VUV — Soft X-ray FELs

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Lecture outline

- FEL physics drivers
  - Practical technological limits to performance
- Options for FEL configurations
  - Oscillator
  - SASE
  - Seeded
    - HGHG
    - Optical manipulations
    - Harmonic cascades
    - SASE self-seeding
- Options for facility configurations
  - Storage ring
  - Single-pass linac
    - Normal conducting
    - Superconducting
  - Energy recovery linac (ERL)
- Some concepts for the future
Machine parameters for VUV – soft x-ray FELs

(1) ELECTRON BEAM ENERGY

\[ \lambda \sim 190 \text{ nm} - 1 \text{ nm} \]

\[ \lambda_{x-ray} = \frac{\lambda_{\text{undulator}}}{2\gamma^2} \left( 1 + \frac{K^2}{2} \right) \]

\[ K = \frac{eB_0\lambda_{\text{undulator}}}{2\pi mc} \]

To efficiently radiate at nanometer wavelength, with state-of-the-art undulators

\[ \lambda_{\text{undulator}} \sim 1 \text{ cm} \]

\[ K \sim 1 \]

\[ \Rightarrow \gamma \sim 3 \times 10^3 \]

\[ E_{\text{beam}} \sim 1 \text{ GeV} \]
Limits to undulator performance

For a planar hybrid undulator with rare-earth cobalt magnetic material and vanadium permendur poles separated by gap \( g \)

\[
B_o \ [T] = 3.33 \exp \left[ -\frac{g}{\lambda_{\text{undulator}}} \left( 5.47 - 1.8 \frac{g}{\lambda_{\text{undulator}}} \right) \right]
\]

K. Halbach, “Permanent Magnet Undulators”, J. Physique, C1, Suppl.2, 44 (February 1983)
SCSS* lased at 49 nm with 250 MeV beam
IN-VACUUM, SHORT-PERIOD UNDULATOR

- Short-period - 1.5 cm
- Narrow-gap - 3.5 mm
- K=1.3
- Undulator length 4.5 m

*SPRING-8 Compact SASE Source

To radiate at 1 nm with this undulator
E = 1.9 GeV

http://epaper.kek.jp/f06/PAPERS/MOAAU04.PDF
Machine parameters for VUV – soft x-ray FELs

(2) MATCHING THE PHOTON BEAM AND ELECTRON BEAM PHASE SPACES

\[
\begin{pmatrix}
\varepsilon_n \\
\gamma
\end{pmatrix}
\sim \frac{\lambda_{x-ray}}{4\pi}
\]

⇒ Electron beam geometric emittance for nanometer x-rays
\[
\varepsilon_n/\gamma \sim 10^{-10} \text{ m-rad}
\]

State of the art \(\varepsilon_n \sim 10^{-6} \text{ m-rad (for } \sim\text{nC bunches)}\)

⇒ \(\gamma \sim 10^4\)

\(E_{\text{beam}} \sim \text{GeV}\)

This is a somewhat soft condition
Injector defines the minimum beam emittance

INTEGRATED SYSTEMS: CATHODE, LASER, ACCELERATING SECTIONS

Low emittance, high quantum efficiency cathodes

Integrated systems

Photocathode laser systems including pulse shaping

Acceleration technologies

Superconducting RF

Normal conducting RF

DC gun

Worldwide R&D efforts are exploring a range of technologies
Machine parameters for VUV – soft x-ray FELs

(3) ELECTRON BEAM LONGITUDINAL PHASE SPACE

\[
\frac{\sigma_E}{E} < \rho
\]

\[P_{saturated} \approx \rho I_{beam} \frac{E_{beam}}{e}\]

For \(\rho \sim 10^{-3}\)

\[\Rightarrow \text{Energy spread for GeV beam} \quad \sigma_E < \sim 100 \text{ keV}\]

Electron beam peak current \(I_{peak} \sim 1 \text{ kA}\)

\[\text{Saturated peak power} \sim \text{GW}\]
**Geometric wakefields in accelerating structures**

A HEAD-TAIL DISTURBANCE WITH STRONG DEPENDENCE ON IRIS APERTURE

\[ w_0(s) = \frac{Z_0 c}{\sqrt{2\pi^2 a^2}} \sqrt{gs} \]

\[ w_1(s) = \frac{2}{a^2} \frac{\sqrt{2} Z_0 c}{\pi^2 a} \sqrt{gs} \]


K. Bane, *Short-range dipole wakefields in accelerating structure for the NLC*, SLAC-PUB-9663, LCC-0116, 2003
Coherent synchrotron radiation (CSR)

COHERENT EMISSION AT WAVELENGTHS COMPARABLE TO BUNCH LENGTH

Coherent radiation for $\lambda > \sigma_z$

Bend-plane emittance growth

$W_s \int \frac{1}{(s-s')^{1/3}} \frac{\partial \lambda(s')}{\partial s'} ds'$

Courtesy P. Emma, SLAC
Microbunching instability arises from shot noise in the electron beam, grows under the influence of CSR and space charge, and introduces a modulation in the bunch energy spread.

