Online Photon Beam Diagnostics for the VUV-FEL at TTF2

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• Required photon beam parameters
• Results from FEL operation at TTF1
• FEL Photon beam diagnostics
Introduction

- Many detectors were chosen based on experience and successful FEL operation at TTF1
- New developments were needed with respect to timing, online beam position and spectrum (“online” = in parallel with experiment)
- Most experiments need online photon diagnostics incl. all beam parameters on a shot to shot basis!!
# Required photon beam parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrum:</td>
<td>spikes ⇒ modes, pulse length wavelength ⇒ electron energy tuning for experimental needs</td>
</tr>
<tr>
<td>Intensity:</td>
<td>SASE optimisation, statistics, saturation, normalisation</td>
</tr>
<tr>
<td>Position &amp; Profile:</td>
<td>stabilisation and focusing</td>
</tr>
<tr>
<td>Timing:</td>
<td>time resolved experiments (&quot;pump-probe&quot;)</td>
</tr>
<tr>
<td>Coherence:</td>
<td>focusing, imaging</td>
</tr>
</tbody>
</table>
Results from FEL operation at TTF1

- FEL pulse energy and shot to shot fluctuations
- Gain curve
- Spectra
- Double slit diffraction patterns / FEL coherence
- Summary of saturation parameters
- Wavelength range
FEL pulse energy / shot to shot fluctuations

Thermopile data ↑

Statistics recorded with MCP →
Gain curve (at 95 nm)

Intensity statistics at \( z = 9 \text{ m} \)

\[
\sigma_E = 0.62 \\
M = 2.6
\]

Steerer magnets in the undulator were used to control the interaction length between \( e^- \) and radiation, i.e., to switch off SASE beyond a certain position in the undulator.
Spectra of single FEL pulses

Short pulse \( (\leq 100\text{fs}) \)

Long pulse \( (200\text{fs}) \)

FEL pulse length variation via bunch compressor settings
Shot to shot spectral fluctuations
Diffraction of 95nm FEL radiation observed by a CCD camera on a Ce:YAG crystal 3m behind the slits (near zone)

Double slit diffraction patterns

parallel slits, each 2mm long, 200µm wide, separation 1mm

crossed slits, 100µm wide, 4mm long
FEL coherence

1. Transverse coherence:

- Double slit separation [mm]
- Transverse coherence

2. Fourier transform of “spiky” spectrum ➔ Longitudinal coherence

- almost(!) full transverse coherence
- limited long. coherence (100% via seeding)
Summary of FEL saturation parameters at TTF1

Wavelength \hspace{1cm} 82-125 \text{ nm}
Pulse energy \hspace{1cm} 30-100 \mu\text{J}
Pulse duration \hspace{1cm} 30-200 \text{ fs}
Peak power \hspace{1cm} 1 \text{ GW}
Average power up to \hspace{1cm} 5 \text{ mW}
Bandwidth (FWHM) \hspace{1cm} 1 \% 
Spot size (FWHM) \hspace{1cm} 250 \mu\text{m}
Angular divergence (FWHM) \hspace{1cm} 260 \mu\text{m}
Peak brilliance \hspace{1cm} \text{up to } 10^{28} \ *
Averaged brilliance \hspace{1cm} \text{up to } 10^{17} \ *

\* = \text{phot./sec/mrad}^2/\text{mm}^2/(0.1\% \text{ BW})
VUV-FEL wavelength range

1\textsuperscript{st} Harmonic

2\textsuperscript{nd} Harmonic

Average of 3100 pulses

\Rightarrow \text{Intensity of 2\textsuperscript{nd} harmonic is about 0.1 \% of the fundamental}

Shortest wavelength ever generated by an FEL !
FEL Photon beam diagnostics

Detector challenges:

• cover full dynamic range: ~ 7 orders of magnitude from spontaneous emission to SASE in saturation

• on-line detectors for single-pulse measurements (response < 100ns)

• low degradation under radiant exposure in the VUV

• ultra-high vacuum compatibility

• assembling under clean room conditions
Detectors

- Ce:YAG and PbWO$_4$ fluorescent crystals
- PtSi photodiodes (calibrated by PTB = German institute of standards)
- YBa$_2$Cu$_3$O$_{7-\delta}$ based thermopiles (= fast bolometer)
- Au wire (50µm diam.) + calibrated MCP (JINR Dubna)
- gas ionisation detector (calibrated by PTB)
- grating monochromator + ICCD (gate down to 5ns)
- fast streak camera (timing)
- autocorrelators / cross-correlators
Detector unit F1

Detectors

PtSi photodiode: $(1 \text{nJ} < E_{\text{pulse}} < 1 \mu J)$

Ce:YAG crystal: $(E_{\text{pulse}} > \text{few \mu J})$

Thermopile: $(E_{\text{pulse}} > \text{few \mu J})$

Double slits in thin foil (diffraction)

Apertures

Pulse energy, beam position + profile, degree of transverse coherence
**MCP Diagnostics Unit**

- Large dynamic range (~7 orders of magnitude)
- Can be scanned to measure beam position and profile
  - Depends on beam position
  - Will not survive long pulse trains
  - The wire produces unwanted diffraction

**O. Brovko, A. Fateev, M. Yurkov et al., JINR Dubna**
Gas ionisation detector

Single photoionisation:

\[ N = N_{ph} \times n \times \sigma \times l \]

- \( N \) = number of electrons or ions
- \( N_{ph} \) = number of photons
- \( n \) = target density
- \( \sigma \) = photoionisation cross section
- \( l \) = length of interaction volume

