• Proceedings will become available through JACoW:
  http://www.jacow.org

• Preliminary proceedings available on conference web-site:
  http://www.elettra.trieste.it/fel2004/proceedings.html
  (papers & slides of oral presentations)

• The abstract booklet, author and affiliation index is available at:
  http://www.elettra.trieste.it/fel2004/abook.html
# Types of free-electron lasers:

- Single-pass devices
- Storage-ring FELs
- High average-power devices

I will just discuss some examples, for an extensive view, please visit:

Types of free-electron lasers:

- Single-pass devices
- Storage-ring FELs
- High average-power devices
Types of free-electron lasers:

- Single-pass devices
- Storage-ring FELs
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Types of free-electron lasers:

- Single-pass devices
- Storage-ring FELs
- High average-power devices

JLAB recirculating FEL

FEL + ERL: Energy Recovery Linac Concept
Types of free-electron lasers:

- **Single-pass devices**: high power / short wavelengths
  - VUV
  - X-ray
- **Storage-ring FELs**: optical properties / spectrum
  - visible
  - VUV
- **High average-power devices**: IR
Single Pass FEL Activity

SC technology / NC technology
Storage Ring & High Average Power FELs

No longer operational
### Existing FELs

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### Proposed FELs

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The ELETTRA Storage Ring FEL

- **Storage ring operation**: 1.0 GeV
- **Tunability range**: 350 – 190 nm
- **Average power**: ≥ 1 W
- **Pulse length (FWHM)**: ~ 5 ps
- **Peak power**: ≥ 40 kW
- **Pulse energy**: ≥ 0.2 mJ
- **Photon flux**: ≥ 10^{18} photons/s
- **Polarization**: circular (linear may also be possible)
- **Repetition rate**: 4.6 MHz
- **Synchronization with synchrotron radiation**: 1:1

*4-bunch operation, **within the laser bandwidth

---

**Figure:**
- Optical cavity length: 32.4 m
- 4.5 m helical undulator

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Critical Issues:

- **Longitudinal stability of electron beam:**
  rountrip time of the optical cavity must match the bunch-spacing

---

M. Trovò
THPOS09
Storage-Ring FELs

Critical Issues:

- **Longitudinal stability:**
  rountrip time of the optical cavity must match the bunch-spacing
  (stability of RF frequency and longitudinal modes)

- **Transverse stability:**
  \[ \lambda = \frac{\lambda_u}{2\gamma^2} \left( 1 + \frac{K_{\text{rms}}^2}{(\theta\gamma)^2} \right) \]
  
  \[ g \propto \frac{1}{\theta^2} \]
  
  typically micron accuracy required
Critical Issues:

- **Longitudinal stability:**
  roundtrip time of the optical cavity must match the bunch-spacing

  S-ACO:

- **Transverse stability:**
  wavelength
  Gain

  **Transverse Cavity Stability!**

  heat-load

  TEM\(_{00}\)  TEM\(_{nn}\)

  more stability  more gain
Cavity Stability

- **Storage-ring FEL**
  Important issue:
  e.g., 1 W of average output power \( \Rightarrow \) 200 W of intra-cavity power

- **High average-power IR FEL**
  e.g., JLAB FEL: > 10 kW average output power, i.e., more than 100 kW average intra-cavity power.

ref: TUCOS02, TUBOS03
High average-power lasers: FEL challenge (JLAB)

- FELs need a high peak current.
  - a factor of 4 growth in the longitudinal emittance due to space charge.
  - longer electron bunches in the injector can reduce space charge effects but reduces the machine acceptance.
  - Halo loss initially limited the average current.

- Resonator FELs need a high average current
  - Bunch spacing must match the cavity length.

