The FERMI@Elettra beamlines: From diagnostics to microfocusing

M. Zangrando

On behalf of the FERMI@Elettra Photon Beam Transport System:
A. Abrami, D. Bacescu, D. Cocco (project leader), I. Cudin, C. Fava,
D. Giuressi, R. Godnig, D. Lonza, F. Parmigiani, L. Rumiz, R. Sergo, C. Svetina

Trieste, October 9th 2008
### FERMI@Elettra parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FEL 1</th>
<th>FEL 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (nm)</td>
<td>100 - 20</td>
<td>40 - 10</td>
</tr>
<tr>
<td>Pulse length FWHM (fs)</td>
<td>50 - 100</td>
<td>100 - 200</td>
</tr>
<tr>
<td>Bandwidth rms (meV)</td>
<td>~20</td>
<td>~5</td>
</tr>
<tr>
<td>Polarization</td>
<td>Variable</td>
<td>Variable</td>
</tr>
<tr>
<td>Peak power (GW)</td>
<td>1 - 5</td>
<td>~0.4</td>
</tr>
<tr>
<td>Photons per pulse</td>
<td>~2 \times 10^{14} (100 nm)</td>
<td>~1 \times 10^{13} (10 nm)</td>
</tr>
<tr>
<td>Brightness (Ph/s/mm²/mrad²/0.1%BW)</td>
<td>~6 \times 10^{32}</td>
<td>~10^{32}</td>
</tr>
<tr>
<td>Power fluctuation (%)</td>
<td>~2.5</td>
<td>&gt; 50</td>
</tr>
<tr>
<td>Central wavelength fluctuation</td>
<td>Within BW</td>
<td>Within BW</td>
</tr>
<tr>
<td>Pointing fluctuation (µrad)</td>
<td>&lt; 5</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Source size FWHM (µm)</td>
<td>290</td>
<td>140</td>
</tr>
<tr>
<td>Divergence rms (µrad)</td>
<td>50</td>
<td>1.5</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>10 - 50</td>
<td>10 - 50</td>
</tr>
</tbody>
</table>
Photon beam transport system

- FEL 1
- FEL 2
- Slits
- Valves
- Gas cell
- 1st mirror(s)
- Spectrometer
- Switching mirror(s)
- 2.5°
- 2.5°
- 5°
- 2.5°
- 10 m
- LDM
- Diprol
- EIS
- I0 monitors
- 10 m
Damage threshold

FEL 1:
100 fs; 5 GW ⇒ ~ 0.5 mJ

FEL 2:
200 fs; 1 GW ⇒ ~ 0.2 mJ

A. Andrejczuk et al. DESY annual report 2001
Damage threshold

**FEL 1:**
100 fs; 5 GW ⇒ ~ 0.5 mJ

**FEL 2:**
200 fs; 1 GW ⇒ ~ 0.2 mJ

Safety margin = 100 (no reflectivity considered)

<table>
<thead>
<tr>
<th>Material</th>
<th>Damage threshold @ 90 nm</th>
<th>Safety angle 100 nm (10/20/40 m)</th>
<th>Estimated damage threshold @ 40 nm</th>
<th>Safety angle 40 nm (10/20/40 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu/Glidcop bulk</td>
<td>~ 500 mJ/cm²</td>
<td>24° / 90°/ 90°</td>
<td>~ 1000 mJ/cm²</td>
<td>41° / 90°/ 90°</td>
</tr>
<tr>
<td>Au coating</td>
<td>40 mJ/cm²</td>
<td>1.9° / 7.6°/ 32°</td>
<td>50 mJ/cm²</td>
<td>4.8° / 20°/ 77°</td>
</tr>
<tr>
<td>Silicon bulk</td>
<td>30 mJ/cm²</td>
<td>1.5° / 6°/ 23°</td>
<td>40 mJ/cm²</td>
<td>2° / 20°/ 40°</td>
</tr>
<tr>
<td>Graphite coating</td>
<td>60 mJ/cm²</td>
<td>2.9° / 11.5°/ 53°</td>
<td>240 mJ/cm²</td>
<td>9° / 40°/ 90°</td>
</tr>
<tr>
<td>YAG bulk</td>
<td>70 mJ/cm²</td>
<td>3.3° / 13.4°/ 68°</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

mJ pulse in the sub ps regime
⇒ 10 or more mJ/cm² @ 10 m
Damage threshold

Valves
FEL 1
FEL 2
Slits
Gas cell
10 monitors
10 m

1st mirror(s)
2.5°
5°

Carbon (2°—3°...)
Mirrors coating

Valves
FEL 1
FEL 2
Slits
Gas cell
10 monitors

1st mirror(s)
2.5°
5°
10 m

Reflectivity

Carbon (2°—3°...)
Gold (2°—3°...)
Nickel (2°—3°...)