- Control with “laser heater” which introduces an incoherent energy spread in the low energy beam
  - *Landau damping*
Wakefields influence beam phase space

ACCELERATOR DESIGN OPTIMIZATION REQUIRED

ACCELERATING STRUCTURE

CSR

∞ E-chirp

E-chirp

BBU

E-chirp

Dispersion

I

E

X

Courtey Simone Di Mitri, Sincrotrone Trieste

J. Corlett, June 2007, Slide 12
Machine parameters for VUV – soft x-ray FELs

(4) GAIN LENGTH

\[ l_{\text{gain}} \approx \frac{\lambda_{\text{undulator}}}{4\pi \rho} \]

For nanometer x-rays, with centimeter period undulator, and \( \rho = 10^{-3} \)

\[ l_{\text{gain}} \sim 1 \text{ m} \]

For saturated SASE FEL operation, undulator length \( \sim 20 \) gain lengths

\[ l_{\text{undulator}} \sim 10 \text{ m} \]
Machine parameters for VUV – soft x-ray FELs

(5) SLIPPAGE

\[ N_u \lambda_{x-ray} \sigma_l \]

For saturated SASE output, \( N_u \sim 10^3 \)

For x-ray pulses at 1 nm

\[ \Rightarrow N_u \lambda_{x-ray} \sim \mu m (\sim \text{femtosecond timescale}) \]

\[ \Rightarrow \text{Can limit minimum duration of “short” pulses at longer wavelengths} \]

*But* there are techniques to overcome this to a significant extent with seeded FELs
FEL configurations

(1) OSCILLATOR

- FEL radiation builds up in optical cavity
- Bunch passage coincides with radiation pulse
- Currently limited in wavelength >~175 nm by availability of mirrors
  - Some advanced oscillator schemes proposed
    - Avoid mirrors
    - Shorter wavelengths with narrow-band reflectors
FEL configurations

(2) SINGLE-PASS SASE FEL

- FEL process builds up in a single-pass of an undulator, from noise within the FEL gain bandwidth
- Avoids use of mirrors
- Allows shorter wavelengths
(3) SEEDED FEL

- Laser and undulator tuned to the same wavelength
- The laser introduces bunching into the electron beam
  - Seeds the FEL process
  - FEL output does not grow from noise
- Can also seed oscillators
Optical manipulations
LASER PULSE USED TO MANIPULATE ELECTRON BEAM ENERGY

- Electron beam couples to E-field of laser when co-propagating in an undulator.
- Over one undulator period, the electron is delayed with respect to the light by one optical wavelength.

\[ \lambda_w = 2\gamma^2 \lambda_L / (1 + \frac{K^2}{2}) \]
Field energy in the far field including laser and undulator light

\[ A = A_L + A_R + 2 \sqrt{A_L A_R \frac{\Delta \omega_L}{\Delta \omega_R}} \cos(\varphi) \]

\[ \Delta E(\varphi) = 2 \sqrt{A_L A_R \frac{\Delta \omega_L}{\Delta \omega_R}} \cos(\varphi) \]

\[ \Delta \omega_R \geq \Delta \omega_L \]

Electron phase relative to laser wave

\[ \Delta \omega_L = \frac{1}{N_L} \]

\[ \Delta \omega_R = \frac{1}{N_U} \]

# optical periods

# undulator periods

Light
Optical manipulations

NUMERIC EXAMPLE

\[ \Delta E(\varphi) = 2 \sqrt{A_L A_R \frac{\Delta \omega_L}{\Delta \omega_R}} \cos(\varphi) \]

\[ A_R = \pi \alpha \hbar \omega_R \]
\[ \omega_R = \omega_L \]
\[ \Delta \omega_R = \Delta \omega_L \]

\[ \hbar \omega_L = 4.5 \text{eV} \]
\[ A_L = 10 \mu \text{J} \]
\[ |\Delta E| = 5 \text{MeV} \]

3rd harmonic Ti:sapphire
100 MW, 100 fs pulse

Compare with \(~0.1 \text{ MeV}\) uncorrelated energy spread

\[ \Delta E_{\text{beam}} \]
10 MeV

100 keV

Time

J. Corlett, June 2007, Slide 20
Bunching of the electron beam
ENERGY MODULATION FOLLOWED BY DISPERIVE SECTION

\[ \Delta E_{\text{beam}} = \frac{R_{56} \Delta E}{E} \]

Energy-dependent path length

Induced current modulation in the electron beam
High-gain harmonic generation (HGHG)  
DEMONSTRATED AT BROOKHAVEN SDL

\[ \lambda_{\text{laser}} = \lambda_{x\text{-ray}}^{\text{modulator}} = \frac{\lambda_{\text{modulator}}^{\text{undulator}}}{2\gamma^2} \left( 1 + \frac{K^2}{2} \right) \]

\[ \lambda_{x\text{-ray}}^{\text{radiator}} = \frac{\lambda_{x\text{-ray}}^{\text{modulator}}}{n} = \frac{\lambda_{x\text{-ray}}^{\text{radiator}}}{2\gamma^2} \left( 1 + \frac{K^2}{2} \right) \]

\[ n \sim \text{a few-several} \]

**e⁻ beam phase space:**

Laser modulates e-beam energy

Bunched beam radiates strongly at harmonic in a downstream undulator resonant at \( \lambda_{\text{laser}}/n \)

High-gain harmonic generation (HGHG)

800-266 nm DEMONSTRATED AT BROOKHAVEN SDL

- Spectrum of HGHG and unsaturated SASE at 266 nm under the same electron beam condition
  - Note SASE at saturation would still be order of magnitude lower intensity

FEL configurations

(4) HARMONIC CASCADE REACHES SHORTER WAVELENGTHS

FEL configurations
“FRESH BUNCH” HARMONIC CASCADE CONFIGURATION

At each modulator, radiation interacts with “virgin” e⁻

- At each harmonic upshift $\lambda \rightarrow \lambda/n$ (modulator to radiator), macro-particle phase multiplied by $n$

- Bunching effects of dispersive section visible in change from $Z=6$ m in 48-nm modulator to $Z=0.4$ m scatter plot in 12-nm radiator
Optical manipulations

