• 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:

- the FEL2004 web-site: http://www.elettra.trieste.it/fel2004
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: IR devices
### Storage Ring & High Average Power FELs

#### Existing FELs

<table>
<thead>
<tr>
<th>Existing FELs</th>
<th>λ (µm)</th>
<th>FWHM (ps)</th>
<th>Current (A)</th>
<th>N (l0)</th>
<th>λ0 (cm)</th>
<th>K (rms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSI FEL (FELIX)</td>
<td>0.38</td>
<td>10</td>
<td>2</td>
<td>0.3</td>
<td>10-20</td>
<td>3.5</td>
</tr>
<tr>
<td>Osaka (iFEL1)</td>
<td>0.55</td>
<td>15</td>
<td>5</td>
<td>0.5</td>
<td>10-20</td>
<td>3.4</td>
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<tr>
<td>Osaka (iFEL2)</td>
<td>0.88</td>
<td>10</td>
<td>68</td>
<td>42</td>
<td>78</td>
<td>3.8</td>
</tr>
<tr>
<td>Tokyo (KHI-FEL)</td>
<td>4-16</td>
<td>2</td>
<td>32-40</td>
<td>30</td>
<td>43</td>
<td>3.2</td>
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<tr>
<td>Nieuwegein (FELIX)</td>
<td>3-250</td>
<td>1</td>
<td>50</td>
<td>50</td>
<td>38</td>
<td>6.5</td>
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<tr>
<td>Duke (MARKIII)</td>
<td>2.7-6.5</td>
<td>3</td>
<td>31-41.5</td>
<td>20</td>
<td>47</td>
<td>2.3</td>
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<tr>
<td>Stanford (SCAFEL)</td>
<td>3-13</td>
<td>0.5-12</td>
<td>22-45</td>
<td>10</td>
<td>72</td>
<td>3.1</td>
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<tr>
<td>Orsay (CLIO)</td>
<td>3-53</td>
<td>0.1-3</td>
<td>21-50</td>
<td>80</td>
<td>38</td>
<td>5</td>
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<tr>
<td>Osaka (iFEL3)</td>
<td>0.3-0.7</td>
<td>5</td>
<td>155</td>
<td>60</td>
<td>67</td>
<td>4</td>
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<tr>
<td>Okazaki (UVSOR)</td>
<td>0.2-0.6</td>
<td>6</td>
<td>607</td>
<td>10</td>
<td>2×9</td>
<td>11</td>
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<td>Tsukuba (NIJI-IV)</td>
<td>0.2-0.6</td>
<td>14</td>
<td>310</td>
<td>10</td>
<td>2×42</td>
<td>7.2</td>
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<tr>
<td>Italy (ELETTRA)</td>
<td>0.2-0.4</td>
<td>28</td>
<td>1000</td>
<td>150</td>
<td>2×19</td>
<td>10</td>
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<tr>
<td>Duke (OK-4)</td>
<td>0.193-2.1</td>
<td>0.1-10</td>
<td>1200</td>
<td>35</td>
<td>2×33</td>
<td>10</td>
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<td>ANL (APSFEL)</td>
<td>0.13</td>
<td>0.3</td>
<td>399</td>
<td>400</td>
<td>648</td>
<td>3.3</td>
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<tr>
<td>DESY (TTF1)</td>
<td>0.08-12</td>
<td>0.04</td>
<td>250</td>
<td>3000</td>
<td>492</td>
<td>2.73</td>
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<td>Orsay (Super-ACO)</td>
<td>0.3-0.6</td>
<td>15</td>
<td>800</td>
<td>0.1</td>
<td>2×10</td>
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<td>Osaka (iFEL3)</td>
<td>0.3-0.7</td>
<td>5</td>
<td>155</td>
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<td>Tokyo (FIR-FEL)</td>
<td>300-1000</td>
<td>5</td>
<td>10</td>
<td>30</td>
<td>25</td>
<td>7</td>
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<td>Netherlands (TEUFEL)</td>
<td>180</td>
<td>20</td>
<td>6</td>
<td>350</td>
<td>50</td>
<td>2.5</td>
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<tr>
<td>Rutgers (IRFEL)</td>
<td>140</td>
<td>25</td>
<td>38</td>
<td>1.4</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>Novosibirsk (RTM1)</td>
<td>3-20</td>
<td>10</td>
<td>50</td>
<td>20-100</td>
<td>3×33</td>
<td>6</td>
</tr>
<tr>
<td>Dresden (ELBE)</td>
<td>30-750</td>
<td>1-5</td>
<td>10-40</td>
<td>30</td>
<td>45</td>
<td>5</td>
</tr>
<tr>
<td>Daresbury (4GLS-IRFEL)</td>
<td>5-100</td>
<td>0.2-1</td>
<td>50</td>
<td>100</td>
<td>100</td>
<td>4</td>
</tr>
<tr>
<td>Novosibirsk (RTM)</td>
<td>2-11</td>
<td>20</td>
<td>98</td>
<td>100</td>
<td>4×36</td>
<td>9</td>
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<tr>
<td>Frascati (SPARC)</td>
<td>0.533</td>
<td>0.1</td>
<td>142</td>
<td>500</td>
<td>6×71</td>
<td>3</td>
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<tr>
<td>TJNAF (UVFEL)</td>
<td>0.25-1</td>
<td>0.2</td>
<td>160</td>
<td>270</td>
<td>60</td>
<td>3.3</td>
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<tr>
<td>Hawaii (FEL)</td>
<td>0.3-3</td>
<td>2</td>
<td>100</td>
<td>500</td>
<td>84</td>
<td>2.4</td>
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<tr>
<td>Harima (SUBARU)</td>
<td>0.2-10</td>
<td>26</td>
<td>1500</td>
<td>50</td>
<td>33,65</td>
<td>16,32</td>
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<tr>
<td>Shanghai (SDUV-FEL)</td>
<td>0.5-0.088</td>
<td>1</td>
<td>300</td>
<td>400</td>
<td>400</td>
<td>2.5</td>
</tr>
<tr>
<td>Frascati (COSA)</td>
<td>0.08</td>
<td>10</td>
<td>215</td>
<td>200</td>
<td>400</td>
<td>1.4</td>
</tr>
<tr>
<td>Daresbury (4GLS-VUV)</td>
<td>0.4-0.1</td>
<td>0.1-1</td>
<td>600</td>
<td>300</td>
<td>150</td>
<td>5</td>
</tr>
<tr>
<td>Daresbury (4GLS-XUV)</td>
<td>0.1-0.01</td>
<td>0.1-1</td>
<td>600</td>
<td>2000</td>
<td>1000</td>
<td>2</td>
</tr>
<tr>
<td>Duke (OK-5,VUV)</td>
<td>0.03-1</td>
<td>0.1-10</td>
<td>1200</td>
<td>50</td>
<td>4×32</td>
<td>12</td>
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<tr>
<td>DESY (TTF2)</td>
<td>0.006</td>
<td>0.17</td>
<td>1000</td>
<td>2500</td>
<td>981</td>
<td>2.73</td>
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<tr>
<td>Italy (SPARX)</td>
<td>0.0015</td>
<td>0.1</td>
<td>2500</td>
<td>2500</td>
<td>1000</td>
<td>3</td>
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<tr>
<td>BESSY (Soft X-ray)</td>
<td>0.0012</td>
<td>0.08</td>
<td>2300</td>
<td>3500</td>
<td>1450</td>
<td>2.75</td>
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<tr>
<td>Trieste (FERMI)</td>
<td>0.001-0.1</td>
<td>0.1</td>
<td>3000</td>
<td>2500</td>
<td>570-1140</td>
<td>3.5</td>
</tr>
<tr>
<td>RIKEN (SPring8 SCSS)</td>
<td>0.00036</td>
<td>0.5</td>
<td>1000</td>
<td>2000</td>
<td>1500</td>
<td>1.5</td>
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<tr>
<td>MIT (Bates X-Ray FEL)</td>
<td>0.0003</td>
<td>0.05</td>
<td>4000</td>
<td>1000</td>
<td>1500</td>
<td>1.8</td>
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<tr>
<td>SLAC (LCLS)</td>
<td>0.00015</td>
<td>0.07</td>
<td>14350</td>
<td>3400</td>
<td>3328</td>
<td>3</td>
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<tr>
<td>DESY (TESLA)</td>
<td>0.0001</td>
<td>0.08</td>
<td>30000</td>
<td>5000</td>
<td>4500</td>
<td>6</td>
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<tr>
<td>Pohang (PAL X-FEL)</td>
<td>0.0003</td>
<td>0.1</td>
<td>3000</td>
<td>4000</td>
<td>6000</td>
<td>1.5</td>
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</tbody>
</table>