Photon energy (eV)

Carbon
Gold
Nickel

10 nm
5 nm
3 nm

30 50 100 200 300 400 500 600 700 800 900 1000
0.0 0.2 0.4 0.6 0.8 1.0
Photon diagnostics

There will be the possibility to measure the following characteristics:

- **Intensity**: **On line**; **Shot by shot**; 1% repeatability, 2-3% precision (calibration dependent)
- **Angular position**: **On line**; **Shot by shot**; $\sim 2 \mu$rad sensibility
- **Divergence**: **NOT On line**; **NOT Shot by shot**; based on YAG crystal measurements
- **Photon energy distribution**: **On line**; **Shot by shot**; Single spectrometer, 12-360 eV sub mV resolution.
- **Arrival time**: **On line**; **Shot by shot**; Visible streak camera (Timing and Synchronization Area) ps resolution
- **Wavefront**: Hartmann sensor (Imagine Optic), Precision $\lambda/50$ at 20-5 nm range or CCD
- **Pulse length measurement**: **NOT On line**; **NOT Shot by shot**;
BPMs and I0 monitors

On line I0 monitor

Collect nA/pA signals using an already internally-developed fA precision acquisition board (ref. D. Giuresi)

Beam Position Monitor

In collaboration with the Instrumentation Group and T-REX lab for prototyping the systems

Applied Voltage (Bias)
+ or - depending on tests/noise

Calibrated with High precision IRD photodiodes (4% absolute calibration, <0.1% repeatability)

P ≈ 10^{-5} mbar

Photon beam

Micrometer precision movement Gap f(hv)

Photon beam
Gas reduction cell

- Maximum attenuation on the whole photon energy range = $10^{-4}$
- Use of different gases at different pressures
- Preservation of coherence, statistics, spectrum, etc.

Gas Absorber Cell:
length = 6 m
There will be the possibility to measure the following characteristics:

- **Intensity**: On line; Shot by shot; 1% repeatability, 2-3% precision (calibration dependent)
- **Angular position**: On line; Shot by shot; ~2 µrad sensibility
- **Divergence**: NOT On line; NOT Shot by shot; based on YAG crystal measurements
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- **Pulse length measurement**: NOT On line; NOT Shot by shot;
Energy spectrometer

Variable Line Spacing grating

G1 \( N_0 = 500 \text{ l/mm}, N_1 = 0.35 \text{ l/mm}^2, \)
Graphite coated
12-90 eV in 1st and 2nd order
\( \Delta E: 0.2 \text{ meV to 3 meV} \)

G2 \( N_0 = 1800 \text{ l/mm}, N_1 = 1.26 \text{ l/mm}^2, \)
Ni coated
30-360 eV in 1st and 2nd order
\( \Delta E: 0.3 \text{ meV to 3-4 meV} \)
Energy spectrometer

~97% to the beamlines
~0.1% to the detector

Preliminary design (L.Cudin)

YAG Crystal to convert XUV into Visible

Nd:YAG measurement @ SuperESCA

Conversion efficiency (Photon out/photon in)

Photon energy (eV)

M.Zangrando - ACTOP08 - October 9th 2008
## Energy spectrometer

<table>
<thead>
<tr>
<th>Photon energy (eV)</th>
<th>Photon per pulse</th>
<th>Bandwidth (meV)</th>
<th>Grating efficiency</th>
<th>Screen efficiency (Vis ph out/XUV ph in)</th>
<th>CCD efficiency</th>
<th>Spot dimension (μm)</th>
<th>Energy resolution (meV)</th>
<th>Expected photon per pixel (10x10 μm²) with demagnification 2:1</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>(~ 2 \times 10^{14})</td>
<td>20</td>
<td>0.1%</td>
<td>0.25</td>
<td>\sim 85%</td>
<td>4.5 μm X13mm</td>
<td>0.3</td>
<td>\sim 250,000</td>
</tr>
<tr>
<td>31</td>
<td>(~ 4 \times 10^{13})</td>
<td>20</td>
<td>0.25%</td>
<td>0.4</td>
<td>\sim 85%</td>
<td>5.9 μm X5.2mm</td>
<td>1.0</td>
<td>\sim 1,200,000</td>
</tr>
<tr>
<td>124</td>
<td>(~ 1 \times 10^{13})</td>
<td>10</td>
<td>0.2%</td>
<td>1</td>
<td>\sim 85%</td>
<td>4.8 μm X1.6mm</td>
<td>2.4</td>
<td>\sim 125,000</td>
</tr>
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</table>

