(Non-invasive) diagnostics on FEL photon beams: general remarks and the case of FERMI@Elettra

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Outline

• Introduction
• What users want
• Layout of the transport system: where can we “diagnose”? 
• Diagnostics: Beam Position Monitors
  Intensity Monitors
  Energy Spectrometer
  TOF-based diagnostics
  Wavefront
  Coherence
  Pulse length
• Conclusions
## FEL Radiation Features

Common characteristics: high peak powers, pulsed structure, high coherence...

<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 - 3</td>
</tr>
<tr>
<td>Pulse length FWHM (fs)</td>
<td>30 - 100</td>
<td>&lt;100</td>
</tr>
<tr>
<td>Bandwidth rms (meV)</td>
<td>~20 - 40</td>
<td>~20 - 40</td>
</tr>
<tr>
<td>Polarization</td>
<td>Variable</td>
<td>Variable</td>
</tr>
<tr>
<td>Peak power (GW)</td>
<td>1-5</td>
<td>~1</td>
</tr>
<tr>
<td>Photons per pulse</td>
<td>~2 (10^{14}) (100 nm)</td>
<td>~1 (10^{13}) (10 nm)</td>
</tr>
<tr>
<td>Brightness (\text{Ph/s/mm}^2/\text{mrad}^2/0.1%\text{BW})</td>
<td>(~6 \times 10^{32})</td>
<td>(~10^{32})</td>
</tr>
<tr>
<td>Power fluctuation (%)</td>
<td>~25</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 ((\mu\text{rad}))</td>
<td>&lt; 5</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Source size FWHM ((\mu\text{m}))</td>
<td>290</td>
<td>140</td>
</tr>
<tr>
<td>Divergence rms ((\mu\text{rad}))</td>
<td>50 (40 nm)</td>
<td>15 (10 nm)</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>10 - 50</td>
<td>10 - 50</td>
</tr>
</tbody>
</table>
Perfect knowledge of:

- Intensity
- Photon energy
- Spectral distribution
- Beam (angular) position
- Pulse length
- Focus size
- Wavefront/Coherence

...OF EACH PULSE & DURING THE EXPERIMENT !!!
Where can we put some diagnostics?

Front end

Beamlines
**Target**: collect both FEL paths, diagnose, and redirect to the beamlines
The $I_0$ monitor:

- Works online and shot-to-shot
- Is transparent
- Measures the number of photons of each pulse (~3% precision, 1% reproducibility)

Ref. E. Braidotti (CAENELS-Elettra)
FLASH Gas Monitor Detector


$p \sim 10^{-5}$ mbar
non invasive

\[ N_{\text{particle}} = N_{\text{photon}} \cdot \sigma(h\nu) \cdot z \cdot \eta \cdot n \]

\(-\)

Photon pulse energy

Mean

Individual pulse trains

Uncertainty <7%

Photon beam position

GMD measurements to be done at FERMI@Elettra
within the IRUVX-PP European Project (FP7) - WP3
Beam (angular) position

The BPM:

- Works online and shot-to-shot
- Intercepts 1% of FEL radiation
- Measures the relative position of each pulse (<2 µm rms)
- Determines the angular movement of the beam (<1 µrad)
Energy spectrometer

The ES:

- Works online and shot-to-shot
- Uses ~3% of FEL radiation
- Measures the photon energy ($\Delta E$: sub-meV to few meV)
VLS gratings

Groove density expanded in Taylor series:

\[ D(y) = D_0 + D_1 y + D_2 y^2 + \ldots \]

- \( D< ; \beta> \)
- \( D> ; \beta< \)

\( \alpha = 2.5^\circ \)

Full beam from source

0\text{th}-order to the beamlines

1\text{st} and 2\text{nd} internal orders to the detector (~0.1\%-3\%)

Focal curve \( r'(E), \beta(E) \)

Movable detector YAG + CCD

I. Cudin

\[ \checkmark \]
### Gratings parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>G1</th>
<th>G2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy range m=1 (eV)</td>
<td>12-30</td>
<td>30-120</td>
</tr>
<tr>
<td>Energy range m=2 (eV)</td>
<td>36-90</td>
<td>90-360</td>
</tr>
<tr>
<td>Energy Resolution (meV)</td>
<td>0.2-2.9</td>
<td>0.3-9.5</td>
</tr>
<tr>
<td>D0 (l/mm)</td>
<td>500</td>
<td>1800</td>
</tr>
<tr>
<td>D1 (l/mm²)</td>
<td>0.35</td>
<td>1.26</td>
</tr>
<tr>
<td>D2 (l/mm²)</td>
<td>1.7x10⁻⁴</td>
<td>6.3x10⁻⁴</td>
</tr>
<tr>
<td>Groove profile</td>
<td>Laminar</td>
<td>Laminar</td>
</tr>
<tr>
<td>Groove height (nm)</td>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td>Groove ration (w/d)</td>
<td>0.60</td>
<td>0.65</td>
</tr>
<tr>
<td>Coating Material / Thickness</td>
<td>Graphite / 50 nm</td>
<td>Gold / 50 nm</td>
</tr>
</tbody>
</table>

