.2 (at 10 nm)
Photons per pulse	10^{14} (at 40 nm)	10^{12} (at 10 nm)
Pulse-to-pulse stability	≤ 30 %	~50 %
Pointing stability [μrad]	< 20	< 20
Virtual waist size [μm]	250 (at 40 nm)	120
Divergence (rms, intensity) [μrad]	50 (at 40 nm)	15 (at 10 nm)

FERMI Brightness



FERMI@Elettra FEL

ELETTRA
Storage Ring FEL

$P \sim N_e^2$

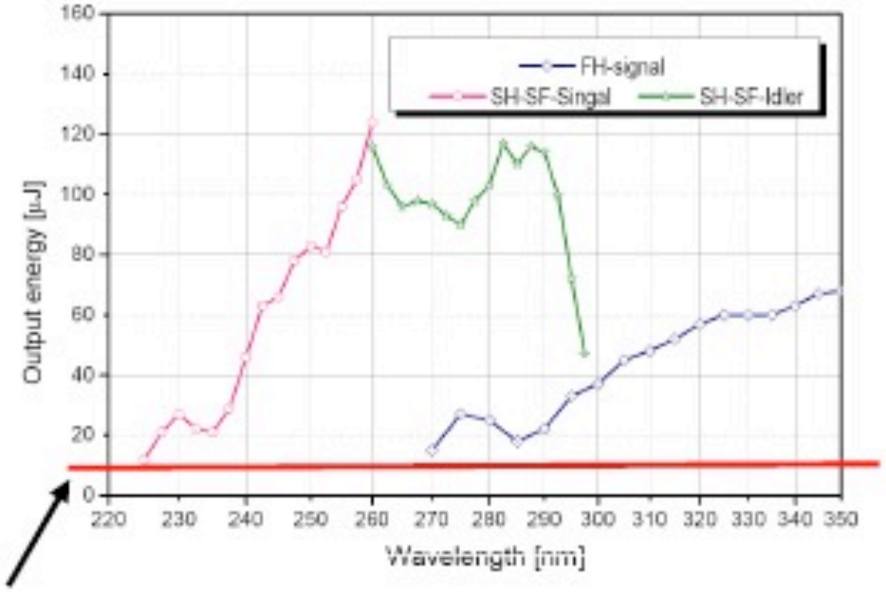
10^{10} Increase

$P \sim N_e$

FERMI Seed Laser: Phase I

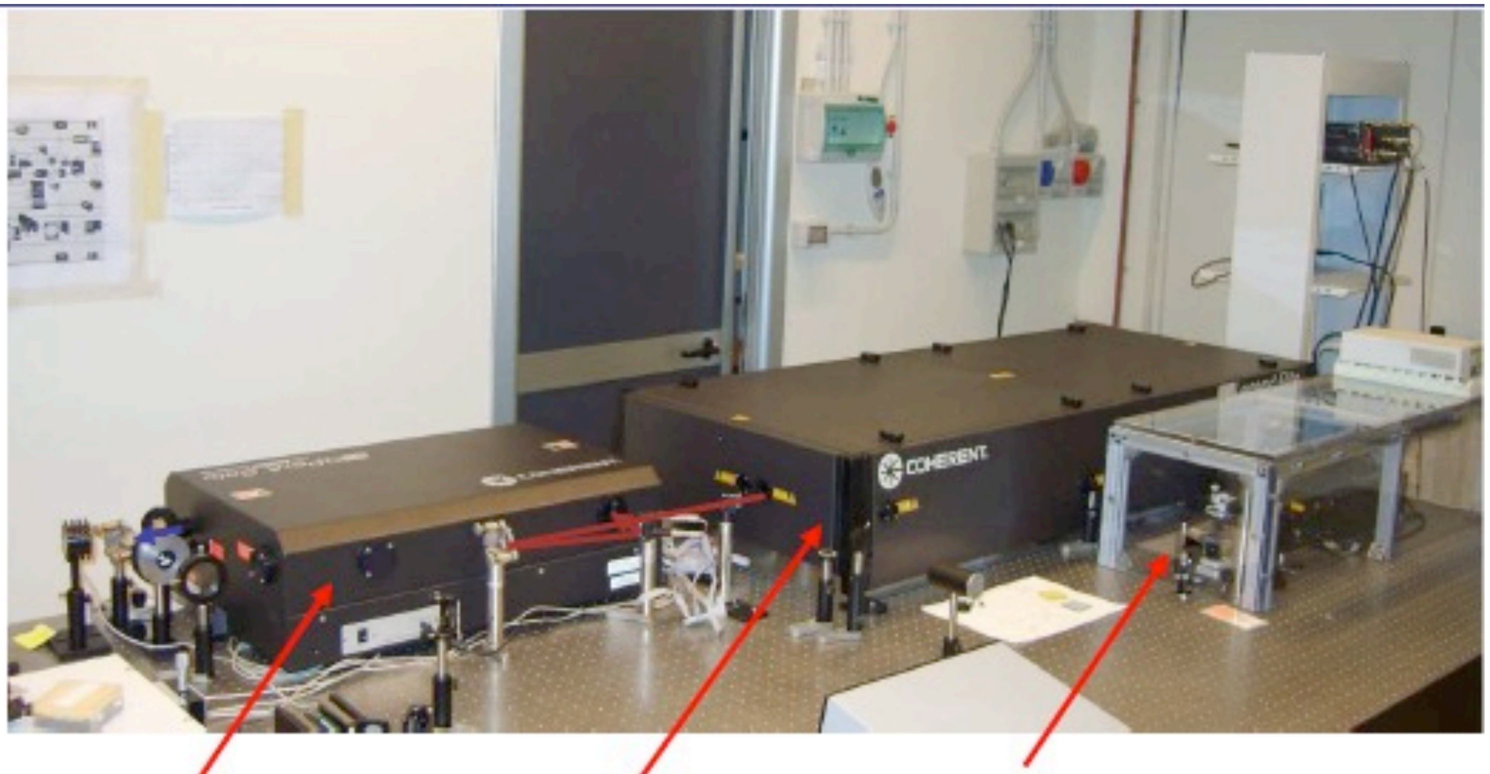
Main works since last MAC

-Tests HE TOPAS completed



100MW level

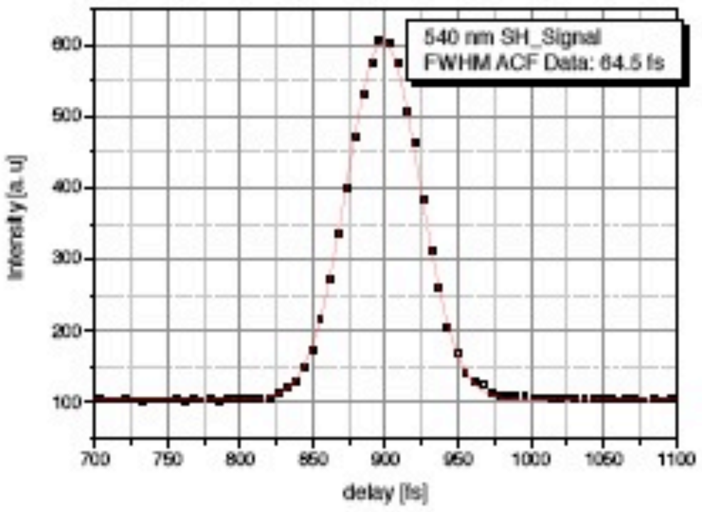
Tuning curve in UV



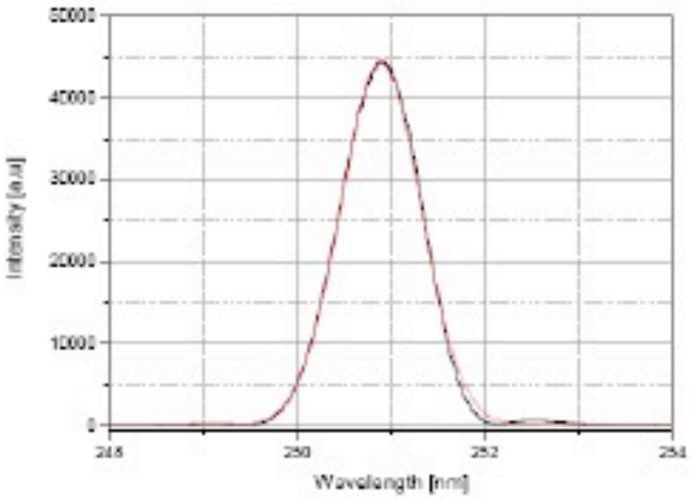
TOPAS

Regen Amp

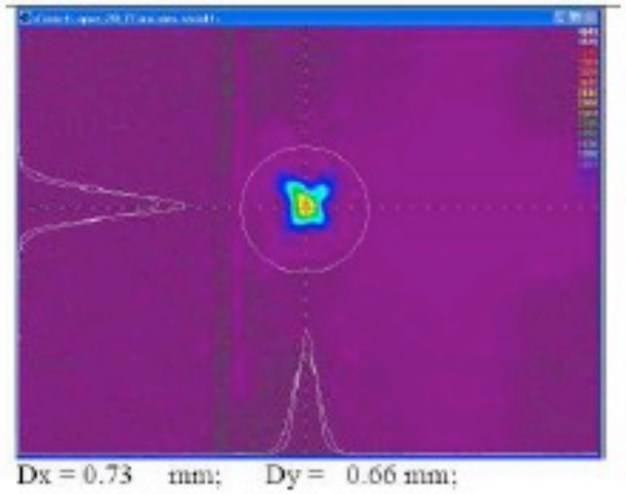
Seed fibre laser



Typical autocorrelator trace



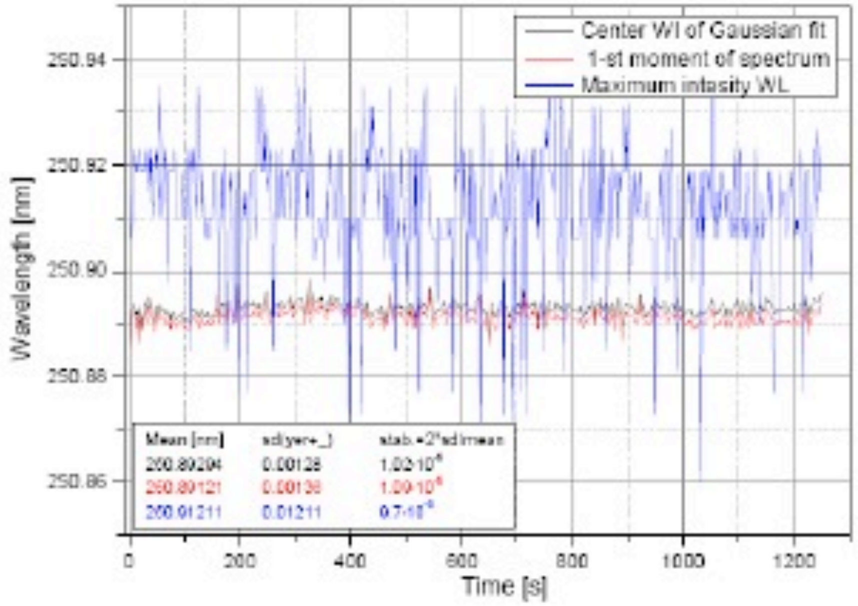
Typical Spectrum



Spatial distribution at focus

Courtesy M. Danailov