ANOTHER EXAMPLE

\[ \Delta E(\varphi) = 2\sqrt{A_L A_R \frac{\Delta \omega}{\Delta \omega_R}} \cos(\varphi) \]

\[ A_R \approx \pi \alpha \hbar \omega_R \]

\[ \omega_R = \omega_L \]

\[ \Delta \omega_R = \Delta \omega_L \]

\[ \hbar \omega_L = 1.5 \text{eV} \]

\[ A_L = 100 \mu\text{J} \]

\[ |\Delta E| = 10 \text{MeV} \]

Few-cycle Ti:sapphire seed laser

\[ 1 \text{ fs} \quad 0.3 \text{ MeV} \]

J. Corlett, June 2007, Slide 27
Enhanced-SASE (ESASE)

(5) OPTICAL MANIPULATIONS IMPART SOME CONTROL OF SASE

- Precise synchronization of the x-ray output with the modulating laser
- Variable output pulse train duration by adjusting the modulating laser pulse
- Increased peak output power
- Shorter x-ray undulator length to achieve saturation

FEL configurations

(6) ATTOSECOND PULSES FROM A SEEDED HARMONIC CASCADE

800 nm spectral broadening and pulse compression
e-beam harmonic-cascade FEL
time delay chicane wiggler tuned for FEL interaction at 800 nm
e-beam 2 nm light from FEL

2 nm modulator chicane-buncher 1 nm coherent radiation
< fs section resonant in 2 nm modulator

1 nm radiator

e-beam dump end station

< fs section resonant in 2 nm modulator

FEL configurations

(7) ULTRAFAST SASE PULSES AT LONGER WAVELENGTH

- Again, a few-cycle optical pulse modulates electron beam
  - This time there is no compression following the modulation
  - Take advantage of the energy chirp in the bunch
  - Tapered FEL keeps the small section of appropriately chirped beam in resonance

Evolution of a 26 nm wavelength pulse along undulator

Example with seed at 30 nm, radiating in the water window
First stage amplifies low-power seed with “optical klystron”
More initial bunching than could be practically achieved with a single modulator
Output at 3.8 nm (8th harmonic)

100 kW
\( \lambda = 30 \text{ nm} \)

1 GeV beam
500 A
1.2 micron emittance
75 keV energy spread

Modulator
\( \lambda = 30 \text{ nm}, L = 1.8 \text{ m} \)

Modulator
\( \lambda = 30 \text{ nm}, L = 1.8 \text{ m} \)

Radiator
\( \lambda = 3.8 \text{ nm}, L = 12 \text{ m} \)

300 MW output at 3.8 nm (8th harmonic) from a 25 fs FWHM seed

Lambert et al., FEL04

M. Gullans, J.S. Wurtele, G. Penn, A.A. Zholents, Optics Communications 274 (2007) 167-175
SASE & seeded FEL properties

Electron beam is 1.5 GeV, energy spread 100 keV, 250 A current, 0.25 micron emittance; laser seed is 100 kW at 32 nm; undulator period 1 cm
Self-seeded SASE FEL

Spectral power distribution

Behind 1\textsuperscript{st} undulator

Behind 2\textsuperscript{nd} undulator
Optical manipulations of the beam
ALLOW PRECISE CONTROL OF THE FEL OUTPUT

- Control of pulse duration
- Control of pulse energy
- Temporal coherence
- Generation of shorter wavelengths in harmonic cascades
- Precise synchronization
- Shorter undulators to reach saturation
Storage ring : Linac : Recirculating Linac

OPTIONS FOR ULTRAFAST VUV—SOFT X-RAY FEL FACILITIES

• Storage rings
  - Electron bunches ~100 ps duration (~10—100 A peak current), highly stable
  - Low-gain seeded FEL
    - Moderate peak brightness, short pulses
  - Repetition rate up to kHz

• Single-pass linacs
  - Electron bunches ~100—1000 fs (~100—1000 A peak current)
  - SASE or seeded FEL
    - High peak brightness, short pulses
  - Repetition rate
    - MHz-GHz CW for superconducting RF
    - ~100 Hz pulses for normal conducting RF

• Recirculating linacs (including energy recovery linacs)
  - Electron bunches ~100—1000 fs (~100—1000 A peak current)
  - Seeded FEL
    - High peak brightness, short pulses
  - Repetition rate up to GHz
ELETTRA: storage ring, seeded FEL

SEEDED COHERENT HARMONIC (CHG) GENERATION IN A STORAGE RING FEL

- 780 nm -> 260 nm demonstrated at ELETTRA
- CHG $10^4$ greater than spontaneous emission
  - 1 kHz seed laser
  - 1 GW seed power (2.5 mJ)
  - 100 fs duration
  - 2 mA bunch current

- Proposal to seed at 260 nm
  \[\Rightarrow\text{Coherent harmonic generation at 87 nm}\]
Accelerating structures
SUPERCONDUCTING OR NORMAL CONDUCTING

Normal conducting
• High accelerating gradient achievable at high frequency
  • >50 MVm\(^{-1}\) at 11 GHz
• High power dissipation in structure walls
  • Operate in pulsed mode for highest gradient
    • E.g. 120 Hz SLAC linac
    • ~ 20 MVm\(^{-1}\)

Superconducting
• Low frequency
  • Larger aperture
  • Reduced geometric wakefields
• Capability to operate with long pulses, or CW, with high gradient
  • High beam power
• Options for beam recirculation and energy recovery
  • ~20 MVm\(^{-1}\) goal for CW operations

\[ R_{BCS} \propto \frac{1}{T} f^2 e^{-\frac{a}{T}} \]

World record SCRF accelerating gradient 59 MVm\(^{-1}\)
Accelerating structures
SUPERCONDUCTING RF TECHNOLOGY UNDER DEVELOPMENT