#### G1 1st order

<table>
<thead>
<tr>
<th>E (eV)</th>
<th>β (deg)</th>
<th>r' (mm)</th>
<th>ΔE sim (meV)</th>
<th>Spot (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>20.4372</td>
<td>2813</td>
<td>0.2</td>
<td>3.71</td>
</tr>
<tr>
<td>16</td>
<td>17.7203</td>
<td>2851</td>
<td>0.3</td>
<td>4.24</td>
</tr>
<tr>
<td>20</td>
<td>15.8767</td>
<td>2880</td>
<td>0.5</td>
<td>4.40</td>
</tr>
<tr>
<td>24</td>
<td>14,5219</td>
<td>2904</td>
<td>0.6</td>
<td>4.92</td>
</tr>
<tr>
<td>28</td>
<td>13,4730</td>
<td>2926</td>
<td>0.8</td>
<td>4.93</td>
</tr>
<tr>
<td>30</td>
<td>13,0303</td>
<td>2937</td>
<td>0.9</td>
<td>4.96</td>
</tr>
</tbody>
</table>

#### G1 2nd order

<table>
<thead>
<tr>
<th>E (eV)</th>
<th>β (deg)</th>
<th>r' (mm)</th>
<th>ΔE sim (meV)</th>
<th>Spot (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>16.7205</td>
<td>2866</td>
<td>0.4</td>
<td>4.45</td>
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<tr>
<td>48</td>
<td>14.5219</td>
<td>2904</td>
<td>0.8</td>
<td>4.95</td>
</tr>
<tr>
<td>60</td>
<td>13.0303</td>
<td>2937</td>
<td>1.1</td>
<td>4.78</td>
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<tr>
<td>72</td>
<td>11.9347</td>
<td>2966</td>
<td>1.4</td>
<td>5.33</td>
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<tr>
<td>84</td>
<td>11.0871</td>
<td>2994</td>
<td>2.2</td>
<td>5.84</td>
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<tr>
<td>90</td>
<td>10.7295</td>
<td>3008</td>
<td>2.4</td>
<td>6.30</td>
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#### G2 1st order

<table>
<thead>
<tr>
<th>E (eV)</th>
<th>β (deg)</th>
<th>r' (mm)</th>
<th>ΔE sim (meV)</th>
<th>Spot (mm)</th>
</tr>
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<tbody>
<tr>
<td>40</td>
<td>19.3944</td>
<td>2827</td>
<td>0.3</td>
<td>3.28</td>
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<tr>
<td>50</td>
<td>17.3668</td>
<td>2856</td>
<td>0.5</td>
<td>3.62</td>
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<tr>
<td>60</td>
<td>15.8767</td>
<td>2880</td>
<td>0.7</td>
<td>3.65</td>
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<tr>
<td>80</td>
<td>13.7959</td>
<td>2919</td>
<td>1.1</td>
<td>3.83</td>
</tr>
<tr>
<td>100</td>
<td>12.3844</td>
<td>2953</td>
<td>1.9</td>
<td>4.18</td>
</tr>
<tr>
<td>120</td>
<td>11.3479</td>
<td>2985</td>
<td>2.0</td>
<td>4.67</td>
</tr>
</tbody>
</table>

#### G2 2nd order

<table>
<thead>
<tr>
<th>E (eV)</th>
<th>β (deg)</th>
<th>r' (mm)</th>
<th>ΔE sim (meV)</th>
<th>Spot (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>18.2948</td>
<td>2842</td>
<td>0.5</td>
<td>3.34</td>
</tr>
<tr>
<td>120</td>
<td>15.8757</td>
<td>2880</td>
<td>0.9</td>
<td>3.31</td>
</tr>
<tr>
<td>150</td>
<td>14.2358</td>
<td>2919</td>
<td>1.6</td>
<td>3.50</td>
</tr>
<tr>
<td>240</td>
<td>11.3479</td>
<td>2985</td>
<td>4.5</td>
<td>4.68</td>
</tr>
<tr>
<td>300</td>
<td>10.2083</td>
<td>3039</td>
<td>7.2</td>
<td>5.18</td>
</tr>
<tr>
<td>360</td>
<td>9.3728</td>
<td>3073</td>
<td>10.6</td>
<td>5.55</td>
</tr>
</tbody>
</table>

C. Svetina
Grating inspection & performances

**G1**

- **LTP** (G.Sostero)
- **White Light Interferometer** (G.Sostero)
- **NC-AFM measurements** (C.Svetina)
  - 
  - $P_y = 23 \AA$
  - Roughness$_{WLI} = 1.2 \AA$
  - 
  - $h = 11.2 \text{ nm}$
  - $d = 0.5 \text{ gr/µm}$