FERMI Seed Laser: Phase I



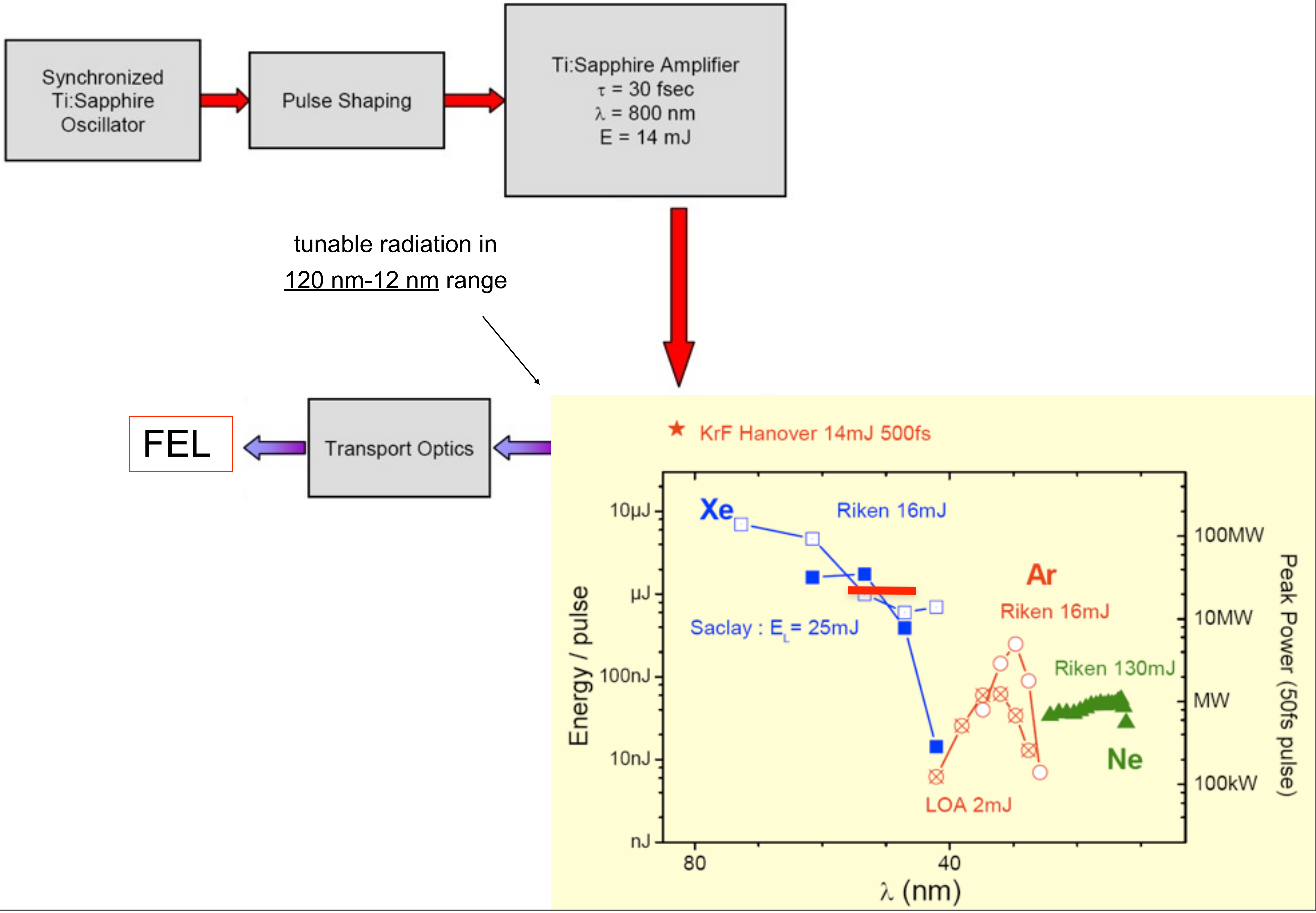
Wavelength stability measurement
at 250 nm (SH-SF-signal)
Center WL Gaussian fit:1x10^{-5}
First moment of spectum: 1.1x10^{-5}
Spectrum peak:9.7x10^{-5}

Parameter	Specs	Measured	Note
Tunability range (nm)	240-360	230-350	
Peak power (MW)	100	>150	Assuming 100 fs
Pulse duration (fs)	100	<100	Estimated, TBM
Timing jitter (fs RMS)	<100 fs	TBM	
Pointing stab. (μrad)	<20	TBM	
Wavelength stab.	10^{-4}	$<10^{-4}$	
Beam quality (M^2)	<1.5	TBM	For SH-SF-Idler

Measured performance for the 100 fs regime (1 ps not needed!)

Courtesy M. Danailov

Seeding with an HHG Source?



Synchronized Ti:Sapphire Oscillator

Pulse Shaping

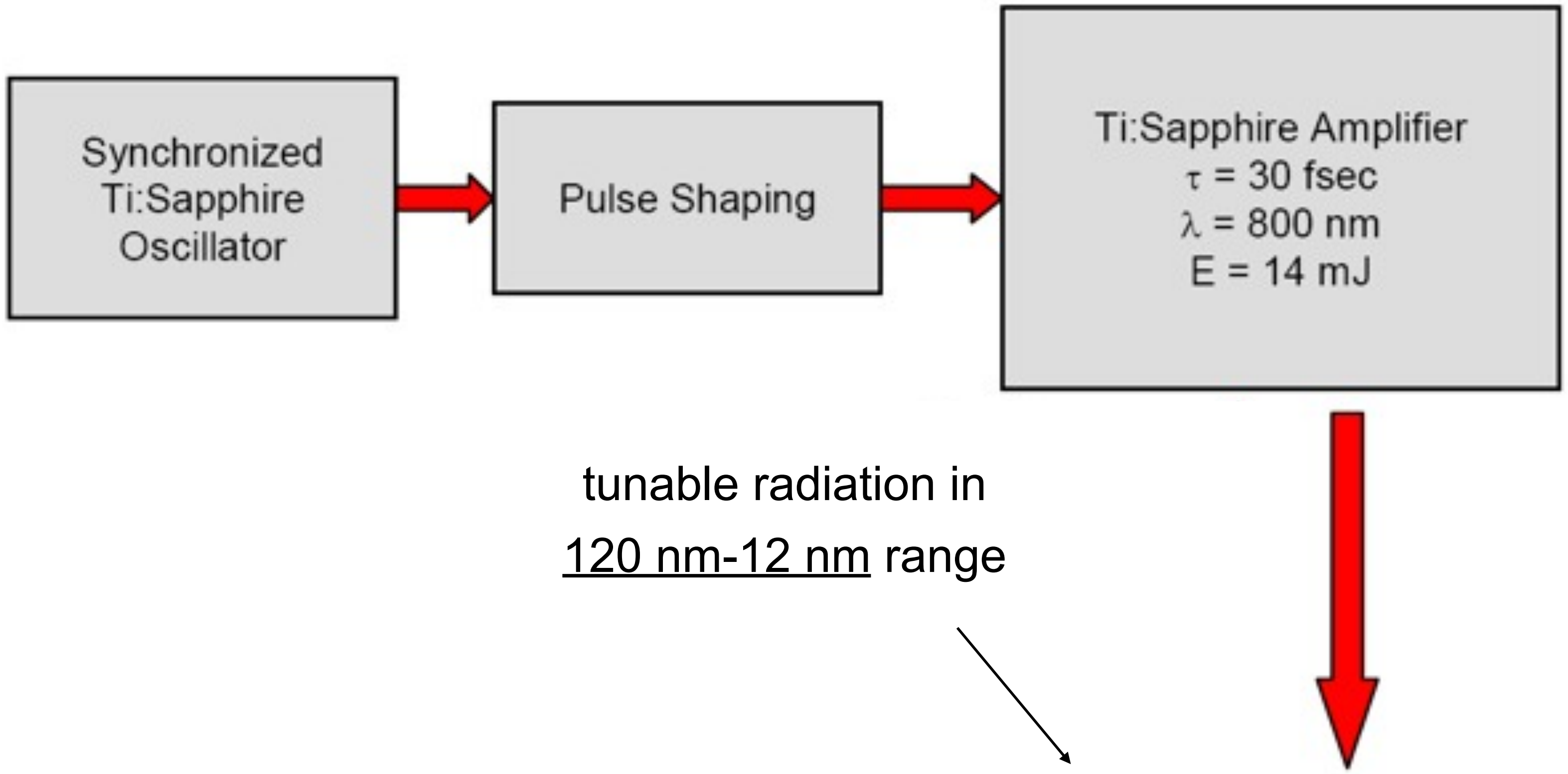
Ti:Sapphire Amplifier
τ = 30 fsec
λ = 800 nm
E = 14 mJ

tunable radiation in
<u>120 nm-12 nm</u> range

Transport Optics

FEL

Seeding with an HHG Source?

