Free Electron Laser Radiation
Interference

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

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

and we get constructive interference if $d=n\lambda$

$$\lambda = \frac{\lambda_0}{2n\gamma^2} \left( 1 + \frac{K^2}{2} + \gamma^2 \theta^2 \right)$$
After an electron travels one undulator period $\lambda_u$ of the sinusoidal trajectory, a plane wave (represented by alternating vertical arrows) overtakes the electron by one resonant wavelength $\lambda_1$. 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”
Growth of the radiation power and the electron beam microbunching as a function of the undulator distance for a high-gain FEL.
The Pierce scaling parameter is defined as

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

\[ [J J] = J_0 (\xi) - J_1 (\xi) \quad \text{Bessel functions} \]

\[ \xi = \frac{K_0^2}{4 + 2K_0^2} \]

\[ k_p = \sqrt{\frac{2I_e}{\gamma_0^3 I_A \sigma_x^2}} \quad \text{longitudinal plasma oscillation wavenumber} \]

\[ I_A = \frac{ec}{r_e} \approx 17 \text{ kA} \quad \text{Alfvén current} \]

\[ r_e \approx 2.8 \times 10^{-15} \text{m} \quad \text{classical radius of the electron} \]

\[ \sigma_x \quad \text{rms transverse size of the beam} \]
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 \( \rho \), and the saturation power is about \( \rho \) times the electron beam power.
Electron motion in the presence of undulator radiation

The undulator magnetic fields gives:

\[ v_x = \frac{eB_0}{\gamma m k_u} \cos (k_u z) = \frac{K_0 c}{\gamma} \cos (k_u z) \]

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

\[ \approx c \left( 1 - \frac{1 + \frac{K_0^2}{2}}{2\gamma^2} \right) - \frac{K_0^2 c}{4\gamma^2} \cos 2k_u z \]

\[ a = \bar{v}_z \]
Electron motion in the presence of undulator radiation

The change in the electron energy in presence of an electric field of the form $E_x = E_0 \cos (k_1 z - \omega_1 t + \psi_0)$ is:

$$mc^2 \frac{d\gamma}{dt} = e v_x E_x$$

$$= \frac{e E_0 K_0 c}{2\gamma} \left\{ \cos [(k_1 + k_u) z - \omega_1 t + \psi_0] 
+ \cos [(k_1 - k_u) z - \omega_1 t + \psi_0] \right\}$$

We define

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

where $\bar{t}$ is the electron arrival time averaged over the undulator period.
Electron motion in the presence of undulator radiation

The change in the electron energy in presence of an electric field of the form $E_x = E_0 \cos (k_1 z - \omega_1 t + \psi_0)$ is:

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$$= \frac{e E_0 K_0 c}{2\gamma} \left\{ \cos \left[ (k_1 + k_u) z - \omega_1 t + \psi_0 \right] + \cos \left[ (k_1 - k_u) z - \omega_1 t + \psi_0 \right] \right\}$$

We define

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

where $\bar{t}$ is the electron arrival time averaged over the undulator period.
Electron motion in the presence of undulator radiation

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:

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

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

we see that the variation of \( \theta \) at the interference condition is extremely 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 exchange. Properly taking into account the fact that the electron’s longitudinal motion also has an oscillatory part as given, we can write

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

which together with

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

are known as the “pendulum equations.” They describe the motion of electrons under the influence of the “ponderomotive potential” due to the combined undulator and radiation fields.
FIG. 4. Electron motion in the longitudinal phase space ($\theta, \eta$) 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.
“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

\[
\lambda_{rad} = \frac{\lambda_0}{2\gamma^2} \left(1 + \frac{K^2}{2}\right)
\]

Where \(\gamma\) is the normalized electron beam total energy and

\[
K = 0.934 \lambda_{rad} [\text{cm}] B_{\text{max}} [\text{T}]
\]

Is the normalized undulator field strength parameter
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 than 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

**FEL Oscillator**

UNDULATOR
NOTE: Requires Mirrors

**Seeded (Amplifier) FEL**

UNDULATOR
NOTE: Requires an Input Light Laser of Proper Wavelength

**Self-Amplified-Spontaneous-Emission (SASE) FEL**

UNDULATOR
NOTE: DOES NOT Require Mirrors or Seed Pulse
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