### Use of a set of visible filters

Nd:YAG measurement @ SuperESCA

Conversions efficiency (Photon out/photon in) vs. Photon energy (eV)
There will be the possibility to measure the following characteristics:

- **Intensity**: On line; Shot by shot; 1% repeatability, 2-3% precision (calibration dependent)
- **Angular position**: On line; Shot by shot; ~2 µrad sensibility
- **Divergence**: NOT On line; NOT Shot by shot; based on YAG crystal measurements
- **Photon energy distribution**: On line; Shot by shot; Single spectrometer, 12-360 eV sub mV resolution.
- **Arrival time**: On line; Shot by shot; Visible streak camera (Timing and Synchronization Area) ps resolution
- **Wavefront**: Hartmann sensor (Imagine Optic), Precision λ/50 at 20-5 nm range or CCD
- **Pulse length measurement**: NOT On line; NOT Shot by shot;
Pulse length measurement

VUV pulse lengths can be measured by:

- Cross-correlation, …, with a short-pulse laser.
  Can be applied to many systems (Above Threshold Ionization of noble gases, pump-probe of molecules, etc.) BUT time resolution is determined by jitter

- Streak camera type techniques: collaboration ST-Hamamatsu for a sub-ps EUV-SXR streak camera (Ref. F. Parmigiani, M. Zangrando)

- Autocorrelation (beam splitting). Precision depends entirely on mechanical design of optics. Requires non-linear phenomena.

Courtesy by K. Prince
Pulse length measurement

Autocorrelation by using Helium!

- first ionization potential is high, 24.6 eV, second is 79.004 eV,
- calculations exist, laser harmonic results exist,
- “canonical” three body system.

For FEL1, we can choose energies below 24.6 for “non-resonant to continuum” or “resonant to continuum” two photon ionization.

For FEL2, we can choose two-photon, double ionization (above 79 eV).

Feasibility
Cross-section is $10^{-50}$-$10^{-53}$ cm$^4$ s.
We estimate count rates of 1 to 100 counts/sec, for a 20x20 micron spot.

Courtesy by K. Prince
Pulse length measurement

\[ \theta_{l\text{min}} = 3.8^\circ \]
\[ \theta_{l\text{max}} = 8^\circ \]
\[ \theta_2 = 4^\circ \]
\[ m_0 = 1200 \text{ mm} \]
\[ m_1 = 630 \text{ mm (Dh=42mm)} \]
\[ m_2 = 2150 \text{ mm} \]

DELAY:
w/o multilayer \(-0.9 \Rightarrow 17 \text{ ps (3 movements)}\)
with multilayer \(-7 \text{ ps} \Rightarrow \text{ ns}\)
Refocusing section

“Focus” on:
- Very high fluence
- Wavefront/coherence preservation
- Decoupled focusing (H vs. V)
- Variable source position

Kirpatrick-Baez system with two “variable shape” plane-elliptical mirrors

Source—M1 ~ 75 m; M2—Exp. chamber ~ 0.8 m

Spot FEL 1: on focus 4x2.5 µm² (~ 3x10¹⁶ W/cm²)
Spot FEL 2: on focus 3.5x2 µm² (~ 7x10¹⁵ W/cm²)
**Wavefront preservation**

**Fermi@elettra case**

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Angle of incidence</th>
<th>shape error p -(\varphi) =0.25</th>
<th>shape error p -(\varphi) =0.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 nm</td>
<td>6°</td>
<td>47</td>
<td>18</td>
</tr>
<tr>
<td>40 nm</td>
<td>3°</td>
<td>95</td>
<td>38</td>
</tr>
<tr>
<td>40 nm</td>
<td>1.5°</td>
<td>191</td>
<td>76</td>
</tr>
<tr>
<td>10 nm</td>
<td>3°</td>
<td>23</td>
<td>9</td>
</tr>
<tr>
<td>10 nm</td>
<td>2°</td>
<td>35</td>
<td>14</td>
</tr>
<tr>
<td>10 nm</td>
<td>1°</td>
<td>71</td>
<td>28</td>
</tr>
<tr>
<td>5 nm</td>
<td>3°</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>5 nm</td>
<td>2°</td>
<td>18</td>
<td>7.2</td>
</tr>
<tr>
<td>5 nm</td>
<td>1°</td>
<td>36</td>
<td>14</td>
</tr>
</tbody>
</table>