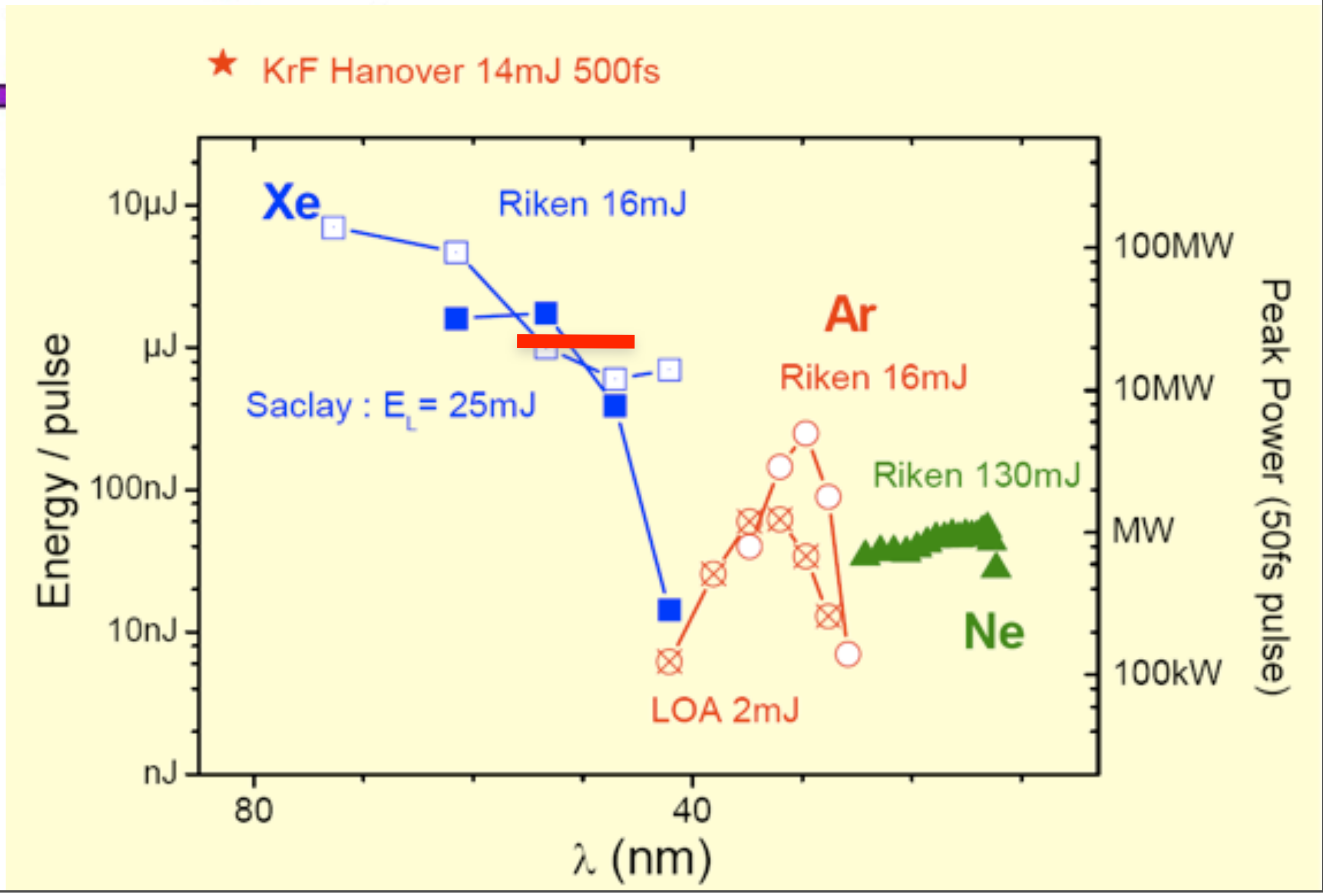


Synchronized Ti:Sapphire Oscillator

Pulse Shaping

Ti:Sapphire Amplifier
τ = 30 fsec
λ = 800 nm
E = 14 mJ

tunable radiation in
120 nm-12 nm range



FEL

Transport Optics

BUT

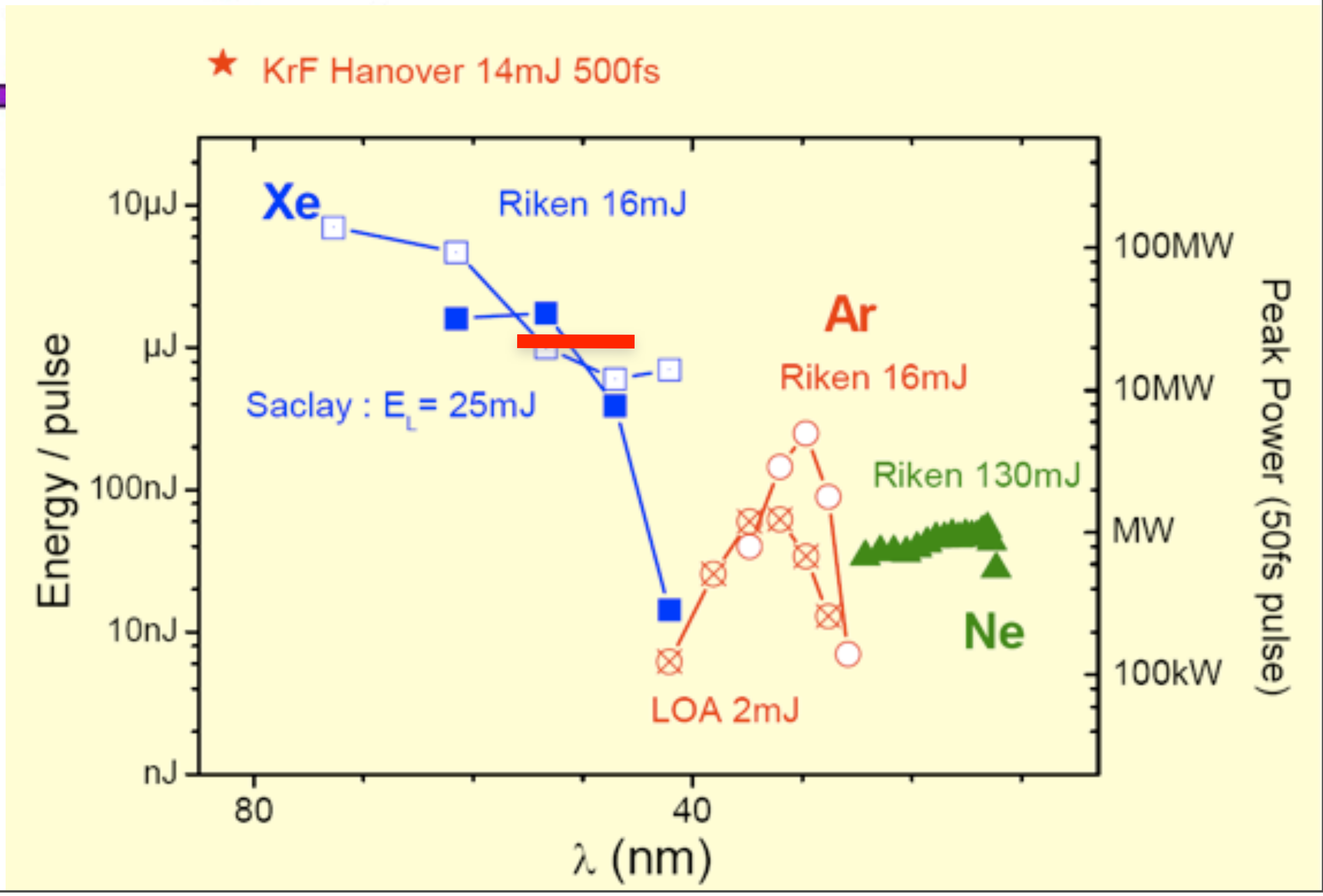
Seeding with an HHG Source?

Synchronized Ti:Sapphire Oscillator → Pulse Shaping → Ti:Sapphire Amplifier

τ = 30 fsec
λ = 800 nm
E = 14 mJ

- Complicated
- Tunability not proven

tunable radiation in
<u>120 nm-12 nm</u> range



FEL ← Transport Optics

BUT

More Comments About an HHG Seed

- Direct Seeding Option
  - But now one is limited to the wavelength cutoff of the HHG system
    - 10 nm perhaps a little shorter.
    - 10 kw to 100 kw
      - *Too low for HGHG seed*
- Pulse length
  - Tends to be on the order of 10 fs to 20 fs, even shorter if needed, but difficult to make significantly longer.

Seeded HHG Source

A “problem” with using a HHG source as a seed is that the power is not that high.

The “problems” with using a plasma laser are the timing stability, pulse duration, and longitudinal coherence.

Combined however they could make an ideal seed for future FELs.

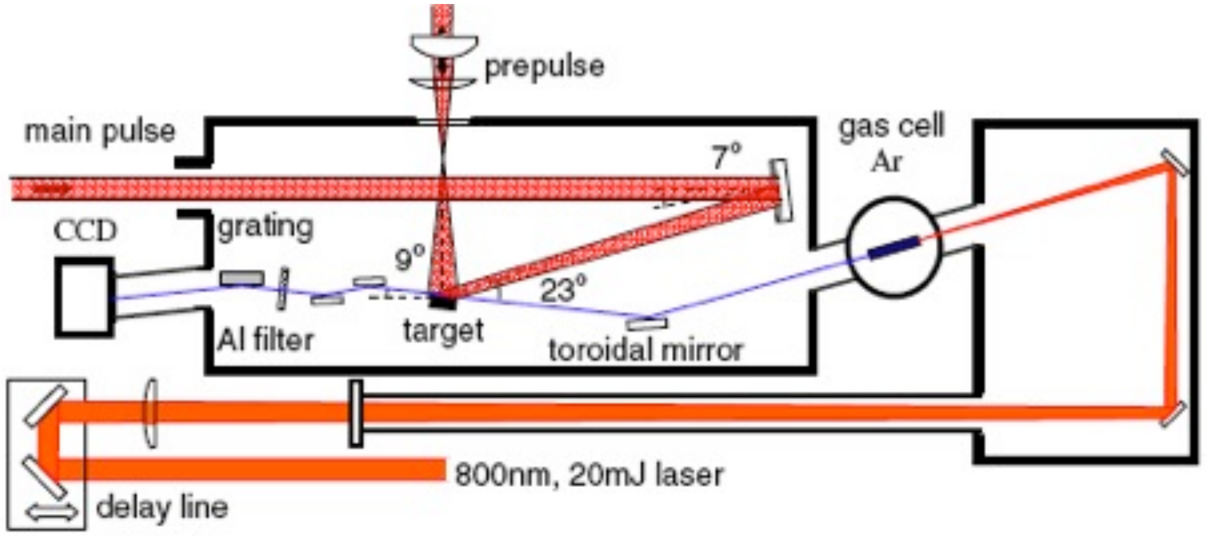


FIG. 1 (color online). Schematic representation of the seeded soft-x-ray-laser amplifier based on a grazing incidence pumped plasma.

Wang et al., Phys. Rev Lett. **97** 123901 (2006)

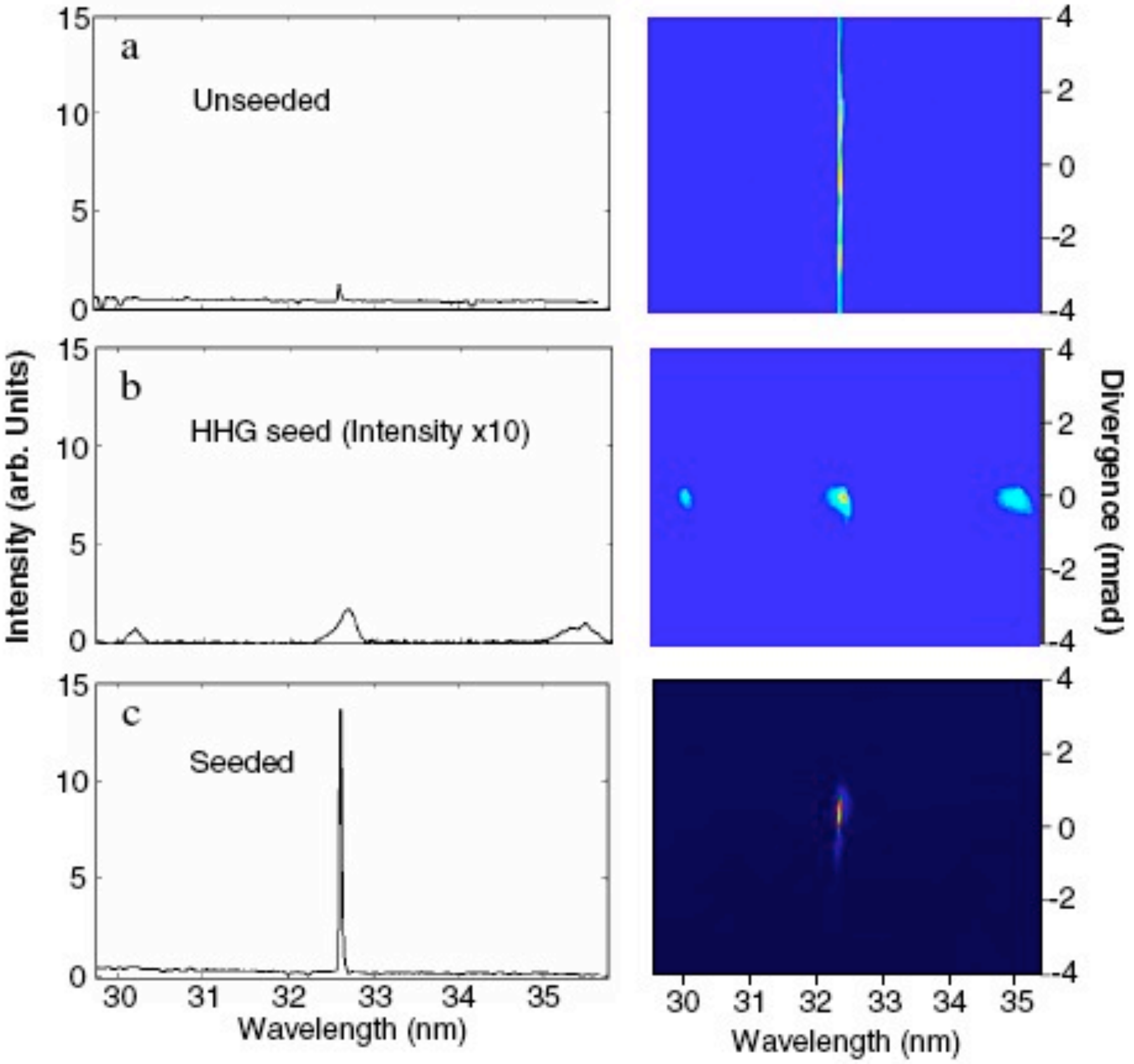


FIG. 2 (color online). Spectra illustrating the relative intensity and beam divergence for the (a) unseeded 32.6 nm soft-x-ray-laser amplifier, (b) high harmonic seed pulse, and (c) seeded soft-x-ray-laser amplifier. The length of the plasma amplifier is 3 mm. The intensity scale of the seed pulse is magnified by 10 times.

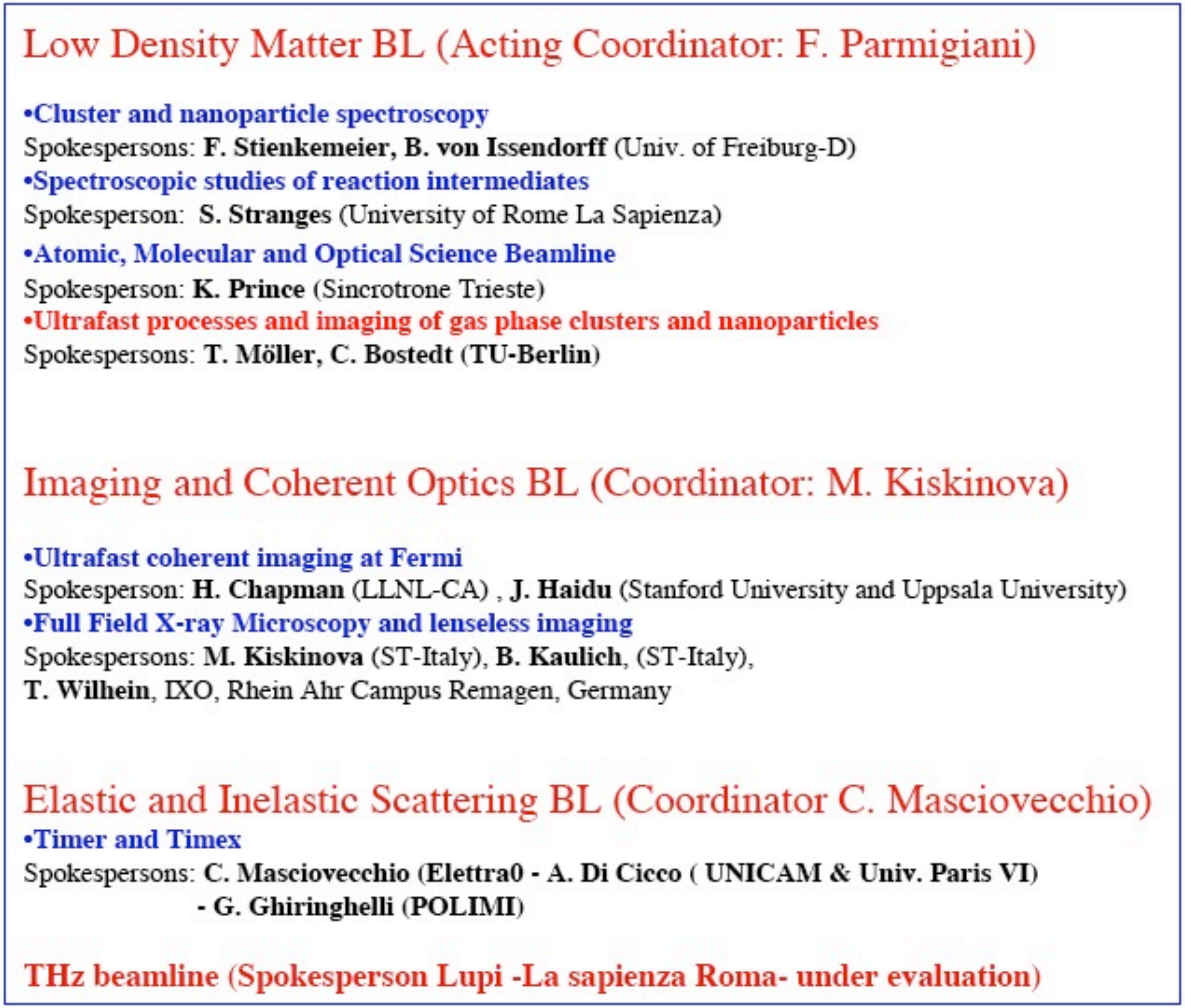
User Requirements & Science

User Requirements

- 100 - 10 nm range (and less) - fully tuneable & polarised coherent radiation
- 100’s MW to GW’s of peak power
- 10^{13} to 10^{14} photons/pulse
- 0.05 to > 1ps photon pulse lengths
- good pointing stability
- reasonable pulse to pulse timing jitter
- good pulse reproducibility ~10% $\Delta I/I$