JLAB recirculating FEL

Injection

Accelerators

Beam break-up limits average current

FEL resonator

3 mA

8 mA

Deceleration

rene.bakker@psi.ch / 10-Dec-2004
High average-power lasers: FEL challenge (JLAB)

- Beam break-up
  - Cavity design: suppression of HOMs
  - Clever optics (damping of transverse motion)

- Nice presentation by T.I. Smith: WEBOS03
High average-power lasers: FEL challenge (JLAB)

- Challenges of recovering the beam
  - RF kicks reversed for recovered beam
  - No two pass BPMs
  - Chromatic effects lead to betatron mismatch, causing beam loss.
  - Need energy/phase correction to third order (octupoles are required)
  - Operating close to crest does not provide enough footroom.
Single Pass Devices

Start-Up from Noise (SASE)

- High-brightness electron source
- Accelerator
- Bunch compressor
- Undulator
- Electron beam
Single Pass Devices

High-brightness electron source

Accelerator

Bunch compressor

SEED

Undulator

Electron beam

Controlled Startup (SEED)
Single-Pass Devices

- **Startup from noise (auto-start): SASE**
  - Relatively easy
  - Flexible for wavelength tuning
  - High output power
  - Spiky

- **Seeded startup**
  - Improved spectral purity
  - Suppression of spiking
  - Control over the \(\mu\)-pulse duration
  - (Longitudinal jitter defined by seed)
Seeded FEL: HGHG (BNL)

0.23 nm FWHM

HGHG

SASE x10^5

Courtesy Li Hua Yu (BNL)
Single-Pass Devices

- **Startup from noise (auto-start): SASE**
  - Relatively easy
  - Flexible for wavelength tuning
  - High output power
  - Spiky

  LCLS, TTF, X-FEL, SPARC, ..... 

- **Seeded startup**
  - Improved spectral purity
  - Suppression of spiking
  - Control over the μ-pulse duration
  - (Longitudinal jitter defined by seed)

  BESSY, FERMI, TTF, LUX, MIT, ....... LCLS, X-FEL, ......
Single-Pass Devices

Storage-Ring is a Spinning-Top

Very Stable and Quiet

Linac is “A Archery”

Shooting is not stable, it is a game, sometimes noisy.

*Courtesy T. Shintake, RIKEN/SPring8, MOBIS01*
## Storage Ring vs. LINAC

<table>
<thead>
<tr>
<th></th>
<th>Storage Ring</th>
<th>LINAC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Machine condition</strong></td>
<td>Steady state</td>
<td>Transient / Pulsed</td>
</tr>
<tr>
<td><strong>Trajectory</strong></td>
<td>Closed orbit (eigen-vector)</td>
<td>Open trajectory (no eigen-vector)</td>
</tr>
<tr>
<td><strong>Damping</strong></td>
<td>Synchrotron damping</td>
<td>No damping</td>
</tr>
<tr>
<td><strong>Beam clearing</strong></td>
<td>Dynamic aperture of machine</td>
<td>No clearing dark currents may propagate</td>
</tr>
<tr>
<td><strong>Noise bandwidth</strong></td>
<td>~1 kHz (narrow tune resonance)</td>
<td>~GHz (no resonance)</td>
</tr>
<tr>
<td><strong>Energy and intensity stability</strong></td>
<td>10^{-5} – 10^{-6}</td>
<td>10^{-2} – 10^{-3}</td>
</tr>
</tbody>
</table>

*Courtesy T. Shintake, RIKEN/SPRING8, MOBIS01 - MODIFIED*
# Beam Energy Stability

<table>
<thead>
<tr>
<th>$\Delta E/E$ (r.m.s or sigma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(10^{-6})</td>
</tr>
<tr>
<td>(10^{-5})</td>
</tr>
<tr>
<td>(10^{-4})</td>
</tr>
<tr>
<td>(10^{-3})</td>
</tr>
<tr>
<td>(10^{-2})</td>
</tr>
</tbody>
</table>

### DESY TTF
- $0.064\%$ for 30 min
- 2x7-cell bunch-to-bunch in macro-pulse

### SPring-8, 1 GeV Linac
- $0.058\%$ for 10 min
- ECS-OFF

### SPring-8 Storage Ring
- Top-up Operation
- $6 \times 10^{-6}$ for 6 days

---

\[ \lambda = \frac{\lambda_u}{2\gamma^2} (1 + K_{rms}^2) \iff \frac{\Delta \lambda}{\lambda} = 2 \frac{\Delta \gamma}{\gamma} \]

\[ \left( \frac{\Delta \lambda}{\lambda} \right)_{FEL} \approx 10^{-4} \]
Sources of jitter

- AC line fluctuations
  power supply fluctuations: gun, RF, orbit, ....