### Proposed FELs

<table>
<thead>
<tr>
<th>Proposed FELs</th>
<th>λ (µm)</th>
<th>FWHM (ps)</th>
<th>Current (A)</th>
<th>N (l0)</th>
<th>λ0 (cm)</th>
<th>K (rms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minneapolis (FEL)</td>
<td>100</td>
<td>4</td>
<td>75</td>
<td>50</td>
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<td></td>
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<tr>
<td>Toronto (BASE)</td>
<td>300</td>
<td>50</td>
<td>100</td>
<td>50</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>MIT (BFEL)</td>
<td>120</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>50</td>
<td>2.5</td>
</tr>
<tr>
<td>Rochester (FEL)</td>
<td>300</td>
<td>50</td>
<td>100</td>
<td>50</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Desy (TTF)</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>50</td>
<td>2.5</td>
</tr>
<tr>
<td>LBL (SIIFEL)</td>
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<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>50</td>
<td>2.5</td>
</tr>
<tr>
<td>Stanford (SCAFEL)</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>50</td>
<td>2.5</td>
</tr>
<tr>
<td>Orsay (CLIO)</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>50</td>
<td>2.5</td>
</tr>
<tr>
<td>Osaka (iFEL3)</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>50</td>
<td>2.5</td>
</tr>
</tbody>
</table>