Science

- chemical reaction dynamics
- study of the electronic structure of atoms, molecules and clusters
- biological systems
- inhomogeneous materials on a microscopic scale
- geophysics and study of extra-terrestrial materials
- material properties under extreme conditions (pressure, temperature, etc.)
- surfaces and interfaces
- nano-structures and semiconductors
- polymers and organic materials
- magnetism and magnetic materials
- superconductors and highly correlated electronic materials



Low Density Matter BL (Acting Coordinator: F. Parmigiani)

- **Cluster and nanoparticle spectroscopy**

Spokespersons: **F. Stienkemeier, B. von Issendorff** (Univ. of Freiburg-D)

- **Spectroscopic studies of reaction intermediates**

Spokesperson: **S. Stranges** (University of Rome La Sapienza)

- **Atomic, Molecular and Optical Science Beamline**

Spokesperson: **K. Prince** (Sincrotrone Trieste)

- **Ultrafast processes and imaging of gas phase clusters and nanoparticles**

Spokespersons: **T. Möller, C. Bostedt (TU-Berlin)**

Imaging and Coherent Optics BL (Coordinator: M. Kiskinova)

- **Ultrafast coherent imaging at Fermi**

Spokesperson: **H. Chapman** (LLNL-CA) , **J. Haidu** (Stanford University and Uppsala University)

- **Full Field X-ray Microscopy and lenseless imaging**

Spokespersons: **M. Kiskinova** (ST-Italy), **B. Kaulich**, (ST-Italy),
T. Wilhein, IXO, Rhein Ahr Campus Remagen, Germany

Elastic and Inelastic Scattering BL (Coordinator C. Masciovecchio)

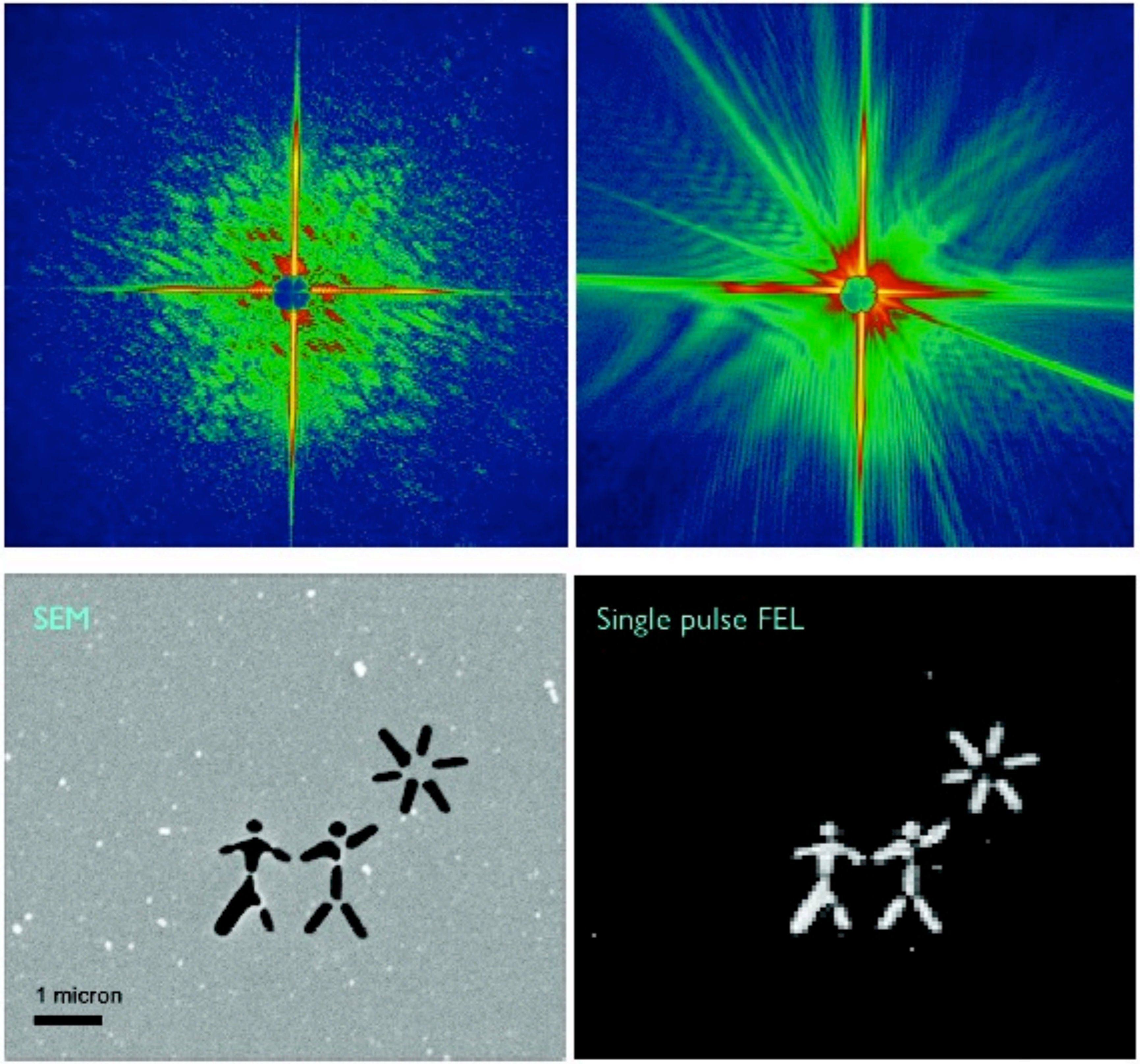
- **Timer and Timex**

Spokespersons: **C. Masciovecchio (Elettra0 - A. Di Cicco (UNICAM & Univ. Paris VI)**
- G. Ghiringhelli (POLIMI)

THz beamline (Spokesperson Lupi -La sapienza Roma- under evaluation)

Ultrafast coherent imaging at Fermi

Spokesperson: H. Chapman (LLNL-CA) , J. Haidu (Stanford University and Uppsala University)



PRL **104,** 225001 (2010) PHYSICAL REVIEW LETTERS week ending 4 JUNE 2010

Electronic Structure of an XUV Photogenerated Solid-Density Aluminum Plasma

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J. Cihelka,[6] D. Doria,[9] T. Döppner,[10] S. Düsterer,[5] T. Dzelzainis,[9] R. R. Fäustlin,[5] C. Fortmann,[10] E. Förster,[2] E. Galtier,[11]
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J. Krzywinski,[15] T. Laarmann,[5] H. J. Lee,[15] R. W. Lee,[10] B. Li,[1] K.-H. Meiwes-Broer,[12] J. P. Mithen,[1] B. Nagler,[16]
A. J. Nelson,[10] A. Przystawik,[12] R. Redmer,[12] D. Riley,[9] F. Rosmej,[11] R. Sobierajski,[17,14] F. Tavella,[5] R. Thiele,[12]
J. Tiggesbäumker,[12] S. Toleikis,[5] T. Tschentscher,[18] L. Vysin,[6] T. J. Whitcher,[1] S. White,[9] and J. S. Wark[1]

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(Received 15 April 2010; published 1 June 2010)

By use of high intensity XUV radiation from the FLASH free-electron laser at DESY, we have created highly excited exotic states of matter in solid-density aluminum samples. The XUV intensity is sufficiently high to excite an inner-shell electron from a large fraction of the atoms in the focal region. We show that soft-x-ray emission spectroscopy measurements reveal the electronic temperature and density of this highly excited system immediately after the excitation pulse, with detailed calculations of the electronic structure, based on finite-temperature density functional theory, in good agreement with the experimental results.

