Project participants

Outline

• Brief introduction to the FEL physics
• The NovoFEL accelerator design and operation
• NovoFEL as three FELs based source of radiation
• The third FEL first experiments
• Nearest and far future plans
FEL principle of operation

The incoming radiation interacts with the incoming beam, resulting in amplified radiation. The synchronization condition is necessary for the energy transfer.

\[ \lambda_0 \approx \frac{\lambda_w}{2\gamma^2} \left( 1 + \frac{K^2}{2} \right) \]

\[ \left\langle \frac{d\gamma}{dz} \right\rangle = \frac{e}{mc^3} \left\langle \mathcal{E}_x V_x \right\rangle \]
FEL principle of operation

FEL oscillator

Equivalent scheme

\[ G(\omega) \]
Energy recovery

- Electron efficiency of FEL is rather low (~1%), therefore energy recovery is necessary for a high power FEL.

- Energy recovery:
  - decreases radiation hazard and
  - makes possible operation at high average current.

- Due to energy recovery, the cost of the building for FEL can be reduced.
NovoFEL Accelerator Design

Energy Recovery Linac

1 – injector, 2 – linac, 3 – bending magnets, 4 – undulator, 5 – dump

Accelerator is the most important part of any FEL. ERL is the best choice for high power FEL.
NovoFEL Accelerator Design

Energy Recovery Linac

1 – injector, 2 – linac, 3 – bending magnets, 4 – undulator, 5 – dump

Accelerator is the most important part of any FEL. ERL is the best choice for high power FEL.
Advantages of the low frequency (180 MHz) RF system

- High threshold currents for instabilities
- Operation with long electron bunches (for narrow FEL linewidth)
- Large longitudinal acceptance (good for operation with large energy spread of used beam)
- Relaxed tolerances for orbit lengths and longitudinal dispersion.

Disadvantages:
low accelerating rate and high power consumption.
NovoFEL Accelerator Design

Gun

Injector
NovoFEL Accelerator Design

- Gun
- Injector
- Main linac
- Dump

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NovoFEL Accelerator Design

- Gun
- Injector
- Main linac
- The first THz FEL undulator sections
- Dump

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NovoFEL Accelerator Design

- Gun
- Injector
- Main linac
- The first THz FEL undulator sections
- Dump
- The second FEL undulator

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NovoFEL Accelerator Design

The first THz FEL undulator sections
The second FEL undulator
The third IR FEL undulator sections

Gun
Injector
Main linac
Dump

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Layout of Injector, Main Linac and Vertical Beamline (the First ERL)

1 – electron gun
2 – bunching cavity
3 – focusing solenoids
4 – merger
5 – main linac
6 – focusing quadrupoles
7 – magnetic mirror
8 – undulator
9 – phase shifter
10 – optical cavity
11 – calorimeter
12 – beam dump
**Electrostatic Gun**

**Power supply:**

\[ U_{\text{max}} = 300 \text{ kV} \]
\[ I_{\text{max}} = 50 \text{ mA} \]
Injector
RF Power Supply

<table>
<thead>
<tr>
<th>Frequency, MHz</th>
<th>180.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power, MW</td>
<td>2 x 0.6</td>
</tr>
</tbody>
</table>
# Electromagnetic Undulators

<table>
<thead>
<tr>
<th></th>
<th>1-st FEL</th>
<th>2-d FEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period, cm</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Maximum current, kA</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Maximum K</td>
<td>1.25</td>
<td>1.47</td>
</tr>
</tbody>
</table>
22 May 2012 – the first time the beam reached the dump after four accelerations and four decelerations

90% of beam current comes to the dump, the working repetition rate 3.75 MHz and average current 3.2 mA are obtained

Only about 3% of beam current is lost with energy > 12 MeV

Less than 1% of beam current is lost at the last track
Magnets and Vacuum Chamber of Bends

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The most attractive ranges for FELs are at very short and at very long wavelength, where there are no other lasers.
Six user stations are available for users
(more than 20 participating institutions)

Station for Spectroscopy and Introscopy
Biology station
Molecular spectroscopy
Metrology station
Chemistry station

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Optical beamlines and user stations
The 1\textsuperscript{st} stage FEL radiation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation wavelength, microns</td>
<td>90 - 240</td>
</tr>
<tr>
<td>Minimum pulse duration, ps</td>
<td>70</td>
</tr>
<tr>
<td>Repetition rate, MHz</td>
<td>5.6 / 11.2 / 22.4</td>
</tr>
<tr>
<td>Maximum average power, kW</td>
<td>0.5</td>
</tr>
<tr>
<td>Minimum relative linewidth (FWHM)</td>
<td>3 \cdot 10^{-3}</td>
</tr>
<tr>
<td>Maximum peak power, MW</td>
<td>1</td>
</tr>
</tbody>
</table>

The obtained radiation parameters are still the world record in terahertz region.
The third stage FEL undulator

\[ \lambda_w \quad 6 \text{ cm} \]
\[ K \quad 0.4 - 2.5 \]
First experiments with 3\textsuperscript{rd} stage FEL