CW operation
- High accelerating gradient
  - Goal ~20 MVm⁻¹
- High repetition rate
- High beam power
- Flexible bunch patterns
- Highly stable cavity fields
  - RF feedback and controls
    - Electron beam energy and timing stability

BNL 703 MHz cryomodule
Cornell 1.3 GHz SCRF cryomodule components
FLASH: single-pass pulsed SCRF linac, SASE FEL

- Bunch charge < 1 nC
- Emittance 2 – 4 mm-mrad
- Peak current 2.5 kA
- Energy spread $10^{-3}$

Courtesy Siegfried Schreiber, DESY
FLASH performance

• Pulse trains of up to 800 μs duration
• Up to 10 Hz repetition rate (currently 5 Hz)
• Change bunch pattern on user request, by control of photocathode laser
  – Number of bunches
  – Different bunch frequencies: kHz, up to MHz
• Fixed gap undulators
  – B=0.48 T, K=1.23, λ_u=2.73 cm, gap=12 mm
  – Tuning by electron beam energy variation
  – 374 – 720 MeV
• Wavelength range (fundamental): 13-47 nm
• Pulse energy average: 100 μJ
• Pulse energy peak: 200 μJ
• Peak power: ~ 5 GW
• Average power: > 100 mW
• Pulse duration (FWHM): 10-50 fs
• Spectral width (FWHM): 0.5-1 %
• Peak brilliance: $10^{29} - 10^{30}$ ph (s 0.1%BW mm mrad)$^{-1}$

Upgrade to 1 GeV, to lase at 6.5 nm, in progress

Courtesy Siegfried Schreiber, DESY
Worlds first harmonic cascade seeded FEL facility
Under construction, first light late 2009
FERMI@elettra: pulsed normal conducting linac, seeded FEL

**FEL-1**: short (40-300 fs) photon pulses at 100-20 nm, peak power ~1 to >5 GW

1-Stage HGHG
- variable polarization output
- 50 Hz rep rate
- 1 micro-pulse per macro pulse

**FEL-2**: narrow-band (< 5 meV) photon pulses at 40-10 nm, peak power ~ 0.5 to a few GW

2-Stage cascade HGHG
- variable polarization output
- 50 Hz rep rate
- 1 micro-pulse per macro pulse

S. Milton, Sincrotrone Trieste
Energy recovery linac (ERL)

- Maintain low emittance of beam from injector
- Spatial coherence at short wavelengths
- Beam energy received in main linac is recovered

✓ 100 mA @ 6 GeV = 600 MW
4GLS
PROPOSAL FOR ERL-BASED FACILITY

VUV FEL
Repetition rate up to 1.3 GHz
Variable polarization
FEL output 3 — 10 eV
Up to 70 μJ per pulse
Minimum pulse duration < 170 fs

XUV FEL
HHG seeded
Repetition rate ~1 kHz
Variable polarization
FEL output up to 8 — 100 eV
Up to 400 μJ per pulse
Minimum pulse duration < 50 fs

J. Clarke, CCLRC Daresbury
A HIGH REP-RATE, SEEDED, VUV — SOFT X-RAY FEL ARRAY

Array of configurable FELs
Each high rep-rate up to MHz
Independent control of wavelength, pulse duration, polarization
Configured with an optical manipulation technique; seeded, attosecond, ESASE

Beam manipulation and conditioning

~2 GeV CW superconducting linac

Beam distribution and individual beamline tuning

MHZ bunch rate, low-emittance, electron gun

Laser systems, timing & synchronization
High rep-rate seeded FEL performance

TIME-DOMAIN EXPERIMENTATION IN THE VUV-SXR REGIME
PARAmeter SPACE COMPLEMENTS OTHER FACILITIES

Average Brightness \([\text{Ph/(s \times 0.1\% BW mm}^2 \text{ mrad}^2])\]

X-Ray Pulse Duration \([\text{ps}]\)

Seeded FEL, 750 fs (1.2 keV)
Seeded FEL, 50 fs (1.2 keV)
Seeded FEL, 100 as (1.2 keV)
Cornell ERL (6 keV)
European XFEL (12 keV)
LCLS (8 keV)
FLASH (200 eV)
BESSY FEL (1 keV)
3rd Generation Storage Rings
2nd Generation Storage Rings

J. Corlett, June 2007, Slide 46
Accelerator R&D required for future FELs

**Injector**
- Cathode (low emittance, high QE, power handling)
- Photocathode laser (pulse shaping, power)
- Accelerating structures (high gradient, low loss)

**Accelerator**
- CW superconducting RF
  - High gradient
  - High Q
  - High reliability

**FEL**
- Seed laser (pulse shaping, tunability, power)
- Short-period undulators

**Accelerator physics**
- Emittance control and manipulations
- Low emittance beam transport
- Bunch compression strategies
- Micobunching suppression

**Other technologies**
- High-resolution diagnostics
- Timing and synchronization systems
APPENDIX 1

VUV – SOFT X-RAY FACILITIES UNDER CONSTRUCTION, PROPOSALS, AND CONCEPTS
## VUV – soft x-ray FEL projects