DOI: 10.1103/PhysRevLett.104.225001 PACS numbers: 52.27.Gr, 71.15.Mb, 78.70.En

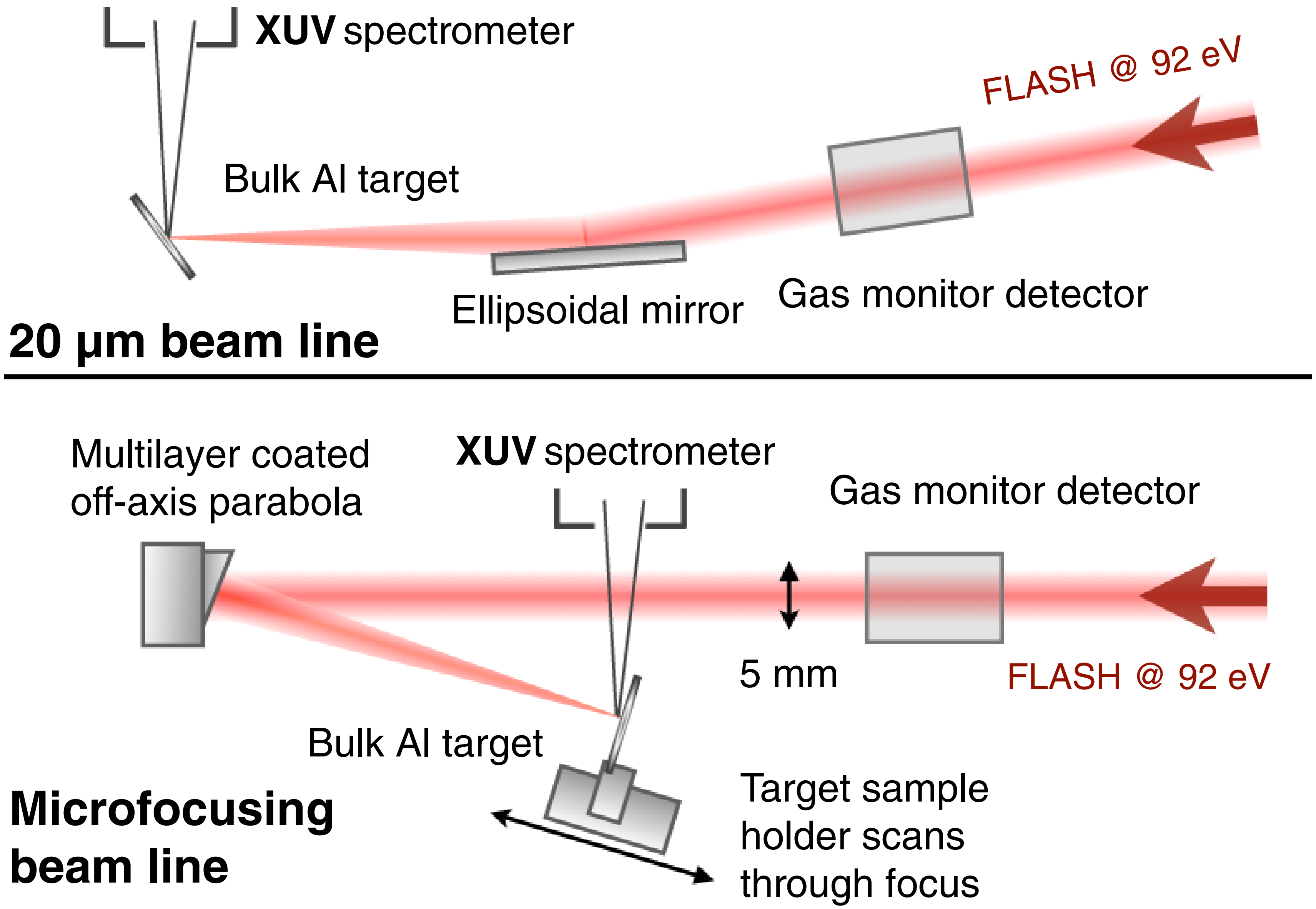
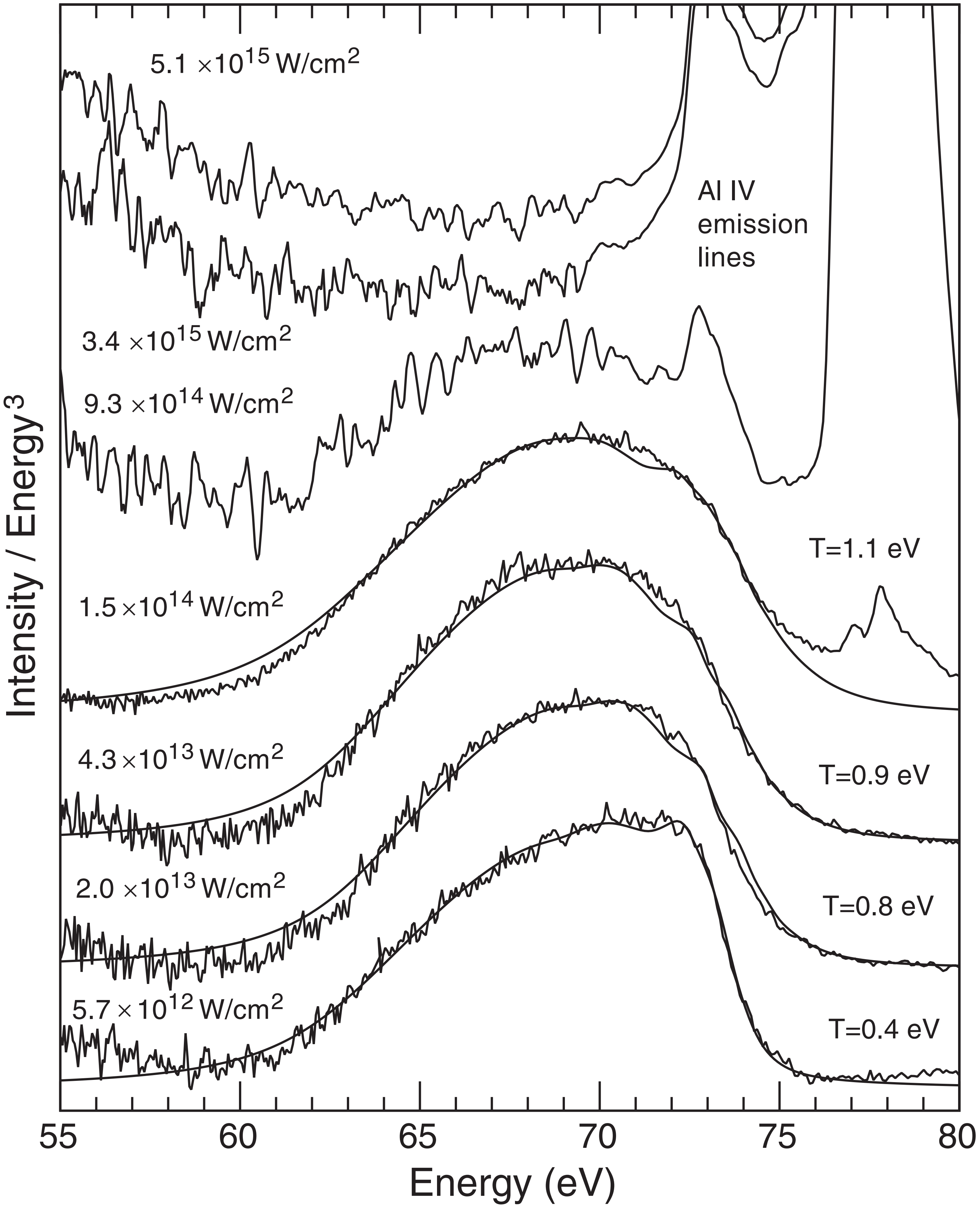
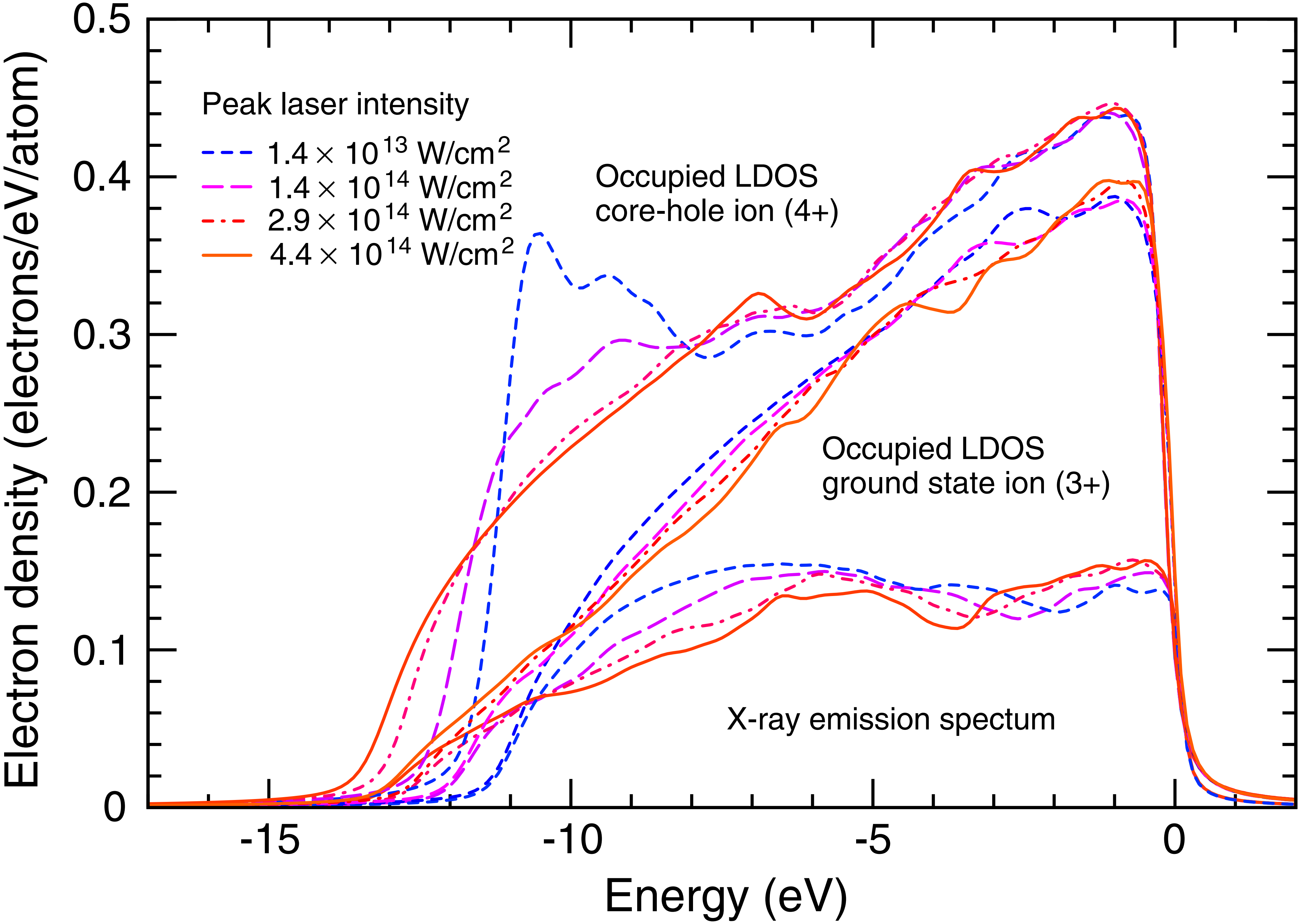


FIG. 1 (color online). Schematic view of the two experimental setups to access a range of intensities between 10^{13}–10^{16} W cm^{-2}.

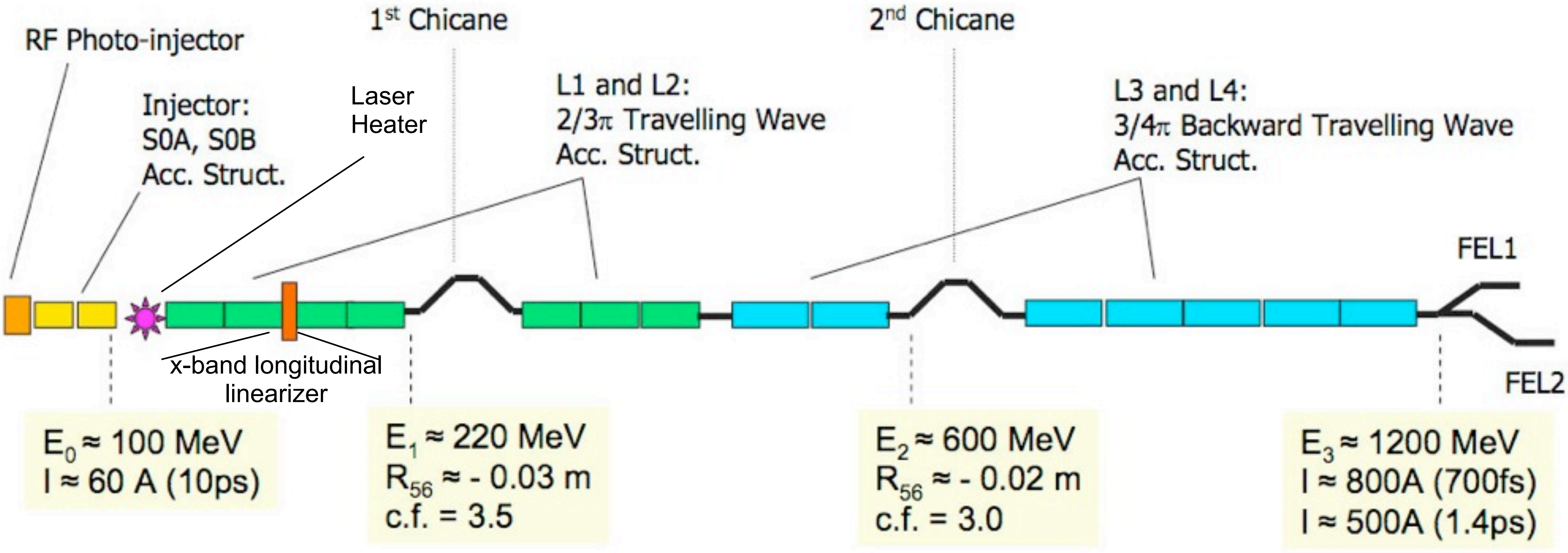


Valence band to 2p emission in solid-density Al for an increasing range of FEL irradiation intensities. QMD calculations are for a final state with 0, 1, 3, and 10 core holes per 32- atom supercell. Emission from atomic transitions in the Al plasma formed later in time as the target expands dominates the spectra at high intensities. Spectra are normalized to the same intensity at 72 eV and offset for clarity.



Calculated local electron density within a sphere centered on a ground state ion and a core-hole excited ion. At low intensities the excited site is seen as an impurity and the bottom of the band is strongly modified. At high intensities the system returns to be free-electron-like but with an increased electron density.

Schematic layout of the FERMI accelerator



RF Photo-injector

Injector:
S0A, S0B
Acc. Struct.

Laser
Heater

x-band longitudinal
linearizer

1st Chicane

L1 and L2:
$2/3\pi$ Travelling Wave
Acc. Struct.

2nd Chicane

L3 and L4:
$3/4\pi$ Backward Travelling Wave
Acc. Struct.