Ok for plane and spherical surfaces. Almost impossible for toroidal, elliptical...

\[
\varphi = \frac{2\delta h \cdot \sin \theta}{\lambda}
\]
Active optics project

\[ x^2 \left( \frac{\sin^2 \theta}{b^2} + \frac{1}{a^2} \right) + y^2 \left( \frac{\cos^2 \theta}{b^2} \right) - x \left( \frac{4f \cos \theta}{b^2} \right) - xy \left[ \frac{2 \sin \theta \sqrt{e^2 - \sin^2 \theta}}{b^2} \right] = 0 \]

where: \[ f = \left( \frac{1}{r} + \frac{1}{r'} \right)^{-1} \]

Need for a 3rd order approximation in shape

Two unequal moments applied at the edges
Active optics project

Higher orders corrected by:
Dynamic variation of the moment of Inertia
Correction of low frequency shape errors
Active optics project

Source – M1 ~ 75 m; M2 - exp cham. ~ 0.8 m,
Spot FEL 1: on focus 4X2.5 μm² (~ 3x10¹⁶ W/cm²)
Spot FEL 2: on focus 3.5X2 μm² (~ 7x10¹⁵ W/cm²)

Correction of low frequency shape errors

Obtained without 3rd order compensation
Active optics project

Mirror profile measurement over days with electrode in operation (30V)
Active optics project

Measurement of the local radius of curvature using strain gauges glued on the back of the mirror.
Focusing systems comparison

Spot at focus

<table>
<thead>
<tr>
<th></th>
<th>H Spot FWHM (μm)</th>
<th>V Spot FWHM (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>6.5</td>
<td>7.1</td>
</tr>
</tbody>
</table>

Spot at focus with 1μrad slope errors

<table>
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<th>H Spot FWHM (μm)</th>
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</thead>
<tbody>
<tr>
<td>Good</td>
<td>6.5</td>
<td>12.7</td>
</tr>
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</table>

\[ (\sim 4 \times 10^{15} \text{ W/cm}^2) \]

\[ (\sim 3 \times 10^{16} \text{ W/cm}^2) \]
EIS focusing system

Simplified to have
“just” 4 angles and 3 wavelength

Higher/lower orders contamination < 1%
**EIS focusing system**

- **Delay required:**
  - $-10 \text{ ps} < \Delta t < 5 \text{ ns}$
  - $-3 \text{ mm} < \Delta t < 1.5 \text{ m}$
  - **Precision:** 10 fs (3µm)

---

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<tr>
<th>Theta 3rd H (deg)</th>
<th>Theta 1st H (deg)</th>
<th>FEL @ 60 nm</th>
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<tr>
<td>1.53</td>
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<td>0.017</td>
<td>0.025</td>
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<td>3.05</td>
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**3 m < length < 5 m**

---

**Multilayer delay line**
**EIS focusing system**

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Delay required:
-10 ps < Δt < 5 ns
-3 mm < Δt < 1.5 m
Precision: 10 fs (3µm)
# EIS focusing system

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<td>0.6</td>
</tr>
</tbody>
</table>

Delay required:
-10 ps < Δt < 5 ns
-3 mm < Δt < 1.5 m
Precision: 10 fs (3µm)
EIS focusing system

Higher/lower orders contamination < 1%

Beam splitting mirror 2°

Co/C
100 layers
d=4.6 nm

Reflectivity (-)

Wavelength (nm)

Intensity 20 nm (1st harm)

Ratio eff. 6.33 nm/eff. 20 nm
1 mirror ⇒ 57
2 mirrors ⇒ 3300
4 mirrors ⇒ 10^7

Source:

\[
\frac{\text{Intensity 20 nm (1st harm)}}{\text{Intensity 6.33 nm (3rd harm)}} \geq 100
\]

<table>
<thead>
<tr>
<th>Material</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 nm</td>
<td>Sc/Si</td>
</tr>
<tr>
<td>20 nm</td>
<td>Mo/Si</td>
</tr>
<tr>
<td>13.3 nm</td>
<td>Mo/Si</td>
</tr>
<tr>
<td>6.33 nm</td>
<td>Co/C</td>
</tr>
</tbody>
</table>
Schedule
THANK YOU FOR YOUR ATTENTION