**36 eV**

- G1 ideal spot at 36 eV
  - FWHM = 5.3 µm
- G1 expected spot at 36 eV
  - FWHM = 8.5 µm

**ΔE = 0.6 meV**

**G2**

- **LTP** (G.Sostero)
- **White Light Interferometer** (G.Sostero)
- **NC-AFM measurements** (C.Svetina)
  - 
  - $P_y = 22 \AA$
  - Roughness$_{WLI} = 1.7 \AA$
  - 
  - $h = 5.1 \text{ nm}$
  - $d = 1.8 \text{ gr/µm}$

**120 eV**

- G2 ideal spot at 120 eV
  - FWHM = 6.1 µm
- G2 expected spot at 120 eV
  - FWHM = 7.1 µm

**ΔE = 2.2 meV**

**ΔE = 2.7 meV**
P.N. Juranić, et al., J. Inst. 4 (2009) 09011

Use of noble gases
Detect the partial cross sections
Low flux to work in single-photon photoionization
Upgradable to higher energies

Unique values for each different ionizing energy
Focus size

Approach using a TOF- setup (FLASH)


Use of noble gases
Used pulse: 38 eV, 25 fs (BL2)
Not dependent on beam position
Determination of beam waist and focus size
Based on saturation effect upon photoionization of rare gases
Extendable to higher (HXR) energies
μm-resolution

Sublinear increase
Ne - hv = 38 eV

\[
N_i(N_{ph}) = N(1 - \exp(-\sigma N_{ph}/A))
\]

\[
= n\sigma N_{ph} \left(1 - \frac{1}{2}\left(\frac{N_{ph}}{A}\right) + \frac{1}{6}\left(\frac{N_{ph}}{A}\right)^2\right)
\]
Craters investigated with Nomarski (DIC) optical microscopy and AFM
PMMA sample used (material removal governed by non-thermal processes)
Used pulse: 32 and 21.7 nm, 25 fs, 10 µJ (BL2)
Beam diameter and shape determined (µm-resolution)

No features of thermal damage

<table>
<thead>
<tr>
<th>ablation feature evaluated</th>
<th>type of microscope</th>
<th>ablation threshold ( F_{th} ) [mJ/cm²]</th>
<th>attenuation length ( l_{att} ) [nm]</th>
<th>focal spot diameter ( 2\rho ) [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>crater area</td>
<td>DIC</td>
<td>(2.6±1.2)</td>
<td>---</td>
<td>(23.0±0.5)</td>
</tr>
<tr>
<td>crater depth</td>
<td>AFM</td>
<td>(2.1±1.1)</td>
<td>---</td>
<td>(24.6±0.6)</td>
</tr>
<tr>
<td></td>
<td>AFM</td>
<td>(1.8±1.4)</td>
<td>(5.9±7.5)</td>
<td>---</td>
</tr>
</tbody>
</table>
Wavefront measurements to be done at FERMI@Elettra within the IRUVX-PP European Project (FP7) - WP3
Beam splitting and delay

Wavefront splitting
Grazing incidence mirrors

Delay line
-2.5 ps < Δt < 35 ps without multilayers
Δt up to 1 ns with ML

Required movement travel and step: ~1m and few µm
Coherence


Wavefront splitting
Grazing incidence mirrors
Measurements taken at 23.9 nm
Visibility, temporal and spatial coherence, and presence of multiple pulse structure determined

51.8 eV photon energy
Peak intensities ~ $1.8 \times 10^{14}$ W/cm$^2$
5 µm-spots

Beam splitting and delay introduced.
The two half-beams are focused in an ionizing region seen by a TOF spectrometer and the He$^{2+}$ is detected.
Conclusions

• Photon beam diagnostics already tested on some FELs

• Existing and developing expertise worldwide

• Photon beam parameters shot-to-shot and online: intensity, photon energy, spectral distribution, position, focus size

• Photon beam parameters NOT shot-to-shot and online: pulse length, coherence, …

• **FERMI@Elettra will benefit from collaborations within the EuroFEL-IRUVX-PP project**
Acknowledgments

• **FERMI@Elettra Photon beam transport group:** Daniele Cocco
  Cristian Svetina  Claudio Fava  Simone Gerusina
  Luca Rumiz

• **ELETTRA Mechanical design group:** Ivan Cudin

• **ELETTRA Detectors & Instrumentation Group**
  Dario Giuressi  Rudi Sergo  Enrico Braidotti (CAENELS)

• **FERMI@Elettra Beamlines coordinators:**
  Carlo Callegari  Maya Kiskinova  Claudio Masciovecchio

• **FERMI@Elettra people**

• **IRUVX-PP people**

...AND YOU FOR YOU ATTENTION!