FEL1

FEL2

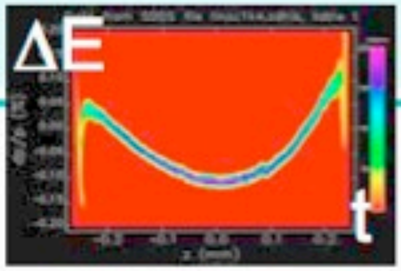
$E_0 \approx 100$ MeV
$I \approx 60$ A (10ps)

$E_1 \approx 220$ MeV
$R_{56} \approx -0.03$ m
c.f. = 3.5

$E_2 \approx 600$ MeV
$R_{56} \approx -0.02$ m
c.f. = 3.0

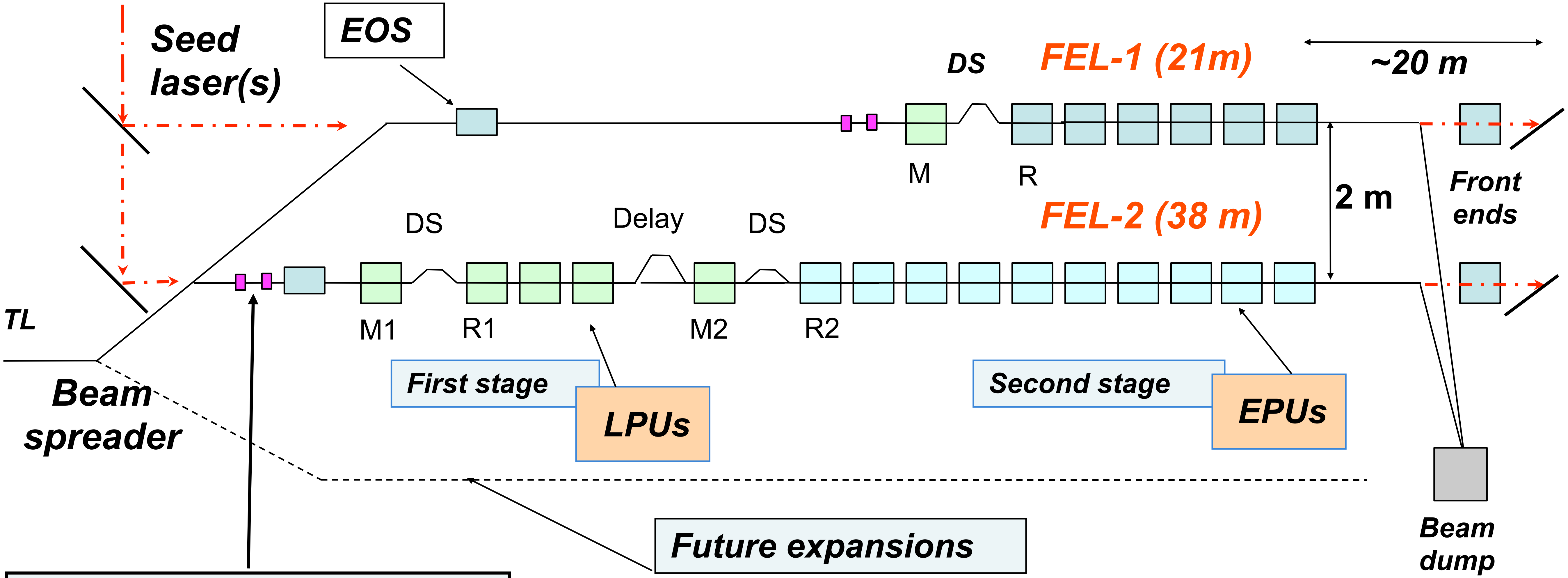
$E_3 \approx 1200$ MeV
$I \approx 800$A (700fs)
$I \approx 500$A (1.4ps)

	"Short" bunch	*"Medium" bunch*	*"Long" bunch*
Bunch length	200 fs (flat part)	700 fs (flat part)	1.4 ps (flat part)
Peak current	800 A	800 A	500 A
Emittance(slice)	1.5 μm	1.5 μm	1.5 μm
Energy spread(slice)	<150 keV	<150 keV	<150 keV
Flatness, $\lvert d^2E/dt^2 \rvert$		<0.8 MeV/ps^2	<0.2 MeV/ps^2



Mostly FEL1 **Mostly FEL2**

Conceptual layout of the FERMI FELs, transport line, spreader and beam dump



2 hi-res BPMs with no optics inside for BBA (min. sep = 5 m)

FEL-2 Configurations
- **<u>Fresh bunch</u>**
- **Whole bunch**
- **HHG seeding**

<u>Description</u>:

- undulator axes separated by 2 m

- transverse/energy collimation incorporated

- space for matching optics, BPMs, EOS, other diag.

- small angles to CSR effects: ~ 6 deg total

Limitation

Is it possible to reach shorter wavelengths (i.e., 10 nm) in a single stage?

Courtesy G. De Ninno

Limitation

Bunching at the *nth* harmonic:

$$b_n = \exp\left(-\frac{1}{2}n^2\sigma_\gamma^2 D^2\right) J_n\left(nD\Delta\gamma\right)$$

n: harmonic number

σ_γ: relative energy spread

D: dispersive section strength

$\Delta\gamma$: relative energy modulation

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b_n significantly different from zero only if: $\Delta\gamma \geq n\sigma_\gamma$

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On the other hand: $\left(\sigma_\gamma\right)_{tot} = \sqrt{\sigma_\gamma^2 + \Delta\gamma^2} \approx \sigma_\gamma\sqrt{1+n^2} < \rho$

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→ Limitation on maximum *n*

Is it possible to reach shorter wavelengths (i.e., 10 nm) in a single stage?

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D: dispersive section strength

$\Delta\gamma$: relative energy modulation

b

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On the other hand: $\left(\sigma_\gamma\right)_{tot} = \sqrt{\sigma_\gamma^2 + \Delta\gamma^2} \approx \sigma_\gamma\sqrt{1+n^2} < \rho$

→ Limitation on maximum *n*

Is it possible to reach shorter wavelengths (i.e., 10 nm) in a single stage?

yes, but only provided that:

the seed wavelength is reduced

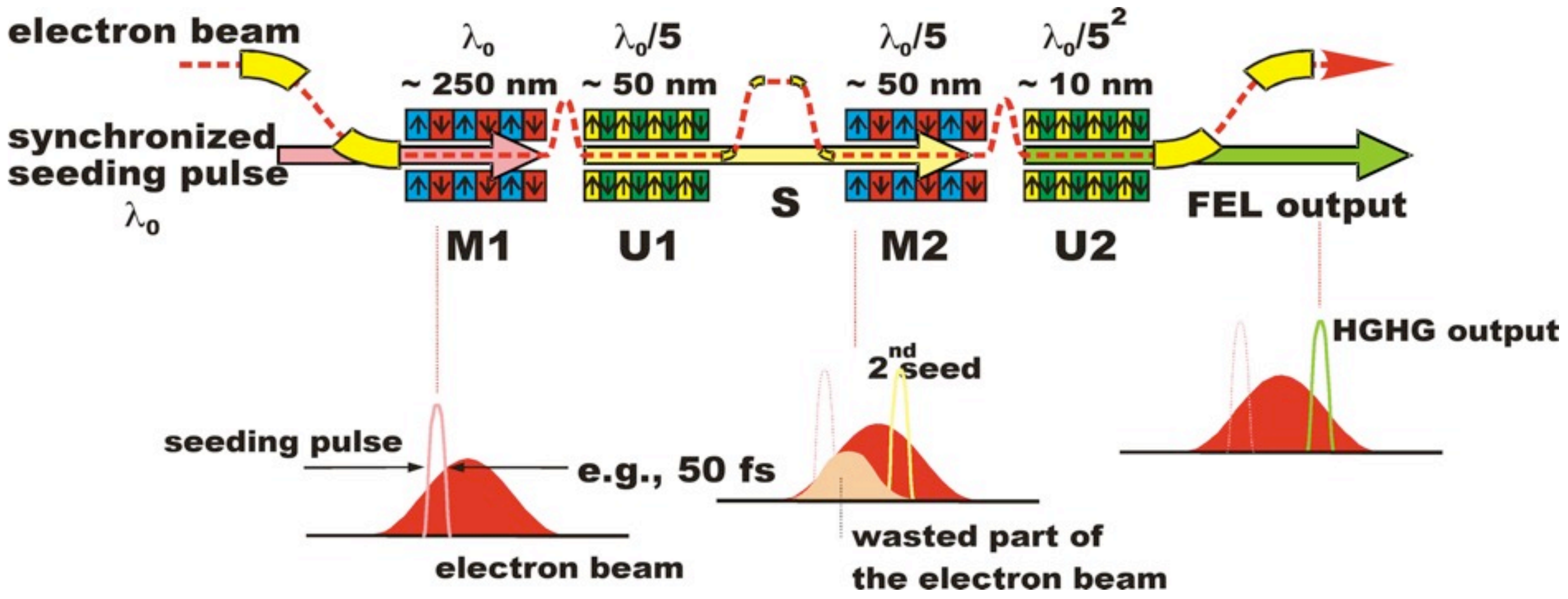
and/or

- the total relative energy spread is reduced

Courtesy G. De Ninno

Cascaded HGHG

2-Stage cascade HGHG

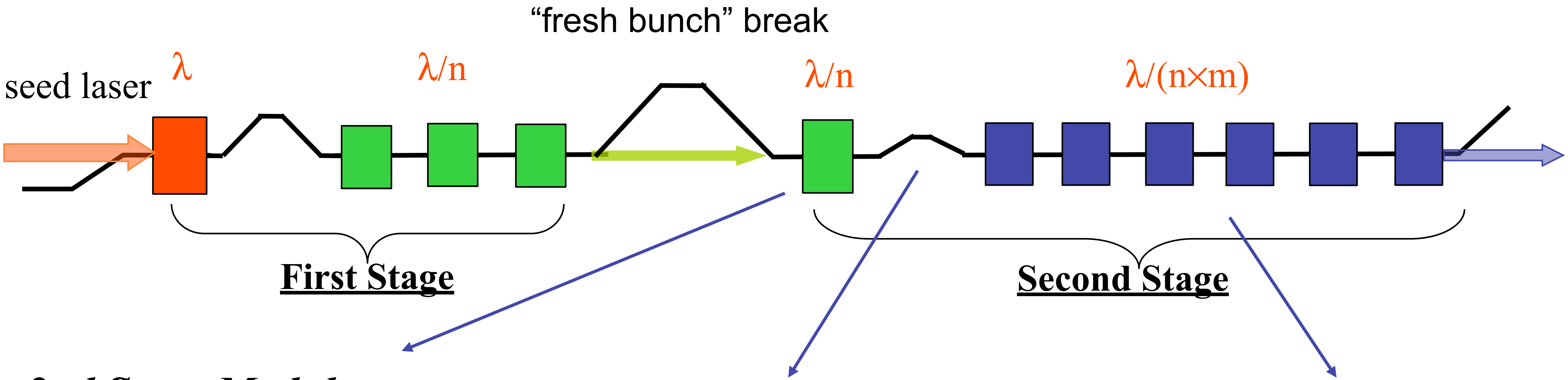


Here one upconverts the frequency by a very large amount. In this example by 25.

But at a price…complexity.

If only the seed wavelength were shorter…

FEL-2 (40-10 nm): fresh-bunch configuration



2nd Stage Modulator

Parameter	*Value*
Type	Planar
Structure	One segment
Period	6.5 cm
K	2.4 - 4
Length	2.08 m

Dispersive section

Parameter	*Value*
R_{56}	~ 6.4 μm (at 10 nm)
Length	~ 1 m

Radiator

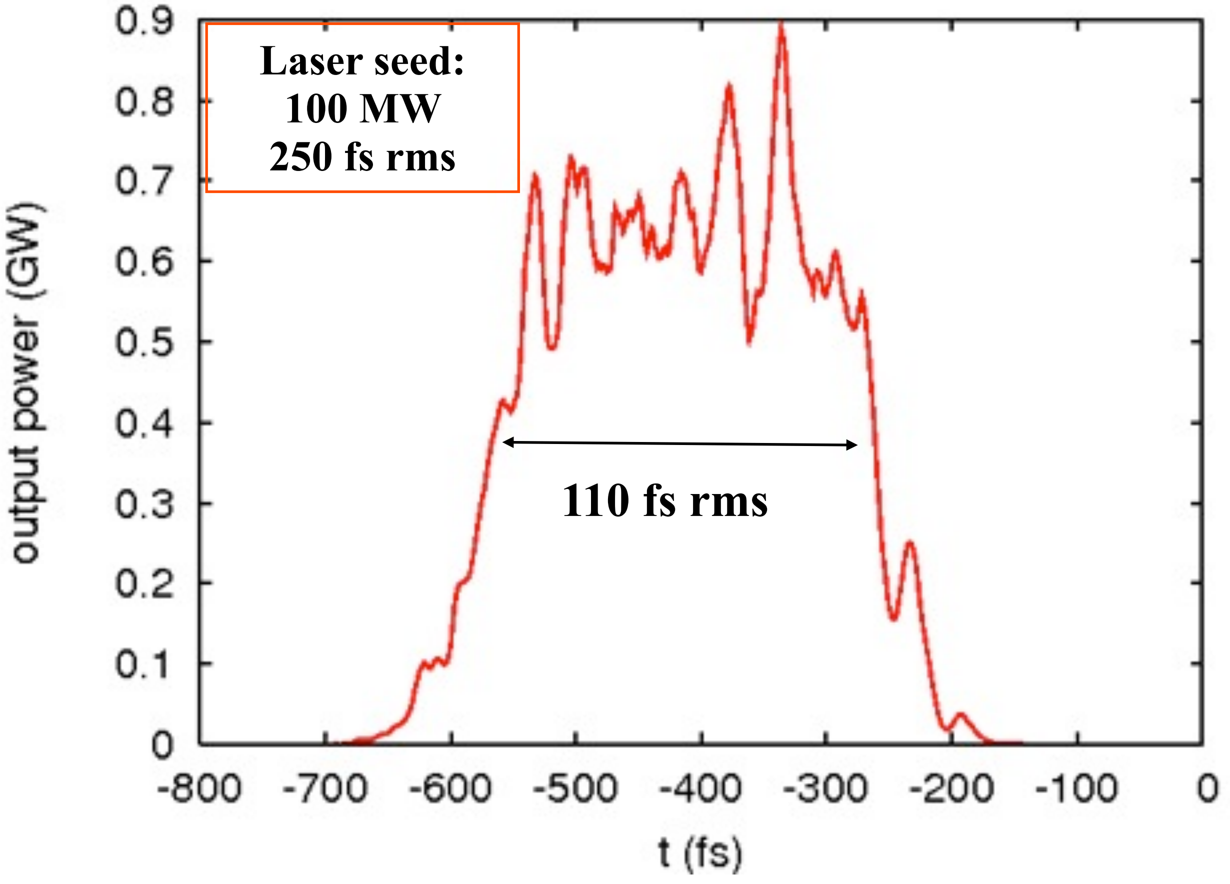
Parameter	*Value*
Type	Apple
Structure	Segmented
Period	5 cm
Segment length	2.4 m
K	1.1 - 2.8
Break length	1.06 m
Total length	19.7 m

