Options for time-resolved experiments at diffraction limited storage ring light sources

S. Di Mitri

ELETTRA SINCROTRONE TRIESTE
How short, and how intense x-ray pulses can be at DLSRs?

Overview of pulse durations, trend, users wish list

Short pulse schemes

- implementation aspects
- (in)compatibility with DLSR

Conclusions

Low-\(\alpha\)

- RF focusing (BESSY-VSR)
- Transverse deflecting cavities
- Magnetic compression
- Laser/electron slicing
Examples of accelerator-based X-ray sources:
- 0.1 – 10 keV photon energy
- # of phs. at the source
- FEL in short pulse mode

Can a DLSR target
~ sub-ps,
> 10 kHz,
> $10^8$ ph/s/0.1%bw or
$10^6$ ph/pulse?

Lattice-invasive?
Standard user operation?
### Wish list from TREES workshop

**Opportunities for Time-REsolved Experiments at Synchrotron light source facilities, Trieste, December 2018**

<table>
<thead>
<tr>
<th>Science Case</th>
<th>$E_{ph}$ [keV]</th>
<th>$\Delta t_{FWHM}$ [ps]</th>
<th>Pump Laser Rep. Rate [kHz]</th>
<th>Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMO</td>
<td>0.005</td>
<td>1–5</td>
<td>10 - 100</td>
<td>PES, PECD, XAS, XES, Coincidences</td>
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<tr>
<td>Chemistry</td>
<td>0.3 - 10</td>
<td>1–5</td>
<td>1 - 1000</td>
<td>XAS, XES, PES, RIXS, XRD, CD</td>
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<tr>
<td>Biology</td>
<td>0.3 - 10</td>
<td>1–5</td>
<td>1 - 1000</td>
<td>XRD, CD, XAS, XES, RIXS</td>
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<tr>
<td>Magnetism</td>
<td>0.3 - 1</td>
<td>1–5</td>
<td>1 - 1000</td>
<td>PEEM, PCS, XAS, RIXS, XMCD</td>
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<tr>
<td>Strongly Correlated Materials</td>
<td>0.3 - 10</td>
<td>1–5</td>
<td>1 - 1000</td>
<td>XAS, RIXS, XMCD, REXS</td>
</tr>
<tr>
<td>Materials science</td>
<td>0.1 - 10</td>
<td>1–3</td>
<td>1 - 1000</td>
<td>XAS, PES,</td>
</tr>
</tbody>
</table>

**Tuneable, up to 10 keV**

**$\sigma_t < 2$ ps (RMS)**

**$< 1$ MHz**

**Single bunch-turn**

**NO “camshaft” bunch**

**NO coherent harmonic generation (seeding, EEHG, etc.)**
**Natural e-bunch duration (2nd and 3rd generation SR)**

- SOR-Ring
- ALADDIN
- NSLS X-Ray Ring
- NSLS VUV Ring
- UV/SOR 1
- ACO
- SPEAR 2
- MAX-LAB
- MAX-II
- DORIS
- Diamond
- SCEL
- Spring-8
- SLS
- ALS

**What trend in 4th generation (DLSR)?**

- $\tau_{\text{bunch}}$ (incl. IBS)
- $\tau_{\text{bunch}}$ (no IBS)
- $\varepsilon_X$ (incl. IBS)
- $\varepsilon_X$ (no IBS)

**Shortening the e-bunches is in conflict with the diffraction limit**

S.C. Leemann PRSTAB (2014)
Low-\(\alpha\) optics

\[ \sigma_{t,R} \approx \sigma_{t,e} \propto \frac{\alpha_c}{\sqrt{V_{RF} f_{RF}}} \]

optics tuning

high RF gradient

DLSRs have natural low \(\alpha_c\)

Short pulses available at all beamlines

Control of higher order-\(\alpha_c\) with multipoles might allow the storage of short and long bunches. Not robust enough, yet.
**Low-\(\alpha\) optics**

\[
\sigma_{t,R} \approx \sigma_{t,e} \propto c \frac{\alpha_c}{V_{RF} f_{RF}}
\]

- optics tuning
- high RF gradient

**Elettra 2.0:** \(\alpha_c \approx 10^{-4}\)

\[
\sigma_{t,R} \approx 4 - 6 \text{ ps, } I_{\text{bunch}} < 25 \mu\text{A}, \text{ below microwave threshold instability}
\]

- RF peak voltage \(> 2 \text{ MV } @ 500 \text{ MHz}\)
- Low flux
  - Machine is dark for other users

**Higher RF voltage shortens the bucket further**

\(V_{RF} = 1.5 \text{ MV}\)

\(V_{RF} = 2.2 \text{ MV}\)