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>Project</th>
<th>Institution</th>
<th>Type of facility</th>
<th>Shortest photon wavelength in the fundamental (nm)</th>
<th>Project status</th>
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</thead>
<tbody>
<tr>
<td>Storage ring</td>
<td>Elettra storage ring FEL</td>
<td>Sincrotrone Trieste, Trieste, Italy</td>
<td>Storage ring FEL</td>
<td>80</td>
<td>Operational</td>
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<tr>
<td>Energy recovery linac</td>
<td>4GLS</td>
<td>CCLRC, Daresbury, U.K.</td>
<td>CW superconducting linac, ERL, spontaneous undulator radiation and seeded FEL component</td>
<td>0.15</td>
<td>Proposal</td>
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<td>Arc-en-Ciel</td>
<td>SOLEIL, CEA Saclay; Ecole Polytechnique; CNRS Orsay; France</td>
<td>CW superconducting linac, ERL, spontaneous undulator radiation and SASE and HGHG FELs</td>
<td>&lt;1</td>
<td>Concept under development</td>
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<td>Single-pass linac</td>
<td>MAX-IV</td>
<td>MAX-Lab, Lund University, Sweden</td>
<td>Pulsed normal conducting linac, HGHG optical klystron cascade FEL</td>
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<td>Proposal</td>
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<td>LBNL NGLS</td>
<td>LBNL, Berkeley, CA, USA</td>
<td>CW superconducting linac, HGHG FEL</td>
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<td>Concept under development</td>
</tr>
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<td>Wisconsin FEL</td>
<td>U. of Wisconsin Synchrotron Radiation Center, and MIT, USA</td>
<td>CW superconducting linac, HGHG FEL</td>
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<td>Concept under development</td>
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<td>BESSY FEL</td>
<td>BESSY, Berlin, Germany</td>
<td>CW superconducting linac, HGHG FEL</td>
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<td>Proposal</td>
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<td>SPARX</td>
<td>INFN, ENEA, Frascati, Italy</td>
<td>Pulsed normal conducting linac, SASE FEL</td>
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<td>Concept under development</td>
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<td>FLASH</td>
<td>DESY, Hamburg, Germany</td>
<td>Pulsed superconducting linac, SASE FEL</td>
<td>6.4</td>
<td>Operational</td>
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<tr>
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<td>FERMI@Elettra</td>
<td>Sincrotrone Trieste, Trieste, Italy</td>
<td>Pulsed normal conducting linac, HGHG FEL</td>
<td>10</td>
<td>Funded for construction</td>
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<td></td>
<td>SDUV-FEL</td>
<td>Shanghai Institute of Applied Physics, Shanghai, China</td>
<td>Pulsed normal conducting linac, HGHG FEL</td>
<td>88</td>
<td>Funded for construction</td>
</tr>
</tbody>
</table>
Wisconsin FEL
4GLS
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SPARX
SDUV-FEL
FERMI@Elettra, Elettra FEL
ELETTRA storage ring FEL
SEEDED OPTICAL KLYSTRON IN A STORAGE RING

External laser seed

Modulator

Dispersive section

Radiator

Coherent emission

Coherent light

e⁻ beam energy modulation

Micro-bunching

G. DeNinno, Sincrotrone Trieste
FLASH overview

- Bunch charge < 1 nC
- Emittance 2 – 4 mm-mrad
- Peak current 2.5 kA
- Energy spread $10^{-3}$

Courtesy Siegfried Schreiber, DESY
FLASH is the shortest wavelength FEL
Lasing at 13.7 nm

Courtesy Siegfried Schreiber, DESY
FLASH time structure

- TESLA type superconducting linac
- Pulse trains of up to 800 µs duration
- Up to 10 Hz repetition rate (currently 5 Hz)
- Change bunch pattern on user request, by control of photocathode laser
  - Number of bunches
  - Different bunch frequencies: 1 MHz, 250 kHz, 100 kHz, up to MHz

Electron beam pulse train
(30 bunches, 1 MHz)

Courtesy Siegfried Schreiber, DESY
• Averaged at 13.7 nm exceeds 70 µJ
• Peak radiation energy ~170 µJ
• Pulse duration estimate around 10 fs
• Peak power exceeds 5 GW
• Fixed gap undulators
  – B=0.48 T, K=1.23, λ_u=2.73 cm, gap=12 mm
  – Tuning by electron beam energy variation 374 – 720 MeV

• Wavelength range (fundamental): 13-47 nm
• Pulse energy average: 100 µJ
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Upgrade to 1 GeV, to lase at 6.5 nm, in progress
FERMI@Elettra at Sincrotrone Trieste, Italy
Worlds first harmonic cascade seeded FEL facility
Fermi accelerator configuration

Single-pass normal conducting linac

- GUN
- Linac 1
  - $E_0 \approx 100$ MeV
  - $I \approx 60$ A (10 ps)

- Linac 2
  - $E_1 \approx 220$ MeV
  - $R_{56} \approx -0.03$ m
  - Compression factor = 3.5

- Linac 3
  - $E_2 \approx 600$ MeV
  - $R_{56} \approx -0.02$ m
  - Compression factor = 3.0

- Linac 4
  - $E_3 \approx 1200$ MeV
  - $I \approx 800$ A (700 fs)
  - $I \approx 500$ A (1.4 ps)

- Bunch compressor 1
- Bunch compressor 2

- X-band linearizer

- Laser heater

- Photocathode laser

- Laser heater

- Bunch length
  - "Medium" bunch: 700 fs (flat part)
  - "Long" bunch: 1.4 ps (flat part)

- Peak current
  - "Medium": 800 A
  - "Long": 500 A

- Emittance (slice)
  - "Medium": 1.5 micron
  - "Long": 1.5 micron

- Energy spread (slice)
  - "Medium": <150 keV
  - "Long": <150 keV

- Flatness, $|d^2E/dt^2|$
  - "Medium": <0.8 MeV/ps
  - "Long": <0.2 MeV/ps

FEL hall (not shown)
Correct for geometric wakefields
SHAPE THE BUNCH CURRENT DISTRIBUTION

\[ W(s) = -\int_{s}^{\infty} w(s - s') \lambda_z(s') \, ds' \]

\[ w(s) = A \frac{Z_0 c}{\pi a^2} L \exp \left(-\sqrt{\frac{s}{s_1}}\right) \]