Log Radiation Intensity

Distance

Saturation

Microbunching Begins

Start up is from noise signal

Wednesday, July 10, 2013
SR or ERL
Spontaneous Radiation

FEL: Free Electron Laser
Coherent Radiation

$N$-electrons
random distribution

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

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

$N$-electrons
micro-bunched

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

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

Optical Power Enhancement
$x \ 10^5 \sim 10^8$
Radiation from Group Electron

Spontaneous Radiation

Randomly positioned Ne electrons.

\[ N_p \approx 100 \]

On-axis power

\[ \frac{\Delta \lambda}{\lambda} = \frac{1}{N_p} \]

Radiation cone \( \sim \frac{1}{\gamma} \)

Regularly positioned Ne electrons.

\[ N_{ch} \approx 1000 \]

FEL Radiation

\[ \theta_{ch} = \frac{1}{\gamma \sqrt{N_{ch}}} \]

\[ \frac{\Delta \lambda}{\lambda} = \frac{1}{N_{ch}} \]
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: $3 \times 10^{22}$
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
Generation of Ultrashort Coherent Vacuum Ultraviolet Pulses Using Electron Storage Rings: A New Bright Light Source for Experiments

G. De Ninno, 1,2 E. Allaria, 2 M. Coreno, 3 F. Curbis, 2,4 M. B. Danailov, 2 E. Karatzoulis, 2 A. Locatelli, 2 T. O. Mentes, 2 M. A. Nino, 2 C. Spezzani, 2 and M. Trovo 2

1 Physics Department, Nova Gorica University, Nova Gorica, SI-5000 Slovenia
2 Sincrotrone Trieste, S.S. 14 km 163.5, Trieste, I-34012 Italy
3 CNR-IMIP (Rome branch), c/o CNR-INFM TASC National Laboratory, Trieste, I-34012 Italy
4 Physics Department, Trieste University, Trieste, I-34100 Italy

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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

radio-frequency cavity

electron bunch

magnetic chicane

radiator

modulator

coherent emission

external laser

\[ \lambda/n \]

\[ \lambda \]
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

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

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.
FEL Seeding a Long Bunch

Seeded FEL
Short bunch

Seeded FEL
Long bunch

SASE

Courtesy of J. Corlett, LBNL
## FERMI FEL Output Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FEL-1</th>
<th>FEL-2 (in discussion)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength range [nm]</td>
<td>100 to 20</td>
<td>40 to 10 (to 3?)</td>
</tr>
<tr>
<td>Output pulse length (rms) [fs]</td>
<td>&lt; 100</td>
<td>&gt; 200</td>
</tr>
<tr>
<td>Bandwidth (rms) [meV]</td>
<td>17 (at 40 nm)</td>
<td>5 (at 10 nm)</td>
</tr>
<tr>
<td>Polarization</td>
<td>Variable</td>
<td>Variable</td>
</tr>
<tr>
<td>Repetition rate [Hz]</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Peak power [GW]</td>
<td>1 to &gt;5</td>
<td>0.5 to 1</td>
</tr>
<tr>
<td>Harmonic peak power (% of fundamental)</td>
<td>~2</td>
<td>~0.2 (at 10 nm)</td>
</tr>
<tr>
<td>Photons per pulse</td>
<td>$10^{14}$ (at 40 nm)</td>
<td>$10^{12}$ (at 10 nm)</td>
</tr>
<tr>
<td>Pulse-to-pulse stability</td>
<td>$\leq$ 30 %</td>
<td>$\sim$50 %</td>
</tr>
<tr>
<td>Pointing stability [µrad]</td>
<td>&lt; 20</td>
<td>&lt; 20</td>
</tr>
<tr>
<td>Virtual waist size [µm]</td>
<td>250 (at 40 nm)</td>
<td>120</td>
</tr>
<tr>
<td>Divergence (rms, intensity) [µrad]</td>
<td>50 (at 40 nm)</td>
<td>15 (at 10 nm)</td>
</tr>
</tbody>
</table>
FERMI Brightness

P \sim N_e^2

10^{10} \text{ 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

Wednesday, July 10, 2013
FERMI Seed Laser: Phase I

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

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

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 120 nm-12 nm range

FEL

Transport Optics

Graph showing energy/pulse vs. wavelength (nm) with data points for different gases and energy levels:
- KrF Hanover 14mJ 500fs
- Xe, Riken 16mJ
- Saclay: E = 25mJ
- Ar, Riken 16mJ
- Ne, Riken 130mJ
- LOA 2mJ

Energy (μJ) vs. Peak Power (MW) for 50fs pulse.
Seeding with an HHG Source?

