Operating Synchrotron Light Sources with a High Gain FEL

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Re-elaborating S. Di Mitri and M. Cornacchia, NJP 17, 113006 (2015)
Idea and Challenges

**Idea:**

- Upgrade an existing storage ring to drive a high gain FEL (i.e., mirrorless)
- \( \lambda \approx \text{EUV and soft X-rays} \)
- \( \langle P_{\text{FEL}} \rangle \geq 1 \text{ W} \)

**Challenges:**

- **Compatibility with multi-bunch IDs operation**
- High e-beam brightness required by FEL
- SR+FEL equilibrium state
- CSR- and MBC-instability

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Non-Equilibrium t-Compression


Compress the bunch duration in half turn:

\[
h = \frac{1}{E_0} \frac{dE}{dz}
\]

“Energy chirp”

\[
C_0 = \frac{\sigma_{z,i}}{\sigma_{z,f}} = \frac{1}{1 + hR_{56}}
\]

“Compression factor”

Beam goes back to equilibrium state.

\[
E = 1 \text{ GeV} \\
Q_b = 0.7 \text{ nC} \\
\sigma_{z,0} = 9 \text{ ps} \\
C_0 = 13
\]
Storage Ring and RF Parameters

- Keep the Elettra DBA-lattice as it is, and lower the beam energy to match $4\pi \varepsilon_x \approx \lambda = 25 \text{ nm}$.

\[ \lambda \propto \frac{1 + K^2}{E^2} \quad \varepsilon_x \propto \frac{E^2}{N_b^3} \]

\[ \sigma_{\delta,\text{cor}} \approx \left(1 - \frac{1}{C}\right) \sigma_{\varepsilon,0} \approx \frac{2\pi \sigma_{\varepsilon,0}}{N_b} \frac{e\hat{V}_{RF}}{\lambda_{RF}} \frac{E_0}{E} \]

- MBA-cells provide low-$\varepsilon_x$ above 2 GeV
  - $R_{56} < 0.1 \text{ m} \quad (\alpha_p < 10^{-3})$
  - Momentum acceptance $> 2\%$
  - $V_{RF} > 50 \text{ MV (S-band)}$

$\sigma_{\delta,\text{cor}} = 1.3\%$, $V_{RF} = 78 \text{ MV}$!!
RF Linacs in a Ring ??

- **SC** HOMs-damped multi-cell cavities might provide $E_z \sim 20$ MV/m, but they stay on for milliseconds...
- **NC** (pulsed) cavities not available (yet) with HOMs damping at $<I> \sim 300$ mA.

- In small rings, RF cavities should be installed in by-pass lines.
  - **Strip-line kickers**: rep. rate 0.1-1 MHz, < 5 ns rise/fall time, < 100 ns flat top, ~1% stability
  - **RF transverse deflectors**
    - [T.Naito et al., NIMA 571 (2009)]
    - [M.Placidi et al., NIMA 768 (2014)]

- For rings larger than $C \sim 500$ m, arc compressors and RF linacs can be internal to the main ring.
- **Swap out injection**
Microwave Instability

- The higher the peak current, the higher the uncorrelated energy spread ⇒ MWI is “naturally” suppressed by a factor $C^2$.

\[
I_{th,0} \approx I_A \left( \frac{\pi R}{\lambda} \right)^{2/3} \gamma \alpha \sigma^2_{\delta,0}
\]

Beam in SR

Compression $\sigma_{\delta,FEL} \propto \hat{I}_{b,FEL} = C_0 \hat{I}_{b,0}$

Beam at FEL

\[
I_{th,FEL} = C_0^2 I_{th,0} \approx 100 I_{th,0}
\]

$I_{th,0}$ in Elettra @ 1 GeV is > 0.3 mA/bunch.

⇒ $I_{th,FEL} \approx 30$ mA/bunch

[E. Karantzoulis et al., IP&T 53, 2010.]
Storage Ring Lattice (DBA)
- At least 3 families of sextupoles, for linear compression, $\varepsilon_x$-control and large DA.
  [S. Di Mitri, M. Cornacchia, EPL 109, 62002 (2015)]
  [S. Di Mitri, NIM A 806 (2016)]

Arcs to/from By-Pass
- Isochronous achromatic lattice.
- CSR-$\varepsilon_x$ growth is suppressed through optics “balance”.
  [D. Douglas et al., JLAB-ACP-14-1751 (2014)]
  [S. Di Mitri et al., PRL 110, 014801 (2013)]
After lasing once every longitudinal damping time \( T_{\text{FEL}} \geq \tau_E \approx 10 \text{ ms} \), the beam “thermalizes” to standard SR-equilibrium state.

\[
\lambda_u = 3 \text{ cm}, \ K = 3, \ \alpha_{\text{TGU}} = 70 \text{ m}^{-1}, \ L_u = 55 \text{ m}
\]

\[
\rho_{\text{TGU}} = \rho_{1D} \left[ 1 + \left( \frac{\eta_y \sigma_{\delta,\text{FEL}}}{\sigma_{\beta,y}} \right)^2 \right]^{1/6}
\]

[P. Baxevanis et al., PRSTAB 7, 020701 (2014)]

\[<P_{\text{FEL}} > \approx 100 \text{ MW} \times 1 \text{ ps} \times 50 \text{ Hz} \times 400 \text{ bs.} \approx 2 \text{ W, } \sim 10^{13} \text{ ph/pulse @ 25 nm} \]
SR + SASE FEL, at Equilibrium

- Lasing ~ every turn \( (T_{\text{FEL}} \ll \tau_E) \) imposes new equilibrium parameters, set by synchrotron radiation damping and FEL excitation.

\[
\frac{d\sigma^2_\delta(t)}{dt} = 2\left(\sigma^2_{\delta,0} - \sigma^2_\delta(t)\right) + \frac{1}{\tau_E} \frac{\Delta\sigma^2_{\delta,FEL}(t)}{C_0 T_{\text{FEL}}}
\]

- Beam energy spread at equilibrium without FEL
- Beam energy spread increases a little at every lasing

**De-compression after lasing minimizes the FEL perturbation.** After every FEL loop:

\[
\sigma_{\delta,i+1} = \sqrt{\sigma^2_{\delta,i} + \Delta\sigma^2_{\delta,FEL}/C_0^2}
\]

1. **Numerical solution** for \( \sigma_\delta(t \to \infty) \), with \( \Delta\sigma_{\delta,FEL} \) as a function of the undulator length [Z. Huang et al., NIM A 593 (2008)].