Wavelength 8.96 µm

Radiation power was about 30 watts

Beam trajectory can be adjusted only before this point
Influence of IR-light to the spin state of photoswitchable copper(II)-nitroxide magnetoactive compound Cu(hfac)$_2$L$^{Pr}$

IR spectra of Cu(hfac)$_2$L$^{Pr}$

EPR spectra of Cu(hfac)$_2$L$^{Pr}$
### Electron beam and radiation parameters

<table>
<thead>
<tr>
<th></th>
<th>1&lt;sup&gt;st&lt;/sup&gt;</th>
<th>2&lt;sup&gt;nd&lt;/sup&gt;</th>
<th>3&lt;sup&gt;rd&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy, MeV</strong></td>
<td>12</td>
<td>22</td>
<td>42</td>
</tr>
<tr>
<td><strong>Current, mA</strong></td>
<td>30</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td><strong>Wavelength, µm</strong></td>
<td>90-240</td>
<td>37-80</td>
<td>8-11</td>
</tr>
<tr>
<td><strong>Radiation power, kW</strong></td>
<td>0.5</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Electron efficiency, %</strong></td>
<td>0.6</td>
<td>0.3</td>
<td>0.2</td>
</tr>
</tbody>
</table>

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Nearest and far future plans

- Optical (SR) diagnostics of electron beam parameters
- Launch the electron gun attenuator for high peak and low average power radiation experiments
- Increase DC gun voltage and improve beam quality in injector
- Optimize electron efficiency of FEL
- Install the new undulator to extend the wavelength range
- Install RF gun
- Launch the electron outcoupling scheme
One of the main FEL advantages is the ability to adjust the wavelength. The wavelength \( \lambda \) can be calculated as:

\[
\lambda = \frac{\lambda_u}{2 \gamma^2} \left(1 + \frac{K^2}{2}\right)
\]

where \( \lambda_u \) is the undulator period, \( K \) is a parameter related to the strength of the magnetic field, and \( \gamma \) is the relativistic factor. 

- **Electromagnetic undulator**:
  - \( \lambda_u = 12 \text{ cm} \)
  - \( K \sim 0 \ldots 1.5 \)
  - \( E_1 \sim 10 \ldots 13 \text{ MeV} \)
  - \( E_2 \sim 20 \ldots 24 \text{ MeV} \)
  - \( E_3 \sim 40 \ldots 46 \text{ MeV} \)

- **Variable gap undulator**:
  - \( \lambda_u = 6 \text{ cm} \)
  - \( K \sim 0.4 \ldots 2.5 \)

- **Variable period undulator**:
  - \( \lambda_u \sim 4.8 \ldots 9.6 \text{ cm} \)
  - \( K \sim 0.42 \ldots 1.79 \)

- **Variation of magnetic field**
  - \( \lambda_u = 12 \text{ cm} \)
  - \( \lambda_u = 6 \text{ cm} \)

- **Variation of beam energy**
  - \( E_1 \sim 10 \ldots 13 \text{ MeV} \)
  - \( E_2 \sim 20 \ldots 24 \text{ MeV} \)
  - \( E_3 \sim 40 \ldots 46 \text{ MeV} \)

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Variable Period Undulator (for the 2nd FEL)

The tunability range of the 2nd FEL will be increased from 37 - 80 to 15 - 80 microns
Variable Period Undulator (for the 2nd FEL)

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Bunch frequency attenuator

Some experiments don’t need to have the high average power radiation regimes

As the lasing depends on the electron gun frequency it’s possible to change it by small step and form the train of radiation bunches with required length and duty ratio.

- Users don’t need to install additional attenuation equipment
- Low electron beam losses and heat the vacuum chambers
- Regimes with high electron bunch charge and peak radiation power
The Third FEL Design and Commissioning

~ 40 m

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RF Gun Test Setup

Vladimir N. Volkov

Latest results on the 100-mA CW RF electron gun for Novosibirsk ERL FEL

January 30, 9:50 – 10:15

<table>
<thead>
<tr>
<th>Measured beam parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy, KeV</td>
</tr>
<tr>
<td>Pulse duration (FWHM), ns</td>
</tr>
<tr>
<td>Bunch charge, nQ</td>
</tr>
<tr>
<td>Repetition rate, MHz</td>
</tr>
<tr>
<td>Average current, mA</td>
</tr>
</tbody>
</table>
Overview of the NovoFEL facility

- The first stage of Novosibirsk high power free electron laser (NovoFEL) based on one track energy recovery linac (ERL) working in spectral range (90 – 240) μm was commissioned in 2003.

- The second stage of NovoFEL based on two track energy recovery linac, working in spectral range (37 – 80) μm, was commissioned in 2009.

- The third stage of NovoFEL based on four track ERL was commissioned on July of 2015. Spectral range now is (8-11) μm. First operation for users was done in 2016.
Thank you for your attention!