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

- \( \tau = 30 \text{ fsec} \)
- \( \lambda = 800 \text{ nm} \)
- \( E = 14 \text{ mJ} \)

Tunable radiation in 120 nm-12 nm range

FEL

BUT
Seeding with an HHG Source?

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

- \[ \tau = 30 \text{ fsec} \]
- \[ \lambda = 800 \text{ nm} \]
- \[ E = 14 \text{ mJ} \]

- **Complicated**
- **Tunability not proven**

**BUT**

- Tunable radiation in 120 nm-12 nm range

**FEL**

**BUT**

- Energy / pulse
  - Xe
  - Riken 16mJ
  - Saclay: \[ E = 25 \text{ mJ} \]
  - Ar
  - Riken 16mJ
  - Riken 130mJ
  - Ne
  - LOA 2mJ
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.
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.

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 $\sim 10\% \Delta I/I$

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

Elastic and Inelastic Scattering BL (Coordinator C. Masciovecchio)

- Timer and Timex
  Spokespersons: C. Masciovecchio (Elettra) - 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)
Electronic Structure of an XUV Photogenerated Solid-Density Aluminum Plasma


1Department of Physics, Clarendon Laboratory, University of Oxford, Parks Road, Oxford, OX1 3PU, United Kingdom
2Institut für Optik und Quantenelektronik, Friedrich-Schiller-Universität, Max-Wien-Platz 1, 07743 Jena, Germany
3CEA, DAM, DIF, F-91297 Arpajon, France
4Laboratory of Molecular Biophysics, Uppsala University, Box 596, SE-751 24, Uppsala, Sweden
5Deutsches Elektronen-Synchrotron DESY, Notkestrasse 85, D-22607 Hamburg, Germany
6Institute of Physics ASCR, Na Slovance 2, 18221 Prague 8, Czech Republic
7Center for Free-Electron Laser Science at DESY, Notkestrasse 85, D-22607 Hamburg, Germany
8University of Hamburg, Luruper Chaussee 149, D-22761 Hamburg, Germany
9Queen’s University Belfast, University Road, Belfast, BT7 1NN, Northern Ireland, United Kingdom
10Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, California 94550, USA
11University Pierre et Marie Curie, LULI, case 128, 4 place Jussieu, 75252 Paris Cedex 05, France
12Institut für Physik, Universität Rostock, D-18051 Rostock, Germany
13Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA
14Institute of Physics PAS, Al. Lotnikw 32/46, PL-02-668 Warsaw, Poland
15SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, California 94025, USA
16Photon Science Research Institute, Science and Technology Facilities Council, Didcot, United Kingdom
17FOM-Institute for Plasma Physics Rijnhuizen, NL-3430 BE Nieuwegein, The Netherlands
18European XFEL GmbH, Albert-Einstein-Ring 19, 22761 Hamburg, Germany

(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: SOA, SOB
  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

**Parameters**

- $E_0 \approx 100 \text{ MeV}$
  - $I \approx 60 \text{ A (10ps)}$
- $E_1 \approx 220 \text{ MeV}$
  - $R_{56} \approx -0.03 \text{ m}$
  - $c.f. = 3.5$
- $E_2 \approx 600 \text{ MeV}$
  - $R_{56} \approx -0.02 \text{ m}$
  - $c.f. = 3.0$
- $E_3 \approx 1200 \text{ MeV}$
  - $I \approx 800 \text{ A (700fs)}$
  - $I \approx 500 \text{ A (1.4ps)}$