Online monitor of single-pulse FEL intensity:
- transparent
- wide dynamic range (spont. rad. to saturation)
- independent of beam position
- no saturation effects
- 6 nm (FEL limit) < \( \lambda \) < 93 nm (Xe abs.edge)
- absolute calibration (~10%)

Collaboration with PTB, Berlin, and Ioffe Institute, St. Petersburg
**Single-shot cross correlator**

1-dim. electron detector array

Concept:
measure exact timing online for every pulse and sort the data

funded by FP6 and HGF

M. Drescher, University Bielefeld/Hamburg
Overview: Photon diagnostics at VUV FEL

- Gas ionisation cell (intensity and position)
- VLS Spectrometer (planned)
- Gas absorber (beam attenuation)
- Streak camera (timing)

*S, intensity and position* (TTF1 units + MCP)

* = NOT “online”
Detector Unit F2 (apertures, detectors, mirror)
Intensity + beam profile
+ diffraction (coherence)
+ deflection into spectrometer

Detector Unit F1 (apertures + detectors)
Intensity + beam profile
+ double slits (coherence)

Grazing incidence grating spectrometer with intensified CCD
Single shot spectrum

“Octopus” (MCPs + photodiodes)
Intensity + beam profile

FEL

Beamline for synchrotron radiation from dipole magnet pulse “arrival time”
(evaluated with streak camera in exp. hall)
alignment laser | "Octopus" | detectors | apertures

FEL dipole radiation
Intensified CCD (minimum gate 5ns)

Spectrometer (grating + premirror)
collaboration with / on loan from INFM Padova

piezo actuated entrance slit
Diagnostics in the Experimental Hall

- Dipole radiation beamline
- EU coll. + Padua
- VLS Grating Spectrometer (planned)
- Coll. with SAS and SRS
- Intensity and position monitor (gas ionization)
- Coll. with PTB, Ioffe Inst.
- Optical laser
- MBI and EU coll.
- Streak Camera
- High resol. PGM monochromator
- Uni HH (BMBF)
- Gas absorber
- ~42m to undulator
## Availability of VUV FEL diagnostics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Detector(s)</th>
<th>Online diagn.</th>
<th>available</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity &amp; Profile</td>
<td>thermopiles, PtSi photodiodes, MCPs</td>
<td>no</td>
<td>now</td>
</tr>
<tr>
<td></td>
<td></td>
<td>no limited</td>
<td></td>
</tr>
<tr>
<td>Intensity &amp; Position</td>
<td>Gas Ionisation Detector</td>
<td>YES</td>
<td>April 2005</td>
</tr>
<tr>
<td>Spectrum</td>
<td>Grazing incidence spectrometer (tunnel)</td>
<td>no</td>
<td>now</td>
</tr>
<tr>
<td>Spectrum</td>
<td>VLS Grating Spectrom.</td>
<td>YES</td>
<td>mid/end 2006</td>
</tr>
<tr>
<td>Timing</td>
<td>Streak camera</td>
<td>YES</td>
<td>April 2005</td>
</tr>
<tr>
<td>Timing</td>
<td>Auto-/Cross-Correlators</td>
<td>YES</td>
<td>? (experimental stage)</td>
</tr>
</tbody>
</table>
Higher Harmonics & Spontaneous Radiation

1. **SASE (FEL) higher harmonics:**

   - 2\textsuperscript{nd} and 3\textsuperscript{rd} harmonic at 1\% to 1 per thousand level (see before)
   - higher (if needed) with special radiators (future!!)
2. Spontaneous undulator radiation:

![Graph showing spontaneous undulator radiation](image)

- Blue line: 200 µrad aperture
- Red line: 500 µrad aperture

Photon counts (s * 0.1% bw) vs. Energy [eV]

Energy levels: 1, 2, 3, 4, ..., harmonic
Spontaneous undulator radiation power in circular aperture
(assuming 1nC bunch charge, 1ps duration / bunch length, 1st harm. @ 30 nm)

a) 200µrad in 50m distance (typical detector size):
   \[ 6 \times 10^3 \text{ W} \rightarrow 6 \text{nJ} \]

b) 500µrad in 50m distance (typical beamline acceptance):
   \[ 3.6 \times 10^4 \text{ W} \rightarrow 36 \text{ nJ} \]

c) No aperture (fully integrated flux):
   \[ 7 \times 10^5 \text{ W} \rightarrow 700 \text{ nJ} \]

FEL in saturation:
3GW for 30fs \(\rightarrow\) 100 µJ

\(\rightarrow\) even without energy discrimination 3-4 orders of magnitude higher
PtSi photodiodes

- radiation hard
- good for low intensity:
  spontaneous emission to ~1 µJ pulse energy (depending on wavelength)
+ calibrated by PTB
- sensitive to higher harmonics
- cannot be used for high intensities (saturates)
**Thermopile detector**

- Good for high intensity: ~10 \( \mu \)J to saturation
- Independent of wavelength
- Cannot be used for long pulse trains
- Laser ablation at high power density

\[ U = \Delta S \cdot \Delta T \cdot \omega \cdot w/d \approx 0.5 \text{ V/K} \]

\[ \Delta S = -10 \mu \text{V/K} \]

Sensitivity for pulses: \( \sim 1 \text{ mV/\mu J} \)

Response time: \( \sim 10 \text{ ns} \)

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S. Zeuner et al.,
Double slit diffraction patterns

setup for FEL diagnostics at TTF1