OPTIMAL DESIGN OF THE ACCELERATOR IMPROVES FEL PERFORMANCE

FERMI FEL configurations

**FEL-1**: short (40-300 fs) photon pulses at 100-20 nm, peak power ~1 to >5 GW

- 1-Stage HGHG
  - variable polarization output
  - 50 Hz rep rate
  - 1 micro-pulse per macro-pulse

**FEL-2**: narrow-band (< 5 meV) photon pulses at 40-10 nm, peak power ~ 0.5 to a few GW

- 2-Stage cascade HGHG

Courtesy S. Milton, Sincrotrone Trieste
FEL-1 configuration
100 - 40 nm

Input seed laser
(240 ≤ λ ≤ 360 nm)

\[ \lambda_{\text{res}} = \frac{\lambda}{n} \quad (3 ≤ n ≤ 6) \]

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>16 cm</td>
</tr>
<tr>
<td>K</td>
<td>3.9 - 4.9</td>
</tr>
<tr>
<td>Length</td>
<td>3.04 m</td>
</tr>
</tbody>
</table>

Dispersive section

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R_{56}</td>
<td>~ 32 mm</td>
</tr>
<tr>
<td>Length</td>
<td>~ 1 m</td>
</tr>
</tbody>
</table>

Radiator

<table>
<thead>
<tr>
<th>Radiator</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Apple</td>
</tr>
<tr>
<td>Structure</td>
<td>~ 5 Segments</td>
</tr>
<tr>
<td>Period</td>
<td>6.5 cm</td>
</tr>
<tr>
<td>K</td>
<td>2.4 - 4</td>
</tr>
<tr>
<td>Segment length</td>
<td>2.34 m</td>
</tr>
<tr>
<td>Break length</td>
<td>1.06 m</td>
</tr>
<tr>
<td>Total length</td>
<td>15.94 m</td>
</tr>
</tbody>
</table>

Total length of FEL-1 ~ 20 m

G. De Ninno, Sincrotrone Trieste
FEL-2 configuration
40 - 10 nm FRESH BUNCH CONFIGURATION

Total length FEL-2 (fresh bunch) ~ 37.5 m

G. De Ninno, Sincrotrone Trieste
- Second stage is radiator only; delay section and second modulator eliminated
- Allows “full” bunch to emit in second stage, but: requires smaller initial $\sigma_\gamma$

**Total length FEL-2 (whole bunch) ~ 50 m**
<table>
<thead>
<tr>
<th>Parameter</th>
<th>FEL-1</th>
<th>FEL-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength range [nm]</td>
<td>100 to 20</td>
<td>40 to 10</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>≤ 30 %</td>
<td>~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 experimental hall

PHOTONS FROM EITHER FEL SWITCHABLE TO ENDSTATIONS

Five initial end stations
FEL 1 & 2 separated by 2 m
Each FEL can reach four

End shield 3 m thick
Mirror hutch 0.8 m thick
Vision for a future light source facility at LBNL

A HIGH REP-RATE, SEEDED, VUV — SOFT X-RAY FEL ARRAY

Array of configurable FELs
Independent control of wavelength, pulse duration, polarization
Configured with an optical manipulation technique; seeded, attosecond, ESASE

Low-emittance, high rep-rate electron gun

Beam manipulation and conditioning

~2 GeV CW superconducting linac

Beam distribution and individual beamline tuning

Laser systems, timing & synchronization

J. Corlett, June 2007, Slide 66
LBNL seeded FEL performance goals

**DRIVEN BY USER NEEDS**

<table>
<thead>
<tr>
<th></th>
<th>Ultrafast</th>
<th>High resolution</th>
<th>Attosecond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength range (nm)</td>
<td>200 - 1</td>
<td>200 - 1</td>
<td>200 - 1</td>
</tr>
<tr>
<td>Repetition rate(^1) (kHz)</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Peak power (GW)</td>
<td>1</td>
<td>1</td>
<td>0.1 - 0.3</td>
</tr>
<tr>
<td>Intensity stability(^2)</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>Timing stability(^3,4) (fs)</td>
<td>10</td>
<td>10</td>
<td>tbd</td>
</tr>
<tr>
<td>Pulse length(^5) (fs)</td>
<td>1 - 100</td>
<td>500 - 1000</td>
<td>~0.1</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>2-3 x transform limit ≤few %</td>
<td>2-3 x transform limit ≤few %</td>
<td>transform limit ≤few %</td>
</tr>
<tr>
<td>Harmonics(^6)</td>
<td>few %</td>
<td>few %</td>
<td>few %</td>
</tr>
<tr>
<td>Source position stability</td>
<td>&lt;10% source size</td>
<td>&lt;10% source size</td>
<td>&lt;10% source size</td>
</tr>
<tr>
<td>Pointing stability (μrad)</td>
<td>~50</td>
<td>~50</td>
<td>~50</td>
</tr>
<tr>
<td>Spot size (μm)</td>
<td>~50</td>
<td>~50</td>
<td>~50</td>
</tr>
<tr>
<td>Divergence (μrad)</td>
<td>Variable, lin/circ</td>
<td>Variable, lin/circ</td>
<td>Variable, lin/circ</td>
</tr>
<tr>
<td>Polarization</td>
<td>tbd</td>
<td>tbd</td>
<td>tbd</td>
</tr>
<tr>
<td>Wavelength stability(^7)</td>
<td>tbd</td>
<td>tbd</td>
<td>tbd</td>
</tr>
<tr>
<td>Background signal(^8)</td>
<td>tbd</td>
<td>tbd</td>
<td>tbd</td>
</tr>
</tbody>
</table>