**Bunch Characteristics**

- **"Short" bunch**
  - Bunch length: 200 fs (flat part)
  - Peak current: 800 A
  - Emittance (slice): 1.5 \text{ \mu m}
  - Energy spread (slice): <150 keV
  - Flatness, $|d^2E/dt^2|$:

- **"Medium" bunch**
  - Bunch length: 700 fs (flat part)
  - Peak current: 800 A
  - Emittance (slice): 1.5 \text{ \mu m}
  - Energy spread (slice): <150 keV
  - Flatness, $|d^2E/dt^2|$:

- **"Long" bunch**
  - Bunch length: 1.4 ps (flat part)
  - Peak current: 500 A
  - Emittance (slice): 1.5 \text{ \mu m}
  - Energy spread (slice): <150 keV
  - Flatness, $|d^2E/dt^2|$:

**Operating Modes**

- Mostly FEL1
- Mostly FEL2
Conceptual layout of the FERMI FELs, transport line, spreader and beam dump

Seed laser(s)

TL

Beam spreader

EOS

FEL-1 (21m)

FEL-2 (38 m)

DS

M1 R1 M2 R2

Delay DS

First stage

LPUs

Second stage

EPUs

Future expansions

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

FEL-2 Configurations

- Fresh bunch
- Whole bunch
- HHG seeding

Description:

- 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
Is it possible to reach shorter wavelengths (i.e., 10 nm) in a single stage?
Bunching at the $n$th harmonic:

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

$n$: harmonic number

$\sigma_\gamma$: relative energy spread

$D$: dispersive section strength

$\Delta\gamma$: relative energy modulation

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

Courtesy G. De Ninno
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\( b_n \) significantly different from zero only if:

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\Delta\gamma \geq n\sigma_\gamma
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Courtesy G. De Ninno
Limitation

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Limitation on maximum \( n \)

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

Bunching at the $n$th harmonic:

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

Where:
- $b_n$: bunching coefficient
- $n$: harmonic number
- $\sigma_\gamma$: relative energy spread
- $D$: dispersive section strength
- $\Delta\gamma$: relative energy modulation

$b_n$ significantly different from zero only if:

$$\Delta\gamma \geq n\sigma_\gamma$$

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
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Planar</td>
</tr>
<tr>
<td>Structure</td>
<td>One segment</td>
</tr>
<tr>
<td>Period</td>
<td>6.5 cm</td>
</tr>
<tr>
<td>$K$</td>
<td>2.4 - 4</td>
</tr>
<tr>
<td>Length</td>
<td>2.08 m</td>
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</tbody>
</table>

Dispersive section

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>$R_{S6}$</td>
<td>~ 6.4 µm (at 10 nm)</td>
</tr>
<tr>
<td>Length</td>
<td>~ 1 m</td>
</tr>
</tbody>
</table>

Radiator

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Apple</td>
</tr>
<tr>
<td>Structure</td>
<td>Segmented</td>
</tr>
<tr>
<td>Period</td>
<td>5 cm</td>
</tr>
<tr>
<td>Segment length</td>
<td>2.4 m</td>
</tr>
<tr>
<td>$K$</td>
<td>1.1 - 2.8</td>
</tr>
<tr>
<td>Break length</td>
<td>1.06 m</td>
</tr>
<tr>
<td>Total length</td>
<td>19.7 m</td>
</tr>
</tbody>
</table>

"fresh bunch" break

Total length FEL-2 ~ 37.5 m

Courtesy G. De Ninno
FEL-2: Results at 10 nm (fresh bunch)

Output power profile

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

(as similar as possible to FEL-1)

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Courtesy G. De Ninno
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.
Using HHG as a Seed?

Trying to reach shorter wavelengths...
with enhanced e-beam parameters

Electron-beam energy: **1.5 GeV**  
Peak current: 750 A  
Energy spread: **100 KeV**

Shortest wavelength: 50 nm  
Peak power: 1-5 MW

Limit at the 9th harmonic  
(5.5 nm)

Power along the radiator  
Radiator period: 4.5 cm

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
Main buildings 3D view 1/10

- Linac switchboard annex
- Undulator service gallery
- Klystron gallery
- Pit - tunnel component main entrance
- Undulator hall
- Linac tunnel
- Linac tech. annex
- Linac bld. main entrance
- Control room & labs. annex