Courtesy G. De Ninno

Total length FEL-2 ~ 37.5 m

FEL-2: Results at 10 nm (fresh bunch)

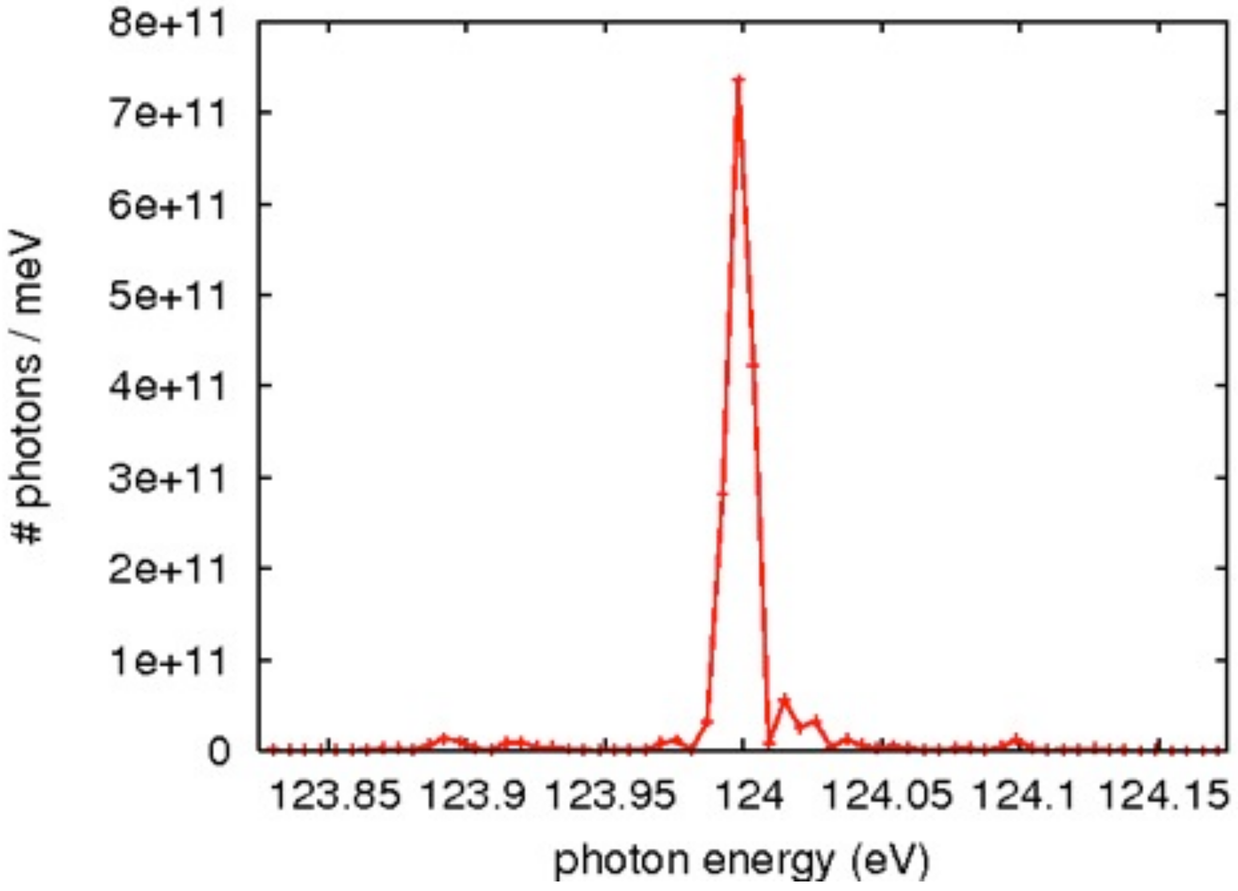
Output power profile



Laser seed:
100 MW
250 fs rms

110 fs rms

Output spectrum

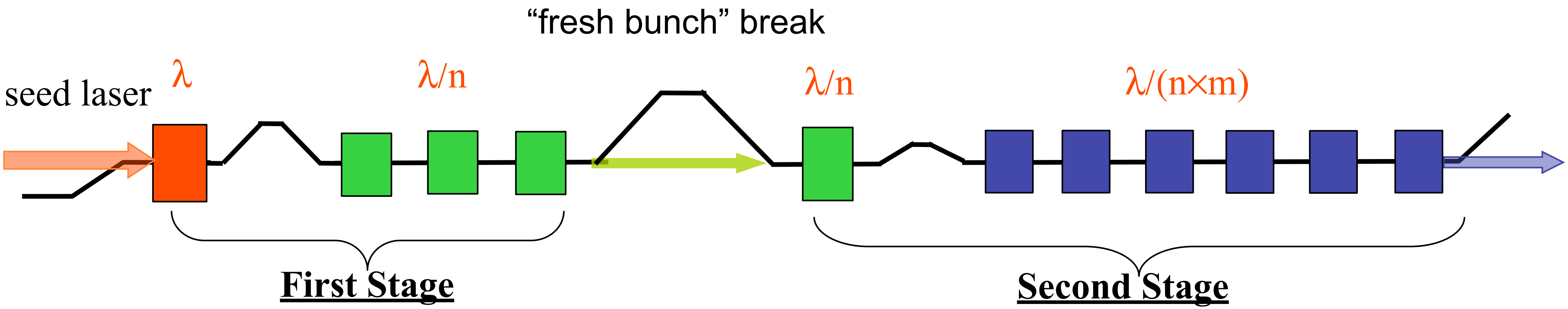


10^{13} photons (93% in single transverse mode)

5 meV bandwidth (rms) (1.5 x transform limit)

Courtesy G. De Ninno

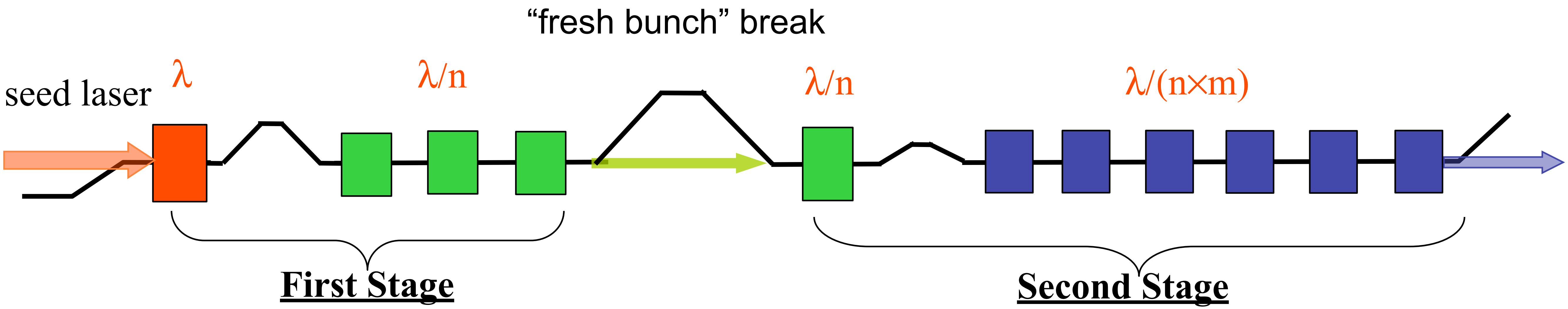
FEL-2 : CDR configuration



But from before remember that this requires either smaller energy spread or shorter wavelength seed

Courtesy G. De Ninno

FEL-2 : CDR configuration



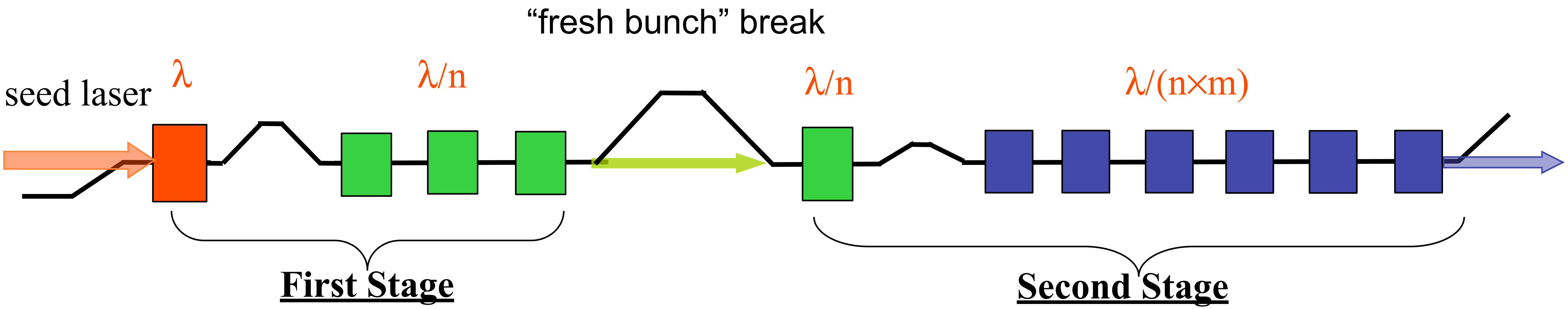
Is it possible to cover the FEL-2 tuning range in a single stage?

(as similar as possible to FEL-1)

But from before remember that this requires either smaller energy spread or shorter wavelength seed

Courtesy G. De Ninno

FEL-2 : CDR configuration



Is it possible to cover the FEL-2 tuning range in a single stage?

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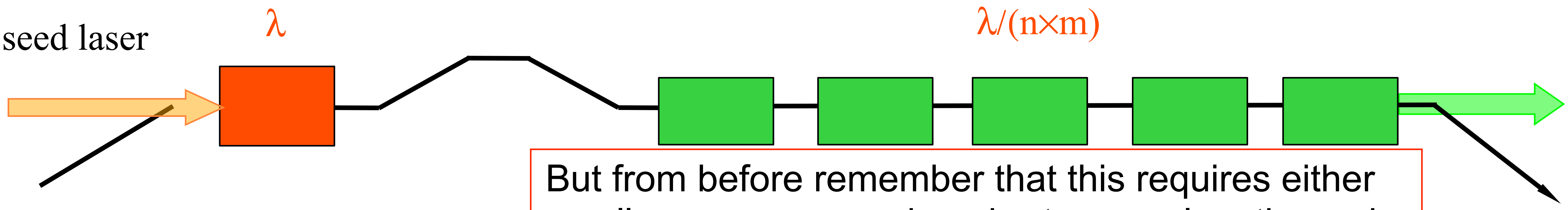


But from before remember that this requires either smaller energy spread or shorter wavelength seed

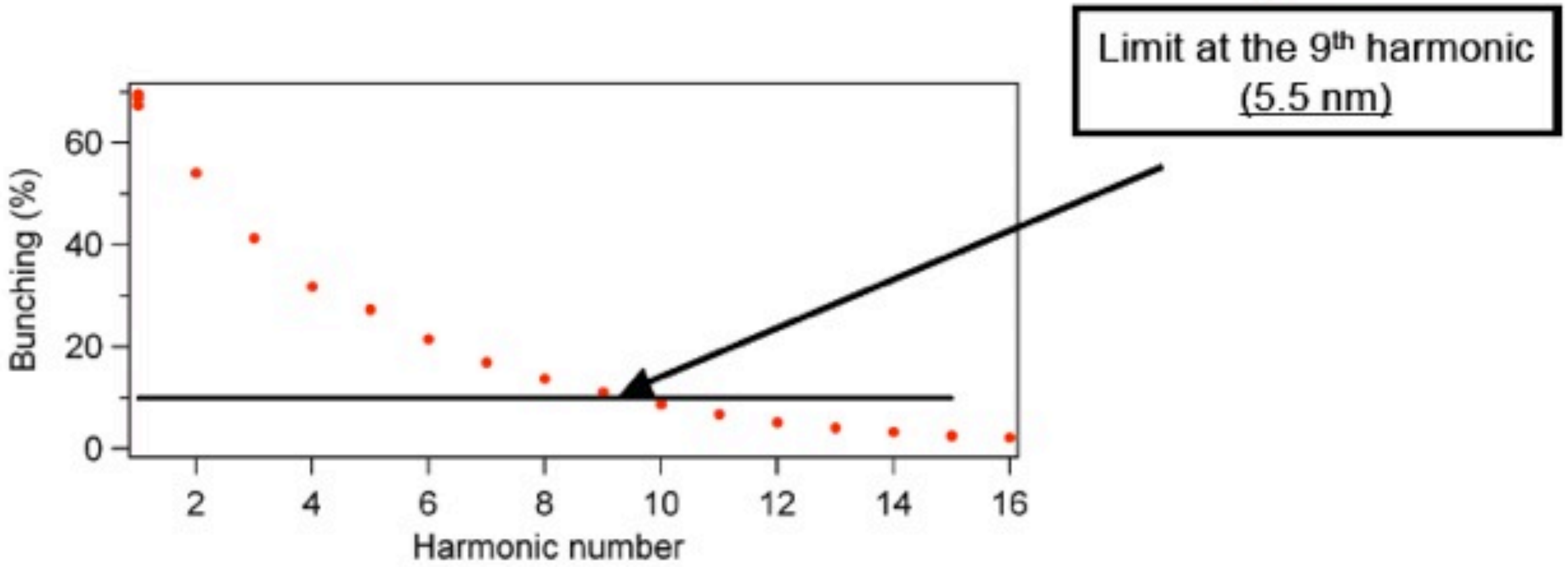
Courtesy G. De Ninno

Using HHG as a Seed?