**NOTES:**
1) 10 kHz initially, need additional gun developments for higher rate, but linac & other infrastructure will accommodate this
2) Most experiments will incorporate a pulse energy measurement, stability then not critical; spectroscopies & non-linear expts more demanding
3) Synchronization available from seeded systems
4) Timing stability for the attosecond mode will need to be developed
5) Capabilities for <20 fs pulse durations to be explored (in R&D plan)
6) Up to third harmonic, may be useful to achieve wavelengths shorter than nm
7) Currently under study for the FERMI project
8) Dependent on FEL configuration and mode of operation
Average brightness versus pulse duration for storage ring, ERL, and FEL sources. Values are shown for optimized brightness at the photon energies indicated, based on available data. For the European XFEL and FLASH this reflects the use of bunch trains. For a 100-kHz seeded-FEL facility utilizing optical manipulations to control pulse duration, a dashed line indicates performance range.
FEL options on PEP
CONCEPT FOR STORAGE-RING BASED FEL - SASE MODE (IN BYPASS)

- Low-emittance lattice with wiggler (including intrabeam scattering)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>4.5 GeV</td>
</tr>
<tr>
<td>Norm. emittance in x/y</td>
<td>0.6 ( \mu )m</td>
</tr>
<tr>
<td>Peak current</td>
<td>300 A</td>
</tr>
<tr>
<td>Bunch length</td>
<td>10 ps</td>
</tr>
<tr>
<td>Energy spread</td>
<td>0.114%</td>
</tr>
<tr>
<td>Undulator period</td>
<td>5 cm</td>
</tr>
<tr>
<td>Undulator parameter</td>
<td>7.75</td>
</tr>
<tr>
<td>Peak magnetic field</td>
<td>1.65 T</td>
</tr>
<tr>
<td>FEL wavelength</td>
<td>10 nm</td>
</tr>
</tbody>
</table>

- Steady-state mode increases energy spread but can operate at ring frequency

“single-pass SASE”

“steady-state SASE”
FEL options on PEP
CONCEPT FOR STORAGE-RING BASED FEL - SEEDED MODE

- Laser seeded storage ring FEL recently demonstrated at Elettra
- Explore HHG laser (~10 fs, 10 nm, 1 MW) to seed a small portion of PEP bunch:

amplifier mode at 10 nm

HGHG mode at 10/3=3.3 nm
J. Corlett, June 2007, Slide 71

4GLS
PROPOSAL FOR ERL-BASED FACILITY

J. Clarke, CCLRC Daresbury
Undulator sources and VUV-FEL
Progressive bunch compression, ~1 ps to 100 fs

100mA, 550 MeV, 2 mm mrad, 77 pC

1.3 GHz CW

VUV FEL
Repetition rate up to 1.3 GHz
Variable polarization
FEL output 3 — 10 eV
Up to 70 µJ per pulse
Minimum pulse duration < 170 fs
4GLS
PROPOSAL FOR ERL-BASED FACILITY - XUV FEL BRANCH

1 nC, 750 MeV, 2 mm mrad, 1.5 kA
1 kHz CW

HHG seeded
Repetition rate ~1 kHz
Variable polarization
FEL output up to 8 — 100 eV
Up to 400 µJ per pulse
Minimum pulse duration < 50 fs
Short pulses and combined sources are key to 4GLS

J. Clarke, CCLRC Daresbury
Three phases project

- ARC-EN-CIEL phase 1:
  Linear accelerator: 220 MeV (or 330 MeV), low energy spread, low emittance
  femtosecond HGHG sources: 100-10 nm, high brilliance and coherence

- ARC-EN-CIEL phase 2:
  Linear accelerator: 1 GeV
  HGHG sources: down to 1 nm

- ARC-EN-CIEL phase 3:
  Additional loops: 2 GeV or increased current
  HGHG sources
  UV FEL oscillator
  VUV and X undulator

Christelle Bruni & Marie-Emmanuelle, SOLEIL
High Gain Harmonic Generation

External seed: High Order Harmonic Generation (HOHG):
- **Experiment demonstration at SPA** (SCSS prototype accelerator):
  G. Lambert et al. (French/Japanesesse collaboration)
- **FEL seeded at 160 nm (H5 in gas) @150 MeV**: Coherent radiation observed at 160 (H1 und.), 52 (H3 und.) and 32 nm (H5 und.)
Recirculation ARC : optical function (A. Loulergue et al.)
BESSY FEL
PROPOSAL FOR LINAC-BASED FEL FACILITY

- VUV-soft x-ray facility using harmonic cascade FEL’s
- TESLA scrf technology developed for CW operations
Wisconsin FEL
CONCEPT FOR LINAC-BASED SEEDED FEL FACILITY

• All undulators operate simultaneously at repetition rate up to 1 MHz each.
• Total number of undulators set by budget.
• Facility lasers and RF components synchronized ~10 fs.