2. Approximate closed-form for \( \sigma_\delta(t \to \infty) \), with \( \Delta\sigma_{\delta,FEL} \) at saturation.

3. **Tracking** of the Beam-Matrix turn-by-turn, for arbitrary undulator length.
The undulator length can be chosen to tune the FEL power vs. the beam energy spread at equilibrium. The FEL can be far from saturation.

Curves are per bunch, per pulse

Energy Spread in the SR

Peak Current at the TGU (normalized to 450 A)

FEL Peak Power

\[ E = 1 \text{ GeV} \]
\[ \lambda = 25 \text{ nm} \]
\[ Q_b = 0.75 \text{ nC} \]
\[ \sigma_{z,0} = 12 \text{ ps} \]
\[ C_0 = 20 \]
\[ \lambda_u = 30 \text{ mm} \]

\(<P_{\text{FEL}}> \approx 1 \text{ MW} \times 1 \text{ ps} \times 0.5 \text{ MHz} \times 400 \text{ bs.} \approx 200 \text{ W, } \sim 10^{11}\text{ph/pulse @25 nm}\)
Tracking the Beam Matrix

- **Beam Matrix** through SR+FEL loop: \( \Sigma_{i+1} = M \Sigma_i M^t \), where \([M]\) describes: bunch length compression \( \rightarrow \) RF focusing \( \rightarrow \) SR damping & anti-damping \( \rightarrow \) SASE FEL \( \rightarrow \) de-compression

![Graphs](image)

- **Beam transverse emittance degrades** due to emission of photons in the dispersive line of the TGU:

\[
\varepsilon_{y,i}^2 \approx \varepsilon_{y,i-1}^2 \left[ 1 + \frac{(\eta_y \sigma_{\delta,FEL})^2}{\varepsilon_{y,i-1} \beta_y} \right]
\]

Efficient lasing below 10 nm looks like really challenging

\[E = 1 \text{ GeV} \]
\[\lambda = 25 \text{ nm} \]
\[Q_b = 0.75 \text{ nC} \]
\[\sigma_{z,0} = 12 \text{ ps} \]
\[C_0 = 20 \]
\[\lambda_u = 55 \text{ mm} \]
Conclusions

- **No physical show-stoppers** to SR-HG SASE-FEL in EUV
  - Expected $P_{\text{FEL}} \sim 1-100 \text{ W}$ depending on the rep. rate of the extraction system (0.05 - 100 kHz).

- **Upgrading existing 3-GeV SRs** requires:
  - 30 - 150 m long TGU
  - 20 - 100 MV RF cavities
  - by-pass lines to host RF cavities / internal arc compressors
  - fast kickers / swap-out inj.-extr. system

- **Emittance growth in the TGU** is main obstacle to efficient lasing below $\sim 10 \text{ nm}$

- Detailed feasibility study is on-going...
Acknowledgments

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Thank You for Your attention
Comparison of SR-FEL Studies

- **Low repetition rate HG-FEL** (lasing every $\tau_E$ or so)

<table>
<thead>
<tr>
<th></th>
<th>$\lambda$ [nm]</th>
<th>#photons/pulse</th>
<th>$P_{pk}$/pulse [MW]</th>
<th>$&lt;P_{tot}&gt;$ [W]</th>
<th>Compatible with ID-Beamlines?</th>
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<tr>
<td>LBNL (1984)</td>
<td>40</td>
<td>$\sim10^{15}$</td>
<td>100</td>
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<tr>
<td>PEP (1998)</td>
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<td>$\sim10^{14}$</td>
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<td>0.03</td>
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<tr>
<td>PEPX (2013)</td>
<td>1.5</td>
<td>$\sim10^{12}$</td>
<td>200</td>
<td>2</td>
<td>NO</td>
</tr>
<tr>
<td>ELETTRA (2015)</td>
<td>25</td>
<td>$\sim10^{13}$</td>
<td>100</td>
<td>2 (400 bs)</td>
<td>YES</td>
</tr>
</tbody>
</table>

**FERMI FEL1**

<table>
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<tr>
<th></th>
<th>$\lambda$ [nm]</th>
<th>#photons/pulse</th>
<th>$P_{pk}$/pulse [MW]</th>
<th>$&lt;P_{tot}&gt;$ [W]</th>
<th>Compatible with ID-Beamlines?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25</td>
<td>$\sim10^{13}$</td>
<td>1000</td>
<td>0.005</td>
<td>Warm Linac</td>
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- **High repetition rate HG-FEL** (lasing every turn or so)

<table>
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<tr>
<th></th>
<th>$\lambda$ [nm]</th>
<th>#photons/pulse</th>
<th>$P_{pk}$/pulse [MW]</th>
<th>$&lt;P_{tot}&gt;$ [W]</th>
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<tr>
<td>PEPX (2008)</td>
<td>3.3</td>
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<td>$\sim10^{11}$</td>
<td>1</td>
<td>200 (400 bs)</td>
<td>YES</td>
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</tbody>
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