*I. Martin et al., PRSTAB 2011*
RF focusing (BESSY-VSR)

\[ V_{\text{rf}}(t = 0) = 2\pi \left( f_{\text{nc}} V_{\text{nc}} + f_{\text{sc,1}} V_{\text{sc,1}} + f_{\text{sc,2}} V_{\text{sc,2}} \right) \]

Short & long bunches stored simultaneously
\[ \sigma_t \approx 0.5 - 3 \text{ ps}, \quad I_{\text{short}} \approx 5 - 50 \text{ mA} \]

At least 1 straight section dedicated to superconducting harmonic cavities
Short bunches from Booster ring (< 35 ps fwhm)

\[ \perp \text{ and } // \text{ instabilities (HOMs)} \]

Low injection efficiency
Crab cavities: “tilt-and-cancel”

\[ \sigma_{t,R} \propto \left( \frac{E}{k_{cc} v_{cc}} \right) \frac{\sigma_{y,1D}}{\sigma_{y,cc}} \sqrt{\sigma_{y'}^2 + \sigma_{r'}^2} \ll \sigma_{t,e} \]

- Electrons y’–z correlation translates into radiation y–z correlation at the slit
  \[ \sigma_{t,R} \approx 1 – \text{few ps, } I_{\text{short}} < 20 \text{ mA} \]

- Two long straight sections occupied
  Optics constraints (large \( \beta_y \), \( \pi \)-phase adv.)
  ⊥ and // instabilities (HOMs)
  Low injection efficiency

Scaled down to 2.4 GeV \( \rightarrow \) approximately ~9 m length required
Crab cavities: “frequency beating”

\[ \sigma_{t,R} \propto \left( \frac{E}{k_{cc} V_{cc}} \right) \frac{\sigma_{y,1D}}{\sigma_{y,cc}} \sqrt{\sigma_{y'}^2 + \sigma_{r'}^2} \ll \sigma_{t,e} \]

\[ E \leq 0.5 \text{ GHz, } 1.5 \text{ MV} \]
\[ \text{SCRF, } 1.75 \text{ GHz, } 0.5 \text{ MV} \]

Elettra 2.0: \( \sigma_{t,R} \approx 1.5 \text{ – } 10 \text{ ps, } I_{\text{short}} \approx 8 \text{ mA} \)
Both short and long pulses stored
Electron optics constraints are relaxed

< 5% of nominal total average flux
RF cavities in one straight section

\( \perp \) and // instabilities (HOMs)
Low injection efficiency
\[ \sigma_{t,R} \approx \sigma_{t,e} \propto \left( \frac{E}{k_{RF} V_{RF}} \right) R_{56} \sigma_{\delta,0} \]

\[ \sigma_{t,R} \approx 0.7 - 2 \, \text{ps}, \]

Short and long bunches at full peak flux at all beamlines

Transparent to DLSR optics

Swap-out injection/extraction

SC injector, MHz stripline kickers for high repetition rate

New ring-to-booster transfer line


S. Di Mitri, JSR 2018
Angular separation (~1 mrad) of sliced electrons

Angular separation of the short radiation pulse

- Angular separation implies modification to a SR lattice
- DL e-beam emittance improves slicing efficiency

Table 1: Overview of the parameters of the BESSY II Femtoslicing source.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray photon energy</td>
<td>400-1400 eV</td>
</tr>
<tr>
<td>(linear and elliptical polarization)</td>
<td></td>
</tr>
<tr>
<td>Repetition rate</td>
<td>6 kHz</td>
</tr>
<tr>
<td>X-ray pulse length</td>
<td>100 fs</td>
</tr>
<tr>
<td>Photons on sample</td>
<td>~ 10^5 ph / s / 0.1% BW</td>
</tr>
<tr>
<td>Intrinsic X-ray / laser synchronization</td>
<td>&lt; 20 fs short term jitter</td>
</tr>
<tr>
<td></td>
<td>&lt; 200 fs day-to-day</td>
</tr>
</tbody>
</table>

Elettra 2.0: consider pure spatial / spectral separation of radiation

Simone.Dimitri@elettra.eu
Pure spatial separation

**WIGGLER**
- **Yb LASER**
  - 1 – 20 kHz
  - 3 – 5 mJ

**UNDULATOR**
- 1.2 m
- 1 – 20 kHz
- 0.3 – 0.7 ps

Electrons from long bunch from slice

1:1 imaging (15 m) slit

Flux Density [ph/s/mm²/0.1%bw]

from long bunch

from slice

simone.dimitri@elettra.eu
Aberration, scattering, mono

Aberrations: slope error ≤ 1 μrad

Scattering: roughness ≤ 0.5 Å

Transverse Gradient Undulator

\[ \Delta \omega / \omega = 8\% \]

SNR at the detector = \( \frac{\text{slicing efficiency}}{\text{background level}} = \frac{10^{-7}}{10^{-10}} = 10^3 \)