### Table 2: Proposed Free Electron Lasers (2004)

- **EXISTING FELs**
  - λ (µm)
  - FWHM (ps)
  - Current (A)
  - N (l0)
  - λ0 (cm)
  - K (rms)

- **PROPOSED FELs**
  - λ (µm)
  - FWHM (ps)
  - Current (A)
  - N (l0)
  - λ0 (cm)
  - K (rms)
### Critical Issues:

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

---

**Storage-Ring FELs**

The ELETTRA Storage Ring FEL

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

**Specifications**

- **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.**
Critical Issues:

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

• **Transverse stability:**
  wavelength
  \[ \lambda = \frac{\lambda_{\text{vac}}}{2\gamma^2} \left(1 + K_{\text{rms}}^2 + (\theta \gamma)^2\right) \]
  Gain
  \[ g \propto \frac{1}{\theta^2} \]

  typically micron accuracy required

---

Critical Issues:

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

• **Transverse stability:**
  wavelength

  S-ACO:
  \[ \operatorname{TEM}_{00} \quad \operatorname{TEM}_{nn} \]

  more stability
  more gain

  Transverse Cavity Stability!

  heat-load
Cavity Stability

- **Storage-ring FEL**
  - Important issue:
    - e.g., 1 W of average output power 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.

---

Diagram showing the JLAB recirculating FEL system with deceleration and acceleration stages, beam break-up limits average current, and current values 3 mA and 8 mA.
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

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)

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 μ-pulse duration
  - (Longitudinal jitter defined by seed)

Seeded FEL: HGHG (BNL)

![Graph showing HGHG and SASE spectra with 0.23 nm FWHM]( 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, .......

---

Storage-Ring is A Spinning-Top

Linac is “A Archery”

Very Stable and Quiet

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

\[
\frac{\Delta E}{E} = \text{r.m.s or sigma}
\]

- **DESY TTF**
  - 0.054% for 30 min
  - 2x7-cell bunch-to-bunch in macro-pulse
- **SPRING-8, 1 GeV Linac**
  - 0.058% for 10 min
  - ECS-OFF
  - ECS-ON
- **SPRING-8 Storage Ring Top-up Operation**
  - 0.009%
  - ECS-ON
- **Modulator Voltage Jitter**
  - 0.035%
  - SCSS Modulator

\[
\lambda = \frac{\lambda_m}{2\gamma} \left(1 + \frac{\kappa}{\kappa_{\text{rms}}}^2 \right) \Leftrightarrow \frac{\Delta \lambda}{\lambda} = \frac{2 \Delta \gamma}{\gamma}
\]

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

*Courtesy T. Shintake, RIKEN/SPRING8, MOBIS01*
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
    typically a (few) micron orbit accuracy

- 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
• General guideline (not necessarily correct):
  – Control orbit up to 10 % of the beam diameter

<table>
<thead>
<tr>
<th>ε_n</th>
<th>E</th>
<th>β</th>
<th>Δ_{x,y}</th>
<th>Machine</th>
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</thead>
<tbody>
<tr>
<td>10^{-6} m rad</td>
<td>2.5 GeV</td>
<td>10 m</td>
<td>4.5 μm</td>
<td>BESSY</td>
</tr>
<tr>
<td>10^{-6} m rad</td>
<td>20 GeV</td>
<td>10 m</td>
<td>1.6 μm</td>
<td>XFEL</td>
</tr>
<tr>
<td>10^{-7} m rad</td>
<td>6.0 GeV</td>
<td>7 m</td>
<td>0.8 μm</td>
<td>LEG</td>
</tr>
</tbody>
</table>

• 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.
**SCSS undulator concept**

Courtesy T. Shintake, RIKEN/SPring8, MOBIS01

---

**Gain Length**

- Electron beam
- Undulator
- Photons beam
- Spontaneous emission
- Modulation / bunching
- Coherent emission
- Saturation

\[ \log(\text{radiated power}) \]

\[ L_g = z_2 - z_1, \quad \frac{P(z_2)}{P(z_1)} = e \]

\[ L_{\text{sat}} \approx 15 \text{ - } 20 L_g \]
Electron beam orbit must be controlled over a few gain-lengths.

Within this distance: gain reduction

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

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

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