J. Bisognano, SRC
Fiber link synchronization

HHG laser seeds at 30 eV

2.2 GeV ebeam

**900 eV Layout**

<table>
<thead>
<tr>
<th>Mod 1</th>
<th>Rad 1</th>
<th>Rad 2</th>
<th>Rad 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 eV</td>
<td>60 eV</td>
<td>300 eV</td>
<td>900 eV</td>
</tr>
</tbody>
</table>

- Buncher magnets
- Spent ebeam is dumped
- 1.4 GW @ 900 eV

J. Bisognano, SRC
APPENDIX 2

TECHNOLOGIES FOR FUTURE FELS
1.2 mm-mrad demonstrated with 1 nC charge
LASER PULSE SHAPING CRITICAL IN PRODUCING HIGH QUALITY BEAMS

http://accelconf.web.cern.ch/AccelConf/e02/PAPERS/TUPRI075.pdf
Laser pulse shaping is critical
TEMPORAL AND SPATIAL SHAPING TO CONTROL PHOTOEMISSION

RF from master oscillator

Yb:KGW Oscillator
150 fs, 1 nJ
80 MHz

grating stretcher

Pulse Shaper

Yb:KGW Regenerative Amplifier

980 nm diode pump

grating compressor

1 mJ, 1048 nm, 7 kHz

photo-switch

Pockels Cell

polarizer

Transverse shaping

Transmissive optics

Deformable mirror

spectral filter (computer controlled)
- spatial light modulator
- acousto-optic modulator

Pulse Shaper (A.M. Weiner)

Dazzler - FastLite Inc.
acousto-optic dispersive filter
(P. Tournis et al.)

TeO2 crystal

Acoustic wave (computer programmable)
- spectral amplitude
- temporal phase

http://okotech.com
Photocathode laser systems design

HIGH POWER FIBER LASER

- 200 W fiber lasers available
  - 1064 nm
  - Stage 1 amplifier
    - 20 µJ at 1 MHz
- Harmonic conversion for some cathode materials
- Stage 1 is sufficient for cathodes with QE > 10^{-3}
  - nC bunches from metals requires ~2 mJ in IR
- Stage 2 amplifier
  - Large mode area amp
  - 200 µJ at 1 MHz
  - nC bunches at ~100 kHz achievable
DC gun and SCRF injector

MULTIVARIATE OPTIMIZATION PREDICTS EXCELLENT PERFORMANCE

Laser pulse

500-750 kV
DC gun, NEA cathode
buncher
solenoids

five 2-cell SRF cavities

http://prst-ab.aps.org/pdf/PRSTAB/v8/i3/e034202

http://prst-ab.aps.org/pdf/PRSTAB/v8/i3/e034202

< 1 mm-mrad
800 pC

Corlett, June 2007, Slide 86
Optical manipulations

NUMERIC EXAMPLE

\[ \Delta E(\varphi) = 2 \sqrt{A_L A_R \frac{\Delta \omega_L}{\Delta \omega_R}} \cos(\varphi) \]

\[ A_R \approx \pi \alpha \hbar \omega_R \]

\[ \omega_R = \omega_L \]

\[ \Delta \omega_R = \Delta \omega_L \]

\[ \hbar \omega_L = 45eV \]

\[ A_L = 5nJ \]

\[ |\Delta E| = 360keV \]

HHG seed, 30th harmonic of Ti:sapphire

Compare with \(~100 \text{ keV}\) incoherent energy spread in the beam
Optical klystron

30 nm, 5 nJ, 50 fs = 100 kW

30 nm, 30 MW

Section of e-beam: modulation

Section of e-beam: bunching

Skrinsky, Vinokurov, 1977
**FEL configurations**

(n) ATTOSECOND SASE PULSES

- Attosecond x-ray pulse using energy modulation with two lasers

Interferometric phase delay controller

STABILIZED TIMING SYSTEM

- Measure delay with frequency shifting interferometer
  - Developed for radiotelescope arrays (ALMA)
  - RF phase = optical phase
- Laser frequency stability = allowable error / total delay
  - Required stability is $10^{-9}$ for 10fs, 2km

```
1530nm
CW fiber laser
C₂H₂ freq. locker

110MHz beat
mixer

f₁ + 110MHz

Faraday rotator 50% mirror

output

+55MHz

freq. shifter

km fiber

piezo, mirror delays

ref. arm

temp. control, 0.01°C

R. Wilcox
```
Comparing two phase stabilized fibers

- Unequal arm Mach-Zehnder interferometer, 3km vs. ~4m
- 2km are LAN fiber, 1km is on spool
- Two arms independently controlled, relative phase measured
Results of two-arm experiment

- Drift from room and outside temperature
- Total correction is ~100ps per day

We can deliver stable relative phase over two fibers
LBNL will deliver timing & synchronization systems to LCLS

R. Wilcox
FEL seed laser
OPTICAL PARAMETRIC AMPLIFIER PROVIDES FEL SEED

- Wavelength tunable
  - 190-250 nm
- Pulse duration variable
  - 10-200 fs
- Pulse energy
  - 10-25 μJ
- Pulse repetition rate
  - 10+ kHz

- Endstation lasers seeded or synchronized to Ti:sapphire oscillator

Endstation synch.
Noise evolution in seeded FEL
SIMULATIONS FOR A 4-STAGE CASCADE 240 nm ⇒ 1 nm

• Input laser seed initialized with broadband
  (a) phase noise
  (b) amplitude noise

• Fields resolved in simulation on 240 nm/c temporal resolution or better
  – Noise reaches minimum at 48-nm stage (slippage averaging)
  – In later stages noise increases due to harmonic multiplication of low frequency components

\[ \left( \frac{P_{\text{signal}}}{P_{\text{noise}}}_\text{out} \right) \approx N^2 \left( \frac{P_{\text{signal}}}{P_{\text{noise}}}_\text{in} \right) \]
Final radiator controls polarization of photon beam

“APPLE” type undulator
Elliptical polarization

Planar undulator
Linear polarization

Electron beam
Laser wakefield accelerator

✓ Step 1: Electron gun: 100 MeV in < 2mm

~ 1% energy spread
~ 1 mm-mrad emittance


J. Corlett, June 2007, Slide 96
Laser wakefield accelerator

✓ Step 2: Accelerator: 1 GeV in < 5 cm

1 GeV achieved

*Potential to use the electron beam in an FEL*