Trying to reach shorter wavelengths...

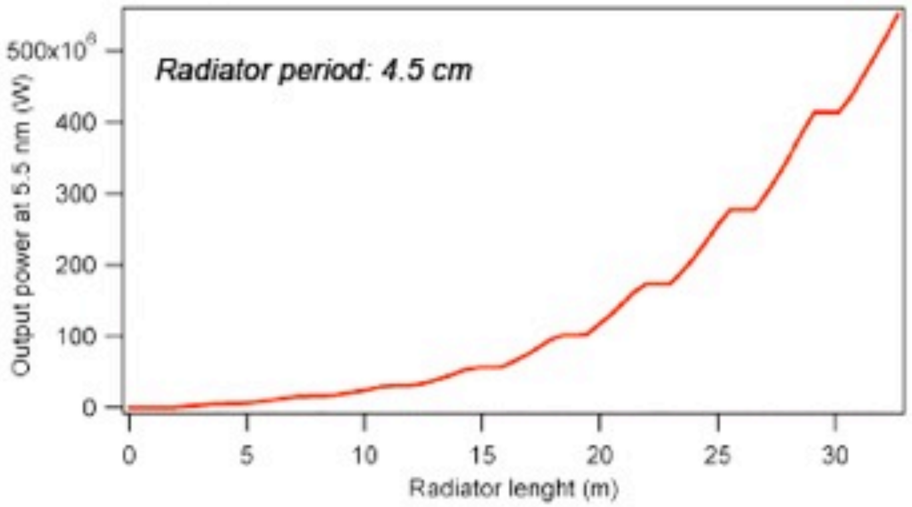
with enhanced e-beam parameters

Electron-beam energy: **1.5 GeV**	Shortest wavelength: 50 nm
Peak current: 750 A	Peak power: 1-5 MW
Energy spread: **100 KeV**	

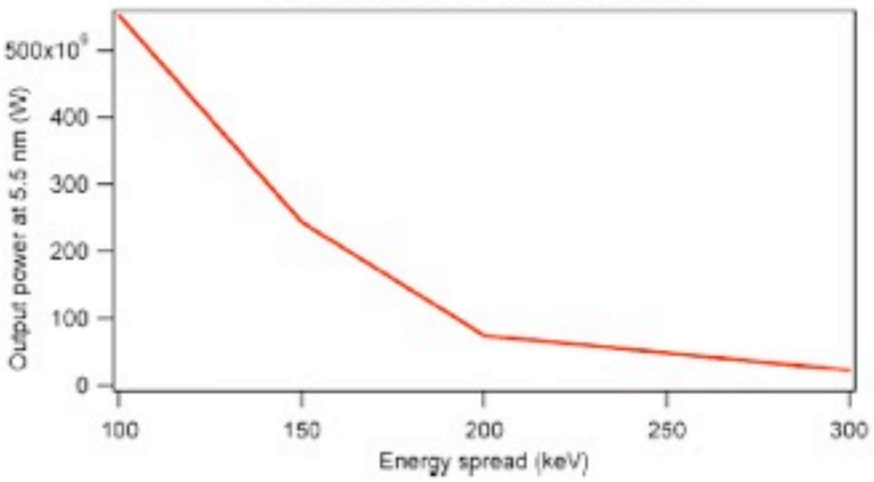


Limit at the 9th harmonic (5.5 nm)

Power along the radiator



Sensitivity to energy spread



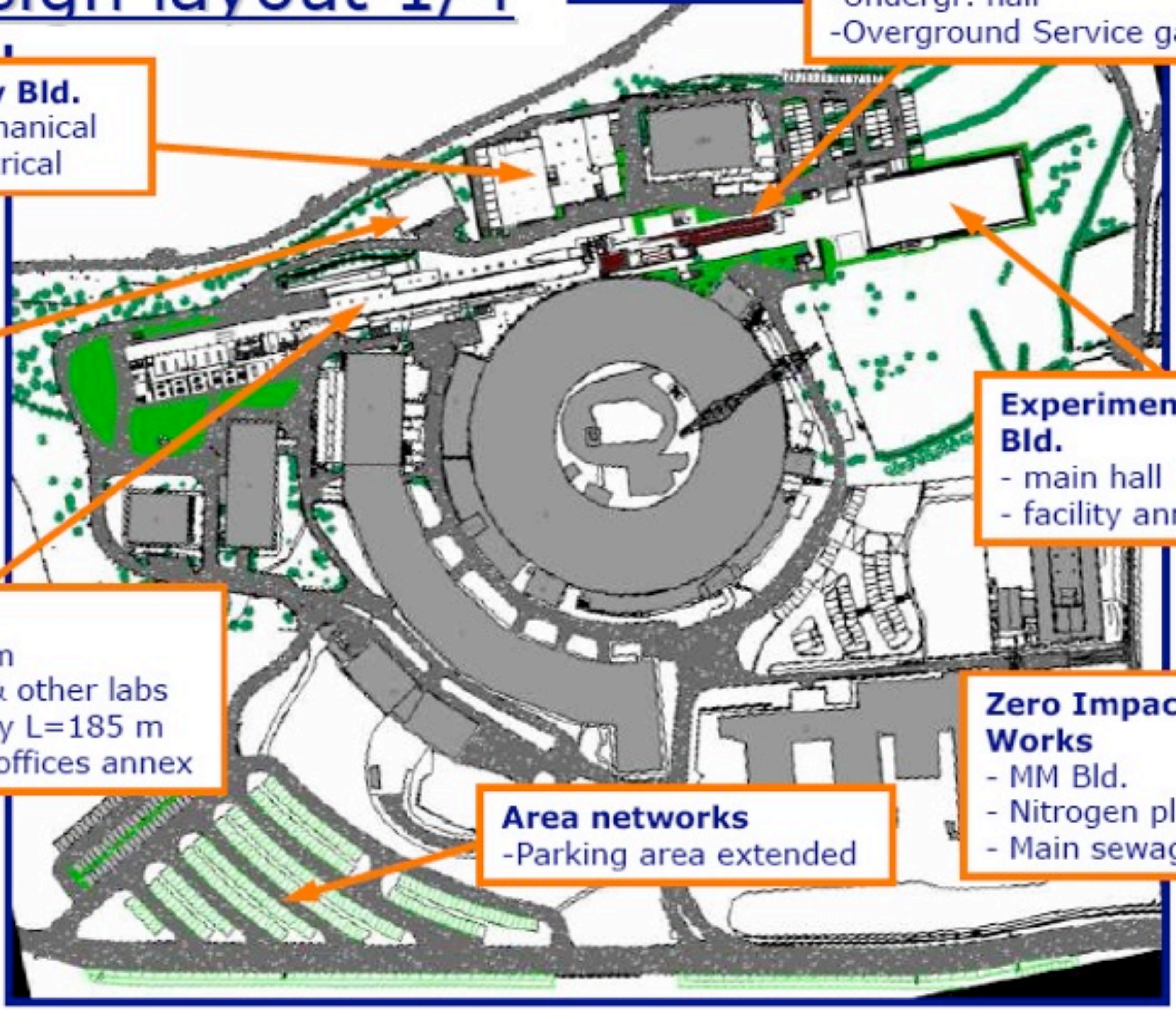
Courtesy G. De Ninno

Switching Gears

- I.e. Semi related topics
- Enough for the current FERMI thought process
- What About the Future
- Two Thoughts
  - Wavelength Shifting using beam gymnastics
  - Attosecond pulses

FERMI Civil Engineering

General design layout 1/4



Utility Bld.
- mechanical
- electrical

Undulator Bld.
-Undergr. hall
-Overground Service gallery

Prefab. Bld.
- labs
- offices

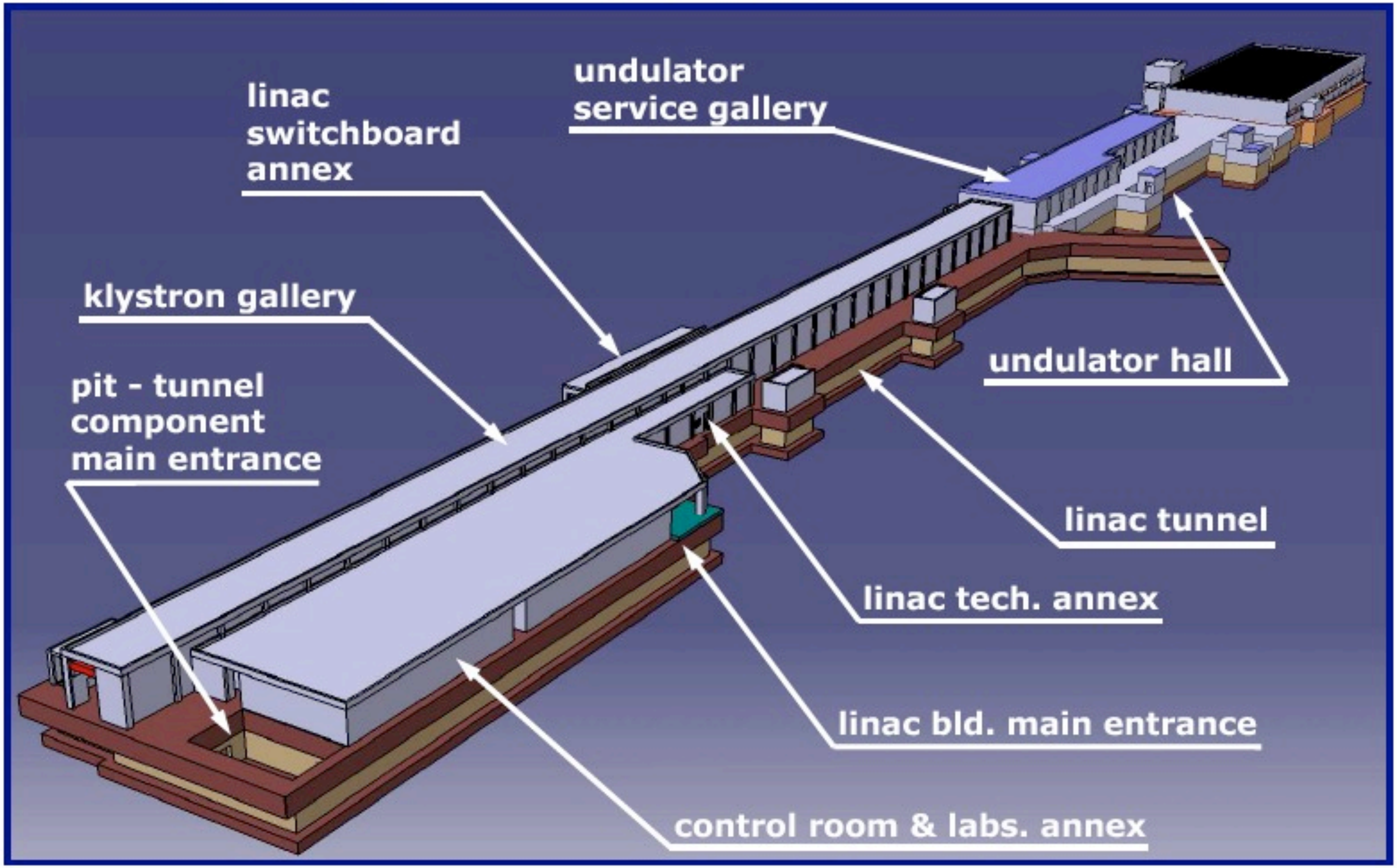
Experimental Bld.
- main hall
- facility annex

Linac Bld.
- extended tunnel L=191m
- undergr. area for laser & other labs
- extended klystron gallery L=185 m
- control room, labs. and offices annex

Area networks
-Parking area extended

Zero Impact Works
- MM Bld.
- Nitrogen plant
- Main sewage plant

Main buildings 3D view 1/10



FERMI@Elettra