- Switch-tune pulse-to-pulse jitter

- Switching noise fluctuations

- AD/DA digitizing noise

- Temperature fluctuations
  LINAC, electrical circuits ....

- Ground motion
  natural, human activity

Feed-back is mostly not possible
Feed-forward:
  - between micro-pulses
  - between macro-pulses
Electron-Beam Stability

• Transverse stability
  – Low energy (injector): transverse emittance dilution
    (depends on the RF-frequency: X-band more sensitive than L-band)
  – Beam break-up at high average current operation
  – High energy (undulator): gain reduction and wavelength jitter

• Longitudinal stability (bunch / RF phase)
  – Energy fluctuations
  – Current fluctuations   FEL gain fluctuations
  – Temporal jitter with synchronized sources
  
  locked to seed laser
  Talking about femto-second and atto-second sources
Transverse Orbit / Undulator

- **General guideline (not necessarily correct):**
  - Control orbit up to 10% of the beam diameter
    - $\varepsilon_n = 10^{-6}$ m rad, $E = 2.5$ GeV, $\beta = 10$ m $\Delta_{x,y} = 4.5$ $\mu$m (BESSY)
    - $\varepsilon_n = 10^{-6}$ m rad, $E = 20$ GeV, $\beta = 10$ m $\Delta_{x,y} = 1.6$ $\mu$m (XFEL)
    - $\varepsilon_n = 10^{-7}$ m rad, $E = 6.0$ GeV, $\beta = 7$ m $\Delta_{x,y} = 0.8$ $\mu$m (LEG)

- **Sextupole fields of undulator may cause tougher constraints, specifically for short-period, small-gap undulators.**

N.B. CSR in magnetic bunch-compressors may kick parts of the electron bunch off-axis in the horizontal plate.
Undulator for XFEL

Courtesy T. Shintake, RIKEN/SPRING-8, MOBIS01
SCSS undulator concept

BPM Alignment System for SCSS

Cavity BPM
HeNe Laser
Laser Iris
Laser & Electron Beam Profile Monitor CCD Camera
Undulator
XY-mover cam-shaft
Temperature Stable Girder
Alignment Station-1
Alignment Station-2

Insert upstream in:

High-rigidity Stone Table supports Undulator Gap Precisely

Undulator, on Stone Table, In situ Field Measurement, Full-Open Chamber

Granite Table or Concrete
Permanent Magnet Array
Gap control motor
Strongback sits inside vacuum

In situ Field Measurement

Note: Vertical Polarization

Courtesy T. Shintake, RIKEN/SPRING8, MOBIS01
Gain Length

\[ L_{\text{sat}} \approx 15 - 20 \, L_g \]

\[ L_g = z_2 - z_1, \quad P(z_2)/P(z_1) = e \]
Electron beam orbit must be controlled over a few gain-lengths.

Within this distance: gain reduction

\[ L_g' = L_g/(1 - x^2) \]

\[ x = \theta / \theta_c, \quad \theta_c = \sqrt{\lambda / L_g} \]

Y.-C. Chae et al (APS) MOBOS03

T. Tanaka, et al., FEL 2003

Over larger distances the overlap between optical field and the electron beam may disappear. In such a case, the micro-bunching will re-initiate the FEL process over a few undulator periods only.
High-Gain Ring FEL

Problems, e.g.,:

• Alignment tolerances for single undulators
• Isochronous bend: $\lambda < 50$ nm
• Stable saturation
• Beam break-up in linac

High-Gain Ring FEL
N.A. Vinokurov, A.N. Matveenko – THPOS45