Additional improvements by: ns-detector gating, TGU
**Pros and cons**

😊 **Low-emittance beam increases the SNR**

$$SNR \propto \sigma_{E,mod} \propto \frac{1}{\sqrt{\sigma_e^2(x,y) + \sigma_L^2}}$$

😊 **Coherent THz emission for laser-electrons synchronization**

🔥 **Short slice survives for 1 turn only**

- **High rep. rate** laser on consecutive bunches
- **Background** issues suggest < 10-20 kHz
State-of-the-art

- $\langle P_L \rangle \approx 50 \text{ W} @ 10 \text{ kHz}$
- $\sigma_{\tau,R} \approx 0.2 \text{ ps}$
- $10^8 \text{ ph/sec/0.1\%bw} = 10^5 \text{ ph/pulse} @ 3 \text{ keV, at the source}$
Electron-slicing

\[ \Delta \theta_y \propto \frac{Q_2}{\sigma_{y,2} E_1} \]

\[ \Delta t_{\text{slic}} \propto \frac{\Delta t_2}{\sin \varphi_{1,2}} \]

Short & long bunches stored simultaneously
\[ \sigma_t \approx 0.01 - 0.1 \text{ ps}, \quad I_{\text{short}} \approx 0.1 - 1 \text{ mA} \]
Slicing efficiency can be higher than in laser-slicing

Background radiation limits the SNR to \(~10\)
Requires MHz e-Gun + Linac + Magnetic Compressor

Efficiency of emission w.r.t. multi-bunch average flux, @ ≤ 1 MHz

Max. Photon Pulse RR:
- 100 – 500 MHz
- 1 – 100 MHz
- 10 – 100 kHz
- 1 – 10 kHz

Somehow compatible with standard user mode

Region of interest for soft x-rays

Slicing

RF Focusing

By-Pass

Crab Cavities

Low-α

σ_{t,R} (RMS) [ps]

0.01 0.5 1.0 5.0 10
Conclusions

- All options offer short pulses at multiple beamlines
- Laser-slicing and crab cavities require dedicated beamline optics set up
- Laser-slicing, crab cavities and RF focusing require one straight section to install new hw
- By-pass is invasive on the infrastructure (injector, kickers, transfer line)

- Not considered here:
  - Direct injection from the FERMI linac (CSR, synchrotron oscillations, availability)
  - Photon pulse manipulation, e.g., fs NIR switches and CPC
Acknowledgments

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Thank you for Your attention

Questions are very welcome!
Diffraction limited radiation (both x and y plane) is guaranteed up to ~keV photon energy.

Bunches shall be elongated up to ~30 ps rms for acceptable lifetime.
## Comparison

<table>
<thead>
<tr>
<th></th>
<th>BESSY II <em>(JSR 2014)</em></th>
<th>Elettra 2.0 <em>(JSR 2019)</em></th>
<th>Elettra <em>(Hybrid)</em></th>
</tr>
</thead>
<tbody>
<tr>
<td><em>&lt;I_b&gt;, E_b</em></td>
<td>5 mA, 1.7 GeV</td>
<td>6 mA, 2 GeV</td>
<td>4 mA, 2 GeV</td>
</tr>
<tr>
<td><em>&lt;P_L&gt; @ RR</em></td>
<td>10 W @ 6 kHz</td>
<td>30 W @ 10 kHz</td>
<td>400 – 1000 kHz</td>
</tr>
<tr>
<td><em>σ_t,ph</em></td>
<td>0.04 ps</td>
<td>0.2 ps</td>
<td>24 ps</td>
</tr>
<tr>
<td>Slicing Efficiency</td>
<td>1e-8</td>
<td>1e-7</td>
<td></td>
</tr>
<tr>
<td>Photon Energy</td>
<td>0.2 – 1.4 keV</td>
<td>1 keV (h=3)</td>
<td>0.1 – 1.7 keV</td>
</tr>
<tr>
<td>Flux @ Source</td>
<td>10^7 ph/sec/0.1%bw #</td>
<td>10^8 ph/sec/0.1%bw</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10^4 ph/pulse #</td>
<td>10^5 ph/pulse</td>
<td></td>
</tr>
<tr>
<td>Flux @ Sample</td>
<td>10^5 – 10^6 ph/sec/0.1%bw #</td>
<td>10^6 – 10^7 ph/sec/0.1%bw</td>
<td>~10^11 ph/sec/0.1%bw *</td>
</tr>
<tr>
<td></td>
<td>10^2 – 10^3 ph/pulse #</td>
<td>10^3 – 10^4 ph/pulse</td>
<td>10^6 ph/pulse</td>
</tr>
</tbody>
</table>

*K. Holldack, JSR (2014) 21*

* courtesy of S. Lizzit